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Secondary Side Photographic Techniques Used in Characterization of Surry Steam Generator

Prepared by R. B. Sinclair

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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Prepared by
R. B. Sinclair

Pacific Northwest Laboratory
Richland, WA 99352

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ABSTRACT

The Steam Generator Group Project utilizes a retired from service pressurized water reactor steam generator as a test bed and source of specimens for research. Program objectives emphasize validation of the ability to nondestructively characterize the condition of steam generator tubing in service. Remaining integrity of tubing with service induced defects is studied through burst and leak rate tests. Other program objectives seek to characterize overall generator condition, including secondary side structure, and provide realistic samples for development of primary side decontamination, secondary side cleaning, and nondestructive examination technology.

Characterization of the generator's secondary side prior to destructive removal of tubing presents a significant challenge. Information must be obtained in a radioactive field (up to 15 R/hr) throughout the tightly spaced bundle of steam generator tubes. This report discusses the various techniques employed, along with their respective advantages and disadvantages. The most successful approach to nondestructive secondary side characterization and documentation was through use of in-house developed pinhole cameras. These devices provided accurate photographic documentation of generator condition. They could be fabricated in geometries allowing access to all parts of the generator. Semi-remote operation coupled with large area coverage per investigation and short at-location times resulted in significant personnel exposure advantages. The fabrication and use of pinhole cameras for remote inspection is discussed in detail.

EXECUTIVE SUMMARY

The Steam Generator Group Project utilizes a removed from service pressurized water reactor steam generator as a research test bed. A primary objective of the Project is determining the validity of current nondestructive examination (NDE) practices used to characterize generator degradation during service. In-service NDE consists mostly of multifrequency eddy current examinations conducted through the primary (inside) side of the steam generator tubing. Due to access restrictions, little inspection is accomplished from the secondary (outside) side of the tubing. The efforts at NDE validation combine primary side examinations with subsequent removal of specimens for destructive metallographic assay. Prior to removal a visual characterization of the secondary side can potentially provide additional inputs into steam generator condition. Visual characterization establishes secondary side structural conditions, location of corrosion product build-up, position of loose parts, and documents corrosion damage. This provides feedback on the primary side NDE results and documents specimen conditions prior to destructive removal from the generator.

Secondary side inspection and characterization presents a number of challenges. The most significant is the need to examine between the very limited spacings in the densely packed bundle of steam generator tubes. These spacings are further constricted due to sludge, corrosion product, and structural deformation during service. This paper describes the various techniques used for visual secondary side characterization including fiberoptics, periscopes, borescopes and miniaturized pinhole cameras. Each technique has its own strengths and weaknesses. The periscope allows remote observations reducing personnel exposure, but its size limits use to the flow lane and top of the tube bundle. Fiberoptics can access all parts of the generator but require great experience in handling, to know what is being examined in the very small field of view. The technique is time consuming, requires staff near the radioactive object, and has problems with optical radiation browning. Borescopes give excellent resolution but require straight line travel. Constricted areas are often impossible to enter, even with the smallest diameter units. Staff exposure tends to be high. Miniaturized pinhole cameras can and were fabricated in geometries allowing access to all parts of the generator. Large depths of field and focus allowed significant areas to be characterized within very brief periods. This technique was the most successful of any attempts. The technique, including details of camera fabrication and use, is described with considerable detail in the paper. Our hope is that this paper provides sufficient detail to transfer the pinhole camera technology to the reader.

INTRODUCTION

During the nondestructive examination phases of the removed-from-service steam generator, the basic photographic problem has been to provide documentation of selected areas of its interior. This documentation is usually in a narrow unlighted space measuring up to 10-1/2 ft. in length, with access provided by a 5" or 2" diameter hole. The work has been accomplished by two methods; direct camera insertion and borescope inspection. Film fog caused by radiation was anticipated to be a problem but has barely been noticeable. Continued careful cleaning and/or the absence of smearable deposits have prevented any equipment contamination to date.

Most of the direct camera photographic inspection has required remote techniques with subminiature cameras, the only exception being the work done through the 15" and 31" diameter openings in the channel head area. This remote work was done with conventional 120 roll film and 35 mm cameras. Larger openings such as the P-1 cut (10" square) and 0° handhole (5" diameter) have only provided access to closely spaced perimeter tubes or to narrow areas called flow slot regions.

As the port size and/or work space decreased, it became necessary to adapt existing photographic equipment and custom build smaller cameras.[1] A market survey of cameras conducted prior to fabrication of these small cameras revealed there to be none available which could meet these basic criteria: 1) small enough to enter a 0.4" space, 2) focusable over 4" to 48" range, 3) electrically activated, and 4) operable up to 11 ft. from any component too large to enter a 0.4" space. Four-tenths of an inch is the smallest distance separating adjacent straight tubes and was thought to be a good reference dimension. Larger and smaller separations are expected to occur.

Because the generator is a self enclosed, densely ordered unit, there is no suitable internal space to permit effective installation of lights for inspection; nor is there any benefit from external sources. All light for direct camera photography has been provided by either a remote electronic flash, sometimes modified, or flash bulbs next to the camera.

Exploration and subsequent photography with borescopes and periscopes has been an important part of the inspection, but their use requires extended time in the radiation zone, generally straight in front of the unshielded hole through which the instrument passes. The mutually complimentary use of subminiature cameras and scopes has been effective in allowing personnel to significantly reduce their on-site study time and exposure to radiation.

This report will discuss the various approaches that have been used for photographic purposes and describe how some equipment and supporting accessories were adapted for this use. Emphasis will be placed on the method of pinhole and tiny lens camera fabrication and use.

APPROACHES

The following instruments have been used to photograph in confined areas of the generator interior: Tessina camera; borescope and periscope; pinhole camera; tiny lens camera. The major advantages and disadvantages of each as related to this effort are summarized in Table 1; however, a more in-depth look at each approach in practice is warranted.

TESSINA CAMERA

This small Swiss-made half frame 35 mm camera has many advantages that make it an excellent tool for remote photography. The total camera measures 2-1/2" x 2" x 1", has a built-in spring wound motor and uses standard cassette 35 mm film (the user must reload this into a special cassette designed for the Tessina). This camera has manual exposure settings, focuses down to 9 inches and works with standard electronic flash units with synch cords. These features allow the user to have the necessary choices and control needed in this kind of photographic work.

One of the Tessina's major advantages, the built-in spring wound motor, can also be considered a disadvantage. After 6-12 firings, or as many as three times per roll, it has to be rewound. When trying to work at a rapid pace in an extremely cramped area and with the camera wrapped to avoid contamination, this feature is a handicap. Electric motor option is not provided by the camera manufacturer and no independent firm has yet been found to motorize this unit, though the search is not completed (a temporary shift in generator requirements to smaller cameras reduced the urgency of this pursuit). Interchangeable lens capability would be a valuable asset but its absence in a camera whose design concept was heavily influenced by pocket portability is understandable.

Adaption to steam generator work required fabricating a remotely operable triggering and locating mechanism and providing an adequate source of light by which good exposures could be made. A narrow aluminum box was fabricated which holds the camera in a vertical position. It contains a small 12 volt solenoid to fire the camera, a removable 45° front surface mirror and has a removable cover that permits easy access to its securely held contents. Convenient camera access facilitates the rewinding procedure (see Figure 1). Light was supplied either by a remote flash tube in reflector, modified from a J.C. Penny Electronic Flash unit or a compact Minolta Pocket Flash 110, used as purchased. A synch cord is necessary for use of either unit with the Tessina. Primarily, both units are made for hot shoe synchronization contacts, but a special synch cord is available for the J.C. Penny Flash. A hot shoe to pc adapter may be used with either, but is absolutely necessary for the Minolta. In use, the Minolta unit is simply tape mounted next to the camera, pointed at the area viewed by the lens.

The tube and reflector assembly was removed from the body of the J.C. Penny unit and epoxy mounted in a small slotted aluminum block. The reflector was cut back in a manner to shorten its depth, and wiring added to extend it 8 to 10 inches from the flash body.

TABLE 1.

Approach Used	Major Advantages	Major Disadvantages
Borescope, Periscope and Fiberscope	1. See as you go and photograph exactly as seen. 2. Requires very little subject to objective work distance. 3. Good angle of coverage and image quality. (Fiberscope image quality may be questionable.) 4. Rotatable withOUT being removed. 5. Continuous focus from next-to objective to infinity. 6. Ready to use as purchased.	1. Requires extended observer time in radiation zone. 2. Must have sturdy support apparatus for best results. 3. Requires accessory light, if periscope. 4. Availability of extended length, small diameter. 5. Cost: Relatively high - up to ~$1000/ft. 6. Browning: Normal glass in scopes will darken with exposure to radiation. Higher cost, radiation-resistent glass can be obtained in same scopes.
Tessina	1. Small size; fully manual operation. 2. Motorized. 3. Focuses from infinity to 9"; nearer with close up lenses. 4. Excellent image quality.	1. Non-interchangeable lens. 2. Spring-wound motor requires frequent rewinding. 3. Minor adaptations needed for this work. 4. Cannot see as you go.
Pinhole	1. Good image quality. 2. Infinite depth of field; no focusing necessary. 3. Extreme wide angle of coverage. 4. Easily fabricated to meet many needs. 5. Inexpensive to build. 6. Very fast on-site operation.	1. Very time consuming procedures. 2. Cannot see as you go. 3. On-site work requires subdued light level.

TABLE 1. (Continued)

Approach Used	Major Advantages	Major Disadvantages
Tiny Lens Camera	1. Excellent image quality. 2. Inexpensive to build. 3. Easily fabricated to meet many needs. 4. Very fast on-site operation.	1. Greater camera-to-subject distance required than with pinhole camera or scopes. 2. Very time consuming procedures. 3. Refocusing and re-aperturing may be required - practical, but time consuming. 4. Cannot see as you go.

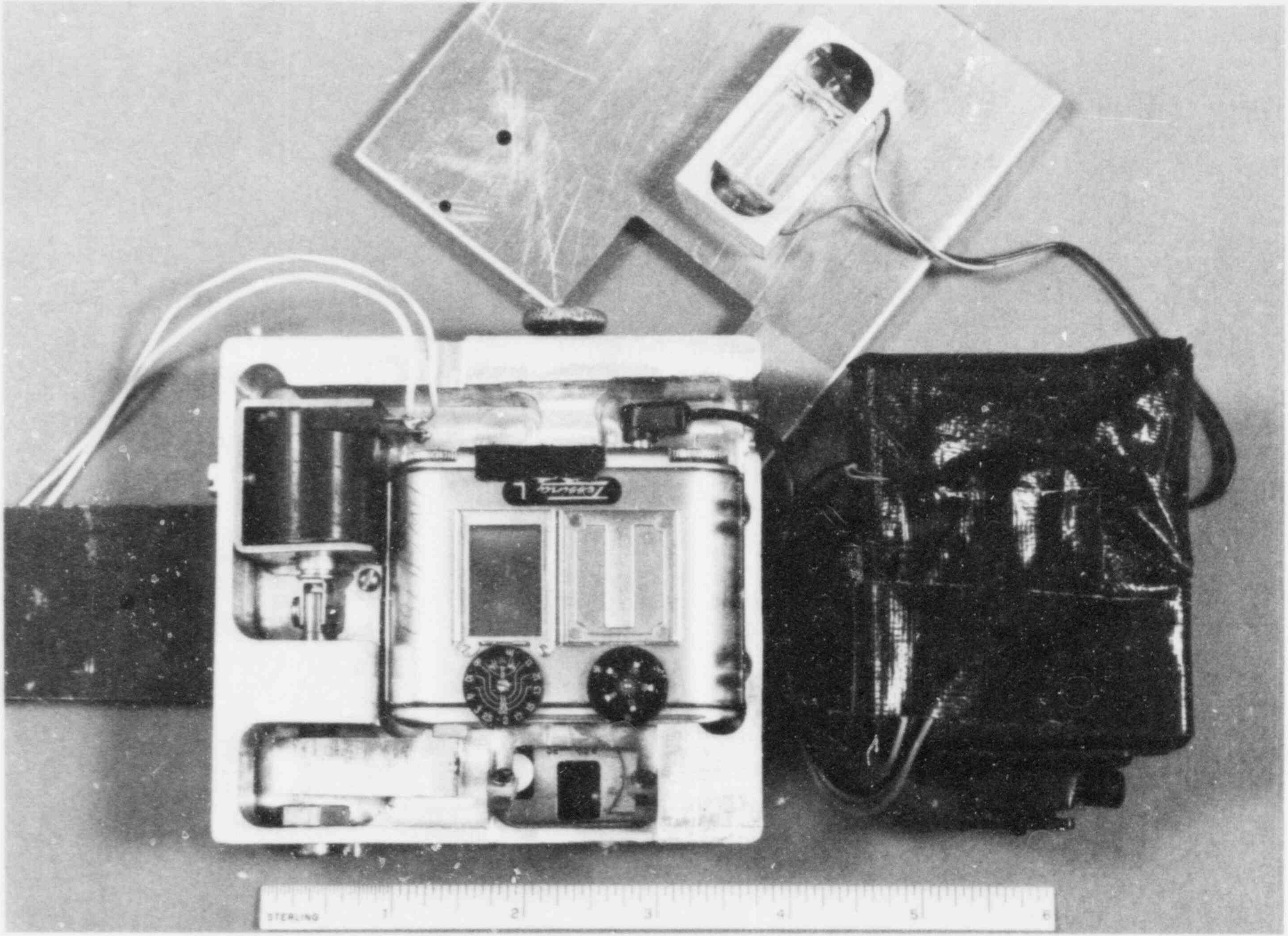


FIGURE 1. Tessina Camera As-Mounted in Aluminum Box Used for Photography of the Interior of the Steam Generator

With tiny screw holes drilled in the aluminum block, this assembly was mounted on the camera box cover in a position directly above the camera lens axis. This alignment enables 90° angle photography, with the camera receiving a reflected image from the mirror. For photography of areas above, below or straight-ahead of the camera location, the mirror was removed and the camera "looked" through a slot cut in the aluminum box. In straight ahead mode the remote flash tube was attached to the outside box edge next to the slot and carefully shielded from the camera lens, with both pointing in the same direction. The work space configuration required using the Minolta unit for photographing above and below the camera location (see Figure 2). In these cases the light unit was positioned in front of or behind the camera box. This flash arrangement was also used for taking photographs from inside the generator looking back towards the pressure vessel, however the camera was mounted differently.

