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HISTORY OF THE SMALL CYLINDRICAL MELTER

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT DE-AC09-76SR00001

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ABSTRACT

The small cylindrical melter (SCM) was designed to provide engineering data useful for operation and design of full-scale glass melters for vitrification of high level radioactive waste. This melter was part of the research and development program for the Defense Waste Processing Facility (DWPF) at the Savannah River Plant (SRP). Extensive corrosion testing of melter materials of construction (Monofrax™ K3, Inconel® 690), simulated radioactive waste glass characterization, and melter component development were conducted in support of the DWPF full-scale melter design.

CONTENTS

INTRODUCTION 11

SUMMARY 11

DISCUSSION 12

Operating History of the SCM 12

Analysis and Causes of Floor Deposits 19

Refractory Wear on Melter Sidewalls 24

Refractory Wear on Melter Bottom 44

Refractory Wear Above the Meltline 44

Wear of Refractory in Throat and Riser Sleeve 44

Electrode Wear 50

Effect of Direct Current on Electrode Wear 67

Wear in the Melter Lid 69

Lid Heater Performance 74

Wear in the Pour Chamber 74

Pour Chamber Heater Performance 82

Thermocouple Performance 84

Tilt Mechanism Performance 85

Melter Drain Techniques 85

Feed Devices and Feed Systems 85

Off-Gas System 86

Television Camera Performance 91

Refractory Disassembly 91

CONCLUSION 100

TABLES

1 Composition of Frit 21B 13

2 Frit 211 + TDS Waste Simulant Mixture Fed to Melter 13

3 SCM Feed History for Campaign 3 16

4 Composition of Frit 131 17

5 Comparison of SCM Melter Campaigns 19

6 Summary of Melter Operating Data for All Three Campaigns 19

7 Chemical Composition of the SCM Melter Lid (M-Board™) 22

8 Chemical Composition of the SCM Sidewalls and Bottom (Monofrax™ K3 Refractory) 22

9 Chemical Composition of the SCM Electrodes (Inconel® 690) 22

10 Chemical Composition of the SCM Feed Materials 23

11 Sidewall Wear as a Function of Melter Campaign 37

12 Comparison of Refractory and Metal Throats 50

13 Comparison of Electrode Wear Data for Campaigns 1, 2, and 3 61

14 Properties of Ram Cement™ 95

FIGURES

1 Inconel® 690 Sleeve Welded into the Worn Throat Region 14

2 Typical Vertical Temperature Profile Taken During a Hot Bottom Incident 18

3 Vertical Section of the SCM 25

4 Horiztonal Section of the SCM at the Top of the Melt Pool 26

5 Melt Chamber at the Beginning of the First Campaign 27

6 Melt Chamber at the End of the First Campaign 28

7 Melt Chamber at the Beginning of the Second Campaign 29

8 Melt Chamber at the End of the Second Campaign 30

9 Melt Chamber at the Beginning of the Third Campaign 31

10 Melt Chamber at the End of the Third Campaign 32

11 Refractory Wear on Wall A-B Versus Melt Depth 33

12 Refractory Wear on Wall B-C Versus Melt Depth 34

13 Refractory Wear on Wall C-D Versus Melt Depth 35

14 Refractory Wear on Wall D-A Versus Melt Depth 36

15 Melt Chamber After Shutdown (South View) 38

16 Closeup of North Wall 39

17 Closeup of East Wall 40

18 Closeup of West Wall 41

19 Melt Chamber After Shutdown (North View) 42

20 Closeup of South Wall 45

21 Inconel® 690 Replacement Sleeve Attachment in Pour Chamber Before Campaign 3 46

22 Closeup of Entrance to Inconel® 690 Riser Sleeve 47

23 Side View of Inconel® 690 Riser Sleeve 48

24 Coordinate Definitions for Throat Wear 49

25 Nominal 3-inch OD Electrode (A) After Campaign 1 52

26 Corrosion of 3-inch Inconel® 690 Electrode 53

27 Nominal 2-inch OD Electrode (D) After Campaign 1 54

28 Corrosion of 2-inch Inconel® 690 Electrode 55

29 Electrodes at the End of Campaign 3 56

30 Electrode A Wear Data 57

31 Electrode B Wear Data 58

32 Electrode C Wear Data 59

33 Electrode D Wear Data 62

34 Radial Wear Rate of Electrode A 63

35 Radial Wear Rate of Electrode B 64

36 Radial Wear Rate of Electrode C 65

37 Radial Wear Rate of Electrode D 66

38 Wiring Diagram for the SCM During Campaigns 1 and 2 68

39 Wiring Diagram for the SCM After Installation of Isolation Transformers (Campaign 3) 70

40 Melter Lid Condition After Campaign 2 71

41 Melter Lid Condition After Campaign 3 72

42 Closeup of Melter Lid Bottom After Campaign 3 73

43 Lid Heaters at the End of the First Campaign 75

44 Lid Heaters at the End of the Second Campaign 76

45 Lid Heaters at the End of the Third Campaign 77

46 Globars and Insulation in the Pour Chamber at the End of the First Campaign 78

47 Globars and Insulation in the Pour Chamber at the End of the Second Campaign 79

48 North View of the Pour Chamber at the End of the Third Campaign 80

49 South View of the Pour Chamber at the End of the Third Campaign 81

50 Pour Chamber Heaters at the End of the Third Campaign 83

51 First Slurry Feed Device Used in the SCM 87

52 Second Slurry Feed Device Used in the SCM 88

53 Third Slurry Feed Device Used in the SCM 89

54 Off-Gas System for Slurry Feeding During Campaign 3 90

55 TV Camera and Viewport Arrangement 92

56 Inner Liner Removed (North Side) 93

57 Ram Cement™ Removed (North Side) 94

58 Four Inches of Monofrax™ K3 Removed (North Side) 96

59 Inner Liner Removed (East Side) 97

60 Ram Cement™ Removed (East Side) 98

61 Four Inches of Monofrax™ K3 Removed (East Side) 99

62 Inner Liner Removed (South Side) 101

63 Ram Cement™ Removed (South Side) 102

64 Inner Liner Removed (West Side) 103

65 Ram Cement™ Removed (West Side) 104

66 Four Inches of Monofrax™ K3 Removed (West Side) 105

HISTORY OF THE SMALL CYLINDRICAL MELTER

INTRODUCTION

The Savannah River Laboratory (SRL) has been charged with supplying basic data information for designing the DWPF. A key step in the vitrification process is the design and successful operation of a glass melter in which the radioactive waste and glass-forming materials (frit) form a homogeneous glass at high temperatures (1150°C). The design life of a DWPF melter is two years. All materials that will be used to construct the melter and various components must be able to survive the harsh operating conditions that will exist over the two year lifetime. The small cylinderical melter (SCM), with a 1.3 ft^2 melt surface area, was designed to test the performance of the various materials of construction when subjected to a variety of simulated radioactive waste and frit compositions. This report summarizes the operation of this melter at the equipment testing facility (ETF) of SRL from October 15, 1979, to February 9, 1982. This time period was divided into three operating campaigns.

SUMMARY

At the end of Campaign 3, the SCM had processed 359 melt volumes of simulated defense waste glass since its initial startup. This is equivalent to 256 days (8.5 months) of continuous operation at 8.0 $lb/hr\text{-}ft^2$ (reference melt flux for the DWPF melter). Thus its operating history and final condition are of particular interest. Results are summarized as follows:

- Inconel® 690 (Huntington Alloys, Inc.) and Monofrax™ K3 refractory (Carborundum Resistant Materials Co.) are satisfactory materials for glass contact. However Inconel® 690 is superior to Monofrax™ K3 in wear resistance at expected melter operating conditions, and it should be used as much as practical in high wear areas, e.g., throat and sidewalls.

- Slurry feeding is a viable feed technique that caused no obvious damage to the Monofrax™ K3 or Inconel® 690.

- The lifetime of the silicon carbide heaters used to provide supplementary heat in the melter plenum can be doubled by use of protective alumina sheaths. However, this type of heater is still a fragile device. Inconel® 690 resistance heaters will be used in the DWPF melter.

- Spinel deposits on the melter floor can be caused by waste rich feed, corrosion of melter construction materials, and low floor temperatures. The presence of such deposits can have serious effects on melter performance.

DISCUSSION

Operating History of the SCM

The small cylindrical melter first achieved ohmic heating on October 15, 1979. It was reached by using the lid heaters to heat the melter loaded with Frit 21B (Table 1). The Frit 21B was gradually replaced by feeding a powder feed of Frit 211 + TDS simulated waste (Table 2). Starting in late December 1979, the melter was fed 8 hours a day, 5 days a week, and idled the remaining time. Campaign 1 ended March 3, 1980, when one of the air-cooled electrodes failed (Electrode Wear section). Approximately 6,000 lb of glass were produced at an average melt flux of 1.45 lb/hr-ft^2 during the first operating campaign.

Following the failure of the Inconel® 690 electrode, all four air-cooled electrodes were replaced with 3-inch-OD solid Inconel® 690 bars which were not cooled. The SCM was restarted on April 9, 1980, with a powder graphite Frit 211 sandwich. The melter was powder fed 24 hours a day, 7 days a week until August 19, 1980. Campaign 2 was terminated when lumps of unmelted feed material were observed in the glass pour stream. Probing of the melter riser through the viewport in the pour chamber with a welding rod indicated that a substantial amount of material had been lost from the Monifrax™ K3 refractory throat. Following shutdown of the SCM, this loss was verified.

During this period, 18,511 lb of glass were produced at an average rate of 4.67 lb/hr-ft^2. The feed was primarily Frit 211 + simulated TDS waste (Table 2), although other simulated waste materials were used for brief periods.

During shutdown before the third campaign, a metal sleeve fabricated from 2-inch sch 40 Inconel® 690 pipe was inserted into the worn throat as a temporary replacement. The sleeve was flanged and welded to the Inconel® 690 pour lip to prevent glass from bypassing the sleeve by flowing along its outer surface (Figure 1).

Isolation transformers were installed on each electrical phase to block the transmission of direct current from the current controllers (SCR's) into the melt pool. DC current was thought to increase corrosion of the electrodes in the melt pool. The electrodes themselves were not replaced at the end of Campaign 2 since they had been replaced at the end of Campaign 1.

TABLE 1

Composition of Frit 21B

Component	Amount, wt %
SiO_2	60.4
B_2O_3	11.5
TiO_2	11.5
Na_2O	6.3
CaO	5.7
Li_2O	4.6

TABLE 2

Frit 211 + TDS Waste Simulant Mixture Fed to Melter

Component	Amount, wt %	Source
SiO_2	41.4	Frit
B_2O_3	7.9	Frit
Na_2O	14.6	Frit
CaO	4.0	Frit
Li_2O	3.1	Frit
Fe_2O_3	14.4	Waste
MnO_2	3.8	Waste
Al_2O_3	3.1	Waste
Zeolite	2.9	Waste
$CaCO_3$	1.8	Waste
NiO	1.7	Waste
$NaNO_3$	0.9	Waste
Na_2SO_4	0.4	Waste

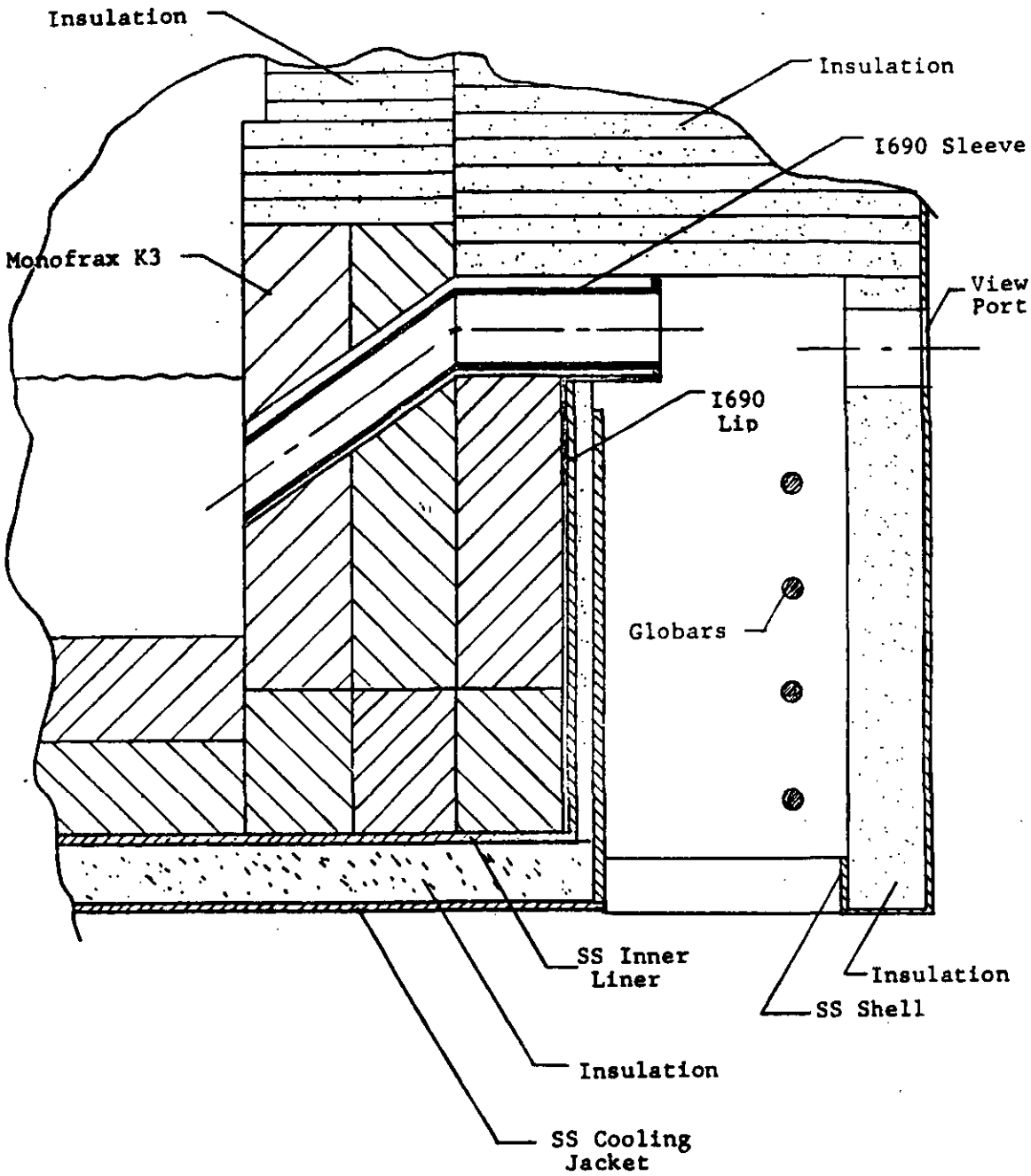

FIGURE 1. Inconel® 690 Sleeve Welded into the Worn Throat Region

Campaign 3 began on September 9, 1980, by passing electrical current through a layer of graphite powder overlying a bed of simulated waste glass in the form of a frit. Powdered feed material was supplied to the melter by use of a screw feeder until February 1, 1981 (Table 3). During this period, the melter was operated as continously as possible while melt rate experiments were conducted to test the validity of a newly developed melt rate theory for powder feeding.

After the melter was idled for approximately two months to permit installation of a slurry feed system, aqueous slurry feeding of Frit 131 and simulated waste began on April 16, 1981. A weld failure in the new slurry feed device occurred shortly after initial attempts at slurry feeding. While the feed device was being repaired, powder feeding was resumed. However, an error in mixing of the frit and waste powders resulted in a frit/waste mixture that was approximately 50 wt % waste. Feeding this material to the melter resulted in the formation of a layer of hot deposits on the melter floor (May 26, 1981).

Once the feed composition was corrected to 72 wt % frit and 28 wt % simulated glass, feeding was resumed. It was thought that the deposits on the floor might be flushed out as feeding progressed, but when this did not occur, pure Frit 131 (Table 4) was fed to the melter in an attempt to dissolve the floor deposits (June 8, 1981). This was apparently successful and powder feeding was resumed only to have the problem promptly reoccur (June 9, 1981). The melter was again flushed with pure Frit 131 (June 10, 1981), the melt pool stirred vigorously with a metal rod, and the melter was then tilted to the maximum angle (+15°) in an attempt to pour out any deposits suspended in the glass bulk by stirring. This temporarily alleviated the "hot bottom" problem.

Slurry feeding was resumed on June 12, 1981, and continued for about three weeks before the bottom again overheated. The melter was again flushed with pure Frit 131, stirred, and dumped by tilting to +15°. Again the hot bottom problem was temporarily alleviated but it began to reoccur at frequent intervals.

Typically the onset of the problem was indicated by a gradual increase in the melt bottom temperature until the bottom reached the upper operating limit (1170°C). At this point, the electrode power level would be decreased slightly while slurry feeding continued. However, the bottom temperature would again slowly increase to 1170°C over a period of a few hours, requiring another power reduction. As this cycle continued, it eventually became necessary to stop feeding since the bulk glass temperature would drop below

TABLE 3

SCM Feed History for Campaign 3

Feed Material	Frit Particle Size Mesh	Comments	Date	Date	Number of Days	Pounds of Glass	Cumulative Glass Produced, lb
Total from Campaign 1 & 2							24511
Campaign 3							
211 + SIM TDS	-20 + 80	Dry Feed	9/9/80	11/24/80	77	9612	34123
131 + SIM TDS	-20 + 80	Dry Feed	11/24/80	12/15/80	21	2100	36223
131 + TDS WFE	-20 + 80	Dry Feed, High Fe	12/15/80	1/21/80	36	9525	45748
131 + SIM TDS	-20 + 80	Dry Feed	1/21/81	2/11/81	20	4352	50100
IDLE		Slurry Feed System Const.	2/11/81	4/10/81	63		
131 SIM Slurry	-50	Run	4/16/81	5/6/81	19	50	50150
IDLE		Repair Feed Device	5/6/81	5/26/81	20		
131 + SIM TDS	-20 + 80	Dry, 50% Waste	5/26/81	5/27/81	2	235	50385
IDLE		Try to Recouperate	5/27/81	6/3/81	6		
131 + SIM TDS	-20 + 80	72/28 Try to Flush	6/3/81	6/4/81	1	150	50535
IDLE		Try to Recouperate	6/4/81	6/8/81	3		
131 Alone	-50	Redissolve Spinel	6/8/81	6/9/81	1	50	50585
131 + SIM TDS	-20 + 80	Dry Feed	6/9/81	6/10/81	1	100	50685
131 Alone	-50	Stir Melter	6/10/81	6/12/81	2	67	50752
131 + SIM Slurry	-50	Run	6/12/81	7/5/81	23	496	51248
131 Alone	-50	Stir Melter	7/5/81	7/6/81	1	20	51268
131 + SIM Slurry	-50	Run	7/6/81	7/9/81	3	47	51315
131 Alone	-50	Flush Melter	7/9/81	7/16/81	7	274	51589
131 + SIM Slurry	-50	Run	7/16/81	9/13/81	59	849	52438
131 Alone	-50	Flush Melter	9/13/81	9/15/81	2	187	52625
131 + SIM Slurry	-50	Run	9/15/81	10/27/81	42	4791	57416
140 + SIM Slurry	-50	Available Feed	10/27/81	11/5/81	9	462	57878
131 Alone	-50	Alternating Slurry & Fresh Fri	11/5/81	11/25/81	20	338	58216
131 + SIM Slurry	-100	Prevent Settling	11/25/81	12/14/81	19	1376	59592
131 + Formate Slurry	-100	Formate Feed	12/14/81	12/15/81	1	217	59809
131 + SIM Slurry	-100	Run	12/15/81	1/15/82	21	536	60345
140 + SIM Slurry	-50	Available Feed	1/5/82	2/9/82	35	2535	62880

TABLE 4

Composition of Frit 131

Component	Amount, wt %
SiO_2	57.9
B_2O_3	14.7
Na_2O	17.7
Li_2O	5.7
MgO	2.0
TiO_2	1.0
La_2O_3	0.5
ZrO_2	0.5

the glass liquidus (930 to 940°C) and the rate of spinel deposition on the bottom would increase. A typical temperature profile taken during one of these events is shown in Figure 2.

Checks of the frit/waste ratio, amount of reducing agent, and agitation of the slurry feed were fruitless. Probing of the melter bottom indicated that a highly viscous material was present which was apparently unable to transport its energy to the remainder of the melt pool by convection.

At one point the melt pool was drained, by use of an evacuated canister, and the bottom was scraped to collect some of the deposits. Analysis revealed that the deposits were spinels. Operating experience with the calcine fed melter (CFM)* indicated that even large amounts of spinel on the melter floor did not lead to a hot bottom. This was further supported by a measured resistivity of 4.7 ohm-cm at 1200°C for the spinel from the CFM melter as compared with a typical glass resistivity of 2.0 to 2.5 ohm-cm at 1150°C.

If the resistivity of the spinel were slightly lower than that of the glass, one would expect the spinel to overheat compared to the surrounding glass.

Slurry feeding, bottom overheating, mechanical stirring, air sparging, and dumping of the melter continued till the end of Campaign 3.

On January 28, 1982, electrode power was cut off and the glass pool was allowed to cool to room temperature in preparation for testing of a new startup technique. On February 3, 1982, a graphite slurry was fed onto the surface of the solidified glass pool and used to restart the melter without the use of lid heat.

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* Previously called the S1941 melter.

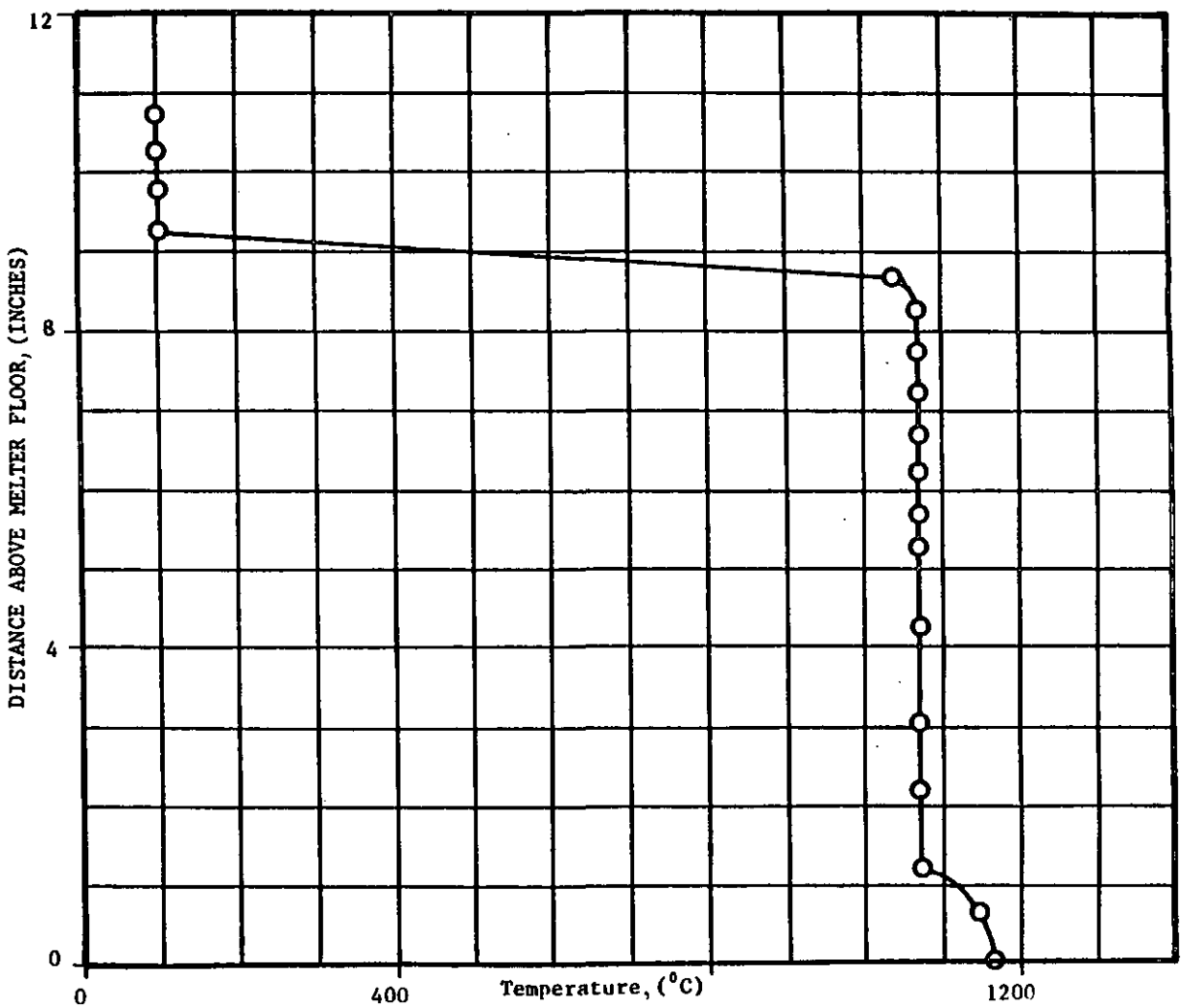

FIGURE 2. Typical Vertical Temperature Profile Taken During a Hot Bottom Incident

Campaign 3 ended on February 9, 1982, after the melter had been operated for 518 days and had melted 38,369 lb of glass. The glass pool was drained to within 1 to 2 inches of the melter bottom by use of an evacuated canister. Comparisons of Campaigns 1, 2, and 3 are given in Table 5. Data, summarized for all three melter campaigns, are given in Table 6.

