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In-Tank Photo Analysis

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September 1995

Prepared for
the Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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Executive Summary

This report documents an analysis performed by Pacific Northwest Laboratory (PNL) of photographs showing the interior of a single shell tank (SST) at the Hanford site. This report shows that in-tank photos can be used to create a plan-view map of the waste surface inside a tank, and that measuring the elevation of the waste surface from the photos is possible, but not accurate enough to be useful at this time.

In-tank photos were acquired for Tanks BX111 and T111. The BX111 photos were used to create the waste surface map and to measure the waste surface elevation. T111 photos were used to measure the waste surface elevation. Uncertainty analyses of the mapping and surface elevation are included, to show the accuracy of the calculations for both methods.

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1.0 Introduction

The Hanford site has 149 single shell tanks containing radioactive and toxic waste. One way to monitor the contents of a tank is to lower a camera into the tank and take pictures. These in-tank photos show the surface of the waste, the walls, the risers (pipes), and sometimes the dome (roof). Such visual monitoring can provide information about the waste inside a tank that is not available through any other source.

The current uses for in-tank photos are to create a collage of the waste surface, to monitor instruments, and to follow general changes of the waste surface and walls. Unfortunately, the photos distort the inside of the tank as a result of the camera position above the waste surface. The distortion prevents the photos from being used to make measurements of features in the tank such as the size of a piece of solid crust. Figure 1 is an example of a photo before the distortion is corrected and Figure 2 is that same photo shown after the distortion is corrected.

One way to gain more information from in-tank photos is to correct the distortion and use the corrected photos to make an accurate plan-view map of the waste surface (waste surface map). The distortion is corrected by transforming the image from the perspective of the camera looking across the waste surface to an undistorted point of view of looking directly down onto the waste surface of the tank from a large distance, as if the top of the tank had been removed. The undistorted view is a result of making the apparent viewing distance from the waste surface so large that light rays reflected from the surface are parallel. The plan-view map of the waste surface is useful for making quantitative measurements of the waste surface, and for identifying the waste surface directly below each riser. Tank BX111 photos taken in July, 1993 are used in this report to make a waste surface map. The BX111 map, Figure 3, shows where the surface of the waste is solid crust (light) and where it is liquid (dark). Figure 3 also shows the orientation of the solid crust pieces relative to each other and to the riser locations.

Another way to derive information from in-tank photos is to use one photo to calculate the surface elevation in the tank. The calculation is possible only if the photo shows at least one riser and its reflection in the waste surface. Figure 4 is a drawing from a photograph in Tank T111, taken in May, 1994, that shows several risers and their reflections. The photo was used to calculate the surface elevation in the tank. From the BX111 photos used to make the waste surface map, one photo was also suitable for a surface elevation calculation.

An analysis of the transformation procedure that generates the surface map of BX111 reveals how sensitive the photos are to the position of the camera, and how accurately the position of the camera must be known in order to get an acceptably small amount of uncertainty in the undistorted (perspective-transformed) image. This analysis is important in showing what changes in the photography process are needed to increase the accuracy of a waste surface map. An analysis of the surface elevation calculations in Tanks T111 and BX111 shows how sensitive the surface elevation is to the inputs of the calculation, and where changes could be made to increase the accuracy.

FIGURE 1 In-Tank Photo before distortion correction.

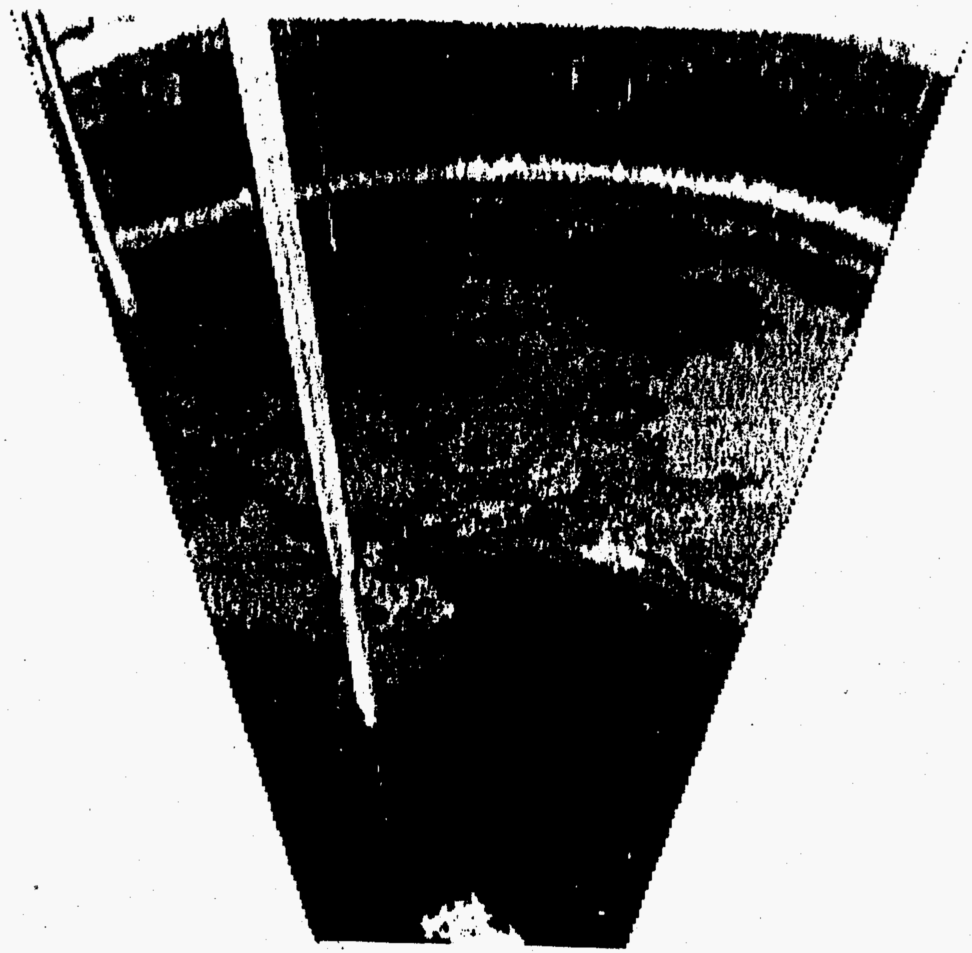

FIGURE 2 In-Tank Photo after distortion correction.

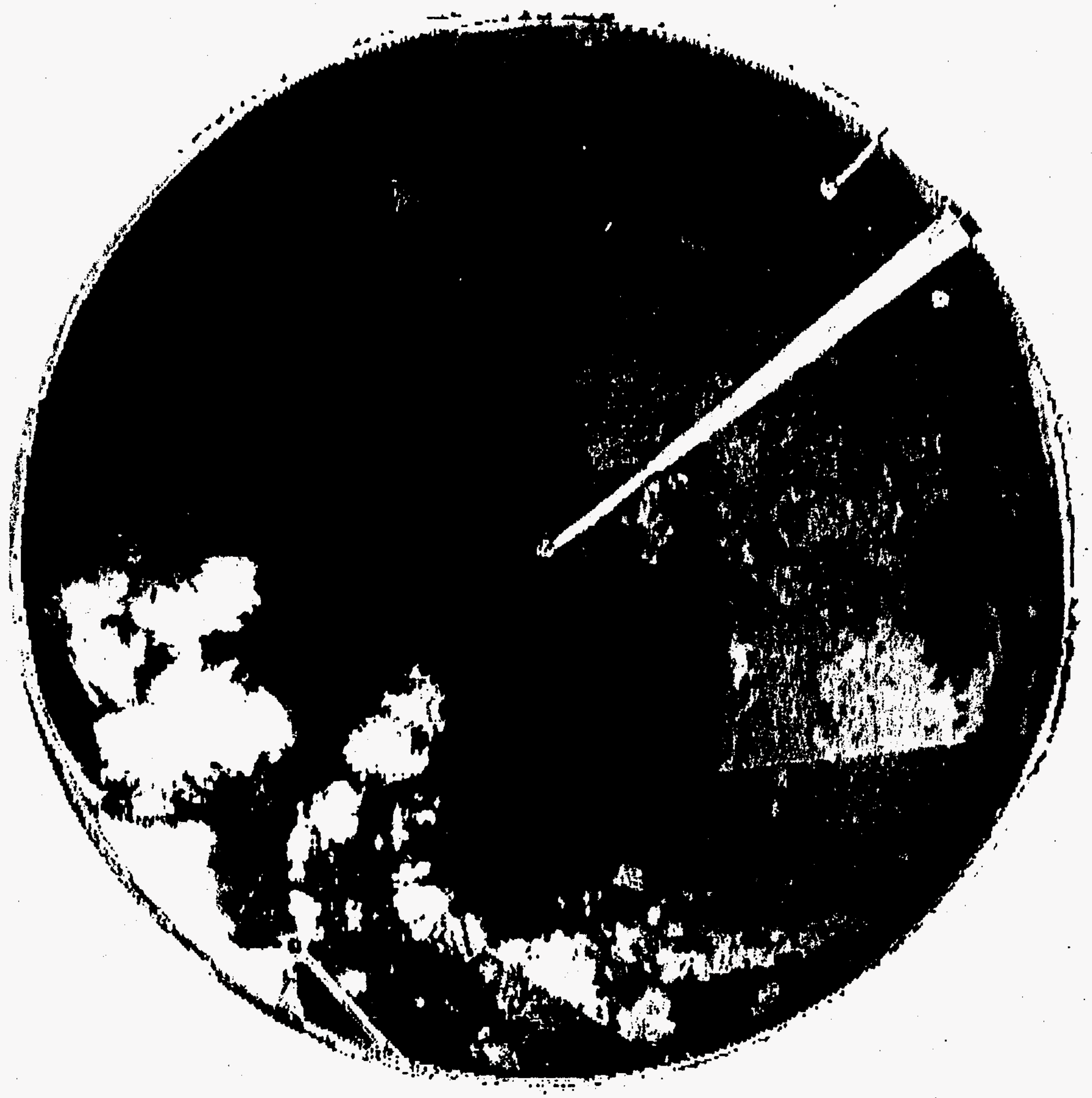

FIGURE 3   Waste surface map of tank BX111.

