INFRARED IMAGING SYSTEMS FOR THE FERROCYANIDE WASTE TANKS AT THE U.S. DEPARTMENT OF ENERGY'S HANFORD SITE

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ABSTRACT

The U.S. Department of Energy's Hanford Site in Washington State has 24 radioactive storage tanks containing ferrocyanide. There is a concern that these tanks could become explosive. Infrared imaging was investigated as a method to determine if high-heat areas (i.e., "hot spots") exist in the tanks. A hot spot is defined as a volumetric region within a waste tank with an excessively warm [220°C (428°F)] temperature that is generated by radioactive isotopes. The thermal image of a hot spot was modeled by computer. This model determined the temperature variation an infrared system must detect. Laboratory and field tests of the imaging system describe the system's capabilities and limitations. Conclusions show that the infrared imaging system is capable of detecting hot spots within the parameters defined by the model and tests.

INTRODUCTION

In the 1950s Hanford Site waste tanks received ferrocyanide-bearing sludges, which resulted from waste concentration efforts. Radioactive wastes in a slurry form were pumped into 24 single-shell waste storage tanks where the solids were allowed to settle. Later other waste forms were added resulting in the ferrocyanide tank waste levels ranging from 0.61 m (24 in.) to 6.12 m (241 in.). A possibility exists that some of the radionuclides could have settled in such a way as to create local concentrations of heat-generating material (e.g., cesium or strontium) or hot spots. If hot spot temperatures are greater than 220°C (428°F), a potentially dangerous condition could be initiated (1). The goal of the infrared (IR) imaging system was to locate hot spot patterns on the surface of the waste indicative of these conditions. The imaging system was required to access the tank dome space through a 0.3-m (12-in.) opening. This report discusses the results of calibrating the imaging system for the tank conditions and the design of the deployment system. The imaging system was field-tested in a non-ferrocyanide radioactive waste tank.

Computer analysis shows that a hot spot would create a noticeable temperature pattern on the surface of the waste (2). This analysis provided patterns against which IR scans can be compared to determine if hot spots were present. Understandably, the depth of the hot spot within the waste has a marked effect on the temperature profiles that are seen on the surface (Fig. 1).

DESCRIPTION OF THE EQUIPMENT

Scanner

The IR imaging system (see Fig. 2) is an FLIR Systems, Inc., Model 7300 consisting of a scanner assembly, image processor, and color display. An additional component of the IR system is the Thermal Image Management System (TIMS) which uses a 386 personal computer. The pertinent manufacturer's specifications are as follows:

Temperature range	Up to 1500°C (2732°F)
Temperature sensitivity	0.1°C typical (at 22°C plus 0.01 cycles/mrad)
Temperature accuracy	± 4.0°C (±7.2°F) or ±4% of reading (whichever is greater).

The IR detectors are cooled to -73°C (-100°F) with a Peltier cooler. Each detector has its own hybrid complementary metal oxide semiconductor multistage amplifier. These multistage amplifiers are sensitive to ionizing radiation. Their total dose life is estimated to be on the order of 1,000 R (3). The scanner was purchased with two standard lenses and one wide-angle lens. The lenses were calibrated with the system at the factory; the calibration data files for each are stored in the image processor. The image processor and scanner are connected with a cable calibrated especially for the system. Exchanging any of the units with uncalibrated equipment will yield inaccurate results.

The processor receives the analog signal from the scanner and modifies it for imaging and radiometric measurements. The processor has outputs to a color display and to the black-and-white video recorder. The IR imaging system has a recording mode that allows for automatic parameter setting. This mode was used for the operation of the IR imaging system in the tank environment.

The TIMS is a post-operation data analysis system that allows the user to evaluate the information in greater detail on a desktop computer. The TIMS processes data from the videotaped input of its frame grabber and processor board. The TIMS transforms the levels of intensity of a black-and-white video signal to the radiometric values of the IR image. Consequently, data must be recorded in black and white with the number of intensity levels, the highest temperature, and the lowest temperature to properly reconstruct the thermal image. Software options allow the user to examine data collected after the scan. Frames of interest are saved in a digital format for future use and create computer generated colors. A variety of histograms, variable emissivity settings, transmission loss settings, digital image storage, and printout features are available.

