INNOVATIVE TECHNOLOGY
Summary Report

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Topographical Mapping System

Tanks Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Topographical Mapping System

OST Reference #130

Tanks Focus Area

Demonstrated at
Fernald Environmental Management Project
Fernald, Ohio
Oak Ridge National Laboratory
Oak Ridge, Tennessee
Hanford Site
Richland, Washington

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE’s Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://OST.em.doe.gov under “Publications.”

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SUMMARY

Technology Summary

Problem

Radioactive waste storage tanks in use at many of the U.S. Department of Energy (DOE) sites are beyond the intended design life. The waste in these tanks must be remediated and the tanks closed. Before these activities are performed, the physical condition of tank interiors must be determined along with detailed information regarding any obstructions and potential problems that may be encountered during installation of retrieval systems. This task is difficult because the tanks are underground and have limited access. The only way to see the physical contents of the tank is to install tools through the tank's openings, or risers.

The Topographical Mapping System (TMS), a three-dimensional (3-D) mapping system that can safely operate in hazardous and radiological environments, has been developed to meet this need. This system provides an accurate 3-D view of the tank interior and gathers data on volume and contents inside storage tanks.

How It Works

TMS is self-contained and reconfigurable system capable of providing rapid, variable-resolution mapping information in poorly characterized workspaces with a minimum of operator intervention. TMS uses structured light to

- create maps of waste topography and tank structures,
- determine surface features and deviations,
- model the tank environment, and
- determine residual tank waste volume.

The system gathers and analyzes data to generate 3-D maps. The data can be used on a stand-alone basis or integrated with other modeling software to generate "world models" of tanks or other work environments. Figure 1 is a time-lapse photograph of the contour lines that result when the laser planes intersect with the mapped surface. The simulated waste surface in the photograph contains sand, simulated saltcake (white rock), and two black vertical pipes.

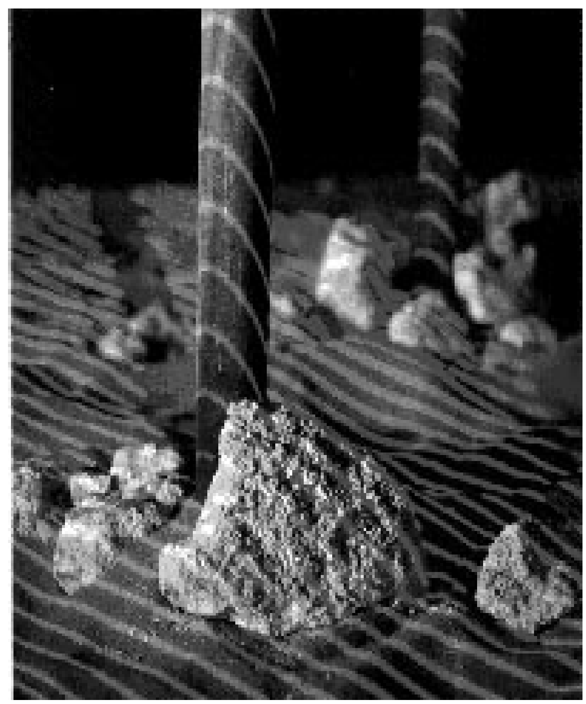

Figure 1. Time-lapse photograph of the structured-light mapping process

Potential Markets

TMS is applicable to all DOE tank sites. TMS has been radiation-hardened to allow for longer in-tank time, which will enable high resolution. It may also be used in industrial operations.

Advantages Over Baseline

A baseline for mapping the tank environment has not been established, but alternate technologies are available. TMS exhibits the following advantages over alternative technologies:

- operates within radiological and hazardous environments,
- can be decontaminated,
- performs faster and more accurately than other methods,
- gathers vital data for response to inquiries on safe waste storage and tank events such as leaks,
- installs in tanks of different sizes, through risers as small as 4 inches in diameter, and
- supports retrieval and closure processes by providing measurements of tank waste volume.

Demonstration Summary

This report covers the period from July 1991 to September 1998 as follows:

- A first-generation prototype was deployed in the K-65 silos at the Fernald site in Ohio in the fall of 1991 to determine the volume of bentonite for capping the waste to control radon emissions.
- A second prototype enhancement was demonstrated at the Hanford Site in June 1994.
- TMS was deployed in Oak Ridge Reservation (ORR) in gunite tanks W-5 and W-6 in February 1997 to perform wall inspections.
- TMS was demonstrated at the Fuel Materials and Examination Facility in a cold-test cell at the Hanford Site in March 1997 to perform a volumetric analysis. A second volumetric analysis was conducted in November of that year using an enhanced volumetric measurement capability.

Key Results

- Surface mapping of Fernald K-65 silos facilitated compliance with U.S. Environmental Protection Agency (EPA) requirements.
- TMS confirmed that there were no significant holes or cracks in ORR tanks W-5 and W-6.
- The accuracy of TMS was verified in the ORR deployments and the Hanford prototype demonstration.
- TMS was able to safely operate in conditions of high radiation levels in flammable gas environments.
- The Hanford prototype demonstration verified that a structured-light mapping system could be installed in tanks of different sizes, with openings as small as a 4-inch-diameter riser.
- The Interactive Computer-Enhanced Remote-Viewing System (ICERVS) 3-D visualization software significantly increased the accuracy of volumetric analysis compared to the previous volume computation method.

Participants

Key parties that contributed to successful Hanford and Oak Ridge deployment of the TMS include

- Tanks Focus Area (TFA),
- DOE Office of Science and Technology (OST),
- DOE Office of Environmental Management (EM),
- DOE Office of Environmental Restoration (ER),
- Oak Ridge National Laboratory (ORNL),
- Pacific Northwest National Laboratory (PNNL), and
- Mechanical Technology, Inc. (MTI).

The DOE Robotics Technology Development Program funded the ORNL-developed prototype system deployed at Fernald in 1991 and the enhanced prototype demonstrated at Hanford in 1994. The 1994 Hanford demonstration was part of a MTI and ORNL Cooperative Research and Development Agreement. The ICERVS tool was developed by the Federal Energy Technology Center.

Commercial Availability

DOE OST sponsored MTI to develop TMS through coordinated efforts with ORNL and PNNL. MTI later sold intellectual property rights for the design to Foster-Miller, Inc., Waltham, Massachusetts (see the "Contacts" subsection). TMS has been commercially available since 1997.

Future Plans
Foster-Miller is continuing to meet with DOE site representatives regarding the use of TMS at DOE sites. Representatives at the Idaho National Engineering and Environmental Laboratory have expressed interest in using ICERVS for decontamination and decommissioning activities at their site. ICERVS is a 3-D visualization system used with TMS to analyze data. It allows for display and analysis of the unusually large data sets generated by mapping underground storage tanks. Foster-Miller is also planning to meet with representatives from commercial nuclear plants to discuss creating design-based drawings for the plants.

Contacts

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Other
All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for the Topographical Mapping System is 130.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

Goals and objectives for TMS uses have varied. TMS was designed to map the interiors of underground storage tanks as part of DOE's waste characterization and remediation efforts. TMS users can obtain both baseline data on tank contents and data on the changes in tank contents and levels brought about by waste remediation steps. The main objective of the Fernald deployment, however, was to verify achieving an EPA requirement of a minimum 12-inch clay cap over the waste. The Hanford prototype demonstration was performed to show that a system could be designed to meet the geometries at the Hanford Site, including installation through a 4-inch-diameter tank riser. Objectives of the ORR deployments were to inspect wall surfaces for cracks, crevices, or signs of structural instability and to validate field-readiness of TMS. The objective of the 1997 Hanford demonstration was to perform a volumetric analysis.

