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South Tank Farm Underground Storage Tank Inspection Using the Topographical Mapping System for Radiological and Hazardous Environments

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Robotics and Process Systems Division

SOUTH TANK FARM UNDERGROUND STORAGE TANK INSPECTION USING THE TOPOGRAPHICAL MAPPING SYSTEM FOR RADIOLOGICAL AND HAZARDOUS ENVIRONMENTS

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ACRONYMS AND ABBREVIATIONS

3-D	three-dimensional
CCD	charge-coupled device
CRADA	cooperative research and development agreement
EEB	environmental enclosure box
EM-50	Office of Science and Technology
EPA	Environmental Protection Agency
ESS	environmental sensor section
FETC	Federal Energy Technology Center
FMEF	Fuel Materials and Examination Facility
FUSRAP	Formerly Utilized Sites Remedial Action Program
GAAT	Gunite and Associated Tanks
HMI	human-machine interface
ICERVS	Interactive Computer-Enhanced Remote-Viewing System
M.A.D.	Measurements Applications and Development
MTI	Mechanical Technology, Inc.
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
rms	root mean square
RTDP	Robotics Technology Development Program
SOW	Statement of Work
SSTs	single-shell tanks
STF	South Tank Farm
TFA	Tanks Focus Area
TMS	Topographical Mapping System
UST	underground storage tank
WCF	world coordinate frame

ABSTRACT

During the winter of 1997 the Topographical Mapping System (TMS) for hazardous and radiological environments and the Interactive Computer-Enhanced Remote-Viewing System (ICERVS) were used to perform wall inspections on underground storage tanks (USTs) W5 and W6 of the South Tank Farm (STF) at Oak Ridge National Laboratory (ORNL). The TMS was designed for deployment in the USTs at the Hanford Site. Because of its modular design, the TMS was also deployable in the USTs at ORNL. The USTs at ORNL were built in the 1940s and have been used to store radioactive waste during the past 50 years. The tanks are constructed with an inner layer of Gunite™ that has been spalling, leaving sections of the inner wall exposed. Attempts to quantify the depths of the spalling with video inspection have proven unsuccessful. The TMS surface-mapping campaign in the STF was initiated to determine the depths of cracks, crevices, and/or holes in the tank walls and to identify possible structural instabilities in the tanks.

The development of the TMS and the ICERVS was initiated by DOE for the purpose of characterization and remediation of USTs at DOE sites across the country. DOE required a three-dimensional, topographical mapping system suitable for use in hazardous and radiological environments. The intended application is mapping the interiors of USTs as part of DOE's waste characterization and remediation efforts, to obtain both baseline data on the content of the storage tank interiors and changes in the tank contents and levels brought about by waste remediation steps. Initially targeted for deployment at the Hanford Site, the TMS has been designed to be a self-contained, compact, and reconfigurable system that is capable of providing rapid variable-resolution mapping information in poorly characterized workspaces with a minimum of operator intervention.

1. INTRODUCTION

This report focuses on the use of the Topographical Mapping System (TMS) for hazardous and radiological environments to perform wall inspection on underground storage tanks (USTs) W5 and W6 of the South Tank Farm (STF) at Oak Ridge National Laboratory (ORNL). The TMS was designed for deployment in the USTs at the Hanford Site. Because of its modular design, the TMS was deployable in the USTs at ORNL. The USTs at ORNL were built in the 1940s and have been used to store radioactive waste during the past 50 years. The tanks are constructed with an inner layer of Gunite™ that has been spalling, leaving sections of the inner wall exposed. Attempts to quantify the depths of the spalling with video inspection have proven unsuccessful. The TMS surface-mapping campaign in the STF was initiated to determine the depths of cracks, crevices, and/or holes in the tank walls and to identify possible structural instabilities in the tanks.

The TMS has been developed by the DOE Tanks Focus Area (TFA) under the sponsorship of the Office of Science and Technology (EM-50). The ORNL-developed surface-mapping system (deployed in the K65 storage tanks at Fernald in 1991) and the prototype surface-mapping system developed under a cooperative research and development agreement (CRADA) (which was demonstrated at the Hanford Site in 1993), were funded by the DOE Robotics Technology Development Program (RTDP) and Mechanical Technology, Inc., (MTI) of Albany, New York. The Interactive Computer-Enhanced Remote-Viewing System (ICERVS) has been developed by MTI for use in DOE characterization and remediation efforts under contract to the Federal Energy Technology Center (FETC).

1.1 ORNL USTS

The primary mission of ORNL during World War II was the processing of pure plutonium metal in support of the Manhattan Project. By-products of this process include radioactive cesium-137 and strontium-90. Between 1943 and 1951, the Gunite and Associated Tanks (GAAT) at ORNL were built to collect, neutralize, and store these by-products. There are currently twelve Gunite tanks and four stainless steel tanks located on the ORNL complex. These tanks hold approximately 284 kL (75,000 gal) of radioactive sludge and solids and over 1.325 ML (350,000 gal) of supernatant. Characterization studies of these tanks in 1994 indicate that the structural integrity of some of the tanks is questionable. Consequently, there is a potential threat to human health through contamination of soil and groundwater. These risks provide the motivation for remediation and relocation of waste stored in the ORNL tanks.

1.2 HANFORD USTS

USTs at DOE sites such as the Hanford[1] Site in southeastern Washington state, contain hazardous, radioactive waste generated by defense material production during the past 50 years. A number of the tanks have been used past their intended design life and are in deteriorating condition; some have leaked contamination into the surrounding environment. Stabilization and remediation of these tanks are high priorities for the DOE Environmental Restoration Program. The TMS will gather vital data needed to respond to ongoing questions about the safe storage of waste materials, and to quickly investigate tank events, such as leaks, that raise safety concerns.

There are 149 single-shell tanks (SSTs) at the Hanford Site. The SSTs range in size from 208,000 to 3,800,000 L (55,000 to 1,000,000 gal). The tanks are cylindrical, constructed with reinforced concrete, and lined with carbon steel. The 208,000-L tanks (there are 16 total) have flat tops and are 6 m (20 ft) in diameter. The larger tanks have domed tops and are 23 m (75 ft) in diameter. Tank heights vary depending on capacity. There is considerable variation in the number, location, and the type of openings in the tops of the tanks, with most having at least one

107-cm- (42-in.) diam opening in the center and one or more 10.16-cm- (4-in.) diam opening around the periphery. The top of a typical tank is 2.5 m (8 ft) below grade.

Currently, the USTs at the Hanford Site contain residual liquids and sludges from past radiochemical separation processes. The original waste consisted of strong acids from the plutonium separation process. The acids were neutralized before they were put in the tanks. The neutralization process caused a complex mixture of solids to precipitate and form a layer of sludge in the bottom of the tanks. To reduce the volume of the liquids, as well as remove radioactive isotopes of cesium and strontium, a waste reduction process was initiated in the 1960s. This program significantly reduced the amount of water (by evaporation) and reduced the concentration of cesium and strontium. The result was a concentrated salt slurry, which was returned to the USTs. The salt slurry is now saltcake. Although the radiation levels in USTs are not fully characterized, it is estimated that radiation levels near the surface of the saltcake in a typical tank are less than 100 R/h.

2. TOPOGRPAHICAL MAPPING SYSTEM

In 1991 ORNL developed and deployed a structured-light-based surface-mapping system in the K65 tanks at the Fernald site[2]. The system was used to determine waste surface data and clay cap surface data. This ensured that the clay cap applied over the waste was a minimum of 30.48 cm (12 in.) deep at all locations per U.S. Environmental Protection Agency (EPA) requirements. In 1993 MTI initiated a CRADA with ORNL for the development of a structured-light-based surface-mapping system for deployment in the USTs at the Hanford Site. The successful CRADA demonstration at the Hanford Site in June 1994 proved that a structured-light-based surface-mapping system could be built to penetrate a 10.16-cm (4-in.) clear aperture and map the inside of a UST to ranges of 13.72 m (45 ft) with an accuracy of 6.35 mm (0.25 in.). Based on the results of the deployment at Fernald and the CRADA, a request for proposals was generated in February 1994 to develop a surface-mapping system that could withstand the radiological and hazardous environments at the Hanford Site. The contract was placed in May 1994 to MTI. The system was delivered to ORNL in June 1996 for acceptance testing, which was completed in February 1997. The TMS was deployed in tanks W5 and W6 of the STF at ORNL in February 1997. After deployment at ORNL, the system was delivered to the Hanford Site and was used to demonstrate volumetric measurement of waste in the Fuel Materials and Examination Facility (FMEF) cold test facility in March 1997.[3]

The development of the TMS was initiated by DOE for the purpose of characterization and remediation of USTs at DOE sites across the country. DOE required a three-dimensional, topographical mapping system suitable for use in hazardous and radiological environments. The intended application is the mapping of the interior of USTs as part of DOE's waste characterization and remediation efforts, to obtain both baseline data on the content of the storage tank interiors and changes in the tank contents and levels brought about by waste remediation steps. USTs initially targeted for TMS deployment at the Hanford Site are defined in the Westinghouse Corporation documents WHC-EP-0352, *Single Shell Tank Waste Retrieval Study*[4], and WHC-SD-RE-TI-053, *Riser Configuration Document for Single Shell Tanks.*[5] The *Topographical Mapping System for Hazardous and Radiological Environments Statement of Work* (SOW)[6] defines the performance specification of the TMS and the environmental conditions under which the TMS must operate. The TMS has been designed to be a self-contained, compact, and reconfigurable system that is capable of providing rapid variable-resolution mapping information in poorly characterized workspaces with a minimum of operator intervention.

2.1 SYSTEM REQUIREMENTS

The primary purpose of TMS is to generate reliable, registered, and accurate three-dimensional (3-D) maps of the internal surfaces of a UST. In addition to the walls, dome, and waste, these tanks also contain salt pumps, air circulator risers, thermocouple trees, and objects that have fallen or have been placed in the tank. Uses for this mapping system include (1) creating and maintaining a current 3-D map of the tank interior as input to a robotic "world model" that is used to test remediation strategies or to plan robot trajectories, (2) tracking the movement of the waste surface as it responds to expanding bubbles of trapped gas, (3) performing a volumetric analysis of the amount of waste removed from the tanks during remediation by mapping the waste before and after remediation activities, and (4) determining how much waste is left in the tank. The fourth application depends on having accurate drawings of the tank or a method by which an accurate description of the tank structure could be constructed.

Performance requirements are based on *Functions and Requirements for the Light-Duty Utility Arm Integrated System*[7] from Westinghouse Hanford Company and Pacific Northwest National Laboratory (PNNL) along with insights and lessons learned at ORNL through previous surface-mapping projects. The major requirements are as follows:

- Accuracy requirements may vary considerably. For example, to track the movement of the waste surface, it may be necessary to measure changes as small as 2.54 mm (0.10 in.). For collision avoidance, measurement errors of 101.6 mm (4.0 in.) are acceptable. The TMS has been specified to provide an accuracy of ±6.35 mm (±0.25 in.) over a range of up to 13.7 m (45 ft).

- Mapping data densities should be at least one point per 150 mm by 150 mm (6 in. by 6 in.) region covering up to 95% of the surfaces in the tank. The time required for mapping cannot exceed 2 h at this data density, although more time would be allowed for mapping at higher densities. The highest density that the TMS is required to provide is one point in every 25.4 mm by 25.4 mm (1.0 inches by 1.0 inches) region of surface (the present system can provide one point every 2.54 mm by 2.54 mm (0.10 in. by 0.10 in.).

- The TMS has been specified to operate in a continuous flux of 5 Gy/h (500 rad/h) and a intermittent peak flux of 10 Gy/h (1000 rad/h) up to a total absorbed dose of 1.0E+4 Gy (1.0E+6 rad) over a 6-month period without failure caused by radiation.

- The TMS has been specified to be deployed through an 88.9-mm (3.5-in.) clear aperture to allow deployment through the 101.6-mm (4-in.) risers at the Hanford Site but can also be deployed through the 304.8-mm (12-in.) or larger risers.

- The TMS has been specified to be Class 1 Division 1 Group B hazardous environment compliant to permit the use of the TMS in tanks that contain volatile gaseous wastes.

- A temperature range of 10 to 50°C (50–122°F) with noncondensing relative humidity of 100% has been specified to allow the TMS to operate in the varying environments that may be found in the tanks at the Hanford Site.

2.2 SYSTEM DESCRIPTION

The TMS is a distributed-architecture, computer-based topographical mapping system that also collects temperature and radiation flux measurements and has a single-point laser range finder. The topographical mapping sensor uses structured light, which is a triangulation-based range measurement technique. A simple structured-light measurement device is illustrated in Fig. 1. The structured-light measurement technique projects a laser plane onto the surface to be mapped. The resulting intersection of the laser plane and the surface produces a contour line annotating the shape of the surface. A camera is used to image the resulting laser plane's contour line. Figure 2 is a time-lapse photograph of the TMS scanning the laser over a simulated waste surface of sand and salt cake. The charge-coupled device (CCD) camera has a vector assigned to each pixel in the CCD array. Every point that is illuminated by the laser line reflection is passed to analytical routines for processing. The analytical routines solve for the intersection of the fixed vector assigned to the pixel in the camera with the equation of the plane of the laser (each intersection of a vector and the laser plane produces an <*XYZ*> point in space). In summary, by combining the range measurement with the kinematics of the sensor head, the TMS is able to determine the <XYZ> description of points located on the surfaces of the interior of the USTs with respect to a world coordinate frame located typically at the bottom center of the tank.

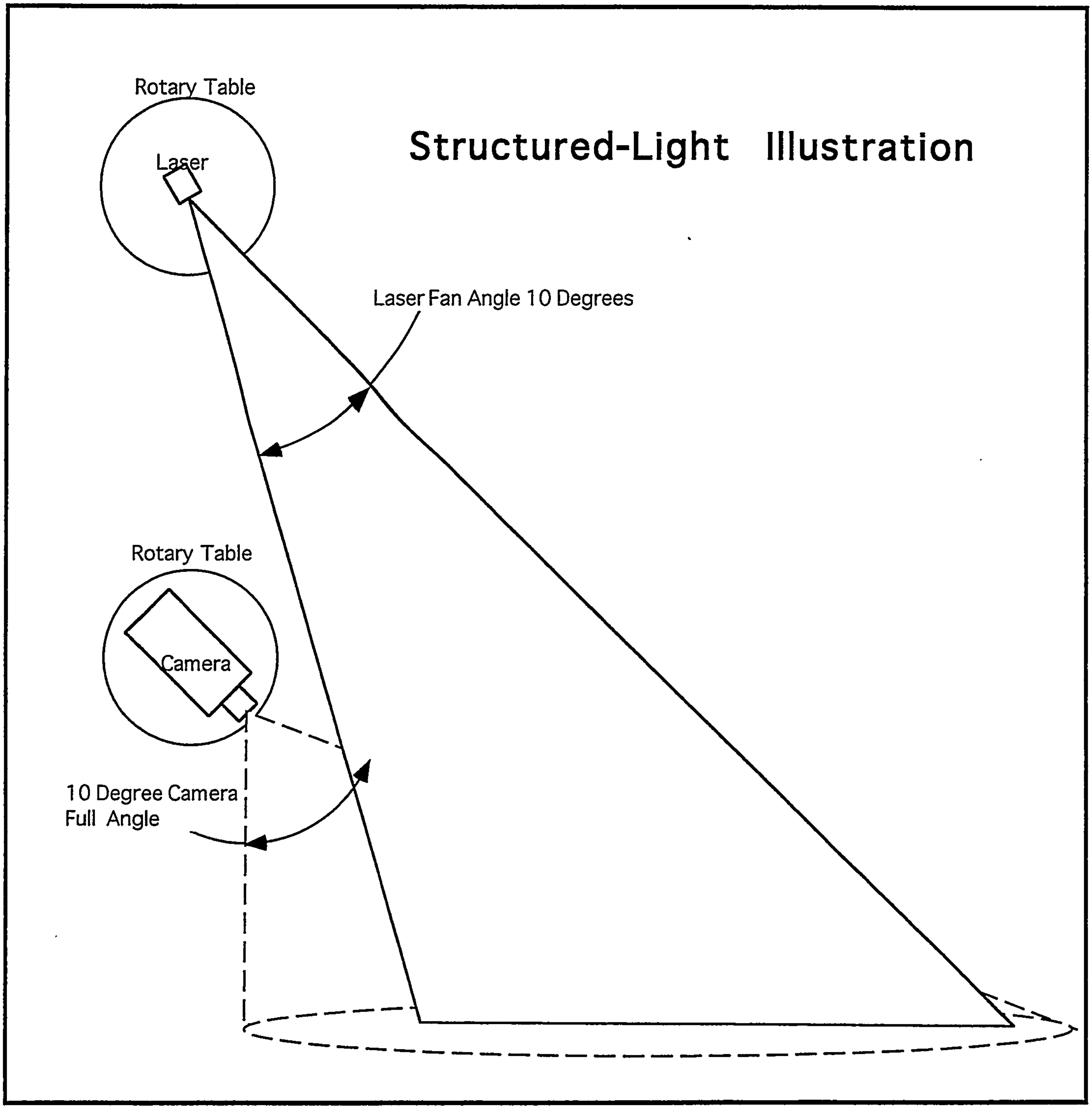

Fig. 1. Structured light for range measurement.

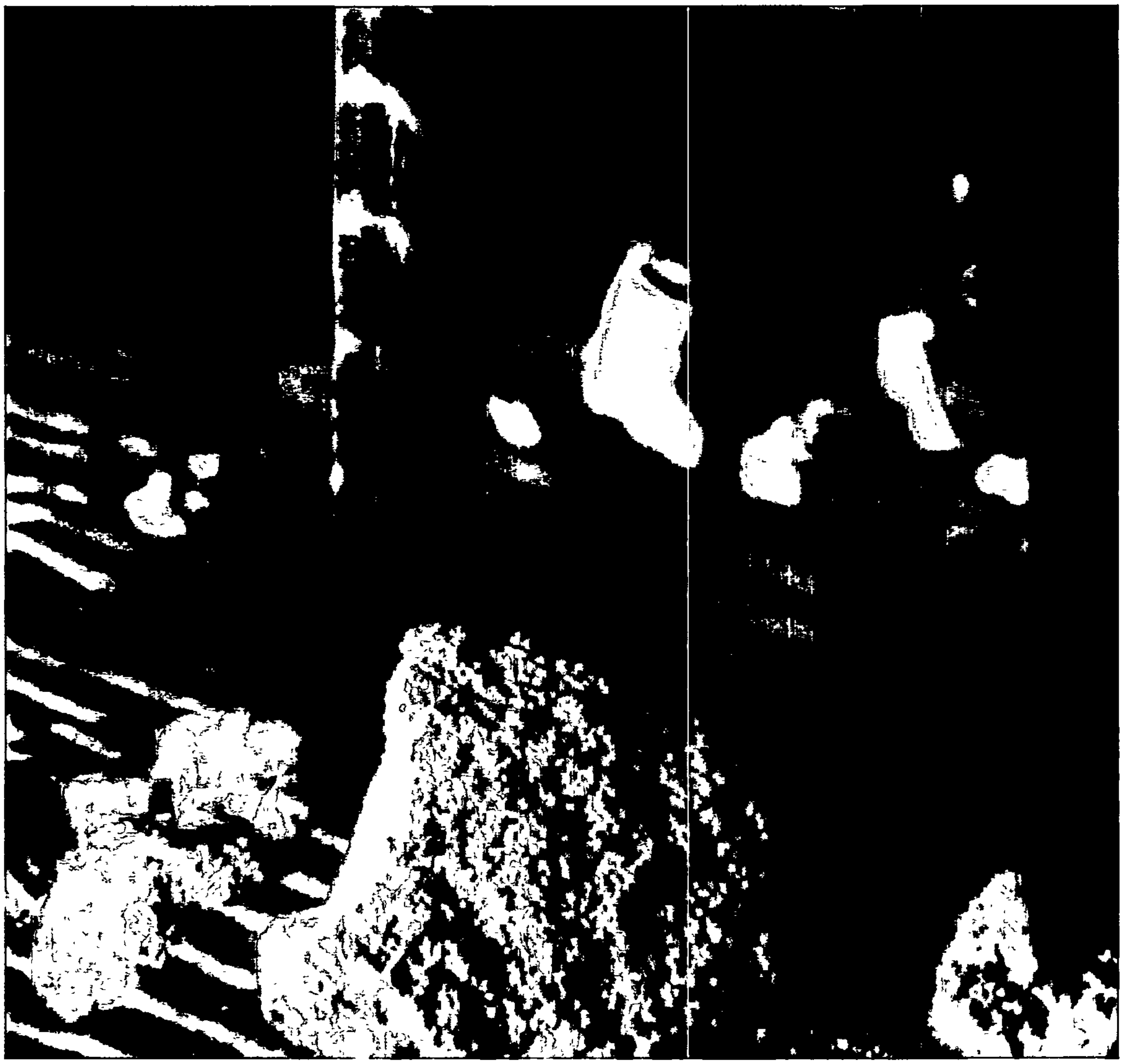

Fig. 2. Time-lapse photograph of the structured-light mapping process. The photograph demonstrates the contour lines that result when the laser planes intersect with the surface to be mapped. The simulated waste surface in the photograph contains sand, simulated salt-cake (white rock), and two black vertical pipes.

The TMS has four major components:

- The sensor head contains the optical metrology sensors that penetrate the vapor space of the tank and provide the topographical map of the interior surfaces.

- The environmental enclosure box (EEB) contains all the support electronics that require close proximity to the sensor head (e.g., frame grabber, motor controllers, and the local computer that runs them).

- The human-machine interface (HMI) is located in the control trailer approximately 274 m (900 ft) away and is used for supervisory control, limited data visualization, and data archiving. The HMI is a UNIX-based scientific and engineering workstation that provides the graphical operator interface and supports the various command, control, and communication functions required for proper system function.

- The plug gauge is used to test the clear aperture of the riser prior to the deployment of the sensor head. The plug gauge also contains the Environmental Sensor Section (ESS), which provides the measurements of temperature, radiation, and range that are used to deploy the sensor head. (The ESS can also be attached to the distal end of the sensor head, or the sensor head can be deployed with a dummy ESS module.)

The 3-D visualization system used by the TMS is the ICERVS.[8] The ICERVS tool allows for display and analysis of the unusually large data sets generated by mapping USTs. Mapping the walls, floor, and dome of typical 75-ft-diam empty tank would generate 3 million data points (or a 180-MB file). The system block diagram is illustrated in Fig. 3; the sensor head deployed in a UST is illustrated in Fig. 4.

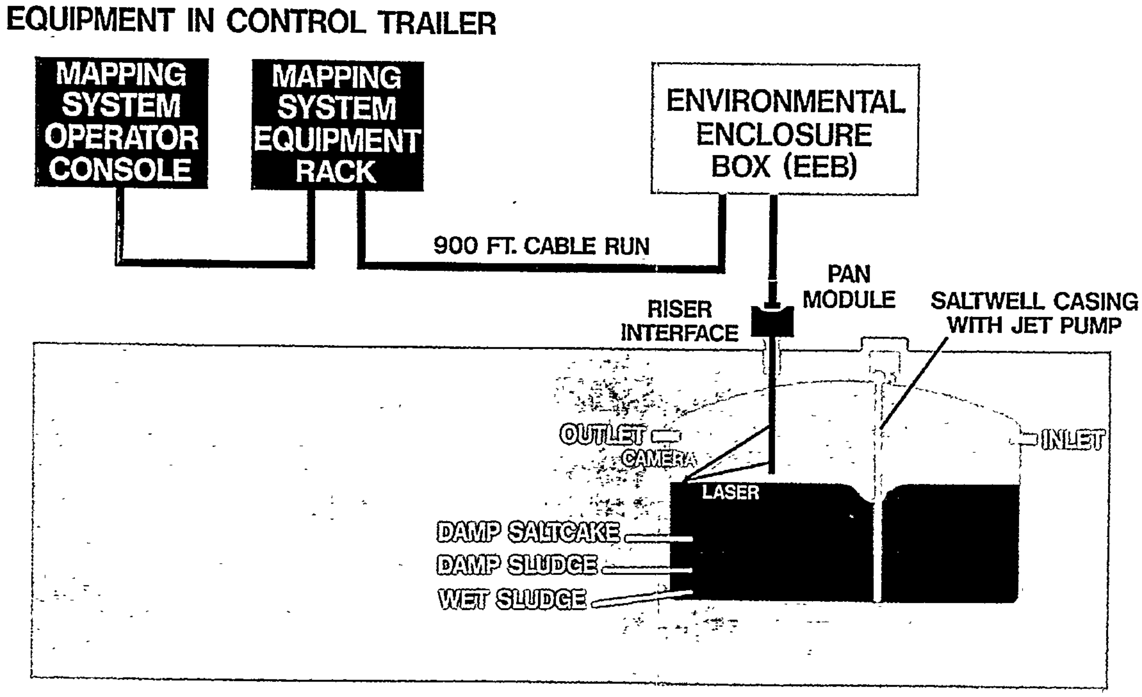

Fig. 3. TMS block diagram.

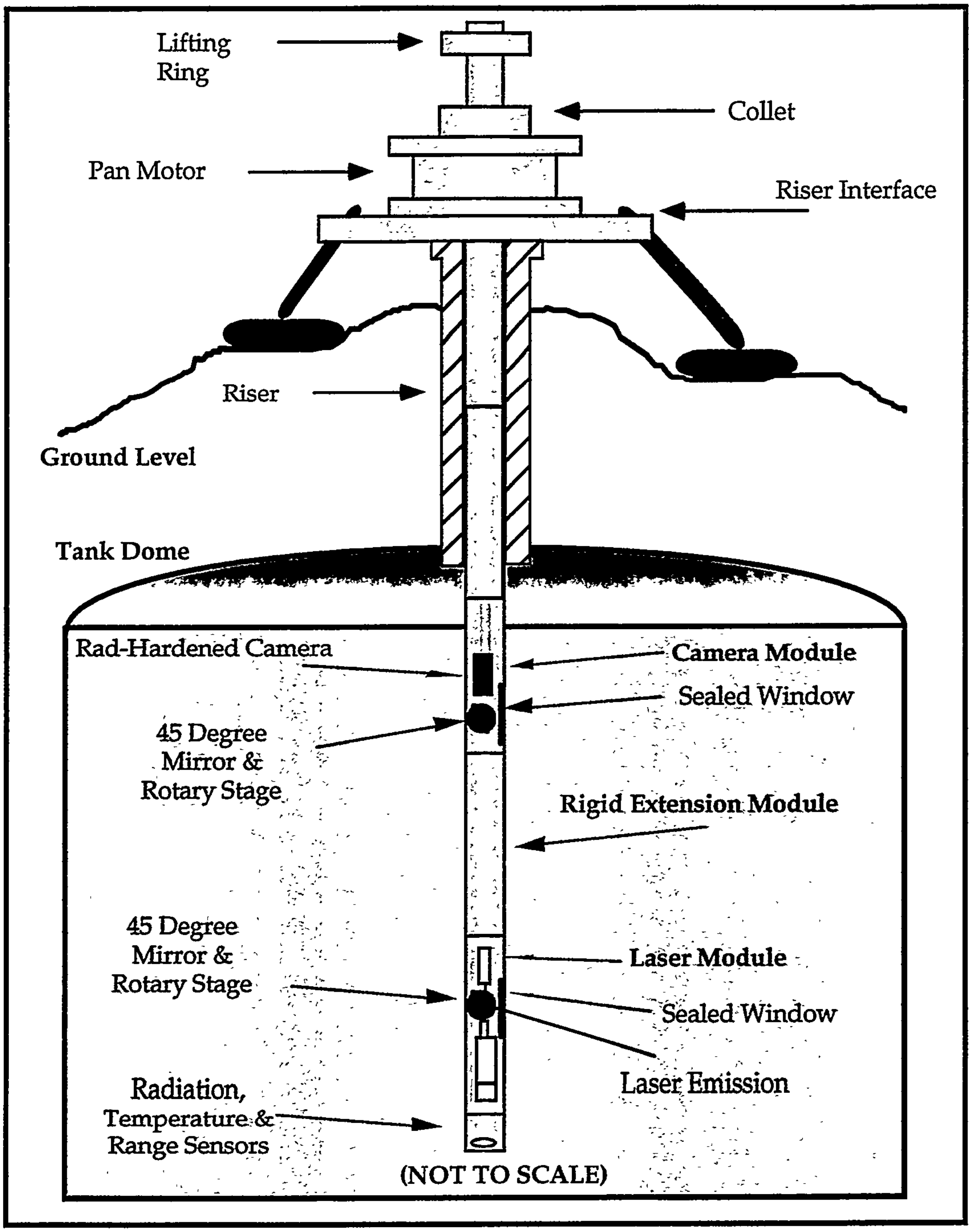

Fig. 4. TMS sensor head deployed in a UST.

Other systems that are needed to deploy the TMS but were not included as part of the contract include the purge gas supply and withdrawal system, the structure used to position and hold the TMS sensor head over the riser (such as a trailer and strong-back), containment systems used to contain the riser openings, containment storage structures, and a 3-D visualization system to analyze the data. These systems, or suitable alternatives, have to be supplied on site as they do not currently exist.

2.3 CALIBRATION AND CHARACTERIZATION

The TMS was calibrated and characterized by MTI and ORNL staff prior to the tank wall inspection performed in the USTs of the STF at ORNL. The TMS has been calibrated and characterized through the use of the high bay and basement in the Robotics and Process Systems Division's facility at ORNL. The TMS sensor head was deployed through a 10.16-cm (4-in.) hole bored in the floor between the high bay the basement. The high bay provided access to the pan motor and the EEB and allowed for overhead crane deployment of the TMS. The testing area in the basement is approximately 18.29 m (60 ft) long and 9.14 m (30 ft) wide. The floor of the basement to the lowered floor of the platform in the high bay is 6.1 m (20 ft), which puts the TMS camera at 5.33 m (17 ft 6 in.) above floor level. This provides for a maximum range of 10.57 m (34 ft 8 in.) from a diagonal that originates at the camera at the proximal end to the bottom of the wall 9.14 m (30 ft) away at the distal end. The minimum range was 5.76 m (18 ft 11 in.) because of the 22° half-angle occlusion area directly beneath the TMS sensor head. This permits angles of incidence that range from 22 to 59.74° the Robotics and Process Systems Division highbay and basement with the deployed TMS is shown in Fig. 5.

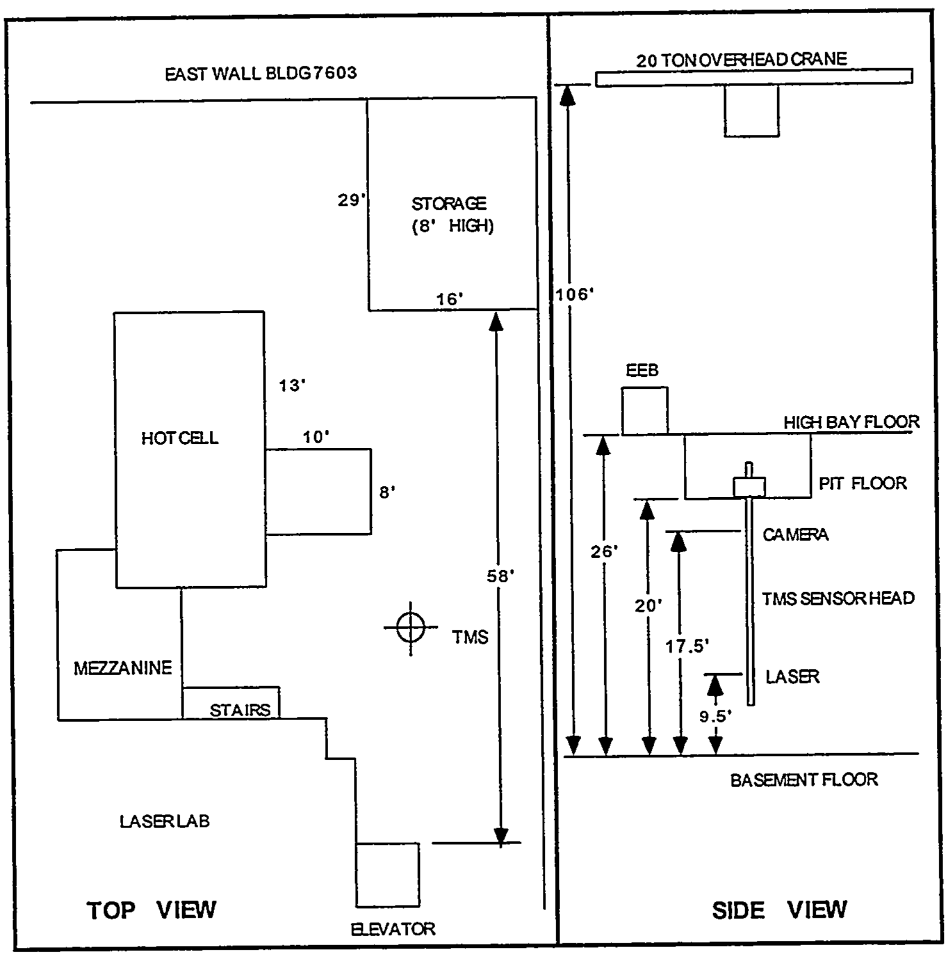

Fig. 5. ORNL Robotics and Process Systems Division facility used to calibrate and test TMS.

