Evaluation of Fourier Transform Profilometry for Quantitative Waste Volume Determination under Simulated Hanford Tank Conditions – 8106

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ABSTRACT

The Hanford Site is currently in the process of an extensive effort to empty and close its radioactive single-shell and double-shell waste storage tanks. Before this can be accomplished, it is necessary to know how much residual material is left in a given waste tank and the chemical makeup of the residue. The objective of Mississippi State University's Institute for Clean Energy Technology's (ICET) efforts is to develop, fabricate, and deploy inspection tools for the Hanford waste tanks that will (1) be remotely operable; (2) provide quantitative information on the amount of wastes remaining; and (3) provide information on the spatial distribution of chemical and radioactive species of interest. A collaborative arrangement has been established with the Hanford Site to develop probe-based inspection systems for deployment in the waste tanks. ICET is currently developing an in-tank inspection system based on 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 (and hence volume distribution) of the target surface, thus reproducing the profile of the target accurately under a wide variety of conditions. Hence FTP has the potential to be utilized for quantitative determination of residual wastes within Hanford waste tanks. We are conducting a multi-stage performance evaluation of FTP in order to document the accuracy, precision, and operator dependence (minimal) of FTP under conditions similar to those that can be expected to pertain within Hanford waste tanks. The successive stages impose aspects that present increasing difficulty and increasingly more accurate approximations of in-tank environments. In this paper, we report our investigations of the dependence of the analyst upon FTP volume determination results and of the effect of gamma radiation on FTP camera and optical components.

INTRODUCTION

As part of an on-going, nation-wide effort to environmentally remediate sites where radioactive materials have been processed for the U.S. government, the U.S. Department of Energy (DOE) is engaged in efforts to retrieve wastes stored in tanks at a variety of DOE sites, including Hanford, Oak Ridge, and Savannah River. Because of the volume of wastes involved, the tank closure effort at the Hanford site is the most extensive and involves both its single-shell tanks (SSTs) and double-shell tanks (DSTs)[1-4].

Before a waste tank can be closed, it is necessary to know how much residual material is left in a given waste tank and the chemical makeup of the residue. Mississippi State University's Institute of Clean Energy Technology (ICET) is engaged in efforts to develop, fabricate, and deploy inspection tools for the Hanford waste tanks that will (i) be remotely operable; (ii) provide quantitative information on the amount of wastes remaining; and (iii) provide information on the spatial distribution of chemical and radioactive species of interest. A collaborative arrangement has been established with the Hanford Site to develop probe-based inspection systems for deployment in the waste tanks.

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. ICET has previously demonstrated that its FTP system can quantitatively estimate the volume and depth of removed and residual material to high accuracy.

ICET's inspection approach is to independently and quantitatively estimate the amount of residual waste by using Fourier-transform profilometry (FTP). FTP was developed by ICET for inspection of an off-line Joule-heated melter at the West Valley Demonstration Project [5]. A submersible version of the ICET FTP system has been deployed in the Oak Ridge Research Reactor pool to characterize aluminum pit corrosion [6]. To date, the ICET FTP system has obtained preliminary results utilizing conditions appropriate for the Hanford waste tanks [7,8].

METHOD OF FOURIER TRANSFORM PROFILOMETRY

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique
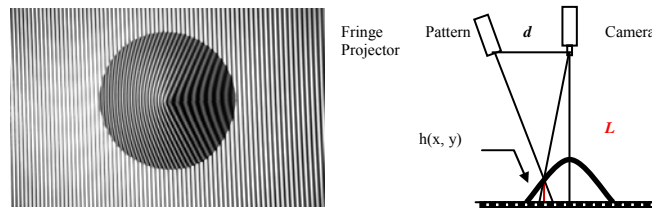

Figure 1. Diagram illustrating the principle of Fourier-transform profilometry.

[9]. 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.

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 [9], the height distribution of the target surface is easily calculated by using Eq. (1).

$$h(x, y) = \frac{L \Delta \Phi(x, y)}{\Delta \Phi(x, y) - 2\pi d f_0} \qquad \text{Eq. (1)}$$

where $\Delta \Phi(x, y)$ gives the phase modulation due to the object-height elevation, $h(x, y)$; L_0 is the distance from the camera aperture to the reference plane; d is the distance between apertures of the projector and of 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).