Structured-Light Mapping Process

The topographical mapping sensor uses structured light, which is a triangulation-based range-measurement technique. Figure 2 illustrates a simple structured-light measurement device. The mapping process involves the following steps:

- The mapping sensor projects a laser plane on the surface to be mapped.
- The resulting intersection of the laser plane and the surface produces a contour line depicting the shape of the surface.
- A camera captures an image of the resulting laser plane's contour line.
- The charge-coupled device camera has a vector assigned to each pixel in the array.
- Every point illuminated by the laser line reflection is passed through analytical routines for processing.
- A surface profile is produced from the data gathered.

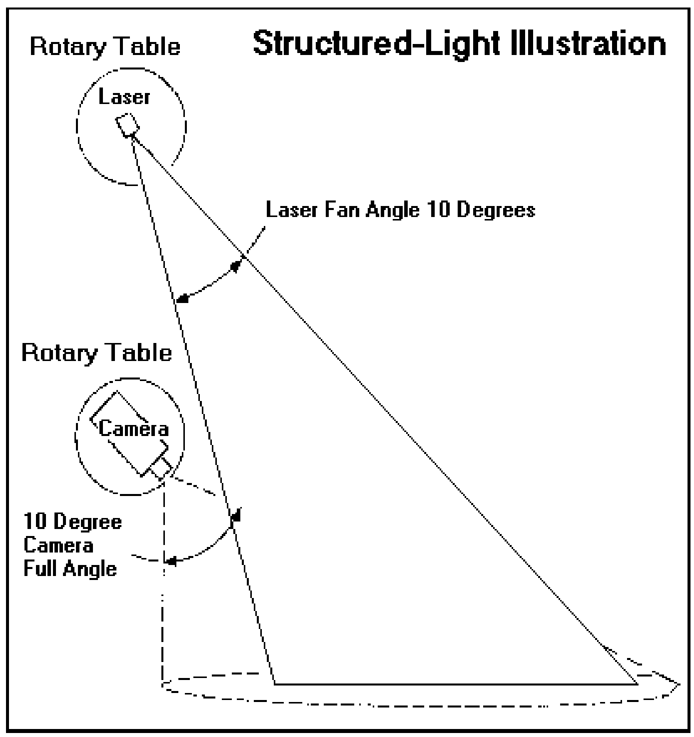

Figure 2. Structured light for range measurement.

Relative Accuracy

Relative accuracy denotes the instrument's precision in measuring the position of one point in space relative to another. In calibration tests prior to the 1997 ORR deployments and Hanford demonstration, the relative root mean square (RMS) error in measurement varied from over 0.40 inches to 0.25 inches (see Figure 3). System error was driven primarily by the lateral error. The axial or range error was very low.

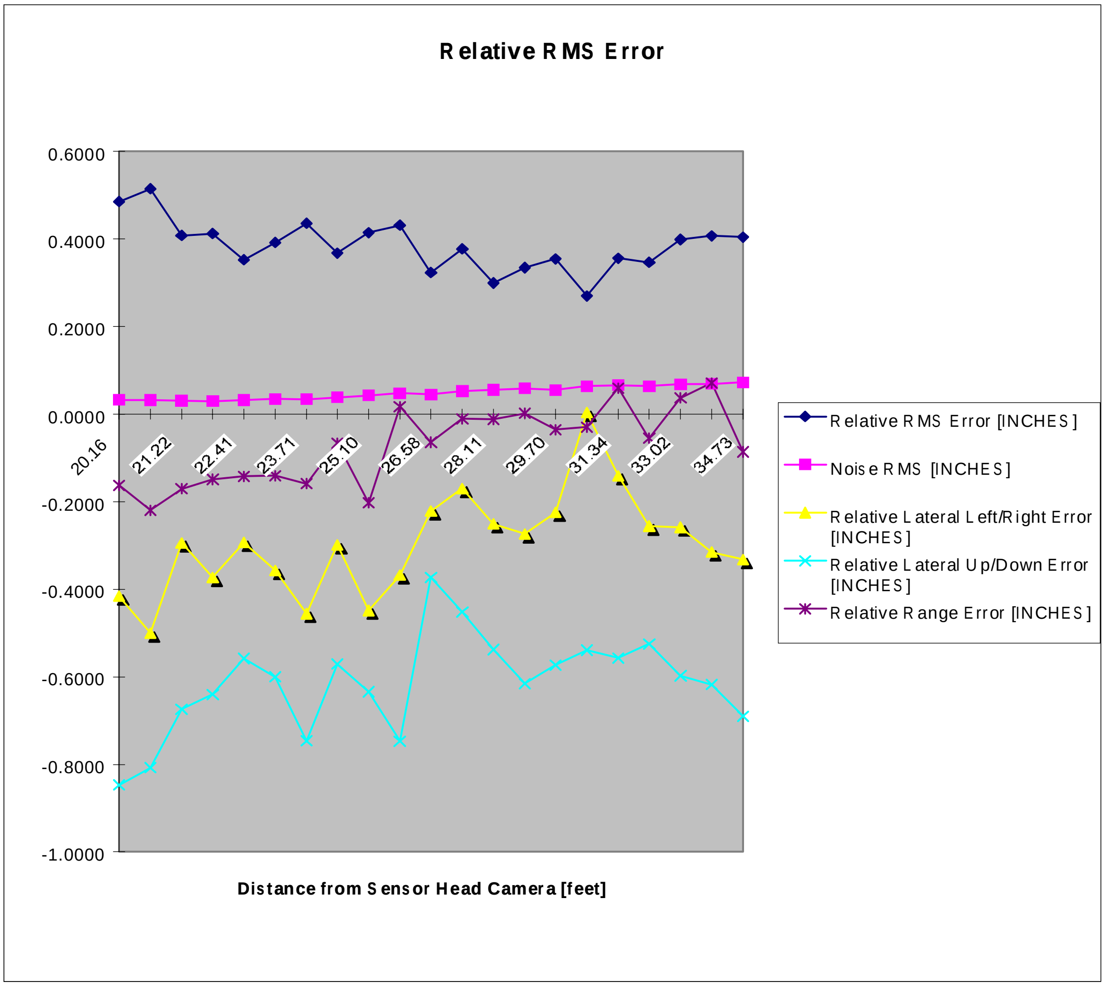

Figure 3. Relative accuracy of the Topographical Mapping System.

Volumetric Analysis Process

Volumetric analysis of an underground storage tank is used to determine the amount of waste removed from a tank and to measure the amount of waste left in a tank. This determination requires that the waste surface be mapped before and after waste removal. Determining remaining waste requires knowledge of the tank bottom either by drawings or by other measurement techniques. Once the bottom is known, a surface map of remaining waste can be registered to a known coordinate frame, and the two surfaces can be subtracted to determine the waste's volume.

Figure 4 is a block diagram illustrating the setup of TMS in an underground storage tank. See Appendix B for additional diagrams and photographs showing the configuration, modules, and components of TMS. The following deployment approach was used.

- Select and acquire a tank volume measurement system.
- Develop calibration procedures, a test plan, and testing procedures.
- Obtain and configure a test facility as necessary.
- Modify the system as necessary to accommodate flammable gas and radiation.
- Design and fabricate a tank interface and balance-of-system equipment.
- Perform calibration and qualification test procedures.
- Conduct a management readiness assessment, and obtain approval for implementation.
- Transport and set up the system at the tank.
- Perform in-tank volume measurements as needed.
- Remove the system from the tank farms, and place the system in storage.
- Analyze data, and generate reports on the tank volume measurements.

