

Quantitative Imaging Evaluation of Corrosion in Oak Ridge Research Reactor POOL

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ABSTRACT

The Oak Ridge Research Reactor (ORRR) was operated as an isotope production and irradiation facility from March 1958 until March 1987. The US Department of Energy permanently shut down and removed the fuel from the ORRR in 1987. The water level must be maintained in the ORRR pool as shielding for radioactive components still located in the pool. The U.S. Department of Energy's Environmental Management (DOE EM) needs to decontaminate and demolish the ORRR as part of the Oak Ridge cleanup program. In February 2004, increased pit corrosion was noted in the pool's 6-mm ($\frac{1}{4}$ "-thick aluminum liner in the section nearest where the radioactive components are stored. If pit corrosion has significantly penetrated the aluminum liner, then DOE EM must accelerate its decontamination and demolition (D&D) efforts. The goal of Mississippi State University's Diagnostic Instrumentation & Analysis Laboratory (DIAL) is to provide a determination of the extent and depth of corrosion. Results from the work will facilitate ORNL in making reliable disposition decisions.

DIAL's inspection approach is to quantitatively estimate the amount of corrosion by using Fourier-transform profilometry (FTP). FTP is a non-contact 3-D shape measurement technique. By projecting a fringe pattern onto a target surface and observing its deformation due to surface irregularities from a different view angle, FTP is capable of determining the height (depth) distribution of the target surface, thus reproducing the profile of the target accurately. DIAL has previously demonstrated that its FTP system can quantitatively estimate the volume and depth of removed and residual material to high accuracy.

INTRODUCTION

The Oak Ridge Research Reactor (ORRR) was designed and operated as an isotope production and irradiation facility at the Oak Ridge National Laboratory (ORNL) from March 1958 until

March 1987 [1,2]. In July 1987, the Department of Energy (DOE) permanently shut down the ORRR. The decision to shut down the ORRR required placing the reactor in a safe configuration until final decommissioning could be accomplished. Removal of all fuel and fuel-bearing components was completed in July 1989 however; several irradiated reactor components were left in the pool until such time as they could be safely removed (at time of D&D). Hazardous chemicals and equipment associated with past operations were also removed. Processes and procedures have been established to maintain a safe and stable condition pending final disposition.

The water level in the reactor pool is maintained to provide shielding for several irradiated reactor components that still remain in the pool. The reactor pool is approximately 60 feet (18 m) long (which runs east-to-west), 11 feet (3.3 m) wide (which runs north-to-south), and 30 feet (9 m) deep, and contains about 125,000 gallons (473 m³) of water. The pool is divided into three sections. The reactor vessel, horizontal beam tubes, and the poolside irradiation facility were contained in the east section of the reactor pool. The middle section of the pool was utilized primarily for the storage of fuel and for the packaging operation involved in preparing spent fuel for shipment. The west section of the pool appears to have been utilized for storage of various experiment and also provided access for transporting items into either of the two hot cells. The water in the pool served as a biological shield while the reactor was operational and also provided cooling for the reactor and for the beam tubes. Since all of the reactor fuel has been removed, the pool water is now being maintained primarily to provide shielding for three highly activated components that resulted from irradiation experiments. These three components located in the middle section of the pool, account for approximately 95% of the total radiological activity in the pool.

The pool is constructed of high-density reinforced concrete with a one-quarter inch (6-mm) thick 6061-alloy aluminum plates welded to aluminum structures embedded in the concrete. Numerous penetrations were made through the pool walls for research purposes during the operation of the reactor. Although these penetrations appear to be well sealed to prevent pool water leaks, the composition of the piping, flanges, and seals associated with these penetrations is not readily available and their long term corrosion resistance is not known.

