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Steam Generator Group Project

Task 10 - Secondary Side Examination

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Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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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.

This report provides information on secondary side characterization efforts. The methods and equipment used are discussed, along with comparisons of benefits offered by various techniques. Details of secondary side steam generator conditions are then presented, emphasizing support plate and U-bend regions.

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INTRODUCTION

This report presents results achieved through September 1983 of the secondary side characterization task (Task 10) of the Steam Generator Group Project (SGGP). The SGGP is a United States Nuclear Regulatory Commission (USNRC) program with joint sponsorship of the Electric Power Research Institute (EPRI) and consortiums from France, Italy and Japan. This project utilizes a removed-from-service steam generator as a research vehicle for studying a number of topics. Corrosion mechanisms associated with operation brought about early shutdown, removal and replacement of steam generators at the Surry 2 nuclear station at Surry, Virginia. Reduced service life of the generators, shortened from 40 to about 6 years, was manifested in the need for plugging about 22% of the Surry 2A generator's 3388 Inconel 600 heat exchanger tubes. After removal from the plant, the generator was stored on-site and later transported to an inspection facility at the Department of Energy's Hanford Works.

Secondary side characterization of the Surry generator has a number of purposes. Typically during service, generator inspection/characterization is conducted via periodic eddy current testing through the primary side (inside) of the steam generator's tubes. Tubes that have greater than allowable degradation are removed from service by plugging at both ends. This primary side inspection provides limited information about the condition of the generator secondary side, such as corrosion product buildup and condition of the support structure. The Task 10 effort at secondary side characterization is providing the first comprehensive visual assessment of nuclear steam generator condition from the shell side. Eddy current indicated defects are viewed from the tubing outer diameter. A general survey is being conducted to establish if tube defects exist that are not being characterized by primary side inspections. The location, extent of accumulation and content analysis of corrosion products and sludge are being established. This information may indicate tube areas subject to potential degradation. Secondary side structural components are being characterized, for example the extent of support plate degradation due to denting in this particular unit. This information will provide direction on the advisability or necessity of secondary side inspections for in-service units. Activities under this task are continuing. This report provides an interim review of the methods developed for characterizing the secondary side, and results to date.

EXPERIMENTAL APPROACH AND EQUIPMENT

Secondary side examination work thus far has concentrated on visual and photographic examinations for operation-induced behavior and possible degradation. Limited sampling and analysis of interior deposits has also been done. To accomplish initial inspection, subsize cameras had to be developed. This was necessary to allow high quality photographic access to degraded regions between tube rows and columns whose nominal separation is less than 0.406 inch (1.0 cm.)and other areas not easily accessible by commercial optical equipment.

Inspection of the secondary side included the use of optical devices, small, high intensity lights, sampling tools and various photographic equipment described below. Initial access to the generator interior was through preshipment inspection ports P-1 and P-4, built-in inspection handholes between the tube sheet and first support plate (referred to as 0° and 180°), and three pairs of 2 inch (5.1 cm.) diameter holes; the latter hole pairs were drilled through the shell between the tube sheet and the 0° handhole but offset slightly to the left and right of the handhole centerline. Locations of the various ports are shown in Figure 1. Row and column arrangement is schematically shown on the one-half tube sheet surface of Figure 2.

Access Ports

P-1 and P-4 are square holes in the flow lane about 10 inches (25.4 cm.) on a side; P-1 is at the first support plate; P-4 is slightly above the lifting trunnion just below the seventh support plate. The 0° handhole and its diametrically opposite 180° location allowed direct access to the tube lane region between the tube sheet and first support plate of the generator. Each handhole was effectively about 5 inches (12.7 cm.) in diameter. Each 2 inch (5.1 cm.) diameter hole pair was oriented with centers 2-1/4 and 7-1/2 inches (5.7 and 19.1 cm.) respectively above the tube sheet. The hole pairs were located about 20 inches (50.8 cm.) right and left of the 0° handhole axial centerline (see Figure 1). All the front or 0° facing ports noted in Figure 1 allowed closest access to the Westinghouse highest numbered tube columns. For example the ports P-1 and P-4 are adjacent to tube Column 94. The 180° handhole penetrates the shell at the first tube column. The tandem 2 inch (5.1 cm.) diameter holes allow access between tube Rows 14 and 15 on both hot leg (left) and cold leg (right) sides.

Internal Lighting

Illumination of the secondary side was provided in several ways. Complimentary lighting for a borescope was provided with a high wattage, 1/2 inch (1.3 cm.) diameter screen-wrapped bulb (500 watt) attached to a long metal tube. A variable voltage source was necessary to prevent the bulb from melting. Forced air cooling was not feasible. In addition small circle focus projector bulbs [providing as small as a 1-1/2 foot (45.7 cm.) circle at 14 ft (4.3 m)] in the range of 50 to 300 watts were used primarily in the tube lane region between the tube sheet and first support plate. Variable voltage power sources were also needed to prevent melting.

Commercial Camera Equipment

Standard 35 mm and 126 size cameras were used for general photography. A Tessina Model L was adapted for use in the tube lane region and Battelle-developed pinhole and fixed-focus cameras were used to photograph regions inaccessible to commercially available cameras. The latter are described in the next section.

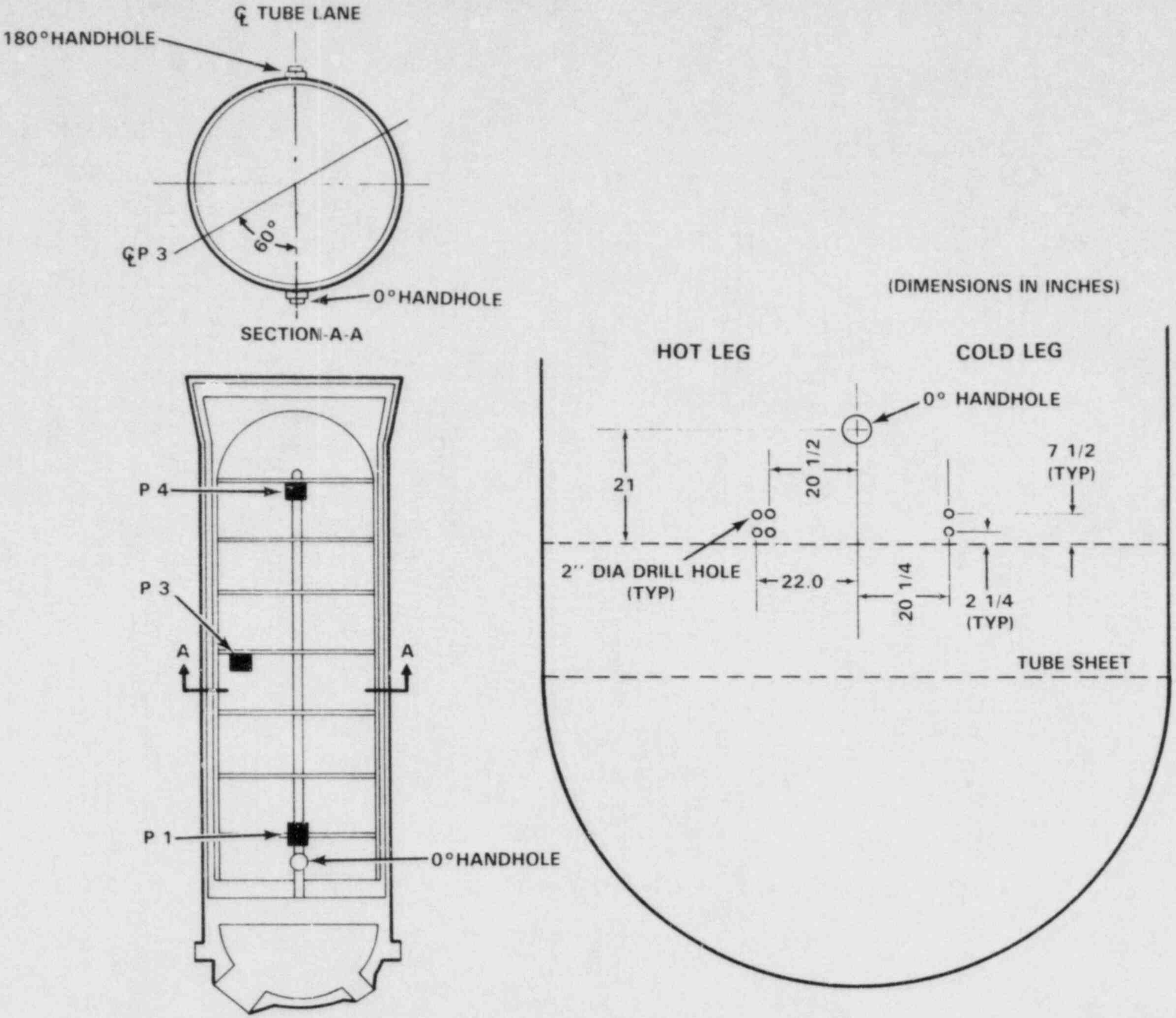

FIGURE 1. Location of Steam Generator Examination Ports

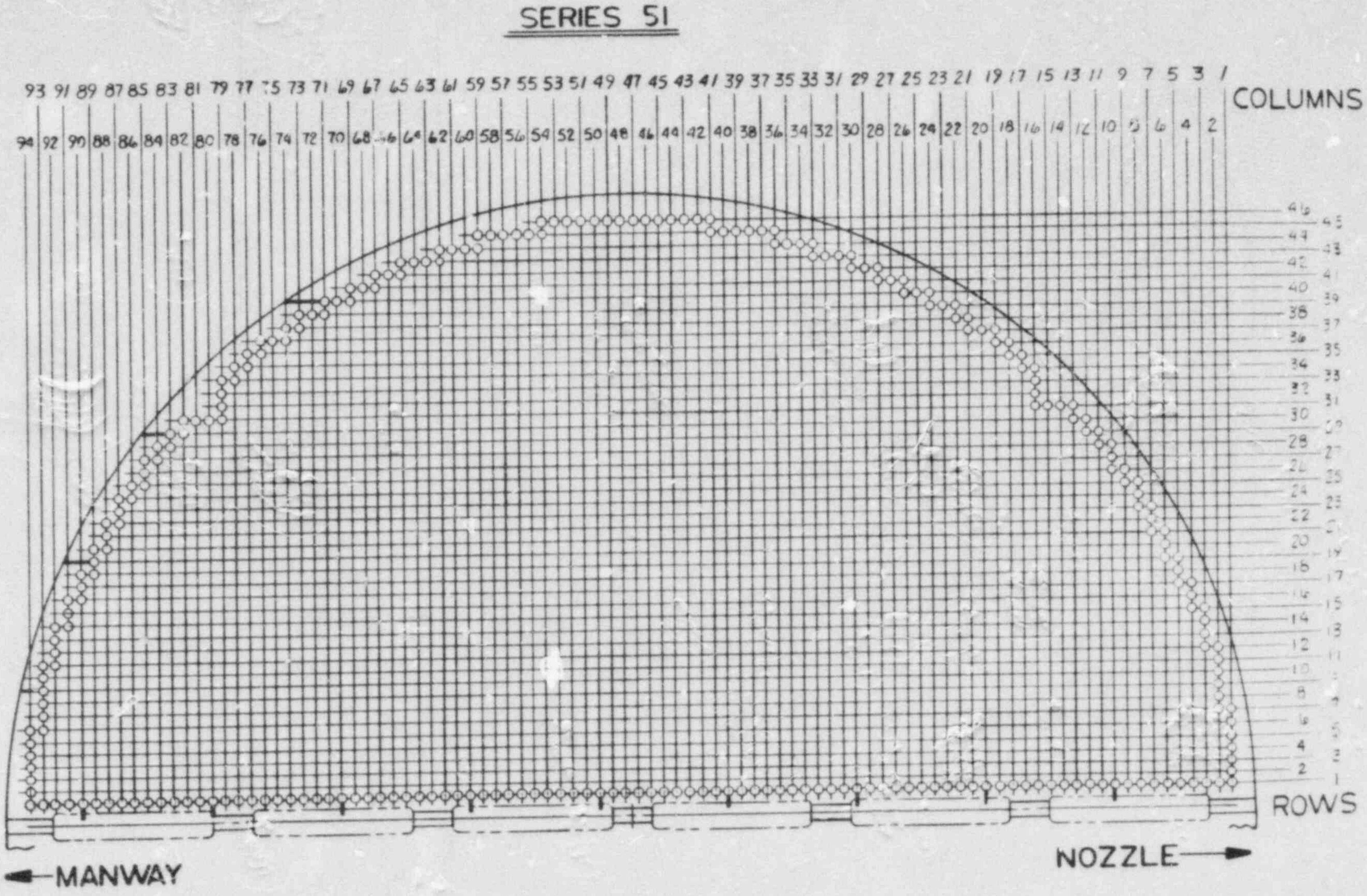

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FIGURE 2. Row and Column Arrangement for a Westinghouse Series 51 Steam Generator

The Tessina camera was placed in a milled aluminum box (as shown in Figure 3). Its dimensions are approximately 1 x 3-7/8 x 4-1/4 inches (2.5 x 9.8 x 10.8 cm.) thick. The box was designed to photograph in forward or side viewing directions. The region in the box adjacent to the camera lens contained an adjustable mirror for taking side-viewing photographs between the tube rows. The box also contained a solenoid-operated film advance mechanism (upper left of figure). A small electronic flash bulb, removed from a commercially available photo flash attachment was adapted to fit on the box cover. When the cover is placed on the box (Figure 4) both side and forward viewing ports can be seen more clearly. The flash can also be placed on the same surface containing the forward viewing port, for improved lighting. The flash power supply can be seen at the right of Figure 4. The Tessina camera utilizes 35 mm film with an image size about half that of a normal 35 mm single lens reflex or range finder camera. It can take up to ten pictures during a single insertion into the tube lane.

Subsize Cameras

Miniature or subsize pinhole (PH) and fixed focus lens (FFL) cameras were developed by Battelle in order to more clearly photograph critical regions of the generator interior that, because of confined spaces, were not readily accessible to commercially available cameras. Pinhole cameras, both round and rectangular in cross-section, were first made from cardboard and later from commercially available round and rectangular brass model builder tubing. One flat and two round pinhole cameras, including one rectangular fixed focus lens camera, are shown in Figure 5. The upper left tube camera has its ends and pinhole containing plate removed from the tube body. The upper right tube camera is assembled and contains a piece of film contiguous to the tube inside surface except for a narrow opening between the film ends at the pinhole. The round cameras are 3/8 inch (1 cm.) in diameter by about 2-1/2 inches (6.4 cm.)long. The flat pinhole camera, at the lower left corner of Figure 5, is about 1/4 inch (.6 cm.) thick by 1/2 inch (1.3 cm.) wide by about 1-3/8 inch (3.5 cm.) long. The flat film is located on the back face of the camera and provides a view with less distortion than the circular film plane of the round cameras. The pinhole cameras had effective f-stops ranging from 64 to about 300 thus providing a very large depth of field. The fixed focus lens camera shown in the bottom of Figure 5 (including the narrow and wide top and back plates, respectively) provided sharper image photos but generally with a lesser field of view and depth of field. The camera is about 0.35 inch (.9 cm.) thick, 1 inch (2.5 cm.) wide and about 2 inches (5.1 cm.) long.

In order to more rapidly photograph larger regions of interest, such as long narrow areas between tube rows and columns, a group of PH or FFL cameras were attached to long, narrow pieces of wood as shown in Figure 6. Three FFL cameras are attached to a wood beam as shown at the bottom of Figure 6 with three round PH cameras just above the FFL cameras. Note also the placement of small (about 0.3 inch (.8 cm.) diameter) flash bulbs at each end of a given camera. These bulbs were

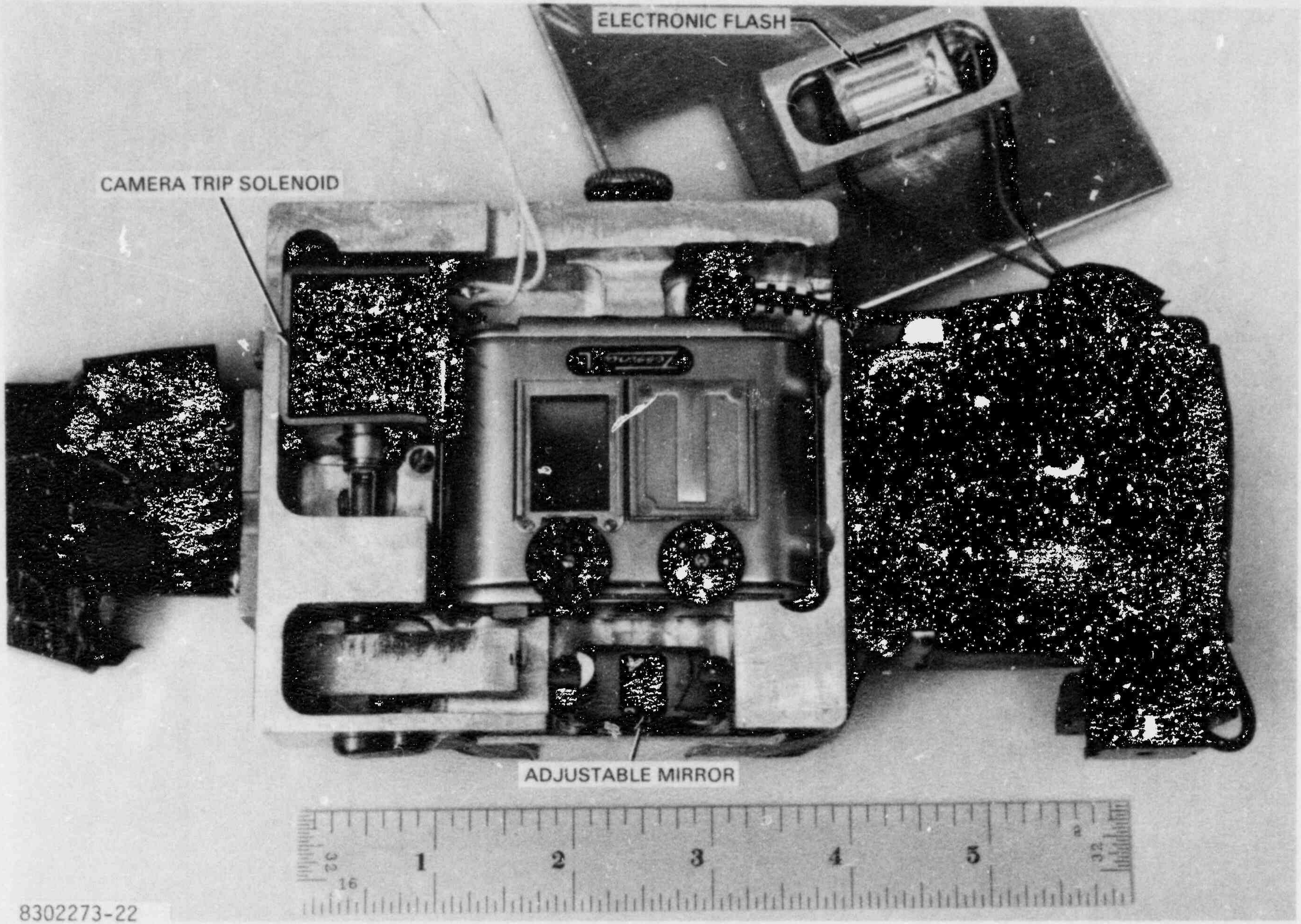

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FIGURE 3. Tube Lane Camera in Milled Aluminum Box With Cover Removed