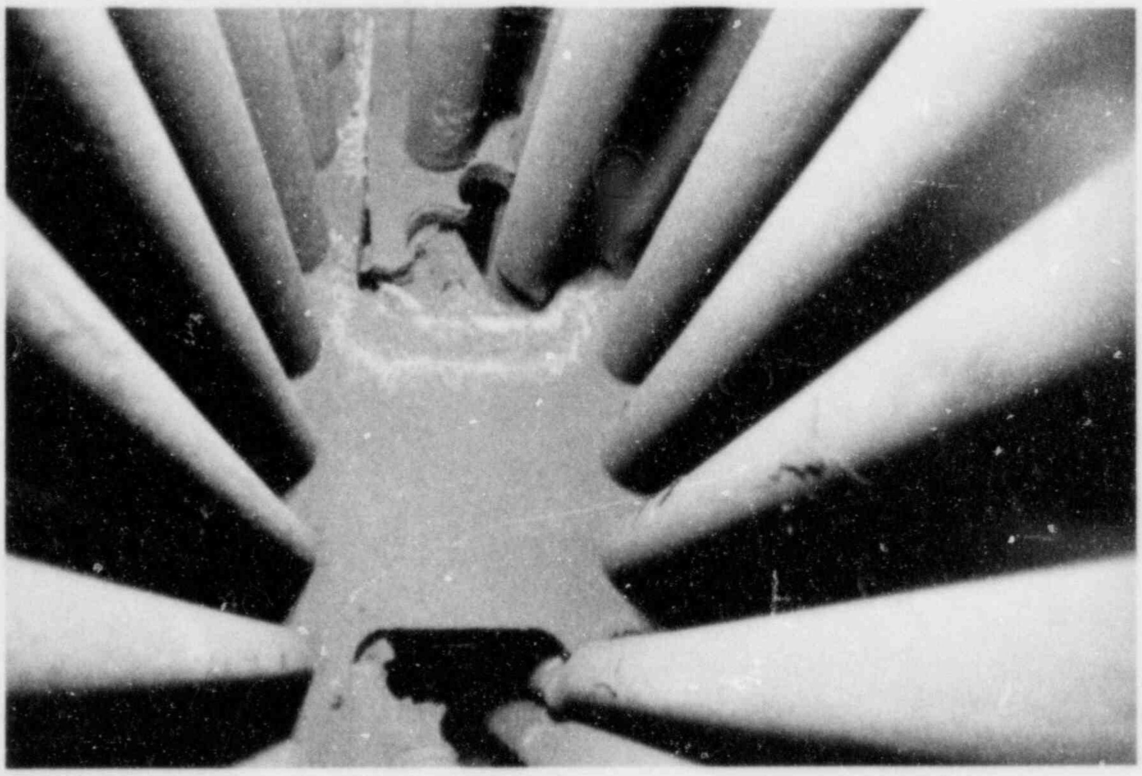
Most work was done with the camera and light box securely mounted on either of several aluminum poles of various fixed lengths or a tripod leg with specially built camera support. This provided an extension capability when working in cramped areas. Solenoid activation to fire the camera was by a detachable 15 foot cord with two 9 volt batteries in series supplying power.

Extensive color documentation of a flow slot region and a limited number of photographs from the U-bend area required many exposure changes. With the extremely short flash durations of the small units used (J.C. Penny electronic flash - 1/1000 second; Minolta pocket flash - 1/5000 second), the exposure is determined by the camera aperture setting (f/number) only; the shutter mechanism only synchronizes the time of flash firing to coincide with its wide open position. The variable speeds play no role when photographing in a completely dark environment. This is not so if the ambient light level is sufficiently high enough to register on film. A ready means of determining the correct f/number as camera-to-subject distance changes is through use of guide numbers. These numbers are usually provided in the information sheet supplied with the flash unit, and generally cover the range of most popular films. For example the Minolta unit has a guide number (GN) of 22 with a 100 ASA (ISO) film. Assume the subject is 2 feet from the camera. The formula is:

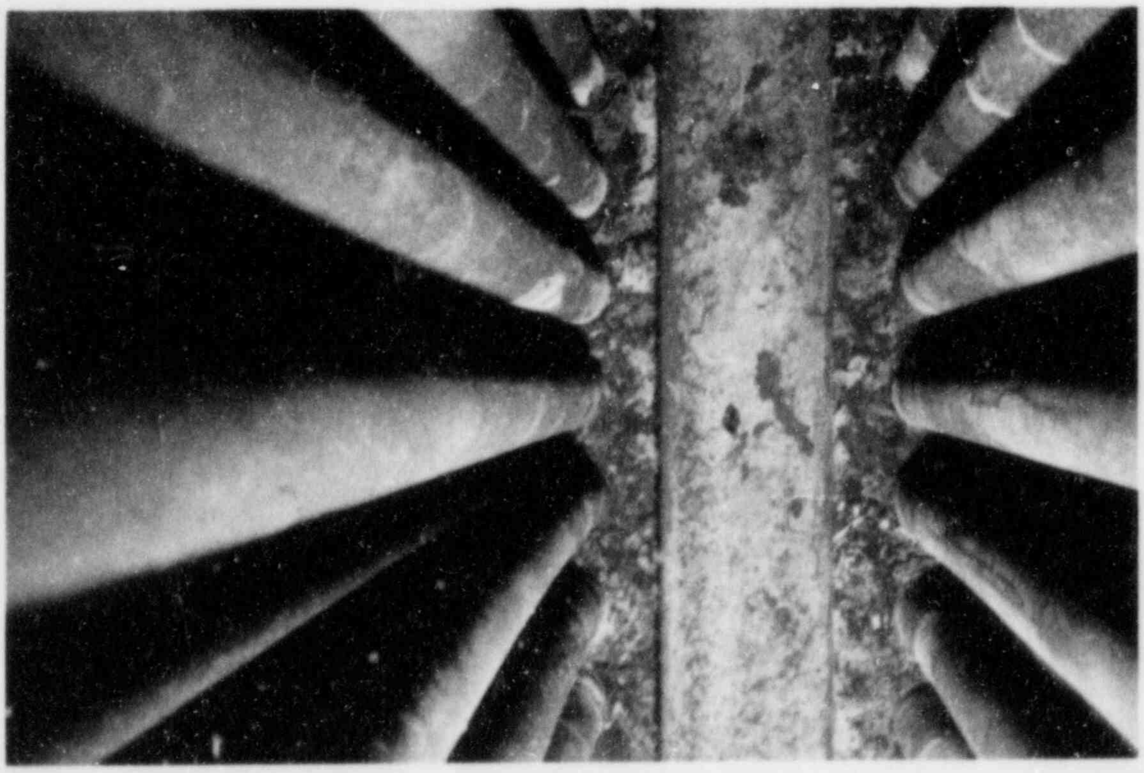
$$\text{F/number} = \frac{\text{Guide Number}}{\text{Flash to Subject Distance, in feet}}$$

$$\text{F/number} = \frac{22}{2} = 11 \text{ or R/11}$$

Final judgement on the effectiveness of a guide number comes from inspection of the negatives. If they are too dense, the GN should be made higher so that an f/number of higher numerical value (and smaller physical size) comes from formula use; if negatives are too thin the GN should be lower.



A



B

FIGURE 2. Photographs Made With Tessina Camera: A) Looking Up Toward Deformed Flow Slot; B) Looking Down Onto Tube Sheet

If a flash unit of unknown characteristics is made available or if modified equipment (changed reflectors or remote tube) is used, a practical method of obtaining a guide number is as follows: Set the flash unit a known distance from the subject, 3 feet for example, and make a number of exposures varying only the camera aperture (keep a record). Choose the best exposed negative from the processed film and note the aperture used, say f/16. Apply the formula:

GN = Flash to subject distance x aperture
GN = 3 feet x 16 = 48.

More accurate GN's are derived when the experimental subject and distance characteristics approximate those of real conditions.

Specifications & Technical Notes

Tessina Camera -

- Size: 2-1/2" long x 2" deep x 1" high
- Lens: 25 mm f 2.8 (53° Angle)
- Aperture Range: f 2.8 - f 22
- Focusing: Continuous from infinity to 9 inches
- Flash Contact: X or M (electronic flash or flash bulbs) via. pc outlet
- Film Size: 14 mm x 21 mm image on standard 35 mm film
- Shutter: 1/2 sec to 1/500 sec, plus B
- Film Advance: Spring wound motor advances film and cocks shutter
- Shutter Release: Mechanical
- Cost: Approx. $400

Minolta Pocket Flash 110 -

- Size: 1" wide x 2-3/16 x 2-5/16
- Synchronization Contact: Hot shoe
- Flash Duration: Approx. 1/5000 second
- Coverage: 36° vertically, 50° horizontally
- Power Source: One 1.5 volt AA battery
- Recycle Time: Approx. 10 seconds
- Guide Number: 22 with ISO 100 film
- Cost: Approx. $25.00

J.C. Penny Electronic Strobe -

- Size: 2-3/8" wide x 3-3/8" high x 1-3/8" deep
- Synchronization Contact: Hot shoe or pc cord
- Flash Duration: 1/1000 second
- Coverage: 35° vertically, 50° horizontally
- Power Source: Two 1.5 volt AA batteries
- Recycle Time: Approx. 10 seconds
- Guide Number: 56 with ISO 100 film
- Cost: Approx. $15.00

Hot Shoe-to-PC Adapter -

- Cost: Approx. $3.00

Film -

Kodacolor II, 36 exposure roll, 150100 used most frequently.
Kodacolor 400, 36 exposure, 150400 used sparingly in dimmer light situations.

- Cost: Approx. $4.00/roll

Aluminum Box -

- Size: Approx. 1" x 4" x 5", milled from Type 6061 machinable aluminum blocks

Front Surface Mirror -

Camera mirror was cut from this product.

- Size: 49 mm square x .75 mm thick
- Cost: $4.50
- Source: Edmund Scientific

12 Volt Solenoid -

- Cost: $3.99

Tripod Leg -

Four extension unit for a Husky Hi-Boy tripod.

- Cost: Approx. $65.00

Other Metal Camera Support -

Hollow steel pole, various length aluminum poles as needed.

- Cost: Varied with product

Miscellaneous -

- Wiring: #22 Stranded
- Switch: Push Button
- Batteries: 1.5 volt AA; 12 volt
- Cost: Inexpensive

BORESCOPE/PERISCOPE/FIBERSCOPE

The major advantages of the scopes are the real time search-and-record capability and off the shelf availability of units that are small enough to perform in 0.4" and smaller spaces. The image quality varies with the diameter of the scope optics and the largest size which fulfills the range of anticipated needs should be purchased. To date, the only scope photographic work has been in the U-bend region with a sectional periscope without a camera adapter. This work required that the scope be firmly supported and the camera, on an independent tripod with a positioning device, was set at the eyepiece. A 105 mm, f2.5 telephoto lens with a shield to prevent stray light from degrading the image was used. The lens aperture was set at f2.5 and focus set to infinity. All image focusing was done with the scope focusing ring as the observer peered through the viewfinder. Most major camera manufacturers have special focusing screens and viewfinders for scope work; these items were not absolutely necessary for this particular effort, but did help. To reduce camera vibration, the shutter was operated with a cable release--this item should always be used. Exposure times averaged 8 seconds on 400 ASA color negative film.