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

where

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

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_0 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.

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 residual material remaining in waste tanks.

FTP EVALUATOR DEPENDENCE

In order to investigate the dependence of FTP volume determinations upon the evaluator, the six non-descript targets were each photographed in different orientations (0°, 72°, 144°, 216°, and 288°) obtained by rotating the targets. This resulted in a data set of 30 images which were subsequently independently analyzed by four members of the ICET FTP team (MM, PRJ, OPN, and ZL). Fig. 2 presents FTP images obtained by rotating one non-descript target.
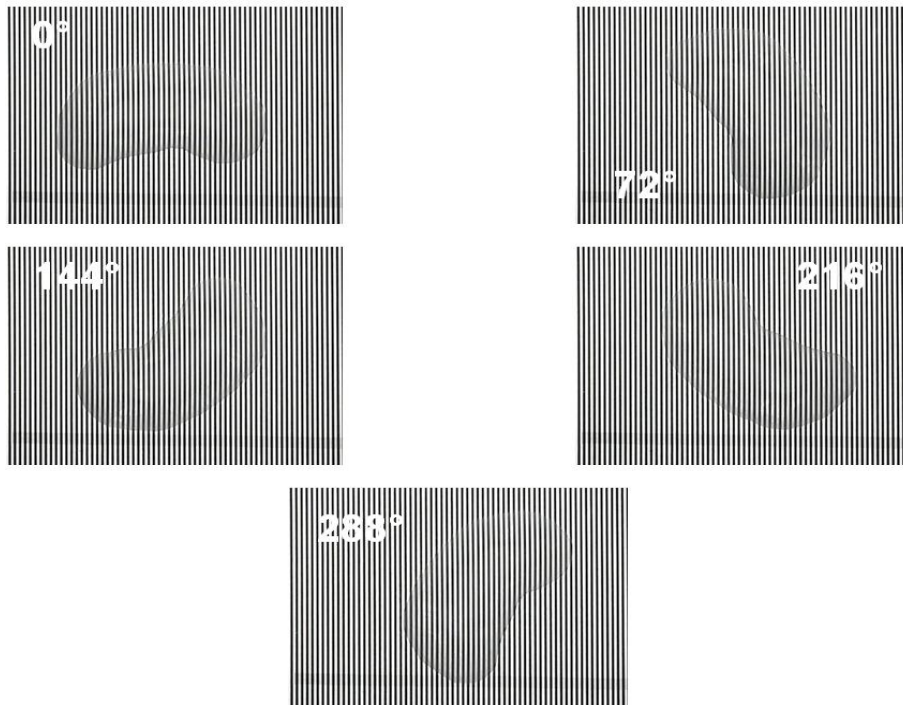

Figure 2. FTP images of non-descript target photographed in five different orientations.

Table I presents the average relative error for each of the independent evaluators for each of the targets, averaged over the FTP determinations of the five different orientations

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obtained by rotating the target. The average listed for each analyst is the average relative error for the 30 volume determinations. The maximum and minimum for each analyst are the maximum and minimum relative errors among the entire set of 30 volume determinations. It can be seen that there is significant difference between the results from most experienced FTP evaluator (ZL, our primary FTP evaluator) and the least experienced (MM). Two of the evaluators (PRJ and ZL) have extensive previous experience with FTP analysis and two of the evaluators (MM ad OPN) had no previous experience with FTP analysis. There is much greater variability among the target relative errors for the previously inexperienced operators than for the experienced evaluators; this variability for the inexperienced operators is due in part to a "learning curve"—i.e., the first targets evaluated have higher errors than the last targets evaluated and the previously inexperienced analysts had no training sessions prior to beginning analyzing these images. In order to simulate an inexperienced evaluator, PRJ, an experienced evaluator, deliberately made errors that he felt an inexperienced evaluator would make; this is reflected in his relatively large relative errors.

Table I. Average relative error (%) in FTP volume determination of non-descript targets by four ICET evaluators.

