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THERMAL CYCLING EFFECTS ON SOLAR CELL INTERCONNECTION TABS ON AN OAO-B SAMPLE MODULE

JULY 1971

GSFC

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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by

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GODDARD SPACE FLIGHT CENTER
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ABSTRACT

Thermal cycling tests (in air) were performed on a sample OAO module incorporating intentionally bent solar cell interconnection tabs. Inspection of the tabs at various intervals during 300 cycles of testing between +104° C and -60° C disclosed a high defect and failure development rate (approximately 25%) both in the bent tabs and in normal tabs. The main failure mode was cracking, leading to breakage, of the tabs. In most cases (approximately 60%) this occurred at the bend adjacent to the solder joint. The secondary location (approximately 20%) was at the point of severe bends and crimps. Since similar tests of a complete flight paddle but under vacuum conditions showed a much lower failure rate and also showed the major failure mode to be solder joint failure, it was concluded that the module test results, either because of differences in workmanship and materials or because the tests were performed in air, were not applicable to prediction of flight paddle performance. However, weakness of the interconnection tabs lead to recommendations for redesign for use on future spacecraft solar arrays. The tests showed that slight bending of the tabs did not result in increased defect rates while severe bending, significantly increased the development of defects.

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THERMAL CYCLING EFFECTS ON SOLAR CELL INTERCONNECTION TABS ON AN OAO-B SAMPLE MODULE

INTRODUCTION

When interconnection tab failures were experienced on the OAO-C (Spacecraft #4) solar arrays during thermal cycling tests, a question was raised as to the reliability of the OAO-B (Spacecraft #3) solar arrays. As a result the OAO-Project Office requested the Solar Power Sources Section to perform sample inspections on each of the OAO-B solar paddles. These inspections were performed and the results were reported in References 1 through 6. These inspections revealed a few of the common deficiencies - broken cells, broken coverglasses, open tabs, bubbles in the adhesive, unclean surfaces, etc. Which are generally well understood and thus could be corrected or disregarded based on engineering decisions. However, the inspections also showed that many of the solar cell interconnection tabs were bent and some were spliced. Since the stability of such tabs was not known, thermal cycle testing (in air) was performed on a sample module to determine the significance of the deficient tabs insofar as flightworthiness was concerned. The Solar Power Sources Section was requested to perform detailed microscopic inspections on the sample module at various stages of the thermal cycling. This report covers the results of those inspections.

PROCEDURE

A sample module (Figure 1), specified to be of flight quality workmanship and typical of the OAO-B solar array, was obtained from Spectrolab, the manufacture of the OAO-B solar paddles. This module was specified to be of flight quality workmanship but including bent and spliced tabs. It was also specified to consist of a substrate, solar cells, and interconnectors the same as on the S/C #3 paddles.

The overall size of the module substrate is 5-3/4" x 10-3/4" x 1-1/4". The cells used are all 2 x 1 cm corner dart cells with two interconnecting tabs each. The cell configuration consists of three cell groups. Two of the groups have two cells in series and three cells in parallel. One of these is located at the top of the substrate and the other at the bottom. The third group is located in the middle of the substrate. This group is made up of seven cells in series by five cells in parallel. All three groups are bonded to a typical OAO paddle substrate section. After the mounting of the cell groups to the substrate, a number of the tabs were bent into the various configurations as indicated in Figures 2a through 2e. In addition, others were soldered as shown in 2f (spliced) and 2g (soldered out of line). Figure 2h shows the normal tab configuration.

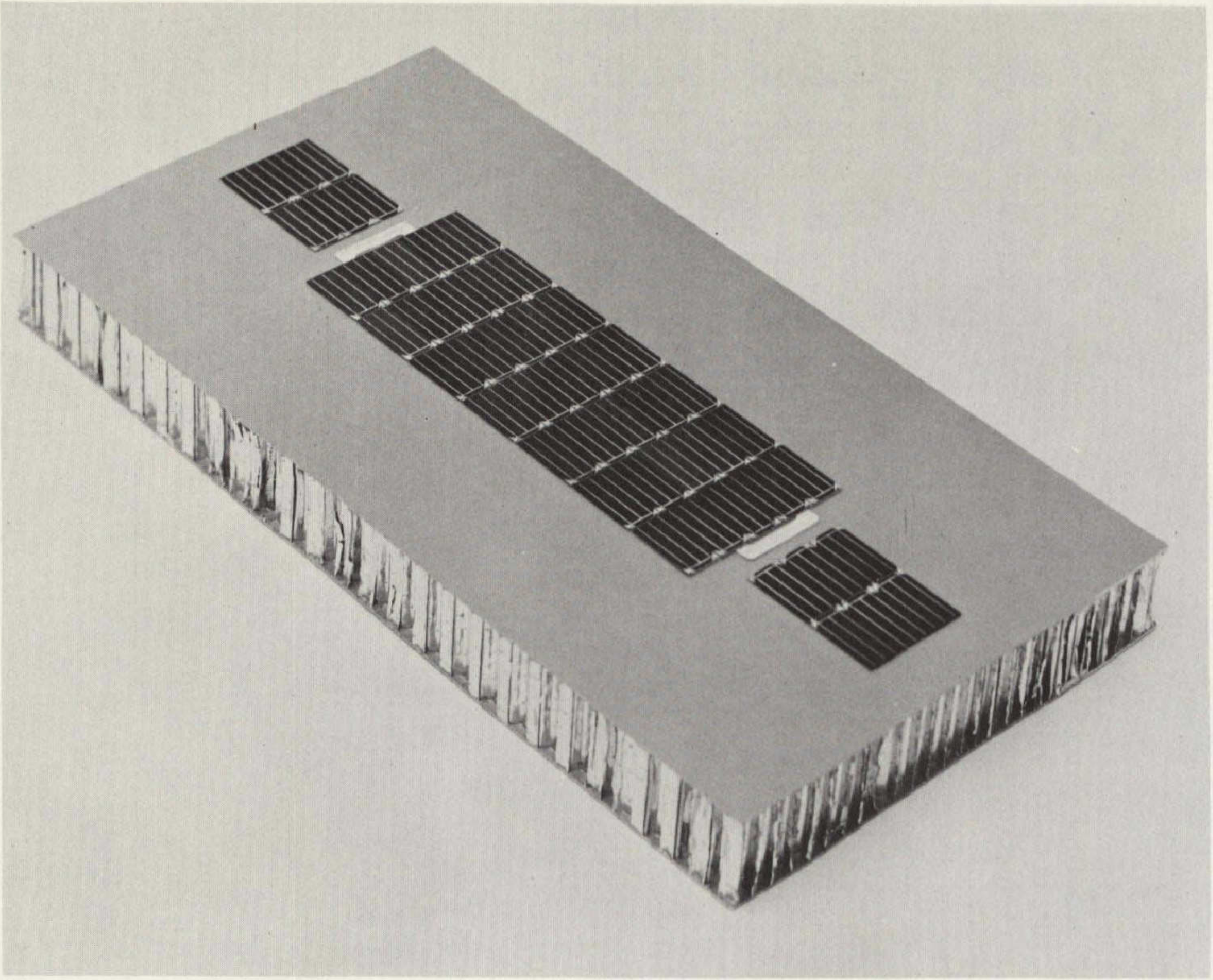


Figure 1. OAO Test Module

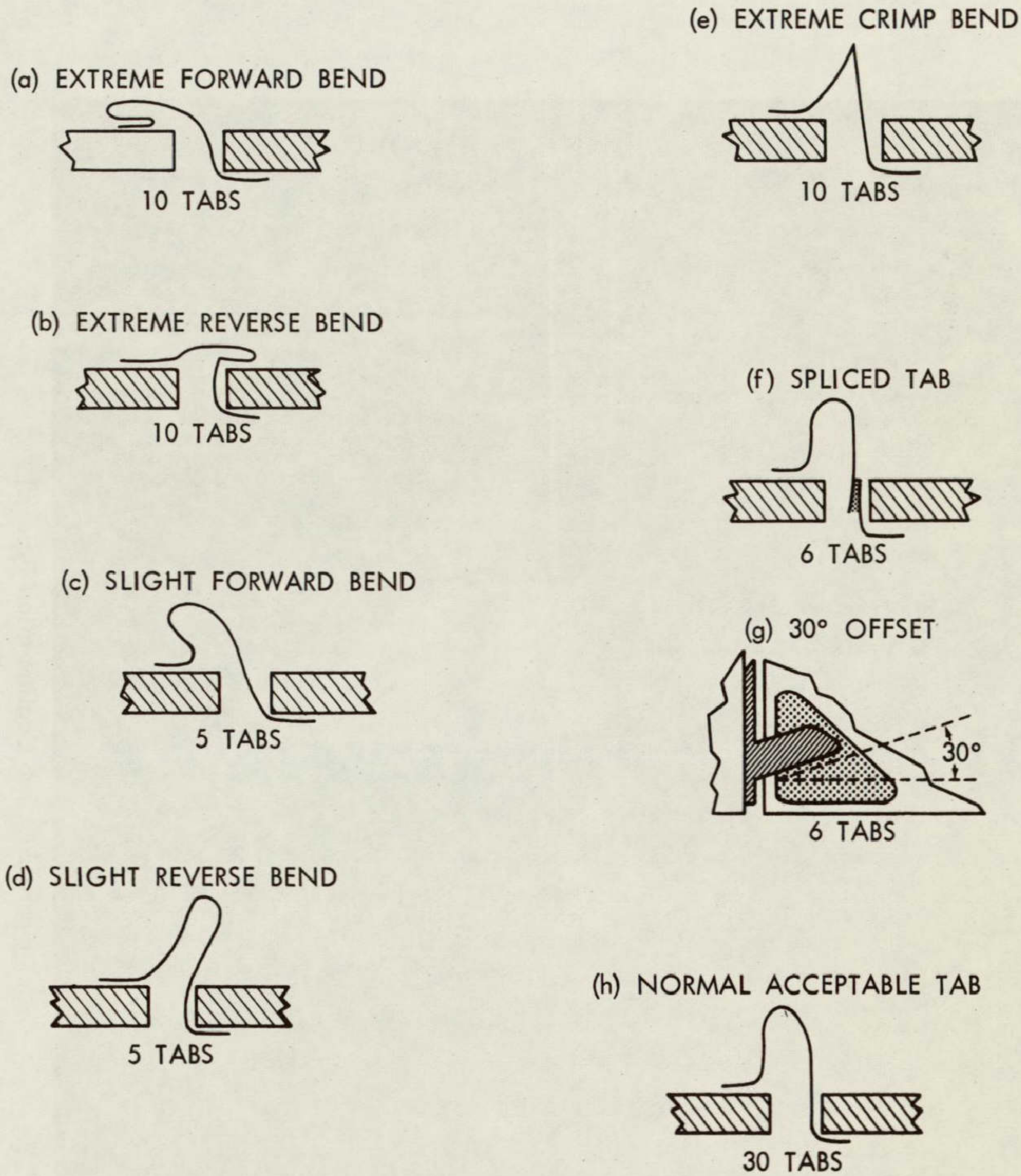


Figure 2. Various Tab Configurations

The photos in Figures 3a through 3h are microscopic photos showing typical tabs of each type on the module. The arrow indicates the typical tab.

The panel as described above was received for an initial inspection prior to testing. Along with the panel, Spectrolab supplied an information sheet showing

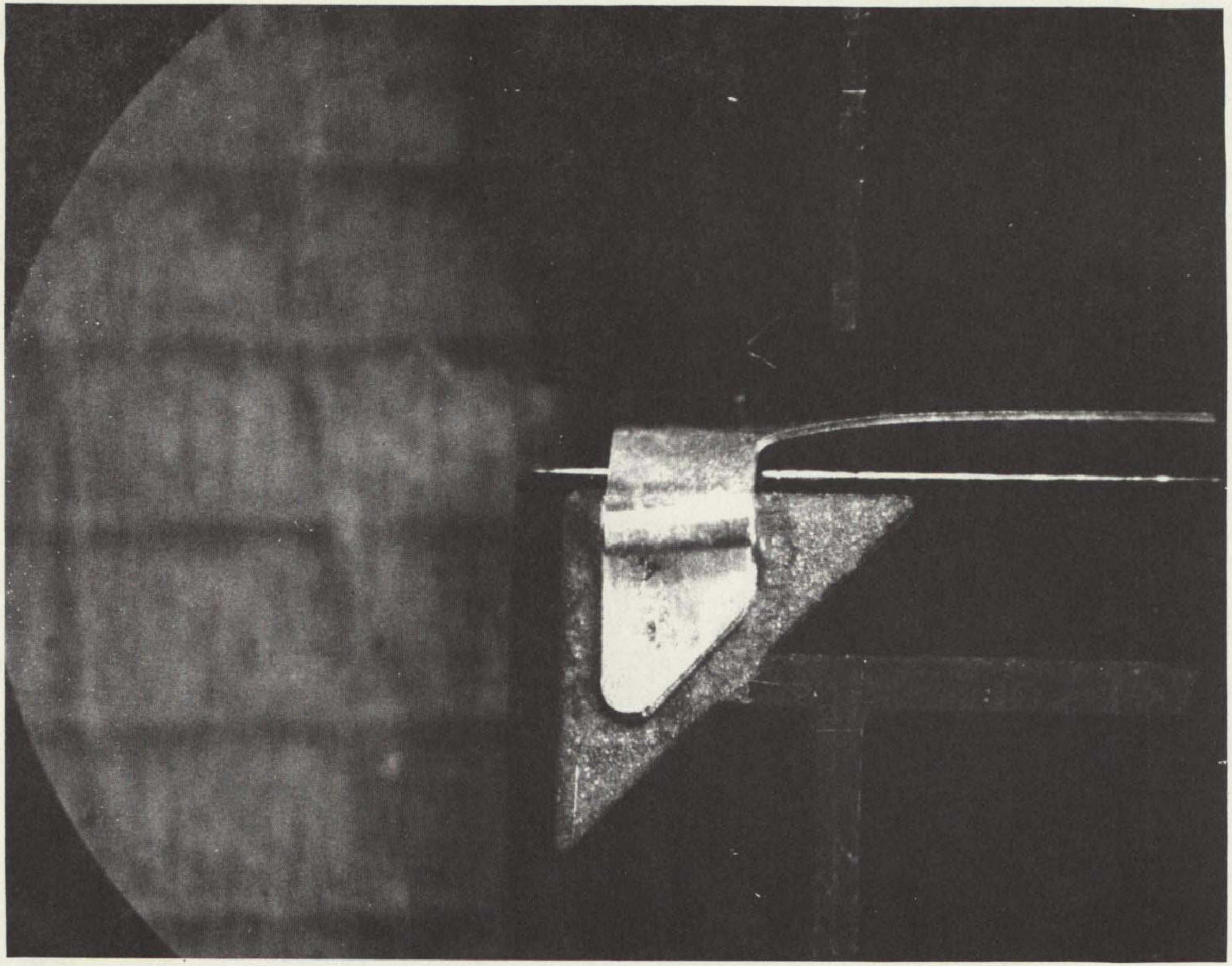


Figure 3a. Tab Configuration Type (a)

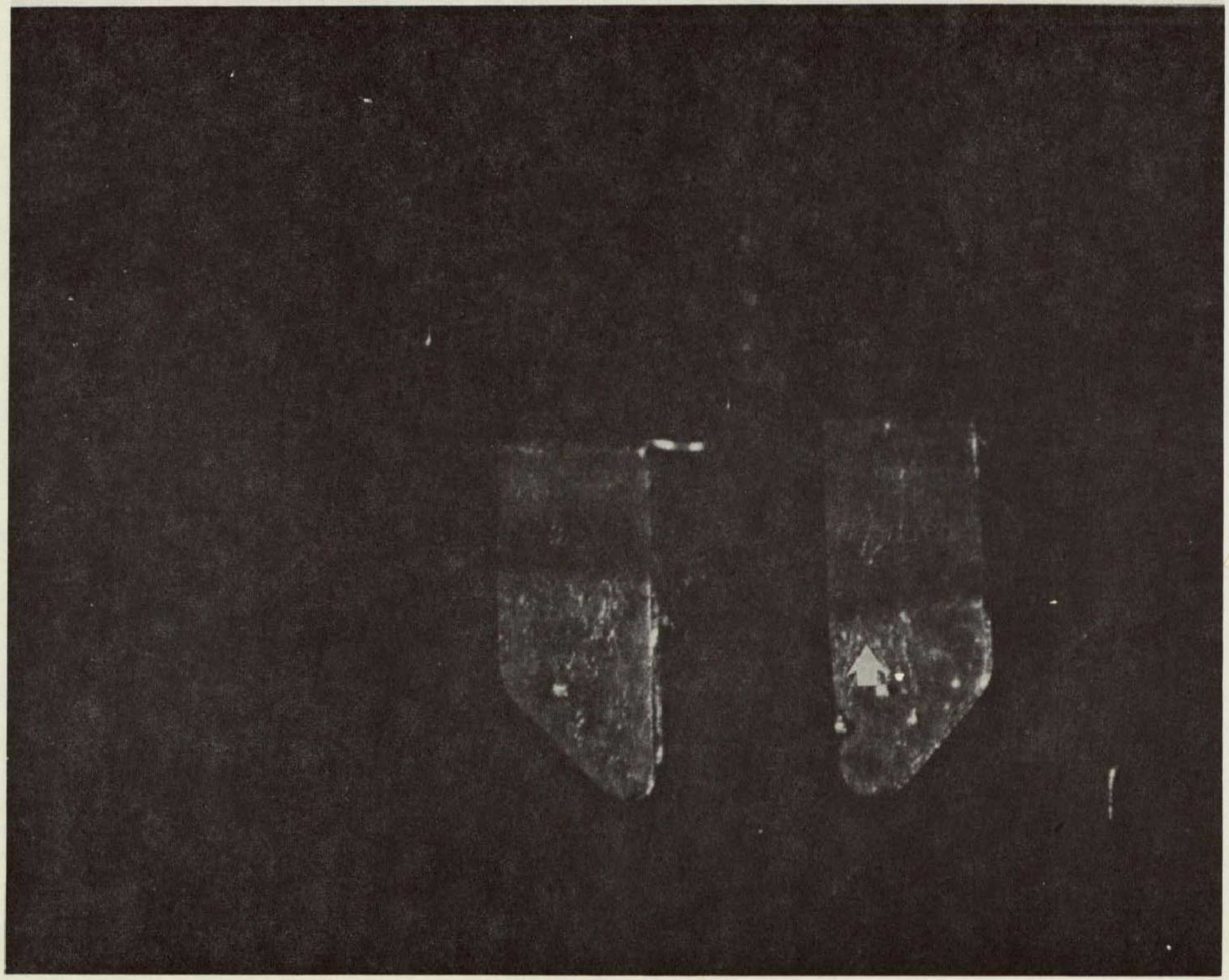


Figure 3b. Tab Configuration Type (b)

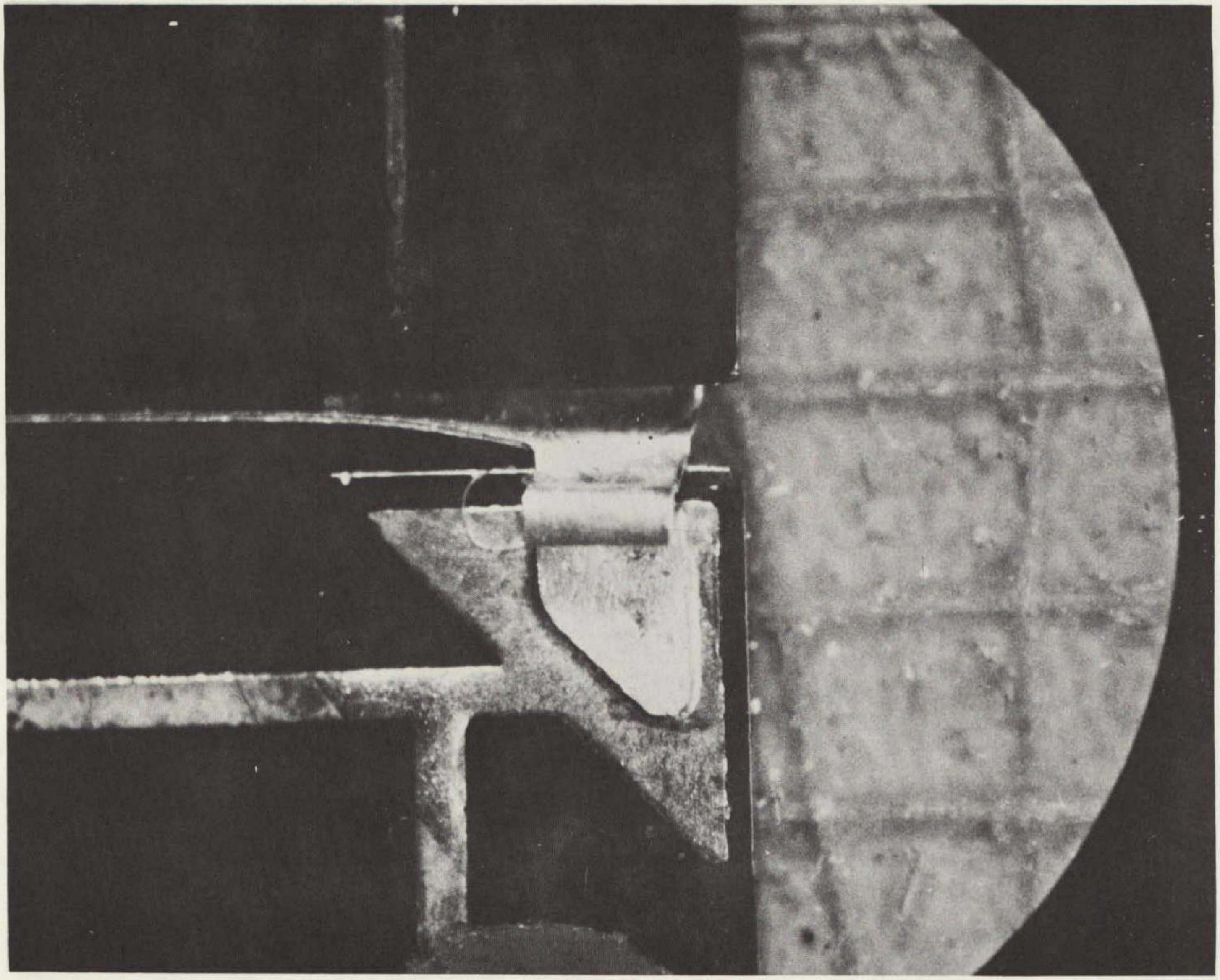


Figure 3c. Tab Configuration Type (c)