Throughout the reactor's operational life and until 2001, the reactor pool water was supplied from ORNL process water that had been treated through a series of individual cation and anion ion exchange resin tanks that virtually eliminated ionic contaminants from the process water. This system was designed and operated to reduce the concentration of elements that could be activated by the reactor's neutron flux and cause a radiation hazard at the facility. Pool water pH data during operation of the ORNL process water system showed an average value of about 5.6 and resistivity of 0.77 megaohms/cm (conductivity of 1.3 microsiemens·cm). The lack of ionic contaminants in the water inhibited the corrosion of the aluminum pool liner.

In 2001 the pool anion and cation exchange water treatment was replaced with a mixed bed deionization system. During the period of operation from 2001 – 2004, pH readings ranged from 5.7 to 5.0 with resistivities between 0.5 and 0.7 megaohms/cm (conductivities between 2.0 and 1.4 microsiemens·cm).

Building surveillance and maintenance personnel have observed a noticeable increase in the accumulation of white aluminum oxide in the reactor pool since the water treatment system change in 2001. Pit corrosion [3-5] is a localized form of corrosion in which metal is electrolytically removed due to the influence of locally significant concentrations of inducing species (such as chlorine ion). This corrosion forms needle-like craters beneath the surface, whose depth is usually greater than or equal to the pit diameter. Except for inside the pits, there is essentially no loss of metal. A visual inspection of the pool in February 2004 by facility management observed numerous points of corrosion on the south wall of the center pool section, and several flanges associated with pool penetrations on the north wall showed extensive aluminum corrosion. One flange especially appeared to be completely covered with white aluminum oxide.

Although the extent of the aluminum oxide build up can be observed, the depth of the corrosion and the potential threat to the integrity of the liner is unknown. Further testing is needed to understand the corrosion rate and extent of oxidation occurring in the pool. Mississippi State University's Diagnostic Instrumentation & Analysis Laboratory (DIAL) has developed and, in collaboration with DOE EM, deployed a submersible Fourier transform profilometry system to characterize the pit corrosion.

METHOD

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique [6]. By projecting a fringe pattern onto a target surface and observing its deformation due to surface irregularities from a different view angle, FTP is capable of determining the height (depth) distribution of the target surface, thus reproducing the profile of the target accurately. If changes are made to the surface and if both before- and after-change images of the surface are acquired under the same conditions, the changes can be determined quantitatively by comparing the two images. The principle of FTP is illustrated in Fig. 1.

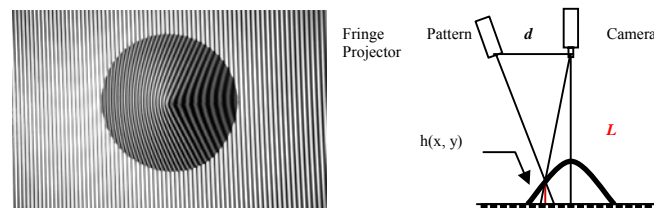


Fig. 1. Diagram illustrating the principle of Fourier-transform profilometry

In Fig. 1, the photo image presents a cone placed on a flat surface with a fringe pattern (repeating fringe lines) projected onto its surface. In this illustration, the cone is the target to be determined. The flat surface is called the “reference plane.” Before the target image (with a certain fringe pattern projected) is acquired, a reference image is also acquired. The reference image shows the reference plane with the same fringe pattern projected onto it. It is important to make sure that during the acquisition of both images, the settings of projector, camera, and fringe pattern remain the same. As observed in the target image in Fig. 1, the fringe lines projected onto the cone are distorted. These distortions are caused by surface irregularities and contain height information

for the target surface with regard to the reference plane. With the distortions properly interpreted, height information can be revealed.