Infrared Scanner Deployment System

Figure 3 shows the IR scanner deployment system. Lead shielding houses the IR scanner to protect the detectors and integrated circuits from radiation damage. Because the housing changes the normal ability of the IR imaging system to cool itself, and because contamination should not enter the housing, a nitrogen purge gas system was designed for the IR imaging system. The pan and tilt unit attaches the IR scanner to the stem, rotates the scanner 358°, and tilts it 90° from vertical to horizontal. The 4.85 m (16 ft) stem houses the hydraulic, gas, and electrical cables. The assembly is supported on a 0.30 m (12 in.) flange by a split clamp welded to a 0.30 m (12 in.) flange plate. The depth of the riser in the tank can be matched to that of the IR scanner by adjusting the

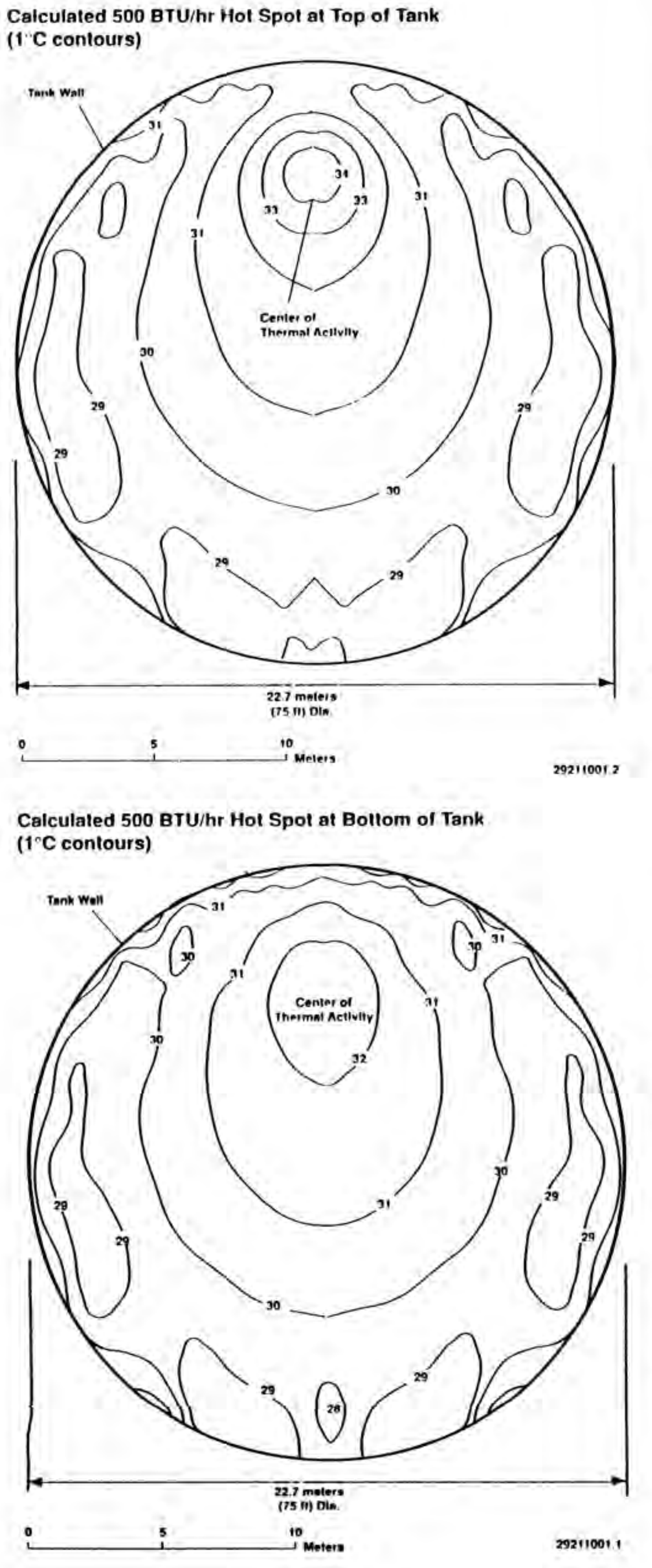

Fig. 1. Computer analysis modeled on tank 241-BY-104 for hot spots.