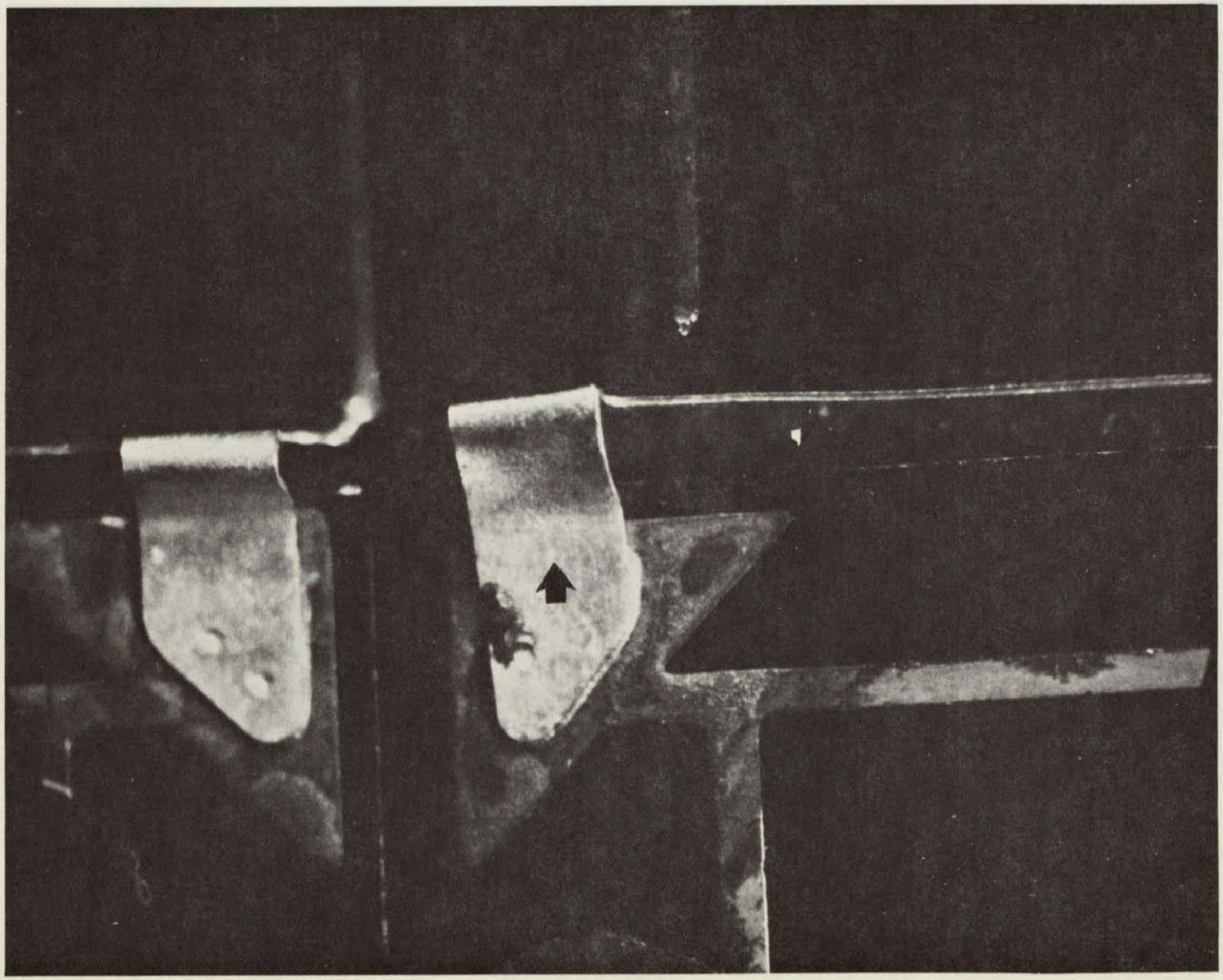


Figure 3d. Tab Configuration Type (d)

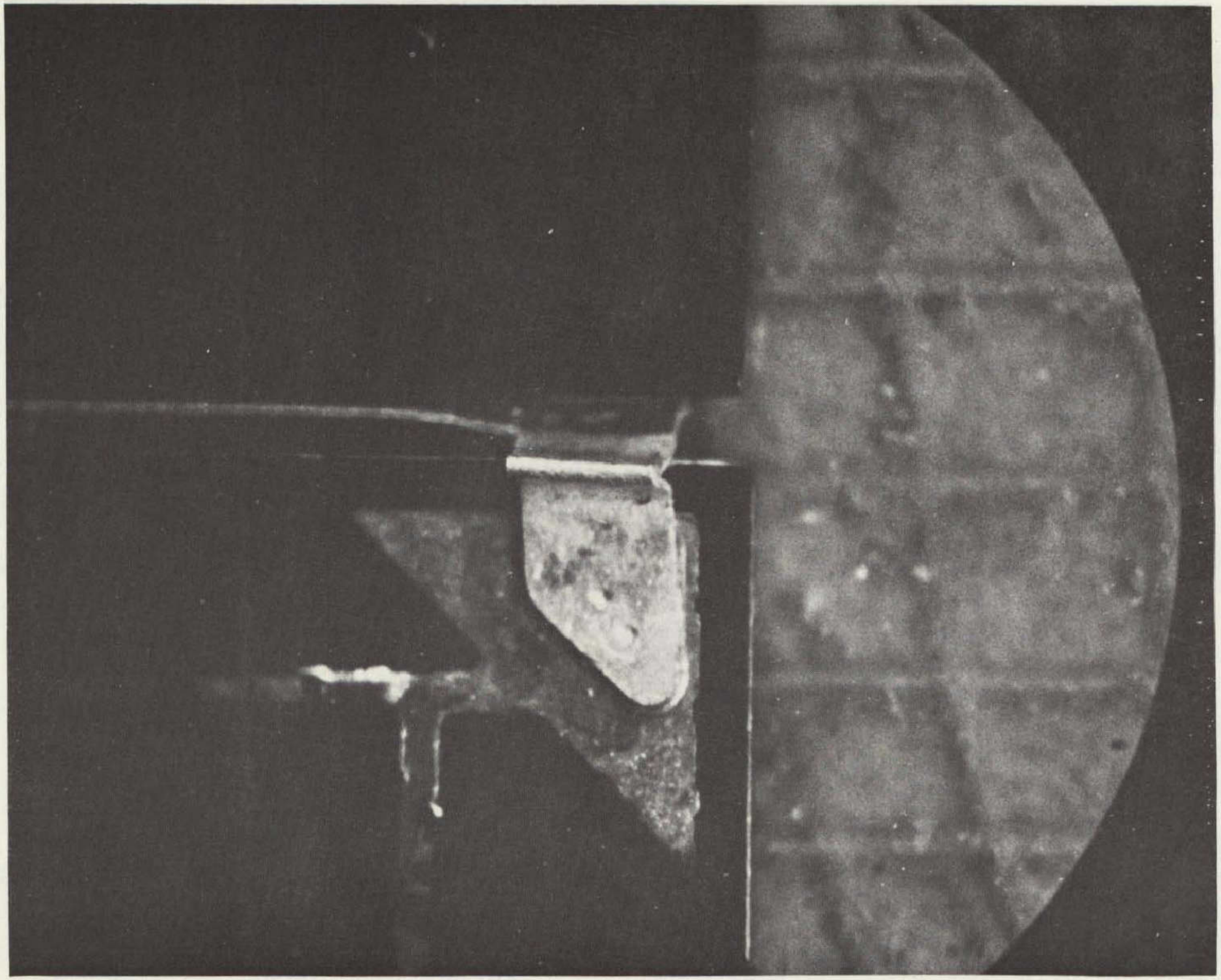


Figure 3e. Tab Configuration Type (e)

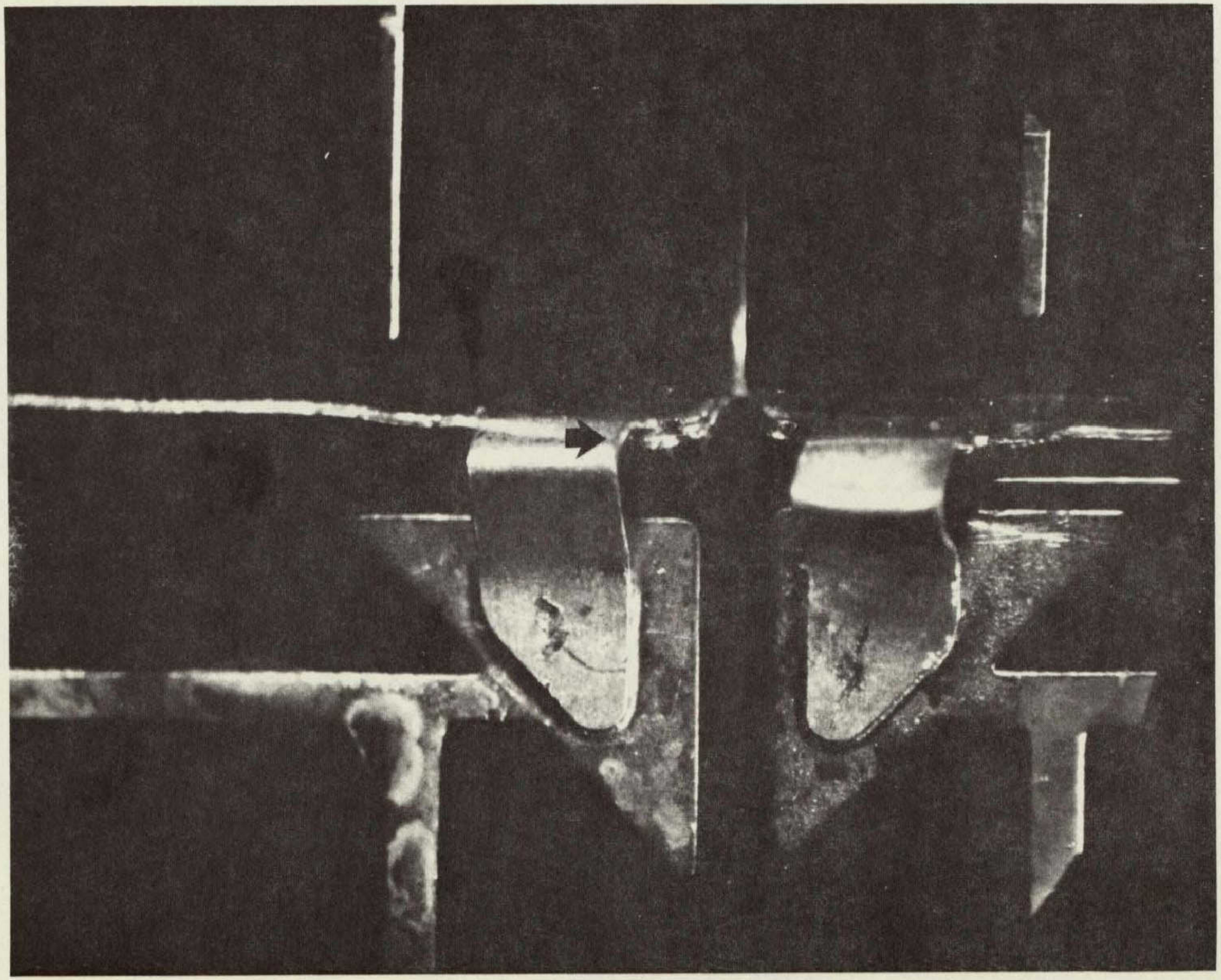


Figure 3f. Tab Configuration Type (f)

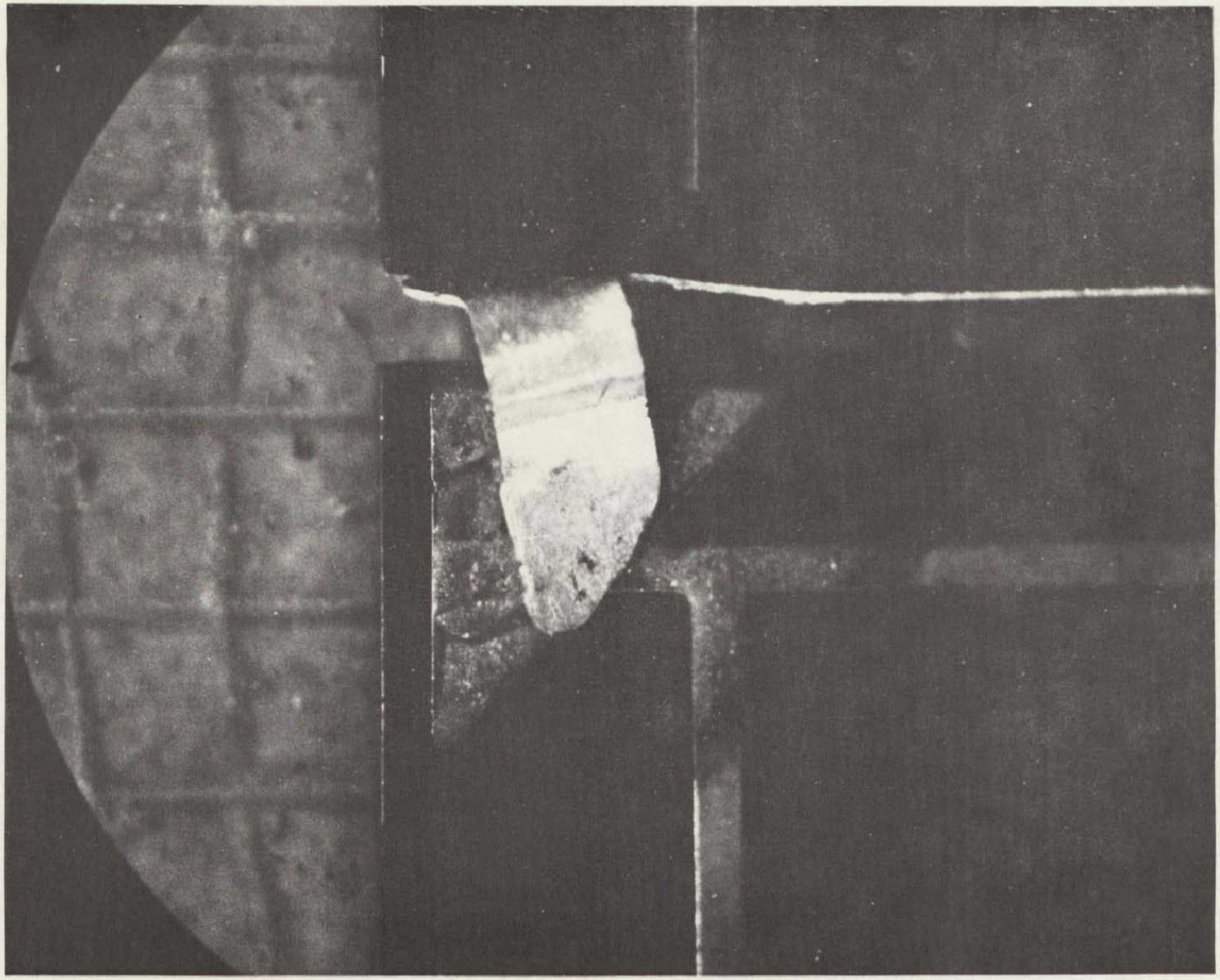


Figure 3g. Tab Configuration Type (g)

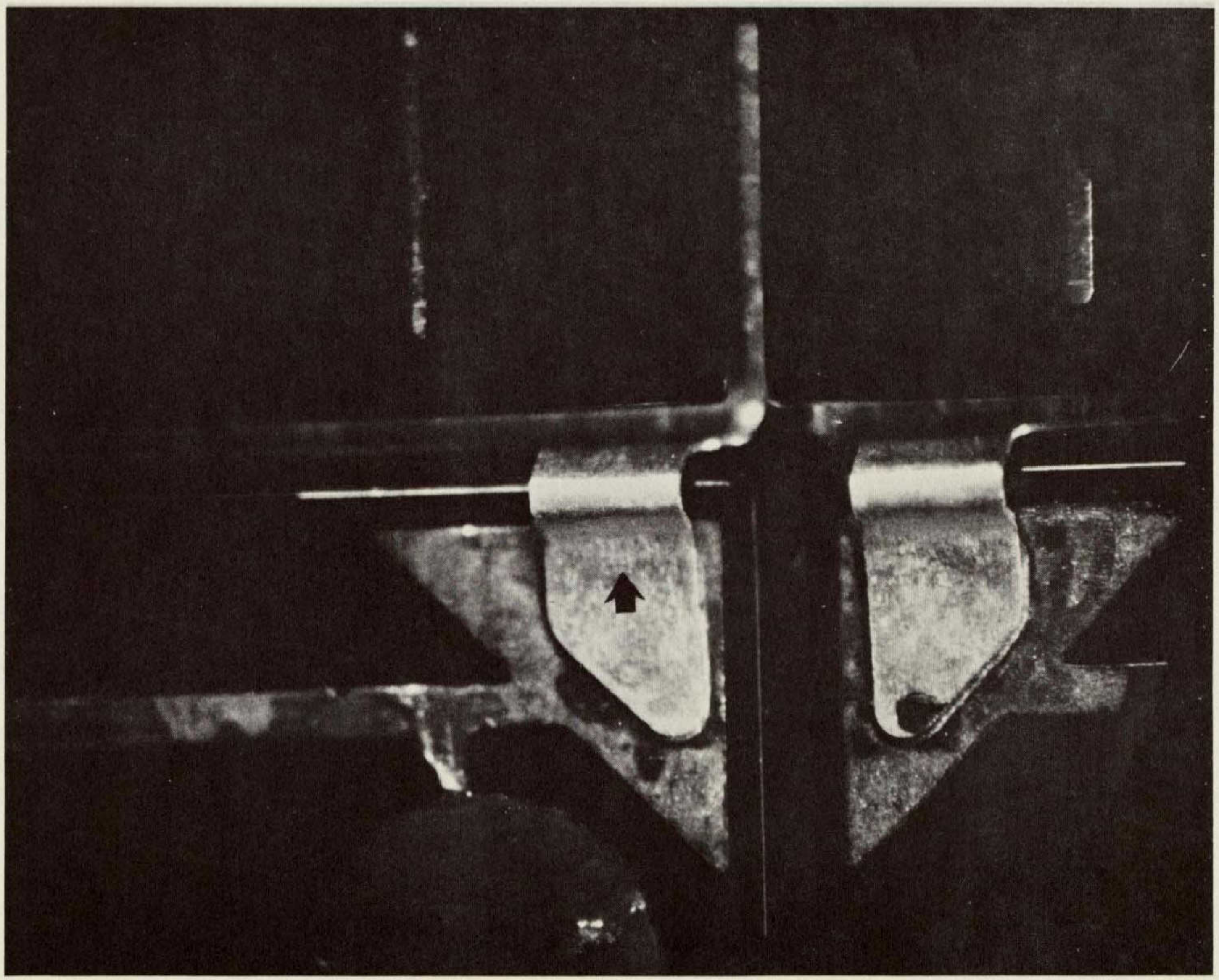


Figure 3h. Tab Configuration Type (h)

the location of each type of the sample tabs (Figure 4). The initial inspection was performed using 30 power magnification. The results of this inspection were recorded.

After the initial inspection the sample module was subjected to the thermal cycling test for 50 cycles. This test was performed between the limits of +104° C and -60° C, the temperatures expected in flight. Typical cycle data are shown in Figure 5.

After the first test of 50 cycles the panel was fully reinspected under 30 power magnification. It was then subjected to a second series of 50 cycles, reinspected, etc., at 50 cycle intervals up to a total of 200 cycles. It was then subjected to an additional 100 cycles bringing the total to 300 cycles. The module was then given a final inspection prior to turning it over to the Materials Engineering Branch (GSFC) for analysis. Their results are given in Reference 7.

RESULTS

At each inspection interval the defects observed were noted on an inspection sheet and were photographed for record. The physical location of the tab in each photo is shown in Figure 6 and the photo number shown on Figure 6 is referenced in its corresponding figure. (Figures 8 through 35.)

Initial Inspection

The initial microscopic inspection results are shown in Figure 7. In general the results confirmed the Spectrolab information sheet. However, the following deviations, which could affect the test results, were noted:

1. Two of the type-f tabs in addition to being spliced were bent. One had a type-d bend and one a type-g.

2. One of the tabs which was supposed to have a type-d (reverse) bend was actually a type-h tab (not bent).

3. Two of the tabs which were supposed to be type-h (normal) were found to be bent. One had a forward, type-c bend, and one had a reverse, type-d bend.

4. In addition it was noted that two tabs had scribe marks on them, two had insufficient solder, and two had excess solder.