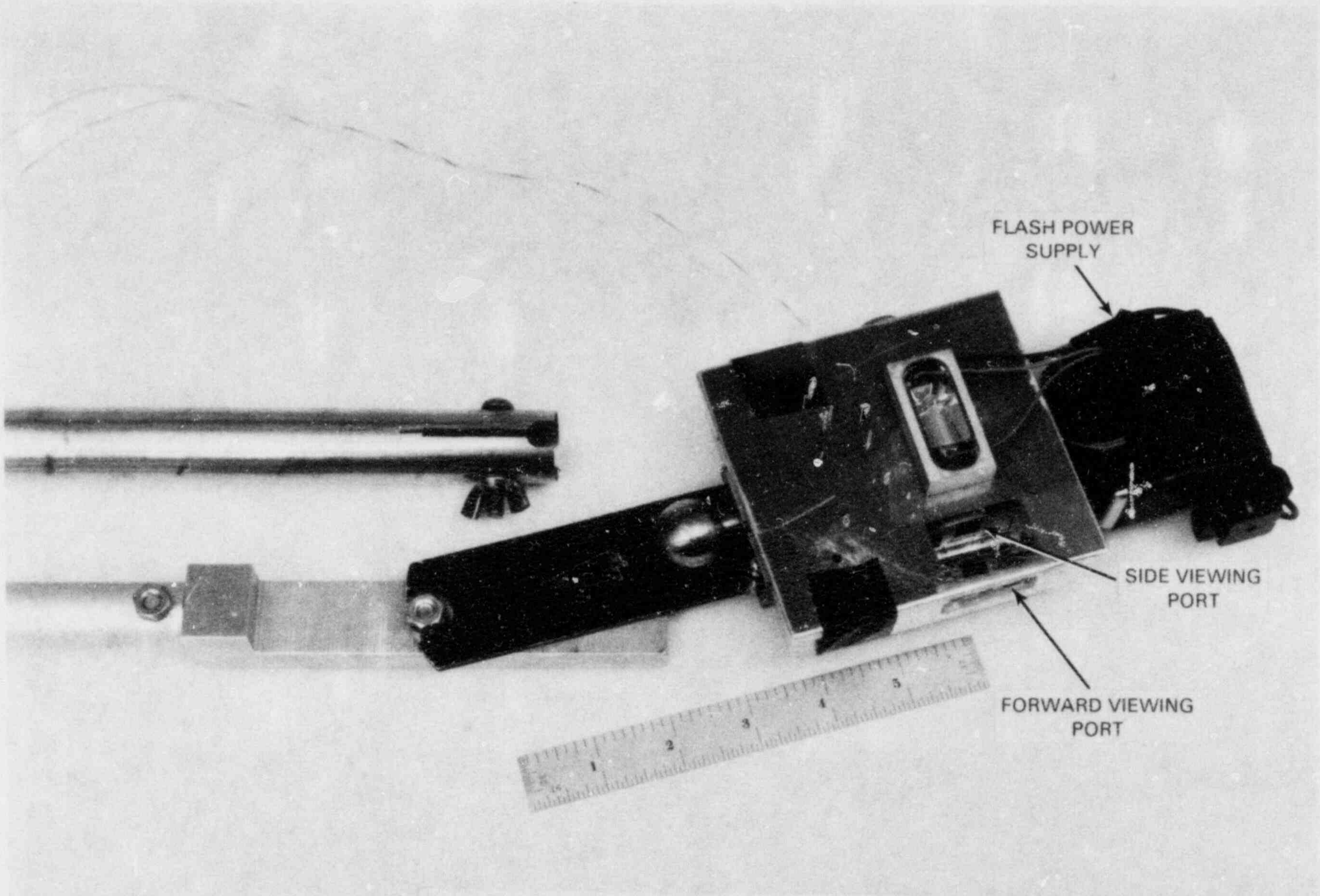

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FIGURE 4. Assembled Tube Lane Camera

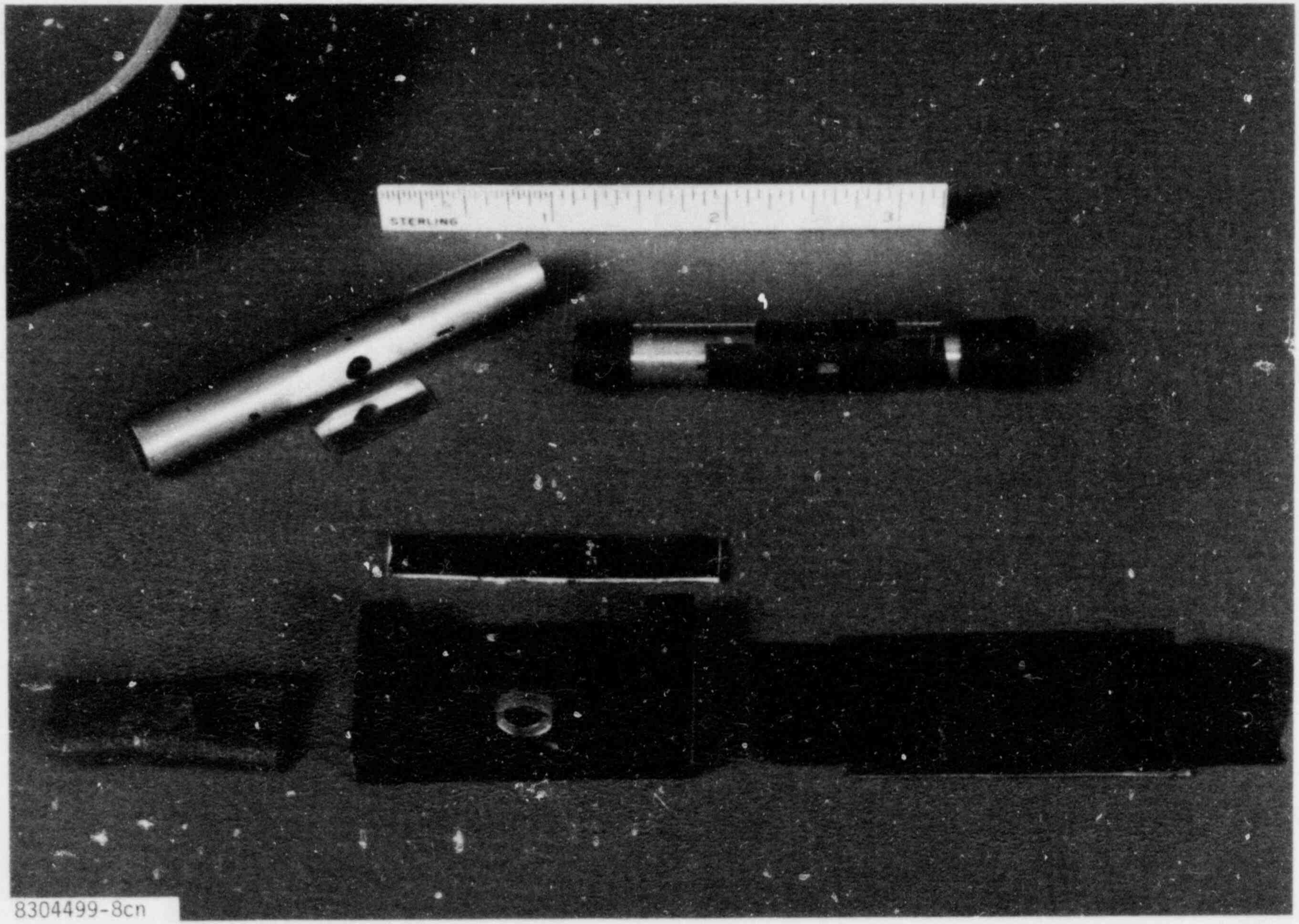


FIGURE 5. Two Round and One Flat Pinhole Cameras and One Fixed Focus Lens Camera

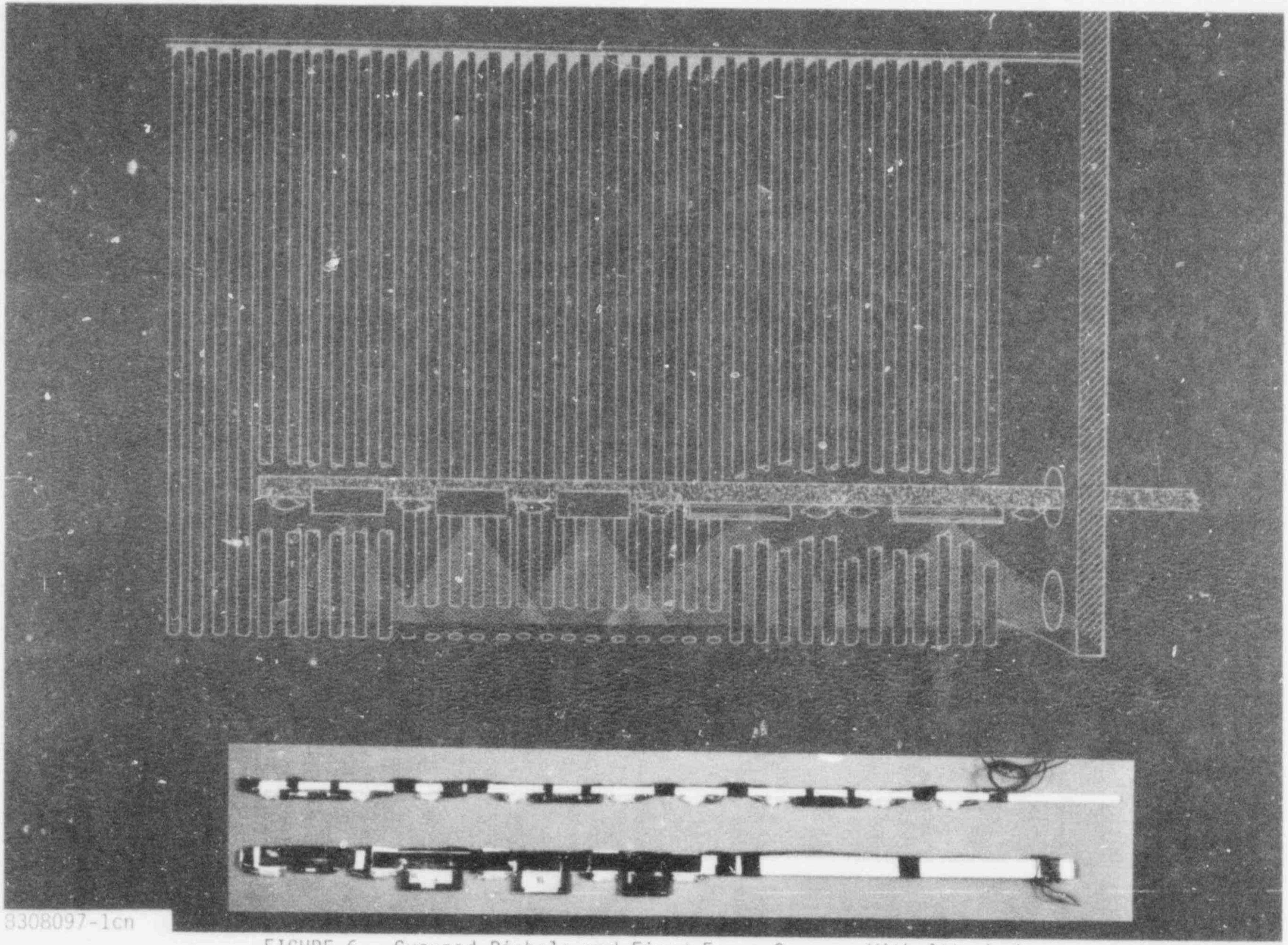


FIGURE 6. Grouped Pinhole and Fixed Focus Cameras With Attached Flash Bulbs for Photographing Regions Between Tubes

removed from commercially available flash cubes or bars and provided necessary lighting for proper exposure. The illustration in Figure 6 shows how photos were taken between tube rows pointing toward the tube sheet or the first support plate through the 2 inch (5.1 cm.) diameter holes.

Optical Inspection Equipment

Optical viewing equipment included a large diameter side viewing [about 3 inch (7.6 cm.) diameter] periscope, a multi-jointed 1/2 inch (1.3 cm.) diameter borescope [up to 20 ft (6.1 m) long] and a 0.35 inch (.9 cm.) diameter by 15 foot (4.6 m) long flexible distal tip fiberscope with a working channel.

A side-viewing periscope was used for overall observation through the larger ports and when the steam generator top was removed (Figure 7). Tangential orientation of the scope minimized radiation streaming exposure to personnel.

The 1/2 inch (1.3 cm.) diameter borescope was used for both observation and photography primarily through ports P-1 and P-4 and the two handholes. Observation of the first row U-bends at P-4 is shown in Figure 8.

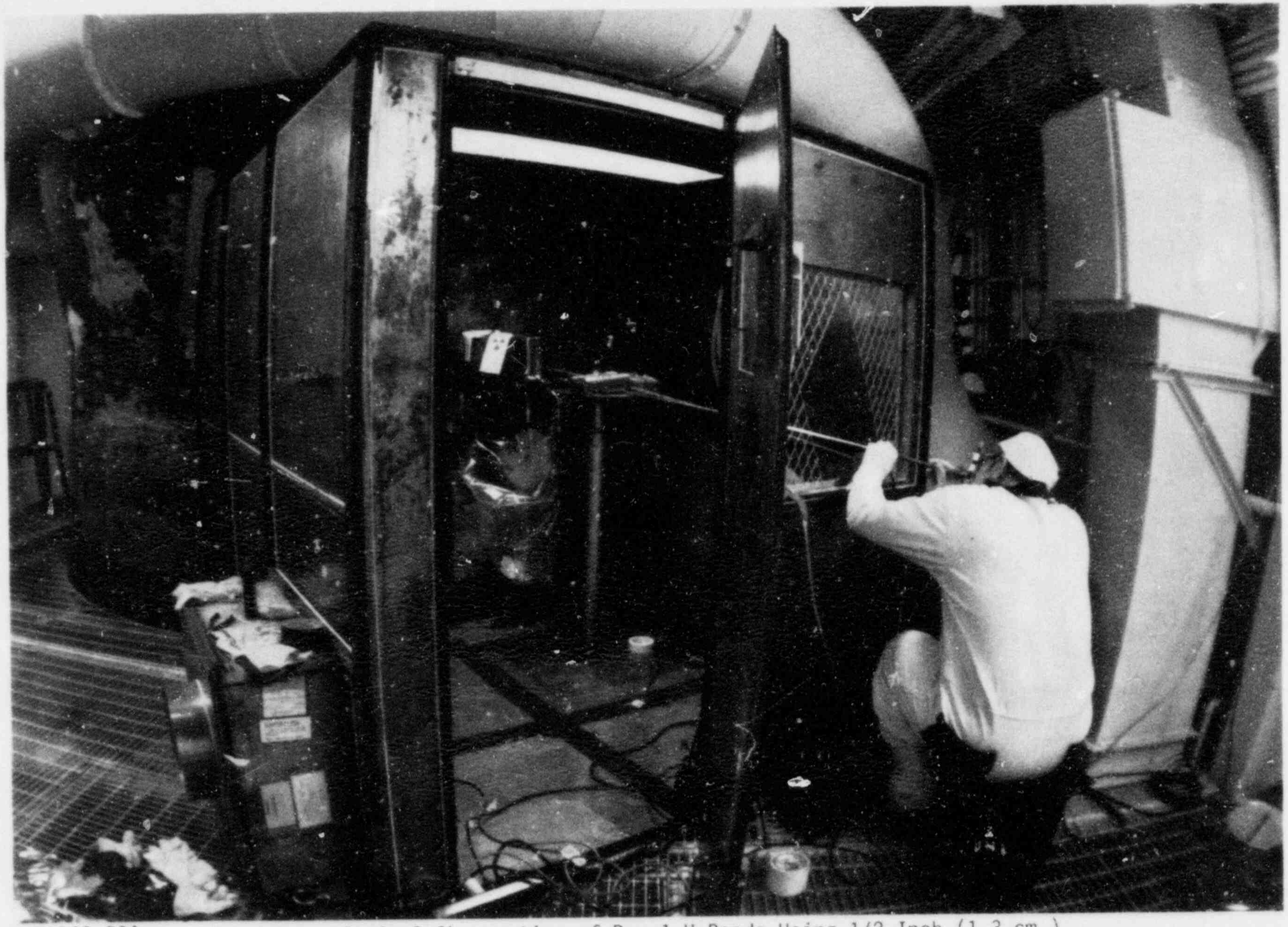
The 0.35 inch (.9 cm.) diameter fiberscope was obtained primarily for its flexible optical accessibility between tubes and rows and around interfering objects. It also has a set of tools that could be manipulated at the distal tip while observing their actions. Manipulation tools included a small forceps, a wire loop, grabber, and brush. Unfortunately, the limited radiation life of the optical fibers (darkening) has precluded further use. We plan to use its working channel coupled to a fiberscope now under order.

Comparison of Optical Inspection Equipment

Primarily because of space limitations inside the multi-tube steam generator, no single optical device has met all of our inspection needs. As noted earlier this problem led us to develop simple, subsize cameras that could fit into narrow or restricted spaces. While allowing a significant improvement in inspection, they too have some limitations. It may be useful to the reader to compare the advantages and disadvantages of the various optical tools that we have used thus far. However, a number of factors affect such comparisons. These cover, but are not limited to, size and accessibility, image sharpness, field of view, depth of field, distortion, lighting adequacy, ease of handling, personnel radiation exposure and human fatigue.

Assuming one can get to the region of interest (size and accessibility), a well-illuminated sharp image is the most important requirement. This is followed closely by field of view. The latter is critical because a narrow field of view makes it more difficult, sometimes impossible, to find (and to return to) a clear and unambiguous point of reference. Knowing how far the inspection tool is inside the generator (and sometimes the angle) is typically the first point of reference. In some

FIGURE 7. Observing Top of Steam Generator With a Multi-Jointed Periscope



8301049-204cn FIGURE 8. Optical Observation of Row 1 U-Bends Using 1/2 Inch (1.3 cm.) Diameter Borescope and Supplementary Light Source cases this has been as much as 10 to 11 feet (3.1 to 3.4 meters). Compare this with between-tube and tube-to-tube distance of 0.41 and 1.28 inches (1.0 and 3.25 cm.), respectively. Further, slight movements of the handle of a 10-11 foot long optical tool will cause relatively large movements at its working end. Thus, a large (> several tube diameters) field of view containing an easily identifiable object allows quick return to that same area and object. In contrast, an optical tool with a relatively high magnification (>5-10X) and a narrow field of view of a relatively featureless object means longer inspection times, more fatigue, and higher radiation exposure. These conditions could possibly preclude return to regions of interest.

Advantages and disadvantages of several optical devices are given in Table 1. The table represents an effort to emphasize the strong and weak points of each tool. Further, the comparisons are not totally rational nor always fair. Each device has advantages that the others do not possess. They do, however, represent our experience in looking at dark colored, rough-textured, curved surfaces in restricted spaces as much as 20 feet (6.1 m) away in a radiation field where ease of handling is often restricted.

Our present borescopes (5/16" [.8 cm.] dia. by 68 inches [1.7 m] long and 1/2" [1.3 cm.] dia. by 20 feet [6.1 m]) allow the sharpest image along with good optical properties. The newer scopes use high intensity tungsten-halogen lights and are much brighter than older, lower wattage models. A single piece borescope is better than the same diameter extendable, multi-jointed borescope because the 'working diameter' of the latter is smaller due to the joints. Three-eights inch diameter appears to be the minimum practical diameter scope for an extendable model. Because of tube sheet hole drilling allowances, a 3/8 inch (1 cm.) diameter borescope will jam or bind in an ostensible 0.41 inch (1.05 cm.) tube-to-tube separation path. Smaller diameters are possible in single piece scopes but are length-limited. Furthermore, some single piece borescopes use radiation sensitive fibers to carry the light to the object with prism devices used to return the image to the viewer. Thus, they have a limited life from radiation browning of the non-image carrying fibers.

Our flexible distal tip, working channel fiberscope is outstanding for obtaining unambiguous samples and bending around corners where no other device could go. It must be guided, though, to its location for distances greater than about one foot (0.3 m); at greater distances it will buckle or collapse unless guided by a tubular member or natural constraints of the structure being examined. For equal diameters a fiberscope has a much lower image quality, a property which is directly related to the number of viewing elements (fibers). Some very high radiation resistant fiberscopes are available but are stiffer, expensive, and contain no working channel (tool capability). The best working distance for our fiberscope appears to be about 1 to 10 inches (2.5 to 25.4 cm.) with lack of resolution precluding effective use at greater and lesser distances. Image brightness can be restrictive in some fiberscopes as light intensity decreases about 6% per foot of length out to the object and the same back for the reduced light reflected from the object.

TABLE 1. Relative Advantages & Disadvantages of Optical Inspection Equipment

		Optical Properties							
Optical Device	Size & Accessibility	Sharpness	Field of View	Depth of Field	Distortion	Lighting Adequacy	Tool Handling	Radiation Sensitivity	Flexibility
Borescope	1/4 to 3/8" dia. (min. practical size) 5' to 20' respectively	E	G	G	G	E-G	Nil	E-P	Rigid
Fiberscope	~5/16" max dia. 10-15' long	P	G	P	G	G-P	E-Nil	E-P	Flexible with moveable tip
Periscope	~3" dia. x 20'	E	E	E	E	E	Nil	G-P	Rigid
Subsize Camera	5/16" dia. or 3/16" thick	E-G	E	E	G	E-G	Nil	E	G

E = Excellent
G = Good
P = Poor

The periscope has high quality optical properties, is good for reduced radiation exposure (long and has a side-viewing capability) but is cumbersome to handle and is limited to openings or spaces greater than 3 inches (7.6 cm.) in diameter. It too has radiation sensitive glass in its construction but is apparently less sensitive than the fibers and fiber-coating chemicals used in some fiberscopes.

The subsize cameras score relatively high in all areas with the exception that one cannot be sure where the photo is being taken and inspection cannot be done in real-time. Simply, one cannot see what he is going to photograph ahead of time and there is a time lag between the act of inspection and the printed photo. Good depth of field and a wide field of view help to minimize the problem of seeing what is to be photographed.

In conclusion, effective inspection of the secondary side of a steam generator requires the use of borescopes, fiberscopes and subsize cameras along with an adequate number of two inch (5 cm.) (or larger) diameter penetrations.

Sampling Equipment

Samples of tube lane sludge and tube deposits were obtained using small scoops attached to long handling tubes. Samples were obtained from several positions along the tube lane through the 0° handhole and between Rows 14 and 15 on both hot leg and cold leg sides. Results are reported in the next section.