The work just described does not represent the most effective procedure but one that is productive if an adapter is not available. Vendors will supply a properly threaded adapter ring that accepts the scope on one side and screws into the camera lens thread on the other to form a perfectly aligned and light tight union. Another method used by some manufacturers is to supply a longer adapter which attaches the camera body, without camera lens, to the scope eyepiece. The eyepiece lens then functions as a camera lens. This approach enables the manufacturer to exert a high degree of quality control by 1) assuring a correct size image on the film, and 2) an image produced solely by scope optics. This eliminates the possibility of poor image quality that may occur in the former method if: 1) a lens of optimum focal length is not used, 2) a lens of poor quality is used, or 3) a combination of both occurs. High quality camera lenses optimized for scope work are available in a range of focal lengths and should be purchased if that method is preferred.

With the camera correctly mounted, the special focusing screens and viewfinders are absolutely essential. These clear screens will enable the observer to work for a longer period of time with minimum eye strain and the camera can be left mounted to the scope while performing search work.

One major disadvantage of scope use in a radiation zone is the lengthy amount of time required for exploration and subsequent photography. Usually the observer is directly in front of the access port and camera exposures typically range from 5 to 30 seconds. This will become even more of a consideration when some future inspections are performed from a small elevator platform placed next to the generator.

Two flexible fiberscopes, an Olympus and a Machida, and one rigid fiberscope by Diaguide have been evaluated in terms of image quality and working range. The larger, rigid scope with its greater number of fibers forming the image area provided the better quality photographs. Images from the two flexible scopes presented a much more obvious fiber pattern. An approximate scope-to-subject range of 1/4" to 3" for these two scopes is appropriate for the sizes of subjects of current interest in steam generator photography. That maximum distance is greater with the rigid scope (see Figures 3 through 5).

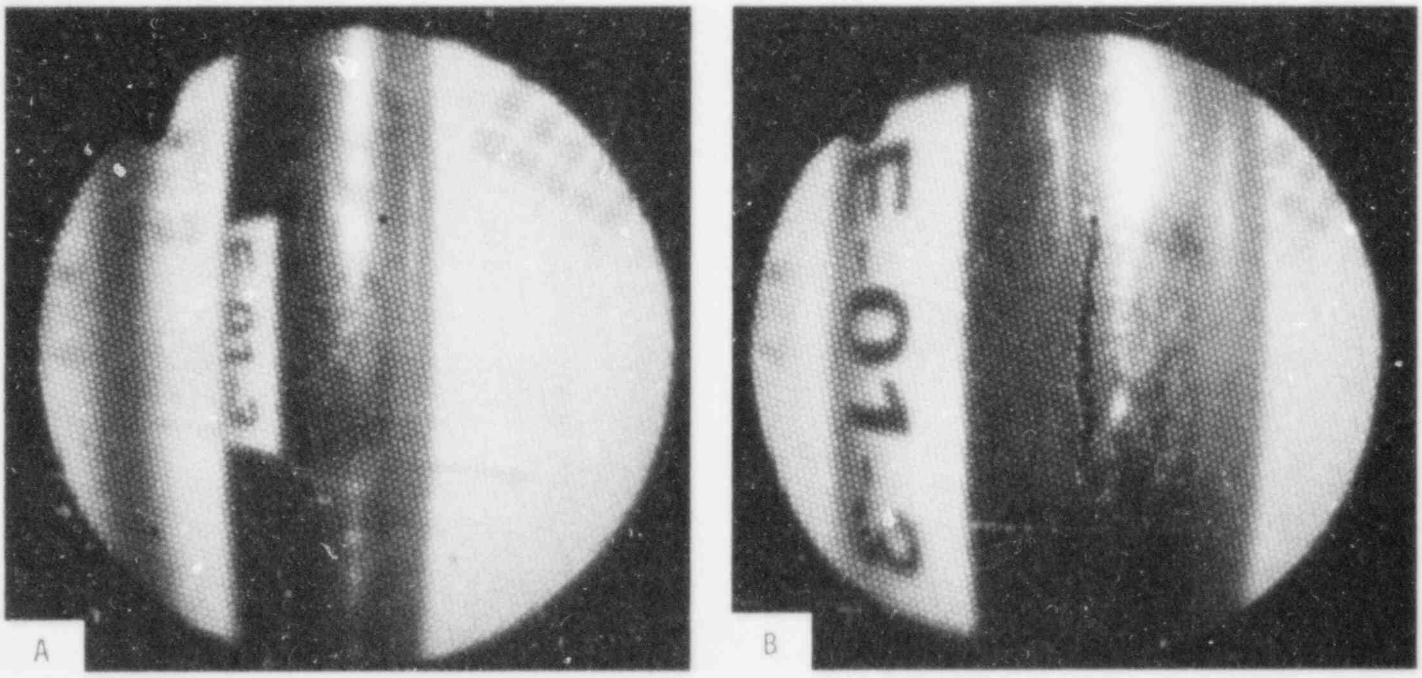


FIGURE 3. Photographs of Sample Steam Generator Tube Taken Through the Olympus Flexible Fiberscope: A) Scope to Subject Distance - 2"; B) Scope to Subject Distance - 3/4"

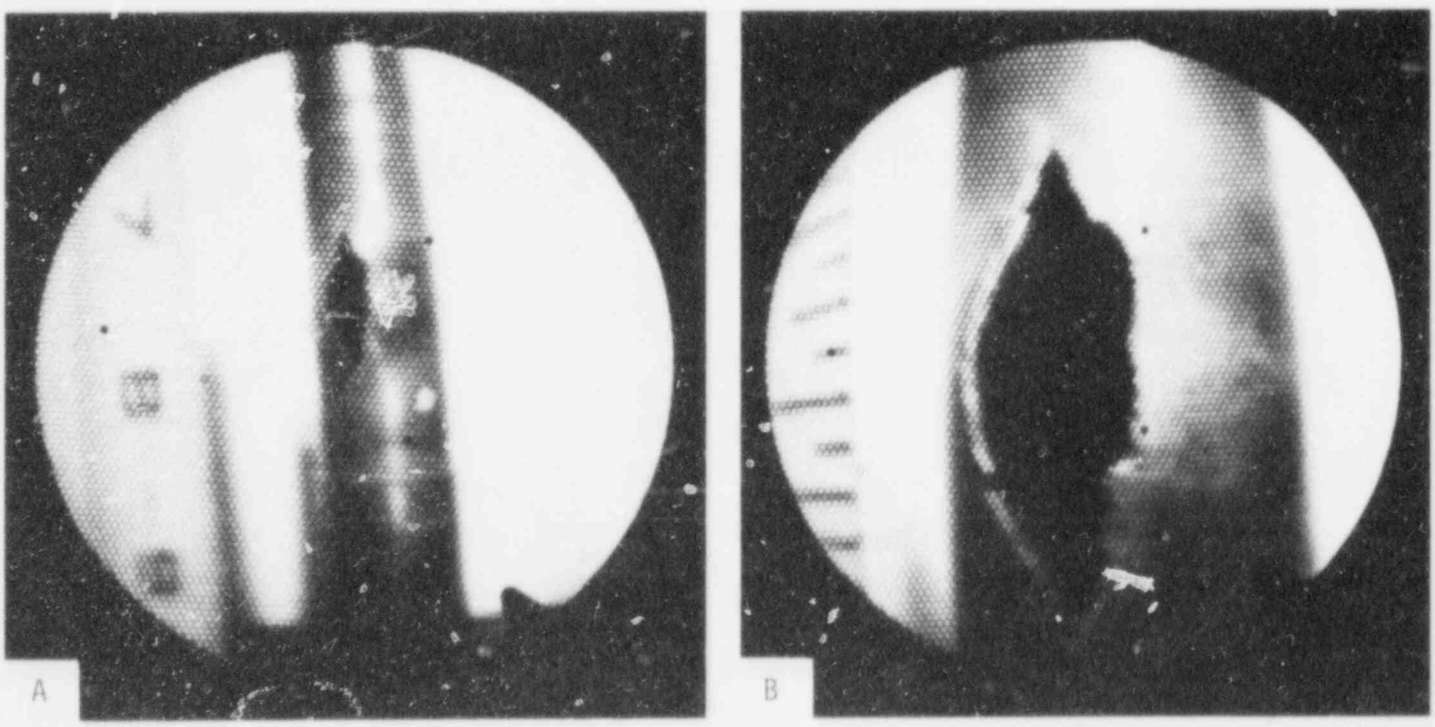


FIGURE 4. Photographs of Sample Steam Generator Tube Taken Through the Machida Flexible Fiberscope: A) Scope to Subject Distance - 3"; B) Scope to Subject Distance - 3/4"

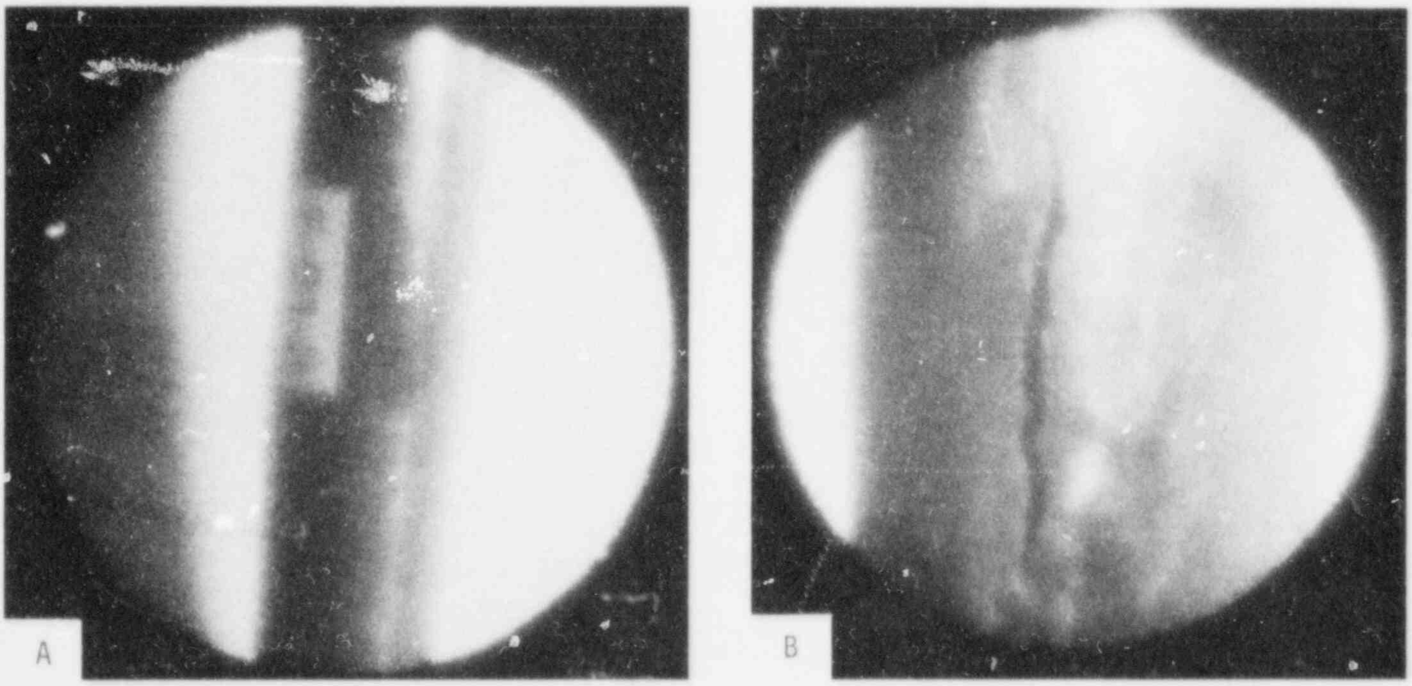


FIGURE 5. Photographs of Sample Steam Generator Tube Taken Through the Diaguide Rigid Fiberscope: A) Scope to Subject Distance - 3-3/4"; B) Scope to Subject Distance - 5/8"