5. Finally, one of the type-h (normal) tabs was found to be cracked.

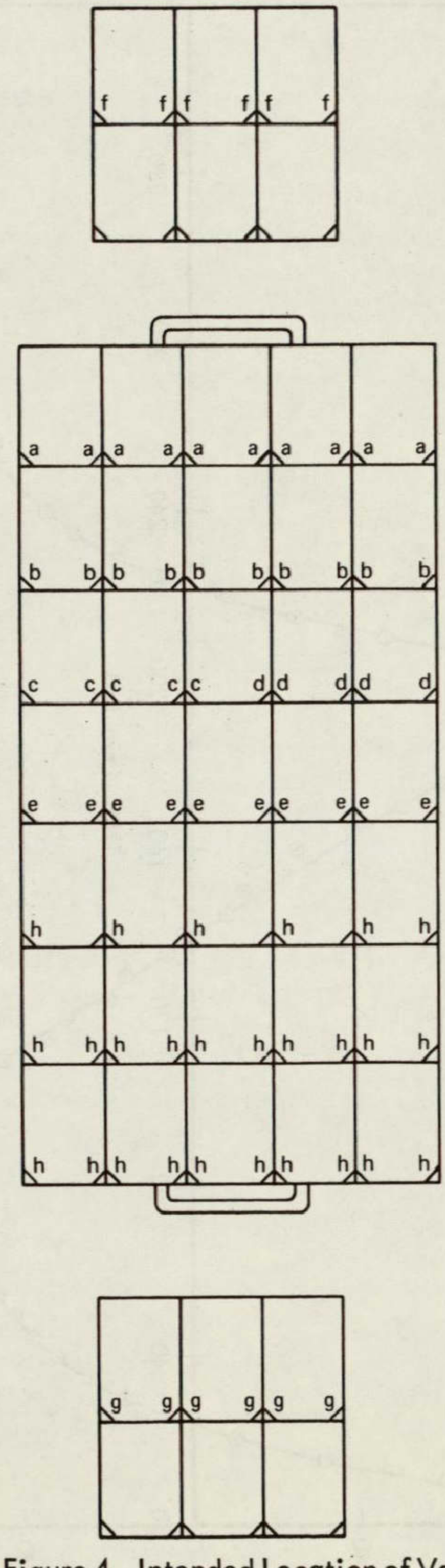


Figure 4. Intended Location of Various Tab Configurations

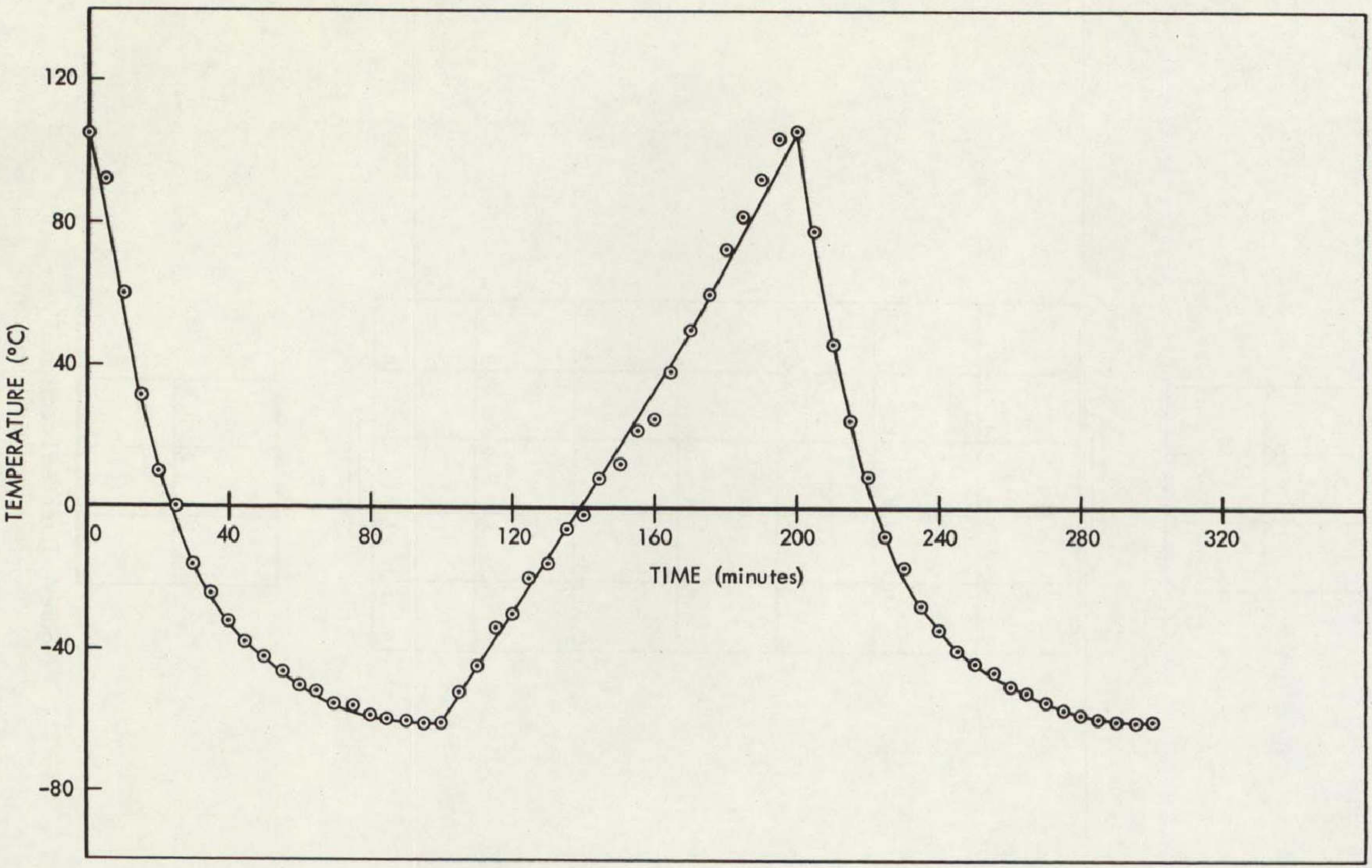


Figure 5. Typical Temperature Cycling (1-1/2 Cycles)

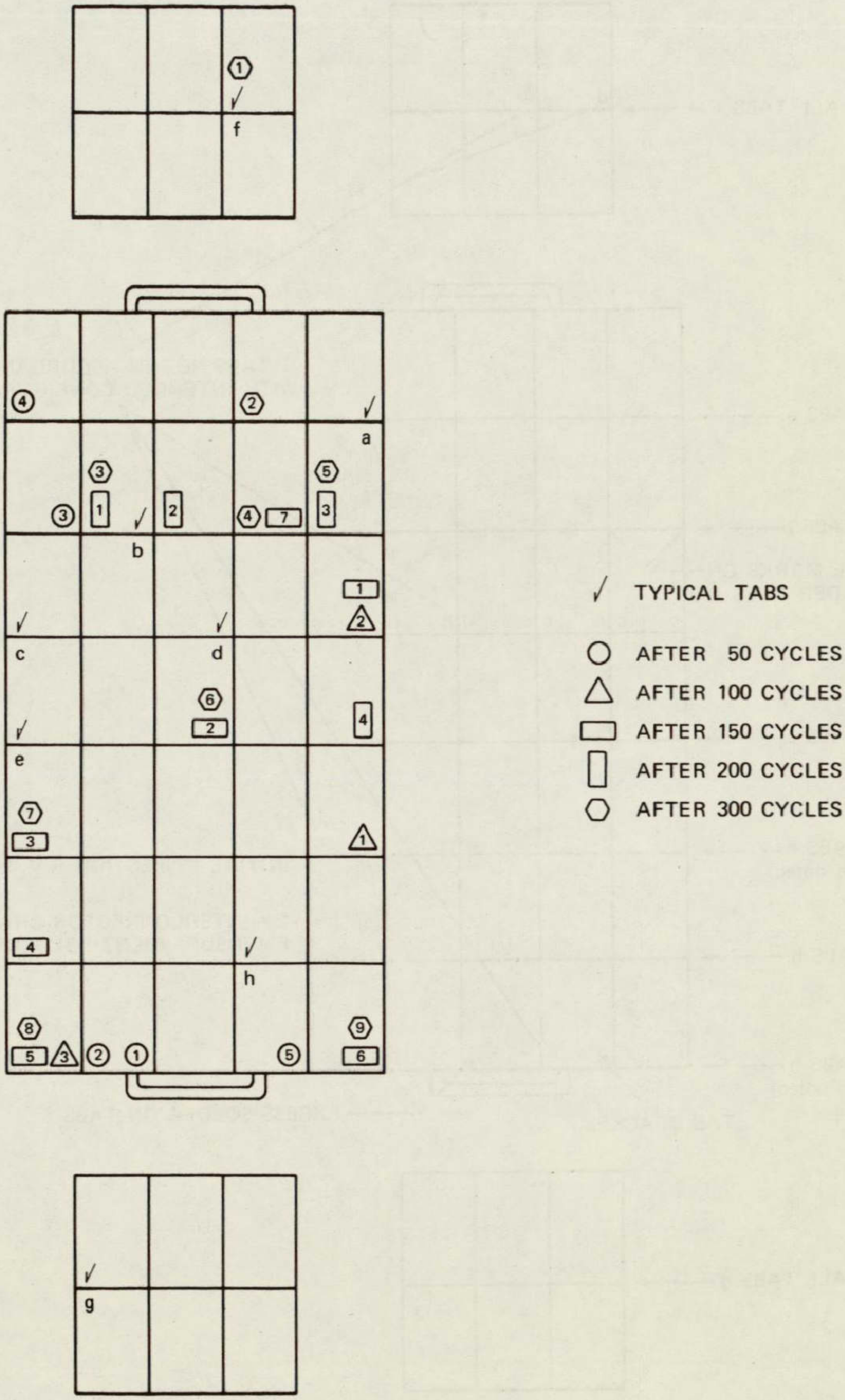


Figure 6. Physical Location of Photos

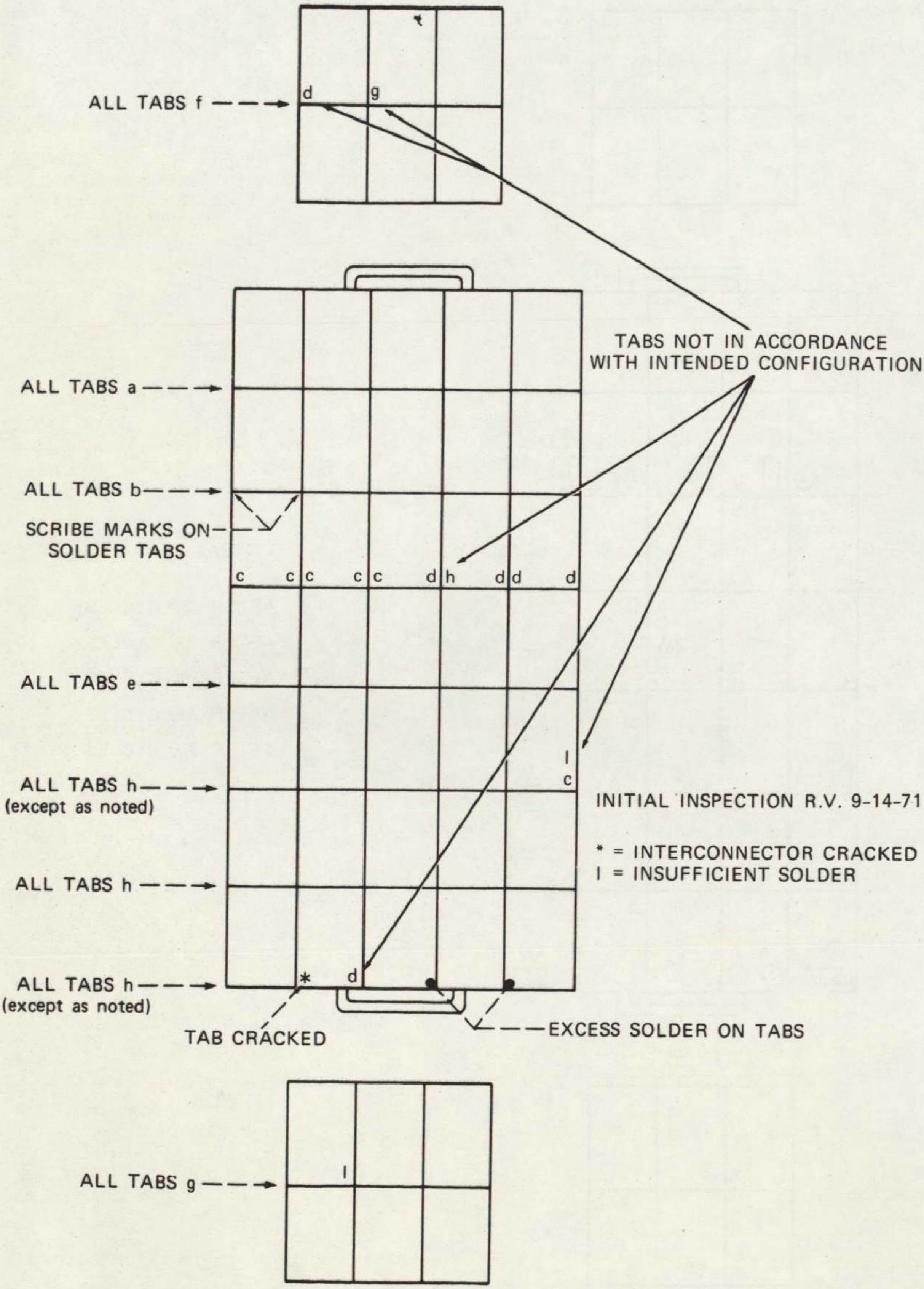


Figure 7. Initial Inspection Results

Inspection after 50 Cycles

Five defects, four cracked tabs and one broken tab, were revealed in the inspection performed after 50 cycles. Each of these is illustrated separately in Figures 8 through 12. (Although cracks may be difficult to observe in the photographs, they were quite evident in the microscopic inspection because of the color contrast between the silver plating on the surface and the copper underneath.) Arrows have been inserted on the photographs to aid in locating the defects.

Figure 8 shows a type-d tab. (This is the tab that was supposed to be type-h but was actually type-d.) A crack is forming in the tab at the bend at the soldered portion of the tab.

Figure 9 shows a broken type-h tab. This tab was beginning to crack when received, as noted in Figure 7. This tab is on the same cell as the cracked tab in Figure 8.

Figure 10 shows a crack forming on a type-b tab. (This photo also includes the adjacent tab which showed a defect after 200 cycles as seen in Figure 23.)

Figure 11 shows a type-a tab. A crack has occurred at the top of the tab where it has been bent.

Figure 12 shows another type-h tab with a crack forming at the bend adjacent to the solder connection.

Inspection After 100 Cycles

Figures 13 through 15 show three additional cracked tabs observed after 100 cycles. In addition, one solder joint failure of a type-f tab was observed. A photograph of this failed tab was inadvertently omitted. However, the solder joint failure - on the cell, not at the splice - was similar to that shown in Figure 27.

Figure 13 shows a crack in a type-c tab. (This tab was one of those in the row of type-h tabs which was found to be a type-c tab in the initial inspection.)

Figure 14 shows a type-d tab with a crack in the tab along the solder contact.

Figure 15 is a type-h tab (on the right) with a crack. (The tab on the left failed after 50 cycles. See Figure 9.)