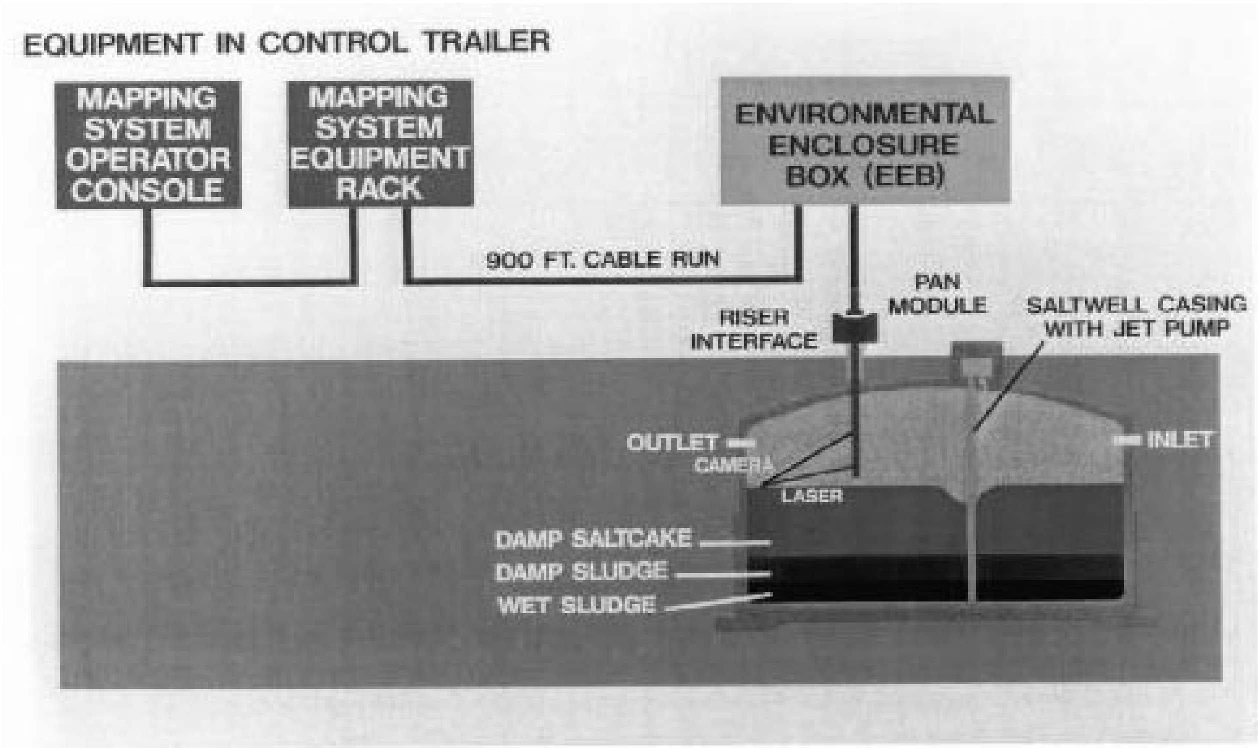

Figure 4. Block diagram of the Topographical Mapping System as installed in a typical underground storage tank.

Key Elements of the Technology and Support Equipment

- TMS consists of the following four major components:
  - A sensor head holds optical sensors that provide actual topographical maps of interior surfaces.
  - An environmental enclosure box holds support electronics that require close proximity to the sensor head (e.g., frame grabber, motor controllers, and the local computer that runs them).
  - A human-machine interface is used for supervisory control, limited data visualization, and data archiving. It is a UNIX-based scientific and engineering workstation that allows the graphical operator interface and supports the various command, control, and communication functions required for proper system operations. It is located in the control trailer approximately 900 ft away.
  - A plug gauge is used to ensure that the riser is clear prior to installing the sensor head. It also contains an environmental sensor section (ESS) that measures temperature, radiation, and range.
- A crane is used to assemble and install TMS.
- The following additional systems are needed to install TMS:
  - a purge gas supply and withdrawal system,
  - a structure to position and hold the TMS sensor head over the riser (i.e., trailer and strong-back),
  - containment systems for riser openings, and
  - containment storage structures.
- ICERVS, a 3-D visualization system, is used to display and analyze data.

System Operation

TMS generates accurate 3-D maps of internal surfaces of an underground storage tank. Table 1 summarizes system operational requirements.

Table 1. System operational requirements

Operational area	Requirement
Operational parameters and conditions	• The sensor head shall be assembled and deployed in a vertical position. • TMS shall fit through a 4-inch-diameter riser (with a 3.5-inch clear opening). • TMS shall operate without failure caused by radiation. • TMS shall be water-resistant and capable of decontamination by liquid spray wash.
Technical skills/training	Workers shall be trained or skilled in the following areas: • operation of remote-controlled equipment, • expertise of a high-level electromechanical technician, • capabilities of a software engineer, • quality assurance and control procedures, • health and safety plans and procedures, and • regulatory requirements.
Secondary wastes	Secondary waste streams should be minimized. Secondary waste streams include contaminated equipment, hardware, plastic sheeting, containers, and associated decontamination wastes.
Concerns/risks	Worker exposure shall be minimized.

SECTION 3
PERFORMANCE

Demonstration Plan

TMS is a proven technology based on an earlier structured-light surface-mapping system prototype developed by ORNL. This prototype was first tested and demonstrated in an empty silo (#4) at the Fernald site in July and August of 1991. Table 2 identifies subsequent uses of this prototype, an enhanced prototype, and the current system, which is capable of operating in hazardous and radioactive environments with higher radiation fields, corrosive atmospheres, and mixed liquid and solid waste tanks.

Table 2. Summary of Topographical Mapping System applications

Location/date	Description	Objectives	Success criteria
Fernald site, Cincinnati, Ohio			
• 9/24–10/11/91 • 11/91 • 12/2–21/91	Deployed prototype in K-65 silos 1 and 2 to scan waste surfaces. Added bentonite clay cap. Obtained final surface maps.	Determine waste surface topography before and after clay cap addition.	Clay cap is minimum of 12 inches deep at all locations.
Hanford Site, Richland, Washington			
• 6/94	Conducted proof-of-principle demonstration of enhanced prototype.	Determine whether site needs can be met.	Prototype shall fit through 4-inch-diameter riser and produce relative accuracy of 0.25 inches within 45-ft range.
Oak Ridge Reservation, Oak Ridge, Tennessee			
• 2/97	Deployed TMS to perform wall inspections on tanks W-5 and W-6 at the South Tank Farm. Both tanks are 50-ft diameter with 12-ft walls and are capped with domes that crest 6 ft above the walls. Central riser extends 7 ft up past the dome, which is bermed with dirt. Height from the central riser top to the tank bottom is 25 ft.	Inspect wall surfaces for cracks, crevices, and/or holes to identify possible signs of structural instability and validate field readiness.	• TMS shall provide accuracy of ±0.25 inches over range of up to 45 ft. • Mapping data densities shall be at least one point per 6- by 6-inch region covering up to 95% of surfaces in tank. Time required for mapping shall not exceed 2 h at this data density. • Operate in a continuous flux of 500 rad/h and an intermittent peak flux of 1000 rad/h up to a total absorbed dose of 1 million rad over a 6-month period without failure caused by radiation.
Hanford Site, Richland, Washington			
• 3/97 • 11/97	Demonstrated volumetric analysis capability in Fuel Materials and Examination Facility cold-test cell using the before-and-after surface map technique on five sand mounds. Demonstrated new ICERVS volumetric measurement capability on same five sand mounds.	Perform volumetric measurements of simulated waste (sand).	Relative accuracy is >0.5 inches over entire range and 0.25 inches within optimal region.

Results

Performance objectives and criteria were achieved. Key results of the technology's applications follow.

