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Office of Environmental Management

Technology Development

ROBOTICS TECHNOLOGY CROSSCUTTING PROGRAM

Technology Summary

June 1995

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June 1995

MASTER

ROBOTICS TECHNOLOGY CROSSCUTTING PROGRAM

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INTRODUCTION

THE NEW APPROACH

PURPOSE

Although positive steps have been taken during the past three decades to remedy the world's environmental problems, the nation's ability to respond to many current and future environmental and economic challenges depends on technological advances produced by a well-organized and productive federal research and development program.

To ensure that such programs focus on the most pressing environmental restoration and waste management problems at the U.S. Department of Energy (DOE), the Assistant Secretary for the Office of Environmental Management (EM) established a Working Group in August 1993 to implement a new approach to environmental research and technology development. The goal of DOE's new approach is to conduct a research and technology development program that will overcome major obstacles in the cleanup of DOE sites. Integral to this new, solutions-oriented approach is an up-front awareness of program needs obtained from customers, users, regulators, and stakeholders. These needs can then be disseminated to the developers of technological solutions.

The key features of the new approach are:

- establishing five focus areas to address DOE's most pressing problems;
- teaming with the customers in EM to identify, develop, and implement needed technology;
- focusing technology development activities on major environmental management problems;
- coordinating management of scientific and development activities in support of EM;
- focusing resources in national laboratories more effectively;
- involving industry in developing and implementing solutions, including technology transfer into DOE and from DOE to the private sector;
- coordinating basic research by involving academia and other research organizations to stimulate technological breakthroughs; and
- enhancing involvement of regulators and stakeholders in implementation of technology develop ment.

DOE has established a framework and strategy for coordinating efforts among DOE organizations, Management and Operations (M&O) contractors, the national laboratories, other government agencies, the scientific community, industry, academia, and the affected public. Full implementation of the new approach is planned for the FY 95/96 timeframe. The new strategy will build upon existing programs and will seek continual improvement of all EM operations and processes.

Prior to implementation of the new approach, EM's Office of Technology Development (OTD) carried out an aggressive national program of applied research and development to meet environmental restoration and waste management needs based on the concepts of Integrated Programs (IP) and Integrated Demonstrations (ID). These concepts, introduced in 1989, were engineered to manage the research, development, demonstration, testing and evaluation (RDDT&E) activities within EM.

An IP was the cost-effective mechanism which assembled a group of related and synergistic technologies to evaluate their performance to solve a specific aspect of a waste management or environmental problem. The problem could be unique to a site or common to many sites. An IP supported applied research to develop innovative technologies in key application areas organized around specific activities required in each stage of the remediation process (e.g., characterization, treatment, and disposal).

An ID was the cost-effective mechanism that assembled a group of related and synergistic technologies to evaluate their performance individually or as a complete system to correct waste management and environmental problems from cradle to grave.

BENEFITS

A keystone for implementation of the new approach is to encourage development of technologies that are better, faster, safer and more cost-effective than those currently available. More importantly, the new approach has been adopted to foster implementation of new and innovative environmental technologies, facilitating the national commitment to long-term environmental, energy, and economic goals.

An important benefit to the new approach is the creation of investment returns for developing new technologies + technology dividends. These technology dividends result from partnerships and leveraging within government and between government and the private sector. The partnerships can consist of technology developers, technology users, problem holders, and problem solvers.

EM technology dividends will include:

- Employment opportunities with new businesses and existing businesses;
- Cleanup of sites posing the greatest threats to human health, safety, and the environment;
- Materials reused and recycled, instead of thrown away or freshly contaminated;
- Pollution prevented;
- More effective and efficient industrial processes, leading to greater U.S. competitiveness globally; and
- Technology transfer to other countries.

By implementing the new approach for the unique environmental problems associated with DOE sites, EM/OTD, scientists, and engineers at the national laboratories stand at the threshold of opportunity to develop new technologies. This work will enhance quality of life through a cleaner environment, improved global competitiveness, and ensure job opportunities for American workers.

FOCUS AREAS

Five major remediation and waste management problem areas within the DOE Complex have been targeted for action on the basis of risk, prevalence, or need for technology development to meet environmental requirements and regulations. Other areas may be added or currently identified areas further partitioned to ensure that research and technology development programs remain focused on EM's most pressing remediation and waste management needs. These major problem areas, termed "Focus Areas," are described below.

Contaminant Plume Containment and Remediation. Uncontained hazardous and radioactive contaminants in soil and ground water exist throughout the DOE Complex. There is insufficient information at most sites on the contaminants' distribution and concentration. The migration of some contaminants threatens water resources and, in some cases, has already had an adverse impact on the off-site environment. Many current characterization, containment, and treatment technologies are ineffective or too costly. Improvements are needed in characterization and data interpretation methods, containment systems, and in situ treatment.

Mixed Waste Characterization, Treatment, and Disposal. DOE faces major technical challenges in the management of low-level radioactive mixed waste. Several conflicting regulations, together with a lack of definitive mixed waste treatment standards hamper mixed waste treatment and disposal. Disposal capacity for mixed waste is also expensive and severely limited. DOE now spends millions of dollars annually to store mixed waste because of the lack of accepted treatment technology and disposal capacity. In addition, currently available waste management practices require extensive, and hence costly waste characterization before disposal. Therefore, DOE must pursue technology that leads to better and less expensive characterization, retrieval, handling, treatment, and disposal of mixed waste.

High-Level Waste Tank Remediation. Across the DOE Complex, hundreds of large storage tanks contain hundreds of thousands of cubic meters of high-level mixed waste. Primary areas of concern are deteriorating tank structures and consequent leakage of their contents. Research and technology development activities must focus on the development of safe, reliable, cost-effective methods for characterization, retrieval, treatment, and final disposal of the wastes.

Landfill Stabilization. Numerous DOE landfills pose significant remediation challenges. Some existing landfills have contaminants that are migrating, thus requiring interim containment prior to final remediation. Materials buried in retrievable storage pose another problem. Retrieval systems must be developed to reduce worker exposure and secondary waste quantities. Another high-priority need is in situ methods for containment and treatment.

Decontamination and Decommissioning. The aging of DOE's weapons facilities, along with the reduction in nuclear weapons production, has resulted in a need to transition, decommission, deactivate, and dispose of numerous facilities contaminated with radionuclides and hazardous materials. While building and scrap materials at the sites are a potential resource, with a significant economic value, current regulations lack clear release standards. This indirectly discourages the recovery, recycling, and/or reuse of these resources. The development of enhanced technologies for the decontamination of these materials, and effective communication of the low relative risks involved, will facilitate the recovery, recycle, and/or reuse of these resources. Improved material removal, handling, and processing technologies will enhance worker safety and reduce cost.

CROSSCUTTING TECHNOLOGIES

Crosscutting technologies are those which overlap the boundaries of the focus areas while providing simultaneous benefits. These technologies may be used in several or all focus area testing and evaluation programs, and include:

Characterization, Monitoring, and Sensor Technology. DOE is required to characterize more than 3,700 contaminated sites, 1.5 million barrels of stored waste, 385,000 m3 of high-level waste in tanks, and from 1,700 to 7,000 facilities before remediation, treatment, and facility transitioning commence. During remediation, treatment, and site closure, monitoring technologies are needed to ensure worker safety and effective cleanup. Cost-effective technologies are needed for all EM characterization requirements.

Efficient Separations and Processing. Separation and treatment technologies are needed to treat and immobilize a broad range of radioactive wastes. In some cases, separations technologies do not exist. In others, improvements are needed to reduce costs, reduce secondary waste volumes, and improve waste form quality. Separations technologies are also needed for environmental restoration of DOE sites, for groundwater and soils cleanup, and for decontamination and decommissioning of facilities. Many separations agents developed for waste treatment can be adapted for environmental restoration needs.

Robotics Technology Development Program. DOE's waste disposal efforts have particular issues+access, safety, final disposal, and cost efficiency. Due to hazardous radiation, massive waste loads, and restricted entry ways, many sites are inaccessible for human labor. It is unsafe to expose humans to radiation, harmful chemicals, and injurious mechanical objects. Human labor requires higher compensation, the need for expensive protective clothing, and stringent decontamination procedures. Robotics systems are safe, efficient, and cost-effective means to automate the handling and processing of mixed waste and characterizing and/or retrieving storage tank waste. Systems can also be designed for surveillance, characterization, cleanup, and decommissioning of retired DOE facilities.

Innovative Investment Area. DOE has set aside funding to foster research and development partnerships within the public and private sector, and to introduce innovative technologies into OTD programs. The Innovative Investment Area supports two types of technologies: (1) technologies that show promise to address specific EM needs, but require proof-of-principle experimentation, and (2) proven technologies in other fields that require critical path experimentation to demonstrate feasibility for adaptation to specific EM needs.

Pollution Prevention. DOE and the Department of Defense (DoD) have similar waste stream pollution problems and common environmental concerns. By combining their resources, these agencies can develop a coordinated interagency environmental research and technology development program that produces cost-effective technological solutions, particularly in the areas of process change or in-process recycling.

Technical Task Plans

Technical Task Plans (TTPs) are used to identify and to summarize work funded and managed by OTD at headquarters, the field, and the national laboratories. These plans include a project summary, technical task description, budget schedule, and milestone schedule. The EM-50 FY 1994 Program Summary (DOE/EM-0216) lists TTPs current as of the date of this document.

All tasks require a TTP number. Each TTP number contains information on the fiscal year in which the task is first funded, the DOE Operations Office funding allotment code, and the laboratory/contractor/university designator. See appendix for further details.

EM Organizational Structure

The Office of Environmental Management (EM) is responsible for managing the cleanup of DOE wastes from past nuclear weapons production and current operations. The EM mission is to bring DOE sites into compliance with all environmental regulations while minimizing risks to the environment, human health and safety posed by the generation, handling, treatment, storage, transportation, and disposal of DOE waste. The EM organization was established to provide focus, accountability, and visibility for DOE's waste management and remediation efforts. See Figure A.

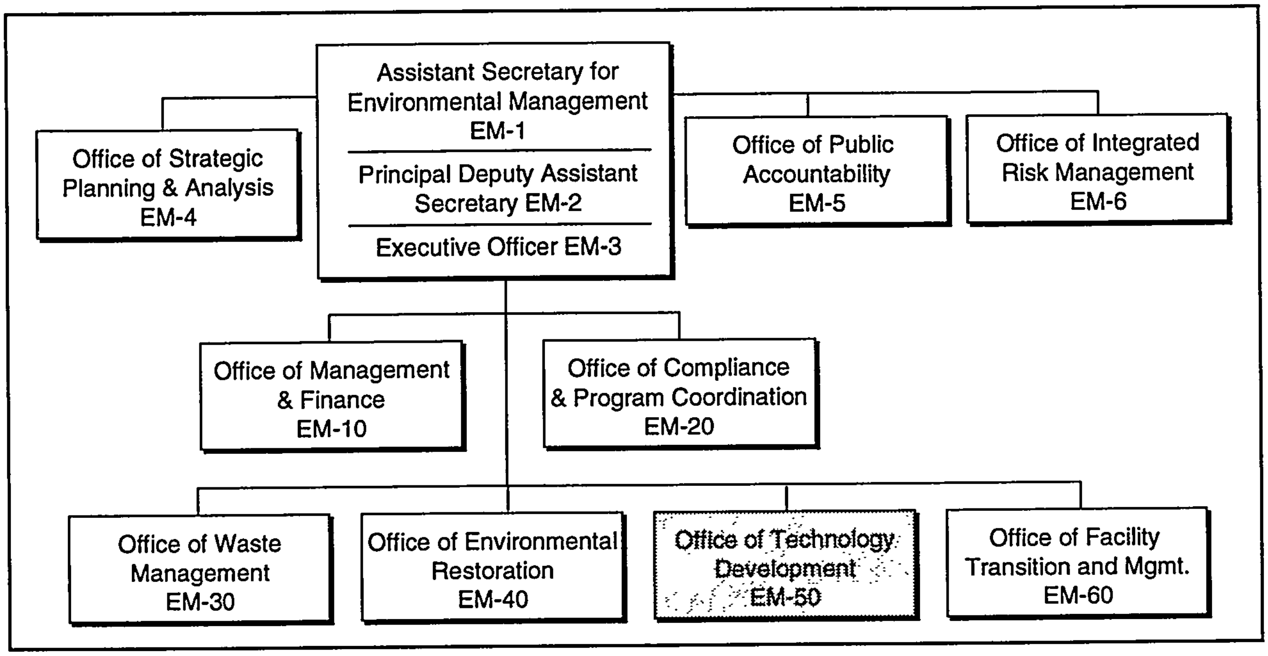

Figure A. The EM Organizational Structure as of May 1, 1994.

OFFICE OF TECHNOLOGY DEVELOPMENT

The Office of Technology Development (EM-50) has the overall responsibility to develop technologies to meet DOE's goals for environmental restoration. OTD works closely with EM-30, -40, and -60 in identifying, developing, and implementing innovative and cost-effective technologies. Activities within EM-50 include applied research and development, demonstration, testing, and evaluation (RDDT&E), technology integration, technology transfer, and program support. See Figure B.

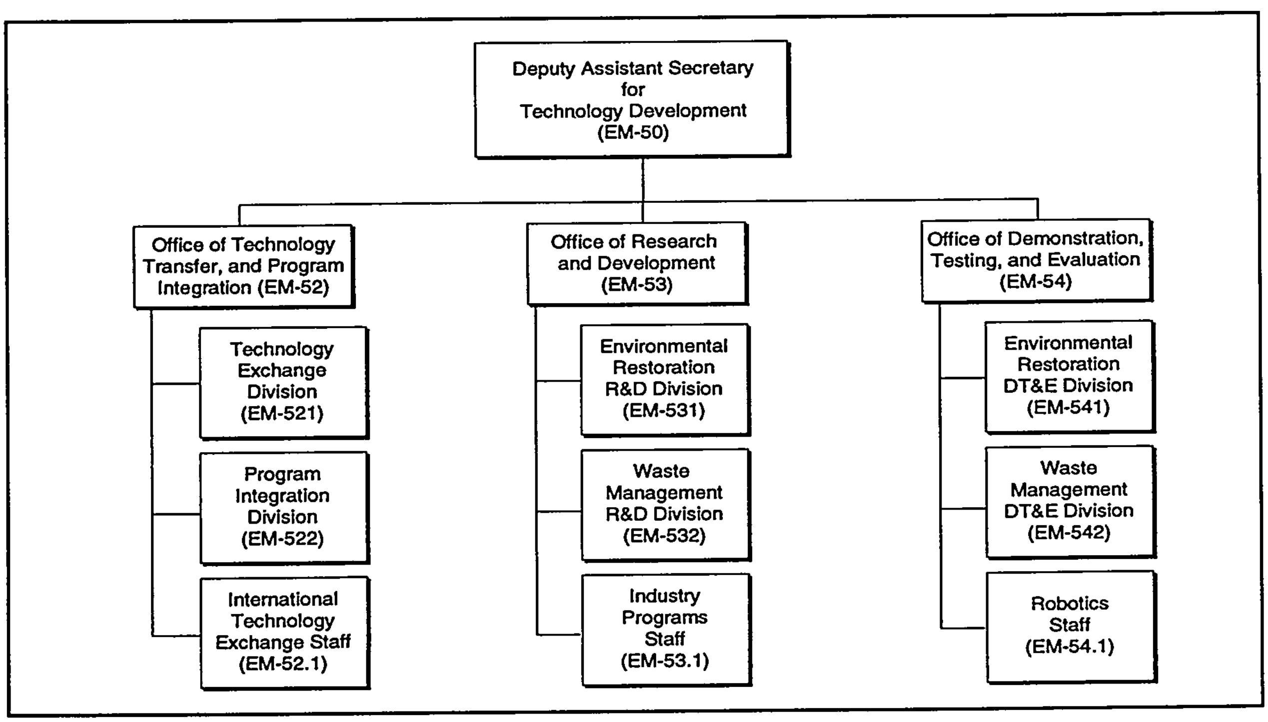

Figure B. The OTD Organizational Structure as of May 1, 1994.

EM-50 ORGANIZATION

The Office of Technology Transfer and Program Integration (EM-52) provides management, financial, and internal program support to line organizations that comprise EM-50. It also provides efforts to encourage and to facilitate the infusion and diffusion of innovative environmental technologies for internal and domestic application through collaborative partnerships with U.S. and foreign industry or organizations, the national laboratories, other federal agencies, and universities. Technology transfer and technology leveraging are important program components. Enhanced communication to internal and external stakeholders is a goal of this Office.

The Office of Research and Development (EM-53) is responsible for establishing applied research and development (R&D) program at DOE sites nationwide. Programs are designed to identify operational needs in environmental restoration, waste operations, and corrective activities, and to provide solutions to key technical issues that, if not solved in a timely manner, would adversely affect DOE's ability to meet its cleanup goal.

The Office of Demonstration, Testing, and Evaluation (EM-54) is responsible for identifying environmental management technologies in the research and development stage that are ready for transition to the demonstration arena. Those technologies are complete systems to demonstrate a solution to a specific problem area. Programs are conducted to advance selected technologies so they can be utilized by DOE to meet its cleanup goal in a cost-effective manner.

OTHER EM ORGANIZATIONS

The Office of Waste Management (EM-30) has program responsibilities for managing waste generated at all DOE sites during weapons processing and manufacturing, research activities, and site cleanup activities. This includes the treatment, storage, transportation, and disposal of several types of waste: transuranic, low-level radioactive, mixed, and solid sanitary wastes. EM-30 is also responsible for the storage, treatment, and processing of defense high-level radioactive waste (HLW), waste minimization efforts, and corrective activities at waste management facilities.

The Office of Environmental Restoration (EM-40) has program responsibilities for assessment and cleanup of inactive hazardous and radioactive facilities and waste sites at all DOE installations and some non-DOE sites. EM-40 oversees program activities to reduce or eliminate risks to human health and the environment.

The Office of Facility Transition and Management (EM-60) has the responsibility to ensure that shut-down facilities are brought to a deactivated state, are properly maintained, and are eventually decontaminated and/or decommissioned or released for other uses.

ROBOTICS TECHNOLOGY DEVELOPMENT PROGRAM OVERVIEW

The Robotics Technology Development Program (RTDP) is a needs-driven effort. A lengthy series of presentations and discussions at DOE sites considered critical to DOE's Environmental Restoration and Waste Management (EM) Programs resulted in a clear understanding of needed robotics applications toward resolving definitive problems at the sites. A detailed analysis of the resulting robotics needs assessment revealed several common threads running through the sites: Tank Waste Retrieval (TWR), Contaminant Analysis Automation (CAA), Mixed Waste Operations (MWO), and Decontamination & Dismantlement (D&D). The RTDP Group also realized that some of the technology development in these four areas had common (Cross Cutting-CC) needs, for example, computer control and sensor interface protocols. Further, the OTD approach to the Research, Development, Demonstration, Testing, and Evaluation (RDDT&E) process urged an additional organizational breakdown between short-term (1-3 years) and long-term (3-5 years) efforts (Advanced Technology-AT). These factors lead to the formation of the fifth application area for Crosscutting and Advanced Technology (CC&AT) development. The RTDP is thus organized around these application areas - TWR, CAA, MWO, D&D and CC&AT - with the first four developing short-term applied robotics. An RTDP Five-Year Plan was developed for organizing the Program to meet the needs in these application areas.

Each application area is coordinated by a DOE contractor at a site/laboratory chosen for its unique expertise or situation as paradigmatic of an EM problem. The Coordinator leads an integrated, multi-member, team of experts chosen from throughout the DOE Complex, private industry and universities.

The DOE Headquarters Robotics Program Manager is responsible for higher level management of the entire program with consultations throughout EM and frequent interactions with coordinators. Overall program direction, as reflected in fiscal emphasis, is a primary responsibility. Another is program integration among several RTDP application areas, various OTD activities supported by the RTDP, and non-OTD offices in EM. Program integration is critical for resource maximization in meeting needs. The Robotics Program Manager's function can summarily be stated as directly managing the RTDP so as to develop and demonstrate efficacious robotics systems, defined as needed by the customer programs, through a Complex-wide integrated approach.

The technology development and program management approach followed by the RTDP can be expressed as:

1) TEAMS - pull together the best from DOE National Laboratories, industries and universities.
2) BROAD APPLICABILITY - focused projects to solve complex-wide problems.
3) NEEDS-DRIVEN - direct contact with sites and customer programs to build required systems.
4) EXTERNAL INTEGRATION - each part of the RTDP is directly mapped onto DOE HQ organization.
5) INTERNAL INTEGRATION - emphasis on solutions to common problems within the RTDP for application to customer programs.
6) NATIONAL PERSPECTIVE - address complex-wide solutions through direct management by DOE HQ.

A brief description of each Technical Application Area appears below, with an elaboration of each area in subsequent sections of this book:

<u>Tank Waste Retrieval (TWR):</u> The TWR Team develops storage tank characterization and retrieval technology using long-reach robot manipulators. The TWR Team is developing a full-scale test bed to examine single and multiple arm concepts. Characterization and retrieval end-effectors with automated control and advanced graphic interfaces are particularly significant.

<u>Contaminant Analysis Automation (CAA):</u> The CAA Team develops fully automated modules which perform a generic task common to analytical chemistry. The modules are chosen for their repeated use in DOE analysis methods

and represent a significant fraction of sample load. The underlying theme is "plug-and-play", — interface standardization, transportability, architectural openness and modularity.