Figure 8. Crack in Type-d Tab After 50 Cycles

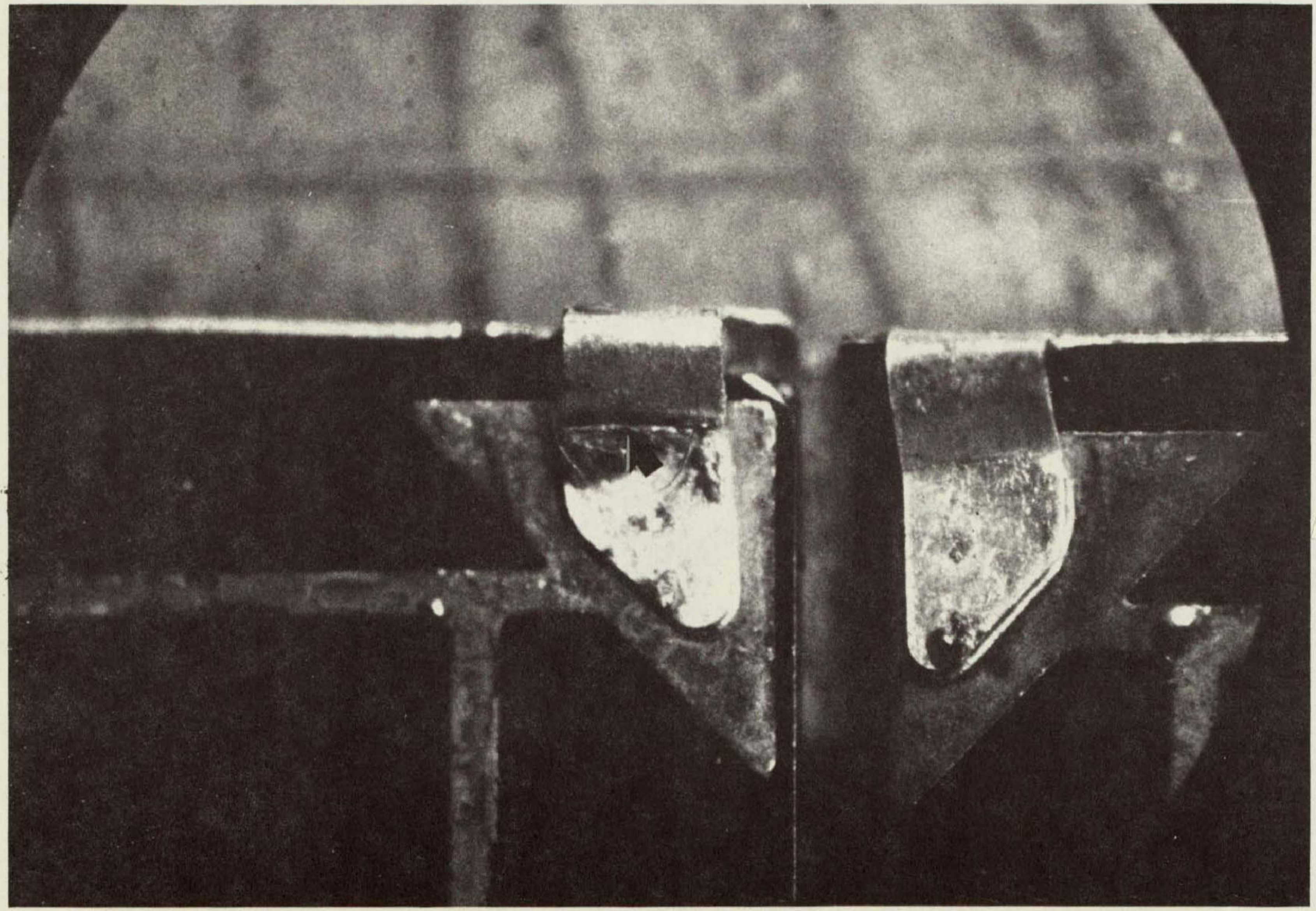


Figure 9. Broken Type-h (Normal) Tab After 50 Cycles

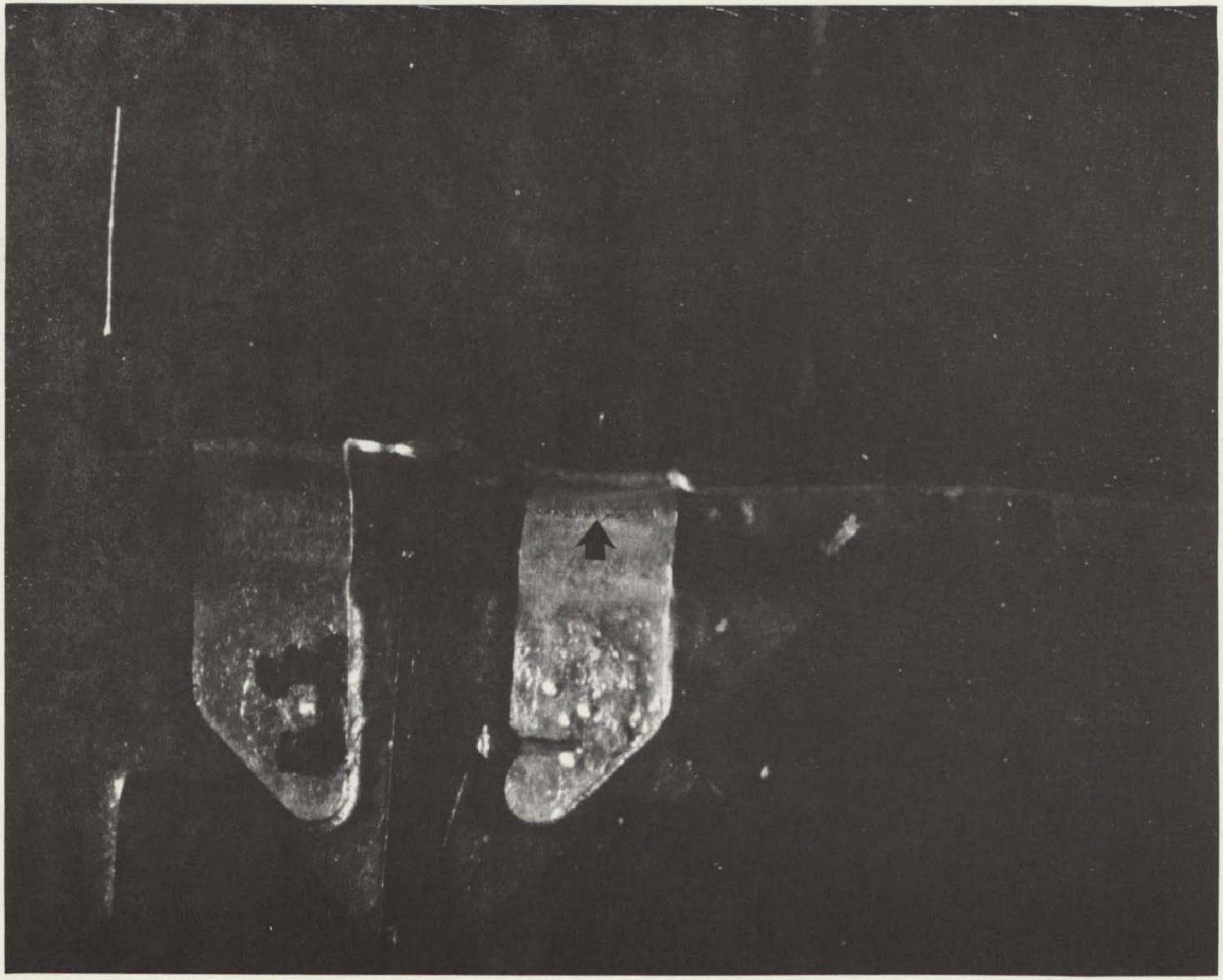


Figure 10. Crack Forming on Type-b Tab After 50 Cycles

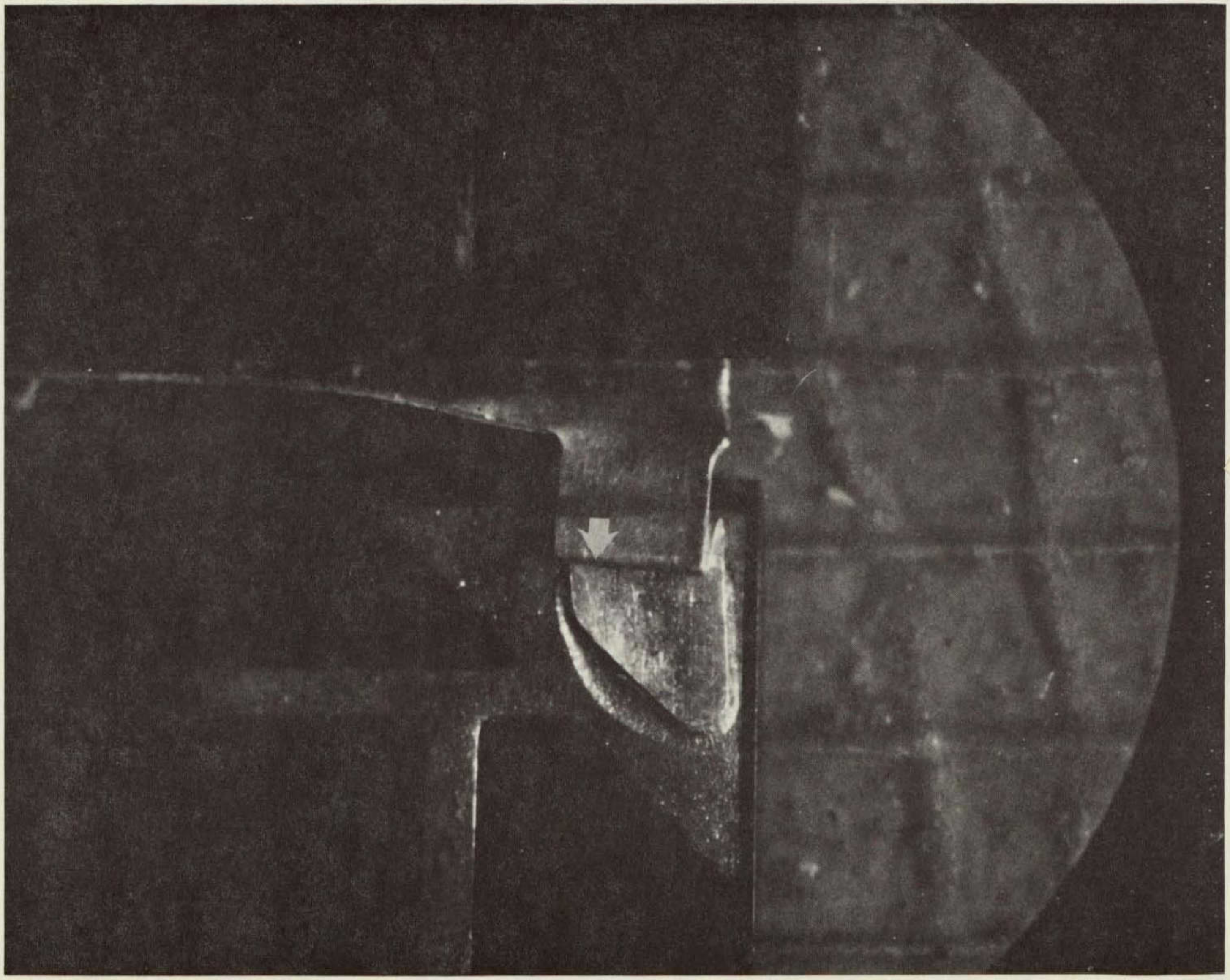


Figure 11. Crack in Type-a Tab After 50 Cycles

Figure 12. Crack in Type-h Tab After 50 Cycles

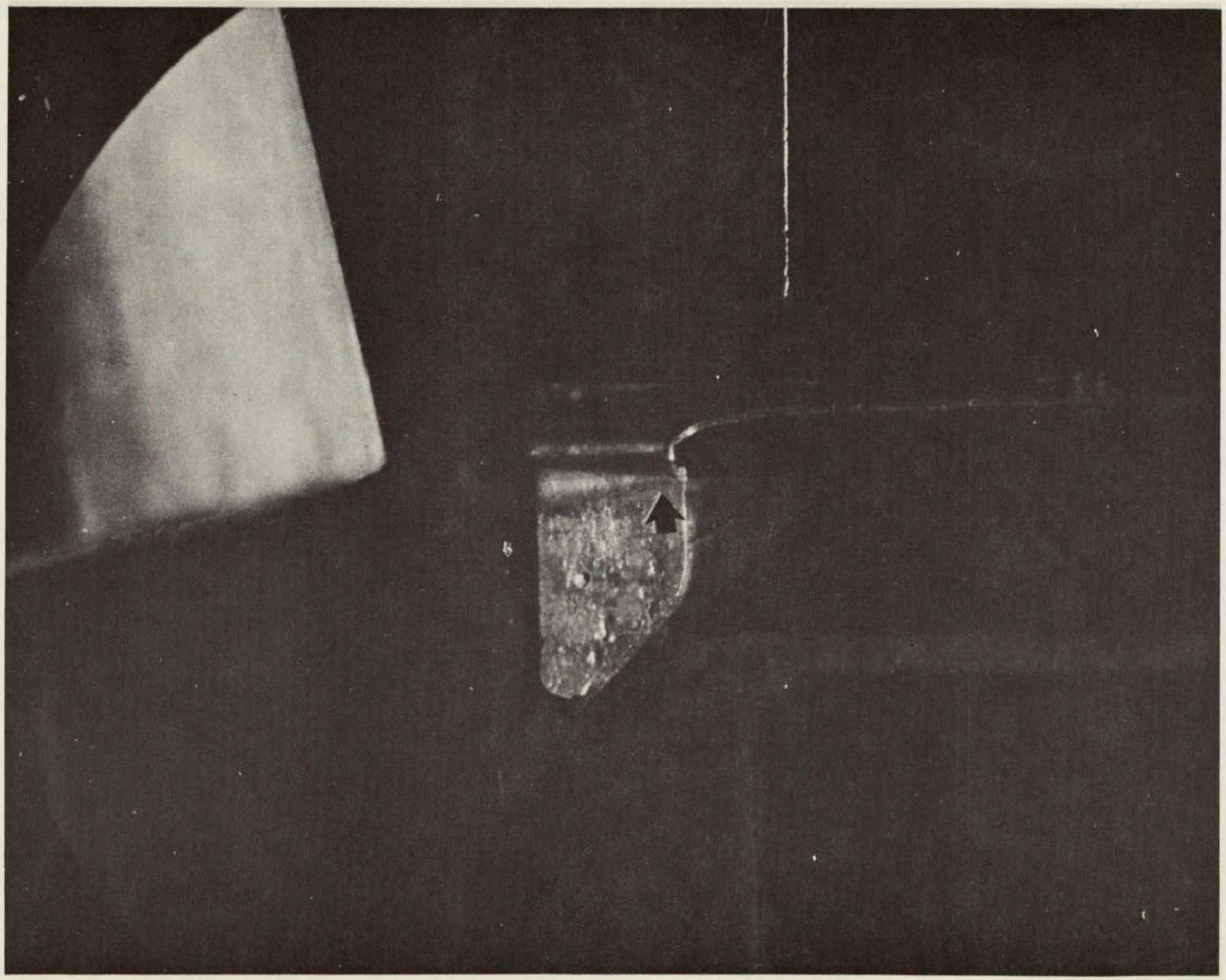


Figure 13. Crack in Type-c Tab After 100 Cycles

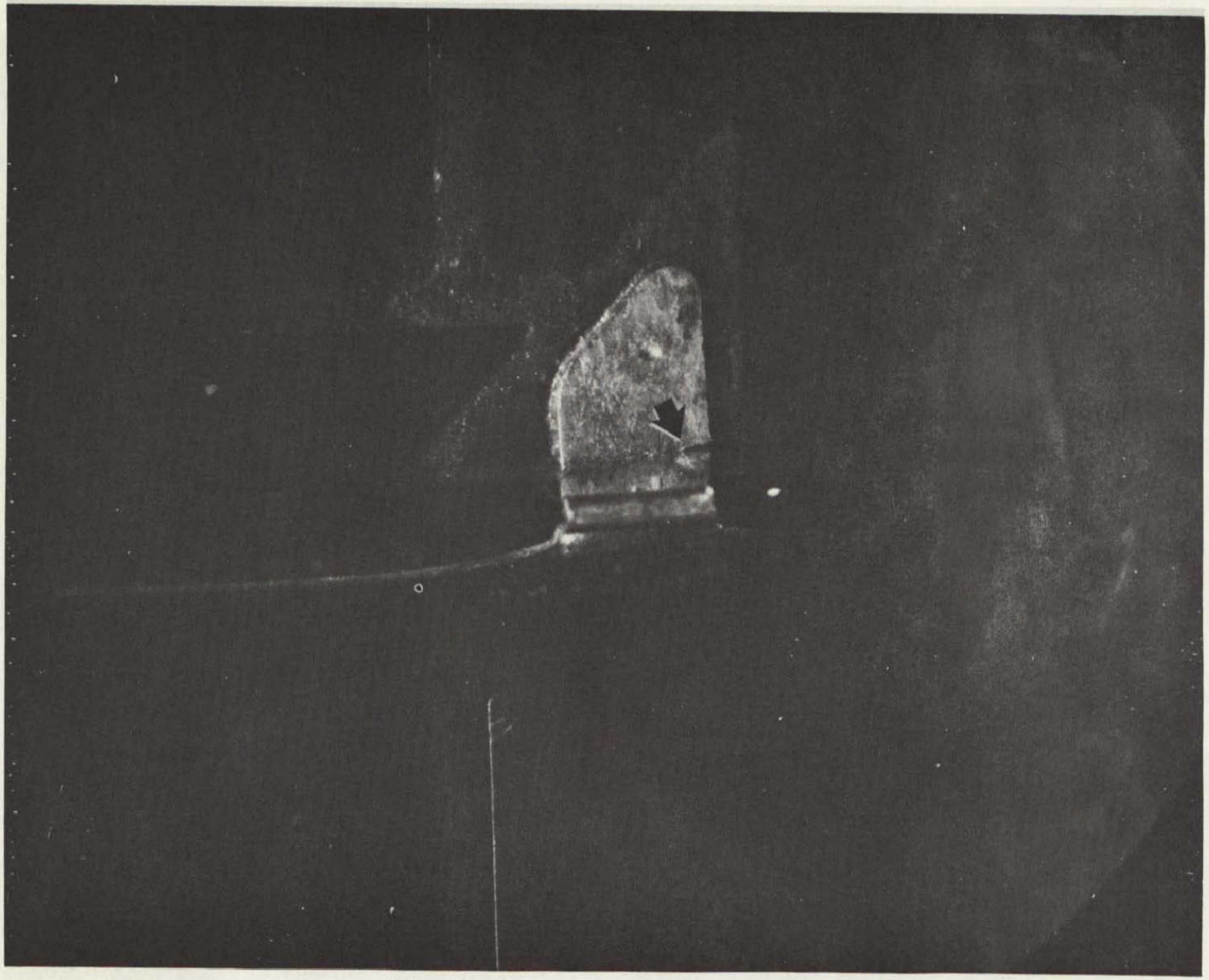


Figure 14. Crack in Type-d Tab After 100 Cycles

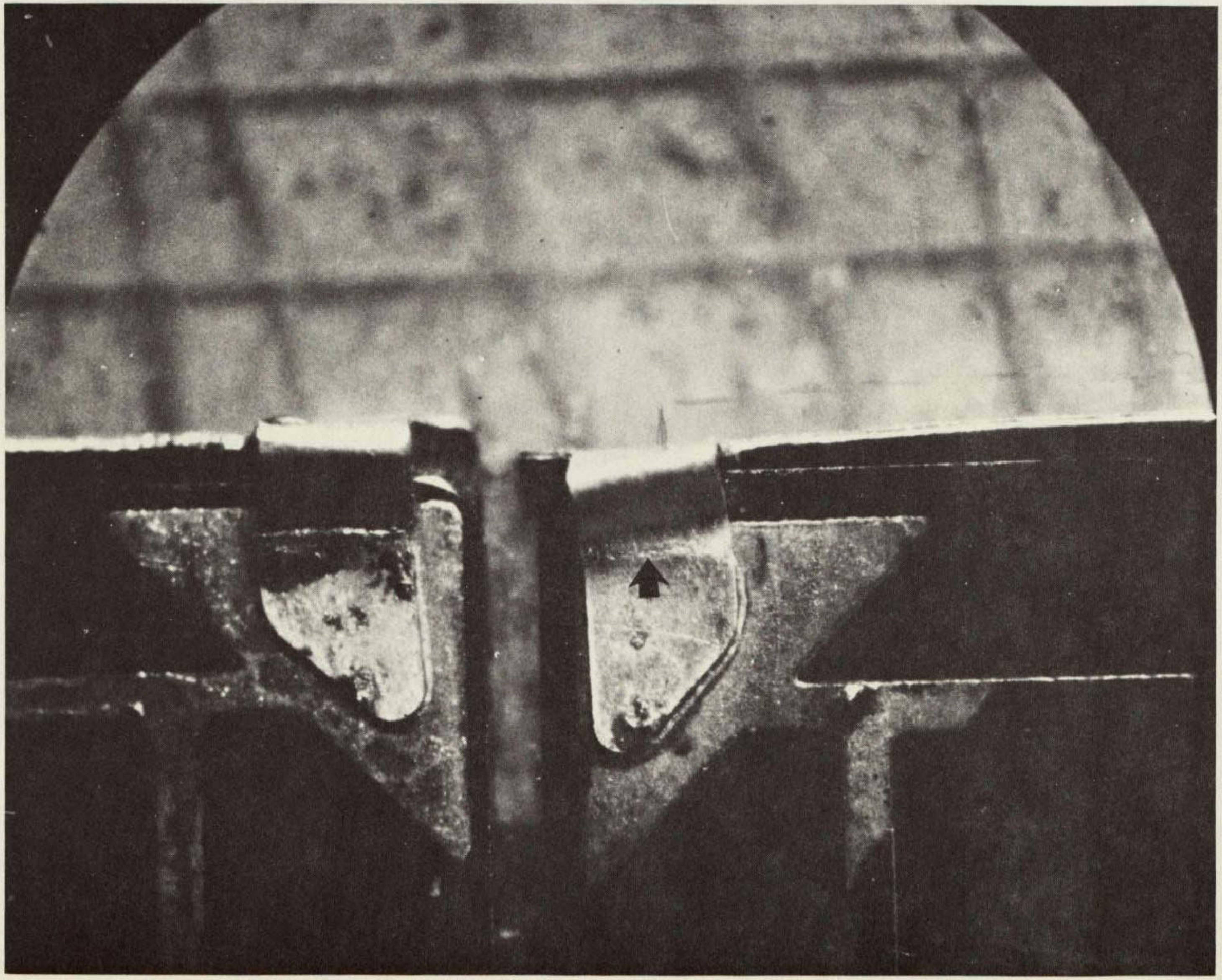


Figure 15. Crack in Type-h Tab After 100 Cycles

Inspection After 150 Cycles

Seven additional cracked tab defects were observed after 150 cycles. They are shown in Figures 16 through 22.

Figure 16 shows a second crack in a type-d interconnector tab. The first crack occurred after 100 cycles as shown in Figure 14. The second crack formed on the back of the interconnector away from the solder tab.

Figure 17 shows a type-e tab with a crack beginning at the bottom of the 90° bend. It is interesting that this crack did not occur at the crimped top where the crack would be expected.

Figure 18 is a type-h tab. A crack is beginning at the 90° bend adjacent to the solder joint.

Figure 19 also shows a crack forming in a type-h tab. This tab is directly below the tab in Figure 18. (See the final inspection sheet Figure 36.)

Figure 20 is again a cracked type-h tab. This tab is directly below the tabs in Figures 18 and 19.

Figure 21 is another type-h tab with a crack forming. This tab is at the opposite end of the same submodule with the defect shown in Figure 20.

Figure 22 is a type-b tab. The crack is beginning to separate at the crimped area at the top of the tab.

Inspection After 200 Cycles

Figures 23 through 26 show the four additional defects observed after 200 cycles.

Figure 23 is a type-b tab with a crack forming. Also shown in this photo is a crack in the adjacent tab which occurred after the 50 cycles test (Figure 10).

Figure 24 is another type-b tab with a small crack beginning.

Figure 25 is also a type-b tab with a crack forming.

Figure 26 shows a crack defect in a type-e tab. Again the crack is at the soldered part of the tab (similar to the one shown in Figure 17) and not at the crimped area as expected.

