DOE/MC/29113 -- 4016
(DE95000086)

Interactive Computer-Enhanced Remote Viewing System (ICERVS) -- Phase II

Topical Report

John Tourtellott

November 1994

Work Performed Under Contract No.: DE-AC21-92MC29113

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Mechanical Technology Incorporated
Latham, New York

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PREFACE

The work documented in this report was performed by Mechanical Technology Incor-porated (MTI) for the United States Department of Energy (DOE) under Phase II of Contract DE-AC21-92M29113 in support of the DOE Environmental Restoration and Waste Management Program under the direction of the DOE Morgantown Energy Technology Center (METC) in Morgantown, West Virginia. It was performed during the period of September 1993 through September 1994. All communication regarding this report should be directed to the Contract Reports Receipt Coordinator at METC.

SUMMARY

The Integrated Computer-Enhanced Remote Viewing System (ICERVS) supports the robotic remediation of hazardous environments such as underground storage tanks, buried waste sites, and contaminated production facilities. The success of these remediation missions will depend on reliable geometric descriptions of the work environment in order to achieve effective task planning, path planning, and collision avoidance. ICERVS provides a means for deriving a reliable geometric description more effectively and efficiently than current systems by combining a number of technologies:

- Sensing of the environment to acquire dimensional and material property data
- Integration of acquired data into a common data structure (based on octree technology)
- Presentation of data to robotic task planners for analysis and visualization
- Interactive synthesis of geometric/surface models to denote features of interest in the environment and transfer of this information to robot control and collision avoidance systems.

A key feature of ICERVS is that it will enable an operator to match xyz data from a sensor with surface models of the same region in space. This capability will help operators to better manage the complexities of task and path planning in three-dimensional (3D) space, thereby leading to safer and more effective remediation.

The Phase II work performed by MTI brought the ICERVS design to Maturity Level IV, Subscale Integrated System, in September 1994. All success criteria were met. During Phase II, MTI revised the ICERVS system requirements and system design to better address the needs of the environmental restoration and waste management (EM) community. A key part of this effort was increased interaction ("focus groups") with relevant personnel developing EM technologies at DOE sites. The most notable result was a restructuring of the ICERVS system architecture into separate but interoperable subsystems based on Unix client-server interfaces. This restructuring enables the volumetric data subsystem and individual sensor subsystems to be developed and managed as independent modules that can be integrated into higher level remediation systems.

In parallel with the Phase II ICERVS effort, MTI developed a structured light mapping system under a Cooperative Research and Development Agreement (CRADA) with Oak Ridge National Laboratory (ORNL). This mapping sensor, designed to map the inside surfaces of underground storage tanks, was integrated with ICERVS and used for demonstration and test.

The Phase II ICERVS was demonstrated in mock-up situations to show performance in three remediation environments: underground storage tanks, buried waste pits, and facility dismantlement. The Phase II ICERVS consists of seven subsystems: demonstration, volumetric data, sensors manager, structured light sensor, simulated laser range finder, simulated Minilab sensor, and remote viewing. All software was designed using object-oriented methodology to promote modularity, code reuse, and reduced life-cycle costs. MTI made extensive use of commercial software libraries to maximize development productivity. Approximately 200 classes were implemented by MTI in C++ source code.

Based on the Phase II success and accomplishments, plus the interest expressed at DOE field sites, MTI recommends continuation of ICERVS to Maturity Level V, Full-Scale Integrated System. The Level V system will include expanded capabilities such as:

- Direct connection to a robotic programming software such as the Deneb IGRIP system.
- CAD software for storage of architectural drawings and object modeling.
- User productivity features such as automatic modeling of simple surfaces and surface templates
- Fabrication, assembly, and integration of instrument stations for installation and demonstration at a DOE field site.

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1.0 INTRODUCTION

This report documents the results of the Phase II development of ICERVS. Supporting the U.S. DOE missions in environmental restoration, ICERVS integrates capabilities for data acquisition, data visualization, data analysis, and geometric model synthesis in a workstation-based system. The following sections trace ICERVS development from intermediate system design, prototyping of critical elements, and detailed design of seven subsystems through implementation of source code and system performance testing. As a result of Phase II, ICERVS has demonstrated the combined capabilities of integration and display of 3D sensor data, and interactive synthesis and display of geometric shapes to model regions in 3D space. Such capabilities are essential to effective, efficient task planning, path planning, and collision avoidance in robotic remediation systems.

1.1 Technical Background

ICERVS is a computer-based system that provides data acquisition, data visualization, data analysis, and model synthesis to support robotic remediation of hazardous environments. Because of the risks associated with hazardous environments, robotic systems must rely on 3D models of their workspace to support both task and path planning with collision avoidance. These 3D models are based on solid modeling methods, in which objects are represented by enclosing surfaces (polygons, quadric surfaces, patches, etc.) or collections of primitive solids (cubes, cylinders, etc.). In general, these 3D models must be created and/or verified by actual dimensional measurements made in the robotic workspace. However, measurement data is empirical in nature, with a typical output being a collection of xyz triplets that represent sample points on some surface(s) in the workspace. As such, empirical data cannot be readily analyzed in terms of the geometric representations used in robotic workspace models. The primary objective of ICERVS is to provide a reliable description of a workspace based on dimensional measurement data and to convert that description into 3D models that can be used by robotic systems. Equally important is presenting the 3D information to operators in real time so that it can be used in conjunction with live video images of the remote workspace. ICERVS will thus serve as a critical factor to allow robotic remediation tasks to be performed more effectively (faster, safer) and economically than with present systems.

To address differing remediation environments and needs, ICERVS is based on a flexible architecture. A typical ICERVS configuration consists of one or more sensor subsystems for data acquisition, a computing platform, and analysis software for data analysis and processing. (The analysis software incorporates what were formerly called the data library and toolkit subsystems.) The data acquisition part of ICERVS is configured with one or more sensor subsystems, depending on the specific application needs. For example, dimensional measurements can be acquired by structured light and/or laser range finder sensors. Material property measurements can be acquired by the various sensors found in the Minilab presently under development by DOE or by off-line means such as core sampling. Each sensor subsystem will typically include a local computer for control and computation.

The local computer from each sensor subsystem will connect to the ICERVS computing platform, which is a standard engineering workstation. The analysis software, which runs on the computing platform, converts sensor data into a common data structure and integrates data from multiple sensor subsystems. The ICERVS data structure is based on octree technology, which provides a number of advantages over traditional 3D modeling methods. With octree technology, ICERVS provides:

- Direct acceptance of empirical data without conversion to polygons or geometric primitives
- A hierarchy of resolution to support iterative refinement of data throughout the life cycle of a remediation project
- Accommodation of data updates to reflect the removal of material during remediation
- Accommodation of incomplete data so that regions can be marked "un-mapped" until measurement data are provided
- A convenient way to make 3D comparisons between measurement data and geometric object models.

The analysis software also provides for visual display of the sensor data from arbitrary viewpoints, with numerous tools for modifying, selecting, or highlighting the data according to its characteristics and/or regions of interest. This allows an operator to analyze data to obtain maximum insight prior to and during robotic operations. These tools include a geometric modeling capability that enables the operator to interactively define and manipulate geometric objects to represent features of interest in the workspace. In waste remediation applications, these features would include barrels, pipes, support structures, instrumentation, or solidified waste. By defining models for these features and passing them to the robotic system, the remediation tasks can be readily accomplished with an accurate 3D description of the "as-is" condition of the workspace.

1.2 Scope

The development of ICERVS is structured in three phases based on the maturity level of its constituent technologies. The features to be developed in each phase are listed in Table 1-1. This report describes the results of Phase II development.

The purpose of Phase I was to achieve Maturity Level III, Subscale Major Subsystems, for those portions that had been demonstrated at the research laboratory scale. The majority of the work in this phase involved development of the basic analysis software. Specifically, this involved creating an octree data structure from simulated sensor data; providing face view display of the sensor data; and creating and manipulating geometric objects to denote features in the sensor data space. Phase I has been completed and has met all success criteria.

The purpose of Phase II was to achieve Maturity Level IV, Subscale Integrated System, in which ICERVS was demonstrated at limited size to enable successful development of a full-scale system. The result of this work was an integrated system that provided a structured light sensor subsystem; software to simulate other sensor subsystems; a remote viewing subsystem; an upgraded computing platform; and analysis software that includes enhanced data analysis and visualization tools, enhanced facilities for creating geometric objects, and an integrated user interface. Phase II has been completed and has met all success criteria.

The purpose of Phase III is to achieve Maturity Level V, Full-Scale Integrated System, in which ICERVS will be demonstrated in an intended application. The result of this work will be a full-scale, integrated system for use in the remediation of underground storage tanks. This system will include a full-scale sensor subsystem based on structured light; interface to a robot controller; facility for accepting geometric models derived from architectural data as input; and enhanced data analysis and visualization tools.