TABLE 5

Comparison of SCM Melter Campaigns

	Campaign 1	Campaign 2	Campaign 3
Dates	10/15/79 - 3/3/80	4/9/80 -8/19/80	9/9/80 - 2/9/82
Time period, days	135	133	518
Feeding mode	Powder	Powder	Powder/Slurry
Electrode firing pattern	90% Adjacent 10% Cross	100% Cross	100% Cross
Feed time, hr/week	40	168	0 - 168
Glass throughput, lb	6000	18511	27010 Powder 11359 Slurry
Average melt flux for Campaign, lb/hr-ft^2	1.45	4.53	2.41

TABLE 6

Summary of Melter Operating Data for All Three Campaigns

Operating time[a]	786 days
Glass throughput	62880 lb (359 melt volumes)
Average melt flux	2.60 lb/hr-ft^2

[a] Idling or Feeding.

Analysis and Causes of Floor Deposits

When the SCM was shut down at the end of Campaign 3, glass samples were chipped from the floor around each of the four electrodes and analyzed by electron microprobe and X-ray diffraction in

an attempt to determine why the melter bottom overheated. Two possible mechanisms were postulated as causes:

1. Reduction of NiO from the melter feed to elemental nickel could cause a drop in resistivity near the melter floor. If the resistivity drop were small, preferential heating near the floor could occur as current preferentially flowed through the metallic deposits. If the resistivity drop were large, most of the current passing between the electrodes would be diverted through the deposits; this would result in little power generation in the glass and also little in the deposits because of their very low resistivity.

2. If the resistivity of the deposits remained comparable to that of the glass, power generation in the deposits would also be comparable to that of the glass. However, the high viscosity of the deposits could severely reduce (or eliminate) convective heat transfer from the deposits to the remainder of the glass. This would leave only heat conduction (which is normally small in the glass bulk) as an energy transfer mode which could cause the deposits to overheat.

Analysis of the glass samples taken from the melter floor revealed that the deposits consisted of mainly spinels - trevorite ($NiFe_2O_4$), magnetite ($FeFe_2O_4$), hercynite ($FeAl_2O_4$) - plus small amounts of a mineral called acmite ($NaFeSi_2O_6$). No elemental nickel was found, which ruled out the first of the two postulated mechanisms. Resistivity of spinels found in the floor of the CFM was 4.7 ohm-cm at 1200°C, which is comparable to that of the glass (2.0 to 2.5 ohm-cm at 1150°C).* This suggests that the second postulated mechanism may be correct.

Convergence of electrical current at the face of an electrode normally causes a higher local power density there with an accompanying temperature rise of 20 to 60°C compared to the glass bulk. If convection were severely impeded, this temperature rise could be much more pronounced, which indeed apparently occurred and led to the deformation of electrode D (Electrode Wear section).

It is interesting to note, however, that spinel deposits in the floor of the CFM did not lead to overheating of the melter floor. In that melter, the normal floor temperature was 920 to 940°C, whereas in the SCM it was 1030 to 1080°C. If the slope of the resistivity curve for spinel is similar to that of the glass, the spinel resistivity at 930°C would be about 2 times greater than at 1050°C. This would result in a 2 times reduction in power

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* Resistivity of deposits from the floor of the SCM could not be obtained because of the extremely high viscosity of the deposits.

generation under otherwise identical conditions. Furthermore, if the resistivity curve for the spinel drops with increasing temperature as it does in glass, a temperature rise from internal power generation would result in an increasingly lower resistivity and higher power generation until a new thermal equilibrium was reached by heat transfer, which apparently happened in the SCM. Thus it appears that although both the CFM and the SCM had spinel deposits on the melter floor, overheating did not occur in the CFM possibly because of the initially colder floor temperature.

Spinel deposits in the CFM are generally thought to have occurred because a significant portion of the melt pool was below the glass liquidus. However, this was not the case in the SCM. The chemical composition of various melter materials and glasses used in the SCM are given in Tables 7 to 10. Note that all the materials of construction contain one or more of the elements found in the spinels, and thus can be regarded as potential sources of material which may deposit on the floor of any melter constructed from them. Unfortunately the glass compositions themselves are also potential sources of spinel and there is no way to tell from the available data whether the spinels came from the melter construction materials, the glass, or both.

Floor deposits in the SCM were moderate (1 to 1-1/2 inches) at the end of Campaign 2 which indicates that spinel deposits from the glass itself can be largely avoided by keeping the melt pool above the glass liquidus temperature. Approximately one third of these deposits were formed by deliberately feeding the melter with the glass pool in the range of 950 to 1050°C to see if floor deposition increased at the end of Campaign 2. The first hot bottom incident actually occurred during Campaign 3 following an error in feed makeup that resulted in a low frit/waste ratio.

If followed, the following recommendations should help reduce floor deposits in future melters:

1. Maintain the glass pool above the glass liquidus temperature at all times. This will probably require adjustment in the electrical power distribution (power skewing) as glass composition varies.

2. Ensure that the correct frit/waste ratio is maintained.

3. Make maximum use of Inconel® 690 in high wear areas because it is the most corrosion-resistant material currently available.

4. Provide as much flexibility in the vertical electrical power distribution (power skewing) within the melt pool as practical. This will provide control over heat generation in deposits on the melter floor when they form.

TABLE 7

Chemical Composition of the SCM Melter Lid (M-Board™)

Component	Wt %
Al_2O_3	45.1
SiO_2	51.9
Fe_2O_3	1.3
TiO_2	1.7
MgO	Trace
CaO	0.1
Na_2O	0.2
B_2O_3	0.08

TABLE 8

Chemical Composition of the SCM Sidewalls and Bottom (Monofrax™ K3 Refractory)

Component	Wt %
Cr_2O_3	27.26
Al_2O_3	60.40
MgO	6.05
SiO_2	1.77
Fe_2O_3	4.21
Na_2O	0.31

TABLE 9

Chemical Composition of the SCM Electrodes (Inconel® 690)

Component	Wt %
Ni	60.0
Cr	30.0
Fe	9.5
C	0.03

TABLE 10

Chemical Composition of the SCM Feed Materials

Component	Frit 211 + TDS Waste (powder feed)	Frit 131 + TDS Waste[a] (powder feed)	Frit 131 + High Fe (powder feed)	Frit 131 + TDS Waste (slurry feed)
SiO_2	41.4	41.7	42.8	40.6
B_2O_3	7.9	10.6	10.9	9.6
Na_2O	14.5	12.7	13.1	11.5
CaO	4.0	—	1.1	—
Li_2O	3.1	4.1	4.2	3.7
Fe_2O_3	14.3	13.8	17.1	—
MnO_2	3.8	3.7	1.1	3.2
Al_2O_3	3.1	3.0	0.4	—
Zeolite	2.8	2.6	2.4	1.9
$CaCO_3$	1.8	1.7	—	2.5
NiO	1.7	1.6	2.9	—
$NaNO_3$	0.9	0.9	—	0.4
Na_2SO_4	0.4	0.4	0.7	0.1
MgO	—	1.4	1.5	1.3
TiO_2	—	0.7	0.7	0.7
La_2O_3	—	0.4	0.4	0.3
ZrO_2	—	0.4	0.4	0.3
Graphite/Coal	0.3	0.3	0.3	0.04
$Fe(OH)_3$	—	—	—	15.5
$Al(OH)_3$	—	—	—	6.5
$Ni(OH)_2$	—	—	—	1.0
NaOH	—	—	—	0.9

[a] For two short periods the SCM was fed Frit 140 + TDS Waste Simulation. This glass composition was similar to Frit 131 + TDS Waste but the Frit 140 did not contain TiO_2, ZrO_2, or La_2O_3.

Refractory Wear on Melter Sidewalls

General construction features of the SCM are shown in Figures 3 and 4 for orientation purposes. Figures 5 and 6 show the condition of the melter at the beginning and end of Campaign 1 (October 15, 1979, to March 3, 1980). Figures 7 and 8 show the condition of the melter at the beginning and end of Campaign 2 (April 9, 1980, to August 19, 1980). Figures 9 and 10 show the condition of the melter at the beginning and end of Campaign 3 (September 9, 1980, to February 11, 1981). The throat is located on Figures 5 through 9 for reference proposes.

Detailed refractory wear patterns are shown in Figures 11 to 14 for the melter walls for Campaigns 1 and 2. Similar measurements were not made at the end of Campaign 3. The photographs in Figures 5 to 10 and the diagrams in Figures 11 to 14 indicate that the melter walls had a pronounced bow shape, with the maximum penetration 2 to 3 inches below the melt line. This corresponds to the maximum temperature region during idling. During feeding, vertical temperature profile measurements indicated that the hottest point was in the center of the tank 4 to 5 inches below the melt surface.

Comparing measurements in Figures 10 to 14 reveals that the maximum wear in the refractory walls occured on walls A-D and B-C. At the end of the first campaign, it was postulated that the increase in wear on these walls was the result of high glass velocity produced by high local power density (high local temperatures) generated by adjacent - firing of electrodes A-D and B-C (Electrode Wear section). At the end of Campaign 2, the dominant factor of the wear rates of the sidewalls was suggested to be glass temperature and not chemical attack due to high glass throughput rate or erosion due to glass velocity. In Campaign 2, 3 times more glass was produced than in Campaign 1 (Table 5), but the average maximum wear rate of the brick increased by only 39%. A high local power density can have some effect as is evident in the data from Campaign 1. In both campaigns, the melter was powder fed Frit 211 + TDS waste.

The composition of the frit also had some effect on the wear rates of the melter sidewalls. In Campaigns 1 and 2, refractory wear was measured only on the bricks in the northeast, southeast, southwest, and northwest corners due to limited accessability on the walls behind the four electrodes (north, east, south, and west walls). In Table 11, limited wear data for Campaign 3 only are compared with data from Campaigns 1 and 2. Though only two data points are available from Campaign 3, there is a noticable reduction in the average of the maximum refractory wear rate. Interpolating the data from Campaigns 1 and 2 gives an average wear rate of 4.46 mils/day at a melt flux of 2.41 $lb/hr\text{-}ft^2$ for Frit 211 + TDS. However, the Frit 131 + TDS waste glass only