EXPERIMENTAL RESULTS

This report covers details of a photographic examination of the tube lane region between the tube sheet and first support plate, initial photos of the outer perimeter of the tube bundle at the tube sheet, and between-tube regions (Rows 14 and 15 at Column 92) across a portion of the tube sheet on the cold leg side. In addition, results of Row 1 U-bend examinations and some trends in U-bend failure conditions are presented with respect to tube location.

Tube Lane Region Between the Tube Sheet and First Support Plate

In this section a series of overall and close-up views are presented of the tube lane region between the tube sheet and first support plate and from the first row, about tube Column 92 to about Column 47. While these photos shown were taken from the 0° handhole, observations and photos from the 180° handhole did not appear different in any significant way. Thus, the latter photos are not presented.

Tube Sheet at the Tube Lane - Sixteen photographs of the tube sheet lane, taken through the 0° handhole with the camera system shown in Figures 3 and 4, were joined together in a montage and are presented in Figure 9. Some of the Row 1 hot and cold leg tubes appear nonperpendicular to the tube sheet due to normal distortion caused by the camera. The camera-to-blowdown pipe distance is about 15-20 inches (38.1 - 50.8 cm.).

Changes in visual appearance in Figure 9 from the handhole region (around Column 92) to the generator center (around Column 45), suggest that vertical hydraulic flow parallel to the lane was greatest near the handhole and least around the generator center, in spite of the flow deflectors (see Figure 12). This is reflected by varying surface conditions and colors*. For example, tubes at the handhole appear to be dull brown in color, possibly with thinner deposits and there are fewer tube deposits laying in the tube sheet/blowdown pipe region. Surface features and color variations appear more distinct toward the center of the tube lane. These conditions are seen more clearly in Figures 10 and 11 which are close-ups of the mid-point and end (generator center) of Figure 9. The conditions noted in the flow lane nearest the 0° handhole are seen more clearly at the bottom of the flow deflector seen in the montage shown in Figure 12. The flow deflector channel box is uniform in cross-section from the top to the bottom of the montage photo; off-angle photography caused unreal distortion of the flow deflector.

Photos were also taken along the tube lane looking toward tube columns on both the hot and cold leg sides. The montage photo of cold leg Columns 46 to 39 shown in Figure 13 were taken from the 180° handhole. Here, individual color variations on the tubes are obvious and it is possible to see about 8 tube depths (see left side of Figure 13 and the expanded view in Figure 14). Photos were also taken to the opposite or hot leg side, with similar results. In general the tubes on the hot leg side appeared to have thicker deposits. Also the deposits were peeling off the hot leg tubes more than the cold leg tubes (see ahead to Figure 22). Finally, the depth of tube deposits was deeper on the hot leg side of the blowdown pipe (this slight difference in deposit height can be seen in the next section in Figure 16). Individual pieces of tube deposits resting on the tube sheet surface in the flow lane region ranged up to about 1/16 inch (.2 cm.) thick.

Close-up photos were taken of selected cold leg tubes and two are shown in Figure 15. Here the tubes are about 1-1/2 inches (3.8 cm.) from the camera. This was accomplished by attaching a magnifying lens over the viewing port (Figures 3 and 4) and resulted in a magnification of about 7X to 8X. The photo clearly shows alternating brown and white deposits, some of which have peeled off. In addition, the deposit appears porous allowing possible ion diffusion during operation.

Central Column Region - Photographs were also taken parallel to the blowdown pipe (from the 0° handhole) and upward along the column for the central support plates. Figure 16 shows the support column between the tube sheet and first support plate. Color variations here may reflect the different water treatment conditions used during operation (phosphate and AVT) along with some extrinsic variation caused by some different lighting conditions used during photography. The color variations nearer the bottom of Figure 16 may be "bathtub ring effects"

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*These colors probably became more vivid after the generator interior was exposed to oxygen during and after drying. Apparently the original tube deposits tended to be gray to black in color.

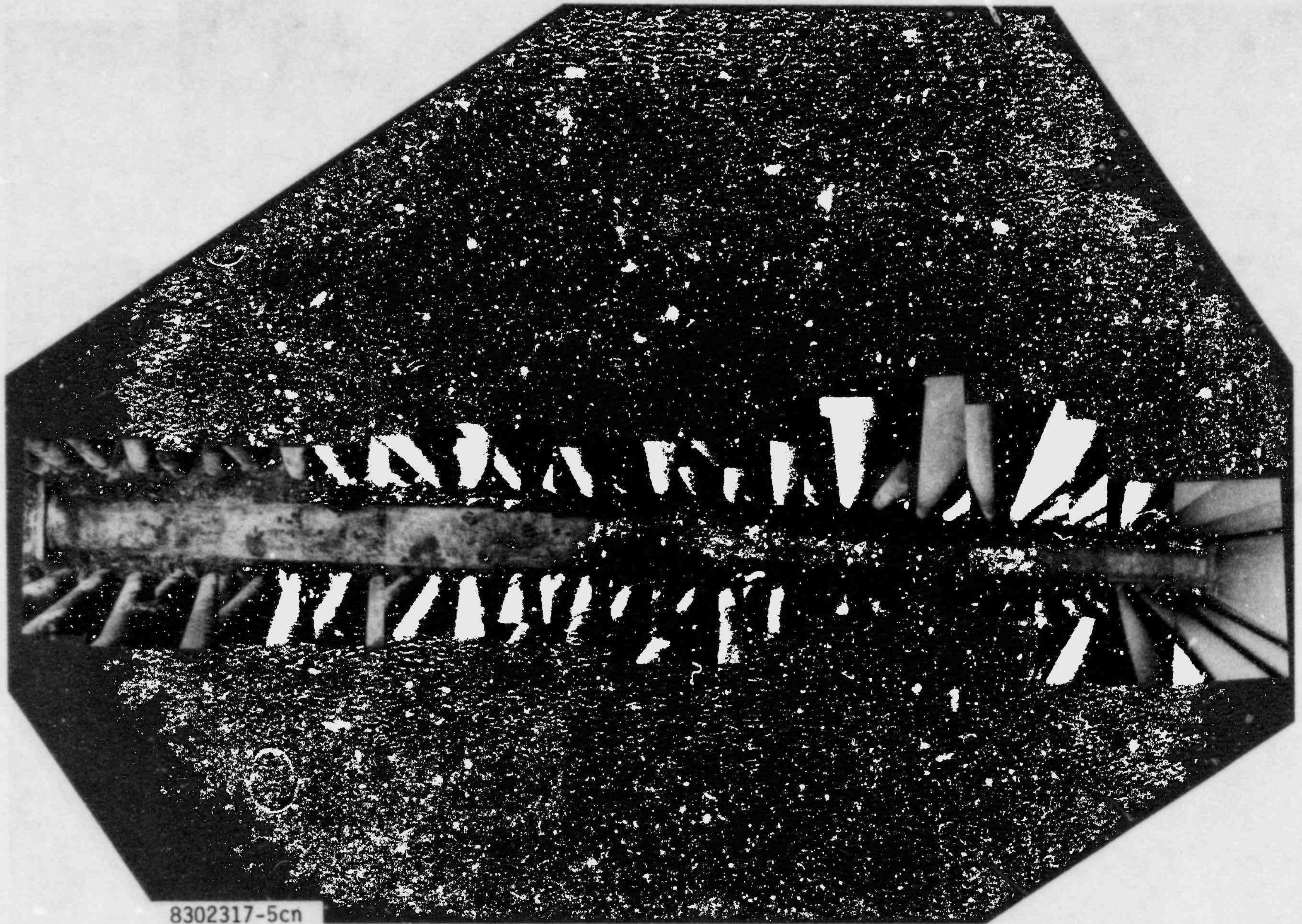

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FIGURE 9. Montage Photograph Looking Toward Tube Sheet and Blowdown Pipe, Column 92 (right) to Column 48 (Left)

FIGURE 10. Close-Up View of Tube Sheet/Blowdown Pipe Region Around Tube Columns 75-80

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FIGURE 11. Close-Up View of Tube Sheet/Blowdown Pipe Region Around Center of Generator

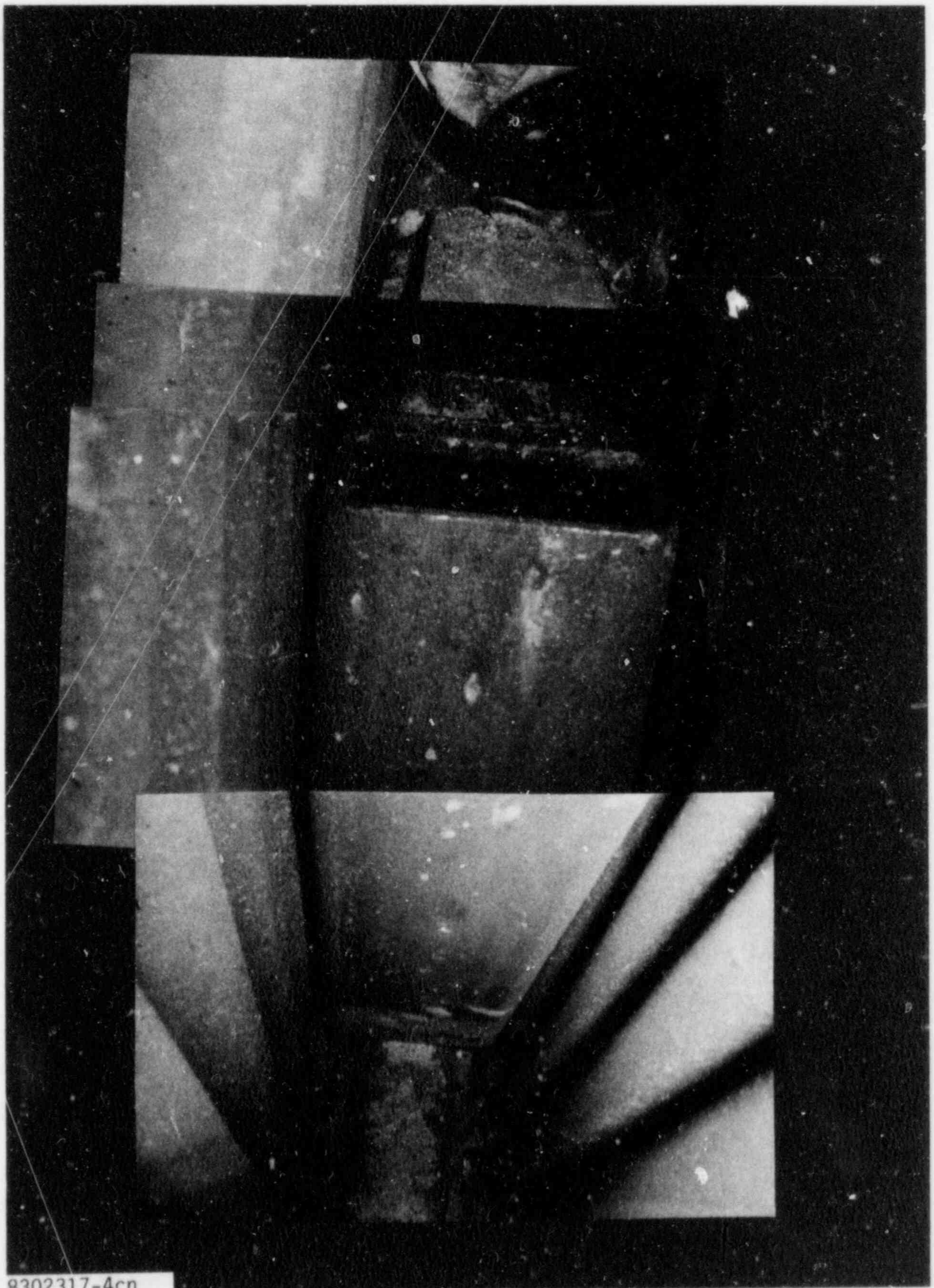

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FIGURE 12. Vertical View of Appurtenance or Flow Deflector, Looking Toward the 0° Handhole

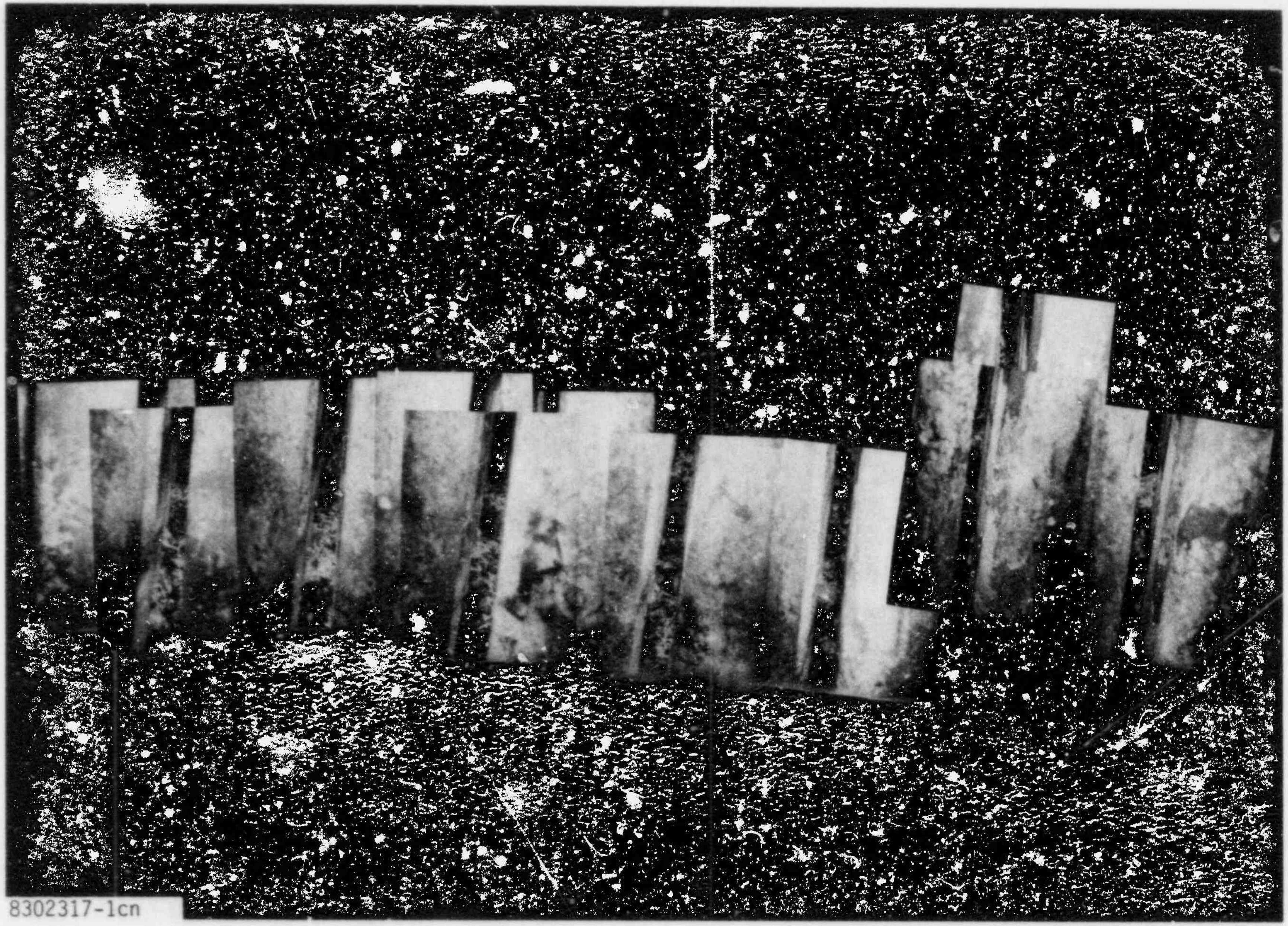
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FIGURE 13. Side View of Tube Lane Cold Leg Region Between About Columns 46 and 39

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FIGURE 14. Higher Magnification View of Gap Between Columns 46 and 45 Cold Leg Side

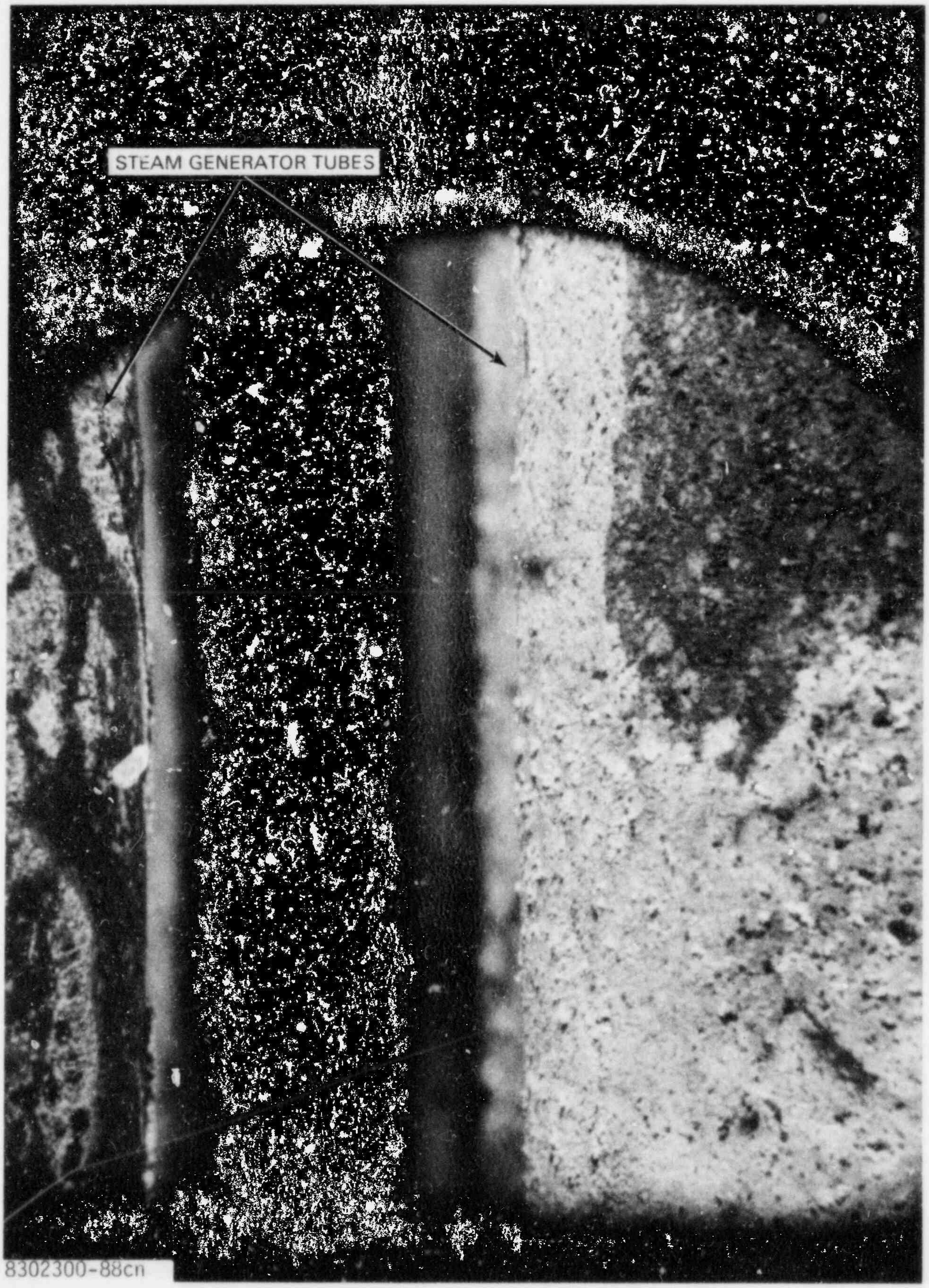

FIGURE 15. Tube Closeup Showing Multicolored Deposits on Adjacent Tubes

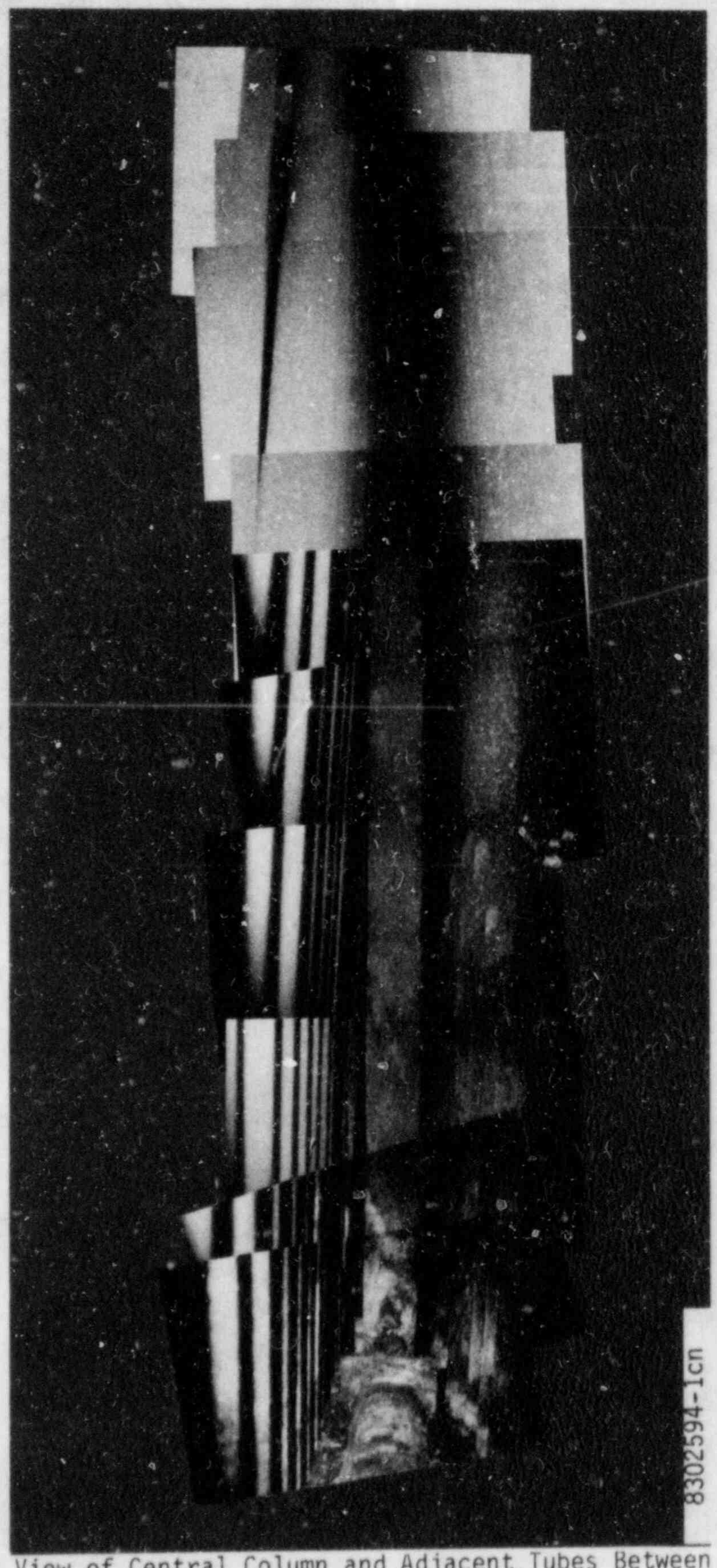

FIGURE 16. View of Central Column and Adjacent Tubes Between Tube Sheet and the First Support Plate, From 0° Handhole