Table 1-1. Phased Implementation of ICERVS Features

Analysis Software	Computing Platform	Sensor Subsystems
Phase I Features		
• Volumetric data – Tree construction and manipulation – Tree structure display – Tree storage display – Tree utility programs • Geometric object data – Object definition – Associated text • Display – Orthogonal projection – Translation – Scaling – Cut planes along major axes – Multiple windows – Pseudo-color display • Model building – Polygon generator – Region of interest – 3D projection (prismatic models)	• Silicon Graphics workstation (Indigo) • Color monitor • GL graphics library	• Simulated data
Additional Phase II Features		
• Volumetric data – Interface to sensors • Geometric object data – Output in IGRIP format • Display – Arbitrary point of view – Arbitrary cut planes – Surface shading – Synchronized video and computer graphics display images • Model building – Arbitrary polyhedron – Sculpting of octree model – Quantitative comparison between volumetric data and geometric object	• Real-time CCTV • Operator control (track ball) for interactive viewing • Control interface to sensor subsystem • Upgraded CPU with additional internal memory	• Full-scale instrument station with – Solid-state camera – Laser illuminators – Positioning in pitch • Sensor controller (PC) – Image analysis – Surface profiling and automatic mapping – Interface to computing platform • Simulated waste tank
Additional Phase III Features		
• Geometric object data – Storage of architectural plans – Input in IGES – Ability to edit IGRIP models • Display with perspective view • Model building – Automatic modeling of simple surfaces – Surface model templates	• Link to robot controller (such as COPILOT)	• Two full-scale instrument stations • Color camera and grid projector • Automatic positioning in azimuth • Absolute tank coordinate system established by surveying tools • Improvements suggested by Phase II experience • Design of hardened station

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1.3 Phase II Tasks

The Phase II ICERVS work was organized into nine tasks as shown in Figure 1-1. Table 1-2 lists the Phase II tasks, summarizes the task results, and lists the sections of this report where more detailed information is provided.

Task 1 - Intermediate System Design. Based on Phase I results, MTI will review and update the requirements for ICERVS, including an evaluation of the TrueSolid software and alternative data formats to IGES. The result will be a modified set of requirements for integrating the various system components. MTI will complete an initial draft of the ICERVS Common Interface for Sensors. MTI will also establish user focus groups in the DOE end-user community.

Task 2 - Sensor Subsystem. MTI will make available a sensor subsystem developed under a CRADA with two national laboratories. This sensor subsystem has two instruments stations. Each station consists of a solid-state camera and a laser projector. Each station will also include the appropriate suspension and positioning hardware for investigating a simulated single-shell tank and will provide for yaw and pitch motions.

MTI will upgrade the software in the structured light system to operate as an ICERVS sensor subsystem. This will involve defining a remote interface (in accordance with the ICERVS Common Interface for Sensors and developing the necessary hardware and software for integration with the analysis subsystem. MTI will also define appropriate interfaces for a laser range finder and MiniLab. In the absence of empirical sensor data from such sensors, MTI will create simple simulators to test these interfaces.

Task 3 - Computer Upgrade. MTI will upgrade the ICERVS computing platform to enhance the functionality of the overall system. This upgrade will minimally include an upgraded CPU, a video monitor, and additional internal memory. The Octree Corporation's TrueSolid software module (or equivalent) to facilitate the octree engine will also be included.

Task 4 - Analysis Software Design. MTI will review and modify the analysis software requirements identified in Task 1, Phase II. MTI will design software modules that implement a Common Interface for Sensors; integrate the TrueSolid package; and enhance the capabilities to include, but not be limited to, the ability to accept and store real empirical data (to encompass material properties), the ability to store and merge object models alongside the data they represent, and the ability to convert data into a suitable format, such as IGES or STEP, to facilitate interaction with robotic controllers. MTI will also design two sets of graphics tools. The first will enhance the system's display capabilities, and the second will improve the system's ability to build three-dimensional geometric objects.

Task 5 - Analysis Software Code and Unit Test. MTI will code, unit test, and integrate the new analysis software and test it in a stand-alone mode to verify functionality. The new analysis software will incorporate data library functions, an interface with TrueSolid, a common interface for sensors, and data output in IGES or an equivalent format.

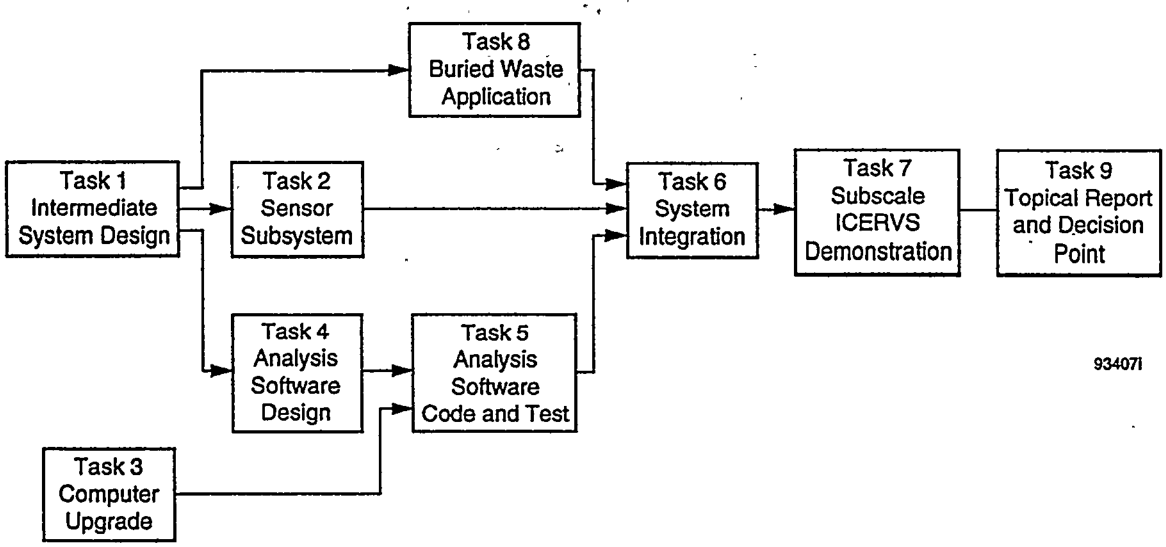

Figure 1-1. Phase II Task Organization

Table 1-2. Phase II Task Summary

Task	Results	Report Section(s)
1 - Intermediate System Design	Captured important DOE insights; refined requirements specification	2.1; 2.2.1
2 - Sensor Subsystem	Remote sensor operation; simulated sensors	2.3.3 - 2.3.7
3 - Computer Upgrade	R4000 processor; 64 MB memory	2.2.2; 2.2.3
4 - Analysis Software Design	Enhanced visualization; enhanced analysis	2.3.2.1
5 - Code and Unit Test	200+ software classes	3.1
6 - System Integration	Verified communications; simulated single-shell tank	3.1
7 - Subscale Demonstration	Demos on September 8 and 23, 1994	3.2
8 - Buried Waste Application	Property visualization and analysis; software delivered to INEL	2.3.2.2
9 - Topical Report		

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Task 6 - System Integration. MTI will:

- Integrate, install, and operate the data library and toolkit analysis software in an interactive mode to ensure compatibility and interoperability
- Design the software elements needed to ensure effective communications between the sensor subsystems and the computing platform
- Write, test, and integrate the necessary computer codes required for data acquisition and interactive viewing
- Implement an operator interface which provides effective control of the structured light sensor subsystem (i.e., cameras, lights, and positioning systems)
- Prepare a computer code that allows the operator to control the video camera view selection and simultaneously display a matching computer image
- Interconnect all system components and verify their joint functionality.

A simulated, single-shell tank will also be prepared for demonstrating the subscale ICERVS.

Task 7 - Subscale ICERVS Demonstration. MTI will demonstrate and verify, at least, a sensor subsystem that automatically and interactively maps the surface and walls of a simulated single-shell tank; a sensor interface to a laser range finder; a sensor interface to a MiniLab subsystem; library analysis software that properly creates and manipulates an equivalent world model in a format compatible with the needs of a robotic controller; analysis software that also demonstrates enhanced viewing and model-building tools; and an ICERVS that demonstrates the ability to match scenes from live TV and the world model as the operator pans the camera.

Task 8 - Buried Waste Application. MTI will finalize the features and performance needed for the buried waste application via discussions with INEL personnel. MTI will perform design modification of the ICERVS architecture and algorithms as needed. MTI will design the analysis software elements to support buried waste application, including enhanced user interface, means for storage and display of multiple material properties, updating of data from excavation activities, tools for registering data from different sensors, interpolation of material properties for analysis and display, and combination of multiple property data via Boolean operations. MTI will generate the necessary software to implement features to support the buried waste application. Each element of code will be unit tested and then tested again at the various levels of integration. MTI will incorporate the buried waste features as part of the ICERVS Phase II demonstration. MTI will install a copy of the ICERVS executable software on an INEL-supplied workstation, provide a limited user's guide, and supply a one-week level of effort for informal training at INEL.

Task 9 - Topical Report and Decision Point. MTI will submit a draft topical report within 60 days prior to completion of Phase II detailing the work completed to date and including the results of the Task 8 Buried Waste Application. Within 30 days after submittal, the COR will accept the draft topical report or recommend changes. Within 30 days after submittal of the topical report, the contracting officer will decide whether to proceed to the next phase. If the contracting officer decides NOT to continue to the next phase, MTI will submit a camera-ready final copy of the topical report within two weeks of this notification from the contracting officer. This report will be used in lieu of a final report.