The floor of the basement was marked off with a metal measuring tape that was positioned for alignment with the *y*-axis of the TMS coordinate system in its home position. The measuring tape was aligned with a theodolite that was centered on the TMS sensor head. Theodolite measurements ensured that the measuring tape was laid out directly down the *y*-axis of the TMS. This permitted measurements made in the measuring-tape coordinate frame to be mapped into the TMS coordinate frame for comparison. To further facilitate the verification and testing of the TMS's ability to accurately measure points in the basement, a Pentax PTS-V Total Station[9] was used to accurately survey points in the basement. After registering the Total Station coordinate space and the TMS coordinate space to a known reference space, the surveyed points were then mapped to TMS coordinate space for direct comparison with the TMS sensor.

The first part of the calibration involved the alignment of the laser and camera modules on their respective rotary stages. The second part of the calibration determined the fixed vectors that are assigned to each camera pixel and the kinematics of the laser and camera rotary stages. The camera vectors are determined by the two-plane camera calibration method[10,11].

The final part of the TMS calibration was to calibrate the five coordinate frames between the three joints and the various modules used to configure the TMS sensor head. The first deployment of the TMS was scheduled for the USTs in the STF at ORNL. As a result, the six calibration targets were placed in positions to optimize the TMS's measurement accuracy for measuring degradations in the ORNL UST walls of tanks W5 and W6 in the STF. Tanks W5 and W6 are 15.2 m (50 ft) in diameter with 3.6 m (12-ft) walls and are capped with domes that crest 1.8 m (6 ft) above the walls. The central riser extends 2.1 m (7 ft) up past the dome, which is bermed with dirt. The height from the top of the central riser to the bottom of the tank is 7.6 m (25 ft). For the ORNL deployment, only the walls of the tank would mapped. (The first deployment at ORNL was to measure cracks and spalling concrete and to detect signs of structural instabilities in the UST walls, so the TMS was optimized for these measurements.)

The results of the characterization of the TMS are presented in Fig. 6. The relative rms error varied from 10.16 mm (0.400 in.) at 3.66 m (12 ft) to 6.35 mm (0.250 in.) at the optimized 7.62 m (25 ft). The system error was driven primarily by the lateral error. The axial or range error was very low, ranging from 0.43 mm (0.0170 in.) at 5.79 m (19 ft) to 1.8 mm (0.0709 in.) at 8.84 m (29 ft). The cubic box that was used to make the measurement was placed on the center of the field of view of the system (which was necessary to keep the entire box within the 10° fan angle of the system). Therefore, the range measurement was always down the center of the field of view. Because the misaligned laser had the biggest visible effect on skewing the resulting surface map, the largest errors were driven by the lateral measurements.

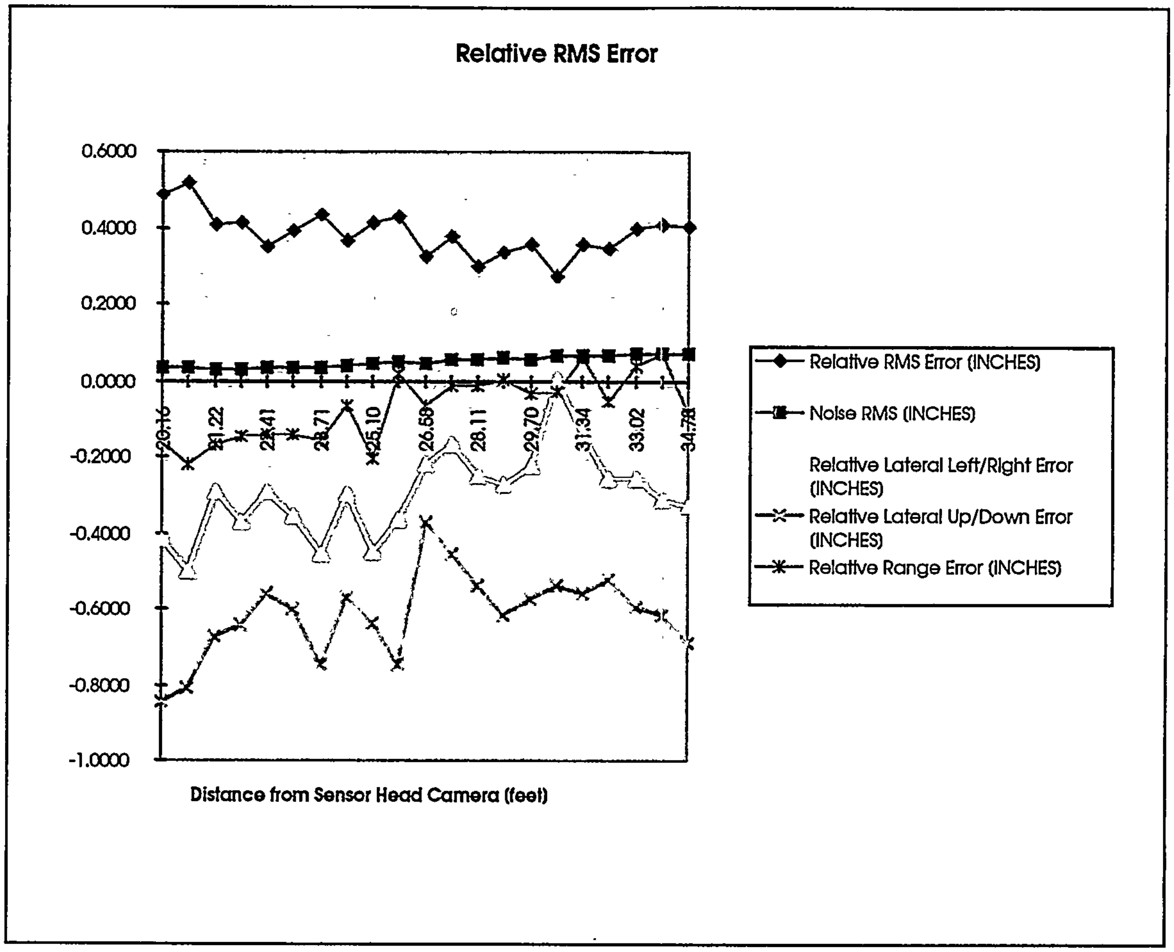

Fig. 6. Relative accuracy of the TMS.

3. STF INSPECTION

The TMS was installed in the central riser of tank W5 first and then tank W6 of the STF. This positioned the TMS sensor head approximately 7.62 m (25 ft) from the walls of the tanks. Prior to installation the levels of the waste in tanks W5 and W6 were measured to be 0.55 m (22 in.) and 0.61 m (24 in.), respectively. The distal end of the TMS was calculated to be 1.35 m (53 in.) above the bottom of the tank. The color camera that was attached to the end of the sensor head added 0.30 m (12 in.) of length. As a result, there was 0.48 m (19 in.) of clearance in tank W5 and 0.43 m (17 in.) of clearance in tank W6 between the color camera and the liquid waste surface. The TMS sensor head's position in the tank is illustrated in Fig. 7.

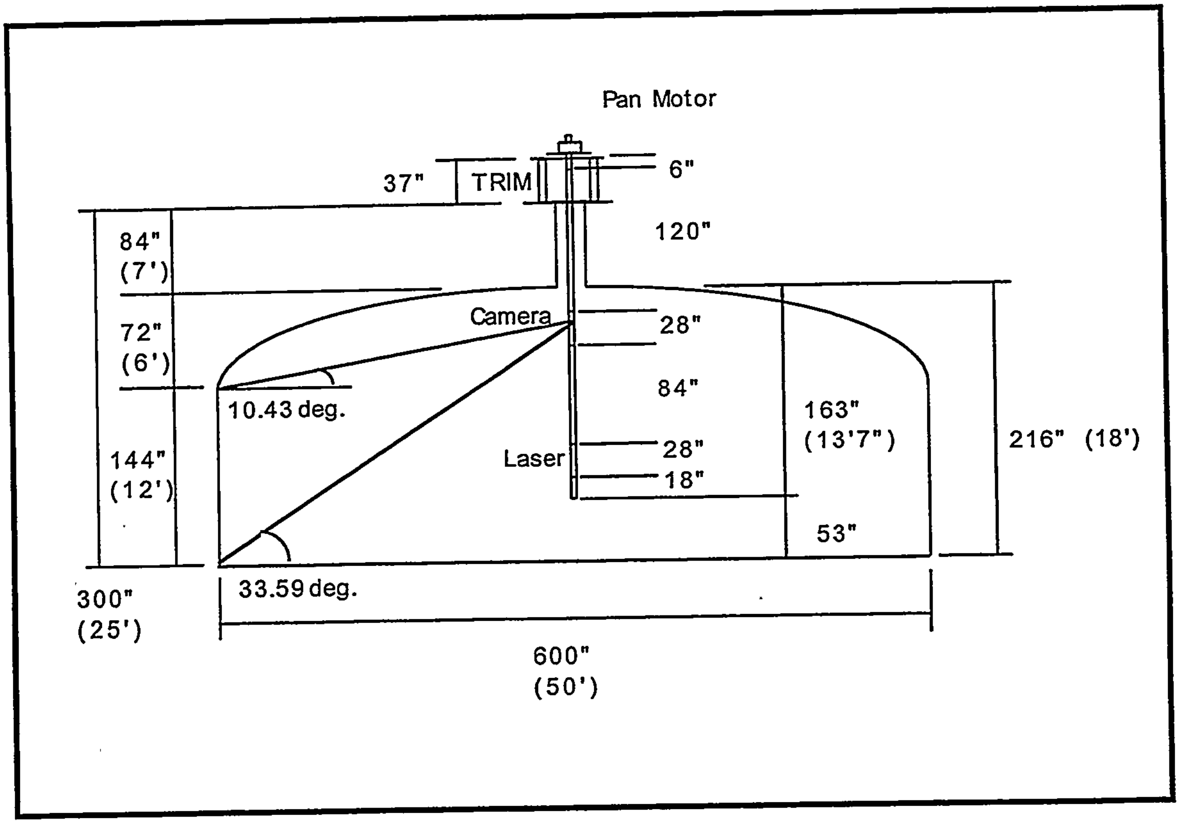

Fig. 7. TMS sensor head's location in an STF UST.

3.1 STF REQUIREMENTS

There were two objectives for the deployment of the TMS in the STF: (1) inspection of wall surfaces for cracks, crevices, or signs of structural instability and (2) validation of field readiness of the TMS. An aerial photograph of the USTs at ORNL is shown in Fig. 8.

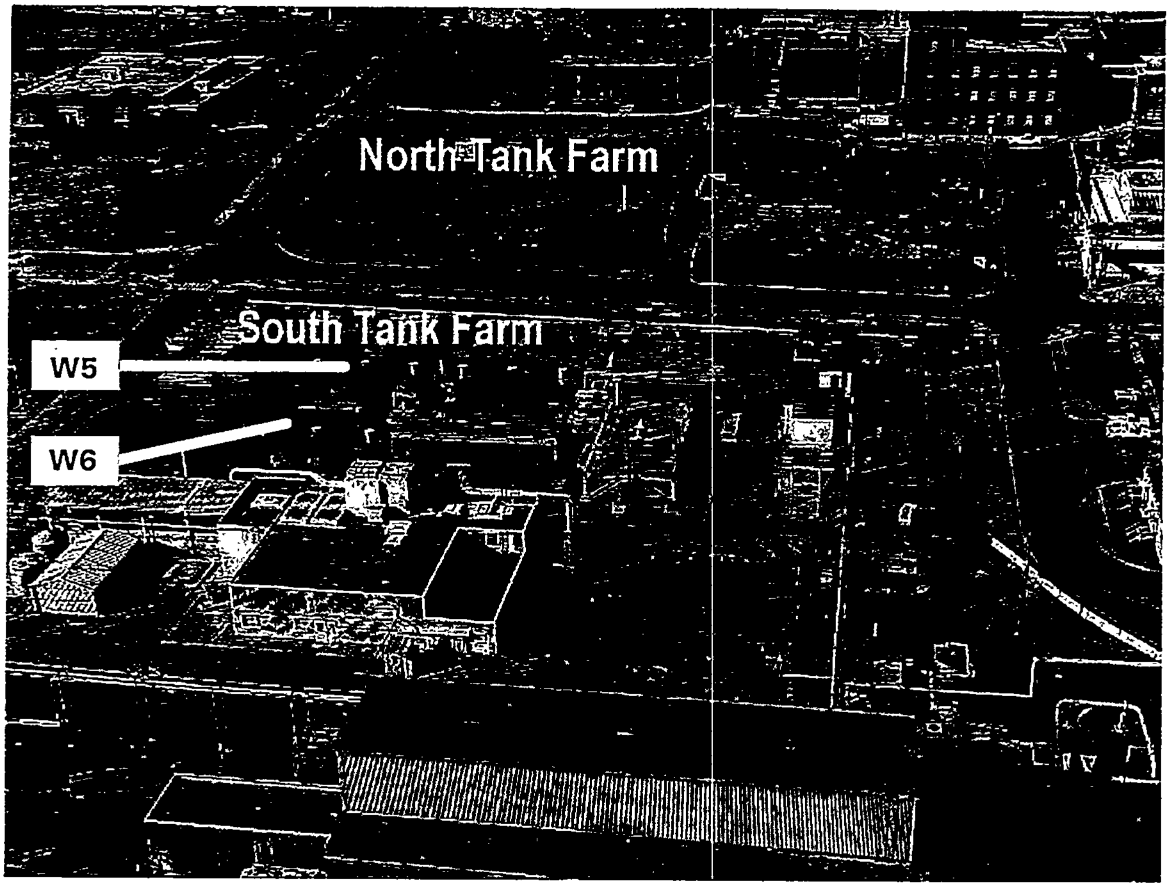

Fig. 8. Aerial photograph of STF at ORNL.

Video inspection of tanks W5 and W6 depicted mottled wall surfaces in both tanks that appeared to be areas where the Gunite liner has spalled off the wall. A photograph of a typical UST wall with mottled surfaces in shown in Fig. 9. Quantitative measures of the affected surface areas and depth of the spalling can not be obtained using simple video inspection. Because the original liner was applied in a 3.81-cm (1.5-in.) layer, a range accuracy of 1.27 cm (0.5 in.) or better would be required to distinguish between regions where the liner is intact and areas where the liner has spalled off. A sampling resolution of one point every 10.16 cm by 10.16 cm (4 in. by 4 in.) would provide sufficient information for evaluating the extent of the spalling. The data would be acquired as <*XYZ*> points relative to a world coordinate frame (WCF) established during installation of the TMS (typically the WCF is set to have its origin at the bottom center of the tank). The WCF origin is determined primarily from existing drawings of the UST. The resulting accumulation of <*XYZ*> data points from the tank walls would build a surface map of the walls in 3-D space. The surface map could then be analyzed to determine the extent of the spalling.

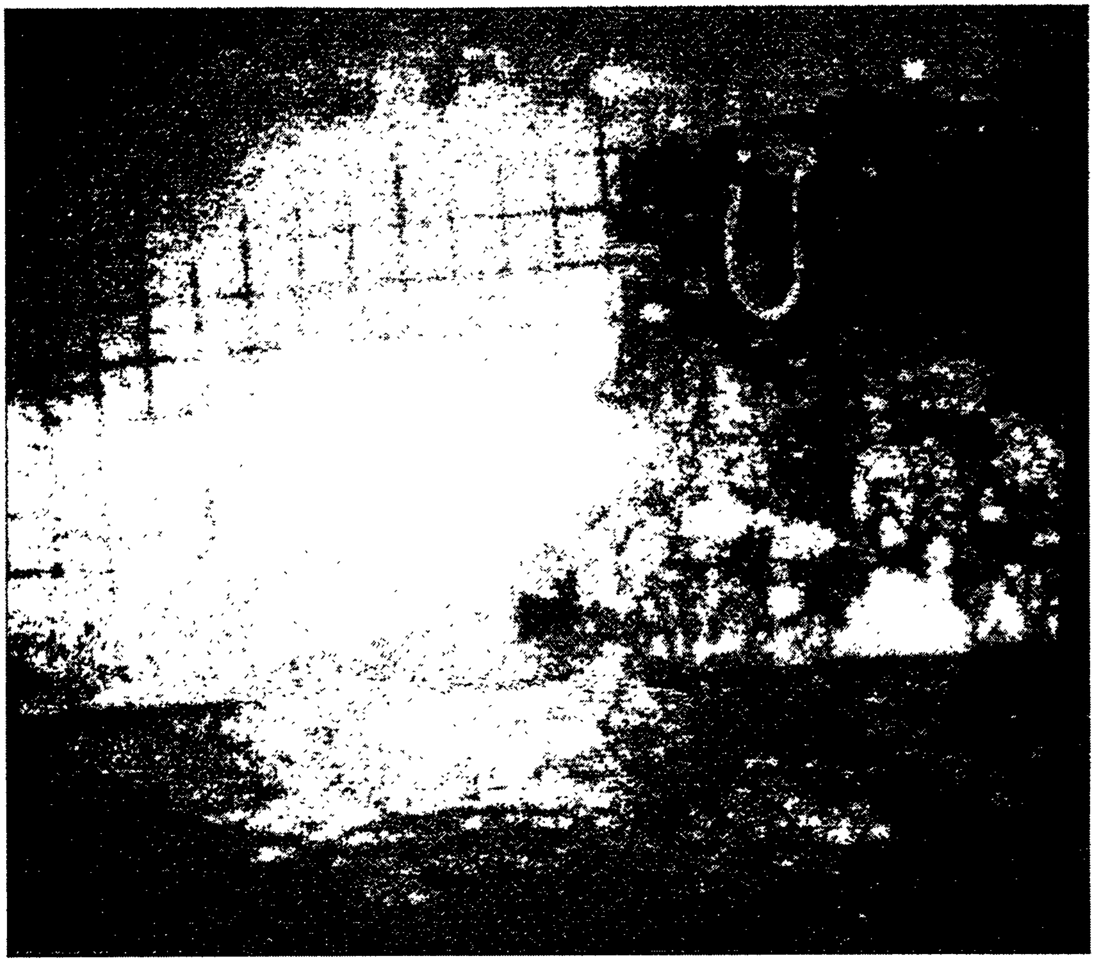

Fig. 9. Typical photo of the tank W5 wall with mottled surfaces.

The TMS has been designed for deployment in the SSTs at the Hanford Site in Washington state. The radiation levels in the Hanford SSTs are typically 1 Gy/h (100 R/h) and therefore pose a much higher radiation exposure than the tanks at ORNL. Deployment of the TMS in the tanks at ORNL provides an intermediate step for testing (1) documentation, (2) contamination control, (3) health and safety, and (4) site interface issues for a radiological site deployment where the magnitude of personnel risk is greatly reduced.

3.2 STF INSTALLATION

After months of testing, calibration, and characterization of the TMS in the high bay and basement of the Robotics Facility, the TMS was ready to be deployed in the STF. The final testing of the TMS included approximately 400 h of operational testing with no failures. This indicated that the TMS could be reliably deployed in a radiological environment. The HMI was loaded in an ORNL bus that was instrumented as a mobile office and laboratory. The bus was provided by the Measurements Applications and Development (M.A.D.) Group of the Life Sciences Division of ORNL. The bus is used for on-site environmental surveys and off-site radiological surveys in support of DOE's Formerly Utilized Sites Remedial Action Program (FUSRAP). The bus enabled the HMI to be tested in its field-deployable configuration prior to arrival at the STF. The bus was driven to a parking area on the edge of the STF with the HMI installed, eliminating the need to set up the HMI at the mapping site.

The TMS configuration had previously been determined from the engineering drawings (drawing numbers W-68336, W-68343, and E-56866) of tank W5 and W6 and from current liquid waste levels measured in the tanks. The 2.13-m (84-in.) extension module provides the greatest accuracy for the range measurements, but could only be used in tanks with a head space greater than 3.66 m (12 ft) [counting the color camera, the installation required a minimum of 3.96 m (13 ft)]. The water levels in the tank indicated that the tanks had 4.88 m (16 ft) of head space. Therefore, the 2.13-m (84-in.) extension module was used. A 3.05-m (10 ft) extension module was used to position the sensor head in the vapor space. This positioned the camera at 43.18 cm (17 in.) below the dome of the central riser and 4.44 m (175 in.) above the liquid waste. The laser was only 1.60 m (63 in.) above the liquid waste (see Fig. 7). Unfortunately, the ESS was being repaired and was not deployed with the TMS, preventing its use for temperature and radiation measurements. The radiation levels, as measured by radiological workers at the top of the central riser, were 0.005 mGy/h (0.5 mR/h) at tank W5 and were 0.05 mGy/h (5 mR/h) at tank W6. The estimated values at the liquid surface are 0.01 mGy/h (1.0 mR/h) at tank W5 and tank W6. As a result, the TMS received 3 Gy (300 R) of accumulated dose from the mapping campaign. The assembly of the TMS sensor head at the STF is shown in Fig. 10. The TMS sensor head installation into tank W5 of the STF is shown in Fig. 11.

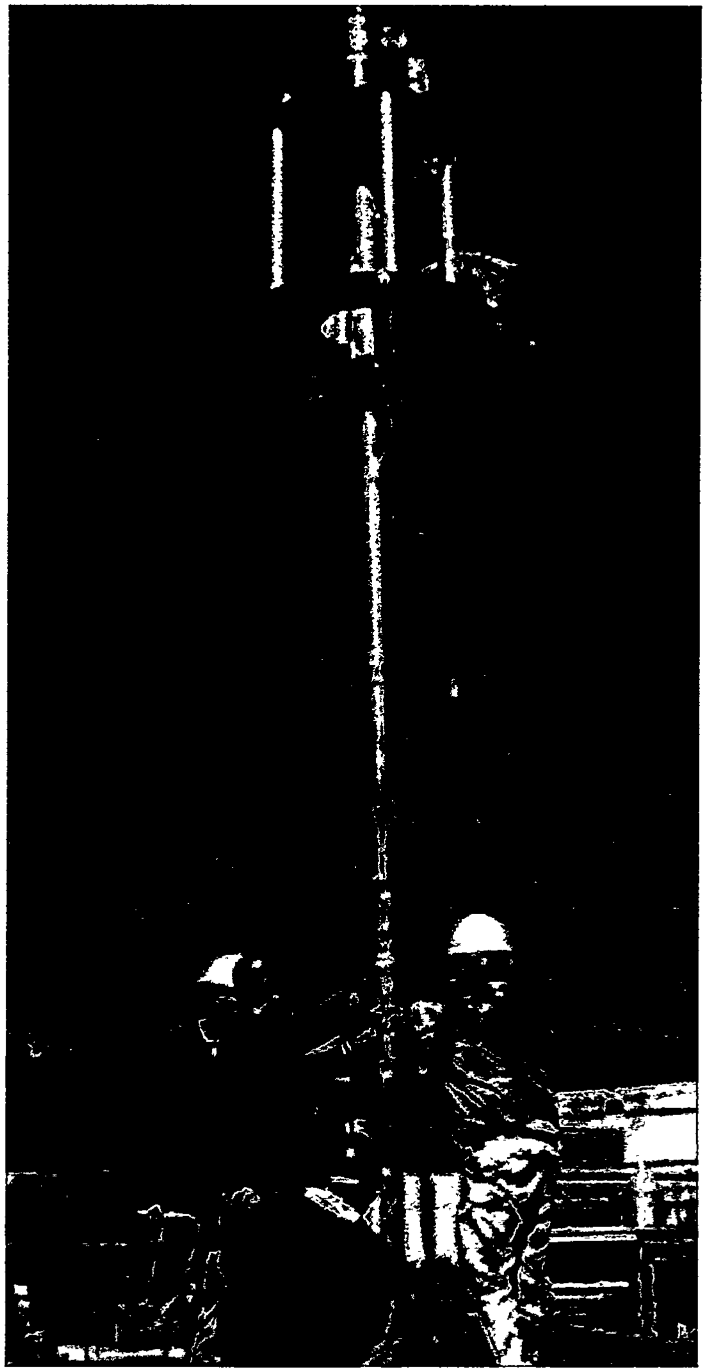

Fig. 10. Assembly of the TMS sensor head at the STF.

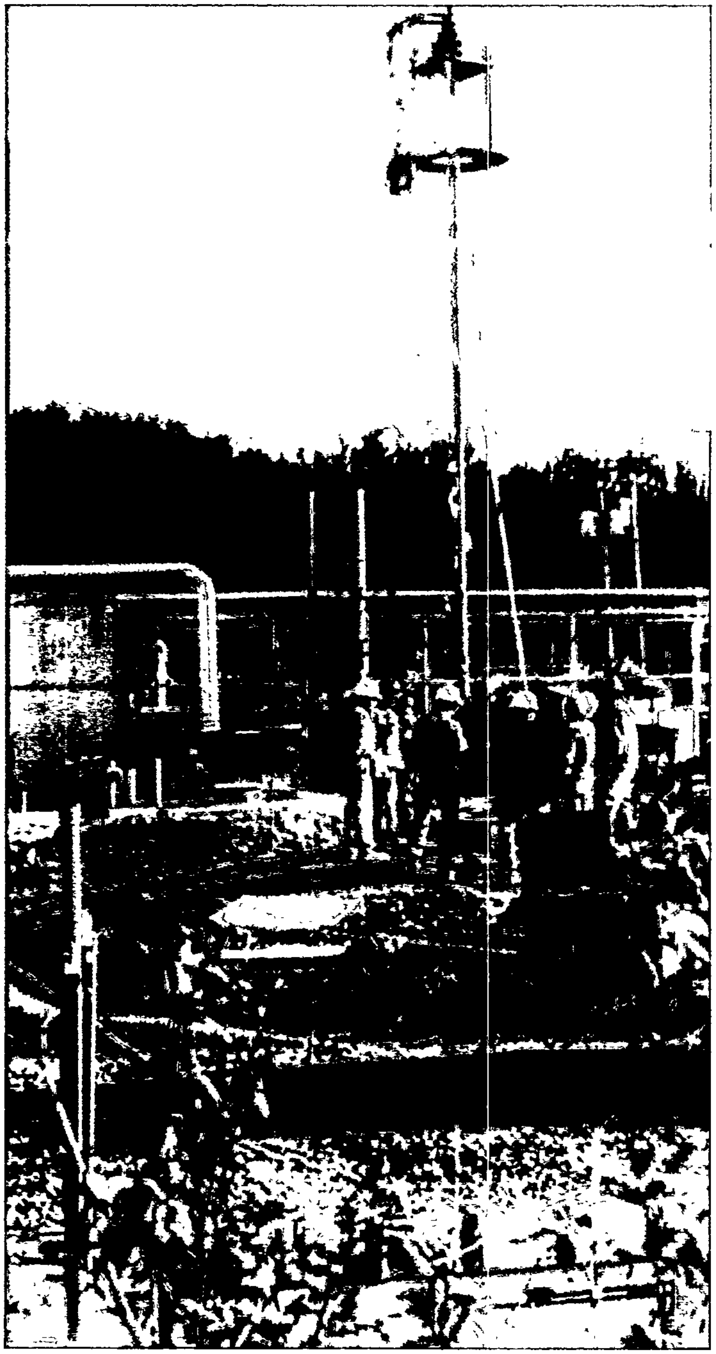

Fig. 11. TMS sensor head installation into tank W5 of the STF.

The TMS was assembled at the STF with the use of a crane. The TMS has been designed to be reconfigurable for different sizes of tanks and to penetrate a 10.16-cm (4-in.) clear aperture. Because of the exacting nature in which the kinematics between the laser and the camera must be known, the sensor head cannot support its own weight in anything other than a vertical position (e.g., it cannot be assembled on its side and then lifted to the vertical position because this would put an excessive amount of axial weight on the structure, which would destroy the calibration).

The TMS had to be assembled in the field. The crane was used to lift the TMS for a top-down assembly at the STF.

To guard against contamination, the TMS sensor head, the EEB, and all exposed cables were enclosed in plastic and wrapped with duct tape. The TMS has a purge system whose purpose is to provide protection from ignition of volatile gases in hazardous environments. The purge system was used at the STF to prevent ingress of airborne contaminants. In addition, the TMS has been designed to be water-resistant to allow it to be decontaminated by a liquid spray wash. The plastic and duct tape were added as an extra precaution to ensure that the unit could be shipped and deployed at the Hanford Site once the ORNL mapping was complete.

Once the TMS was fully assembled, a separate lighting and color camera system was installed at the distal end of the sensor head. With all systems installed, the TMS sensor head was ready for insertion into tank W5.

3.3 TANK W5 INSPECTION

The 10.16-cm (4-in.) and 2.54-cm (1-in.) resolution mappings of the walls of tank W5 were performed without the use of the additional color camera or lights. Location of the dome-wall interface and the water-wall interface was performed using the laser and the camera on the TMS. With the minimum and maximum wall height established, the scan plan for each section of the wall was entered into the system and the walls were mapped. Once the lights in the tank were activated, the tank was visually inspected for cracks and crevices in the tank walls as well as for signs of structural instability.

The 10.16-cm (4-in.) resolution mapping of all exposed walls in the tank took approximately 4 h and the 2.54-cm (1-in.) resolution mapping took approximately 9 h. During the visual inspection, any mottled surfaces were defined as suspect areas. The suspect areas were mapped at 0.635-cm (0.25-in.) resolution. A 0.635-cm (0.25-in.) high-resolution map of a 1.2 m by 1.2 m (4 ft by 4 ft) section of the wall took approximately 30 min and typically required 30 min of setup. Each suspect area that was mapped at high resolution was photographed and videotaped.

After the tank walls were mapped at low resolution and suspect areas were mapped at high resolution, risers and vertical pipes penetrating the dome were also mapped and photographed. The risers and vertical pipes helped to orient or register the locations of the surface maps to known markers inside the tank.

The 3-D visualization tool was not set up for analysis of the mapping data during the W5 mapping. As a result, the mapping of suspect areas required a visual inspection of the walls using the sensor head camera. Once a suspect area was noted, the area was mapped. Most of the areas that appeared to be deep holes in the walls turned out to be exposed bitumen. The bitumen however proved to be difficult to map. The reflectance properties between the bitumen and the Gunite had a large variance. The sensitivity of the camera could be turned down low enough to map the bitumen but the surrounding Gunite produced high enough reflectance to generate significant noise in the captured image. The image-processing algorithm then would treat each noise or glare spot as a laser point that it would pass to the analysis software in an attempt to solve for an <*XYZ*> point. With a lot of noise, the analysis algorithms would take hours to analyze the raw data points and then would generate thousands of erroneous <*XYZ*> data points. Even though this problem could be resolved in the laboratory by implementing more robust noise filters or restricting the mapping to a region of interest in the sensor field of view, a quick field-implementable solution was not possible. However, the laser line could be seen in the raw video on the display in the control trailer. The laser line could be seen to be straight, having little structure in the dark areas. This confirmed that the dark areas were bitumen and not holes. The videotape of the laser being scanned through suspect bitumen areas serves as the verification that the areas were not holes.

As shown in photos and surface maps of the suspect areas, wire mesh and tar were exposed at many places on the wall surfaces. The wire mesh that was exposed by spalling Gunite appeared to be 5.08 cm by 5.08 cm (2 in. by 2 in.). At most places where wire mesh could be seen it was still under a thin layer of Gunite and at most protruded from the wall approximately 0.396 cm (0.156 in.) or less. There were some cases in which the Gunite layer had spalled off leaving the bitumastic layer and/or wire mesh exposed. The most prominent example of this can be seen in suspect area 5 (see Appendix A). Of all the suspect areas examined in tank walls, no penetrations were found that were more than 1.25 in. Appendix A has surface maps of all suspect areas mapped in high resolution. Appendix C has the corresponding photos for UST W5. Appendix E contains the corresponding photo log, and Appendix G has the corresponding log for the videotapes. Appendix B contains high-resolution surface maps for UST W6. Appendixes D, F, and H contain supporting information for the W6 mapping activities.

3.4 TRANSFER FROM W5 TO W6

Prior to the transfer from W5 to W6, the water level in tank W6 was remeasured. The TMS sensor head had 134.6 cm (53 in.) of clearance to the bottom of the UST. The water level in tank W6 was measured to be 60.96 cm (24 in.). Including the color camera at the distal end of the TMS sensor head, this left 43.18 cm (17 in.) of clearance from the camera to the supernatant. This was not enough difference to require the sensor head to be reconfigured for tank W6. As a result, the transfer from tank W5 to W6 was done without disassembly and reassembly of the TMS sensor head. As the TMS sensor head was lifted out of the tank, radiological workers wiped the exposed plastic down and measured surfaces for contamination. The TMS sensor head was then transferred to tank W6. While the sensor head was out of the W5 tank, the color camera was quickly examined and repaired (the problem turned out to be a loose wire). The transfer from W5 to W6 is shown in Figs. 12 and 13.

Fig. 12. Removal of the TMS sensor head from tank W5.