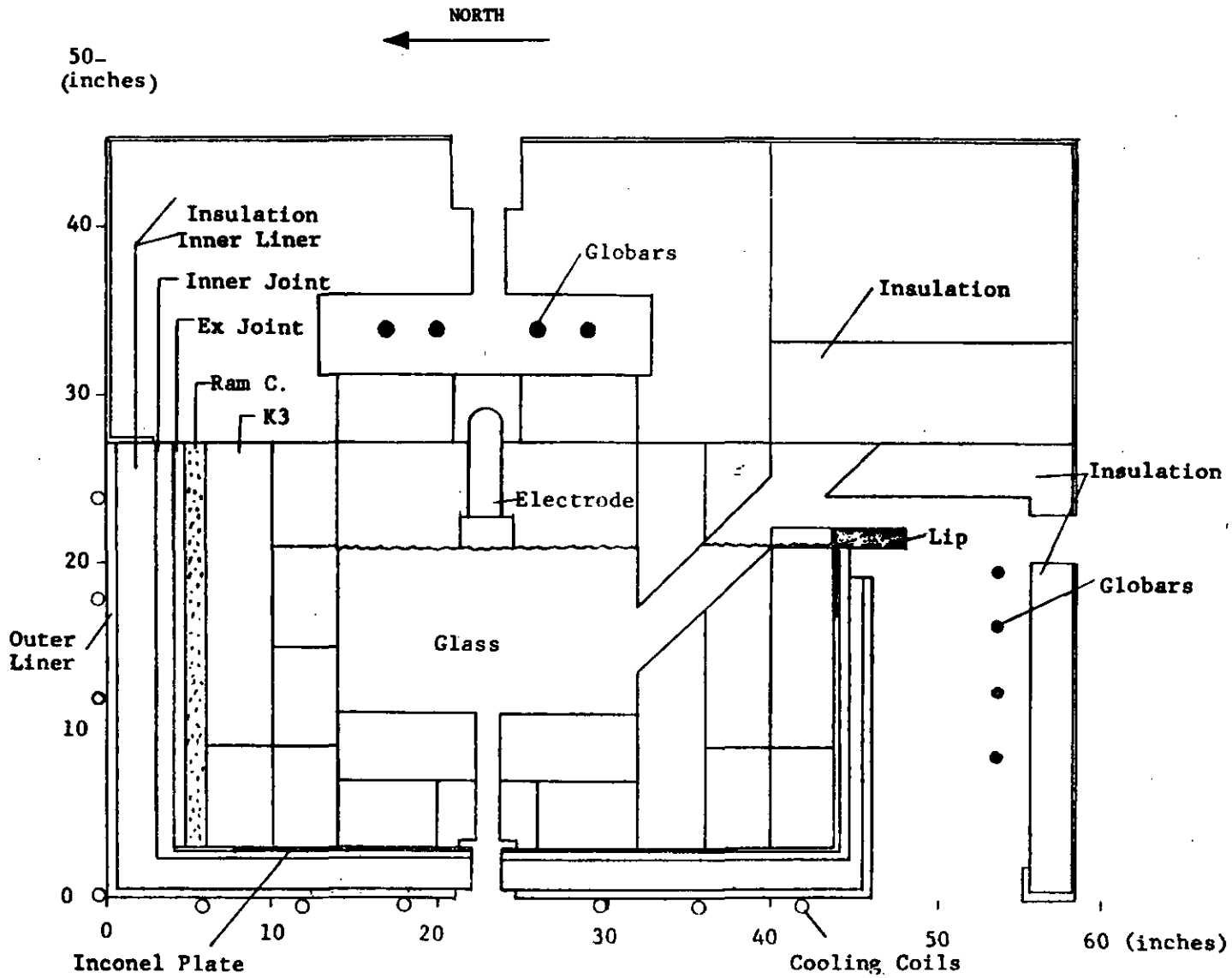

FIGURE 3. Vertical Section of the SCM

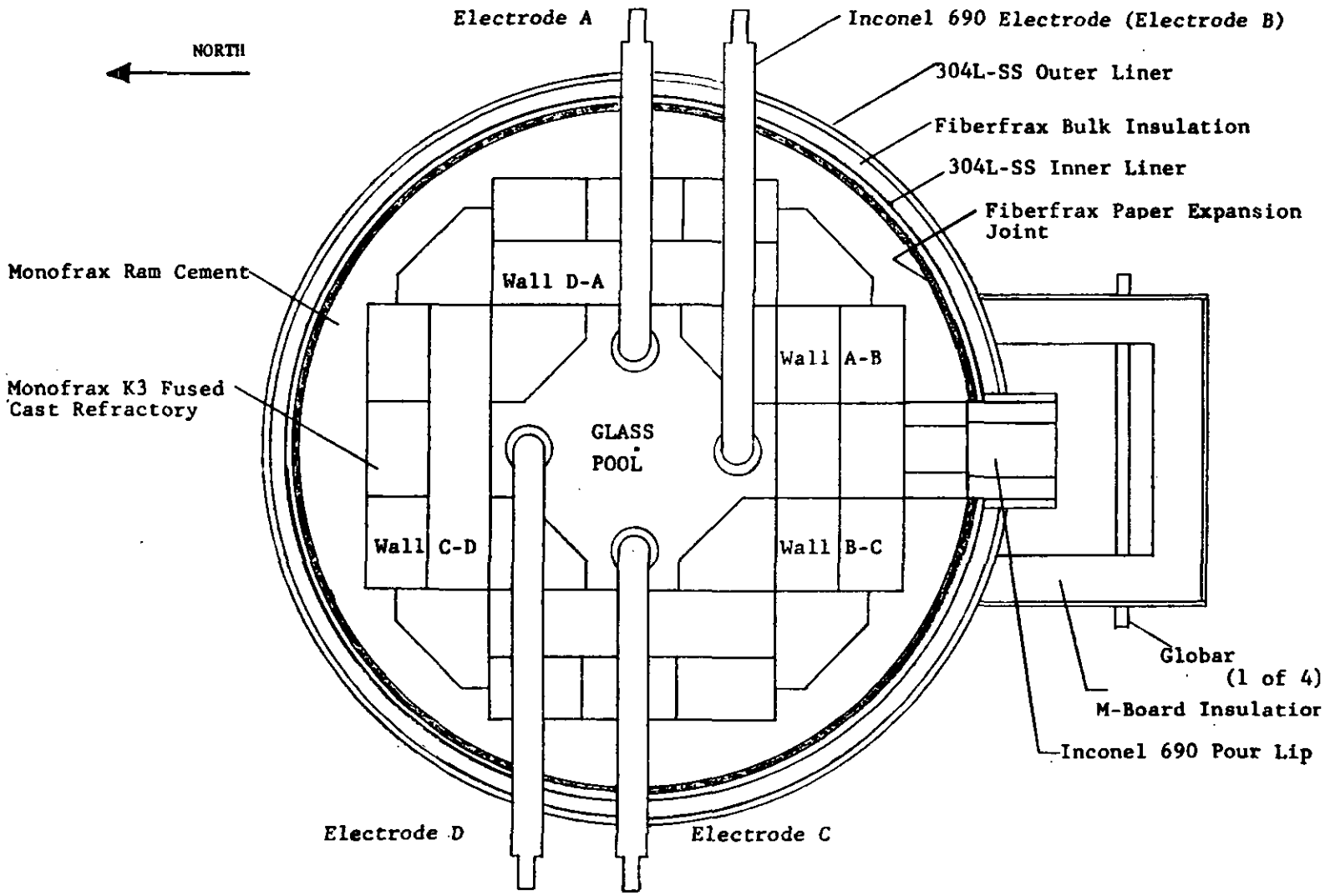

FIGURE 4. Horizontal Section of the SCM at the Top of the Melt Pool

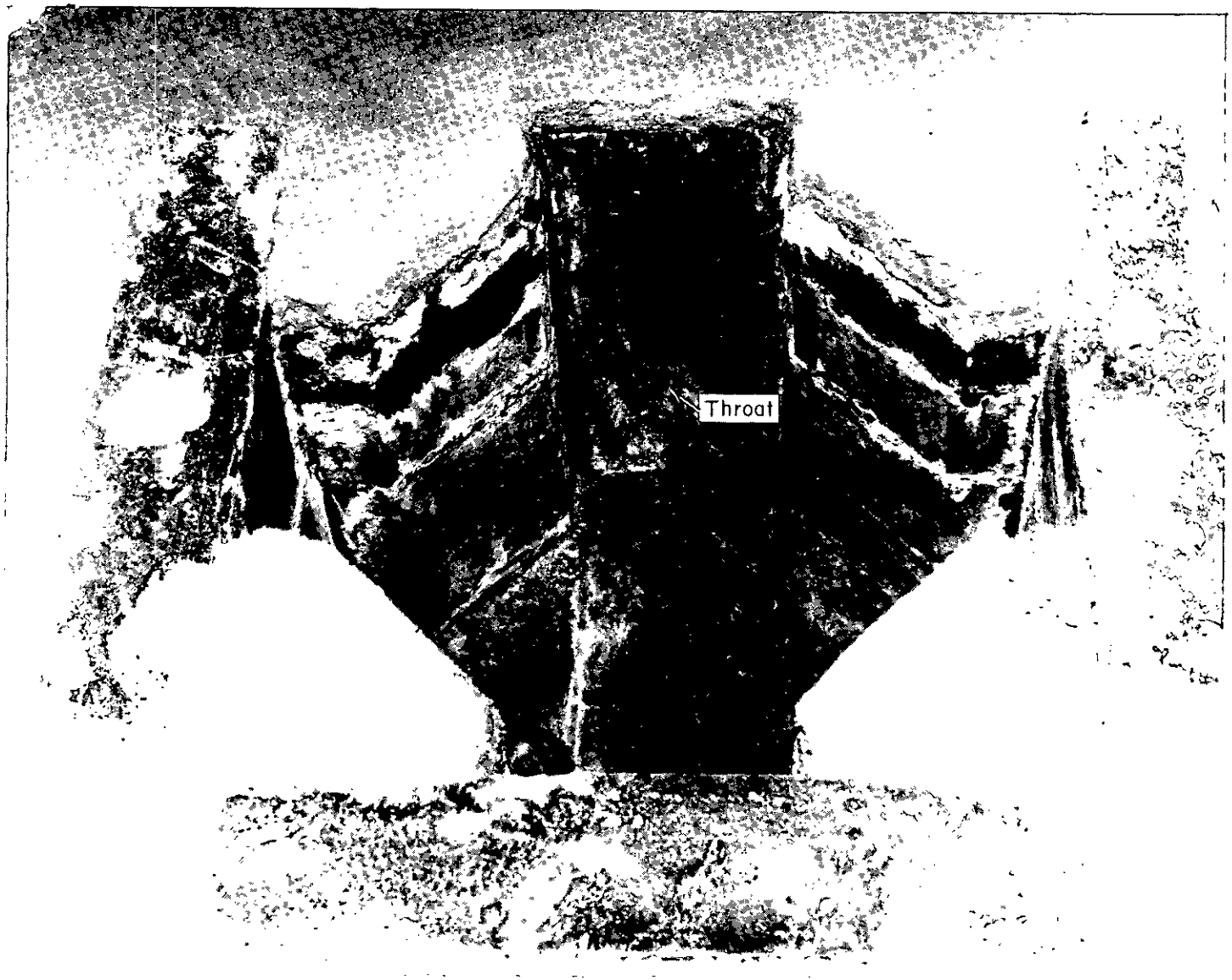

FIGURE 5. Melt Chamber at the Beginning of the First Campaign

FIGURE 6. Melt Chamber at the End of the First Campaign

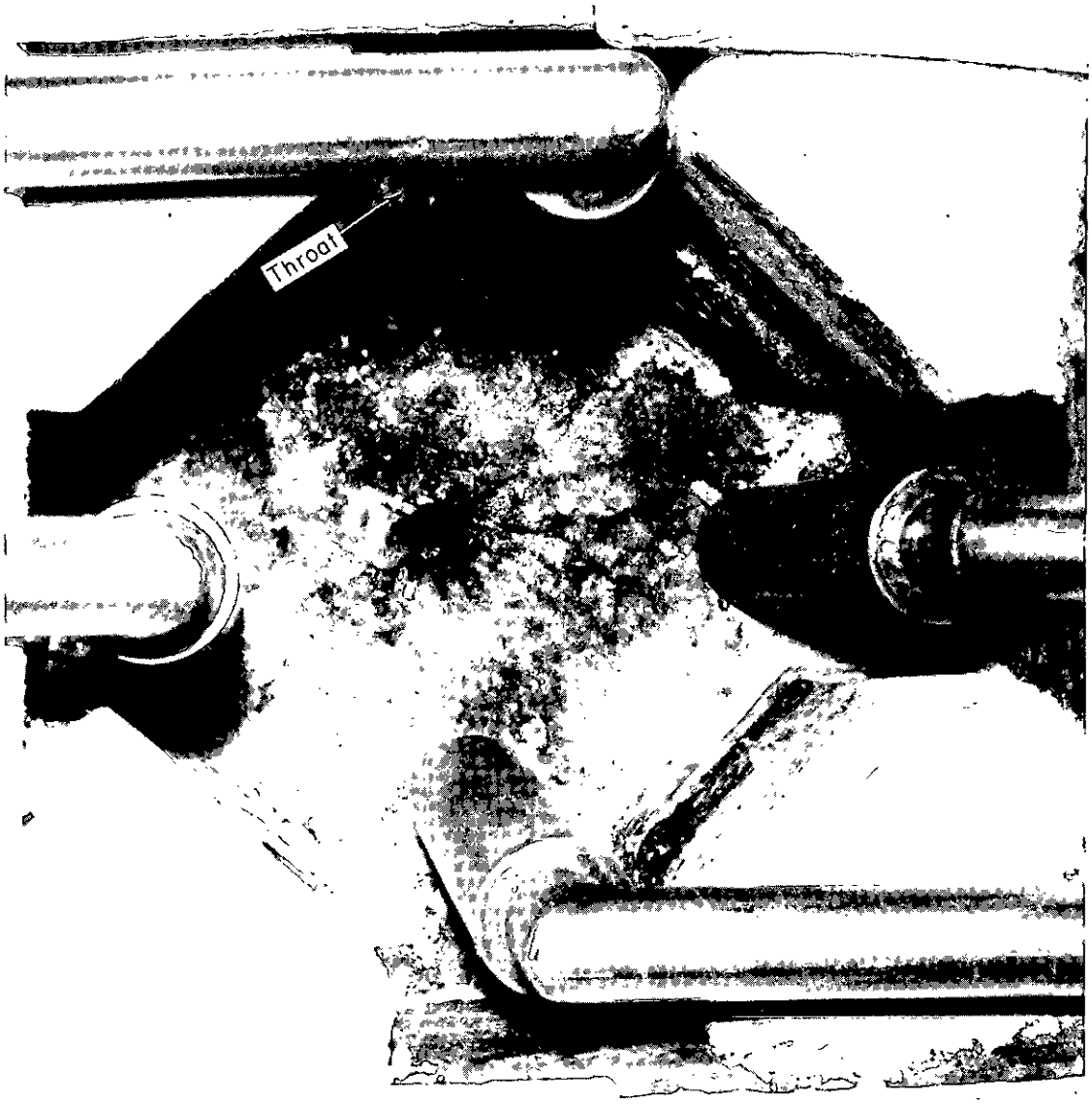

FIGURE 7. Melt Chamber at the Beginning of the Second Campaign

FIGURE 8. Melt Chamber at the End of the Second Campaign

FIGURE 9. Melt Chamber at the Beginning of the Third Campaign

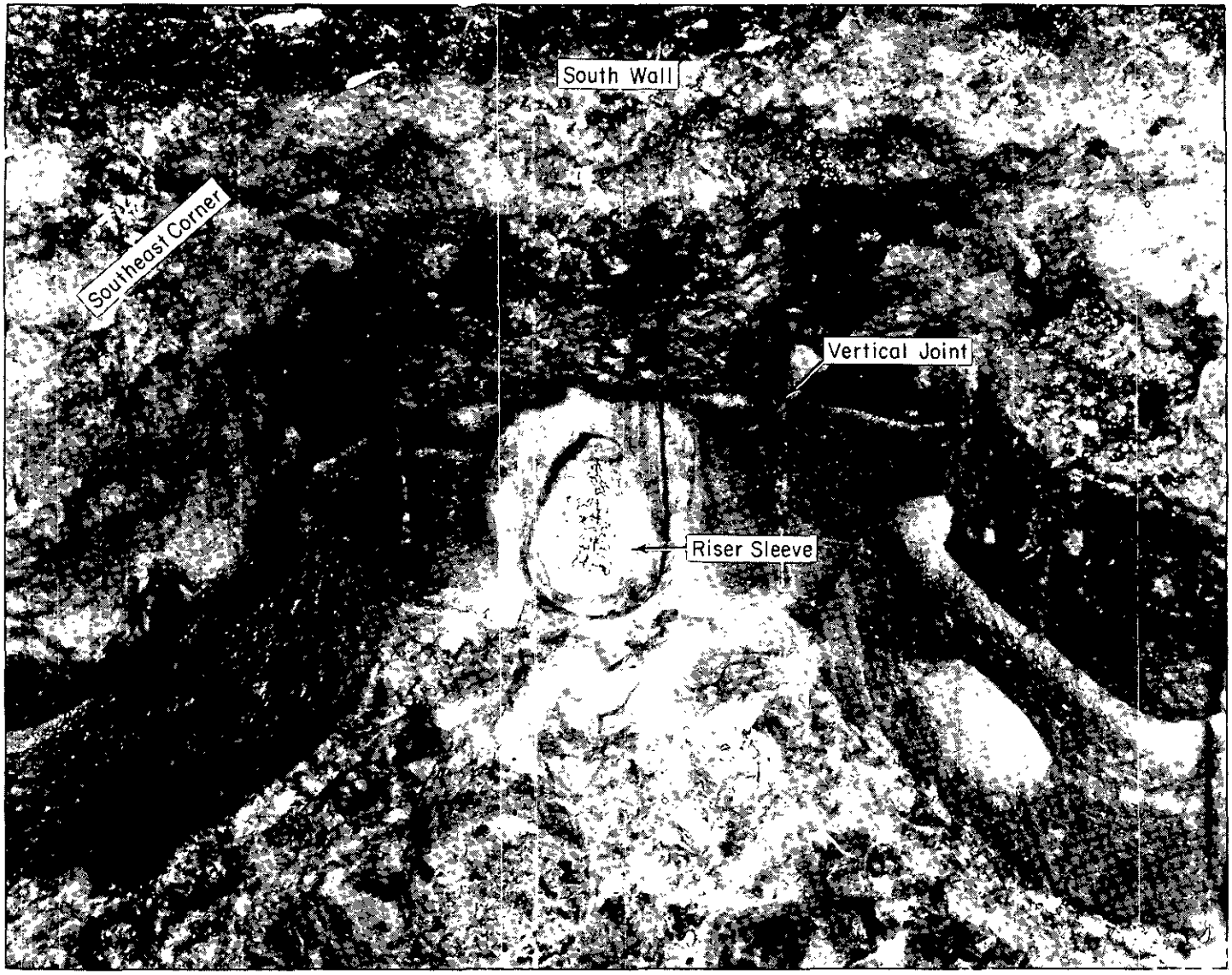

FIGURE 10. Melt Chamber at the End of the Third Campaign

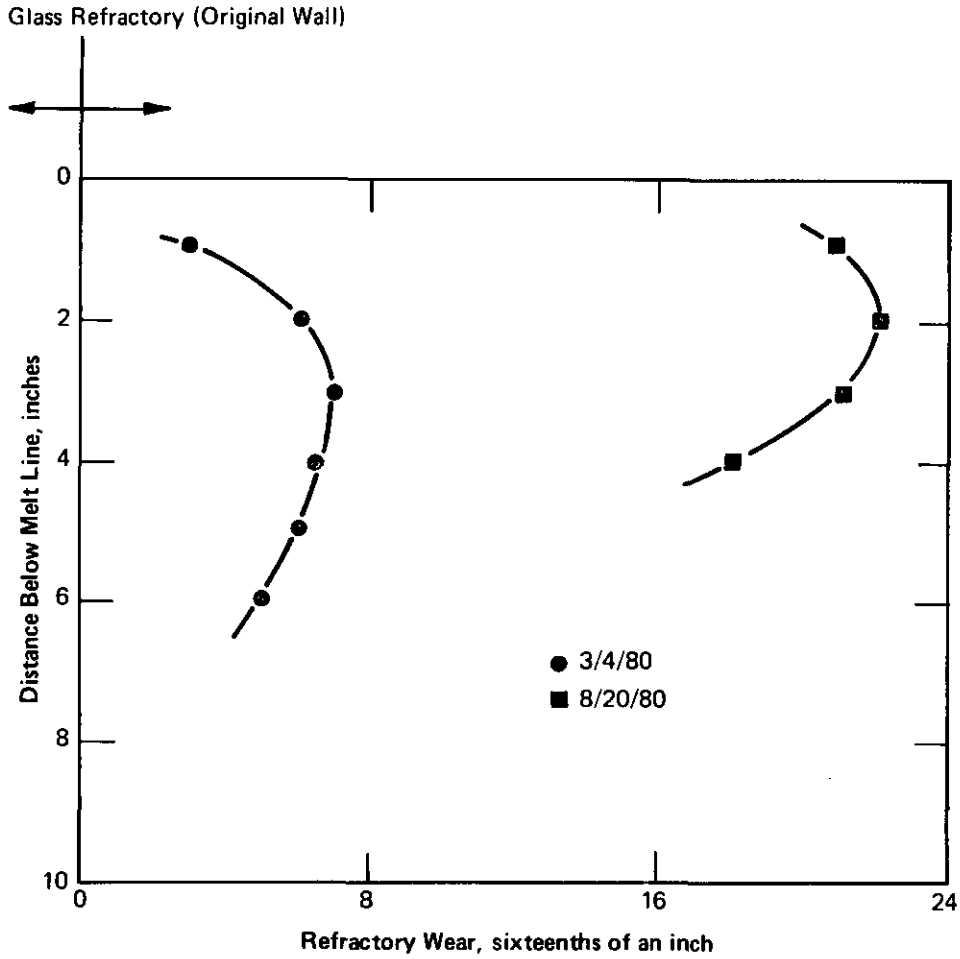

FIGURE 11. Refractory Wear on Wall A-B Versus Melt Depth

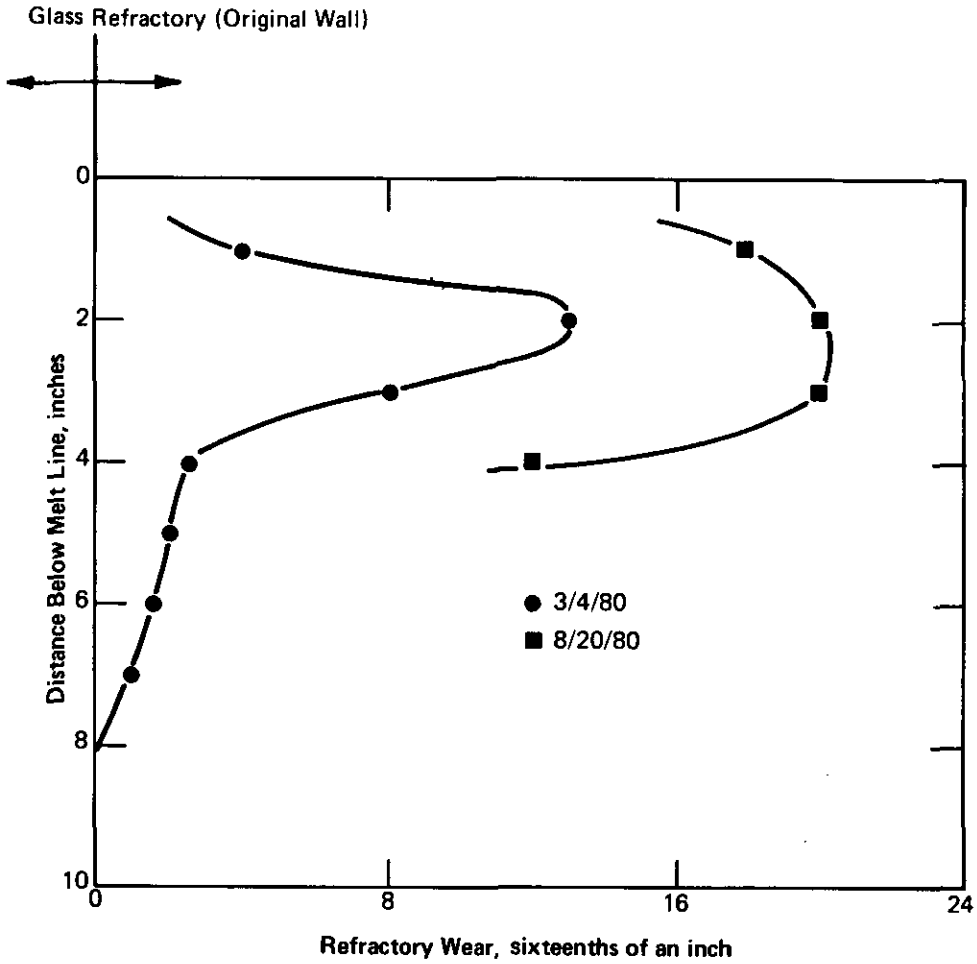

FIGURE 12. Refractory Wear on Wall B-C Versus Melt Depth

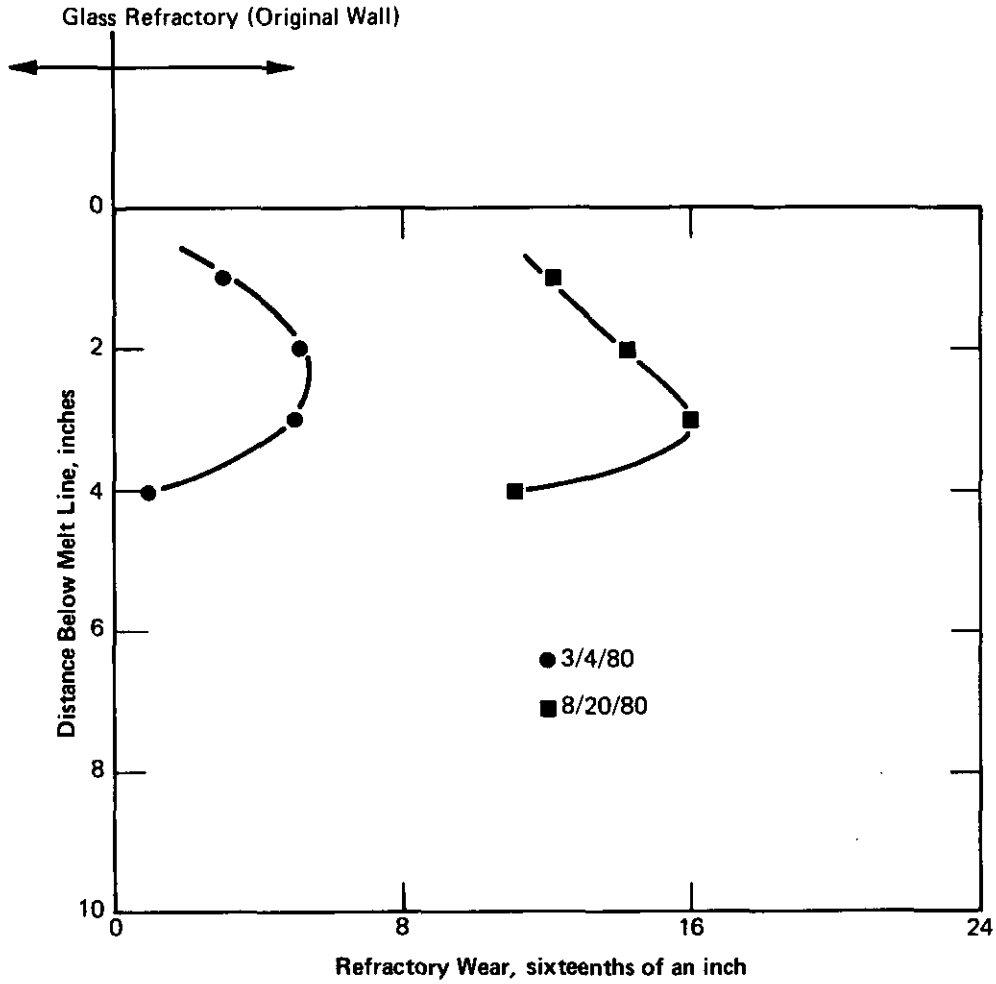

FIGURE 13. Refractory Wear on Wall C-D Versus Melt Depth

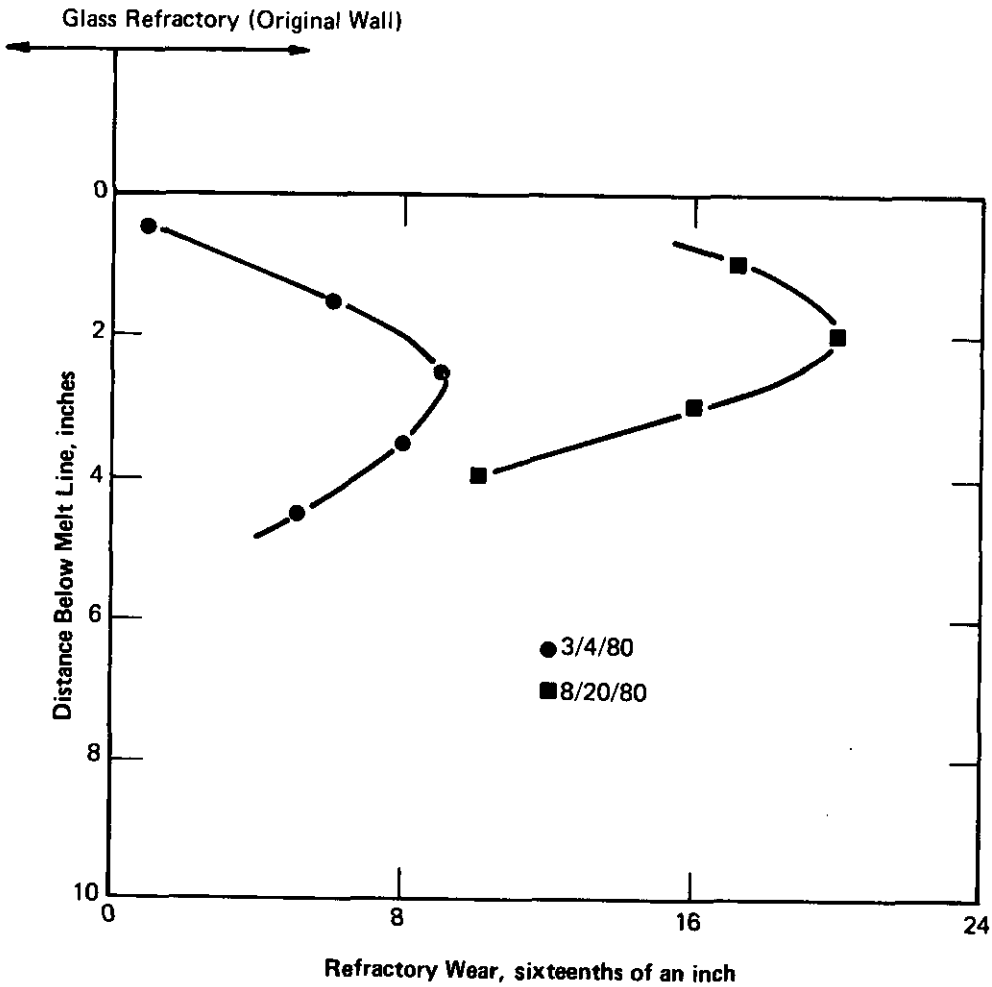

FIGURE 14. Refractory Wear on Wall D-A Versus Melt Depth

TABLE 11

Sidewall Wear as a Function of Melter Campaign

Maximum Refractory	Campaign 1	Campaign 2	Campaign 3
Wear (mils/day)			
- Northeast wall	4.17	5.73	Brick lost
- Southeast wall	3.24	7.52	Excessive deposits
- Southwest wall	6.02	3.71	1.69
- Northwest wall	2.45	5.17	1.93
- Average	3.97	5.53	1.81
Predominant feed material	Frit 211 + TDS Waste	Frit 211 + TDS Waste	Frit 131 + TDS Waste
Average melt flux ($lb/hr\text{-}ft^2$)	1.45	4.53	2.41

resulted in 1.81 mils/day. This suggests that the composition of frit affects the corrosion rate.

The apparent dependence of wear rate on melt flux has been reported for Frit 211 + TDS waste. No other similar study has been conducted for other frit compositions.

After the third campaign, the SCM was disassembled for inspection (Refractory Disassembly section). Figures 10 and 15 through 19 show the inside of the melter.

Figure 10 is a closeup of the south wall where the throat was located. This wall had the only exposed vertical joints in the melter and their condition is generally poor compared to that of the horizontal joints in the melter. However, this may simply be due to the proximity of these joints to the throat where glass velocity was highest.

Extensive refractory wear is apparent all around the throat and there is vertical cracking at the top. The generally smooth contour of the wear pattern and its symmetry seem to indicate that refractory loss was not due to spalling but instead was simply due to corrosion/erosion mechanisms. In addition, the dimensions of the throat are essentially the same as those measured at the end of Campaign 2 which was terminated due to excessive loss of

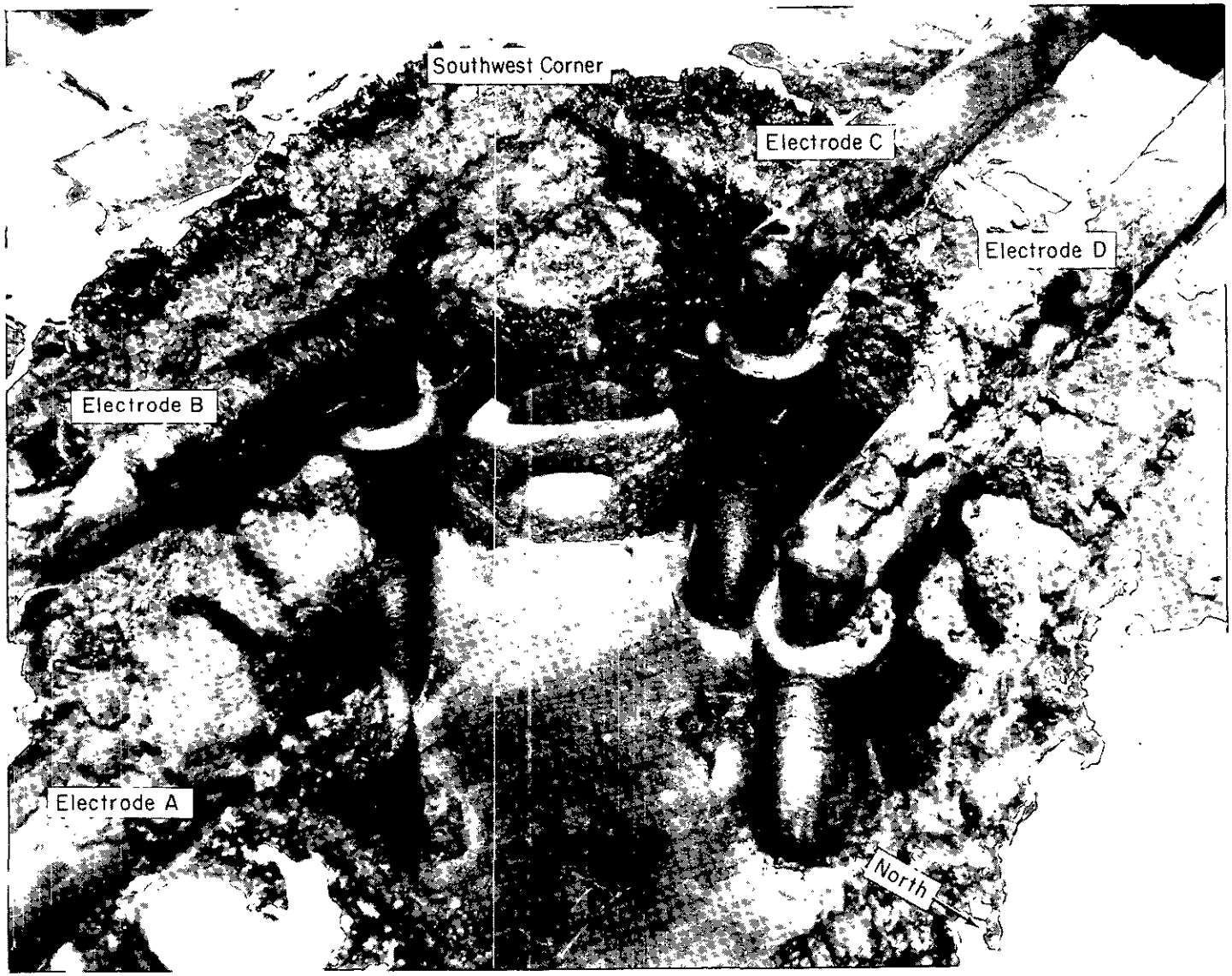

FIGURE 15. Melt Chamber After Shutdown (South View)