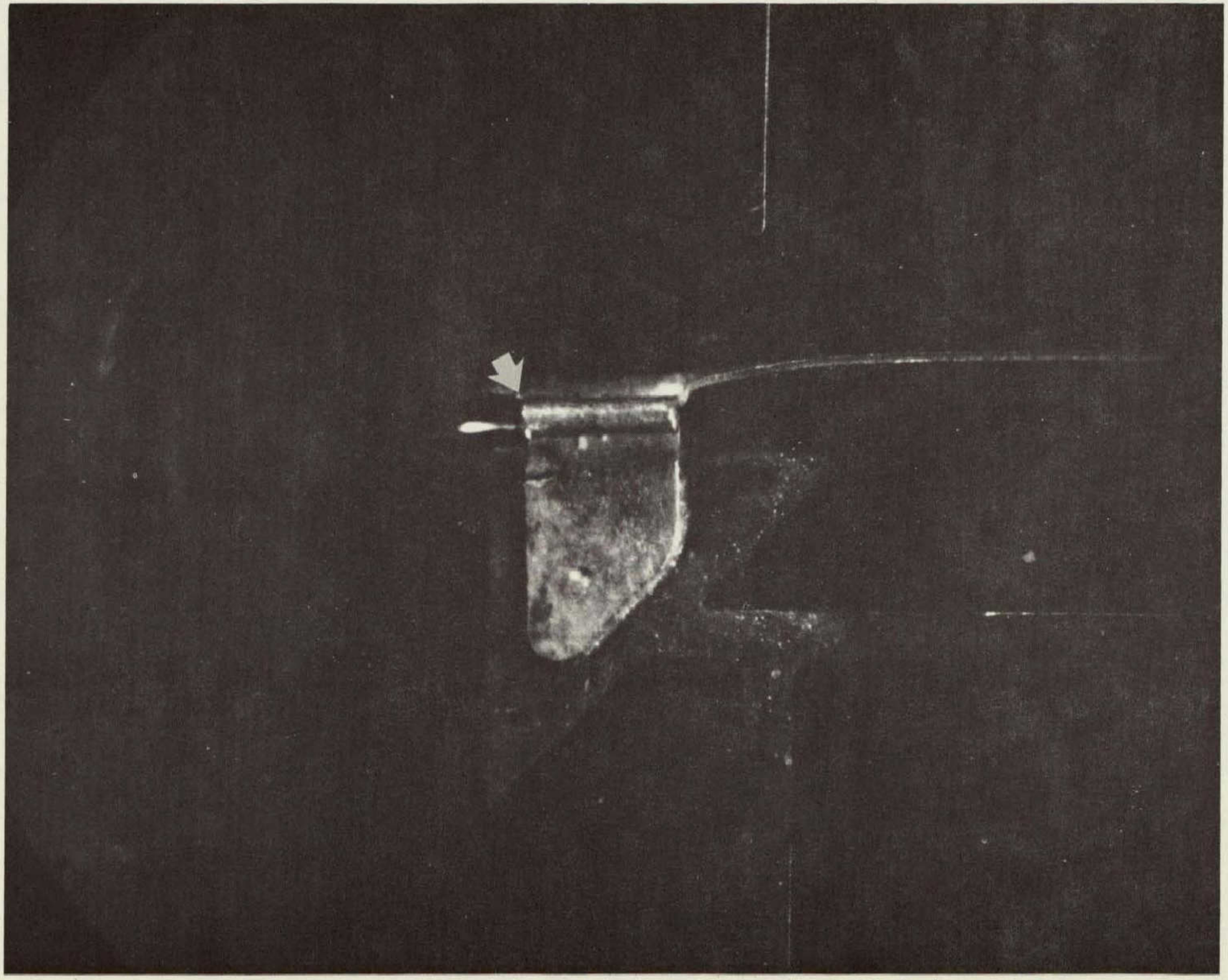


Figure 16. Second Crack in Type-d Tab After 150 Cycles

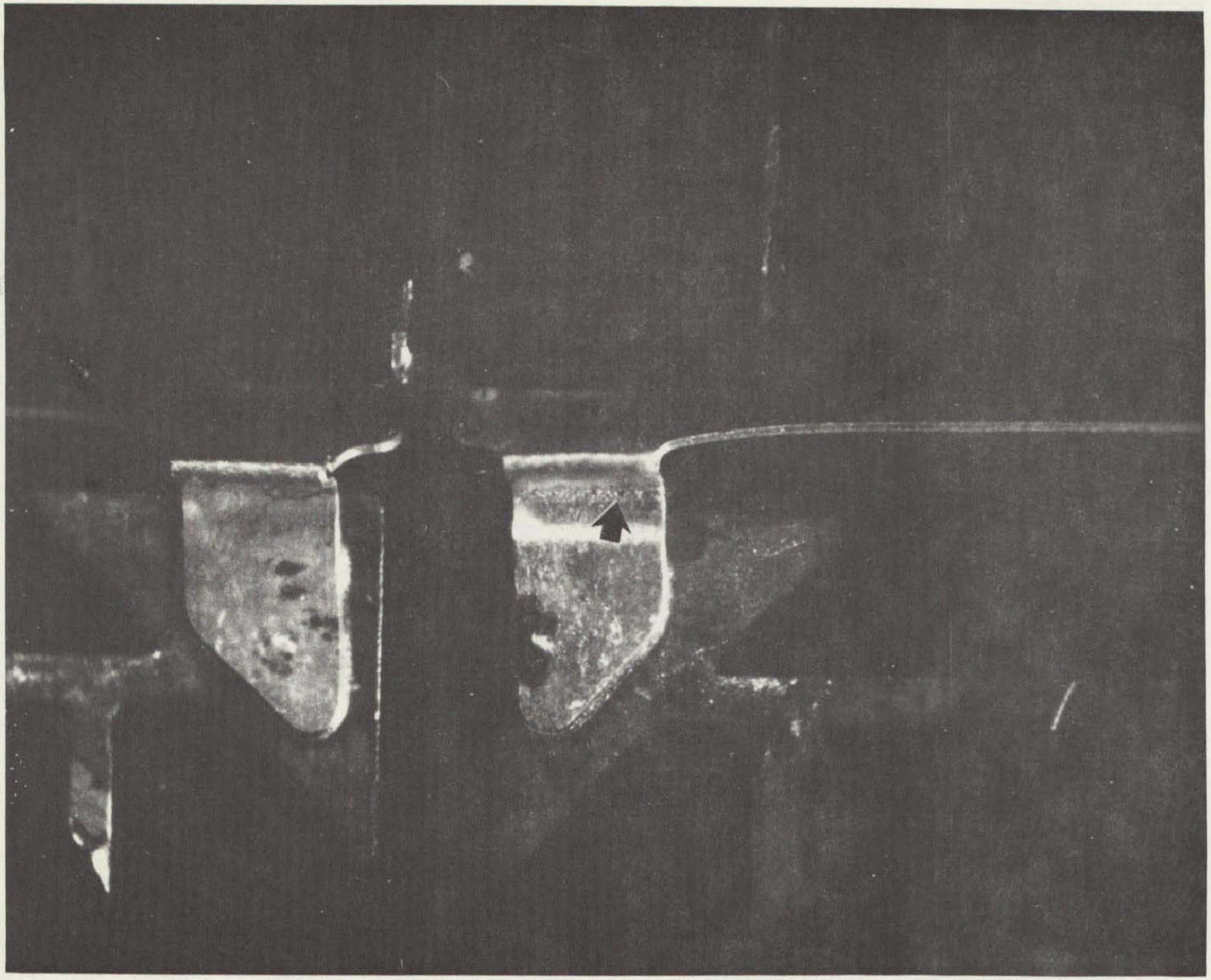


Figure 17. Crack Beginning in Type-e Tab After 150 Cycles

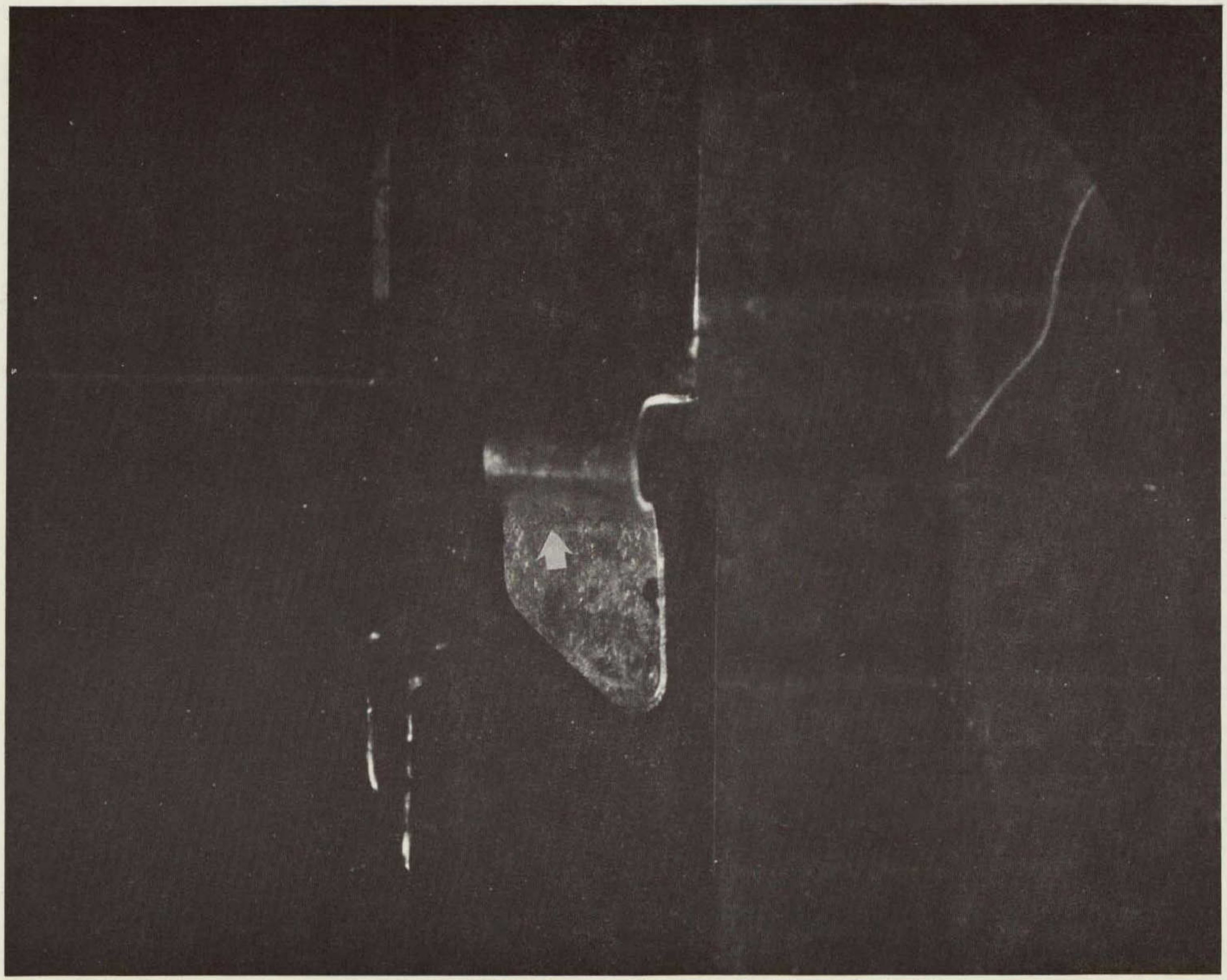


Figure 19. Crack Forming in Type-h Tab After 150 Cycles

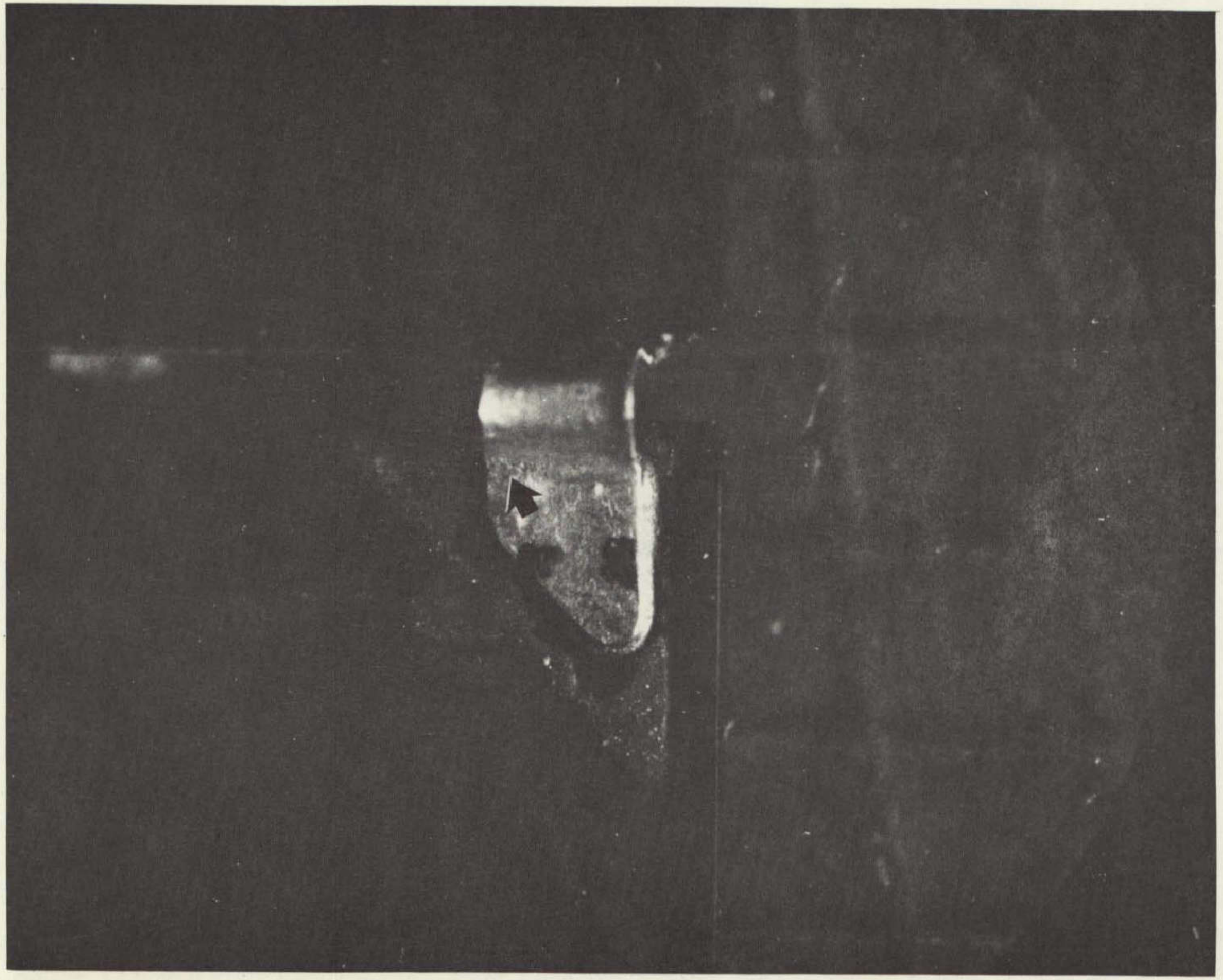


Figure 18. Crack Beginning in Type-h Tab After 150 Cycles

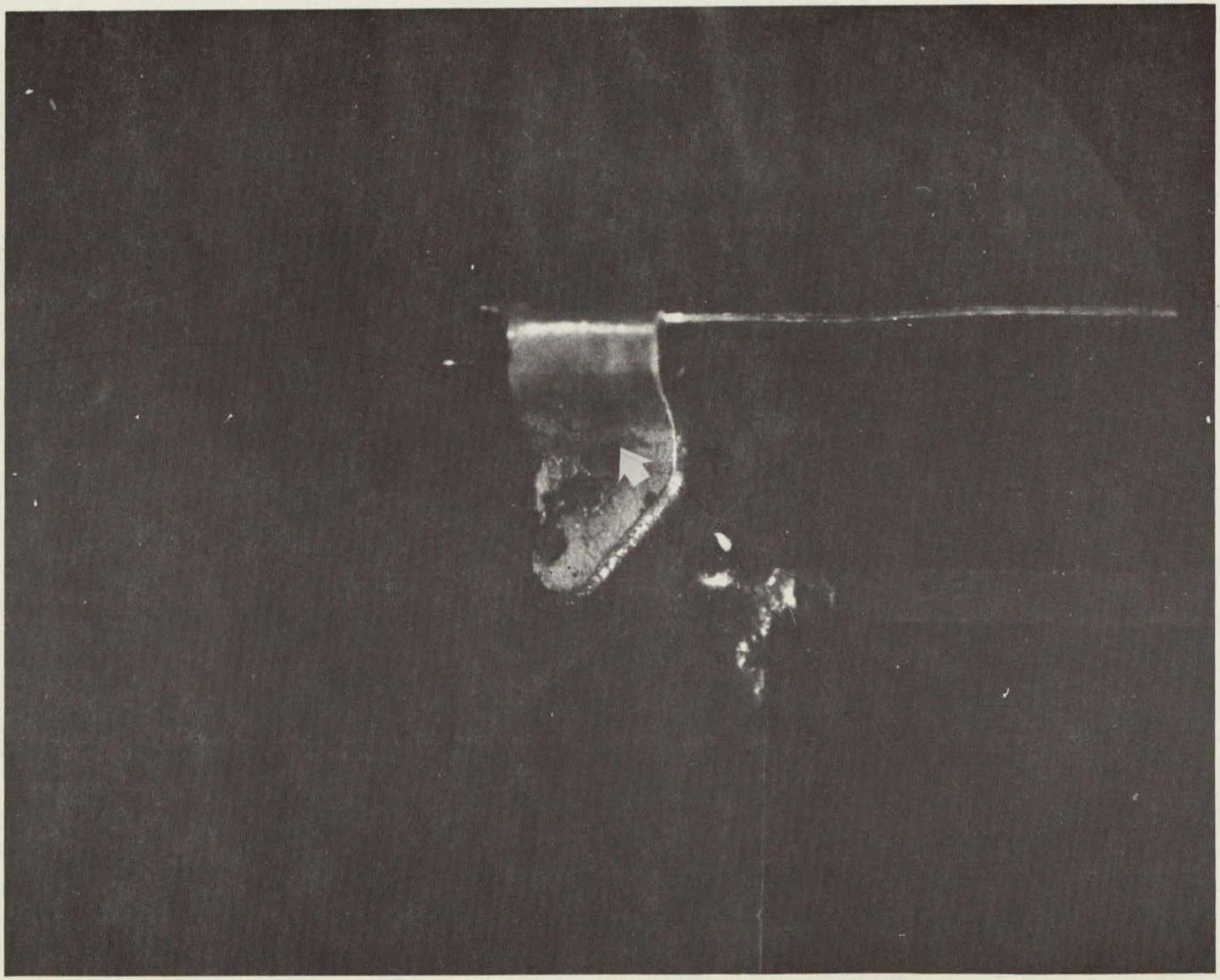


Figure 21. Crack Forming in Type-h Tab After 150 Cycles

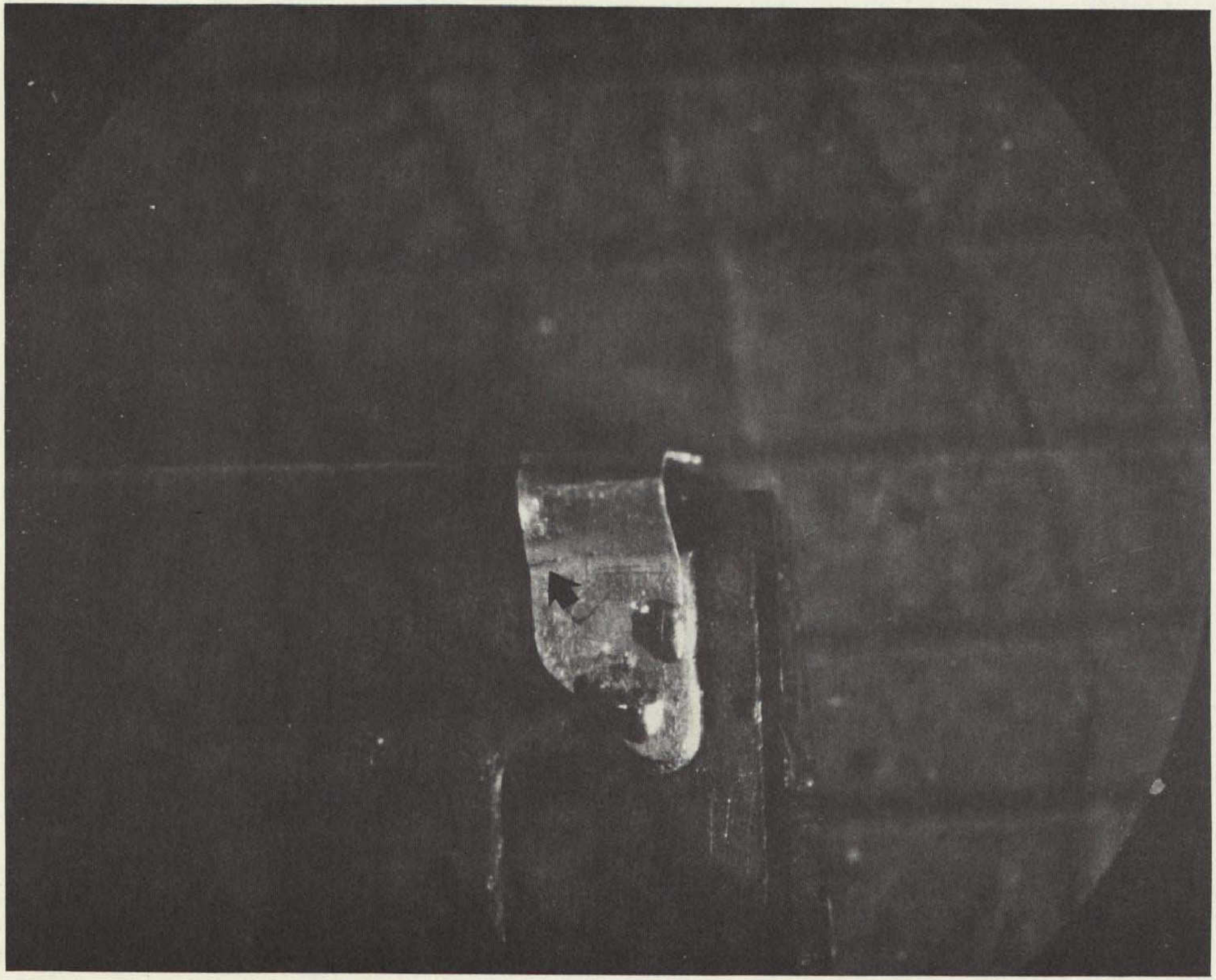


Figure 20. Cracked Type-h Tab After 150 Cycles

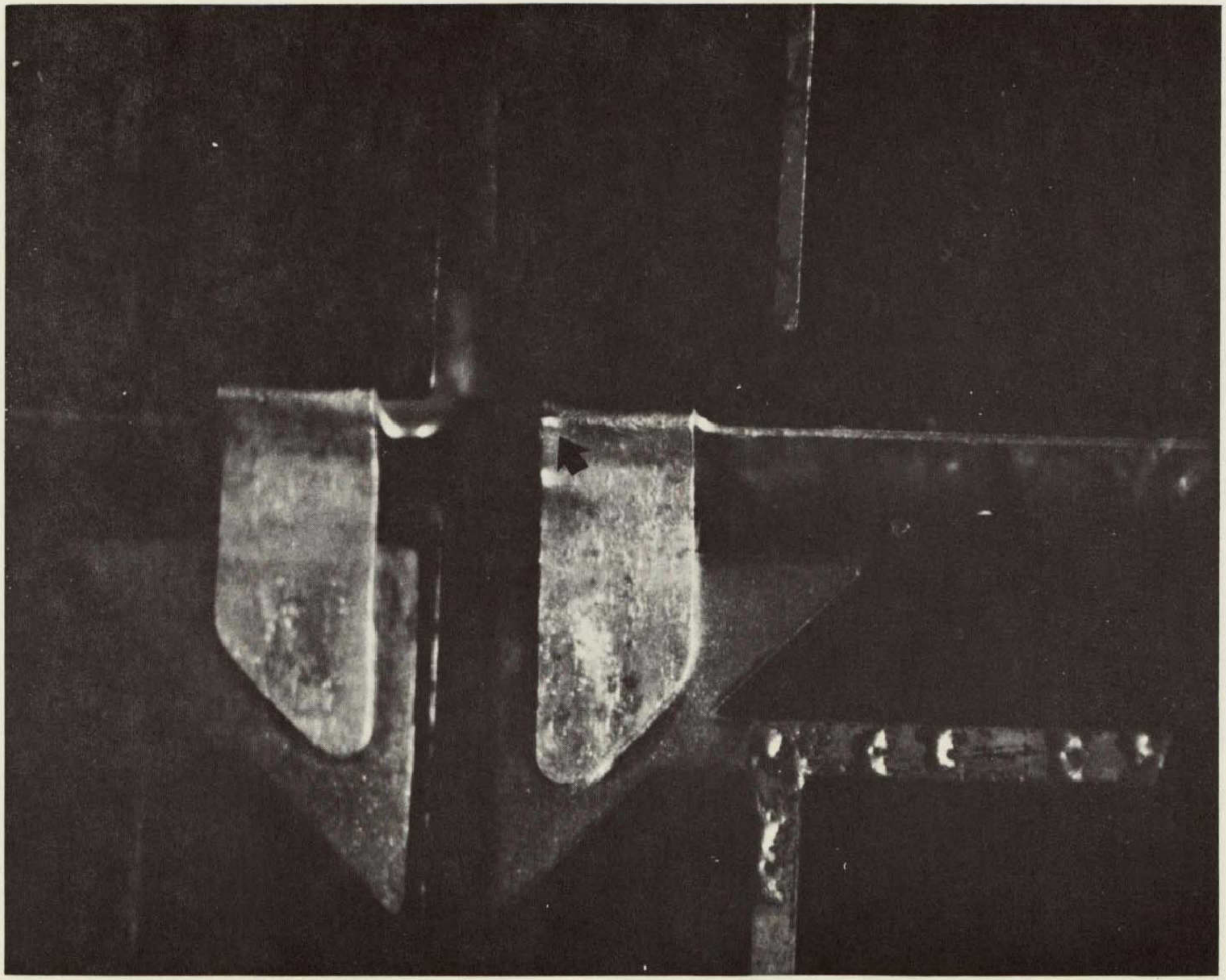


Figure 22. Crack in Type-b Tab After 150 Cycles

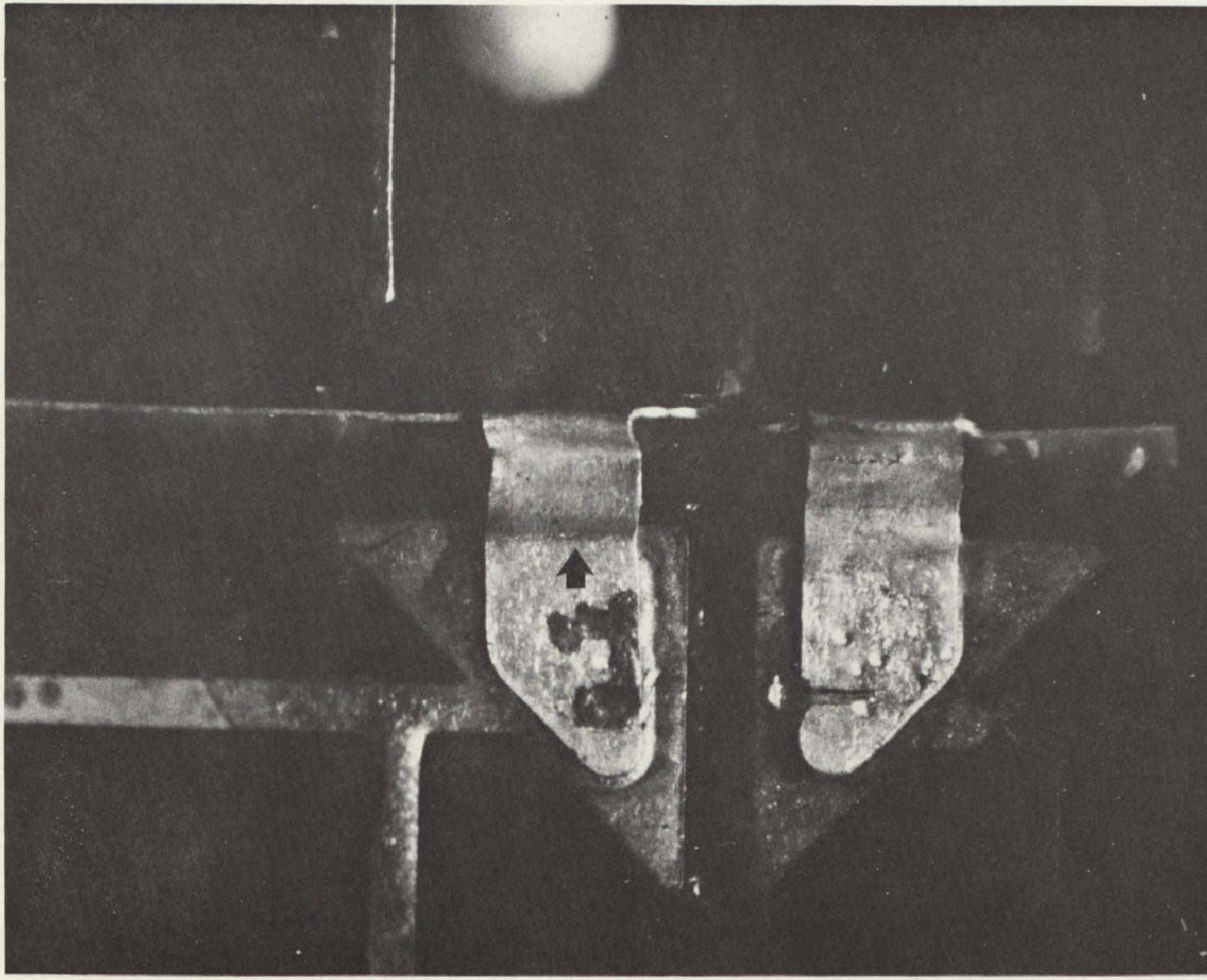


Figure 23. Crack Forming in Type-b Tab After 200 Cycles

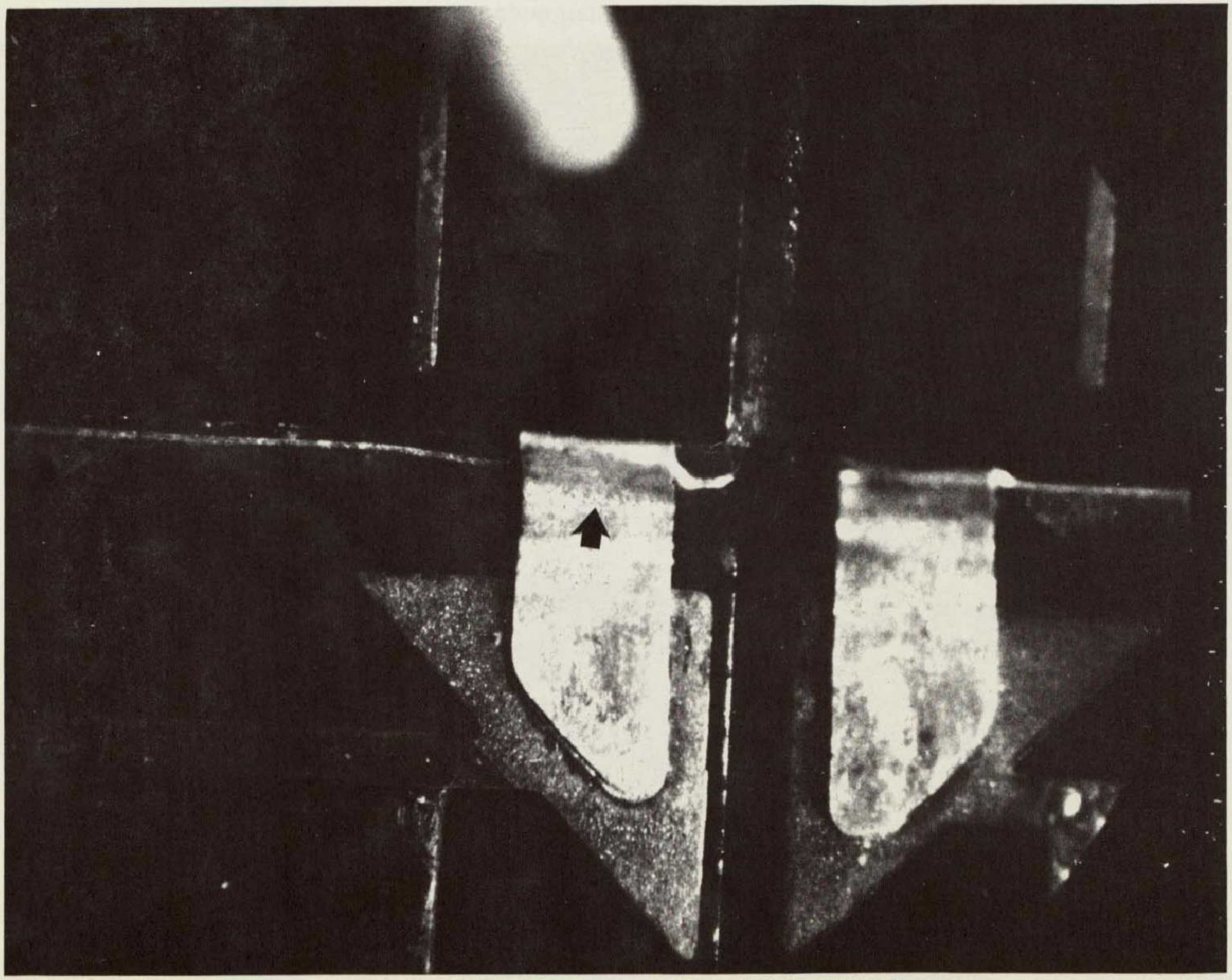


Figure 25. Crack Forming in Type-b Tab After 200 Cycles

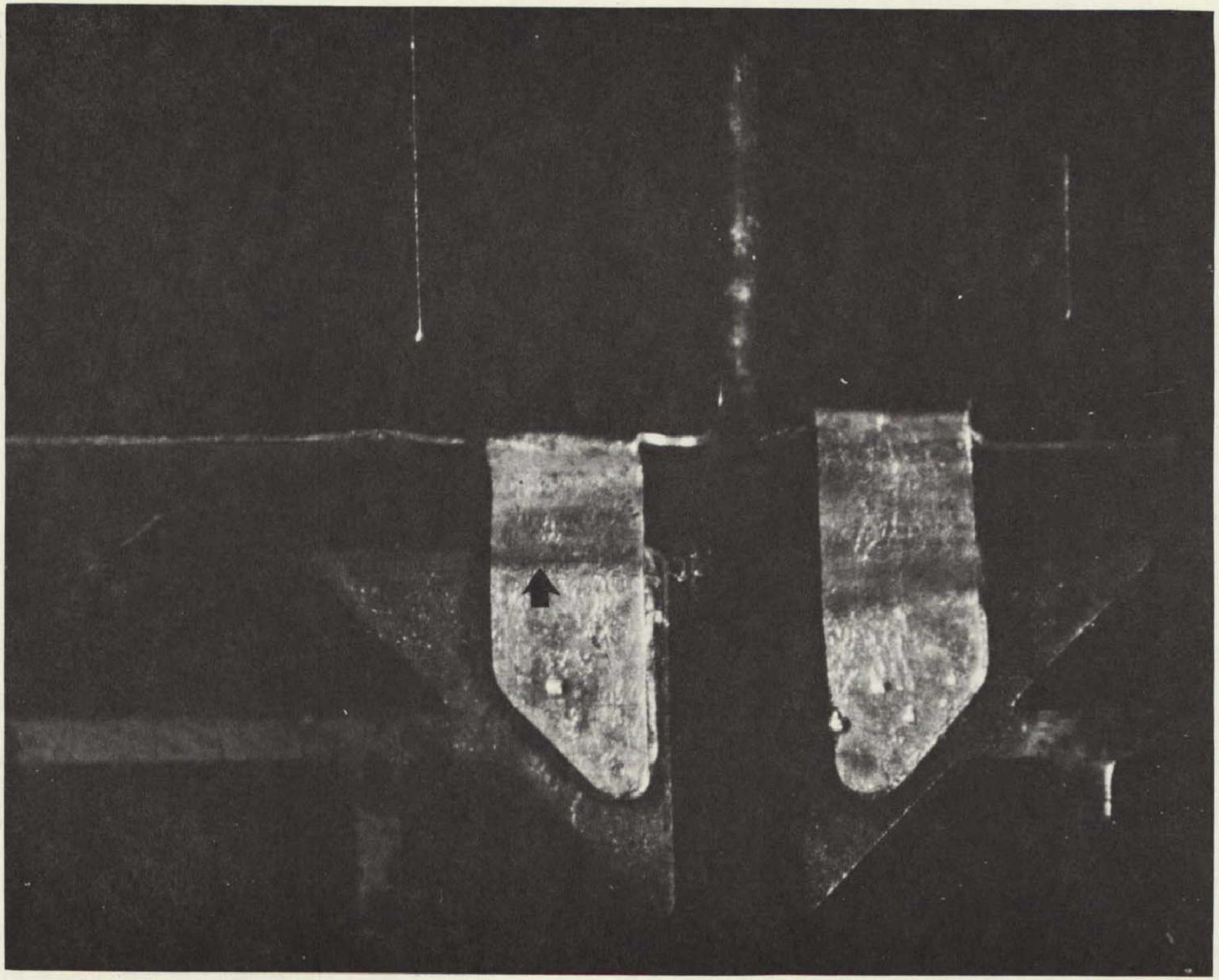


Figure 24. Crack Beginning in Type-b Tab After 200 Cycles

Inspection After 300 Cycles

Defective and failed tabs observed after 300 cycles are shown in Figures 27 through 35. These nine defects consist of six tabs previously cracked which failed open, one failed solder contact, and two new cracked tabs.

Figure 27 is a type-f tab. The solder contact failed in this case as in the case of the type-f tab at 100 cycles.

Figure 28 shows a new cracked type-a tab.

Figure 29 shows a type-b tab. This tab has now become completely open. It showed as a defective crack after 200 cycles (Figure 23).

Figure 30 shows a new defect in a type-b tab. The tab is cracked.