Mixed Waste Operations (MWO): The MWO Team develops systems for front-end handling and pre-processing of mixed waste container and contents, plus handling of the final waste forms after processing. Automated inspection of stored waste containers is also a major aspect of the MWO group. Graphical modeling and automation of operations with graphics viewing is a key approach to facilitating operations programming.

Decontamination and Dismantlement (D&D): The D&D Team works on automating the D&D process from surveillance to facility characterization to surface decontamination to hot cell dismantlement. The goal is to maximize efficiency while minimizing human exposure. The work centers around vehicular and crane deployed dual-arm systems using advanced sensors, control and operator interface technologies.

Crosscutting & Advanced Technology (CC&AT): The CC&AT Team develops technologies used throughout the RTDP. Projects are directed toward a generic, graphical robot controller based on an integrated multisensory system, plus systems analysis and modeling/simulation. Coupling sensor-based modeling with automated programming of robot operations is a key approach to developing faster, safer, and less expensive waste clean-up systems.

The Robotics Technology Development Program is discussed in detail in the following chapters and includes specific points of contact. Central point of contact for the program is:

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ROBOTICS TANK WASTE RETRIEVAL OVERVIEW

Section 1.0

1.0 ROBOTICS TANK WASTE RETRIEVAL OVERVIEW

The Robotics Tank Waste Retrieval (TWR) Team provides cost-effective manipulator-based technologies for characterization and retrieval of waste from underground storage tanks. Coordination is the responsibility of Pacific Northwest Laboratory, with contributions from the Idaho National Engineering Laboratory, Oak Ridge National Laboratory, and Sandia National Laboratories. Universities include the University of Florida, the University of Tennessee, and Georgia Institute of Technology. The Team works closely with industry to meet program objectives. A baseline concept for a manipulator-based retrieval system is shown in Figure 1.0. The crosscutting technology developed by TWR directly applies to the Radioactive Tank Waste Remediation Focus Area.

The TWR Team provides enhanced research and development tools centered around a robotics test and development facility and a comprehensive computer-based simulation network shared among the contributing laboratories. Retrieval-focused robotics technologies are developed and integrated as part of the test bed for demonstration. The team directly responds to technology needs identified by waste tank remediators. It provides robotics technology inputs for tank remediation planning and procurements.

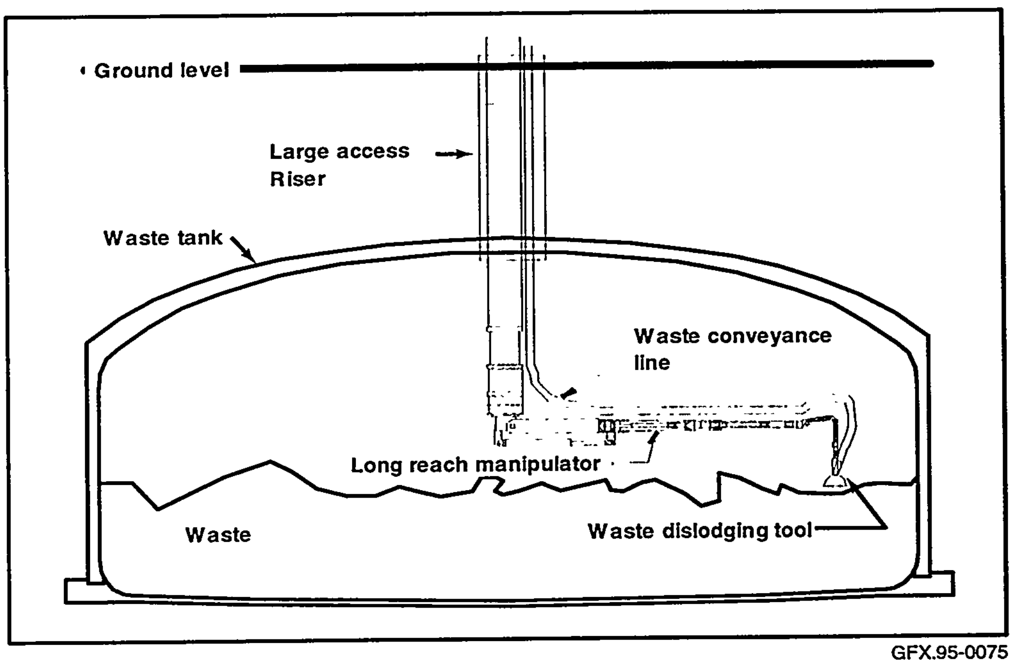

Figure 1.0. Manipulator-Based Retrieval System Concept.

1.1 ROBOTICS DEVELOPMENT TEST BED SYSTEM

TASK DESCRIPTION

Test Bed: The robotics test bed is a fully functional full-scale, comprehensive development facility for the evaluation of new manipulator-based retrieval technologies. The test bed, large portions of which are being procured from commercial industry, will be fully operable in FY96. The test bed will be used for development, testing, and demonstration of waste retrieval methods, equipment, and procedures. It plays a crucial part in the validation of simulation codes that are provided as another tool in this effort.

Specifically, the test bed provides: (1) first assessments of functionality of generic, very large robotic systems, (2) testing and demonstration of new concepts for control of large, physically flexible manipulator links, (3) testing and demonstrating new concepts for graphical supervisory control, and (4) initial testing and demonstration of waste retrieval end-effectors.

Simulation: A high-fidelity simulation is part of this task and enables rapid evaluation of vendor designs and development concepts. Simulation extrapolates experimental data retrieved from the test bed and other test resources to match scale and configurations of planned retrieval systems. Simulation rapidly defines parametric relationships in processes and controls. With this feature, the range of parameter values selected for actual testing can be much smaller, thereby improving the productivity of the development cycle immensely. Further, simulation permits timely evaluation of designs produced. Simulation capability includes process and controls modeling, and queuing modeling, as well as kinematic and dynamic models.

Plug-and-play: This concept allows creation of hybrid virtual/real systems for training experiment and demonstration. Software-predicated simulation modules for essentially any part of a waste-retrieval system can be combined with real system increments that exist in actual hardware to form a hybrid system that performs as a complete hardware system. Interface protocols for the simulations are identical to those of the actual hardware they replicate. Thus, simulations can be "plugged and played," along with actual hardware to examine integrated system performance well before all increments of the actual system are fabricated.

High-Speed Communications System: A high-speed digital communications system connects simulation and experimental equipment that is distributed among the contributing laboratories. This communications capability is a first implementation of the data highway supporting operation of robotic systems from remote nodes (other laboratories). It also supports combination of hardware and software assets (as in *Plug-and-play*) that reside at the various connected laboratories and universities to form an integrated test and demonstration capability. To maximize the benefits of the communication system, plans are to expand the link to include all contributors, encompassing laboratories, universities, and major industrial collaborators.

TECHNOLOGY NEEDS

The robotics test bed, simulation, and communications capabilities are necessary as sophisticated design and evaluation tools to support planned retrieval actions. Capability for integrated testing of all robotics-based aspects of waste retrieval is required. Newly conceived methods must be tested and demonstrated as an increment of a robotic system.

Effort is ongoing to perform near-real-time simulation of dynamic systems. Currently, the immense computational load that conventional dynamic modeling requires is not compatible with near-real-time solutions. Innovative computational schemes are being sought.

Initial plug-and-play modules have been produced; however, many more must be completed to provide a comprehensive system modelling capability.

ACCOMPLISHMENTS

A contract was placed with a commercial robotics team to produce the test bed manipulator system that will be ready for experimental use in FY96. As a companion to the test bed manipulator, design of a waste tank mock-up was initiated. The robotics test bed will be comprised of commercially available, standard robotic systems.

The supervisory control system for the test bed was specified and contracted. The system will be utilized with existing robotic test equipment until the test bed manipulator arrives. In the interim, research will be performed to develop optimized human-machine interface arrangements and improved control approaches.

Each of the contributing laboratories invested in stand-alone simulation and modelling capabilities, which include kinematic and dynamic modelling of proven merit in evaluating potential configurations for the robotic test bed. Other analyses were performed as a basis for the reference design of a waste retrieval system to be used at Hanford, WA.

A first demonstration of remote operations was completed using existing digital communications equipment. A large-scale robot located at Pacific Northwest Laboratory was successfully operated from Sandia National Laboratories. Experimental data were transmitted to the Sandia operator in real time.

BENEFITS

Robotics Tank Waste Retrieval (TWR) provides a cost-effective robotics technology base for retrieval of waste from underground storage tanks. The purpose of this task, as an increment of TWR Robotics, is to provide tank waste retrieval design and evaluation tools centered around a full-scale robotics test bed, a highly capable computer-based simulation system, and a high speed communications network. These individual elements are combined synergistically to create a world-class tank waste retrieval technology development capability.

COLLABORATION/TECHNOLOGY TRANSFER

National User Facility: The new test bed, simulation, and communications system are viewed as a national resource available as a user facility/asset to be utilized by all interested developers. The new test bed, being developed with commercial industry involvement, provides a robotic development and demonstration environment that is fully typical of robot configurations to be later employed in tank waste retrieval.

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1.2 TECHNOLOGY DEVELOPMENT

TASK DESCRIPTION

The purpose of this task is to perform research, development, and demonstration supporting manipulator-based tank waste retrieval, utilizing the tools provided in Task 1. Research, development, and demonstration provide a performance baseline for components and integrated retrieval systems, while addressing specific retrieval solutions and practical methods. Work is performed collaboratively by four national laboratories, associated universities, and industry.

TECHNOLOGY NEEDS

Multiple robotics technology needs have been defined in collaboration with tank waste remediators. Each need forms the basis for a development task.

Long Reach Manipulation: Existing openings in underground waste storage tanks are limited in size. Manipulator payload and reach requirements dictate significant mechanical flexibility, both static and dynamic, that must be mitigated.

Human-Machine Interface: Improved capabilities in teleoperation (human in-the-loop) and robotic (autonomous) operation are needed. During waste retrieval operations, it is required to remotely supervise and direct large manipulators. Highly productive teleoperated operations must be available that include an accurate and complete perception of the work space for the human operator. Robotic control modes must also be selectable for performance of routine, repetitive actions. Autonomous functions also are needed to oversee actions of the operator, limiting these actions to avoid unsafe conditions, such as collisions.

System Reliability and Safety: Needs have been identified to improve reliability and productivity of complex mechanical systems operating in the hostile in-tank environment. Consideration must be given to Safety Class requirements for critical waste retrieval system functions. These are functions that, if corrupted, could cause risk to the public, operators, or substantial monetary loss of equipment. Most of the advanced robotics control technology is implemented in software, where conventional safety systems in critical equipment such as reactor safety systems, have traditionally been predicated on hard-wired circuitry. If software-based safety systems are to be accepted, a new standard of robustness must be achieved.

Workspace Mapping: Sensor-based workspace mapping systems are sought that will provide a near-real-time capability to produce a three-dimensional digital map of the workspace that can be refreshed in a piece-wise fashion as changes occur in the workspace, as when waste is removed. The workspace map is displayed to the human operator and is the basis for robotic path planning and collision avoidance. Methods to reject spurious data and to improve mapping speed are being researched.

ACCOMPLISHMENTS

To date, many of the robotics-based retrieval technologies described here were developed and demonstrated individually. The next step is to consolidate these developments and evaluate their performance as increments of a complete retrieval system. To accomplish this, the robotics test bed will be utilized to maximum benefit. Plans are to integrate these advanced technologies into the test bed, perform evaluations, and provide the results to waste-tank remediators and industry.

Long Reach Manipulation: Accomplishments to date include development of active and passive methods to damp vibrations in long-reach manipulators. These approaches were tested successfully on simplistic manipulator geometries. Many potential kinematic arrangements for waste retrieval manipulators were investigated to ascertain optimal configuration for waste retrieval and maximum stiffness, leading to selection of a best kinematic configuration for large underground waste storage tanks.

Human-Machine Interface: Significant improvements in human-machine interface were achieved through development and demonstration of a graphic-based supervisory control system. An image of the tank internals, predicated on the workspace mapping system, was provided in which a model of the manipulator system mimics actual manipulator movements in real time.

Another part of human-machine interface development has involved establishing bases for productivity values of manipulator-based retrieval systems. Assessments were completed that estimated the time required to perform retrieval tasks utilizing both teleoperated and autonomous tasking. These data provided a benchmark comparison of various man-machine interfaces and for evaluation of man-in-the-loop versus autonomous task performance.

Work Space Mapping: Mapping systems predicated on laser range finders and structured light were tested and characterized with respect to accuracy and operational limitations. Map refreshment rates of several minutes were achieved. A standard data base manipulation approach was selected that is compatible with graphical supervisory control and with robotic controller requirements.

BENEFITS

The research described directly solves issues identified jointly by waste tank remediators and robotics developers. This work is complementary to research being performed in other DOE development programs, including the Light Duty Utility Arm and the Characterization Program. Implementation of these technologies fulfills manipulator-based waste retrieval system requirements, contributing to improved productivity and safety. Manipulator-based waste retrieval also offers the least possible addition of liquids, which is an issue with tanks that are known to leak.

COLLABORATION/TECHNOLOGY TRANSFER

Cooperative Research and Development Agreements (CRADAs) have been established in several technology subtasks. Work is ongoing with commercial industry to improve dynamic stability of large manipulator components through active control and passive methods.

Two CRADA partners involved in the TWR technology development arena include Schilling Development, Inc., for their teleoperated control methods for flexible link manipulators, and CIMCORP, for their telescoping mast technology.

Several universities collaborate by performing applied research in the previously described development areas. These include:

The University of Florida, performing retrieval systems simulations, characterization of very large hydraulic manipulator components, and work space mapping data interpretation;

The University of Tennessee, developing optimized methods for control of redundant degree of freedom manipulators and work space mapping and data interpretation; and

The Georgia Institute of Technology, providing research in control of flexible manipulators, advanced human-machine interface concepts, and independent end point tracking.

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ROBOTICS CONTAMINANT ANALYSIS AUTOMATION

Section 2.0

2.0 ROBOTICS CONTAMINANT ANALYSIS AUTOMATION

The Robotics Contaminant Analysis Automation (CAA) team's mission is to advance the development, implementation, and commercialization of technologies to automate DOE and private contract environmental laboratories. This mission responds to the increasing demand for chemical characterization of soil samples, storage tank contents, and water samples to identify elemental, isotopic, and compound content prior to remediation efforts.

The crosscutting technology developed by this program directly applies to the following focus areas:

- Landfill Stabilization;
- Contaminant Plume Containment and Remediation; and
- Mixed Waste Characterization, Treatment, and Disposal.

DOE oversees significant amounts of radioactive and hazardous wastes that are stored, buried, or still being generated at many sites within the United States. Projections for sampling requirements range from one to ten million sample determinations per year by the end of the DOE cleanup process.

Today, no automated commercial systems are available to automate these laboratories. Initial market surveys revealed that modular and standardized software and hardware are needed if these automated systems are to have the throughput, reliability, and transportability required.

Another factor leading toward the modularity concept is the need for systems that can be operated by a technician not versed in environmental chemistry. To provide valid data and timely sample analysis results, the CAA team realized that it is necessary to ruggedize these systems so that they can be transported to and operated directly at the remediation site. The concept of on-site sample analysis using CAA technology is shown in Figure 2.0.

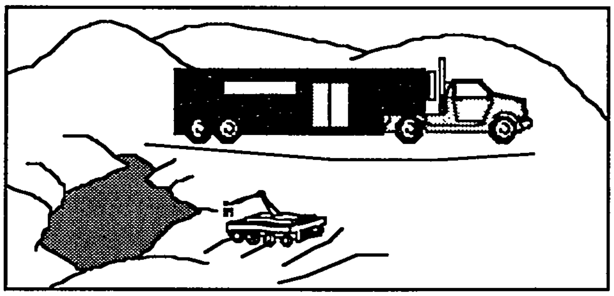

Figure 2.0. On-Site Sample Analysis.

The CAA team has made substantial progress over the past year toward its goal of automating the environmental analytical laboratory under a standardized and modular paradigm known as the Standard Analysis Method (SAM). This diverse and talented team, composed of five DOE National Laboratories, three respected universities, and several private industrial partners has developed and validated the initial technology necessary to demonstrate this new automation paradigm. To date, a suite of 14 Standard Laboratory Modules (SLMs), the backbone of this integrated technology, have been designed, developed, and validated. Also, a detailed survey of the environmental market and its needs were commissioned to help focus and prioritize the development. CAA is now working with private industrial partners to further develop the SAM System architecture and standards while aiding the commercialization of these instruments.

The DOE laboratories involved in the CAA effort include Pacific Northwest Laboratory, Idaho National Engineering Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, and Los Alamos National Laboratory as the coordinating laboratory. Participating CAA team-member universities include the Universities of Texas at Austin, Tennessee at Knoxville, and Florida.

2.1 THE STANDARD LABORATORY MODULE AND STANDARD ANALYSIS METHOD

TASK DESCRIPTION

The purpose of this task is to develop standardized laboratory automation addressing sample preparation, analysis, and data interpretation. The foundation of this task is the standard laboratory module (SLM). An SLM is defined as a logical grouping of laboratory unit operations that perform a subtask of an analytical protocol. Laboratory unit operations include weighing, grinding, manipulation, liquid handling, conditioning, separation, measurement, control, data handling, and documentation. The CAA Program is also establishing hardware and software interface specifications for SLMs that will allow individual SLMs acquired from multiple vendors to become building blocks for automated systems of higher complexity. The SLM standard interface will allow a "plug-and-play" approach to linking SLMs. SLMs concerned with sample preparation combine to form the sample preparation module, those that are involved with the transduction of chemical information into the electronic regime combine to form the analytical instumentation module, and finally, those that take the electronic data and convert them into information constitute the data interpretation module. At the highest level of automation complexity is the standard analysis method (SAM). The SAM is a combination of those SLMs that perform the entire characterization process: sample preparation, analysis, and data interpretation (see Figure 2.1).

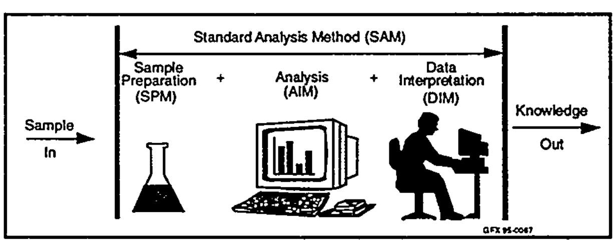

Figure 2.1. The Standard Analysis Method (SAM) Concept.

SLMs can either be hardware or software. For sample preparation functions, SLMs tend to be more hardware-oriented, while in the data-handling and interpretation arena, they are more software-intensive. Each SLM expects to interact with a host controller that passes information and schedules other SLMs in the proper sequence. Another feature of the SLM is that it can also function independently. This feature will be used to full advantage when the SLMs are brought into the laboratory. As they are developed, technicians can begin to take advantage of the automation, working incrementally toward a fully automated system.

When SLMs are assembled into a fully automated SAM, samples are moved between SLMs by robots. The SAM also coordinates and controls the consumables and service required by each SLM. The SAM will include supply racks for disposables, clean and dirty labware, reagent reservoirs, and other system resources that do not fit the SLM definition. These support devices are call standard support modules (SSM). The SAM controller will monitor SSM consumables, ensuring a supply for the individual SLMs.

TECHNOLOGY NEEDS

Sample analysis requirements for DOE, as projected by the Analytical Services Division (EM-263), indicate an increase from the FY93 level of roughly 750,000 samples per year to well over 2 million samples in FY95. The DoD requirements for sample analyses are projected to be equal to or greater than DOE's. Although DOE has significantly more mixed waste samples, the predominate chemical analysis needs for effective and efficient waste remediation are largely the same within the DOE and DoD; namely the analysis of extracted organics and metals. Of primary concern to both DOE and DoD laboratory managers are the problems with data quality and long sample turn-around times. Solving these specific concerns will be some of the important and pervasive benefits realized from the technology development and commercialization of laboratory automation strategies by the CAA task area.

Through a DOE needs assessment, the CAA Project Team selected the sample preparation, constituent analysis, and data interpretation elements of the semivolatile organic analysis for the initial test and demonstration of the plug-and-play automation strategy. Future work required by the CAA project to realize the fully integrated and automated environmental analysis laboratory involves the development of three essential and related tasks.

First, prototypical SLM and SAM Systems must be developed that address the automation and integration issues encountered in the analysis of volatile organic compounds with gas chromatography-mass spectrometry detection, metals with inductively coupled plasma optical emission detection, and radioactive isotopes with alpha, beta, and gamma counting and inductively coupled plasma-mass spectrometry detection. Preliminary models of just the metals and radiochemical SAMs indicate the need for from 12 to 15 new SLMs.

Second, a high-level means of representing the chemical knowledge embodied in regulatory protocols must be developed in a form interpretable by computer systems. This representation must provide an automated translation of the encapsulated knowledge into the specific tasks to be executed by the SLMs and SAMs.

Third, the chemistry embodied in regulatory protocols must be developed from the perspective of automated chemistry instead of developing automated hardware to mimic manual procedures. Transfer of the CAA technology to the private sector is a continuing element of CAA project plans. Working relationships with system integrators and SLM manufacturers will be continually sought through development contracts and CRADAs.

Another area of major need is development of Data Interpretation Modules (DIMs) to validate the raw data generated by the CAA systems without significant chemist intervention. Linking the CAA System with commonly used Laboratory Information Systems (LIMS) will also be necessary to fully integrate the CAA technology into DOE and DoD environmental laboratories. In addition, the standards and instrumentation developed by the CAA team will be directly applicable to private industrial needs. The technology can be configured into systems for use in markets such as pharmaceutics, food and flavors testing, petrochemicals, agrochemical, and drug testing.