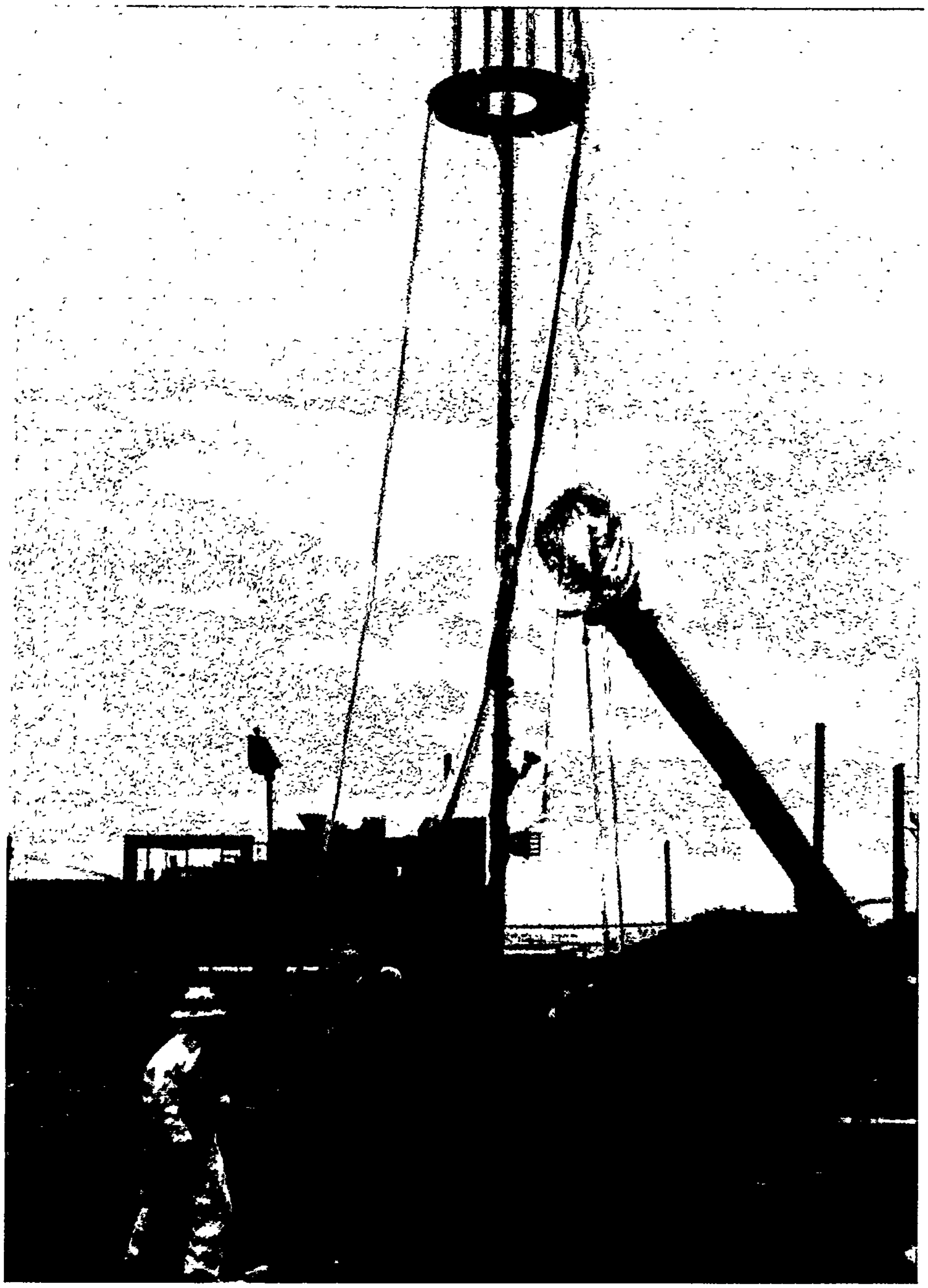

Fig. 13. Transfer of the TMS sensor head from tank W5 to tank W6.

3.5 TANK W6 INSPECTION

Mapping in tank W6 was accompanied by the use of lights and a color camera. The color camera had pan and tilt as well as 12:1 zoom. This provided for better visual inspection of suspect areas in the tank. After the walls were mapped at first 10.16-cm (4-in.) resolution and then again at 2.54-cm (1-in.) resolution and suspect areas were mapped at low resolution, the risers and vertical pipes penetrating the dome were mapped, photographed, and videotaped.

The mapping and visual inspection in UST W6 found similar anomalies as were observed in UST W5. Again the dark mottled surfaces were observed, surface-mapped, and manually scanned with the laser while being videotaped. The results confirmed that the dark mottled areas in tank W6 were also bitumen exposed when the inner layer of Gunite had spalled from the tank wall (or in some cases, as a result of being heated up and having run through openings in the Gunite).

One new anomaly was discovered in tank W6. Tank W6 contains a cave-like depression in the upper 1.2 m (4 ft) of the 3-m (10-ft) walls that is 10.8 cm (4.25 in.) deep around the complete circumference of the tank. At the 1.8-m (6-ft) level on the wall there is a white, marble-like ledge at the beginning of the depression. This is illustrated in suspect areas 2, 3, and 5 of Appendix B. Further study will be required to completely characterize and understand the nature of the structure. It is possible that the tank was constructed with the upper depression. The inner part of the depression shows the same erosion signs of exposed wire mesh and bitumen as was seen in tank W5. All of the surface-mapping data are electronically archived for further analysis and examination. Even though the color figures in Appendix B show a great deal of information about the UST walls, the data can only be examined to the fullest extent with the 3-D visualization tool.

Appendix B has surface maps of all suspect areas mapped in high resolution; Appendix D has the corresponding photos. Appendix F contains the corresponding photo log, and Appendix H has the corresponding log for the videotapes.

3.6 REMOVAL FROM THE STF

Once the mapping of tank W6 was complete, the TMS sensor head was removed. While the TMS sensor head was being withdrawn from the tank, radiological workers wiped down the exposed surfaces and measured the surfaces for contamination. The sensor head was then disassembled and closely checked for contamination.

3.7 RESULTS

3.7.1 UST Surface-Mapping Results

There were no significant penetrations in the exposed portions of the walls of the inspected USTs. Portions of the first layer of Gunite have eroded, leaving sections of the wall with exposed wire mesh and bitumastic. The exposed bitumen is a tar-based sealant that was applied before that last 3.81 cm (1.5 in.) of Gunite and wire mesh were applied to the wall. The bitumen gave the impression that deep penetrations existed in walls during previous video inspection campaigns of the USTs. In addition, there were many places where the bitumen had heated up and had run through openings in the walls. Exposed bitumen was also running down the walls. No eroded areas in the W5 tank were found to be more than 3.81 cm (1.5 in.) deep. Tank W6 contains a cave-like depression in the upper 1.22 m (4 ft) of the 3.05-m (10-ft) walls that is 10.8 cm (4.25 in.) deep around the complete circumference of the tank. Further study will be required to completely characterize and understand the nature of the structure. It is possible that the tank was constructed with the upper depression; the inner part of the depression shows the same erosion signs of exposed wire mesh and bitumen as was seen on the walls in tank W5. Unless multiple layers of Gunite, wire mesh, and bitumastic were applied to the walls, this would indicate that the tank was constructed with the depression as opposed to the depression being worn out by caustic or acidic liquid chemicals over time.

3.7.2 TMS Deployment Results

The requirement to wrap the TMS sensor head and the external color camera and lights in plastic originated from a concern that the TMS sensor head might become too contaminated to ship to the Hanford Site. The TMS is designed to be decontaminated and could have been deployed without the additional plastic wrapping and duct tape. The camera and light additions to the TMS sensor head reduced the need to penetrate a second riser but greatly complicated the application of plastic and duct tape that had to be applied to the TMS sensor head as well as the camera and lights. In addition, the camera and lights were not ready to be deployed at the time the TMS was deployed. Deploying the camera and lights separately from the TMS would have eliminated these problems. In addition, without a camera or light in the tank during the TMS installation, the TMS had to be deployed blind. This posed a risk of rubbing the TMS against the side of the riser as well as submerging the TMS sensor head into the liquid waste. If the camera and lights had been previously deployed in the tank, they could have been used to watch the TMS sensor head as it penetrated the tank vapor space. In addition, a set of lights should be installed at the top of the TMS. This would allow the installation personnel to see the sides of the riser as the sensor head is being installed.

The sensor head received approximately 3 Gy (300 R) of accumulated dose from the mapping campaign and experienced no failures. The only sign of any effects from the radiation was salt-and-pepper noise on the camera video. The effects of this noise were easily filtered out by averaging algorithms in the image-processing software. The radiation had no measurable long-term effects on the system.

4. FUTURE WORK

More work is required on the TMS system before it can be used effectively to perform such functions as measuring the volume of the waste in a UST or building a 3-D model for robotic path planning. There are three areas that need work. First, the laser pointing system needs further calibration to improve the absolute accuracy of the system. When the calibration was performed at ORNL it was believed that if the misalignment in the laser pointing could be carefully characterized and incorporated into the kinematic model, the system should be able to operate within the required specifications of +/- 0.25 inches at 45 ft. However, this has not proven to be true. Because of the interaction among the 45° pointing mirror, the rotary table, and the laser, the laser must be pointing perfectly horizontal when the rotary table is at 0°. After the laser is aligned and the system is calibrated, a full characterization needs to be performed to determine the system accuracy over its targeted measurement space.

Second, the volumetric analysis capability needs to be added to the ICERVS 3-D visualization software. The present ORNL-developed tool can only determine the volumes for very structured environments with no vertical surfaces present. ICERVS can more easily deal with the unstructured environments of the USTs because of the use of the octree database. In addition, the identification and elimination of structural elements within the UST that should not be in the waste volumetric calculation can easily be achieved by functions within the ICERVS tool.

Third, the error model that indicates the confidence of the measurement based on (1) range, (2) contrast, (3) signal-to-noise ratio, (4) camera sensitivity, (5) laser power, (6) angle of incidence, (7) kinematics of the sensor head, (8) temperature, and (9) radiation needs to be determined and characterized. Presently the TMS has been characterized along one horizontal plane extending out the *y*-axis of the sensor in the home position. The characterization needs to be extended to include multiple such characterizations on horizontal planes every 1 m (3.2808 ft) over the entire measurement space. This would allow arrays of characterization data to be formulated for axial range, lateral range, and angle of incidence over the targeted measurement space. In addition, more data need to gathered on the TMS's capability to surface-map surfaces of varying texture and therefore reflectance and absorption properties. For the present characterization, most of the measurements were performed only one time. A subset of the data points needs to be collected multiple times in an effort to gather statistics on the system's repeatability.

In addition, there are a few improvements that could be made to the system that would greatly improve its versatility as well as it deployability. A set of lights distributed about the sensor head would greatly aid in installation and removal through the riser as well as tank inspection. Lights could also be added to the extension modules or the dummy ESS. This would allow the lights to be designed for decontamination as opposed to adding lights to the outside of the sensor, which further restricts the aperture of the penetration. In addition, a zoom camera with a dedicated pan-and-tilt mechanism could be added to the bottom of the ESS.

A strong-back and trailer could be used to deploy the TMS sensor head. The strong-back would be approximately 10.67 m (35 ft) in length. The strong-back would support the TMS in a lateral position and would allow the TMS to be configured on its side and then lifted with a crane to a vertical position. This would eliminate the necessity to top-down assemble the TMS sensor head with a crane. The strong-back could be enclosed in a 10.67-m (35-ft) trailer that also serves as a containment box for transporting the TMS sensor head between deployment sites.

5. FUTURE PLANS

A proposal has been written by PNNL and ORNL for deploying the TMS in UST AX104 at Hanford during FY 1998 to measure the remaining waste left in the tank. The TMS is also being considered for deployment in UST CY106 to measure the effectiveness of vendor-supplied sluicing equipment.

6. REFERENCES

1. W. W. Jenkins, *Remote Handling Equipment for the Removal of Waste from Single-Shell Tanks at the Hanford Site*, WHC-SA-0934-FP, 1990.

2. B. L. Burks, *Waste-Surface Mapping of the Fernald K-65 Silos Using a Structured Light Measurement System*, ORNL/TM-12185, Oak Ridge National Laboratory, 1992.

3. G. A. Armstrong, A. F. Pardini, *Demonstration of Volumetric Analysis using the Topographical Mapping System at Hanford*, ORNL/TM-13438, Oak Ridge National Laboratory, 1997 (in publication).

4. J. C. Fulton, *Single Shell Tank Waste Retrieval Study*, WHC-EP-0352, 1992.

5. S. A. Krieg, et al., *Riser Configuration Document for Single Shell Tanks*, WHC-SD-RE-TI-053, 1990.

6. B. L. Burks, B. E. Bernacki, and G. A. Armstrong, *Topographical Mapping System for Radiological Environments*, 1993.

7. C. M. Smith, *Functions and Requirements for the Light-Duty Utility Arm Integrated System*, WHC-SD-TD-FRD-003 Rev.0, March 1994.

8. *Interactive Computer-Enhanced Remote-Viewing System (ICERVS)*, Final Report, November 1994–September 1996, Mechanical Technology, Inc.

9. *Pentax PTS-V Series Electronic Total Station Instruction Manual*, ASAHI Precision Co., LTD., 1994.

10. Guo-Qing Wei, Song De Ma, *Two Plane Camera Calibration: A Unified Method*, National Lab of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences, Beijing, 1991.

11. F. W. DePiero, *Camera Calibration in a Hazardous Environment Performed in Situ with Automated Analysis and Verification*, ORNL, Fifth Annual ANS Topical Meeting, 1993.

12. G. A. Armstrong, B. L. Burks, B. E. Bernacki, A. F. Pardini, *Topographical Mapping System for Hazardous and Radiological Environments*, October 1995, ANS Winter Meeting.

13. R. Gamache, *A Topological Mapping System for Radiological Environments*, Mobile Mapping Symposium, Ohio State University, Columbus Ohio, May 24-25, 1995.

14. J. Wagner, *Mapping of Waste Surfaces*, DOE Conference on Environmental Commerce, Chattanooga TN, October 1993.

15. J. Tourtellott, *Visualization and Modeling of 3-D Image Data in Remote Robotic Applications*, SPIE Proceedings on Intelligent Robots and Computer Vision, Philadelphia, PA, Vol. 2588, Oct. 25–28, 1995.

16. J. Tourtellott and J. Wagner, *Interactive Computer Enhanced Remote Viewing System*, DOE Conference on Partnering, Morgantown WV, October 1995.

APPENDIX A

W5 SUSPECT AREAS SURFACE MAPS

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Areas 1–7 & Risers

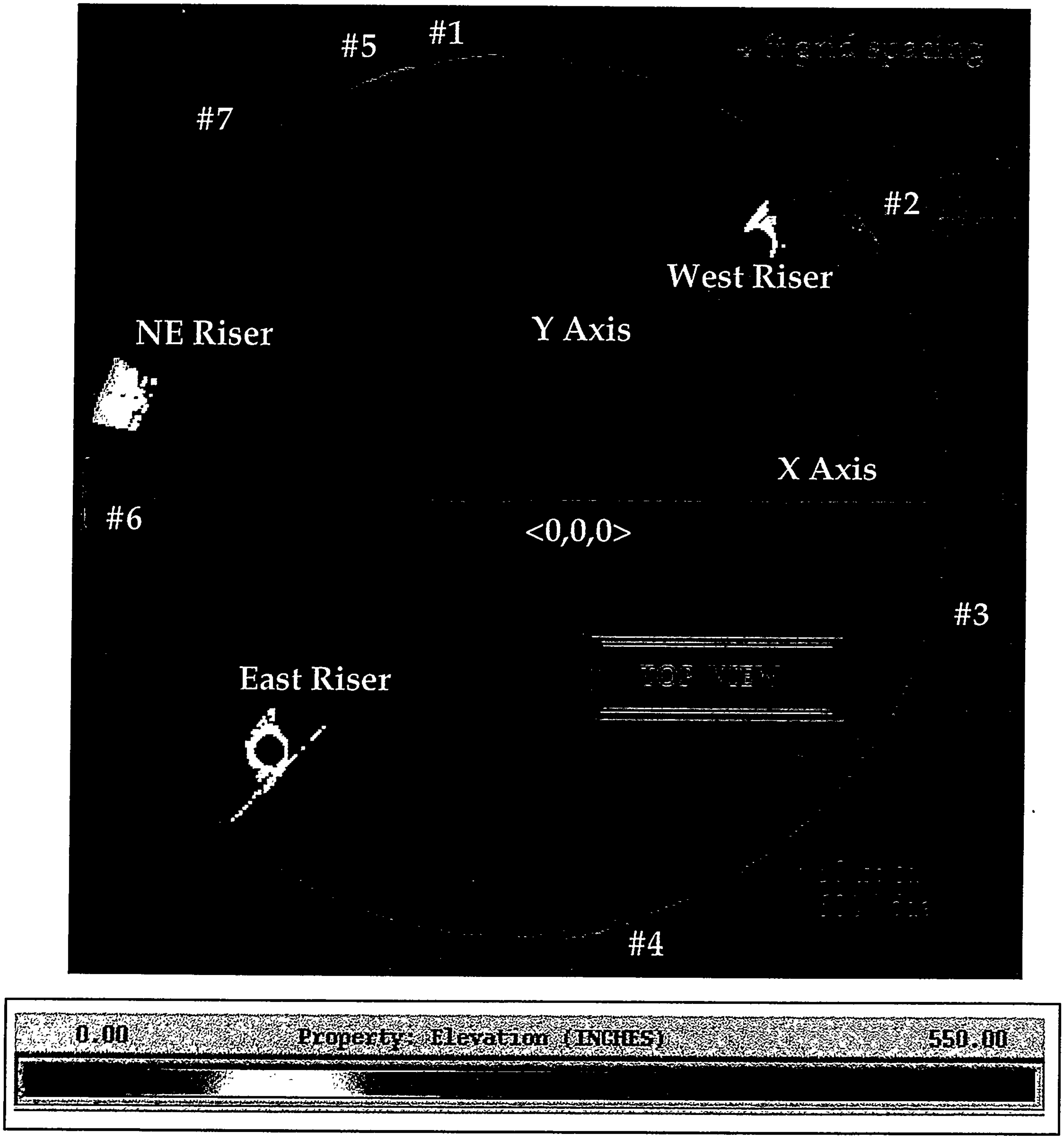

Figure A.1. UST W5 with all suspect areas and three risers.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

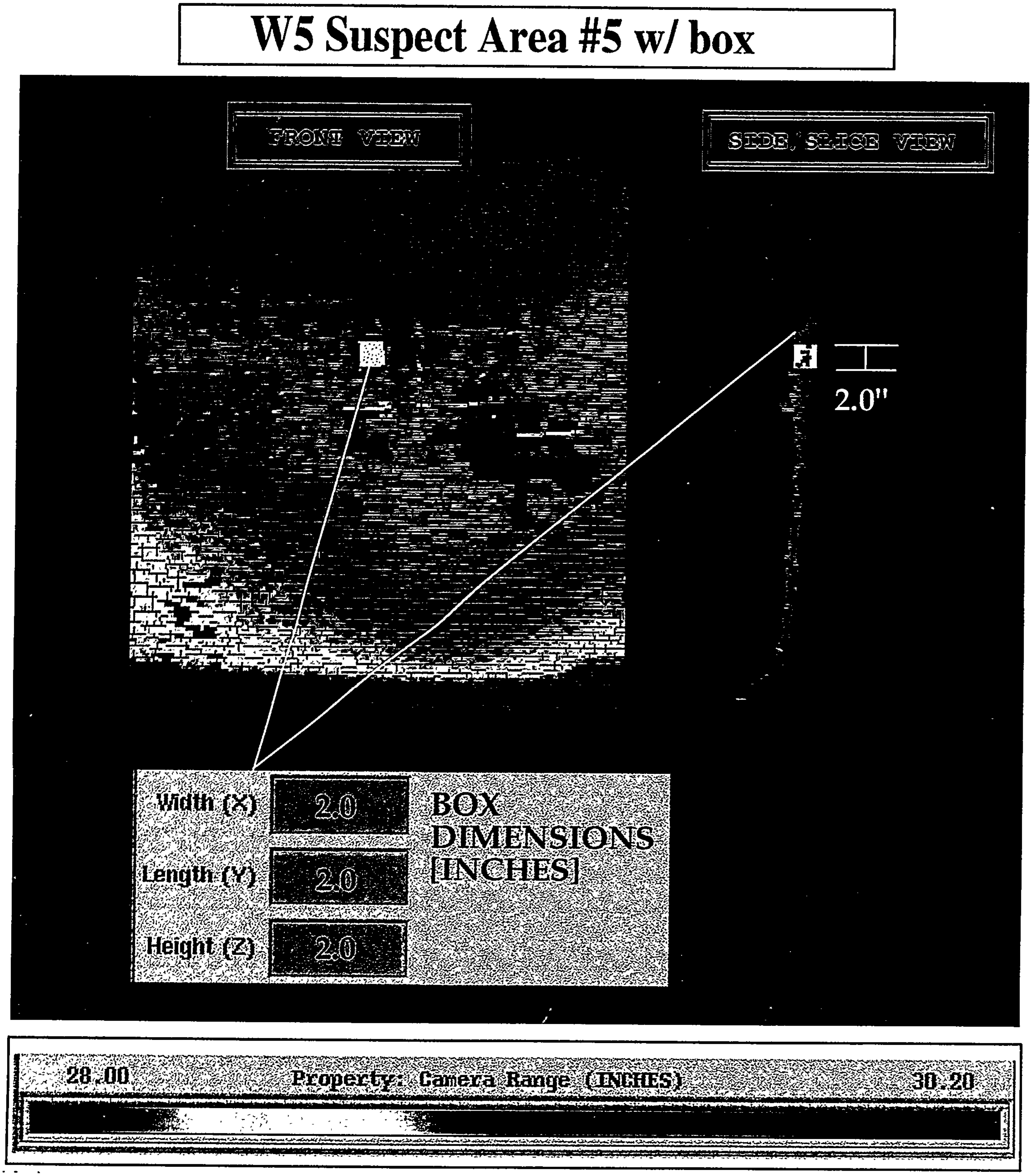

Figure A.2. UST W5 suspect area 5 surface map with wire mesh dimensioned using a 2 inch cube.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #1

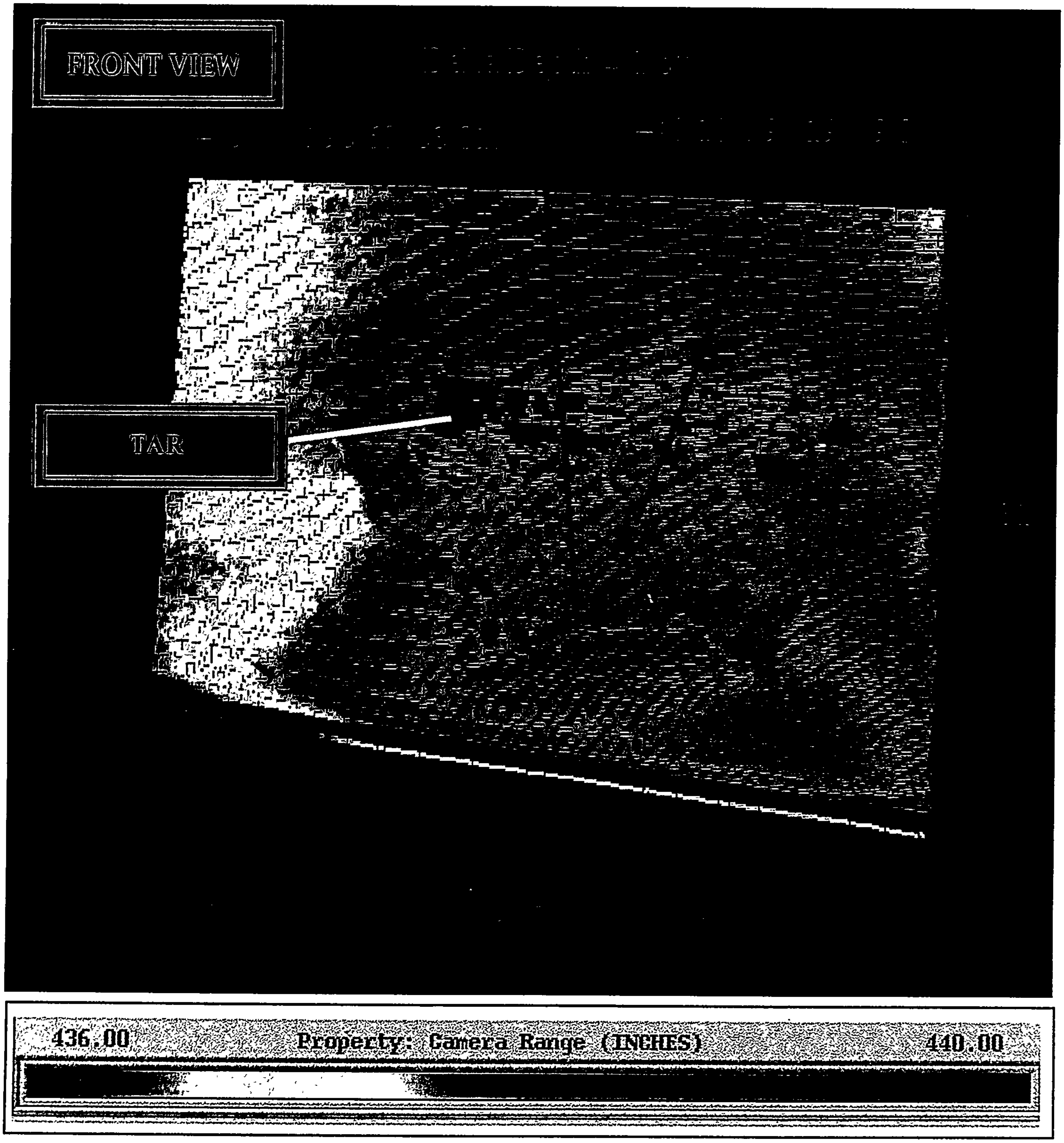

Figure A.3. UST W5 suspect area 1 surface map.

ORNL South Tank Farm

Underground Storage Tank Wall Inspection

W5 Suspect Area #2

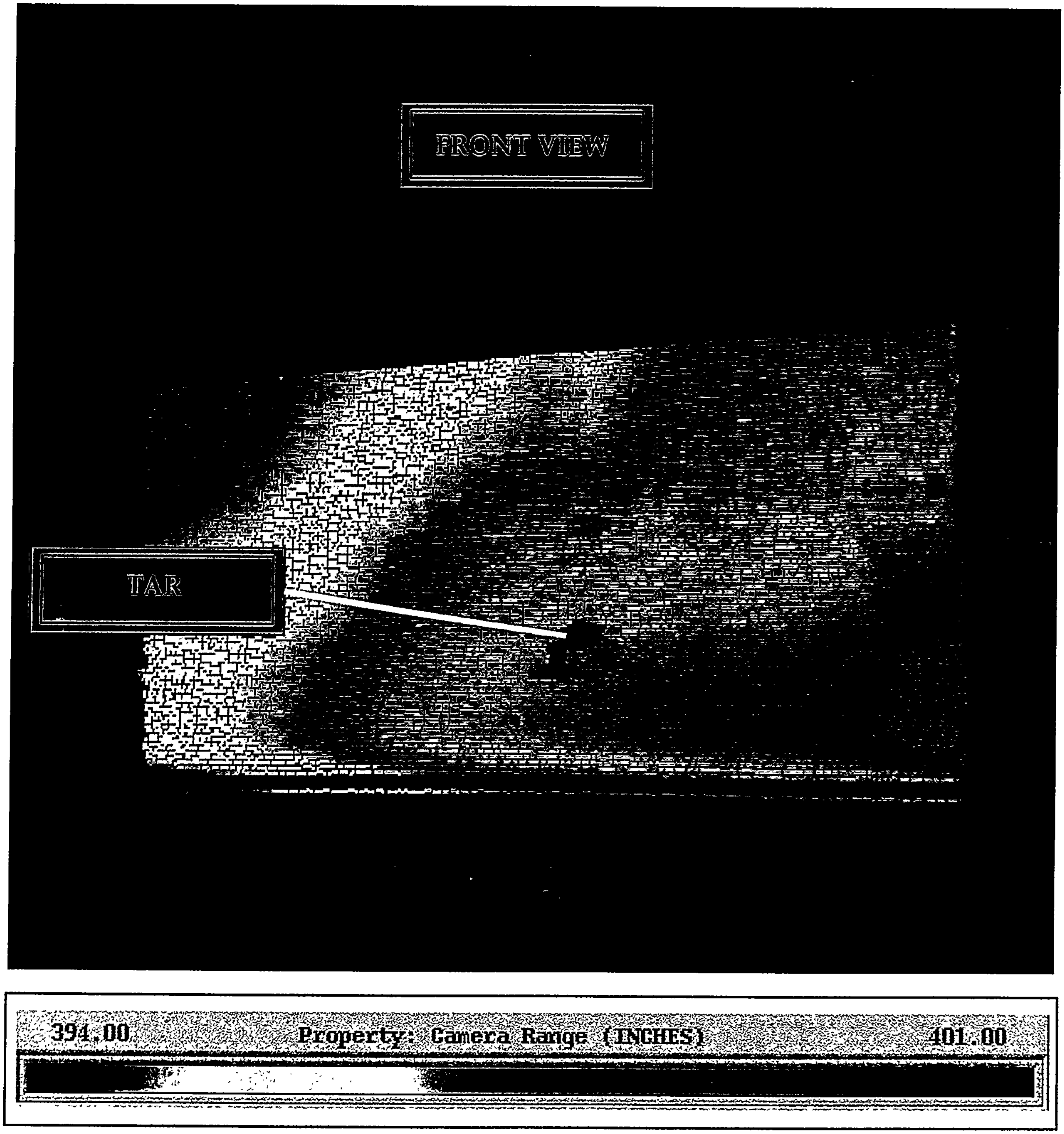

Figure A.4. UST W5 suspect area 2 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #3

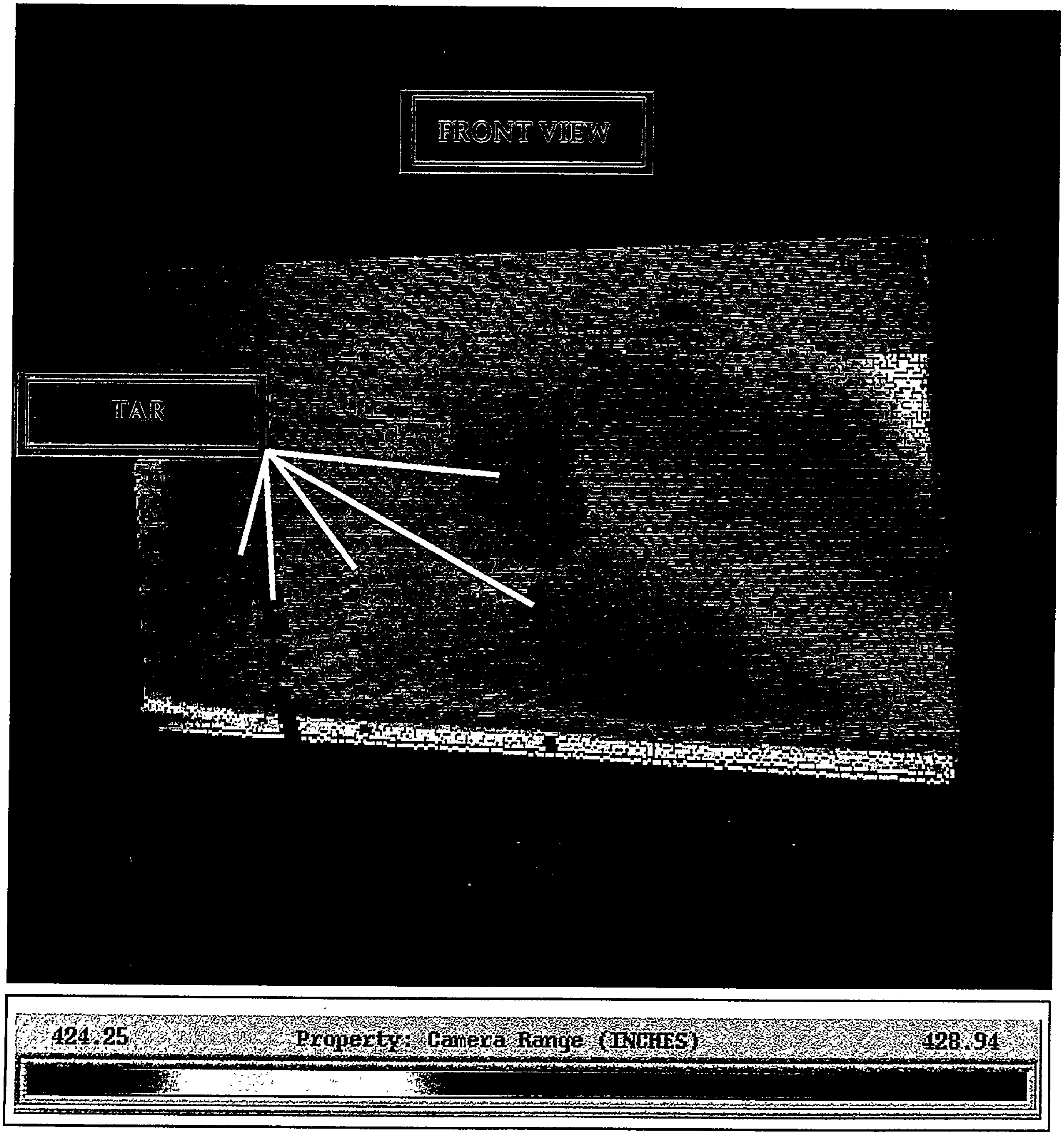

Figure A.5. UST W5 suspect area 3 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #4