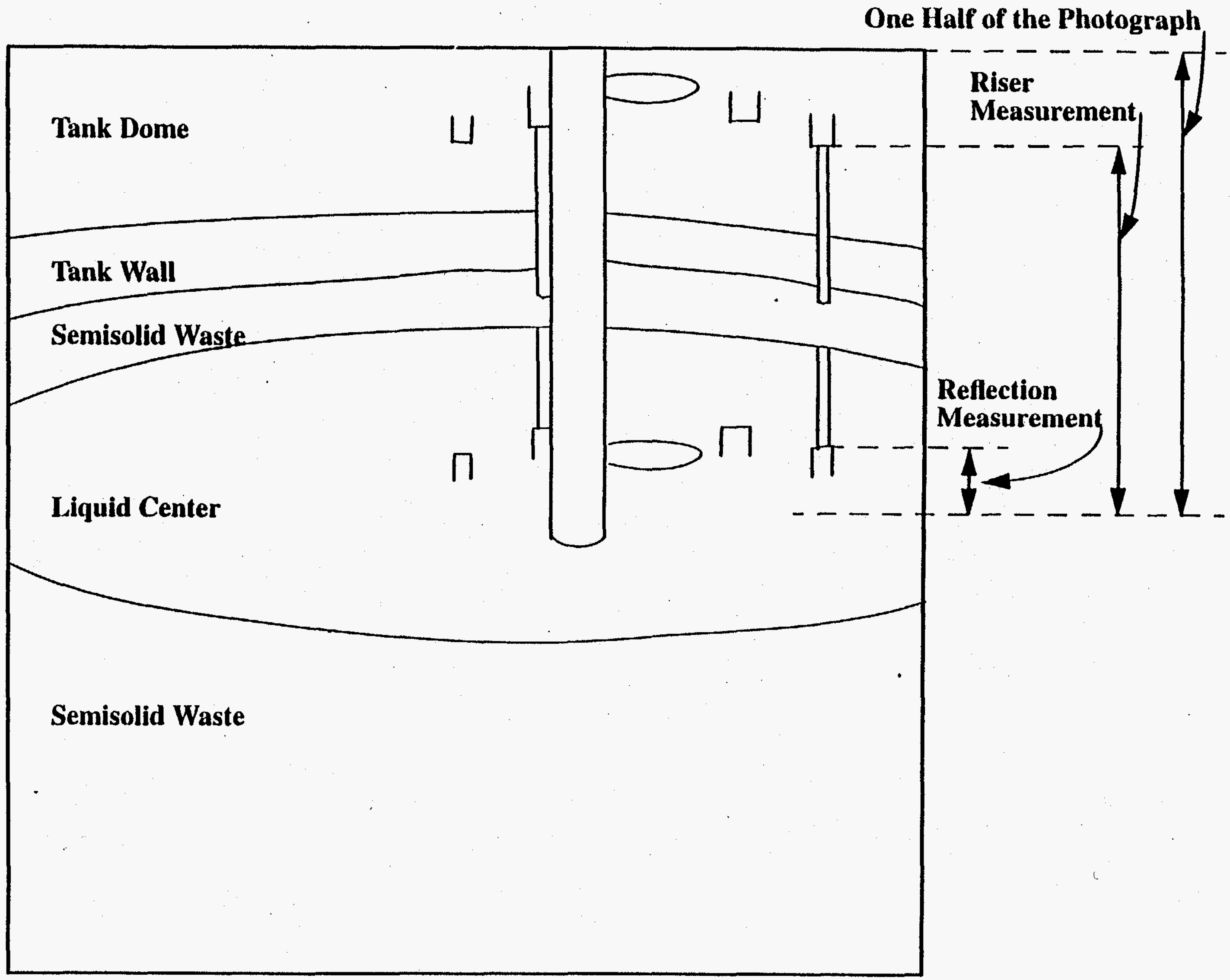

FIGURE 4 Drawing of photograph from tank T111 used for surface elevation calculations.

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2.0 Background

BX111 is a 550,000-gallon tank 75 feet (23 m) in diameter by 18 feet (5.5 m) tall. The tank bottom is slightly dished for a total of one foot (.3 m) in the center of the tank, and the dome (or roof) of the tank rises 12 feet (3.7 m) above the top of the side wall at the center of the tank. Figure 5 is a general tank cross-section, showing the camera position.

The camera that is lowered into the tank through a riser uses 2 1/4 inch (60 mm) color film with a Hassiblad 80 mm lens. The lighting for the photos comes from a flash attached above the camera. The camera is attached to a rigid metal frame (cage) that is attached to a flexible hose, and the cage and camera are surrounded with plastic. The camera-cage-hose assembly is lowered into the tank and then rotated as a unit before snapping each picture.

Inside the cage, the platform on which the camera is mounted can be tilted to hold the camera at any angle from horizontal. The photographers regularly use three approximate tilt angles to capture the entire waste surface on film: -20 degrees, -50 degrees, and -80 degrees from horizontal. These tilt angles are approximate because they are set by aligning the camera platform with a mark on the cage. With the camera positioned at each tilt angle, the camera-cage-hose assembly is rotated to take a series of photographs. For the BX111 map, six photographs were used from the -20 degree tilt series, nine photographs from the -50 degree tilt series, and four photographs from the -80 degree tilt series. Figure 6 shows the fields of view of the camera at the different tilt angles. Figure 7 shows how the three series of photographs cover the entire waste surface. For Tank T111, the tilt angle was approximately -10 degrees from horizontal, since the photos were intended to show the liquid waste surface at the center of the tank, and not the entire waste surface.

The waste in the tanks being photographed is often, though not always, radioactive. This poses a health risk to the person whose job it is to take the pictures. To minimize personal exposure, and exposure of the film to radioactivity, the photographer rotates the camera and snaps the pictures very quickly. This causes the camera and cage to swing while the pictures are taken. The swing affects the camera's tilt angle, its height above the waste, and its position under the riser; all of which are inputs to the perspective transformation that corrects the distortion in the image.

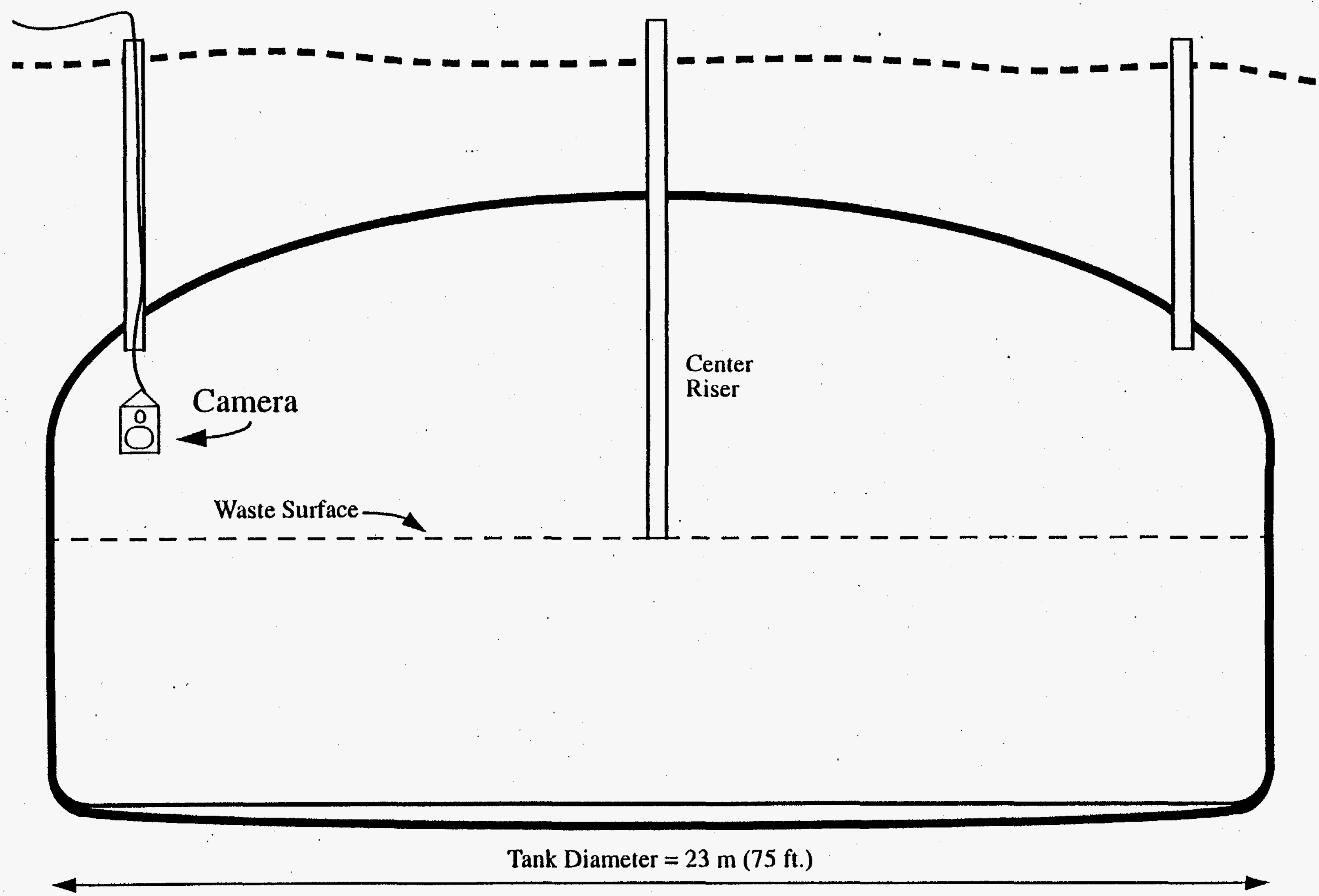

FIGURE 5 Single shell tank cross section.

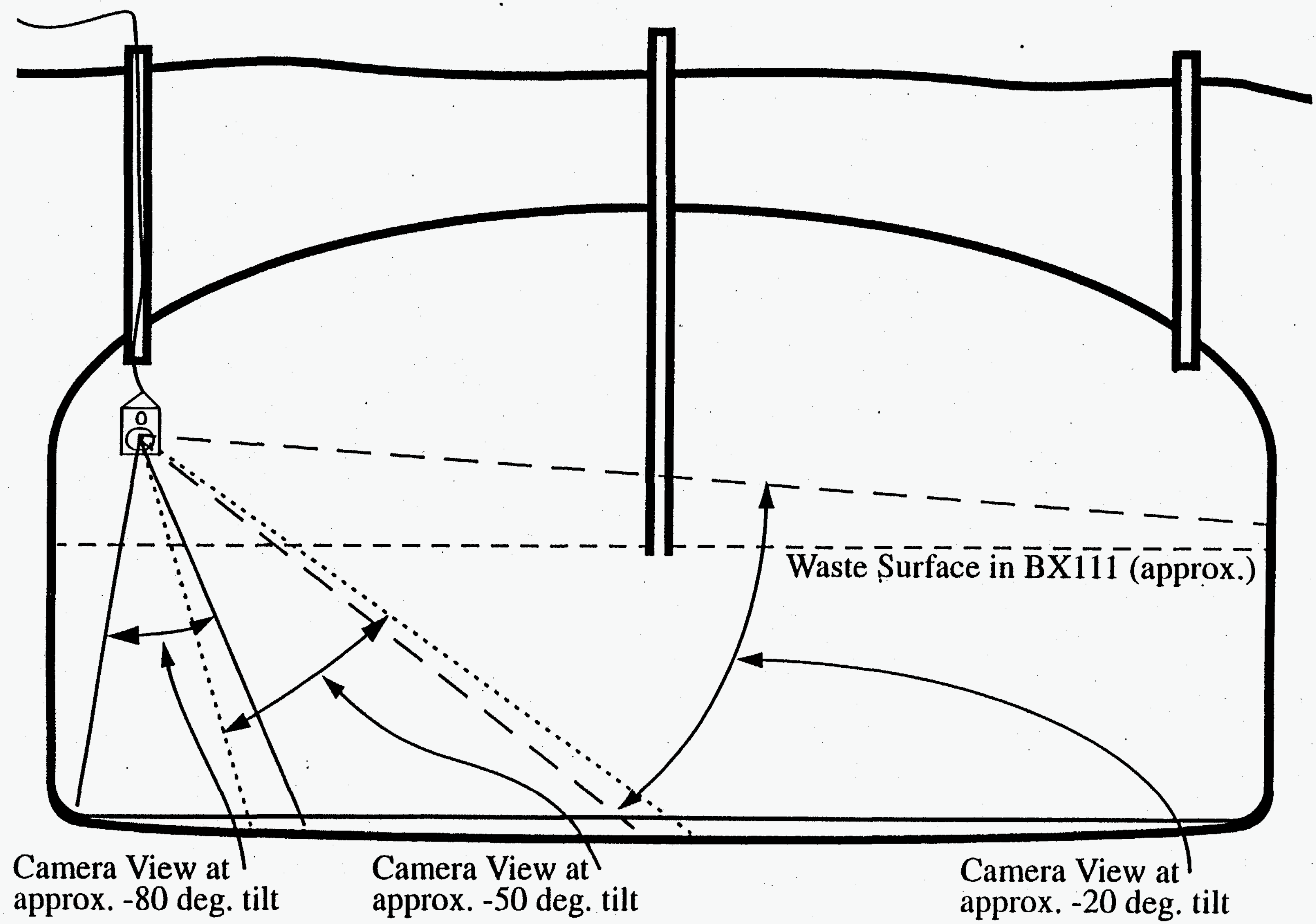

FIGURE 6   Camera positions and fields of view at approximately -20°, -50°, and -80°.