Deployment of First Prototype System in Fernald K-65 Silos in 1991
This mapping system provided an elevation profile of waste in the K-65 silos, where visual inspection only showed mounds of waste without the ability to determine depth variations. This profile enabled operations staff to ensure that a minimum 12-inch-thick bentonite clay cap was evenly distributed in the K-65 silos to comply with EPA requirements. Data also provided planning information for future removal of the cap and waste, verification of waste volumes historical data, and headspace volume calculations needed to support radon data logging. Specific details and surface maps are contained in ORNL/TM-12185 (Burks et al. 1992).

Demonstration of Second Prototype at the Hanford Site in 1994
This proof-of-principle demonstration was successful in verifying system installation through a 4-inch-diameter opening and surface mapping accuracy of 0.25 inches within a 45-ft range.

Deployments of TMS in ORR Tanks W-5 and W-6 in 1997
Table 3 summarizes results of TMS deployments in ORR tanks W-5 and W-6. TMS verified that there were no significant penetrations in exposed portions of the tank walls. See Armstrong, Burks, and Van Hoesen 1997 for further details, including TMS surface maps and inspection logbooks.

Table 3. Results of Topographical Mapping System deployments in ORR tanks W-5 and W-6

Area	Tank W-5	Tank W-6
Accuracy	Relative accuracy of 0.25 inches was achieved within a range of 25 ft.	Relative accuracy of 0.25 inches was achieved within a range of 25 ft.
Mapping data densities and time limits	• The 4-inch resolution mapping of all exposed tank walls took ~4 h; 1-inch resolution mapping took ~9 h. • A 0.25-inch, high-resolution map of 4- by 4-ft wall section took ~30 min and required 30 min of setup. • TMS confirmed that areas appearing to be deep holes were exposed bitumen (tank sealant).	• The 4-inch resolution mapping of all exposed tank walls took ~4 h; 1-inch resolution mapping took ~9 h. • A 0.25-inch, high-resolution map of 4- by 4-ft wall section took ~30 min and required 30 min of setup. • Areas suspected to be holes were exposed bitumen. • A cavelike depression was discovered in the upper 4 ft of the 10-ft walls. It is 4.25 inches deep around the circumference of the tank. Further study is required to characterize it.
Radiation effects	• Radiation had no measurable long-term effects on system. • Salt-and-pepper noise on video was only sign of radiation effects; averaging algorithms in image-processing software easily filtered them out. • Sensor head received ~300 Roentgens (R) of accumulated dose from mapping campaign and experienced no failures. • Radiation levels at top of central riser were 0.5 mR/h. • Estimated values at liquid surface were 1.0 mR/h.	• Radiation had no measurable long-term effects on system. • Salt-and-pepper noise on video was only sign of radiation effects; averaging algorithms in image-processing software easily filtered them out. • Sensor head received ~300 R of accumulated dose from mapping campaign and experienced no failures. • Radiation levels at top of central riser were 5 mR/h. • Estimated values at liquid surface were 1.0 mR/h.

Demonstration of TMS at the Hanford Site in 1997
Table 4 summarizes volumetric analysis results using the original ORNL computational software and the enhanced ICERVS volumetric analysis function. The data show the maximum height of each sand mound as well as the approximate amount of sand used to build the mound ("Container volume"). Part of

the inaccuracy using the ORNL software comes from the imprecise measurement of the sand. The second known source of error comes from TMS itself. Armstrong et al. 1997 contains specific details on the demonstration, including TMS surface maps. MTI 1997 has further explanation of error sources and test results using the enhanced volumetric measurement function.

Table 4. Volumetric analysis results

Test	Height (inches)	Container volume (cubic inches)	TMS measurement (cubic inches)	Relative accuracy using ORNL software (%)	Relative accuracy using ICERVS function (%)
Table top	2.2	555	515	93	99
Mound 1	4.4	1109	894	81	91
Mound 2	2.7	222	165	75	95
Mound 3	1.7	111	85	77	95
Mound 4	4.9	1,553	1,340	86	99

Figure 5 illustrates test results produced using the new ICERVS function for "Right Sandbox—Mound 4." A cylindrical tank volume model was created with a diameter of 25 inches and a height of 8 inches. The tank model encloses the mound of sand on the tabletop. The goal was to find the volume of data (or sand) that is enclosed in the tank model. Figure 5 shows the data enclosed with a semitransparent cylinder object (tank volume model). The computed surface mesh, also shown, has been translated up in the "Z" dimension to enable the mesh to be seen.

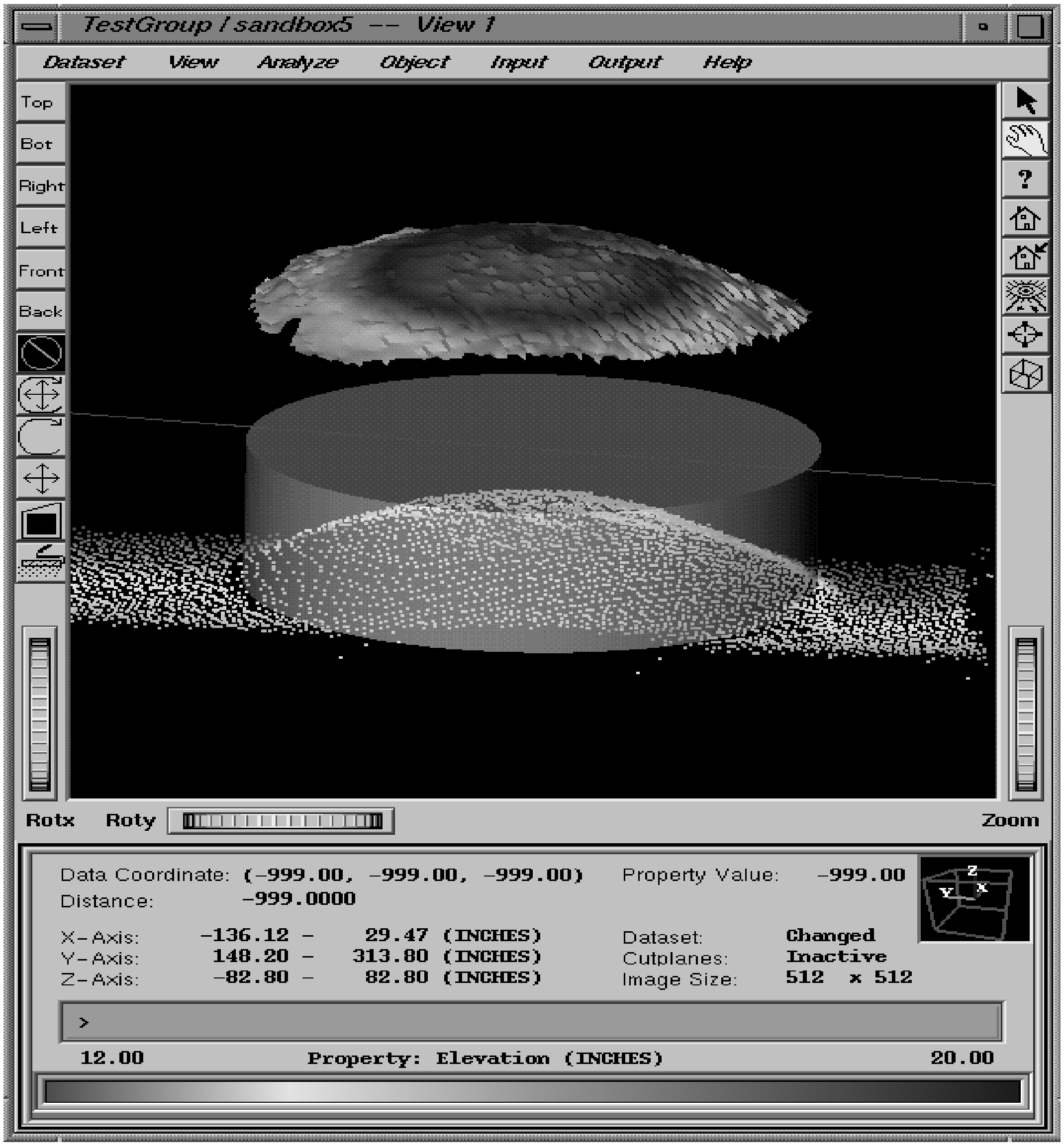

Figure 5. Visual display of "Mound 4" volume measurement using new computational function.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

PNNL and ORNL conducted a market survey in 1998 to identify commercially available systems for accurately measuring tank waste volume. Of the 20 technologies identified and evaluated, TMS was the only one that passed all evaluation criteria. One other system, Reigl's LD 90-3, was determined to be a viable technology although it did not meet all evaluation criteria.