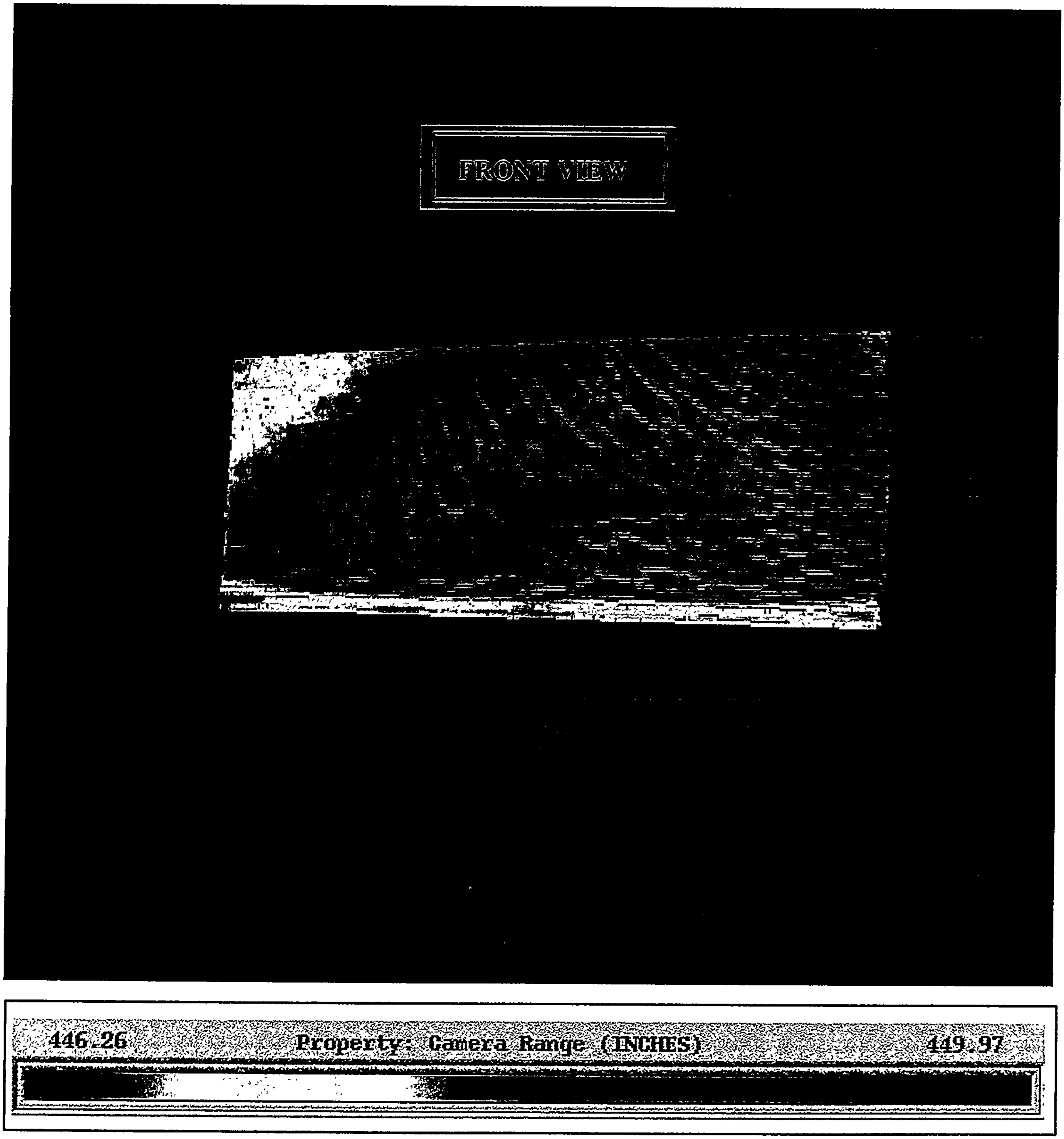

Figure A.6. UST W5 suspect area 4 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #5

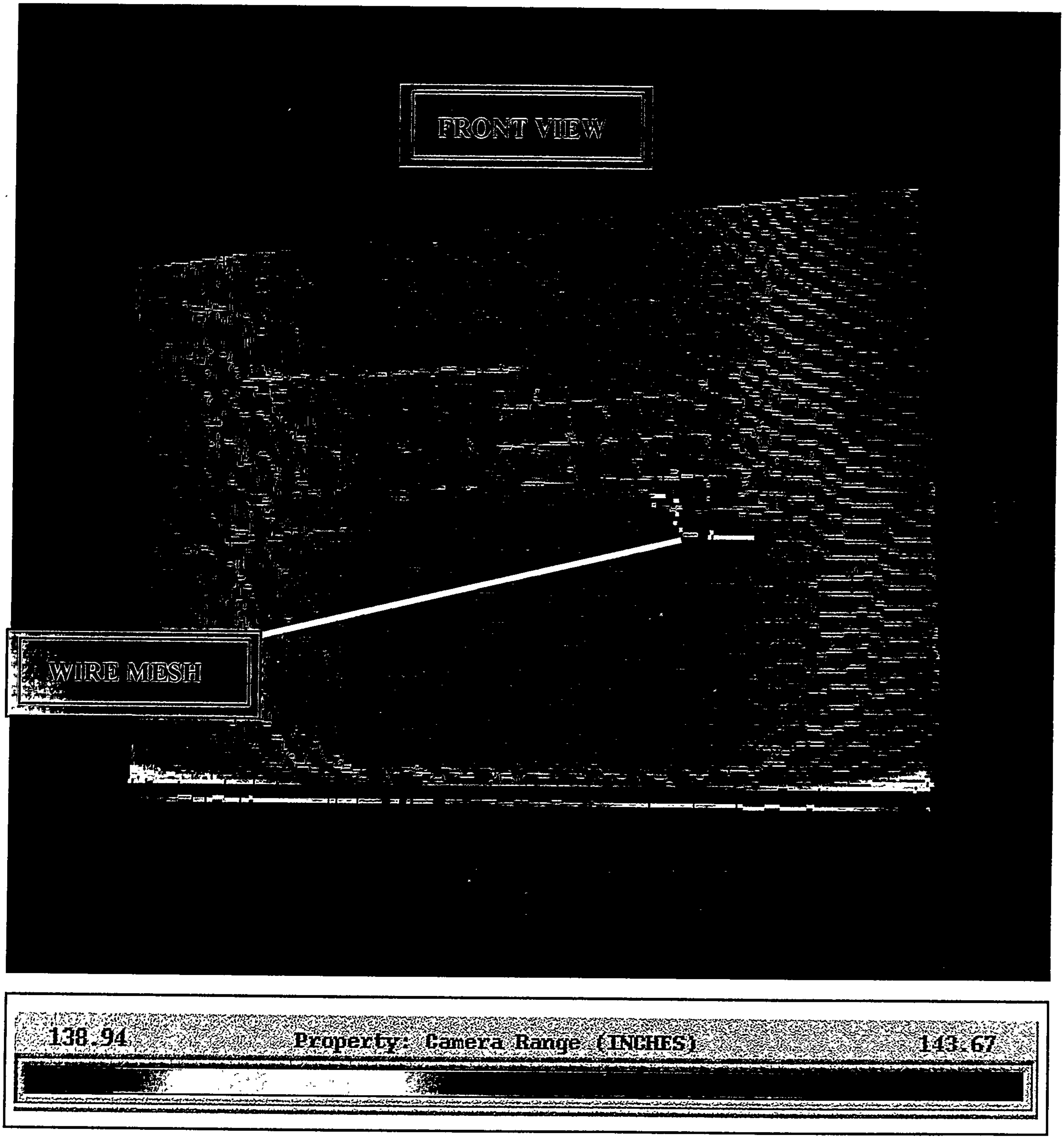

Figure A.7. UST W5 suspect area 5 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #6

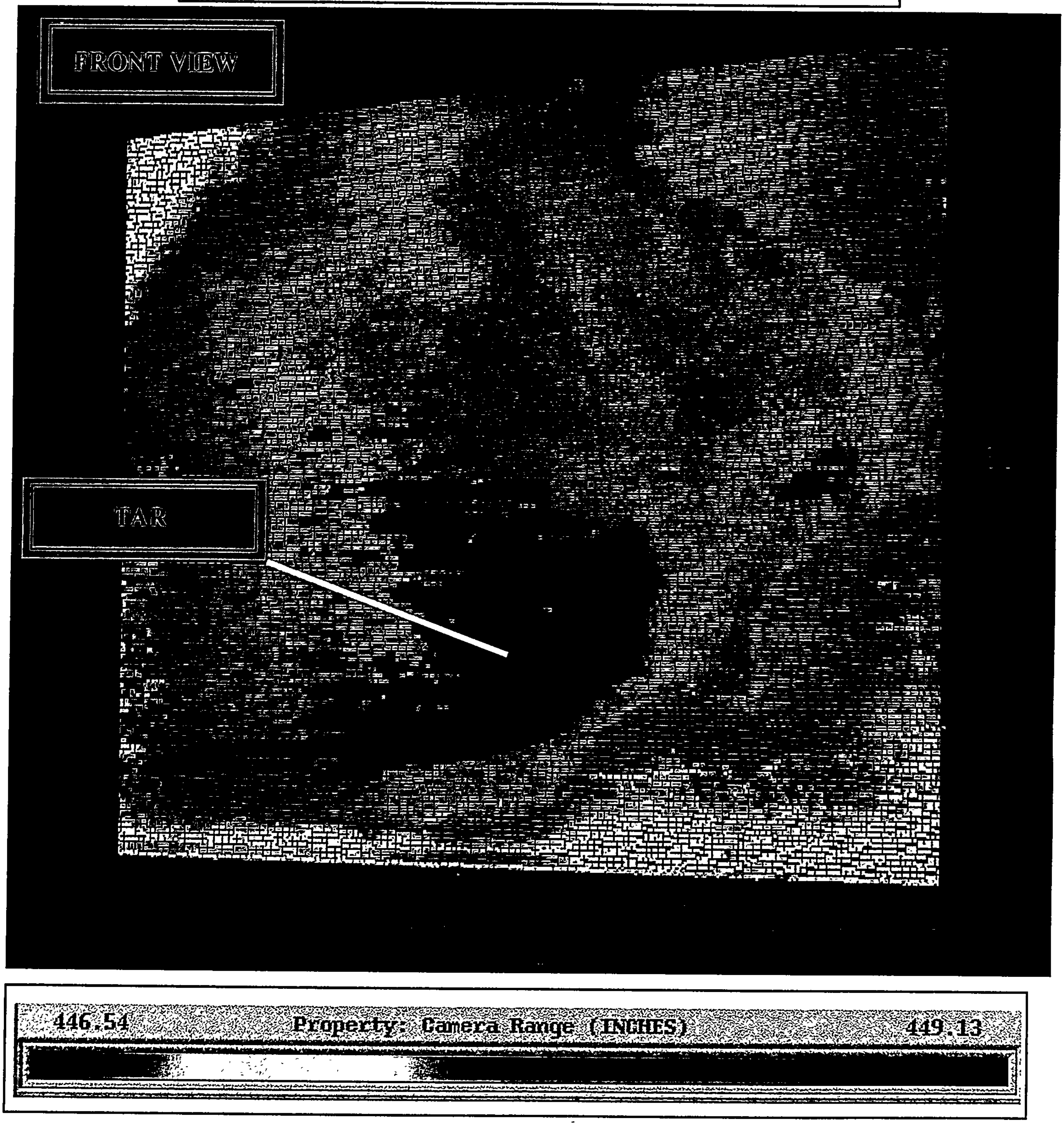

Figure A.8. UST W5 suspect area 6 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W5 Suspect Area #7

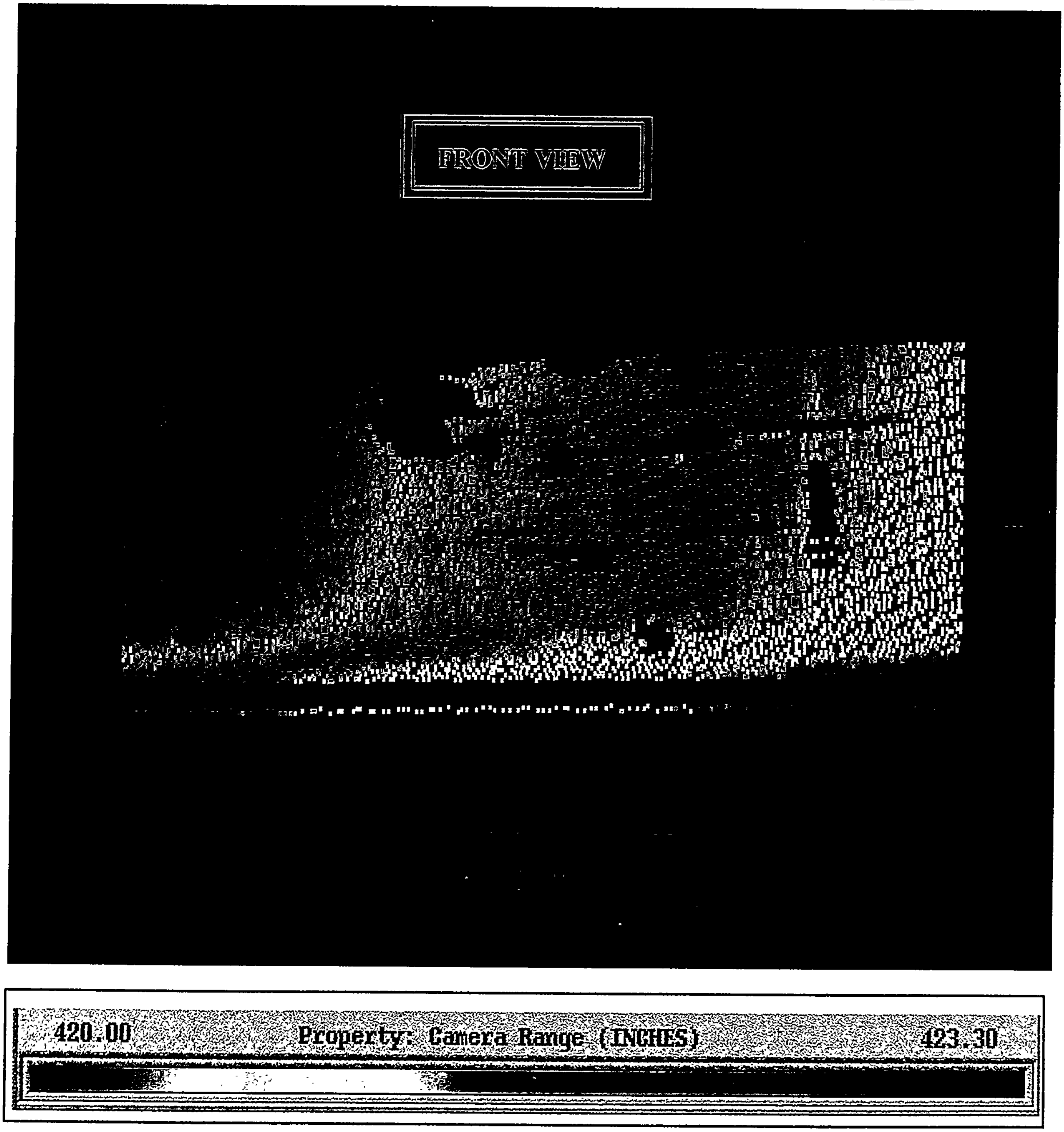

Figure A.9. UST W5 suspect area 7 surface map.

APPENDIX B

W6 SUSPECT AREAS SURFACE MAPS

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Areas 1–7, 9–12 & Risers

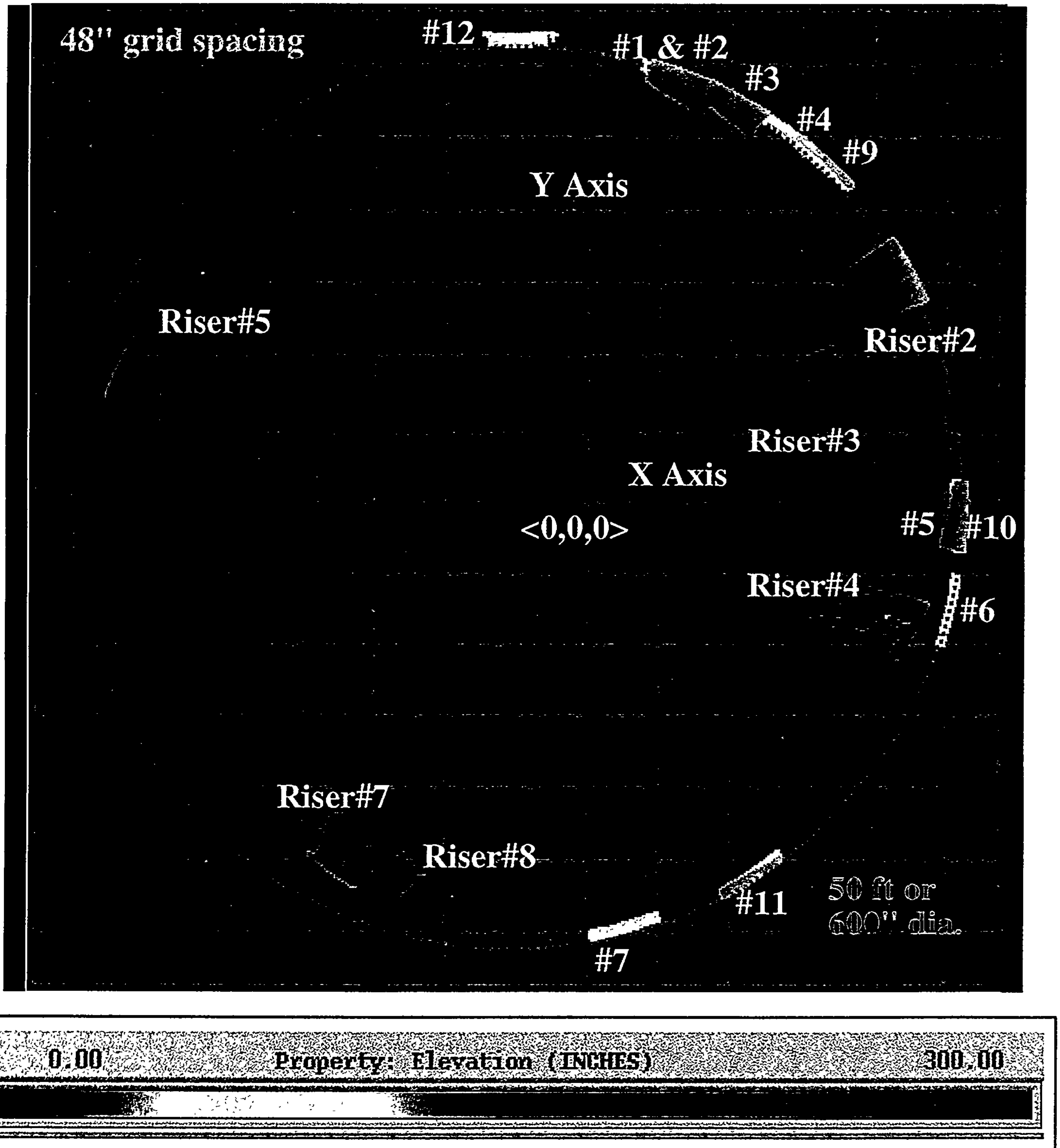

Figure B.1. UST W6 surface maps of suspect areas and risers.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #1

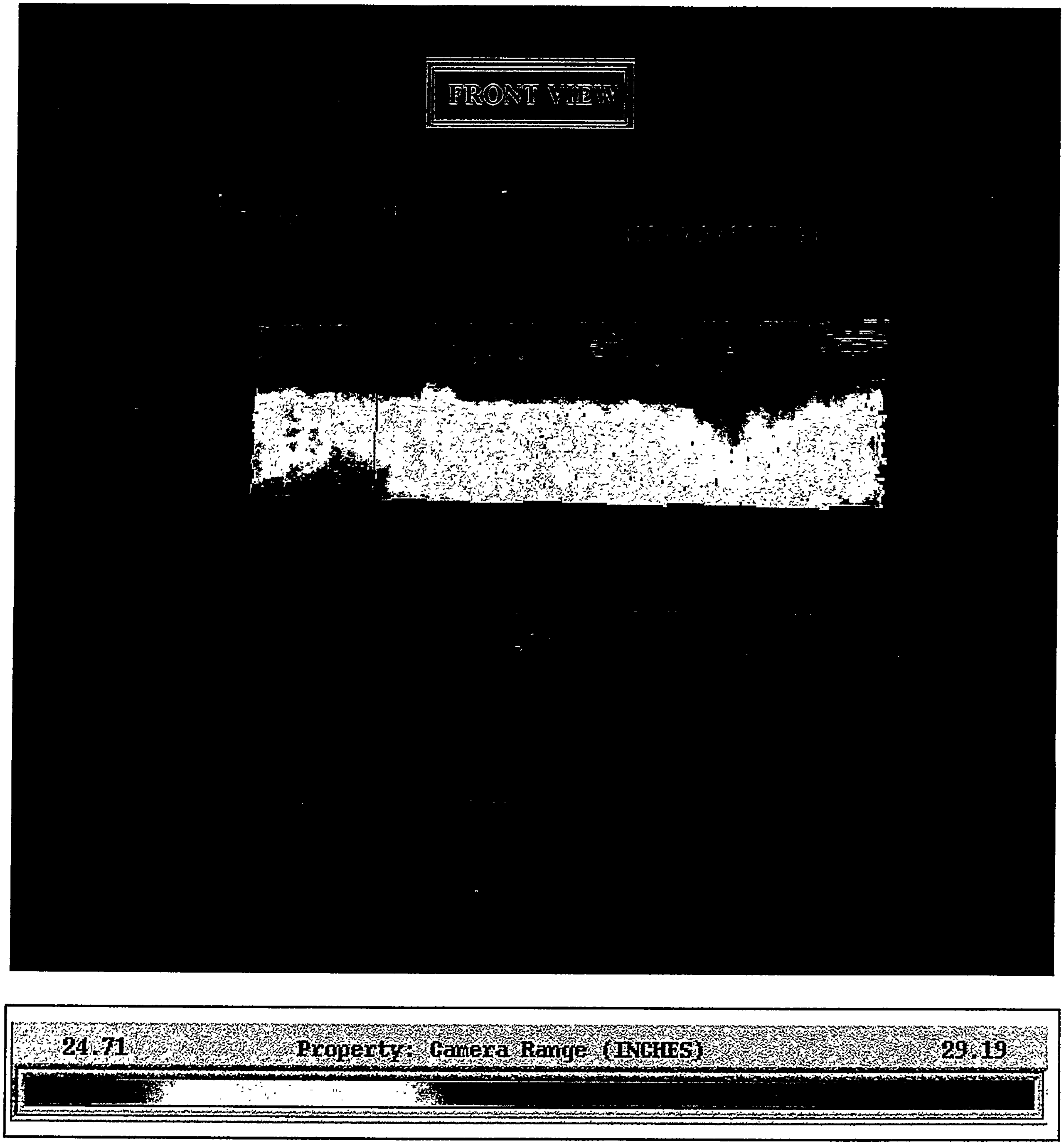

Figure B.2. UST W6 suspect area 1 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #2

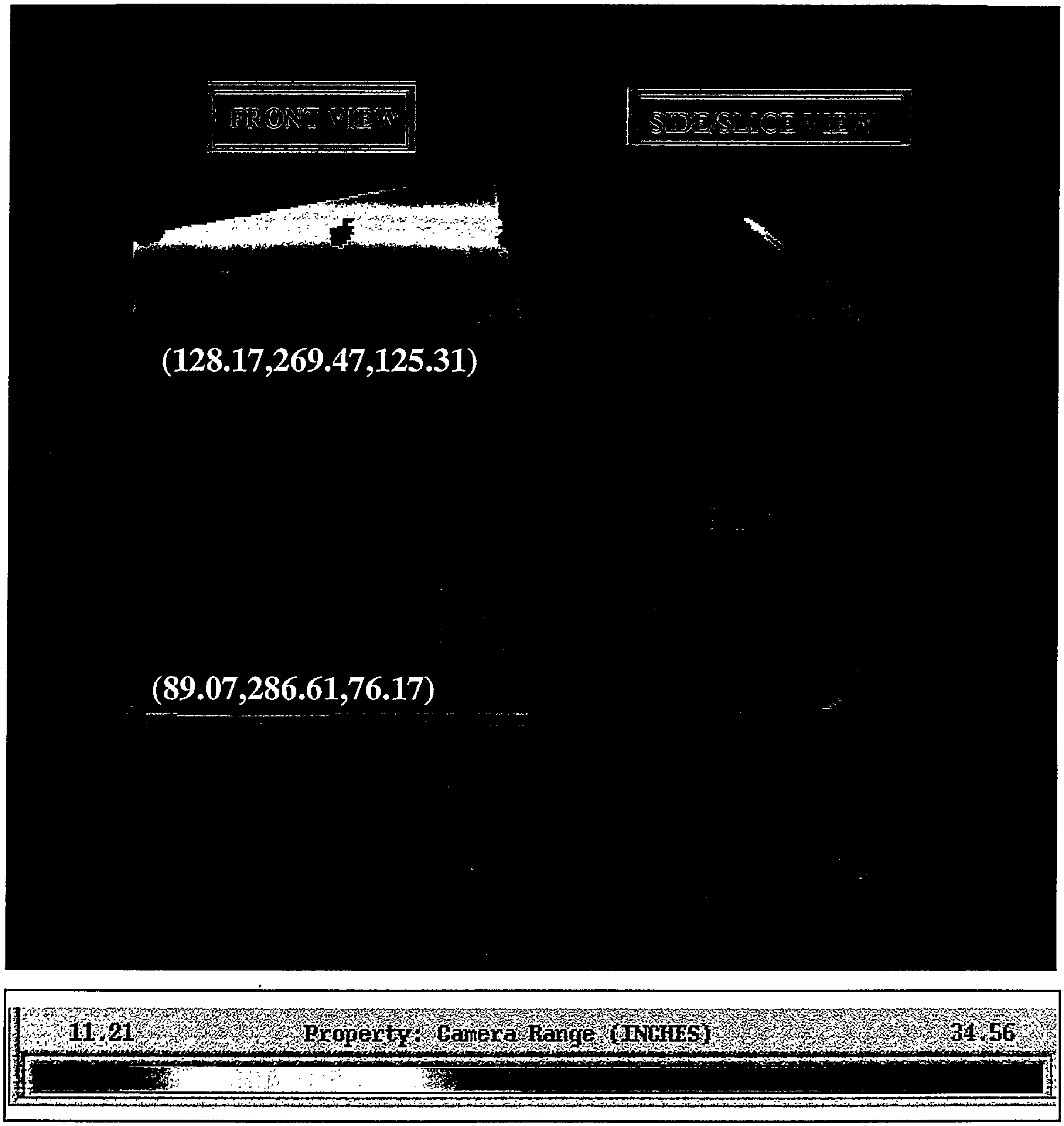

Figure B.3. UST W6 suspect area 2 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #3

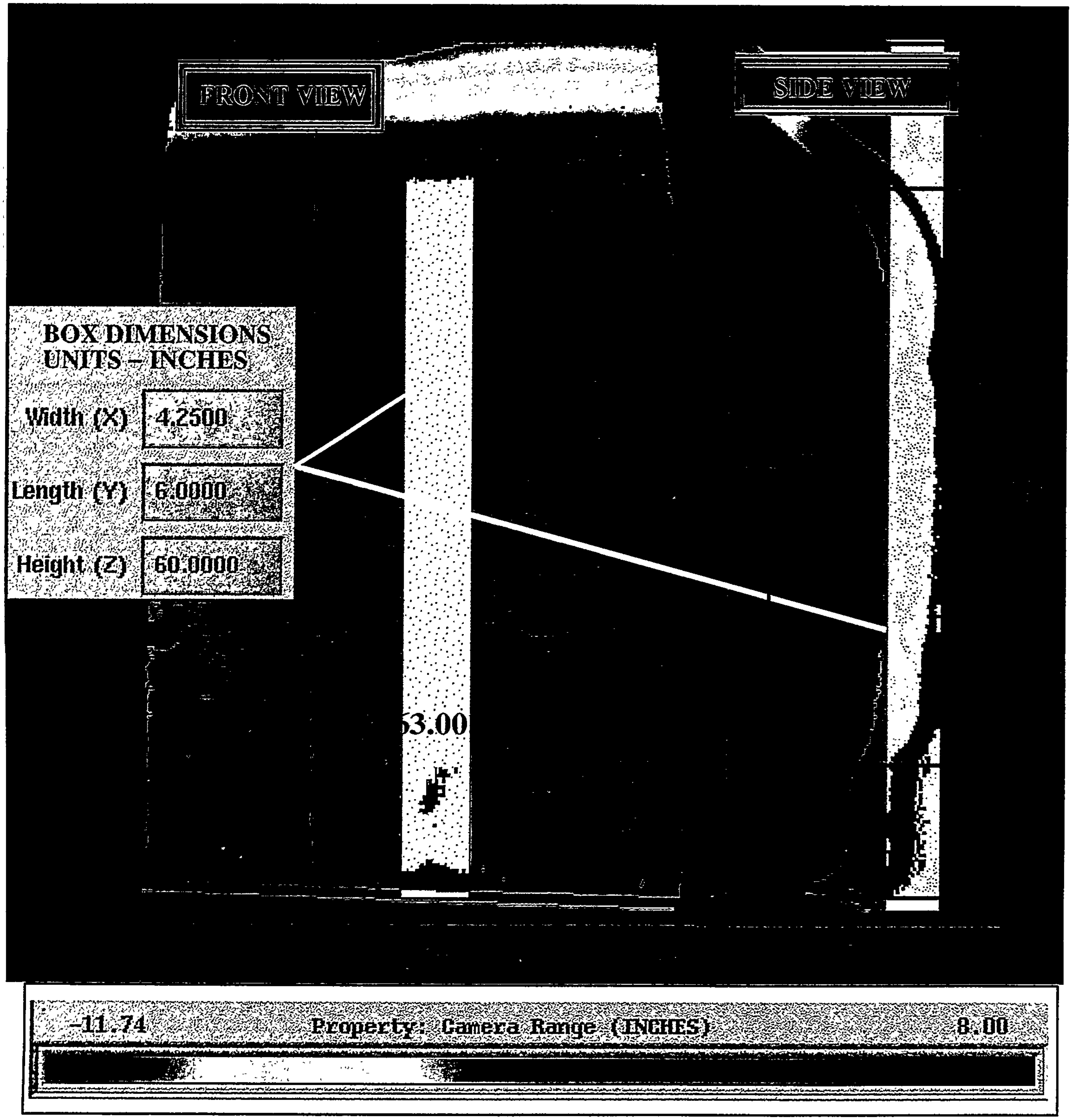

Figure B.4. UST W6 suspect area 3 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #4