caused by previous sludge piles or possibly where water draw down occurred and was subsequently allowed to stand for a period of time. The color variations near the bottom are more clearly seen in Figure 17. Note also the slightly higher sludge deposit on the left or hot leg side. Referring back to Figure 16 and progressing upward, the distinct change in tube brightness (at the top) was caused by a change in location of the electronic flash to the face of the aluminum camera box which contains the forward viewing port as shown in Figure 4. Progressing further upward one can see a piece of metal, apparently wedged between the Row 1 tubes on the hot leg side. This piece of metal may have been broken out of the first support plate which is slightly above the top of the photo in Figure 16. The camera could not be moved further up toward the plate due to the narrowing gap caused by movement of the hot leg tubes toward the cold leg side. A closeup view of the metal fragment is shown in Figure 18. The fragment is estimated to be about 1/2 by 7/8 inch (1.3 by 2.2 cm.) in area. Another tube support plate fragment was removed during the post-shipment examination. A third fragment was seen on top of the seventh support plate. More fragments are expected to be found as access to the second through sixth support plates occurs.

First Support Plate - Photographs of the bottom side of the first support plate were taken from both 0° and 180° handholes. The camera had to be kept several feet below the plate due to closure of the tube lane as noted previously. The montage photos taken through the 0° handhole are presented in Figure 19. The first flow slot, next to the 0° handhole, is almost closed while the second and third are entirely closed. In all three flow slots the movement is essentially all from the hot leg side. Photos taken from the 180° handhole (not shown) reveal the same behavior in the second and third slots with some slight variation in the first slot (adjacent to the 180° handhole). In the latter, the first slot appears to display about 80% of its closure from the hot leg side with the remaining 20% from the cold leg side.

Growth of corrosion products in the annular region between the Inconel tubes and the carbon steel support plate, referred to as denting, is believed to be the primary reason for collapse of the flow slots. The flow slot closure represents hot leg movement of about 2-1/2 inches (6.4 cm.). Such movement for periodic intervals of 16 inches (40.6 cm.) (width of slots) suggests that movement in the opposite direction (toward the shell wall) may also have occurred. It is probable that the relatively rigid "hard spot regions" (solid portions of the support plate) have contributed to an outward growth of a given plate. Thus regions of the support plate may have moved enough to force the wedge and block contacts at each support plate against the shroud and the shroud against the shell. Actual forces causing such movement are not known but may be crudely estimated. For example the ligament distance between each tube is about 0.406 inch (1.0 cm.), [1.281 inch (3.3 cm.) center-to-center tube separation less one tube diameter of 0.875 inch (2.2 cm.)] less the spacing originally around each tube. Assuming corrosion product growth is uniform in all directions parallel to the plate, the resulting plate deformations, at least on the hot leg side, are probably uniform deformations producing a biaxial stress field. To

FIGURE 17. View of the Bottom of the Central Column and the Blowdown Pipe, From 0° Handhole

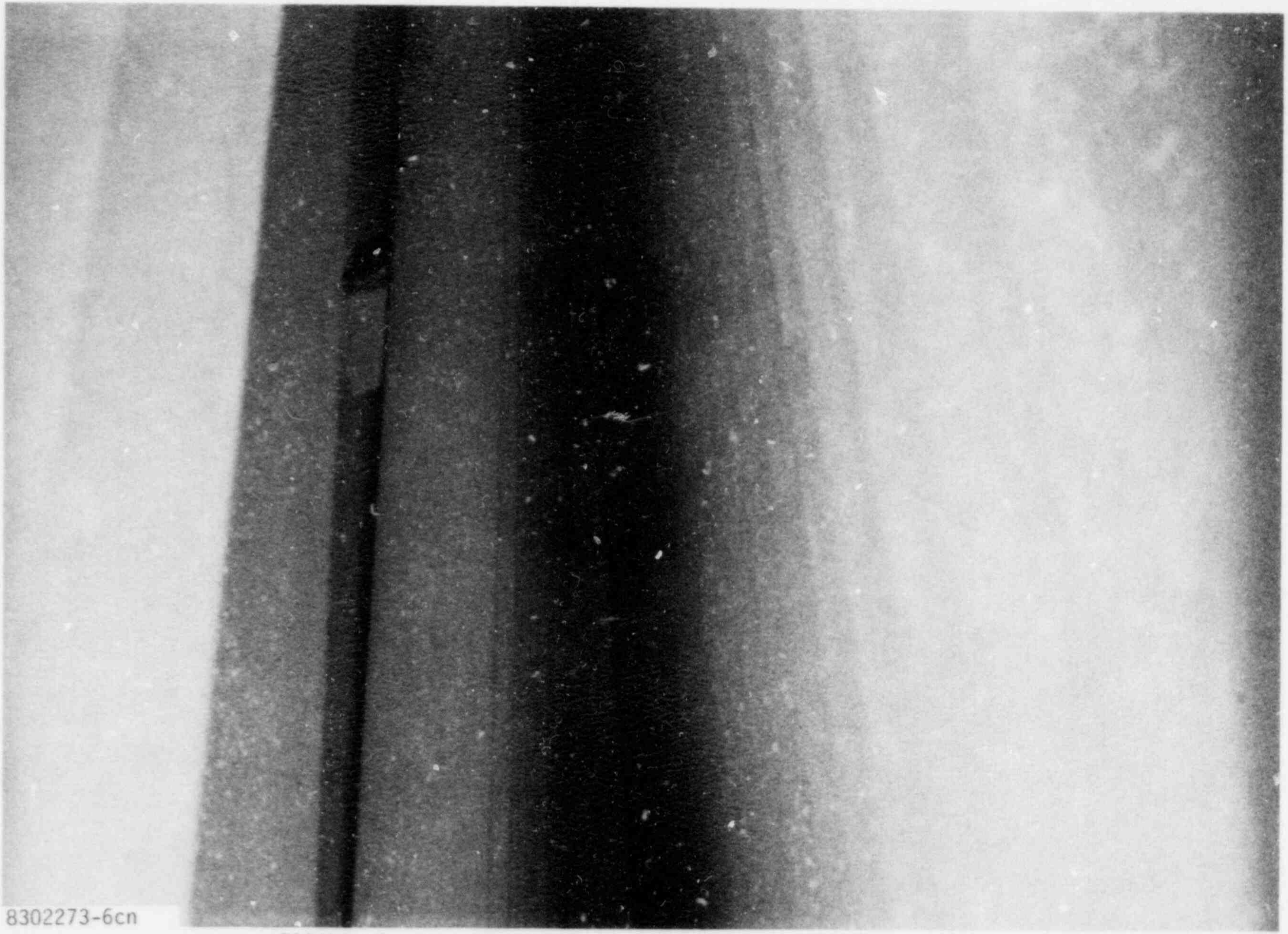

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FIGURE 18. Possible Tube Sheet Fragment Wedged Between Tubes, Hot Leg Side, Slightly Under First Support Plate

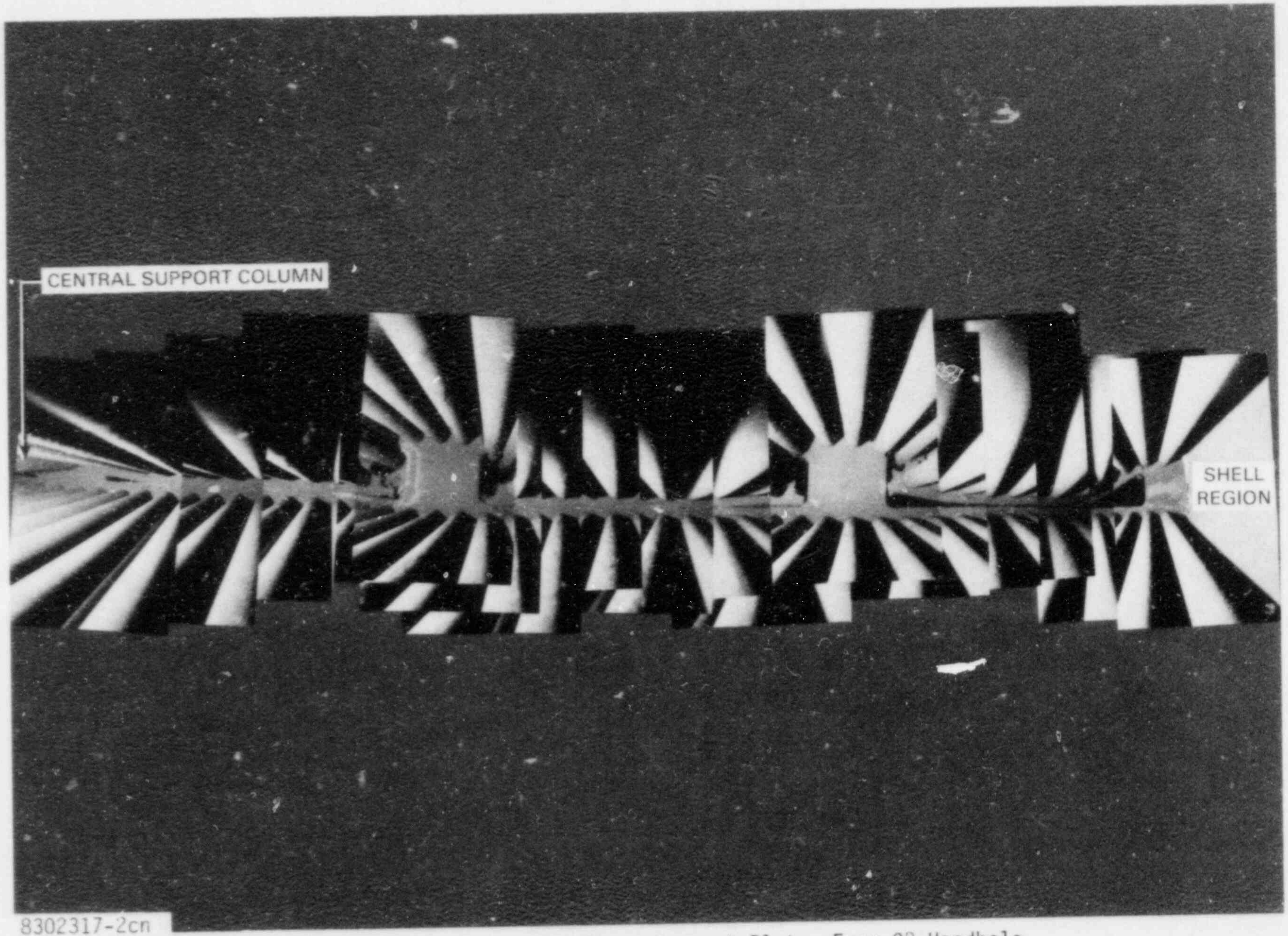

FIGURE 19. Bottom Side of First Support Plate, From 0° Handhole

simplify load calculation we assume that x and y deformations are independent with essentially uniaxial strains in the respective directions. Then the forces in the x-direction are caused by x-direction expansion and similar for the y-direction. This is not true, of course, but does allow a more simple estimate of tube support plate in-plane loadings that might be transmitted toward the shell. The tube sheet material is designated ASTM A285C which has a minimum yield stress of 30 ksi (206.8 mPa). If one assumes a quasi-creep condition for compression of say, 25,000 psi (172.4 mPa), then each 0.406 by 1 inch (1.0 x 2.5 cm.) thick ligament for each tube row and column independently applies a load of about 25,000 psi x 0.406 in^2 (172.4 mPa x 0.000645 m^2) or about 10,000 lbs (44,482 Newtons). This crudely extrapolates to a total 'biaxial' force of about 94 x 10,000 or 940,000 lbs (4.181 Mega Newtons) in both x and y directions at each support plate.

Referring back to Figure 19, a close-up view of the 'hard spot' region between the second and third flow slots is shown in Figure 20. Besides complete closure of each adjacent flow slot, extreme creases in tubes near each flow slot corner can be seen. Some of these creased tubes may have cracked throughwall. Furthermore, debris can be seen adjacent to the hard spot (Figure 20). Recall that this photo was taken looking upward at the first support plate, thus the debris might have come from flow slot breakage in the adjacent or second support plate, or are possibly spalled tube deposits. Broken support plate sections have been found in several locations in the generator.

Tube Sheet Region Between Rows 14 and 15, CL and HL Side

Typical examples of the versatility of the Battelle-developed subsize cameras to provide photographs in confined spaces are seen in Figures 21 and 22. The photographs in Figure 21 were taken by inserting the camera through the top 2 inch (5.1 cm.) diameter hole (cold leg side) seen schematically in Figure 1. The "a" view taken with a pinhole camera shows the lower 2 inch (5.1 cm.) diameter drilled hole through the shell, tube Rows 14 and 15 at Column 92, and the top of the tube sheet between the rows. The shiny debris is metal chips from the shell wall drilling. View "b" taken with a fixed focus camera is a closeup of the tube sheet showing the sludge pile on the surface along with a few fragments of tube scale spalled off from above. Figure 22 is similar except that the pinhole camera photograph (top) is joined with a series of fixed focus camera photos (bottom). In addition, a photograph was taken looking up at the bottom of the first support plate. Both support plate photos are the same. One emphasizes the adjacent tubes while the other emphasizes the support plate. An expanded view of Figure 22b is presented in Figure 23. Here spalling tube deposits and the bottom of the first support plate can be seen in greater detail.

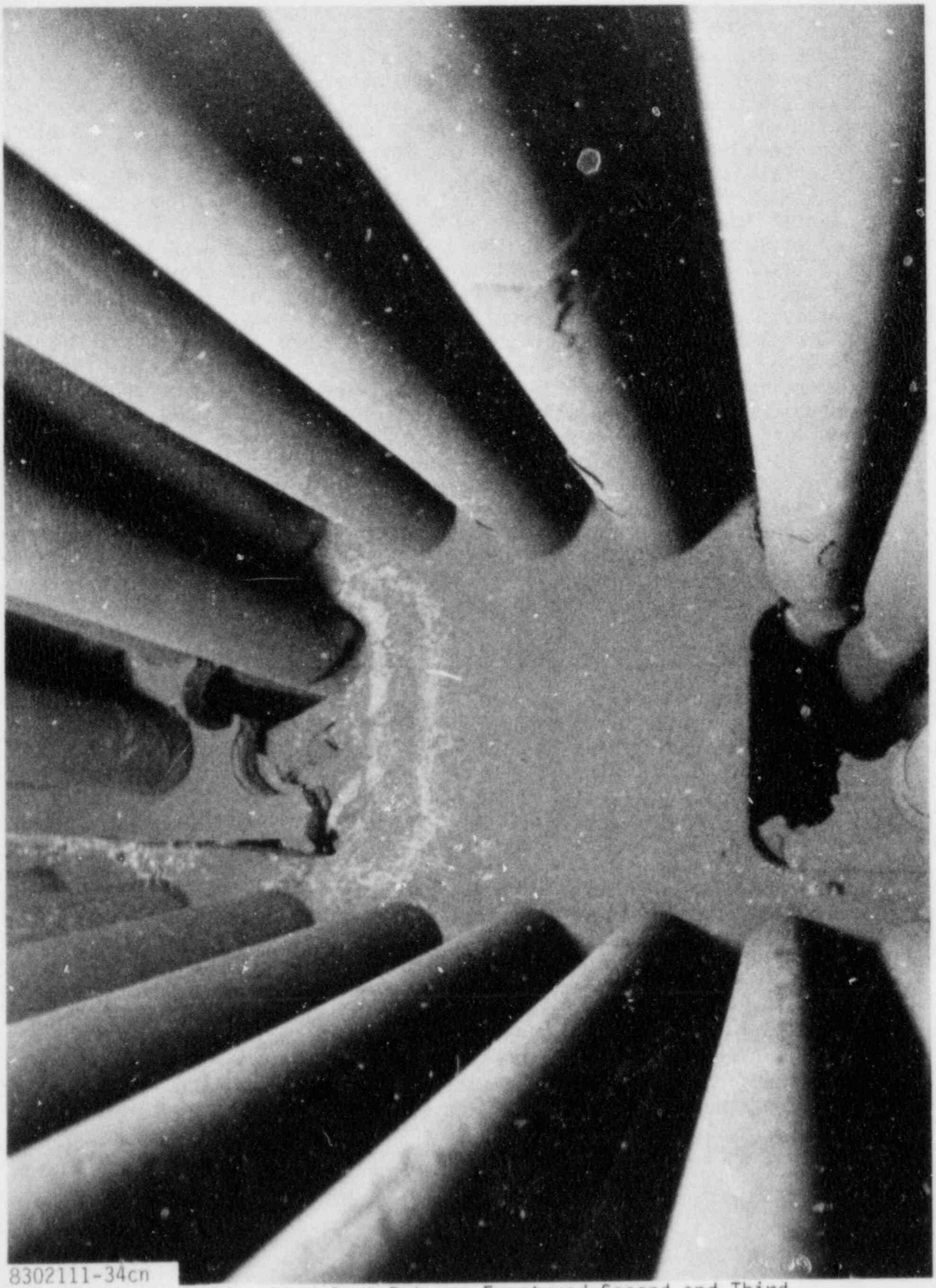

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FIGURE 20. Hard Spot Between Fractured Second and Third Flow Slot in First Support Plate (Looking Up)