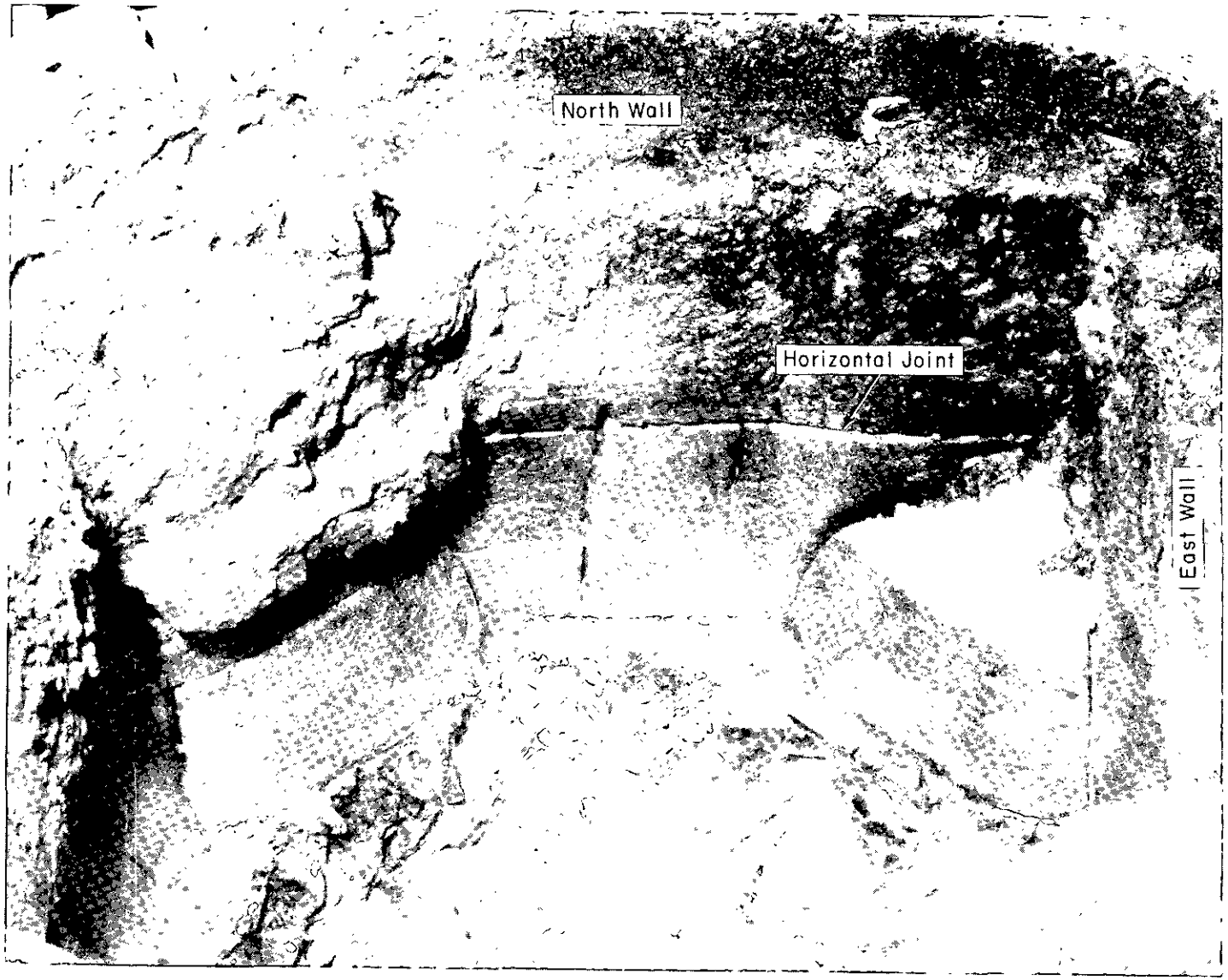

FIGURE 16. Closeup of North Wall

FIGURE 17. Closeup of East Wall

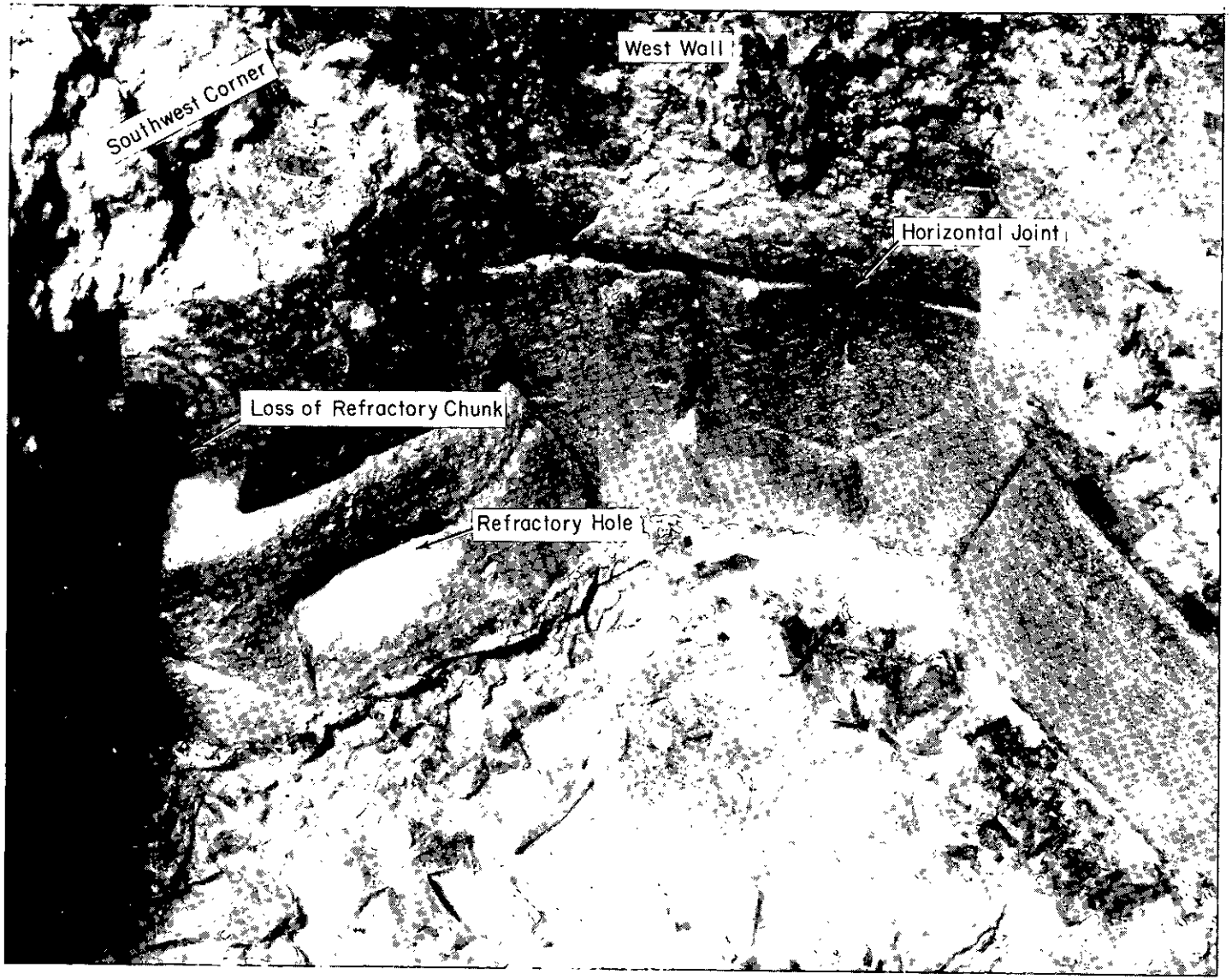

FIGURE 18. Closeup of West Wall

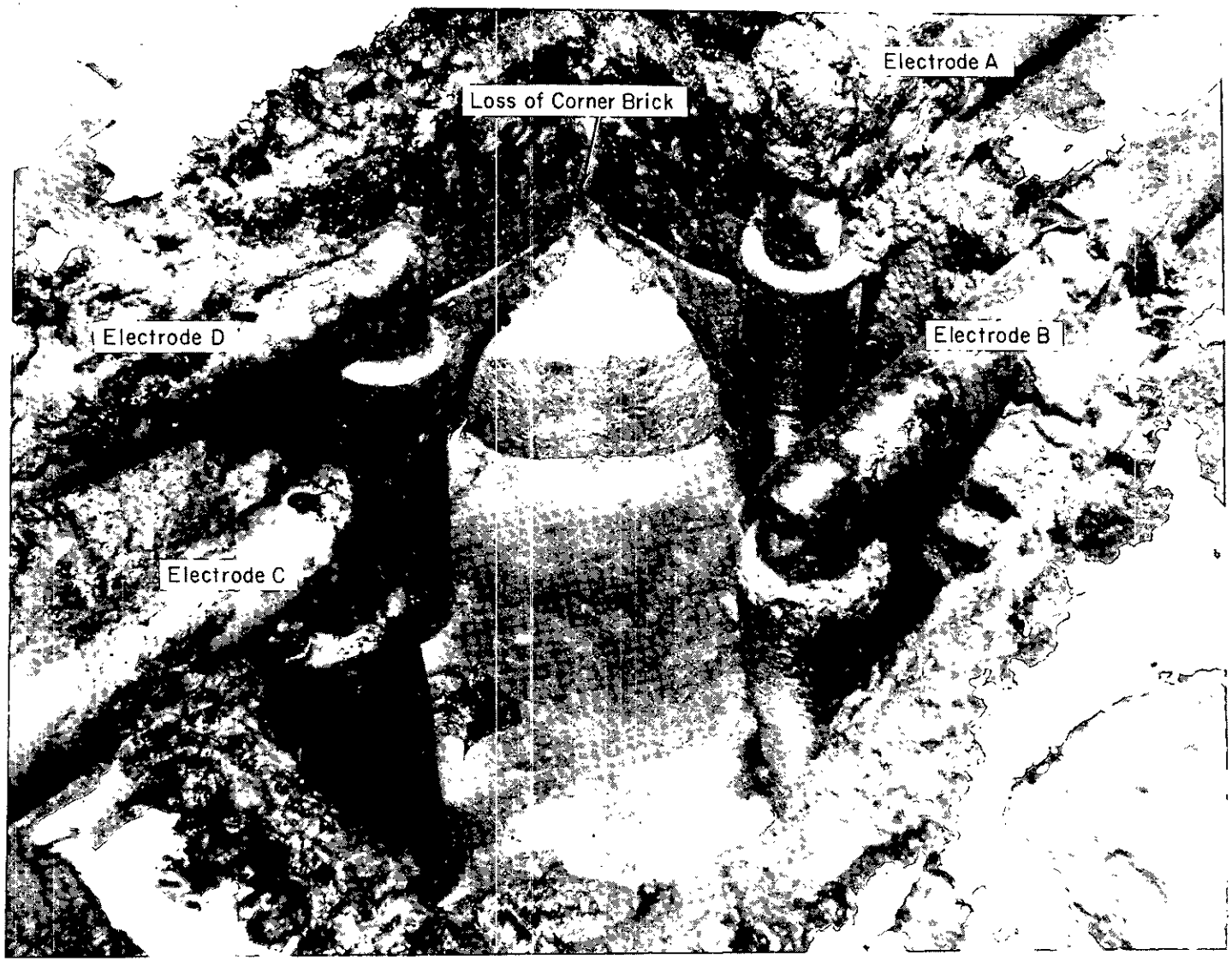

FIGURE 19. Melt Chamber After Shutdown (North View)

Monofrax™ K3 refractory in the throat. The Inconel® 690 riser sleeve which replaced the throat is discussed in more detail in the Wear of Refractory in Throat and Riser Sleeve section.

Figure 15 shows a large hole in a corner brick in the southwest corner. When the melter was new, this hole was approximately 0.5 inch in diameter and 0.25 inch deep. It apparently was the result of cutting into a portion of the vug formed when the brick was manufactured. At the end of the melter lifetime (Figure 15), this hole had increased to roughly 2 inches in diameter and 1 inch deep.

Figure 16 is a closeup of the north wall after removal of the electrodes. Two vertical cracks are apparent beneath the horizontal joint in the brick, but they penetrated less than 1 inch into the wall.

Figure 17 is a closeup of the east wall. Both vertical and horizontal cracks are visible but the penetration depth is only 1 to 2 inches.

Figure 18 is a closeup of the west wall. Both vertical and horizontal cracks are apparent but again the depth of penetration was only 1 to 2 inches. One small chunk of refractory was lost from a brick in the southwest corner, and the refractory hole previously mentioned is again visible.

Figure 19 is the north view of the melt chamber immediately after shutdown with 1 to 2 inches of glass still on the melter floor. An evacuated canister was used to drain the melter. The suction pipe of the canister was not inserted all the way to the melter bottom to prevent the floor deposits from clogging the pipe. One corner brick on the northeast wall apparently fell into the melt pool at some point during Campaign 3. Portions of the brick were subsequently found embedded in the glass remaining on the melter floor. Note, however, that the corner bricks were simply installed to make an otherwise square tank approximately round to match the geometry of the CFM. These bricks were not interlaid with any larger bricks on the north, south, east, or west sidewalls to reduce shifting. Thus no particular significance is attached to the loss of this corner brick.

The deposits above the meltline on the sidewalls and electrodes are similar to deposits observed at the end of Campaigns 1 and 2. They apparently result from splatter and entrainment and are generally high in waste and low in frit.

Refractory Wear on Melter Bottom

Inspection of the refractory bricks removed from the melter floor showed negligible wear. However, the floor deposit (Analysis and Causes of Floor Deposits section) probably protected the bricks to some extent. The refractory wear that would have occurred if the floor had remained free of deposits thus is not known.

Refractory Wear Above the Meltline

Figures 16 through 20 show the condition of the Monofrax™ K3 bricks on the sidewalls above the meltline. Apart from a moderate cracking, deposits, and slight pitting, the refractory appeared to be in very good condition at the end of Campaign 3.

Wear of Refractory in Throat and Riser Sleeve

After the end of Campaign 1, it was observed that the refractory that made up the throat and riser had seriously eroded/corroded. The top of the throat was worn away, and a large crack in the face of the throat (Figure 6) apparently was connected to a hole in the roof of the throat, about 2 inches from the throat face. This extensive crack emerged at the meltline, and had been penetrated by glass. There was also a horizontal void 2-1/2 inches deep at the joint of the throat faceblock, leading away from the melting chamber. The riser block behind the throat exhibited virtually no wear.

Campaign 2 was terminated when unmelted material was observed in the glass discharge stream. After the melter was drained and shut down, examination of the throat section revealed that the hot face of the throat had eroded/corroded away up to the meltline, thus allowing unmelted material to enter the pour stream (Figure 8). The throat region was repaired by inserting an Inconel® 690 sleeve made from 2-inch schedule 40 pipe through the throat/riser section. The sleeve was then welded to the stainless steel inner liner to prevent glass from flowing around the sleeve and into the pour stream. Figure 9 shows the throat of the Inconel® 690 pipe in the melt chamber and Figure 21 shows the attachment of the sleeve to the inner shell in the pour chamber.

The condition of the Inconel® 690 sleeve at the end of Campaign 3 is shown in Figures 22 and 23. Its performance is compared with that of the Monofrax™ K3 refractory in Figure 24 and Table 5. The Monofrax™ K3 throat failed due to excessive wear at the end of Campaign 2 after only 24,511 lb of glass passed through it. In contrast, the Inconel® 690 sleeve was still performing satisfactorily at the end of Campaign 3 after passing 38,369 lb of glass.

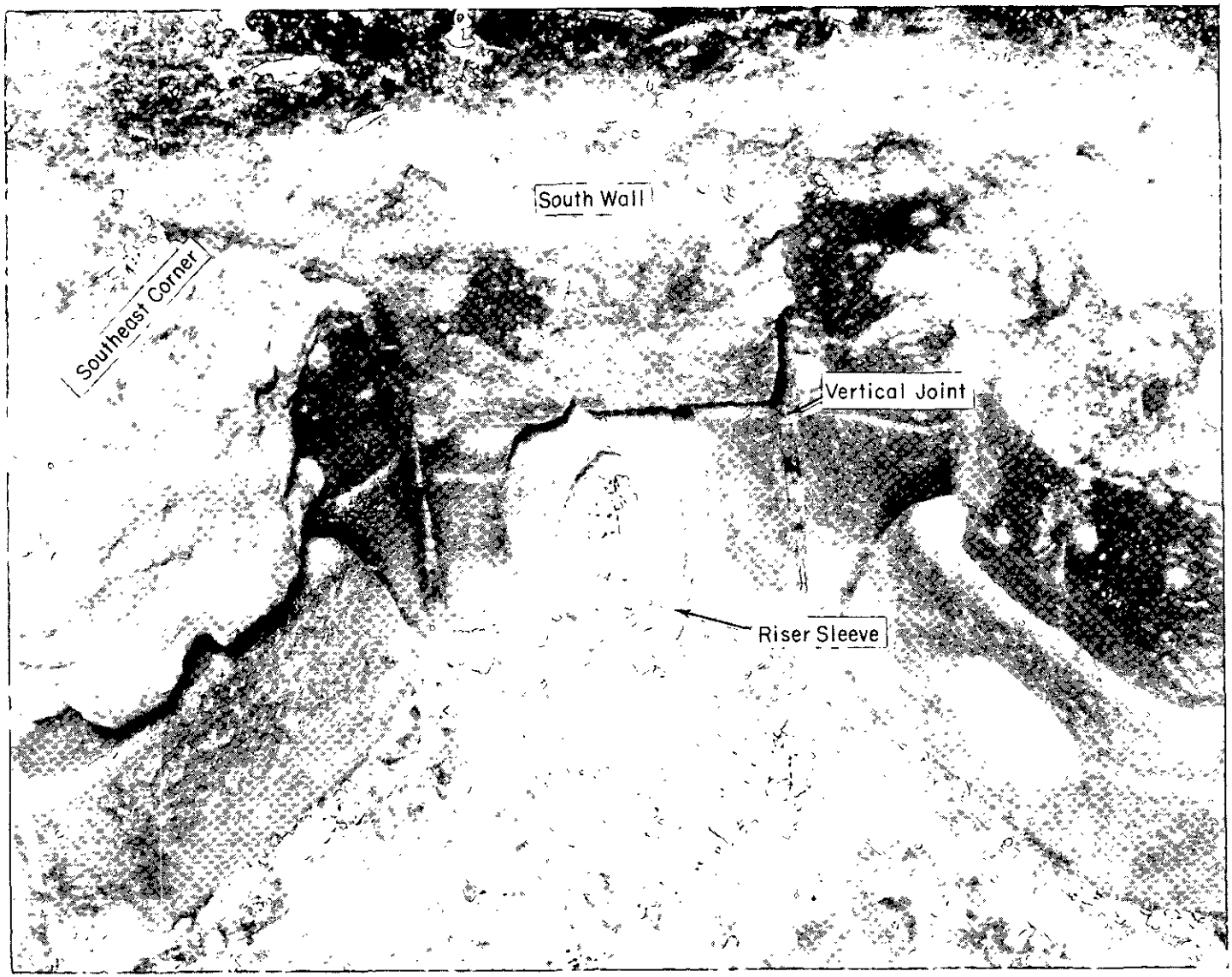

FIGURE 20. Closeup of South Wall

FIGURE 21. Inconel® 690 Replacement Sleeve Attachment in Pour Chamber Before Campaign 3

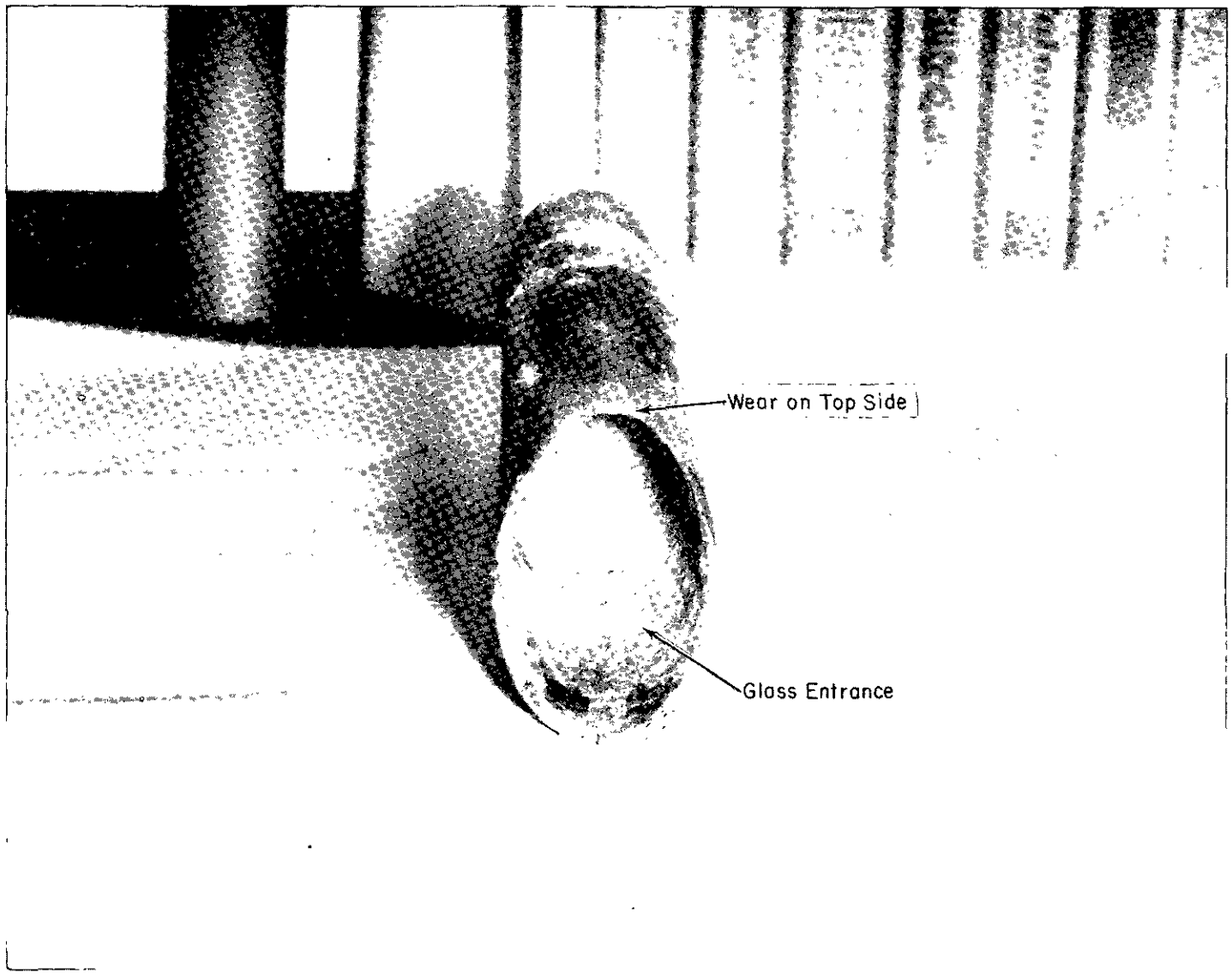

FIGURE 22. Closeup of Entrance to Inconel® 690 Riser Sleeve

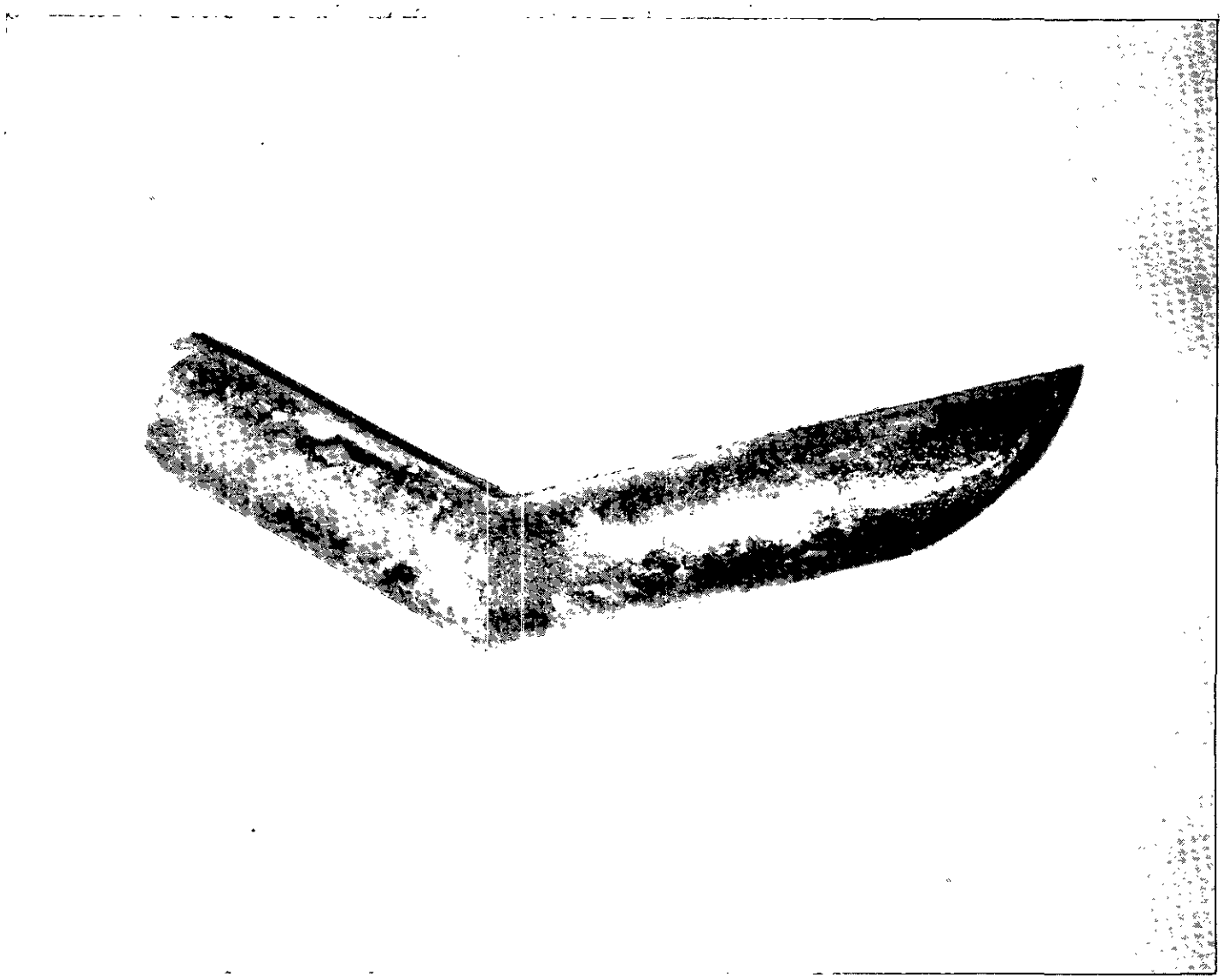

FIGURE 23. Side View of Inconel® 690 Riser Sleeve

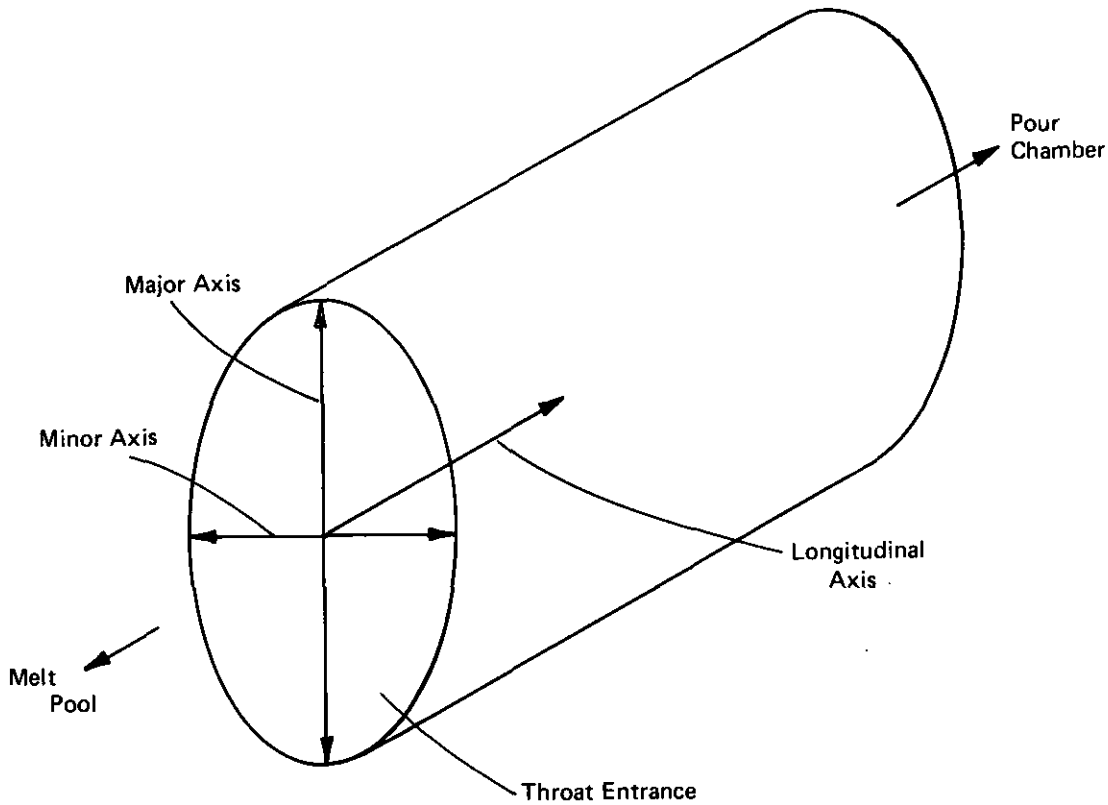

FIGURE 24. Coordinate Definitions for Throat Wear

However, it had worn through at its lower end (Figure 22) on the top side.