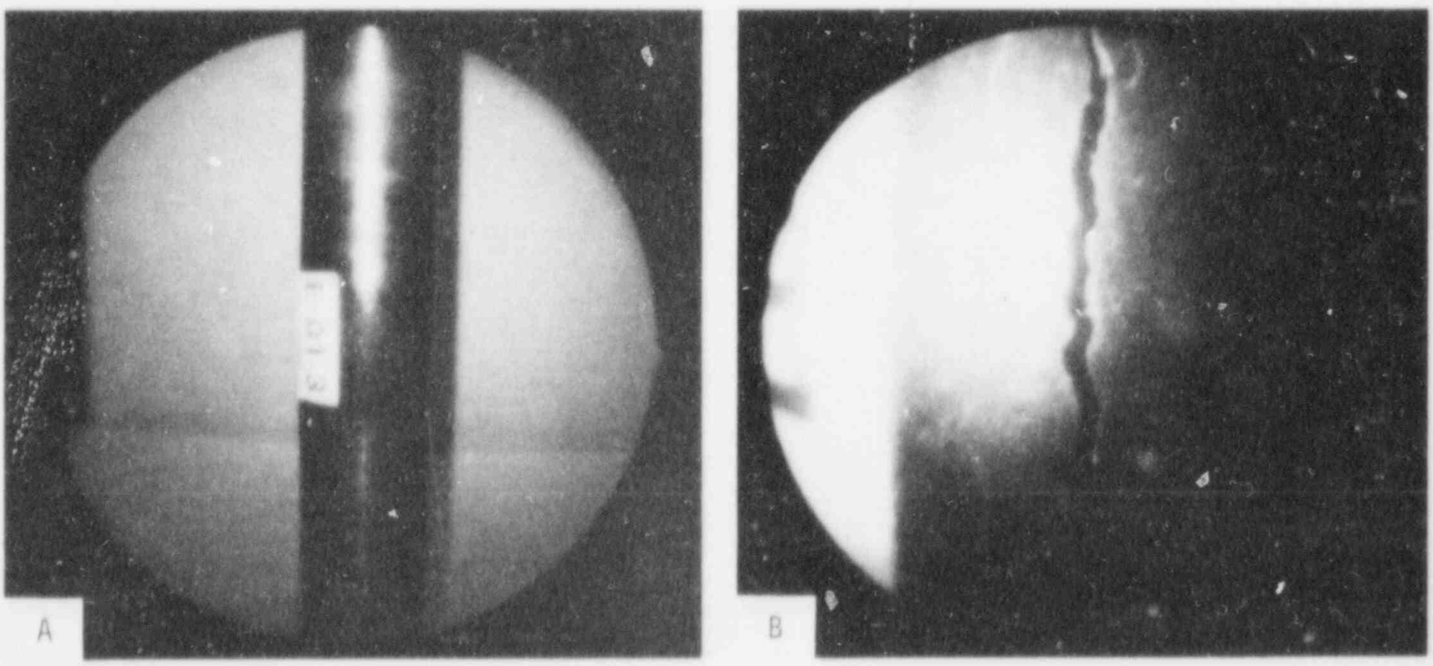


FIGURE 6. Photographs of Sample Steam Generator Tube Taken Through the Lenox Borescope: A) Scope to Subject Distance - 4-1/8"; B) Scope to Subject Distance - 9/16"

A borescope has a built-in light source, a periscope does not; this is the main distinction between the units, and in itself implies some different applications. Two periscopes and one borescope have been used in this work. One periscope is a 3" diameter unit whose image quality is illustrated in Figure 7. This test photograph was taken by the camera lens method. The other periscope is the smaller 1/2" diameter unit which performed the U-bend work referred to earlier, also by the camera lens method. No test photographs were taken, but an example of the work produced is shown in Figure 8. The 1/4" diameter Lenox borescope's image quality is shown with test photographs in Figure 6. These photographs were made using the camera body and adapter method.

A comparison of images from these six scopes reveals the following:

1) A large diameter scope provides better image quality than a smaller diameter.

2) Finer subject detail is resolved by periscopes and borescopes than by fiberscopes of comparable size.

3) The far limit working distance within which good image detail may be expected is greater for borescopes and periscopes than for fiberscopes.

Photographic Equipment Used

1) Nikon F3 Camera Body (Cost Approx. $450).

2) Nikon Type M Focusing Screen (Cost $24.00).

3) Nikon 2X Eyepiece Magnifier, #2315 (Cost $29.00).

4) Nikon DW2 6X Focusing Finder, #2317 (Cost $155.00).

5) Nikon 105 mm f2.5 Auto Nikkor Lens (Cost $150.00).

6) Nikon Cable Release (Cost $8.00).

7) Kodak Kodacolor 400 Film, 36 exposure roll (Cost Approx. $4.00).

8) Husky Hi-Boy Tripod (Cost Approx. $180.00).

Listing of this particular camera and related accessories here, and of other equipment throughout this report, is not meant to be an endorsement but a presentation of the particular items used in this project with their approximate cost.

PINHOLE CAMERA

Sources of information on pinhole cameras are numerous. The accounts on which this work was based are Field Photography, by Alfred Blaker, 1976, published by W.H. Freeman and Co., and Photo Lab Index, published by Morgan and Morgan.

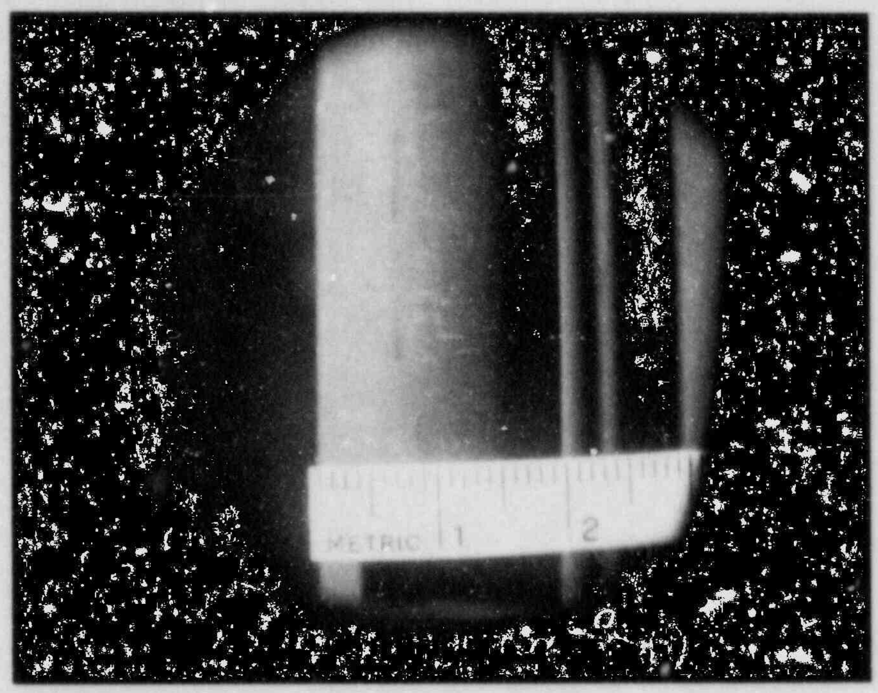


FIGURE 7. Photograph Showing Image Quality of 3" Diameter Periscope - Scope to Subject Distance - 3/4"

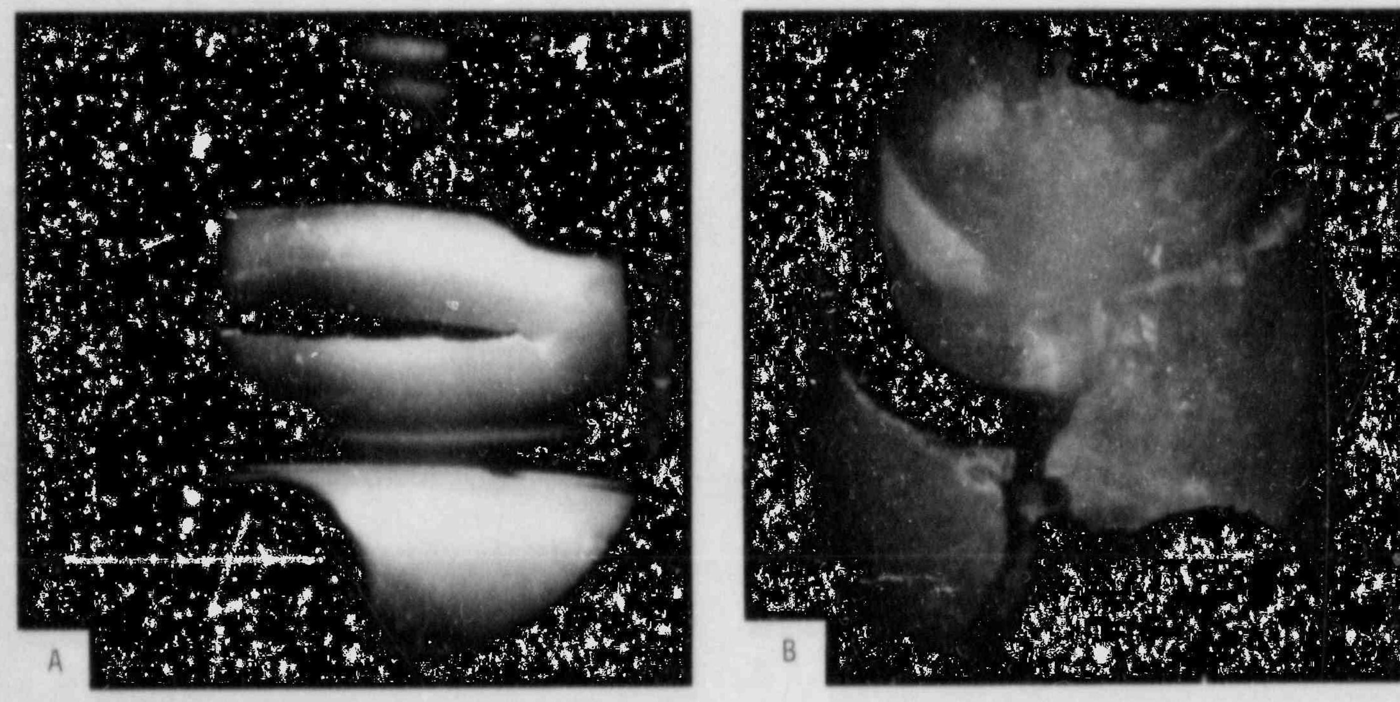


FIGURE 8. Photographs Taken Through the 1/2" Diameter Periscope: A) Looking Up at U-Bends (Scope to Subject Distance - 2" - 2-1/2"); B) Showing Tube Support Plate Intersection and Dent in Steam Generator Tube (Scope to Subject Distance - 3/4" - 1")

The pinhole camera and tiny lens camera discussed in the next section have many outstanding features that have been well suited to this project.

In simplest form, a pinhole camera is a light tight box which uses a hole (of formula derived size) on one side to form an image on film placed on the other side (see Figure 9). The hole itself is not a lens, but it does have its own imaging characteristics of good image quality, infinite depth of field and extreme wide angle of coverage (see Figure 13). These features cannot be appreciated enough when remote work is being performed in an essentially blind manner.

In photographing the generator U-bends, the pinhole cameras were inserted in sets of 4 on one pole and 5 on another. This allowed coverage of approximately 2-1/2 ft. per work session. Because these cameras have no shutters, a subdued lighting environment outside the generator is necessary. This has no effect on the photographic effort itself, but may temporarily inhibit the progress of other types of work.

If extensive use can be made of a particular camera design, it is advisable to standardize dimensions and fabricate a fairly large number of these so that many pictures can be taken per work session. Standard dimensions may warrant the purchase of professionally made pinholes from an optics firm. As no comparison has been made of these precision pinholes vs. the hand-made pinholes for this work, data comparing cost, time and visual merit are absent. Later parts of this section give in-depth information on how to make these cameras and prepare them for field work. After reading this the main disadvantage of pinhole use--the time consuming procedure--will be very apparent. Not being able to see exactly what is being photographed, as in scope work, is another disadvantage when precise instrument positioning is needed to record the feature of interest.

Pinhole camera development began with test work using various rectangular, square and round shapes between 0.25" and 0.375" in thickness or diameter. Evaluation of image quality and problems associated with handling the small pieces of film to be used through the cutting, processing and printing stages were of prime concern. Tests showed that while size is an obvious factor, a good image can be obtained with all diameters within the stated range while permitting the camera body to be long enough to allow a practical size film handling area. This is important in preventing scratching of dry film and for providing an adequate leader for attachment to a larger piece of film for machine processing.

