2.3.3 Open Contacts

Open contacts appear as horizontal traces on the curve tracer. To preclude clearing an open circuit the voltage applied during testing was limited to ±5 volts. In the case of open circuit contacts, an insulating layer was present in the contact interface that would not conduct at a 5 volt level. Four of the fifty-one contacts tested were open and all were on malfunctioning horns. All of the open contacts (two on one horn) were on horns that had been in a fire environment.

2.4 Selection of Units for Cross-Section and Surface Analyses

Eight of the seventeen horns tested on the curve tracer were selected for preliminary analysis. The remaining nine horns were set aside for possible testing later in the protocol. All of the eight horns selected for preliminary testing were optically inspected and each contact area photographically documented.

2.4.1 Optical Inspection and Photographic Documentation

Figure 3 shows the separable contacts on a typical smoke detector horn. The three contacts B, S and F are indicated on the photograph. Figure 4 is a conceptual cross-section of the horn disk and contacts. Figure 5 shows a close up of a bifurcated horn contact F from an older horn. All 6 of the smoke detectors in this phase of the test protocol that were reported as field failures had bifurcated contacts. Figure 6 shows a close up of a dimpled horn contact F on the newer horns. Both the new samples used in this phase were of this type. Figure 7 shows a close up of horn contact B on the older horn. To perform the auger (AES) surface analysis the contacts were removed from the horns. Figures 8 and 9 show the actual contact areas for the older and newer spring contact configurations. A rather heavy film was noted on the older contact shown in Figure 8. This film was detected visually on all three of the reported field failures tested in this section of the test protocol.

2.4.2 SEM Inspection of Contacts

Before the four horns used to document contact area materials were potted for cross-sectioning scanning electron microscope (SEM) photographs were taken of each contact area. Representative pictures of bifurcated and dimpled contacts appear in Figure 10 and 11, respectively. Energy Dispersive Analysis by X-Rays (EDAX) surface analyses were made on each of the four horns prior to potting. Table 1 summarizes the results of this analysis. Because of the relatively high beam voltages used by the SEM the depth of the surface analyses was about 1 micron. Even with this sensitivity both sulphur and chlorine are prominent on the older units and sulphur was also present on the newer units.

2.5 Potting and Cross-Sectioning of the Horns

There was some problem in developing a good technique for potting the horns. This was overcome and the four horns were potted and cross-sectioned.

2.6 Documentation of Contact Area Materials

After the four horns were cross-sectioned each of the materials shown in Figure 4, the conceptual cross-section of the horn disk and contacts, were analyzed using EDAX. Table 2 lists the results of this EDAX investigation for each horn. This completed the preliminary investigation using the SEM.

TABLE 1: RESULTS OF EDAX SURFACE ANALYSES

S/N	Location	C	O	Si	S	Ca	Cr	Fe	Ni	Cl	Ag	Al	K	N	Sn	Pb
6	B Contact Pad	•	X	X	X	•	X	X	X							
6	S Contact Pad		•	•	X					X	X					
6	S Contact	•	X	X	X	•	X	X	•			•	•			
6	F Contact Pad	•	•	•	X					X	X					
32	B Contact Pad	X	X					X	•			X				
32	S Contact Pad	X	X	X	X				X	X	X					
32	F Contact Pad	X	X	•	X				X	X	X					
36	B Contact Pad	•	X	•		•		X	•	•		X				
36	S Contact Pad	•	•	X	X					•	X	•				
36	F Contact Pad	•	X	X	X					X	X	•				
49	B Contact Pad													•	X	
49	S Contact Pad				X						X					
49	S Contact														X	X
49	F Contact Pad				X						X					

Key X = Significant Level • = Detectable Level

TABLE 2: SUMMARY OF MATERIALS USED ON SMOKE DETECTOR HORNS

	S/N 6	S/N 32	S/N 36	S/N 49
Contact Material Contact Plating	Fe, Cr, Ni, None	Fe, Cr, Ni None	Fe, Cr, Ni None	Fe, Cr, Ni Sn, Pb
Piezo-Electric Disk Piezo-Electric Metalization Insulating Coating	Pb, Zr, Ti, O Ag* None	Pb, Zr, Ti, O Ag* Si, Mg, C, O, Cl	Pb, Zr, Ti, O Ag* Si, C, O, Cl	Pb, Zr, Ti, O Ag Si, Mg, C, O, Cl
Metal Header Disk Header Plating	Fe, Cr, Ni None	Fe, Cr, Ni None	Fe, Cr, Ni None	Fe, Cr, Ni Sn

*A surface film was detected on the piezo-electric disk metalization. EDAX identified the layer to contain sulphur and silver.

2.6.1 Optical UV Test for Organics and Sample Preparation

Horns on the four units scheduled for auger analyses were then disassembled to reveal the terminal pad and the contact mating areas to allow performance of an optical UV test for organics. No organics were found as a result of this testing. Also at this time the samples to be surface analyzed on the auger were prepared.

2.6.2 Auger (AES) Surface Analyses and Depth Profiles

AES measurements were taken at 24 locations on the four contacts and terminal pads of the 4 horns selected for surface analysis. A summary of these analyses are shown in Table 3. Both sulphur and chlorine are present in all four samples. AES is more sensitive to surface contamination than the EDAX which explains why chlorine was found even in the new smoke detector.

After the surface analyses were finished depth profiles were run at seventeen locations. The results of the depth profiling appears in Table 4. The surface material was sputtered away at a known rate while elemental measurements were being made. As each element dropped in intensity the thickness of the layer containing that element could be determined. Following the depth profiles another AES scan was run. The residual non-base material elements found after profiling are recorded in the last column of Table 4. Films of 2000A were detected at several locations. Those units that had been in a fire situation had thicker films.

2.6.3 Fourier Transform Infra Red (FTIR) Tests

FTIR tests were run on some of the horn contacts to determine if the films visible (see Figure 8) on the horn contacts were organic in nature. No organic films were detected. The absence of organic films on contacts of fielded horns means that outgassing of polymeric materials used in smoke detector construction can be ruled out as a source of detrimental films on smoke detectors. It also means that Finnegan Triple Mass Spectrometer testing will not be required.

2.7 Develop Failure Root Cause Hypothesis

Based on all of the data collected in the first half of the test protocol, a root cause hypothesis was developed. Fretting corrosion in the presence of sulphur and/or chlorine was selected as the most likely cause of contact failure. In order to test this theory it was decided to run temperature cycling in the presence of evaporating water (simulated cooking). In order to maximize the number of cycles the thermal cycle profile shown in Figure 12 was selected. This allowed for 500 thermal cycles in 10 days and 10 hours.

TABLE 3: RESULTS OF AES SURFACE ANALYSES

			Elements Detected on Surface														
Location	Terminal	S/N	Si	Pb	S	Cl	K	C	Ag	N	Sn	O	Fe	Ni	Na	Al	Remarks
C	B	14	X		•	•	•	X	•	•	•	X	X	•	X		NIF
T	B	14	•		•	•	•	X		•		X	X	•	X		NIF
B_T	B	14			•			X				X				X	NIF
C	S	14	X	•	X			X	•	•	•	X	X	•			NIF
B_C	S	14	X		X		•	X		•		X	X		X		NIF
C	F	14	•	•	X	•		X	X	•		X	X	•	X		NIF
T	F	14			X	•		X	X			X					NIF
B_T	F	14			X	X		X	X			X					NIF
C	B	35				X		X		•		X	X	•	•		IF
T	B	35	•	•		X		X		•		X	X	•		•	IF
C	S	35	•		•	X		X	X	•		X	X	X	•		IF, OC
T	S	35	X	•		X		X	•	•		X	•	X			IF, OC
B_C	S	35	•			X		X	•	•		X	X		•		IF, OC
C	F	35	•			X		X	•	•		X	X	•	•		IF
T	F	35	•		X	X		X	X			X	X	X			IF
C	B	39	•		•	X		X		•		X	X	•	•		IF, HFD
T	B	39	X			X		X		X		X	•		•		IF, HFD
C	S	39	•		•	X		X		X		X	X	•	•		IF, OC, HFD
B_C	S	39	•		X	•		X	X	X		X	•		•		IF, OC, HFD
C	F	39	•		•	X		X		X		X	X		•		IF, NLC, HFD
C	B	50	X	X	•	X		X			X	X		•			N
C	S	50	•	X	X	X		X			X	X		•			N
B_C	S	50	•	X	X	X		X			X	X		•			N
C	F	50	X	X	X	X		X			X	X					N

Location Keys:
- C = Contact area under spring loaded half of contact
- T = Terminal area on ceramic disc or metal rim under spring loaded contact
- B_T = Background reading near T but not in contact area
- B_C = Background reading near C but not in contact area

Element Key: X = Significant peak • = Detectable peak

Remark Keys:
- NIF = Not in fire
- N = New unit
- OC = Open contact
- NLC = Non-linear contact
- HFD = Heavy fire damage

TABLE 4: AES DEPTH PROFILE SUMMARY

		Element Depth, A Units								
Horn S/N	Location	O	C	S	Cl	Si	K	Na	Profile Depth	Residual Non-Base Material Elements After Profile
14	Contact B	300	40	25	--	25	25	25	450A	C, O
14	Terminal B	100	40	70	--	30	30	30	450A	C
14	Contact S	300	300	300	--	--	--	--	550A	C, O, S, Ag
35	Contact B	2000	2000	--	2000	--	--	--	2000A	C, O, Cl
35	Contact S	1500	2000	1400	2000	--	--	--	2400A	O, Cl
35	Terminal S	--	1300	--	1000	--	--	--	2250A	O, Cl, Si, Ni
35	Terminal F	30	100	--	--	--	--	--	450A	0, S, Cl, Si
39	Contact B	700	1200	--	700	--	--	--	1300A	C
39	Contact S	200	1000	--	300	--	--	--	1300A	C, N
39	Terminal S	--	2000	--	2000	--	--	--	3450A	O, S, Cl, Si
39	Contact F	350	700	--	--	--	--	--	777A	C
39	Terminal F	--	200	200	200	--	--	--	300A	S, Cl, Si
50	Contact B	600	30	--	60	--	--	--	450A	O, Cl
50	Terminal B	400	30	--	80	--	--	--	450A	O, Cl
50	Contact S	900	25	--	--	--	--	--	370A	O, Cl
50	Contact F	600	30	--	300	--	--	--	600A	O, Cl
50	Terminal F	400	30	--	--	--	--	--	450A	O

2.8 Accelerated Testing

Horns from 20 smoke detectors were selected from the 50 supplied by CPSC. These 20 horns (60 contacts) were measured on the curve tracer to obtain V/I curves and several more intermittent (non-linear) contact characteristics were found. The results of this testing and the contact resistance measurements made on all 60 contacts are recorded in Table 5. Finally all horns were functionally tested using the test button on the smoke detector test platform. All horns except serial number 16 functioned properly.

TABLE 5: RESISTANCE MEASUREMENTS ON HORNS AS RECEIVED FROM CPSC

Horn	I/V Tests			Resistance			Test
#	B	S	F	B	S	F	Button
2	S	S	S	.18	.68	.30	Func
7	I	S	S	3.5	.33	4.14	Func
8	S	I	S	1.07	55.0	6.55	Func
11	S	S	S	3.18	.83	.11	Func
12	S	S	S	.69	.58	4.72	Func
15	S	S	S	.29	.37	.61	Func
16	O	S	S	∞	.03	.08	Malfunc
18	S	I_C	I_C	5.62	.15	.28	Func
21	S	S	S	.42	.55	30.2	Func
26	I_C	S	S	2.81	1.11	39.4	Func
28	S	I	I	2.80	260	2300	Func
29	S	S	S	.17	8.32	7.12	Func
34	S	S	S	.79	1.87	91	Func
37	S	S	S	122	.10	.10	Func
41	I_C	S	S	500	.20	.21	Func
42	S	S	S	.65	.15	.17	Func
43	S	S	S	.65	.40	.21	Func
44	S	S	S	.33	.26	.63	Func
45	S	S	S	2.75	.36	.36	Func
46	S	S	S	.88	.27	.24	Func

S = Short (Linear)
I = Intermittent (Non-Linear)
I_C = Intermittent (Non-Linear) Cleared to Linear
O = Open

The 20 horns were then placed in the oven and thermal cycled for a total of 500 cycles. Figure 12 shows the time/temperature plot for each cycle. After the 500 cycles the V/I curves, resistance measurements and functionality tests were run. The results of this testing is recorded in Table 6.

After 500 thermal cycles, horns 16 and 41 malfunctioned. The contact resistances for the remaining horns generally went up although 10 of the 60 contacts actually had lower contact resistances. This is the type of behavior that would be expected for fretting corrosion. As fretting takes place the film surface changes lowering some resistances but the additional corrosion on formerly exposed areas tends to raise resistances. This erratic resistance behavior raises the mean resistance of the population and eventually causes contacts to remain open.

TABLE 6: RESISTANCE MEASUREMENTS AFTER 500 TEMPERATURE CYCLES

Horn	I/V Tests			Resistance			Test
#	B	S	F	B	S	F	Button
2	I_C	S	S	75	.98	2.26	Func
7	S	I_C	S	226	.97	28.4	Func
8	S	S	S	122	38.7	43.1	Func
11	S	S	S	2.68	.91	.21	Func
12	S	S	S	1.43	3.87	7.21	Func
15	S	S	S	4.68	1.08	.62	Func
16	O	S	S	∞	.08	.09	Malfunc
18	S	S	S	197	.34	.77	Func
21	I	S	S	10.23	1.96	21.1	Func
26	I	S	S	446	2.35	141	Func
28	S	I	I	13.1	822	63,000	Func
29	S	S	S	20.6	11.2	4.17	Func
34	I	S	S	435	1.02	1.68	Func
37	I	S	S	322	1.06	.43	Func
41	O	S	S	∞	.08	.08	Malfunc
42	S	S	S	6.48	.09	.12	Func
43	S	S	S	4.26	.84	4.31	Func
44	S	S	S	75.5	3.38	16.5	Func
45	S	S	S	9.65	.14	.47	Func
46	S	S	S	30.2	.16	.78	Func

S = Short (Linear)
I = Intermittent (Non-Linear)
I_C = Intermittent (Non-Linear) Cleared to Linear
O = Open

A second series of 500 thermal cycles was run on the same 20 horns. The results of the testing after a total of 1000 cycles is recorded in Table 7. Horn 42 malfunctioned as well as horns 16 and 41. Again the general population of contact resistances measured went higher than the readings taken after 500 cycles and 9 out of the 60 contact resistances actually dropped. However, only 5 of the 60 contact resistances were lower after 1000 cycles than in the "as received" condition.

TABLE 7: RESISTANCE MEASUREMENTS AFTER 1000 TEMPERATURE CYCLES

Horn	I/V Tests			Resistance			Test
#	B	S	F	B	S	F	Button
2	I_C+IV	S	I	870	1.02	7.16	Func
7	I	S	S	1196	3.75	4.01	Func
8	I	S	I_C+IV	434	192	15.9	Func
11	S	S	S	3.03	2.93	.41	Func
12	S	S	S	250	7.3	12.3	Func
15	S	S	S	28.6	1.08	1.66	Func
16	O	S	S	∞	.28	.22	Malfunc
18	I	S	S	1.83	.48	2.30	Func
21	S	S	S	275	4.75	88	Func
26	S	S	S	303	4.14	192	Func
28	I	I	I	178	193	83,000	Func
29	I	S	S	108	85	5.80	Func
34	S	S	S	3200	.80	2.12	Func
37	I	S	S	322	.54	.31	Func
41	O	S	S	∞	.25	.23	Malfunc
42	I	O	S	108	∞	.27	Malfunc
43	I_C	S	S	10.2	.47	3.31	Func
44	S	S	S	10.1	3.74	29.2	Func
45	S	S	S	76.4	.34	.78	Func
46	S	S	S	202	1.09	1.38	Func

S = Short (Linear)
I = Intermittent (Non-Linear)
I_C = Intermittent (Non-Linear) Cleared to Linear
O = Open

Seventeen of the 20 horns undergoing the accelerated testing of 1000 thermal cycles are of the type shown in Figures 13a and 13b. They are ruggedly constructed and the horns must be unsoldered to reveal the contacts. Also if the detector is disassembled it will probably be destroyed. For future discussion this style of horn will be referred to as

Type A. Three of the 20 horns were of the type shown in Figures 14a and 14b. This is basically a three-piece horn which can be easily disassembled and reassembled without a soldering operation. For future discussion this style of horn will be referred to as Type B. The fact that the critical contacts can be easily tampered with by curious people makes this horn less robust than the Type A horn. Also when reassembled the piezoelectric disc can be reversed making the smoke detector malfunction. Based on the 1000 cycle test the Type B horns appear significantly less reliable than the Type A horns. None of the Type A horns failed after 1000 thermal cycles while all three Type B horns failed.

In order to determine what contamination might have been added to the horns during the accelerated testing, a strip of clean aluminum foil was placed in the tray holding the horns. The only material present in the surface analysis results of the aluminum foil was aluminum. Therefore, the 1000 cycle test was a thermal cycling test with some additional humidity. The only contaminants involved were those present on the horns at the start of the test.

One way to analyze the contact resistance population shift with increasing number of thermal cycles is to look at the percentage of resistance values by decades versus the number of cycles. Table 8 is a summary of that data.

TABLE 8: CONTACT RESISTANCE VALUES VERSUS TEMPERATURE CYCLES

	Percentage of Resistances by Decades						Open Contacts
Number of Cycles	0-1 Ohm	1-10 Ohms	10-100 Ohms	100-1000 Ohms	1000-10,000 Ohms	10,000-100,000 Ohms	%
0	63.3	23.3	5.0	5.0	1.7	0.0	1.7
500	31.7	30.0	20.0	13.3	0	1.7	3.3
1000	21.7	31.7	13.3	21.7	3.3	1.7	5.0

The data in Table 8 clearly shows the shift in contact resistance distribution for the number of thermal cycles.

The accelerated testing has established two things. First and foremost that it is possible to induce horn failures by thermal cycling, and second, that thermal cycling increases the contact resistance of the horns. This substantiates the theory that failures are caused by fretting corrosion.

2.9 UL 217 Corrosion Tests

Six new smoke detectors were supplied by CPSC to IITRI for standard corrosion testing specified in UL 217. Three of the units were designated A, B and C and tested to assure functionality using the test button. These units had their horns removed and were tested at ORS using the SEM. The remaining three units designated X, Y and Z were only tested functionally, using the test button, to assure that they were operating properly before the start of test. Figures 15, 16 and 17 are EDAX plots for contact S horn A, contact F horn B and contact B horn C, respectively. A slight amount of sulphur was detected at contacts F and S (the silver plated pads) while none was detected at contact B. This is expected since sulphur and silver have an affinity for each other. These EDAX results were compared to the results after the UL testing.

After the testing at ORS the horns were reinstalled in the smoke detectors. All six smoke detectors were checked for functionality using the test buttons prior to shipment to UL for corrosion testing. During corrosion testing two smoke detectors were exposed to SO_2, two were exposed to H_2S and two were exposed to a mixture of SO_2 and H_2S. Table 9 identifies each unit and the test gas to which it was subjected.

TABLE 9: SMOKE DETECTORS FOR UL CORROSION TESTS

Unit Identification	Test Gas	Pre-Test Function Test
A	SO_2	Passed
B	H_2S	Passed
C	SO_2/H_2S	Passed
D	SO_2/H_2S	Passed
E	H_2S	Passed
F	SO_2	Passed

After the smoke detectors were returned by UL, all six were tested using the test buttons and functioned properly. The horns were then removed and contact resistance measurements were made. Measurement results are shown in Table 10. These low contact resistances are a strong indication that the UL 217 corrosion tests do not accelerate horn contact degradation.

TABLE 10: CONTACT RESISTANCE AFTER UL CORROSION TEST

Unit Identification	Test Gas	Contact Resistance in Ohms		
		B	S	F
A	SO_2	.47	.26	.20
B	H_2S	.25	.23	.29
C	H_2S/SO_2	.19	.35	.26
X	H_2S/SO_2	.20	.49	.24
Y	H_2S	.16	.27	.23
Z	SO_2	.64	*	*

*Because of the horn construction, no test could be made

Each horn was then documented photographically and delivered to ORS for surface analyses. The horns subjected to SO_2 have less film deposits than the H_2S testing while those exposed to the combination of H_2S and SO_2 have the most deposits.

Units A, B and C were investigated with SEM and EDAX before and after the corrosion testing. No noticeable visual difference could be found for any unit. However, the EDAX testing showed some differences. Figures 15 and 18 show the before and after tests of Unit A, Terminal S. The only difference is the increase in sulphur. Figures 16 and 19 show the before and after tests of Unit B, Terminal F. Again the only difference was an increase in the sulphur. Figures 17 and 20 show the before and after tests of Unit C, Terminal B. In this case there was no difference between the before and after plots. This testing again shows how benign the corrosion tests are concerning the horn contacts. The silver, which has an affinity for sulphur, did show an increase in sulphur, but the tin plated area did not show any significant amount of sulphur either before or after testing. A post corrosion EDAX test was run on the silver pad at contact F for Unit C. This plot (Figure 21) showed that the sulphur level was similar to the post corrosion EDAX tests on Units A and B.

Horns X, Y and Z were prepared for auger surface analyses and depth profiling. For each sample a surface analysis was run on terminal S plus terminal B on sample X. Then each sample was depth profiled followed by another surface analysis. The sputtering rates for each sample was as follows:

Sample X terminal S	1-30 minutes, 7 angstroms/minute 30-80 minutes, 20 angstroms/minute
Sample X terminal B	Entire profile, 10 angstroms/minute
Sample Y terminal S	Entire profile, 10 angstroms/minute
Sample Z terminal S	Entire profile, 10 angstroms/minute

Figures 22 through 33 are the pre- and post-sputter surface analyses and the depth profiles for the four samples tested.

Note that the surface analyses on the silver "S" contacts show what appears to be a thick carbon layer. Due to an overlap of the silver and carbon peaks between 260 and 280 eV, this is an artifact due to the presence of silver and not carbon.

Sulphur was the only significant contaminant noted in the auger testing. Table 11 summarizes the depth level of the sulphur layer for each sample.