Part of the superior performance of the Inconel® 690 sleeve can be attributed to the drop in the general corrosion rate in Campaign 3 which was apparently due to a change from Frit 211 to Frit 131. However, the Inconel® 690 sleeve not only out performed the Monofrax™ K3 in the throat region, but also in the melt pool. This is supported by comparison of Inconel® 690 electrode wear with Monofrax™ K3 sidewall wear (Table 12).

TABLE 12

Comparison of Refractory and Metal Throats

Material	Days In Service	Glass Throughput (lbs)	Comments
Monofrax™ K3	268	24511	Upward wear of 2 in. to near meltline on major axis. Minor axis enlarged 0.70 in. Wear on longitudinal axis of 1 to 1.5 in.
Inconel® 690 (2 inch sch 40 pipe)	518	38369	Wore through 0.154 in. wall to top side along major axis for 1.0 in. along longitudinal axis. Little wear on minor axis.

Electrode Wear

During Campaign 1, the SCM had electrodes of two different sizes. One pair of electrodes (A & B, Figure 4) was made from 3-inch sch 40 Inconel® 690 pipe. The other two electrodes (C & D, Figure 4) were made from 2-inch sch 40 Inconel® 690 pipe. All four electrodes were air-cooled. For 90% of the first campaign, electrode A fired to electrode D and electrode B fired to electrode C, which was termed adjacent firing. The remaining 10% of the time the electrodes cross fired (electrode A fired to C and electrode B

fired to D). When first installed, the electrodes were inadvertently wired for adjacent firing. After a power outage, the error was discovered and the melter was rewired correctly.

The wiring error led to the discovery that, for the same lid power input, the SCM could be powder fed 27% faster when adjacent firing of the electrodes was used than with cross firing. Apparently stronger convection cells were established with adjacent firing, creating better heat transfer to the feed pile. During Campaigns 2 and 3 the electrodes were cross fired. No other experiments were conducted for adjacent firing of the electrodes.

Campaign 1 ended when a hole developed in electrode A approximately 3 inches below the melt line. As Figures 25 to 28 show, the wear was very different on the nominal 3-inch-OD electrodes compared to that for the nominal 2-inch-OD electrodes. The larger electrode was attacked severely below the melt line, with little attack at the melt line (Figure 25). The extent of penetration depended markedly on position for this electrode, being greatest in the direction of maximum current flow (Figure 26). The small electrodes (higher current flux) showed relatively little wear below the melt line, but extensive localized necking at the melt line (Figure 27). There was little dependence of extent of penetration on position around the electrode (Figure 28).

The reasons for the drastically different wear patterns are not clear, but followup work by SRL and Huntington Alloys (manufacturer of the Inconel® 690) after Campaign 1 showed that the larger electrode underwent sulfidization and removal of chromium. The smaller electrodes were exposed to severe oxidizing conditions at the melt line. Both sources agreed that DC electrolysis was the most likely cause of the electrode wear. The difference in the diameters of the electrodes apparently also had some effect.

Before the start of the second campaign, the four pipe electrodes were replaced with four 3-inch-OD solid Inconel® 690 bars. Air-cooling of the electrodes was deleted because it was not needed to reduce the corrosion rate. The second campaign ended when the throat refractory failed and allowed unmelted feed to be discharged in the pour stream. The throat refractory was replaced with an Inconel® 690 sleeve (Wear of Refractory in Throat and Riser Sleeve section).

The wear patterns for the bar electrodes at the end of Campaigns 2 and 3 are shown in Figures 29 to 32. The location of the micrometer when each measurement was made is also shown. These measurements assume that the wear about the centerline of the bar was symetric. Maximum electrode wear occurred 4 to 5 inches below the melt surface for powder feeding of Frit 211 + TDS simulated waste. This corresponded to the location of the hottest temperature when the melter is being fed. Data from a physical model of the SCM indicated that this was the region where fresh feed (relatively

FIGURE 25. Nominal 3-inch OD Electrode (A) after Campaign 1

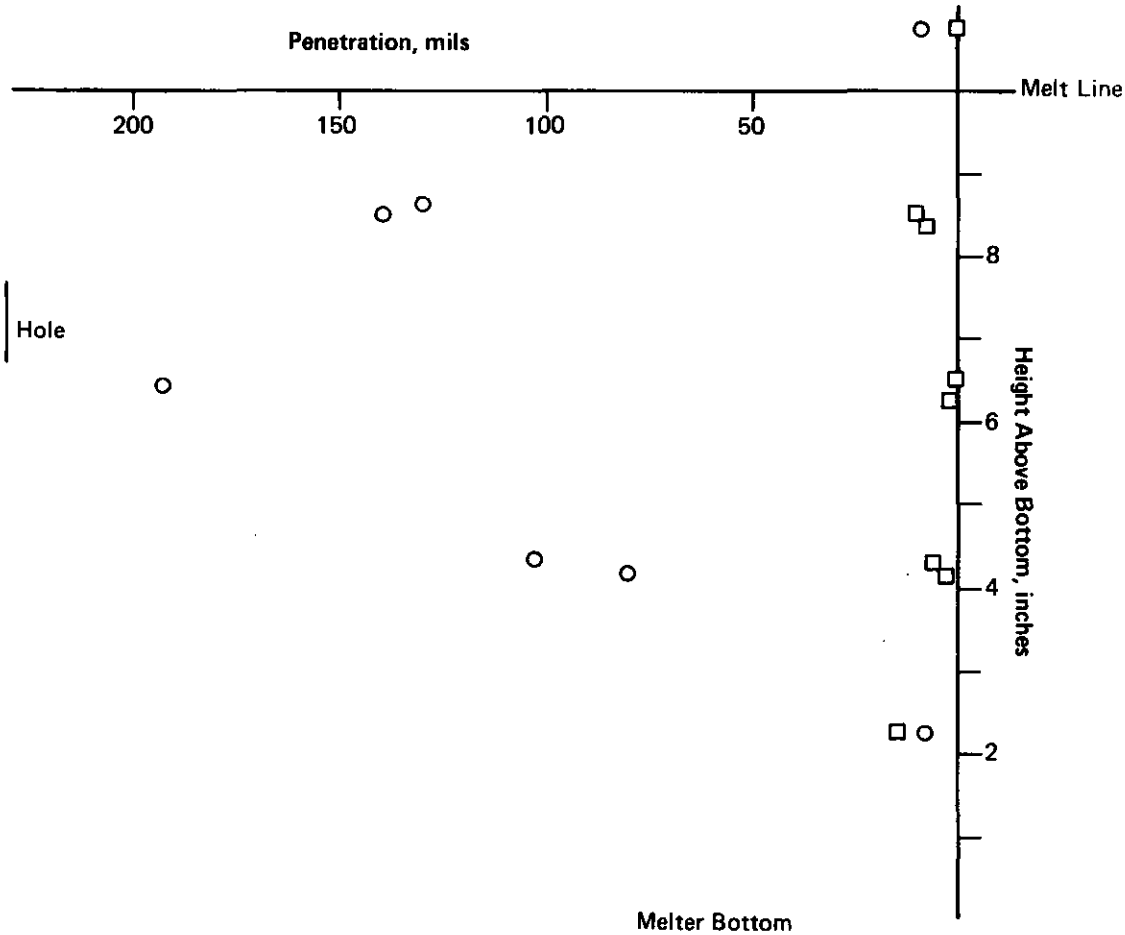

FIGURE 26. Corrosion of 3-inch Inconel® 690 Electrode. Circles are from side facing 2-inch electrode, squares are from rear of electrode.

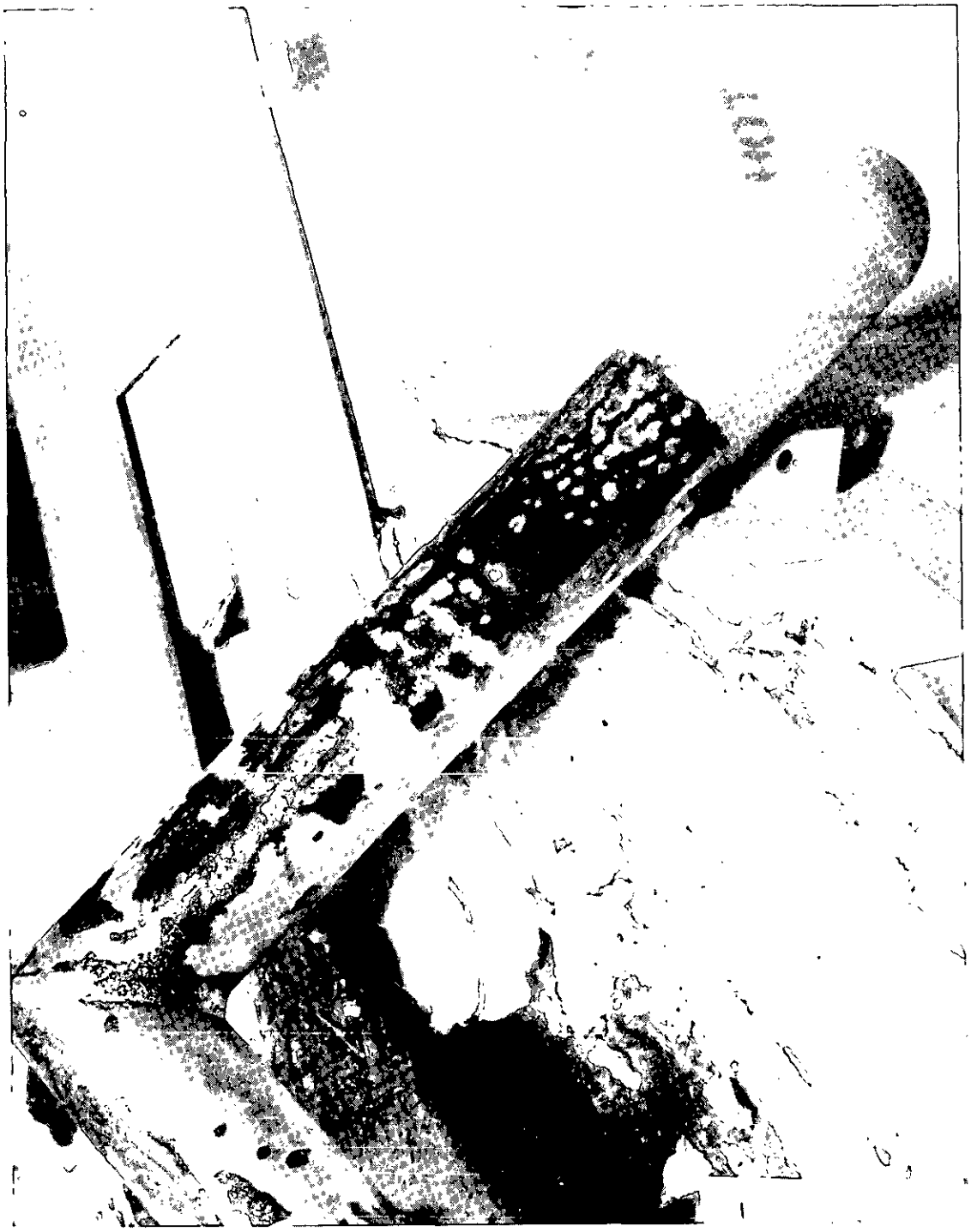

FIGURE 27. Nominal 2-inch OD Electrode (D) After Campaign 1

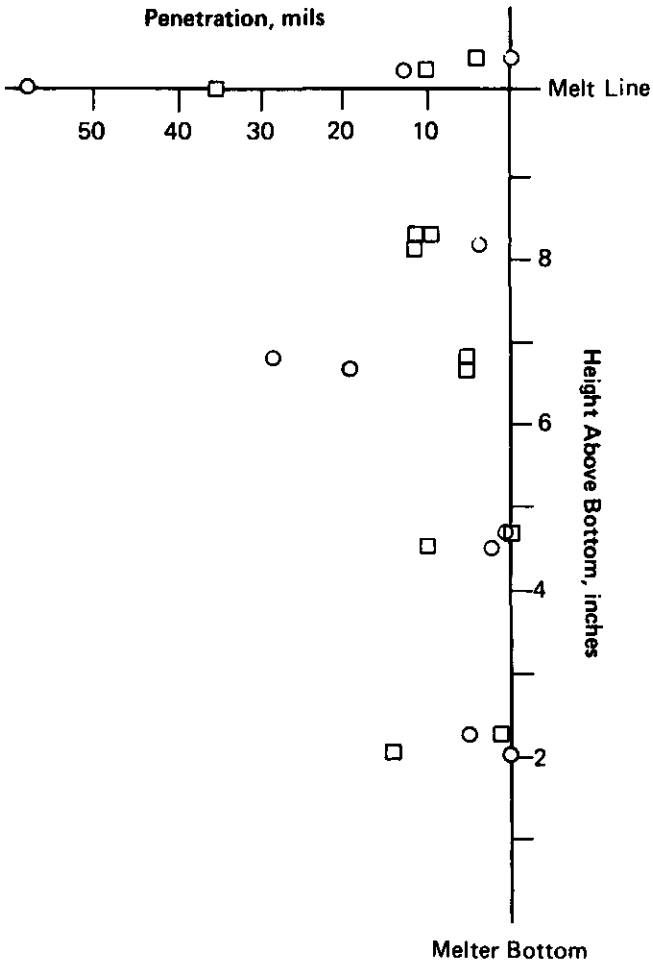

FIGURE 28. Corrosion of 2-inch Inconel® 690 Electrode. Circles are from side facing failed electrode, squares are from rear of electrode.

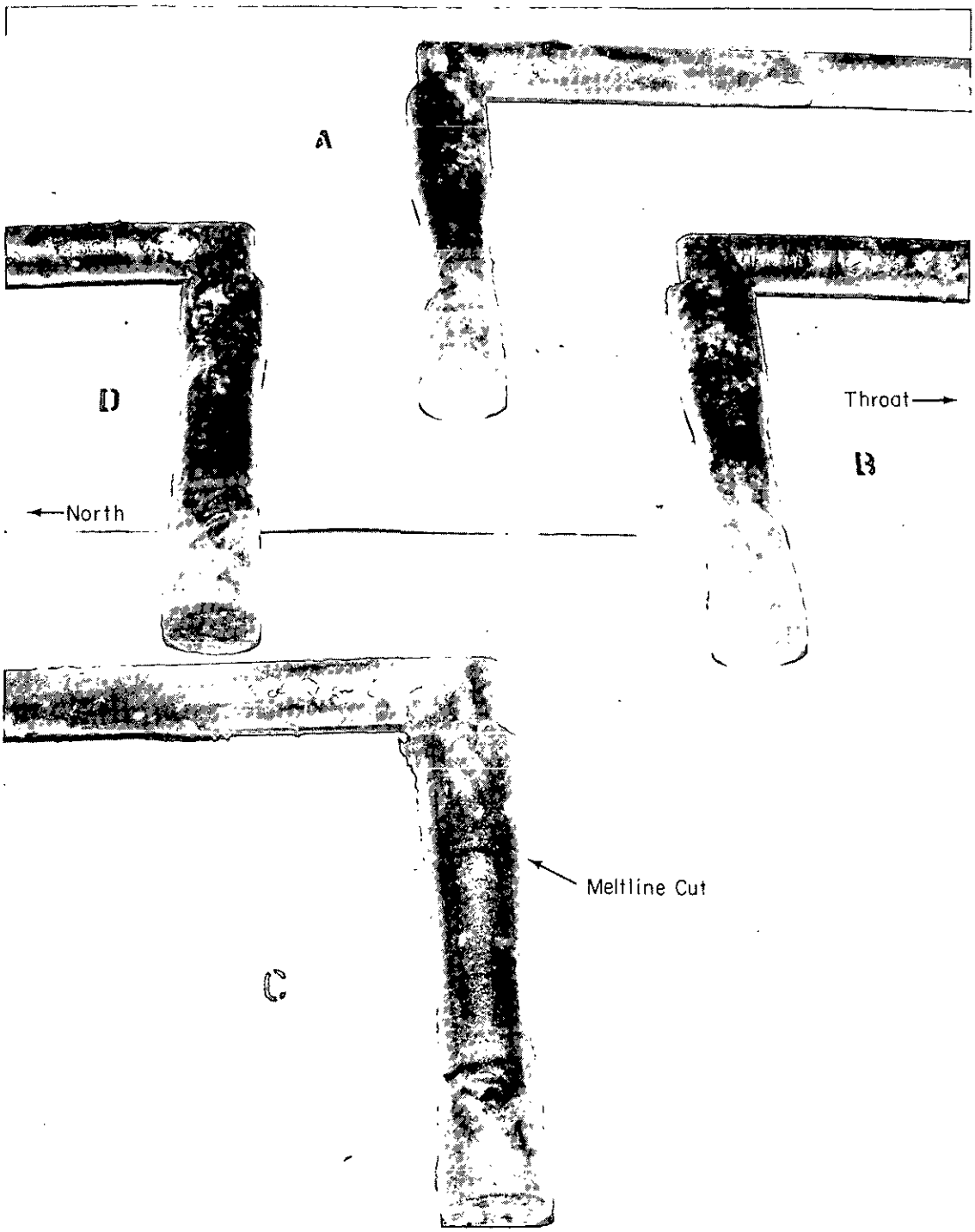

FIGURE 29. Electrodes at the End of Campaign 3

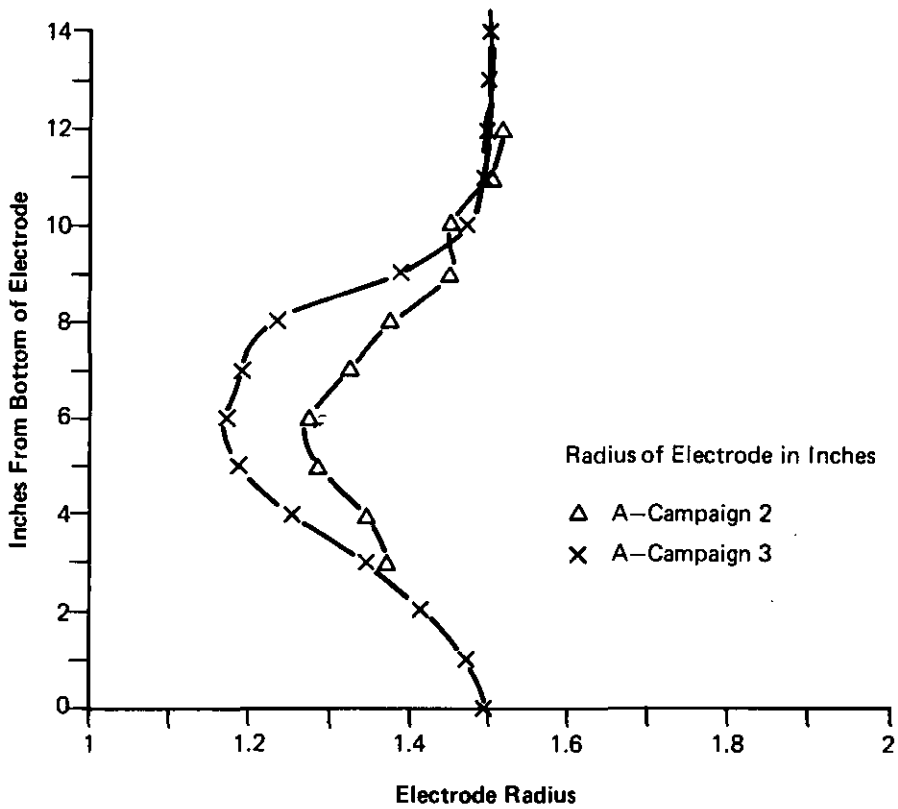

FIGURE 30. Electrode A Wear Data

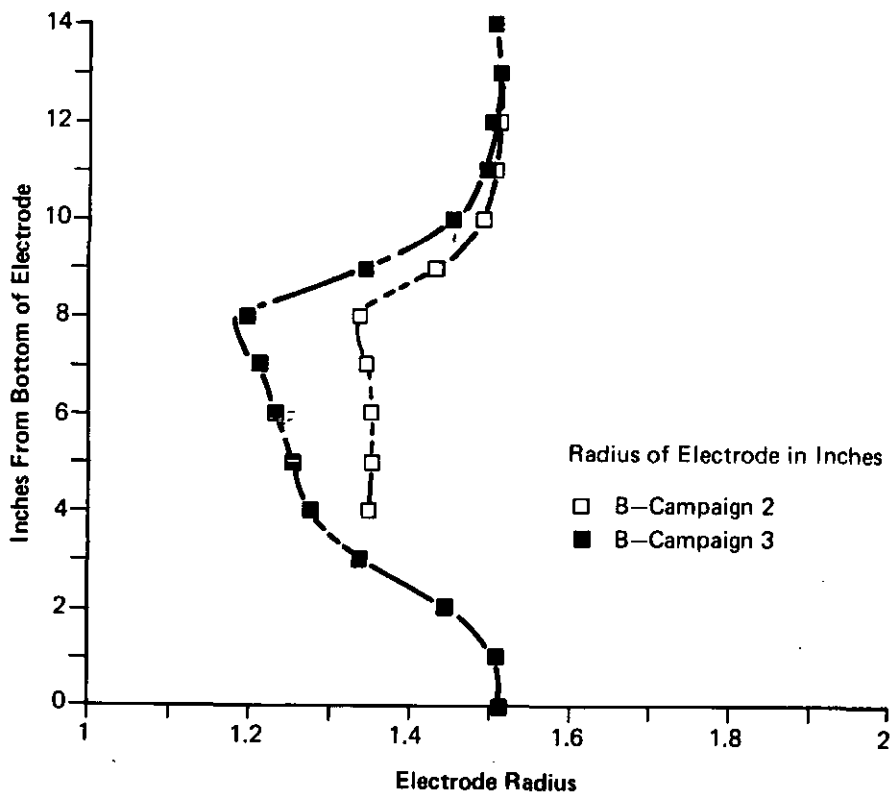

FIGURE 31. Electrode B Wear Data

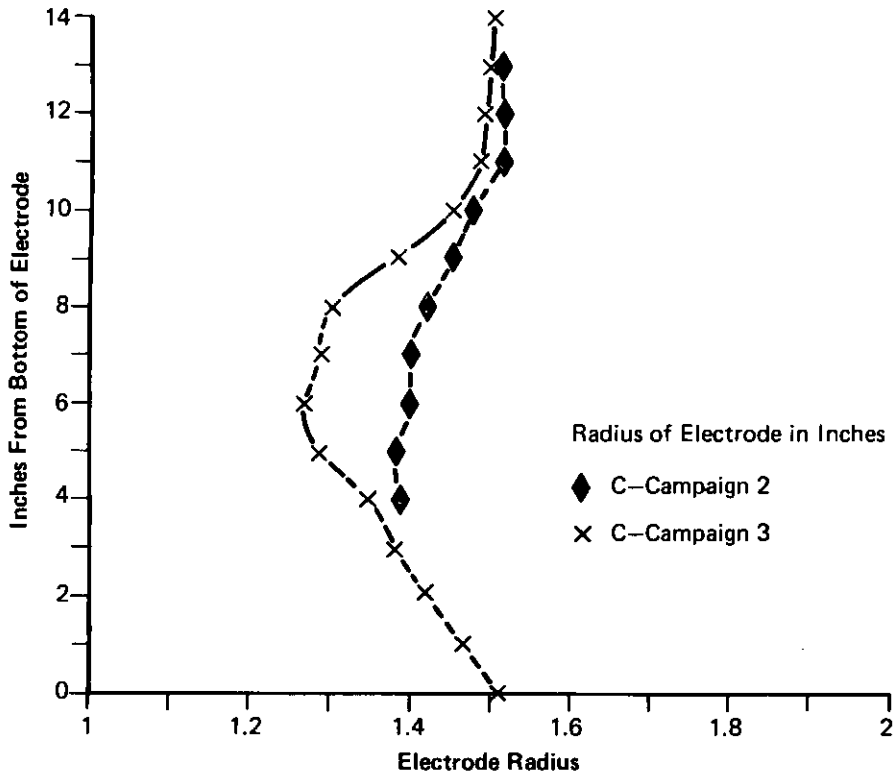

FIGURE 32. Electrode C Wear Data

oxygen rich) first contacted the electrodes. The combination of these two effects probably accounted for the axial shape of the electrode wear patterns.