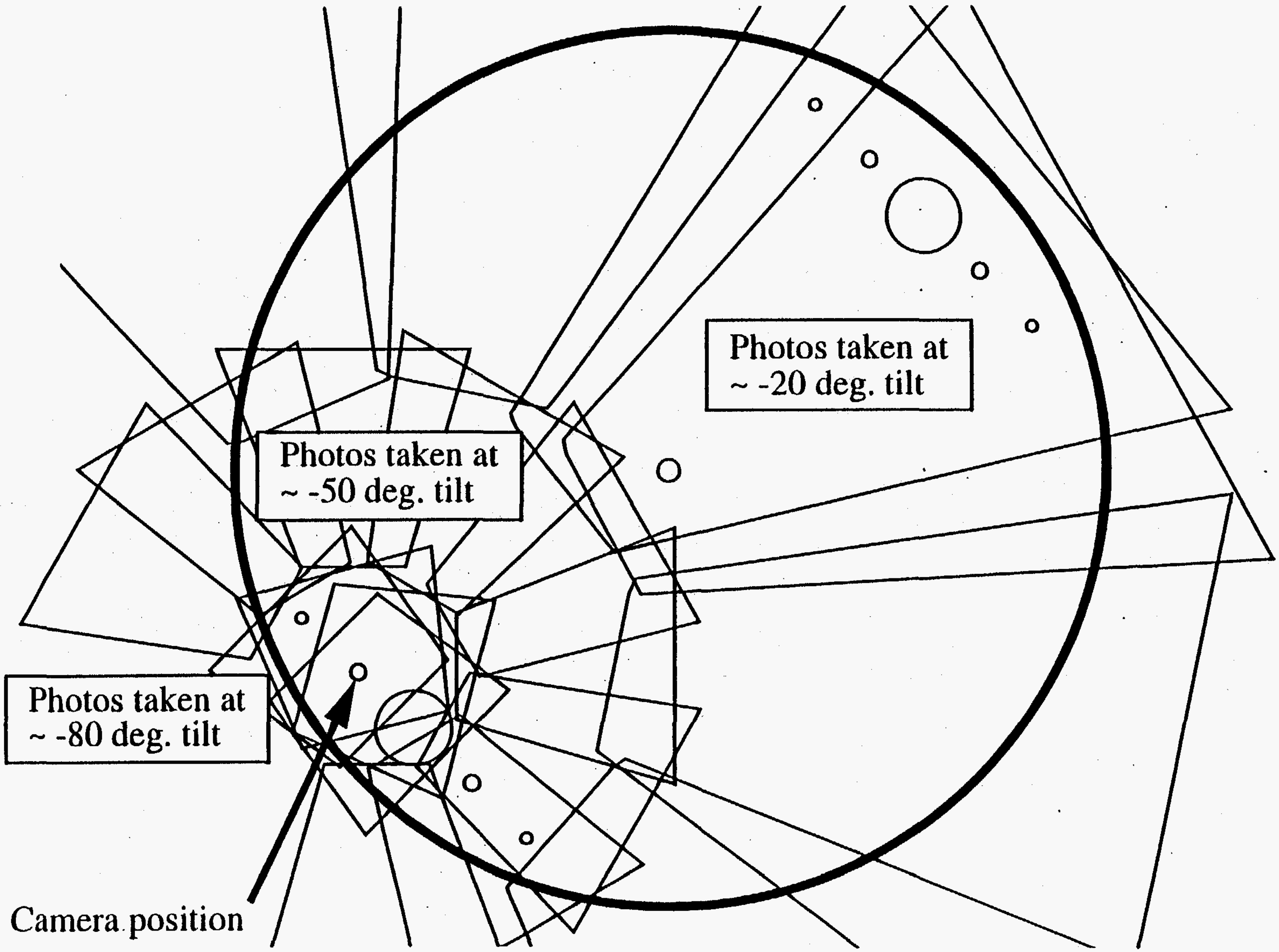

FIGURE 7 Plan view of a tank showing riser locations and outlines of 19 photographs that cover the waste surface.

3.0 Tank Waste Surface Mapping

3.1 Geometry to correct perspective distortion

Figure 8 shows the geometry of the perspective transformation that corrects the distortion in the image. The negative is positioned above the waste at the left side of the figure. The transformed image is shown across the bottom of the figure as part of the waste surface. The transformation takes a distorted square image and turns it into an undistorted quadrilateral, as shown in Figure 9. One assumption made in the transformation is that the distorted square image captures an equal field-of-view horizontally and vertically. Another assumption made in the transformation is that the waste surface, both liquid and solid, is flat. Since some of the solid crust shown in the BX111 photos rises above the liquid, this assumption is untrue. More complicated calculations, done on photos taken in stereo or at different heights in the tank, would allow the elevations of the solid waste surface to be mapped. The perspective transformations described in this report are used only to correct the image of the waste surface in the photos. The walls of the tank, since they are not in the plane of the waste surface, are not corrected for distortion.

3.2 Perspective transformation equations

Two sets of equations correct the perspective distortion in a photo. The first set of equations (1 through 11) calculates the four corner positions of the transformed image. The second set of equations uses those four corners to calculate a 3 by 3 matrix used to change the perspective of the photos by assigning the value of the electronic image at every point (or pixel) in the distorted image to its proper place in the undistorted image.

Image distance, i, is the distance from the negative to the center of the camera lens. It is calculated using the thin lens equation (Halliday and Resnik 1978)

$$i = \frac{1}{\frac{1}{f} - \frac{1}{o}}, \qquad \text{(EQ 1)}$$

where f is the focal length of the lens and o is the object distance, Figure 10.

The camera angle, a_c, is one half of the total view angle of the camera and is given by

$$a_c = \operatorname{atan}\left(\frac{n}{2i}\right), \qquad \text{(EQ 2)}$$

where n is the negative size (i.e. the length of one side of the square negative) and i is the image distance.

The angles from the vertical to the upper and lower sides of the transformed image, a_v, are calculated by

$$a_v = 90° - d_t \pm a_c, \qquad \text{(EQ 3)}$$

where d_t is the tilt of the camera from horizontal, Figure 11.

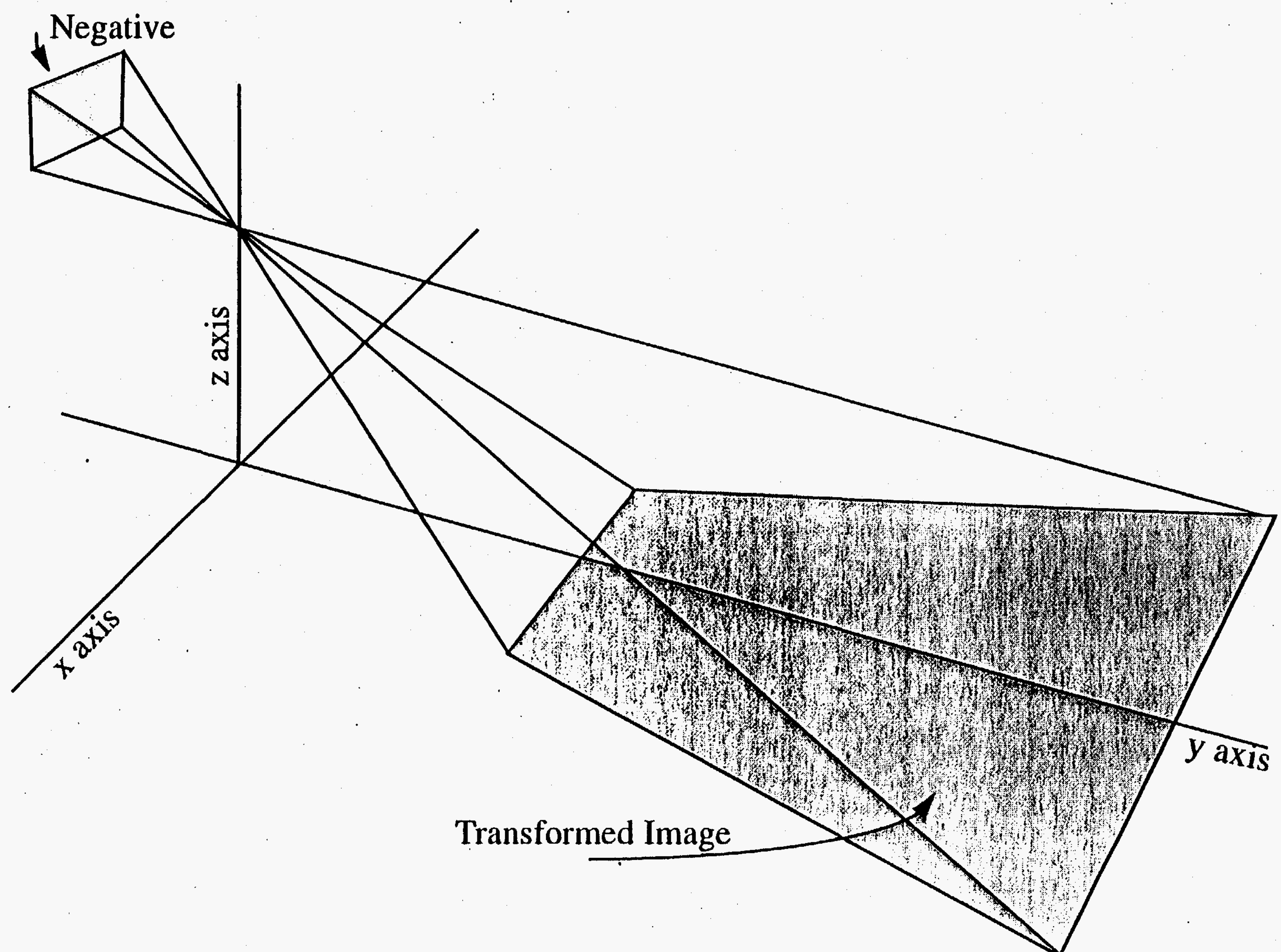

FIGURE 8 Perspective transformation geometry (not to scale).