2.0 ICERVS DESIGN

This section summarizes the design activities conducted during Phase II, including updating of ICERVS mission profiles and system requirements, system-level design, subsystem design, and code and unit test activities. Further design details are documented in MTI's "ICERVS System Design Report Phase 2" (November 30, 1993) and "ICERVS Subsystem Design Report Phase 2" (April 22, 1994).

2.1 Mission Profiles and System Requirements

Previously in Phase I, MTI established a set of mission profiles in conjunction with personnel at DOE field sites and national laboratories. Three missions of broad scope were chosen to ensure generality in the design of a suitable architecture: remediation of underground storage tanks, retrieval of buried waste sites, and dismantling of experimental and/or production facilities. From the mission profiles, a set of system requirements were defined and allocated to Phase I, II, or III of ICERVS development.

In Phase II, MTI increased interaction with DOE personnel in order to develop an improved understanding of the operational and user interface needs associated with using ICERVS in typical environmental restoration and waste management (EM) missions. A number of informal focus groups were held at DOE sites based on their experience and background:

- Hanford Tank Operations - underground storage tank characterization and waste retrieval
- Idaho National Engineering Laboratory (INEL) - buried waste retrieval
- ORNL - decontamination and dismantlement (D&D), human factors in telerobotic control.

From these interactions, a number of important distinctions and/or revisions were made. For example, MTI learned at Hanford that system operators are not intimidated by sophisticated graphical user interfaces, and, in fact, prefer them to command-line systems. At INEL, MTI learned that buried waste retrieval will be performed in a sequence of discrete dig face steps, and that sensor data interpretation will involve estimating gross features instead of detecting individual objects. At ORNL, MTI learned that sensor-based models are important for providing "camera views" that are not physically available and that software tools to improve operator productivity are a primary need. In general, MTI learned that the sensor suite will be configured specific to each remediation site, based on the characterization results and remediation plan. MTI also learned that dimensional registration of different data sets is an important need that will not, in general, be addressed by individual sensors and their platforms. Based on the information provided from these discussions, MTI revised the mission profiles and system requirements. Overall, there are 82 system requirements grouped into 10 categories. Of these 82 requirements, 12 were already implemented in Phase I, 46 were identified to be completely implemented in Phase II, 13 were identified to be partially implemented in Phase II, and the remaining 11 were identified as design influence, and will be implemented in Phase III. Table 2-1 presents a summary of the ICERVS system requirements.

Table 2-1. Summary of ICERVS Requirements

Number	System Requirement	Phase	Notes
R1	**DATA REPRESENTATION**		
R1.01	Octree: spatial data	I	
R1.02	Octree: property data	III	Partial for Phase II
R1.03	Octree: spatial interpolation	II	
R1.04	Octree: linear resolution 1:512, expandable	I	
R1.05	Geometric: polyhedral objects	I	
R1.06	Geometric: geometric primitives	II	
R1.07	Geometric: associated text each object	I	
R1.08	Geometric: 100 objects, expandable	I	
R1.09	Geometric: enter architectural and robot plans	III	Design influence
R1.10	Octree: sensor data	III	Partial for Phase II
R1.11	Octree: property data interpolation	II	
R2	**OBJECT MODELING**		
R2.01	Library of primitives/templates	II	
R2.02	Standard templates	II	
R2.03	User-defined templates	III	Partial for Phase II
R2.04	Automatic waste surface modeling	III	Design influence
R2.05	Synthesize 2-D polygons	I	
R2.06	Synthesize 3-D polyhedra	II	
R2.07	Dimensioning tools	II	
R2.08	Attach text to geometric objects	I	
R3	**COMPUTER GRAPHICS DISPLAY**		
R3.01	Translation and scaling	I	
R3.02	Display coordinate axes	II	
R3.03	Parallel cut planes	II	
R3.04	Display geometric object text data	I	
R3.05	Shaded or wire frame geometric object display	II	
R3.06	Update display as points received	I	
R3.07	Pseudocolor octree data	II	
R3.08	Color geometric objects by category	II	
R3.09	Text display view parameters	II	
R3.10	Save/Recall view parameter set	II	
R3.11	Multiple windows displaying same data	I	

Table 2-1. (continued)

Number	System Requirement	Phase	Notes
R3.12	View tracks sensor station attitude	II	
R3.13	Display 2.5-D surface map	II	Completed in Phase I
R3.14	Display views of spatial and property data	III	Phase I, II: orthographic Phase II: orthographic and perspective
R4	**VIDEO DISPLAY**		
R4.01	Monitor for each camera plus one for processing	III	Partial for Phase II
R4.02	Display wire frame geometric objects over video	III	Design influence
R4.03	Real-time CCV	III	Phase II: camera on sensor
R4.04	Flexible color TV camera	III	
R5	**MANIPULATION AND ANALYSIS**		
R5.01	Copy octree	II	
R5.02	Set region within octree to selected state	II	
R5.03	Operator delete geometric objects	II	
R5.04	Scan object for consistency with octree	II	
R5.05	Compare octree and object data	II	
R5.06	Compare two octrees, compute difference	II	
R5.07	Compute 2.5-D surface map from octree	II	
R5.08	Compute difference between 2.5-D surface maps	II	
R5.09	Surface connectivity	III	Design influence
R5.10	Tools for registering data from different sensors	III	Partial for Phase II
R5.11	Combine property data via Boolean operations	II	
R6	**MISCELLANEOUS FUNCTIONS**		
R6.01	Edit system parameters	II	
R6.02	Save/Retrieve waste site data sets to/from disk	I	
R6.03	Build octree from backup raw data	II	
R6.04	Maintain operator log	II	
R6.05	Multiple system of units	II	
R6.06	Define disassembly data	III	Design influence
R6.07	Establish application data structure	II	
R6.08	Support multiple active data sets per waste site	II	
R6.09	Support multiple active waste sites	II	
R7	**DATA INTERFACE**		
R7.01	Input: x,y,z position	II	

Table 2-1. (continued)

Number	System Requirement	Phase	Notes
R7.02	Input: optional resolution	II	
R7.03	Input: optional property value	II	
R7.04	Input: optional sensor location	II	
R7.05	Input: station angles during visual inspection	II	
R7.06	Output: geometric model data	II	
R7.07	Output: 2.5-D surface map data	II	
R7.08	Input: sensor data	III	Phase II: simulate laser range finder and Minilab
R8	**OPERATOR INTERFACE**		
R8.01	Graphic Tools	II	
R8.02	Provide operator help function	III	Design influence
R8.03	Provide hard copy output	III	Design influence
R9	**SENSORS**		
R9.01	Teleoperate position and rate commands	II	
R9.02	Teleoperate display line of sight	III	Partial for Phase II
R9.03	Teleoperate text display station angles	III	Partial for Phase II
R9.04	Automatically map surfaces	II	
R9.05	Operator parameters	II	
R9.06	Draw/display scan paths	II	
R9.07	Continual backup of raw data	II	
R9.08	not used		
R9.09	Operate sensor remotely from computing platform	II	
R9.10	Surface mapping sensor	III	Partial for Phase II
R9.11	Sensor performance	III	Partial for Phase II
R10	**SITE ENVIRONMENT**		
R10.01	Surface characteristics	III	Design influence
R10.02	Illumination and visibility	III	Design influence
R10.03	Environmental considerations	III	Design influence
R10.04	Design constraints	III	Design influence

2.2 System-Level Design

2.2.1 General System Design Philosophy

In reviewing the various remediation missions, it became evident that ICERVS can be used in applications with differing data requirements and therefore using different sensors, processing algorithms, and data stores. To address these differing remediation environments and needs, the Phase II ICERVS system design was matured to a more open, flexible architecture. In general, an ICERVS consists of a computing platform, one or more sensor subsystems, a volumetric data subsystem, and an interface to a higher-level supervisory application.

The system configuration implemented in Phase II is shown in Figure 2-1 and consists of seven subsystems. Three of these subsystems, the demonstration, volumetric data, and sensors manager subsystems, compose what was referred to as the "analysis software" in earlier ICERVS documents. The structured light sensor subsystem, was developed outside the ICERVS program and loaned to ICERVS to support Phase II testing and demonstration. Table 2-2 summarizes the Phase II ICERVS subsystems.

In Phase I, it also became clear that ICERVS will not be used as a stand-alone system, but rather will be integrated into a higher-level, overall remediation system. For that reason, in Phase II MTI matured the original ICERVS system design from a monolithic to an open architecture made up of configurable/modular subsystems. Each of the seven subsystems in Figure 2-1 is an independent Unix process, and communicates externally through client-server connections based on Unix-network sockets. With this design, ICERVS subsystems can be readily integrated and used in higher-level systems. The individual subsystems can be run transparently across a network of Unix workstations.

In Phase II, MTI continued to use object-oriented methodology to provide design abstraction, promote software reuse, and effectively partition design complexity. ICERVS software is implemented in C++ source language. In the source code implementations, user interface code and problem domain source codes were maintained in separate partitions.

2.2.2 Computing Platforms

In Phase II, MTI utilized a Silicon Graphics Indigo (SGI) Entry workstation as the primary computer platform. The workstation was upgraded from that used in Phase I, and now includes an RISC 4000 CPU, 64-Mbyte local memory, 1000-Mbyte hard disk, 19-in. color monitor, and standard keyboard and mouse. MTI augmented this with a second workstation, a Sun SPARC Classic system. The Classic includes a SPARC CPU, 16-Mbyte local memory, 424-Mbyte hard disk, 15-in. color monitor, and standard keyboard and mouse.