Successful accomplishment of the current and future CAA tasks will provide environmental analysis laboratories with systems that will allow them to meet their customer expectations, namely improved data quality, customized services, improved turnaround time, and reduced sample analysis costs.

ACCOMPLISHMENTS

The CAA team has developed 14 SLMs to date. Four of these modules have been successfully chemically validated by an independent DOE environmental laboratory using a testing methodology suitable to, and more rigorous than, that of the Environmental Protection Agency (EPA). Formal reports have been written, and two have been submitted to the EPA for approval.

The following SLMs were delivered this year:

- Concentration;
- Microwave Digestion;
- Microwave Sample Preparation;
- Solvent Recovery;
- Organic Filtration; and
- Solution Transfer.

The following SLMs were chemically validated this year:

- Sonication (report submitted to EPA);
- Drying Column (report written but not submitted to EPA);
- Gel Permeation Chromatograph (GPC) (report submitted to EPA);
- Concentration;
- Microwave Digestion;
- Soxhlet (For PCBs and some semi-VOC);
- Solution Transfer;
- Organic Filtration;

Other Accomplishments

- Specifications for the Mobile Laboratory Test Bed written and procurement initiated;
- CRADAs with Hewlett-Packard Company and Thru-put Systems, Inc., completed;
- Task Sequence Controller (TSC) software completed;
- A prototype Data Interpretation Module (DIM) for PCB analyses of soil (EPA Method 8080) completed;

- Development of a DIM for EPA metals; and
- Prototype HCI was completed.

Benefits

- Allow greater fraction of the remediation budget to be spent on actual cleanup due to significant decrease (automated sample analyses costs one-third less than current methods) in sample analysis costs.
- Faster sample analysis turnaround for faster site characterization and cleanup.
- Lower cost of sample analysis will allow more samples to be taken, enabling fuller characterization of sites before cleanup. A fuller characterization results in more economical cleanup activities which are targeted to better defined contaminants in site maps.
- Increased accuracy and precision of each analysis as a result of the automated processing of samples.

Collaboration/Technology Transfer

Two CRADAs have been structured this year for work applied to the development of the DIM; one with Hewlett-Packard Company and another with Thru-Put Systems. In addition, the CAA team has solicited interest from several potential industrial partners for collaboration in the role as Systems Integrator. A broad and innovative Technology Transfer Plan structured by the CAA team was developed to accomplish commercialization of developed prototypical systems.

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TASK DESCRIPTION

The goals of the system software development are to:

- Develop plug-and-play interface specifications for laboratory subsystems and laboratory software;
- Establish a standard for specifying analysis methods so they describe validated chemistry and are independent of any particular set of SLMs that execute the method; and
- Define an information model that enables the automated laboratory to archive sufficient data to satisfy regulatory and legal requirements.

To achieve these goals, the CAA team is developing software modules for a control system, user interface, and database. The team is also developing specifications for the interfaces among these modules.

SLMs are plug-and-play building blocks for the automated analytical chemistry laboratory. Each SLM can perform a subset of the operations required to implement automated chemical analyses, or SAMs. A SAM is programmed into the automated laboratory as a hierarchical script of chemical operations. The Task Sequence Controller (TSC) processes these scripts by expanding them into the primitive operations that can be performed by the individual SLMs. It provides a single point of control over the SLMs in the laboratory. The database stores and provides access to all required information on the individual SLMs, samples, and methods in order to enable system operation and ensure full QA/QC records. Figure 2.2 shows these logical components of the automated laboratory and the relationships among them. The single arrow lines represent control connections, while the double arrow lines represent information exchange.

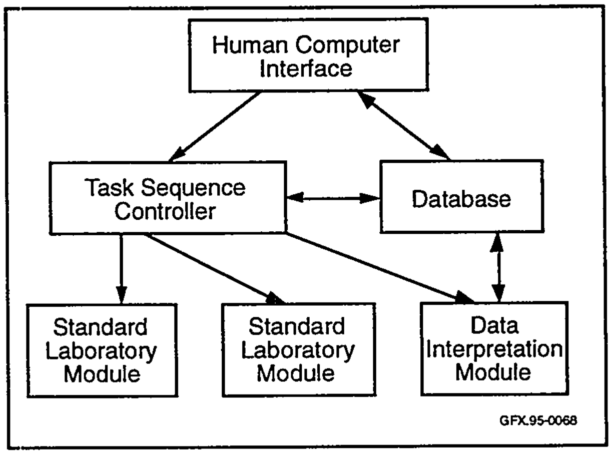

Figure 2.2. The CAA Software Architecture.

The key to modular chemistry is standardized interfaces between the components of the automated laboratory. All laboratory modules and subsystems must conform to a standard interface specification to ensure stylized interaction protocols. The SLM interface defines the interactions between the TSC and the SLMs attached to it. A supervisor-subsystem connection between the TSC and SLMs enforces a single point of control for on-line SLMs in the laboratory. The plug-and-play SLM interface requires standard mechanisms to permit the supervisor to determine the capabilities of the SLMs, since the interface is independent of the operations an individual SLM performs. The TSC must also be able to coordinate physical interactions with an SLM (e.g., input and removal of samples and supplies), instruct the SLM to perform desired operations, and perform various error handling functions. The SLM interface consists of a set of commands and events, a process state behavior, an interaction protocol, and a capabilities data set.

The TSC is modeled after supervisory workcell controllers being developed and used for manufacturing environments. It performs tasks such as resource allocation and management, process monitoring, etc. Traditionally, flow of material through the workcell is often driven by workcell capabilities and configuration. This means that production information is embodied in the workcell. Reconfiguration of this workcell requires reprogramming of the controller. Incorporation of new or improved capabilities into the workcell might require significant controller reprogramming.

In contrast, the TSC is driven by what is termed the "smart item," where analysis information is associated with the item being operated in the laboratory. This analysis information is entered into the controller as a method script programmed independent of any particular set of devices that may perform the chemical operations. Reconfiguration of the laboratory requires no change in controller or method scripts.

The database module is a distributed, C++ object-oriented database management system with internal client/server capabilities that permit data storage on different devices. An external user interface will enable the analytical chemist to browse through the database and select data for analysis. Database functionality is defined by the information needs of laboratory system setup and initialization, sample tracking, system maintenance, and data analysis. Sufficient data must be stored to legally support the analytical results.

The database design was based on the Analytical Data Interchange and Storage Standards constructs and the Consortium on Automated Analytical Laboratory Systems Modularity and Data Communications Standards. Modifications support CAA hardware components, provide easy waste tracking, and supply additional information necessary for the fully automated system.

The HCI provides an easy-to-use graphical user interface to a CAA laboratory for monitoring, control, and information access. The HCI is implemented using G2, a real-time expert system shell. It is programmed as a set of G2 knowledge bases that provide functionality for user access control, process monitoring, sample entry, bench layout control, and method script monitoring and editing. In addition, user interfaces are being constructed for individual SLMs to facilitate stand-alone operation.

Technology Needs

System software that completely tests all interface specifications is required to satisfy our goal of plug-and-play automated chemistry. In addition, a grammar for chemical method description is being developed.

Future system software development will focus on a method manager system that ensures that everything required for validated chemistry happens from a system standpoint. This module will ensure that calibrations, maintenance operations, and control analyses, are performed as required.

Accomplishments

- A standard interface specification for SLM communication and control interactions was developed. A testbed of hardware and software modules is being implemented to test and enhance this specification.
- A TSC was installed on the testbed and integration with SLMs was initiated. The TSC has begun integration with the HCI and database.
- A database communications interface with other software modules was established. An initial database capable of storing and retrieving information was implemented. This schema is being enhanced as testbed activities continue.
- An HCI with functionality for user access controls, process monitoring, and sample entry was developed. This HCI has communication and control interfaces with both the TSC and the database. Testing of the HCI is in progress.

Benefits

The current state-of-the-art in laboratory automation is the implementation of "islands of automation." Laboratories will often buy one or two pieces of automated process equipment to address bottlenecks in their analysis processes. Industrial focus has been on the analytical instrument that performs the final determination (e.g., a gas chromatograph), and comparatively little attention has been paid the sample preparation and data interpretation arenas. With our modular architecture, analytical laboratories can implement automation a few steps at a time and be confident that their system will be expandable with little or no custom integration work required.

COLLABORATION/TECHNOLOGY TRANSFER

The CAA Program is actively seeking an industry partner to develop a commercially available set of automated laboratory system software modules, including a control system, user interface, and database archiving system.

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None at this time.

TASK DESCRIPTION

The CAA Program is developing laboratory automation in an SLM format. One of the goals of the CAA Program is to link an automated analytical instrument module (AIM) and automated DIM under the SLM format. The AIM is the element of the automated laboratory that performs the analysis on an aliquot of the prepared sample. This module will be a commercially available instrument that has been interfaced to the automated laboratory controller. The DIM is a software module in the automated laboratory that delivers chemical knowledge about the sample from the raw data generated by the AIM.

The current target for the demonstration of automated analysis and automated data interpretation is EPA Method 8080 for organochlorine compounds and polychlorinated biphenyls (PCBs). A gas chromatography (GC) instrument is incorporated into the automated laboratory and explores the automated interpretation of the chromatograms generated from each sample. Method 8080 is used to detect and quantitate Aroclors. Aroclors are the trade name for the mixtures of PCBs sold commercially. EPA method 8080 is targeted because chromatographic analysis of environmental samples for Aroclors, fuel spills, and other multicomponent materials are among the most difficult analyses to perform. As illustrated in Figure 2.3a, the complexity of the chromatogram often inhibits the identification and quantification of the sample components.

Pattern recognition tools will be used in the automated analysis system to replace the intuitive pattern recognition performed in manual data interpretation by an experienced chemist.

These techniques will identify peak patterns from Aroclor/PCB mixtures in the complex chromatograms of environmental samples. Standard pattern recognition methods will alleviate the inefficiency and lack of uniformity that result from subjective data interpretation decisions by a human expert. Current development includes principal component analysis, multiple linear regression, correlation, and neural network pattern recognition analysis methods.

The pattern recognition results will be interpreted in an expert system-driven DIM. Expert-level rules and procedures will be incorporated into the expert system DIM that will draw conclusions and provide confidence measurements from the data processing results. Figure 2.3b illustrates the expert system control of the data processing steps. The DIM will have two operational modes: (1) an on-line mode that performs data analysis, controlled by the automation controller via the SLM protocols, and (2) an off-line mode that provides the analytical chemist with the tools required to build automated data analysis methods and review the raw data, analysis process. Other tasks required of the DIM include integrity validation of the raw data, the feedback of information to the TSC to ensure proper sample processing, automated quality control

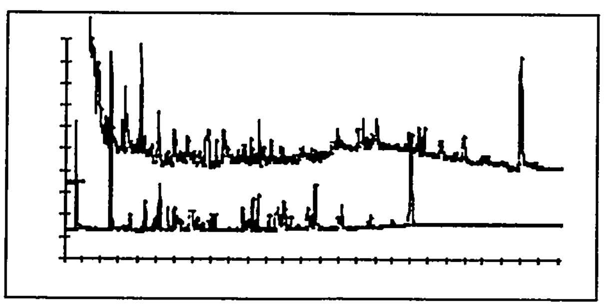

Figure 2.3a. Gas Chromatograms from an Environmental Sample and the Chromatogram of an Aroclor Standard.

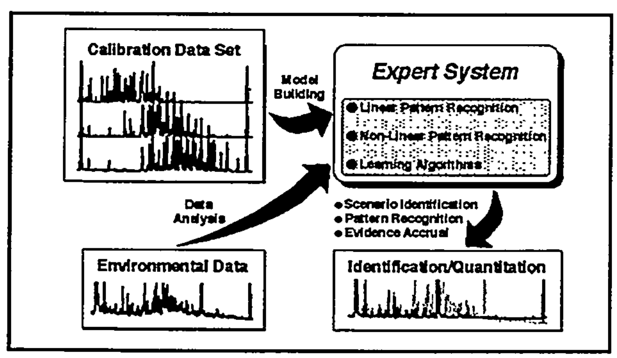

Figure 2.3b. Expert System Control of Data Processing Steps.

and quality assurance functions, and an interface to the laboratory database.

The data interpretation expert system is being developed in a standard format. Other analytical instruments will be incorporated into the automated laboratory and the techniques for analyzing their data integrated into the DIM. In addition to the GC, automated data analysis is being developed for gas chromatography, mass spectrometry, and atomic absorption spectroscopy instruments.

Technology Needs

There are several demonstrations of pattern recognition techniques applied to data analysis. However, no analytical methods have been developed for routine use in environmental laboratories. In the CAA Program, pattern recognition methods will be developed for data analysis. The applications will be tested and validated. The expert system integration of these techniques into routine methods will both enable automation of data analysis and provide a powerful aid to environmental chemists.

Accomplishments

- To test and demonstrate pattern matching calibration model concepts, a typical calibration data set for the simultaneous analysis of Aroclors 1242, 1254, and 1260 according to EPA SW-846 Method 8080 was acquired. These Aroclors were selected because they were the primary mixtures sold and because state-of-the-art separations technology does not resolve all of the PCB structural isomers or congeners. This data set was used to test principal component analysis pattern recognition.
- A principal component analysis of the Aroclor calibration data set was completed. The standard deviation of the Aroclor 1254 calibration function was 18 ppb. Essentially identical results were obtained for the other two Aroclors. The results clearly indicated that data interpretation techniques based upon pattern matching concepts could be implemented.
- Multiple linear regression, correlation, and neural network pattern recognition analysis was applied to the Aroclor data. The expert system DIM drew upon the different strengths of the method to synthesize a final result.

Benefits

Currently, 40 percent to 60 percent of the cost of sample analysis is attributed to data interpretation and data validation. Facilitating this effort with the automation being developed in the CAA Program will result in significant cost savings in sample analysis.

The instrumentation automation being developed in the CAA Program will make the current generation of laboratory testing instruments more robust. These instruments will be able to diagnose samples and instrument problems and take corrective action to ensure that subsequent samples are analyzed successfully. When incorporated into a fully automated laboratory, the instruments will be able to recommend additional sample preparation steps that are necessary to a successful analysis.

Collaboration/Technology Transfer

Participants in the data interpretation automation effort include:

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Industrial collaborators:

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Elling, J. W. *Automated Chromatographic Data Interpretation Using an Expert System,* ACS Special Topics Symposium on Emerging Technologies in Hazardous Waste Environments VI, Atlanta September 1994.

2.4 CHEMICAL VALIDATION OF STANDARD LABORATORY MODULES

TASK DESCRIPTION

The CAA Program is developing SLMs for the automated analysis of trace contaminants in environmental samples. Each of these modules will automate one or more of the methods outlined in the EPA Test Methods for Evaluating Solid Waste (SW-846). Each module developed is scheduled to undergo analytical validation by a validation team. Validation of the individual SLMs will verify that:

- Analytical data generated by the automated system are consistent with data generated by manual methods;
- Individual SLMs are capable of achieving the analytical requirements of trace environmental analysis; and
- The SLMs are able to withstand the rigors of automated environmental analysis.

Analytical data that must be consistent with manual data includes:

- Method detection limits;
- Surrogate recoveries;
- Matrix spike and spike duplicate recoveries; and
- Recoveries of spiked compounds from quality control samples.

In order to be compatible with trace environmental analysis, automated analytical modules must also meet other requirements such as the ability to handle a diverse range of sample matrices and the ability to generate blank samples free of undesirable contaminants. Finally, in order to be used in an environmental laboratory, other problems such as software and hardware stability, ease of use and maintenance, and sample throughput must also be evaluated before the final production of modules prototype SLMs are released for commercialization.

In order to evaluate the criteria outlined above, the Environmental Chemistry Group validation team designed a series of tests that are consistent with the requirements for analytical methods currently in use. These tests include method blank contamination and cross-contamination evaluations, a method detection limit evaluation, the analysis of quality control samples, and the analysis of "real" environmental samples. These tests provide information on the overall performance of the automated system. Various matrices ranging from blank materials to silty environmental samples have been used to evaluate the performance of the SLMs in terms of the adequacy of the data generated, the mean time between failures, and the mode of failure.

TECHNOLOGY NEEDS

One estimate of the future need within the DOE and the DoD is given by the EPA document, "Cleaning Up the Nation's Waste Sites: Markets and Technology Trends." This document states that as many as 7,000 DoD sites and 4,000 DOE sites may require characterization and cleanup. This technology enhances the analytical processes used to characterize these sites and could result in significant cost savings.

ACCOMPLISHMENTS

- The sonication report was submitted for approval to the EPA Office of Solid Waste.
- The gel permeation chromatography (GPC) and Soxhlet SLMs were validated. The report for the GPC system is nearing completion. An analytical procedure detailing the validation approach is also nearing completion.

- The High-Volume Concentrator, designed by Idaho National Engineering Laboratory, was validated.
- Method and instrument validation were provided in support of the Organics SAM demonstration scheduled for 1995.

BENEFITS

Improved sample throughput has been demonstrated using the Soxhlet SLM. This system processed 23 samples by using a full-time equivalent employee compared to five full-time equivalent days required for the same analysis performed using traditional methods. Considering labor as one of the most expensive components of environmental analysis, this three-fold improvement in throughput represents significant cost savings to the DOE. Improved precision has been demonstrated using the CAA-developed High-Volume Concentrator that processed 42 samples over a three-day period with an overall relative standard deviation of less than 5 percent.

COLLABORATION/TECHNOLOGY TRANSFER

During the validation of each of the SLM modules, the validation team is collaborating with the CAA Program design engineering teams responsible for the fabrication of the specific SLMs. Innovations and suggestions that are developed within the validation team are transferred to the entire CAA Program.

The CAA Program is currently interested in CRADAs and contracts with third-party laboratories qualified to perform validation. This third-party validation will involve beta testing of SLM technology and provide third-party feedback with a variety of sample data.

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2.5 TECHNOLOGY TRANSFER IN THE CAA PROJECT

TASK DESCRIPTION

The CAA Program consists of an aggressive team of national laboratories, universities, and industry participants whose goal is to develop and automate analytical sample analysis systems for DOE. This team is structuring a large and innovative Technology Transfer Plan, based on DOE Headquarters involvement, to accomplish the commercialization of the prototypical systems. See Figure 2.5.

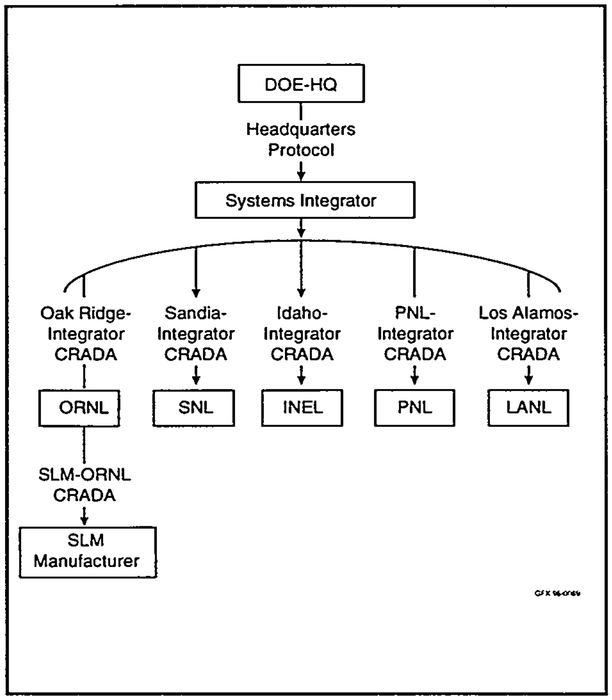

Figure 2.5. Headquarters Protocol and Guidance Document.

These integrated systems will be necessary for the rapid, cost-effective, and precise chemical characterization of environmental remediation projects. The effective transfer of this technology into the automation marketplace for manufacture and commercialization is critical for the success of the CAA mission.

The current laboratory automation paradigm consists of limited capability islands-of-automation that do not integrate into a systems architecture to provide an analysis path for the remediation effort. Today, the chemist must perform most aspects of sample analysis manually. By designing and transferring to industry partners systems that are based upon the SAM architecture, the CAA is working toward a standardized and modular system that provides a plug-and-play approach to laboratory automation. SAMs are integrated systems comprised of standardized instruments, known as SLMs, that automate a portion of an environmental method.

The CAA Program is also a highly collaborative effort comprised of engineering teams in five DOE national laboratories. Three academic institutions, the University of Florida, the University of Tennessee, and the University of Texas support the CAA Program. The CAA Program has relationships with companies, ranging from Proprietary Information Agreements (PIA) and CRADAs to other small procurement contracts. Many SLM manufacturers will be directly contracted by a systems integrator, or engaged for SLM development via a CRADA involving one or more of the participating CAA national laboratories.

TECHNOLOGY NEEDS

Government and industry face similar problems with respect to characterizing and remediating sites potentially contaminated with radioactive and hazardous wastes. The first step in cleaning up sites is to determine if they are contaminated, and if they are, characterizing the contaminants. Currently, DOE and its contract laboratories perform 2 to 3 million determinations each year.

In collaboration with industry and the involved DOE laboratories, the CAA Program is developing SLMs that address two analysis methods that will be commercialized first, the EPA regulated methods 3540 and 3550 (the Soxhlet and Sonication extraction of semi-volatile contaminants from soils). The integrated SAMs that will automate these methods will be part of a full alpha demonstration to be held at Los Alamos National Laboratory in May 1995. Market assessments, both internal to DOE and within the general laboratory automation market, have assisted the CAA team in identifying future SAMs. Evaluation and the actual contracting of SLM manufacturers for these first SAM Systems began in 1993.