Reigl LD 90-3 is a long-distance, noncontact range sensor that uses "time of flight" to determine range. An electrical pulse generator periodically drives a semiconductor laser diode, sending out infrared pulses that are collimated by the transmitter lens. Pulses strike the target and are reflected to the sensor head. The signal received is focused on a photodiode by the receiver lens. The photodiode generates an electrical signal that latches a clock. The quartz-stabilized clock measures time between transmitted and received signals. Table 5 presents advantages and disadvantages of the top two technologies.

Table 5. Comparison of the top two technologies

Technology	Advantages	Disadvantages
Topographical Mapping System	• Successes include mapping waste surfaces and measuring waste volumes in radioactive waste storage tanks at ORR and Fernald. • Relative accuracy of ±0.25 inches up to range of 45 ft can be achieved. • Operations in high-radiation and flammable-gas environments are possible. • Capabilities include decontamination. • Costs savings can be realized.	• Calibration is critical to obtain high-accuracy measurements and requires a specially equipped and configured test facility. • To preserve calibration, TMS must be assembled and installed vertically and transported fully assembled (32 ft long). • See Section 7 "Technology Limitations and Needs for Future Development" for further desired improvements.
Riegl LD 90-3 range sensor	• Successes include several industrial applications requiring significant temperature changes. • Accuracy is adequate, and calibration does not require high-level precision. • System is very durable and has few moving parts. • Easily transported and can be deployed using relatively simple deployment mast.	• Accuracy is not as high as that produced by TMS. • No demonstrated experience in radiation environments. • Modifications are required to operate in flammable-gas atmospheres. • Use of standard fiber optics may cause performance degradation due to irradiation. • Integrated volumetric measurement software is not included.

Table 6 compares 20 technologies. Acquisition costs of these technologies do not include costs required to modify the systems for deployment in radiological or hazardous environments, deployment through a 4-inch-diameter opening, or modification to add the ability for decontamination. Appendix C contains additional alternative technologies not included in the survey, most of which are not commercially available.

Table 6. Results of market survey

Model and manufacturer	Accuracy	Resolution	Range (m)	Measurement time (h)	Durability	Rad experience	Flammable gas	Laser safety (class)	Deployable in 12-inch riser	Cost ($K)
Single Point Time-Of-Flight (TOF) Laser Range Finders										
AccuRange 4000 Acuity Research, Inc.	2.5 mm	5 cm	>20	<48	Good	No	No	I	Yes	3
LD 90-3 Riegl USA	10 mm	10 mm	>20	<24	Very good	No	No	I	Yes	15
Power Spectra Dynamics Engineering, Inc.	2.5 cm	6 cm	>20	<8	Good	No	No	I	Yes	3
LEM 300-GEO Jenoptic Laser	5 cm	5 cm	>20	<48	Good	No	No	I	Yes	15
Data Disto RS232 Leica	3 mm	0.1 mm	>20	>48	Good	No	No	I	Yes	2
Triangulation-Based, Displacement-Sensor Systems										
KL130 Displacement Meter Anristsu America, Inc.	1 mm	0.001 mm	<20	>48	Good	No	No	I	Yes	10
LMS 200 SICK Optic-Electronic	1 mm	1 mm	>20	<48	Good	No	No	I	Yes	10
CyberGage CyberOptics	1 mm	0.03 mm	<20	>48	Good	No	No	I	Yes	7
LK/LC Series Keyance	1 mm	0.04 mm	<20	>48	Good	No	No	II	Yes	7
MicroTrak 7000 Mechanical Technologies, Inc.	1 mm	0.02 mm	<20	>48	Good	No	No	IIIb	Yes	8
SLS 50000 Selcom	1.5 mm	0.05 mm	<20	>48	Good	No	No	IIIb	Yes	8
Integrated Ranging Systems, Including Structured Light, Phase Comparison Techniques, And Tunable Lasers										
Topographical Mapping System Mechanical Technologies, Inc.	5 mm	1 mm	>20	<24	Good	Yes	Yes	IIIb	Yes	None
PRIME CalPoly State University	1 mm	1 mm	>20	>48	Fair	No	No	I	Yes	200
LASER AM LRF Perceptron, Inc.	5 mm	5 mm	<20	<24	Fair	No	No	I	Yes	50
Odetics AM LRF Odetics, Inc.	5 mm	1 mm	<20	<24	Fair	No	No	I	Yes	100
K2T Franklin Scanner K2T, Inc.	2 cm	5 mm	>20	<24	Good	No	No	II	Yes	50
FM Laser Range Finder Coleman Research Corp.	1 mm	1 mm	>20	<24	Good	No	No	IIIb	Yes	350
Laser Eye Atomic Energy of Canada, LTD	5 cm	5 mm	>20	>24	Good	No	No	IIIb	Yes	200
LMS-Z210 Riegl, USA	2.5 cm	5 cm	>20	<1	Very good	No	No	I	Yes	90
Photogrammetry Techniques										
STARCAM VX Optronics Corp.	8 mm	5 mm	>20	<24	Fair	No	No	IIIb	Yes	15

Further details of this survey are located in Armstrong, Pardini, and Samuel 1998.

Technology Applicability

Potential applications for TMS include all DOE tank sites as well as industrial operations. Parameters and requirements to be considered for implementing this technology include the following:

- TMS is capable of installation in a minimum 3.5-inch-diameter opening (i.e., 4-inch-diameter riser).
- The sensor head must be assembled and installed in a vertical position.
- Desired accuracy and mapping data densities must be determined.

Future technology selection considerations will be based upon users' accuracy and resolution requirements along with simplicity of installation and operation.

Patents/Commercialization/Sponsor

TMS has been commercially available since 1997. TMS was developed by MTI through coordinated efforts with ORNL and PNNL. MTI later sold intellectual property rights to Foster-Miller, Inc. DOE TFA sponsored development of the technology through OST. Key parties involved with development and implementation of this technology are listed in Section 1 under "Demonstration Summary."

SECTION 5
COST

Methodology

Since a baseline technology does not exist for mapping tank contents, costs for deployment of TMS are compared to Reigl LD 90-3. Both of these technologies are considered viable alternatives at the Hanford Site. The deployment approach for conducting a volumetric analysis is outlined in Section 2. Rough-order-of-magnitude (ROM) cost estimates are provided for each step of the deployment process.

The following assumptions apply:

- Costs are based on 1998 dollars.
- Acquisition cost for TMS is $0 because DOE already owns the system.
- Measurements will be performed using the before-and-after surface-mapping technique.
- Most of the liquid in the tank has been removed.
- Bare areas of the tank bottom can be readily identified, allowing an estimate of the tank bottom location.
- The system fits through a 12-inch-diameter, 16-ft long, vertical pipe. Costs for modifying a system to match TMS' ability to fit through a 4-inch-diameter riser are not included.
- Maximum system weight is 3,000 pounds.