Figure 31 is another type-b tab that became completely open. The interconnector was found to be cracked after the 200 cycle test (Figure 25).

Figure 32 is a type-e tab that opened. It was noted as being cracked after 150 cycles.

Figures 33, 34 and 35 are all type-h tabs each of these tabs were found to be cracked after 150 cycles. Now all three have become open.

SUMMATION AND DISCUSSION

The progression defects noted at each interval of testing is given in Table I and in Figure 36. The location of the various defects is summarized in Table II. Two types of failures were observed. In the one case the tab cracked and later failed completely; in the other the solder joint to the cell failed. Twenty cracked tabs and two failed solder joints were observed.

One cracked tab was noted on the initial inspection. Since it was a type-h (normal) tab, it is probably a result of a fault in fabrication such as a faulty shaping tool. In addition, nineteen of the eighty two tabs cracked during one phase or another of the testing. Of this total of twenty cracked tabs, thirteen cracked adjacent to the solder junction on the cell. Seven of these were type-h (normal) tabs. The six remaining tabs were: two type-b, one type-c, two type-d, and one type-e. (When such cracks occur on type-a tabs they are difficult to observe because the tab configuration obscures this area from inspection.) This bend is clearly a weak point in the normal interconnection and could be aggravated by the cold working in bending the tabs to the desired configuration.