In FTP, a Fourier transform is first applied to both reference and target images. Then a region of interest in the transformed spectral image, which usually consists of one complete spectrum of the image being transformed, is selected. Inverse Fourier transforms are then applied to the selected spectral region of both images, to extract the phase information. Thereafter, there are two phase images (reference and target) available for further processing. By subtracting the reference phase image from the target phase image, a difference phase image is generated. Since phase information describes how fringe lines are spaced in an image, this difference phase image describes how the spacing of fringe lines of the target image varies from that of the reference image. Therefore, the difference phase image is directly related to the height distribution of the target surface, which caused the difference in fringe line spacing. As derived by Takeda and Mutoh [6], the height distribution of the target surface is easily calculated by using Eq. (1).

$$h(x, y) = \frac{L\Delta\Phi(x, y)}{\Delta\Phi(x, y) - 2\pi df_0} \quad (\text{Eq. 1})$$

where $\Delta\Phi(x, y)$ is the phase modulation due to the object-height elevation, $h(x, y)$; L is the distance from the camera aperture to the reference plane; d represents the distance between apertures of the projector and the camera; and f_0 is the fundamental frequency of the observed fringe pattern on the reference plane (in lines/cm).

The resolution of FTP measurements is defined as the height (depth) that a single pixel in an acquired image can resolve. It is denoted as Δh_p , and can be obtained from (Eqs. 2 and 3).

$$\Delta h_p = L\Delta\phi_p / [\Delta\phi_p - 2\pi df_0] \quad (\text{Eq. 2})$$

where

$$\Delta\phi_p = 2\pi n_{line} / X_{pixel} \quad (\text{Eq. 3})$$

and $\Delta\phi_p$ stands for the phase shift that a single pixel in the acquired image is able to resolve, n_{line} is the total number of repeating fringe lines in the image, and X_{pixel} is the horizontal image dimension (in pixels). Obviously, the L and d parameters, the density of fringe lines, the dimension of the acquired image, the focal length (F.L.) of the camera lens, and the projector's projected field angle all affect the resolution of FTP measurements. In an experiment where $L = 763$ cm (~25ft), $d = 100$ cm, $X_{pixel} = 512$, the repeating frequency of fringe lines before projection was 300 lines per inch, a Kodak Carousel 4200 projector was used, and a camera lens with 150-mm focal length was used, a resolution of 0.49 cm/pixel has been achieved. In the ORRR pool initial measurements, where $L = 15$ cm (~0.5ft), $d = 6$ cm, $X_{pixel} = 640$, the repeating frequency of fringe lines before projection was 250 lines per inch, a projector with 28mm focal length was used, and the acquired image width was 37mm, a resolution of 0.16mm/pixel was achieved.

Two key issues are involved in FTP. The first one is that there is a slope limitation to height measurement. With L (the distance from the camera to the reference surface) and d (the distance between the camera and the projector) fixed, the maximum slope that can be measured is one third of L/d . The other key issue is phase unwrapping [7, 8]. The phase values generated from

inverse Fourier transforms are all wrapped in the range of $-\pi$ to π , which causes discontinuities of 2π in phase images. These discontinuities must be resolved by applying phase unwrapping techniques to the wrapped phase data. Choice of a certain phase unwrapping algorithm may have remarkable impact on the accuracy and efficiency of the FTP computation.

Fourier transform profilometry is fast, efficient, and inexpensive in comparison with other commonly used profilometry techniques, such as laser profiling methods. FTP provides an ideal quantitative means of determining the volume of materials.

APPLICATION

To apply FTP optical inspection capability to characterization of the pit corrosion of the aluminum liner in the ORRR pool, a submersible FTP system has been designed and is under development at the Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University. This is a modification of our previously developed FTP system [9-12]. Given the radioactive nature of the facilities involved in this inspection, the system is separated into two major constituents. One is a submersible FTP module, containing a camera, a fringe-projection system, and a utility light, all encased within a metal box of dimensions 20 inches (50.8 cm) wide x 20 inches (50.8 cm) deep x 8 inches (20.3 cm) high. The FTP system is controlled and data acquired by way of a series of cables that pass through the box to a remote control/data acquisition computer. The other is a crane/winch deployment system to lower the submersible FTP module into the pool and, with the assistance of guide wires, position it in front of a corrosion pit. The crane/winch is mounted on a moveable bridge crane that sets atop the pool and spans the 11-ft (3.3-m) width of the pool. Personnel on the bridge crane are attired in appropriate personal protection equipment (PPE) for a radioactive environment.