ACCOMPLISHMENTS

- PIAs were executed with potential systems integrators; a decision regarding which industrial partner will be the systems integrator should be made by early 1995.
- CRADAs were signed with ABC Laboratories, Thru-Put Systems, Inc, Varian, Lockheed, Neuralware, and Hewlett-Packard Company.
- A large procurement for a mobile environmental laboratory platform was contracted.

COLLABORATION/TECHNOLOGY TRANSFER

The CAA Technology Transfer Plan begins with a Headquarters-level Protocol and Guidance document. See Figure 2.5. This guidance document provides the detail of CAA Program management, responsibilities, and team interactions. This CAA Protocol will be signed by each of the five participating laboratories, the systems integrator, and DOE. Mentioned in this Protocol are two CRADAs; one to be put in place between each national laboratory and the systems integrator, and another to be used for contracting SLM manufacturers by the CAA Team Laboratories. Both CRADAs detail the CAA Program licensing rights and intellectual property flows while referencing, and being bound by, the Headquarters Protocol.

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ROBOTICS FOR MIXED WASTE OPERATIONS

Section 3.0

3.0 ROBOTICS MIXED WASTE OPERATIONS

The Mixed Waste Operations (MWO) team is one of five technical groups that comprise the Robotics Technology Development Program. It is composed of six DOE laboratories and sites that are working with industry and universities to develop state-of-the-art technology to store and treat low-level and transuranic mixed wastes. The team works closely with the Mixed Waste Focus Area identifying and prioritizing needs and opportunities to clean up over 240,000 cubic meters of low-level mixed waste at DOE sites. Actual cleanup is expected to generate about 300,000 cubic meters of mixed low-level waste over the next five years. During this time, the waste will be monitored during storage, then treated and disposed of in accordance with federal and state regulations. Robotics is playing an integral part in this cleanup effort with faster, safer, and more cost-effective methods.

Robotics MWO is coordinated through the Savannah River Technology Center, with Clyde Ward as the lead Technical Coordinator and Randy Singer as Alternate Coordinator. Team participants include representatives from the following DOE sites:

- Fernald Environmental Management Project (FEMP);
- Idaho National Engineering Laboratory (INEL);
- Lawrence Livermore National Laboratory (LLNL);
- Oak Ridge National Laboratory (ORNL);
- Sandia National Laboratory (SNL); and
- Savannah River Technology Center (SRTC).

Major objectives of MWO are presented in the following chapters and include specific points of contact.

3.1 AUTOMATED WORKCELL MODEL UPDATING

TASK DESCRIPTION

Computer models of the environment are being used for graphical programming, path planning, and collision avoidance of robots being developed for mixed waste treatment facilities. This task will demonstrate, test, and evaluate systems to update a typical mixed waste workcell model accurately, quickly, and easily. See Figure 3.1.

A structured light system from Sandia National Laboratories (SNL) and Mechanical Technologies, Inc. (MTI) has been installed in the Telerobot facility at Savannah River Technology Center (SRTC). The Telerobot facility is typical of the environment expected in mixed waste facilities. An initial demonstration of proof of principle has been performed and the system modeling speed and accuracy has been improved. Automatic entry of the information derived by the structured light system into the computer model with a minimum of geometric shapes (while retaining required accuracy) is being developed.

Operator interaction to quickly and accurately enter repetitive and familiar objects, such as 55-gallon drums, is being developed. Competitive systems, i.e., laser camera systems, will be evaluated for this application in the future and compared to structured light for speed, accuracy, and ease of entry into the simulation model.

TECHNOLOGY NEEDS

Model-based technology being developed for path planning and collision avoidance will be important in the efficient and safe operation of mixed waste facilities using the Generic Intelligent System Control (GISC). The graphical simulation capabilities of GISC require an accurate and current model to be useful. Because of the high volume of different containers and high volume of different waste items that will be transported through mixed waste treatment facilities, a system to automatically and constantly update the model of the workcell will be required. This system must be accurate, fast, and easy to operate.

ACCOMPLISHMENTS

MTI, SNL, and SRTC have demonstrated this technology in a simulated mixed waste workcell at SRTC. The workcell is approximately 20 feet by 20 feet in area. A metal box, representing a large waste item such as a glovebox, was placed in the workcell but not entered into the model. The structured light system used four identical stations at each corner of the workcell to model the box. Each station has two precise stages with very accurate feedback that act as a pan and tilt mechanism. These stages manipulated a camera and laser line generator (laser and lens). One station passed the laser line across the workcell, while a camera on a second station tracked the line. By repeating this with two to four laser/camera pairs, the shape and location of the box was calculated. This information was then automatically entered into the graphical simulation system as a model of the box. The model was accurate to ± 1 inch in this application. The modeling process took approximately 15 minutes in the initial demonstra-

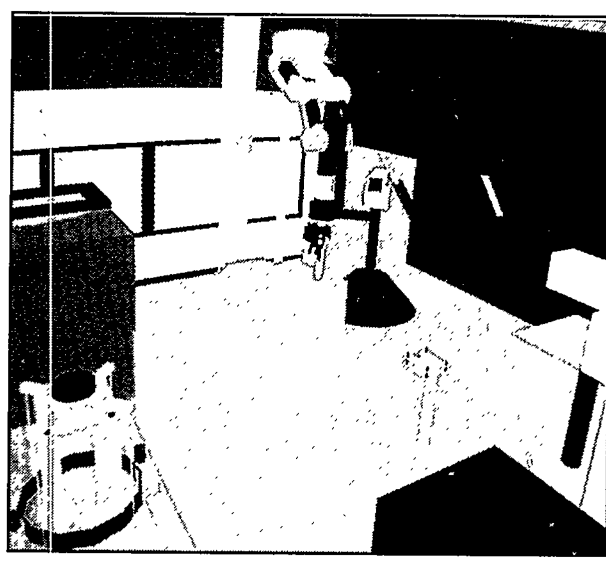

Figure 3.1. Automated Workcell Model Updating.

tion. Software improvements have reduced this time to less than two minutes. MTI has developed new hardware that could reduce the total time to less than 30 seconds.

Benefits

This technology permits model-based control to be implemented in typical mixed waste facilities with constantly changing and moving containers and materials. It will allow tasks to be planned, previewed, and programmed based on accurate, up-to-date information on the facility. Reliable collision-free paths can be planned and executed. This technology can automatically model an item in a workcell in 1/2 to 2 minutes that would require 30 to 60 minutes, if performed manually. It also eliminates the risk and exposure that manual measuring would require.

Collaboration/Technology Transfer

SNL has a CRADA with Mechanical Technologies, Inc. (MTI) on a structured light modeling system. MTI, with assistance from SNL, has provided a structured light system to the SRTC that demonstrated automated updating of a typical mixed waste workcell model. As improvements in accuracy and speed are developed, they will be available for technology transfer to industry. MTI now offers this technology commercially.

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3.2 Waste Item Characterization and Sorting

Task Description

This task will develop a system for remote characterization of mixed waste material while still in a drum or other container and after removal from the container. Characterization is used for sorting waste items before treatment and for the inspection of items after treatment. Lawrence Livermore National Laboratory (LLNL) has demonstrated characterization on the contents of a whole waste drum and on individual mock waste items removed from a drum using non-intrusive methods, i.e., non-destructive evaluation (NDE) and non-destructive assay (NDA) technologies. See Figure 3.2a.

Autonomous Radiography (both Real Time and Digital Radiography (RTR and DR), Computed Tomography (both Transmission and Active & Passive Computed Tomography (TCT and A&PCT), X-Ray Fluorescence (XRF), Spectroscopy Radiation Detection (SRD), and Eddy Current Metal Detection (ECMD) are being developed for the characterization of whole drums and single items placed in trays (singulation). See Figure 3.2b. The most important sorting criteria will be based on information from the Mixed Waste Focus Area and the Mixed Waste Treatment Project. Technology to accomplish this priority sorting is being developed. This task will leverage previous work accomplished at LLNL, and appropriate equipment available at LLNL.

Technology Needs

Mixed waste treatment facilities will have to characterize most or all of the items entering the facility to determine their acceptability and sort them for the different treatment processes. Characterization is also used during the inspection process to verify that treatment is adequate. Characterization of the contents of an entire container (drum, box, or bin) may be necessary to determine if containers can enter the facility, to consolidate material types, and for omnivorous treatment, i.e., the plasma hearth process.

Characterization and sorting of material removed from waste containers will be necessary for the treatment processes that require specific material, i.e., decontamination of lead and other valued metals. Individual item characterization can also provide higher resolution, accuracy, and confidence factors over whole container characterization.

The characterization and sorting of hundreds of thousands of cubic meters of mixed waste items in the DOE complex must be done efficiently and accurately. Remote characterization and sorting would also reduce exposure, risk of injury, and the generation of secondary waste from personal protective clothing and tools.

Accomplishments

Based upon program objectives, pertinent regulations, and an assessment of the non-intrusive inspection and characterization methods available, a characterization system to satisfy these requirements is being developed. Methods used in this system are radiography, computed tomography, gamma ray spectroscopy, x-ray fluorescence, and eddy current metal detection. This system can non-intrusively determine the approximate type and quantity of different materials, including radioactive materials, inside the waste drum or object, and show the location of the material in a 3-D representation. The different types of material are color-coded in a 3-D display to provide clear representation of the data. This equipment is at Lawrence Livermore National Laboratory (LLNL). Depending on the resolution and accuracy desired, this operation presently can take hours. However, techniques and equipment modifications to speed the process without a reduction in resolution or accuracy are being investigated. Initial tests of this same technology to characterize typical mixed waste items have had encouraging results. Cross-sections and 3-D models of waste items have been generated that indicate the location of different types of material.

A system to characterize dry heterogeneous material has been demonstrated by LLNL. Typical mixed waste items were characterized with and without the single or multiple plastic bags that are typical packaging for this material. Selected mock waste items have been characterized to unambiguously identify hazardous inorganic materials on the surface of objects. The presence of heavy metals within objects can also be ascertained. The volume of material using computed tomography and surface area densities using x-ray fluorescence can be determined to within a few percent. Minimum detectable amounts of materials have been calculated and confirmed for radiography/computed tomography and x-ray fluorescence technologies. These detection limits depend upon all elements that are present, and range down to the sub-milligram per square centimeter level for heavy elements detected by radiographic and tomographic methods. Surface detection limits are below the microgram per square centimeter level when using x-ray fluorescence technology. Integrating radiography with tomographic data sets has demonstrated the efficiency improvements possible compared to using these technologies used separately. A technique was developed to use only radiographic data where the material is homogeneous (a fast process), and then switch to tomography in those areas where heterogeneity is detected (a slower process).

The characterization methods described above would most effectively be employed in the work area and treatment cell itself. Ideally, the characterization would be done robotically, and either automatically or semi-automatically in order to improve efficiency and safety. The information received from the characterization system is used to sort the trays for different treatment options. Trays are automatically diverted from the main conveyor onto side conveyors that would be sent to different treatment processes in an actual waste facility. In some cases, the material could be conveyed into another cell and processed in gloveboxes. Highly contaminated items or specific types of contamination on items could remain inside the plastic bags and be isolated in a glovebox to segregate contamination and aid in contamination control.

BENEFITS

Whole drum non-intrusive characterization allows the determination of drum contents without the time and risk required for opening the drum. Non-intrusive NDE and NDA technologies can characterize information in a computer-generated record that is easy to interpret and digitally archived. Individual object characterization gives higher resolution, accuracy and confidence factors than whole drum characterization. It does not necessarily require the time and risk of removing the plastic film surrounding each waste item.

Automated/semi-automated object characterization will improve the accuracy for sorting and inspection techniques. Automated sorting eliminates the labor required for this monotonous, yet demanding task and provides a reliable and predictable disposition according to preselected specifications. Automated/semi-automated non-intrusive characterization of whole containers and individual waste items will reduce costs associated with treatment, recycling and disposal of waste.

COLLABORATION/TECHNOLOGY TRANSFER

This technology, being developed by LLNL, will be available for transfer to industry when it is mature. LLNL is already teaming with Bio-Imaging Research (BIR), Inc. to commercialize the whole drum characterization technology.

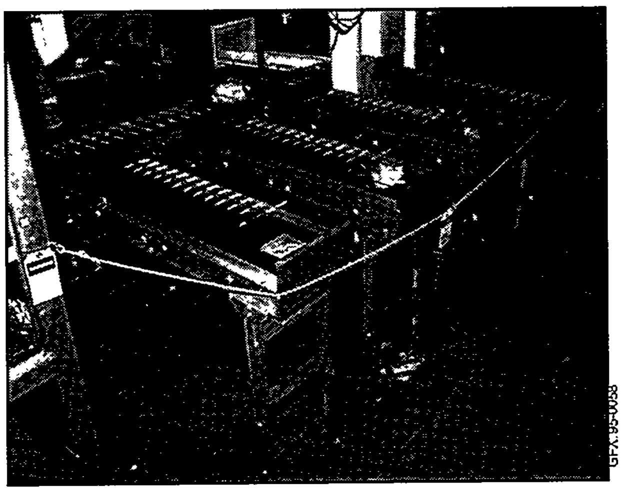

Figure 3.2a. Waste Characterization Conveyor Passing Through Characterization Stations.

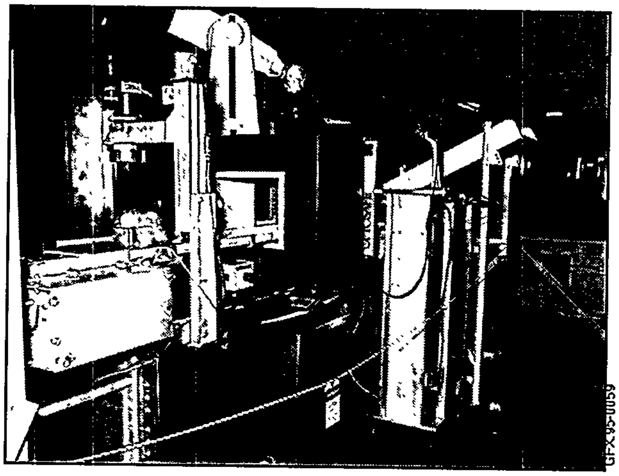

Figure 3.2b. Trays of Waste Automatically Sorted.

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TTP Numbers: SR113201 and SF213201

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3.3 WASTE CONTAINER OPERATING AND TRANSPORTATION

TASK DESCRIPTION

This project is developing technology for the remote opening and transport of waste drums. This project will specifically address (1) opening of boxes and bins, and (2) transport of drums, boxes, and bins in and between facilities.

The concept for remote drum opening includes a vertical-axis, rotating chuck for 30-, 55- and 83-gallon drums. There are two opposing towers on either side of the chuck. Idler wheels to support the drum are engaged from one tower. Tools are deployed from the opposite tower as the drum is rotated. After the drum is cut and the top is removed, other tools are deployed to cut the plastic liner. The drum is positioned in the drum opener and cut portions are removed by a gantry robot with a drum lifter end-effector.

The concept for remote box and bin opening is the deployment of special tools by a gantry robot to cut the top of the box and bin. The ganty robot will allow the remote opening of many different-sized boxes and bins. High pressure liquid nitrogen cutting (cryogenic cutting) is being tested and evaluated as a tool for cutting both metal bins and wood boxes.

The existing material transport control systems in place at the Fernald Environmental Management Project (FEMP), which are thought to be typical of systems at other DOE sites, are being investigated. It is anticipated that computer-aided dispatch and monitoring of materials handling vehicles at FEMP and other sites will provide optimized transport and documentation. An investigation of state-of-the-art material transport to and from facilities is also being conducted. The results and conclusions of this investigation will be used to guide technology development in this area.

TECHNOLOGY NEEDS

Tens of thousands of drums, bins, and boxes of waste will have to be transported inside waste treatment facilities. Manual handling would be a safety risk, especially with the large number of drums, bins, and boxes that will be processed over the life of a facility. The large bins and boxes would likely be transported by overhead crane. Another task in the Mixed Waste Operations Robotics Program, Swing-Free Crane Control, addresses this issue.

There are many options for remote drum transport. However, if a gantry robot with a suitable work envelope and load capacity is available, a drum lifting end-effector can quickly and reliably move drums in a precise path. This end-effector can also precisely locate them in machines that require top loading, such as a drum and liner opener. This concept does not require the floor space, or the large volume of components that will eventually become waste and the maintenance of a large conveyor system. Also, a gantry robot is much more flexible. As needs change within a facility, material flow and storage locations can easily be changed with a drum lifting end-effector on a gantry robot. Stacking of drums to minimize use of floor space is feasible with this concept.

Waste containers must be opened in waste treatment facilities to remove their contents. Many of the drums and bins, as well as their fasteners will be corroded and deteriorated so that removal of the lids would be difficult. Manual opening of the containers would risk injury from exertion, power tools, and sharp edges. Remote container opening would reduce risk of injury, reduce secondary waste from personal protective clothing, and increase throughput.

For metal drums and metal drums with plastic liners, the drum may be chucked and rotated while special tools are used to cut the drum and the liner. Many different sizes of boxes and bins must be accommodated. For wood boxes and metal bins, a process that does not ignite the wood container or the combustible material inside the container is required. This process should not be compromised by contact with material inside the containers. Saws that cut wood boxes can be ruined by contact with nails in the box and metal objects inside the box. Thermal cutting, such as plasma arc cutting, can cut open a metal bin, but would ignite the combustible material inside the bin.

As the site cleanup effort increases, the volume of waste containers requiring transport within the site will increase. A safe and efficient material handling system is required for this container transport.

ACCOMPLISHMENTS

A drum lifter end-effector has been designed, built, and tested. See Figure 3.3a. It has been tested with a 55-gallon drum that weighed over a thousand pounds and performed well even with deformed drums. The drum lifter included an Applied Robotics tool changer that allowed it to be picked up, operated, and returned by a suitably equipped and compatible gantry robot. It has sensors that measure relative force and displacement of the lifting straps. These sensors are monitored and used for control during operation. It has demonstrated picking up and loading a drum into a remotely operated drum opener and removing parts of the drum and liner after cutting. The drum lifter has been tested and evaluated. Potential improvements have been identified.

A drum and liner opening system has been built and demonstrated remote opening of a 55-gallon drum and 0.090-inch thick plastic liner. See Figure 3.3b. Tools and supports were deployed from opposing masts and were remotely manipulated up and down on the mast and in and out. A sharp-edged wheel has been used to cut the metal drum. Both a powered saw and a parting tool have been used to cut the plastic liner. Many sensors were used on the equipment to remotely monitor and control operation of the system. Many different types of tools and different techniques were tested on this system during the testing and evaluation. Cutting of the drum and liner was accomplished in less than fifteen minutes.

Cryogenic cutting, using high-pressure liquid nitrogen was developed and demonstrated. It has cut through both carbon steel and plywood, representing bins and boxes. The system has also been installed on a gantry system in preparation for demonstration of opening of bins and boxes. A wooden box was cut open at a speed of thirty inches per minute. Metal cutting tests indicated that seven hours would be required to cut open a metal drum. Improvements, particularly in speed, are expected as development continues.


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Figure 3.3a. Drum Lifter End-Effector.

BENEFITS

Use of a drum lifter on a gantry robot provides precise, reliable, and repeatable transport of drums in a mixed waste facility. It also improves safety by removing the operator from close proximity to the moving drum. It reduces transport time over manual methods and reduces the risk of damage to the drum, other material, or equipment in the facility.

Remote drum and liner opening reduces the risk of injury from exertion, power tools and sharp edges. It reduces secondary waste from personal protective clothing and increases throughput. Opening of a drum and liner can be accomplished remotely in less than 15 minutes. It takes more than 20 minutes just for an operator to suit up, monitor, and remove protective clothing. This technology has been developed, tested and evaluated before inclusion in the Waste Characterization Facility (WCF) at INEL, which increases the probability of successful operation.

Cryogenic cutting uses liquid nitrogen, so no heat is produced. This feature is important in opening metal bins with combustible material inside, so that high-temperature methods, like plasma arc cutting, are unacceptable. Cryogenic cutting also produces no secondary waste stream. Wood cutting of 30 inches per minute is quite competitive with many cutting methods and much faster than water jet cutting, which also produces a secondary waste stream. Metal cutting rates will improve as development continues to be competitive with other metal cutting processes.

COLLABORATION/TECHNOLOGY TRANSFER

The tool changer for the drum lifter is the first electrically actuated tool changer developed by Applied Robotics. This product is now commercially available.

The drum and liner opening equipment designed and installed at the Savannah River Technology Center is similar in concept to the proposed WCF at INEL. The concept drawings of the drum and liner opening equipment for the WCF were provided by Merrick & Company. Many of these concepts were included in the SRTC final design. Initial testing of the SRTC equipment has identified tools and techniques that will open drums and liners. Other types of tools and techniques were tested to optimize the process. The optimization tests were conducted by SRTC and Merrick & Company and will aid in the design of actual equipment for the WCF and other mixed waste facilities.

Multiple CRADAs are being negotiated with different companies on cryogenic cutting. Each CRADA addresses a different aspect of the cryogenic cutting system.