FIGURE 21. View of Shell and Tube Sheet at Rows 14 and 15, Cold Leg Side

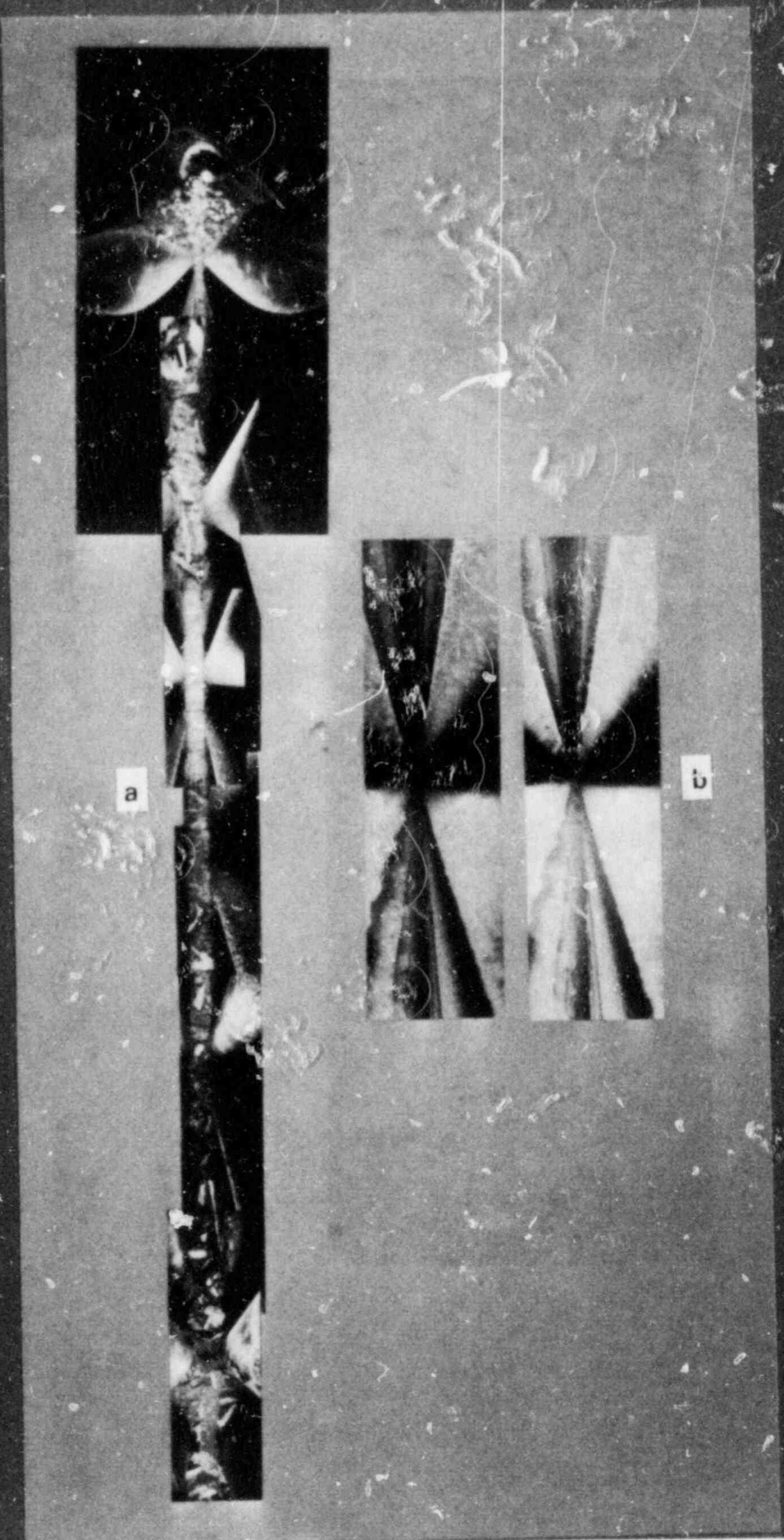
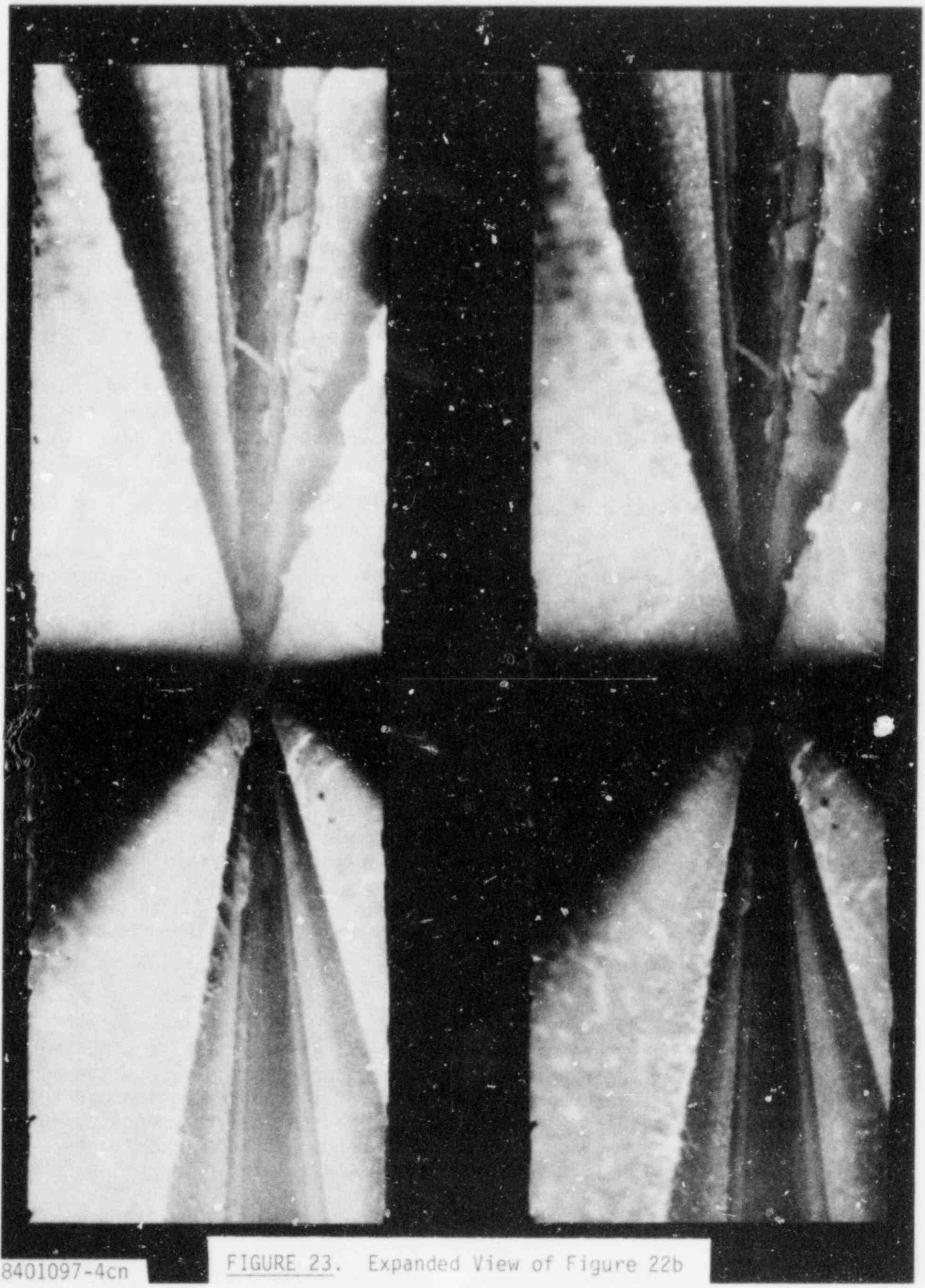


FIGURE 22. View of the Shell and Tube Sheet (a) and Looking Up Toward First Support Plate (b) at Rows 14 and 15, Hot Leg Side



8401097-4cn

FIGURE 23. Expanded View of Figure 22b

First Row U-Bends

All but two of the 94 Row 1 U-bends* were examined with a borescope as shown in Figure 8, through the P-4 penetration. Observations and notes were made for each tube examined and photos taken of salient or characteristic conditions. Many of the conditions noted or photographed will be examined in more detail later in the program when tube removal begins. The results described below, particularly those relating to states of tube failure or fracture, are obvious in some cases while inferred in others. The distribution and number of different types of failures thus may vary slightly as more detailed failure analysis becomes possible. Later in this document failure conditions of the U-bends are compared with position (hard versus soft spots). First, tube surface conditions are compared and related to position.

Tube Surface Conditions - The entire U-bend intrados surface region from support plate (#7) to the U and back on the opposite side of the tube lane showed varying surface conditions dependent on both position and failure condition. Tube failures are discussed in the next section.

Generally the tubes had surface deposits below the U varying from rough (Figure 24) and what appears to be relatively thick, to smooth (Figure 25) and relatively thin, perhaps 1 to 3 mils (.03 to .08 mm.). Further, the rough deposits generally became smoother when progressing toward the U then rough again when approaching the plate. The smooth deposit (Figure 25) tended to exist over a greater portion of the U then the rough deposit shown in Figure 24. Further, these more uniformly smooth, dull brown color tubes existed primarily in the hard spot regions of the support plate. The smooth character of the deposits are believed to be due to lack of operation-induced bending of the tube in hard spot regions as compared with the increased bending that was caused by hourglassing of the flow slot regions. Figure 26 shows a shiny area possibly resulting from the deposit spalling off the tube due to the greater inward bending and resulting increased compression in the intrados tube surface. Note also a possible flow abrasion to the right of the shiny region. Alternately this could be staining from post service leakage out of the tube. The adjacent tube had fractured, thus a flow abrasion effect is possible. Location of the smooth, dull brown colored tubes (hard spots) along with the tubes with shiny intrados surfaces (soft spots) are shown in Figure 27**.

---

*Two U-bend tubes were not examined due to difficulties in simultaneous adjustments of the supplementary light source and borescope through flow slots that were hourglassed to about 1 inch separation and the accompanying problem of establishing fixed optical reference points along the U-bend region. Inner row U-bends had been removed in Columns 1-10, thus Row 2 was viewed in these locations.

**Further views of the many U-bend intrados surface shiny areas can be seen in the section "Tube Failure Conditions".

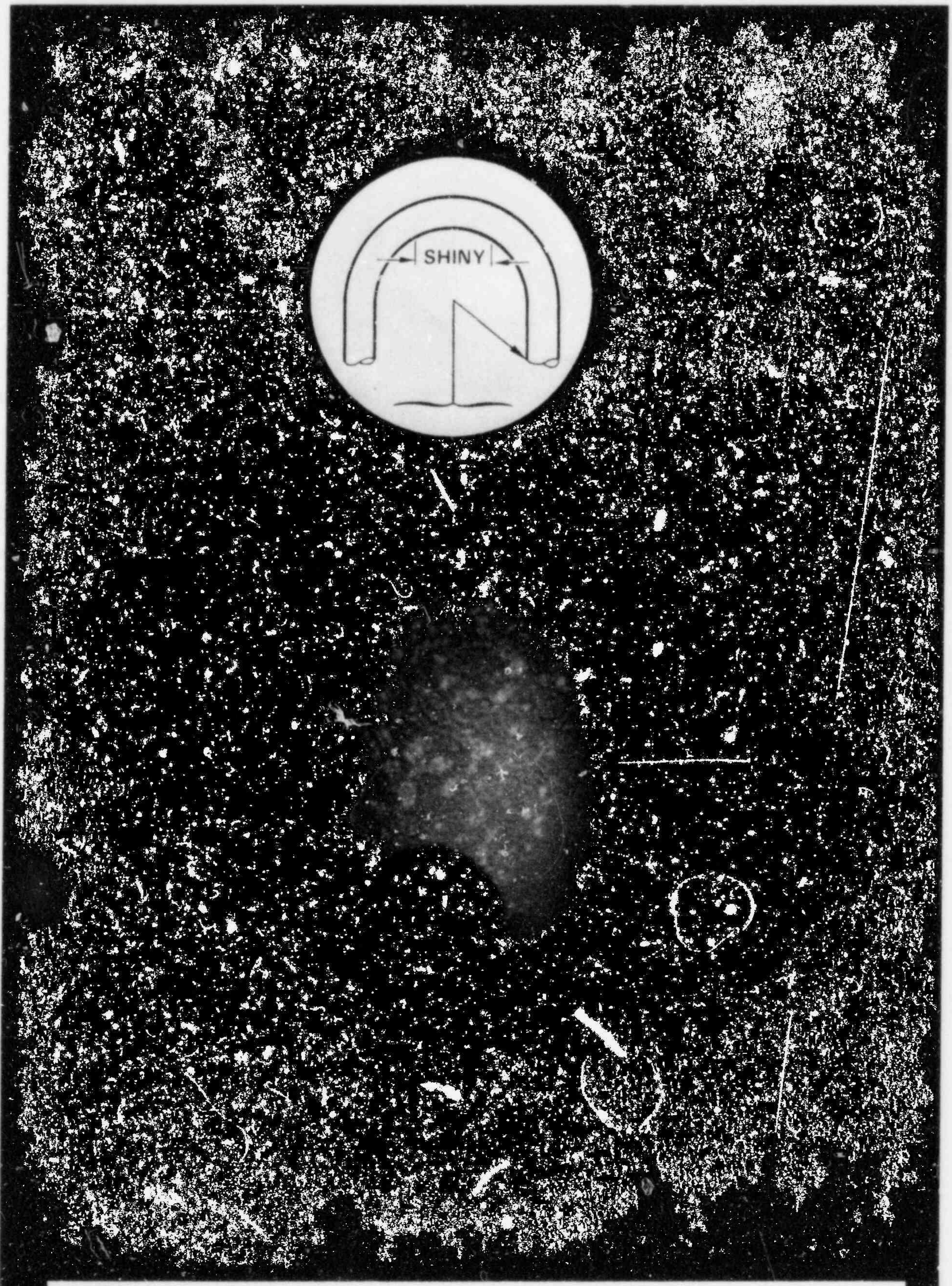


FIGURE 24. Adherent Deposit, Toward Base of U-Bend Tube, Column 51

8401097-5cn

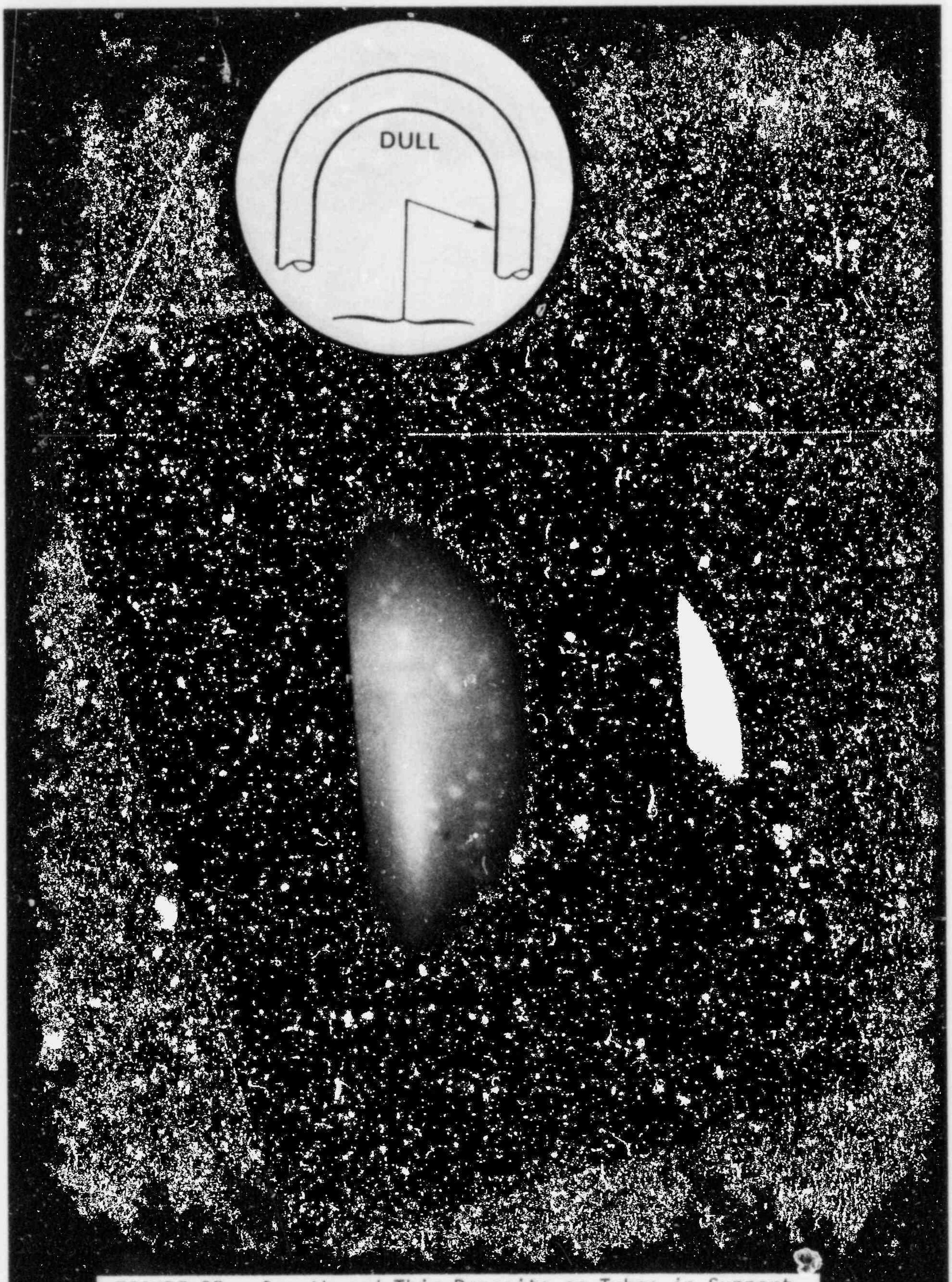


FIGURE 25. Smooth and Thin Deposits on Tubes in Support Plate Hard Spot Regions, Column 82

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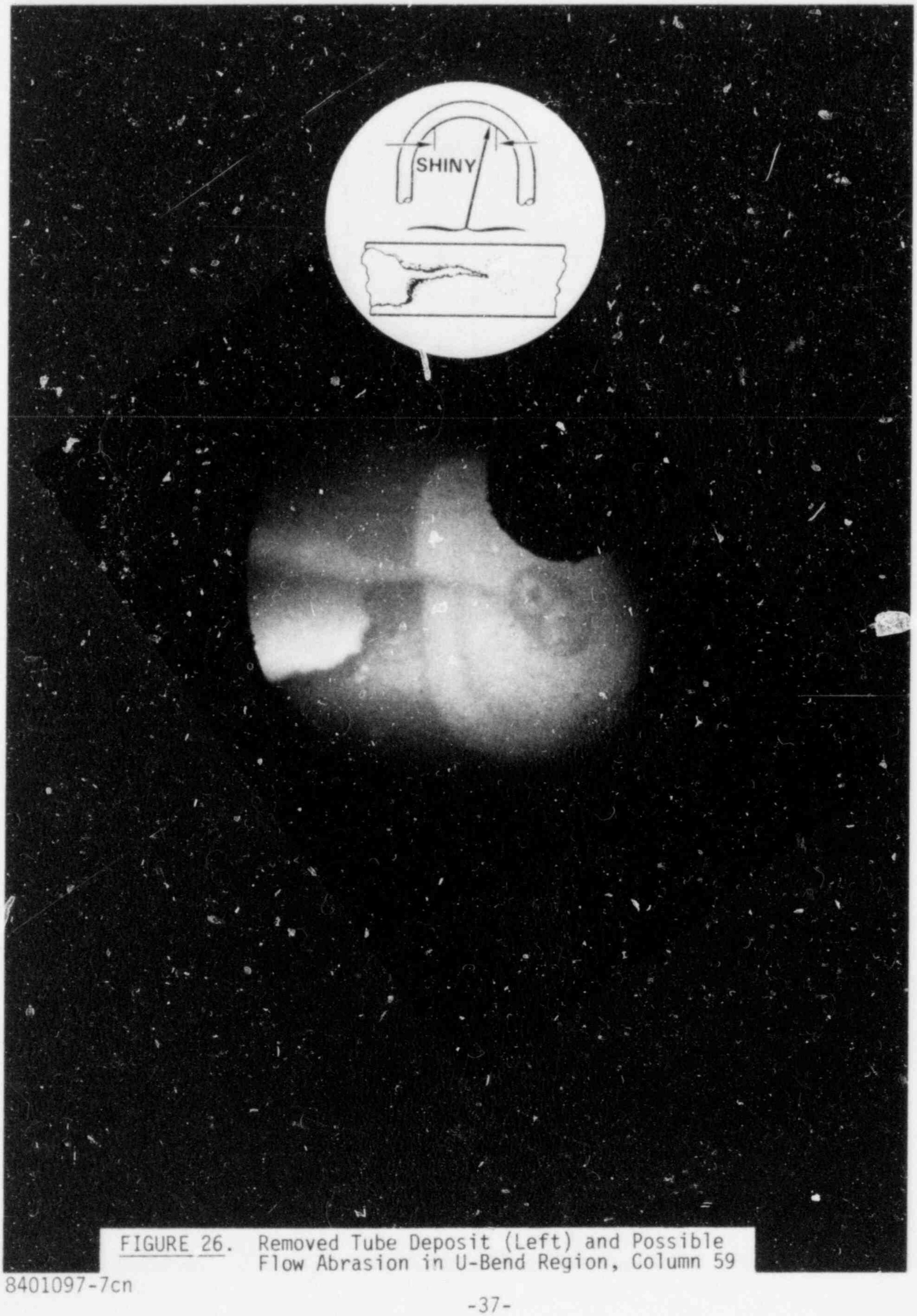
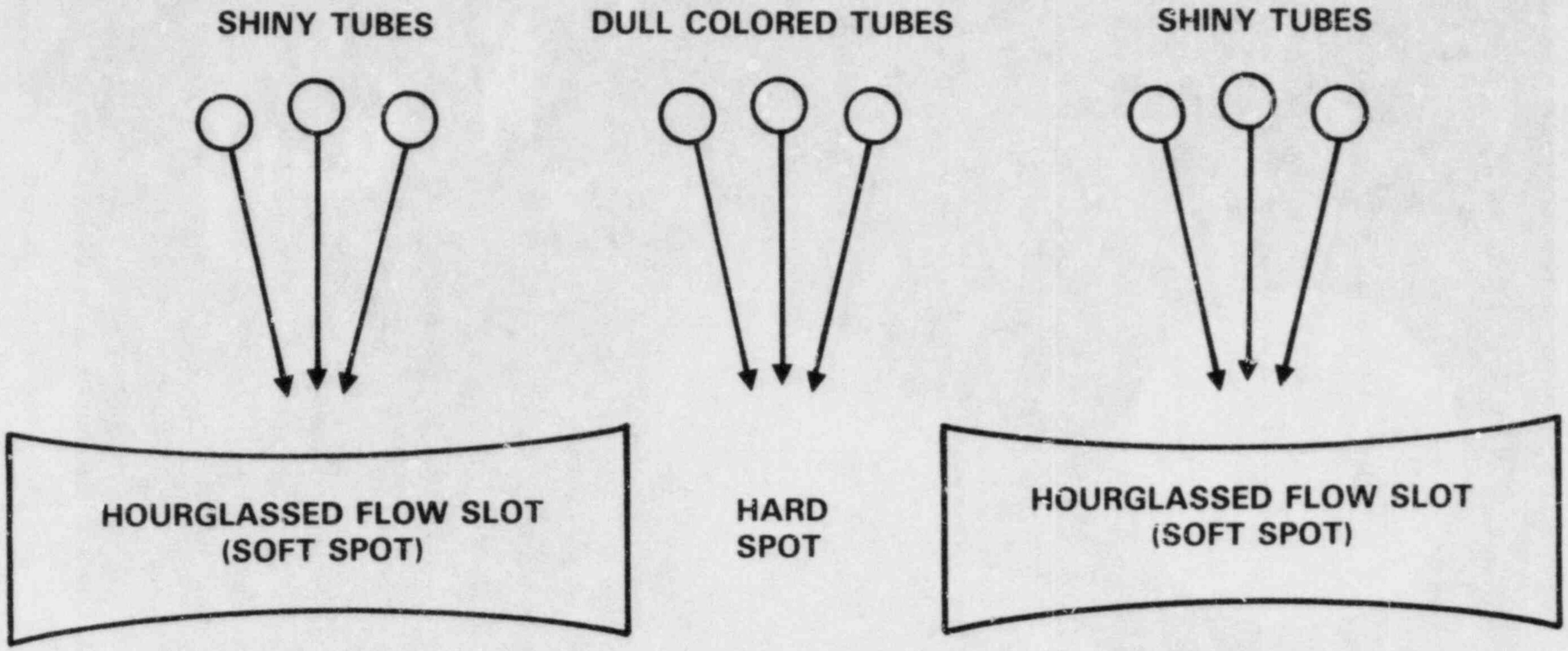