2.2.3 Commercial Software

In addition to the Unix operating system and X Window System that comes standard with each workstation, MTI selected and used a number of commercial software packages to reduce the overall programming effort. These software packages are briefly described in the following paragraphs.

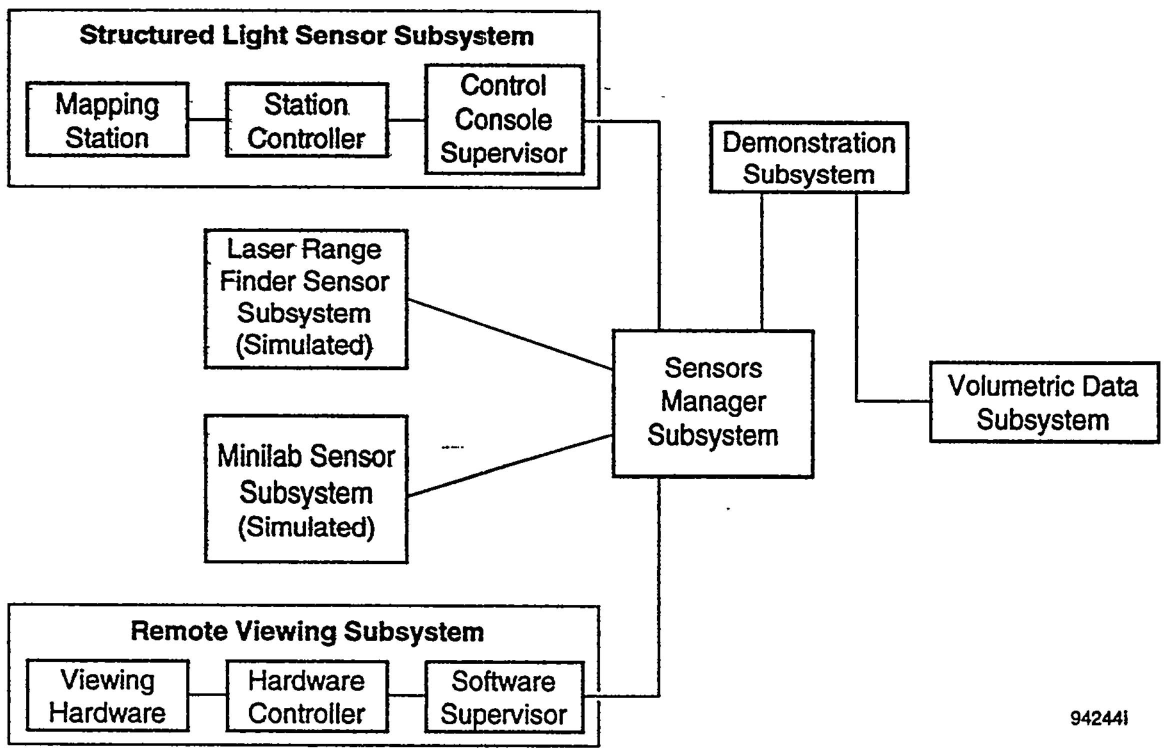

Figure 2-1.- Phase II ICERVS Configuration

Table 2-2. Phase II ICERVS Subsystems

Phase II Subsystem	Primary Function	Hardware/Software Configuration
Demonstration	Top-level user access to other subsystems	Software only (SGI platform)
Volumetric Data	Data integration, visualization, analysis, and geometric modeling	Software only (SGI platform)
Sensors Manager	Manages data transfers between sensor subsystems and application/client(s)	Software only (SGI platform)
Structured Light Sensor	Maps the interior surfaces of underground storage tanks	• Mapping station (hardware) • Station controller hardware and software (PC/DOS platform) • User interface software (Sun platform)
Simulated Laser Range Finder	Generates representative sensor data from files	Software only (SGI or Sun platform)
Simulated Minilab Sensor	Generates representative sensor data from files	Software only (SGI or Sun platform)
Remote Viewing	Provides remote, live video view of workspace	• Viewing camera, lens and pan/tilt • Hardware controller • User interface software (SGI platform)

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To keep commonality among user interface designs, both workstations run the OSF/Motif graphical user interface on top of X Windows. To facilitate the design of user interface windows, menus, dialog boxes, etc., MTI used the UIM/X Graphical User Interface Management System from Uniras, Cambridge, Massachusetts. UIM/X is a comprehensive system that lets users create graphical user interfaces and automatically generate Motif source code. MTI also used the Uniras agX/Toolmaster library for a number of high-level graphical functions such as creation of axes and grids for data display, and interpolation of sensor data.

MTI used several class libraries developed by Rogue-Wave of Corvallis, Oregon: Tools.h++, a set of classes providing structured and unstructured collections, string/character manipulation, and file management; Math.h++, a set of classes providing numerical capabilities including linear algebra and manipulation of vectors and matrices; and RWCanvas.h++, a class library for 2D and 3D graphical object management and interaction.

The bulk of the Phase II volumetric modeling capabilities are performed by the TrueSolid library developed by Octree Corporation of Cupertino, California. TrueSolid provides a broad range of volumetric modeling capabilities based on a patented octree technology. Benchmark tests run by MTI early in Phase II confirmed that the TrueSolid library provided significant performance and memory advantages over other volumetric software packages.

2.3 Subsystem Design

Each of the seven subsystems identified in the system-level design and shown previously in Figure 2-1 was assigned a subset of the system-level requirements and designed using object-oriented methodology and the commercial software libraries described above.

2.3.1 Demonstration Subsystem

In Phase II, the demonstration subsystem provides for overall control of ICERVS, serving as a client application to both the volumetric data subsystem and the sensors manager subsystem. The demonstration subsystem is a single Computer Software Configuration Item (CSCI) that runs on the SGI platform. In a complete remediation system, the functions of this subsystem would typically be provided by an overall supervisory controller. In Phase II, this subsystem essentially provides a vehicle for demonstrating the other ICERVS subsystems.

The subsystem maintains a set of sites (a site being a distinct remediation workspace such as an underground storage tank, buried waste pit, or D&D facility) so that ICERVS can be demonstrated for a variety of remediation applications. The demonstration subsystem provides user commands to open the volumetric data subsystem and sensor subsystems that are on line. It also provides a "connections" capability to support automatic routing of data from one sensor subsystem to a selected data set within the volumetric data subsystem. The demonstration subsystem provides the top-level user interface for the Phase II system. This user interface is a main window with a set of top-level menus as shown in Figure 2-2. The demonstration subsystem also maintains an application data structure, which includes system-level parameter files and a structured set of parameter and data files for each site.

The demonstration subsystem is implemented in 55 MTI software classes, 22 associated with the human interface component and 33 associated with the problem domain component.

2.3.2 Volumetric Data Subsystem

The volumetric data subsystem provides the data storage, 3D visualization and analysis, and geometric modeling functions required by remediation systems. This subsystem is implemented in software on the SGI platform. Overall, the volumetric data subsystem is implemented in 75 MTI software classes, 58 associated with the human interface component, and 17 associated with the problem domain component. This subsystem functions as a server process. A key software class in this subsystem is the data set, which stores the collection of sensor data and geometric objects that characterize a particular site at a discrete time or state.

2.3.2.1 Baseline Capabilities. The volumetric data system provides a variety of features to let users create, manipulate, and analyze data sets. Operator functions are provided in a set of graphical user interface windows. These windows provide data visualization, data analysis, and graphical editing of geometric objects. A typical view window is shown in Figure 2-3. The figure shows a topographical map of an underground storage tank in Fernald, Ohio. The data was provided by engineers from Oak Ridge National Laboratory. The display options include arbitrary viewpoint (rotation, translation, scaling), pseudo-coloring of property data, and cut planes. Analysis functions include data set combining, region clearing, volume computation, data interpolation, and data registration. Most of the volumetric functions are provided by the TrueSolid software library, including the combined rendering of sensor data and geometric objects. MTI implemented a software class to encapsulate a single interface to TrueSolid. This software class may have reuse value in other DOE applications that involve volumetric modeling.

Graphical editing of geometric objects is provided by a set of classes built on top of the Rogue-Wave RWCanvas.h++ graphics library. The primary geometric primitive is a prismatic shape, characterized by a front and rear "face", each having the same number of vertices, connected by simple facets. A typical set of editing windows is shown in Figure 2-4. The entire object or either face can be rotated, translated, or scaled via a control panel. The individual vertices on either front or rear face can be interactively edited in separate 2D windows. Second-order primitives can also be created and edited parametrically, and all geometric objects can be put in an object library for later reuse. Various text data, such as name, operator ID, general description, and category can be attached to each object by the user. The set of geometric objects for a data set can be exported as a file in IGRIP format.

2.3.2.2 Added Capabilities for Buried Waste Applications. To support buried waste applications under project Task 8, MTI expanded the volumetric data subsystem capabilities, particularly in the area of material properties. The original design, which provided for a single property value to be associated with each dataset, was expanded to provide up to sixteen user-defined properties. Many of the visualization and analysis capabilities of the volumetric data subsystem were expanded to utilize material properties. For example, property data can be updated at any time (just like dimensional data) to reflect changes that occur during an excavation mission. Also, for each view window, the system now allows the user to select a material property for coloring the display. The interpolation function was expanded to provide interpolation of material property data in addition to the surface interpolation computed for dimensional data.