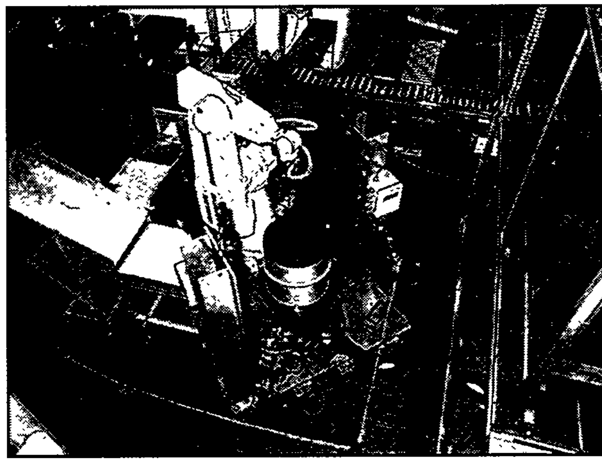

Figure 3.3b. Drum and Liner Opening System.

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None at this time.

3.4 WASTE ITEM SINGULATION

TASK DESCRIPTION

This task will develop a capability for remote removal of individual waste items (singulation) from their initial containers. These singulated items will be typical of solid, dry, heterogeneous, mixed waste. This task will enhance teleoperator capabilities and develop autonomous capabilities for singulation of waste objects from drums, bins, and boxes. Autonomous operation will provide the highest productivity, but due to the variety and uncertainty of waste items, teleoperation will be required for some of the waste items. This task will enhance teleoperation capabilities with remote viewing, force control, and other techniques to increase productivity with equipment suitable for mixed waste facilities. See Figure 3.4. This task will also develop autonomous capabilities, including automated modeling technology, autonomous grasping, collision avoidance, and force control to provide autonomous singulation for a majority of waste items. Initial work is using manipulators with a capacity of 40 pounds or more to include most waste items in drums. Initial autonomous singulation development is for repetitive shapes, such as lead bricks. Future work will expand to manipulators with a capacity of 200 pounds or more to include all of the items expected in drums and many of the items expected in bins and boxes. The manipulators must be appropriate for operation, maintenance, and repair in mixed waste treatment facilities.

TECHNOLOGY NEEDS

Throughout many years of operation in mixed waste facilities, high volumes of solid, dry, heterogeneous, mixed waste must be removed from drums, boxes, and bins and individually separated (singulation) for characterization and treatment. In some cases specific materials must be removed that are incompatible with treatment processes, such as lead or mercury. Opening the containers may produce sharp and jagged edges and the objects, i.e., glass vials and motors, may have sharp edges and be difficult to lift. Manual removal of these items would expose personnel to radiation and hazardous material and would create safety risks. Any cuts or wounds to personnel in this environment will be potentially contaminated. An extended reach would be required for heavy items at the bottom of drums. Remote singulation is needed to reduce risk and exposure of personnel, to increase throughput and to reduce the secondary waste generated from manual operation (personal protective equipment).

ACCOMPLISHMENTS

Teleoperated singulation has been demonstrated with a Programmable Universal Manipulator for Assembly (PUMA) robot with a payload of approximately 40 pounds. A JR3 force sensor was attached to the wrist to measure forces and moments. A Robohand tool changer allowed the use of many different end-effectors. To provide efficient use of this industrial robot in a teleoperated mode, a Generic Intelligent System Control (GISC) compatible software module called SMART (Sequential Modular Architecture for Robotics and Teleoperation) was used. SMART allows the use of many different master input devices. A Dimension 6 force ball by CIS was handled to manipulate the PUMA during the demonstration. This device was handled by the operator to remotely control the robot, using external cameras and cameras on the robot to find the objects. The force sensor was used to prevent excessive forces and moments that could damage the robot, the waste items, or surrounding equipment from being developed during singulation. The force sensor was also used to determine the weight of the waste item. Waste items from a drum and a pile were deposited in trays at the inlet to a waste item characterization system.

Autonomous singulation was achieved for lead bricks. These objects were randomly deposited in a pile and a structured light system was used to acquire a range image of the pile. From the range image data, a surface model was generated articulating the location, orientation, and relative height of the objects in the pile. Using the surface model information, a stable grasp of the unknown shaped objects was planned algorithmically by using a ranking system in the grasp planning algorithm. Based on this algorithm, the manipulator is directed to pick up the highest object in the pile using a selected pose. This operation continued until all bricks were removed from the pile and placed in a stack without human intervention.

BENEFITS

The main benefit of teleoperated or autonomous singulation is the removal of the human from a hazardous environment requiring strenuous activity, risk of injury, and in particular, risk of contamination. The mixed waste will contain glass and other objects that can cause not only cuts, but contaminated cuts. A waste drum is 35 inches deep and would require an awkward, extended reach to lift an object. This type of physical activity has a high risk of injury. Remote object removal from a drum, coupled with remote drum opening, being developed under a separate task, would remove the operator from this hazardous environment and eliminate the exposure and risk of injury inherent in manual operation. It would also reduce the secondary waste generated by protective clothing and potentially increase throughput and efficiency, since dress out for manual operation would not be required.

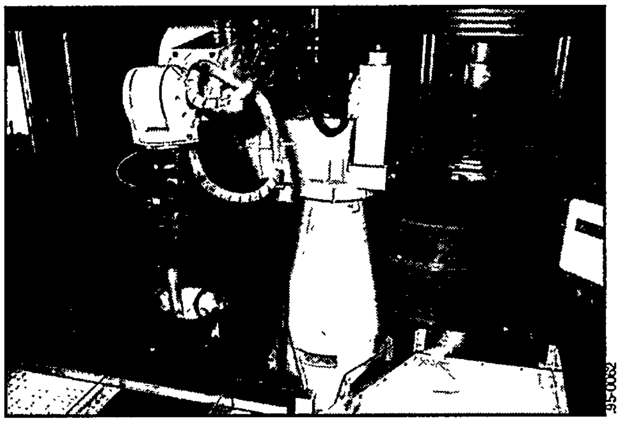

Figure 3.4. Robotic Waste Removal and Characterization.

Manual material handling of a large number of repetitive mixed waste objects, such as lead bricks, can be accomplished in protective clothing or in gloveboxes. However, repetitive lifting of these heavy objects, particularly with the extended reach required in a glovebox, can cause chronic injuries. This operation can be accomplished autonomously, eliminating the labor required for this task and also eliminating the human exposure and risk of injury.

Manual removal of larger and heavier items from boxes and bins would present even higher risk of injury, so that remote operation would provide corresponding benefits.

COLLABORATION/TECHNOLOGY TRANSFER

Sandia National Laboratories, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, and Savannah River Technology Center are collaborating on this task. Initial singulation was accomplished on a commercially available PUMA robot by Staubli and is available for technology transfer. Future work will develop this technology for higher payload robots, potentially a PaR Systems gantry robot, which will also be available for transfer. Some of the structured light modeling technology has already been transferred by SNL and ORNL to Mechanical Technologies, Inc. (MTI) through CRADAs. Additional modeling technology will be available in the future.

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3.5 STORED WASTE AUTONOMOUS MOBILE INSPECTOR

TASK DESCRIPTION

The objective of this task is to develop a Stored Waste Autonomous Mobile Inspector (SWAMI) to demonstrate the potential for drum inspection and floor survey in waste drum warehouses. See Figure 3.5. This system will show the feasibility to augment the current manual inspection and provide documentation, inventory, and radiation data that is not currently available from manual inspection. The robot is based on the Help Mate mobile robot by Transitions Research Corporation. SWAMI will be able to navigate autonomously through simulated drum storage warehouses and capture a video image of each drum. It will read the bar coded number of the drum, and store the image, drum, number, time, date, and physical location in an on-board computer system. This information will be downloaded into an off-board computer database at the end of each run. The images and inventory information from previous inspections will be stored in this database for comparison, documentation, and trending analysis. The inventory information will also be transferred to the site database, so that the inventory will be updated every time an inspection is completed. SWAMI will also perform a radiation survey of the floor in the aisles during each inspection. SWAMI will stop and notify appropriate personnel if high contamination is encountered during the inspection. The radiation data will be downloaded into the off-board computer after each inspection and radiation maps of both alpha and beta/gamma levels in the aisles will be generated. These radiation maps will also be stored in the computer for documentation and trending analysis. The radiation survey technology is based on the Semi-Intelligent Mobile Observing Navigator (SIMON) developed previously on a Cybermotion mobile robot.

SWAMI will use the Generic Intelligent System Control (GISC) for supervisory control of all subsystems. GISC is the computer architecture and software being used throughout the DOE Robotics Technology Development Program to minimize costs and development time and maximize reuse and compatibility of software.

A second generation mobile inspector, SWAMI II, is being developed specifically for drums of waste stored in facilities at the FEMP. SWAMI II will include an image analysis system to identify rust spots and rust streaks. It will also have a structured light system and analysis system to identify drum dents and blisters. It will interface with the drum computer database at FEMP. SWAMI II will be able to autonomously drive backward to operate in the aisles at FEMP, many of which are dead-ended. This system will be tested at FEMP and meet objectives mutually agreed upon with the Ohio Environmental Protection Agency.

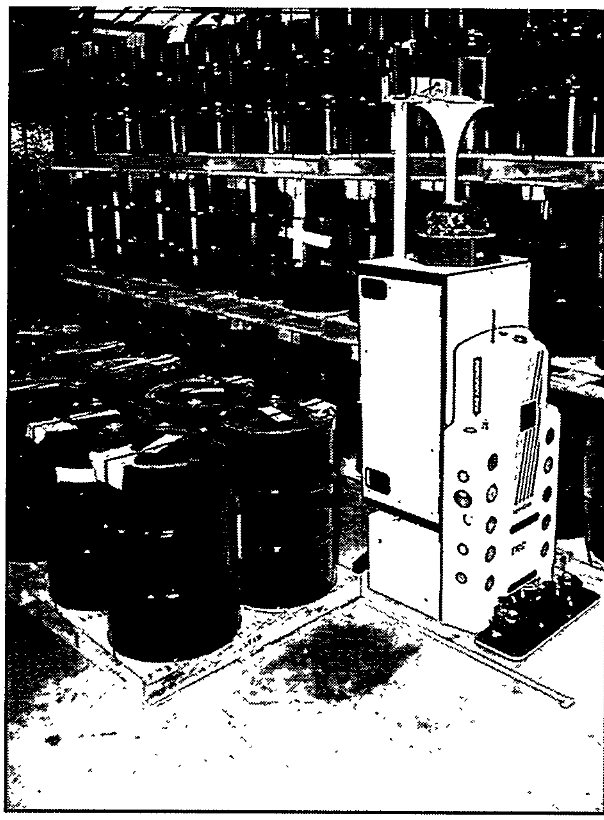

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Figure 3.5. Stored Waste Autonomous Mobile Inspector (SWAMI).

TECHNOLOGY NEEDS

There are tens of thousands of drums of low-level radioactive, hazardous and mixed waste stored at each of several major DOE sites. EPA regulations require weekly inspection of these drums. This is currently done manually and is a monotonous task. Manual inspection provides very limited documentation on the condition of these drums and inventories are updated on an infrequent basis. Robotic and vision systems can augment and improve the efficiency, documentation, and accuracy of drum inspections and inventory.

If a spill of radioactive material occurs, the inspectors can spread the contamination throughout the facility before the contamination can be detected on their shoes when they monitor at the warehouse exit. It has been shown at SRTC that a mobile robot can detect floor contamination more reliably and accurately than manual surveys conducted over a long period of time.

ACCOMPLISHMENTS

SWAMI was demonstrated in a drum storage warehouse mockup with typical 55-gallon drums on pallets stacked up to three levels high. SWAMI navigated through the open-ended aisles carrying a radiation detector and six sets of bar code readers, cameras, and strobe lights to gather information. The drum images were compressed and stored on-board the robot during the inspection. Radiation data and corresponding positions were also stored on-board. At the end of the inspection, all data was downloaded to an off-board computer while the robot was being recharged. The uncompressed drum images along with the drum numbers, dates, and positions (warehouse coordinates of the robot) were displayed on the off-board computer after the inspection. Radiation maps of data taken during an inspection were displayed. SWAMI also located a radiation source placed in the aisle and provided immediate notification over the radio link as well as stopping and flashing on-board lights.

Additional technology were developed and demonstrated to meet the Fernald application. A bar code reader capable of reading the Fernald label was demonstrated. A bench-scale structured light system demonstrated the ability to find dents in blisters on a drum surface.

BENEFITS

SWAMI can augment manual inspection by providing superior documentation of drum conditions and more reliable inventory auditing compared to typical manual operations. It can also provide more thorough floor survey than manual surveys over a long period of time. Cost/benefit analysis indicates a cost savings of $98,000 per year per 10,000 drums over manual methods with superior documentation and auditing. Estimated installed cost for each SWAMI are $200,000 to $300,000, depending on facility conditions and quantity purchased. This represents a payback period of 2-3 years for a single SWAMI.

COLLABORATION/TECHNOLOGY TRANSFER

Martin Marietta Astronautics is developing a vision analysis system through a Program Research and Development Announcement (PRDA). This system will analyze the drum images and detect rust spots and streaks (potential leaks). These suspect images would be presented to the operator for disposition. The operator can compare these images to previous images of the same drums taken by SWAMI to determine if these rust spots and streaks were there previously and if they are increasing in size or intensity. This technology will be added to SWAMI and SWAMI II to increase the ability of the operator to locate drums requiring action.

The SRTC has been working closely with Transitions Research Corporation (TRC) to develop its mobile robot, HelpMate, for this application. TRC has limited the HelpMate to hospital applications up to this time. TRC modified the Helpmate for the SWAMI application with special sensors to navigate between pallets and calibrate position, and a unit to hold the radiation sensors. The technology developed at SRTC includes off-board control and display, on-board control, radio ethernet communications, image recording, image compression, image storage, bar code reading, radiation survey, and radiation data display. This technology will be available to TRC and other mobile robot companies, such as Cybermotion, for commercialization. The radiation mapping software is being copyrighted to facilitate the transfer of this software to the mobile robot industry.

The on-board supervisory system was developed by the University of South Carolina. It is the first commercial mobile robot to use the Generic Intelligent System Control (GISC) for operation. Dent and blister recognition technology and vehicle position determination technology are being developed by the Georgia Institute of Technology. This technology will be integrated into SWAMI II and tested at Fernald. The University of Michigan is developing technology to provide collision avoidance while driving backwards. This is required on SWAMI II for the Fernald application, which will require backing out of aisles.

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3.6 SWING-FREE CRANE CONTROL

TASK DESCRIPTION

Swing-free crane control allows a load suspended from a cable on a gantry crane to be moved without inducing any undesired swing. The basic swing-free technology has been patented by SNL. The initial technology required prior knowledge of the period of swing, which is dependent on the pendulum length, and prior knowledge of the desired path of the load. As part of this task, SNL developed operator-in-the-loop swing-free control. This allows the operator to control the movement of the load in real time with a standard crane pendant or other input device, so the path does not have to be preprogrammed. As part of this task, SNL also has developed sensor-based, swing-free crane control where a sensor at the top of the cable measures cable displacement, so that swing-free control can be automatically implemented regardless of the period of swing. All of this technology has been demonstrated on a gantry robot at SNL. ORNL is developing sensor-based control for a gantry crane. The main objective of this task is to implement all of this technology on a standard, AC motor-driven gantry crane, and transfer it to industry, so that it is available for use in mixed waste facilities or in any facility that incorporates a gantry crane. Implementation of this technology on a gantry crane is being developed, demonstrated, tested, and evaluated by ORNL.

TECHNOLOGY NEEDS

Drums and particularly large, heavy containers, such as boxes and bins would likely be transported by overhead crane in mixed waste facilities. Operation of an overhead crane, especially by inexperienced operators, can cause severe swinging of the load which is dangerous to the operator and can damage the load or the facility. Swinging can also significantly increase the time required to move loads, particularly the time required to manually dampen out the swing before a load can be lowered. These problems are increased in a remote facility due to the distance of the operator from the load and restricted vision. A system to automatically provide swing-free transport of loads with a gantry crane, regardless of the weight, height, or path of the load would increase throughput and safety in mixed waste facilities or in any facility utilizing a gantry crane.

ACCOMPLISHMENTS

The basic swing-free technology has been patented by SNL and demonstrated on a gantry robot. The swing-free technology was transferred to ORNL where it and new algorithms have been demonstrated on a gantry crane. The crane is a standard, 30 ton, AC motor-driven crane, using new vector drives recently made available from industry. Swing-free operation of this crane with an operator in the loop has been shown to reduce swing from 30 cm to 3 cm. Algorithms developed by ORNL produced swing-free crane operation over a wide period of swing, depending on the pendulum length. With these algorithms, swing-free operation was demonstrated over a range of 25 percent to 100 percent of cable length. ORNL developed and tested different sensors at the top of the cable to measure cable displacement, so that swing-free control could be automatically implemented even when outside influences, such as bumping the load, are encountered.

BENEFITS

This technology permits loads to be transported without inducing significant swing. Swing has been reduced from 30 cm to 3 cm with this technology. This eliminates the need for manual intervention with tag lines or other means to control the load, which increases safety and reduces time required for moving loads. It eliminates the need for manual dampening of swing after a load has been moved before it can be set down, which, depending on operator skill, can save many minutes per load. The elimination of swing drastically reduces the potential for injury to personnel and damage to the load, other material, and facilities during transportation with gantry cranes.

COLLABORATION/TECHNOLOGY TRANSFER

SNL and ORNL are seeking gantry crane manufacturing companies interested in implementing this technology on new cranes and companies interested in retrofitting existing cranes with this technology. Convolve, Inc. has expressed interest in commercializing the swing-free crane technology. It is anticipated that additional interest from industry in this valuable technology will be generated as the results of this effort are publicized. The SNL patent number is 4,997,095.

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3.7 AUTOMATED HANDLING FOR WASTE PROCESSING OPERATIONS

TASK DESCRIPTION

This task will develop and demonstrate remote and autonomous robotic systems for mixed waste processing operations. The immediate goal is to identify and develop an automated system for handling and treating high-priority non-combustible mixed waste debris to meet RCRA disposal guidelines. This goal includes the integration of autonomous surface modeling, intelligent robotic controls (automated grasp planning, path planning, and surface following), and flexible mechanical grasping for the handling of the mixed waste and surface decontamination using selected surface treatment tools. This task will leverage previous work accomplished at LLNL.

TECHNOLOGY NEEDS

Many different processes will be required in mixed waste treatment facilities to treat and place the many different mixed waste streams into proper final waste forms. These processes must be reliable, efficient, and safe. Remote and autonomous operation will be required to achieve this. For example, manual manipulation of lead bricks for decontamination would be monotonous. It would also risk injury from extended reach and continuous lifting of heavy loads, and risk injury from manipulation in front of a frozen CO_2 pellet blast nozzle. Robotic manipulation would provide uniform manipulation during decontamination for the highest efficiency. In blasting and surveying, the programmed operations would be uniform, complete and reliable.

ACCOMPLISHMENTS

Over FY93 and FY94, the Waste Processing Operations team developed and demonstrated autonomous and teleoperated waste stream characterization, material handling, and surface decontamination of complex shaped waste objects in a glove box processing system. Automated cleaning of easily characterized shapes such as bricks was performed in FY93, along with teleoperated cleaning of complex shapes. In FY94, the emphasis was on extensive technology development and demonstration of automated material handling technologies integrated with an industrial waste treatment system for the treatment of non-combustible waste objects. This technology scheme used surface decontamination as an initial catalyst while keeping other waste treatment and processes such as plasma hearth furnace and vitrification as options for future extensibility.

A glove box gantry robot is in operation at LLNL. It is capable of remote operation of many treatment processes for mixed waste operations. The robot is enclosed in a glove box so that glove ports may be used for maintenance and to address unusual situations. The robot is modular so that components may be replaced by use of the gloveports. It is electrically actuated and can operate in different types of glove box atmospheres (air, nitrogen, argon, partial vacuum, etc.). It is capable of teleoperation as well as programmed operation and has a lifting capacity of 80 pounds. A parallel jaw gripper with innovative tip designs was used to perform operations and manipulate objects in the glove box. The robot has been used to pick up and transport complex waste objects, manipulate them in front of a frozen CO_2 blasting nozzle, and manipulate contact inspection tooling on the surface of the object.

A key technical accomplishment was improving the intelligent robotics for more portability of the automated material handling capabilities. An integrated approach for developing a 3-D surface model that could be used to generate a 3-D representation was developed. The range image data was acquired using a stereo vision system or the ORNL structured lighting system. The data structure is IGES-compatible and allows for transfers to Auto Cad and graphic simulation systems. The LLNL team used this common data structure in model-based, collision-free, workcell path planning, grasp planning of waste objects, and object surface path planning/surface following. In addition, the resources for these processes were combined to maximize resource uses and allow for the easy transfer of information between systems.

A frozen CO_2 blasting system for simulated surface decontamination of complex shaped waste objects was demonstrated. CO_2 blasting is well-established for manual decontamination throughout the DOE and commercial nuclear power complexes. The technique uses a high velocity stream of solid CO_2 pellets for contaminant removal. Pellet impact and the volume change associated with sublimation are responsible for the effective surface cleaning. Principal attributes of the CO_2 decontamination included using an established industrial capability for surface decontamination that is used by the aircraft and food processing industries, and generates almost no secondary waste stream. The CO_2 blasting capability was well suited to the mixed waste treatment stream (metal debris and lead). Information acquired using automated surface modeling and following on the location of remaining contamination could be used to reblast only those specific areas. Use of robotics for this operation assures complete and uniform blasting and inspection. This technology could also be applied to different treatment processes where accurate following of the surface of a waste item is required.