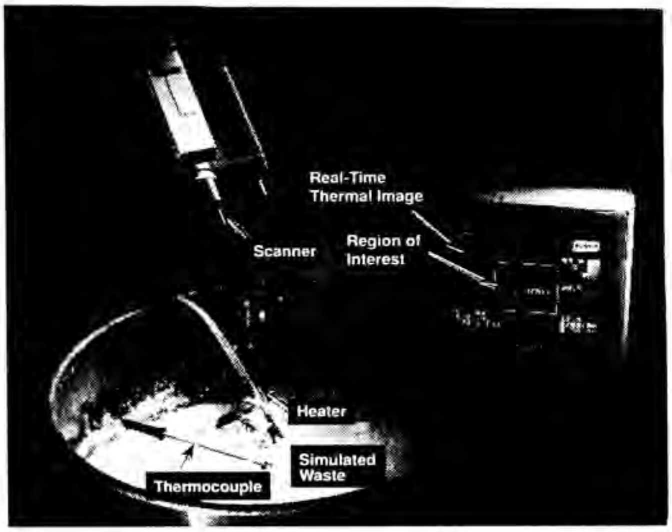

Fig. 2. Infrared scanner system.

flange and clamp. Overall length of the assembly is approximately 5.8 m (19 ft); the approximate weight is 386 kg (850 lb).

Additional equipment to run the IR scanner includes the hydraulic pump and controller for the pan and tilt, the nitrogen gas purge supply, and the computer control and video recording equipment for the IR imager. A containment sleeve encases the entire assembly from the flange connection down to the IR scanner. The lens and the purge gas filter are open to the dome space atmosphere.

LABORATORY TESTS OF INFRARED IMAGING SYSTEM

The radiometric measurement of the IR source is a function that is derived from the target temperature, atmospheric attenuation, target material emissivity, angle of incidence, and background radiation. These factors affect the data quality gathered by the IR imaging system, and these results are described below.

The objectives of IR imaging system laboratory tests were as follows: 1) determine the radiometric sensitivity of the system for waste material temperatures, 2) define the effects of the waste tank environment (i.e., atmospheric attenuation, waste surface emissivity, angle of incidence, ambient temperature variations, and gamma radiation fields as they may appear in ferrocyanide waste tanks), and 3) test general mechanical functions.

Calibration by Black Body Standard

This test was used to determine the accuracy and sensitivity of the IR imaging system under ideal conditions. It provides a baseline for data analysis (4).

A black body is an ideal source of radiation (usually associated with IR radiation) for which the wavelength distribution is dependent only on its temperature in accordance with Planck's radiation law. The black body used in this test had a 7.7 cm round target ($\varepsilon = 0.99 \pm 0.005$) with a National Institute of Standards and Technology traceable resistance temperature detector accurate to 0.1°C.

The IR imaging system measured temperatures of the black body source set at typical in-tank surface temperatures of 20 to 54.4 °C (68 to 130°F). To control variables of the test, the IR imaging system was aligned perpendicular to the