Round Pinhole Cameras

The first pinholes made for generator inspection were of the round tube shape (see Figure 9), 0.344" diameter and cut 2-1/2" long. These were used for initial photographs in newly drilled 2" diameter holes on both hot and cold leg sides (see Figure 10). Since then, a variety of other situations have arisen which have demanded new sizes and expanded the pinhole's applications. Lateral left and right views between third and

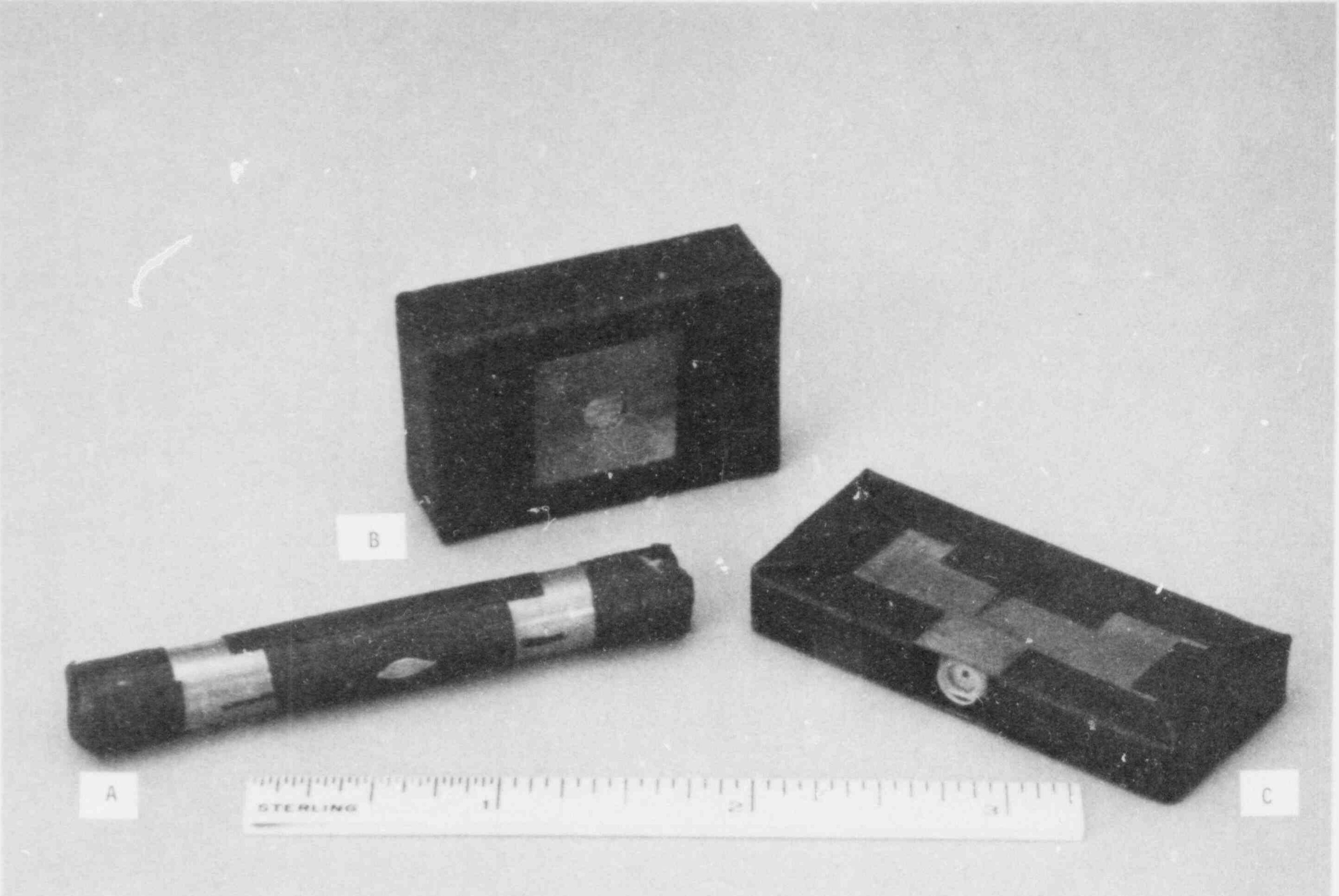


FIGURE 9. Cameras Fabricated for Use in Surry Generator: A) Round Pinhole Camera; B) Rectangular Pinhole Camera; C) Tiny Lens Camera

FIGURE 10. Photograph Taken With Round Pinhole Camera Looking Back Towards 2" Diameter Opening in Shell

fourth row U-bend tubes called for a narrower tube since the cameras were actually laying on the third row tubes and some maneuverability was desired in case a tube(s) was badly deformed. A shorter camera (1-1/2") was also necessary in this case to allow the lights on each end to be closer together and avoid a shadow area in front of the camera. The area to be photographed began immediately in front of the pinhole and extended 4" directly ahead. The most convenient length for round cameras of this type, if length can be chosen, is 2-1/2". This permits the size 120 roll film stock to be trimmed in one direction only. Usually the maximum diameter of the tube is determined by the situation, but a practical lower limit when using Kodak's Kodacolor II roll film, size 120, seems to be an ID of 0.25 inches. The upper limit would be an approximate ID of 0.5 inches, as a rectangular camera with this film width can be used instead. The rectangular camera focal length should be shorter and it will give ample coverage without the distortion characteristics of the round camera.

Materials for Assembly -

Metal tube: Should be sturdy but easily workable. Brass was chosen because of ready availability in a wide range of closely stepped sizes.

Brass shim stock, .001" - .003" thick.

Black photographic tape.

Vernier Dial caliper.

The following items were also used : Small needle, electric drill, drill bits (1/16" through 1/32"), honing (Arkansas) stone (medium surface), small file, 7X magnifier, 12" ruler, hacksaw, #0000 steel wool, emery paper (400 grit), permanent marker, small piece of wood (approx. 1" thick x 4" x 6"), scissors.

Procedure - See Figure 11

1) Select the largest diameter tube which will fit into (and come back out of) the available work space and remove a 2-1/2" long section.

2) Mark the center (lengthwise) of this tube and very carefully drill a 1/16" hole through one side, being careful not to extend the drill to the other side of the ID. Make the hole larger with progressively larger drills until it is 5/32" in diameter.

3) Use the small file to smooth rough edges where the tube was cut and drilled. Follow with fine sandpaper. Use twisted sandpaper to smooth the inner surface of the tube. Repeat on the inner surface with #0000 steel wool.

4) Put the depth extension end of the caliper in the drilled hole and measure the distance from the OD to the rear ID of the tube. (In 1/4" [0.250] brass tube this is usually 0.235".) This is the focal length of the camera.

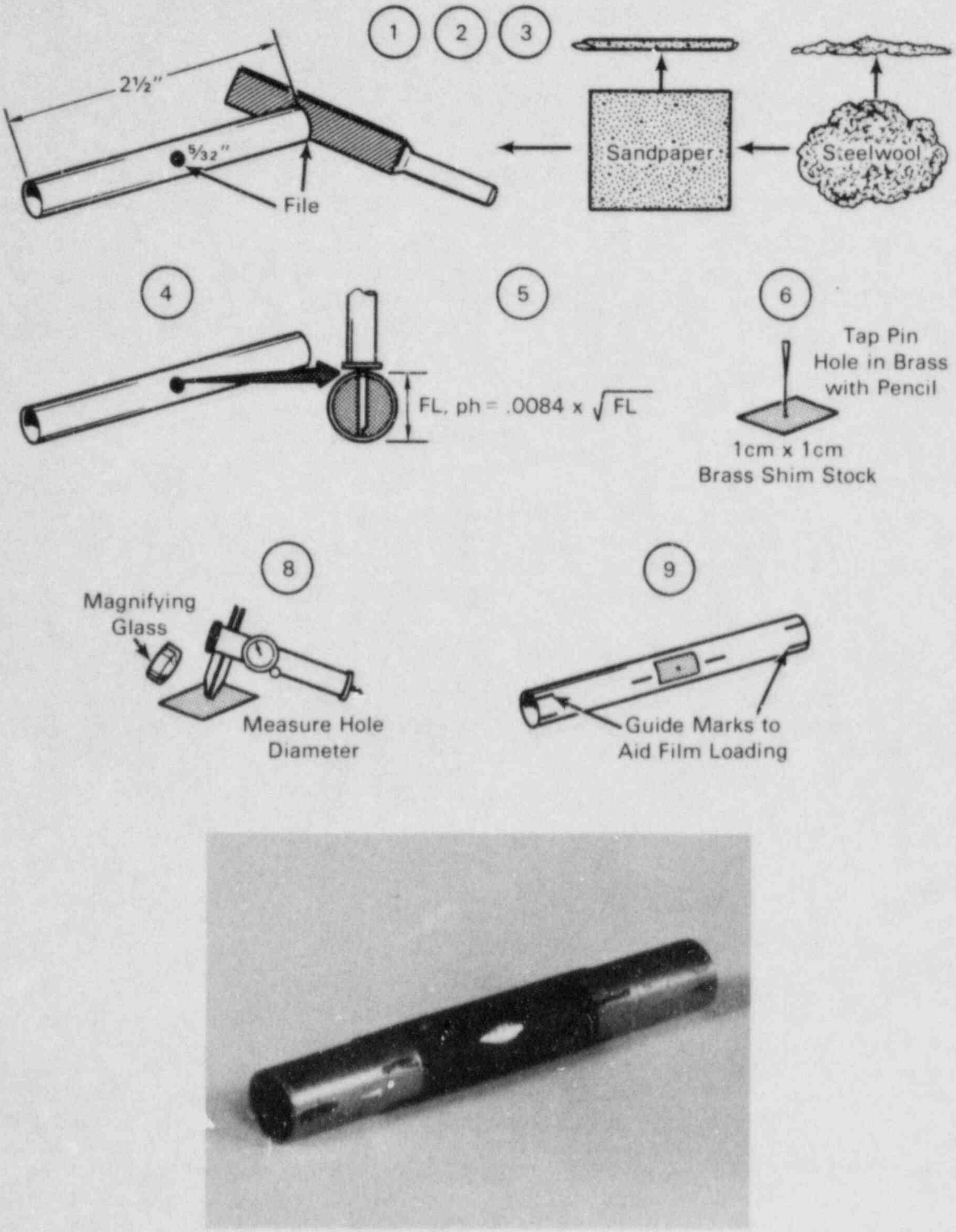


FIGURE 11. Procedure for Fabrication of Round Pinhole Camera

5) Use this measurement (f.l.) to determine the size of the pinhole.

$$\text{Pinhole diameter} = 0.0084 \times \sqrt{f.l.}$$

6) Remove a 1 cm x 1 cm section from the 0.001" brass shim stock. Place on the piece of wood and with the small needle carefully make a very tiny hole in the center. The needle is gently tapped with a pencil or other lightweight object. This hole should be smaller than needed as subsequent smoothing will enlarge it somewhat.

7) Rub this hole gently on the Arkansas stone to smooth its irregular edges.

8) Set the caliper gauge to the width given by the formula. Place on the hole and with the aid of a magnifier make the hole larger by drilling with a needle from both sides and smoothing with the Arkansas stone until its size matches the present caliper width.

9) Securely tape this plate on the brass tube, with the pinhole centered over the tube hole. Mark the pinhole orientation lengthwise on the tube with a permanent marker.

The camera is now ready for loading with film. An infrared viewer is essential for the following steps because it enables excellent visual observation in a completely dark room. It should be mounted at eye level by some means so that both hands are free.

<u>Material Needed</u> -

- Infrared Viewer Scope - Cost: $785.00
- Size 120 Film
- Black Photographic Tape
- Small Light Proof Box
- Scissors
- Brass Tube - next size smaller than camera size
- Small Rotary Paper Trimmer

<u>Film Loading Procedure</u> - See Figure 12

1) Darken room; be sure there are no light leaks.

2) Remove paper backing from the 120 roll film. This paper should be tossed out and a small light tight box provided to keep film in.

3) Cut film to predetermined size using the paper trimmer. The best film size is that which, when placed in the tube, will not cover any part of the 5/32" tube hole on the ID but is so wide that its in-camera curvature flattens it to the tube wall. Some trial and error will quickly give results. The cutting of film to be used for pictures must be done very carefully to avoid scratches and fingerprints. It is recommended that the film emulsion side be kept up to avoid abrasions from the trimmer. A truly good method of performing this operation has not been worked out.