Benefits

Manual decontamination of waste stream objects, such as lead bricks, is a strenuous, monotonous task that can result in chronic injury. Automated material handling for decontamination and survey would not only remove the risk of injury, but provide a much more reliable and repetitive operation. Each decontamination and survey would be uniform when completed with programmed operation. The completeness and reliability of monotonous manual tasks that require manipulation at a slow rate, at a fixed distance, over the entire surface, for a large number of objects would decrease over time. However, the reliability of automated handling would remain the same over time. Automation of material handling operations would eliminate significant labor requirements and protect the operator from unknown hazards.

Collaboration/Technology Transfer

LLNL, ORNL, SNL, and SRTC have collaborated on this task. LLNL has collaborated with International Business Machines (IBM) to develop an electric gantry robot suitable for operation in a glove box. LLNL is also collaborating with Cimetrix to enhance its Robline robot control system to be compatible with the GISC. LLNL and SRTC have worked with Alpheus to provide a stationary frozen CO_2 blast system for decontamination of lead bricks. ORNL has a CRADA with Mechanical Technologies, Inc. (MTI) on a structured lighting modeling system suitable for modeling waste items. All of this technology is available for transfer to industry.

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ROBOTICS DECONTAMINATION AND DISMANTLEMENT (D&D)

Section 4.0

4.0 ROBOTICS DECONTAMINATION AND DISMANTLEMENT (D&D)

There are a large number of contaminated facilities including hot cells, canyons, glove boxes, and reactor facilities at DOE sites that must eventually undergo some form of decontamination and dismantlement (D&D). As facilities transition from operational use, they will be deactivated and prepared for continuing surveillance and maintenance (S&M). Deactivation and S&M activities pose many of the problems that will need to be addressed in ultimate D&D; emphasis is placed on characterization, data capture, and selective D&D in order to define and minimize risk and costs associated with possible long-term S&M status. Overall emphasis of OTD's Robotics D&D Program is to focus on systems and capabilities that can be used in facility deactivation and ongoing S&M activities with extended application to final facility D&D tasks.

The crosscutting technology developed by D&D applies to the following focus areas:

- Radioactive Tank Waste Remediation; and
- Facility Transitioning, Decommissioning, and Final Disposition

4.1 SURVEILLANCE AND MAINTENANCE RISK AND COST REDUCTION EVALUATION METHODOLOGIES

TASK DESCRIPTION

The Surveillance and Maintenance (S&M) Risk and Cost Reduction Evaluation Methodologies activity provides for the development of analysis methodologies for the evaluation of risk and cost/benefit tradeoffs associated with robotics systems in reducing facility S&M costs. Applications for robotic systems during both facility deactivation and continuing S&M are considered. Assessment of methodologies will be performed and include data collection regarding deactivation and ongoing S&M tasks to define pertinent parameters for the development of a meaningful evaluation methodology. From the assessment of methodologies, a final strategy/approach will be selected to be used for ongoing S&M evaluations. Evaluations on candidate facilities will be performed to test and refine the methodology.

TECHNOLOGY NEEDS

A methodology is needed to assist in evaluating the level of activities to be performed during facility deactivation and ongoing S&M to properly address the combination of risk and cost associated with various activity scenarios. Use of robotic or remote systems as part of those activities needs to be properly represented to understand the true potential impact and payoff. The development cost, operational cost during deactivation and S&M, and the potential for ultimate use during final D&D are parameters that are included in evaluations relative to the use of robotic and remote systems for these tasks.

ACCOMPLISHMENTS

This activity was initiated in the third quarter of FY94. Accomplishments during FY94 included:

- Through collaboration with JBF Associates, Inc., existing risk analysis methods were surveyed. The best-suited approaches were determined. Parameters pertinent to robotic operations/applications that are used as inputs for evaluating risks, costs, and benefits were defined and integrated into a measurement scheme. A planning methodology was established. A prototype computer code was written that served as an analysis tool for implementing the methodology.
- The methodology was demonstrated at INEL on September 7-8, 1994. The demonstration goal was to remove dirt and loose material from the off-gas cell floor at a waste calcining facility. The preferred cleanup option was found to be remote liquid decontamination. Methods for identifying areas where research and development would have the greatest impact on the decision to use robotics were discussed and demonstrated. The lead for this task will move from ORNL to SRTC in FY95. SRTC will become familiar with prior work and complete the review and assessment of the methodologies. SRTC's refined/updated method will be applied to a DOE facility.

BENEFITS

This method will provide a fairer representation of robotic technology during decision-making and greater application of technology for facility S&M and D&D, including:

- Lower costs and greater benefits;
- Mitigation of risks during S&M and D&D; and
- Research and development directions based on D&D and S&M decisions and statement of needs.

Collaboration/Technology Transfer

This technology is being jointly developed by ORNL, SRTC, SNL, and INEL.

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4.2 Mapping, Characterization, and Inspection System

Task Description

The Mapping, Characterization, and Inspection System activity provides for the development and demonstration of a multi-purpose mobile robotic system for facility mapping, contaminant characterization, and inspection functions associated with facility S&M. See Figure 4.2. Development will begin on hierarchical data acquisition, data management, and data display for three-dimensional facility mapping, contaminant mapping and record keeping, as well as contamination/configuration tracking. The mobile robotic system will initially perform floor characterization using radiation sensors to generate contaminant information to be used as the initial data for the facility mapping system. The facility mapping system will provide the capability to capture facility geometry data upon which contaminant data may be mapped. Facility mapping captures characterization data and identifies candidate areas for selective D&D that can then be evaluated relative to minimizing ongoing S&M risks and costs. As activities occur, the mapping system can be updated to reflect current conditions and to maintain facility configuration information for eventual D&D activity planning, control, and monitoring. This task will interact and incorporate mapping technologies developed through DOE/EM, OTD funded PRDA contracts with Mechanical Technology, Inc., and Coleman Research.

Technology Needs

Facility deactivation and S&M activities place emphasis on characterization and data capture in order to define the condition of the facility and minimize the risk and costs associated with possible long-term S&M activities required prior to final D&D. Physical and contaminant characterization of a facility in question can be performed manually or with remote or robotic system assistance. Data generated from these activities must be captured in a form that is readily usable for visualization of the facility, equipment, and possible contaminants. The data will also provide input for control purposes to remote or robotic systems to be used during deactivation, S&M, or final D&D. Such a system can also provide a long-term record of facility configuration and condition as deactivation, S&M, or D&D activities take place.

A system to perform floor characterization needs to be developed for the hundreds of acres of floor space at DOE facilities which require characterization and ultimate decontamination. The floors must be characterized before, during, and after any decontamination activities. Floor characterization of these huge areas by manual methods is slow, prone to error, and generates excessive secondary waste from worker protective clothing. Mobile robotic systems are faster, produces more reliable, repeatable data, and reduce waste and personnel exposure.

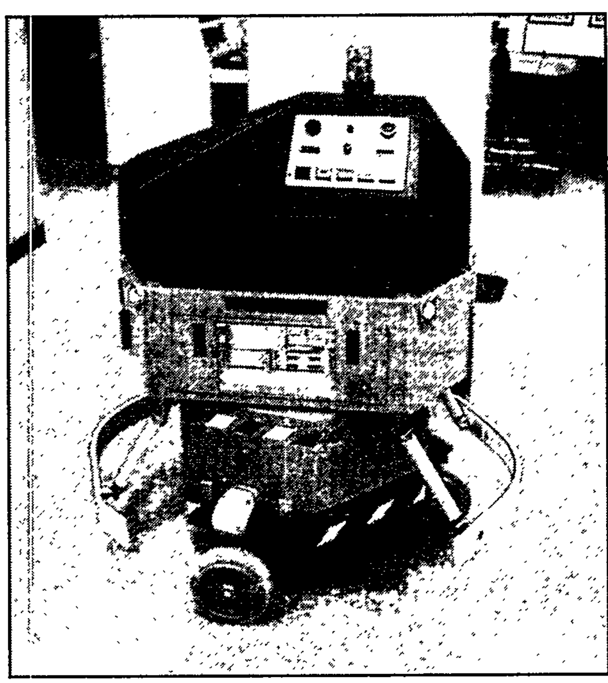

Figure 4.2. Mobile Automation Characterization System (MACS).

ACCOMPLISHMENTS

This activity was initiated in FY94. Past accomplishments and future plans include:

- Requirements and conceptual design were developed for the facility mapping system during the first half of FY94.
- Capabilities developed by industry (primarily under DOE PRDA contracts) were evaluated for completeness and functionality. Additional functions were prototyped to provide an initial system capability for demonstration in the fourth quarter of FY94. This demonstration was given to an audience consisting of the D&D National Coordinator and reviewers from the National Academy of Sciences.
- In FY95, data from the facility mapping system will be integrated into system control and simulation capabilities using the interfaces defined in FY94.
- As an initial implementation of the data gathering characterization system, specifications for a floor characterization system based on previous work at SRTC and requirements determined for use of the system in the Oak Ridge K-25 Site process buildings will be established and complete in early FY95.
- An industry procurement for the floor characterization system was placed the third quarter of FY94. System integration and testing of the floor characterization system are targeted for the second quarter of FY95 for radiological contamination sensing.
- In FY95, increased automation capabilities and a subsystem for enhanced access of restricted spaces will be added to the floor characterization system.

BENEFITS

Automated floor characterization offers the following advantages:

- Cost reduction with simultaneous and round-the-clock operations.
- Data quality enhancement through improved scan rate control.
- Precise record keeping through automated data collection and storage.
- Survey data comparisons not feasible by manual methods.
- Elimination of tedious tasks.

COLLABORATION/TECHNOLOGY TRANSFER

This technology is being jointly developed by the ORNL, SRTC, INEL, and SNL. It will include industry interactions with Mechanical Technology, Inc., and Coleman Research.

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4.3 Selective Equipment Removal System

Task Description

The Selective Equipment Removal System (SERS) has been developed to demonstrate and evaluate a mobile telerobotic system suitable for performing selective D&D functions applicable to pre-S&M facility preparations. The SERS uses a reconfigurable dual-arm work module (DAWM) to demonstrate inspection, decontamination, and equipment removal operations. DAWM has been deployed from an overhead transporter for initial SERS demonstrations. See Figure 4.3a. Evaluations will be performed in FY95 and FY96 through interaction with the OTD-funded PRDA contract at Carnegie Mellon University (CMU)/RedZone Robotics, Inc., for the development of a mobile work system. See Figure 4.3b. SERS tasks have included development of operator control console capabilities, development of scene generation and analysis capabilities, and a tooling compatibility study, along with a remote tool set. Interfaces to a facility mapping capability will be established to allow data exchange for graphics and control functions as that technology is developed.

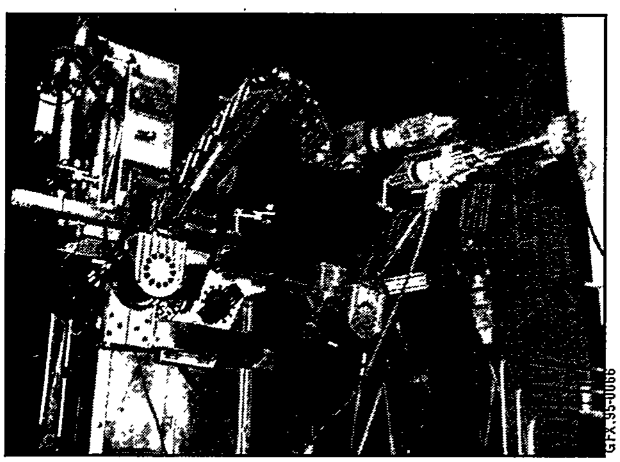

Figure 4.3a. Overhead Transporter Deployment of DAWM.

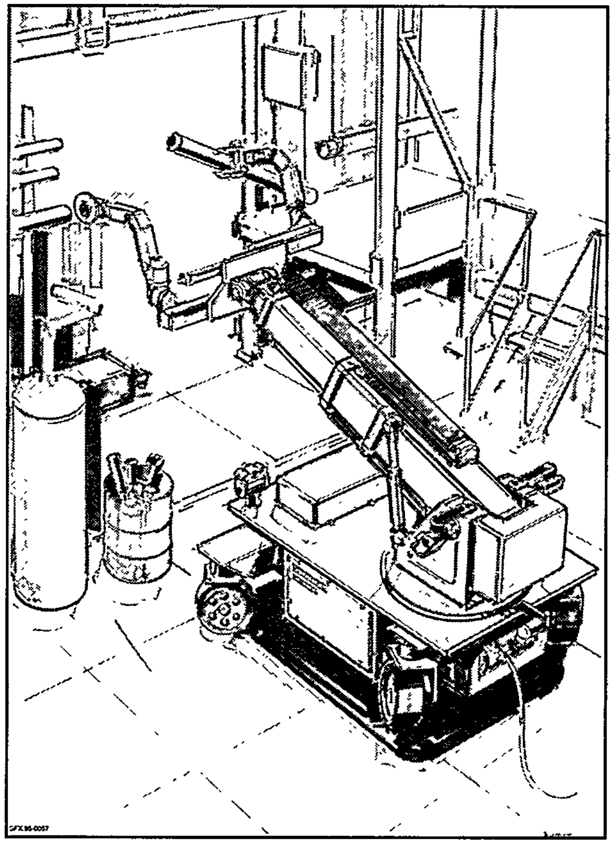

Figure 4.3b. CMU/RedZone Mobile Vehicle Deployment Option.

Technology Needs

Hazards associated with contaminated hot cells, canyons, glove boxes, and reactor facilities at DOE sites are radiation, radiological contamination of the equipment to be removed, and hazardous chemicals associated with the processes performed at the facilities. Because of these hazards, deactivation, S&M, and ultimate D&D will have to be performed remotely. D&D operations include disassembly of process equipment, cutting pipes, size reduction of equipment to be removed, transport of pipe and equipment out of the facilities, decontamination of equipment before removal from a facility, and decontamination of floors, walls, and remaining equipment in facilities to be refurbished. Robotics may also be needed to dismantle the facility structure. Hardened robotic systems for facility D&D can provide capabilities to accomplish these operations safely with workers away from the work site.

Facility deactivation activities place emphasis on selective D&D in order to minimize the risk and costs associated with potentially long-term S&M activities and final D&D. For pre-S&M facility preparations, or ongoing S&M activities, a remote system capable of being deployed for selective D&D can eliminate high risk or high S&M cost contaminants or equipment.

ACCOMPLISHMENTS

This activity was initiated in FY94. Past accomplishments and future plans are expected to include:

- Initial SERS subsystem fabrication, modification, and integration was completed in FY94. Specific subsystems include a dual-arm work module, deployment from an overhead transporter, operator control console, task space scene analysis system, and high- and low-level control system capabilities required to provide teleoperation, telerobotic operation, and robotic operation. The overhead transporter deployed SERS began task demonstration in the fourth quarter of FY94 at ORNL.

- Human-machine interfaces and automation enhancements will be developed to support various modes of mobile deployment. Cost effectiveness of telerobotic equipment inspection, decontamination, and removal will be evaluated.

- In FY96, vehicle deployment and demonstration of SERS will be completed via integration with the vehicle system being developed under DOE PRDA contract at CMU.

- Expansion and evaluation of automation features will continue in FY96 to extend the range of work tasks.

BENEFITS

Development of SERS will provide the capability to demonstrate and evaluate a mobile telerobotic system suitable for performing selective decontamination and dismantling functions applicable to pre-S&M facility preparations. Overhead transporter and vehicle-based deployment of the DAWM system provide the two primary mobility options for SERS operation in pre-S&M and eventual D&D telerobotic tasks. Remotely deployable telerobotic systems remove workers from direct exposure to contaminants and industrial hazards.

COLLABORATION/TECHNOLOGY TRANSFER

This technology is being jointly developed by ORNL, SNL, and PNL and will entail interactions with The University of Tennessee and Carnegie Mellon University.

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4.4 SMALL PIPE CHARACTERIZATION SYSTEM

TASK DESCRIPTION

The Small Pipe Characterization System (SPCS) activity provides for the design, procurement, fabrication, integration, and demonstration of a system for characterizing contaminants in pipes with internal diameters between two and three inches. See Figure 4.4. Identification and mapping of contaminants in piping is a major concern during facility deactivation. An understanding of the types of contaminants present and the extent of contamination are primary drivers for decisions regarding decontamination and/or dismantlement; all of which affect initial deactivation cost, ongoing S&M risk and cost, and eventual D&D strategy and cost.

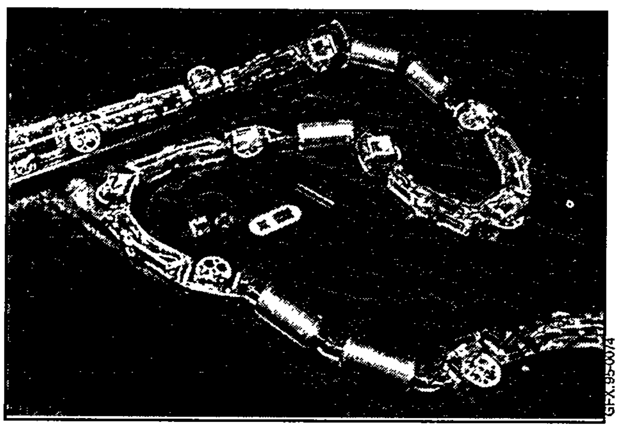

Figure 4.4. Small Pipe Characterization System Being Inserted Into 2 Inch Pipe.

TECHNOLOGY NEEDS

Across the DOE Complex, there are numerous facilities identified for D&D with piping that have been placed on the contaminated list because of internal contamination risk. Much of this piping is inaccessible since it is buried in concrete or runs through hot cells. Currently there are no robotic/remote systems capable of characterizing pipe in the two- to three-inch size range. Characterization of this piping is essential before, during, and after D&D activities. Identifying those sections of the piping that are actually contaminated can greatly reduce the amount of material sent to waste handling facilities and/or the amount of secondary waste generated performing unneeded decontamination.

ACCOMPLISHMENTS

This activity was initiated in FY94. Present accomplishments include:

- Functional requirements and a conceptual design of the SPCS were developed to define expected performance through valves, bends, and intersections. Insertion and retrieval processes and travel distances were also defined.
- A detailed design of the SPCS was developed. A prototype system was built that will operate in two- to three-inch pipe.
- Testing and evaluation of the SPCS were performed in two and three-inch pipe.
- Demonstration of the SPCS operating in two- and three-inch piping was completed at the end of FY94.

BENEFITS

This technology makes it possible to characterize previously inaccessible piping. Determining the absence or presence of contamination and the extent of contamination in piping will reduce the costs of D&D activities by treating only the affected areas. It also reduces the amount of generated secondary waste from uncontaminated piping. Personnel exposure will be limited only to areas with uncontaminated piping.

Collaboration/Technology Transfer

This technology is being developed by INEL. A Cost Share Agreement is being negotiated with Foster-Miller, Inc., to provide design enhancements and facilitate transfer of the SPCS technology to Foster-Miller for potential commercial development. Foster-Miller has requested a cross license to all rights, inventions, technical data, and know-how relating to the SPCS.

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Bibliography of Key Publication

None at this time.

4.5 INTERNAL DUCT CHARACTERIZATION SYSTEM

TASK DESCRIPTION

The Internal Duct Characterization System (IDCS) activity provides for the design, fabrication, procurement, and demonstration of a remotely operated system for visually inspecting ventilation ductwork and characterizing selected chemical and radiological contaminants that are internally located in ventilation ductwork. See Figure 4.5. The system includes contaminant sampling and decontamination capabilities. The identification and mapping of contaminants in ductwork is a major concern during facility deactivation. An understanding of the types and extent of contamination will be primary drivers for decisions regarding decontamination and/or dismantlement. These decisions will affect initial deactivation cost, ongoing S&M risk and cost, and eventual D&D strategy and costs.

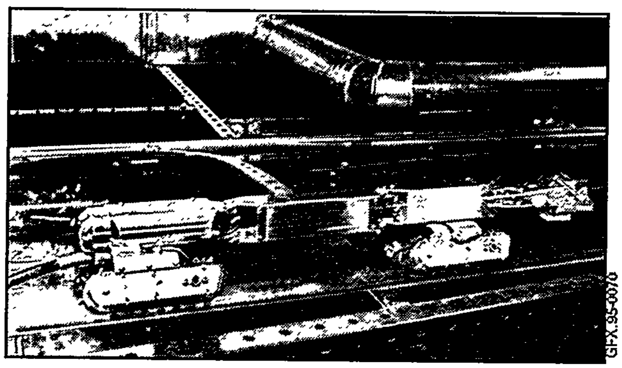

Figure 4.5. Internal Duct Characterization System in 8-Inch Round Duct.

TECHNOLOGY NEEDS

Across the DOE Complex, there are numerous facilities identified for D&D that have been placed on the contaminated list because of the risk of internal contamination in ductwork. Most of this ductwork is inaccessible because it is buried underground, encased in concrete, or runs through hot cells. Ductwork characterization is extremely difficult because of airflow control devices, varying sizes and the geometry of ductwork, and numerous changes in duct direction. Characterization of this ductwork is essential before, during, and after D&D activities. Identifying sections of the ducts that are not contaminated greatly reduces the amount of material sent to waste handling facilities for decontamination/disposal. Conventional methods have been applied to the characterization of ductwork with some success, but this has been at the risk of human exposure to high levels of contamination. Commercially available remote ductwork characterization systems are limited in their capabilities. A robotic/remote duct characterization system with extended travel capability is needed that can perform chemical and radiological contaminant characterization and selected hot spot decontamination or partial ductwork dismantlement.