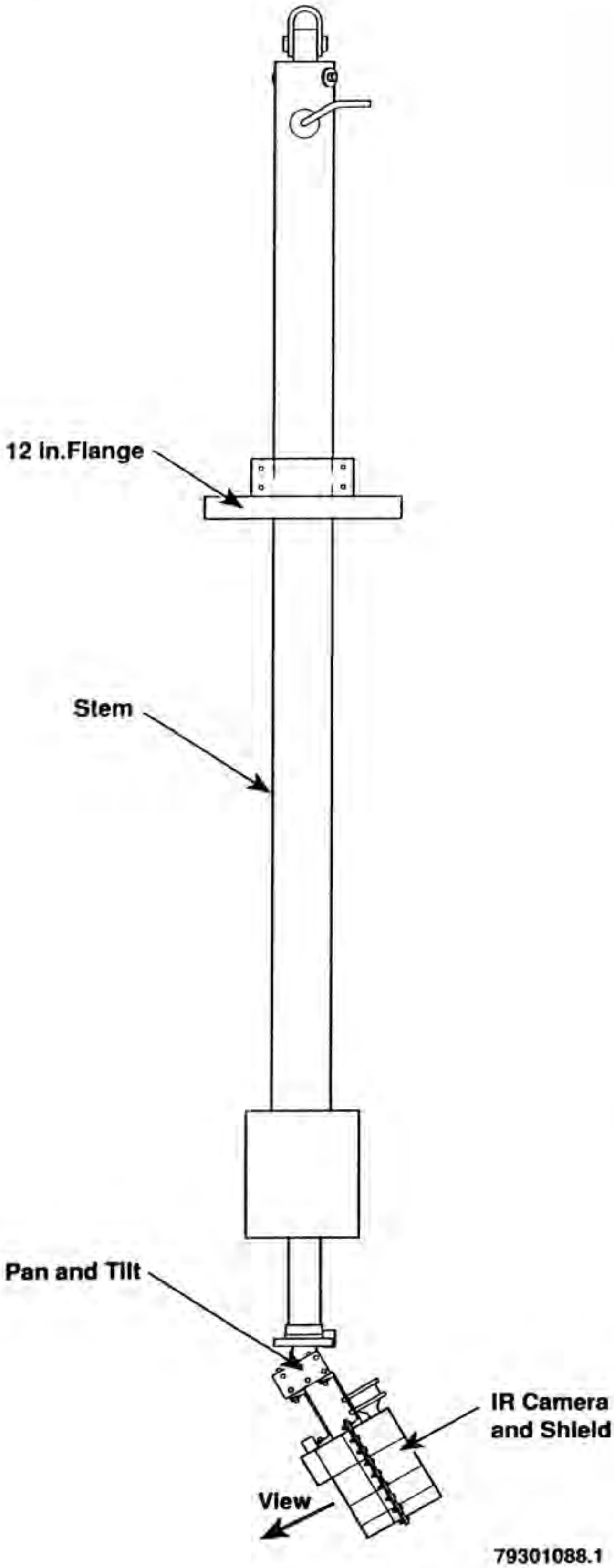

Fig. 3. Drawing H-2-81787.

source at a distance of 1 m (3.3 ft), at which distance transmission losses are negligible.

Under ideal conditions, this system is capable of measuring actual temperatures to within ±0.50°C (±0.90°F), and the temperature sensitivity can be determined to within ±0.15°C (±0.27°F). However, sensitivity performance will not be this high during in-tank operation.

Emissivity

The IR image processor allows for a variable emissivity setting to aid in the analysis of radiometric readings. This test was performed to determine the emissivity range of the expected ferrocyanide waste surface. For most materials, emissivity varies with wavelength, chemical composition, temperature, surface roughness, and angle of incidence. Three simulants were developed and tested: one by Pacific Northwest Laboratory (PNL), and two by the Westinghouse Hanford Company (Westinghouse Hanford) Chemical Engineering Laboratory. The emissivities were determined by comparison to the same surface with a known emissivity and direct temperature measurement.

A waste tank simulant was prepared and analyzed by PNL based on the process chemicals and end products of the uranium recovery process (5). In addition, two more simulants were made by Westinghouse Hanford based on a 1976 core sample taken of the 241-BY-104 waste tank and on samples taken from evaporator bottoms (4). Emissivities of the simulants were studied at different angles of incidence. Emissivity was determined by comparing the IR imaging system temperature reading with the value measured by a RTD and by comparing the IR imaging system temperature reading of an emissivity coated surface rated at 0.95 and the temperature reading of an adjacent simulant surface.