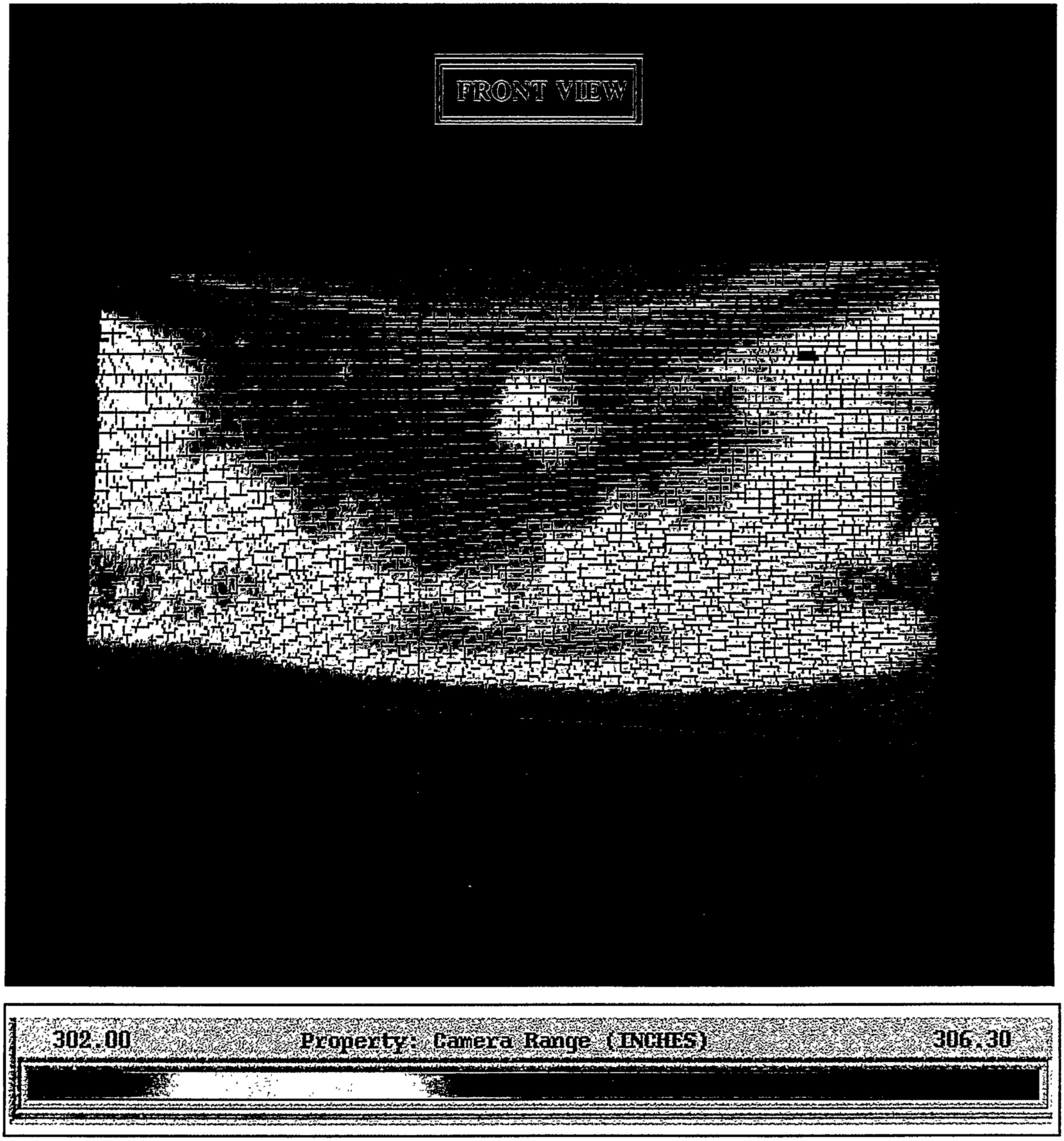

Figure B.5. UST W6 suspect area 4 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #5

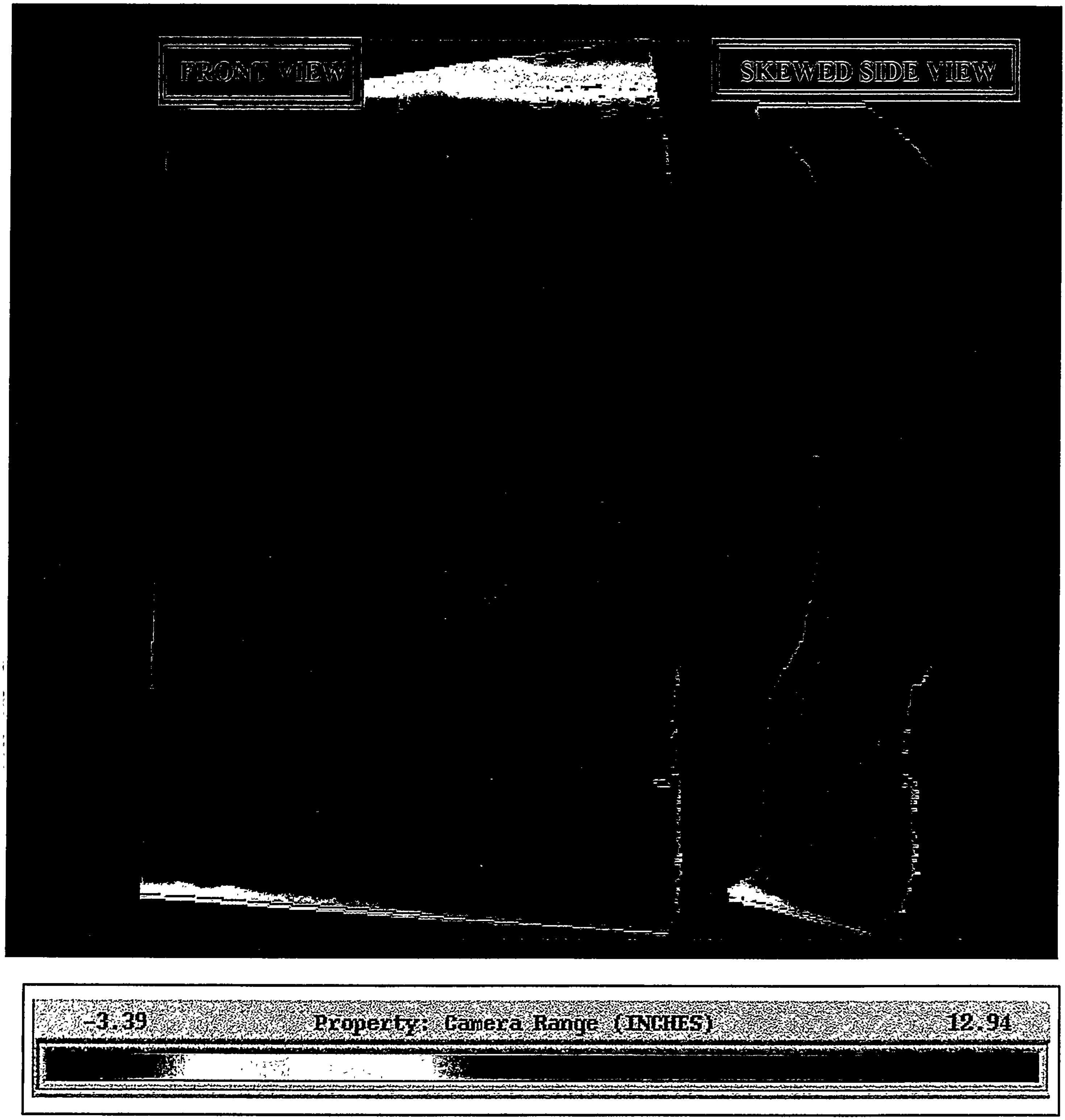

Figure B.6. UST W6 suspect area 5 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #6

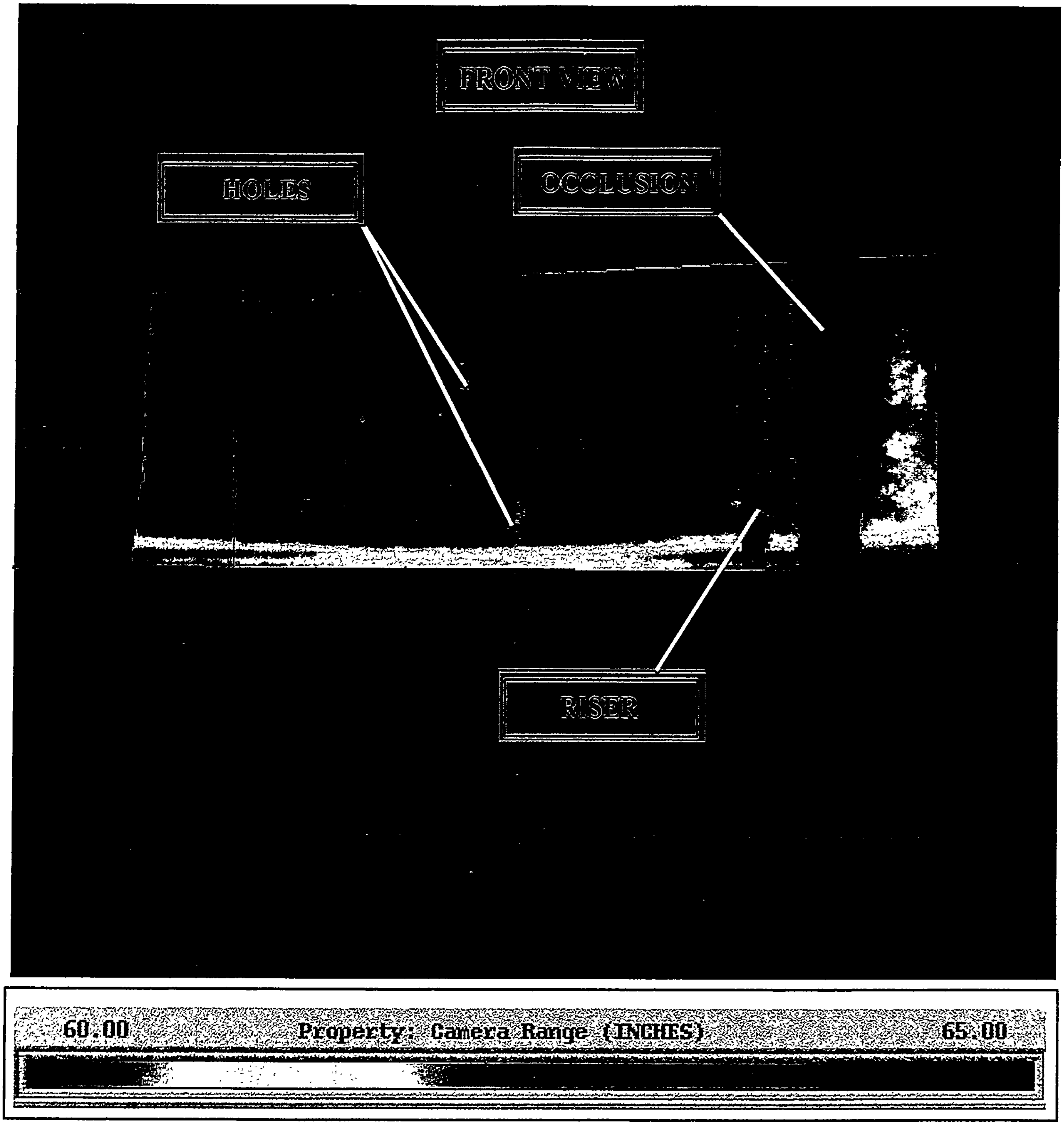

Figure B.7. UST W6 suspect area 6 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #7

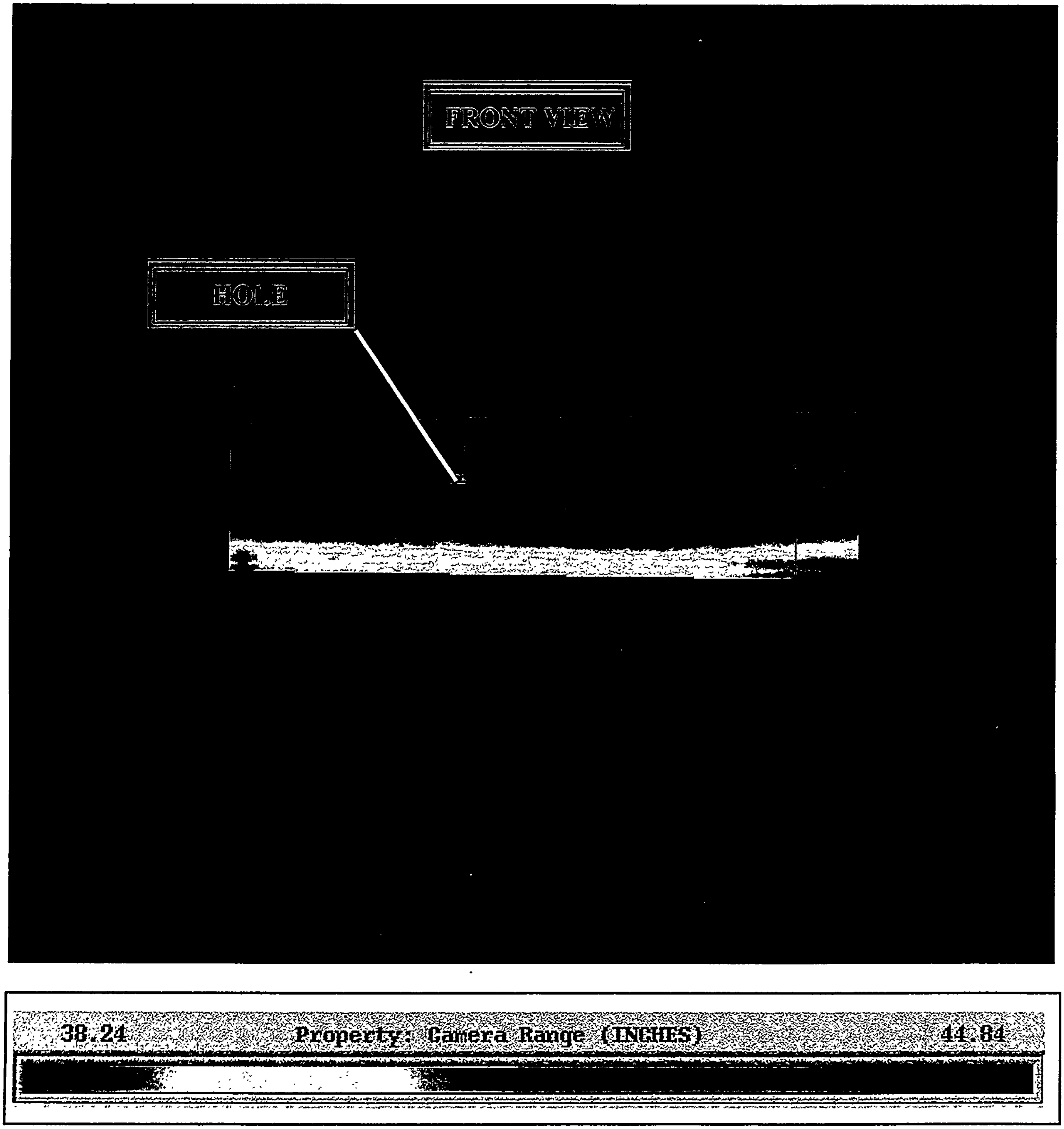

Figure B.8. UST W6 suspect area 7 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #9

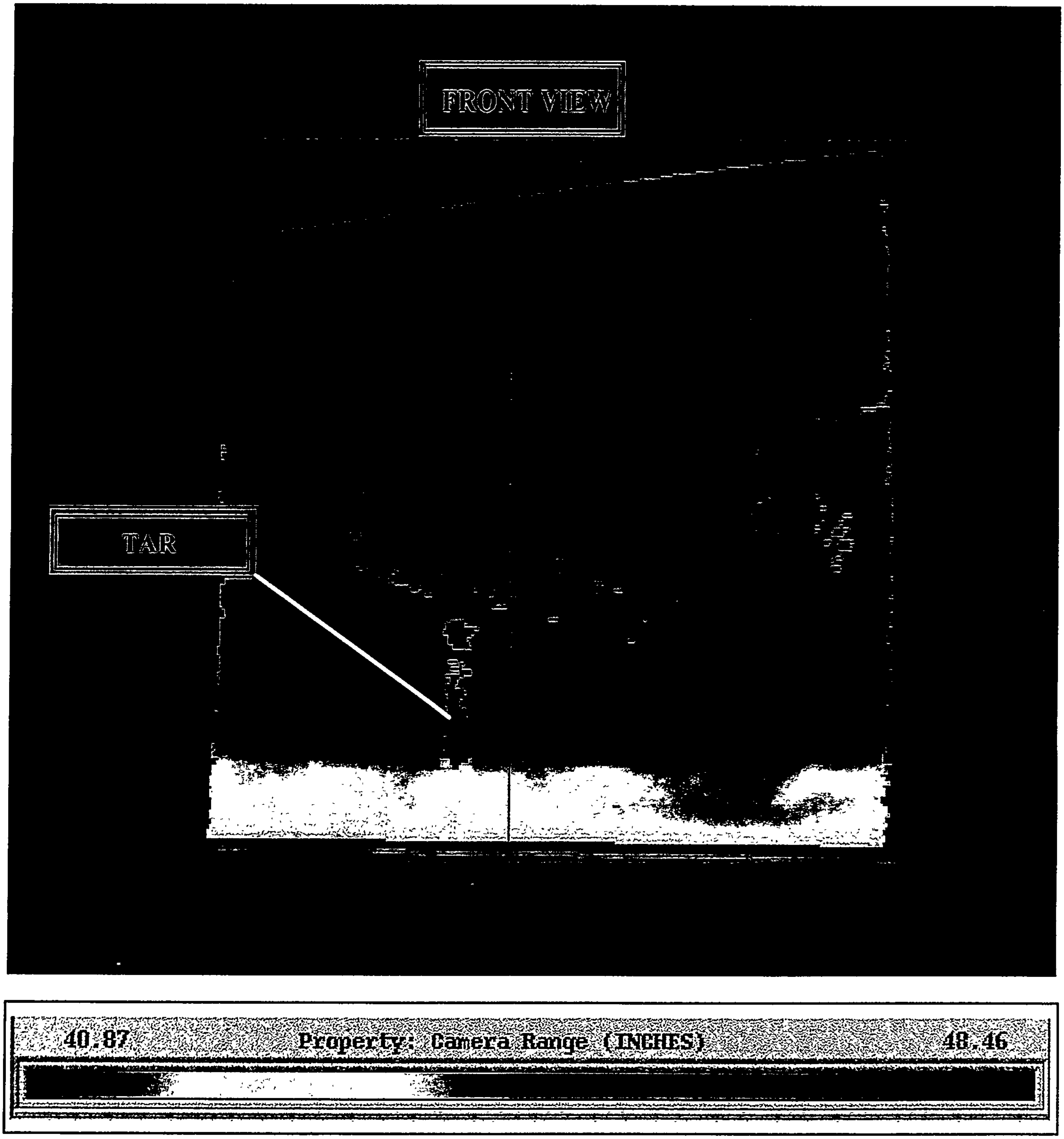

Figure B.9. UST W6 suspect area 9 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #10

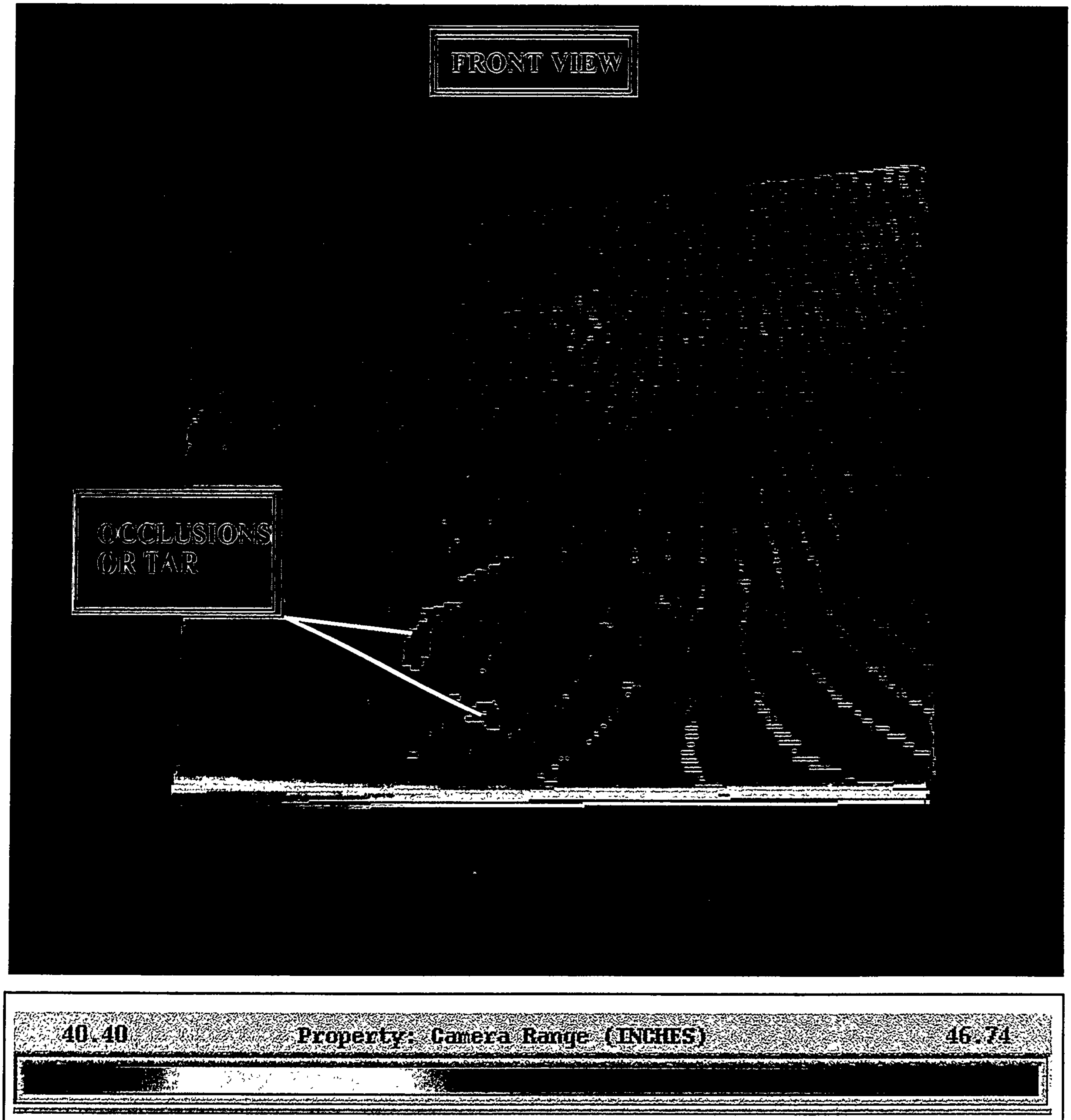

Figure B.10. UST W6 suspect area 10 surface map.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection

W6 Suspect Area #11

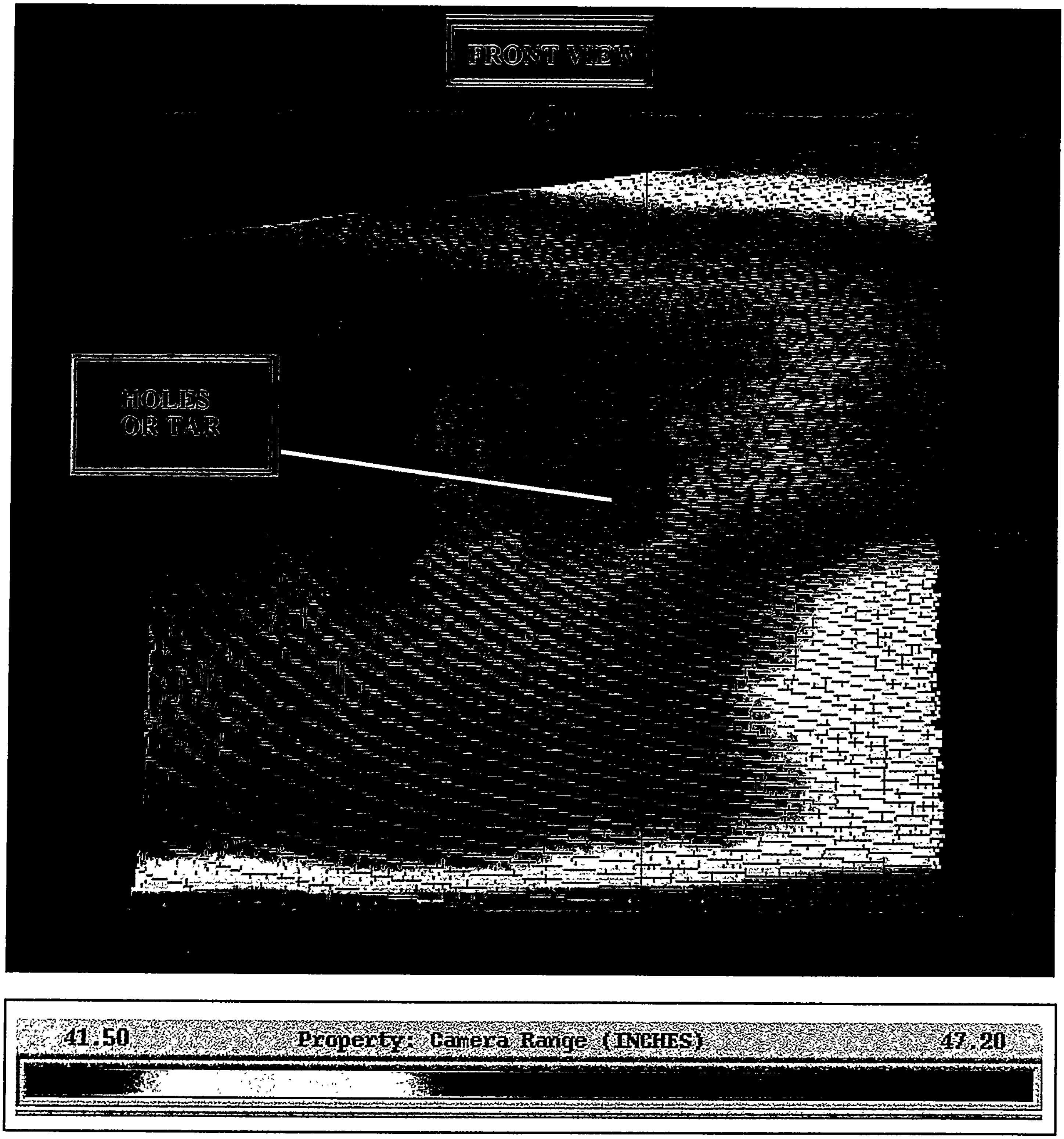

Figure B.11. UST W6 suspect area 11 surface map.

APPENDIX C

W5 SUSPECT AREAS AND RISERS PHOTOGRAPHS

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #1

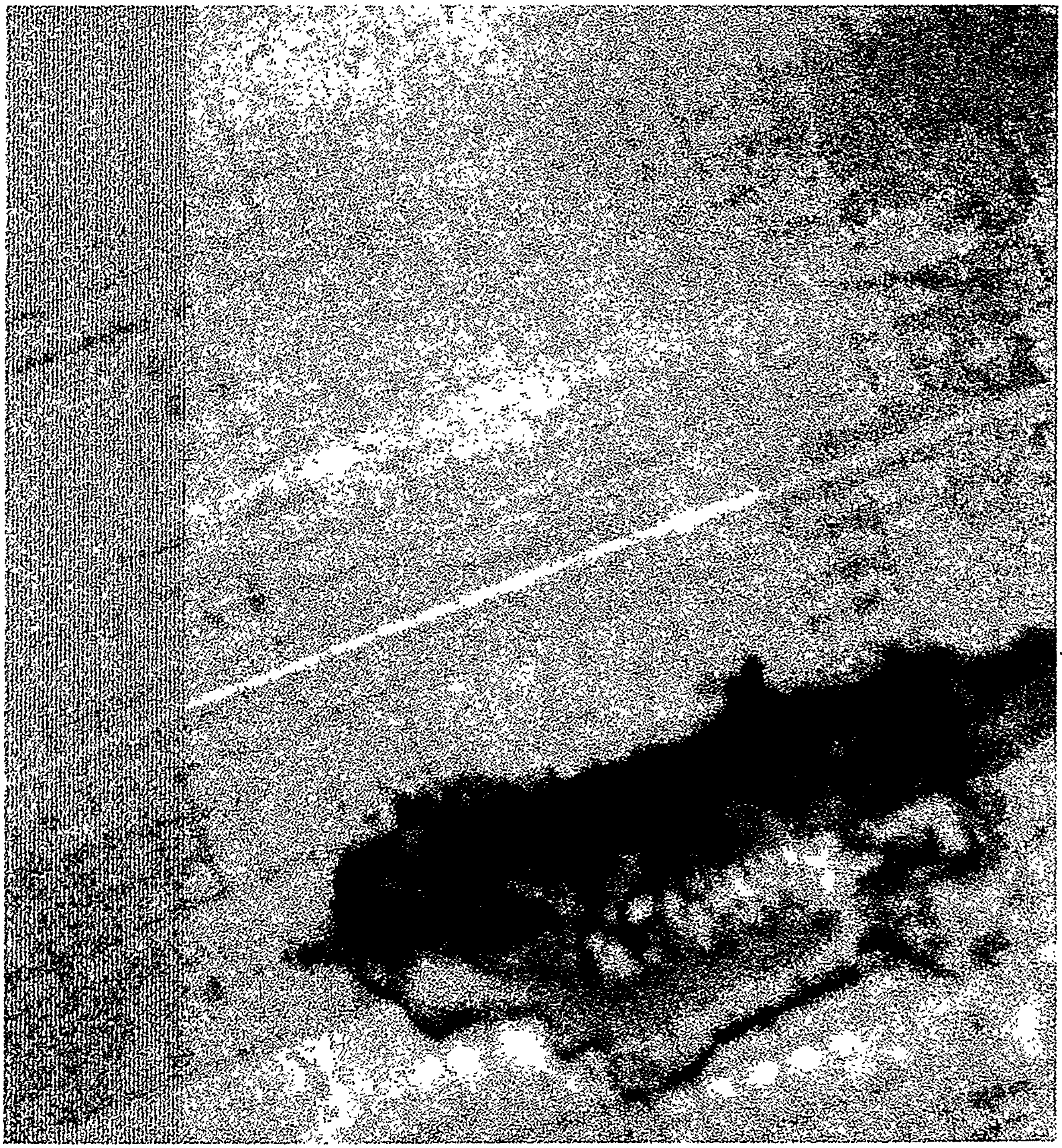

Figure C.1. UST W5 suspect area 1 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #2

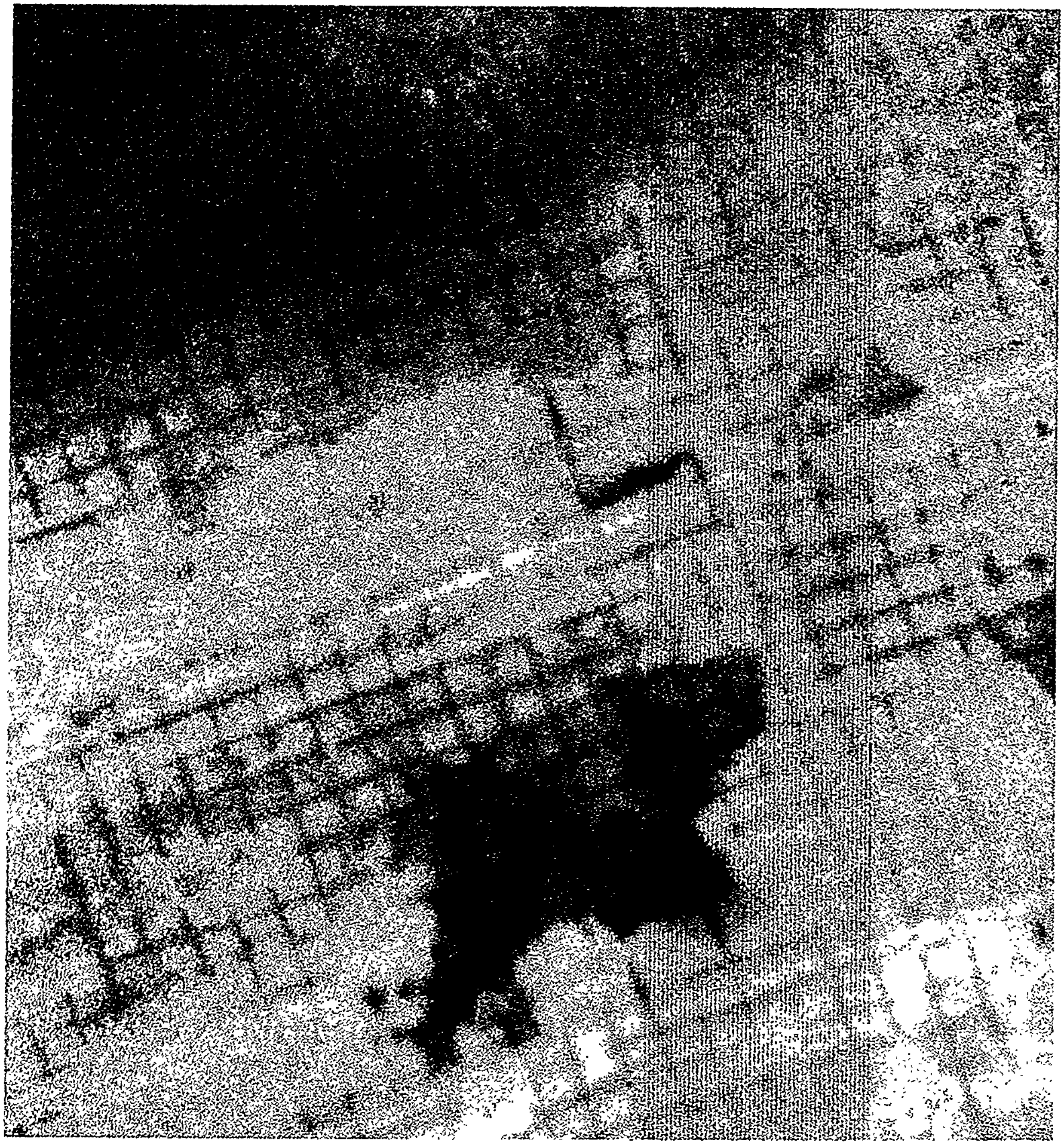

Figure C.2. UST W5 suspect area 2 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #3