TABLE 11: SUMMARY OF SULPHUR LAYERS ON HORNS RUN IN THE UL CORROSION TESTS

Sample	Contact	Test Gas	Thickness of the Sulphur Layer
X	S	H_2S/SO_2	400A
X	B	H_2S/SO_2	0A
Y	S	H_2S	180
Z	S	SO_2	80

Figure 25, the pre-sputtering surface analysis on terminal B of horn X shows only a slight trace of sulphur. Both silicon and chlorine have higher levels than the sulphur. Horn X was selected for this testing because it should have had the thickest layer of contamination and confirms the EDAX surface analysis on horn C (Figure 20). This data also indicates that the UL 217 testing did not stress contact B (non-silver). Finally, based on the contact resistance measurements (see Table 10) it is apparent that the UL 217 corrosion testing provides minimal stressing of the horn contacts.

Smoke detectors A, B, C, X and Y contain type A horns which are described earlier in the report. However, the horn from smoke detector Z is neither type A or B and, for future reference, will be called a type C horn. Figure 34 shows (see arrows) the three type C horn contacts which are easily accessible by removing the back of the detector. The horn element (shown in Figure 35) which is loosely contained by the front portion of the smoke detector housing can fall out during disassembly of the smoke detector if the back section is not carefully removed. When this happens, damage to the horn element and/or contacts is possible. Also an inexperienced person could reassemble the smoke detector with the horn in backwards. Since all of this can be accomplished simply and without a soldering operation this type of horn can be assumed to be less reliable than the type A horns. Figure 36 shows a close-up of contact F. The intent of this design is to have a sharp point contacting the horn element.

3.0 SUMMARY

As a result of Task II testing efforts, several important items were documented and are discussed in the following paragraphs.

3.1 Open Contact Failure Mechanism

It has been established that the separable horn contacts used for smoke detectors can fail in an open condition with extended exposure to contaminants (i.e., chlorine, sulphur) and temperature cycling. However, even though this is now a proven failure mechanism its occurrence is not a high probability but there is room for improvement. Additionally information obtained in discussions with CPSC, UL and GAFB (Griffiss Air Force Base) fire department personnel indicates that this mechanism usually starts after 4 to 5 years of field use. The May 1994 Consumer Report article on Smoke Detectors states that smoke detectors should be replaced after ten years. No reasoning or data is given for this lifetime. Warranties on the same detectors covered in the Consumer Report article ranged from 90 days to 5 years. Half of the models had 5 year warranties which seem more in-line with the information gathered by IITRI for this report. It was also reported by GAFB that those in smoking areas were more prone to failure than those in non-smoking areas.

The accelerated temperature cycling testing performed confirmed that fretting corrosion is the most likely failure mechanism. Because fretting corrosion depends on relative motion between the two separate halves of the contact, the resistance buildup at the contact is slow and irregular and includes both a lowering and raising of contact resistance with time. The fretting process is one of alternating increases and decreases of contact resistance. The whole process, on a statistical basis, is one that slowly builds up contact resistance until the contact becomes open. Relative motion on a high resistance contact breaks down the corrosion film and can cause the contact to conduct again. This explains why most of the reported field failures that were collected by CPSC and sent to IITRI for evaluation functioned properly when tested at CPSC and IITRI.

3.2 Films Found in Contact Areas

Surface analyses showed that both chlorine and sulphur are present in contact areas of all horns tested that were reported as failures in the field. Film thicknesses up to 2000A were measured on the contact areas.

Fourier Transform Infra Red (FTIR) testing and ultraviolet microscopy confirmed that there were no organic films in the contact areas.

3.3 UL 217 Corrosion Testing

The results of the Underwriters Laboratory smoke detector testing using the UL 217 corrosion test, showed this to be an ineffective procedure. This was especially true for non-silver contact areas.

3.4 Horn Construction

Three basic horn constructions were involved in Task II testing and are referred to in this report as Types A, B and C horns. The type A horn uses essentially a monolithic construction meaning any attempt to disassemble it will most likely destroy the horn. Also, the type A horn contacts are protected from accidental damage because the type A horns have to be unsoldered to reveal their contacts. On the other hand, the type B and C horns can be easily disassembled and critical contacts can be destroyed. There is also the possibility that the piezoelectric discs in both the B and C horns could be replaced upside-down causing the horn to become inoperative.

To preclude owners from rendering their smoke detectors inoperative during cleaning/disassembly, consideration should be given to require that smoke detector horns be of the "monolithic" type. This would mean that in order to get at the critical separable contacts there would have to be a soldering operation thereby minimizing disassembly of the horn.

3.5 Failure Modes/Corrective Action

As stated previously the only failure mechanism found throughout the entire smoke detector effort was associated with the horn separable contacts. In addition horn reliability characteristics are not included in the UL217 reliability prediction procedure (this will be discussed in detail in the UL217 critique). The improvement of separable contact reliability would be a significant advance in the reliability of smoke detectors and result in longer lifetimes for smoke detectors. The onset of smoke detector wearout could be moved from the present 4 to 5 years out to over 10 years. To accomplish this the following corrective actions are recommended:

- Model smoke detector horn reliability characteristics and add appropriate factors to UL217 reliability prediction procedure

- Develop a horn vendor/user qualification procedure to determine horn acceptability prior to use in a smoke detector

3.6 Corrosion Mechanism Analysis

In sections 2.12 and 2.13 and 3.1 it was established that fretting corrosion was the major failure mechanism involved with the separable contacts of smoke detector horns. In order to have fretting corrosion two conditions are necessary. One is the presence of contaminants and the other is relative motion between the two halves of the contact.

3.6.1 Contaminants

The major contaminants affecting separable contacts are common gases such as SO_2, H_2S, Cl_2 and NO_2. Most current work evaluating film formation on contacts employs the mixed flowing gas technique.[1] The majority of the data collected has been using test/class III. This consists of 100ppb of H_2S, 20ppb of Cl_2 and 200ppb of NO_2. The test is run at 70% relative humidity with an operating temperature of 30°C. The purpose of using mixed flowing gases is to take advantage of their interaction to accelerate film growth over single gas testing. NO_2 in particular[2] acts as a catalyst in the film growing process.

More recently[3] it has been demonstrated that amorphous S_iO_2 can be formed on contact interfaces in the presence of silicone vapors causing the growth of a glass non-conductive film. Since silicone vapors are common by products of the decomposition of oils, rubbers, etc. and since silicon and oxygen were present on many of the surface analyses (see Table 3), this mechanism cannot be ruled out at this time.

3.6.2 Relative Motion

Temperature cycling is the major cause of relative motion between contact halves. The horns are constructed of materials (plastics, metals, ceramics) that have different thermal coefficients of expansion. Tests should be run using temperature cycling in the presence of mixed flowing gases to simulate and/or accelerate actual field usage. Another important factor in relative motion and fretting corrosion is the contact forces. Higher contact forces will improve fretting corrosion problems.

References:

(1) Abbott, W.H., "Corrosion Still Plagues Electronic Packaging," *Electronic Packaging and Production*, August 1989, pp. 28-33.

(2) Guinement, J., et. al, "Search for a Test Simulating Indoor Corrosion of Electrical Connections," *1982 Proceedings For Testing and Failure Analysis*, pp. 115-124.

(3) Tamai, T., "Formation of S_iO_2 on Contact Surface and Its Effect on Contact Reliability," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol. 16, No. 4, June 1993, pp. 437-441.

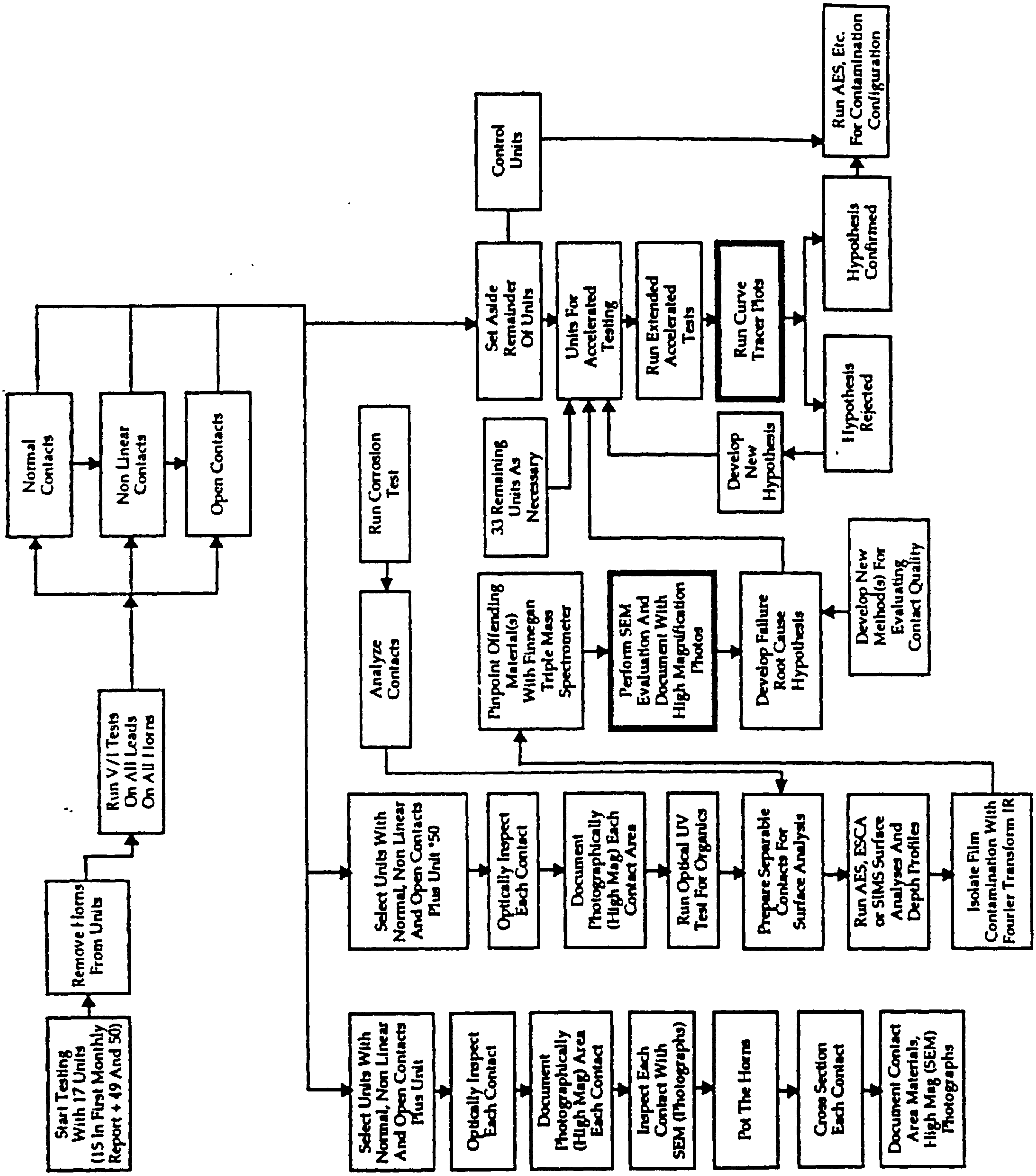


FIGURE 1: TEST PROTOCOL FLOW CHART

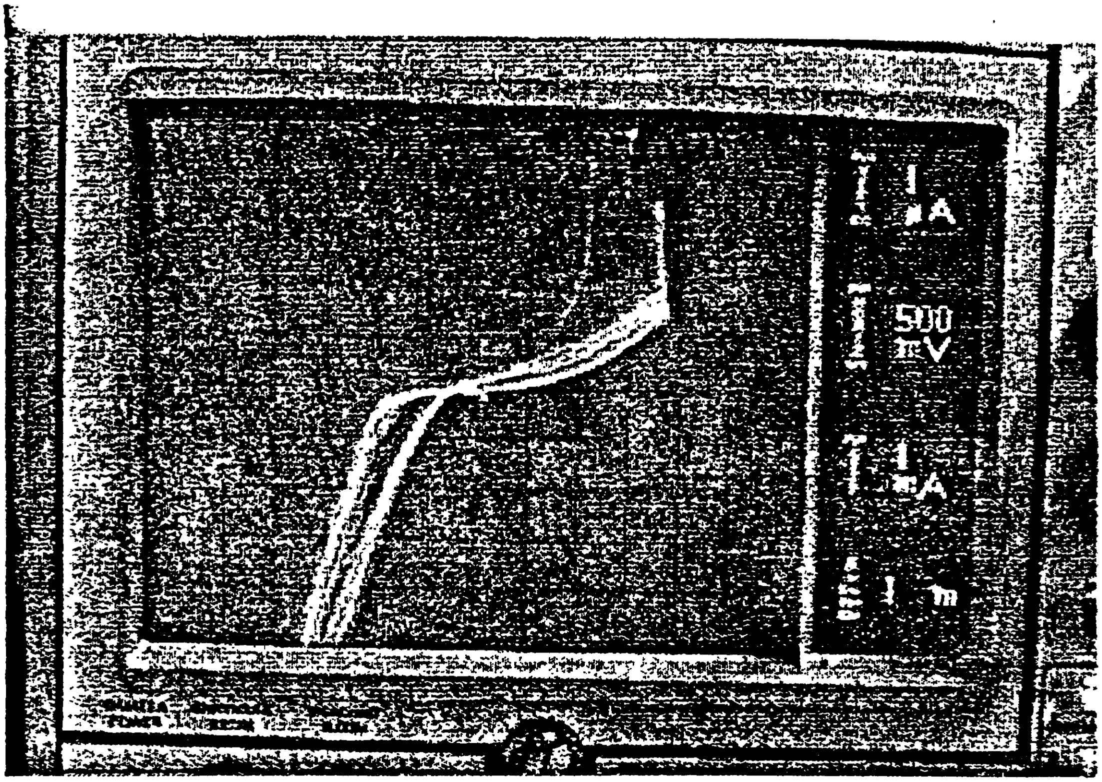


FIGURE 2: NON-LINEAR V/I CHARACTERISTICS OF A SMOKE DETECTOR HORN CONTACT

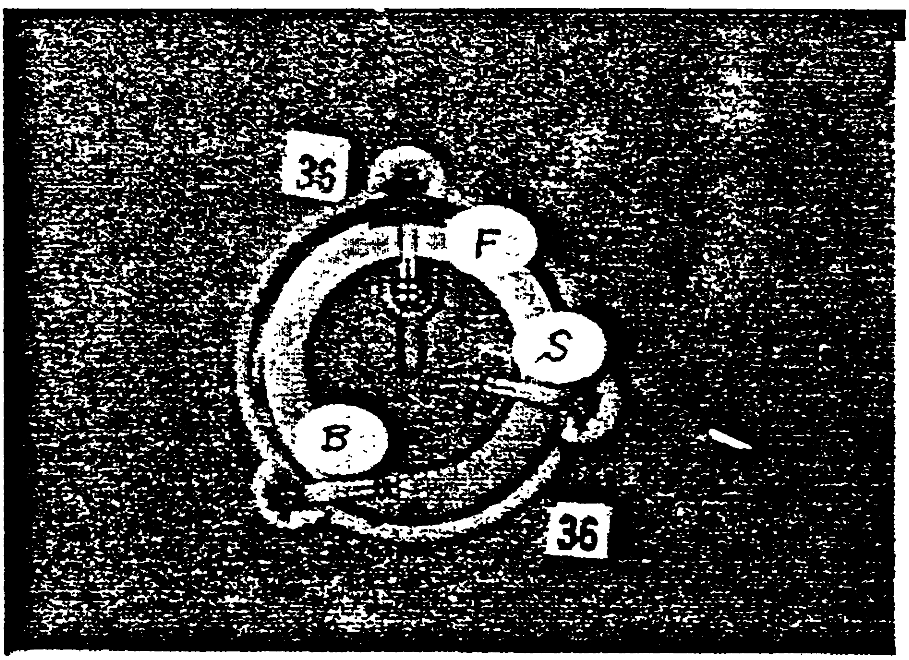


FIGURE 3: SEPARABLE CONTACTS ON A SMOKE DETECTOR HORN (1.25X)

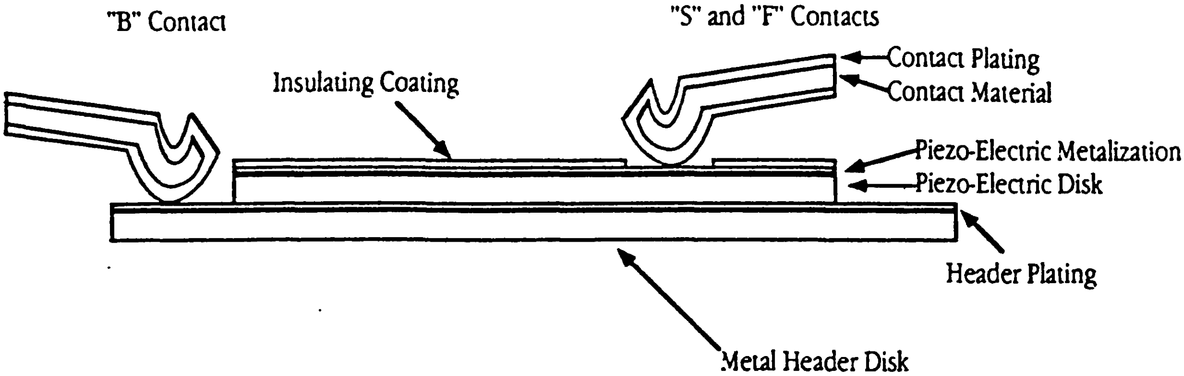


FIGURE 4: CONCEPTUAL CROSS-SECTION OF HORN DISK AND CONTACTS

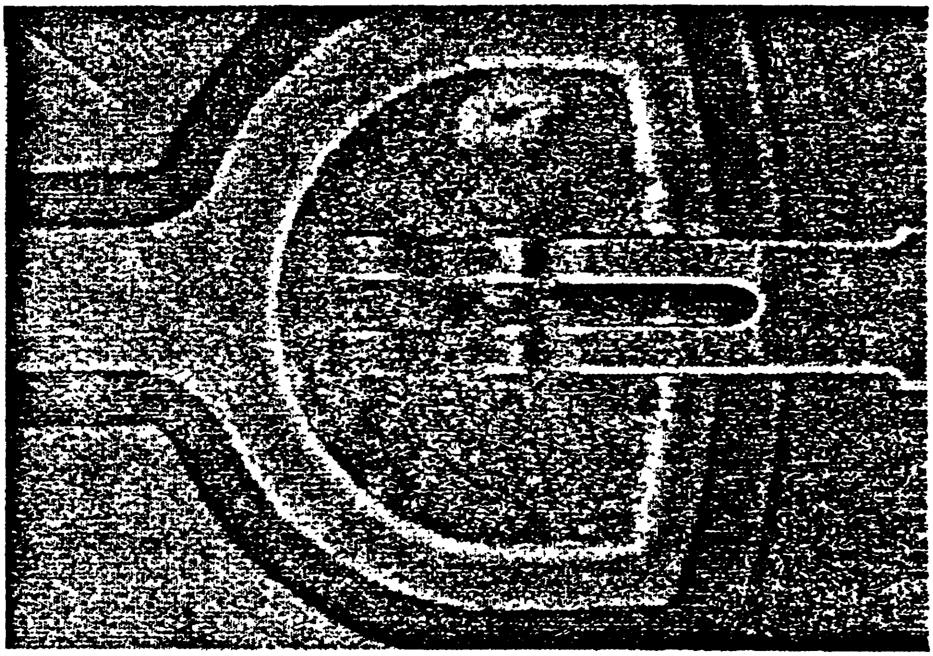


FIGURE 5: BIFURCATED CONTACT F ON OLDER HORNS (12X)

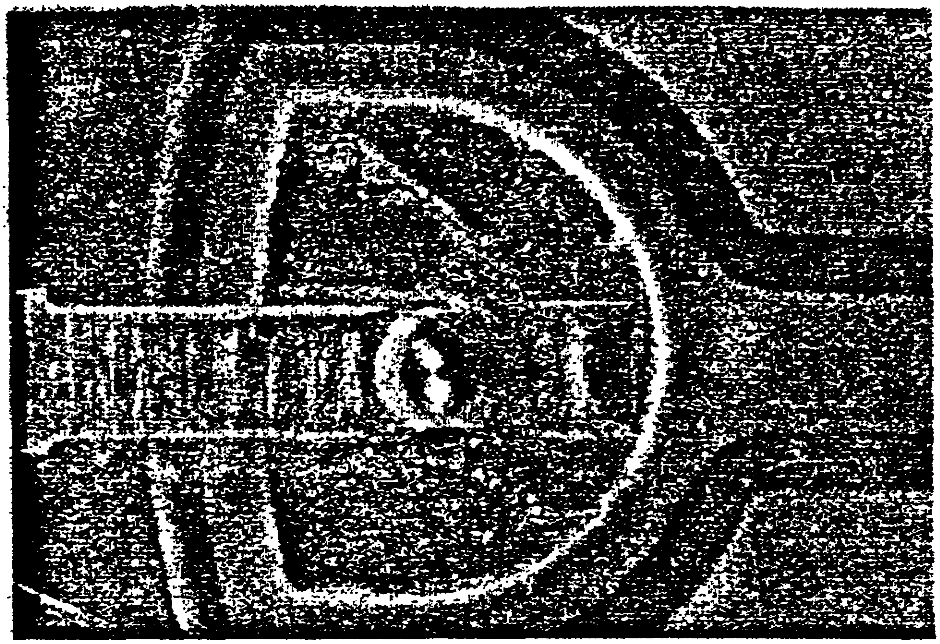


FIGURE 6: DIMPLED CONTACT F ON NEW HORNS (12X)