Target	"True" Volume	MM	PRJ	OPN	ZL
S5	421.8 cm^3	103.8%	25.15%	-3.9%	-1.5%
S6	647.1	48.3%	31.4%	8.05%	4.3%
S1	1027.8	15.1%	25.9%	13.0%	3.4%
S2	1070.2	11.9%	35.8%	9.6%	3.2%
S4	1070.65	50.0%	25.5%	3.5%	0.7%
S3	1954.1	5.8%	19.25%	6.7%	3.0%
Average (Min, Max)		39.15% (1.05, 113.6)	27.2% (7.6, 48.8)	6.2% (-12.2, 28.0)	2.2% (-5.2, 7.8)

With regard to the question of whether target volume affects operator reproducibility, the answer (given the current evaluator reproducibility results) depend upon whether or not MM's results are included or not, and if included, how. The results for the various targets are summarized in Table II. As noted above, MM is a technician with no previous experience with FTP and the range of her FTP volume determination errors is significantly greater than those of the other three evaluators; this wider range of error is due to a "learning curve." When all of MM's results are included, a linear regression yields relative error (%) = 32.5% + (–0.01341)*"true" volume (cm^3), with a goodness-of-fit R^2 value of +0.820 and a standard error of 3.68. Consequently, the trend is that the larger the target volume, the smaller the relative error. However when all of MM's results are omitted, a linear regression yields relative error (%) = 11.7% + (+0.000143)*"true" volume (cm^3), with an R^2 value of 0.00042 and a standard error of 4.11. The trend is then that the relative error is independent of target size; this conclusion is supported both by the slope (which is essentially zero) and by the R^2 value (which indicates that the average relative error and the target's true volume are completely independent of each other). If it is assumed that MM's results for S4, S5, and S6 constituted a training session and include

MM's results for S1, S2, and S3 with those of the other evaluators, a linear regression yields relative error (%) = 12.1% + (–0.00054)*"true" volume (cm^3), with an R^2 value of 0.0061 and a standard error of 4.03. Again the trend is that the relative error is independent of target size. It should be pointed out that all the targets are relatively small: the largest target volume (1954.1 cm^3) is only 0.06900 ft^3. A more extensive investigation will be required to characterize the volume dependence (if any) for larger volumes. However, the present results clearly demonstrate that reliable volume determinations can be obtained by even previously unexperienced evaluators using the FTP technique.

Table II. Average relative errors (ARE) for the six non-descript targets, including and omitting the results of MM. The relative errors are in %; the uncertainties correspond to one standard deviation.

Target	"True" Volume	ARE w MM	ARE w/o MM
S5	421.8 cm^3	30.9 ± 45.4	6.6 ± 15.8
S6	647.1	23.0 ± 20.8	14.6 ± 15.15
S1	1027.8	14.3 ± 12.1	14.1 ± 13.5
S2	1070.2	15.1 ± 14.7	16.2 ± 16.6
S4	1070.65	19.9 ± 21.5	9.9 ± 13.7
S3	1954.1	8.7 ± 8.2	9.65 ± 9.05
Average		18.7 ± 20.45	11.8 ± 14.2

EFFECT OF RADIATION ON CAMERA PERFORMANCE

The ability to obtain reliable results from FTP images is dependent upon obtaining images of sufficient image quality. Since radiation is known to degrade camera performance, we have investigated the effect of prolonged gamma radiation on the performance of the cameras and optical components (specifically Ronchi filter and optical diffuser) used in the ICET FTP system. MSU's Cs-137 gamma irradiator (CDV 794 model 2) has an irradiation chamber of 8 inches (20 cm) length by 13.5 inches (34 cm) wide by 11 inches (28 cm) tall. The floor of the chamber is tilted at 45°; a holder/base was inserted so that the components were held horizontally. The nominal maximum irradiation rate in the center of the chamber is 306 roentgen (R)/hour. There are three lower irradiation rates: each successive rate is an order of magnitude weaker than the previous one. In order to characterize how the gamma radiation rate varies with position within the irradiation chamber, ten pocket chamber dosimeters (0-20 R range) were positioned in the gamma irradiation chamber, as shown in the drawing and photo in Fig. 3. The results of this characterization are presented in Table III.