In order to accurately determine the extent of pit corrosion, it is important to know exactly the distance from the camera to the object of interest (distance L in Fig. 1). This is accomplished by using three standoffs of known length attached to the submersible FTP box wall that faces the pit corrosion. The standoffs are removable and can be replaced by other standoffs of different length. Currently the standoff between the exterior of the submersible FTP box and the pool wall is 6 inches (15 cm). Each standoff has a contact sensor to insure that the submersible FTP box is parallel to and in contact with the pool wall.

The deployment procedure is to lower the submersible FTP system into the ORRR pool using the crane/winch and position it directly in front of a corrosion pit. Final positioning is performed using the utility light and video from the camera. A grid pattern is projected onto the pool wall and FTP images of the corrosion pit acquired. The utility light is turned back on and the grid pattern light turned off. A metal brush on a long handle is used to scrap off the corrosion, using the camera video to monitor the process; this is accomplished without moving the submersible FTP box. The choice of a metal brush is based upon experiments previously performed on the pit corrosion material in the ORRR pool; it was found that vigorous cleaning with a scrub brush did not appear to remove any of the corrosion material, that cleaning with a bristle pad could remove some of the corrosion material, and that cleaning with a metal brush easily removed almost all the corrosion material. At this point in the characterization procedure, the utility light is turned off and the grid pattern light turned back on. FTP images of the cleaned surface are recorded.

Analysis of the FTP data yields the volume of the corrosion material. By assuming a particular chemical composition/mixture for the corrosion material and using the diameter of the corrosion pit opening (which may be less than a millimeter), estimates of the corrosion pit depth will be calculated. If the outline of the corrosion pit opening is discernible in the FTP images, no further action will be taken to clean the corrosion pit. However, if the outline of the corrosion pit opening is not discernible, a water jet mounted on a long-handled metal pole will be lowered into the pool and the minimum force will be used to dislodge corrosion material from the pit in order to avoid water leaking through the pit should the pit be deep enough to completely penetrate through the aluminum liner.

INITIAL RESULTS

Measurement experiments have been conducted under simulated conditions during pre-deployment practice sessions at DIAL. The experimental setup is shown in Fig. 2. For these experiments, the FTP box was submerged under water contained in a plastic trough. An aluminum plate (supported by a wooden frame) was submerged under water and utilized to simulate the pool wall, with targets placed on its surface. The standoff between the exterior of the submersible FTP box and the simulated pool wall was 6 inches (15.24 cm). Both regular targets of known size (aluminum cones) and irregular targets of unknown size (made from caulk) were measured. Table I presents numerical results from typical experiments for aluminum cones, which have reasonable measurement accuracy given the small size of the targets. Fig. 3 provides more detailed results from these experiments. The images produced demonstrate a high fidelity in reconstructing the original shape of both the cone and the irregular target.