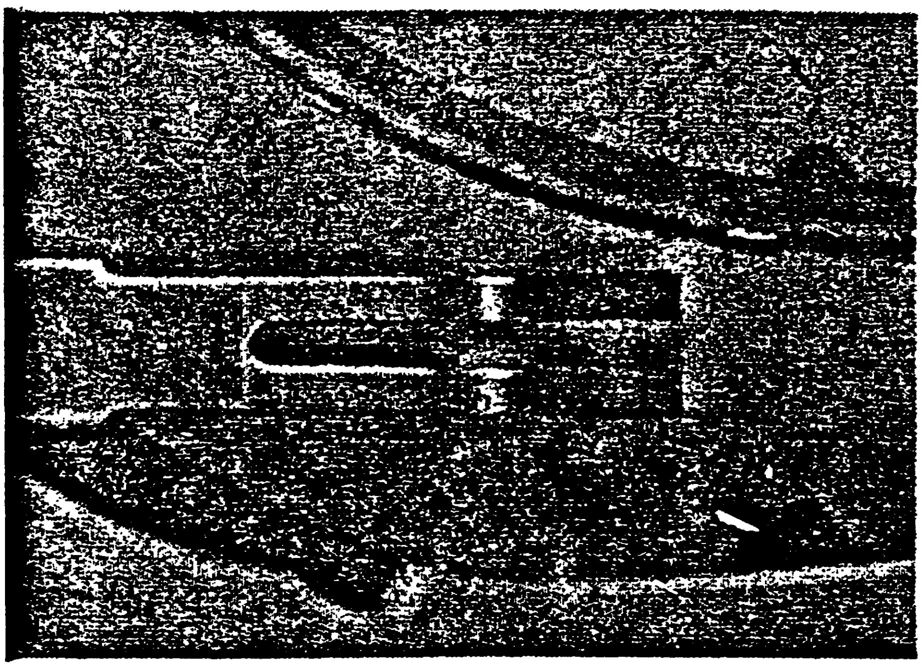


FIGURE 7: BIFURCATED CONTACT B (12X)

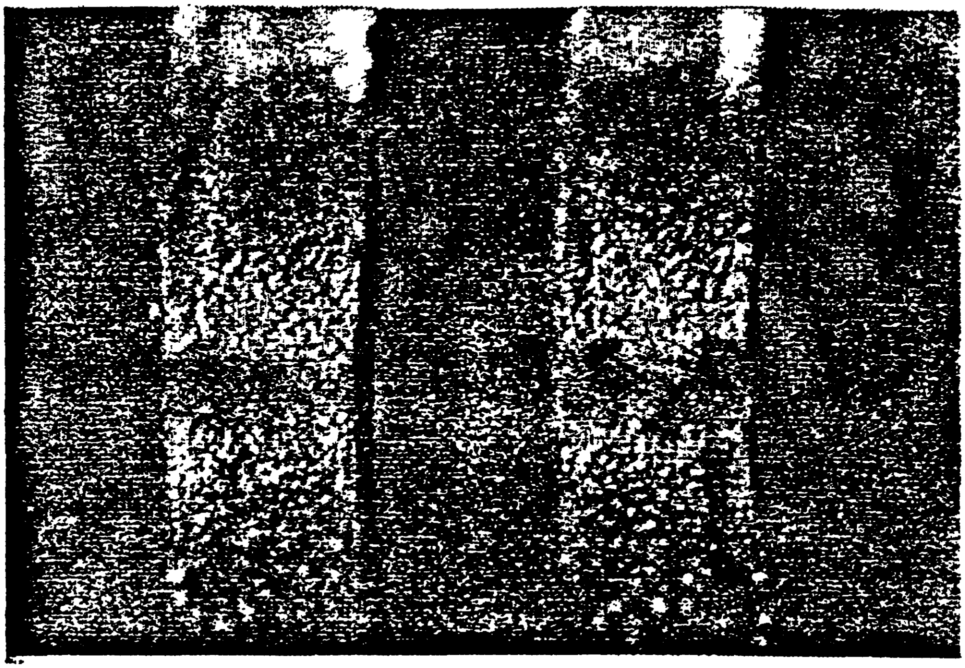


FIGURE 8: BIRFURCATED CONTACT SEPARATED FROM HORN (50X)

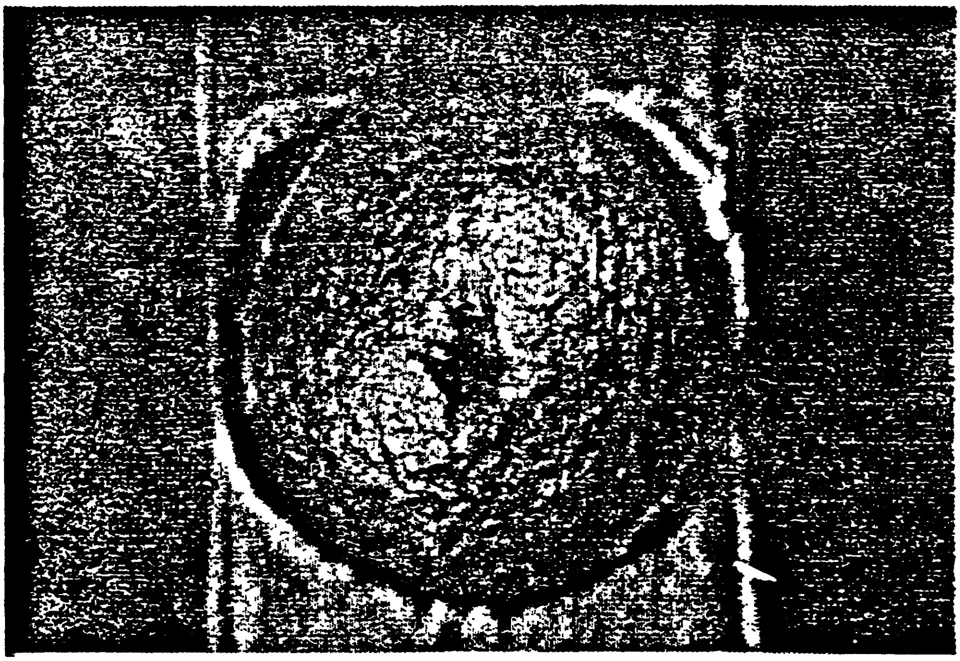


FIGURE 9: DIMPLED CONTACT SEPARATED FROM HORN (50X)