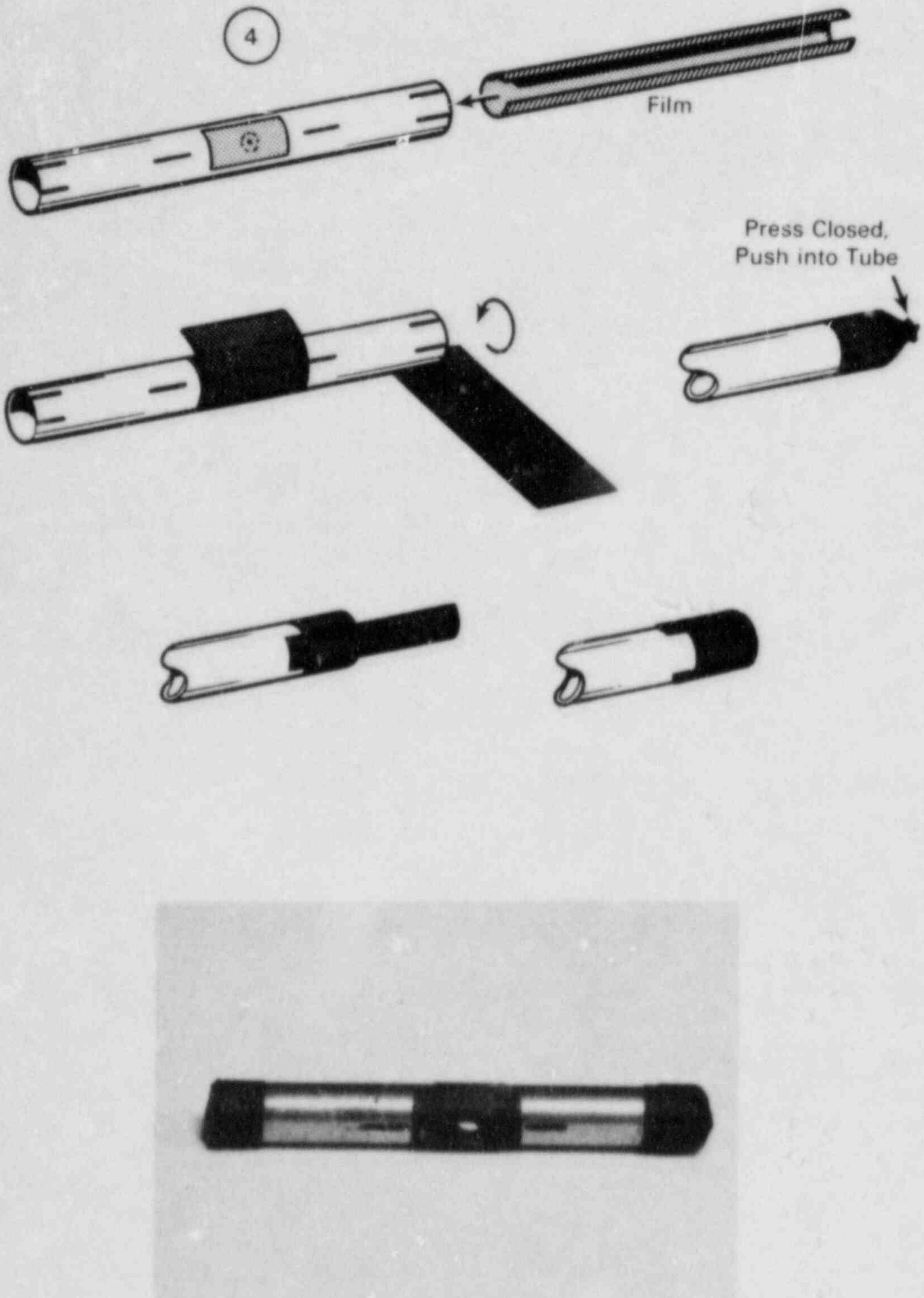


FIGURE 12. Film Loading Procedure for Round Pinhole Camera

4) Insert the film in the tube with emulsion side facing the pinhole. The next-smaller-size tube is useful here if the film is incorrectly inserted, and in subsequent film removal steps, as it permits the film to be easily pushed out.

5) Tape the ends of the loaded camera to make it light tight and cover the pinhole with a strip of black tape.

6) Place any unexposed film in the light proof box. Room lights may be turned on.

Rectangular Pinhole Camera

There are three basic sizes of these cameras used for generator work; body depths are 3/8", 5/16" and 3/16" (refer back to Figure 9 for photograph of rectangular pinhole camera). The lengths, 1-1/2", and height, 1" and 3/4", are similar in each type. They were developed mainly for passing through 2" diameter holes and photographing up, down, forward and backwards in the 4-1/4" space between the pressure vessel and outermost tubes. Since the camera-to-subject distance was so short, an extremely wide angle of coverage was needed. A more recent application was photographing the entire 10'6" length area just underneath the tube U-bends, looking up at tubes for one set of pictures and down at the support plate for the second set (see Figure 13). The 3/8" deep model was best suited for this work because it gave the best image size/area covered relationship. At least one stereo camera was made in each basic size that has provided a three dimensional view of a selected area.

Materials Needed -

Same as with round pinholes, plus these additions:

- Flat Black Spray Paint
- Spruce Wood Strips, 3/8" x 1/8" x 4'
- Brass Strips, .025" x 1" x 12"
- Razor Saw
- 5-minute Epoxy

Procedure - See Figure 14

1) Cut two 1-1/2" lengths from a brass strip.

2) Drill a 5/32" diameter hole in the center of one plate and smooth.

3) From a 3/8" wide wood strip cut two 1-1/2" pieces and two 3/4" pieces.

4) Apply epoxy to a long edge of each piece of wood and attach to the brass plate with the hole to form a box.

5) When dry, spray paint the inside of the box and one side of the other plate flat black. Let dry.

B

FIGURE 13. Rectangular Pinhole Camera Photographs Taken: A) Looking Down at Support Plate With Deformed Flow Slot; B) Looking Up at U-Bends

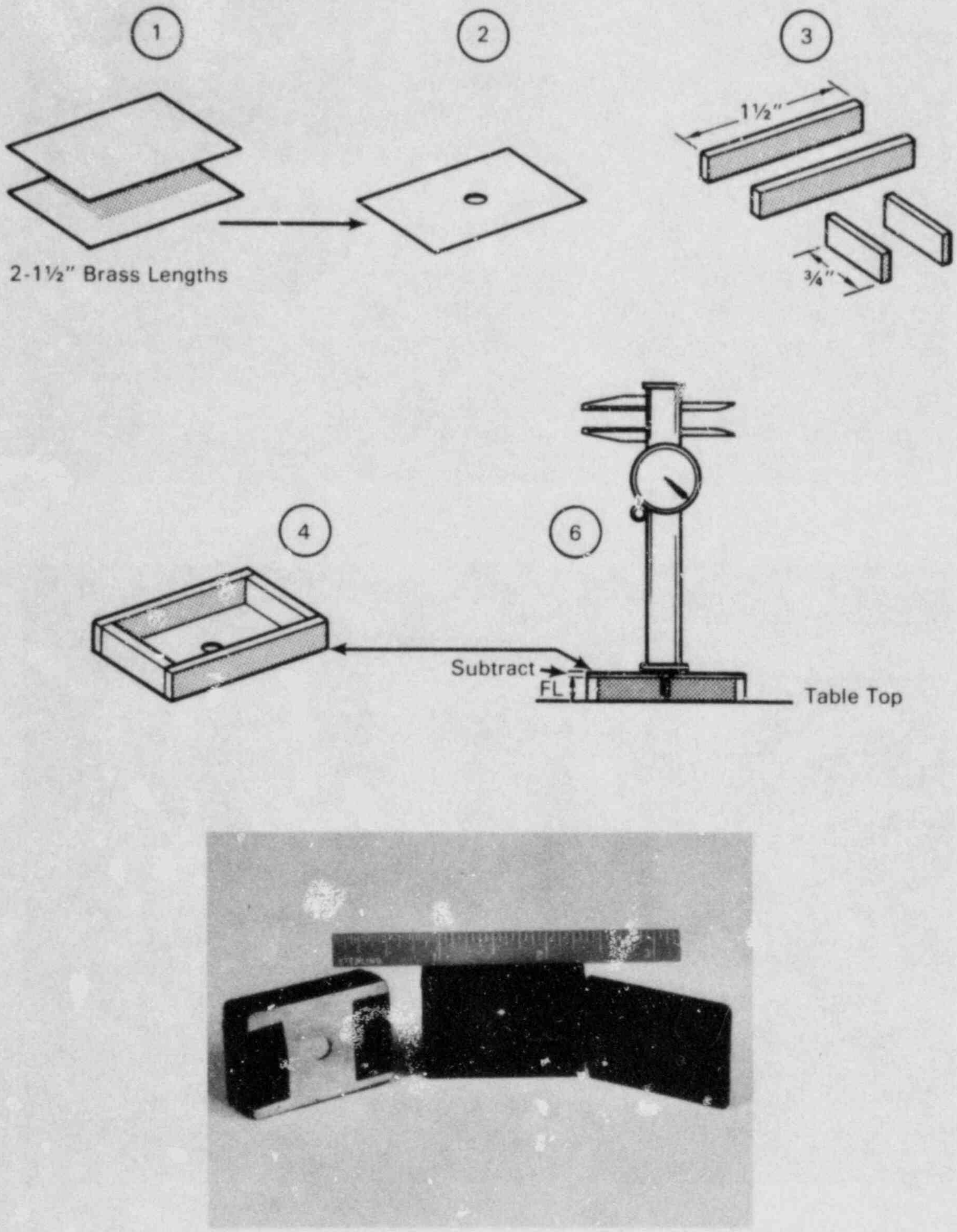


FIGURE 14. Procedure for Fabricating Rectangular Pinhole Camera

6) To get the focal length, set camera on a flat surface, brass plate with hole side up. Use the depth extension of the caliper in the hole to measure the distance from the camera OD to the flat surface. Subtracting the thickness of the brass plate from this number will give the FL. (The pinhole aperture will be placed on the inside surface of the camera.)

7) Perform steps 5 through 8 from round pinhole procedure.

8) Securely tape this plate on the inside of the camera hole, with the pinhole carefully centered.

Film Loading Procedure - See Figure 15

The similarity to round pinhole loading conditions should be evident, with only minor differences.

1) Cut a piece of film to 1-1/2" x 1".

2) Place on the rear opening, with emulsion facing pinhole.

3) Put cover plate over this film and secure it (the plate) to the camera body with a short piece of tape on each end.

4) Make the camera light proof by centering on a 6" long piece of photographic tape (long dimension of camera parallel with tape length) and wrapping to seal the perimeter.

5) Cover pinhole. Room lights may be turned on.

Reflex Pinhole Camera

Mention should be made of this unique design. The pinhole image entering the front of the camera is mirror reflected 90° to a piece of film placed on the side of the camera. The advantage of this camera is that it provides an undistorted view of an extremely wide field while permitting use of a narrow body. The disadvantages are 1) the wide image expands so rapidly in the camera body that camera structural components cause vignetting, 2) camera size is large in relation to negative size, and 3) the special pinhole and mirror configurations make fabrication and loading difficult. Two prototype reflexes were built and their performance verified by tests, but they were never used.

TINY LENS CAMERA

While these cameras do not share the extreme coverage and infinite depth of field capability of the pinholes, their image sharpness over a reasonable field (approx. 35°) is excellent (see Figure 16). An aperture placed behind the lens to control exposure and increase depth of field permits a useful, but limited, distance working range without needing to refocus. For generator work, the preferred focal lengths have been 16 mm and 18 mm. These have permitted camera sizes small enough to freely pass through a 2" diameter hole and enter the 0.4"