Results of both studies were in agreement for the emissivity and for the angle of incidence. The test performed by Westinghouse Hanford indicated that the emissivity of the simulant was 0.95, which is close to the 0.94 emissivity PNL had determined. Varying the angle of incidence demonstrated that the scanner could view the waste tank surface up to a 60° angle of incidence without reducing the IR intensity detected from the surface (see Fig. 4). The roughness of the simulant surface promotes uniform emission over a large range of incident angles.

Atmospheric Attenuation

Transmission losses are caused by atmospheric attenuation resulting from the different absorption bands present over the operating range of the IR imaging system (wavelengths of 3.2 to 5.6 μm). Most of this attenuation is created by water vapor and carbon dioxide. The IR radiation in the 4.2 to 4.4 micrometer band (carbon dioxide) is almost completely absorbed for viewing distances over 3 m (10 ft). Attenuation caused by the different humidities will vary depending on viewing distance (4).

Ferrocyanide tanks have moderate waste surface temperatures and ambient dome space temperatures. The maximum waste temperature measured is 54.4°C (130°F), with the usual surface temperature averaging around 27°C (81°F). Dome space temperature varies between 18°C and 27°C (64°F and 81°F) in ferrocyanide tanks.

To predict thermal transmission loss for in-tank IR imaging, the computer code LOWTRAN 7 was used (6). The program calculates thermal loss for different atmospheres

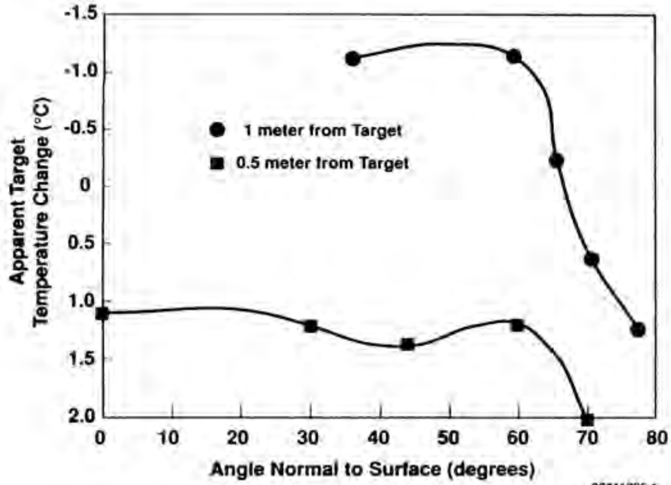

Fig. 4. Emissivity at varying angles of incidence.

defined by the following parameters: humidity, distance, source temperature, environmental temperature, background radiation, and wavelength. Different attenuations were obtained in the laboratory by varying the distance between the scanner and the source for the available humidities, which varied between 30% and 60% RH.

The practical maximum distance for viewing in the tank dome space is 14 m (46 ft). As can be seen in Fig. 5, the atmospheric attenuation is calculated to be less than 2.2°C (4.0°F) in a typical ferrocyanide waste tank.

The thermal loss associated with atmospheric attenuation is negligible for hot spot detection. Detection capability will be reduced by approximately 2%, which is the amount given by the ratio of the thermal loss to the waste temperature. Further work is needed to quantify the effect of relative humidity higher than 50%.