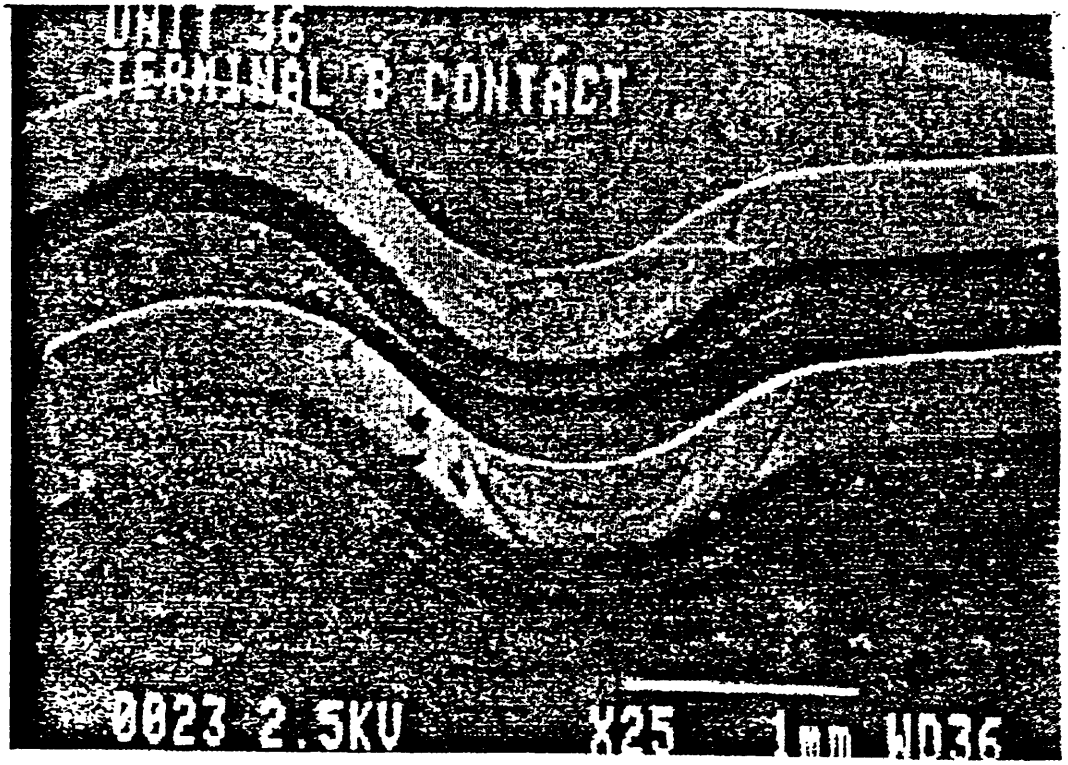


FIGURE 10: SEM PHOTOGRAPH OF A BIFURCATED CONTACT

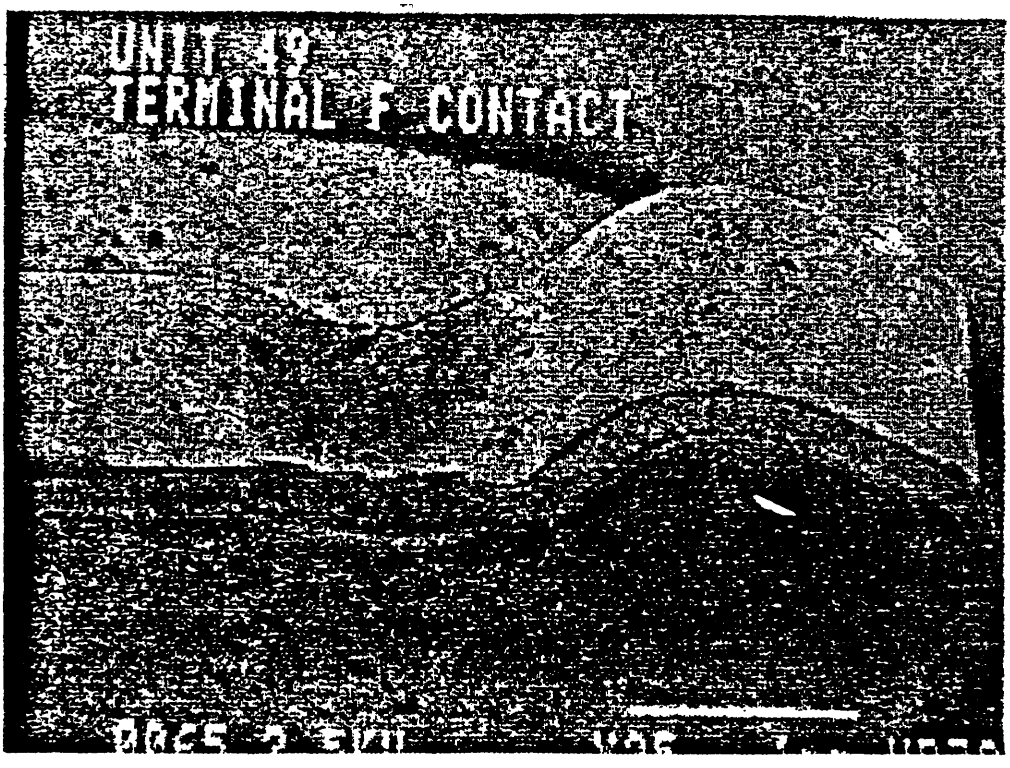


FIGURE 11: SEM PHOTOGRAPH OF A DIMPLED CONTACT

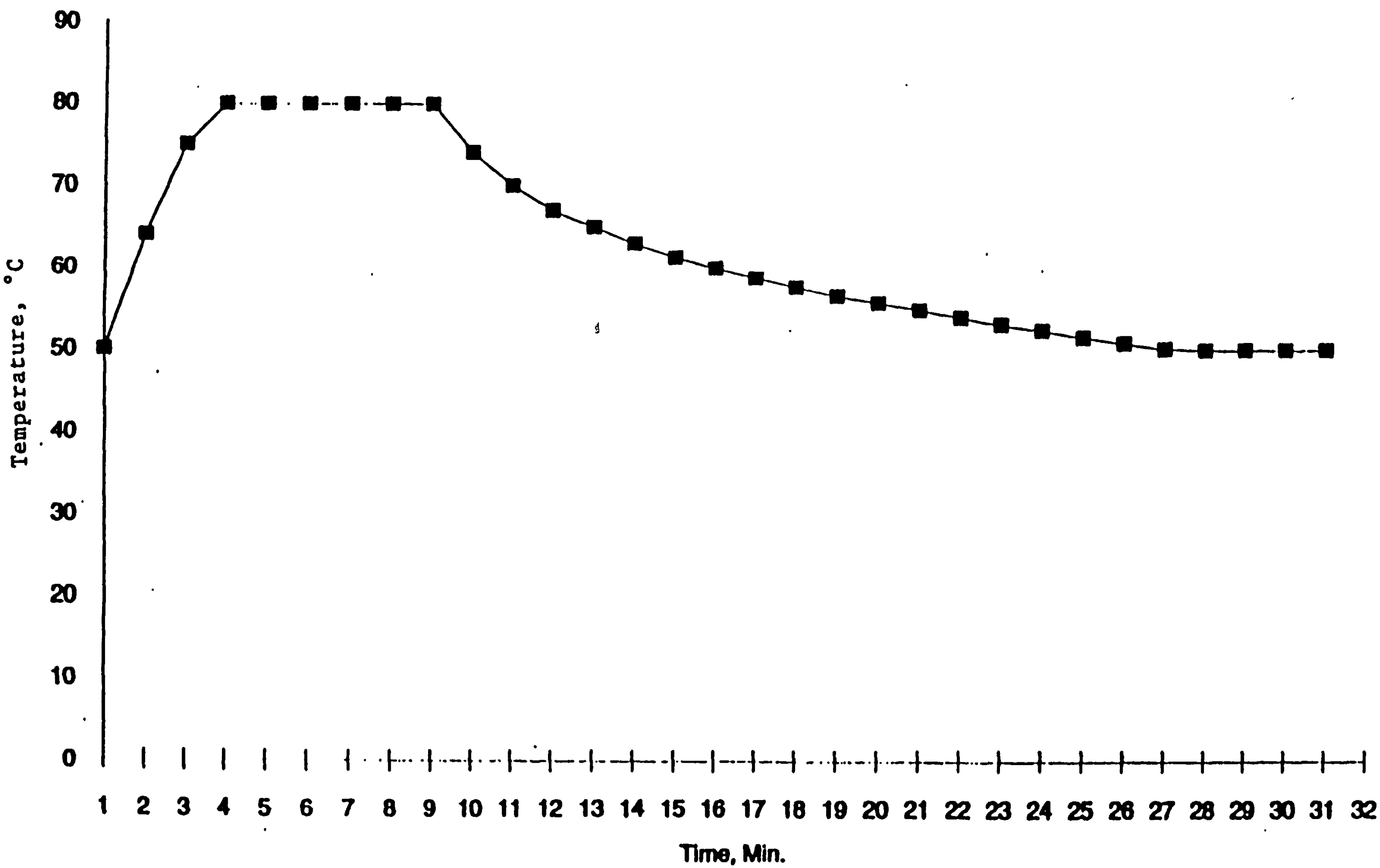


FIGURE 12: TEMPERATURE CYCLE PROFILE FOR ACCELERATED SMOKE DETECTOR HORN TESTS

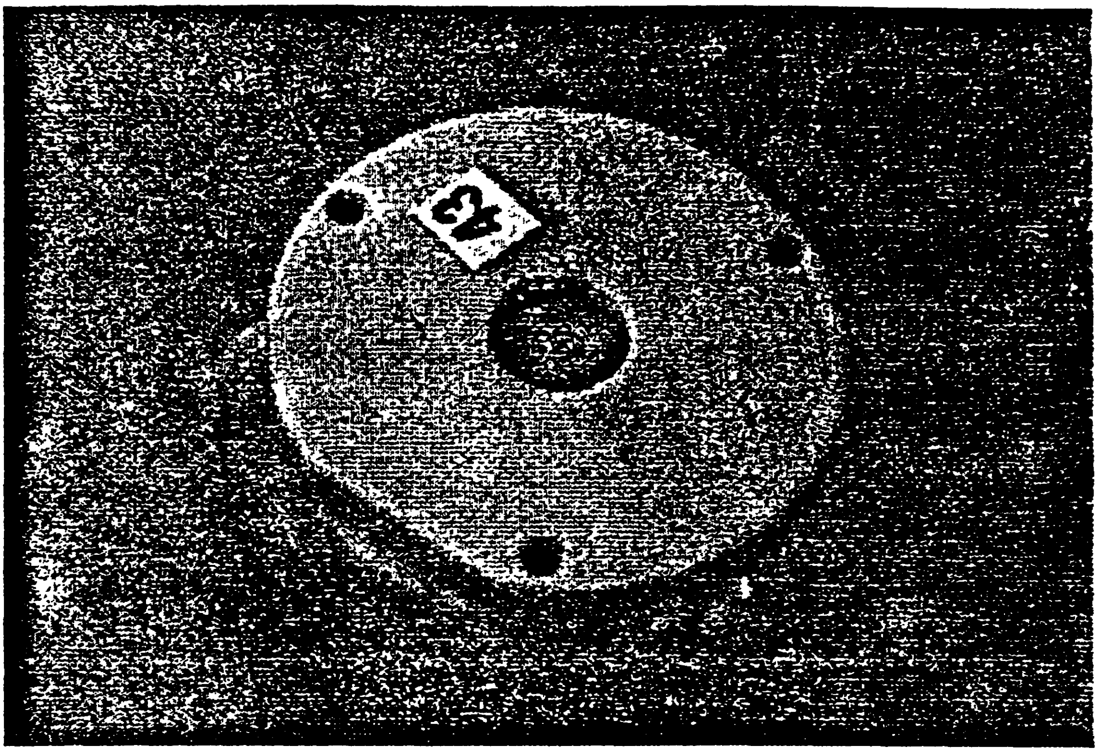


FIGURE 13a: TOP VIEW TYPE A HORN

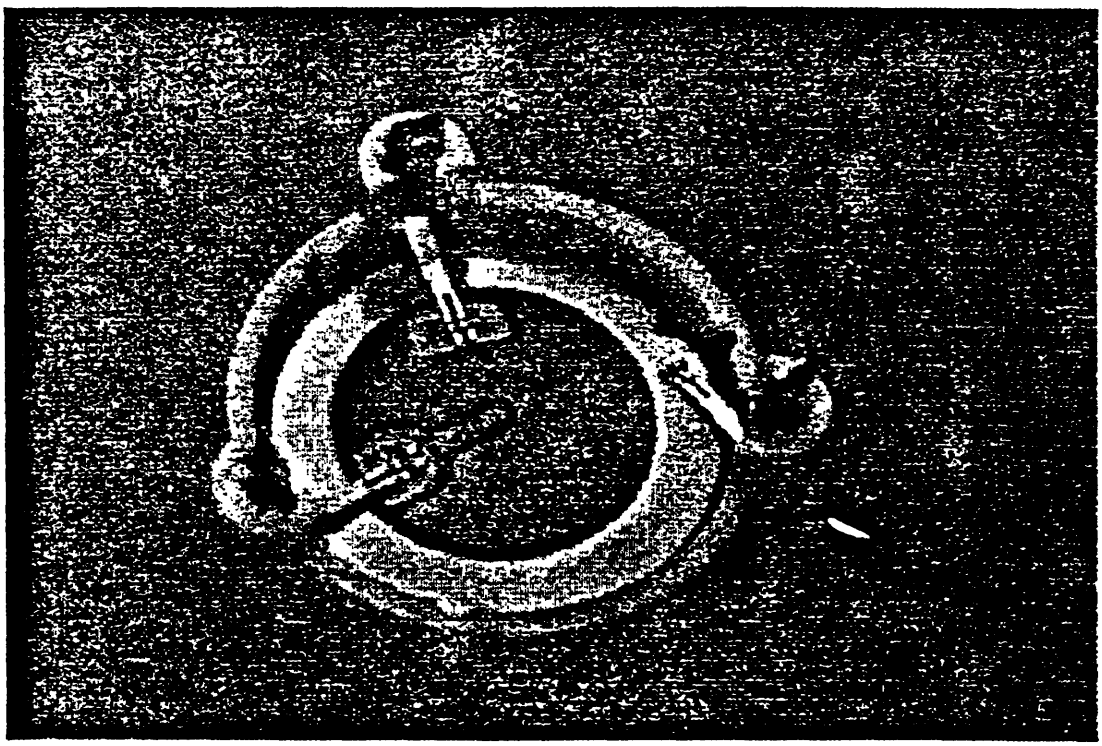


FIGURE 13b: BOTTOM VIEW TYPE A HORN

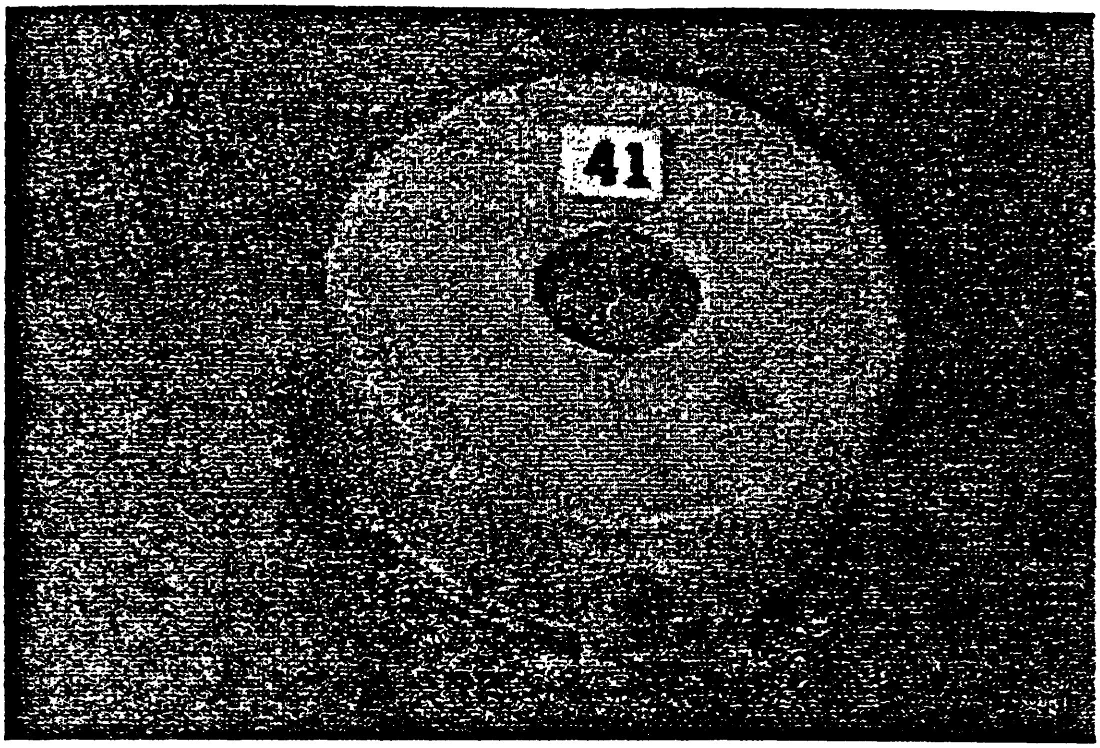


FIGURE 14a: TOP VIEW TYPE B HORN

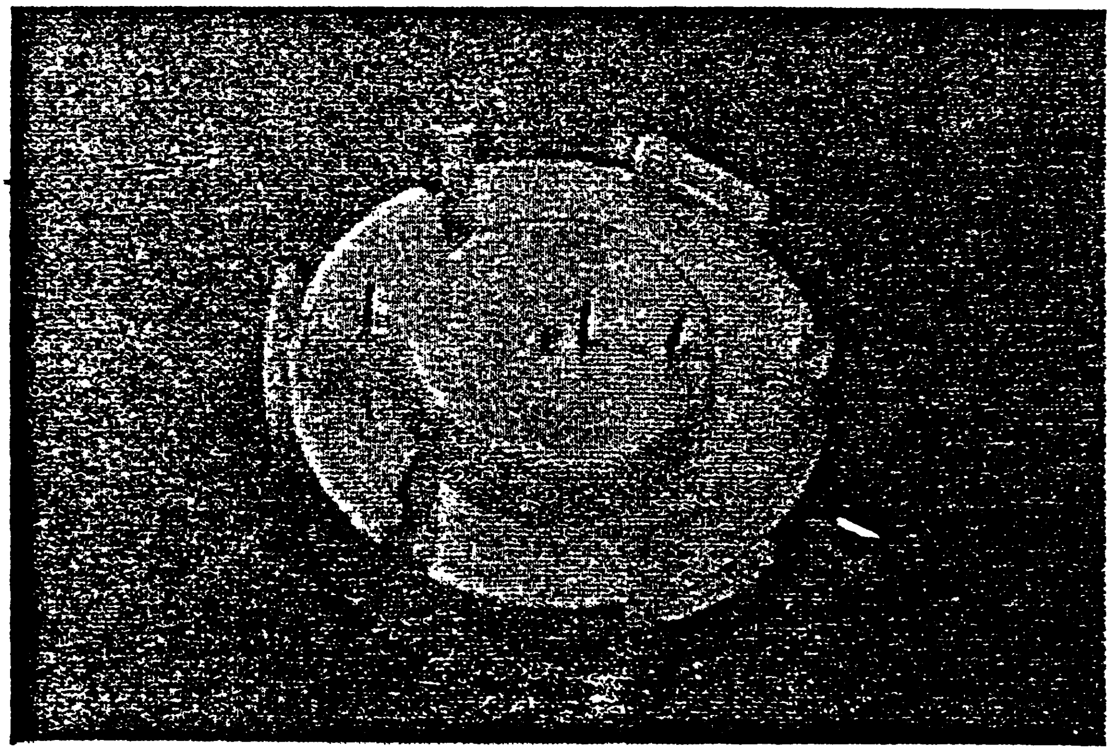


FIGURE 14b: BOTTOM VIEW TYPE B HORN

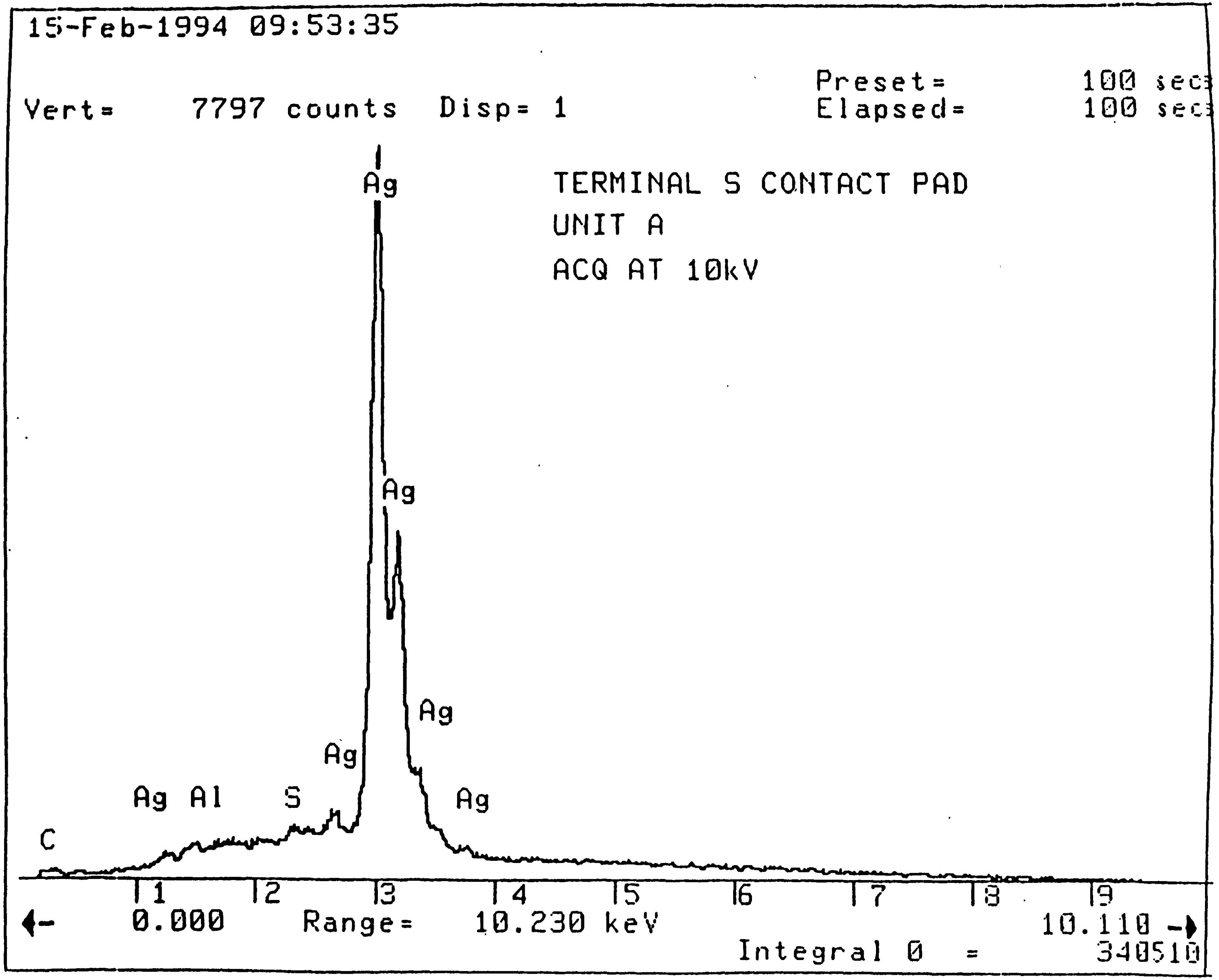


FIGURE 15: BEFORE CORROSION TEST - SO_2

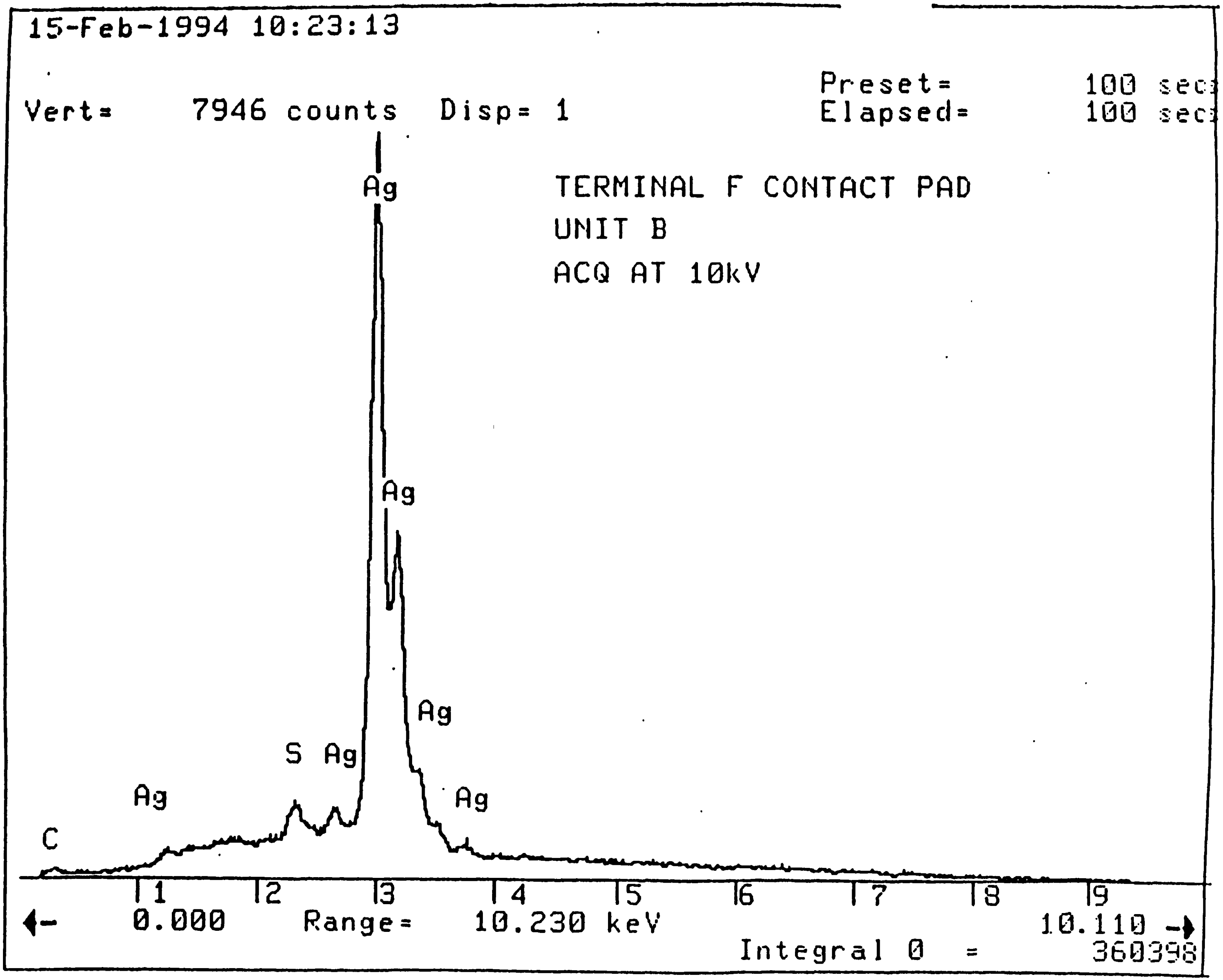