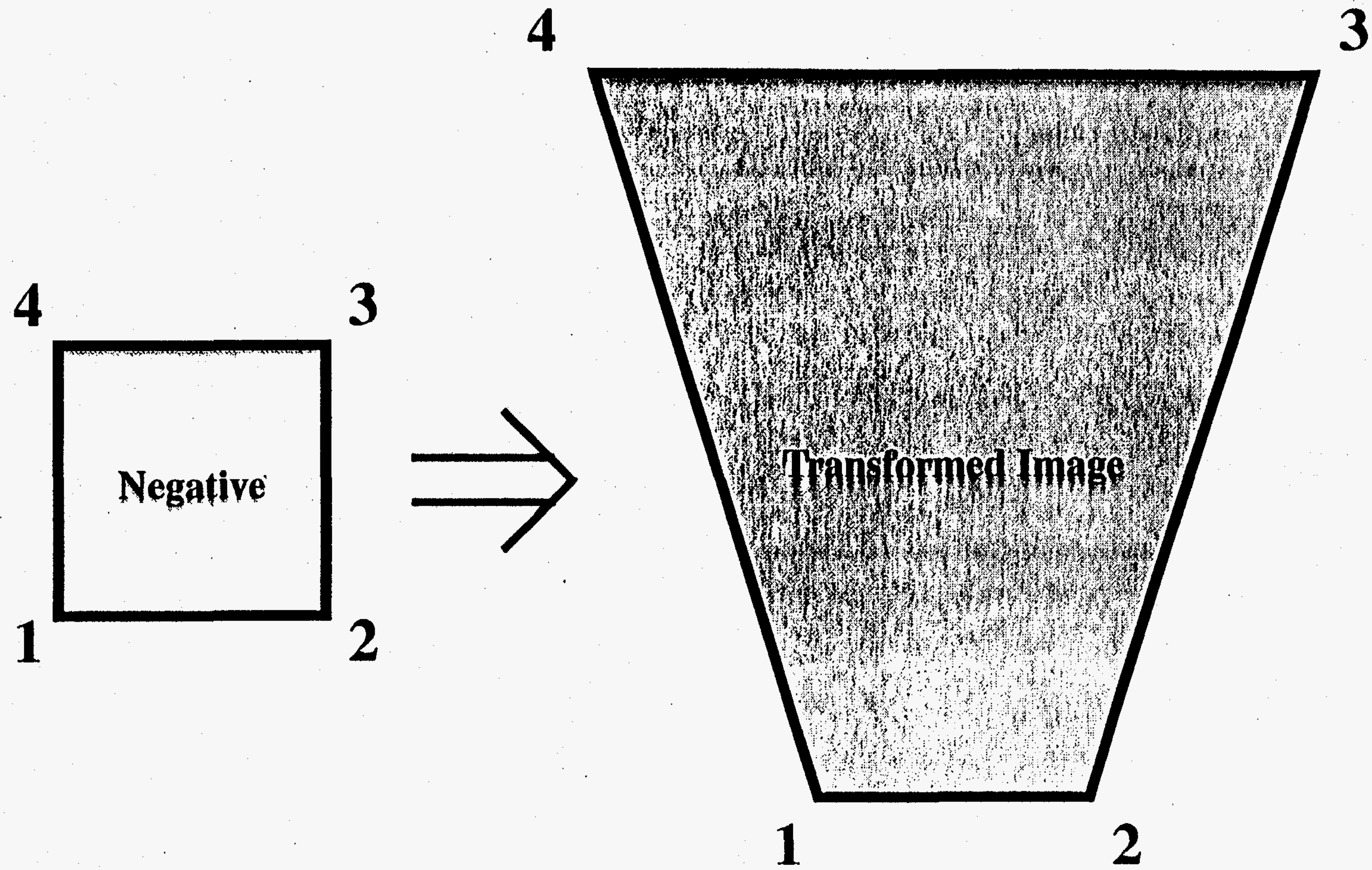

FIGURE 9   Mapping of a square negative into the transformed image.

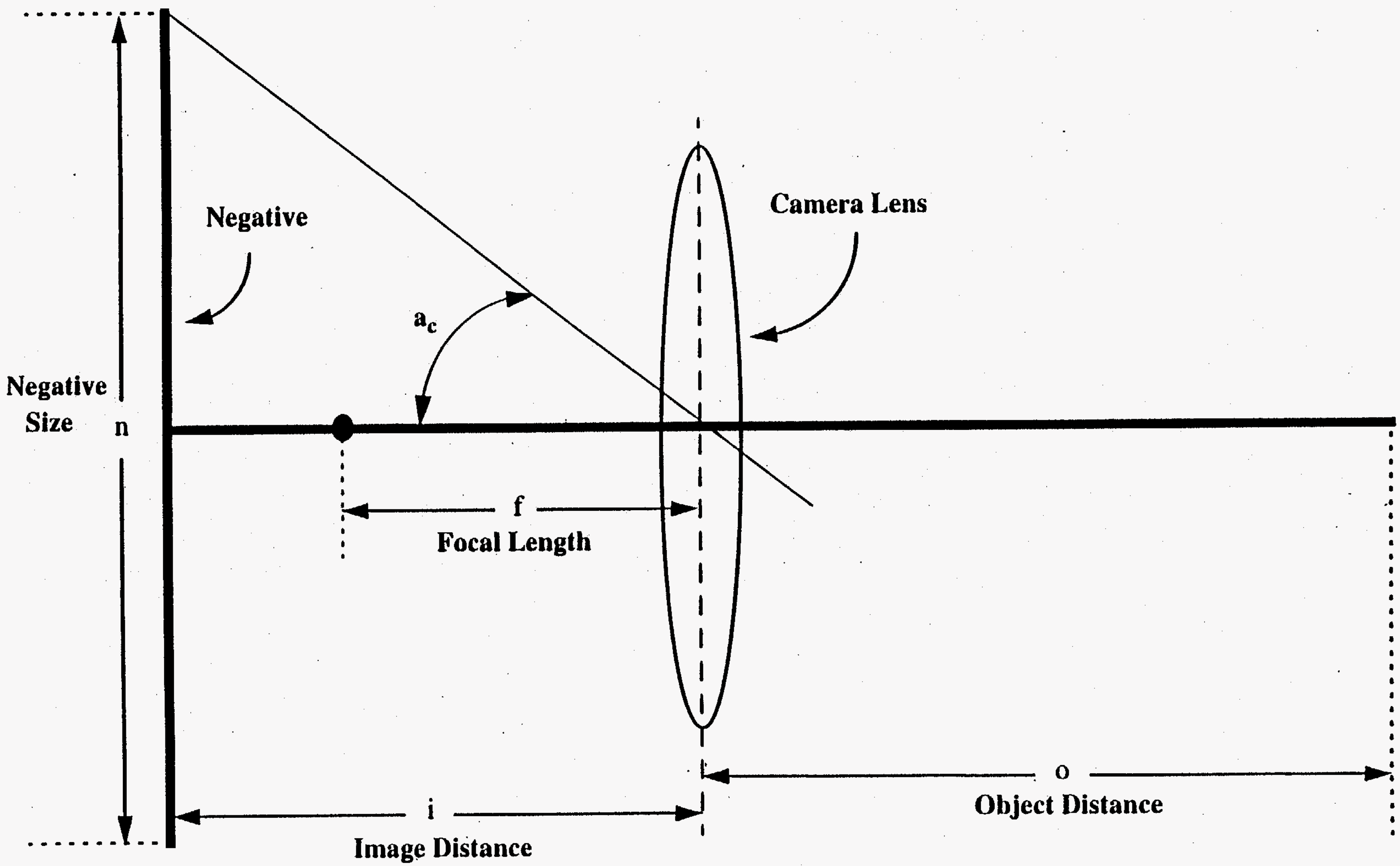

FIGURE 10 Camera internal configuration.

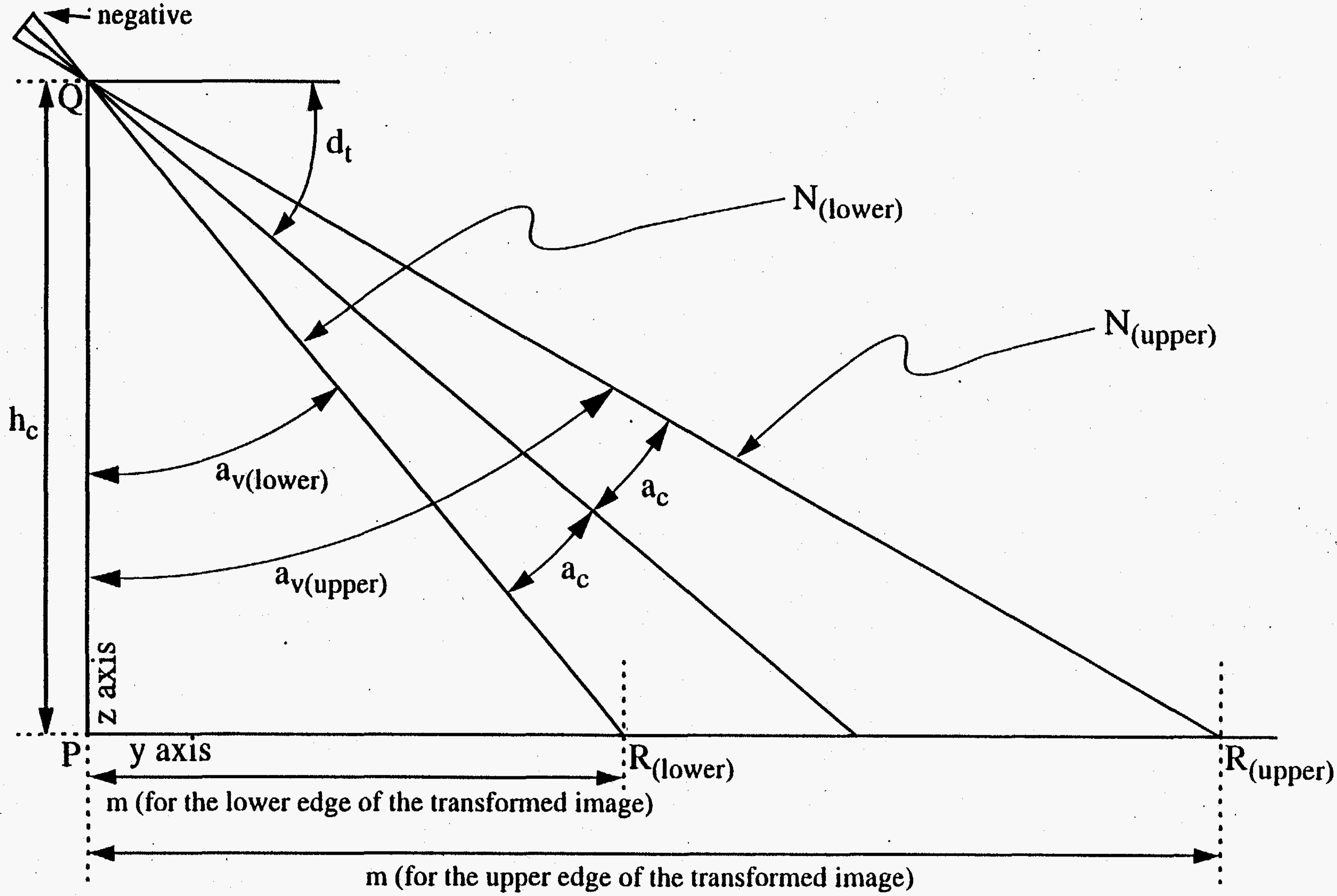

FIGURE 11 Side view of the perspective transformation geometry.

The line N, used to define triangles PQR (Figure 11) and TQR (Figure 12) is defined as

$$N = \frac{h_c}{\cos(a_v)} . \qquad \text{(EQ 4)}$$

The length of one half of the upper or lower side of the transformed image, s, is

$$s = N\tan(a_c) . \qquad \text{(EQ 5)}$$

The distance, m, from directly below the camera to the upper or lower edge of the transformed image is

$$m = h_c \tan(a_v) , \qquad \text{(EQ 6)}$$

where h_c is the height of the camera above the waste.

The angle, a_t, between the y-axis and a nonparallel side of the transformed image, is, from Figure 12,

$$a_t = \operatorname{atan}\left(\frac{s}{m}\right) . \qquad \text{(EQ 7)}$$

The corner positions of the transformed image are identified by polar coordinates. The angular coordinates of the corner positions are

$$\theta = a \pm a_t , \qquad \text{(EQ 8)}$$

where a is the pan angle (an azimuth angle that describes where the camera is pointing in the waste surface plane). Using the plus sign results in calculating the angle for the farther corners and using the minus sign results in calculating the angle for the nearer corners of the transformed image, Figure 12.