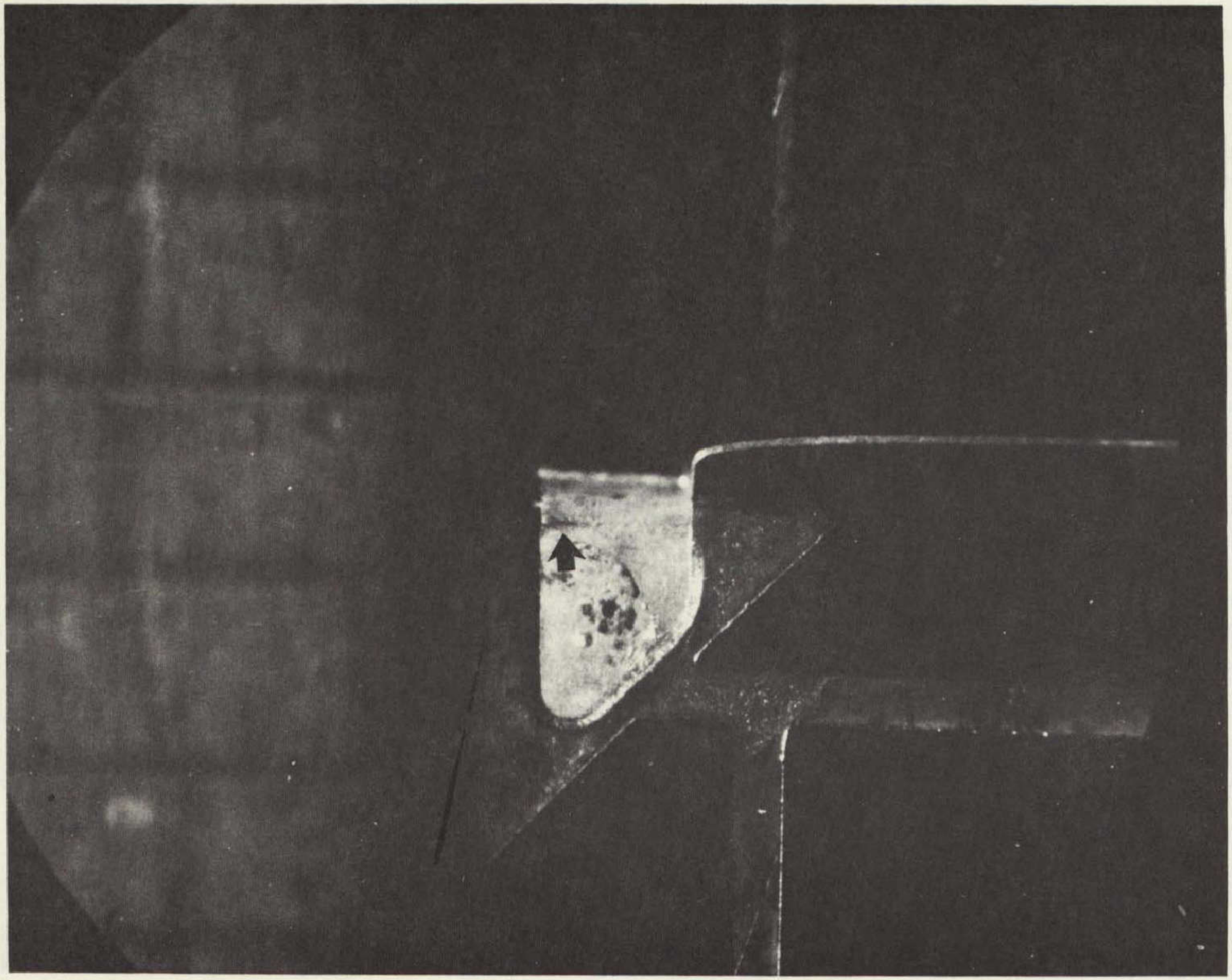


Figure 26. Crack in Type-e Tab After 200 Cycles

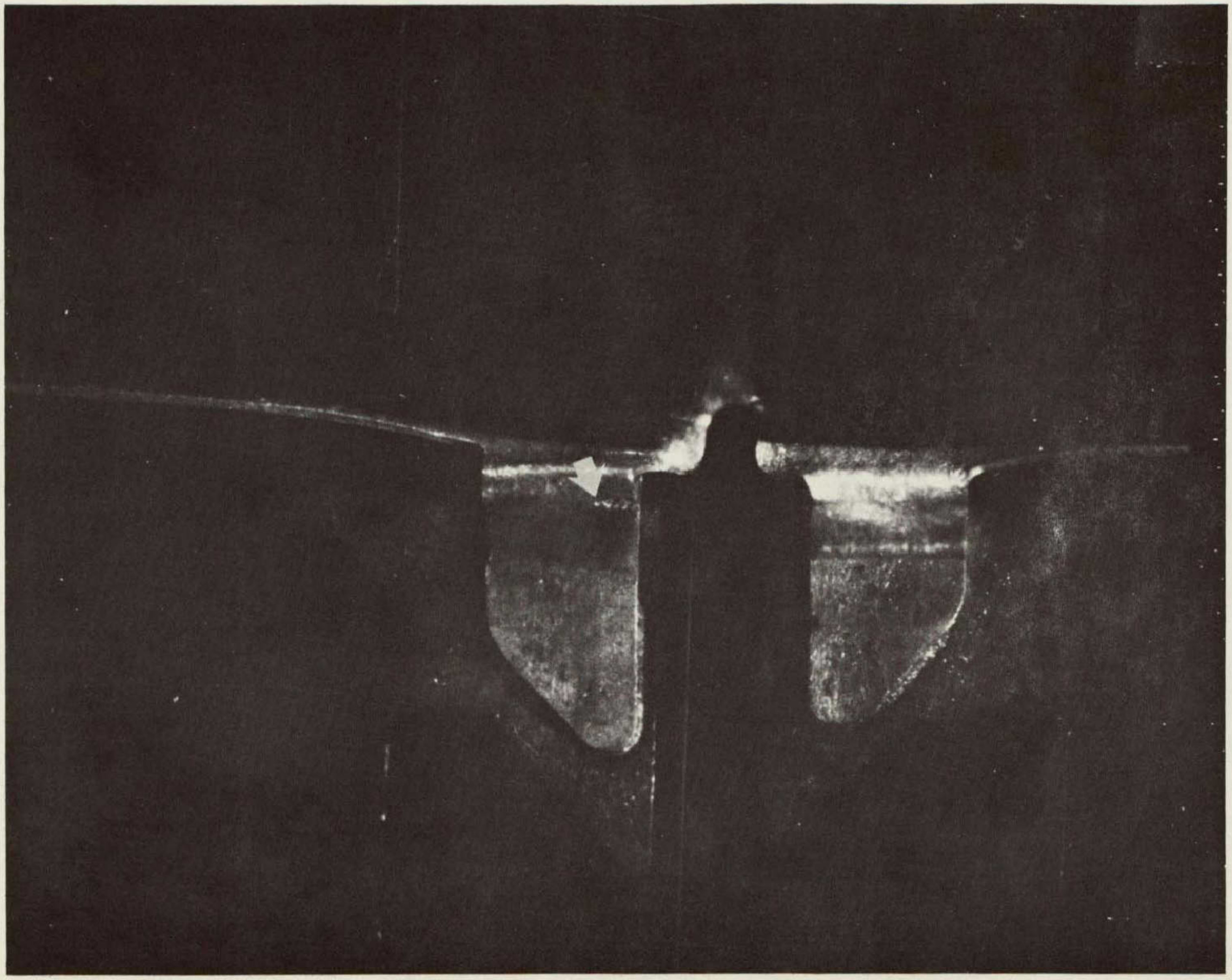


Figure 28. Crack in Type-a Tab After 300 Cycles

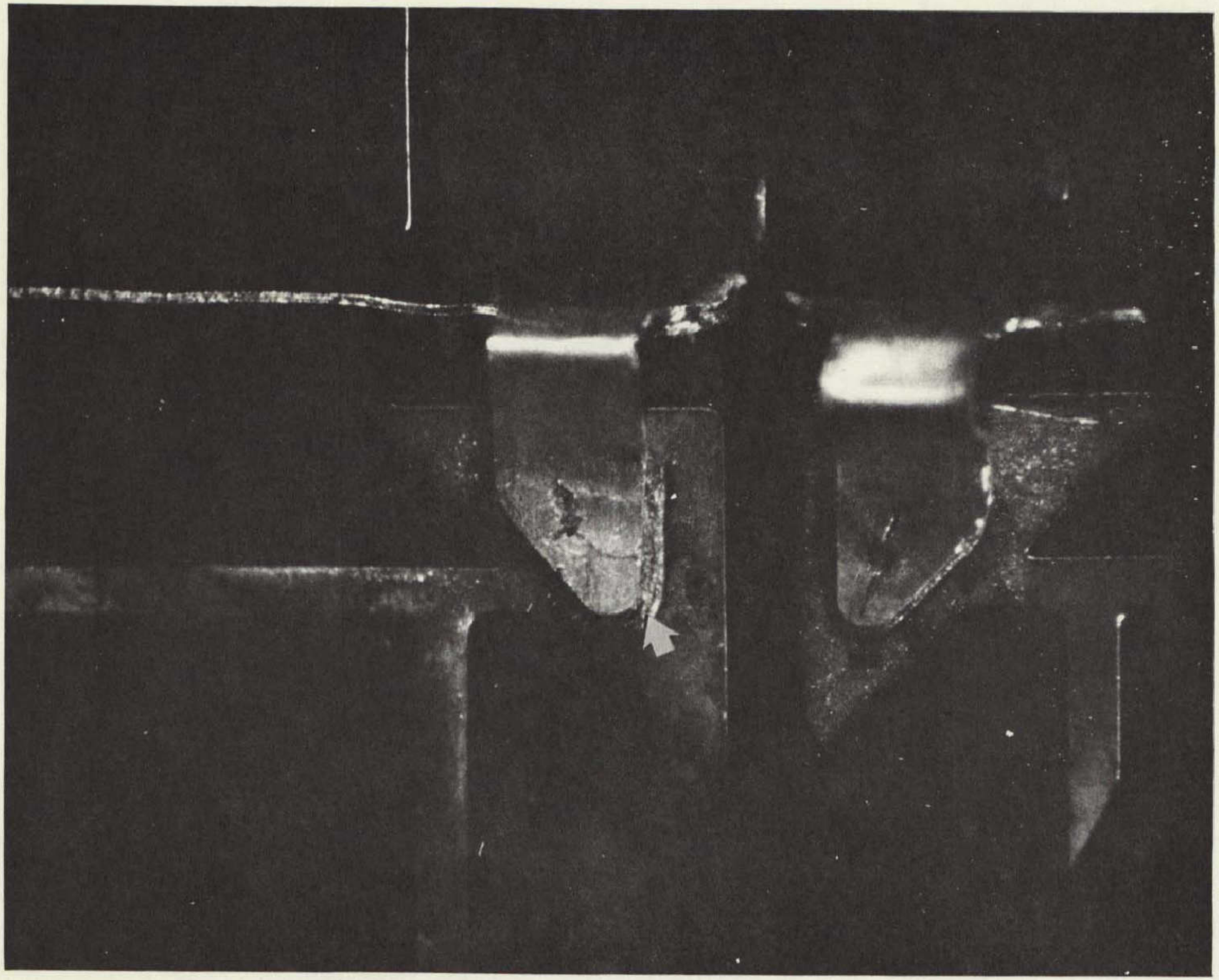


Figure 27. Solder Contact Failure in Type-f Tab After 300 Cycles

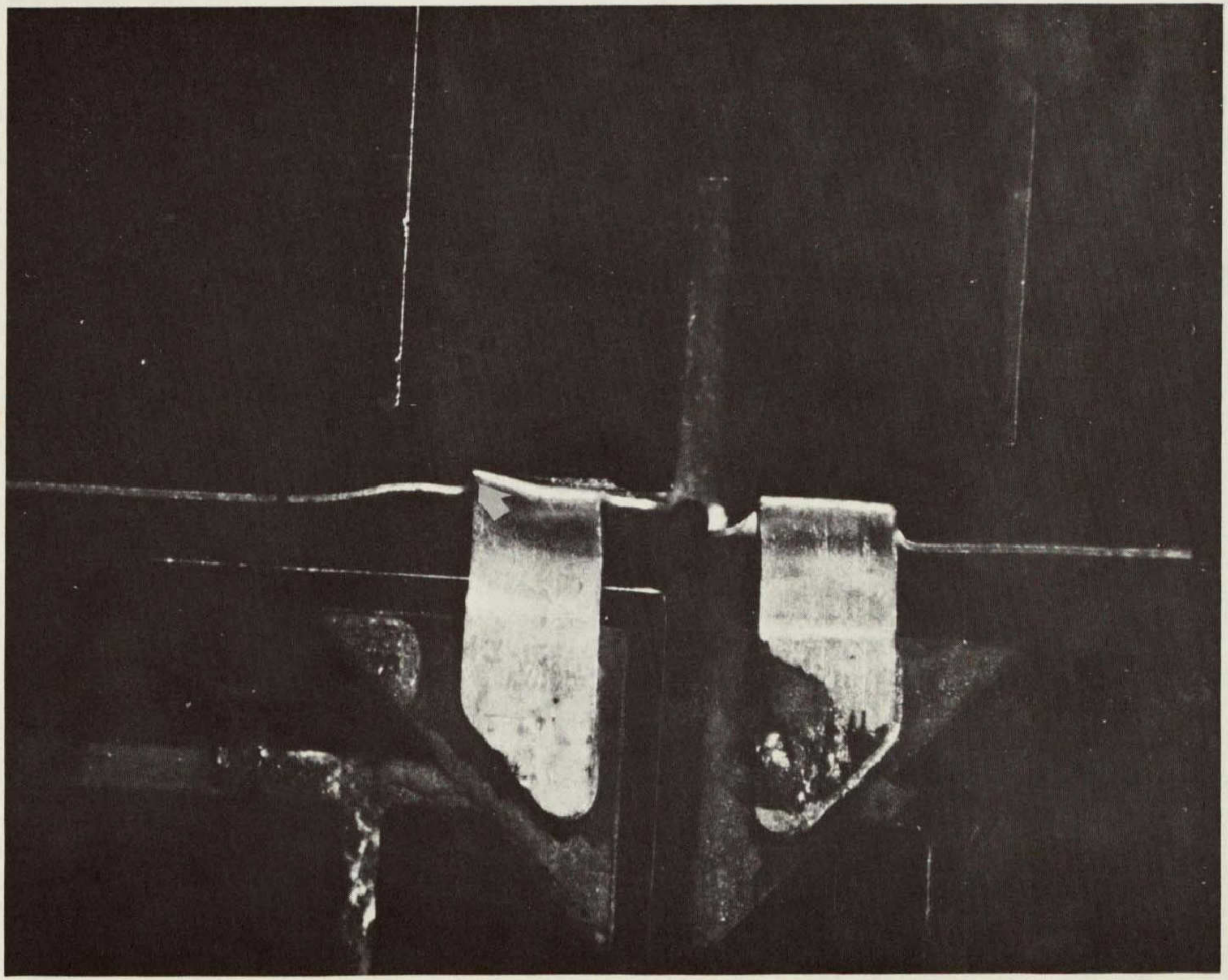


Figure 30. Cracked Type-b Tab After 300 Cycles

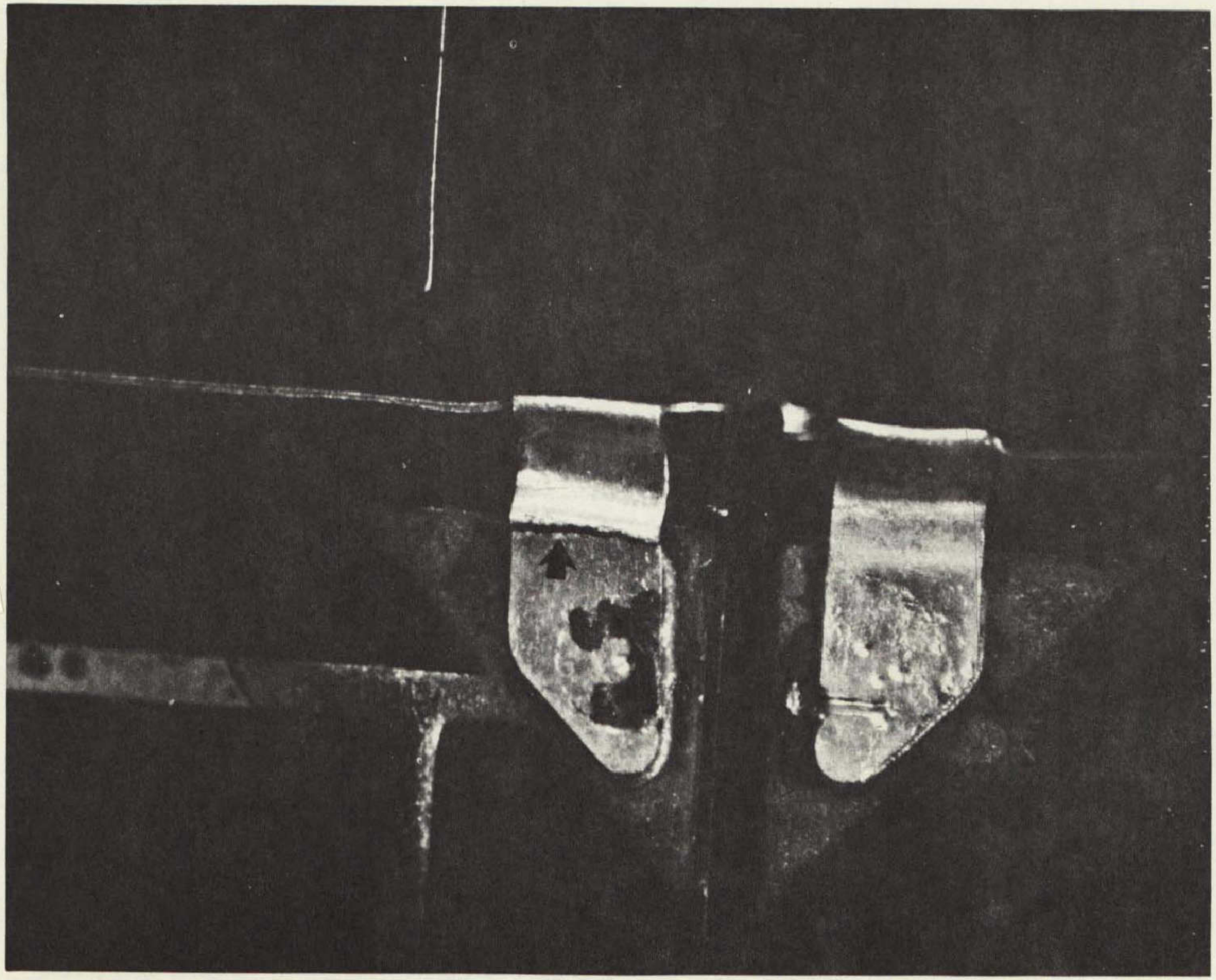


Figure 29. Open Type-b Tab After 300 Cycles

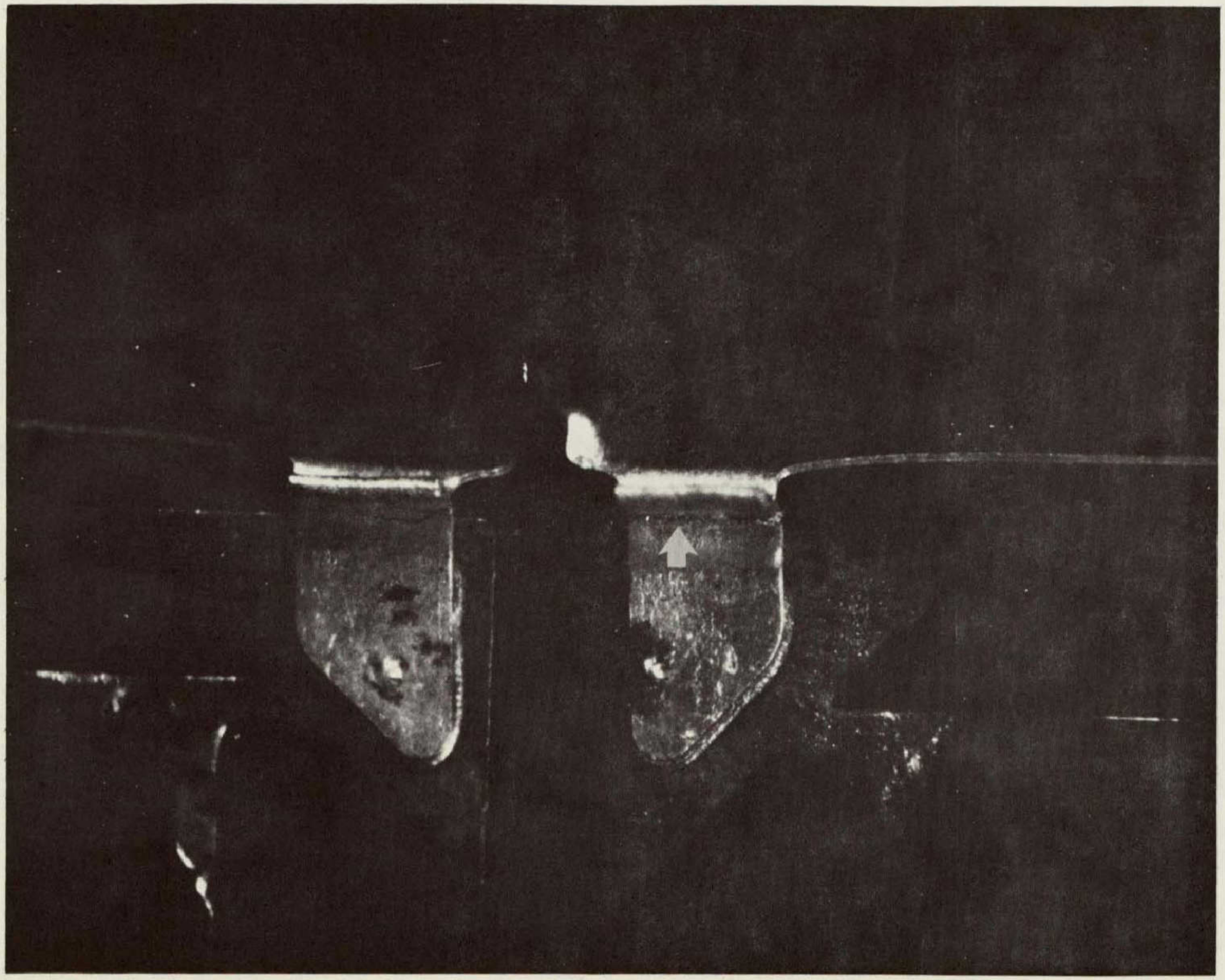


Figure 32. Open Type-e Tab After 300 Cycles

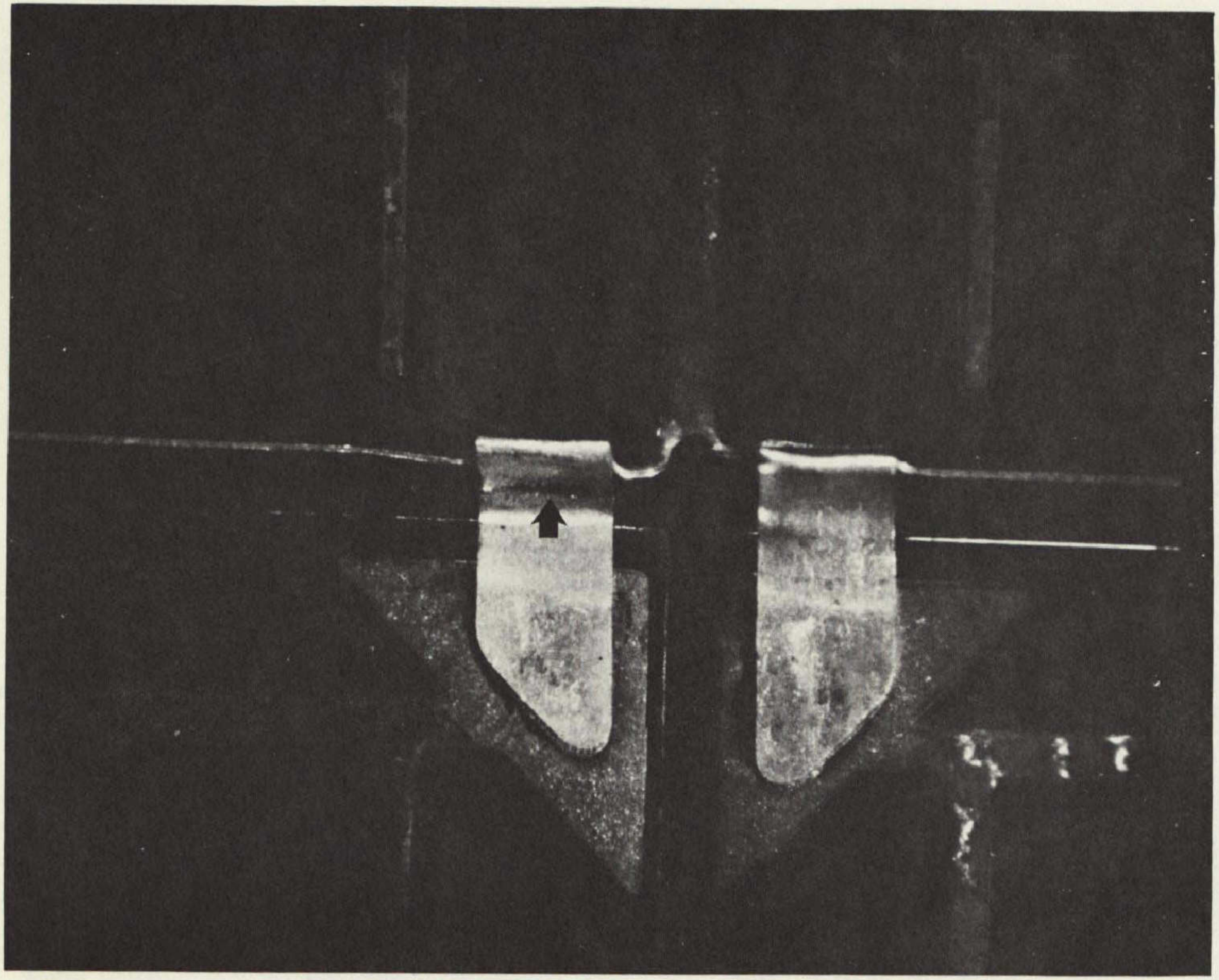


Figure 31. Open Type-b Tab After 300 Cycles

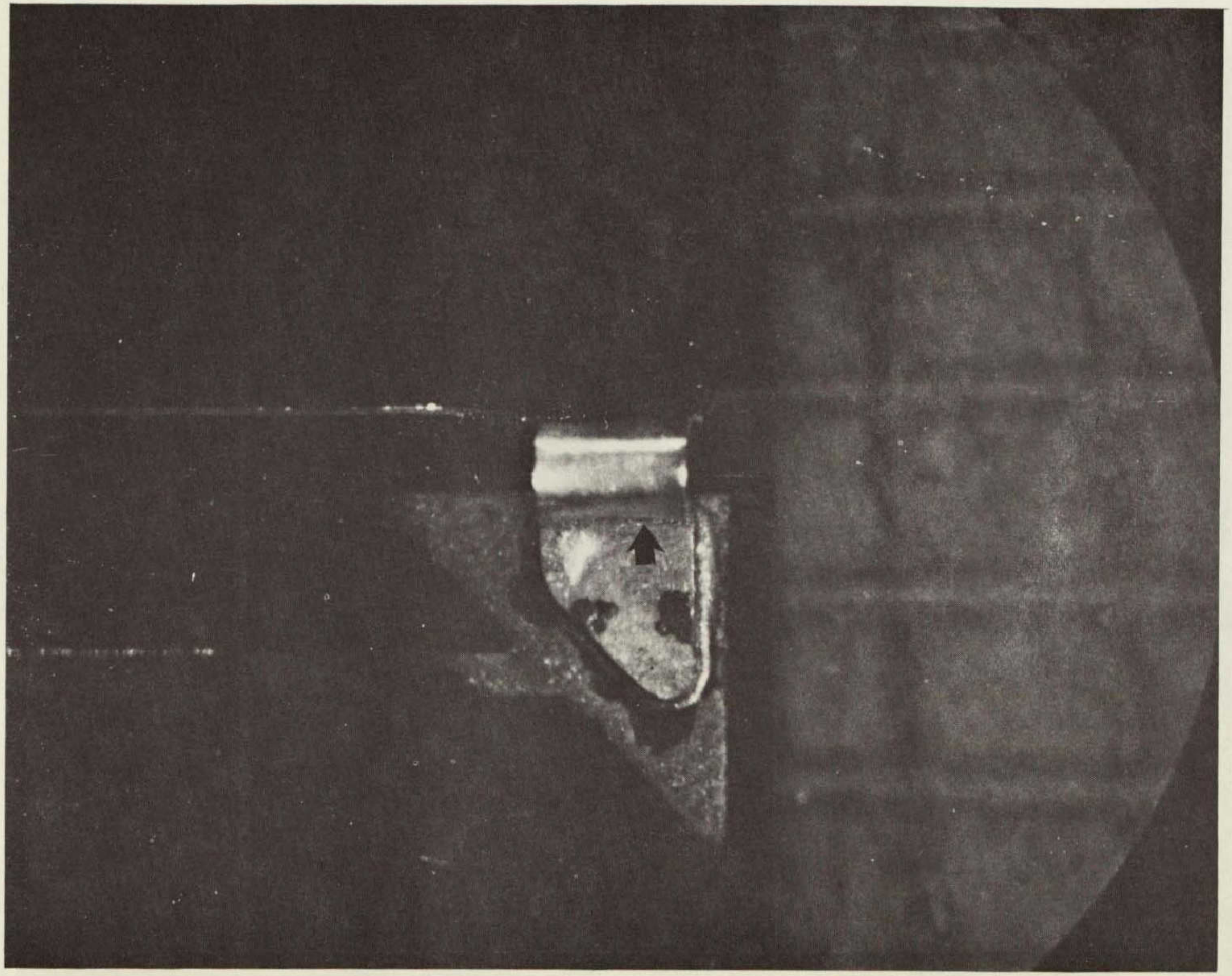


Figure 33. Open Type-h Tab After 300 Cycles

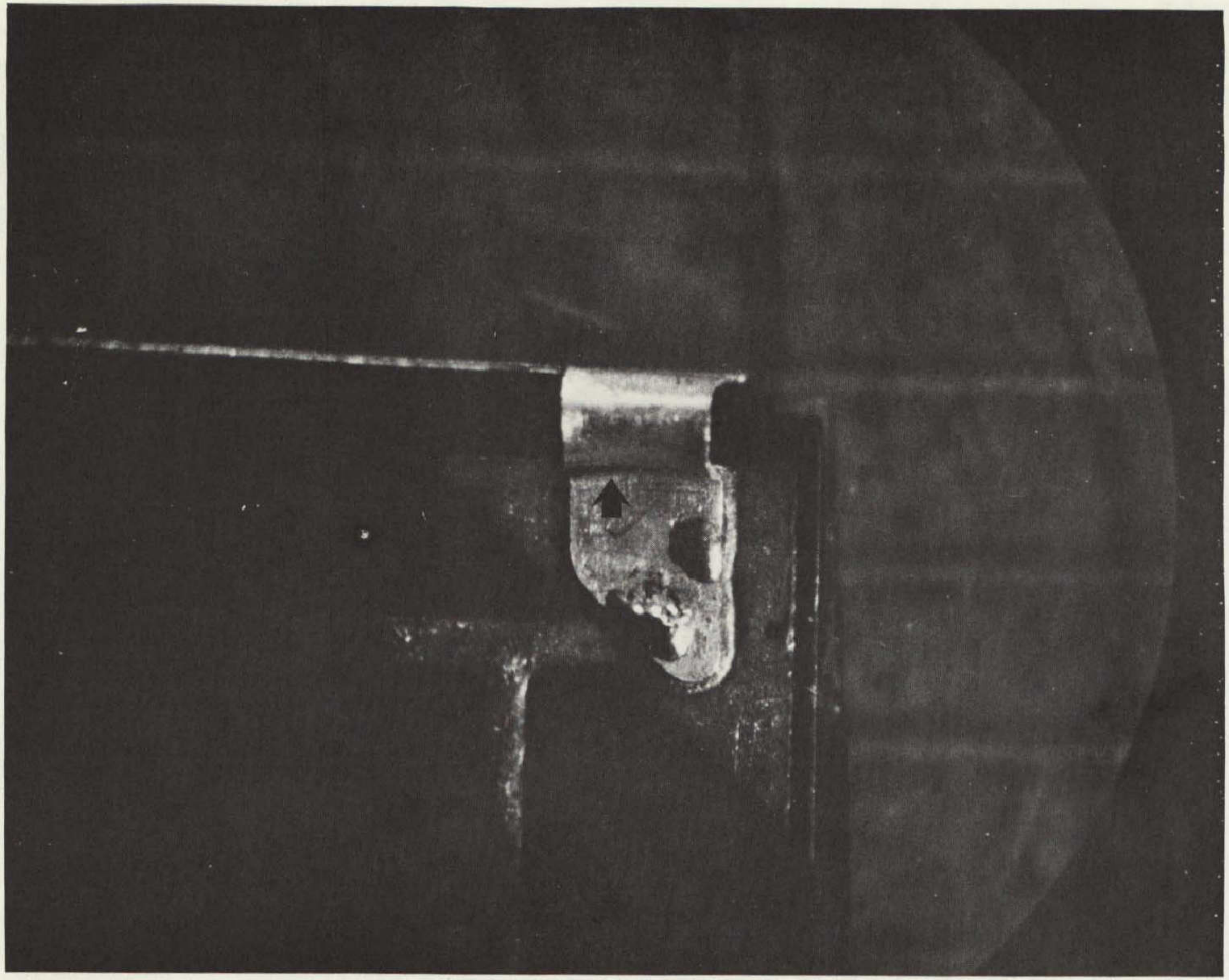


Figure 34. Open Type-h Tab After 300 Cycles

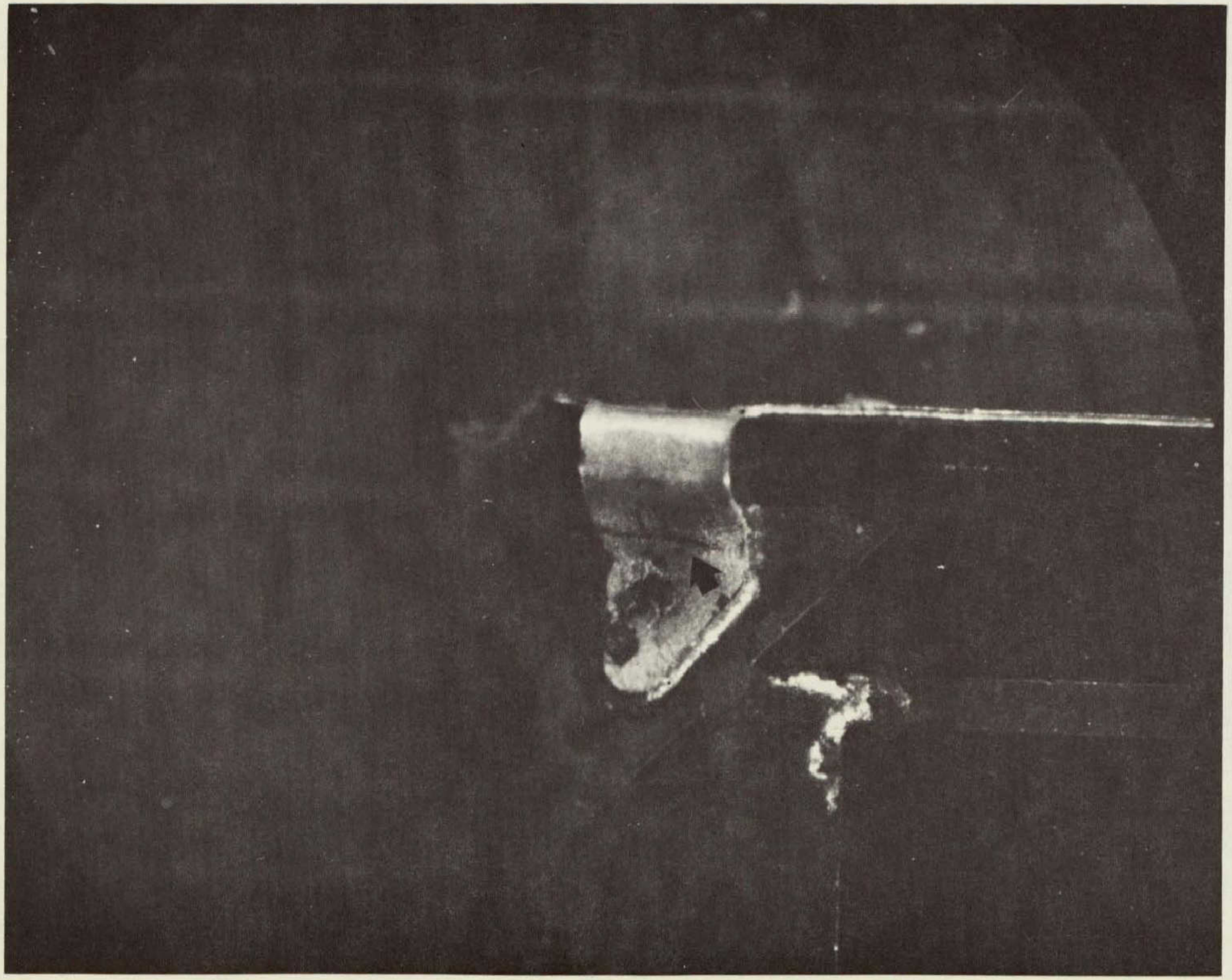
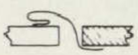
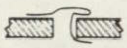
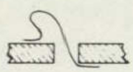
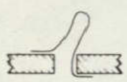
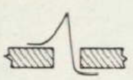
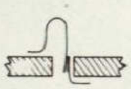
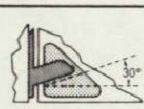
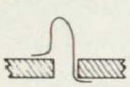


Figure 35. Open Type-h Tab After 300 Cycles

Table I
Progression of Defects and Failures

Type	Tab, Configuration	Total* Tabs	Total Accumulated Defective Tabs					
			Initial	After 50 Cycles	After 100 Cycles	After 150 Cycles	After 200 Cycles	After 300 Cycles
a		10	0	1	1	1	1	2
b		10	0	1	1	2	5	$6^{(2)}$
c		6	0	0	1	1	1	1
d		5	0	1	2	$2^{(X)}$	$2^{(X)}$	$2^{(X)}$
e		10	0	0	0	1	2	$2^{(1)}$
f		6	0	0	$1^{(s)}$	$1^{(s)}$	$1^{(s)}$	$2^{(s)}$
g		6	0	0	0	0	0	0
h		29	1	$2^{(1)}$	$3^{(1)}$	$7^{(1)}$	$7^{(1)}$	$7^{(4)}$
	Total Tabs	82						
	Total Defects		1	5	9	15	19	22
	Total Failures			1	2	2	2	9

*Includes tabs not bent as intended. Does not include bent type-f tabs.

(1) One of the defective tabs has failed completely open.
(2) Two of the defective tabs have failed completely open.
(4) Four of the defective tabs have failed completely open.
(s) Failures on type-f tabs were solder joint failures.
(X) One defective tab has cracks in two places.

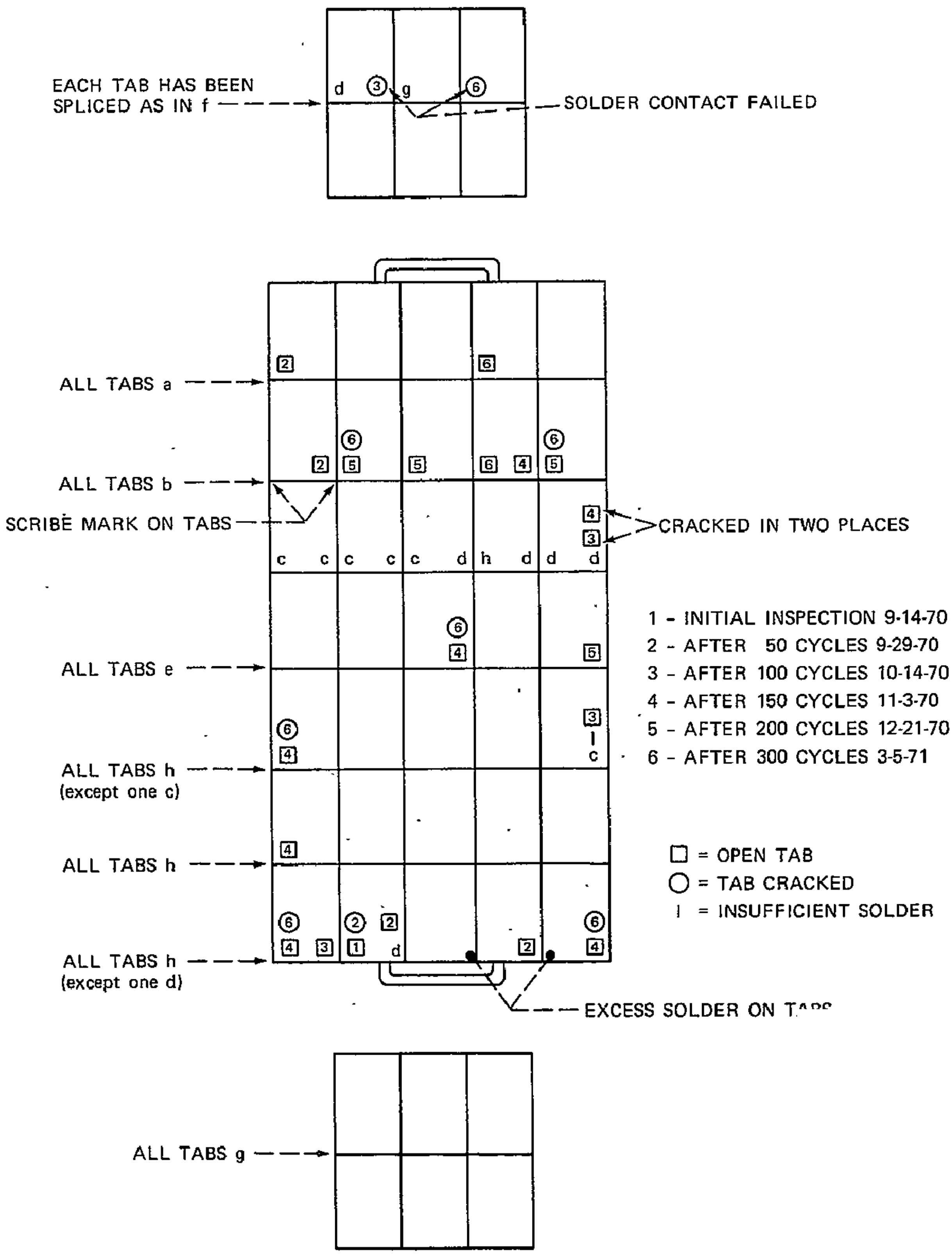


Figure 36. Final Inspection Results

Table II
Defect Locations

Tab Type	Cracked Tabs			Solder Failures	Total Number of Defects
	At Bend At Solder Joint	At Crimp or Severe Bend	At Base of Crimp or Severe Bend	At Solder Joint	
a		2			2
b	2	2	2		6
c	1				1
d	2				2
e	1		1		2
f				2	2
g					0
h	7				7
Total	13	4	3	2	22

Six of the cracked tabs were reverse bent type-b tabs. As described above, two of these were cracked at the bend at the solder joint. The crack on two other tabs was located away from the cell at the lower end of the reverse bend, an area possibly weakened during the reshaping of the tab. The remaining two were at the extreme back crimp where high strain is expected. Both of the cracked a-type tabs with an extreme forward bend had cracks located at the high strain area at the extreme forward crimp.

The last cracked tab was a type-e tab which cracked at a location away from the cell at the lower end of the crimp. This location is similar to two of the cracks on the type-b tabs where reforming the tab could have weakened it.

Seven of the cracked interconnections proved to be catastrophic failures resulting in an open contact. Since these occurred within the 300 cycle test, it the cycling. It may be conjectured that working of the tab to produce the bend resulted in weakening of the tab and that where "excess solder" was used it gave some slight reinforcement to the weakened area and distributed the stresses produced by the cycling. The buildup of stress on the peripheral tabs has been previously noted on modules prepared for ATM (Apollo Telescope Mount) (Reference 8). In any case these failures will lead to catastrophic electrical failure of the cell group. As shown in Figure 36, 6 out of 10 of the tabs at the end of the cell group have defects and 3 of these have failed open in 300 cycles.

ADDITIONAL DATA

It should be noted that subsequent to the testing of this module, an entire OAO paddle was thermal vacuum cycled for 278 cycles. A complete inspection of this paddle showed many tab defects. Of a total of 9,812 tabs, 382 (3.9%) were found open at the solder joint (solder failure) and 25 (0.25%) were cracked (Reference 9). This result was significantly different from the results for the test module. The percentage of defects was significantly reduced and the common defect mode, solder failure as opposed to cracked tabs, was quite different. This result indicates that the testing in air (the module) led to serious differences compared to testing in a vacuum (the paddle). This final set of data indicates that the module test results are not valid for assessment of the OAO solar paddles.

CONCLUSIONS

1. The results of the thermal cycle testing of the OAO sample module lead to the following conclusions:

   a. The 300 cycles of testing is more than adequate to provide necessary data on the types of defects observed. Continued testing would not likely produce new information regarding these defects.

   b. Defect and failure rates even for the normal tab configuration are unacceptably high.

   c. Slight bending of the tabs did not lead to significant changes in the defect rate, however, severe bending, especially in the reverse direction, resulted in a significant increase in the defect development rate.