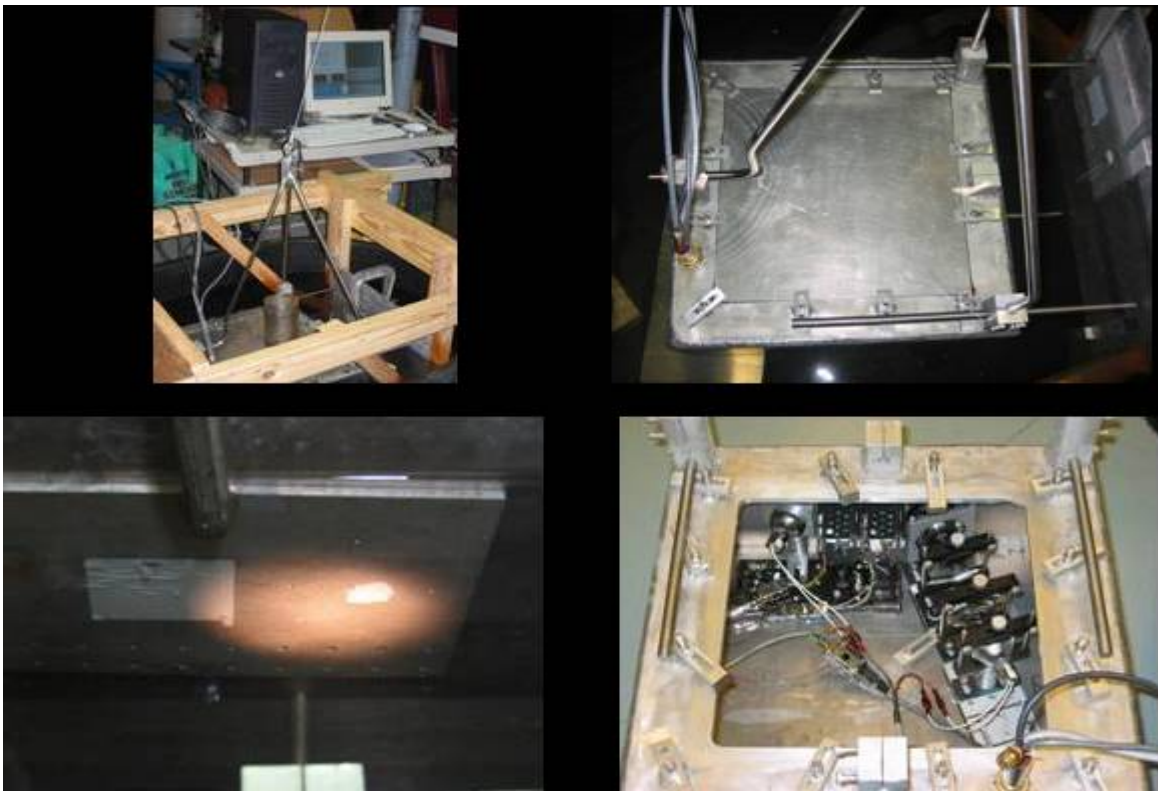


Fig. 2. Setup of simulation experiments conducted at DIAL: (Top-left) the FTP box in the trough and the computer system; (Top-right) the FTP box submerged under water; (Bottom-left)

the target plate illuminated by the fringe pattern projector; (Bottom-right) optical components and cameras inside the box.

Table I. Typical Numerical Results for Aluminum Cones (reference objects).

Exp. #	Camera-to-Target (L) (mm)	Camera-to-Projector (d) (mm)	Measured Peak Height (mm)	Truth Data (mm)	Error (mm)
1	166.9	60.0	5.20	6.31	1.11 (18%)
2	166.9	60.0	9.52	12.98	3.46 (27%)