The radial coordinates of the corner positions are

$$r = \sqrt{(m)^2 + (s)^2} . \qquad \text{(EQ 9)}$$

The x and y coordinates of the corner positions are

$$x = r\cos(\theta) \text{ and,} \qquad \text{(EQ 10)}$$
$$y = r\sin(\theta) . \qquad \text{(EQ 11)}$$

The second set of equations use the x and y coordinates of the four corners of the transformed image to calculate a 3 by 3 matrix that turns the original distorted image into the corrected transformed image. The matrix changes the original image by taking the coordinate of each pixel in the original image and locating it in the transformed image. The general form of the linear

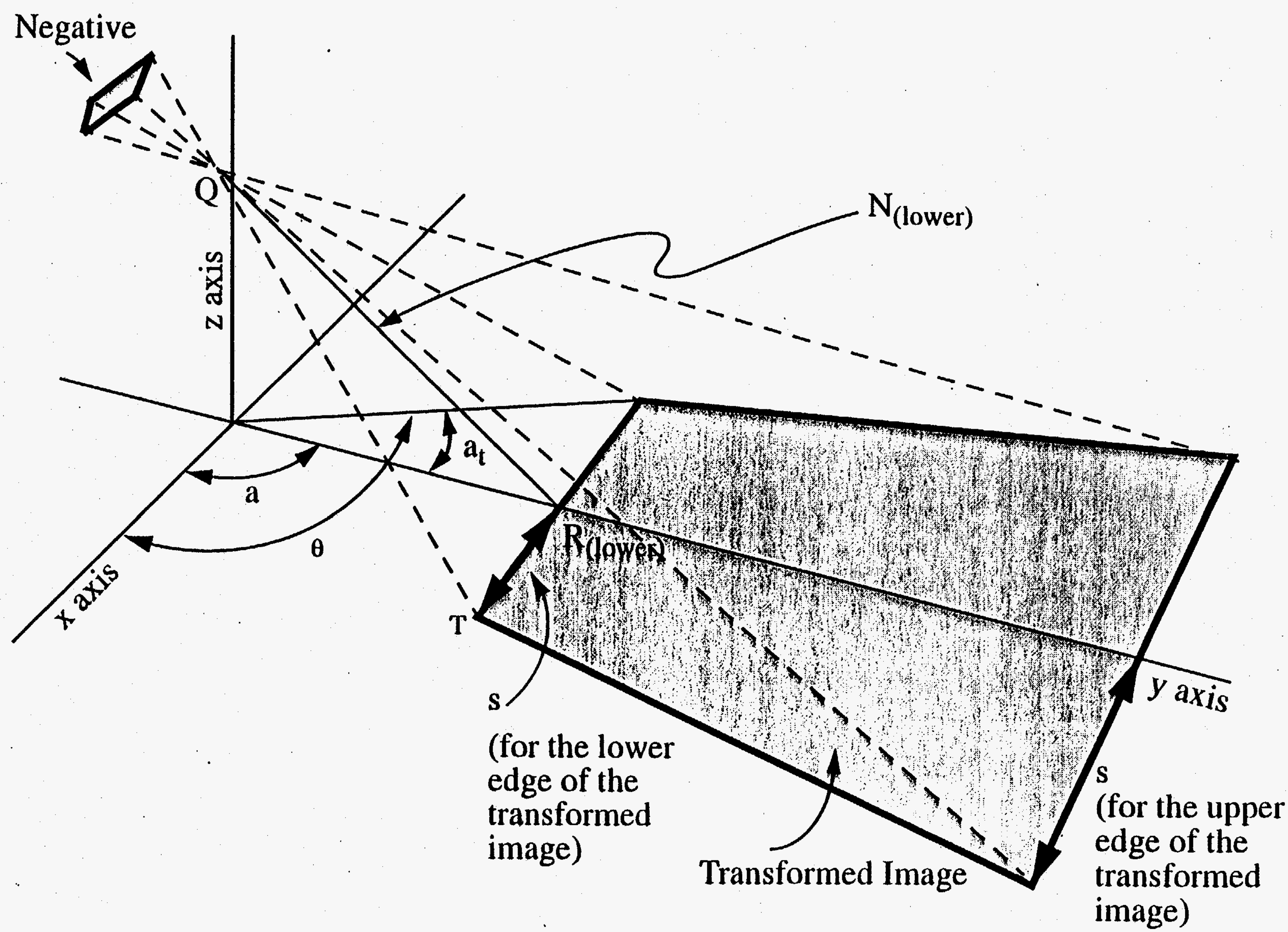

FIGURE 12 Transformation geometry showing angles used to locate corners of the transformed image.

equation that does the coordinate transformation is (Wolberg 1990)

$$[x', y', w'] = [u, v, w] \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} . \qquad \text{(EQ 12)}$$

The (u,v,w) coordinate is for one pixel in the original image and the (x', y', w') coordinate is for the corresponding pixel in the final transformed image [3]. The coordinates in the image are expanded to three dimensions to accommodate scaling in the transformation. The w in the original coordinates and the w' in the transformed coordinates are the scaling for each location. The final coordinates for each pixel are found by dividing x' and y' by w':

$$x = \frac{x'}{w'} \text{ and,} \qquad \text{(EQ 13)}$$

$$y = \frac{y'}{w'} . \qquad \text{(EQ 14)}$$

Once the transformed coordinates for a pixel are found, the values for the three color layers of red, green, and blue from the original pixel location are assigned to the pixel's transformed location, to create the transformed image.

3.3 Making the surface map

Mapping a waste surface involves correcting distortions in the original photos and combining the undistorted photos into one map. The map of BX111 created with the procedure described in this section is shown in Figure 3. The steps in making a surface map are:

1. Scan the 8-inch by 8-inch color prints at 400 ppi (pixels per inch). The result is an image that is approximately 3200 by 3200 pixels. There are three bytes of storage for each pixel in the image—one byte each for the red, green and blue values of that pixel. The colors are stored as 8-bit values (range 0 to 254). At this resolution, one image uses 32 Megabytes of storage.
2. Crop the edges where the scanner went beyond the photograph. The choice of how much to crop on each image was made interactively, since each photograph was positioned differently on the scanner.
3. Rotate the images to align their borders with the display window borders. This step is necessary to remove rotation that may occur when the photo is placed on the scanner.
4. Remove the distortion in the original images by applying the perspective transformation. The geometry of this transformation is shown in Figure 8.
5. Rotate and translate the undistorted images to fit them into a tank outline. The fitting process lines up the tank-wall/waste-surface edge shown in the transformed image to the tank wall in the tank outline. The digitized tank outline, Figure 13, shows the location of the wall, risers and pipes, and is obtained by digitizing the plan-view blueprint of the tank.
6. Combine all the individual images into one waste surface map. The individual images are combined by comparing the values for each pixel where two images overlap. The value chosen

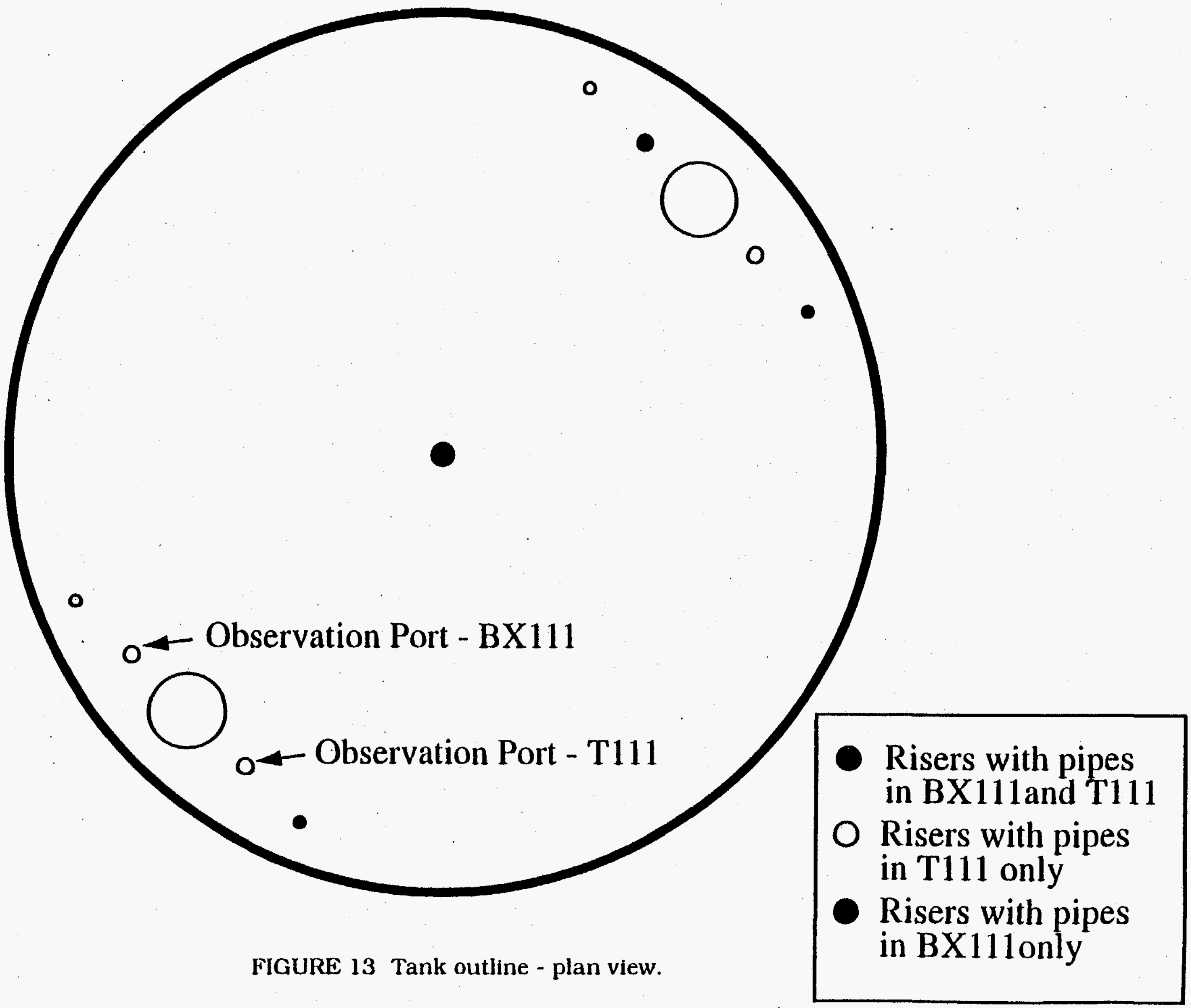

FIGURE 13 Tank outline - plan view.

for a pixel is the higher value found (closest to 254 of the range 0 to 254). Each color is considered separately when choosing the values for one pixel. Choosing the higher value for each pixel has the effect of maximizing the amount of solid waste shown in the final map. If one of two overlapping images shows solid waste where the other shows liquid, the higher valued solid waste would be chosen for the final map, overwriting the liquid shown in the other image.

The size of the final map included in this report is set so that each pixel represents one square inch of waste surface. Thus the map is 900 pixels in diameter, and the tank is 900 inches (75 feet, 23 meters) in diameter. Maps can be made at higher resolutions, the restrictions being the amount of storage available for images, and the image size that the program creating the map can handle.

Once a waste surface map is constructed, the pixel values can be manipulated to gain more insight into the tank waste surface. One way to manipulate the map is to set all of the pixel values to 0 or 254. The map shown in Figure 14 was constructed by resetting all the pixels in the red layer. The red layer of the map was used because it simplified the process of making the image and it best represented the solid and liquid surface when visually compared to the full color map. Pixels valued at 95 or higher were set to 254, and pixels valued at 94 or lower were set to 0. Manipulating the map in this way allows an estimate of the amount of waste surface that is solid (pixels valued at 254) versus liquid (pixels valued at 0). Figure 14 shows approximately 28% of the waste surface as solid crust, and 72% as liquid.

Creating a best fit for the transformed image was accomplished in two ways. For the complete map shown in Figure 3, the photos taken at -20 degrees tilt were fit using four control points within each image. These control points were identified on the tank outline and on the two overlapping photos on the image being fit (which was transformed but did not fit into the tank — see Figure 15). A second transformation was made from the positions of the four control points in the already constructed map and in the image being fit. This second transformation was used to transform all of the pixels of that image so it fit into the tank outline and to the other previously placed photos.