Gamma Radiation Effects

The maximum expected gamma radiation dose rate for the IR imaging system components as shown in Fig. 3 is approximately 20 R/hour (7). This radiation field could change the response (i.e., accuracy and sensitivity) and cause

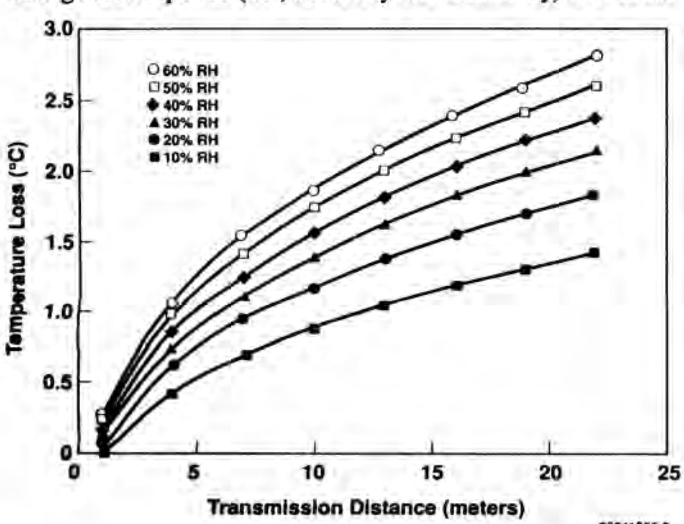

Fig. 5. Temperature loss calculated in a typical ferrocyanide tank.

unwanted short-term effects of more radiation-sensitive components, such as integrated circuits or detector arrays.

To test for this potential effect, the IR scanner was mounted to read the temperature of an aluminum plate while in the presence of a ^{137}Cs gamma field (4).

The scanner was able to register a 0.2°C (26.8 to 27.0°C) [0.4°F (80.2 to 80.6°F)] temperature gradient across the plate. Additionally, the scanner could detect a 1.3°C (2.3°F) change in plate temperature when the room air conditioner came on. However, none of these readings were affected by the presence or absence of the gamma radiation field.

Effects of long-term doses were estimated using data gathered from documentation of the components of the scanner. The expected life of this equipment is 1,000 R total integrated dose (3).

Ambient Temperature

The scanner is enclosed in a purged, shielded container when it is used in a waste tank. The effects of operating the scanner in an environment different than the one it is viewing were studied. The imaging processor compensates for background IR radiation by measuring the temperature of the scanner and matching it to an internal reference surface temperature. This internal reference surface temperature must be controlled to be approximately the same as that of the transmission path (i.e., ambient).

The IR scanner was operated in an environmental chamber to measure how local environmental temperature influenced the reading it produced. The local environment temperature was controlled using a purge gas (i.e., nitrogen). The internal temperature response of the scanner to a varying cooling rate was measured.

Temperature accuracy was determined to be within the scanner manufacturer specifications at +4.0°C (+7.2°F) above ambient. The purge rate found to keep the scanner in the enclosure within the + 4.0°C (+ 7.2°F) range was 0.7 ± 0.1 L/s (1.5 ± 0.2 ft^3/min) during laboratory tests. The time to attain ambient temperature is important to minimize the radiation exposure during installation. Twelve to 48 minutes were required for warm-up depending on the difference between the IR system temperature at start up and the ambient temperature.

System Performance Under In-Tank Conditions

This laboratory test combined several variables to determine the temperature ranges the IR imaging system could detect. The variables were distance, humidity, and angle of incidence; emissivity was constant over the test surface. The IR imaging system also viewed various surface shapes (e.g., convex regions, concave regions, and flat regions) to determine the effects of surface geometry.

A laboratory test was set up using a pit at a Hanford Site facility. The setup simulated the configuration expected in waste tanks (8).

The data indicate that the IR radiometric measurements do not differ from the true temperature by more than ±2.0°C (±3.7°F) within 2-sigma confidence limits. Temperature sensitivity under in-tank conditions is within ±0.28°C (±0.50°F).

Acceptance Test

The IR imaging system test was to verify the electrical and mechanical components as required to perform in an in-tank test. The specific components tested were the pan and tilt unit, the nitrogen purge system, the IR imaging system and the contamination control bag (9).

The pan and tilt unit was tested for the limits of pan rotation, tilt azimuth and for the default position for loss of power or hydraulic failure. The nitrogen purge gas cooling system was operated during testing of the other parameters to establish real-time nitrogen use. The IR imaging system was tested for operation using the blackbody calibration procedure for two temperature points [21.5°C and 50.3°C (70.7°F and 122.5°F)]. The contamination control bag was tested under the expected field conditions for interference with the pan and tilt and interfacing with the riser.