ACCOMPLISHMENTS

This activity was initiated in FY94. Accomplishments include:

- Requirements and procurement specifications for the IDCS were developed in the first half of FY94.
- An industry procurement of the IDCS was completed in the second half of FY94.
- Testing and evaluation of the IDCS in a variety of ductwork sizes and geometries was performed after delivery.
- A demonstration of the IDCS operating in a mockup ductwork system was completed at the end of FY94.

BENEFITS

This technology allows characterization of ductwork that could not have been otherwise characterized.

Determining the absence or presence of contamination and the extent of contamination in ductwork will reduce the costs of D&D activities by allowing the ductwork to be handled appropriately versus treating all ductwork as contaminated. It will also reduce the amount of secondary waste generated since uncontaminated ductwork will not need to be decontaminated. It will reduce human health risk because sections of ductwork that pose health risks will have been identified prior to exposure. Use of this technology to perform in situ decontamination would provide additional benefit in the areas listed above.

COLLABORATION/TECHNOLOGY TRANSFER

This technology is being developed by INEL in collaboration with private industry. Performance requirements for this task were developed at INEL, but all design and fabrication was performed by a team of two Canadian companies; Inuktun Services, Ltd., and Automation Systems Associates, Ltd., both located in British Columbia. All the technology developed under this activity is now commercially available, with the patent rights held by the industrial partners.

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BIBLIOGRAPHY OF KEY PUBLICATIONS

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ROBOTICS CROSSCUTTING AND ADVANCED TECHNOLOGY

Section 5.0

5.0 ROBOTICS CROSSCUTTING AND ADVANCED TECHNOLOGY

Program elements within the Robotics Technology Development Program share common technology needs. These technology needs remain the primary focus of the Cross Cutting and Advanced Technology (CC&AT) team. The FY94 CC&AT Program addresses the following technology areas:

- Controls;
- Sensing Systems;
- System Analysis;
- Robot System Simulation;
- Co-operating Multi-Arm Manipulation; and
- University Research and Development.

The CC&AT Program is coordinated by SNL, with participation by PNL, LANL, and ORNL.

The six CC&AT technology areas are presented in more detail in the following chapter. Specific points of contact are included. SNL contacts for the CC&AT Program are Daniel S. Horschel, Lead Technical Coordinator, and Scott Slezak, Alternate Coordinator.

5.1 CONTROLS

TASK DESCRIPTION

This task develops advanced control approaches for application to robotic systems used in the remediation of DOE waste sites. Particular attention has been directed toward the growth of a Generic Intelligent System Control (GISC) approach that supports the development and reuse of highly modular software in diverse projects. Building software libraries that can be accessed electronically and used to implement advanced control systems rapidly is a key activity. Documentation and training classes are available.

TECHNOLOGY NEEDS

Many operations associated with waste site characterization and cleanup will be performed remotely in order to reduce the exposure of remediation technicians to hazards. These remote operations must be performed quickly, safely, and economically. Traditional remote technologies are frequently slow and tedious, and they lead to errors and accidents. Technology is needed which assists operations personnel by automating tedious tasks, ensuring safety and adherence to standard operating procedures, and reducing the time and costs required to complete remote operations.

Modular systems require control technologies combining existing remote handling technologies with integrated systems are capable of solving difficult waste clean-up tasks. This technology needs to be highly modular to support insertion of new technologies as they become available. Plug-and-play system integration scenarios are needed, in which new capabilities are synthesized by removing old modules and plugging in new ones without extensive reworking of the rest of the system. Reuse of well-characterized software modules improves software reliability. Advanced operator interfaces that enable remediation technicians to use remote systems safely and easily without extensive training are needed. These interfaces will allow sites with waste clean-up needs to access the best technology available. Faster and safer remote operations will be designed through use of computer algorithms to automatically plan and program robot operations while allowing operators to maintain supervisory control.

ACCOMPLISHMENTS

- Generic Intelligent System Control approach was defined and used on:
  - multiple application area demonstrations including waste retrieval from tanks,
  - waste facility operations,
  - decontamination and dismantlement, and
  - contaminant analysis automation.
- Advanced operator interfaces were demonstrated in:
  - graphical programming that allows non-programmers to safely operate largeintegrated robot systems, and
  - force reflection that allows operators to feel forces generated during robot operations.
- Established collaborative interfaces which enable users and developers to access and test robotic hardware systems from remote locations.
- Libraries of modular, reusable software (termed GISC-Kit) were made available and extensively used within RTDP.
- Documentation was made available and hands-on interactive classes taught.

- Advanced robot control algorithms were developed for automated oscillation damping.
- Advanced electronic networking technologies are under development to increase software sharing and team-based development.

BENEFITS

The GISC approach accomplishes the following goals:

- Integrates computer models of the robot and its environment with real-time sensing to automate tasks where possible.
- Allows seamless transfer to operator control when needed.
- Continually monitors operator commands by the computing system for safety.
- Interrupts potentially hazardous operations automatically.
- Enables remediation technicians with little programming experience to program remote clean-up operations safely and easily through intuitive graphic interfaces.
- Allows operators to see and change robot movements before they occur by graphically previewing intended robot actions.

Automation of tedious operations greatly speeds remote operations, and the control of task sequences allows coordination of the operation of many different pieces of equipment to accomplish complex tasks ranging from retrieval of waste to contaminant analysis in laboratory environments.

COLLABORATION/TECHNOLOGY TRANSFER

All integrated system projects performed within RTDP are team-based and involve multiple laboratories and industry. The generic systems control environment provided by the GISC approach and extensive re-use of control software stimulates collaborative technology development and expedites implementation of large integrated demonstration systems. Multiple laboratories contribute to the GISC-Kit.

Commercial industrial interest in the GISC approach is keen because it stimulates transfer to the industrial sector. A CRADA has recently been initiated to further commercialize GISC software and provide commercial sources for this technology. Licensing agreements with commercial bridge crane suppliers are under discussion to transfer technology that allows crane operations without payload oscillation.

University Partners:

- Pennsylvania State University.

Industrial Partners (under CRADAs):

- Deneb Robotics, and
- PaR Systems, Inc.

Commercial Status of Technology:

- Key graphical programming telerobotics technologies are available from Deneb, Inc. These technologies include network-based connections from a graphical environment to robot systems and new TELIGRIP products.
- CIMSYS/ISOE GISC compatible interface product available from PaR.
- SMART telerobotic technology has been licensed to Micro Dexterity.

Site and Company Responsible for Integrating Technology:

- Sandia National Laboratories.

Intellectual Property Rights:

- GISC was developed with a team approach. The OTD RTDP team designed the technology at a series of National Institutes of Standards and Technology (NIST) coordinated meetings. However, graphical programming and many of the enabling system components are owned by SNL.

Licenses Applied for or Granted:

- Patent applied for SMART technology.

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TASK DESCRIPTION

This task develops integrated sensing systems needed for the successful operation of faster, safer, better, and more economical robotics systems for hazardous waste cleanup applications. Sensor systems under development include sensors associated with the real-time safe control of robots and integrated modular sensor systems for mapping of the robot's work environment. These sensors will guide robot operations automatically and monitor operator commands for safety. This task focuses on the integration of existing sensors with robotic systems. It develops only sensors unique to robotic needs that are not under development elsewhere.

Sensor systems which detect potential collisions between robots and objects will significantly enhance the safety of remote operations. Sensors that create a field around a robot and sense the approach of an object have been developed. These rugged capacitance-based sensors can be easily attached to robot manipulators for use in harsh environments and are under development. They can be used with microelectronic interfacing technology to allow easy deployment on a wide variety of robot platforms. See Figure 5.2a.

In addition, integrated compact sensor systems that can be deployed using robotic systems are under development in a MiniLab project. See Figure 5.2b. A plug-and-play architecture allows chemical, radiological, optical, electrical, and physical sensors to be reconfigured according to site needs. Laser-based geometry sensing systems allow computers to automatically program robots to complete operations while avoiding collisions. Accurate robotic deployment of these sensor systems allows correlation of multiple sensor scans using statistical techniques to extract information not available from single sensor readings or uncorrelated scans. The major emphasis in future development activities within this task focuses on sensor fusion and automated data interpretation.

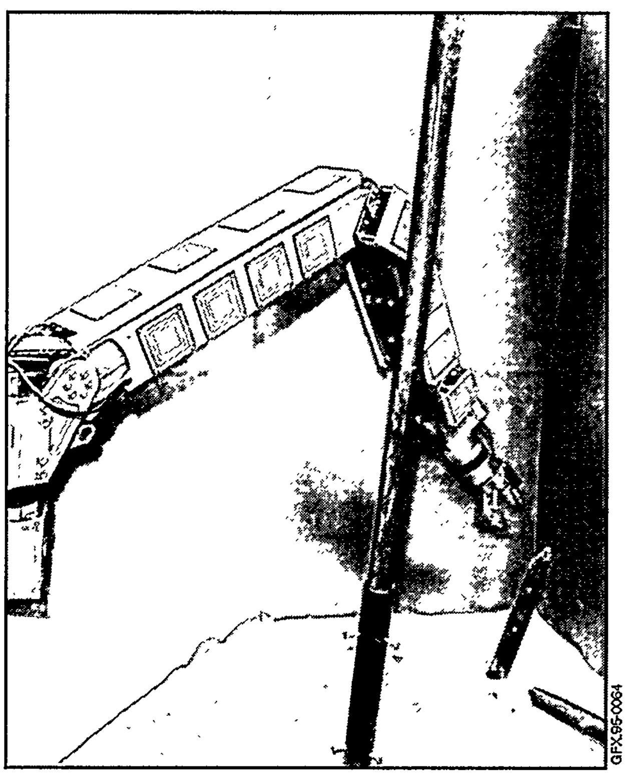

Figure 5.2a. Whole Arm Protection Sensor.

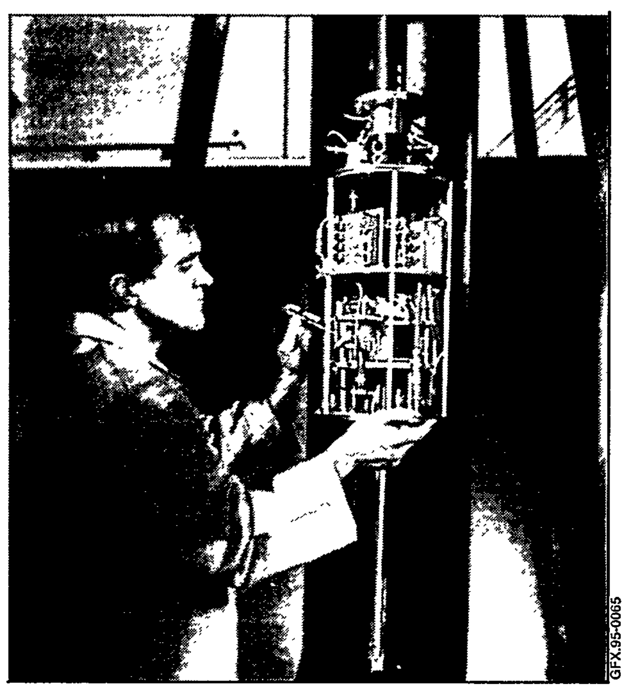

Figure 5.2b. MiniLab.

Technology Needs

Remote operations in hazardous waste sites must be performed quickly and safely. Unfortunately, experience with remote manual operations indicates that such operations are slow, and that operator tedium can lead to reduced safety. Sensors alert operators of remote equipment about potentially unsafe operations or movements that might cause inadvertent collisions with objects such as risers in underground storage tanks. In addition, sensors gather information on remote environments to provide maps that can be used to verify the safety of operator commands and automate certain tedious and repetitive operations. Finally, sensors allow safe contact of remote equipment, such as long reach robot arms, with objects and materials in hazardous environments.

Accomplishments

- Prototype integrated MiniLab sensing system for robotic mapping of waste environments has been developed and demonstrated at Hanford using a wide variety of commercially available sensors.
- Multi-client, flexible, data acquisition system has been developed and demonstrated to gather data from MiniLab and other application-specific end effectors.
- Hardened sensors for whole-arm collision avoidance sensing in harsh environments have been developed and demonstrated on a robotic manipulator.
- A structured lighting system was delivered and installed at the Mixed Waste Operations Facility at the Savannah River plant. Data processing time for structured lighting technology has been decreased by a factor of twenty.
- A sensor fusion framework has been developed and demonstrated which combines an expert system knowledge base with signal processing routines, statistical pattern recognition techniques, and model-based search methods. This framework has been successfully applied to assessment of gas chromatography data, guidance of magnetometer analysis, and recognition of MiniLab penetrometer data.

Benefits

The MiniLab sensor head technology provides the capability to perform some sample analyses in situ. This capability reduces the need for samples removed from tanks and analyzed in laboratories. Cost savings will result because:

- Expenses associated with removing and analyzing waste samples are no longer incurred;
- Personnel exposure to radiation in both sample retrieval and sample analysis areas will be reduce; and
- More rapid characterization will occur since the analysis is done in situ.

Whole-arm collision avoidance sensors avoid robot collisions that can damage costly equipment and even result in contamination of the environment. These sensors are important for the safe operation of robots during clean-up operations.

The sensor fusion system developed to date will eventually be incorporated into intelligent characterization and excavation systems. Considerable time and expense will be saved by automating sensor interpretation within the system. Here, computers will perform extensive data analysis that would otherwise require a team of experts. Depending on the task, results from the sensor fusion system could be used either to control equipment directly or provide the operator with assistance and warnings.

Collaboration/Technology Transfer

A CRADA is in place with Merritt Systems, Inc. to commercialize advanced capacitance-based sensing technology for collision avoidance applications.

A CRADA with Mechanical Technology, Inc. was successfully completed. Through this CRADA, MTI developed a structured lighting system that can be deployed into the 4-inch riser pipes at Hanford.

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5.3 SYSTEMS ANALYSIS

TASK DESCRIPTION

A large number of technological options exist for the clean up of waste sites exists. While robotics technologies can reduce the cost and time for waste cleanup and increase personnel safety, those advantages need to be analyzed to ensure that the most promising robotics technologies receive the highest priority. System analysis helps developers and their customers determine the magnitude of challenges they face. System analysis also supplies a method to review possible alternative solutions and an impetus to create new solutions.

The goal of the system analysis effort is to provide decision makers with the tools to help guide the technologies developed and pursued by the DOE. Moreover, it provides proponents and providers within RTDP of other technologies with tools to show how best to invest their efforts and budgets.

TECHNOLOGY NEEDS

Because of the hazardous nature of many waste sites, human entry is limited. Past experience shows that conventional, remotely operated equipment is slow and tedious. Economic costs and benefits of computer assisted robotic devices need to be evaluated to help direct and prioritize technology development efforts within RTDP. Increased safety and reduced operating and training costs resulting from the automation of tedious remote tasks need to be assessed.

RTDP requires the development of general techniques for evaluation of all robotics technology development efforts. RTDP Crosscutting and Advanced Technologies (CC&AT) focused early on the development of cost/benefit analyses based upon sound life cycle cost assessment approaches. These cost/benefit techniques will be applied across RTDP to guide development activities.

Factors considered for analysis include the costs of human supervised robotic systems and benefits including:

- Reduced exposure to hazardous environments;
- Reduced operating and life cycle costs;
- Reduced training costs; and
- Increased safety.

Results from the application of the system analysis tools can be used to review all RTDP projects and integrate information from each one of them to provide DOE with a first analysis of the projects which can evaluate their potential costs and benefits based on life cycle costing techniques.

ACCOMPLISHMENTS

SNL performed several systems analyses evaluating the cost/benefit of applying robots to selected EM applications. The most complete analysis evaluated the application of robotics technology to the handling of TRUPACT containers at the Waste Isolation Pilot Plant (WIPP). This analysis showed that robot systems were typically more cost-effective than manual TRUPACT unloading methods. Automated robot systems were faster and reduced operator radiation exposure to near zero.

Unquantified benefits of the robot system include:

- Automation of the quality assurance audit trail;
- Reduced litigation expenses due to perceived threats;
- Elimination of human errors; and
- Higher quality of operations because of the reliability of robot operation.

BENEFITS

Efforts in system analysis applied to the robotics program can assist users of the technology by:

- Providing a method of determining benefits and costs of widely varying options;
- Allowing customers and users to make decisions based on objective measurement of options; and
- Helping to simplify the task of guiding policy and making hard decisions.

COLLABORATION/TECHNOLOGY TRANSFER

Future work in the area of systems analysis will involve the continued development of tools to guide prioritization and development of technologies.

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None at this time.

TASK DESCRIPTION

This task was initiated in FY94 to develop and use techniques for simulating a robot system using verified algorithms and models. Validated simulation tools are needed for the design and evaluation of unique and costly robot systems envisioned for remediation activities across the DOE Complex. The task will result in a library of simulation modules that can be easily selected and integrated to allow DOE and the national laboratories to simulate and evaluate design performance parameters of a robot system before it is purchased or committed to hardware. The completion of this task will enable advanced robot systems to be designed faster and will help ensure that the design selected and fabricated is the best design for the requirements of the remediation task.

TECHNOLOGY NEEDS

Some of the robot systems required for the remediation of the DOE sites are unique and are estimated to cost millions of dollars for the robot system alone, where the cost specifically excludes management and the balance of plant costs. Design and analysis tools that can model structural performance, control behavior, suitability to accomplish desired tasks, and the interaction of end effectors do not exist in one integrated package. Many key simulation parameters unique to these robots do not exist at all. Thus, the need to evaluate vendor proposals becomes critical as the DOE robot systems become more costly and unique. Further, RTDP is developing a test bed for arm-based retrieval technology development. This test bed, among other things, will be used to validate simulations dealing with dynamic test bed and adaptive control of a flexible manipulator.

Through the use of the test bed, the RTDP researchers will be able to assess one entire system, and, with modification of the hardware, some additional variations about performance and controllability can be addressed. This simulation task will provide DOE researchers with tools that can be used to influence design and assess system performance before costly modifications are made, or new systems are fabricated. Simulation modules will be validated against real hardware systems, such as the RTDP long reach arm test bed, and then applied to conceptual and prototype designs.

ACCOMPLISHMENTS

This new simulation task developed the Distributed Collaborative Workbench (DCW), which leveraged research within the CC&AT programs in recent fiscal years. The DCW focuses on providing a modular simulation environment, such that users can plug-and-play resources, either virtual or real, over local and wide-area networks. The DCW provides a testbed to develop the simulation toolkit for assembling resources (hardware and software) in a collaborative system as shown in Figure 5.4. In addition, the DCW couples its simulation environment with intelligent front ends in order to simplify their use by non-experts.

The design of the DCW architecture provides a graphical iconic platform for configuring and controlling intelligent resources such as supervisors

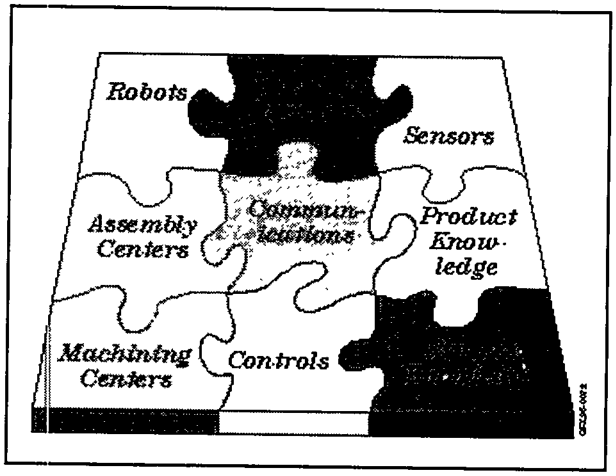

Figure 5.4. Simulation Toolkit for Assembling Resources.

(operator interfaces, graphical programming, task sequencer controllers, etc.) and systems (robots, machining equipment, intelligent tools, etc.) over local and wide-area networks. The DCW architecture incorporates SNL's Generic Intelligent System Controller (GISC) Toolkit. The DCW framework provides a modular environment utilizing interface requirements that describe resources in a plug-and-play mode. This flexibility allows for continued extension of the toolkit to include new modules as they become available. The system resources are characterized by their type (virtual or real), operational modes (autonomous, teleoperational, etc.), and interface configurations (capabilities and connections). At the Robotics Forum, the DCW demonstrated configuring an operator interface with various robot input devices to control a virtual robot and also a real robot located at a remote facility.

BENEFITS

This research utilizes an information-based software architecture that provides the capability of sharing resources and facilities utilizing the growing NII. This approach emphasizes merging the virtual environment with the actual environment as demonstrated with the DCW. That is, the same controls, communications, and interface routines used in the virtual environment are also used with the hardware in the real environment. This project enables the computer and the hardware to be brought to the user's desk. This method will reduce research costs and increase capabilities for designing and integrating systems. By minimizing capital costs and maximizing team-based technology development, true collaborative systems can be developed with shortened development cycles and cost effective solutions.

COLLABORATION/TECHNOLOGY TRANSFER

Collaboration among the RTDP participants will extend to university researchers as the work progresses toward simulation task and the use of inter-laboratory high-speed data communications to foster team development and application of the simulation and validation activities. Industrial partners will also be encouraged. Initially, simulation efforts will build on the visualization tools available through industry and universities. These tools will be extended and integrated, as appropriate, to develop a robust library of design and evaluation tools for DOE researchers. As the simulation tool library matures, specific tools or the entire library would be transferred to the robot manufacturers as design and evaluation tools.

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None at this time.