The other way to fit the image to the tank outline is to adjust the inputs that create the perspective transformation. This produces transformed images that fit the tank outline but do not fit to each other. Using a photograph taken at -20 degrees tilt that included three risers in the image, the best fit of the three risers and the tank wall was achieved using a value for the tilt angle of -14.2 degrees. The nominal tilt angle was - 20 degrees, so the difference of 5.8 degrees was used as the tilt angle delta for our uncertainty analysis (see next section).

In evaluating the fit of a transformed image, it became apparent that the tilt angle is also affected by cropping the photograph. Since the tilt angle is measured on the camera at the center of the lens, an uncropped photo satisfies the assumption that the center of the lens is aligned with the center of the photograph. When a negative has been cropped, the amount that is lost on each side is unknown, so the original center of the negative is also unknown. Measuring the amount lost due to cropping on the BX111 photographs showed that the center of the cropped photograph could be displaced by 1.4 degrees. The geometry for this calculation is shown in Figure 16.

Additionally, the tilt angle is affected by the swing of the camera. The amount of tilt attrib-

FIGURE 14 Map of BX111 showing the solid (white) vs. liquid (black) waste surface.

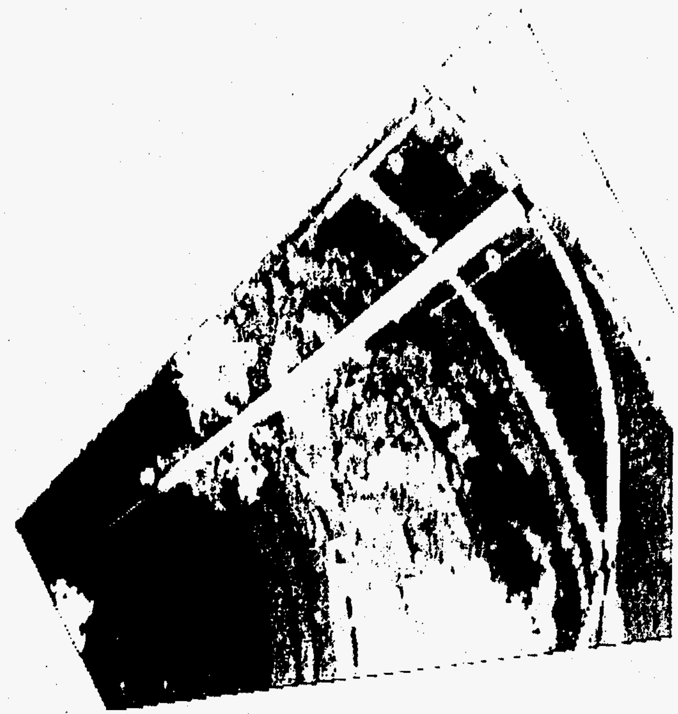

FIGURE 15 Transformed image placed into tank outline before using control points to fit the image.

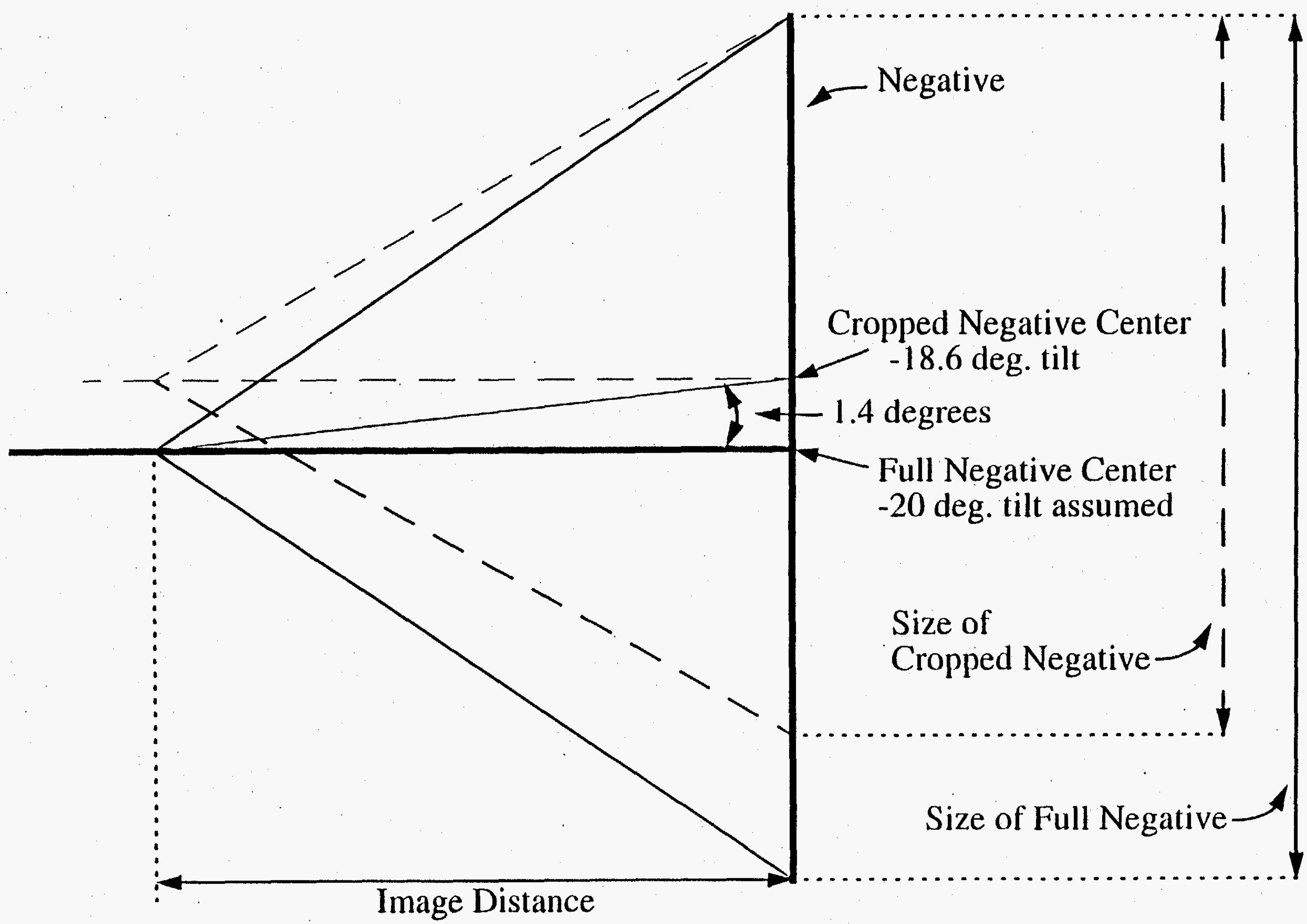

FIGURE 16 A cropped negative vs. a full negative.

utable to the swing can be up to one degree assuming the hose suspending the camera is sitting against the edge of the riser at the top and against the opposite edge of the riser at the bottom. This amount can have a significant effect on the perspective transformation of the image. The assumption in the uncertainty analysis is that the best-fit transformation includes the uncertainty in the tilt angle due to the swing of the camera.

3.4 Uncertainty analysis of tank mapping

An uncertainty analysis of the transformation equations reveals which inputs have the greatest effect on the output, in this case the transformed image. Knowing which inputs have the most effect on the output helps to identify possible improvements in the process of transforming an image. For the map making process, uncertainties arise in two areas: the uncertainty in the exact position of the camera and the uncertainty in the lens focusing distance. These uncertainties translate into a poor fit of the transformed images to the tank outline and to each other.

The current map of BX111 was made with photographs from cropped negatives, resulting in a larger uncertainty in the tilt angle. Future maps will not have this problem because the photographs will include the entire negative.

The deltas for the inputs shown in Tables 1 through 4 (fourth column) come from a variety of sources, as follows:

- The height of the camera delta is an estimate given by one of the photographers.
- A tilt angle delta of 5.8 degrees was found experimentally from the best fit of two photographs to the tank wall and risers. The transformed images fit the tank outline best when a tilt angle of -14.2 degrees (-20+5.8) was used to transform the images (see previous section). An additional 1.4 degrees of uncertainty for BX111 are a result of using cropped photographs to make the map, (see Figure 16), increasing the BX111 tilt angle delta to 7.2 degrees (5.8 degrees plus 1.4 degrees).
- The pan angle delta is from the standard deviation of the pan angles found after fitting the series of photos taken at a -20 degree tilt. The photos were supposed to be at 30 degree intervals of azimuth, but when the images were fit together they were found not to be. The standard deviation from 30 degrees was 3.5 degrees.
- The delta for the negative size is based on the assumption that the best ruler used in this process is accurate to 1/16th of one inch.
- The focal length delta was supplied by the manufacturer of the lens.
- The object distance delta is an estimate based on the numbering scale on the camera's focusing ring. The object distance referred to here is not the distance between the camera and an object anywhere in the photo, but rather the camera lens focus setting. It is a fixed number once set, and is a specific number for each photo. It does not change based on what part of a photo is being looked at.

The uncertainties are calculated by fixing the values of all but one variable, taking the derivative of the mapping equation (Equations 9-11) with respect to the remaining variable, and then multiplying the derivative value by the delta for that variable. The desired deltas were back calculated from a desired uncertainty of approximately 2.5 inches (6.4 cm), or 0.3 percent of the tank width, chosen because it assures that the waste projected to be under a 4-inch riser is at least in part actually below the riser.

The results of the uncertainty analysis for the photos taken at -20 degrees tilt are in Table 1.

Table 1: Uncertainties - Worst Case at -20 degrees tilt (upper corner)

	Value	Derivative	Delta	Uncertainty (in.)	Desired delta
Camera Height	155.6	34.	6.0 in.	204.	0.0736 in.
Tilt Angle BX111 map only	20.°	2980	7.2°	21400.	0.00084
Tilt Angle Future maps	20.°	2890.	5.8°	17300.	0.00084
Pan Angle	0.°	92.2	3.5°	323.	0.0271
Negative Size	2.1	24400.	0.0625 in.	1520.	0.000103 in.
Focal Length	3.1693	16300	0.0012 in	19.5	0.000154 in
Object Distance	510.	0.628	180.0 in	113.	3.98 in

Table 2: Uncertainties - 3/4 Length Case at -20 degrees tilt (upper corner)

	Value	Derivative	Delta	Uncertainty (in.)	Desired delta
Camera Height	155.6	5.48	6.0 in.	32.9	0.456 in.
Tilt Angle BX111 map only	20.°	80.	7.2°	576.	0.0313°
Tilt Angle Future maps	20.°	80.	5.8°	464.	0.0313°
Pan Angle	0.°	14.9	3.5°	52.1	0.168°
Negative Size	2.1	384.	0.0625 in.	24.	0.00651 in.
Focal Length	3.1693	256.	0.0012 in	0.307	0.00976 in.
Object Distance	510.	0.00989	180.0 in	1.78	253. in.

Table 3: Uncertainties - Medium Case at -50 degrees tilt (upper corner)

	Value	Deriva-tive	Delta	Uncertainty	Desired delta
Camera Height	155.6	1.73	6.0 in.	10.4	1.44 in.
Tilt Angle BX111 map only	50.°	10.2	7.2°	73.2	0.246°
Tilt Angle Future maps	50.°	10.2	5.8°	59.0	0.246°
Pan Angle	0.°	4.7	3.5°	16.5	0.532°
Negative Size	2.1	105.	0.0625 in.	6.55	0.0238 in.
Focal Length	3.1693	69.9	0.0012 in.	0.0839	0.0358 in.
Object Distance	510.	0.0027	180.0 in.	0.486	926. in.