Cost Analysis

Table 7 is a cost comparison for tank volume measurement at the Hanford Site using TMS versus Reigl LD 90-3. Table 7 includes the potential cost savings from using the 3-D mapping system to prove that the residual waste volume meets closure criteria. Without accurate waste volume measurements, tanks must be sluiced for a longer time or a follow-on retrieval system must be installed to ensure adequate waste removal. With accurate waste volume measurements, it might be possible to reduce sluicing requirements and to avoid installation of follow-on retrieval equipment.

Table 7. Cost comparison for tank volume measurement at Hanford

Item	Estimated costs for Topographical Mapping System	Estimated costs for Reigl LD 90-3	Comments
Development and capital costs	TMS system already available for Hanford use	Need to purchase plus incur development and radiation-hardening costs	Only TMS fits in a 4-inch riser and can be decontaminated
Deployment costs	Estimated cost of $270K or a $30K deployment cost savings compared to Reigl LD 90-3	Estimated cost of $300K	Savings may be greater than shown from TMS compared to using other systems due to uncertainties
Potential cost savings	Up to several million dollars in potential savings from reduced sluicing time plus potential elimination of a follow-on retrieval system	Less savings than with TMS due to increased uncertainties	

Capital Costs

Table 8 shows the Hanford cost comparison for TMS and Reigl LD 90-3 (Armstrong, Pardini, and Samuel 1998). A capital cost was not included for TMS at the Hanford Site, because it was already developed by EM-50. Although not included in the comparison, the initial cost for the TMS prototype was around $1 million: DOE funded MTI for $675,000 and MTI provided $300,000. A ROM cost estimate to build another TMS for the explosive-gas and high-radiation environment of an underground storage tank is

$750,000. This figure includes engineering to incorporate modifications recommended in ORNL reports, updating the design for out-of-production components, and substituting new parts with improved capability.

Deployment Costs

ROM cost estimates are provided in Table 8 for each step in the deployment process for tank volume measurements.

Table 8. Cost analysis of deployment of top two technologies at Hanford

Deployment step	Estimated costs for Topographical Mapping System ($K)]	Estimated costs for Reigl LD 90-3 ($K)
Select and acquire system	0	15
Develop calibration procedures, test plan, and testing procedures	10	18
Obtain and configure test facility as necessary	5	3
Modify system as needed to accommodate flammable gas and radiation	15	25
Design and fabricate tank interface and balance-of-system equipment	60	70
Perform calibration and qualification tests	45	35
Conduct management readiness assessment and obtain approval	50	40
Transport and set up system	15	10
Perform in-tank volume measurements as needed	45	50
Remove system from tank farms and place in storage	10	7
Analyze data and generate reports	19	26
Total costs	**274**	**299**

As shown in the individual steps in Table 8, overall deployment costs are lower for TMS than for the second leading system. TMS costs an estimated $270K to perform a volumetric waste analysis, compared to approximately $300K for the second leading technology. Deployment cost savings may be much greater, depending upon requirements and unexpected costs that could result from using other systems due to so many uncertainties. Reasons for the deployment cost savings include:

- Calibration and testing procedures have been written for TMS and were used during the Fernald and ORR deployments. These documents could be modified with less effort than modifying manufacturer's procedures for the Reigl LD 90-3. Costs would be an estimated $10K for TMS compared to $18K for the Reigl LD 90-3.

- TMS is designed to accommodate environments of flammable gas and radiation, thereby requiring less capital funding for modifications as opposed to the Reigl LD 90-3, which does not have any accommodations for these environments. Approximately $15K is needed for TMS modifications for additional equipment to meet requirements at the Hanford Site as compared to $24K needed for the Reigl LD 90-3.

- Significant previous experience deploying TMS will help minimize actual performance of the in-tank volume measurements. TMS requires two deployments to obtain measurements, while the Reigl LD 90-3 requires three deployments. Costs are $45K for TMS, compared to $50K for the Reigl system.

- TMS has specialized software that performs data analysis and report generation; the Reigl system does not. These activities can be performed for $19K with TMS compared to $26K for operator - assisted analysis with Reigl.

Cost Benefits
An additional cost benefit of $70K is estimated from the use of TMS data to reduce sluicing time at Hanford. The sluicing cost reduction is based on the following assumptions (U.S. DOE Richland Operations Office 1997):

1. Reduced waste volume requiring evaporation

   - Assume one additional week of sluicing, 100 gal/min, 6 h of operation.
   - Cost = 30 h operation x 6000 gal/h = 180,000 gal x $0.75/gal to evaporate = $135,000/tank
   - If water were recirculated, this volume would be reduced as much as 75% to approximately $33,750.

2. Reduced cost of riser-opening crew cost due to schedule reduction

   - Assume one additional week of sluicing, 16-man crew required to open a riser, open two risers.
   - Assume a riser-opening crew = two pipefitters, two riggers, two electricians, two millwrights, two health protection technicians, two supervisors, one crane operator, two tank farm operators, and one tank farm manager.
   - Cost = 16 crewmen x 4 h/day x 2 risers x $35/h = $4,480/day x 5 days/week ≅ $22,400/week.

3. Reduced cost of sluicing operations crew cost due to schedule reduction

   - Assume one additional week sluicing, four-man crew/riser, two risers.
   - Assume two sluicing operations crews = 2 x (one health protection technician, two operators, and one person in charge).
   - Cost = four crewmen x 6 h/day operating x two risers x $35/h = $1,680/day x 5 days/week ≅ $8,400/week.

Total (summary) cost savings = $65K/tank (rounded to $70K).

If deployment of a follow-on retrieval system were required, it would cost millions of dollars per tank. If TMS data shows regulators that the risk associated with leaving residual waste in the tank is acceptable, a follow-on retrieval system could be eliminated from consideration.

Cost Conclusions

Cost savings are achieved with TMS by the following means:

- Many costly modifications required for alternative technologies (e.g., radiation hardening) are not necessary.
- More precise, accurate measurements can be obtained.
- The amount of sluicing required can be reduced.
- The need for follow-on retrieval systems is potentially eliminated.
- Decontamination is possible so the system can be reused.

Although the Fernald application is not addressed in the above analysis, Burks et al. 1992 reported that the Fernald deployment saved money by reducing the amount of bentonite required to isolate tanks from the environment. Bentonite is placed on top of the tank waste to retard emissions of radon gas. Total investment in the prototype system used at Fernald was approximately $1.2 million and includes $700K in development costs to ORR, $85K in development support costs to Sandia National Laboratories, and $500K in coordination and deployment costs to Fernald. A savings of $13 million was achieved at Fernald using the prototype system by eliminating the purchase, retrieval, and treatment of 37,400 ft^3 of excess bentonite, representing an approximate 10-to-1 return on investment.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

- Site-specific regulatory drivers for remediation of tank wastes at the ORR include

  – Oak Ridge Federal Facility Agreement and Consent Order (between EPA Region IV, DOE, and Tennessee Department of the Environment and Conservation) and
  – Tennessee Department of Environment and Conservation Commissioner's Order for the ORR Site Treatment Plan.

- At the Hanford Site, the Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) is the main regulatory driver for remediation of tank wastes.

- Sites must comply with DOE Order 5820.2A/435.1 and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, where applicable.

- CERCLA was applicable during the Fernald deployments. The next section discusses how TMS meets CERCLA criteria.