2.3.3 Sensors Manager Subsystem

The sensors manager subsystem provides a link between sensor subsystems and the demonstration subsystem (or other applications). Implemented in software on the SGI platform, this subsystem provides a server interface to the demonstration subsystem and a client interface to each sensor subsystem. It also manages data transfer between sensors and applications, and provides an architecture for preprocessing of sensor data. The sensors manager does not implement a user interface.

To facilitate communications, the sensors manager includes C++ base classes for implementing ICERVS clients and servers. These base classes are used by all ICERVS subsystems. The classes use Ethernet and Unix sockets based on TCP/IP; however, the design is modular to allow other protocols to be used. The base classes provide command formatting and parsing. Overall, the sensors manager subsystem is implemented in 23 MTI software classes.

The sensors manager also provides an architecture for preprocessing sensor data. This architecture is based on the concept of a logical sensor, which is an abstraction of a complete data-gathering activity. A logical sensor incorporates data acquisition from one or more physical sensors, processing of sensor data, and routing of processed data to the system destination. Logical sensor capabilities were designed but not implemented in Phase II.

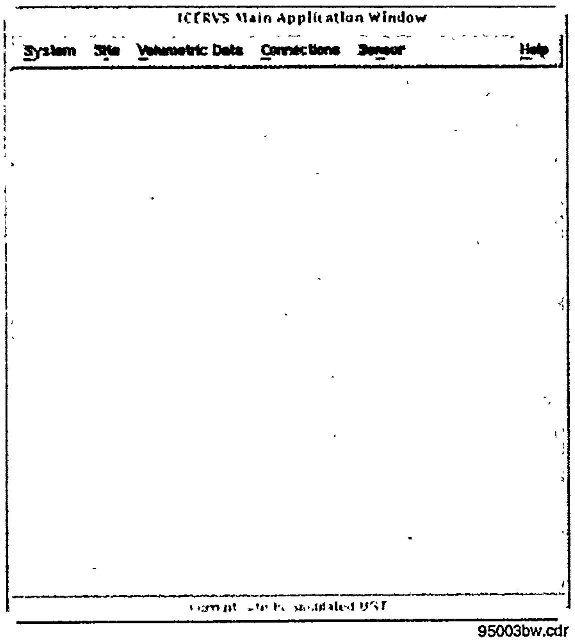

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Figure 2-2. Demonstration Subsystem Top-Level User Interface Window

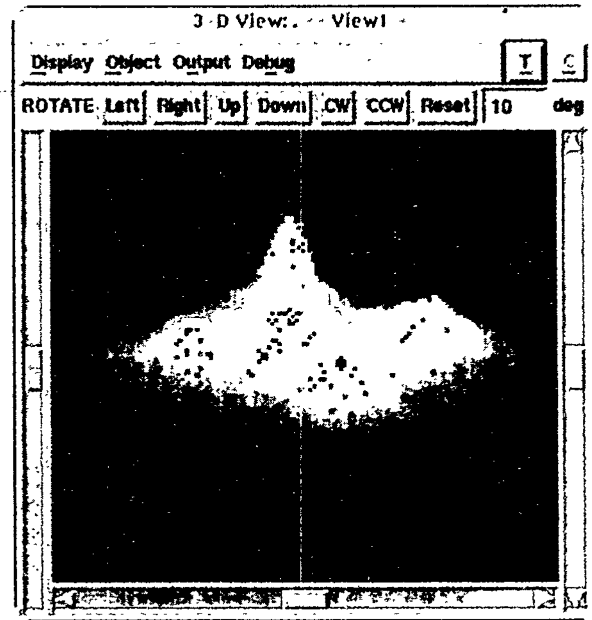

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Figure 2-3. Typical Volumetric Data Subsystem View Window

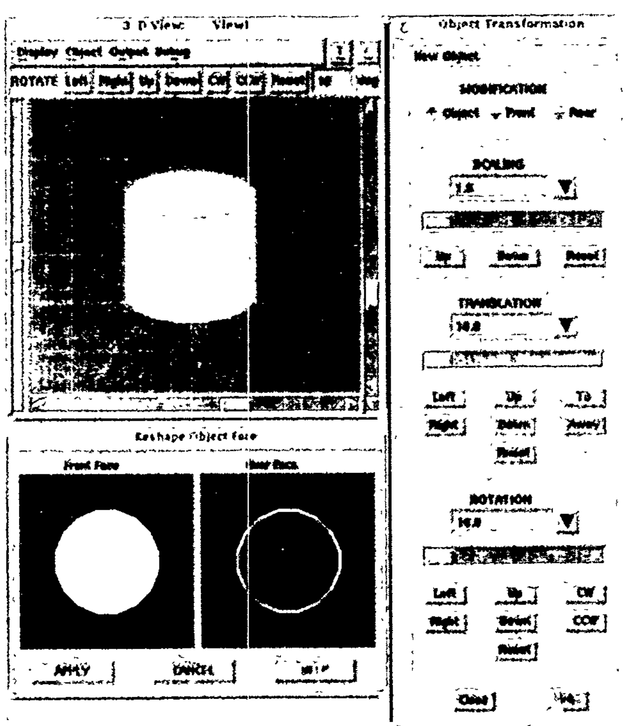

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Figure 2-4. Typical Geometric Editing Windows

2.3.4 Structured Light Sensor Subsystem

Outside the scope of the ICERVS program, the structured light sensor subsystem was jointly developed by MTI, Sandia National Laboratories and ORNL under two CRADA agreements. The purpose of this subsystem is to map the interior surfaces of underground storage tanks. A second-generation prototype was first demonstrated in February 1994 and subsequently loaned to ICERVS to serve as the primary data source for testing and demonstration in Phase II. The structured light sensor subsystem demonstrated an accuracy of 0.28 in. and an estimated mapping time of 2 hr for a typical tank.

This subsystem includes both hardware and software. Referring back to Figure 2-1, the subsystem is made up of three main components. The mapping station, which is the hardware that is placed in the tank, is shown in Figure 2-5. It consists of separate laser and camera modules assembled in a long tube that fits down the 4-in. diameter risers in typical tanks. Each module has an optical mirror with independent tilt motor to provide scanning of tank surfaces. The overall mapping station has a third motor to provide pan motion. The vertical displacement between camera and laser modules establishes the basic geometry for measuring 3D coordinates by triangulation.

The mapping station is connected by an umbilical cable to the station controller, which consists of a 486/PC, developmental software, and electronics modules to support the mapping station motors, camera, and laser. Included in the 486/PC is a video digitizer and image processor to convert the camera module images of the laser beam into pixel coordinates. The station controller also includes software to convert the pixel coordinates into calibrated xyz coordinates.

The station controller sends its xyz data by Ethernet to a Sun Classic workstation that runs the control console software. The control console provides the main operator interface and map data storage/display. The main user interface, shown in Figure 2-6, presents plan and elevation views of the mapped workspace. The workspace views are colored to indicate the height (z-coordinate) of the measured data in the plan view and distance from the sensor in the elevation view.

To operate in ICERVS, the control console software was upgraded to allow it to be run as a Unix network-server process, using the socket-based classes developed for the sensors manager subsystem.

2.3.5 Simulated Laser Range Finder Subsystem

Because the ICERVS design was refined to support diverse sensor types, it was desirable to incorporate multiple sensors in the Phase II demonstration. One sensor that is likely to be used extensively in DOE environmental remediation missions is a laser range finder. These sensors work by modulating a laser beam and scanning it over a surface of interest. The reflected image of the laser is detected, and the measured (relative) amplitude or frequency/phase shift is proportional to the line-of-sight distance. Lacking access to or availability of actual laser range finder hardware, MTI implemented software to simulate the behavior of a representative system. This software runs on either the SGI or Sun computing platform and implements a Unix network-server process using the base class developed for the sensors manager subsystem. The