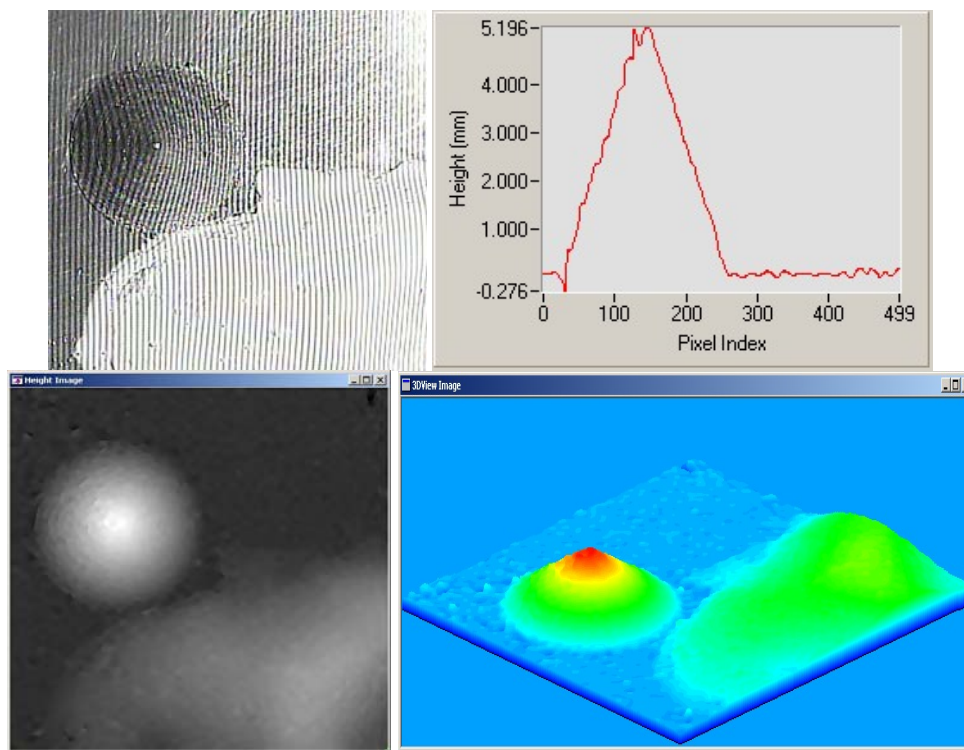


Fig. 3. Typical images generated from the simulation experiments: (Top-left) target image with projected fringe pattern; (Top-right) reconstructed 1-D profile along the horizontal cross section at the peak of the cone; (Bottom left) reconstructed 2-D profile; (Bottom right) reconstructed 3-D profile. There were two targets in this experiment: an aluminum cone with known size, and an irregular target with unknown size made from caulk.

The measurement error was mainly due to distortions of the images of submerged objects. Because of the refraction of light described by Snell's law, images of submerged objects will differ from those of the same object in air. Based on Snell's law of refraction, the method of similar triangles, and geometric identities, a tentative correction procedure has been derived [12]. Consider a FTP camera lens of width w that is a distance L from the bottom surface, as shown in Fig. 4. If h is the true height of the submerged object of interest, h' is the apparent (measured)

height of the object of interest, d is the true distance from the center of the object to a line normal to the FTP camera, d' is the apparent (measured) value of distance d , and p is the depth of the liquid, then

$$h = p - \frac{\tan \theta_{r,1} - \tan \theta_{r,2}}{\tan \theta_{i,1} - \tan \theta_{i,2}} (p - h') \quad (\text{Eq. 4})$$

and

$$d = d' - (p - h') \tan \theta_{r,2} + (p - h) \tan \theta_{i,2} \quad (\text{Eq. 5})$$

where $\theta_{r,1}$, $\theta_{r,2}$, $\theta_{i,1}$, and $\theta_{i,2}$ are defined in Fig. 4 and

$$\tan \theta_{r,1} = \frac{d' + 0.5w}{L - h'} \quad (\text{Eq. 6})$$

$$\tan \theta_{r,2} = \frac{d' - 0.5w}{L - h'} \quad (\text{Eq. 7})$$

$$\tan \theta_{i,1} = \frac{n_r \tan \theta_{r,1}}{\sqrt{n_i^2 + (n_i^2 - n_r^2) \tan^2 \theta_{r,1}}} \quad (\text{Eq. 8})$$

and

$$\tan \theta_{i,2} = \frac{n_r \tan \theta_{r,2}}{\sqrt{n_i^2 + (n_i^2 - n_r^2) \tan^2 \theta_{r,2}}} \quad (\text{Eq. 9})$$