FIGURE 26. Removed Tube Deposit (Left) and Possible Flow Abrasion in U-Bend Region, Column 59



8308533-1

FIGURE 27. Typical Location of Dull and Shiny Intrados U-Bend Surfaces Relative to Flow Slot Position in the Seventh Support Plate

Support Plate Features - U-bend tube intersections with the seventh support plate are shown in Figures 28 and 29. Tube deposits generally build up in the tube to support plate annulus and between tubes. In addition, deposits between tubes (Figure 28) have also trapped some small metal spheres or beads. These beads were apparently produced during cutting of the generator from its steam separator. Prior to removal the generator was filled with water just above the tube bundle. A torch was then used to cut the shell and shroud. The beads or small, liquid metal spheres were rapidly quenched by the water; many were left on the secondary side following removal of the water. Such beads, thought to originate from condensate polishers, were found in all areas examined with the borescope, namely the seventh support plate and the first support plate. In addition, hourglassing of support plate flow slots typically resulted in fractures of the corner regions (also shown in Figures 19 and 20). The corner fracture shown in Figure 29 also shows the extent of bending produced in the tube; additional metal beads are also seen. Another fracture frequently found near collapsing flow slots was in ligaments separating flow holes as seen in Figure 30 the so-called "islanding phenomenon".

Tube Failure Conditions - As noted above, the U-bend intrados surface conditions varied from dull to shiny when traversing across the seventh support plate from hard spot to soft spot regions, etc. In addition, fracture or cracking appears to follow the same relationship. While only 21 fractures were definitely sighted with the borescope, it was possible to rationally infer that as many as 50 to 66 tubes (about 53 to 70%) were cracked and that they were located predominantly in regions adjacent to soft spots in the seventh support plate. (This is discussed later under Tube Failure Trends.) Because observations were limited to the intrados tube surfaces, the nature of the failures, and hence their driving forces, must await further extrados surface observation coupled with metallurgical failure analysis techniques. What can be stated and inferred about crack lengths, orientations and geometry is presented below along with salient photographic illustrations.

In the following figures (Figures 31-38) taken of the first row U-bend arches, virtually all cracks appear, or can be implied to be, dominantly axial in orientation. They vary in position from the bottom of the U-bend (0° on the intrados surface) to the sides (±90°) and on the extrados surface (180°); a few of the latter can be seen due to the intrados side being open wide enough to allow observation of the extrados crack. Sometimes the extrados cracks were open far enough to be seen as jagged edges between the tubes. Crack lengths are as great as three tube diameters or slightly more. Some cracks are tight, some flap-like in character, some gap open in the 'plane' of the intrados surface while others appear fishmouth in character. The latter, of course, do not have a singular orientation with respect to a given U-bend.

The axial flap-type crack seen in Figure 31 (tube Column 91) also occurred in several other locations. Referring to this figure, one can also see the relatively large shiny areas in the intrados surface (Columns 89 to 92) along with flow slot hourglassing and the further compressive bending of the intrados surface. As one progresses further

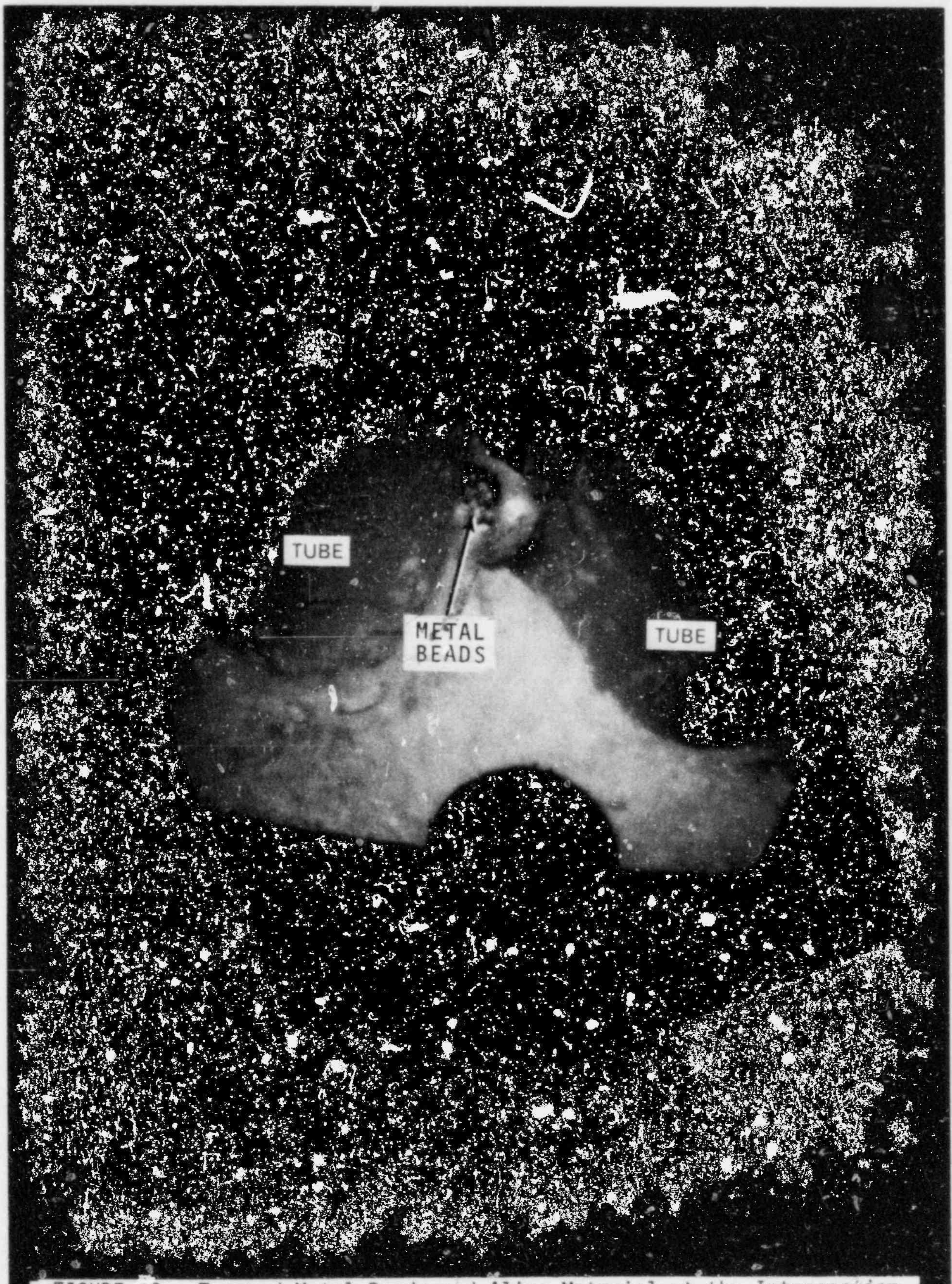


FIGURE 28. Trapped Metal Beads and Alien Material at the Intersection of Tube Columns 40 and 41 in the Seventh Support Plate

8401097-8cn

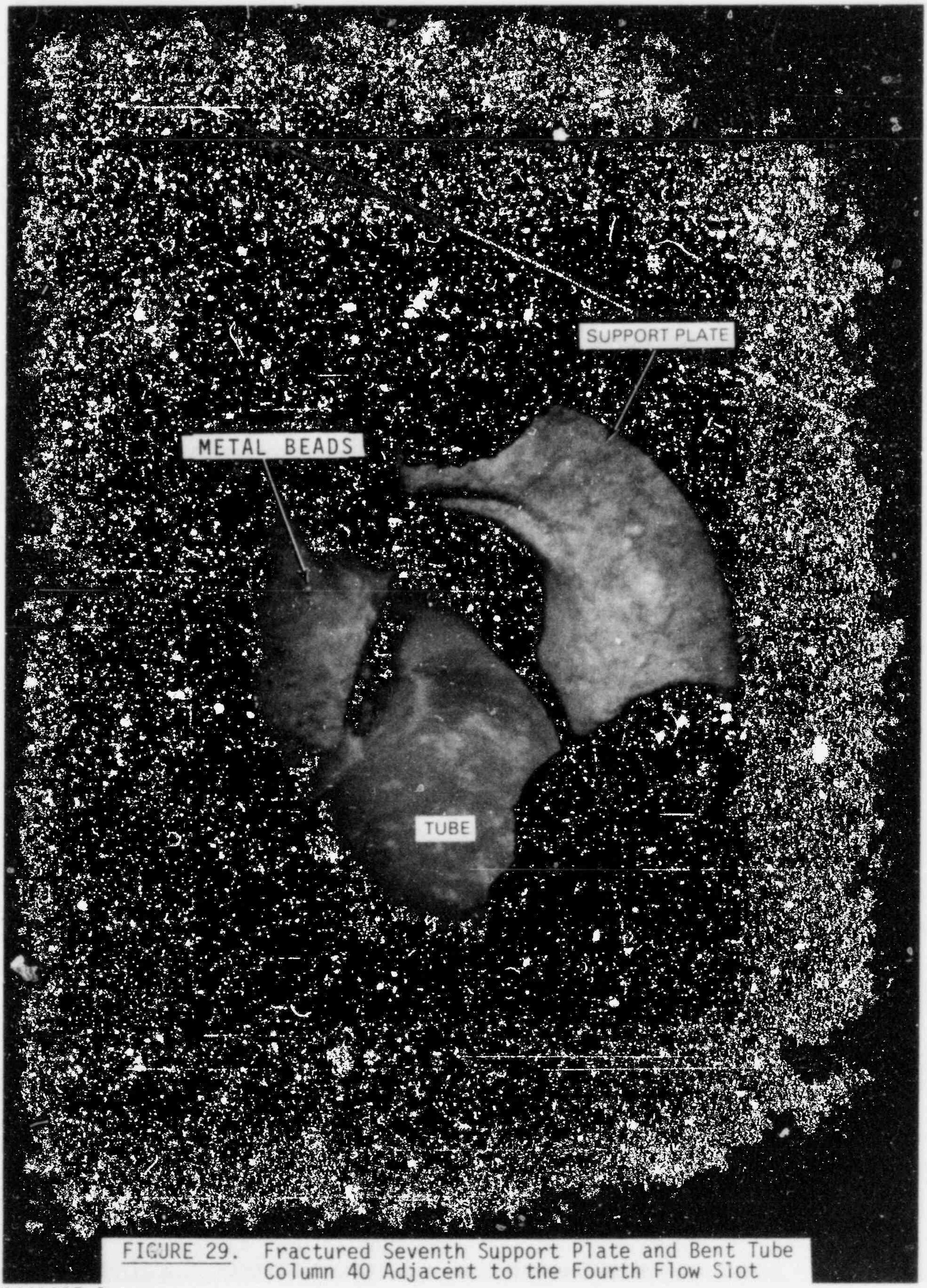


FIGURE 29. Fractured Seventh Support Plate and Bent Tube Column 40 Adjacent to the Fourth Flow Slot

8401097-9cn

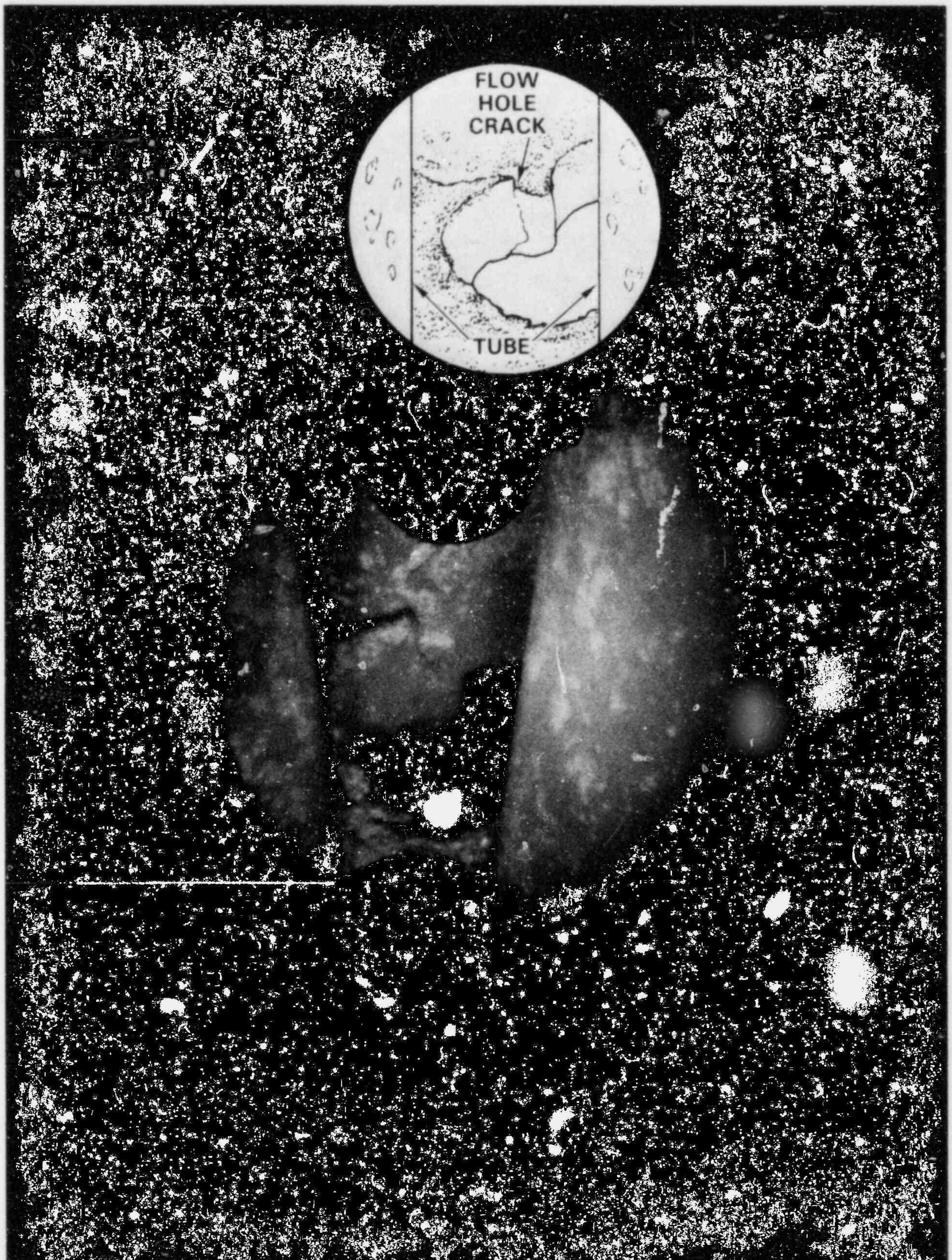


FIGURE 30. Flow Hole Fracture Between Tube Columns 45 and 46 in Seventh Support Plate Adjacent to Fourth Flow Slot

8401097-10cn

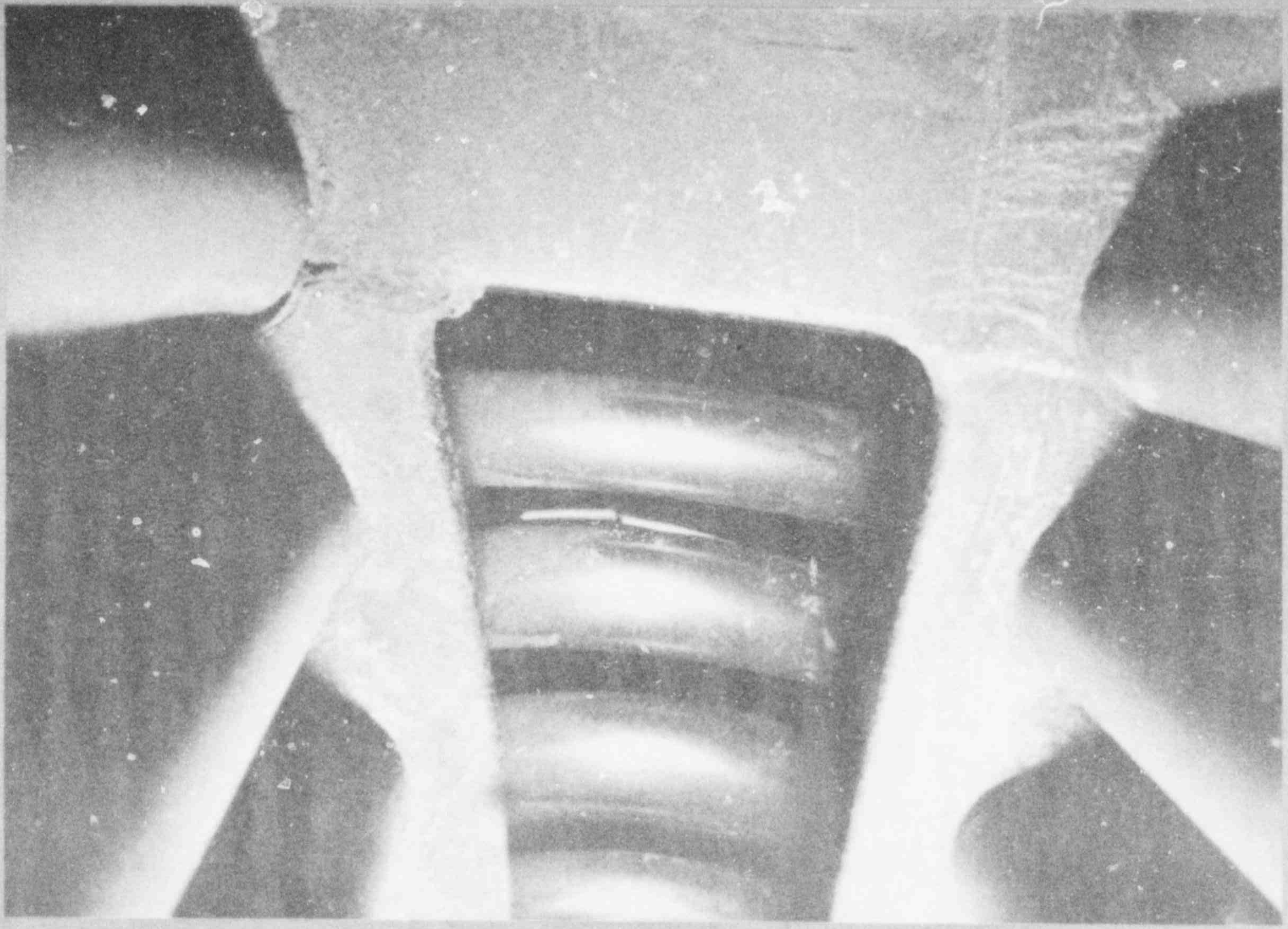


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FIGURE 31. Axial Flap-Type Cracks in Tube Column 91