Maximum wear on electrodes B, C, and D (Table 13) was consistent with the velocity field generated by gravitational forces when the melter was tilted for pouring. Table 13 shows that electrode A experienced the highest wear rate of all four electrodes in Campaigns 1 and 2. This suggested a dominating wear mechanism other than glass temperature and velocity.

The melter had always experienced problems with DC voltage transmission to the glass pool due to switching of the current controllers (silicon controlled rectifiers or SCR's) during the first two campaigns. Switching was always more erratic on phase 1 than on phase 2. Phase 1 fired through electrodes A and D during 90% of Campaign 1, and through electrodes A and C for the remainder of the campaigns. It has been postulated that an electrochemical cell which developed around electrode A because of the DC potential was responsible for the abnormally high wear rate on this electrode. Why electrodes C and D were not affected as well is not known. Isolation transformers were installed on both electrical phases at the end of the second campaign in an attempt to reduce electrode wear by blocking the transmission of direct current from the SCR's into the melt pool (Effect of Direct Current on Electrode Wear section).

As mentioned in the Operating History section, the third operating campaign ended when the melter experienced a hot bottom problem and in conjunction with its shutdown for installation of a second small research glass melter. The appearance of the electrodes at the end of Campaign 3 is shown in Figure 29. All four electrodes show a small cut near the melt line. The shape of the electrodes at the end of Campaign 3 is shown in Figures 30 through 33. The radial wear on all four electrodes is plotted in Figures 34 through 37 for Campaign 3, based on the change in electrode diameter that occurred from the end of Campaign 2 to the end of Campaign 3. For electrodes A, B, and C, the wear rate in the melter plenum was 0.020 to 0.050 mils/day. In the glass pool, the maximum wear occurred 1 to 3 inches below the melt line and varied from 0.253 to 0.278 mils/day for electrodes A, B, and C.

Electrode D apparently experienced some high temperature creep. Figure 33 shows a larger reduction in diameter for electrode D in the plenum compared to electrodes A, B, and C. In the area 1 to 3 inches below the melt line, electrode D experienced very little change in diameter. At more than 4 inches below the melt line, the diameter actually increased during Campaign 3. This suggests that electrode D slumped downward during the campaign enough to completely distort the wear pattern seen on the other three electrodes. Actually this distortion is not surprising.

TABLE 13

Comparison of Electrode Wear Data for Campaigns 1, 2, and 3

	Campaign 1	Campaign 2	Campaign 3
Electrode material	Inconel® 690	Inconel® 690	Inconel® 690
Electrode geometry			
A	3 in. sch 40 pipe	3 in. solid bar	3 in. solid bar
B	3 in. sch 40 pipe	3 in. solid bar	3 in. solid bar
C	2 in. sch 40 pipe	3 in. solid bar	3 in. solid bar
D	2 in. sch 40 pipe	3 in. solid bar	3 in. solid bar
Air cooling	Yes	No	No
Nominal electrode Temperature, °C	1000	1150	1150
Predominant glass	Frit 211 + TDS Waste	Frit 211 + TDS Waste	Frit 131 + TDS waste
Average melt flux lb/hr-ft^2	1.45	4.53	2.41
Isolation transformer	No	No	Yes
Feed material	Powder	Powder	Powder/slurry
Maximum wear rate, mils/day			
A	1.59	1.82	0.273
B	1.40	1.50	0.278
C	0.59	0.984	0.253
D	0.59	0.376	Creep
Average	1.04	1.17	0.268

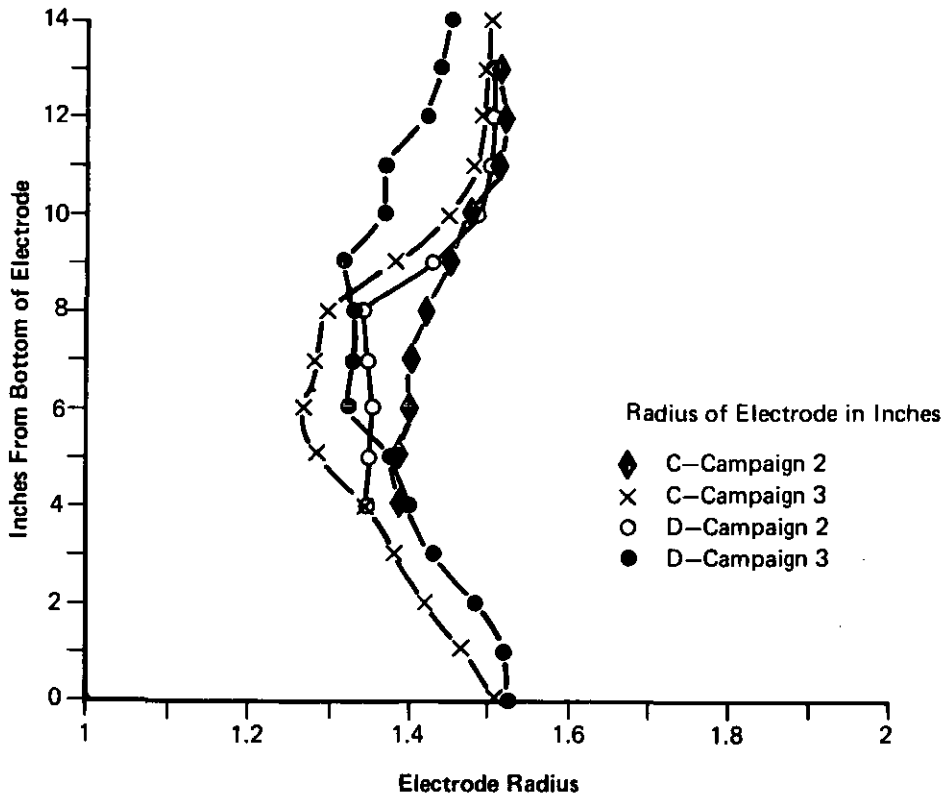

FIGURE 33. Electrode D Wear Data

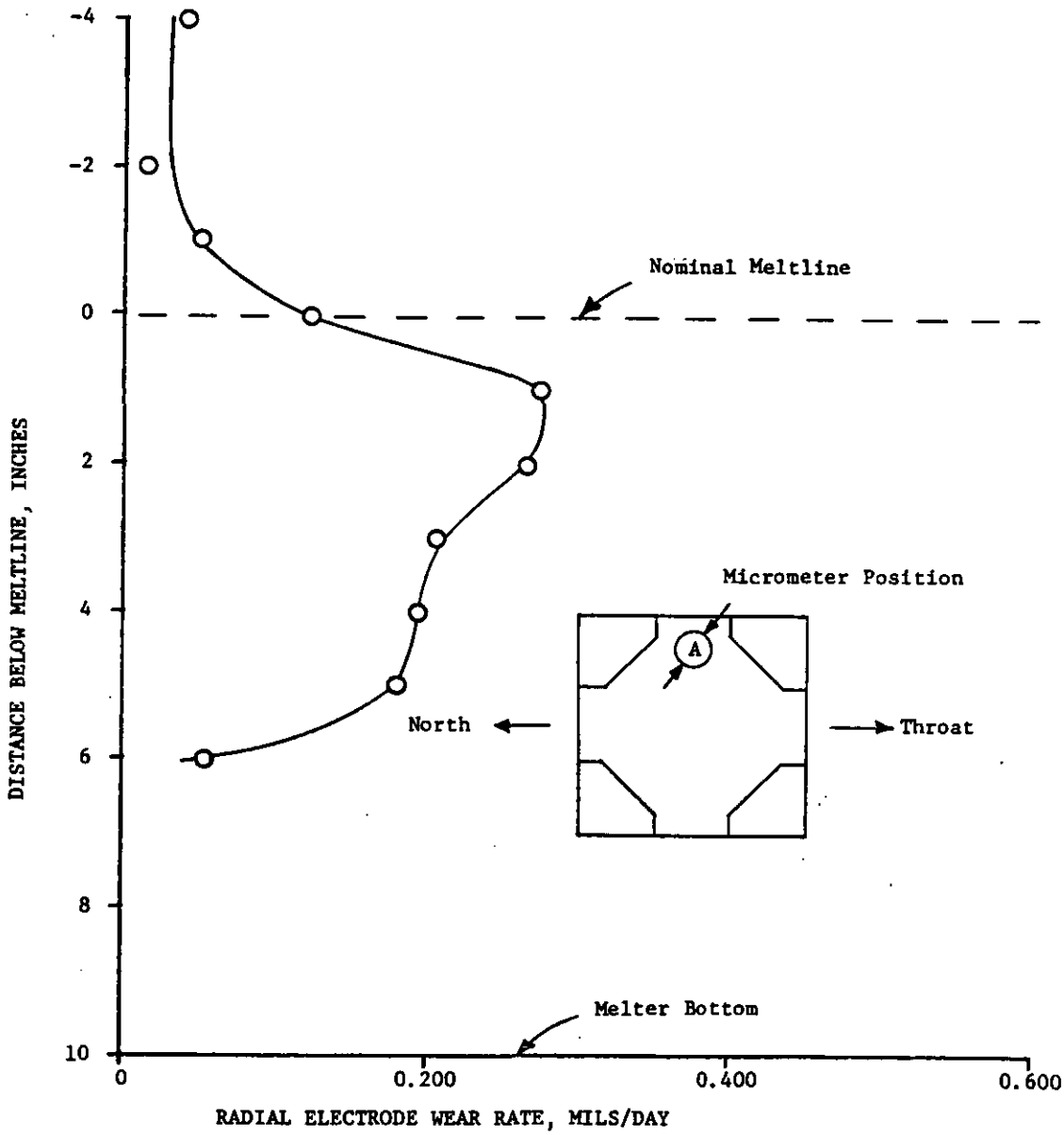

FIGURE 34. Radial Wear Rate of Electrode A

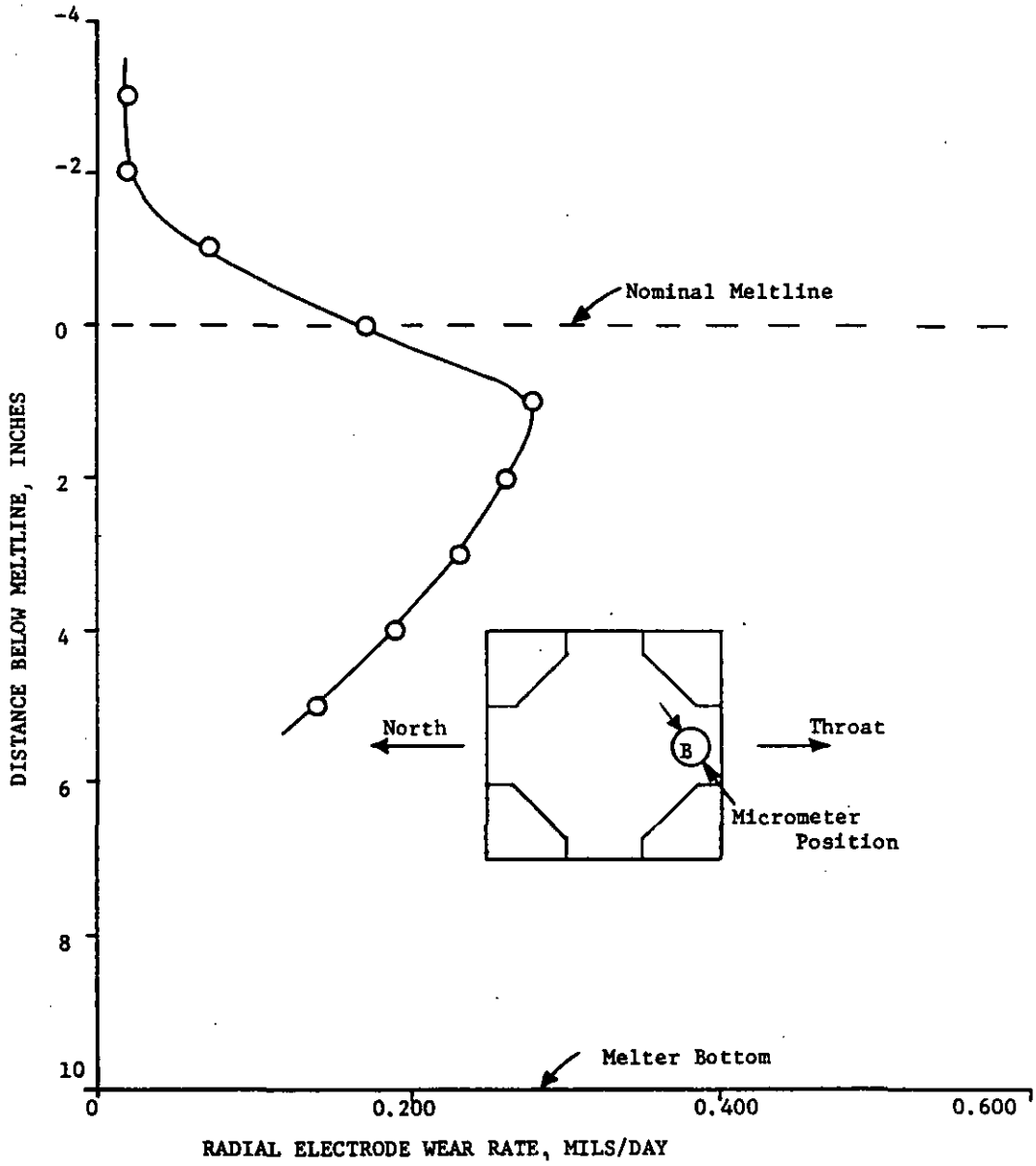

FIGURE 35. Radial Wear Rate of Electrode B

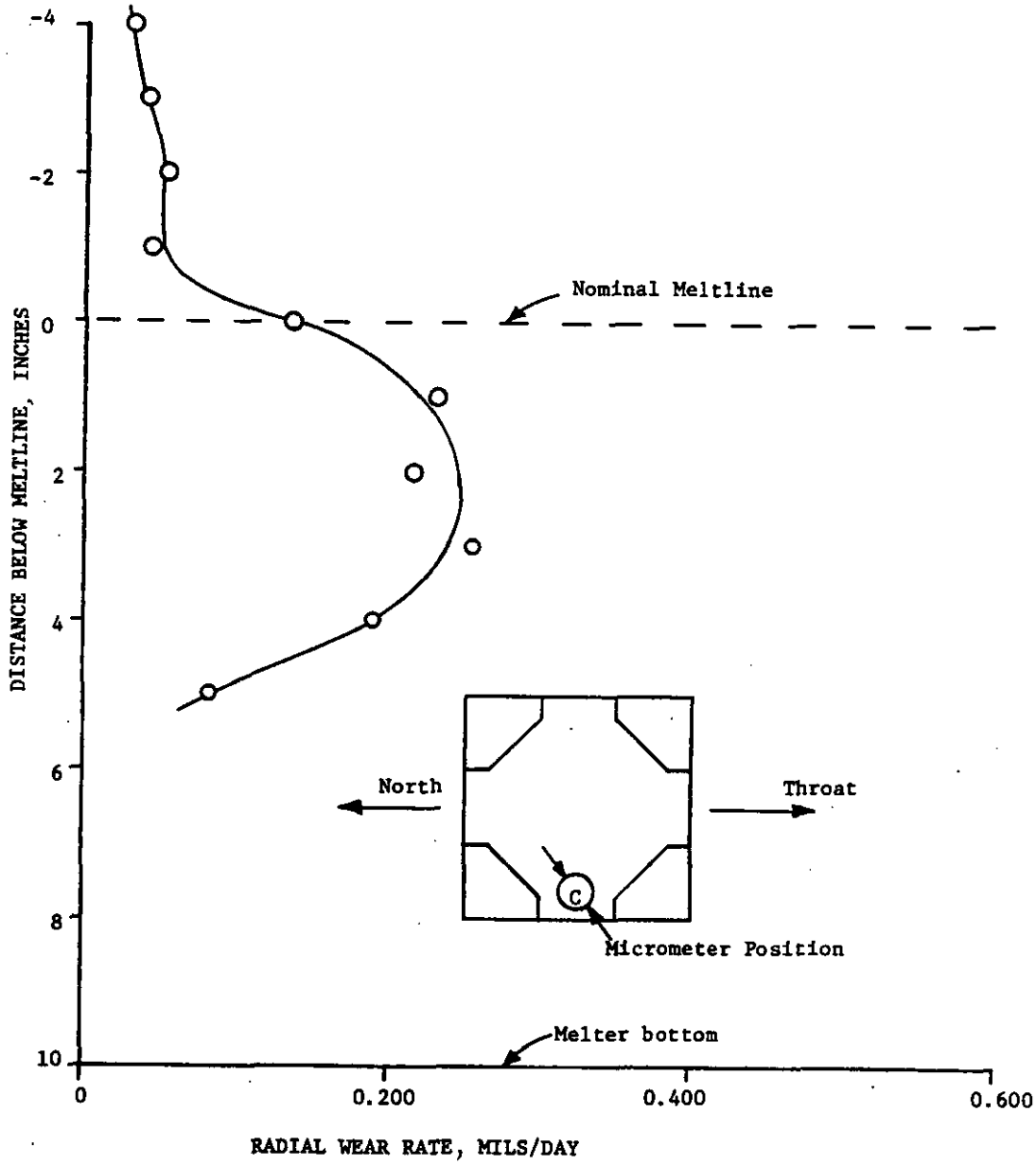

FIGURE 36. Radial Wear Rate of Electrode C

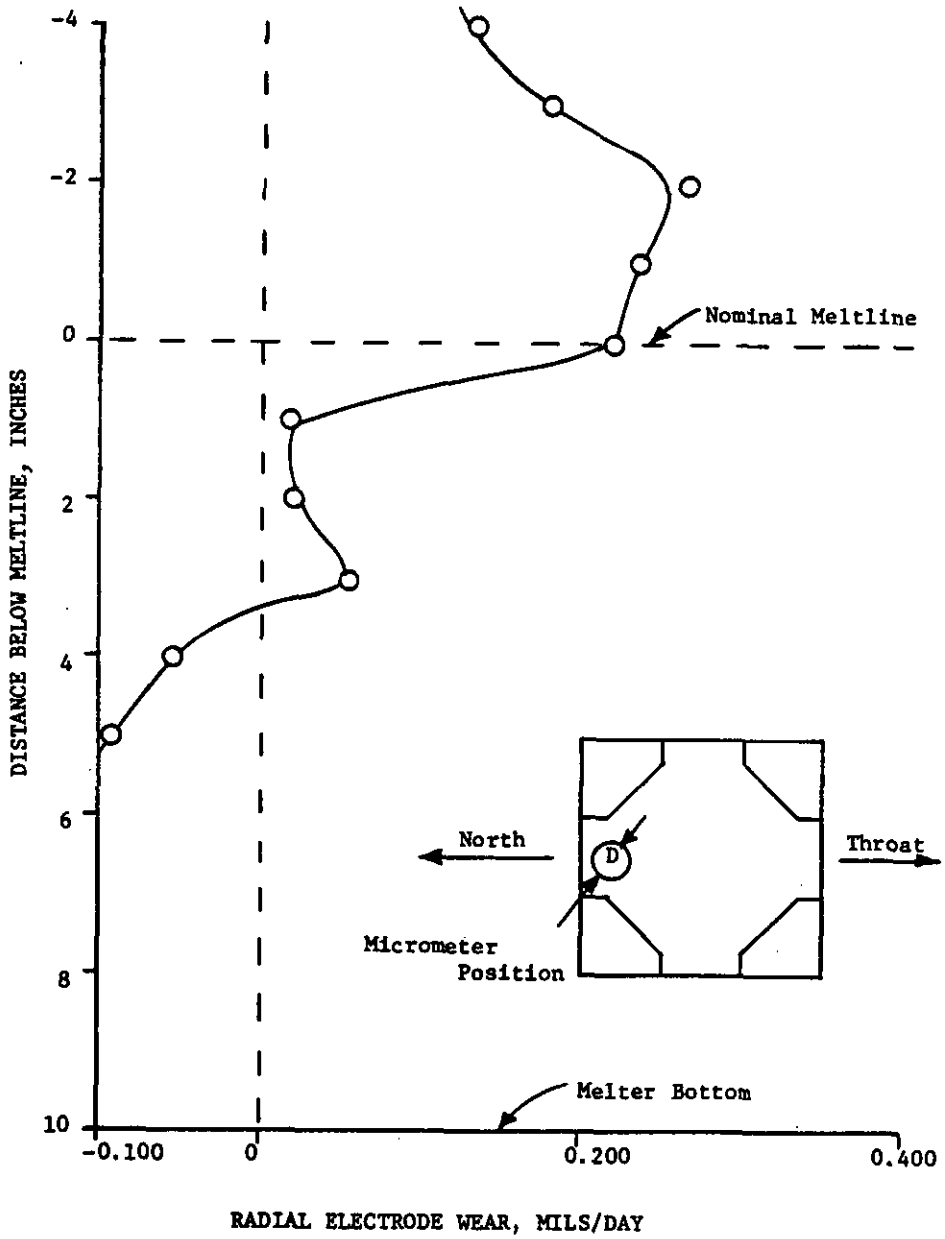

FIGURE 37. Radial Wear Rate of Electrode D

On several occasions when difficulties were experienced with a hot bottom in the melter, a thermocouple probe of the melt pool indicated that glass near 1300°C* was present near the bottom of electrode D. Simultaneously, control thermocouples in the thermowell near the melt center were indicating temperatures of 1170 to 1200°C.

Comparison of electrode wear data for the three operating campaign is given in Table 13. Several observations can be made from these data. Comparing electrode wear data for Campaigns 1 and 2 shows that air-cooling and a threefold increase in melt flux had very little effect on electrode wear. The corrosion mechanisms for the first two campaigns must have been the DC potential, the frit composition, and the temperature of the electrodes.