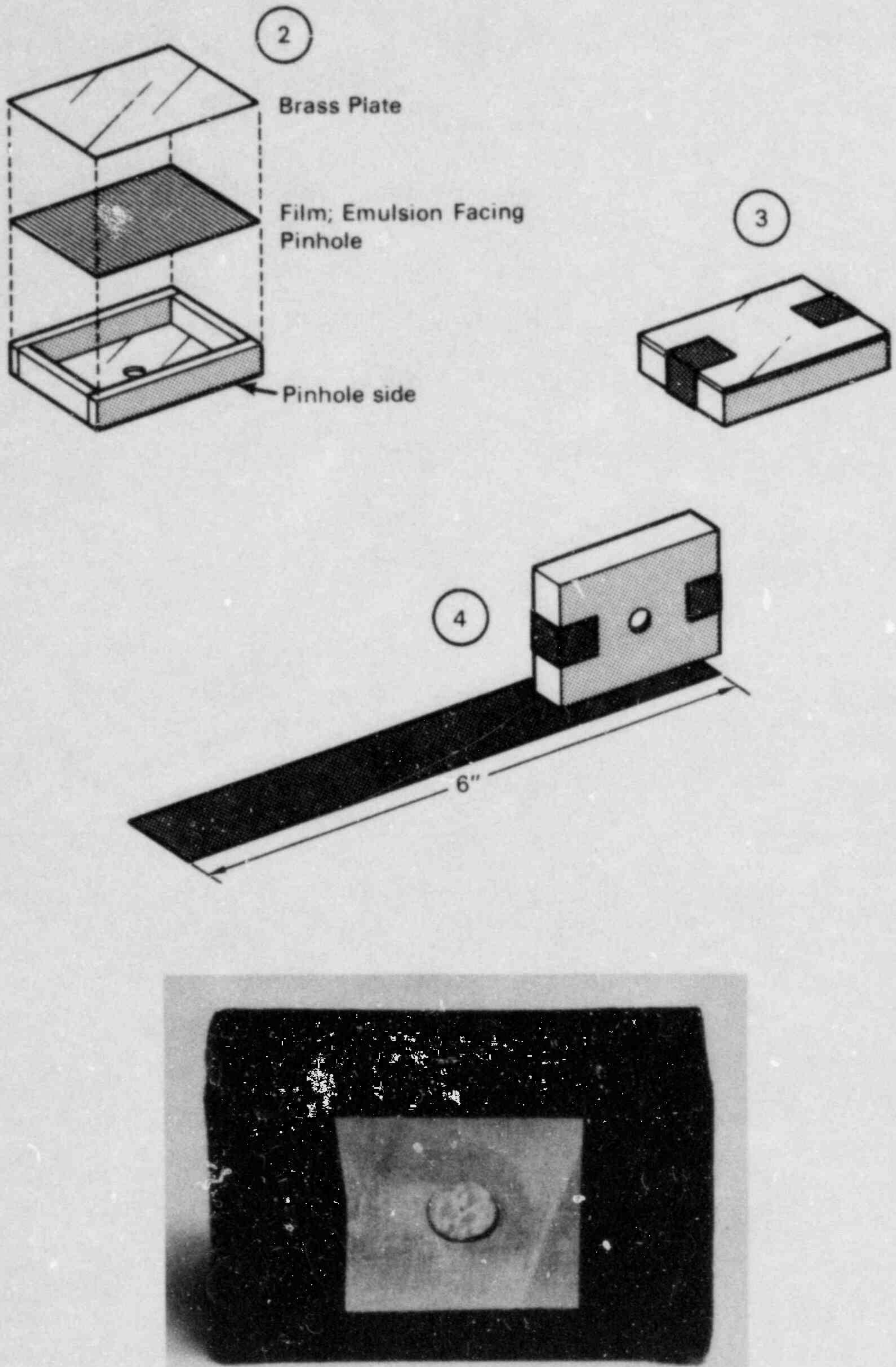


FIGURE 15. Film Loading Procedure for Rectangular Pinhole Camera

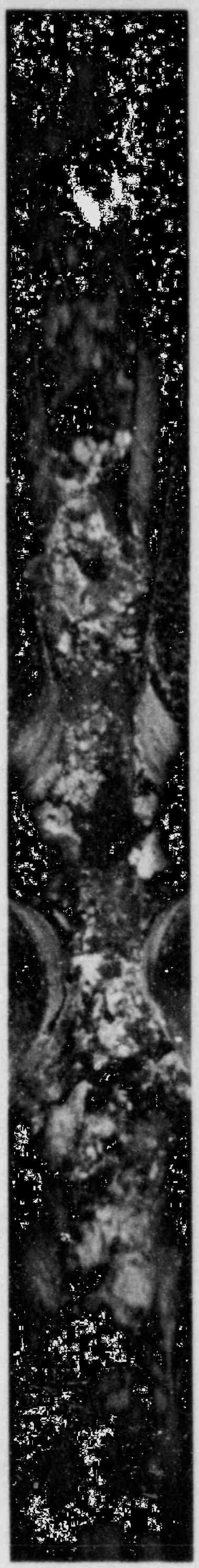


FIGURE 16. Photograph Taken With Tiny Lens Camera Looking Down at Tube Sheet Between Tube Rows

space between tubes, while providing good subject coverage. Focal lengths less than this, particularly in the 8 mm range, give images that are too small and edge distorted. It should be kept in mind that simple, inexpensive lenses are used. More expensive ones would offer some corrections but size and cost advantages would be lost. Beyond 22 mm, the camera size begins to present a problem, though the larger image at times is desirable. Their fabrication procedure is more involved than with pinhole cameras because the lens must be mounted and placed in the camera at a distance from the film plane derived from calculations using lens focal length and distance from subject matter. In all cases, if the lens camera will fit into the work space and provide adequate subject coverage, its use is preferred over the pinhole. The main disadvantages of using the tiny lens cameras are basically identical to those discussed in pinhole use and need not be repeated.

The 2" diameter hole entry to the 0.4" space between tubes and camera-to-subject (tube sheet) distance of 6" presented a good situation for using a narrow body camera with a lens. Though some pinhole work was done, the major portion of work was done with the sharper imaging camera since most of the desired information fell within its range of view and depth of field. The basic camera size is 1/4" wide x 2" long x 1" high (refer back to Figure 9 for a photograph of the tiny lens camera). The space between tubes was not consistent; narrower than 0.4" dimensions made an even narrower 3/16" wide camera necessary. Fortunately, lenses of smaller diameter were available in required focal lengths, 16 mm and 18 mm. (There are slight variations in camera sizes and lens FL and diameters because changing conditions demand different equipment. Because of the high number of cameras needed for the most efficient work and not knowing what future demands will be, older models are not discarded but kept in the system.) A 2" length was early selected because it provided 1) a good image length for mosaic overlap, 2) was long enough to reduce chances of camera turning and wedging between tubes, and 3) provided a good handling length. Successful insertions and retrievals and a desire to improve image quality at overlap points, has led to fabrication of shorter (1-1/2") cameras. These are used 6 per pole rather than 4, as with the 2" cameras, and their spacing is reduced so that each camera has to cover less subject length area to compensate for reduced negative image length. The camera and light bearing modules average 22" in length and can be put on varying length poles. Six cameras is the maximum number because of weight and strength considerations when working beyond 5 ft. and trying to keep pole bowing to a minimum. Flat wood poles are used; the various widths and depths useable have the strength necessary to completely traverse a 10-1/2 ft. distance with current loads, and they can easily be modified to fit changing conditions. The ultra thin 1-1/2" long x 3/16" wide cameras were used in single style to pass through a very narrow section of tubes. Light was provided by a remote electronic flash lamp. Because this type of flash arrangement allows only one camera to photograph at a time, some nine to fourteen ultra thin cameras were made.

Materials Needed -

Same as rectangular pinhole, plus the following items:

- Brass Strip, .025" x 1/4" x 12"
- Lens, 18 mm FL, 5 mm diameter - Cost: $2.00
  Source: Edmund Scientific

Procedure - See Figure 17

1) Cut two 1-1/2" lengths from a 1" x 12" x .025" brass strip.

2) Cut three pieces from a 1/4" x 1/2" wood strip, one 1-1/2" long, and two 3/4" long.

3) To one of the cut brass plates, epoxy the three pieces of wood; when dry, angle cut the aperture as shown in Figure 17.

4) Drill a 9/16" diameter hole in the 1/4" wide brass, approx. 1/4" from one end and centered. Cut off at approx. 1/2" from the end so that the hole is centered lengthwise.

5) Very carefully epoxy the lens over this hole, being sure not to get any cement near the center area of the lens.

6) Use this formula to determine the distance from the center of the lens edge to the film plane:

$$V = \frac{U \times F}{U - F},$$ where V = lens to film distance
U = lens to subject distance = 6" or 152.4 mm
F = focal length of lens = 18 mm

$$V = \frac{152.4 \times 18}{152.4 - 18} = 20.4 \text{ mm}$$

7) Shim up both sides of angled cut equally and level with thin strips of wood, cardboard, or layers of photographic tape until its distance positions the lens correctly. This will recess the lens in the camera body, providing a lens shade for flare avoidance.

8) Spray paint this interior (without lens) and one side of the second brass plate.

9) Make a 0.015" aperture in 0.003" shim stock, scissor cut to approximately 1/4" x 1/4" (with aperture in center) and mount on back of brass lens plate with tape. This aperture controls both depth of field and light quantity admitted by lens. With the focus calculated, and with light output variability limited, exposure will be controlled more by aperture size and film choice. Tape mounting of the aperture allows it to be changed.

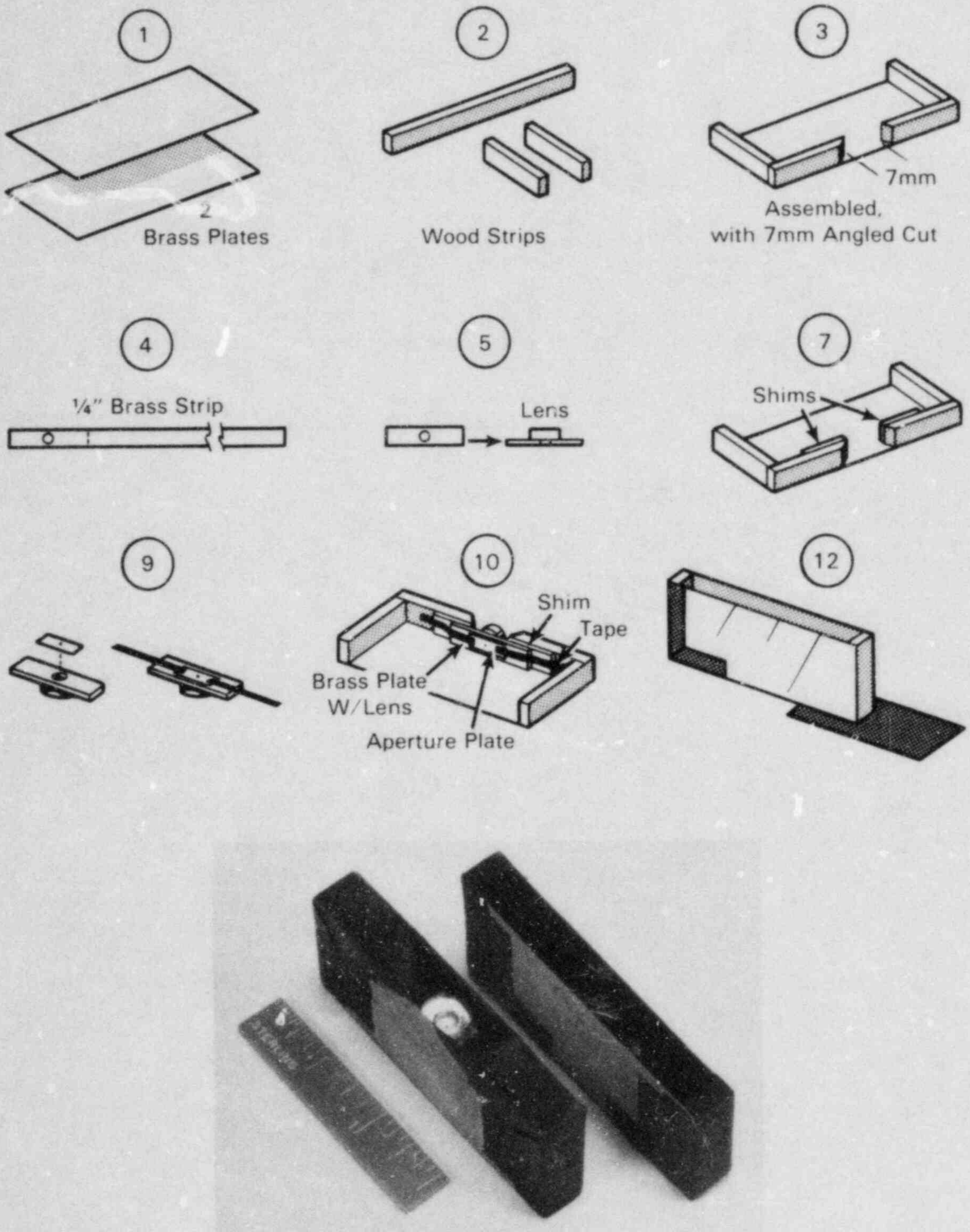


FIGURE 17. Procedure for Fabricating Tiny Lens Camera

10) Secure lens assembly in position with black tape (aperture in).

11) Put the other brass side on the camera and make it light tight on the inside with tape, being careful not to obstruct the aperture.

12) Apply tape to the outside as shown.

13) Cut a film pressure plate from sturdy mounting board--or make one from the brass strip--paint the film side black.

Film Loading Procedures - See Figure 18

Loading is very similar to the pinhole procedure, except that narrow strips of film cut to the camera length and width are used.

1) Place a piece of the cut film on the camera near the opening, emulsion side facing lens, and cover with the pressure plate.

2) Secure with a small 3/4" piece of tape crossing plate at 90° angle, and adhere to both sides of the camera body.

3) Cut a piece of tape 2-1/2" long. Place on the plate lengthwise with axis, so that 1/2" is free on both ends of the camera body.

4) Adhere tape to the camera body with light pressure to make light proof.

5) Cover the recessed lens with tape. Room lights may be turned on.