Table 4: Uncertainties - Medium Case at -50 degrees tilt (lower corner)

	Value	Deriva-tive	Delta	Uncertainty in the placement of the farthest corners of the transformed image	Desired delta (For an uncertainty of 2.4-2.5 in.)
Camera Height	155.6	0.534	6.0 in.	3.2	4.68 in.
Tilt Angle BX111 map only	50.°	3.17	7.2°	22.8	0.788°
Tilt Angle Future maps	50.°	3.17	5.8°	18.4	0.788°
Pan Angle	0.°	1.45	3.5°	5.08	1.72°
Negative Size	2.1	34.5	0.0625 in.	2.15	0.0725 in.
Focal Length	3.1693	23.	0.0012 in.	0.0276	0.109 in.
Object Distance	510.	.000887	180.0 in.	0.16	2820. in.

This worst case scenario, for the upper corners of the transformed image at -20 degrees tilt, shows that every input needs to be known with much greater accuracy.

Table 2 lists the uncertainties for the upper corners at the - 20 degree tilt, after removing the top 1/4 of each image. This uncertainty table shows that the camera height, tilt angle, pan angle, and negative size are the inputs that need to be known more accurately, (focal length and object distance are known with sufficient accuracy).

Table 3 shows the uncertainties for the photos taken at -50 degrees tilt. The table shows that the same inputs need to be known with more accuracy. These numbers are for the upper corners of the transformed image.

For the lower corners of the transformed image, the inputs are known to much better accuracy, as shown in Table 4. The pan angle, tilt angle and camera height all need to be known more accurately, but the improvements needed to reduce the uncertainty to less than 2.5 inches would be reasonable to achieve.

In summary, the camera height, tilt angle, pan angle, and negative size need to be measured more accurately in order to achieve an uncertainty of 2.5 inches or less. Tables 3 and 4 are the most important for mapping a waste tank if photos could be taken from risers on opposite sides of the tank. A set of photos from two opposite riser locations, taken at a -50 degrees tilt angle and a -80 degrees tilt angle, would cover most of the waste surface with photos that have improved accuracy when compared to photos taken at -20 degrees tilt angle.

After evaluating the uncertainties in the equations of the perspective transformation (Equations 9-11), it is clear that in-tank photos can be used to make a waste surface map. The next section of this report explores the use of in-tank photos to measure the elevation of a tank's waste surface.

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4.0 Waste Surface Elevation Calculation

4.1 Geometry of the surface elevation calculation

Figure 17 shows the geometry of the surface elevation calculation. The size of the negative is shown out of scale in order to make the geometry more evident. Two light rays are shown coming from the riser on the right; one travels directly to the negative, and the other is reflected off the surface of the liquid waste and then travels to the negative.

4.2 Surface elevation equations

The liquid waste surface acts as a mirror in the tank. Figure 18 shows the two light rays from the riser in more detail.

Image distance, i, is calculated as before, from equation (1). The angle α between the two light rays at the camera lens is

$$\alpha = \operatorname{atan}\left(\frac{r}{i\left(\frac{s_p}{s_n}\right)}\right) - \operatorname{atan}\left(\frac{ref}{i\left(\frac{s_p}{s_n}\right)}\right). \qquad \text{(EQ 15)}$$

where s_n is the size of the negative, s_p is the size of the photograph, ref is the distance in the photo between the riser reflection and the center line, and r is the distance in the photo between the riser and the center line.

The angle between the direct ray and the horizontal is k, and is defined as

$$k = \operatorname{atan}\left(\frac{h_r - h_c}{d_a}\right). \qquad \text{(EQ 16)}$$

where h_r is the elevation of the riser, h_c is the elevation of the camera, and d_a is the distance across the tank from the camera to the riser.

The difference between α and k is the angle θ.

$$\theta = \alpha - k . \qquad \text{(EQ 17)}$$

The distance d_{MN} is the length of line segment MN shown in Figure 18.

$$d_{MN} = \frac{h_r - h_c}{\tan(\theta)} , \qquad \text{(EQ 18)}$$

The length of line segment LM is x_{LM}:

$$x_{LM} = \frac{d_a - d_{MN}}{2.0} , \qquad \text{(EQ 19)}$$

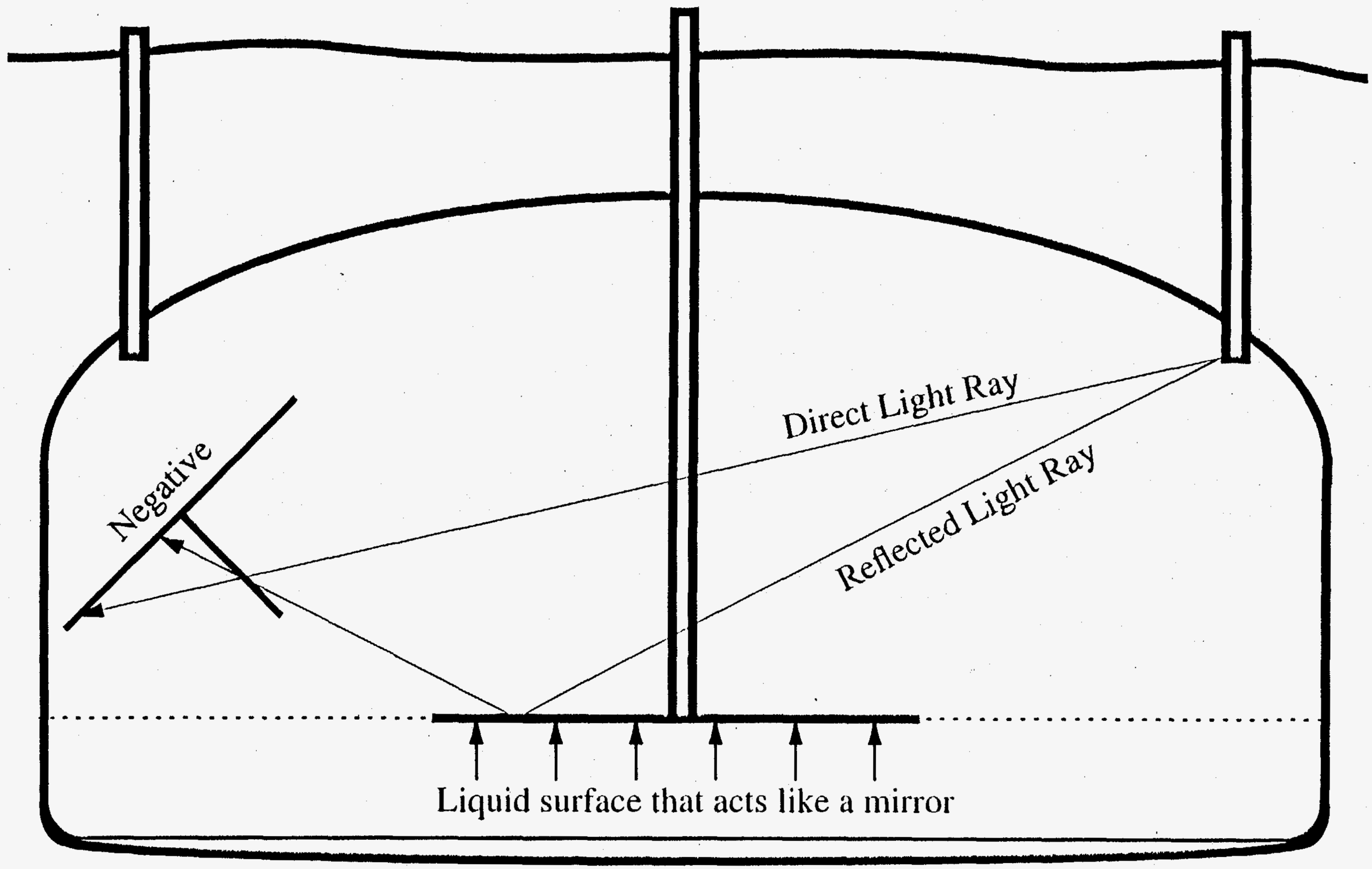

FIGURE 17 Reflection geometry in tank T111 (not to scale).

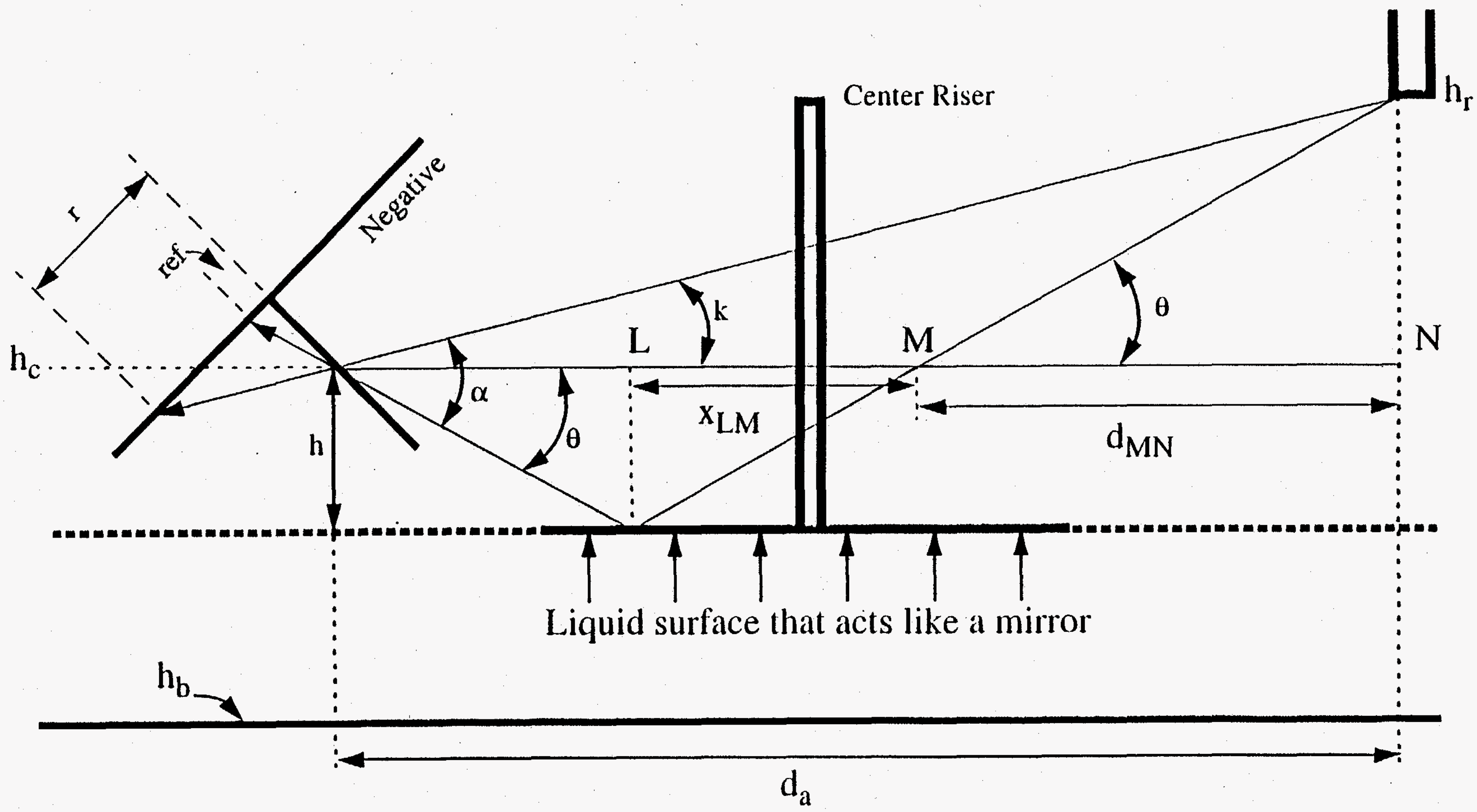

FIGURE 18 Surface elevation calculation geometry (not to scale).