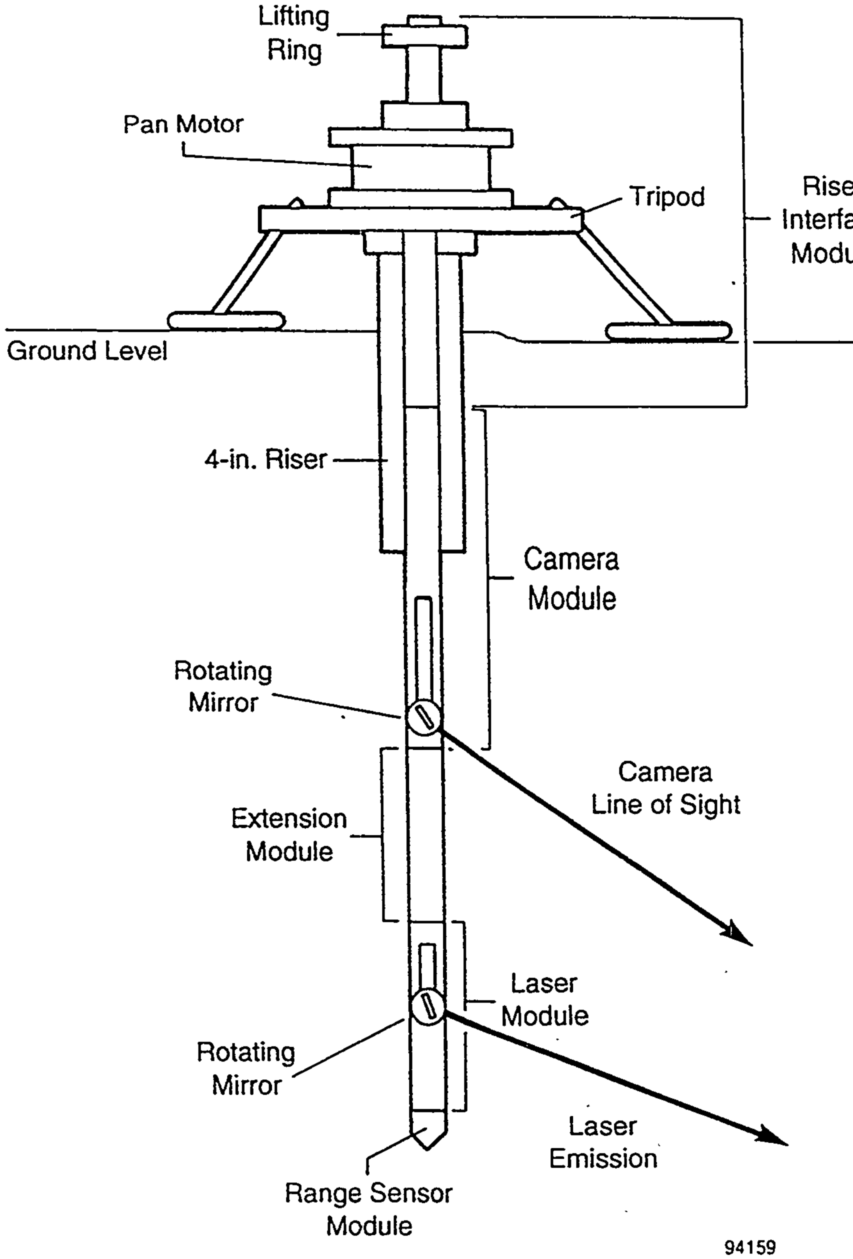

Figure 2-5. Structured Light Sensor Mapping Station

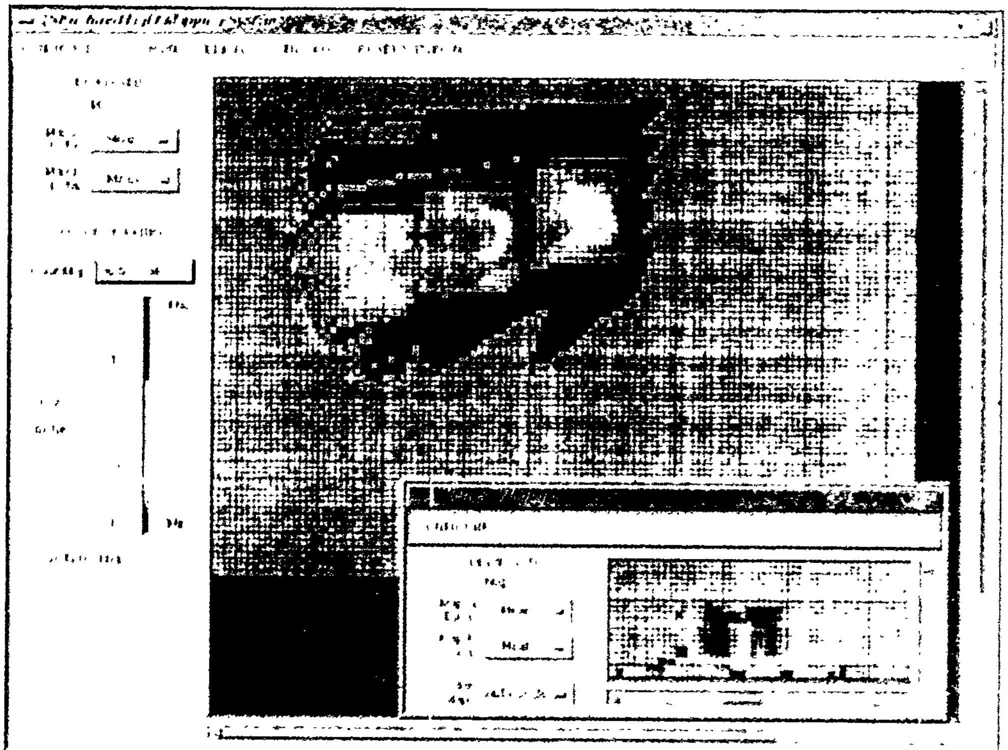

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Figure 2-6. Structured Light Sensor User Interface software reads data files that were generated from laser range finder measurements and transfers them to the client application under user control. The software provides a simple user interface window to let users enter data filenames and initiate data transfer to the client application.

2.3.6 Simulated Minilab Sensor Subsystem

Another sensor subsystem that will be used extensively in DOE environmental remediation missions is the Minilab being developed by Sandia National Laboratories. The Minilab is sophisticated data acquisition system that can control a broad range of devices measuring dimensional, physical/geophysical, chemical, and radiological properties. It was desirable to include a Minilab subsystem in Phase II to demonstrate the material property capabilities of ICERVS.

Again, lacking access to or availability of actual hardware, MTI implemented a software subsystem to simulate the behavior of a typical Minilab. This software is very similar to the simulated laser range finder subsystem, and the two subsystems share some common source code. The software runs on either the SGI or Sun computing platform and implements a Unix network-server process using the base class developed for the sensors manager subsystem. It provides the same user interface window to let users enter data filenames and initiate data transfer to the client application.

For Phase II, data files were provided to MTI by INEL. These data files were generated from five experiments performed at the INEL Cold Test Pit, which was constructed for testing buried waste characterization and retrieval strategies. In the experiments, INEL generated a series of dig faces by excavating several feet into the ground and scanning at different depths. The equipment used include magnetic, electromagnetic and volatile organic compound (VOC) sensors.

2.3.7 Remote Viewing Subsystem

The remote viewing subsystem was implemented to demonstrate the expected use of remote cameras in typical remediation systems and their relation to the ICERVS display. This subsystem includes both hardware and software. As shown earlier in Figure 2-1, the remote viewing subsystem has three main elements: the viewing hardware is a commercial video camera with zoom lens and pan/tilt motion; the hardware controller is a commercial electronics package that provides motion control; and the software supervisor is software that runs on the SGI workstation. The software provides simple keyboard and spaceball controls for pan, tilt, and zoom control. The software supervisor also converts the pan/tilt angles into line-of-sight data (3D origin and direction vector) that is sent to the client application on operator command. This capability can be used in ICERVS to set the viewpoint for a computer graphic display of the corresponding data set.

3.0 SYSTEM PERFORMANCE TESTING

3.1 Unit and Subsystem Testing

ICERVS testing was performed at the class, subsystem, and system level. More than 200 classes were written in C++ source and unit tested using local test code included in each class source file. Each subsystem was integrated and tested independently. To facilitate subsystem testing, Unix client and server programs were written to connect to a subsystem and provide user control and data access. Overall system integration and testing were completed using the system demonstration plan described below.

3.2 ICERVS Demonstration

The ICERVS Phase II demonstration was presented in September 1994. To realistically present the ICERVS features, the system demonstration was divided into three parts portraying remediation activities at an underground storage tank, a buried waste site, and a D&D facility. The demonstration took place in MTI's large-scale test facility (see Figure 3-1), which includes the structured light sensor described in Section 2.3.4 and a mock-up underground storage tank with simulated waste.

The first part of the system demonstration portrayed the use of ICERVS supporting the remediation of an underground storage tank. The structured light sensor was used to map pallets of simulated waste and a simulated tank wall. The volumetric data subsystem was used to provide 3D visualization of the sensor data. Figure 3-2 shows a typical view of the data, which consisted of 20,000 points. The remote viewing subsystem was used to demonstrate how the scene would be viewed remotely, and how the volumetric data display can be made to match the same viewpoint as the remote viewing subsystem. During the demonstration, a portion of the simulated waste was removed and the region remapped to show how ICERVS can be updated as a retrieval process proceeds. Figures 3-3 and 3-4 show a close-up of this region before and after simulated waste removal.

The second part of the system demonstration portrayed the use of ICERVS to support buried waste retrieval. The major focus was material property capabilities. The simulated Minilab sensor was used to supply test data from the INEL dig face characterization experiments, as described in Section 2.3.5. The basic procedure is to read in a sequence of dig faces from one experiment. Different material properties were displayed in multiple view windows, and interpolation and derived properties were demonstrated. Figure 3-5 shows a typical view of multiple dig faces interpolated and colored by material property.

The third part of the system demonstration portrays the use of ICERVS to support the dismantling of a D&D facility. The simulated laser range finder sensor was used to supply test data from a small pipe assembly. In the volumetric data subsystem, data from different sensor poses were combined into one data set using interactive registration, and geometric objects were created and edited to match features of interest in the data set display. Figures 3-6 and 3-7 show the sensor data before and after registration.