FIGURE 16: BEFORE CORROSION TEST - H_2S

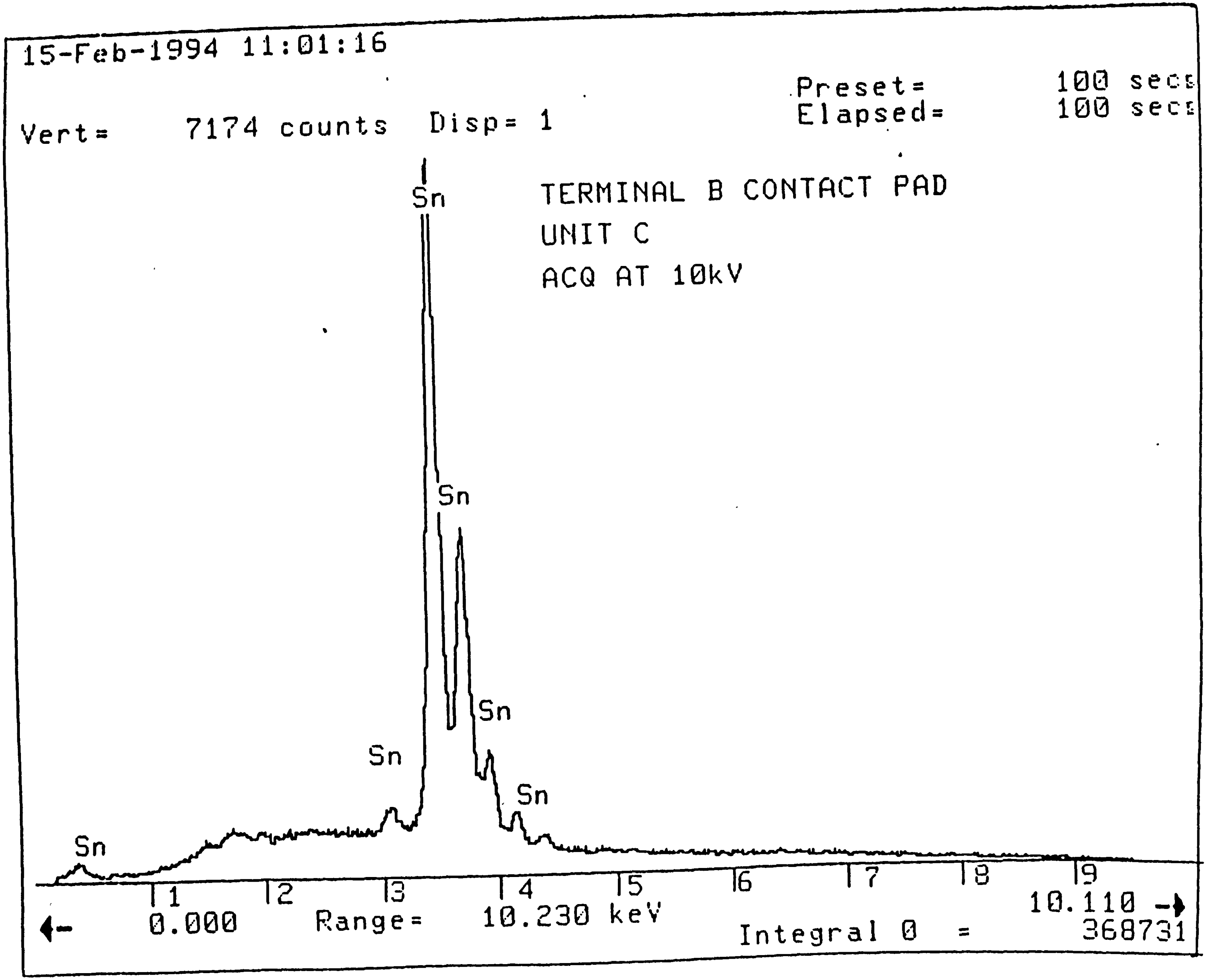


FIGURE 17: BEFORE CORROSION TEST - H_2S/SO_2

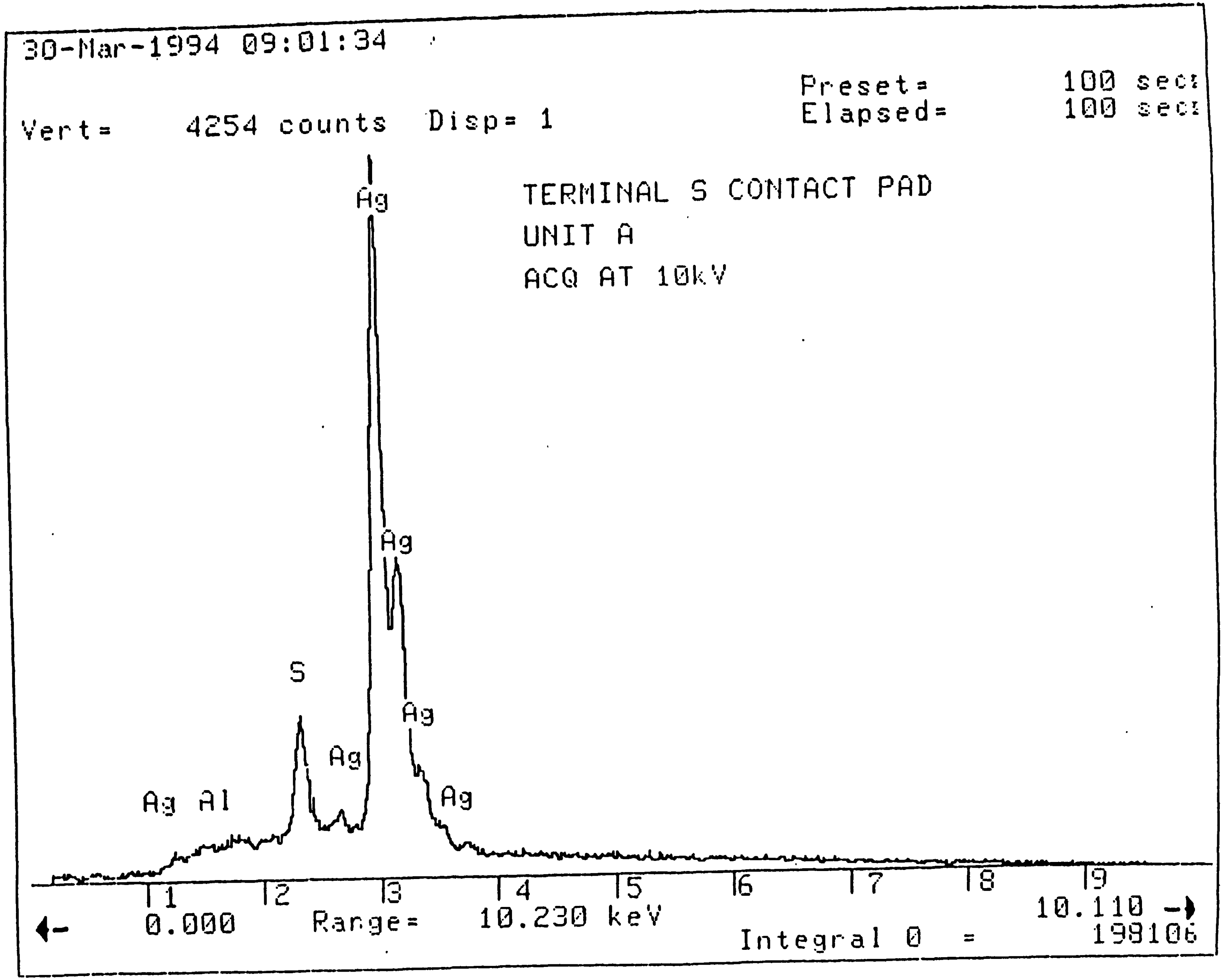


FIGURE 18: AFTER CORROSION TEST - SO_2

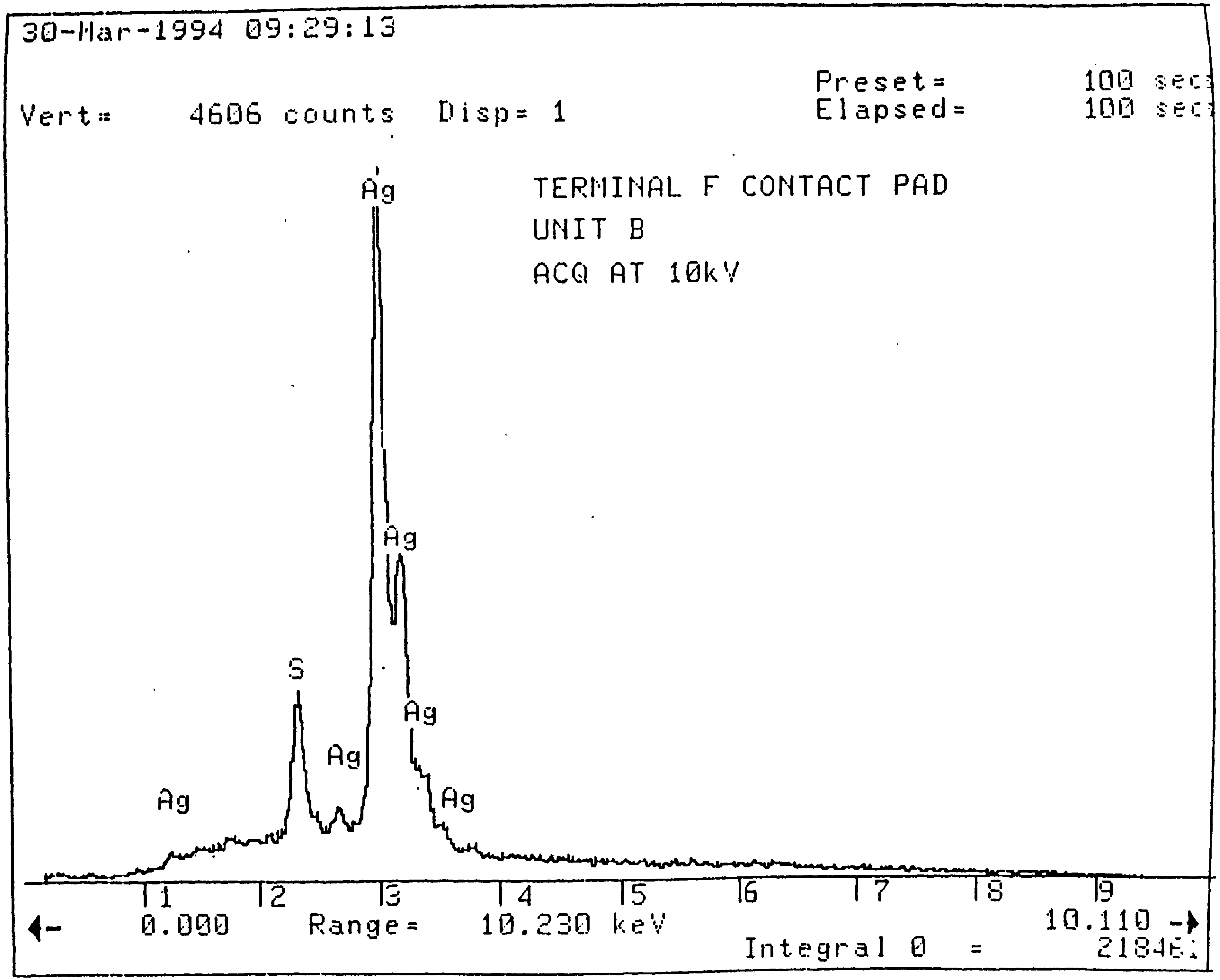


FIGURE 19: AFTER CORROSION TEST - H_2S

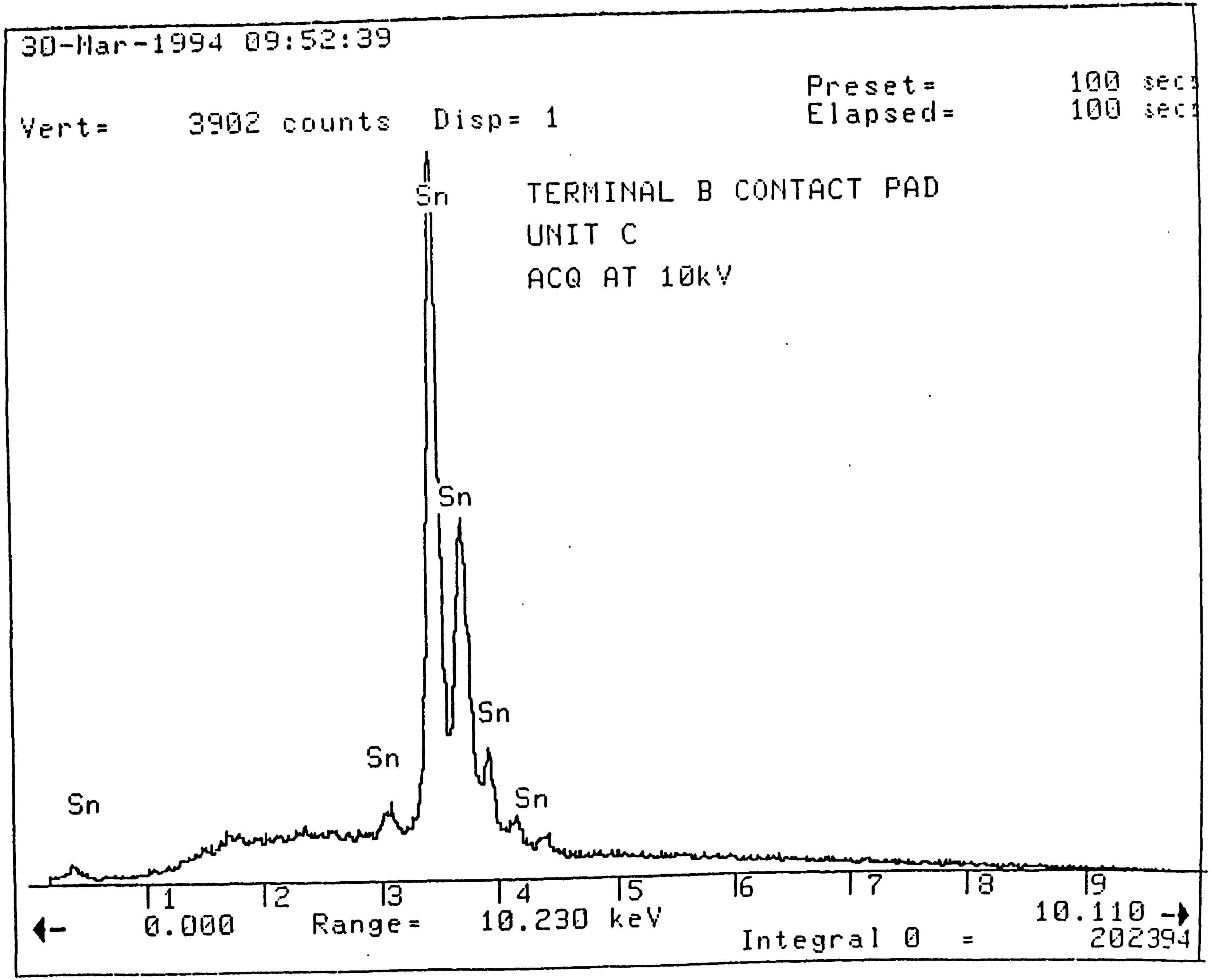


FIGURE 20: AFTER CORROSION TEST - H_2S/SO_2

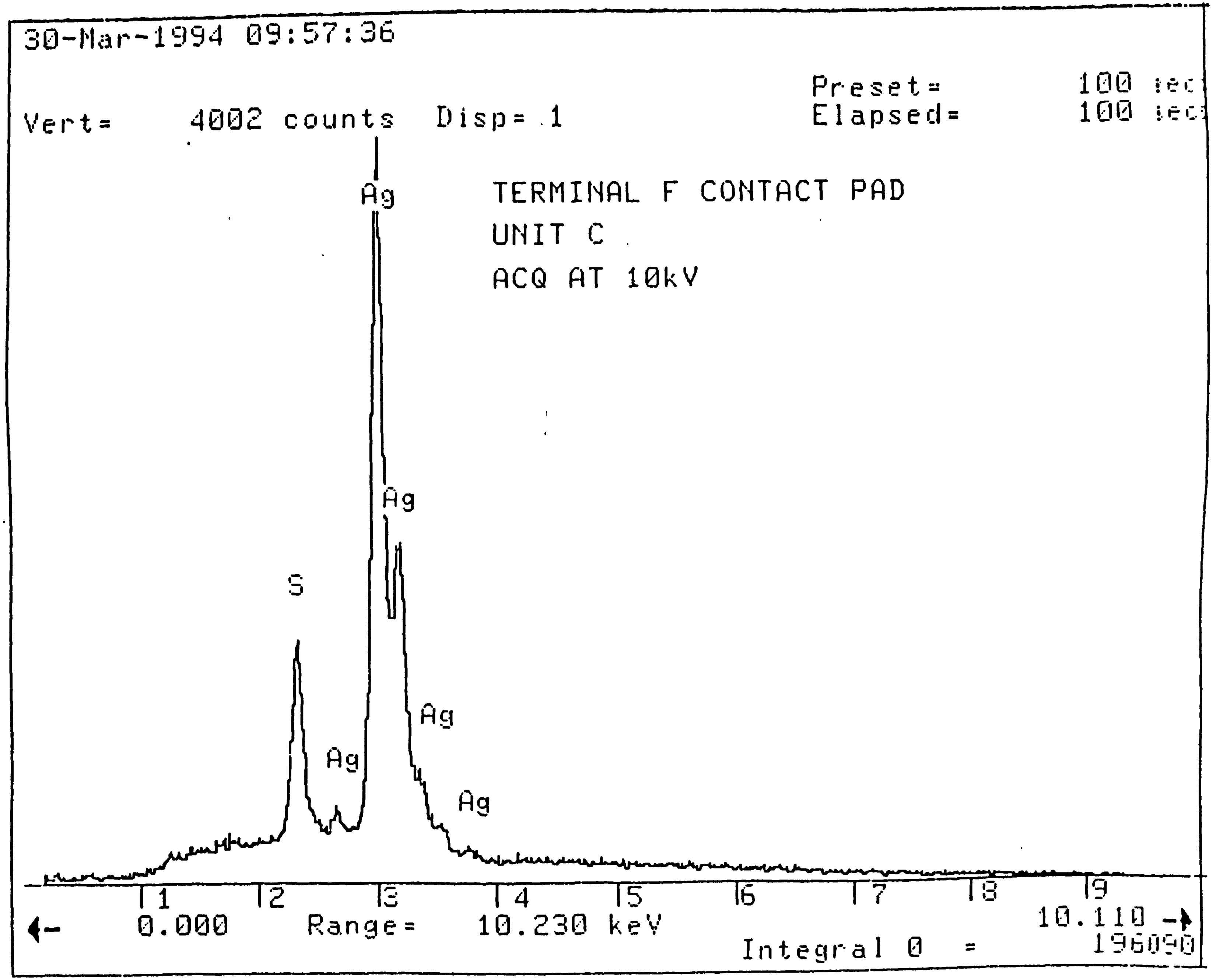
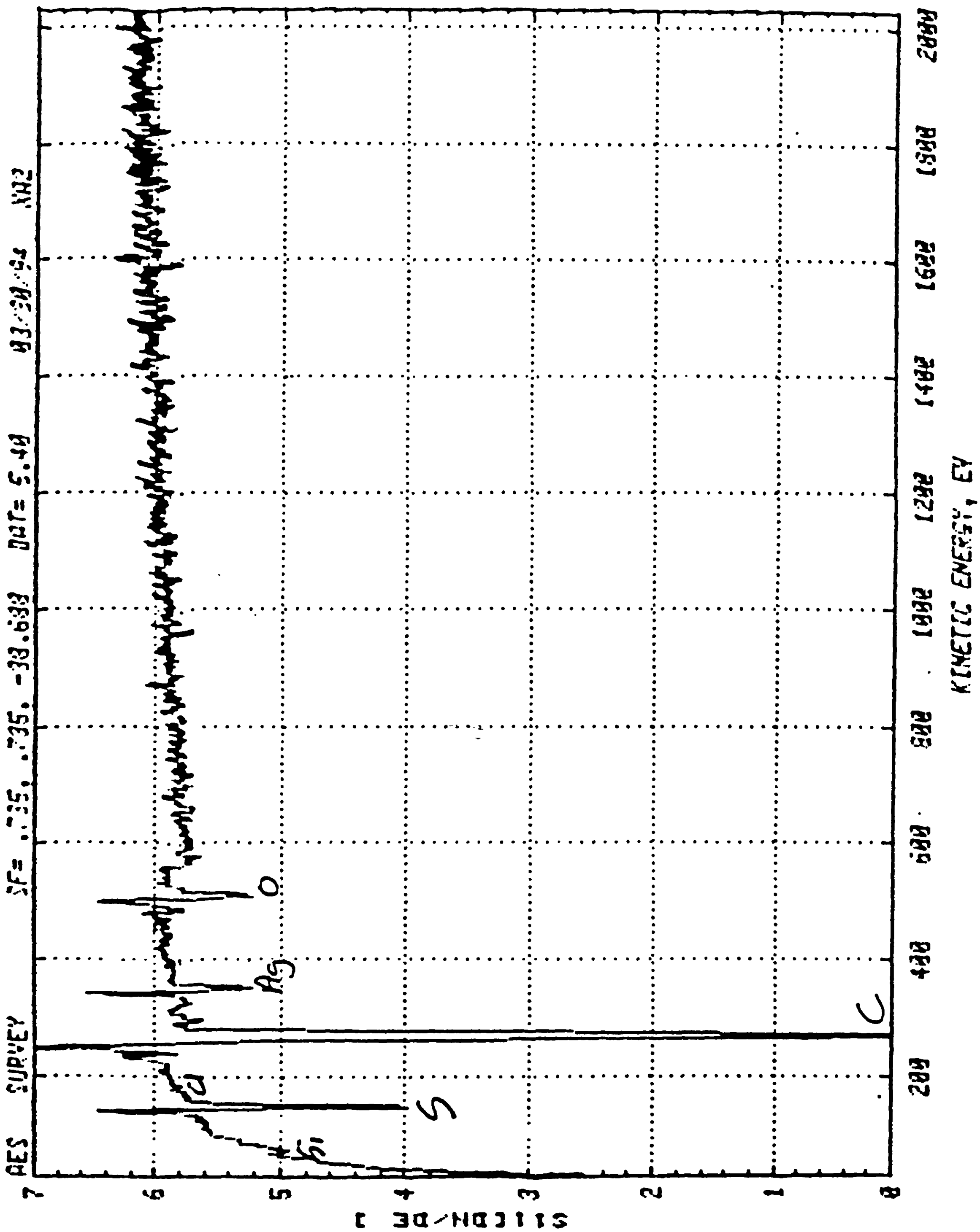
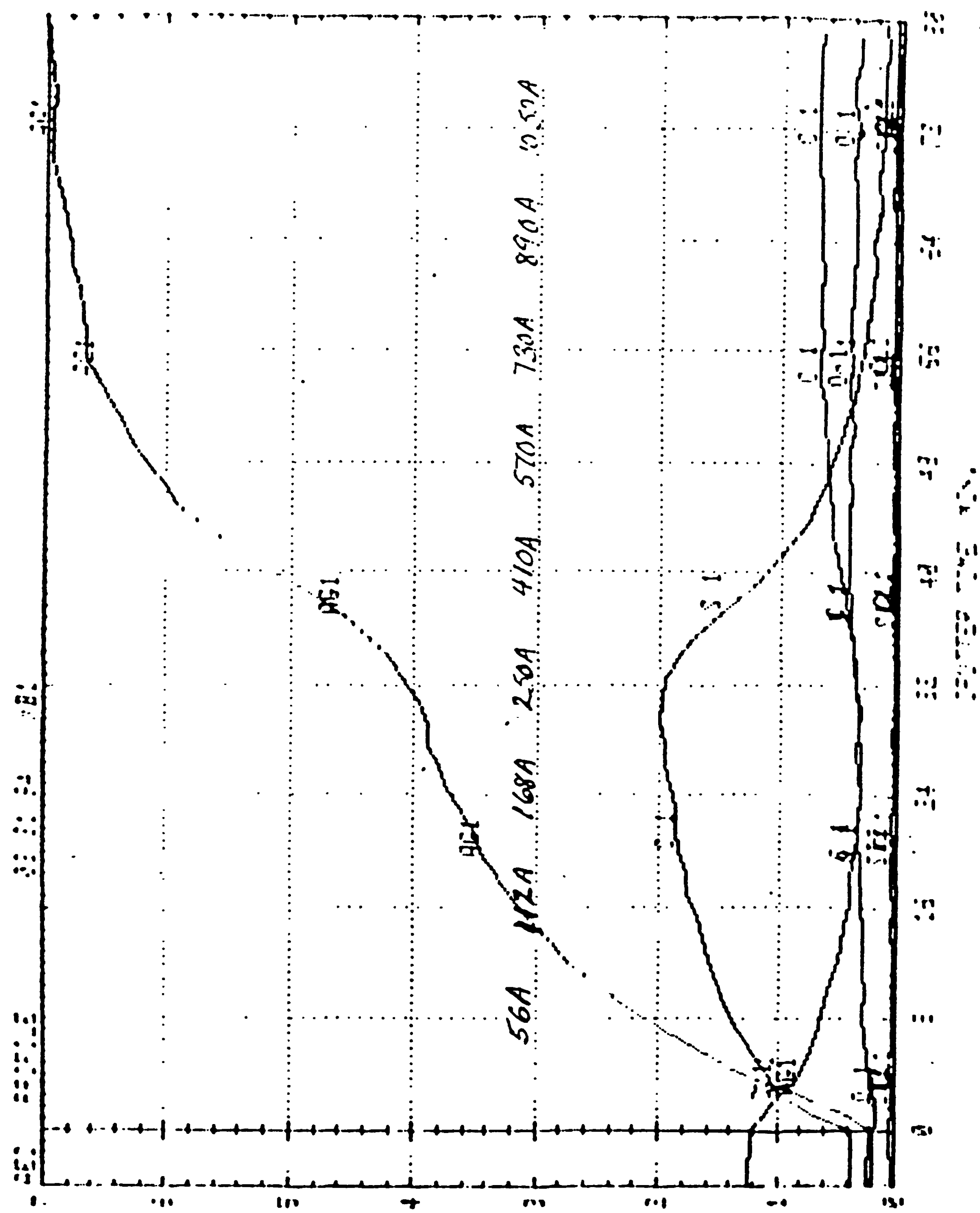


FIGURE 21: AFTER CORROSION TEST - H_2S/SO_2



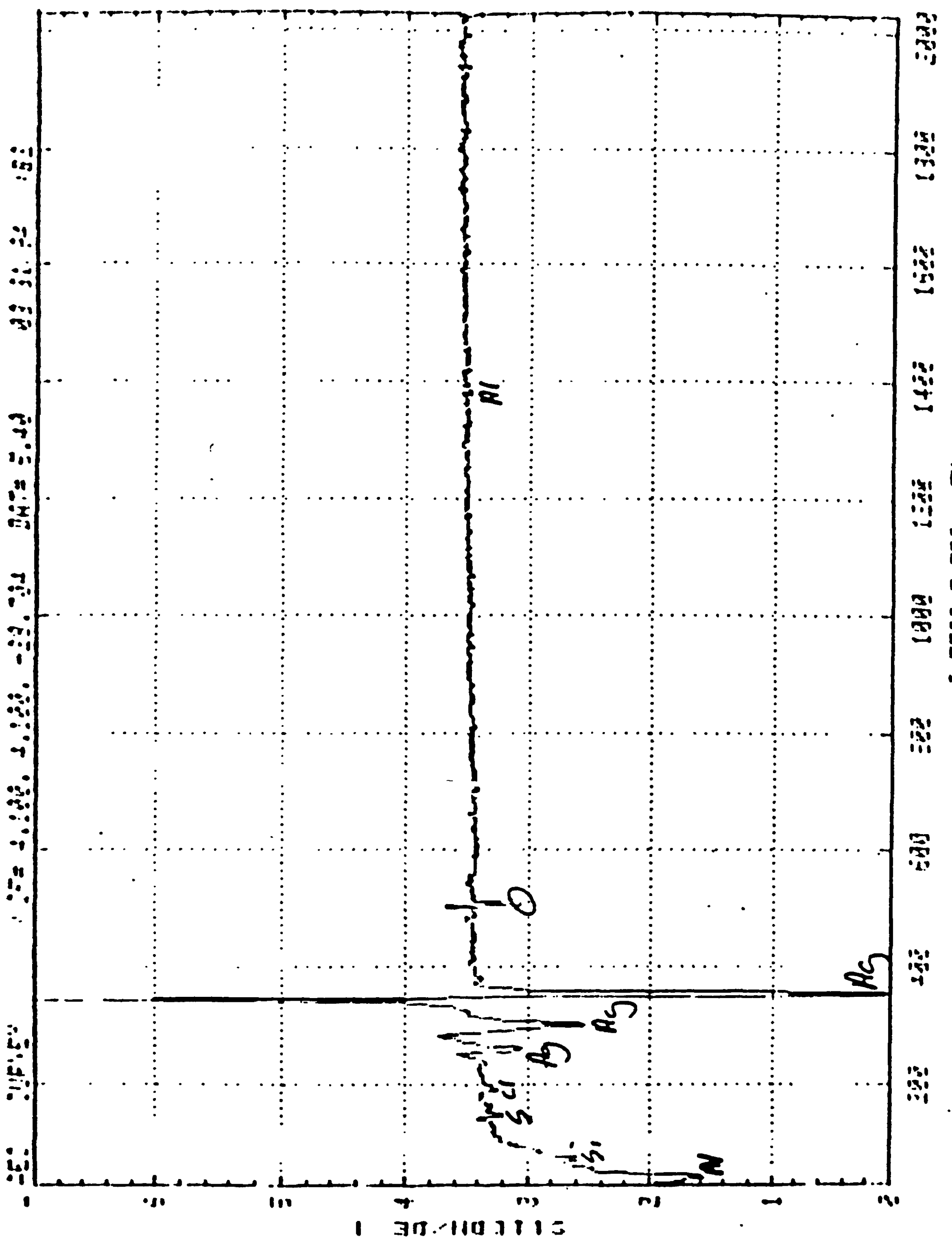
Auger elemental survey of Sample X, Terminal S

FIGURE 22



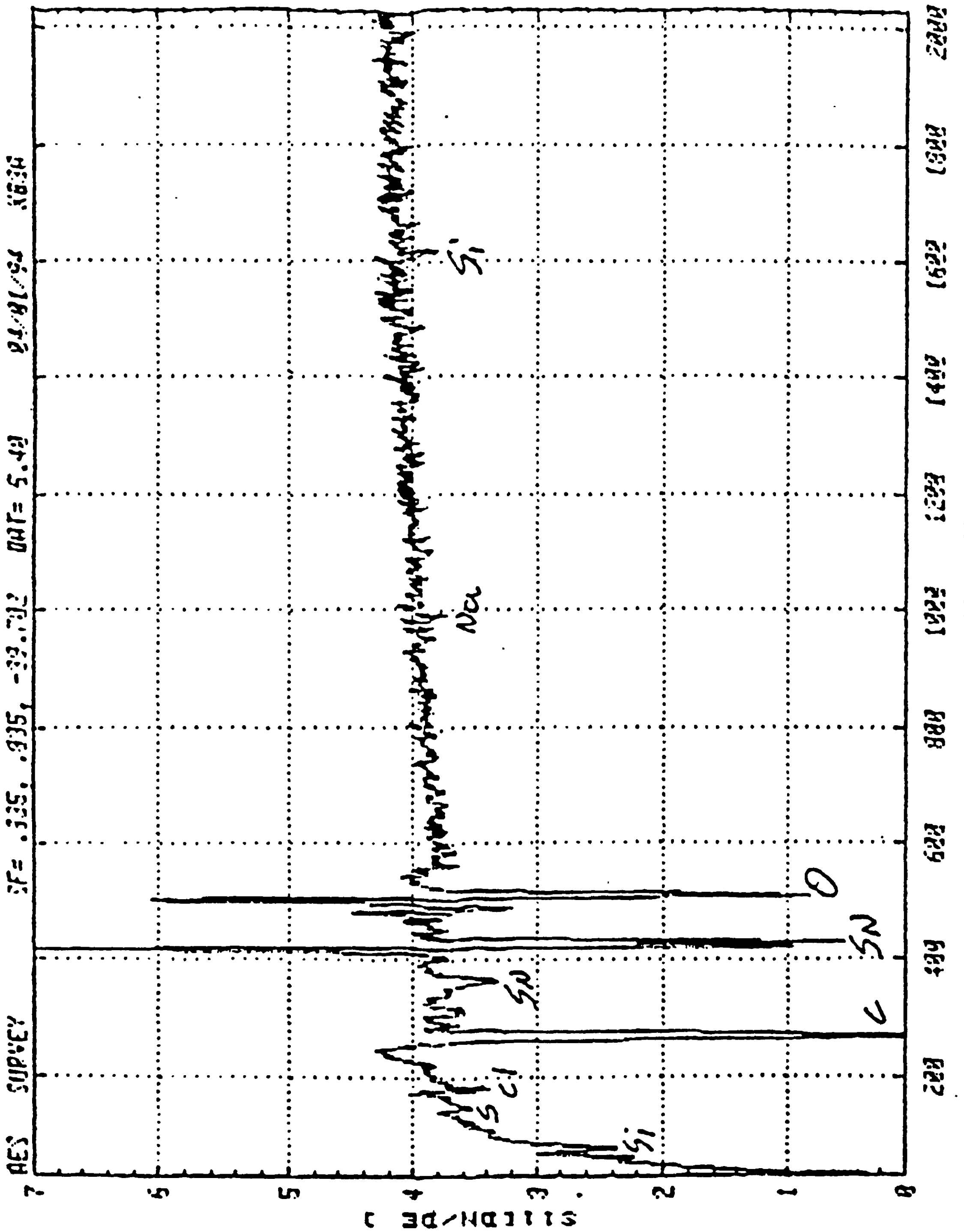
Auger depth profile of Sample X, Terminal S