   d. The spliced tab configuration led to solder joint failure. This problem would not be eliminated even if the interconnector problems are removed, so it is considered to be an undesirable repair method.

is reasonable to assume that the remaining cracked tabs would fail if testing continued. In view of the progression of defects (Table I) it is equally reasonable to assume that new cracks and failures would also occur with continued cycling.

The other failures were in two of the f-type tabs where the solder contact failed. The tab lifted from the solder contact of the solar cell. Failure occurred within the solder leaving solder on both the tab and the cell. The splice on the back of this tab may cause an increased stress on the solder connection during thermal cycling because of the reduced length of the overall stress relief loop.

In view of the limited number of tabs of each type tested, detailed comparisons cannot be made, however, some general comparisons can be made from the test results. In general, defect development rates were high for each tab type including the type-h (normal) tab.

The highest percentage of defects was found in the type-b tabs where 6 out of 10 became defective. Defects in these tabs were found in three separate places as shown in Table II. This result, along with the fact that type-a tabs cannot be fully inspected and may have had more defects than noted, indicates that severe tab bending will increase failure rates.

Defects of type c, d, e, and h tabs ranged from 1 out of 6 (17%) to 2 out of 5 (40%). Type-h tab failures, 7 out of 29 (24%) were in the middle of this range indicating that slight bending of the tabs does not produce significant effects on the failure rates.

Type-f tabs failed in the solder joint unlike the other types where defects were in the form of cracked tabs. This indicates that splicing the tab results in a weaker solder joint at the cell or in the transmission of higher stress to the solder joint during cycling. In any case the failure rate, 2 out of 6 (33%) is in the same range as for other tabs.

The type-g tab showed no defects or failures. This unexpected result may be indicative of a stronger configuration. However, in view of the small number of tabs, the evidence is considered inconclusive.

Of particular concern is the high number of defects observed in the type-h normal tabs where 7 of 29 cracked and 4 of these were catastrophic failures within 300 cycles. It is noted that all of these defects occurred at the bend at the solder joint and that they were all observed on tabs on the periphery of the module. In addition it is noted that the two tabs with "excess solder" did not show defects. This condition indicates a tab design problem or a fabrication and assembly problem. The tabs were too weak at the bend at the solder joint to withstand

e. The majority of defects and failures of the tabs occurs at the bend at the solder joint. This is a high stress area.

f. No failures occurred on the type-g tabs, however, limitations of the test and in the test data preclude any conclusion that this is a desirable configuration.

2. Considering the later test results on a complete solar paddle, the following conclusion is drawn:

a. The results of the test of the sample module in air are not applicable to the flight paddles. Either the materials and workmanship were significantly different or the testing in air resulted in drastically increased defect development rates and significantly different defect and failure modes compared to testing in a vacuum.

RECOMMENDATIONS

1. With regard to module testing in general, the following recommendations are made:

a. Thorough testing of sample modules should be performed prior to fabrication of flight panels.

b. Thermal cycle testing should be performed in a vacuum to insure validity of the test results.

c. Since further assurance of test validity will be gained by certainty that materials and workmanship are similar to that on flight paddles, additional testing during fabrication is recommended.

2. With regard to this test in relationship to the OAO flight paddles, the following recommendations are made:

a. The fabrication procedure should be reviewed, particularly the forming of the tabs.

b. With adequate care, bent tabs can and should be avoided.

c. For tab repair, a new submodule should be used or the cell at the defect should be lifted and a new interconnector added. Tabs should not be spliced.

d. During inspections of flight paddles, special attention to peripheral tabs is recommended.

3. With regard to future interconnector designs, the following recommendations are made:

   a. Past designs have concentrated on stress analysis at the top of the tab relief loop. This analysis should be extended to the high stress area at the bend at the solder joint.

   b. This high stress area should be relieved through design changes for future flight applications.

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3. Internal Memorandum, Clara Vermillion to Michael Husich, Subject: "Inspection of the Lower Right Inboard OAO-B Solar Array," August 12, 1970.

4. Internal Memorandum, Clara Vermillion to Michael Husich, Subject: "Inspection of Upper Left Outboard OAO Solar Array," August 15, 1970.

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