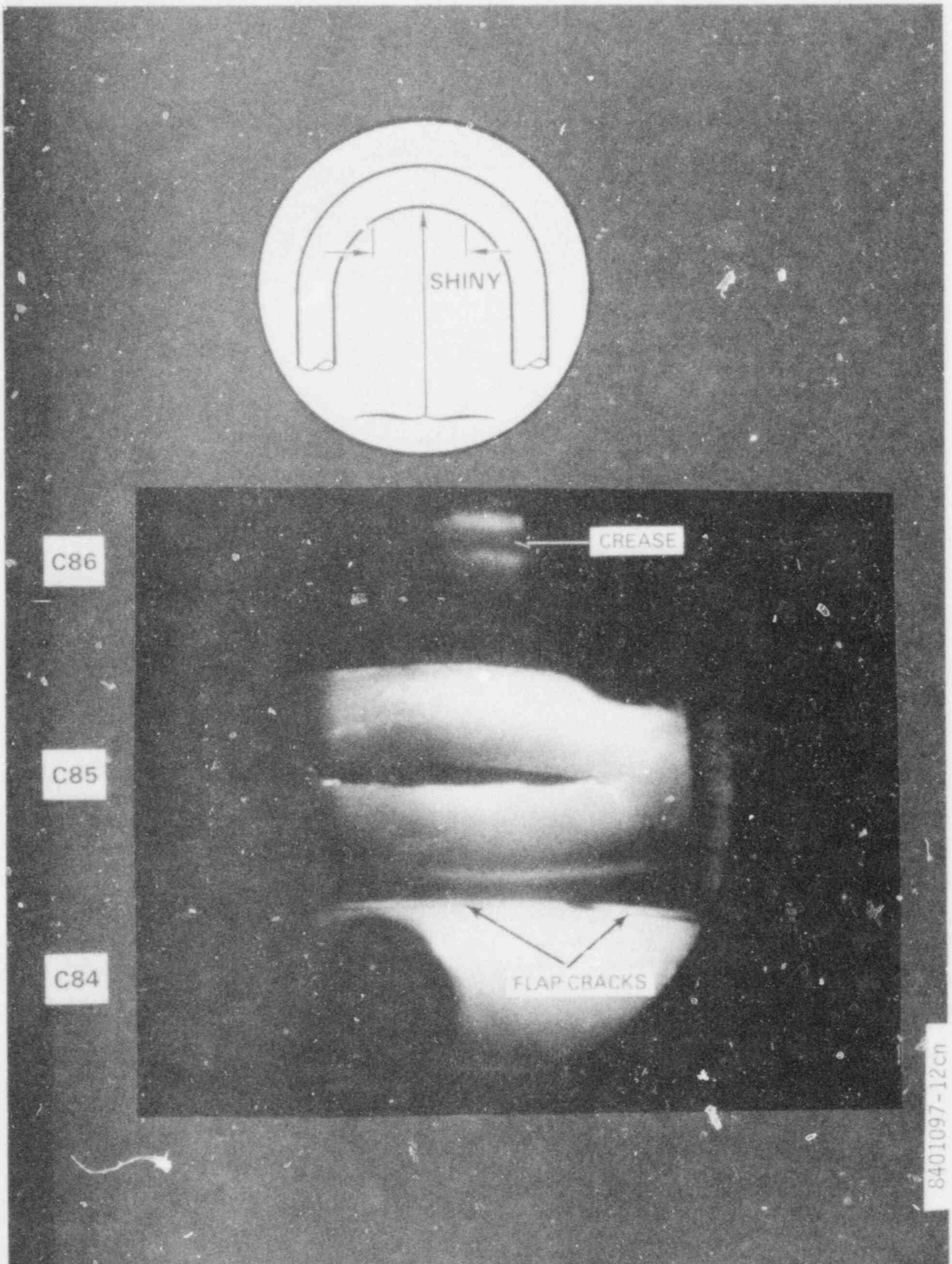

FIGURE 32. Multiple Tube Failure Conditions: Flap-Type Crack in Column 84, Intrados and Extrados Cracks in Column 85 and a Crease in Column 86

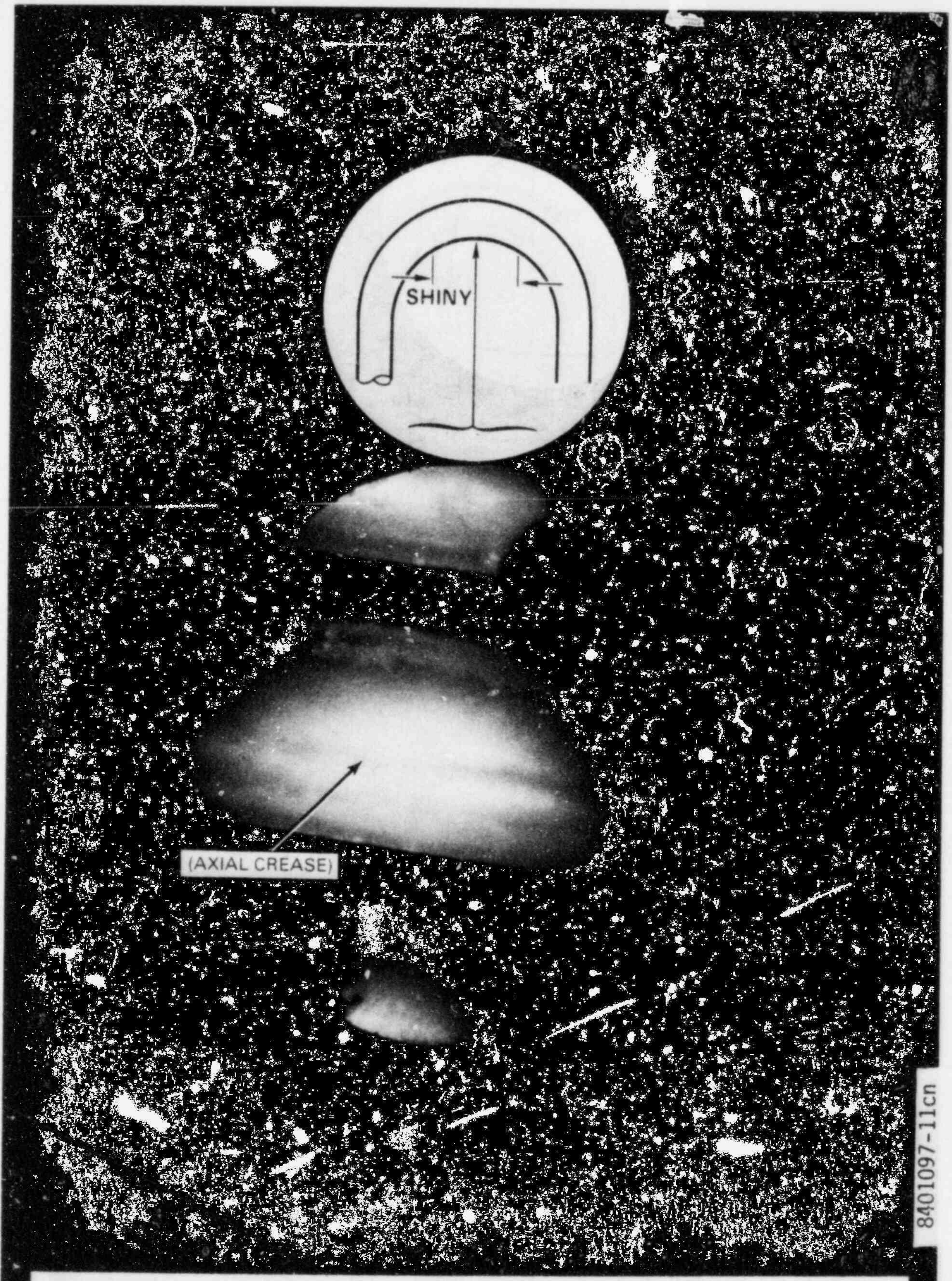

FIGURE 33. Typical Large Axial Crease in U-Bend Intrados Shiny Region

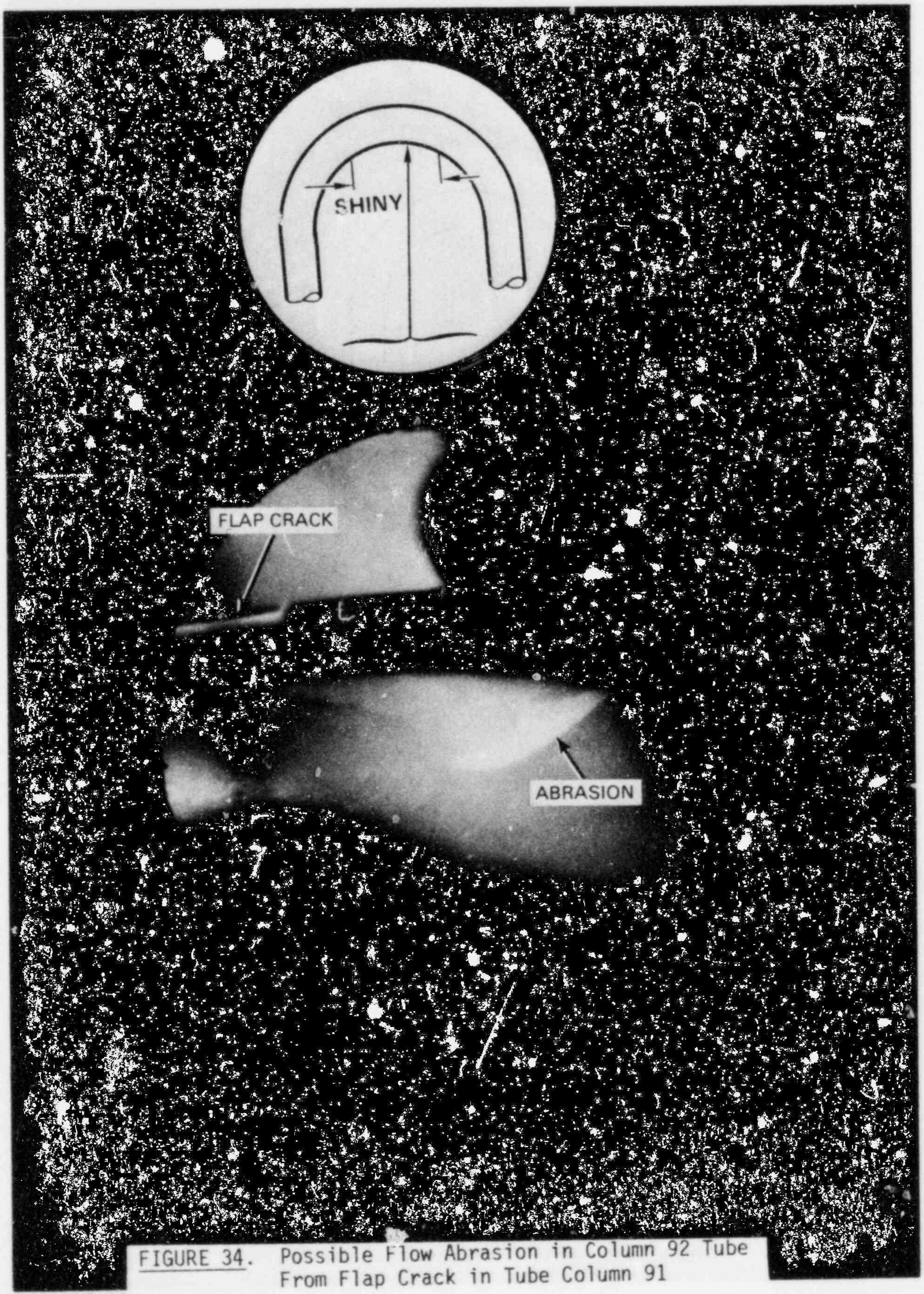

FIGURE 34. Possible Flow Abrasion in Column 92 Tube From Flap Crack in Tube Column 91

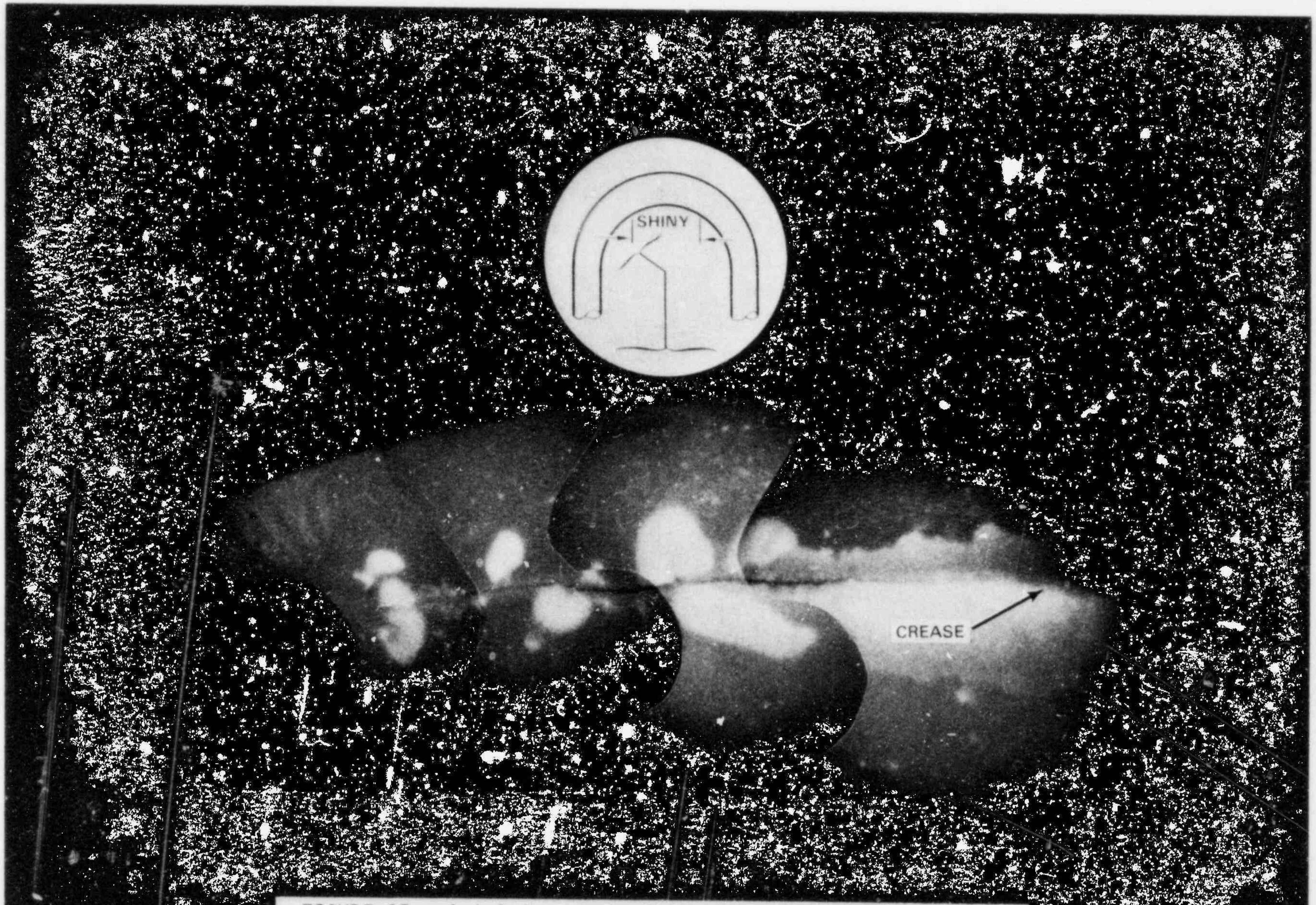

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FIGURE 35. Axial Crease in Shiny Area of U-Bend (Right) With Emerging Crack and Possible Flow Markings

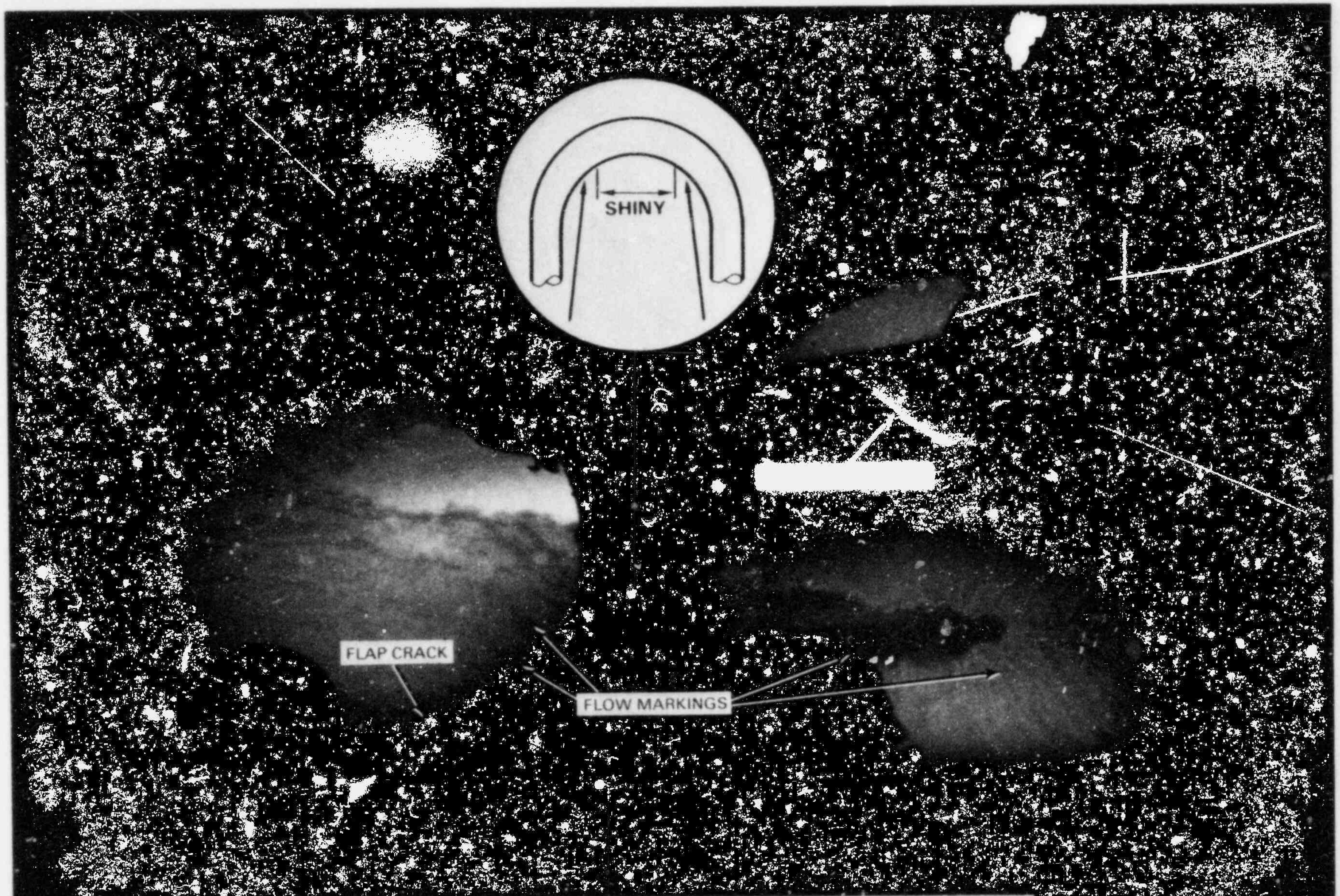

FIGURE 36. Fishmouth Crack in Tube Column 67. Possible Flow Markings and Creases are also Evident