FIGURE 23



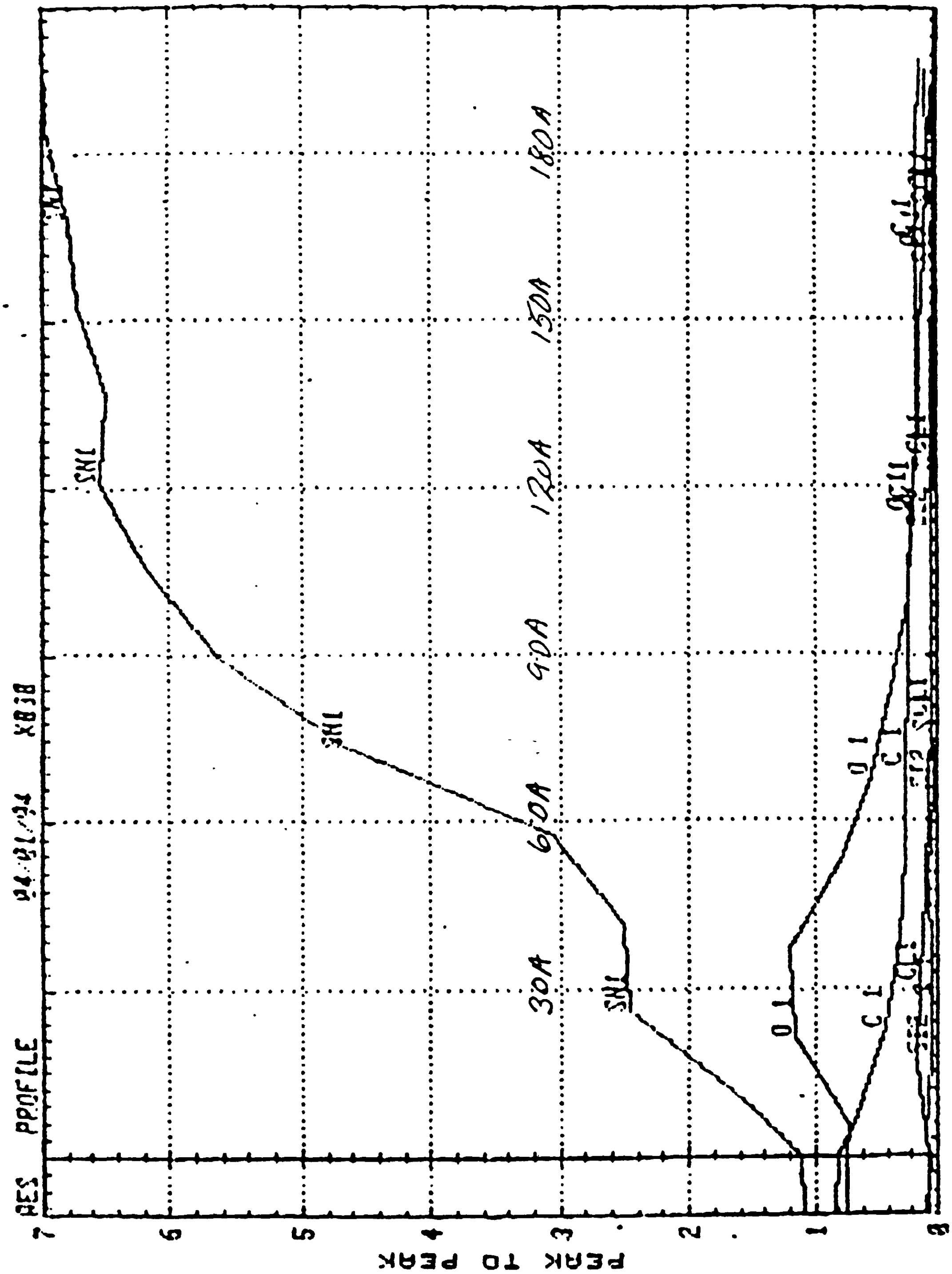
Auger elemental survey after profile of Sample X, Terminal S

FIGURE 24



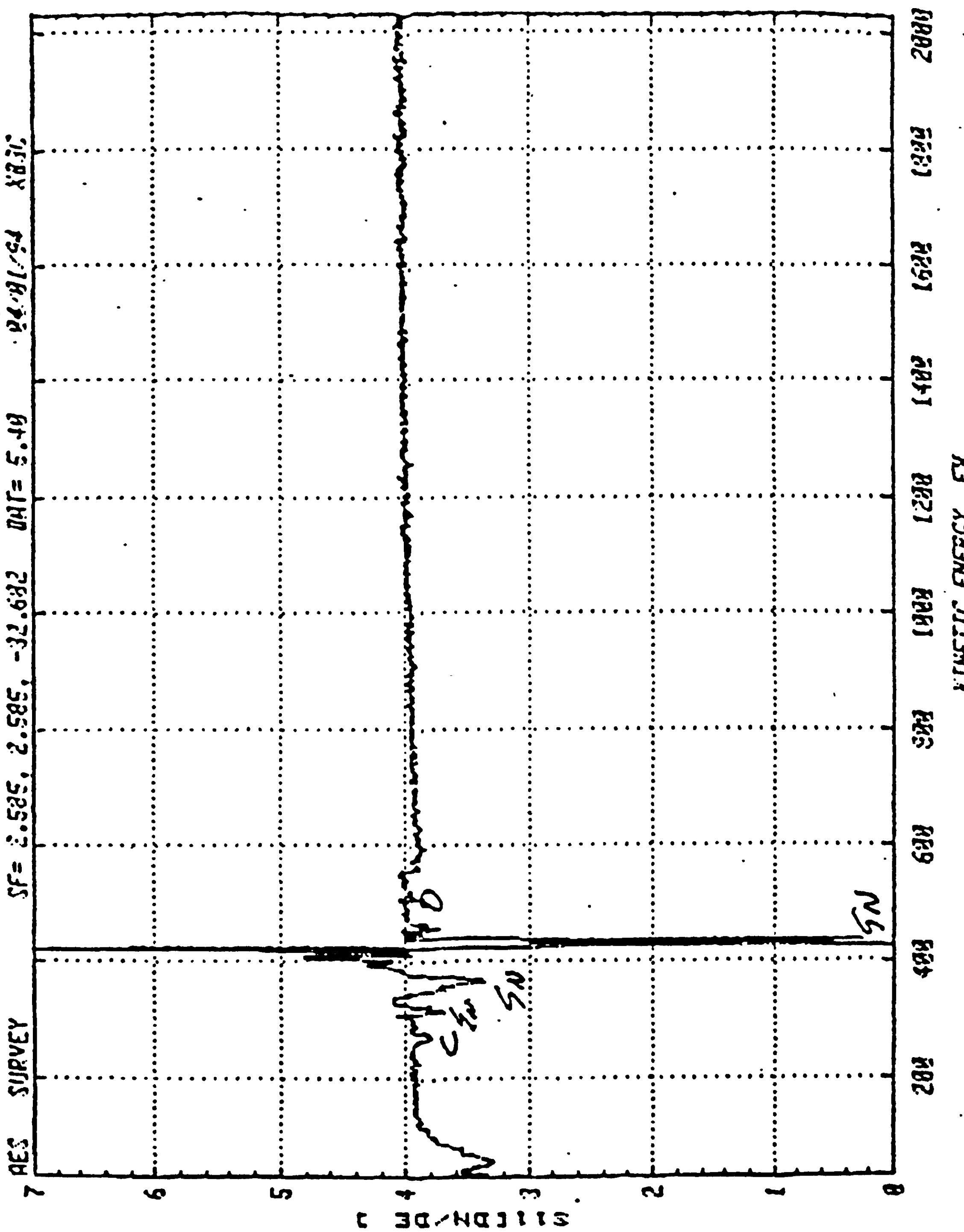
Auger elemental survey of Sample X, Terminal B

FIGURE 25



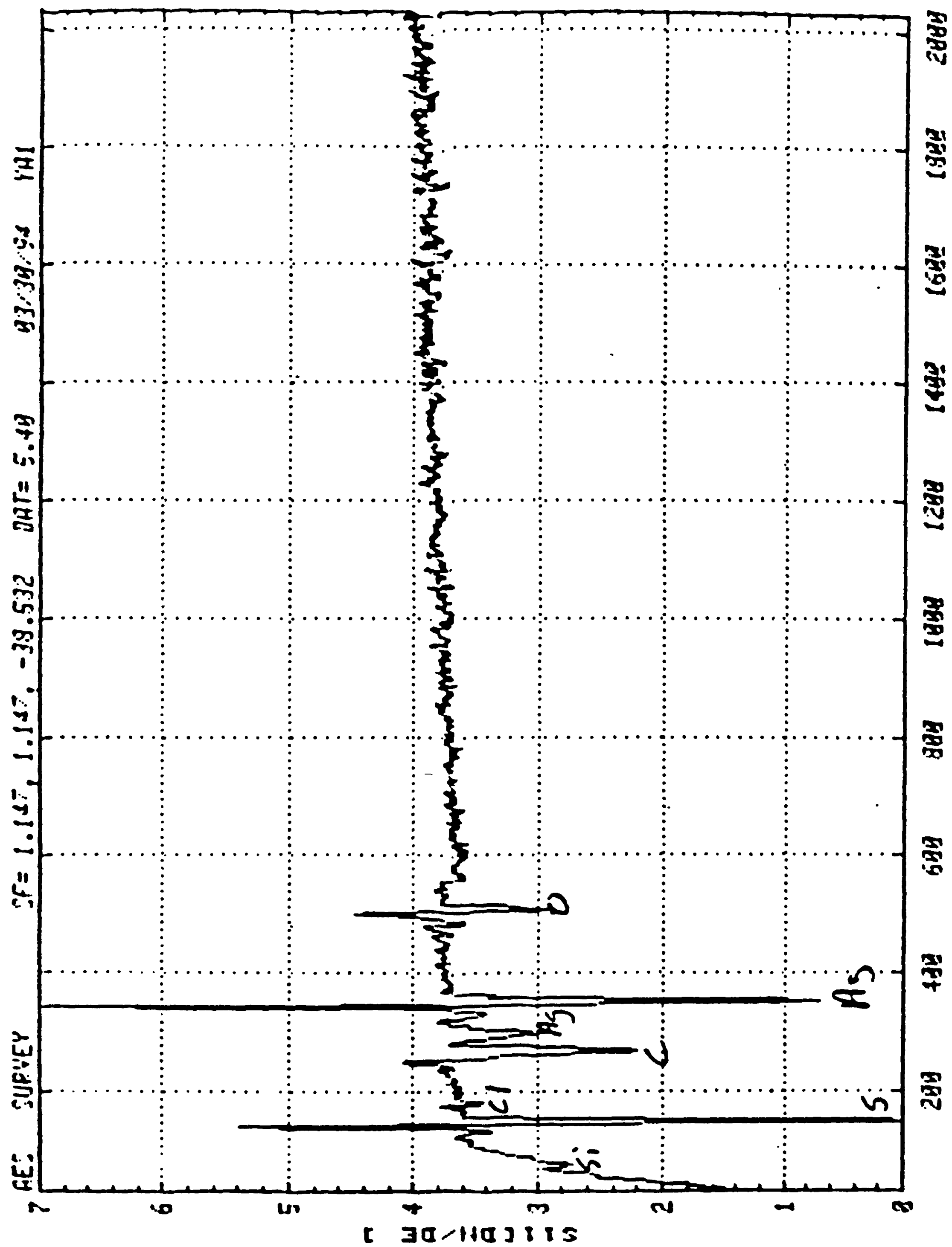
Auger depth profile of Sample X, Terminal B

FIGURE 26



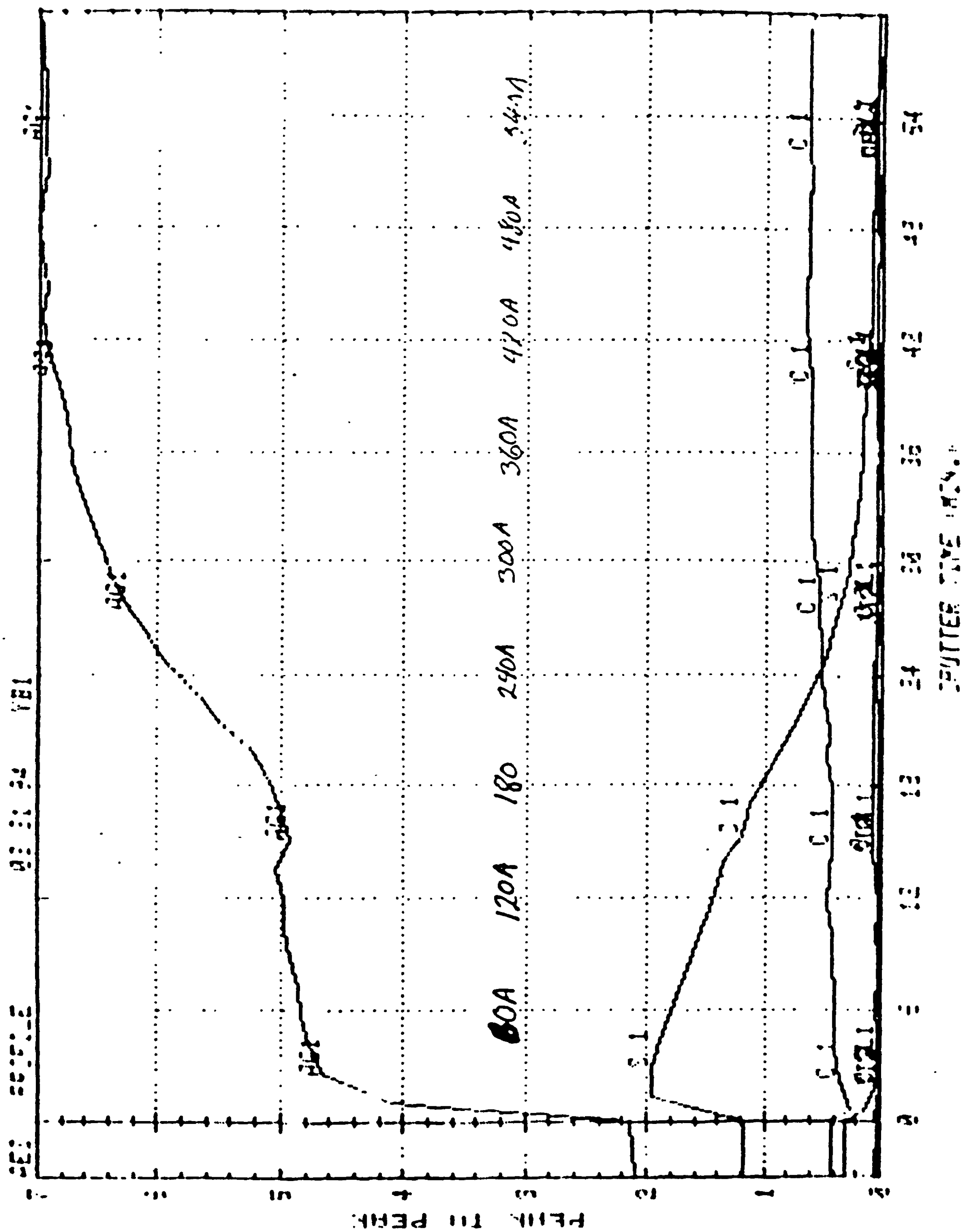
Auger elemental survey after profile of Sample X, Terminal B

FIGURE 27



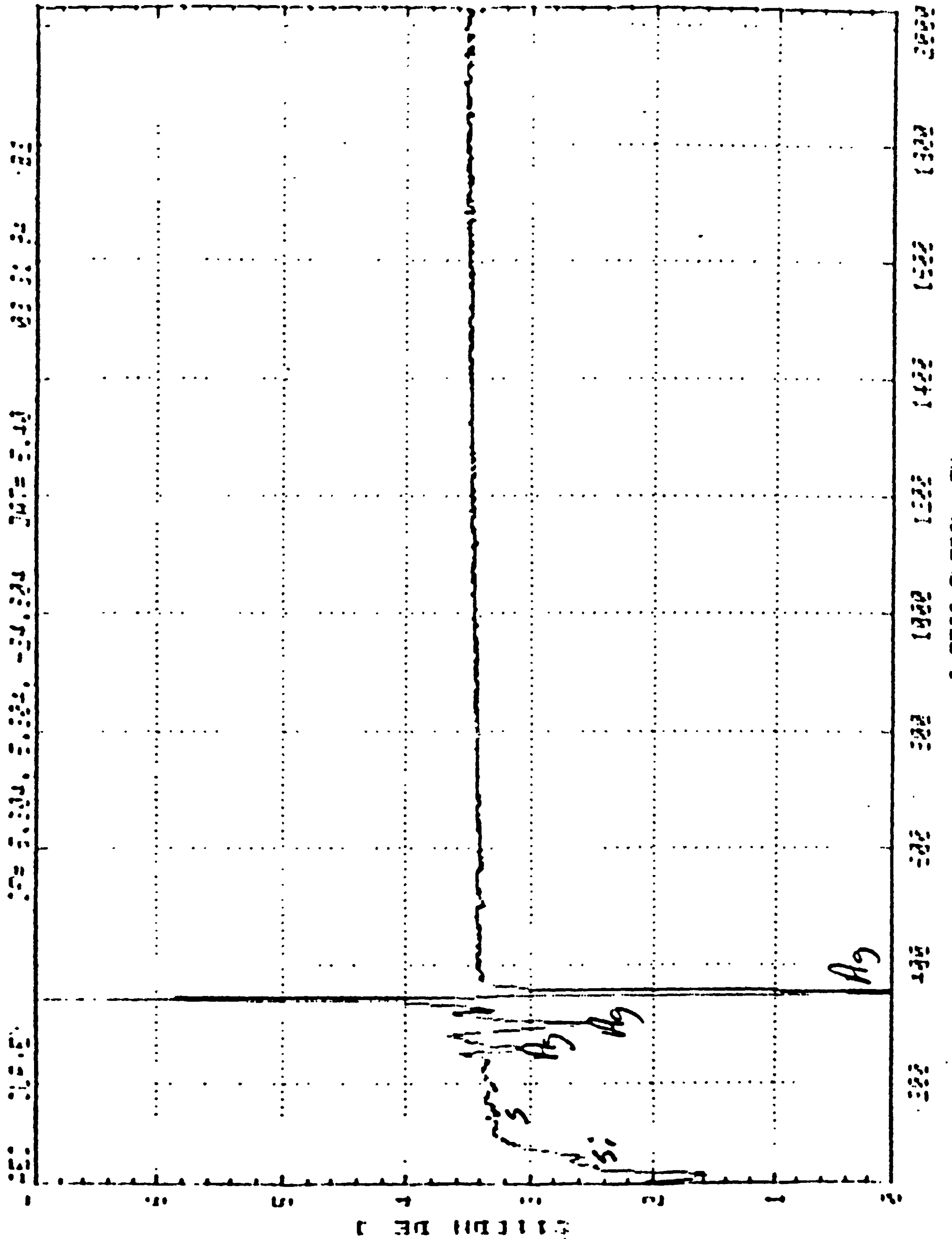
Auger elemental survey of Sample Y, Terminal S

FIGURE 28



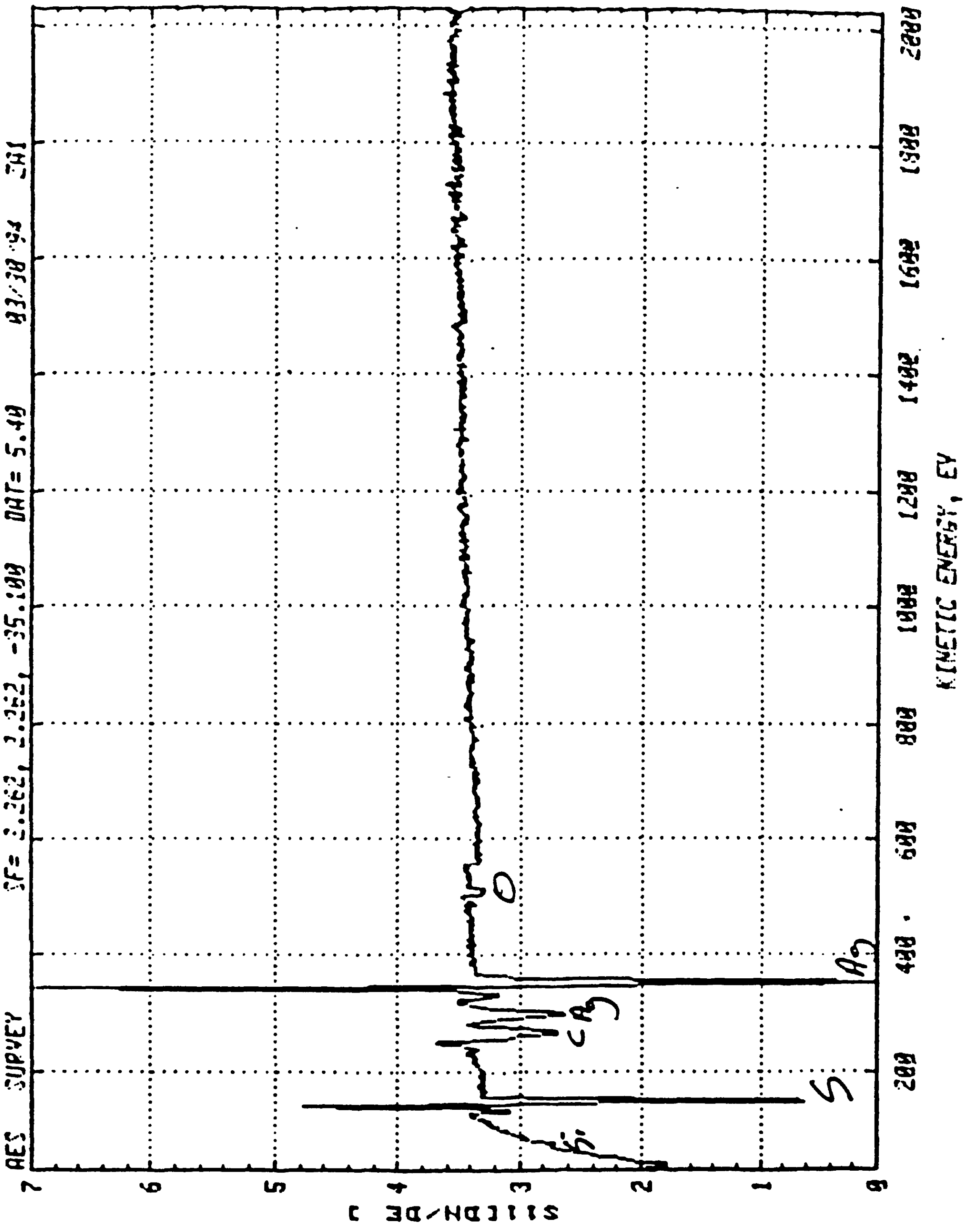
Auger depth profile of Sample Y, Terminal S