Comparison of electrode wear data for Campaigns 2 and 3 shows a reduction of 4.4 times in the average maximum wear rate in Campaign 3. Previous tests in which wear data for Inconel® 690 thermowells in the SCM were compared indicated only a small drop in wear rate when changing from Frit 211 + TDS waste to Frit 131 + TDS waste, possibly a slight increase as the melt flux increased, and no effect from the installation of the isolation transformers. The data in Table 13 indicate that electrode wear in Campaign 3 follows the general trend of thermowell wear, but does not match on a quantitative basis. However, during Campaigns 1 and 2 in which only powdered Frit 211 + TDS waste was fed, thermowell wear and electrode wear were in good quantitative agreement.

During the initial experiments with slurry feeding in the SCM, there was concern over possible damage to the electrodes due to thermal shock caused by the aqueous slurry as well as possible electrode embrittlement due to reducing conditions in the glass pool. There was no obvious electrode damage from either of these effects. However, a detailed metallurgical examination of the electrodes has not yet been performed.

Effect of Direct Current on Electrode Wear

When the SCM was originally built, the silicon-controlled rectifiers (SCR's) used for current control in the melt pool were installed on the secondary side of the Scott-Taylor transformer used to power the melter (Figure 38). Experience with uncontrolled direct electrical current (DC) in the melt pool generated by SCR's led to the installation of a potentiometer to the SCR for each electrode pair to provide a means of zeroing DC current generated by the SCR controller. During Campaign 1, these potentiometers were adjusted manually on an hourly basis to keep the DC current

* Inconel® 690 melts at 1340 to 1360°C

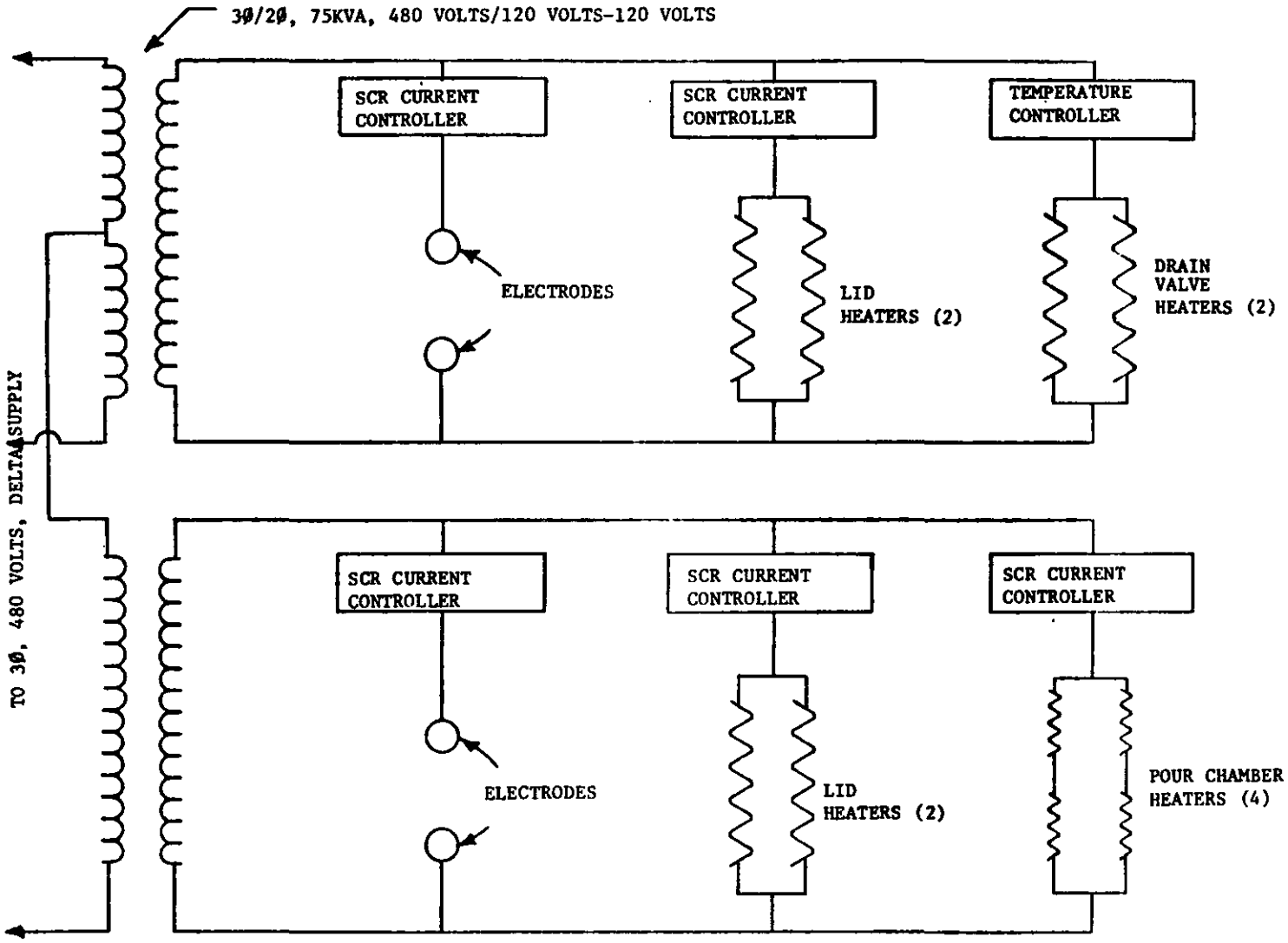

FIGURE 38. Wiring Diagram for the SCM During Campaigns 1 and 2

in the melt pool at a minimum. Occasionally the DC voltage indicated on a digital voltmeter on the control console would drift significantly outside of its usual range and could not be zeroed by use of the potentiometer. This unusual behavior typically lasted for a few hours to a few days.

When Campaign 1 was terminated due to failure of electrode A, DC current control with the potentimeters was believed to have been inadequate and DC current in the melt pool was felt to have accelerated electrode wear. To eliminate DC transmission from the SCR's to the melt pool, isolation transformers were installed at the end of Campaign 2 (Figure 39). Table 13 shows that there was definite reduction in electrode wear during Campaign 3, but it is not possible to separate the effect of the isolation transformers from the effects of glass composition and melt flux. However, thermowell wear tests conducted in Campaigns 2 and 3 suggested that the DC control technique used in Campaigns 1 and 2 was adequate since there was no change in thermowell wear rate when DC was eliminated in Campaign 3.

Wear in the Melter Lid

The melter lid was constructed from a Type 304L SS shell filled with layers of 1-inch thick M-Board™ (product of Babock & Wilcox Co.) bonded together with Kawool Cement™ (product of Babock & Wilcox Co.). Type 304L SS plates (approximately 6-inches square) with rods were attached to the shell and used as hangers to support the M-Board™ (Figure 40). Generally extensive cracking of the M-Board™ occurred during removal of the lid at the end of Campaigns 1 and 2; this necessitated its replacement before starting the next campaign was started.

The condition of the melter lid exposed to glass vapors is shown in Figure 40 at the end of Campaign 2 and in Figures 41 and 42 at the end of Campaign 3.

Glassy deposits completely coated the inside of the melter lid in the plenum region (Figure 42) and caused the loss of 1 to 2 inches of M-Board™ in various locations over the course of Campaign 3. Presumably, this lid material went into the melt pool and because of its alumina/silica composition, may have contributed significantly to the deposits on the melter floor. The Type 304L SS hangers were also lost. Based on these results, the use of M-Board™ [and other similar insulating boards, e.g., Fiberfrax™ (Product of Carborundum Co.)] is not recommended in regions of a melter where molten glass vapors and splatter are present unless the intended period of use is only a few months.

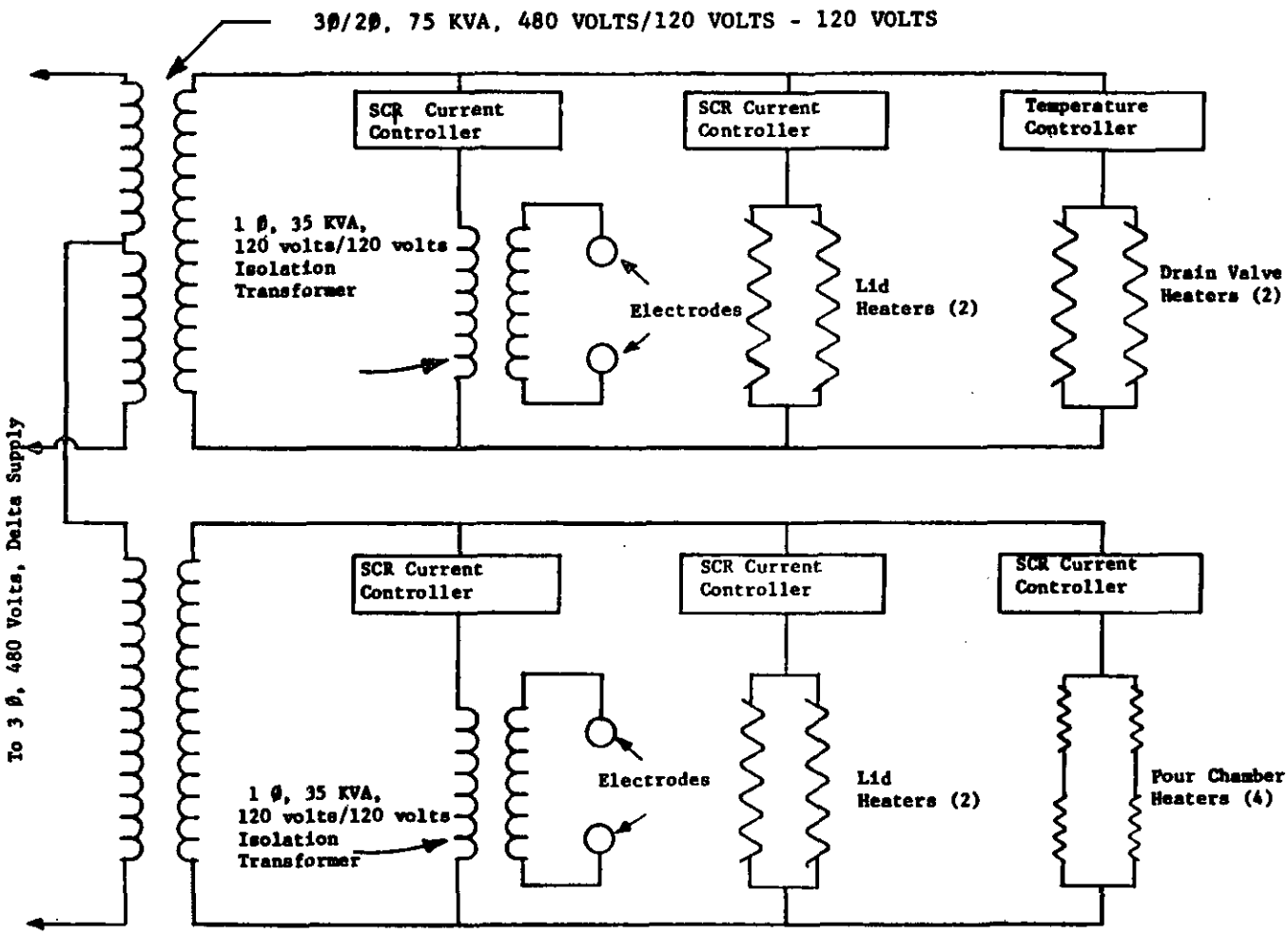

FIGURE 39. Wiring Diagram for the SCM After Installation of Isolation Transformers (Campaign 3)

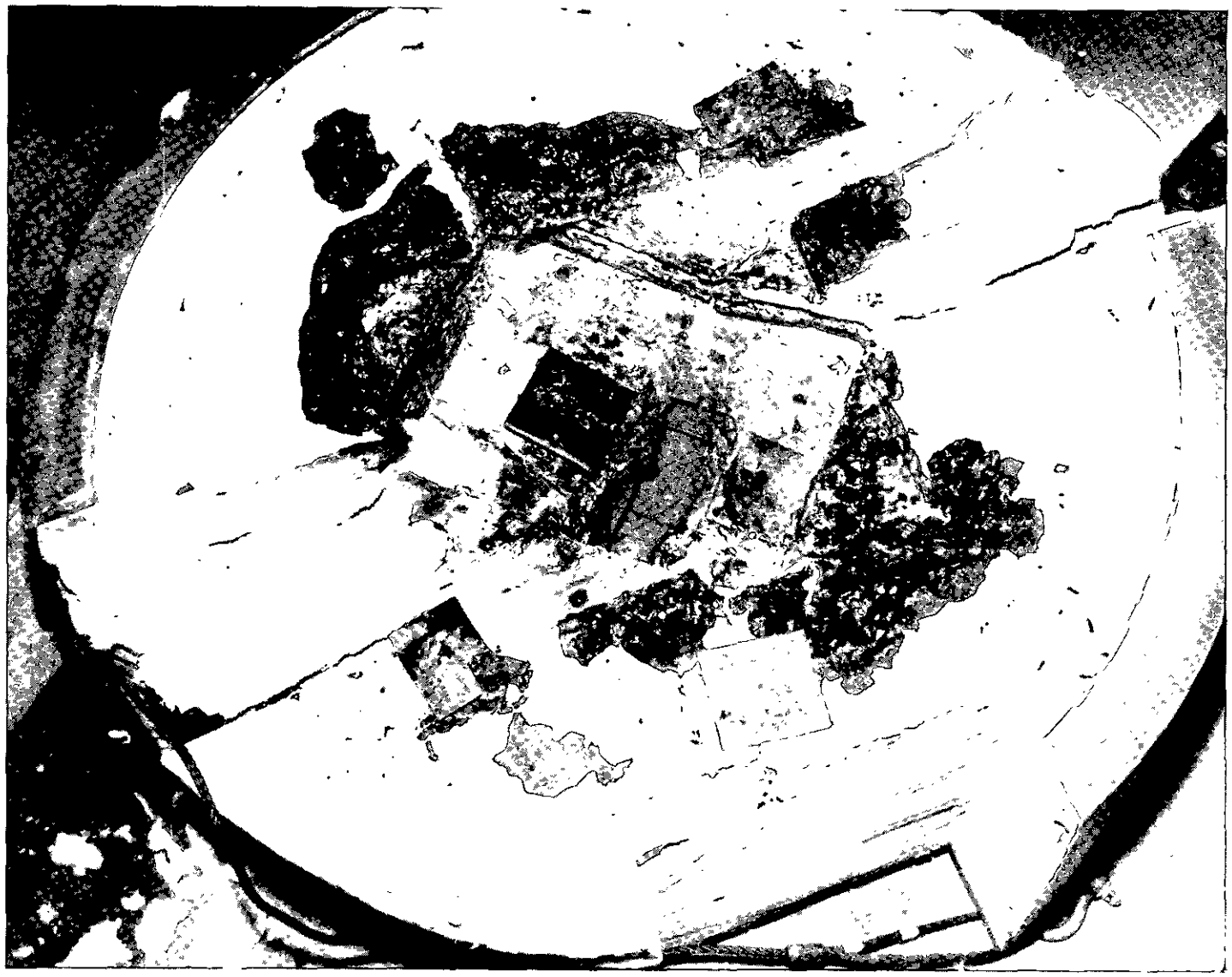

FIGURE 40. Melter Lid Condition After Campaign 2

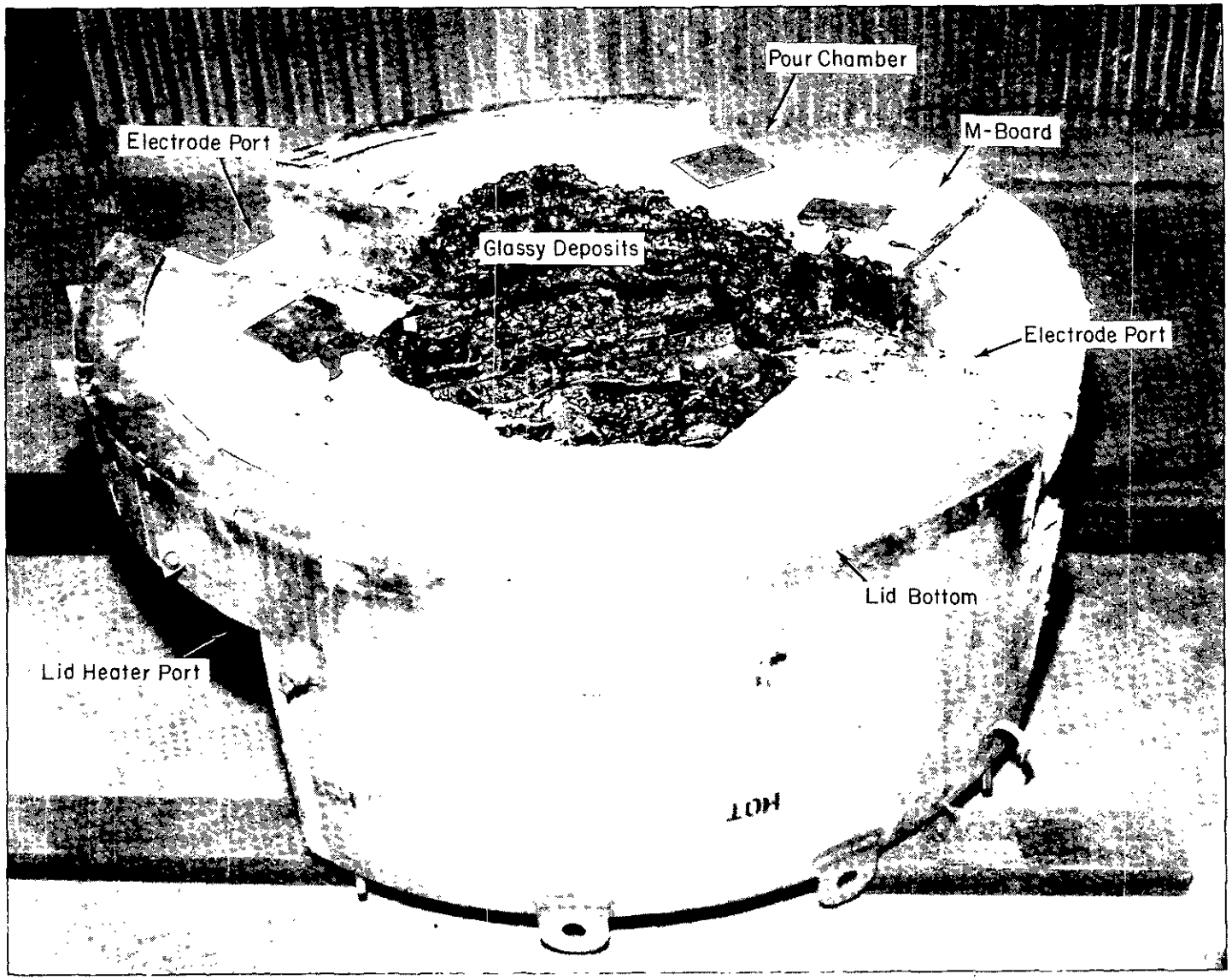

FIGURE 41. Melter Lid Condition After Campaign 3

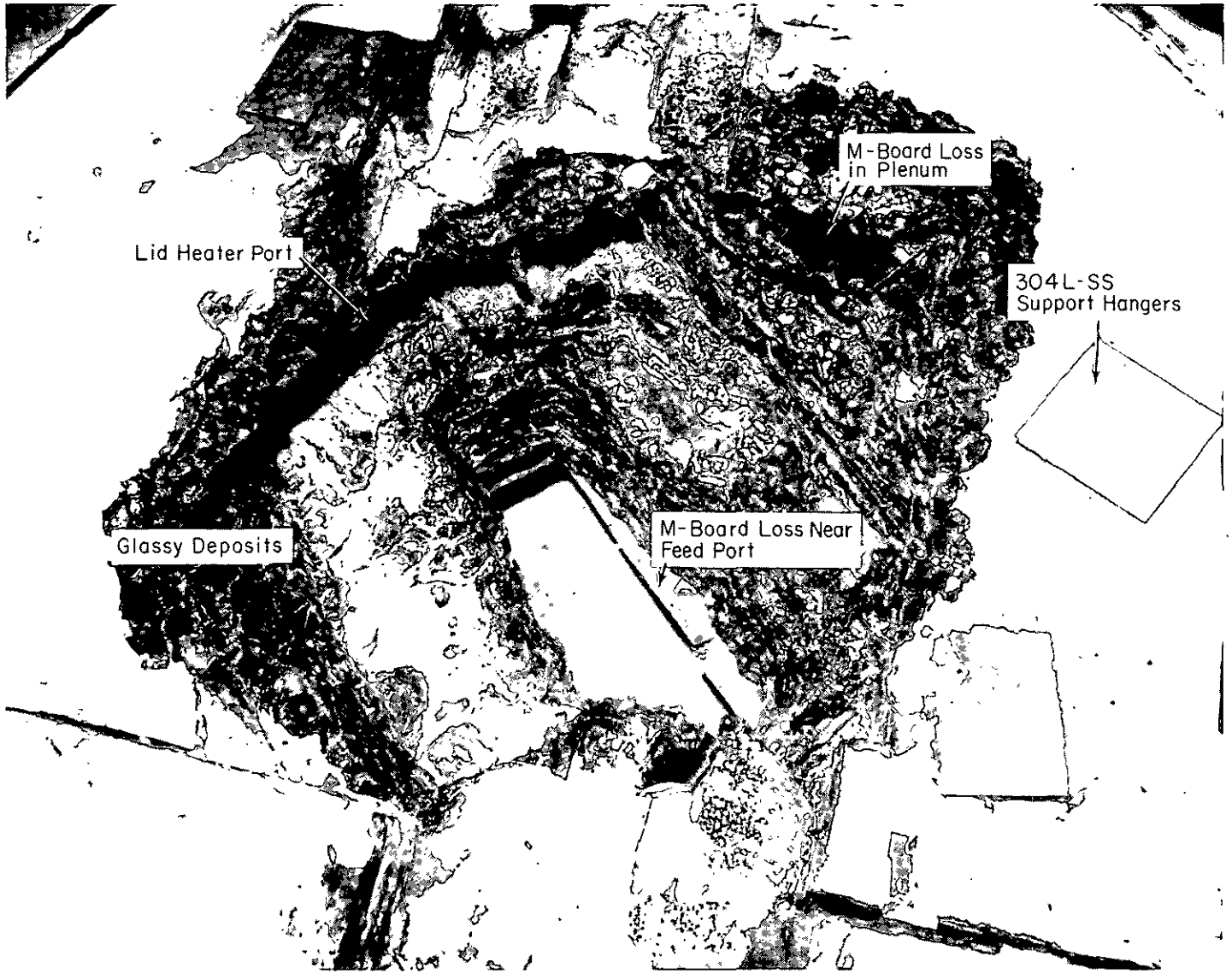

FIGURE 42. Closeup of Melter Lid Bottom After Campaign 3

Lid Heater Performance

Silicon carbide resistance heaters [Globars™ (product of Carborundum Co.)] were used to provide supplementary heat in the melter lid throughout all three campaigns. With brief exceptions, the lid heaters operated continuously from initial startup (September 25, 1979) to the end (February 9, 1982). Figures 43 to 45 show the condition of the lid heaters after the first, second, and third campaigns, respectively.

In the first two campaigns, the lid heaters were unsheathed, located directly above the glass melt, and exposed to dust from incoming feed plus vapors from the glass pool. One silicon carbide heater failed near the end of Campaign 2 (Figure 44).

At the beginning of Campaign 3, two heaters used in Campaigns 1 and 2 were reinstalled in the melter lid (heaters 3 and 4 in Figure 45) for additional testing. These two heaters were unsheathed and failed about one mouth into Campaign 3. The total service time for these heaters was about 10 months.

Two new heaters (Nos. 1 and 2 in Figure 45) were also installed at the start of Campaign 3. These two heaters were protected from dust, splatter, and entrainment by alumina sheaths. They were operated continuously throughout Campaign 3 and were still operational when the melter was finally shut down. Some cracking and heavy glass deposits were found on the alumina sheaths (Figure 45), as well as some glass deposits on the heaters themselves where glass had migrated through the cracks.

The aluminum terminal straps and clamps used to bring electrical power to the heaters are shown in Figure 45; they generally appear to be in good condition.

The alumina sheaths improved the lifetime of the heaters from 268 days for unsheathed heaters to 518+ days for the alumina-sheathed heaters. Inconel® 690 sheaths may be superior to alumina sheaths and they are being tested in the small cylindrical melter-2 (SCM-2) and in the LSFM melter.

Wear in the Pour Chamber

The pour chamber was basically a rectangular box welded to the south end of the melter, lined with M-Board™ insulation, and heated with silicon carbide heaters (Globars™). Glass was poured from the top of the riser sleeve (which is welded to the pour lip) down into a canister below by tilting of the entire melter (Figure 1).