Figure C.3. UST W5 suspect area 3 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #4

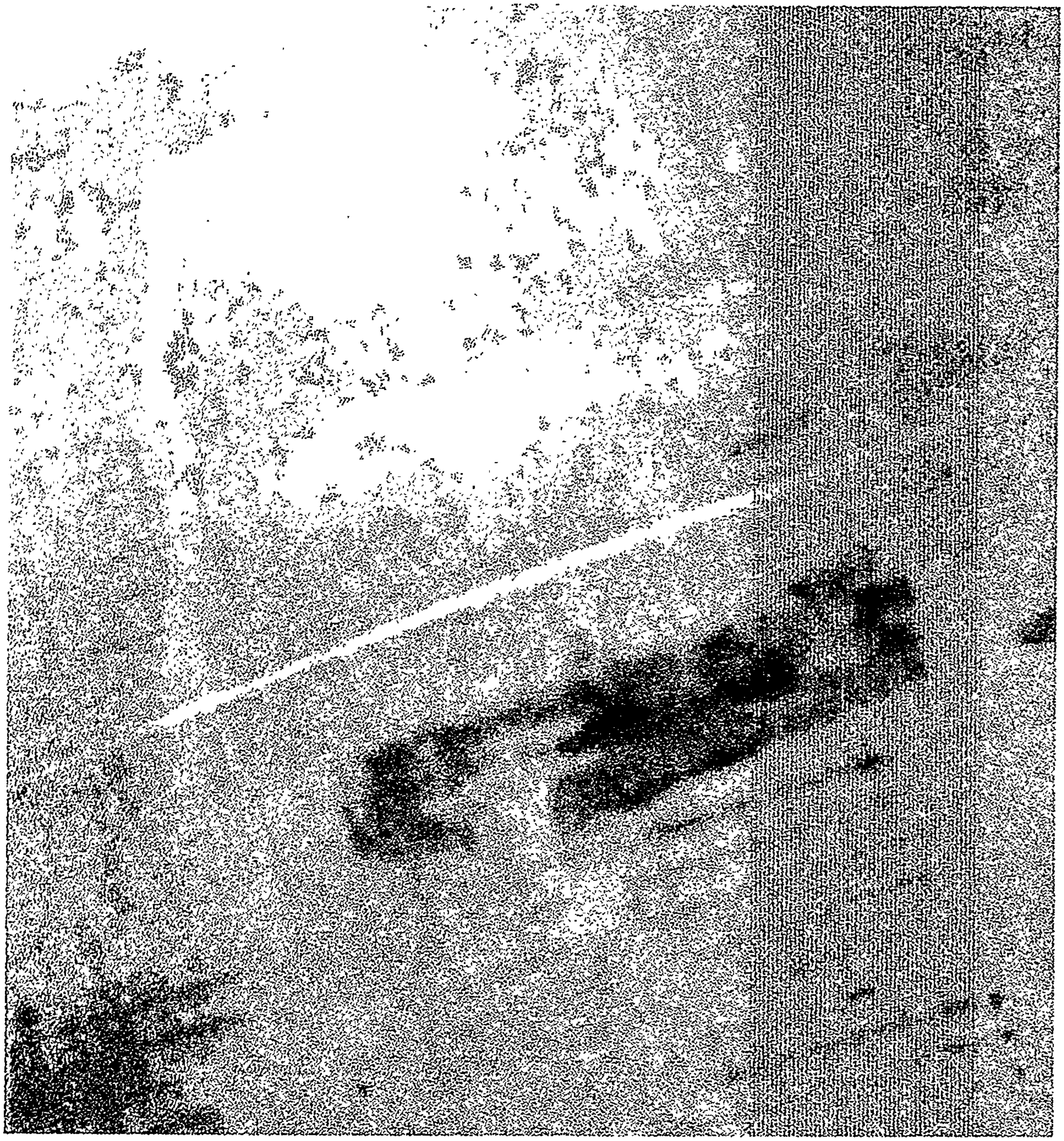

Figure C.4. UST W5 suspect area 4 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #5

Figure C.5. UST W5 suspect area 5 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #6

Figure C.6. UST W5 suspect area 6 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W5 Suspect Area #7

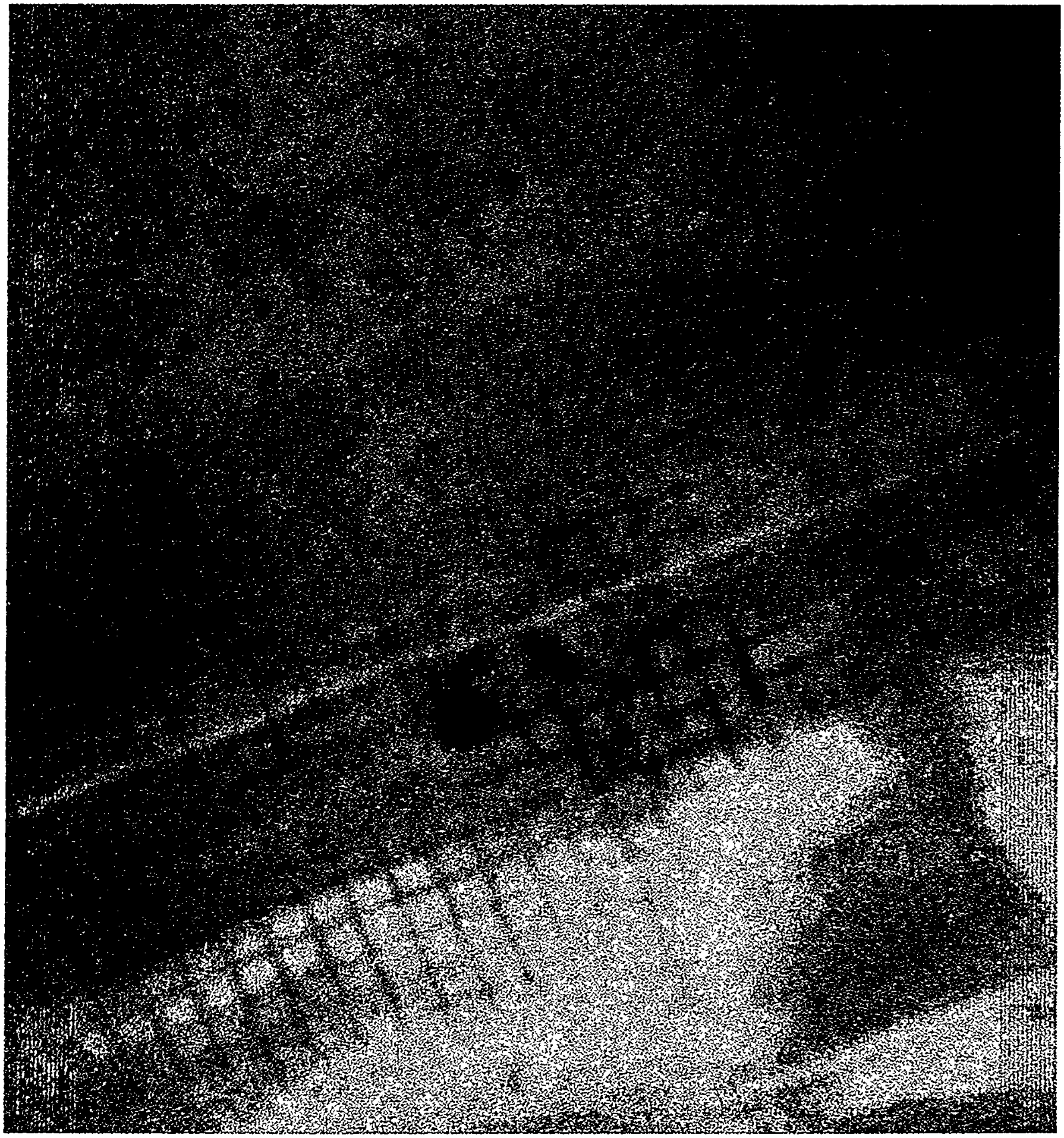

Figure C.7. UST W5 suspect area 7 photograph.

APPENDIX D

W6 SUSPECT AREAS AND RISERS PHOTOGRAPHS

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #1

Figure D.1. UST W6 suspect area 1 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #2

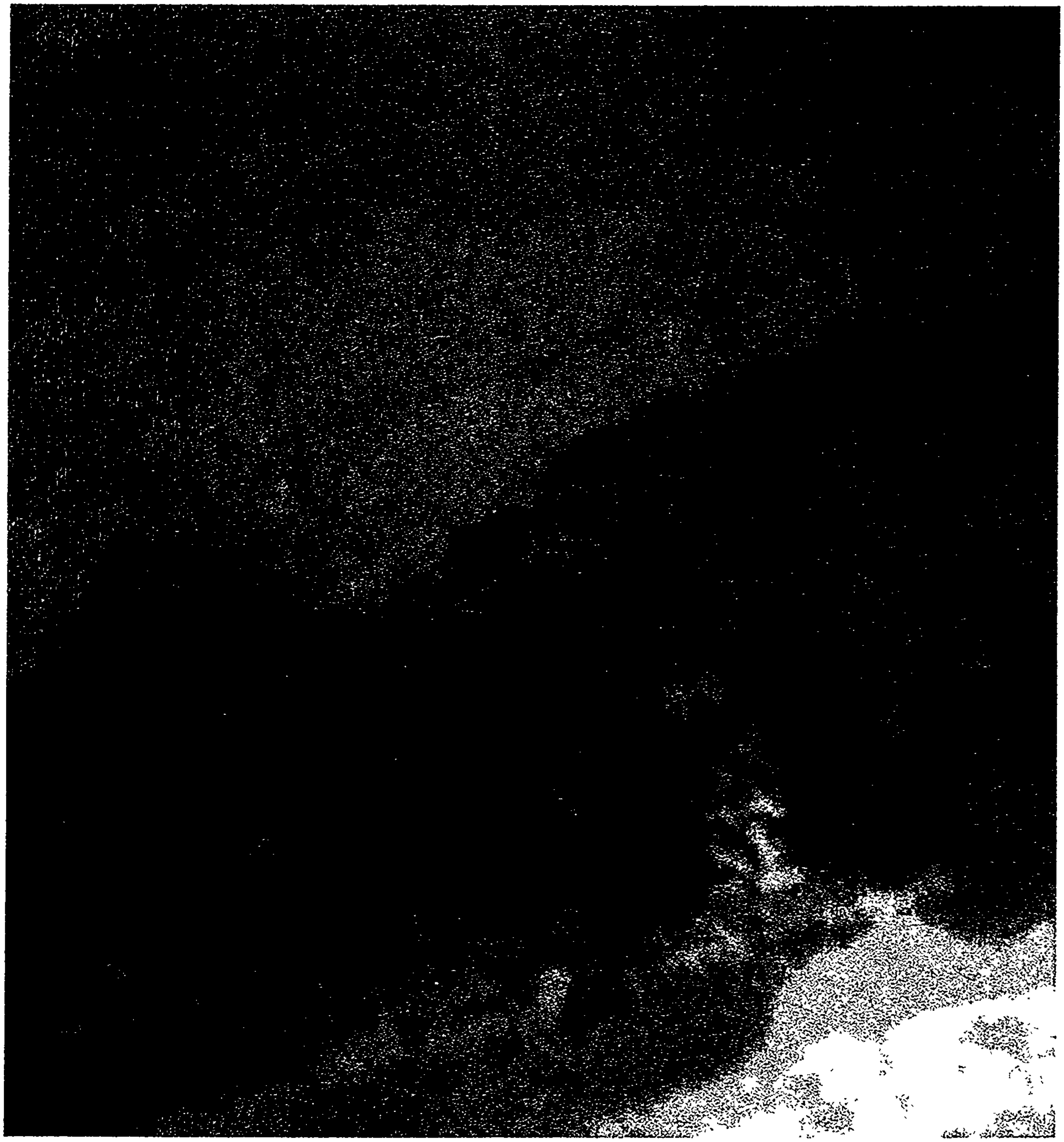

Figure D.2. UST W6 suspect area 2 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #3

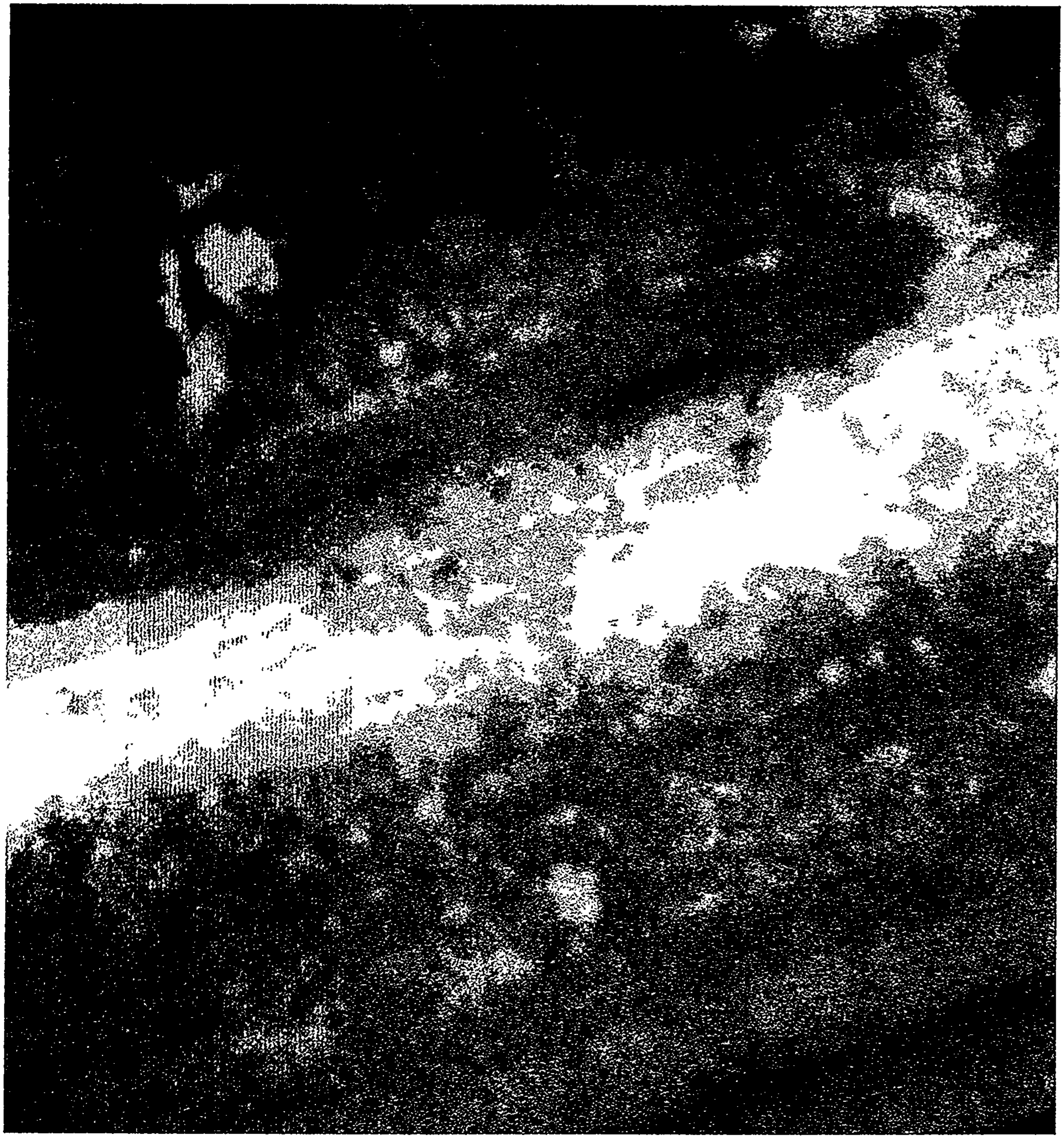

Figure D.3. UST W6 suspect area 3 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #4

Figure D.4. UST W6 suspect area 4 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #5

Figure D.5. UST W6 suspect area 5 photograph.

ORNL South Tank Farm

Underground Storage Tank Wall Inspection

W6 Suspect Area #6

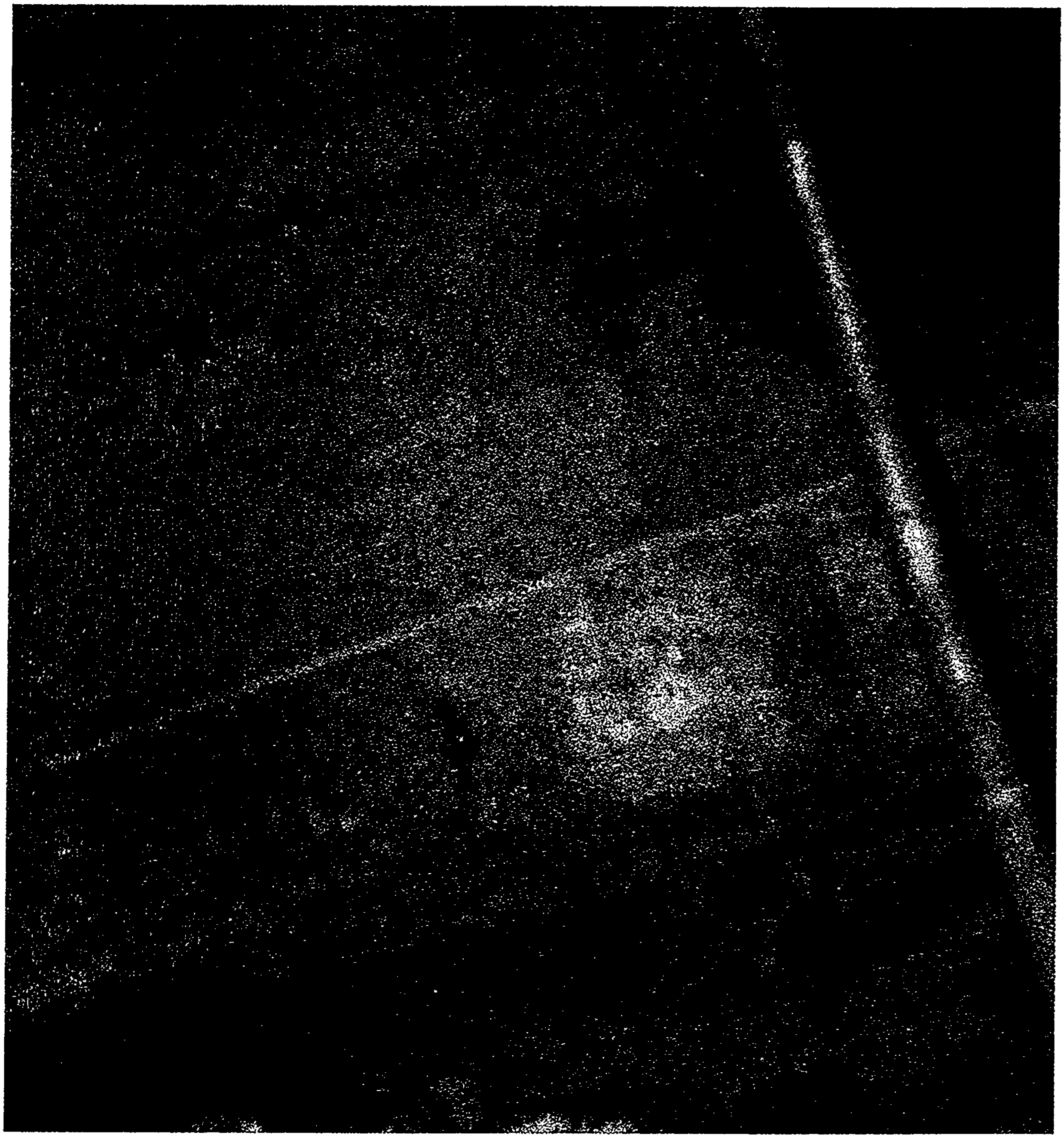

Figure D.6. UST W6 suspect area 6 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #7

Figure D.7. UST W6 suspect area 7 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #9

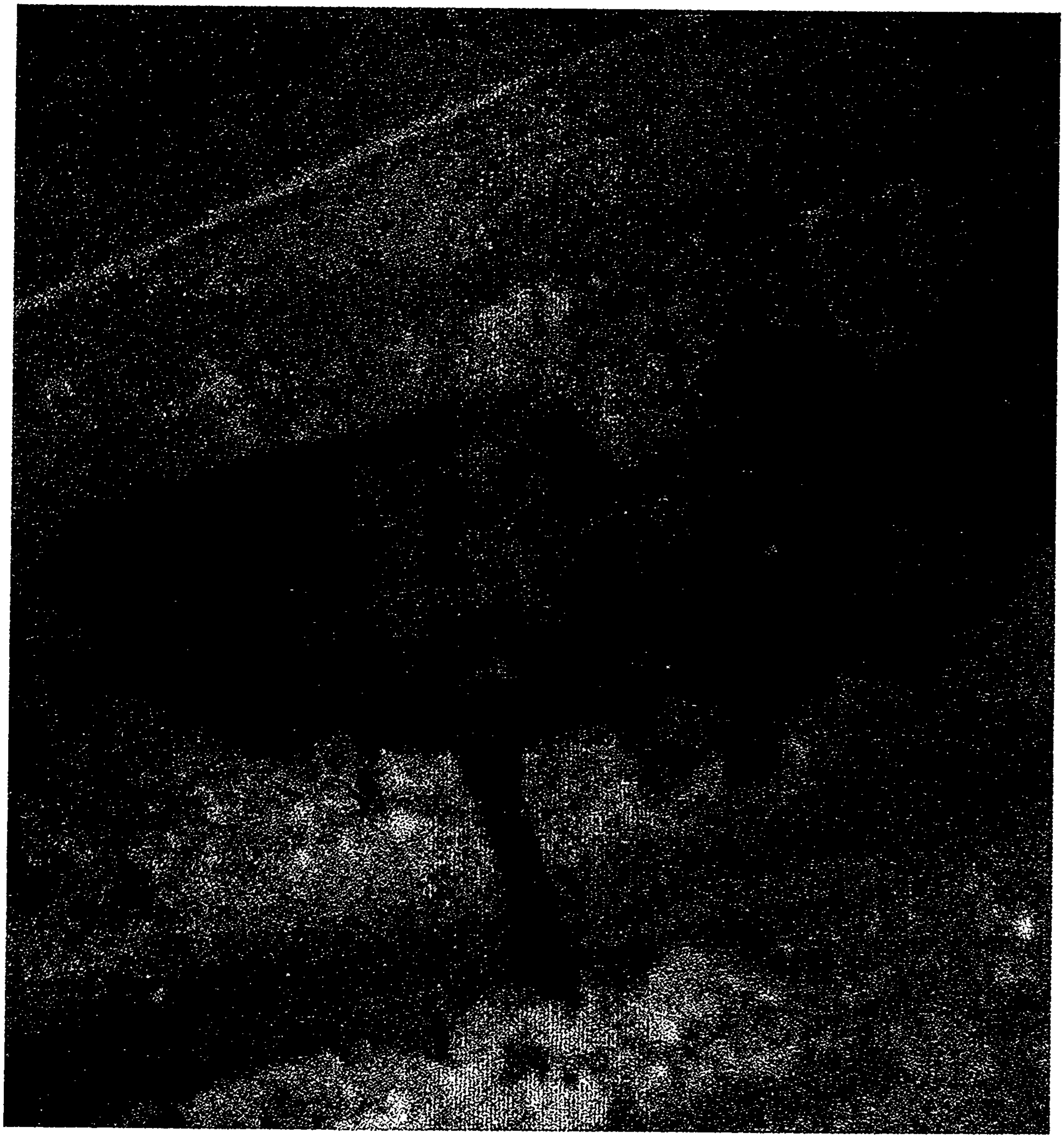

Figure D.8. UST W6 suspect area 9 photograph.

ORNL South Tank Farm

Underground Storage Tank Wall Inspection

W6 Suspect Area #10

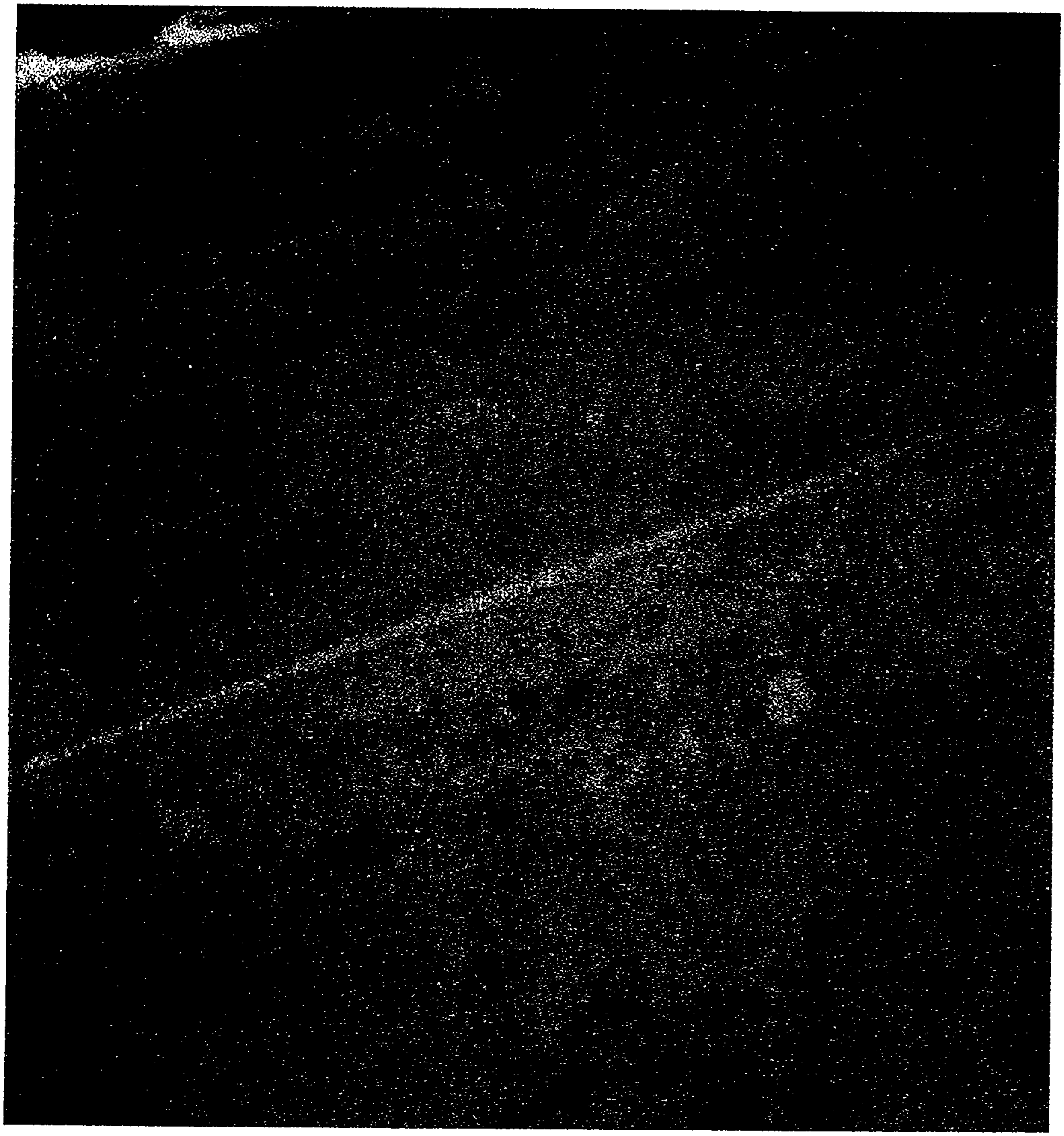

Figure D.9. UST W6 suspect area 10 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #11

Figure D.10. UST W6 suspect area 11 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Suspect Area #12

Figure D.11. UST W6 suspect area 12 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #1

Figure D.12. UST W6 riser 1 photograph.

ORNL South Tank Farm

Underground Storage Tank Wall Inspection

W6 Riser #2

Figure D.13. UST W6 riser 2 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #3

Figure D.14. UST W6 riser 3 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #4

Figure D.15: UST W6 riser 4 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #5

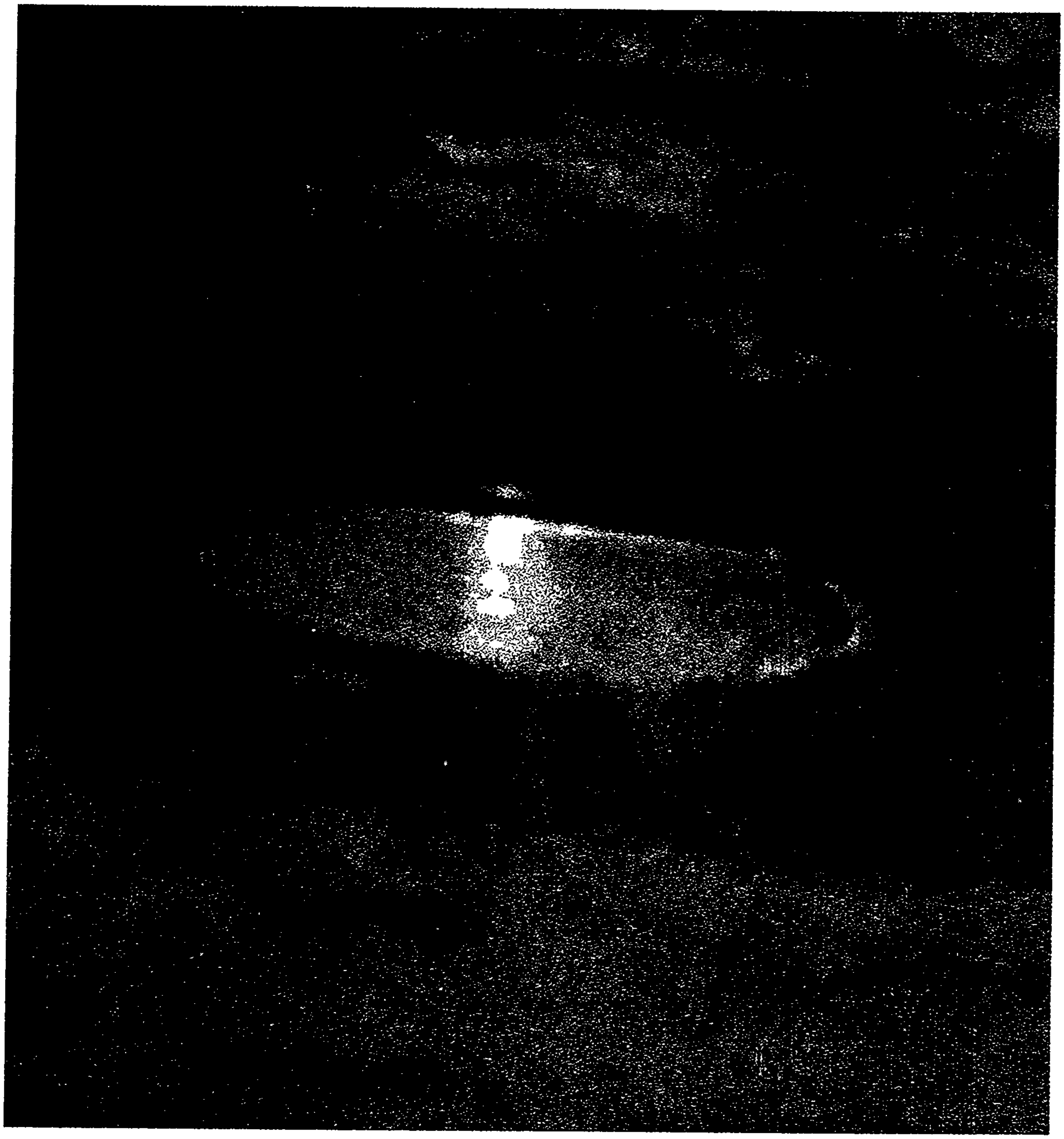

Figure D.16. UST W6 riser 5 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #6

Figure D.17. UST W6 riser 6 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #7

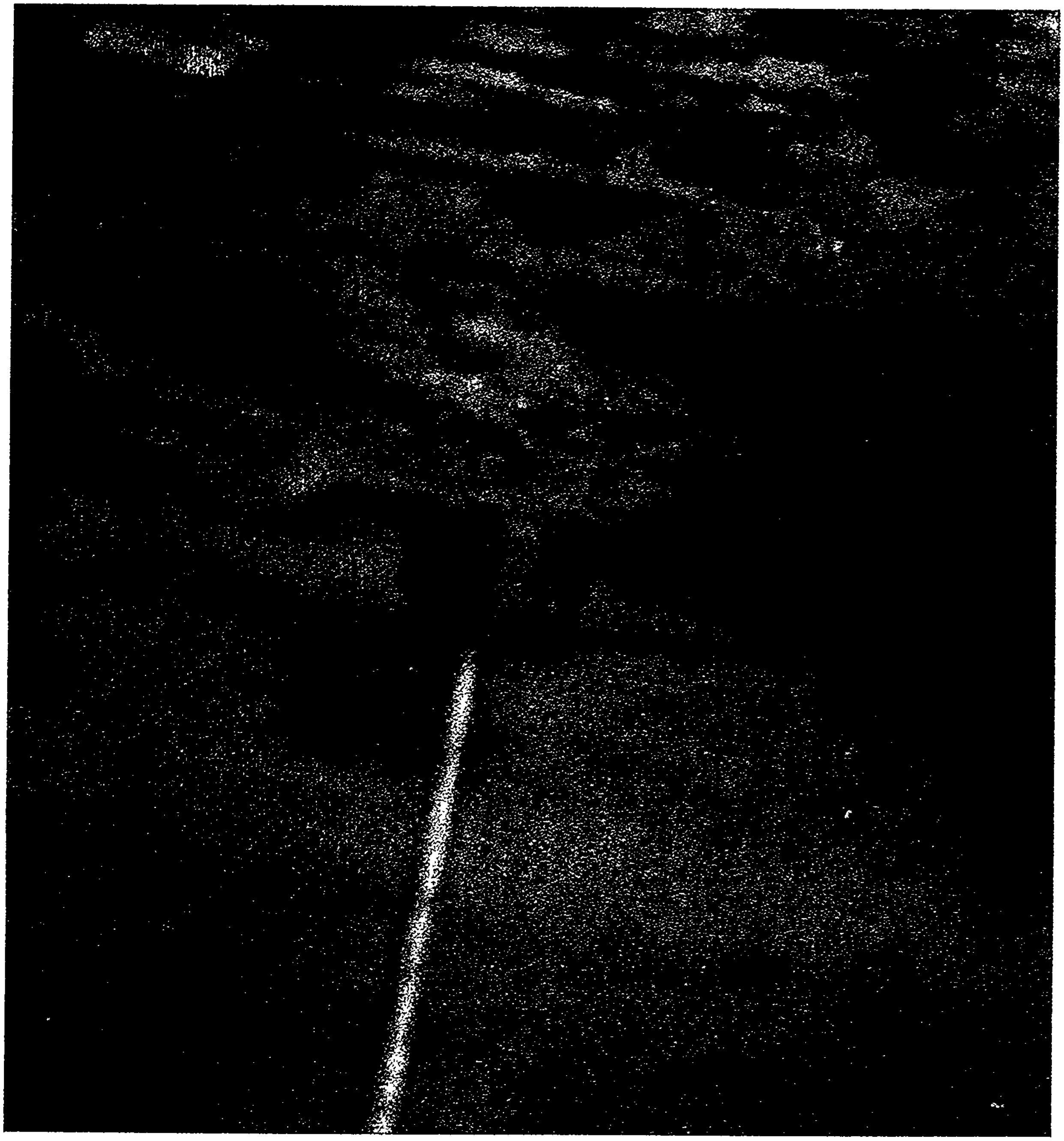

Figure D.18. UST W6 riser 7 photograph.