FIGURE 29



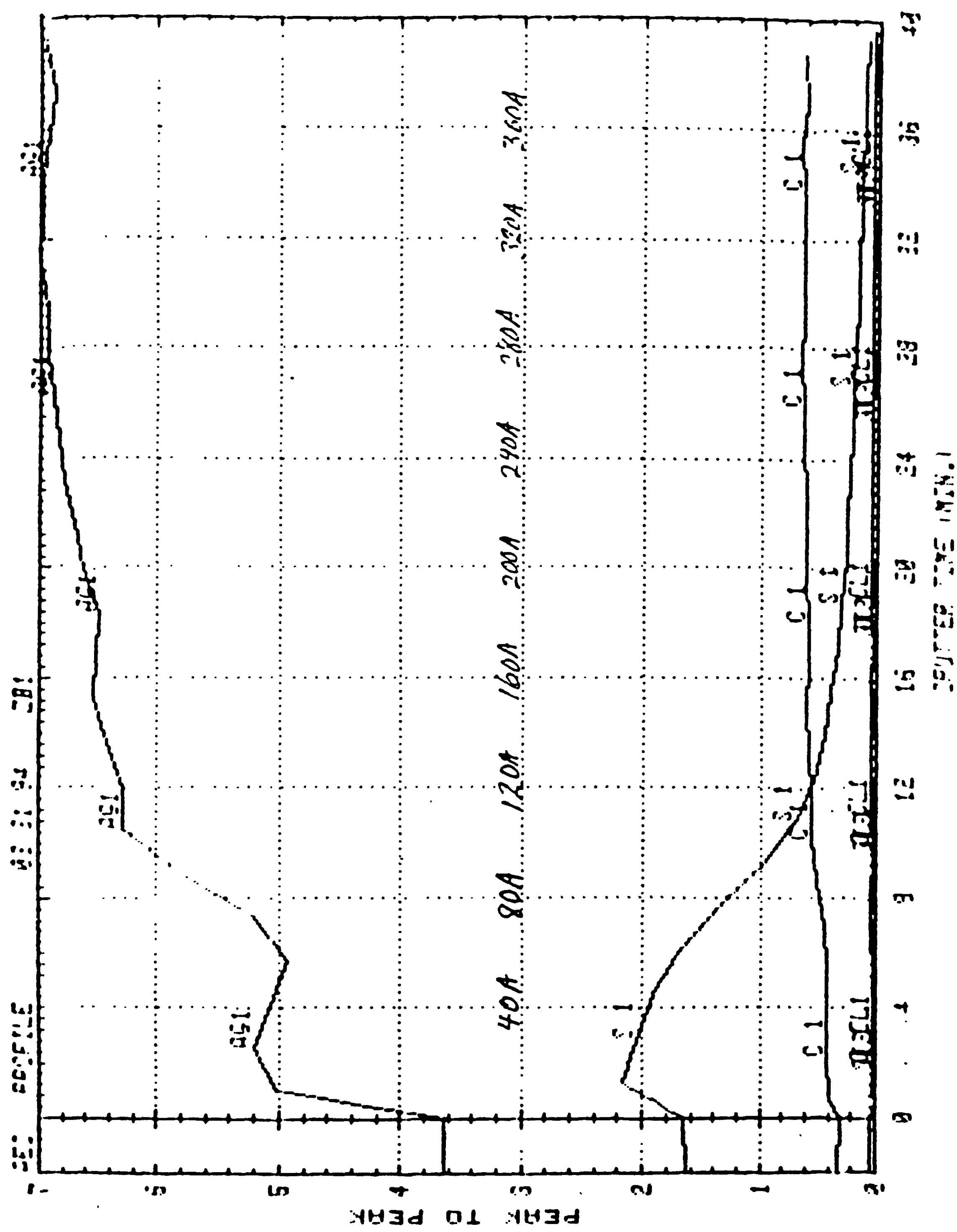
Auger elemental survey after profile of Sample Y, Terminal S

FIGURE 30



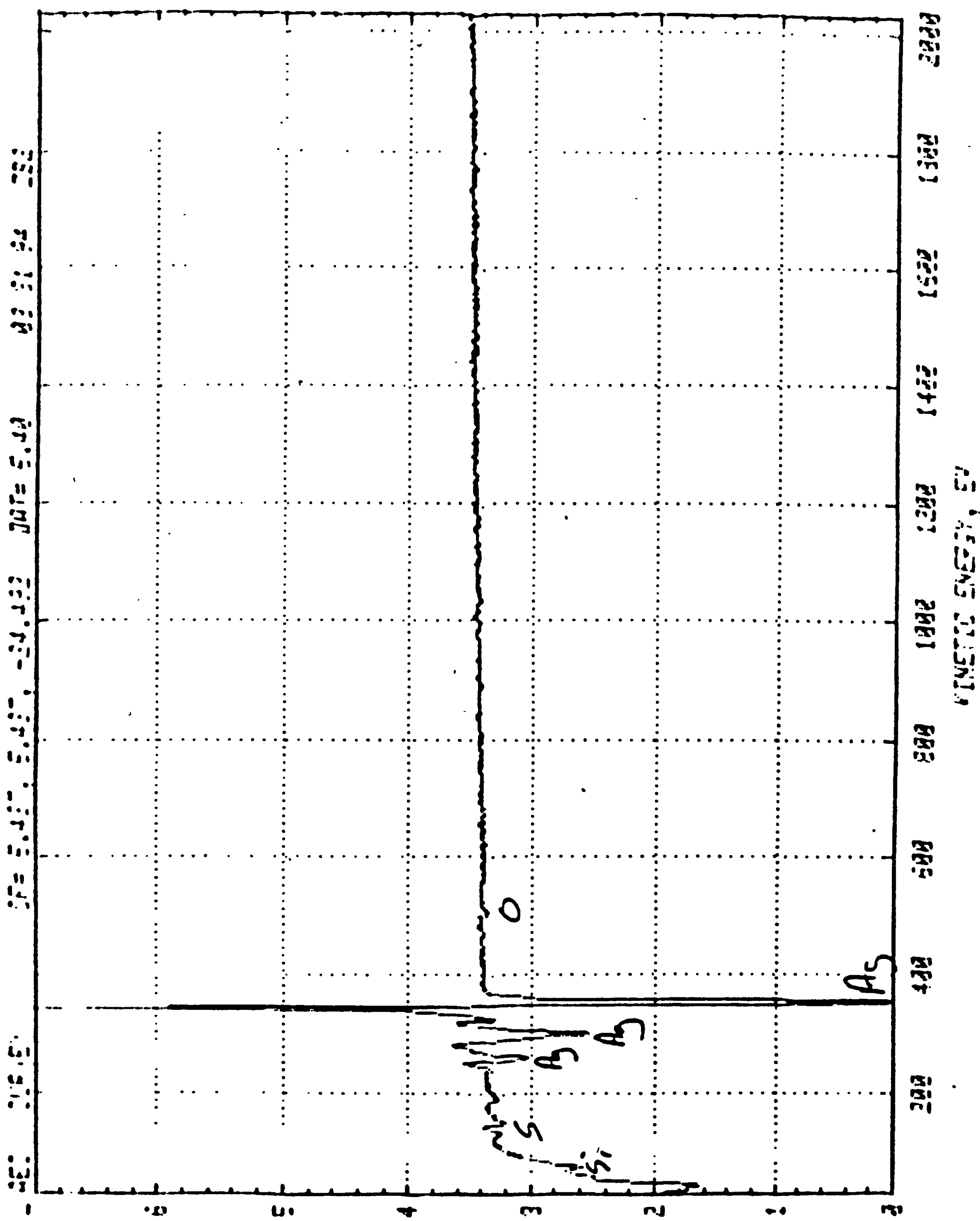
Auger elemental survey of Sample Z, Terminal S

FIGURE 31



Auger depth profile of Sample Z, Terminal S

FIGURE 32



Auger elemental survey after profile of Sample Z, Terminal S

FIGURE 33

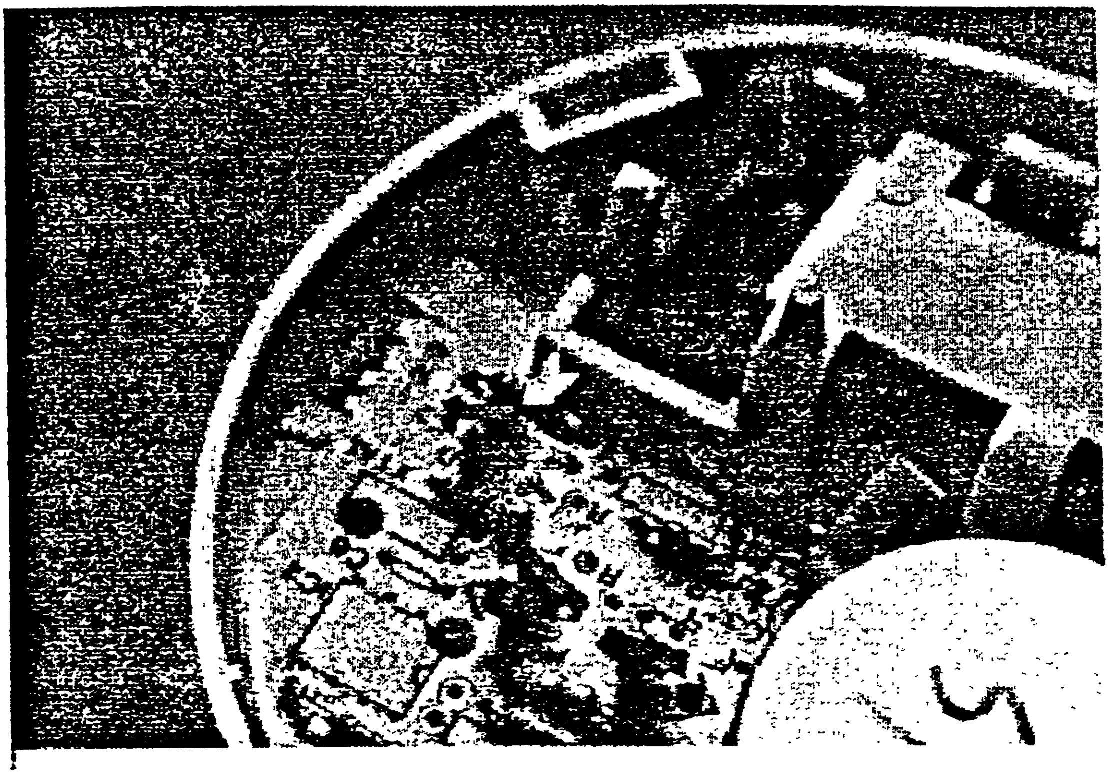


FIGURE 34: HORN CONTACTS ON SMOKE DETECTOR Z

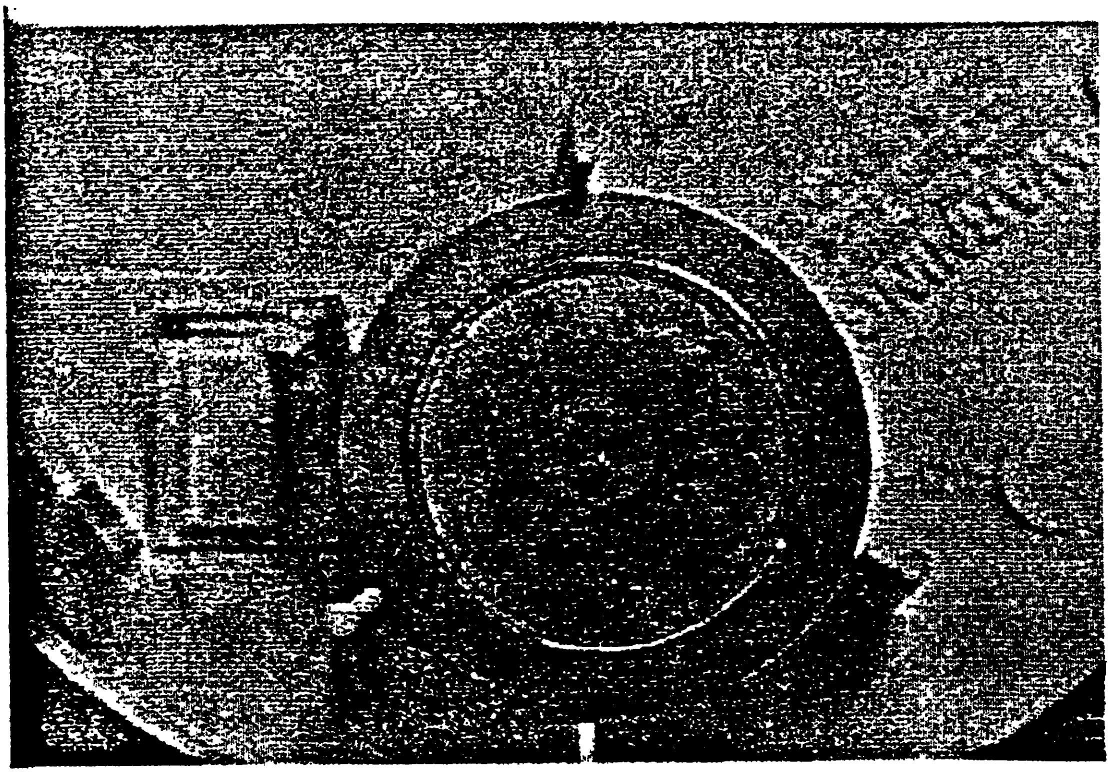


FIGURE 35: HORN ELEMENT IN SMOKE DETECTOR Z

FIGURE 36: CLOSE-UP OF CONTACT F ON HORN Z

APPENDIX B

TASK III & IV REPORT

June 28, 1994

STUDY OF DETERIORATION OF SEPARABLE ELECTRICAL CONTRACTS IN SMOKE DETECTORS

Contract No. CPSC-C-93-1139
IITRI Project No. A06393

TASK III AND IV PROTOCOL IMPLEMENTATION REPORT

Prepared for:

U.S. Consumer Product Safety Commission
Attn: Ms. Julie I. Shapiro/USCPSC
10901 Darnestown Road
Gaithersburg, MD 20878-2611

Prepared by:

Mr. John P. Farrell
IIT Research Institute
201 Mill Street
Rome, NY 13440-6916

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Task III and IV Report
Critique and Recommendations
For Additions/Changes to UL217

1.0 INTRODUCTION

The information developed in Tasks I and II was used to perform Task III of the CPSC smoke detector program that required a review and evaluation of UL217 "Standard for Single and Multiple Station Smoke Detectors" to identify inadequacies. Also, a comparison of the corrosion and deterioration of naturally aged smoke detectors with UL217 accelerated aged smoke detectors was to be made. The findings of Tasks I, II and III are to be used to develop recommendations for the improvement of UL217. This report describes those weaknesses identified in UL217 which permit separable contacts that deteriorate in the field to meet the requirements of the standard. Recommendations are provided to ensure that smoke detectors operate satisfactorily over the expected life time. The Task III and IV reports have been merged for clarity and because the corrosion testing results and evaluation are included in greater detail in the Task II report.

During the review of UL217 both minor an major items were noted. The major items are covered in the main body of this report and the minor items are reported in Appendix A.

The major items to be discussed are:

- Corrosion testing
- Separate qualification procedure/standard for horns (referred to as the alarm sounding appliance in UL217)
- Horn damage during routine handling
- Reliability prediction
- Self wiping contacts, contact lubricants and soldered contacts

2.0 CORROSION TESTING

Six new smoke detectors were supplied to IITRI by CPSC for standard corrosion testing specified in UL217 (para. 62.1.2 and 62.1.3). The detailed results of this testing are discussed in the March 1994 monthly report number 6 and the Task II report.

Three corrosion tests using two horns in each test were run. These corrosion tests were:

1 - Standard 10 day SO_2 test
2 - Standard 10 day H_2S test
3 - 10 day combined H_2S and SO_2 test

After completion of the corrosion testing all six smoke detectors functioned properly. Surface analyses and depth profiles were then run on the contacts and contact pads. The horn configuration includes separable contacts B, F and S identified in a conceptual cross section drawing (Figure 1). Only the silver plated contact pads of terminals F&S showed any signs of sulfur. The depth of the sulfur layer ranged from 80Å (angstroms) on the units exposed to SO_2 to 400Å on units exposed to the combined gases. Units tested with H_2S only had a sulfur level of 180Å. On the basis of the above the SO_2 test is not needed. The H_2S or the combined testing would only be marginally useful for the silver plated contacts and useless for the non-silver contact pair (Terminal B).

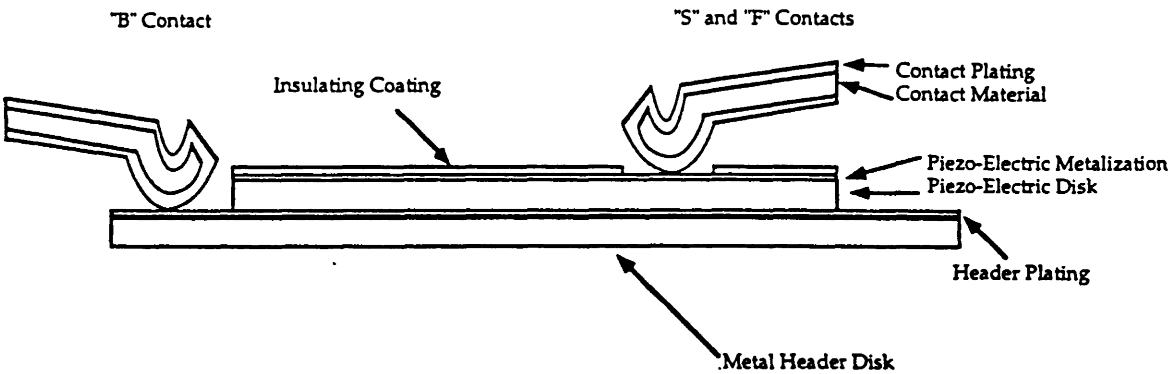


FIGURE 1: CONCEPTUAL CROSS-SECTION OF HORN DISK AND CONTACTS

However, the results of the analysis of smoke detectors submitted to standard corrosion testing does not agree with the SEM analysis of contaminants on the separable contact surfaces, selected from smoke detectors that failed in the field. The field results revealed that both sulfur and chlorine were prominent. Additionally, contact resistances measured after the corrosion testing were much lower than the measurements taken on contacts from smoke detectors that failed in the field.

It was established in this effort's testing and reported on in monthly reports that fretting corrosion was the major failure mechanism involved with the deterioration of smoke detector horn separable contacts. Fretting corrosion is one of several corrosion mechanisms (e.g., pore corrosion, corrosion product creep) that can occur at connector interfaces. The generation of fretting corrosion products requires two conditions. The presence of contaminants and relative motion between the two halves of the contact. Temperature cycling is the major cause of relative motion between the separable contact halves because the horns are constructed of materials (plastics, metals, ceramics) that have different thermal coefficients of expansion.

The summarization of this effort's testing results leads to the conclusion that the UL217 corrosion testing does not simulate the field environment that smoke detectors are exposed to in an accelerated manner. Therefore, it is recommended that the Battelle Flowing Mass Gas (FMG) technique replace the existing corrosion testing of UL217. Many of the environmental tests in use today including the UL217 corrosion testing, employ single gases, either H_2S or SO_2 and employs these two gases sequentially not in combination. Analysis of these tests results in general have not been correlated with field results. Battelle studies indicate that the films generated by mixed gas testing appear to have similar chemistries and electrical effects to those from field experience[1]. Table 1 illustrates the various environments defined for FMG testing. The majority of the data collected has been from results using test/class III. The gas mixture for test/class III consists of 100ppb of H_2S, 20ppb of Cl_2 and 200ppb of NO_2. The test is run at 70% relative humidity with an operating temperature of 30°C. The purpose of using mixed flowing gases is to take advantage of their interaction to accelerate film growth over single gas testing. NO_2 in particular[2] acts as a catalyst in the film growing process.

TABLE 1: FMG ENVIRONMENTS BY COMPOSITION

Test/Class	Gas Concentration, ppb			% RH	T, °C
	H_2S	Cl_2	NO_2		
I	-	-	-	-	-
II	10	10	200	70	30
III	100	20	200	70	30
IV	200	50	200	75	50

More recently[3] it has been demonstrated that amorphous SiO_2 can be formed on contact interfaces in the presence of silicone vapors causing the growth of a glass non-conductive film. Since silicone vapors are common by-products of the decomposition of oils, rubbers, etc., and since silicon and oxygen were present in many of the surface analyses this mechanism cannot be ruled out at this time.

It is further recommended that a test program be defined to evaluate new coating and contact technologies and the effect of using temperature cycling during FMG testing. This testing would further refine the mixed flowing gas testing recommended for inclusion in UL217 while also evaluating new technologies. A suggested test approach is as follows:

- Prepare test plan similar to test protocol plan of this effort
- Test units
  - 70 horns or detectors/environment
  - 20/vendor w/o stabilant
  - 10/vendor w/stabilant
  - 5/vendor control
- Perform testing per selected gaseous environments with temperature cycling
- Correlate data with existing program data
  - Smoke detector field data
  - Battelle data
  - UL217 test data

- Modeling
  - Contact lifetime
  - Failure modes
  - ΔR Testing

- Evaluate new coatings and contact technologies

- Results
  - Refined mixed flowing gas testing
  - Contact life times
  - Evaluation of new coatings and contact technologies

Another important factor in relative motion and fretting corrosion to be considered is contact force. The effect of higher contact forces on minimizing fretting corrosion problems should be evaluated. It is recommended that a procedure for the measurement of contact force be investigated.