During the Phase II demonstration, a number of potential improvements, particularly in the area of usability, were suggested by DOE attendees. These will be evaluated and, where practical, incorporated in the next phase of ICERVS development.

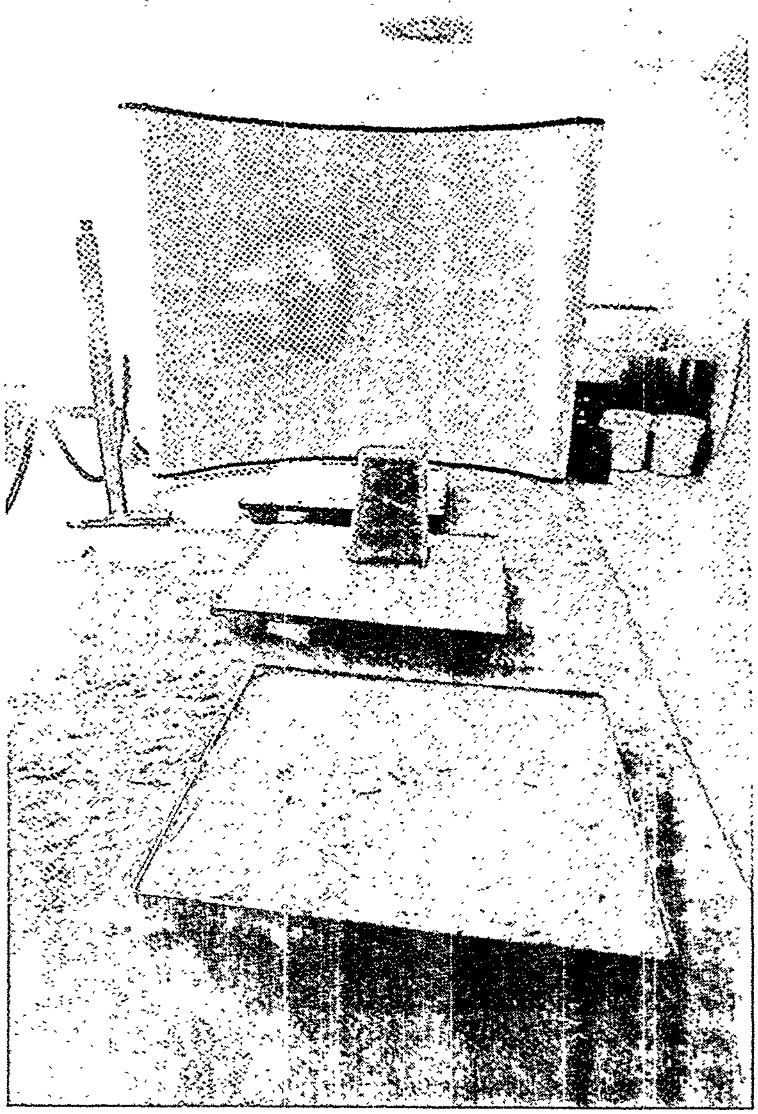

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Figure 3-1. MTI's Large-Scale Test Facility for ICERVS Demonstration