The pan rotation was 0° to 357°. The tilt moved between 0° and 86°. The unit went to default position (less than 5° tilt) on loss of power or hydraulics. The cooling system operated at the specified flow rate for 1 hour and 37 minutes. The IR imaging system and the contamination control bag operated as specified.

The pan unit was required to rotate between 0° to 359° rather than 0° to 357°; the tilt was required to view up to 90°, rather than 86°, but because the scanner's field of view overlaps, an entire tank can be effectively scanned.

Summary of Laboratory Testing

The results of the laboratory tests on the IR imaging system are as follows:

- Temperature sensitivity--Under ideal conditions, ± 0.15°C (±0.27°F). In-tank conditions, ± 0.28°C (± 0.50°F).
- Emissivity of ferrocyanide waste simulants--0.94 to 0.95. Up to a 60° angle of incidence does not affect radiometric readings on the surfaces measured.
- Atmospheric attenuation--Negligible (approximately 2% within the temperature range of the tank). The practical maximum distance for viewing in the tank dome space is 14 m (46 ft). Further work is needed to quantify the effects of higher than 50% relative humidity.
- Expected life in radiation field--1000 R (3). No effects were noticed in the radiometric readings during operation in a gamma radiation field up to 20 R/hour.
- Ambient temperature operation--The internal temperature of the camera must be kept at + 4.0°C (+ 7.2°F) of the ambient temperature for accurate readings. The flow rate required to achieve this is 0.7 ± 0.1 L/s (1.5 ± 0.2 ft^3/min).
- Temperature accuracy--Under ideal conditions, ± 0.50°C (±0.90°F). Under in-tank conditions, ± 2.0 °C (±3.7°F).

CONCLUSION

A field test was conducted of the IR imaging system. The system was installed in Tank 241-S-110 just below the surface of the dome (Fig. 6). IR scanning of the tank began facing due south at a tilt angle of 20.5 degrees. Staying at due south, subsequent images were taken and recorded on videotape at 20, 35, 50, 70, and 90 degrees. After panning the scanner to both stops and all required tilt angles, the tank scan was complete. Figure 6 shows a typical scan.

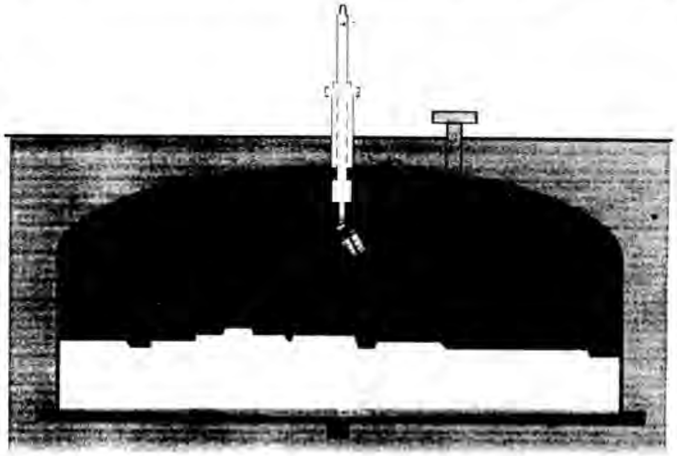

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Fig. 6. Installation and infrared image in a non-ferrocyanide tank.

The goal of this effort was to characterize the performance of IR imaging technology for application in determining thermal patterns indicating hot spots in the Hanford Site ferrocyanide tanks. The IR imaging system, as designed and tested, will detect and provide data to generate a reliable surface temperature contour map, based on the computer model. There are some limitations; the results are not guaranteed for tanks of greater depth than the model [3.94 m (155 in.)] and for parameters outside those tested. It is believed but not verified that the majority of the ferrocyanide tanks fall within these boundaries.

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