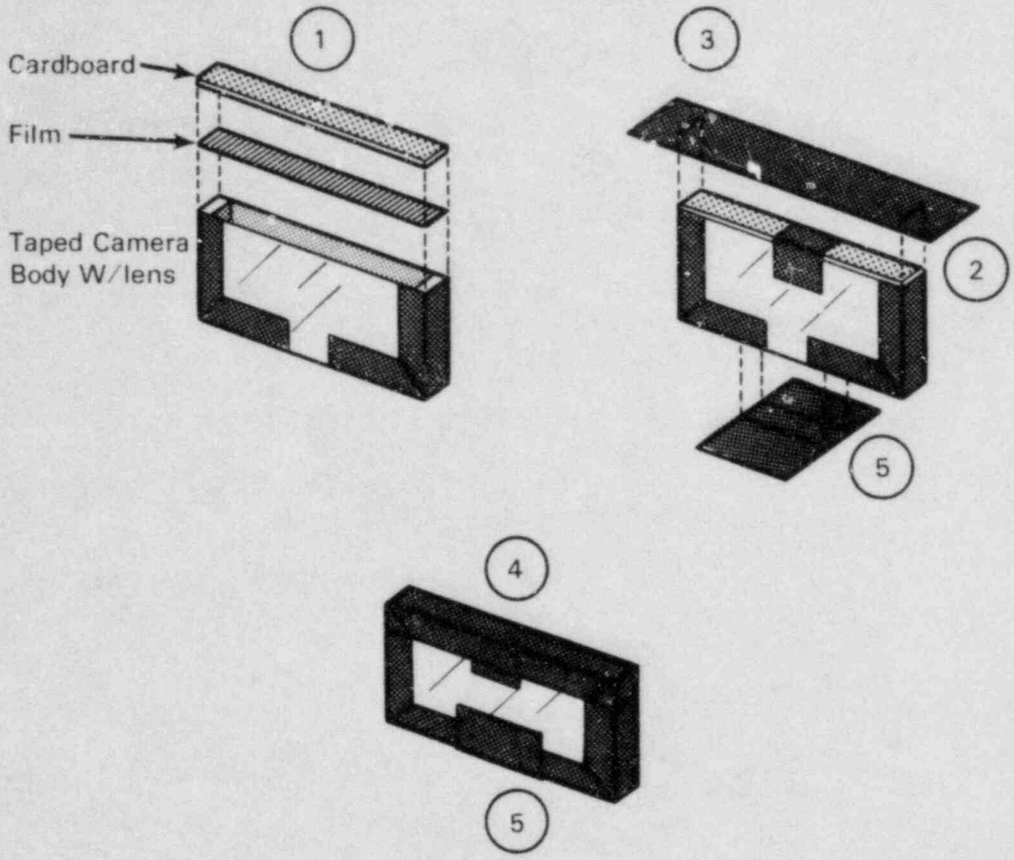
LIGHTING

All lighting for pinhole and tiny lens cameras was provided by flash bulbs or electronic flash.

Flash Bulbs

General Electric Co. flashcubes (not Magicubes) were used when working in the 0.4" lane space. The diameter of individual bulbs is 0.32". They provided ample light and expanded only slightly at the base when fired. Bulb expansion could conceivably cause binding problems in narrow spaces and is an important consideration. The brightest bulbs tested were from Polaroid SX-70 flashbars, but bulging could be a problem. Less bright and less expansive were SX-660's. All of these bulbs have been used in other less confined areas where greater light output was needed and the work space nullified any concern of bulb growth.

In use, the wood pole is parallel wired as shown in Figure 20, and white tape is placed at bulb areas to act as reflectors. Every effort is made to ensure bulb retrieval and prevent binding: between the white tape and bulb is a piece of double-sided tape; a piece of transparent tape is wrapped around the pole and adhered to both sides of the bulb; the wire leads from each bulb are tightly connected to the firing wire contacts.



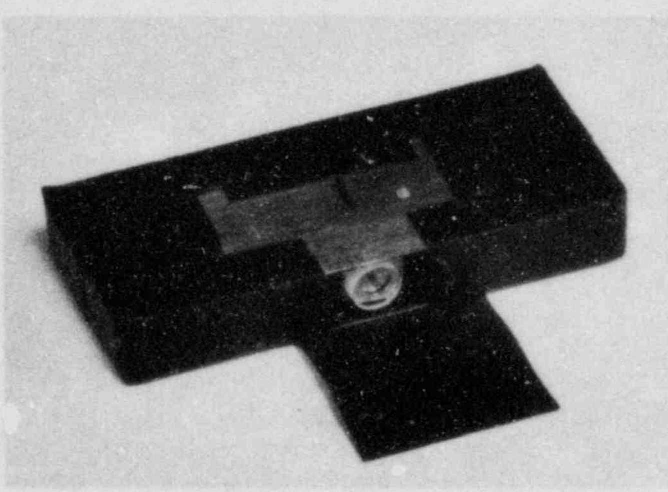


FIGURE 18. Film Loading Procedure for Tiny Lens Camera

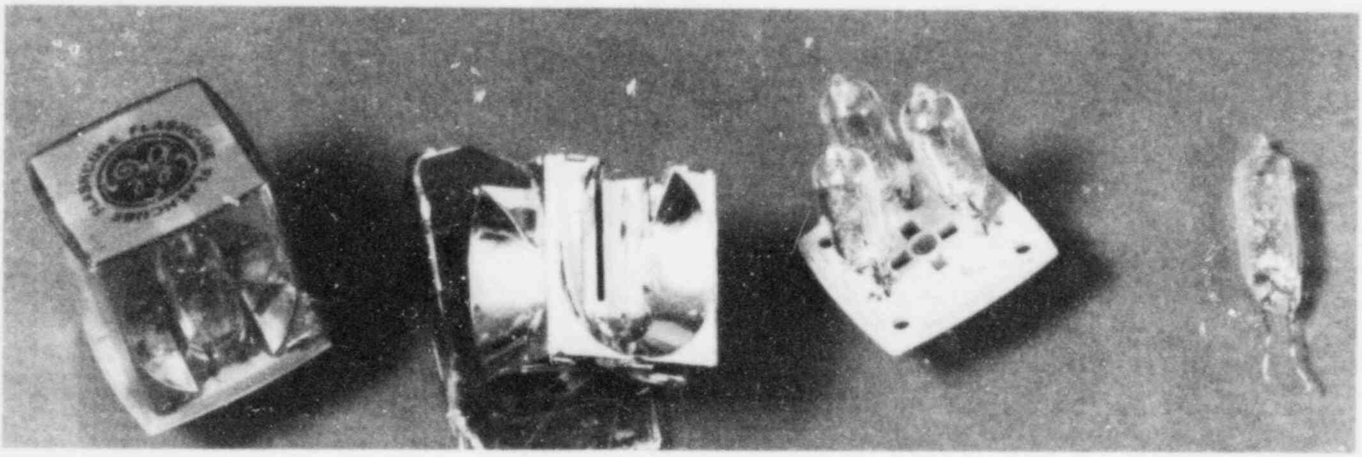


FIGURE 19. Removal of Individual Flash Bulb From Flashcube

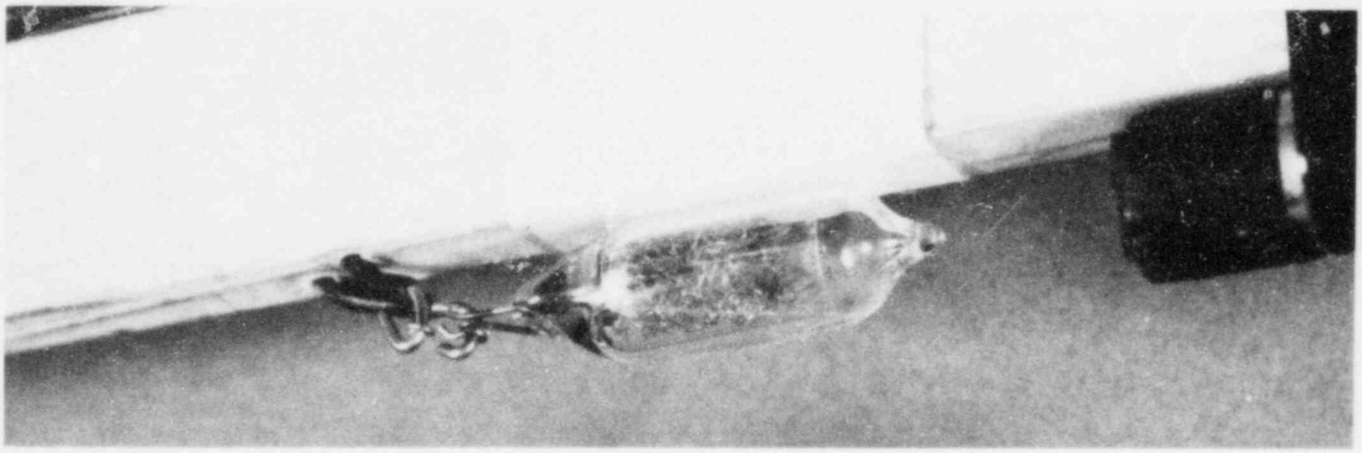


FIGURE 20. Flash Bulb Mounted for Use

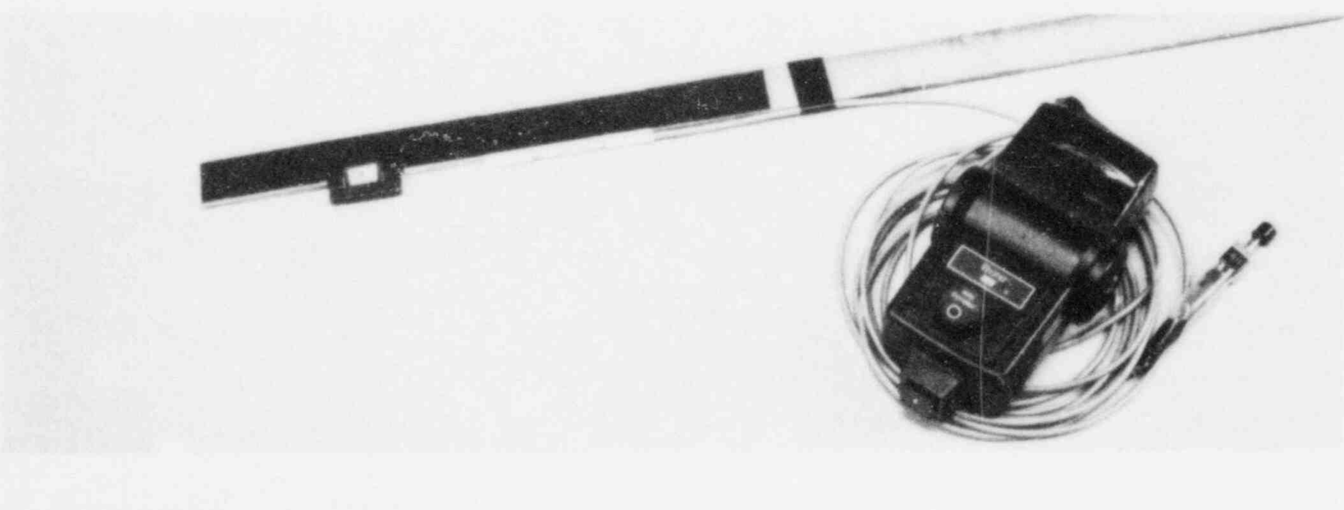


FIGURE 21. Modified Vivitar 283 Flash Unit With Ultra Thin Camera

All bulbs per pole are fired simultaneously with a battery case containing three size D batteries.

Material Needed -

- Flashcubes
- Pocketknife
- Needlenose Pliers
- A small box with tissue on bottom

Procedure - See Figure 19

1) Remove the plastic bulb cover from the flashcube with pocketknife.

2) Carefully remove each of the four bulbs from the plastic base by straightening the looped wires (do not cut them).

3) Carefully put in the box. Too many bulbs should not be crowded together because static electricity may cause them to accidently fire.

Electronic Flash - A Vivitar 283 flash unit was modified for use in those areas impassable by flash bulbs. This work consisted of putting the flash tube on 12 ft. of 2-wire shielded cables and increasing the capacitance of the trigger circuitry. Firing is by a push button switch (see Figure 21).

Vivitar 283 Electronic Flash

- Flash Duration: Approx. 1/1000 second
- Coverage: 43° vertically, 60° horizontally
- Recycle Time: Approx. 9 seconds
- Power Source: 4 AA batteries
- Guide Number: 120 with ISO 100 film
- Cost: Approx. $70.00

CONCLUSION

Each of the approaches discussed in this report has its own unique set of advantages which makes it particularly applicable to a given range of inspection needs. As these needs change, further adaptation of current equipment and development of new methods may occur. The participants in this remote photographic inspection effort offer this report as an additional source of information which may be of benefit to others engaged in similar work.

REFERENCES

1. R. B. Sinclair, 1983, "Novel Photographic Approaches to Inspection of Nuclear Components." Paper presented at the Steam Generator Nondestructive Examination Workshop, June 27, 1983, Charolette, North Carolina.

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16. ABSTRACT (200 words or less)

Characterization of the generator's secondary side prior to destructive removal of tubing presents a significant challenge. Information must be obtained in a radioactive field (up to 15 R/hr) throughout the tightly spaced bundle of steam generator tubes. This report discusses the various techniques employed, along with their respective advantages and disadvantages. The most successful approach to nondestructive secondary side characterization and documentation was through use of in-house developed pinhole cameras. These devices provided accurate photographic documentation of generator condition. They could be fabricated in geometries allowing access to all parts of the generator. Semi-remote operation coupled with large area coverage per investigation and short at-location times resulted in significant personnel exposure advantages. The fabrication and use of pinhole cameras for remote inspection is discussed in detail.

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