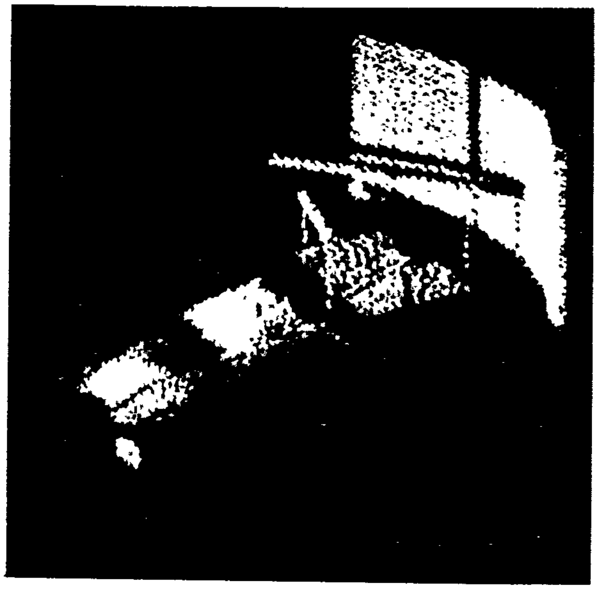

Figure 3-2. MTI Simulated Single-Shell Tank

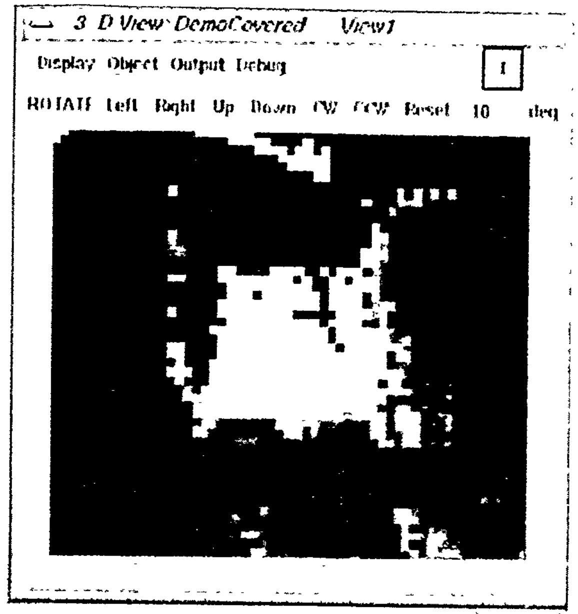

Figure 3-3. Close-up of Bentonite before Removal

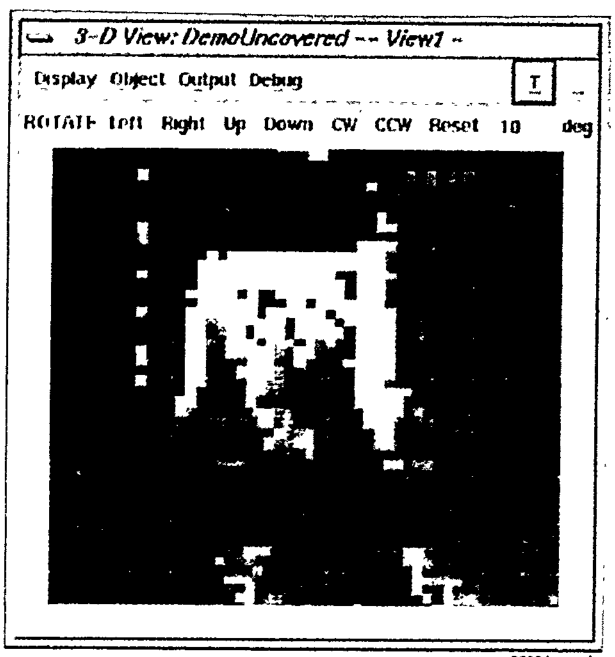

Figure 3-4. Close-up of Bentonite Pallet after Removal

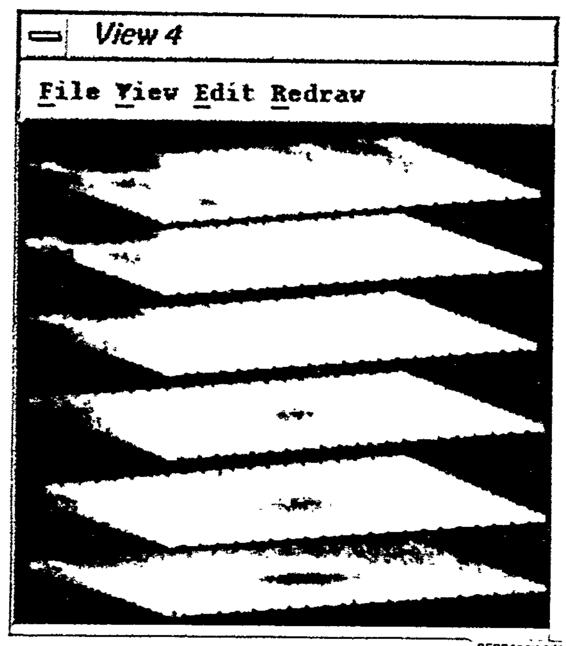

Figure 3-5. Material Property Data at Different Stages of an Excavation

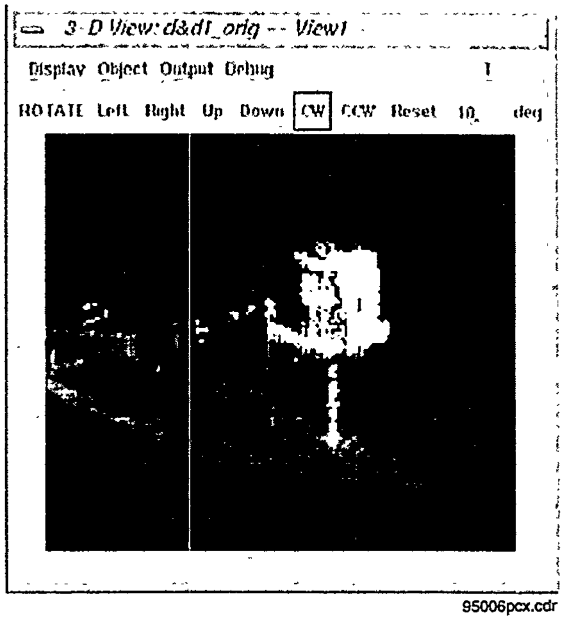

Figure 3-6. Pipe Assembly Mapped at Five Different Sensor Poses

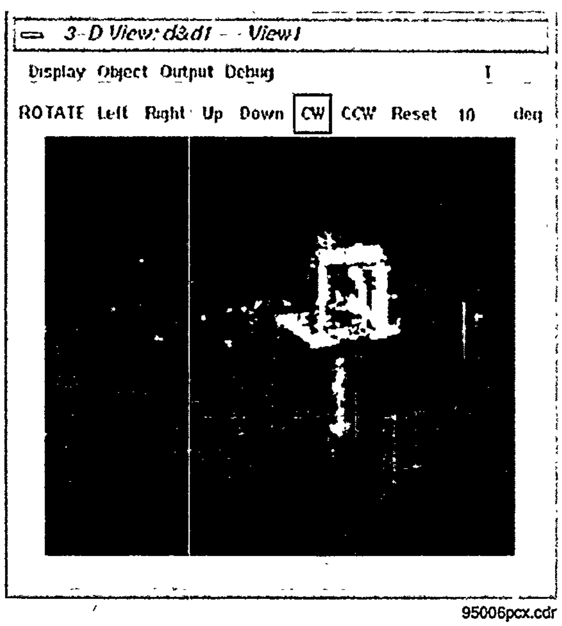

Figure 3-7. Pipe Assembly after Data Registration

4.0 RESULTS

All success criteria established for the Phase II development effort were achieved. These criteria are listed below, and specific results for each are discussed in the succeeding paragraphs.

- The sensor subsystem automatically and/or interactively maps the surface and walls of a simulated single-shell tank.
- ICERVS properly creates a volumetric data base for the simulated single-shell tank and maintains an equivalent world model in a form compatible with the needs of robotic controllers.
- ICERVS demonstrates enhanced viewing and model-building tools.
- ICERVS displays corresponding (matching) scenes from a live video camera and the computer's world model as the operator pans the camera.
- ICERVS provides material property capabilities to support buried waste applications.

4.1 Surface Mapping of Simulated Single-Shell Tank

Testing in MTI's large-scale test facility showed that the structured light sensor subsystem reliably maps various surfaces, including a floor covered by loose granular soil, bentonite and saltcake samples, pipes, and a six-foot vertical wall. These features are representative of surfaces found inside single-shell underground storage tanks. Mapping was done at full-scale dimensions, and other testing by MTI has shown sensor accuracy to be better than one inch. The ICERVS demonstration showed that mapping can be directed either by user-interactive scan path planning or automatically via pre-stored scan paths. A typical scan path plan resulted in a map of 20,000 data points.

4.2 Volumetric Database of Single-Shell Tank

The Phase II demonstration showed that the data acquired by the structured light mapping system can be transferred via a Unix socket-based, client-server connection from the sensor to the volumetric data subsystem and there used to create an ICERVS "dataset". The dataset can then be viewed using the capabilities described below.

4.3 Enhanced Viewing and Model Building

The Phase II ICERVS demonstrated many new or improved capabilities for viewing and interacting with data, for example, arbitrary viewpoint, various color mapping options, surface interpolation, generalized prismatic shapes and poses, wireframe and solid-shaded object display, and (quantitative) volume measurements. These features improve the effectiveness of ICERVS in helping operators comprehend a scene in order to carry out subsequent remediation activities. Also demonstrated was the generation of an IGRIP part file, which provides an interface to a world model in a form compatible with robotic controllers.

4.4 Matching Scenes

The matching scene functionality was successfully demonstrated, although accuracy was limited by a number of factors, including limited accuracy of the pan/tilt encoders; estimated zoom/scale factor; coarse calibration of the pan/tilt mechanism; and orthographic projection of the dataset versus perspective view of the camera. Nonetheless the matching scene function was successfully demonstrated in the form of a "snap" function invoked by the user to change the dataset viewpoint to match the remote viewing camera. The results exhibited a slight dimensional offset between the two scenes, which was certainly within the range of dimensional uncertainty.

4.5 Material Property Capabilities

The material property capabilities developed to support buried waste applications were also successfully demonstrated. These included property display with color mapping, property interpolation, display of data from multiple/sequential dig faces, and "derived" property computed by arithmetic combinations of properties. A distribution tape of the ICERVS software was also prepared and sent to Mr. L. Eric Greenwade of INEL for use in the BWID dig face characterization and virtual world generation projects under his direction.

5.0 CONCLUSIONS

- Successful demonstration of the Phase II system shows that ICERVS has reached Maturity Level IV, Subscale Integrated System. From a technical perspective, the system is ready to proceed to full-scale deployment.

- The Phase II system met or exceeded all success criteria established for this phase of development: automatic mapping of a realistic workspace (simulated underground storage tank); creation of a volumetric database for dimensional and material property sensor data; creation and editing of geometric models to represent physical objects in the workspace; and correspondence between live video and the computer model of the workspace.

- The octree technology on which ICERVS is based provides an effective means for the visualization and analysis of general 3D sensor data such as will be developed in environmental remediation missions. Features such as color mapping and arbitrary viewpoint make ICERVS particularly well suited for data interpretation tasks.

- The geometric modeling tools, based on generalized prismatic shapes, provide an effective way to generate geometric objects that can be passed to robotic controllers for incorporation into their world model.

- The integration and display of combined 3D sensor data and geometric objects is an important step toward more productive analysis of remediation workspaces. With ICERVS, operators can compare xyz data from sensors with geometric (CAD) models of the same region in space and view both sets of data in the same view and coordinate system. As a result, operators will be able to better manage the formidable complexities of task and path planning in 3D space. ICERVS will thus provide an important payback in terms of operator effectiveness and efficiency as well as reduce the likelihood and frequency of operator error, leading to safer robotic remediation.

- The increased interaction with DOE site personnel greatly influenced and improved the design of the Phase II system. Continuing this interaction will greatly benefit ICERVS and the EM program.

- The use of commercial software (TrueSolid, Uniras agX/Toolmaster and UIM/X, and the Rogue Wave class libraries) greatly facilitated the software development and improved the quality of the overall system.

6.0 RECOMMENDATIONS

With the successful demonstration of ICERVS at Maturity Level IV, Subscale Integrated System, and the continued interest by personnel at DOE field sites, MTI recommends proceeding to develop the technology to Maturity Level V, Full-scale Integrated System.

As planned in MTI's original ICERVS proposal (December 1991), the Phase III work will include the fabrication of a structured light sensor subsystem for mapping the interior of underground storage tanks. MTI's CRADA investments have resulted in a working prototype with the demonstrated capabilities needed by DOE. This was confirmed in May 1994, when MTI was awarded a contract by Martin Marietta Energy Systems at ORNL to develop a full-scale, radiation-hardened topographic mapping system. This new system is an upgrade of the CRADA design and will be installed in the LDUA Cold Test Facility at Hanford. The ICERVS Phase III sensor subsystem will be based on this new design and will include a further upgrade for tandem-mode operation. In tandem-mode operation, two mapping stations are used cooperatively to enhance the overall mapping beyond that of two independent mapping stations.

The Phase III system will also provide further enhancements to the ICERVS volumetric data subsystem. These include, for example, importing of CAD-based architectural plans, display with perspective view, integration with a robot controller such as Deneb's IGRIP, and a number of usability improvements. These features will ready ICERVS for initial deployment in an underground storage tank characterization and retrieval mission.

MTI recommends that the Phase III ICERVS be demonstrated at DOE's LDUA Cold Test Facility in Hanford. This facility provides a mock-up tank section and has the mechanical and electrical interfaces for the structured light sensor. More importantly, Mr. Gary Kiebel at Westinghouse Hanford Company (WHC) plans to integrate ICERVS into the LDUA system. Because LDUA is already procuring one mapping station from MTI through the Martin Marietta contract, MTI recommends that only one mapping station be manufactured under Phase III ICERVS to provide a two-station configuration for demonstration at the LDUA facility. (The original ICERVS plan called for three mapping stations to be manufactured in Phase III.).

Following the LDUA demonstration, MTI recommends that the structured light sensor subsystem be transferred to the Tank Waste Remediation Systems Group (EM-30) at Hanford, as requested by Mr. Keith E. Myers and Mr. David Forehand. There, the sensor will be incorporated into current characterization efforts that involve placing chemical and radiological sensors into "hot" tanks.

Based on discussions with Mr. Robert Barry at ORNL, ICERVS also appears to be very desirable as part of the Facility Mapping System (FMS) being developed by ORNL for D&D applications. There are a number of requirements identified for D&D applications that have not been included in past and present ICERVS requirements. Examples include displaying nonscalar data such as fast Fourier transforms (FFTs) or chromatography spectra, displaying multiple properties by color in one view, and displaying graphics over video. Because ICERVS is otherwise well-suited to D&D applications, MTI recommends incorporating these D&D features into ICERVS under a "D&D Application" task in Phase III.

Close interaction between MTI and DOE field sites and national laboratories has proven extremely beneficial to the ICERVS development to date, and MTI intends to continue these discussions and interactions throughout Phase III and beyond.

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