The height of the camera above the liquid is

$$h = x_{LM} \tan(\theta) \, . \qquad \text{(EQ 20)}$$

And the surface elevation, L, is

$$L = h_c - h - h_b \, . \qquad \text{(EQ 21)}$$

where h_c is given, h is calculated above, and h_b is the elevation of the bottom of the tank side-wall.

4.3 Uncertainty analysis of surface elevation calculation

The methods currently used to measure a tank's surface elevation are accurate to within 1/10th of one inch. The goal for calculating the surface elevation from a photograph is to be as accurate as the current methods. Table 5 and Table 7 summarize the uncertainty analyses for Tank BX111 and Tank T111 respectively. The sources for the delta values are:

- The riser measurement, reflection measurement, photo size and negative size deltas are 1/16th of one inch, corresponding to the smallest identifiable unit of difference as seen on the photo, in the electronic version of that photo, and on the negative.
- The object distance delta is an estimate by a tank photographer based on the numbering on the lens focusing ring.
- The focal length delta was supplied by the lens manufacturer.
- For BX111, the riser elevation delta is an estimate by the author of how much the riser length might differ from the length shown on the blueprint. The riser bottom elevation is calculated by taking the top elevation minus riser length.
- For T111, the length of the riser is not found on the blueprints, so the riser bottom elevation is an estimate made by subtracting the riser length recorded on the photographer's notes from the riser top elevation.
- The camera height delta was estimated by one of the tank photographers
- The sidewall bottom elevation value was taken from the Riser Configuration Document of 1986. This value was assumed to be accurate, and thus the delta is zero.
- the delta for the distance from the camera to the riser is the maximum distance the camera assembly can swing while in the tank. This swinging of the camera causes a displacement that is calculated from the riser geometry and the length of the hose-cage-camera assembly and assumes that the distance between the risers as measured from the tank blueprint is accurate.

Table 5: Uncertainties for Surface Elevation Calculation for BX111

Surface Level Calculation Inputs	Value in.	Derivative	Delta in.	Uncertainty in.	Desired delta (for > 0.05 uncertainty)
Riser Measurement	3.83	34.2	0.0625	2.1	0.0015
Reflection Measurement	-1.87	36.7	0.0625	-2.3	0.0014
Focal Length	3.1693	63.3	0.0012	-0.08	0.0008
Distance Across Tank	757.	0.25	4.2	1.0	0.2
Riser Bottom Elevation	7650.	1.1	2.0	-2.2	0.045
Camera Height	7630.	1.1	6.0	6.6	0.045
Object Distance	510.	.0025	180.0	0.44	20.4
Photo Size	8.	24.9	0.0625	-1.6	0.002
Negative Size	2.1	94.9	0.0625	5.9	0.0005
Sidewall Bottom Elevation	0.0		0.0	-	0.05

Table 6: BX111 Calculated Surface Elevations

Photos taken from Riser #3	Calculated surface elevation, in.	Measured surface elevation, in.	Difference, in.
Riser #5 Tank BX111	96.15	79.0	+17.15
Riser #7 Tank BX111	99.43	79.0	+20.43

The BX111 photograph had two risers suitable for calculating a surface elevation. Table 5 shows that none of the inputs has an uncertainty less than the target uncertainty range of 0.05 inches. Table 6 shows the calculated surface elevations for the two risers in BX111. Calculations for both risers produced a surface elevation higher than the value of 79.0 inches that was measured with the LOW (liquid observation well).

The largest uncertainty in Table 5 is 6.6 inches, yet in Table 6 the calculated surface elevations for risers #5 and #7 are both greater than 17 inches higher than the measured surface elevation. The calculated surface level elevations are 3.28 inches from each other (a difference that is smaller than the largest uncertainty).

Table 7: Uncertainties for Surface Elevation Calculation for T111

Surface Level Calculation Inputs	Value in.	Derivatives in.	Delta in.	Uncertainty	Desired delta (for > 0.05 uncertainty)
Riser Measurement	3.17	30.4	0.0625	1.9	0.0017
Reflection Measurement	.436	32.4	0.0625	-2.0	0.0015
Focal Length	3.1693	26.1	0.0012	-0.03	0.0019
Distance Across Tank	760.	0.11	4.2	0.47	0.49
T111 Riser Bottom Elevation	7880.	1.02	12.0	-12.2	0.049
Camera Height	7860.	1.02	6.0	6.1	0.049
Object Distance	510.0	0.001	180.0	0.18	49.6
Photo Size	8.	10.3	0.0625	-0.64	0.0049
Negative Size	2.1	39.2	0.0625	2.45	0.0013
Sidewall Bottom Elevation	0.0		0.0	-	0.05

Table 8: T111 Calculated Surface Elevations

Photos taken from Riser #2	Calculated surface elevation	Measured surface elevation	Difference
Riser #5 Tank T111	171.97	161.1	+10.87
Riser #6 Tank T111	170.18	161.1	+9.08
Riser #7 Tank T111	170.92	161.1	+9.82
Riser #8 Tank T111	175.22	161.1	+14.12

The T111 photo had four risers that were suitable for calculating a surface elevation. The uncertainties in the T111 surface elevation calculation are shown in Table 7. The focal length is the only input with an uncertainty less than the 0.05-inch target. The riser bottom elevation delta is larger for T111 than BX111 and the larger uncertainty for that input reflects that difference.

The large delta for the riser bottom elevation in T111 is a result of not being able to locate the blueprint showing the exact length of the risers. The riser length used in the calculations was taken from the working notes of the photographers. These notes state the length of a 12-inch riser (the observation riser) to be 16 feet. The 4-inch riser bottoms are clearly shown in the photograph as lower in elevation than the 12-inch riser bottoms. For the surface level calculation, the difference between the 4-inch and 12-inch riser bottoms was assumed to be 3.0 inches, which is close to the difference that exists in Tank BX111.

The largest uncertainty in Table 7 is 12.2 inches. In Table 8 the calculated surface elevation for riser #8 is higher than the measured surface elevation by 14.12 inches - a difference that is larger than the largest uncertainty. Risers #5, #6 and #7 have calculated surface elevations that are higher than the measured value and differences between the calculated and measured values which are smaller than the largest uncertainty in Table 7. The calculated surface elevations have 5.04 inches difference from each other.

Table 9: T111 Riser #6 Calculated Surface Elevations Over The Uncertainty Range

Riser Bottom Elevation	Camera Height	Calculated Surface Elevation	Measured Surface Elevation	Difference from Measured
7893.72 (+12 in)	7864.44 (-6 in)	182.51	161.1	+21.41
7881.72	7858.44	170.18	161.1	+9.08
7869.72 (-12 in)	7852.44 (+6 in)	157.73	161.1	-3.37

Table 9 shows the calculated surface elevations over the maximum range of uncertainty caused by the combination of the uncertainties in the riser bottom elevation, which is ± 12.0 inches, and in the camera height, which is ± 6.0 inches. The combination of deltas produces a calculated surface elevation that ranges from approximately -3.5 to +21.5 inches, relative to the measured surface elevation of 161.1 inches. This shows the effects of the largest uncertainties in the worst case scenario.

Two problems in calculating the surface elevation are that the camera height is not known precisely, and the camera is not prevented from swinging while taking photos. The unknown camera height, and the possible rotation in the images caused by the swinging, affects the surface elevation calculations. The uncertainty analysis assumes that there is no rotation of the image.

The results of the surface elevation calculations show for T111 and BX111 the calculated surface elevations are significantly larger than the measured surface elevations. Each tanks calculated values, however, do show good agreement. T111 calculated values are within 5.04 inches of each other and BX111 calculated values are within 3.28 inches of each other. The close agreement of the calculated surface elevations for each tank suggest a systemic error, not an input error.

The change of the derivative values between Table 5 and Table 7 is evidence that the surface elevation equations are nonlinear. The calculated surface elevations also indicate that the equations are nonlinear because T111 has a larger camera height delta and smaller differences between the calculated and measured surface elevations than BX111 which has a smaller camera height delta.

One possible cause of the large differences between the calculated and measured surface elevations, for both T111 and BX111, is distortion in the original photograph caused by the camera lens. BX111 and T111 photos have a magnification at the edge of the image that is larger than the magnification at the center of the image. This causes a pincushion distortion in the photographs where the image of a square object has sides bowed inward. The pincushion distortion can be removed from the original images with image processing.

It is also possible that some of the difference between calculated and measured surface elevations is caused by temperature and density variations of the air inside the tank. Air temperature and density changes cause light rays to be refracted and bent away from a straight path. If a light ray inside the tank was bent it would cause the surface elevation equations to produce an inaccurate elevation, since the equations assume the light is traveling in a straight path. Calculated surface elevations that are higher than measured surface elevations would be caused by a layer of cooler more-dense air sitting on top of the waste surface. A layer of warmer less-dense air sitting on top of the waste surface would cause the calculated surface elevations to be lower than the measured surface elevations.

5.0 Summary and Recommendations

In-tank photographs can yield new information about the waste inside a tank by providing visual evidence of changes that are not easily identified by other means. The photographs, when corrected for perspective and combined, provide good maps of the waste surface overall and at specific sites, such as directly below a riser. The photographs provide some insight into liquid waste surface elevations but at this time the results are not accurate enough to use. Some changes in procedure and equipment are recommended to improve the accuracy of the waste surface maps, and the surface elevation calculations.

The recommended procedural changes are to include the entire negative in the enlargement, to develope an electronic procedure to correct lens distortion, to record the focus setting of the camera lens, and to align the photograph carefully for scanning. The recommended equipment changes are to experiment with using a more sophisticated camera lens and to build a new apparatus that holds the camera steady or that keeps the camera out of the tank.

Including the entire negative in an enlargement is important because cropping the negative during enlargement changes the size of the negative, and the final size can be different for each enlargement. Including the full negative and some of the surrounding film guarantees that the whole negative is contained in the enlargement. In the BX111 photographs, about 1/12th of one inch of image from each side of the negatives was not transferred to the 8-inch by 8-inch photograph.

Improving the uniformity of the magnification in the initial images could be accomplished by developeing a procedure to electronically correct the lens distortion in the photos, or by using different, more sophisticated, lens configurations when obtaining photos. This would improve surface elevation calculations and could possibly benefit waste surface mapping.

Recording the focus setting, or object distance, of the lens would allow a more accurate calculation of the image distance. Improving the calculated image distance would make the perspective transformation more accurate.

The most beneficial improvement in equipment would be to build an apparatus that holds the camera in a rigid frame so it does not swing, or one that keeps the camera out of the tank, or both. The camera is currently lowered into the tank anchored in a rigid cage that is suspended from a large flexible hose. The process of rotating the apparatus causes the camera and cage to swing. A framework that holds the camera rigid would improve the accuracy of the transformed images. Keeping the camera outside the tank would allow more time to focus the lens on different parts of the tank. The hurry related to using the current apparatus is because the film in the camera and the person standing close to the riser are exposed to high levels of radiation. A series of lenses and mirrors could bring the image out to the camera, and exposure of the film and of the person taking the pictures could be reduced.

Finally, the digitizing process could be improved by carefully aligning the photograph when placing it on the scanner. This is a step in the procedure where a rotation in the image can be introduced from a source other than the camera position.

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6.0 References

[1] Halliday, D., R. Resnik. 1978. Physics. John Wiley and Sons, New York. Page 976, equation 44-19.

[2] Wolberg, George. 1990. Digital Image Warping. IEEE Computer Society Press, Los Alamitos, California. Page 52, equation 3.4.1.

[3] Wolberg, George. 1990. Digital Image Warping. IEEE Computer Society Press, Los Alamitos, California. Pages 54-56.