Secondary Waste
Alternative systems may generate more secondary wastes than TMS. The Reigl LD 90-3 requires three deployments to obtain a volumetric measurement, compared to two with TMS. More required labor will produce more wastes from personal protective equipment. The Reigl system is not capable of decontamination, and additional wastes may be generated from uncertainties or unknown factors of using this system in a radiological environment for the first time.

CERCLA Evaluation
This section summarizes how TMS addresses the nine CERCLA evaluation criteria.

1. Overall Protection of Human Health and the Environment

   - Radiation exposure to workers is minimized during installation and operation due to TMS' modular and compact design, which allows for quick installation, remote-controlled operations, use of personal protective equipment, and personnel training.

   - Tank wastes can be more accurately characterized and more safely remediated, reducing threats to human health and the environment.

2. Compliance with Applicable or Relevant and Appropriate Requirements

   - TMS was designed and deployed according to applicable regulatory requirements.

   - Criteria, procedures, and controls are in place.

3. Long-Term Effectiveness and Permanence

   - TMS can be used to measure waste volume to support retrieval planning and assess performance after retrieval campaigns.

   - TMS can assist in documenting residual waste volume, which is required in tank closure activities.

   - Implementation can be accomplished faster than with alternative technologies, thus reducing cost and risks, increasing efficiency and safety, and accelerating tank remediation and closure schedules.

4. Reduction of Toxicity, Mobility, or Volume through Treatment

   - TMS maps waste contents and identifies changes in waste contents and levels after remediation efforts. These data assist in determining effects of remediation activities and future steps needed. (E.g., TMS was used to verify thickness of a bentonite clay cap used at Fernald to reduce the level of toxic gas emissions. This verification was required to support a DOE Removal Action Milestone defined in the Amended Consent Agreement with EPA under CERCLA sections 106 and 120.)

   - TMS has a purge system that provides protection from ignition of volatile gases in hazardous environments.

5. Short-Term Effectiveness

   - Radiation exposure to workers is maintained as low as reasonably achievable through remote-controlled operations, established procedures and controls, and thorough training to qualify workers.

6. Implementability

   - The system's modular design simplifies installation and operations.

   - TMS is radiation-hardened.

   - Worker exposure is minimal.

   - A control system exists for remote operation and monitoring of the system.

7. Cost

   - Cost data are provided in Section 5.

8. State (Support Agency) Acceptance

   - Ohio state representatives worked with DOE and EPA on deployments at the Fernald site.

9. Community Acceptance

   - DOE holds meetings with the public to discuss and provide statuses of DOE waste programs. Fact sheets and newsletters providing technology updates are also distributed to the public.

Safety, Risks, Benefits, and Community Reaction

The previous section provides information on safety, risks, and community reaction. Key benefits are discussed in Section 1 under "Demonstration Summary."

SECTION 7
LESSONS LEARNED

Implementation Considerations

TMS applications identified vital insights that may be helpful in future uses of the technology. Some of the lessons learned are provided in the following list.

- TMS verified that there were no significant penetrations of the gunite tank walls at ORR, although earlier video inspections had indicated otherwise.

- Bitumen proved to be difficult to map during the ORR deployments.

- Additional plastic wrapping and duct tape used in the ORR deployments as an extra precaution from TMS receiving too much contamination were unnecessary and created added complications. The TMS design enables it to be decontaminated.

- The camera and light additions to the TMS sensor head deployed at ORR reduced the need to access a second riser.

- The camera and lights should have been deployed separately from TMS. This arrangement would have eliminated problems by enabling the following activities.

  – The camera and lights could have been used to watch the TMS sensor head as it entered the tank.
  – Additional wrapping would have been simpler to apply to the camera and lights.
  – Extra time and flexibility could have been achieved with separate deployments.

- Electrical connections should be verified before deployment to avoid malfunctions. A loose wire prevented the camera and lights from functioning during the ORR Tank W-5 deployment. As a result, TMS had to be deployed blind. This action posed a risk of rubbing TMS against the side of the riser as well as submerging the TMS sensor head into liquid waste.

- The 84-inch extension requires a minimum of 13 ft of headspace. The 10-ft extension module positions the sensor head in the vapor space, if needed.

- Volumetric analysis capability was added to the ICERVS 3-D visualization software in September 1997. This capability significantly reduced error compared to previous volume computation methods.

- The absolute accuracy of TMS was improved through enhancements to the laser pointing system incorporated after the last TMS demonstration in 1997.

Technology Limitations and Needs for Future Development

The following improvements are suggested to increase efficiency, effectiveness, and versatility of TMS.

- To effectively measure waste volume in underground storage tanks or build a 3-D model for robotic path planning, software modifications to the error model need to be incorporated to accommodate different variables such as range and angle of incidence.

- Additional lights are needed.

  – A set of lights should be installed at the top of the TMS to aid in system installation, tank inspection, and system retrieval.

  – Lights should also be added to the extension modules. Lights could be designed for decontamination.

- A separate set of floodlights should be used to illuminate the tank and avoid installing TMS into a dark tank. These lights would reduce the risk of submerging TMS into tank waste.

- A zoom camera with a dedicated pan-and-tilt mechanism should be added to the bottom of the ESS.

- Improved calibration methods would increase volume accuracy.

- A strong-back and trailer could be used to deploy the TMS sensor head more easily. The strong-back should be approximately 35-ft long and should support the TMS in a lateral position. It should allow TMS to be configured on its side and then lifted with a crane to a vertical position. This action would eliminate the need for top-down assembly of the TMS sensor head with a crane. The strong-back could be enclosed in a 35-ft trailer that also serves as a containment box for transporting the TMS sensor head between deployment sites.

- A control trailer could be purchased to house the control station for TMS. An additional trailer could serve as a maintenance trailer for repairing and performing limited recalibration of the TMS camera and laser modules in the field.

Technology Selection Considerations

TMS can operate in environments with high levels of radiation and is capable of decontamination. Its can be deployed in a 4-inch-diameter riser, whereas alternative systems require a 12-inch diameter opening. The system is deployed independently of other equipment. Facilities and equipment must be available to allow a vertical assembly and installation.

Desired accuracy, resolution, and timeframes must fall within TMS' capabilities. Custom software processes its data and computes volumes at accuracies >98%. The minimum data acquisition rate for mapping the floor of a 75-ft diameter tank is 2 h at a data density of one point per 6- by 6-inch area.