A calibration diagram drawn on a 1/16-inch thick stainless steel plate was placed right in front of the camera, against the opposite wall of the chamber to which the camera was pointed. The stainless steel plate with calibration diagram is utilized 1) to simulate the housing of the FTP probe and 2) to check if the camera's sensors are functional. During the test process, the camera periodically (initially every five minutes) captured images of the calibration diagram. Consistently darkened or brightened pixels ("bad pixels") are an indication that the camera's sensors have been damaged.
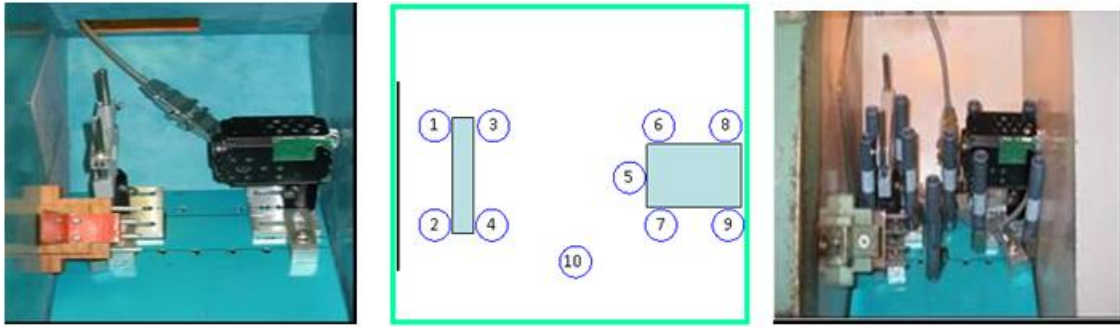
Figure 3. From left to right, photograph of camera and FTP optical components (Ronchi filter and optical diffuser mounted side-by-side in aluminum filter mount) inside gamma radiation chamber; schematic of location of ten pocket chamber dosimeters; and photograph of pocket chamber dosimeters and FTP camera and components in chamber.

Table III. Cs-137 gamma radiation rate (in R/hour) as a function of position with radiation chamber.