3.0 SEPARATE QUALIFICATION PROCEDURE/STANDARD FOR HORNS

Horns (referred to as an alarm sounding appliance in UL217) have been the only cause of smoke detector failures noted in this study. The high resistance observed at the horn separable contact interfaces was the only horn failure mechanism.

The horn (piezoelectric disk, separable contacts) is not only a vital component of a smoke detector, it has potential for other uses (e.g., carbon monoxide detectors). Therefore, consideration should be given to develop a procedure to require demonstration of an acceptable level of horn quality and reliability before inclusion in smoke detectors. Also the fact that the horns failure rate contribution is not included in smoke detector reliability predictions means that the reliability of horns could vary by vendor depending on his procurement/test procedures. Standard reliability testing is already required by UL217 for other components (e.g., microcircuits). The procedure could be as simple as assessing a vendor's quality practices and performing horn contact resistance measurements and corrosion testing on a periodic basis.

It is recommended that a horn qualification procedure that would be performed on a sample basis be developed in accordance with the following procedure:

1. Determine what horn vendor qualification procedures/testing presently exist.

2. Survey horn vendors to determine what testing and quality controls are used.

3. Survey manufacturers of smoke detectors to determine what testing/quality controls they require from horn vendors and testing/quality controls they perform in-house (e.g., incoming inspection through out-going product).

4. Develop and coordinate a sound cost effective horn qualification procedure.

It is recommended that a committee of knowledgeable individuals from appropriate organizations (e.g., CPSC, UL, NIST, IITRI) be formed to develop the technical requirements for a horn qualification procedure.

Another element to consider would be the provision of information on intermetallic contacts identifying compatible couples to minimize corrosion through galvanic action. Inclusion of this information in UL217 would require review and approval of separable metal contact materials by the UL.

The following excerpt on intermetallic contact requirements from MIL-R-39016 "Relays, Electromagnetic, Established Reliability, General Specification for" describes the rationale and procedure used to minimize corrosion through galvanic action. If appropriate this could be tailored for inclusion in UL217.

> 6.6 Intermetallic contact. The finishing of metallic areas to be placed in intimate contact by assembly presents a special problem, since intermetallic contact of dissimilar metals results in electrolytic couples which promote corrosion through galvanic action. To provide the required corrosion protection, intermetallic couples are restricted to those permitted by table IX. Table IX shows metals and alloys (or plates) by groups which have common electromotive forces (EMF) within 0.05 volt when coupled with a saturated calomel electrode in sea-water at room ambient temperatures. All members of a group are considered as completely compatible, one with the other. Compatible couples between groups have been specified in table IX based on a potential difference of 0.25 volt maximum. To simplify any arithmetic involved, table IX shows, in addition to EMF against a calomel electrode, a derived "anodic index" with Group 1 (gold, etc.) as 0 and Group 18 (magnesium, etc.) as 175. Subtraction of a lower group anodic index gives the EMF difference in hundredths of a volt.
>
> 6.6.1 Groups. Table IX sets up 18 primary groups. It may be noted that neither the metallurgical similarity or dissimilarity of metals is the parameter for selection of compatible couples. All members within a group, regardless of metallurgical similarity, are considered inherently nonsusceptible to galvanic action, when coupled with any member within the group; for example, such dissimilar metals as platinum and gold. Similarly, such basically dissimilar alloys as austenitic stainless steel,

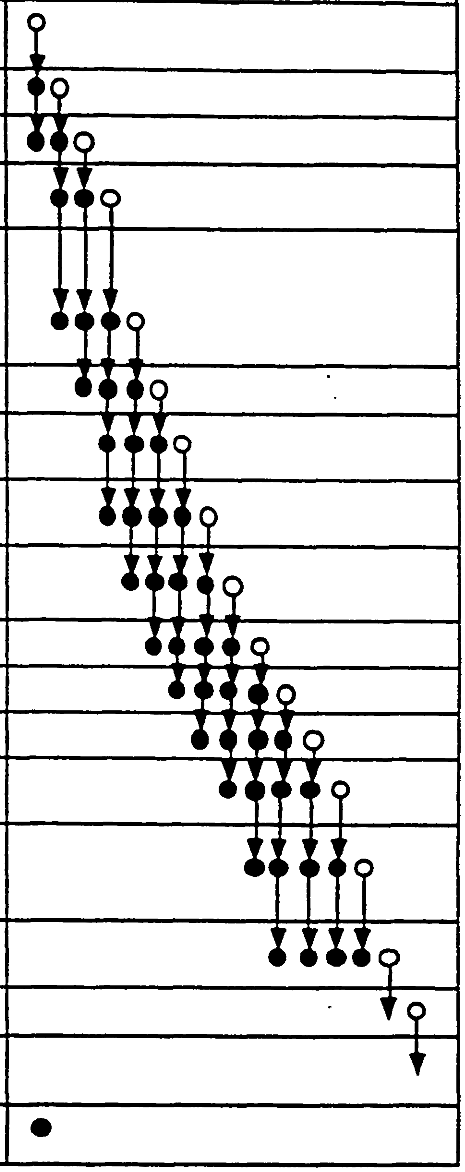
silver-solder, and low brass (all members of Group 5) are inherently nonsusceptible when coupled together.

6.6.2 Compatibility graphs. Permissible couple series are shown in table IX by the graphs at the right. Members of groups connected by lines will form permissible couples. A 0 indicates the most cathodic member of each series, a 0 an anodic member, and the arrow indicates the anodic direction.

6.6.3 Selection of compatible couples. Proper selection of metals in the design of equipment will result in fewer intermetallic contact problems. For example, for sheltered exposure, neither silver nor tin require protective finishes. However, since silver has an anodic index of 15 and tin 65, the EMF generated as a couple is 0.50 volt, which is not allowable by table IX. In this case, other metals or plates will be required. It should be noted that, in intermetallic couples, the member with the higher anodic index is anodic to the member with the lower anodic index and will be susceptible to corrosion in the presence of an electrolytic medium. If the surface are of the cathodic part is significantly greater than that of the anodic part, the corrosive attack on the contact area of the anodic part may be greatly intensified. Material selection for intermetallic contact parts, therefore, should establish the smaller part as the cathodic member of the couple, whenever practicable.

6.6.4 Plating. When base metals intended for intermetallic contact form couples not allowed by table IX, they are to be plated with those metals which will reduce the potential difference to that allowed by table IX.

TABLE IX: COMPATIBLE COUPLES (SEE. 6.6). 1/

Group No.	Metallurgical category	EMF (volt)	Anodic index (0, 01v)	Compatible couples
1	Gold, solid and plated; gold-platinum alloys wrought platinum (most cathodic)	+0.15	0	
2	Rhodium plated on silver-plated copper	+0.05	10	
3	Silver, solid or plated; high silver alloys	0	15	
4	Nickel, solid or plated; monel metal, high nickel-copper alloys	-0.15	30	
5	Copper, solid or plated; low brasses or bronzes; silver solder; German silver; high copper-nickel alloys; nickel- chromium alloys; austenitic corrosion-resistant steels	-0.20	35	
6	Commercial yellow brasses and bronzes	-0.25	40	
7	High brasses and bronzes; naval brass; Muntz metal	-0.30	45	
8	18 percent chronium type corrosion-resistant steels	-0.35	50	
9	Chronium, plated; tin, plated; 12 percent chronium type corrosion-resistant steels	-0.45	60	
10	Tin-plate; terneplate; tin-lead solder	-0.50	65	
11	Lead, solid or plated; high lead alloys	-0.55	70	
12	Aluminum, wrought alloys of the duralumin type	-0.60	75	
13	Iron, wrought, gray, or malleable; plain carbon and low alloy steels, armco iron	-0.70	85	
14	Aluminum, wrought alloys other than duralumin type; aluminum, case alloys of the silicon type	-0.75	90	
15	Aluminum, cast alloys other than silicon type; cadmium, plated and chromated	-0.80	95	
16	Hot-dip-zinc plate; galvanized steel	-1.05	120	
17	Zinc, wrought; zinc-base die-casting alloys; zinc, plated	-1.10	125	
18	Magnesium and magnesium-base alloys, cast or wrought (most anodic)	-1.60	175	

1/ Compatible Couples - Potential difference of 0.25 volt maximum between groups.

4.0 HORN DAMAGE DURING ROUTINE HANDLING

During IITRI's engineering evaluation of horn construction techniques it was observed that routine maintenance/disassembly of smoke detectors could destroy critical elements. This is described in the Task II Test Protocol Implementation Report, para. 3.4 Horn Construction. The following recommendation is offered to preclude horn element damage (i.e., piezoelectric disk, separable contacts).

- Provide precautions and instructions on the smoke detector housing concerning disassembly of the horn.

5.0 RELIABILITY PREDICTION

The reliability requirements of UL217 Section 4 'Detector Reliability Prediction' and supplement SA - 'Smoke Detector Reliability Prediction' were evaluated and the following concerns were identified.

The latest version of UL217 dated May 10, 1993 did not revise Section 4 or the supplement SA. All references to MIL-HDBK-217B 'Reliability Prediction of Electronic Equipment' are incorrect because the latest version of this document is MIL-HDBK-217F, Notice 2. This can be rectified by a simple change the deletion of the revision letter, B in this case, because standard protocol is to use the latest document revision. This change will probably improve predicted smoke detector reliability due to piece part failure rate improvements contained in latest version of MIL-HDBK-217.

A more serious problem is that the horn, including the piezoelectric disk and its contacts, are specifically omitted from the reliability prediction procedure contained in the prediction supplement SA.

Since the results of this study identified the horn's separable contacts as the major reliability driver it is recommended that the horn failure rate contribution be included in all smoke detector reliability predictions. However, since MIL-HDBK-217 does not contain horn failure rate data the following interim solutions are offered. The Reliability Analysis Center (RAC) Report NBS-GCR-79-160 "Reliability Modeling of Smoke Detectors" sponsored by the US Department of Commerce, National Bureau of Standards provides guidance on average failure rates for horns (See Table 2).

TABLE 2: AVERAGE FAILURE RATES FOR MISCELLANEOUS PARTS 1/

Part Type	Average Failure Rate (Failures/10^6 hrs.)
Horns	
Electromechanical	0.25
Electronic (on-board oscillator)	0.084
Electronic (no on-board oscillator)	0.011

1/ Values are based upon the assumption that the parts will be replaced before their respective wear-out periods are reached.

IITRI personnel are presently analyzing the separable contact resistance data that resulted from the accelerated testing performed during this effort. The results, if appropriate, could be used in lieu of Table 2 failure rates. Weibull analysis is being utilized in conjunction with chi-square confidence levels to estimate lower bound characteristic contact life. Estimation of the number of temperature cycles to failure is also being accomplished based on resistance data but may be of limited value due to the large extrapolation distances. This analysis will be included in the final report for this contract.

Additional discussion on aspects of UL217 prediction philosophy are included in Appendix A, page A-1 (comments on page 8, para. 3.6, page 9, para. 4.1 and para. 4.2.6).

6.0 SELF WIPING CONTACTS, CONTACT LUBRICANTS, AND SOLDERED CONTACTS

Self wiping contacts have been used successfully in relay contacts for years to produce low and constant contact resistance. This is accomplished by a defined wiping action produced by designed overtravel. The overtravel principle permits an exact calculation of the wiping path, so that a compromise can be chosen between breakdown of the insulating film and material abrasion.

There are three basic mechanical motions that occur between contacts. These are rocking, rotation and sliding. The first two are more detrimental from a fretting corrosion aspect than the last because the sliding motion is also a self-cleaning action.

The application of the self-wiping contact for use in smoke detector horns was evaluated by IITRI and is not considered a viable approach at this time. As previously stated relays use a well defined and controlled wiping path to create the needed wiping or sliding motion. The mating of the separable contacts is not a well defined or controlled action and will cause rocking and rotational motions which are detrimental to fretting corrosion. Even though SEM photographs of the separable contacts show sliding or slipping motion it is very small in comparison with the relay sliding motions.

The other two methods investigated for minimizing fretting corrosion were the use of nonporous noble metals for both sides of the contact and the use of an appropriate protective lubricant. The development of nonporous noble metal contacts is neither cost effective nor practical for low cost smoke detectors. However, protective lubricants appear to offer an attractive, low cost solution. Preliminary tests were run using Stabilant 22 (a product of D.W. Electrochemicals Ltd., Ontario Canada). Data sheets, application notes and evaluations of Stabilant 22 are included in Attachment 1. The two horns that were tested using Stabilant 22 exhibited marked improvement over untreated horn contacts. The average contact resistance dropped from 47 ohms to 4.8 ohms upon application of the Stabilant 22. After an additional 1000 temperature cycles the average contact resistance dropped to 1.75 ohms. Although this testing was not sufficient to completely evaluate stabilants for smoke detector separable contacts the results were promising. It must be pointed out that galvanic action caused by mismatched contact materials can still be a problem even though reliability will be improved.

Soldered connections are presently being used in some smoke detectors to replace the separable contacts. Soldered contacts have been discussed with others and are considered a solution to the problem of separable contact deterioration. A properly designed and fabricated solder joint will eliminate separable contact contamination and fretting corrosion problems (the only smoke detector failure mode identified in this program) and provide sound electrical and mechanical connections. It is recommended that soldered connections be considered as a replacement for separable connectors.

7.0 SUMMARY

The test and evaluation portion of this program has resulted in a technical review and critical assessment of smoke detectors and UL217. Several options/observations concerning smoke detector corrosion testing results, the need for a different corrosion test, a horn qualification procedure, handling/maintenance precautions, various contact configurations/enhancers and reliability prediction procedures have been offered. The need for additional testing to support some recommendations was identified.

In summary IITRI recommends that a Flowing Mixed Gas Test and the Horn Qualification Procedure be added to UL217 to improve horn reliability.

References:

(1) Abbott, W.H., "Corrosion Still Plagues Electronic Packaging," Electronic Packaging and Production, August 1989, pp. 28-33.

(2) Guinement, J., et. al, "Search for a Test Simulating Indoor Corrosion of Electrical Connections," 1982 Proceedings For Testing and Failure Analysis, pp. 115-124.

(3) Tamai, T., "Formation of S_iO_2 on Contact Surface and Its Effect on Contact Reliability," IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. 16, No. 4, June 1993, pp. 437-441.

APPENDIX A

COMMENTS ON UL217

The following items, listed by UL217 paragraph number, were noted while reviewing the document:

Page 8, para. 2.1.3

Change the phrase "its recognized rating" to "the derated value in a UL approved component derating document" - clarity

Page 8, para. 3.5

Add "alarm sounding appliance (horn)" to list of limited life components - editorial

Page 8, para. 3

Add "alarm sounding appliance (horn) - the device that generates the audible signal intended to indicate an emergency fire condition" to glossary - editorial

Page 8, para. 3.6, page 9, para. 4.1 and para 4.2.b

It is recommended that these paragraphs be reviewed to determine if they are adequate to provide the level of reliability expected from smoke detectors.

The definition of a reliable component (para. 3.6) states that it should have a predicted failure rate of 2.5 or less failures per million hours which appears to be a worst case number. This is not representative of many of the included components which are much less (e.g., microcircuits). Additionally only 2 of these reliable components are needed to exceed the detector units maximum failure rate of 4.0 failures per million hours (para. 4.1).

Para 4.2b states that any component evaluated by specific performance tests need not be included in the failure rate calculation. One of the examples given is the audible signal appliance which this program identifies as the major failure mechanism. In general this philosophy would be acceptable with highly reliable components and a rigorous performance test procedure. This is not the case in this instance, in fact, it is suspected that the performance test of activating the test button can negate a contact failure. This subject of reliability prediction is further addressed in the main body of this report.

Page 10, para. 9.2.1

Add at the end of this paragraph "or can cause possible damage to the alarm sounding appliance contacts or piezoelectric disk" - clarity

Page 27, para. 32.1

The temperature requirement of 135°C is not consistent with para. 9.6, page 11, temperature requirement of 140°C. The correct temperature should be used in both places.

Page 31, para. 34.4.2

add (d) Failure Modes and Effects Criticality Analysis (FMECA). This evaluation will enhance the reliability of smoke detectors.

Page 38, para. 38.1.1

Add "(a), (b) and (c)" before below in second sentence for clarity

OD used in "a" and "b" tables should be defined or referenced at the point (first time used) OD - Optical Density

Page 70, Table 48.1

Add "alarm sounding appliance as a component" - editorial

Page 79, para. 54.1.1

Third line after to "add the following" - editorial

Page 84, para. 59

Consider adding the allowance for the use of commercial ESD equipment

Attachment 1 includes copyrighted material which has been removed for public distribution of this report.

APPENDIX C

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] Bryant, M.D., J. Moulin, "Time-Wise Increases in Contact Resistance Due to Surface Roughness and Corrosion," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol. 14, No. 1, March 1991.

[2] Emmons, W.D., J. Chang, J. Stankus, W.H. Abbot, R. Sharrar, T. Wutka, and H. Stackhouse, "Connector Stability Test for Small System Connectors," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol. 14, No. 1, March 1991.

[3] Whitely, J.H. and R.D. Malucci, "Contact Resistance Failure Criteria," *Proceedings of the Ninth International Conference on Electrical Contact Phenomena*, 1993.

[4] Bock, E.M. and J.H. Whitely, "Tunnel Film Resistance Utilizing Non-Linear Constriction Resistance Measurements," *Proceedings of the Holm Seminar on Electrical Contact Phenomena*, 1970.

[5] Stepke, E.T., "Electrical Conduction Processes Through Very Thin Tarnish Films Grown on Copper," *Proceedings of the Holm Seminar on Electrical Contact Phenomena*, 1967.

[6] Bock, E.M., and J.H. Whitley, "Fretting Corrosion in Electric Contacts," *Proceedings of the Holm Seminar on Electrical Contacts*, 1974.

[7] Freitag, W.O., "Wear, Fretting and the Role of Lubricants in Edge Card Connectors," *Proceedings of the Holm Seminar on Electrical Contacts*, 1975.

[8] Theisen, P.J., and K.A. Forsell, "Connector Dependent Fretting Corrosion Test System," *Proceedings of Holm Seminar on Eletrical Contacts*, 1979.

[9] Guinement, J., et. al, "Search for a Test Simulating Indoor Corrosion of Electrical Connections," *Proceedings For Testing and Failure Analysis*, 1982.

[10] Abbott, W.H., "The Performance of Electronic Connectors in Flowing Mixed Gas Laboratory Environments," *Proceedings of the 14th International Conference on Electrical Contacts*, 1988.

[11] Sharma, S.P., J.H. Thomas III, and F.E. Bader, "Development of a Gentle Accelerated Corrosion Test," *Electrochemical Society Journal, Solid-State Science and Technology, December*, 1978.

[12] Abbott, W.H., "The Development and Performance Characteristics of Mixed Flowing Gas Test Environment," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol. II, No. 1, March 1988.

[13] Abbott, W.H., The Corrosion of Copper and Porous Gold in Flowing Mixed Gas Environments," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* Vol. 14, No. 1, March 1991.

[14] Stennett, N.A., T.P. Ireland, and D.S. Campbell, "Powered Testing of Electrical Contacts in Mixed Flowing Gases," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* Vol. 14, No. 1, March 1991.

[15] Abbott, W.H., "Materials, Environment, Motion, and Electrical Contact Failure Mechanisms," *Proceedings of the Holm Conference on Electrical Contacts,* 1989.

[16] Antler, M., et al, Panel Discussion, "Importance of Environment on Contact Performance," *Proceedings of the Holm Seminar on Electrical Contacts,* 1979.

[17] Tamai, T., "Formation of S_iO_2 on Contact Surface and Its Effect on Contact Reliability," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* Vol. 16, No. 4, June 1993.

[18] Ishino, M., and Shoichi Mitani, "On Contact Failure Caused by Silicones and An Accelerated Life Test Method," *Proceedings of the Holm Conference on Electrical Contacts,* 1977.

[19] Garte, S.M., "The Effect of Design on Contact Fretting," *Proceedings of the Holm Seminar on Electrical Contacts,* 1976.

APPENDIX D

GLOSSARY

GLOSSARY

Auger Electron Spectroscopy (AES) - The energy analysis of low energy Auger electrons produced when an excited atom relaxes in a radiationless process after ionization by a high energy electron, ion or x-ray. AES is used to determine the elemental composition of very thin surface layers.

Cross-Section - A procedure to illustrate the downward projection of a surficial geology along a vertical plane.

Depth Profiling - The use of AES spectral data collected from a film exposed to ion beam sputtering, which continually exposes fresh surface, to identify film chemical composition.

Energy Dispersive Analysis by X-Ray (EDAX) - A tool which is used in conjunction with a SEM to analyze x-rays generated by the SEM electronic beam scanning of the material to be evaluated. The impingement of the x-rays on the EDAX detector allows the spectral analysis of surface elements.

Fourier Transform Spectroscopy - A spectroscopic technique in which all pertinent wavelengths simultaneously irradiate the sample for a short period of time, and the absorption spectrum is found by mathematical manipulation of the Fourier transform so obtained.

Fretting Corrosion - Surface damage usually in an air environment between two surfaces, one or both of which are metals, in close contact under pressure and subject to a slight relative motion.

Interface Resistance. Resistance caused by the imperfect contact between two materials at an interface.

Sputtering - The ejection of atoms or groups of atoms from the surface of a material as the result of heavy-ion impact.

Scanning Electron Microscope (SEM) - A type of electron microscope in which a beam of electrons sweeps over the specimen. The specimen secondary electrons which are generated by the beam are measured and used to trigger a cathode-ray-display. The SEM yields high resolution surface topography photographs at magnifications up to 200,000x.

Surface Analysis - A procedure in which analytical data is used to determine the physical characteristics of a medium.

Thermionic Emission - The liberation of electrons or ions from a substance as a result of heat.

Tunneling (Current) - Electron flow in a two terminal electronic device having an extremely thin potential barrier to electron flow explained by quantum and wave mechanics that allows electrons to pass through the barrier from one contact to the other.

Weibull Distribution - A general distribution, which is suitable for describing the life characteristic of a population of items. The general expression for the Weibull cumulative distribution function is defined for F (t = o) = 0 as:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

β = <u>Weibull Slope</u> - The shape parameter of the distribution and equal to the slope of the line drawn through the failure data plotted on Weibull probability paper.

θ = <u>Characteristic Life</u> - The scale parameter of the distribution and always equal to the life at 63.2% failure on the Weibull curve.