ORNL South Tank Farm
Underground Storage Tank Wall Inspection
W6 Riser #8

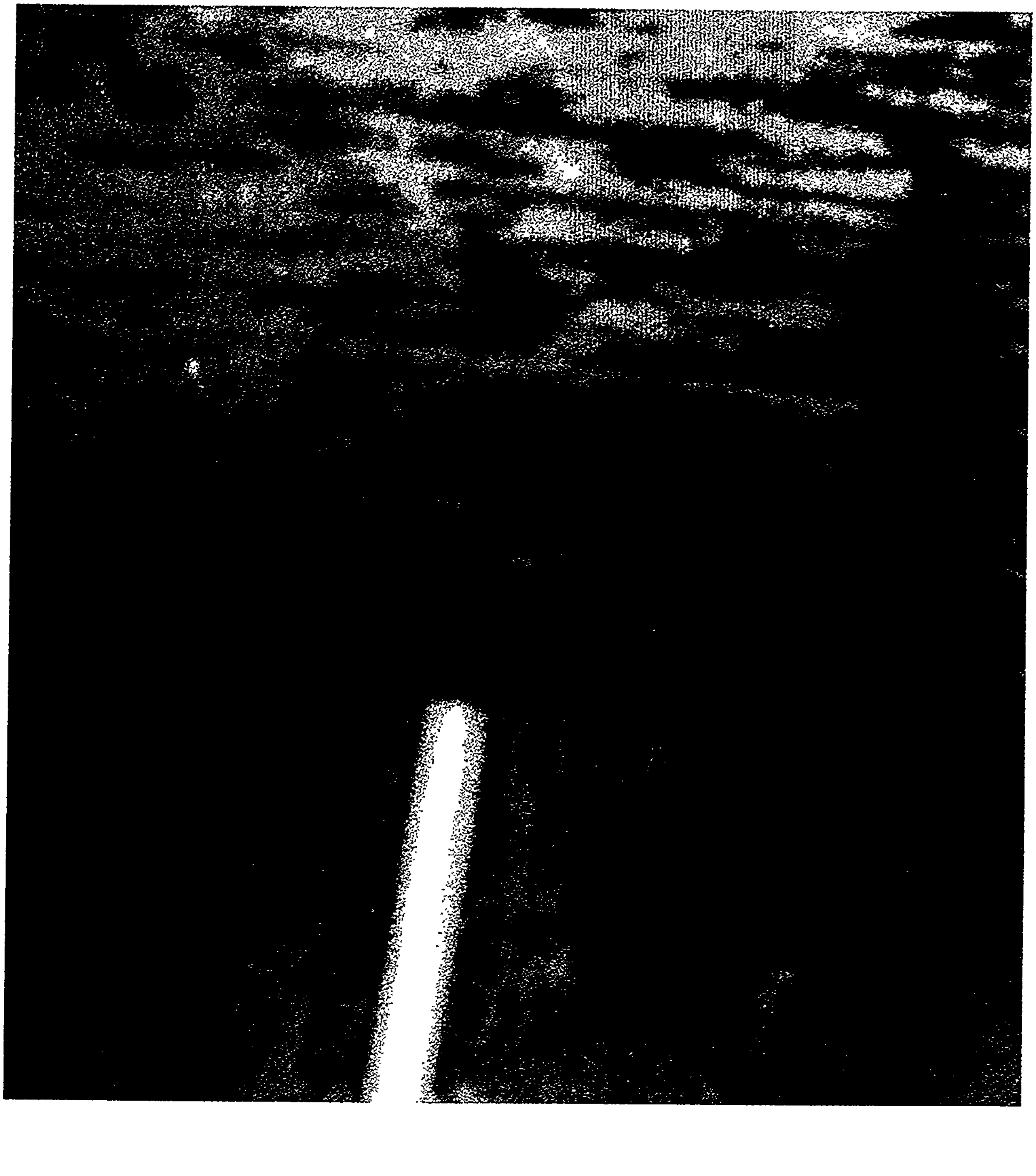

Figure D.19. UST W6 riser 8 photograph.

APPENDIX E

W5 TMS INSPECTION LOGBOOK

Table E.1. South Tank Farm UST wall inspection, 16 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W5	1	Running Pig	2/20	0.25			On first look, this area seemed to be sticking out from the wall. The surface mapped revealed that it is a depression rather than a protrusion.	
W6	2	Petrified Fish Fossil	2/20	0.25			Exposed tar areas mapped to ensure that they were not holes. Even though I did not get measurement data in the tar areas, I was able to determine while watching the laser line sweep through the area that the area was not a hole.	
W5	3	Bleeding Wall/ Carlsbad Caverns	2/20	0.25			Tar bleeding out of the wall. The white marble-like rock in the wall looks like quartz rock that has built up or accumulated over time. Again the ICERVS display shows that this area is actually a depression.	

Table E.1. South Tank Farm UST wall inspection, 16 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W5	4	Battleship Galactica	2/20	0.25			Some of the concrete has been dislodged in a pattern that appears to match the location of the wire mesh. The wire mesh apparently rusted from the water in the concrete and then expânded, cracking the concrete, which then released with time along with the wire mesh. The erosion here has not exposed the underlying layer of tar.	
W5	5	Protruding Wire Mesh	2/20	0.25			Eroding concrete has left exposed wire mesh behind. The erosion has begun to expose the tar underlining. The ICERVS display reveals that some of the wire mesh is sticking out from the wall a few inches. The exposed wire mesh allowed us to confirm that the wire mesh is 2.0 in. by 2.0 in.	

Table E.1. South Tank Farm UST wall inspection, 16 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W5	6	Fish, Bear, and Cave	2/20	0.25			The dark area (that I call the cave) was mapped to ensure that it was not a hole. Again even though the TMS did not get many data points in the tar, the laser line could be seen while sweeping through the area, confirming that the "cave" was not a hole. The white pattern to the right (that I'm calling the bear) maybe an old layer of the original first layer. I'm speculating here in an effort to posit a reason why there is such a large color variation in the concrete here compared with other places.	
W5	7	Small Hole and exposed wire mesh	2/20	0.25			I'm having a little trouble registering the photo and the surface map here. I think I'll have to work on this one some more. All the drop-out areas shown in the surface map seem to have the makings of a tar area as they don't appear to have any cone-like areas showing the beginnings of a penetration in the wall.	

APPENDIX F

W6 TMS INSPECTION LOGBOOK

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	1	Marble-like Ledge	2/22 7:22 a.m.	0.25			I surface-mapped this originally to measure the depths of the cervices in the surface variations. This turned out to be the beginning for the ledge to the 4.25-in. cave-like depression area that exists on the upper ~4 ft of the wall all the way around the tank. None of the crevices were more than 1.5 in. deep.	'/selma/tms/tms_data/w6-hole1.pth', created on 02/22/97 07:22:13 EST #v 0.25, 107.0, 282.8, 65.28, 109.1, 288.5, 81.29
W6	2	Cave-like Depression	2/22 8:22 a.m.	0.25			This is the area just above area #1.	'/selma/tms/tms_data/w6-hole2.pth', created on 02/22/97 08:22:13 EST #v 0.25, 112.0, 281.20, 74.270, 106.2, 267.7, 139.2

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	3	Cave-like Depression and Marble-like Ledge	2/22 8:50 a.m.	0.25			This is a surface map of areas #1 and #2.	'/selma/tms/tms_data/w6-hole3.pth', created on 02/22/97 08:50:13 EST #v 0.25, 146.10, 266.80, 65.75, 137.3, 251.6, 135.20
W6	4	Marble-like Ledge #2 ,	2/22 8:50 a.m.	0.25			Similar to area #1. As it turns out, the ledge and the depression go all the way around the entire tank. I left this in just in case someone wanted to have another high-resolution scan of a "ledge" area.	

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	5	Chalk Outline of Clown	2/22 10:53 a.m.	0.25	−91	23	More cave-like depressions in the walls. This location had what looked like tar marks on it. If so this demonstrates that there is more than one layer of tar (assuming that the missing 4.25-in. area is now missing) or that the tank was made this way, and we are seeing the same uniform wear of the first 2.5 in. of Gunite and wire mesh down to the first layer of tar as we saw in tank W5. The dark tar marks outline the figure of a clown with a large pointy hat. Just to the left of the clown are two large mounds.	

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	6	Two Small Holes	2/22	0.10	-103	20	Two small holes just to the left of the riser and below the laser line.	Scanplan file: '/selma/tms/tms_data/w6-hole6.pth', created on 02/22/97 12:55:13 EST #v 0.1000, 294.200, -73.130, 72.720, 297.900, -74.020, 89.420
W6	7	Small Hole w/Water Stain	2/22 1:14 p.m.	0.10	-164.6	20.6	Small hole with a water stain around it. It did rain on us Thursday and Friday. We had water dripping into the tank from the risers. I didn't see any drips from this hole.	'/selma/tms/tms_data/w6-hole7.pth', created on 02/22/97 1:02:13 EST #v 0.1000, 74.120, -286.100, 69.530, 75.830, -292.700, 79.020

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	8			0.25	-42	17	Didn't map area 8. This was on the 180° pan angle and the TMS software as well was at the limit switch on the pan motor (both of which prevent the system from going more than ±180°). There is nothing new here, just more marble-like stone on the ledge that looked like it was pretty jagged.	'/selma/tms/tms_data/w6-hole8.pth', created on 02/22/97 1:02:13 EST #v 0.2500, -4.212, -298.600, 101.100, -4.179, -300.900, 117.400
W6	9	Dripping Tar and Exposed Wire Mesh	2/22 1:48 p.m.	0.25	-42°	17°	Exposed tar and wire mesh in the cave-like depression area of the upper portion of the wall. So either the tank was constructed with a depression in the upper 4 ft or there is more than one layer of tar and wire mesh.	'/selma/tms/tms_data/w6-hole9.pth', created on 02/22/97 1:49:13 EST #v 0.2500, 206.200, 223.900, 70.470, 210.300, 228.500, 115.700

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	10	Spalling Concrete (shallow)	2/22 3:36 p.m.	0.25	−93.37	12.88°		'/selma/tms/tms_ data/w6- hole10.pth', created on 02/22/97 2:24:13 EST #v 0.2500, 302.100, - 20.750, 76.900, 304.600, - 20.830, 116.800
W6	11	Spalling Concrete (shallow) and exposed wire mesh	2/22	0.25	−147	12/20		'/selma/tms/tms_ data/w6- hole11.pth', created on 02/22/97 3:37:13 EST #v 0.2500, 159.900, - 252.300, 76.580, 181.400, - 286.400, 113.800

Table F.1. South Tank Farm UST wall inspection, 11 April 1997, Gary A. Armstrong

Tank	Suspect area	Name	Date	Resolution (inches)	Pan angle (degrees)	Camera angle (degrees)	Description	Scan plan file
W6	12	Spalling Concrete (shallow) and exposed wire mesh	2/22 4:03 p.m.	0.25	0	13	There may be a problem here. It appears as if the laser line would not scan up This data looks very suspicious? The surface map data shows an ~4-in. step discontinuity. The surface map is curving like it's mapping the dome, but the dome typically starts at 122 in. The photo doesn't show an obvious step discontinuity, and the dome does not appear to be in the photo either. To look at the dome-wall interface requires a camera angle of about 10.5°. I don't think this scan and the photo go together? It looks as if I got part of the dome at the home position. But the *Z* values are too low for the dome. I'll look at the big map to see if I got this kind of a map around the dome. If I didn't. I think I'll consider this a fluke. I didn't see anything like this in the home area of the w6-quarter1.map data	'/selma/tms/tms_data/w6-hole12.pth', created on 02/22/97 4:03:13 EST #v 0.2500, 4.164, 307.100, 93.580, 5.08, 368.800, 102.900

APPENDIX G

W5 VIDEO INSPECTION LOGBOOK

NOTE: During the observations noted in the following tables, the camera was looking through a redirection mirror. As a result, left is right and right is left, so apparent clockwise (CW) motion is really counter-clockwise (CCW) motion. The following tables contain descriptions of what you would see in the video, so you have to compensate for the effect of the mirror.

Table G.1. Log of South Tank Farm mapping campaign

Time (hours:minutes:seconds)		Suspect area	Description
Start	Stop		
Tank W5, videotape 1 of 2, G. A. Armstrong			
0:00	0:02		CCW pan
0:02:27	0:02:40	3	You get a brief look at it. Good look at what looks like tar bleeding out of the walls
0:02:58		3	Risers—one of which is agitating the liquid below
0:02		3	Continue CW pan
0:04:34	0:37:30	4	
0:37:50			Initialization (return to home)
0:40:34	0:40:40	2	Quick look at the 'Petrified Fish Fossil'
0:41:11	0:41:23	3	You get a brief look at it. Good look at what looks like tar bleeding out of the walls.
0:42:50			Agitating riser/sensor (Robert Shaw)
0:44:30	0:49:00		Manual sweep of laser line through a tar area. Looks like a helicopter but I didn't scan it with the TMS. You can see that there is not much structure change with the laser line so the area is not very deep.
0:46:08	0:47:08		Lights out—demonstrates the change in reflectance between the concrete and the tar
0:48:49			Scanning up a portion of the wall
0:49			CW to Home
0:50			Back to mid-portion of wall and then CW pan
0:51	0:52:36	5	Manual scans, lights out looks like a real scan.
0:54:23			Lights on
0:55:39	1:04:30		Lights out—looks like a real scan
1:04:30	1:13:50		Lights on
1:14			Back to home, about 2–3 ft above the water level
1:17:13	1:18:44		Lights out, manual scan—looks like tar
1:18			Lights on, CW
1:20:06		6	The cave is suspect area #6. Here we look at the fish.
1:21:36		6	Polar bear—lights out, manual scan
1:23:09		6	Cave
1:32:30		6	Lights out—looks like a real scan
1:48		6	Lights on
Tank W5, videotape 2 of 2, G. A. Armstrong			

Time (hours:minutes:seconds)		Suspect area	Description
Start	Stop		
0:00	0:13:52	7	Conclusion of mapping
0:38:50		7	Initialization
0:40:30	0:44:30	"The Eye"	This is a little higher up than the rest, say about 6–7 ft above the water level just to the left of the "Cave" or area #6. Manual scan of the area looks like a 1–2-in.-deep-depression (did not scan with the TMS)
0:45:50	0:47:50	"The Cave" 6	Suspect area (Abe Lincoln) just to the left of 4-in. pipe near "The Cave." It looks like a bust of Abe Lincoln.
0:50			Inspection of area to the right of the 4-in. pipe
0:51:30			Riser penetration in the dome
1:02:22	1:12:01		Lights out—possible real map of the riser, this may be the northeast riser?
1:13:17			New suspect area ("Kickball in a Sewer Tank")
1:13:35	1:14:18		Lights out—manual scan
1:14:50			Continue panning
1:15:22	1:15:57		Lights out—manual scan of area just to the right of the last area
1:19:39			Good look at wall-dome interface
1:20			Lights out just briefly?
1:21:30	1:33:35		Leave wall-dome interface going down and then lights off
1:33:35			Pan CW
1:34:31			Up and down at the "helicopter." Manual scan
1:35	1:36:37		Lights off, manual scan of "helicopter." You can see the laser line through the helicopter. It looks very straight so this could not be a very deep depression, probably 1–2 in. at most
1:38	1:39		CW Pan to home (not an initialization, however). In the home position, you can see the pig's tail just to the right.
1:39	1:43:25		Sit at home
1:43:25			CCW pan just above the water level. You pan by the "Petrified Fish" (#2), "Bleeding Wall" (#3), and "The Starship" (#4)
1:47			Stop at the "Helicopter"
1:47			CW pan
1:47:55	2:02:57		Stop at agitator sensor (Robert Shaw)

APPENDIX H

W6 VIDEO INSPECTION LOGBOOK

NOTE: During the observations noted in the following tables, the camera was looking through a redirection mirror. As a result, left is right and right is left, so apparent clockwise (CW) motion is really counter-clockwise (CCW) motion. The following tables contain descriptions of what you would see in the video, so you have to compensate for the effect of the mirror.

Table H.1. W6 video inspection logbook

Time (hours:minutes:seconds)		Suspect area	Description
Start	Stop		
Tank W6, videotape 1 of 3, G. A. Armstrong			
0:00	0:02		CCW pan
0:00:00	0:03:12	1	Close to home. This is the marble-like area that I found about 6 ft up all around the periphery of the tank. I could tell from the laser line that this area was jagged, so I mapped it in an effort to find the depth of the variations
0:03:28			Lights out—manual scan
0:05:40			Lights on—manual scan of laser line
0:08:39			Go to Home—initialization of TMS
0:09:12		2	Down to water level and CW. Manual scan of laser line over marble-like area
0:14:31	0:35:50		Lights out—surface map of area
0:41:50			Up to ceiling
0:45:54			View of riser #1 (don't have surface map of riser #1)
0:47	0:52:25	3	Surface map
0:56:10			Home (EEB PC crashed)
0:57			Surface map
1:16:28			Lights on—just below riser #1. Good view of wall-dome interface
1:18:29			Down to the water
1:19			Back up the wall (tar visible)
1:22:17			Home. Good view of the dome. The dome in W6 looks very clean. There appears to not be much tar and the dome is a lot smoother in W6 than in W5
1:25:39			Down to water and then CW
1:27		4	Lights out. This is another view of the marble-like area around most of the periphery of the tank about 6 ft up the wall
1:27:35			Lights on
1:30			Home
1:31			Down and CW along marble-like layer around the tank
1:33:57			Looks like a measurement of the water level
1:36:45			Up to ceiling. There is a very clean and smooth section of the wall here
1:39:47	2:03:09		Surface map
Tank W6, videotape 2 of 3, G. A. Armstrong			

Time (hours:minutes:seconds)		Suspect area	Description
Start	Stop		
0:00	0:02:22		Tank wall with thin riser on the left
0:02:46			CW—large white marble-like area
0:04			Manual scan of laser line over large marble-like area
0:06:43			Home—initialization
0:08:12			CW—Apparently there is some tar on the ceiling
0:08:33			Down to water level
0:09:49			Up to dome
0:11:29	1:25:43		Surface map
1:27			CW
1:32	1:59:29	6	Surface map. There is a riser to the left of the suspect area. There are two small holes visible in the middle of the area. It looks as if the concrete around the wire mesh has let go, exposing the wire mesh and the next layer of concrete
2:02:14			Home
Tank W6, videotape 3 of 3, G. A. Armstrong			
0:00	0:01	6	
0:01			CW
0:01:42			Large white marble-like area
0:03		7	Small hole w/water stain in marble-like area just below the tar. Most of the water stain appears to be to the right of the hole
0:04:59			CW
		8	Suspect area 8 could not be mapped; multiple attempts; all failed
0:06:32	0:09:15		Up to tar area with wire mesh evident in the concrete above the tar. This appears to be an area where the concrete, the wire mesh, and most of the tar have worn away
0:09:22			CW
0:09:40	0:13	9	Exposed tar section with tar running down the wall
0:13			CW
0:14:33			Riser
0:14:50		10	Small exposed area of wire mesh. Possible hole
0:16:20			Home and then CW
0:16:39			Back to Suspect Area #10
0:17:08		11	Exposed wire mesh. White stain on the wall
0:19:34			Tar area
0:19:40		12	Just below the home location
0:20:14			Tar area
0:20:29			CCW
0:22			Risers
0:22:29			Home
0:23:20		12	

Time (hours:minutes:seconds)		Suspect area	Description
Start	Stop		
0:23:20			CCW
0:25:02			Risers
0:25:35			CW pan back to home, mid-level on the wall, stopping at Suspect Area #12
0:34:20			Home
0:35:08			Down and CW, slow steady pan
0:36:20			Stop at 180°
0:37:04	0:37:50		CCW—slow pan back to home
0:37:50			Home
0:39:12	0:40:43	Riser 1	
0:40:48		Riser 2	
0:42:03	0:42:49	Riser 3	
0:43:04		Riser 4	Two or three risers here, one of which is a peripheral riser
0:44:13			CW back to opposing peripheral riser
0:45:20	0:46:26	Riser 5	Dripping water
0:46:58		Riser 6	Robert Shaw agitating sensor
0:48:15	0:48:25		CW by two more risers
0:48:36			CCW—slow, steady pan at wall-dome interface
0:49:49			CCW—slow, steady pan
0:50:58			CW—slow, steady pan
0:52:05			Home and down
0:53			CCW mid-level pan, slow and steady
0:54			Up to top of dome, losing focus badly, and back down to the water
0:55:00			CW—slow and steady, just above the water level
0:56:10	0:57:04		CW—slow and steady, just above the water level
0:57:13	0:58:09		CCW—slow and steady, just above the water level
0:59:11			Up and off

APPENDIX I

TMS DIAGRAMS AND PHOTOGRAPHS

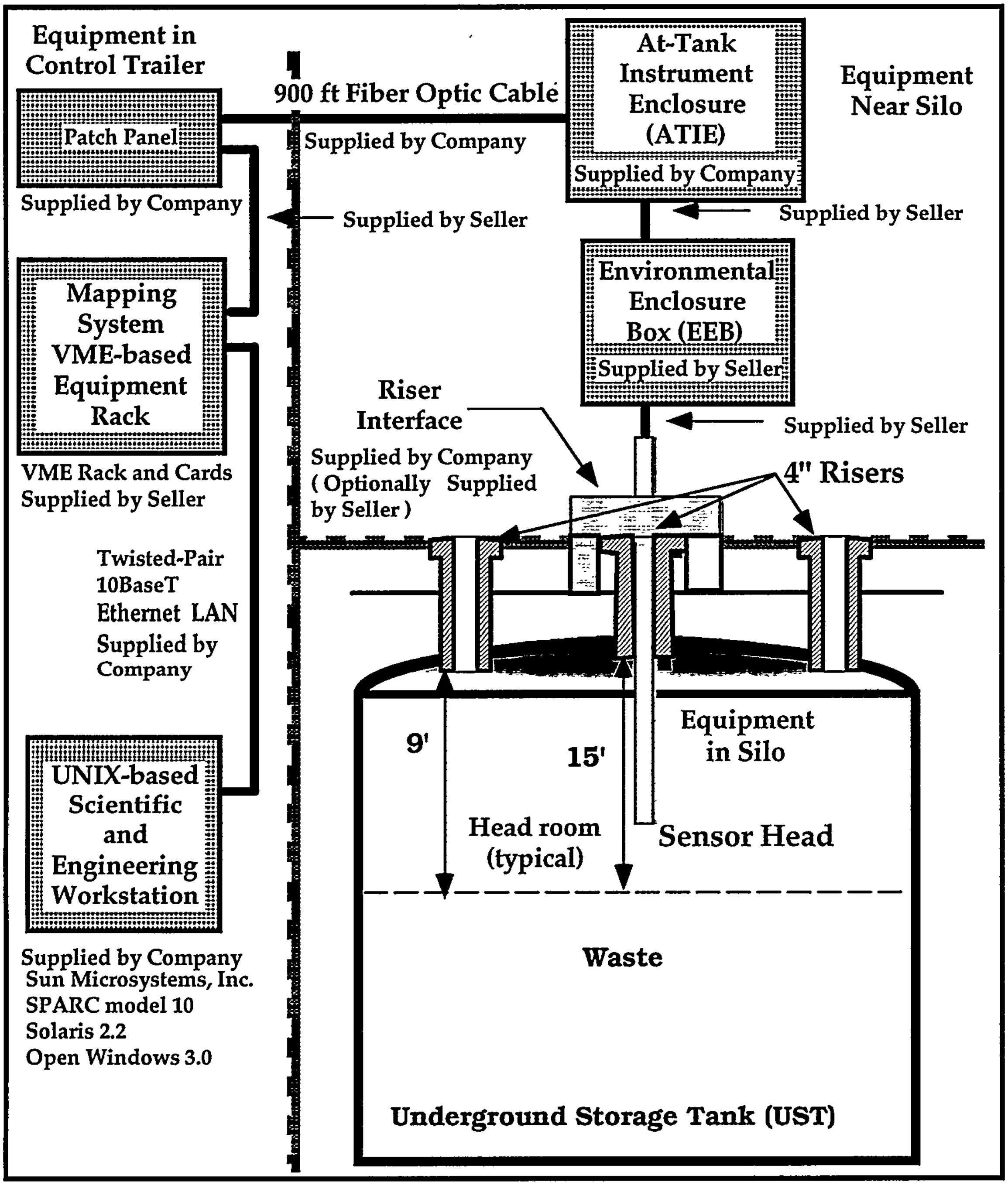

Fig. I.1. Block diagram of the topographical mapping system.

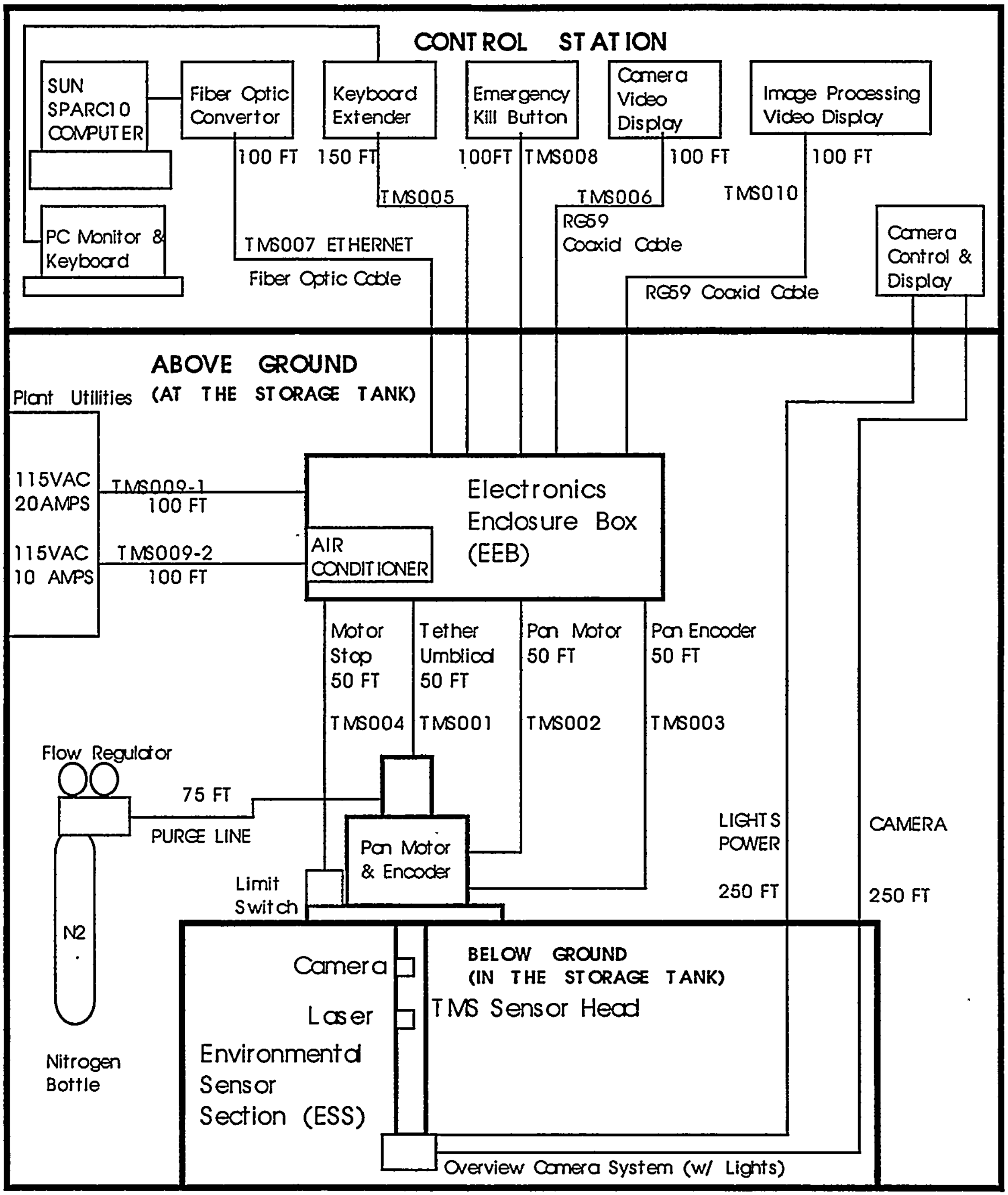

Fig. I.2 TMS cable diagram.

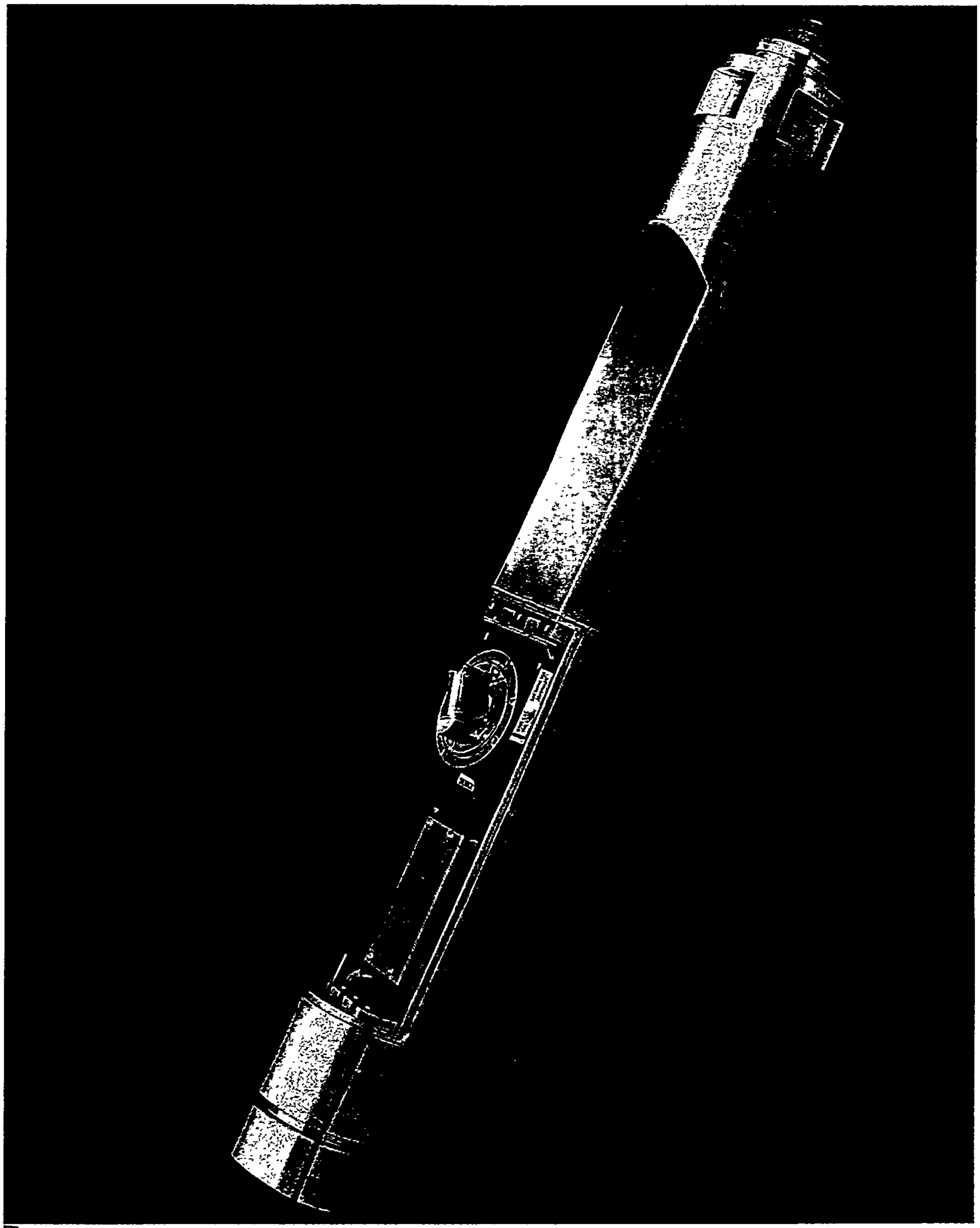

Fig. I.3 TMS laser/camera module.