APPENDIX A
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APPENDIX B
DIAGRAMS AND PHOTOGRAPHS

TMS Diagram

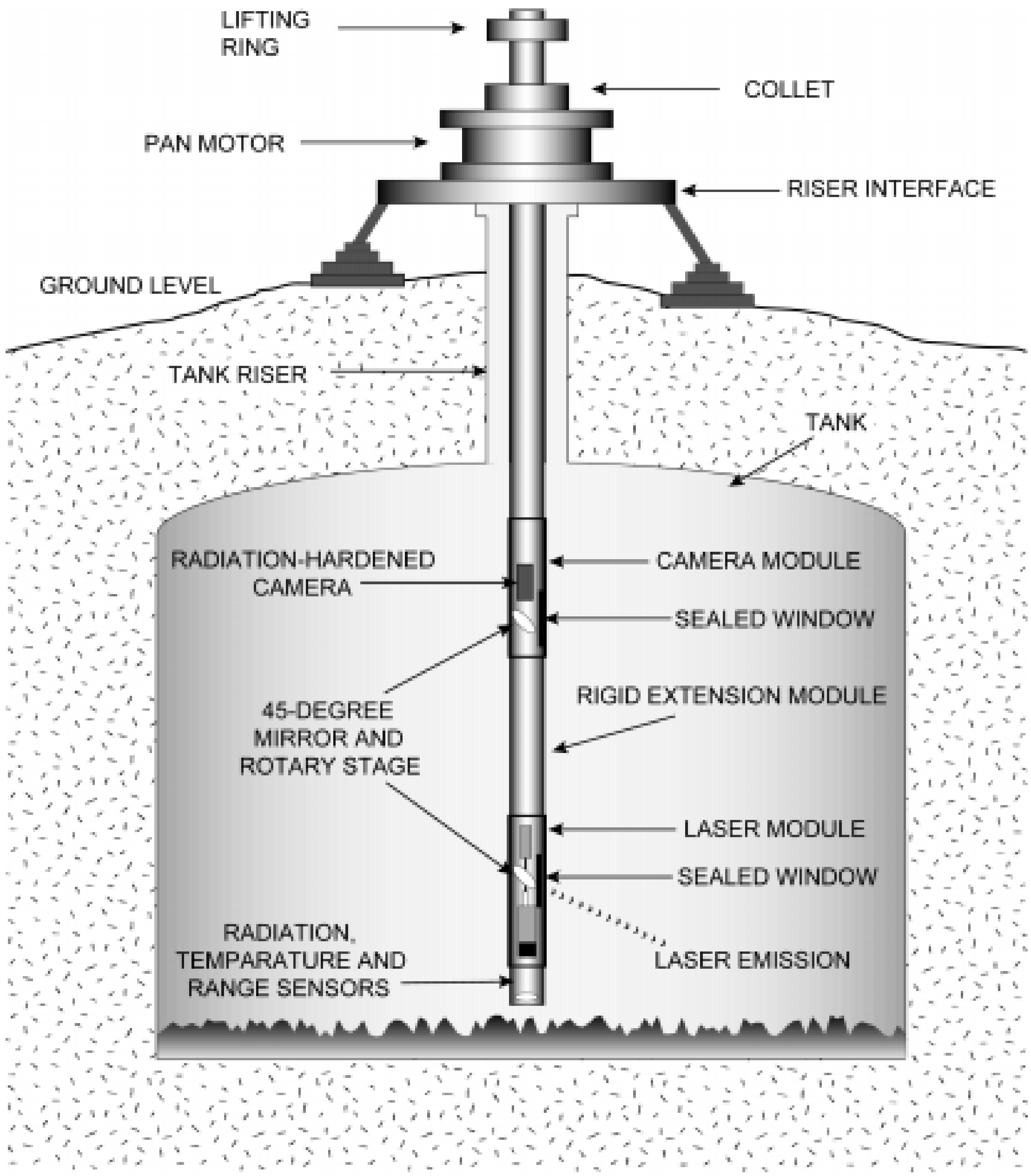

Figure B1. Configuration of the Topographical Mapping System as deployed in an underground storage tank (not to scale).

Figure B2. Laser/camera module.

Figure B3. Pan motor adapter module.

Figure B4. Topographical Mapping System installation into ORR Tank W-5.

APPENDIX C
MARKET SURVEY

The market survey included only those technologies that are commercially available. Table C1 identifies additional alternative technologies that were not included in the market survey. Most are not commercially available.

Table C1. Additional alternative technologies

Technology	Advantages	Disadvantages
Laser range finders • Laser radar – Time-of-flight (TOF) – Amplitude modulation (AM) – Frequency-modulated coherent laser radar (FMCLR) • Active-triangulation range finders using synchronized scanners (i.e., laser range finder developed by SPAR Aerospace Limited)	• FMCLR has submillimeter resolution at working distances in excess of 15 m and may be useful for measuring surface location at point where depth measurements are taken. • SPAR laser range finder is based on mature technology and is more versatile than fringe projection–based structured-light system produced by Lockheed or the stereo vision–based system by NASA. • SPAR laser range finder has full-featured software including ability to perform in-tank registration using known landmarks. • SPAR has a trade-off between data acquisition speed vs resolution, but resolution required can be selected without regard to recalibration. • Discontinuities with SPAR present no problem since method is a single-point approach. • Signal to noise is inherently greater than methods that rely on projected stripes or grids.	• Overall, accuracy is not good when compared to TMS due to – limited calibration techniques, – instabilities in mechanical scanners, and – sensitivity to amplitude changes in returned signal. • New laser radar system has been produced that provides high data density and good accuracy (errors <0.040 inches). However, significantly higher data acquisition time is required to achieve these results. • TOF and AM methods are not applicable to high-resolution surface mapping due to – low signal-to-noise ratio, – significant working distance requirements, and – ambiguous range information, unless sophisticated encoding schemes are used. • FMCLR is a single-point measurement device requiring long mapping times.
Laser mapping system	• Based on structured light. • Commercially available from Computerized and Advanced Technologies Company.	• Not radiation hardened. • Not suitable for underground storage tanks as system sits on tripod and contains scanning laser and camera.
Fringe projection–based structured-light system	• In study performed by ORNL, fringe projection system showed impressive, dense, surface maps of objects within limited range. • Shows promise in applications needing high resolution within narrow field of view. • May be useful in measuring local topology where depth measurements are taken.	• Cannot produce high resolution for wide ranges such as 75-ft diameter tanks as does TMS. • Can become confused by step discontinuities in measurement surface and cannot be reconfigured in situ. • Difficult to register data collected by this system with a world coordinate frame.

Technology	Advantages	Disadvantages
Stereo vision	• Shows excellent aptitude for providing collision avoidance data.	• Data produced by has insufficient resolution for world mapping tasks (i.e., topographical mapping of waste surfaces in large underground storage tanks). • Pattern recognition problems exist. • Algorithms are not scientifically based. • Skilled operators are required to establish correspondences. • Processing can take hours or days. • NASA has had limited success in computerizing this process for navigation of planetary rovers. • Not commercially available for purchase due to required operator involvement; however, services are available.
Theodolites	• Practiced users can achieve errors <0.010 inches when working with special targets. • Theodolites are used in manufacturing applications to “shoot in” a production jig or fixture with aid of strategically placed targets. Time and data sensitivity is not critical for these applications. • “Smart” theodolite systems are now available and significantly reduce setup and alignment times.	• Must be used manually for locating one point at a time. • Significant time is required for setup, alignment, and checkout. • Data collection is still very time-consuming for “smart” theodolites. • Survival in high-radiation areas is questionable.
Moiré patterns	• Data density is high. • Data acquisition time is low.	• Measurement errors are large (0.050 inches) due to mechanism that creates array of lines. • With some systems, data must be collected in dark. • Limited to items smaller than breadbox.
Laser interferometer (SMX, formerly Chesapeake laser)	• Provides submillimeter resolution and accuracy at 20–30 m.	• Line of sight cannot be broken. All measurements are made relative to reference frame, and retroreflector must be used for measurement. • Slow because target must be moved manually so that system can track it. • Measurement points must be within reach of person or device positioning reflective target. • Data density is determined by time devoted to data acquisition. • Reflective target is expensive and frail, will shatter on impact if dropped, and must be positioned for every measurement point. • Questionable whether system could withstand humid environment with high radiation and high temperatures.

APPENDIX D
ACRONYMS AND ABBREVIATIONS

AM	amplitude modulation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOE	U.S. Department of Energy
EM	Environmental Management
EPA	U.S. Environmental Protection Agency
ER	Environmental Restoration
ESS	environmental sensor section
FMCLR	frequency-modulated coherent laser radar
ICERVS	Interactive Computer-Enhanced Remote-Viewing System
MTI	Mechanical Technology, Inc.
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
OST	Office of Science and Technology
PNNL	Pacific Northwest National Laboratory
R	Roentgen
RMS	root mean square
ROM	rough order of magnitude
TFA	Tanks Focus Area
TMS	Topographical Mapping System
TOF	time of flight
3-D	three-dimensional