5.5 COOPERATING MULTI-ARM MANIPULATION

TASK DESCRIPTION

There are many instances in DOE waste cleanup efforts that either require, or could benefit from, the use of two manipulators when using robotic systems for remote handling or remediation activities. To date, much of the work on dual arms has focused on the use of two arms of a similar type. The RTDP's CC&AT team continued work using this approach, but it also expanded efforts to include dissimilar arms such as:

- hydraulic and electro-mechanical;
- gantry;
- pedestal and mobile; and
- varying levels of multiple cooperating robots.

This effort continued to develop generic technologies that can be used for the control and cooperation of multiple arm robotics systems. Efforts of university researchers through the university R&D Program were incorporated into the control algorithms used within RTDP, and then transferred to other RTDP task areas.

Additional areas of development include dexterous, general purpose, end-effectors to support enhanced manipulation in remote environments. Current robot end-effector technologies typically support only parallel jaw grippers. Multi-fingered hands that support fine manipulation are needed in most all waste cleanup scenarios that require handling hazardous materials. A design effort that identifies critical manipulation skills has begun within the university R&D sector, and followed by a cooperative university/laboratory development activity.

TECHNOLOGY NEEDS

The use of two robot arms will be essential for many of the intrusive activities required in the selective retrieval of hazardous components in a decommissioned facility or to handle and resize the large variety of objects at buried waste sites. For reasons of safety, it will often be required for one arm to hold an object, while the second arm frees the object by cutting or unbolting it. The use of two arms has the benefit of providing structure in the robot's workcell, thereby speeding operations. It will allow those operations to proceed more expeditiously in both characterization and retrieval activities.

The combination of screening tank waste, or soil, with one manipulator while a second arm performs retrieval activities will result in faster, safer, and more economical remediation activities because it will not be necessary to constantly change end effectors. Many other scenarios exist that would benefit from the use of two simultaneously deployed dexterous arms. This task develops those generic technologies for multi-arm control to be applied to the specific needs of RTDP technical areas.

ACCOMPLISHMENTS

Most of the work to date in the controls area in CC&AT is in developing enabling technologies to allow rapid advances to be made. A key element of the work to date has been to develop control technologies that support the rapid integration of advanced hardware technologies as they become available. This work has been accomplished largely by the use of reusable software modules for the control of robot systems that were developed by RTDP. The software tool kit is collectively known as GISC-Kit software.

The modular nature of the software allows for easy reuse and easy expansion and integration of new technologies. During FY94 the GISC-Kit software development for dual-arm manipulation was expanded to include many new software modules. Advances in task sequence control, supervisory control, advanced path panning, and automated generation of robot programming were achieved. This progress culminated in the demonstration of three robot arms at SNL working in true coordination with each other, all being controlled by one task sequence controller and a single operator input. The goal is to provide an intelligent controls environment that integrates the operator as a supervisor, not a provider, of detailed control instructions.

At ORNL, a DAWM was assembled and placed into initial testing. The DAWM is comprised of two robot arms mounted on a variable width and rotatable shoulder assembly that provides enormous flexibility for cooperative and coordinated actions by the two arms. Initial testing of the DAWM was done using telerobotic controls to operate the unit in a decontamination and dismantlement test facility. The multi-arm controls developed at SNL under the CC&AT program will demonstrate coordinated robotic control of the DAWM.

Advances in low-level control algorithms for dual-arm manipulation were achieved by incorporating university research.

BENEFITS

The development of cooperative dual-arm manipulators provides three substantial benefits over single-arm robots:

- Faster clean-up operations are possible because less robot time is spent on changing end-effectors and because more cumbersome waste forms can be handled;
- More economical cleanup operations due to faster operations, which result in savings in operators and support personnel costs; and
- Safer activities because dual arm manipulators can perform tasks in hazardous environments that cannot be done by single-arm manipulators.

Early demonstrations of coordinated control of multi-arm manipulators and telerobotic operation of the DAWM have shown that large, awkward objects that could not be handled with single manipulators can be handled remotely using dual manipulators. Cost/benefit studies were initiated to quantify the extent of the time and cost savings resulting from multi-arm manipulators. Initial results indicate that the cost savings will far exceed the cost to develop the multi-arm capability.

COLLABORATION/TECHNOLOGY TRANSFER

The research areas that support multi-arm manipulation are being addressed in CC&AT, while application of the technologies are sponsored by the specific programs that have a need for dual arm manipulation, such as D&D, Tank Waste Retrieval, and Buried Waste remediation activities.

As part of CC&AT, a University Research and Development effort was established at Washington University in Saint Louis, to bring university expertise to bear on this technology area. The principal investigators, Professors Tzyh-Jong Tarn and Antal K. Bejczy, are supporting this effort.

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None at this time.

TASK DESCRIPTION

SNL coordinates CC&AT development for OTD. CC&AT is one of the elements of OTD's RTDP. A major goal of CC&AT is to develop broadly applicable robotics technologies that improve safety while reducing the time and cost for hazardous and radioactive waste clean-up.

In support of this goal, RTDP (through SNL) issues periodic requests for proposals to the University community for needs-based research occurring at the forefront of robotics technology. Every year, the previous year's university-based research is reviewed. Projects that have produced important results and that continue to support RTDP's needs are extended. The University R&D Program has been in existence over the past four years. Fourteen research projects are currently funded. It is the intent of the OTD RTDP to extend this program to approximately twenty projects in the near future.

TECHNOLOGY NEEDS

The history of the University R&D Program includes many distinguished participants. In 1991, goals were addressed by RTDP team members in the following areas:

- Robotic system failure mode analyses, Rice University;
- Reflex control for robot preservation and reliability, Case Western Reserve University;
- Whole arm sensing for collision prevention, University of Wisconsin, Madison;
- Subsurface mapping of waste sites, New Mexico State University;
- Hardened micro-sensors for robot control, University of Florida, Gainesville;
- Real-time control using computer vision, Carnegie Mellon University;
- Software for control during unknown joint failures, Purdue University; and
- Algorithms for the stable control of large robot manipulators subject to structural vibrations, Georgia Institute of Technology.

In 1992, the University R&D Program was expanded to address six other RTDP identified needs:

- Reconfigurable and modular robotic systems, Carnegie Mellon University;
- Applications of virtual reality concepts to robot system control, Pennsylvania State University;
- Dual manipulator cooperative control, Washington University, St. Louis;
- Icon-based software programming, Carnegie Mellon University;
- Control of force-reflecting telerobotic systems, University of Tennessee; and
- Real-time servo control using computer vision, University of Minnesota.

In 1993, the University R&D Program was expanded to address an additional goal:

- Machine health monitoring and prediction, Colorado School of Mines.

The University Program is expected to grow from two to five more technical needs areas during 1995 and 1996.

ACCOMPLISHMENTS

University researchers have been supporting needs that cut across the RTDP programs and specific task areas. Several areas addressed by the University Program include safety and reliability issues related to placing robotic systems in hazardous environments. These issues include:

- Impact of kinematic and actuator redundancy on robot system reliability and safety;
- Fault tree analysis of robot systems;
- Software safety;
- Hardened micro sensors; and
- Machine health monitoring.

The efforts of the universities to address safety issues unique to the cleanup of the DOE Complex have been demonstrated on robot systems at the national labs, allowing the research to be rapidly applied to the demonstration systems developed by the RTDP. Similar progress is being made in the following areas:

- Incorporation of servo control code for dual arm manipulation;
- Modular robotics;
- Control of force-reflecting telerobotic systems; and
- Algorithms for control of large robot manipulators.

This work applies to several RTDP task areas including:

- Tank Waste Retrieval,
- Decontamination and Dismantlement, and
- Buried Waste.

Several university programs support more specific needs in RTDP. For example, New Mexico State University is applying data interpretation algorithms to geo-physical sensor data to develop detailed subsurface maps of objects.

The university program has resulted in a close collaboration among the national labs and the university researchers, with their technical expertise focused on two important issues:

- New technologies applicable to DOE and national site cleanup, and
- Advanced research and development capabilities with highly qualified researchers, and enhanced laboratory capabilities.

This cooperation results in rapid technology transfer from sources to the field as well as reduced development time and costs.

BENEFITS

This collaboration between the national labs and university researchers focuses applied research toward the needs in the DOE Complex to provide new technologies applicable to DOE and national site cleanup.

Though research (university or other) is inherently difficult to quantify, projects performed under the university programs are addressing the issues of safety and speed, with resultant cost savings. In general, advances in robotics that allow substitution of mechanisms for human workers tend to improve safety. Due to the cost of human operation within hazardous environments, the use of robotics usually results in substantial cost savings. In addition, robotic systems may generate a significantly smaller secondary waste stream. Because such systems do not need continual protective clothing renewals and associated human-related equipment, they can often be easily decontaminated.

Specifically, New Mexico State University's program is applying data interpretation algorithms to geo-physical sensor data to develop detailed subsurface maps of objects. This program has had the most direct impact on the clean up of buried waste sites, and has been using real geo-physical data that was collected from sites in the DOE Complex: INEL and Sandia. The benefits of this program will include faster access to objects in known locations, safer access from increased knowledge, and cost savings due to object-specific excavation.

COLLABORATION/TECHNOLOGY TRANSFER

Areas in which university-based research will be pursued in a given year are determined by the CC&AT team based upon the RTDP Five Year Plan and site clean up needs. The CC&AT team members include representatives from PNL, LANL, LLNL, ORNL, and SNL.

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DOE Business Opportunities

Section 6.0

6.0 DOE BUSINESS OPPORTUNITIES

WORKING WITH THE DOE OFFICE OF ENVIRONMENTAL MANAGEMENT

DOE provides a range of programs and services to assist universities, industry, and other private-sector organizations and individuals interested in developing or applying environmental technologies. Working with DOE Operations Offices, as well as management and operating contractors, EM employs a number of mechanisms to identify, integrate, develop, and adapt promising emerging technologies. These mechanisms include contracting and collaborative arrangements, procurement provisions, licensing of technologies, consulting arrangements, reimbursable work for industry, and special consideration for small business. EM facilitates the development of subcontracts, R&D contracts, and cooperative agreements to work collaboratively with the private sector.

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS (CRADAS)

CRADAs are mechanisms for collaborative R&D. They are agreements between a DOE R&D laboratory and any non-federal source to conduct cooperative R&D that is consistent with the laboratory's mission. The partner may provide funds, facilities, people, or other resources. DOE provides the CRADA partner with access to facilities and expertise; however, external participants receive no federal funds. Rights to inventions and other intellectual property are negotiated between the laboratory and the participant. Certain generated data may be protected for up to five years. Several companies may combine their resources to address a common technical problem. Funds can be leveraged to implement a consortium for overall program effectiveness.

PROCUREMENT MECHANISMS

DOE-EM procurement mechanisms are for technology development in the form of unsolicited proposals and formal solicitations, although the latter are preferable. The principal contractual mechanisms used by EM for industrial and academic response include Research Opportunity Announcements (ROAs) and Program R&D Announcements (PRDAs).

EM utilizes the ROA to seek advanced research and technologies for a broad scope of cleanup needs. The ROA supports applied research ranging from concept feasibility to full-scale testing. In addition, the ROA is open continuously for a full year following the date of issue and includes a partial procurement set-aside for small businesses. Typically, ROAs are published annually in the Federal Register, announced in the Commerce Business Daily, and provide multiple awards.

PRDAs are program announcements which solicit a broad mix of advanced development and demonstration proposals. A PRDA requests proposals for a wide-range of technical solutions to specific EM problem areas. Multiple awards, which may have distinct approaches or concepts, are generally made. Numerous PRDAs may be issued each year.

EM awards grants and cooperative agreements if 51% or more of the overall value of the effort is related to a public interest goal. Such goals include possible non-DOE or other federal agency participation and advancement of present/future U.S. capabilities in domestic and international environmental cleanup markets. They may also include technology transfer, advancement of scientific knowledge, or education and training of individuals as well as business entities.

For more information about PRDAs and ROAs, contact:

Tom Martin
U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880, MS I07
Morgantown, West Virginia 26507
(304) 285-4087

LICENSING OF TECHNOLOGIES

DOE contractor-operated laboratories can license DOE/EM-developed technology and software. In situations where DOE retains the ownership of a new technology, the Office of General Counsel will serve as the licensing agent. Licensing activities are conducted according to existing DOE intellectual property provisions.

TECHNICAL PERSONNEL EXCHANGE ASSIGNMENTS

Personnel exchanges provide opportunities for scientists from private industry and DOE laboratories to work together at various sites on environmental restoration and waste management problems. Private industry must contribute substantial cost-sharing for these personnel exchanges. To encourage such collaboration, the rights to any resulting patents go to the private sector company. These personnel exchanges, which can last from three to six months, result in the transfer of technical skills and knowledge.

CONSULTING ARRANGEMENTS

Laboratory scientists and engineers are available to consult in their areas of technical expertise. Most contractors which operate laboratories have consulting provisions. Laboratory employees who wish to consult can sign non-disclosure agreements, and are encouraged to do so.

REIMBURSABLE WORK FOR INDUSTRY

DOE laboratories are available to perform work for private industry and other federal agencies, as long as the work pertains to the mission of a respective laboratory and does not compete with the private sector. The special technical capabilities at DOE laboratories are incentives for the private sector to use DOE's facilities and contractor expertise. An advanced class patent waiver gives ownership of any inventions resulting from the research to the participating private sector company.

INTERACTIONS WITH SMALL BUSINESSES

EM seeks the participation of small businesses in its RDDT&E programs (1) through collaborative efforts with the National Laboratories, or (2) directly via solicitations issued by the DOE Small Business Innovation Research (SBIR) Program Office and the Small Business Technology Transfer (T2) Pilot Program (STTR). EM also has established a partial procurement set-aside for small firms (500 employees or less) for applied research projects through its ROA.

For further information about SBIR and STTR programs, please contact:

U.S. Department of Energy
Small Business Innovation Research Program Hotline
ER-16 GTN
Washington, D.C. 20585
(301) 903-5707

EM Center for Environmental Management Information

The EM Center for Environmental Management Information is designed to provide ready access to prospective research and business opportunities in waste management, environmental restoration, and decontamination and decommissioning activities. The Center can identify links between industry technologies and program needs. It connects potential partners to an extensive complex-wide network of DOE headquarters and operations office contacts.

To reach the EM Center for Environmental Management Information, call 1-800-736-3282.

Offices of Research and Technology Applications

The Offices of Research and Technology Applications (ORTA) serve as technology transfer agents for the federal laboratories. They coordinate technology transfer activities among laboratories, industry, and universities. ORTA offices license patents and foster communication between researchers and technology customers.

ORTA Contacts:

Laboratory	Contact	Phone Number
Ames Laboratory	Todd Zdorkowski	(515) 294-5640
Argonne National Lab	Shari Zussman	(708) 252-5361
Brookhaven National Lab	Margaret Bogosian	(516) 282-7338
Fermilab	John Vernard	(708) 840-2529
Idaho National Engineering Lab	Ann Rydalch	(208) 526-1010
Lawrence Berkeley Lab	Cheryl Fragiadakis	(510) 486-6467
Lawrence Livermore National Lab	Dave Conrad	(510) 422-7839
Los Alamos National Lab	Pete Lyons	(505) 665-9090
Morgantown Energy Technology Ctr	Rodney Anderson	(304) 285-4709
National Renewable Energy Lab	Dana Moran	(303) 275-3015
Oak Ridge Institute/Science & Ed	Mary Loges	(615) 576-3756

Laboratory	Contact	Phone Number
Oak Ridge National Lab	Bill Martin	(615) 576-8368
Pacific Northwest Lab	Marv Clement	(509) 375-2789
Pittsburgh Energy Technology Center	Kay Downey	(412) 892-6029
Princeton Plasma Physics Lab	Lew Meixler	(609) 243-3009
Sandia National Lab	Warren Siemens	(505) 271-7813
Savannah River Technology Center	Jack Corey	(803) 725-1134
Stanford Linear Accelerator Center	Jim Simpson	(415) 926-2213
Westinghouse Hanford Company	Dave Greenslade	(509) 376-5601

ACRONYM LISTING

Section 7.0

7.0 ACRONYM LISTING

AIM	Analytical Instrument Module
A&PCT	Active & Passive Computed Tomography
BIR	Bio-Imaging Research
CAA	Contaminant Analysis Automation
CC&AT	Crosscutting and Advanced Technology
CMU	Carnegie Mellon University
CRADAs	Cooperative Research and Development Agreements
D&D	Decontamination & Dismantlement
DAWM	Dual-Arm Work Module
DCW	Distributed Collaborative Workbench
DIM	Data Interpretation Module
DoD	Department of Defense
DOE	U.S. Department of Energy
DR	Digital Radiography
ECMD	Eddy Current Metal Detection
EPA	Environmental Protection Agency
FEMP	Fernald Environmental Management Project
GC	Gas Chromatography
GISC	Generic Intelligent System Control
GPC	Gel Permeation Chromatography
HCI	Human Computer Interface
IBM	International Business Machines
IDCS	Internal Duct Characterization System
IGES	Initial Graphics Exchange Standard
INEL	Idaho National Engineering Laboratory
LANL	Los Alamos National Laboratory
LIMS	Laboratory Information System
LLNL	Lawrence Livermore National Laboratory
MACS	Mobile Automated Characterization System
MTI	Mechanical Technologies, Inc.
MWIP	Mixed Waste Integrated Program

MWTP	Mixed Waste Treatment Project
MWO	Mixed Waste Operation
NDA	Non-destructive Assay
NDE	Non-destructive Evaluation
NIST	National Institute of Standards and Technology
OTD	Office of Technology Development
ORNL	Oak Ridge National Laboratory
PCBs	Polychlorianted Biphenyls
PIA	Proprietary Information Agreements
PNL	Pacific Northwest Laboratory
PRDA	Program Research and Development Announcement
RCRA	Resource Conservation and Recovery Act
RTDP	Robotics Technology Development Program
RTR	Real Time Radiography
S&M	Surveillance and Maintenance
SAM	Standard Analysis Method
SERS	Selective Equipment Removal System
SIMON	Semi-Intelligent Mobile Observing Navigator
SLMs	Standard Laboratory Modules
SMART	Sequential Modular Architecture for Robotics and Teleoperation
SNL	Sandia National Laboratory
SPCS	Small Pipe Characterization System
SRD	Spectroscopy Radiation Detection
SRTC	Savannah River Technology Center
SWAMI	Stored Waste Autonomous Mobile Inspector
TCT	Transmission Computed Tomography
TRC	Transitions Research Corporation
TSC	Task Sequence Controller
TWR	Tank Waste Retrieval
WCF	Waste Characterization Facility
WHAP	WHole Arm Protection Sensor
WIPP	Waste Isolation Pilot Plant
XRF	X-Ray Fluorescence

APPENDIX

Section 8.0

8.0 APPENDIX

TECHNICAL TASK PLANS

Technical Task Plans (TTPs) identify and summarize funded work managed by OTD at headquarters, the field and the national laboratories. All tasks require a TTP number, which contains eight characters assigned by DOE Headquarters. The format consists of two alpha characters followed by six numerical characters. Characters 1 and 2 designate the DOE Operations Office/Funding Allotment Code. Character 3 denotes the laboratory/contractor/university designator. Character 4 denotes the fiscal year in which the task is first funded. The below characters reflect TTPs from FY94-95.

Characters 1, 2 & 3

AL0 Albuquerque Operations Office

AL1 Los Alamos National Laboratory (LANL)

AL2 Sandia National Laboratory, Albuquerque (SNLA)/Martin Marietta

AL3 Sandia National Laboratory, Livermore (SNLL)

AL4 Kansas City Plant (KCP)/Allied-Signal Aerospace

AL9 RUST GEOTECH

CH0 Chicago Operations Office

CH1 Ames Laboratory

CH2 Argonne National Laboratory (ANL)/University of Chicago

CH3 Brookhaven National Laboratory (BNL)/Associated Universities, Inc.

CH5 National Renewable Evergy Laboratory

FN0 Fernald Environmental Management Project (FEMP)

FN1 Fluor Daniel Environmental Restoration Management Company

HQ0 OTD Headquarters

ID0 Idaho Operations Office

ID1 Idaho National Engineering Laboratory (INEL)/EG&G

ID4 Westinghouse Idaho Nuclear Company

ID6 Babcock & Wilcox, Inc

ID7 Lockheed Idaho Technology Company

ME0 Morgantown Energy Technology Center (METC)

NV0 Nevada Operations Office

OH0 Ohio Operations Office

OH1 Fernald Environmental Management Project (FEMP)

OH2	EG&G Mound Applied Technologies
OR0	Oak Ridge Operations Office
OR1	Martin Marietta Energy Systems (MMES)
OR3	Oak Ridge Institute for Science and Education
PE0	Pittsburgh Energy Technology Center
PE1	MSE, Inc.
RF0	Rocky Flats Environmental Technology Office
RF1	Rocky Flats Plant/EG&G
RL0	Richland Operations Office
RL2	Kaiser Engineers Hanford Company (KEH)
RL3	Pacific Northwest Laboratory (PNL)/Battelle Memorial Institute
RL4	Westinghouse Hanford Company
SF0	Oakland Operations Office
SF1	Lawrence Berkeley Laboratory (LBL)/University of California
SF2	Lawrence Livermore National Laboratory (LLNL)/University of California
SF3	Energy Technology Engineering Center (ETEC)
SR0	Savannah River Operations Office
SR1	Westinghouse Savannah River Company (WSRC)

Character 4

1	FY 1991
2	FY 1992
3	FY 1993
4	FY 1994
5	FY 1995
6	FY 1996
7	FY 1997
8	FY 1998
9	FY 1999
0	FY 2000