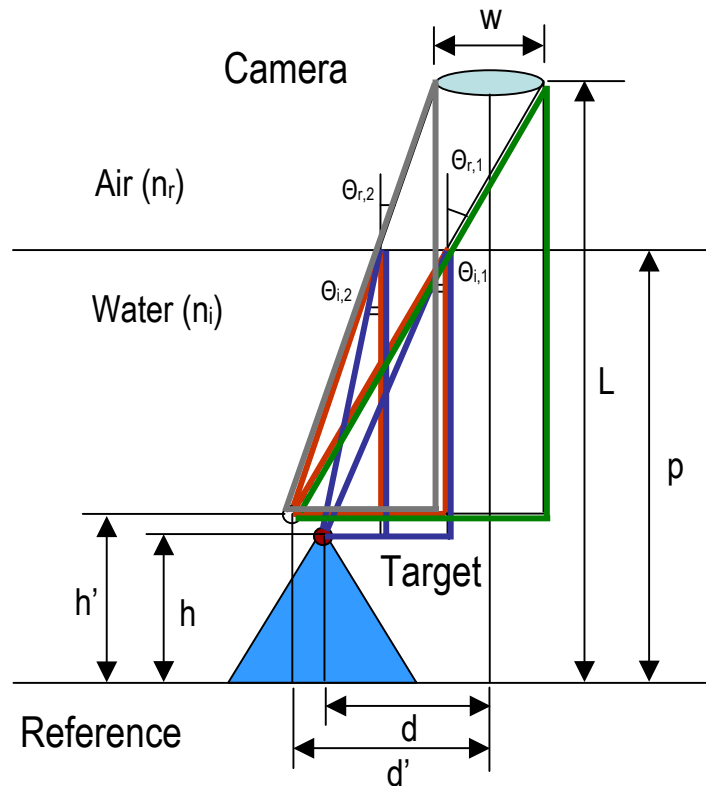


Fig. 4. Schematic defining apparent (measured, as indicated by single prime) and true distances and angles for derivation of correction method

This correction procedure will be tested and improved in the near future. Other procedures for correcting the distortions will also be explored. It is expected that after the application of these correction procedures, the measurement accuracy will be enhanced.

The FTP method requires comparison of an image of the object of interest and of an image of a reference plane at the same distance and under the same experimental conditions. The effect of still and flowing water on the FTP measurement uncertainty has been investigated. The results are summarized in Table II. Mixing target images and reference images acquired under different conditions lead to uncertainty in volume of about 2-3% and to uncertainty in heights of about 6-7%. Therefore, under the current experimental settings, the flowing condition of water expected in the ORRR pool will not introduce significant uncertainty to the measurement results.

Table II. Effect of Various Flow Conditions on Reproducibility of Underwater FTP Determinations.

Conditions	Measured Volume (mm ³)	Measured Max Height (mm)
Target – Still Water Reference – Still Water	229.74	1.17
Target – Flowing Water Reference – Still Water	234.66 (+2.1%)	1.18 (+0.85%)
Difference	4.92	0.01
Target – Still Water Reference – Flowing Water	224.17 (-2.1%)	1.10 (0%)
Target – Flowing Water Reference – Flowing Water	228.86	1.10
Difference	4.69	0.00
Target – Still Water Reference – Still Water	229.74	1.17
Target – Still Water Reference – Flowing Water	224.17 (-2.5%)	1.10 (-6.0%)
Difference	5.57	0.07
Target – Flowing Water Reference – Still Water	234.66 (+2.5%)	1.18 (+6.8%)
Target – Flowing Water Reference – Flowing Water	228.86	1.10
Difference	5.80	0.08

INITIAL SYSTEM DEPLOYMENT

The initial deployment of the submersible FTP probe into the ORRR pool occurred on December 9, 2005 (see Fig. 5). Because of limited time, only a few pit corrosions were examined. At this time, a preliminary report is being prepared. During this initial deployment, only a metal brush was used to remove pit corrosion material from the wall; this removed most, but not all the pit corrosion material. The pit corrosion diameters were not discernible in this initial attempt. We are refining our pit corrosion material removal technique for future deployments. The resistance of the aluminum liner was found to be significantly larger than anticipated as indicated by the inability of our contact sensors to properly sense contact with the walls. The contact sensor system is being redesigned. Since chemical analysis of the pool water has repeatedly shown that it has very low levels of radioactive species, very little radioactivity was expected to be deposited on the exterior of the submersible box; in practice, detectable radioactivity was observed by swabbing the exterior of the submersible box. This may be due to materials previously deposited on the ORRR aluminum liner walls being agitated during cleaning of the walls with a metal brush and subsequent deposit onto the box. Subsequent deployments of the FTP system into the ORRR pool for more extensive pit corrosion characterization are planned for 2006.