Location	R/hour
1	54
2	60
3	34.5
4	32.7
5	21.6
6	12.6
7	15
8	12
9	12
10	3

For these studies, a color SONY FCB-78B block camera was used since it is similar to cameras currently used for waste tank inspection. The Ronchi filter (which has black lines on BK7 glass) and the diffuser (which is polycarbonate plastic mounted in a metal mounting ring) are located side-by-side using an aluminum lens holder with a space in between (Fig. 4). This assembly is placed between the camera and the calibration diagram plate, close to the calibration diagram plate (Fig. 3). A piece of thin metal (not shown in Fig. 3) was placed between the camera and the light bulb inside the test chamber; in this way, the camera viewed light that was transmitted through the diffuser, through the Ronchi filter (rather than light that reflects off their front surfaces), and also from the thin metal sheet. The position of the assembly guaranteed that the camera was focused on both the assembly and the calibration diagram plate at the same time so that in a single image, both were observed. In order to test for color fidelity of the camera, four colored lines (each a different color) were drawn on the thin metal sheet; these lines were positioned so to appear in the camera image between the Ronchi filter and the diffuser (Fig. 4).
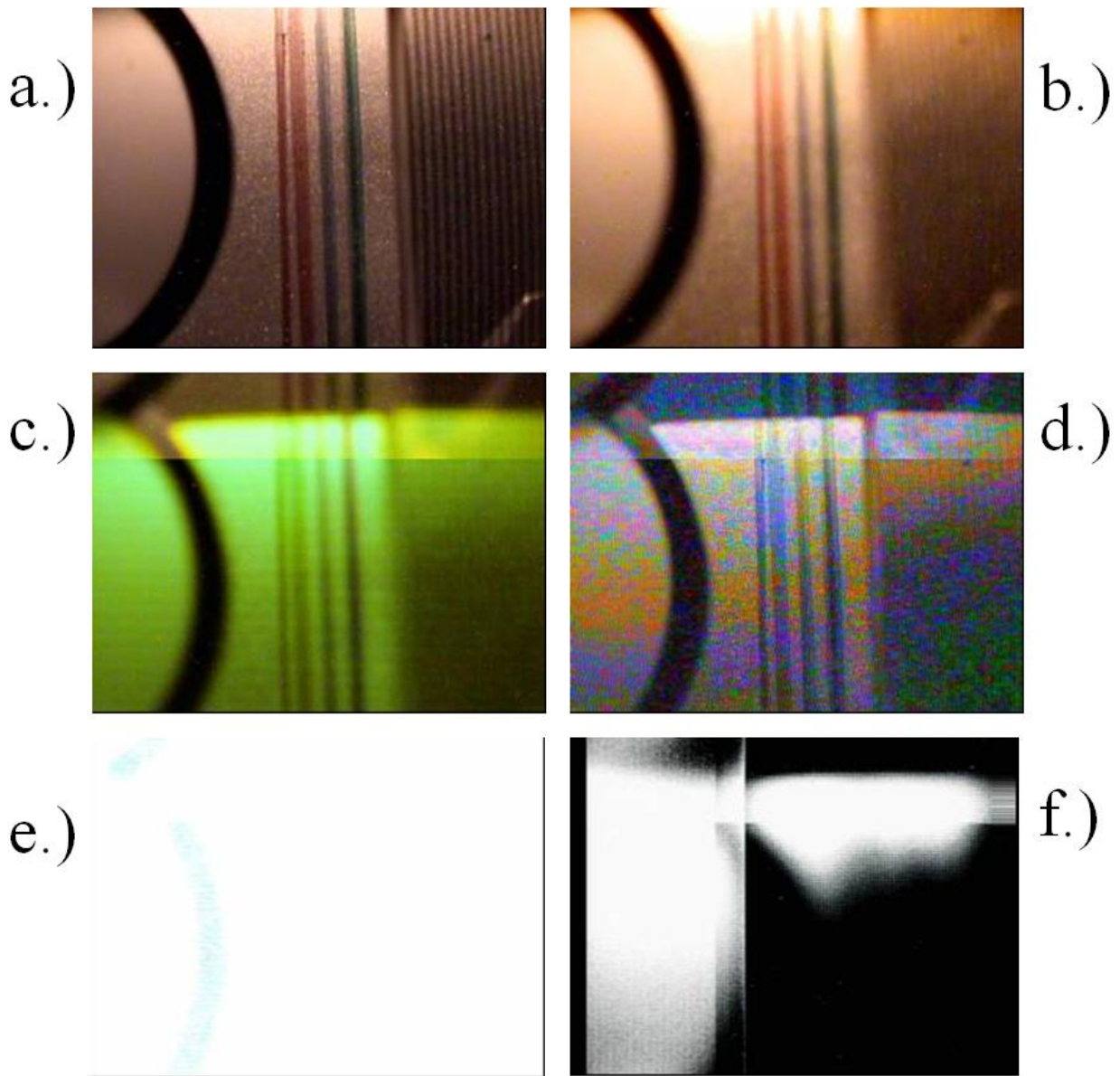
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Figure 4. Photographic images of diffuse (left part of images), colored lines (center of images), and Ronchi filter (right of images). a.) Typical image acquired at beginning of gamma radiation testing. b.) Image acquired during 182nd hour of testing. c.) Image acquired during 193rd hour of testing. d.) Image acquired during 197th hour of testing. e.) Image acquired during 198th hour of testing. f.) Image acquired during 207th hour of testing.

As mentioned above, the camera captured images periodically during the test process. In addition to the bad pixels, the images were also checked to see if there were any changes in the appearance of either the Ronchi filter or the diffuser (Fig. 4). Any changes observed indicate property changes of the materials. Changes were monitored "off-line" by a computer remotely located at ICET. The average intensity within each of the

selected regions of interest (ROI) was determined after each image was stored. There was one ROI for the diffuser, one ROI for the Ronchi filter, and one other ROI that covered the whole image and was used as an indication of the camera sensors integrity.

To detect changes for one specific ROI between two stored images, average intensity value for that ROI in one image were subtracted from the value in the other image. Assuming that radiation exposure within that ROI is constant over time, this subtraction cancels out the extra intensity value due to incoming gamma rays and exactly reveals changes caused by material degradation. To verify the constancy assumption, 100 images were saved at a 0.5-second interval within the first minutes of the start of the test. The average and standard deviation of the intensity were calculated for the selected ROIs using these initial images and verified the constancy assumption.

To make periodic image acquisition possible, the camera was to be connected to a computer outside the test chamber and located right beside the gamma irradiation unit. During the test process, that computer continuously controlled image acquisition and saved the captured images both on a hard drive on that computer and also (via wireless transmission) on a network hard drive located at ICET. The images were stored on both hard drives in case there should be a temporary problem with wireless transmission. The images stored on the ICET hard drive were examined during the test to determine whether the test should continue or be terminated.