8401097-1cn

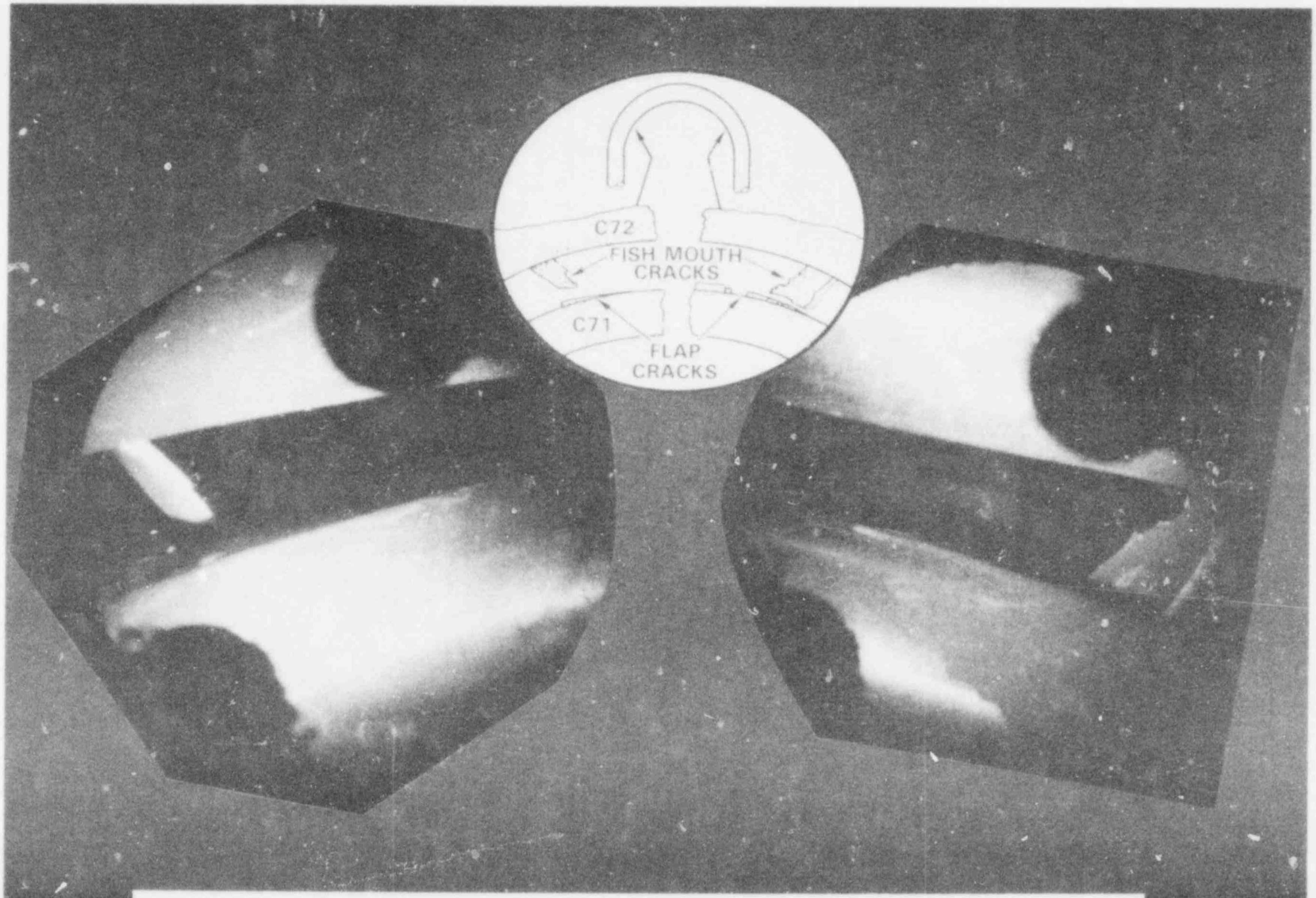

FIGURE 37. Combined Fishmouth Cracks and Flap Cracks in Tube Columns 71 and 72

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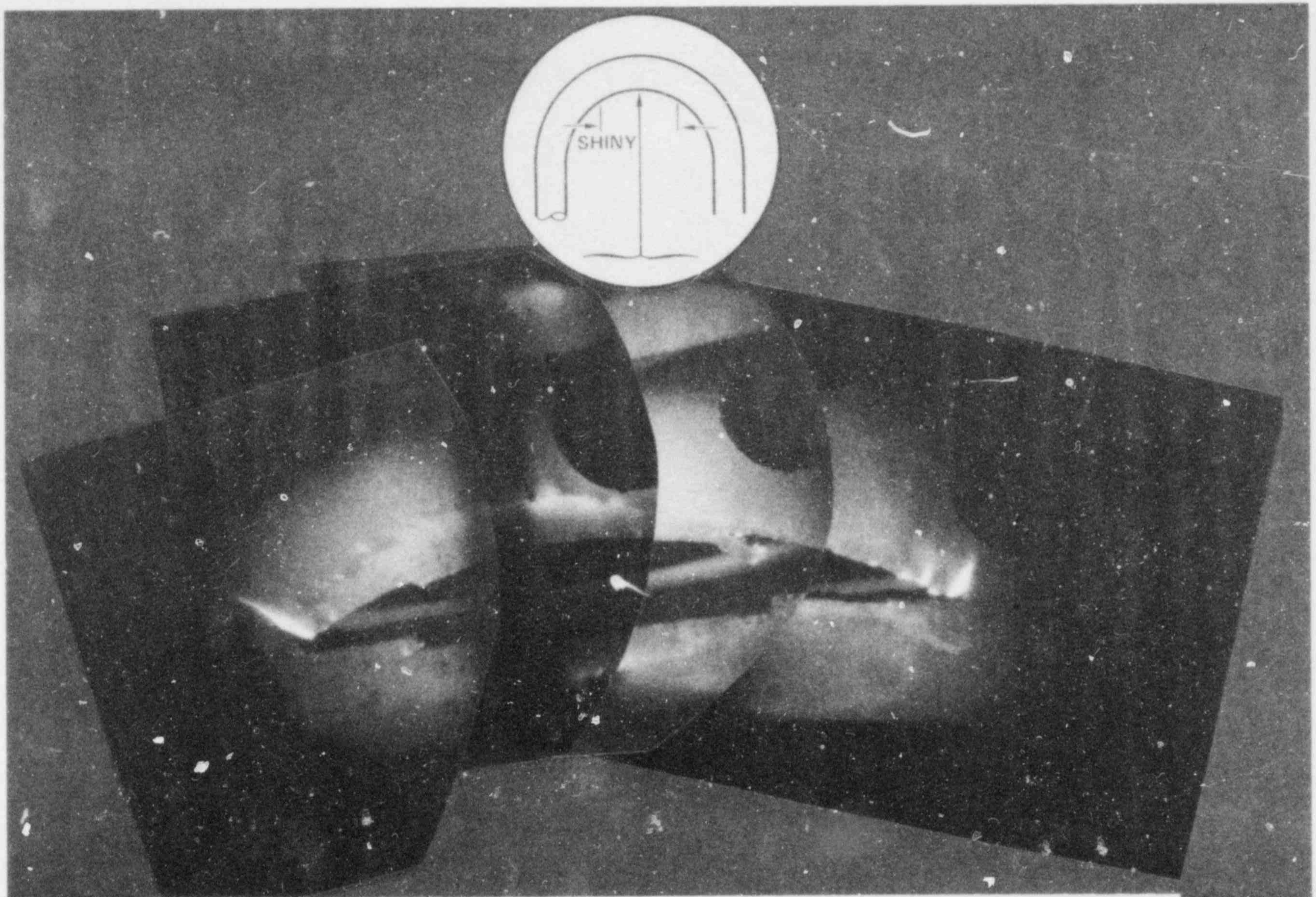

FIGURE 38. Long, Gaping Axial Cracks in Column 59 Intrados and Extrados Surfaces

8401097-3cn

into the generator, Figure 32 shows 90° flap-type cracks in Column 84, a gaping axial crack in Column 85 with a probable gaping axial crack in the extrados surface, and a barely visible axial crease in Column 86.

A more definitive axial crease in a shiny area is shown in Figure 33 (tube Column 89). Axial creases were seen in 31 tubes with lengths as great as three tube diameters. Note also that shiny areas can also be seen around the gaping crack in Figure 32, Column 85.

Another flap crack (90°) is presented in Figure 34. A possible implication here is that the crack in Column 91 may have opened up during service allowing primary water to partially abrade the thin deposit of film on the Column 92 tube.

The premise that an axial crease may be a crack that has not yet penetrated through the surface from the tube interior can be supported by Figure 35. Here as one progresses from right to left in the figure, the crease in the shiny area eventually becomes a crack which extends toward the intersection of the U with the straight section tube. The source of the intermittent shiny areas adjacent to the crack is not clear. Perhaps primary flow leakage from the crack could have produced the markings.

Fishmouth cracks, which have been indicated to be likely service failures, also occurred. Some are shown in Figures 36 and 37. Several additional conditions can also be seen in Figure 36. For example there are possible flow markings on both sides of the Column 67 photos and a possible flap crack on the bottom left photo. Further, both fishmouth and flap cracks are visible in Figure 37 and the fishmouth crack surfaces touch the adjacent tubes. They appeared to be located 90° to 120° away from the bottom (intrados) of a given U-bend.

Several tubes were seen with very long gaping cracks as characterized by Figure 38. There is an obvious parallel crack in the extrados surface. Further, the next tube at the top of the photo may have a flap crack which is touching Column 59. It is not clear how this failure occurred but it should be noted that the generator laid on its side through one below-freezing winter at Hanford before it was installed in the SGEF. Furthermore, the Surry 2 mausoleum, used to store the generator prior to shipment to Hanford, was also unheated. Since some tubes are known to have been partially filled with water, freezing-type failures cannot be ruled out at this time.

Tube Failure Trends - Based on the consistency of first row U-bend intrados surface conditions with plate position, an attempt was made to see if general trends might also exist in tube failures. From the observations made it appears possible to infer that as many as 50 to 66% of the first row U-bends were cracked.

A summary of the U-bend failure observations was made with the following results: Twenty-one (21) first row U-bends were determined directly to be cracked, generally in the axial direction. Eleven (11) were cracked mainly in the extrados surface; they could be determined directly due to their jagged edges being visible from the intrados side or due to their fishmouth or flap-like character.

Five (5) were cracked in the intrados or bottom surface. Further, five (5) were cracked in both top and bottom surfaces. As noted before, the crack lengths ranged up to about three tube diameters or slightly more. In addition, visible cracks appeared only in those tubes with shiny intrados surfaces. No dull tubes appeared to have any cracks.

Sixty-six (66) U-bends, generally occurring in soft spot regions, had shiny areas. Thirty-one (31) of those tubes with shiny areas contained axial creases. These creases are believed to represent cracks that initiated on the inside surface of the tube and are growing toward the outside of the intrados surface. One possibility is that the creases are produced as a result of a plastic hinge caused by an axial crack opening first in the extrados surface. Of course, further examinations after the tubes are removed are necessary to confirm the possibility. Further, if the sequence of extrados cracking followed by intrados crease is valid, then the 31 creased U-bends along with the 19 cracked tubes represent a total of 50 cracked U-bends, or about 53% of the first row. Furthermore, if all shiny tubes contain cracks, as many as 66 tubes (about 70% of the first row) could be cracked.

Analysis of Surface Debris

Samples were obtained from the top layer of accumulated deposit/debris on selected tube sheet and tube support plate secondary surfaces. Sample locations were several points adjacent to the blowdown pipe, at three points between Rows 14 and 15 (both hot and cold leg sides), and two points along the top of the first tube support plate. In addition, two samples were obtained from the area between the generator shell and tubes at the tube sheet. Access points for sample retrievers were the 0° handhole (blowdown pipe area), P-1 (first support plate), and 2 inch (5.1 cm.) drilled hole pairs near the 0° handhole (hot leg and cold leg). Samples were prepared by reacting with KOH plus KNO_3, fusing in a zirconium crucible and dissolving in HCl. An analysis by element was then obtained on an inductively coupled plasma emission spectroscope (ICP). Results of the analysis by specimen location are given in Table 2. As can be seen, samples are primarily oxides of Cu and Fe. Cu exists also in elemental form. Zn is the third most predominant element present, but the source of the Zn is unknown at this time. Limited sample size precluded extensive analysis. In addition to those cations shown in Table 2, future analyses are expected to include anions such as Cl^-, $PO_4^=$, and $SO_4^=$.

DISCUSSION OF RESULTS

The first step in analyzing the degraded Surry 2A steam generator is to obtain access then measure, observe, catalog, sample, and eventually metallurgically analyze the degraded regions or components. Access to the secondary side is limited for several reasons. There are only two

TABLE 2. COMPOSITION OF SELECTED TUBE SHEET SURFACE DEBRIS SAMPLES

SAMPLE NO.	ACCESS PORT	LOCATION	TOTAL DETECTED**	ELEMENTAL COMPOSITION (wt% AS METAL)																
				Al	B	Ca	Co	Cr	Cu	Fe	Mg	Mn	Na	Ni	Si	Sr	Mo	Ti	Zn	P
I	2" DRILL HOLE (HL)	30" IN FROM SHELL EXTERNAL SURFACE	83.1	0.1	*			0.1	16.8	58.7	0.4	0.4	*	1.3	0.1		*	*	4.5	0.7
II	2" DRILL HOLE (HL)	20" IN FROM SHELL EXTERNAL SURFACE	78.8			0.3		0.1	14.8	57.4	0.4	0.3		1.1					3.6	0.8
III	2" DRILL HOLE (HL)	10"-20" IN FROM SHELL EXTERNAL SURFACE	108(+)			0.7			17.1	83.9		0.8	0.6	1.4		*			3.5	
A	2" DRILL HOLE (HL)	BETWEEN SHELL AND TUBES	82.0			*		*	4.5	74.3		1.0	*	0.6	0.2		0.2	0.1	1.1	
B	2" DRILL HOLE (CL)	BETWEEN SHELL AND TUBES	83.3	0.2		0.3		0.1	4.9	74.3		1.0	0.1	0.6	0.2		0.2	0.1	1.1	
1	0° HANDHOLE	CL SIDE BLOW-DOWN PIPE, NEAR CENTER SUPPORT ROD	85.9			0.3		0.1	10.7	66.0		0.2	3.3	1.1					4.1	
2	0° HANDHOLE	HL SIDE BLOW-DOWN PIPE, NEAR CENTER SUPPORT ROD	87.8			0.1		0.1	17.0	65.1		0.3	0.6	1.1					3.5	
3	0° HANDHOLE	CL SIDE BLOW-DOWN PIPE, ~1/2 DISTANCE TO CENTER	83.9	0.2		0.5		0.2	17.6	56.3	0.3	0.3	0.4	1.9	*	*		*	5.5	0.7
4	0° HANDHOLE	HL SIDE BLOW-DOWN PIPE, ~1/2 DISTANCE TO CENTER	84.9			0.2			5.6	76.7		0.2	0.4	0.4	*				1.4	
5	P-1	~COLUMN 75, TOP OF FIRST SUPPORT PLATE	85.6	0.1		*	*	0.3	28.8	50.4		0.3	0.1	1.5	*			*	4.1	
6	P-1	~COLUMN 65, TOP OF FIRST SUPPORT PLATE	85.9	0.1		0.1		0.1	26.3	47.4	0.2	0.3	0.1	3.3	*			*	7.6	0.4

---

*DETECTED BUT <1 PART PER THOUSAND

**NOTE: UNDETECTED ELEMENTS PRIMARILY C, O, N, CAUSING TOTALS NORMALLY < 100%

(+)POSSIBLE DILUTION CORRECTION ERROR (RATIOS REALISTIC) service ports and three pre-shipment penetrations. Once inside, the 'tight' internal generator dimensions, coupled with in-service deformation and distortion of the seven support plates due to the denting process, prevent easy access for most observation equipment. Furthermore, general cutting of the shell and shroud, except for a region near the tube sheet has not yet been possible. Care must be taken not to destroy evidence related to other research tasks. For example, eddy current data from the heat exchanger tubes could be altered when making penetrations or by removal of access-interfering tubes. Finally, radiological and economic reasons prevent the fabrication of many large openings. Thus the early stages of secondary side evaluation had to be done with a minimum of new penetrations. When entrance did occur, it had to be done with small equipment having minimal interactive effect.

With these initial limitations, efforts were made to use subsize, remote optical observation and lighting equipment and small photographic devices. The intent was to categorize the state of internal damage or behavior and, where possible, photographically record such information. This was successfully done using small, Battelle-developed camera systems. These allowed internal access between tubes where nominal separation is frequently less than 0.4 inch (1.0 cm.) and in deformation-compressed regions of tube support plates. A commercial borescope was used to assess the state of the U-bends.

Observations and photographs of the tube lane above the tube sheet, showed variations in tube surface deposit color* and character. These indicated that secondary water flow in the lane was unevenly distributed; it was greater near the handholes (periphery) and decreased significantly as the generator center was approached, in spite of the peripheral flow deflectors. Further, the tube deposits on the hot leg side were thicker and peeled off more profusely than on the cold leg side. These deposits totally covered the more densely packed sludge pile. In addition, the deposits appeared relatively porous and showed color variations with depth as various layers peeled off from a given tube. Further analysis of the nature of these porous and color-variable deposits is necessary, but their appearance does suggest that ion diffusion through the deposits is possible and perhaps that color variations could be related to different secondary water treatments or conditions. On a larger scale, in the tube lane one could see other intermittent markings like bathtub ring effects that might be related to previous sludge pile accumulations or water draw down and hold.

Deformation damage in the first support plate from the ubiquitous tube denting process resulted in essentially complete closure of the flow slots. Further, the closure occurred dominantly from the hot leg side. In addition, an apparent piece of broken support plate was seen wedged

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*Exposure to oxygen in the air and drying out is believed to have altered the original gray-to-black deposit color. Present color differences, however, probably represent differences that existed prior to dryout.

between Rows 1 and 2 hot leg tubes near the generator center. The fragment appeared to be crawling downward with a resultant wedging of the Row 1 tube toward the tube lane. Flow slot closures also produced severe creasing and crushing of adjacent tubes, and in some cases may have resulted in tube wall penetration. Because of the extreme closure and hence fracture of the flow slot corners, it is believed that many other fragments of support plate will be found.

The denting process has probably resulted in a large net force, pushing some of the support plates outward as well as in toward the flow slots. Crude estimates of the total biaxial force could approach 1000 kips (4.45 Mega Newtons) per plate thereby forcing the shroud closer to the shell. Deformation of the shroud is visible when viewing along the downcomer.

Concerning the U-bend tubes, variations in surface color and deposits and deformation and fracture conditions appeared to be effected by, and related to, the flow slot directly below in the seventh support plate. The seventh support plate also showed flow slot closure but to a lesser degree [about 1 inch (2.5 cm.) open] than the first support plate and the deformation appeared to be relatively uniform from both hot and cold leg sides. High levels of deformation in the flow slot corners, like that in the first support plate, caused many local fractures and cracks to occur within many nearby flow holes. The borescope was constrained so close to the fragment that photography was not practical. It was estimated to be about 1 inch (2.5 cm.) in its greatest dimension. Only the 'bottom' or intrados surface of the U-bends could be readily seen. As observation progressed away from the bottom of the intrados surface (0°) toward the midplane region between the intrados and extrados surface (±90°), less detail could be seen unless the tube had deformed and fractured outward in those regions.

Concerning surface conditions, the Row 1 U-bends located at hard spots (about 22 tubes) were generally smooth, dull brown in color with relatively thin deposits, probably less than 1 to 3 mils (.03 to .08 mm.). In contrast, the U-bends in soft spots (about 72 tubes) tended to have shiny areas (66 total) that are believed to be due to spalling of the relatively thin deposit. In turn, the spalling was probably produced by the increased bending induced by the nearby flow slot hourglassing; furthermore the hourglassing apparently deformed 21 of the tubes enough to produce cracks in the U-bend regions. For completeness of discussion, the straight sections below the U-bends appeared to have similar rough surface deposits independent of location.

Tube failures showed a similar distribution relative to flow slots as did variation in surface conditions on the bottom of the U-bends. Failures, or more specifically fractures, as noted above, were seen in 21 tubes located primarily in soft spot regions. They were generally 'axial' in orientation, and ranged from tight to gaping with lengths as great as three tube diameters or more. Five tubes had cracks in both intrados and extrados surfaces wide enough to see the next tube row. Further, some tube fracture surfaces touched the adjacent tube or tubes.

Some cracks were in the zero (0) degree location. Flap-type cracks and fishmouth cracks were seen around the 90 or 270° degree locations. The latter varied in location but were generally 90 to 120° away from the bottom of the U-bend. It should be noted that some of these failures could have occurred after removal of the generator from Surry. For example, the generator was stored outside during one winter at Hanford. Since some tubes contained limited amounts of water, cyclic expansion through periodic freezing could not be ruled out as a tube failure mode at this time.

Axial creases in many of the U-bend shiny areas are thought to be precursor cracks. They apparently start on the primary side and grow toward the secondary side. Creases were seen in 31 soft spot tubes independent of the 21 fractured tubes containing shiny borders adjacent to their cracks. This primary to secondary crack growth process is suggested by the one tube that had an intrados crack that appeared to have propagated through a crease. Crease lengths ranged up to about three tube diameters.

The total number of cracked Row 1 U-bends could be greater than represented by the 21 directly observed fractures. If the 31 creased tubes do contain cracks, these along with the previous 21 specimens represent more than half of the Row 1 U-bends. Furthermore, it remains a possibility that more than two-thirds of the first row may be cracked if all 66 of the shiny surface specimens suffer from the same process. Since inner row U-bends were preventatively plugged early in generator life, most of this damage possibly occurred after the tubes were removed from service. Denting continued support plate deformation even after early plugging efforts.

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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.

This report provides information on secondary side characterization efforts. The methods and equipment used are discussed, along with comparisons of benefits offered by various techniques. Details of secondary side steam generator conditions are then presented, emphasizing support plate and U-bend regions.

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