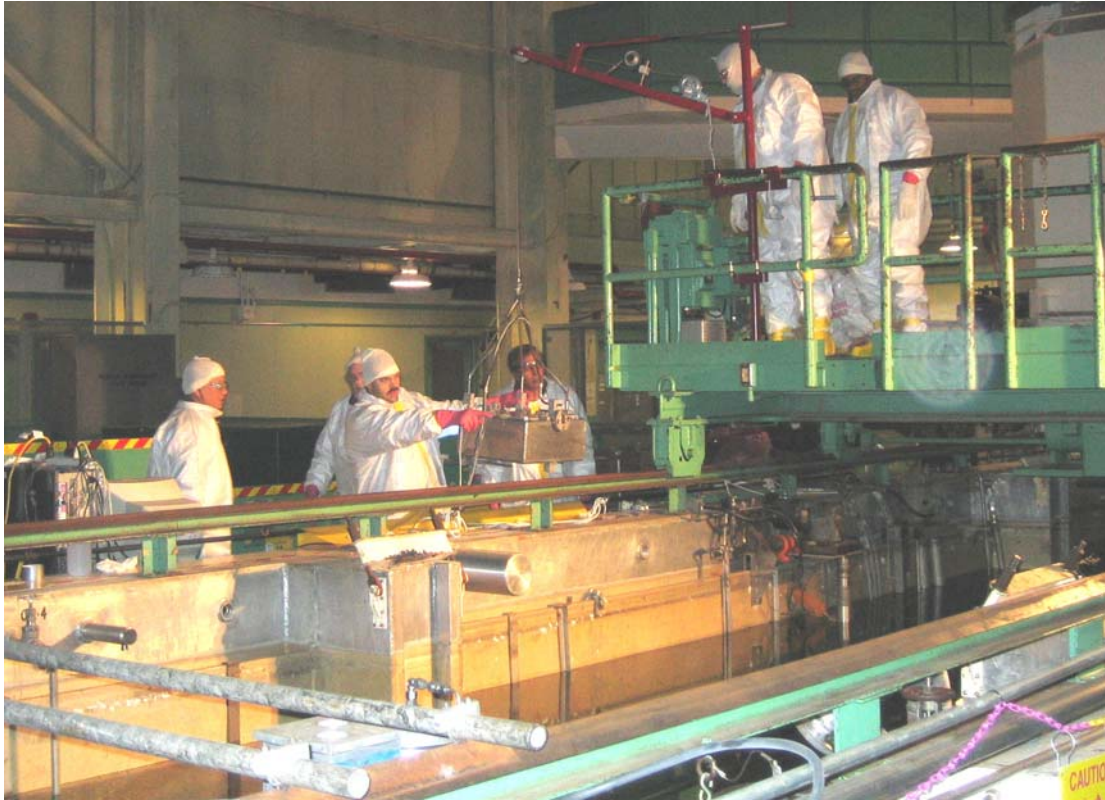


Fig. 5. Initial deployment of submersible DIAL FTP probe system into ORRR pool on December 9, 2005. The submersible FTP probe is being lowered by a winch into the pool, with assistance from DIAL and ORNL personnel.

CONCLUSION

A quantitative imaging system based upon Fourier-transform Profilometry is being developed and an initial deployment to characterize the extent of pit corrosion in the aluminum liner of the Oak Ridge Research Reactor pool has occurred. A preliminary report is being prepared; subsequent deployments are planned for 2006. The precision and accuracy of this system have been characterized under simulated conditions. The results of the corrosion characterization effort will enable DOE EM to make reliable decisions with regard to disposition of the ORRR pool.

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