During the test, the camera was placed in manual mode with fixed parameters. With ICET's camera control software, the camera continuously captured images of the Ronchi filter and the diffuser and saved an image for every five minutes. Before each image was saved, a lens initialization procedure was implemented to initialize/move the zoom and focus of the camera lens. The camera parameters were then reset to their original values and an image was saved. A successful camera lens initialization indicates that all involved components of the camera, such as motors, gears, and signaling cables, work properly. The results of this examination/exercise show up in the saved image right after the procedure.

Low Dose Gamma Radiation Test

Initially a test at a low radiation level was conducted. The camera and FTP components were positioned as shown in Fig. 3. This test lasted for a period of 62 days of continuous exposure. The Ronchi filter and light diffuser were exposed to ~45 R/hr, camera front end was exposed to ~21.6 R/hr, and the camera CCD (charge coupled device) detector, which is located near the back end of the camera module) was exposed to ~12 R/hr. The accumulated gamma radiation exposure was calculated to be about 66 kR, 32 kR, and 17 kR for filter/diffuser, camera front lens, and camera CCD, respectively. During this test period, images of the test components were periodically captured and saved. An analysis of saved images reveals that, the average intensity levels within selected regions of interest for each component do not show any obvious changes throughout the test. This consistency indicates that there were no significant property changes caused by the gamma radiation in the component materials. After one week of the testing, several bad

pixels were observed. These bad pixels remained for several weeks and then disappeared near the end of the test. There were no other bad pixels observed except for these "self-recovered" ones. With the lens initialization procedure implemented before each image was saved and the 19000+ saved images, the integrity of camera components were maintained throughout this test.

High Dose Gamma Radiation Test

A second radiation test at a much higher radiation rate level was performed and camera moved so that the camera's CCD sensor was located at 4.5" (11.4 cm) from the irradiation-side wall. For this test, a new set of test materials were utilized, including a new camera. With the new scale and location, the diffuser and Ronchi filter were irradiated at 466 R/hr and the camera CCD was irradiated at 215 R/hr. This test of high rate exposure lasted for approximately 9 days (214 hours), with a total accumulated radiation exposure of 46 kR for the CCD sensor and 100 kR for the diffuser and Ronchi filter.

The first camera abnormal performance was observed during the 170th hour. The camera video out synchronization signal did not properly work for about 2 hour and then system re-synced itself. During the 182nd hour, camera video out synchronization signal again failed to operate properly for about three hours, at which time, the system re-synced itself, but images were out of focus and overexposed, as shown in Figure 4 (b). During the 193rd hour, there were not only problems with focus, exposure, and synchronization, but also greenish streaks occur all over the picture, as shown in Figure 4 (c). During the 197th hour, the greenish streaks changed to colored streaks, as shown in Figure 4 (d). During the 198th hour, the image became mainly white with a "color" ring from the diffuser mounting ring, as shown in Figure 4 (e). During the 207th hour, the images become black and white, as shown in Figure 4 (f). While the black-and-white image pattern stayed the same and the white intensity decreased over time, the system stopped saving images after the 214th hour.

After the high radiation level, visual examination of tested components reveals that: 1) the Ronchi filter (BK7 glass) turned a light yellowish color; 2) there is no obvious deterioration of the diffuser (polycarbonate), but it does show decreased light transmission when compared with a diffuser of the same type, but without exposure to radiation; and 3) the camera lens shows light yellowish color, too.

It should be noted that the tested camera (total gamma radiation exposure of 46 kR on CCD sensor) exceeded the destruction gamma exposure expected by Hanford personnel [10]. The experience of Hanford is that cameras, similar to ours, typically have 25% bad pixels with an accumulated radiation exposure of about 15 kR, and are typically "dead" with an accumulated radiation exposure of about 20 kR.

SUMMARY AND CONCLUSIONS

We have demonstrated that volume determination using the Fourier transform profilometry (FTP) technique is relatively insensitive to evaluator. Moreover, good results can be obtained, even by previously inexperienced evaluators.

Since FTP utilizes a black-and-white grid pattern, it is not sensitive to degradation of the color fidelity of the camera system. Thus, preliminary results suggest that reliable FTP data can be obtained almost until complete equipment failure due to radiation damage. Additional radiation damage testing is planned to explicitly investigate degradation of FTP measurement uncertainty as a function of total accumulated gamma radiation exposure.

ACKNOWLEDGMENTS

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