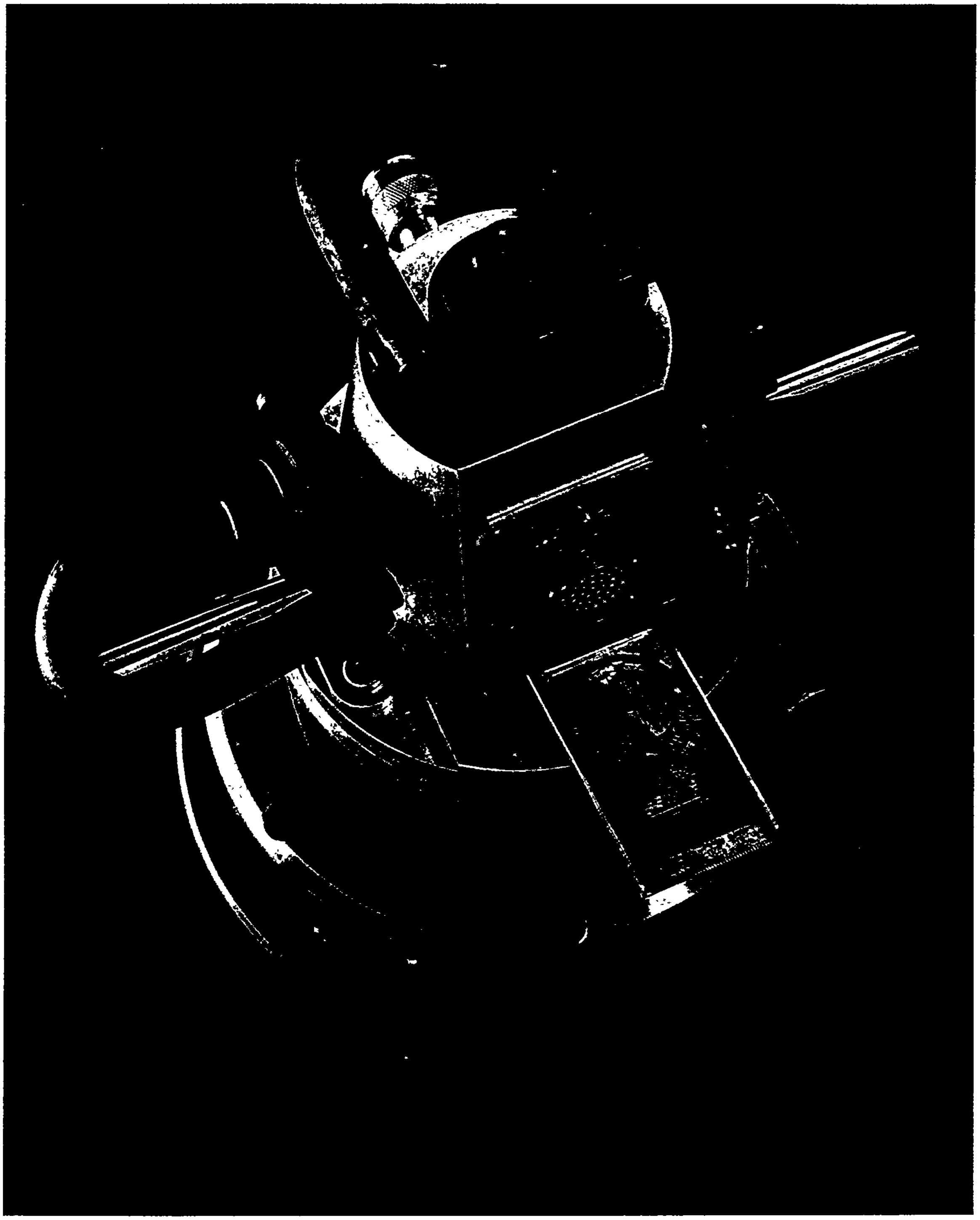

Fig. I.4 TMS pan motor adaptor module.

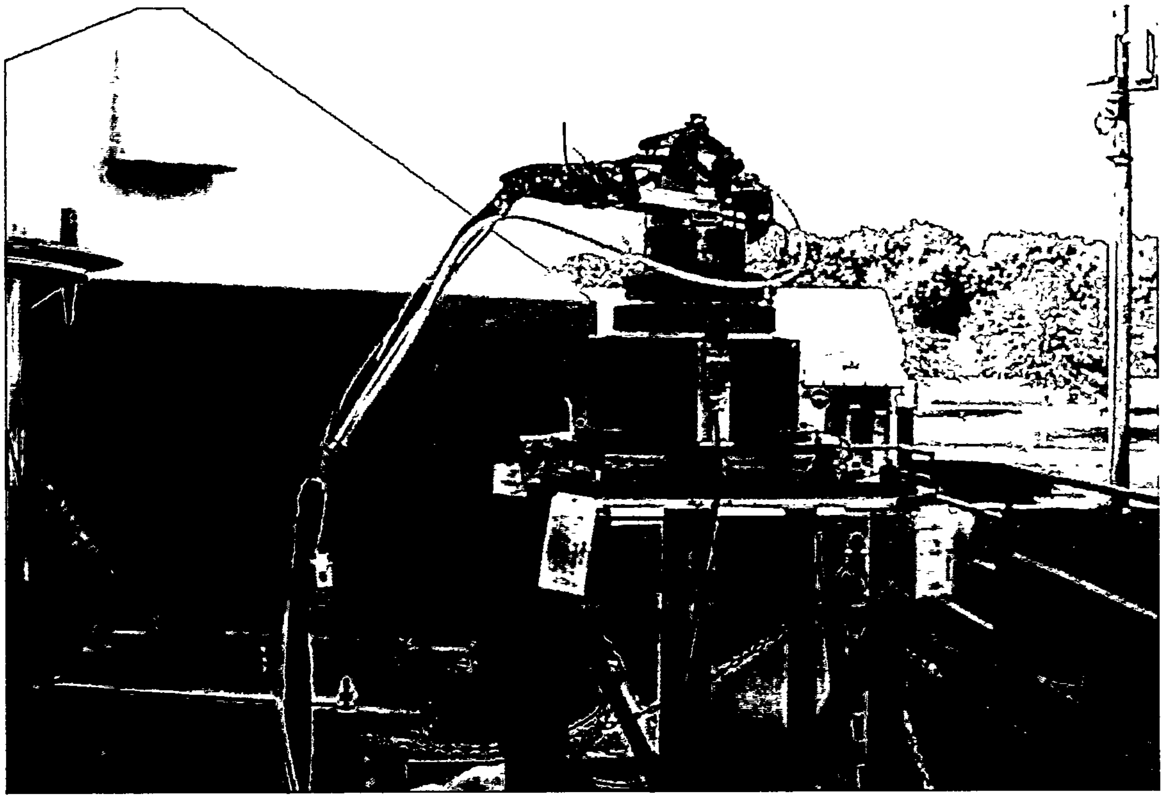

Fig. I.5. TMS deployed on the bridge of RPSD's Technology Test Facility.

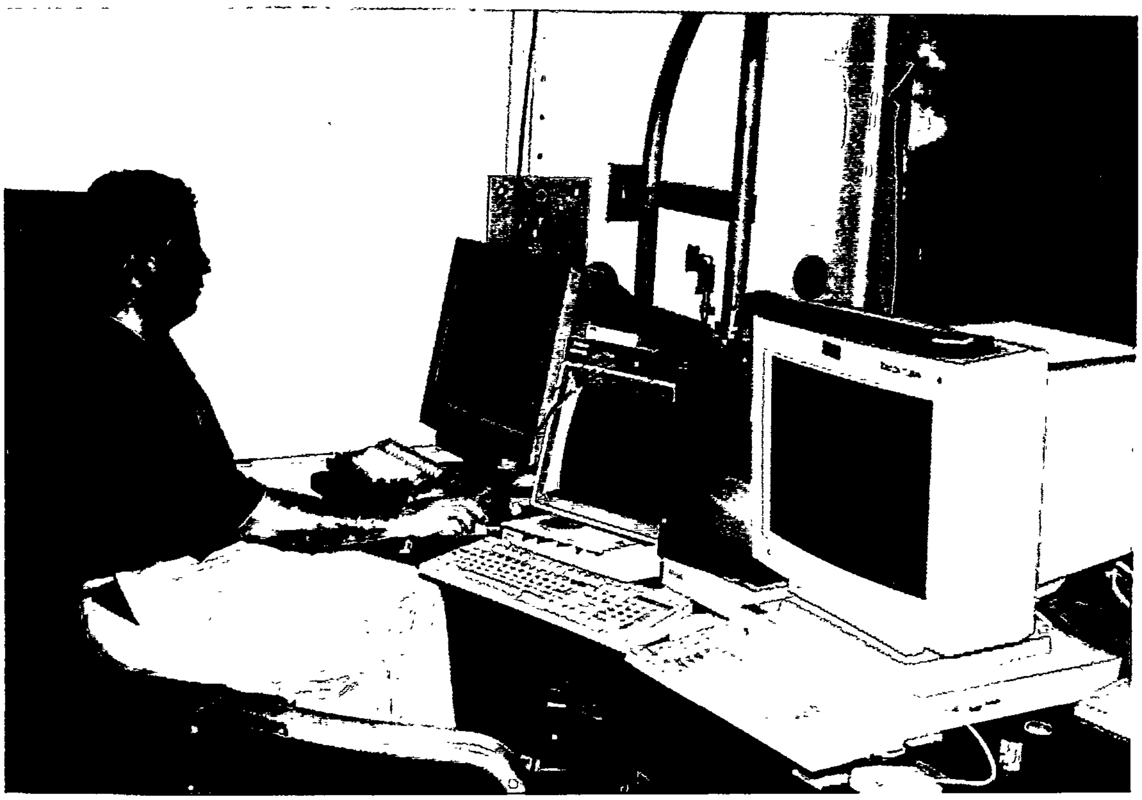

Fig. I.6. TMS control station.

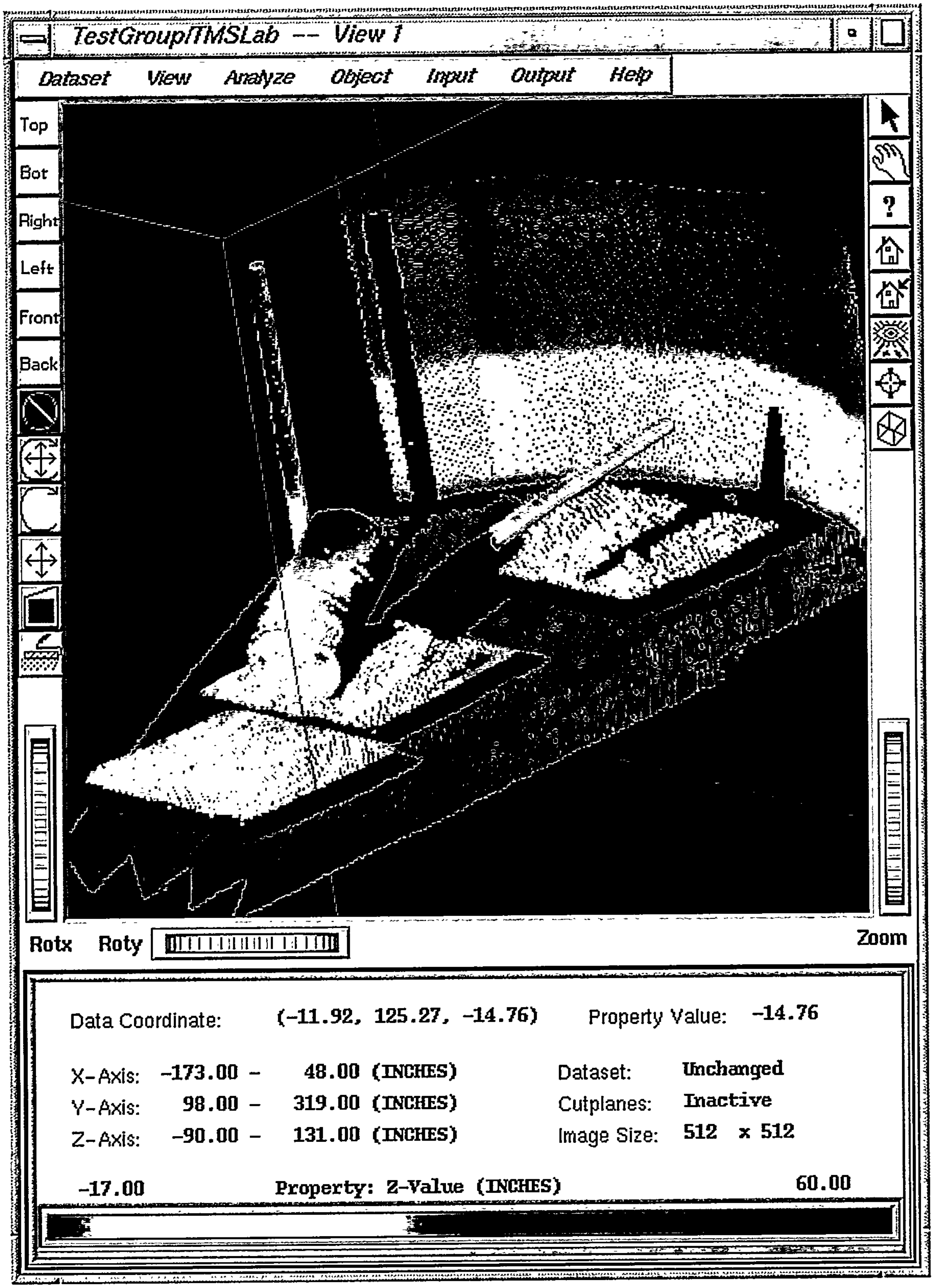

Fig. I.7. Surface map of MTI's Optics Lab, Albany, New York, displayed with ICERVS.

APPENDIX J

TYPICAL UST DIMENSIONS

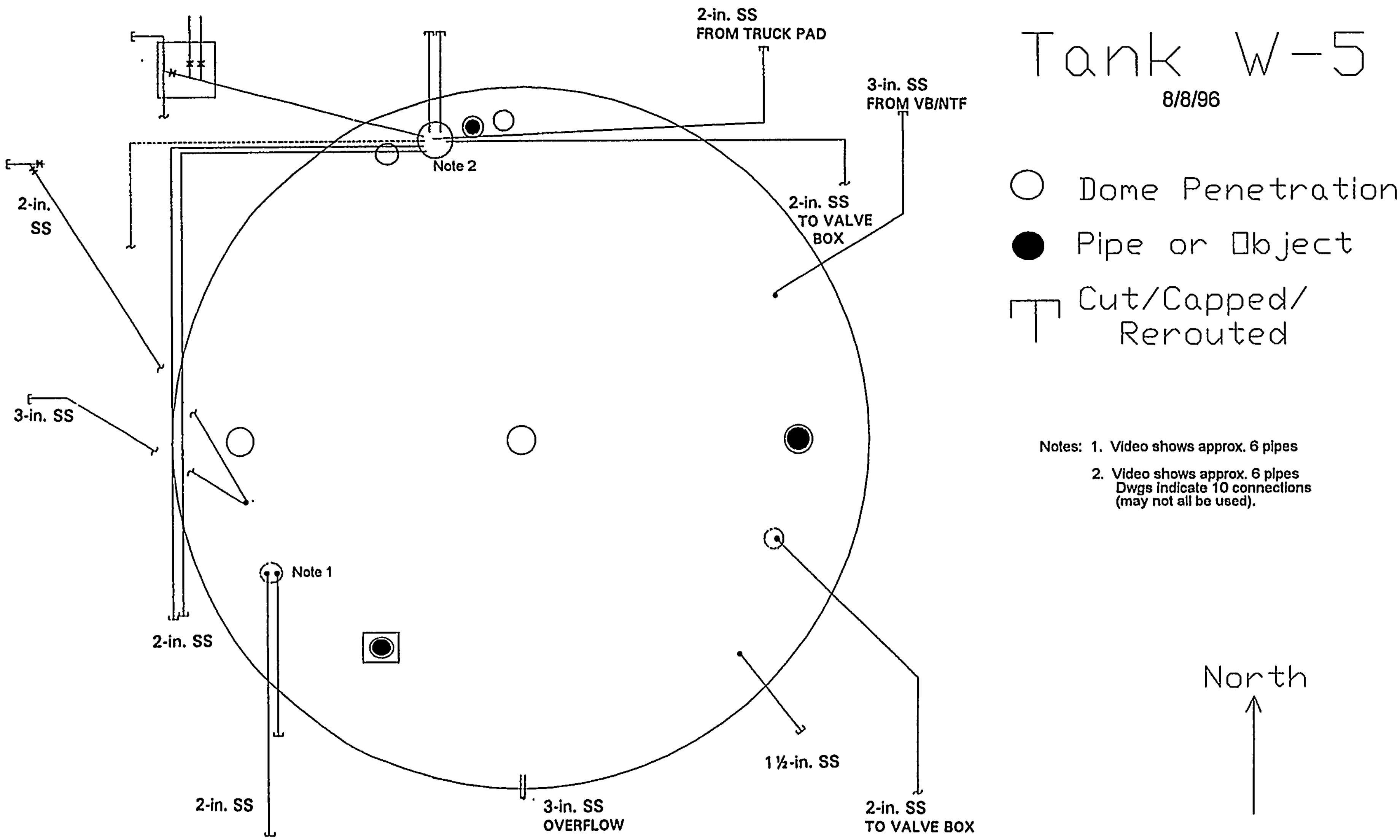

Fig. J.1 Tank W5 risers.

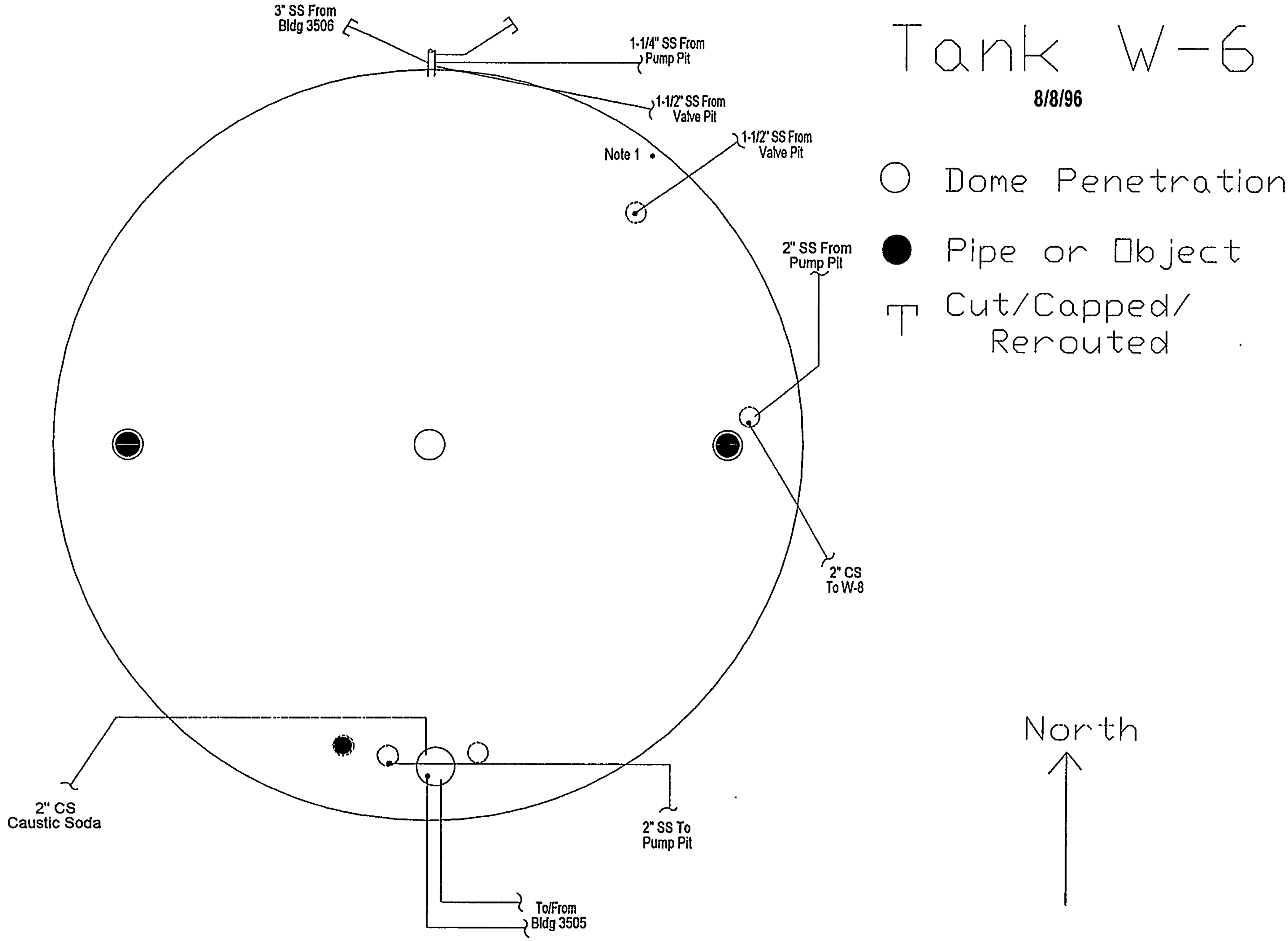

Fig. J.2 Tank W6 risers.

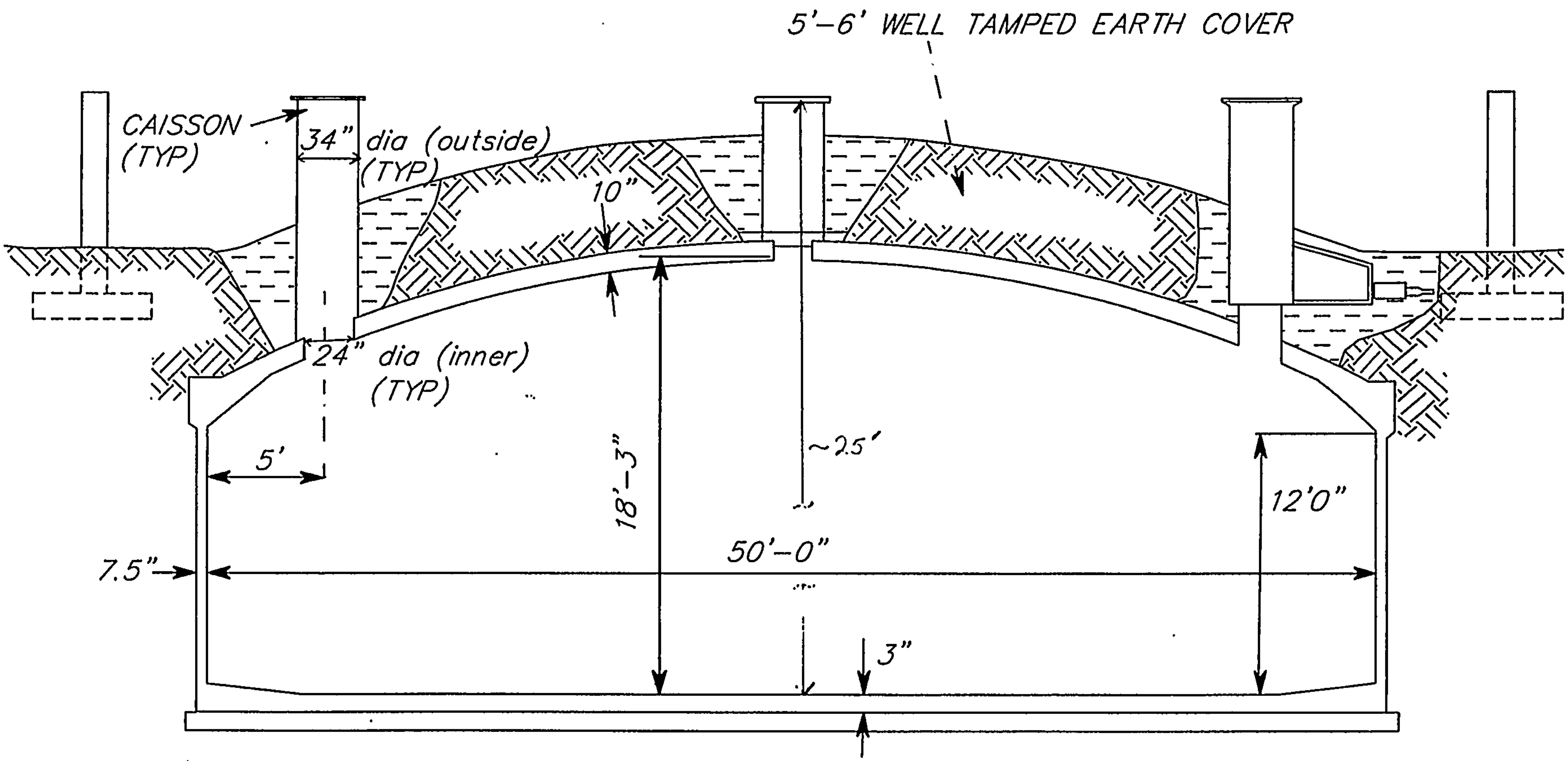

Fig. J.3 Typical 50-ft-diam Gunite tank cross section.

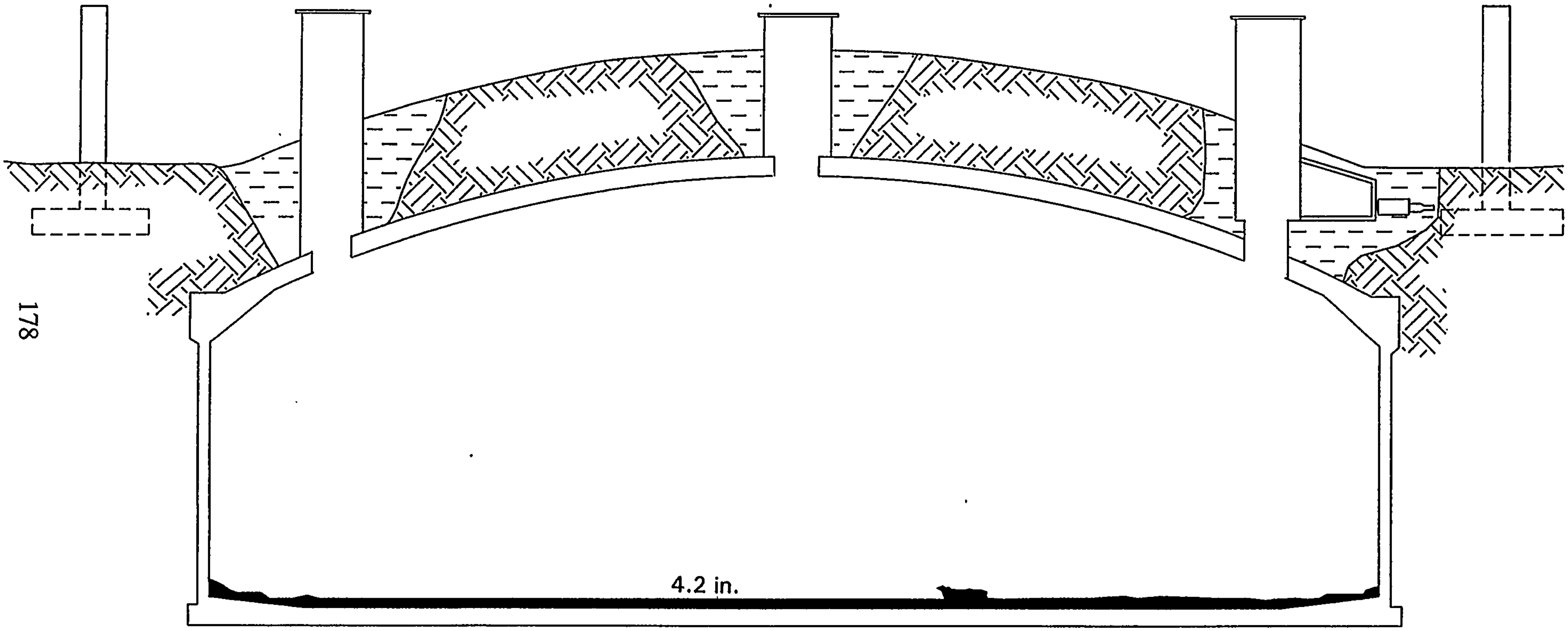

Fig. J.4 Tank W6 estimated residual.

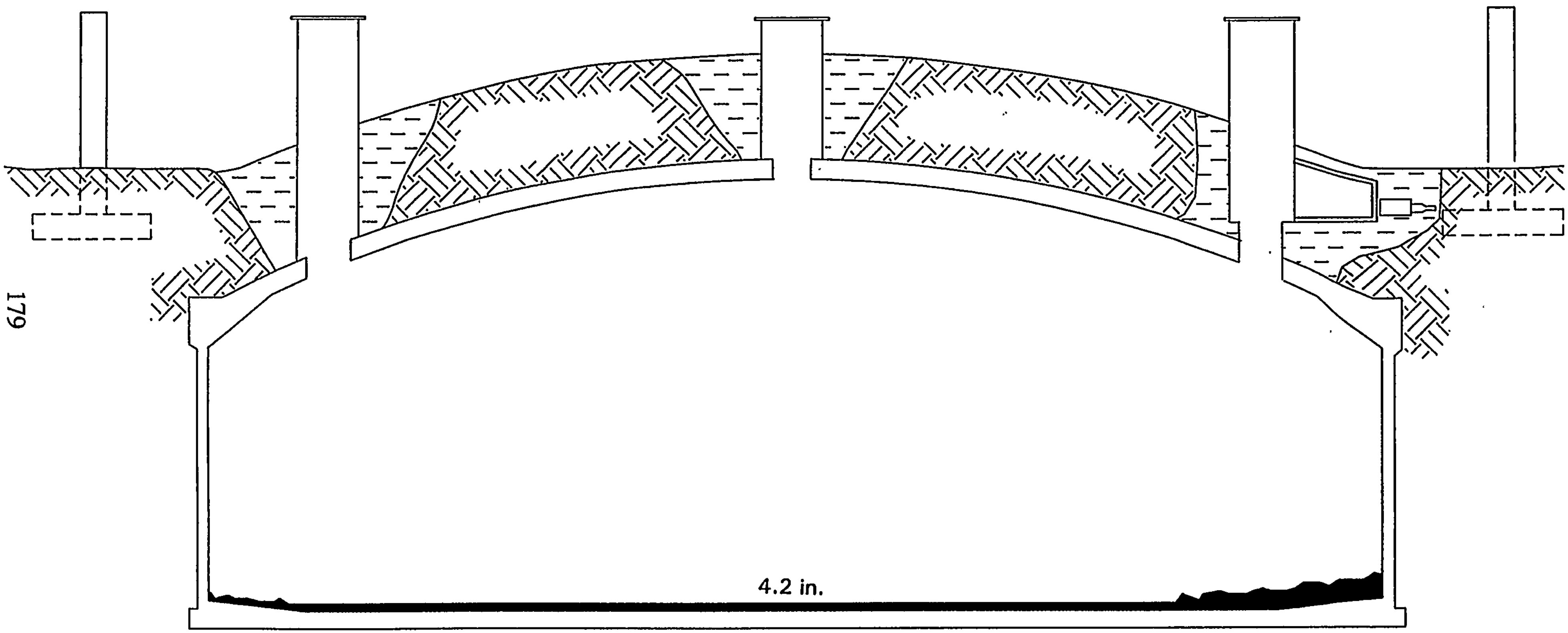

Fig. J.5 Tank W5 estimated residual.

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