The condition of the pour chamber at the end of Campaigns 1,2, and 3 is shown in Figures 46 to 49. The M-Board™ insulation in

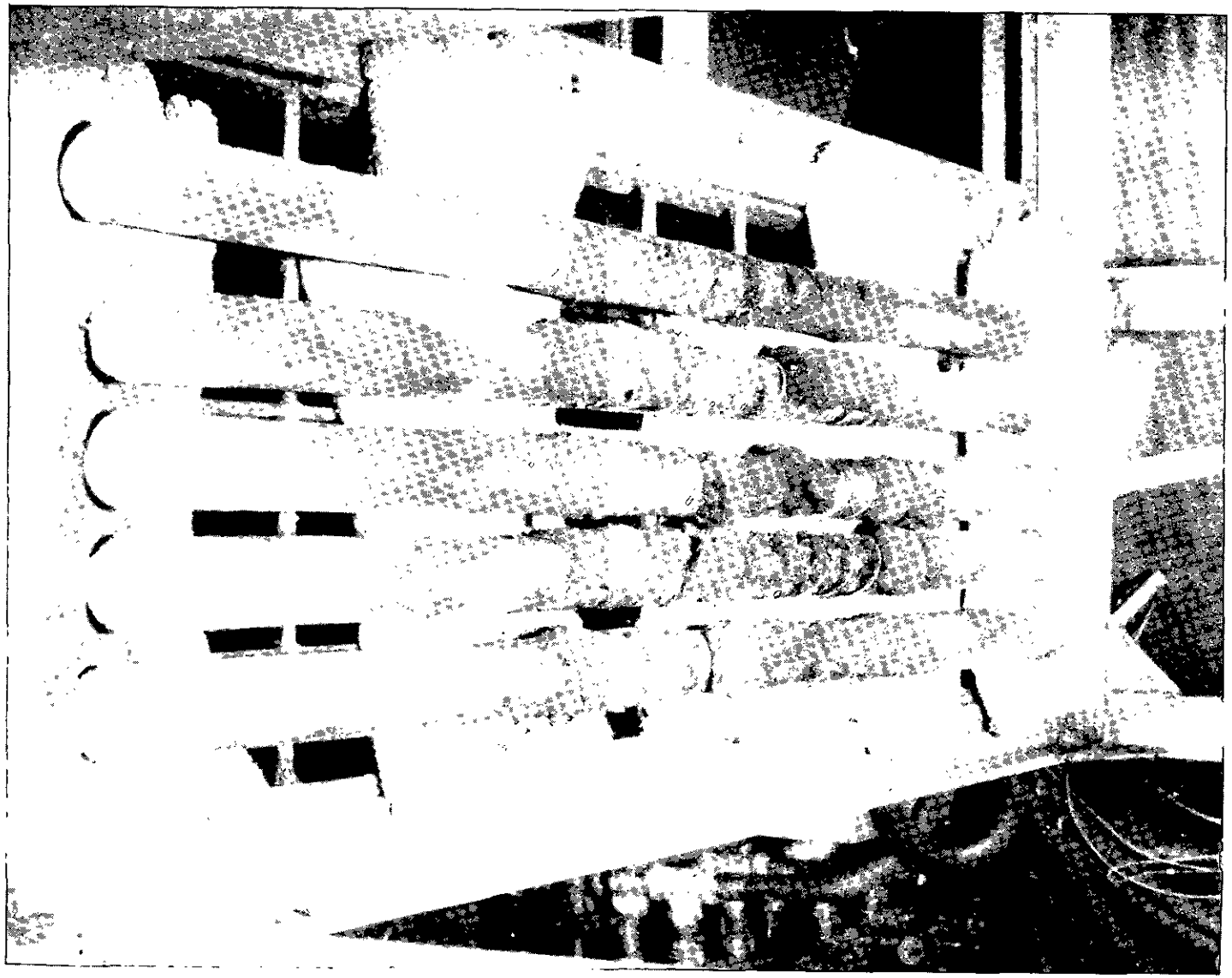

FIGURE 43. Lid Heaters at the End of the First Campaign

FIGURE 44. Lid Heaters at the End of the Second Campaign

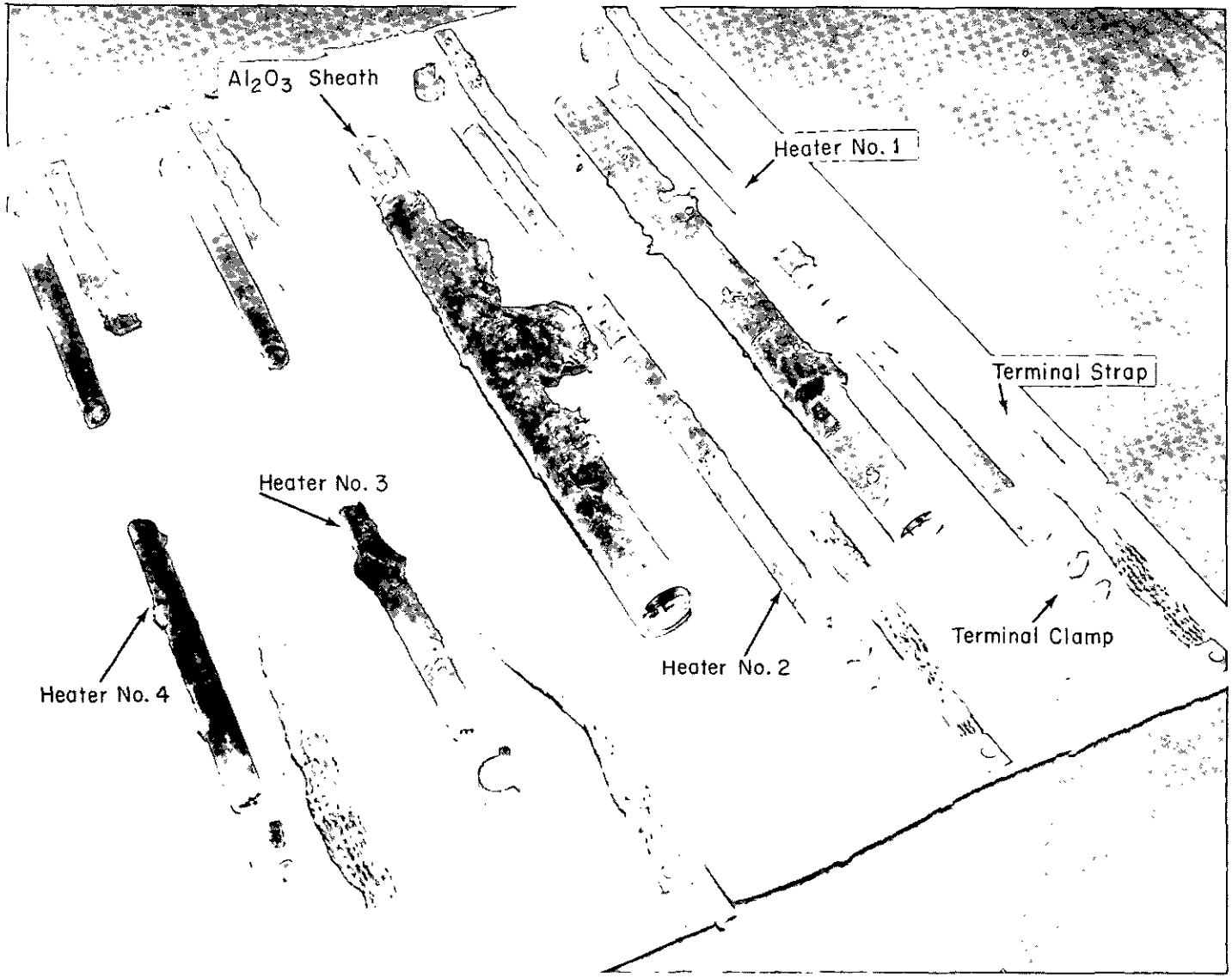

FIGURE 45. Lid Heaters at the End of the Third Campaign

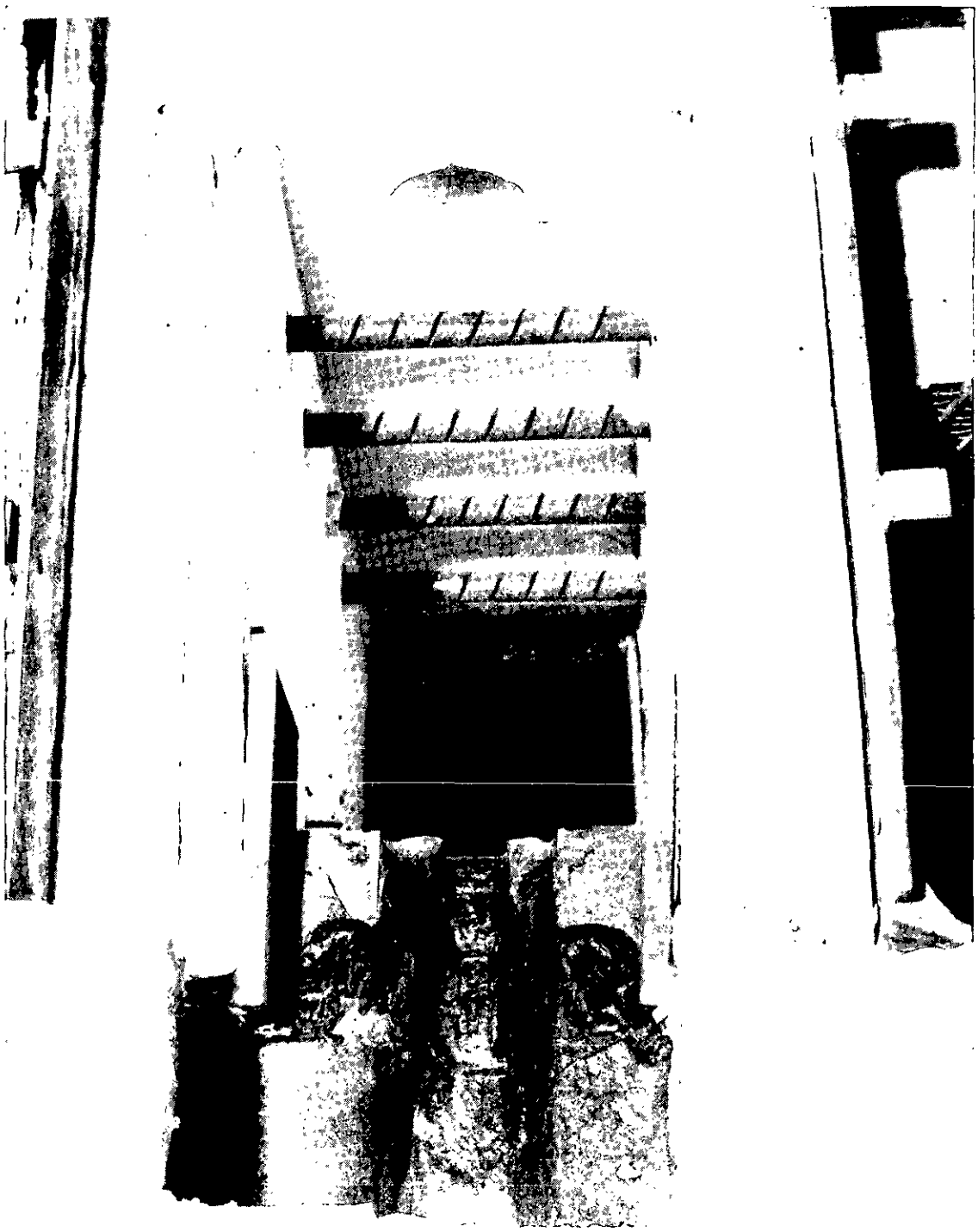

FIGURE 46. Globars and Insulation in the Pour Chamber at the End of the First Campaign

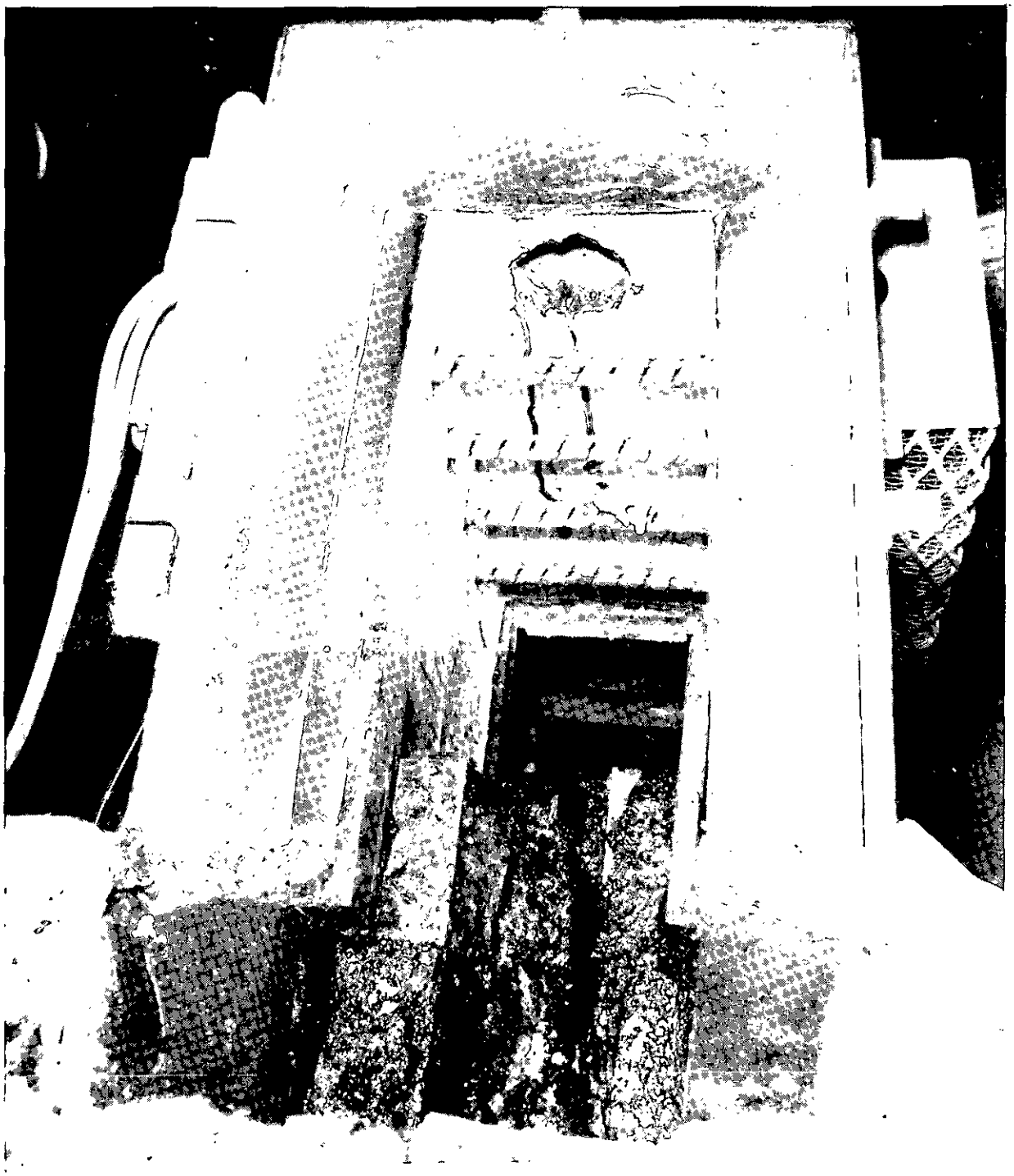

FIGURE 47. Globars and Insulation in the Pour Chamber at the End of the Second Campaign

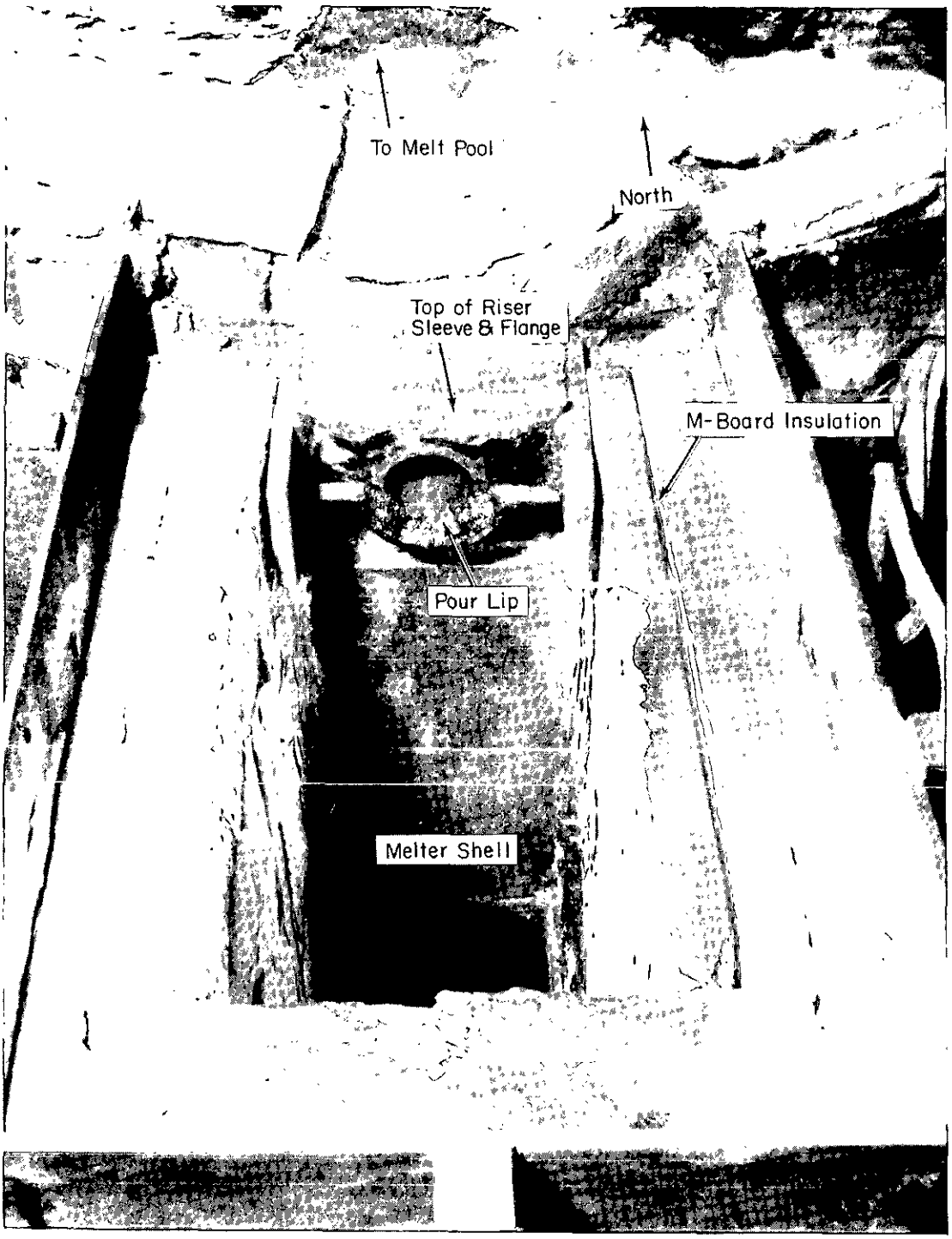

FIGURE 48. North View of the Pour Chamber at the End of the Third Campaign

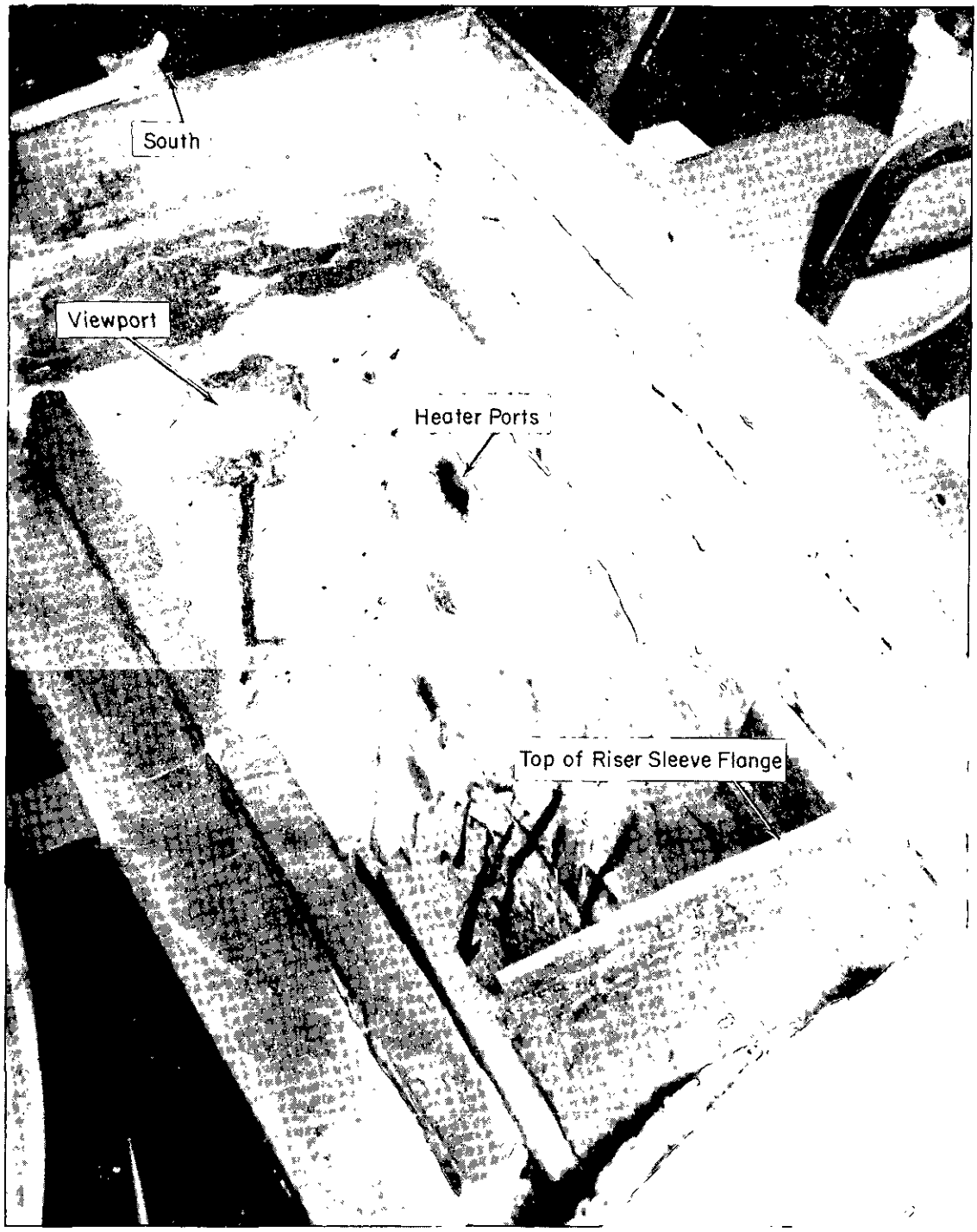

FIGURE 49. South View of the Pour Chamber at the End of the Third Campaign

these photographs is the original material installed before the start of Campaign 1. Some glassy deposits are present on the interior walls but the insulation generally appears to be in good condition. This is in sharp contrast to the appearance of the same material in the melter lid after it was used only during Campaign 3 (Figure 40). The difference, of course, is that there is much less splatter and entrainment in the pour chamber even though glass vapors are present.

The Inconel® 690 pour lip (Figure 48) was in service throughout the entire life of the melter. Virtually no wear occurred on this lip. All of the glass poured during Campaigns 1 and 2 was in direct contact with this lip. The riser sleeve installed at the end of Campaign 2 prevented additional glass contact except right at the edge where glass poured from the melter into the canister. Nominal operating temperature at the top of the pour lip was 850 to 950°C.

The top of the riser sleeve and the welded flange used to prevent glass from bypassing the sleeve are shown in Figure 21. Both of these components were made from Inconel® 690 and showed negligible wear.

In Figure 48, a portion of the Type 304L SS melter shell can be seen where it passes through the pour chamber. Water-cooled coils were attached to this shell on both sides (east and west) of the pour chamber such that its operating temperature was always somewhat lower than that of the pour lip. Although a slight oxidation layer was present on the shell in this region, the shell appeared to be in very good condition.

Pour Chamber Heater Performance

The silicon carbide heaters (Globars™) used in the pour chamber are shown in Figure 50. Heater 1 failed during the startup period of Campaign 1 because a small piece of M-Board™ insulation fell out of the top of the pour chamber. This heater was replaced and all four heaters were then operated throughout Campaigns 1 and 2 (268 days).

During Campaign 3, the condition of the Inconel® 690 riser sleeve was checked frequently by probing the sleeve with a welding rod inserted through the viewport in the pour chamber (Figure 49). This occasionally allowed glass to drip onto the heaters (primarily heater 1) when the probe was withdrawn from the sleeve. This, in turn, led to the failure of heater 1 early in Campaign 3.

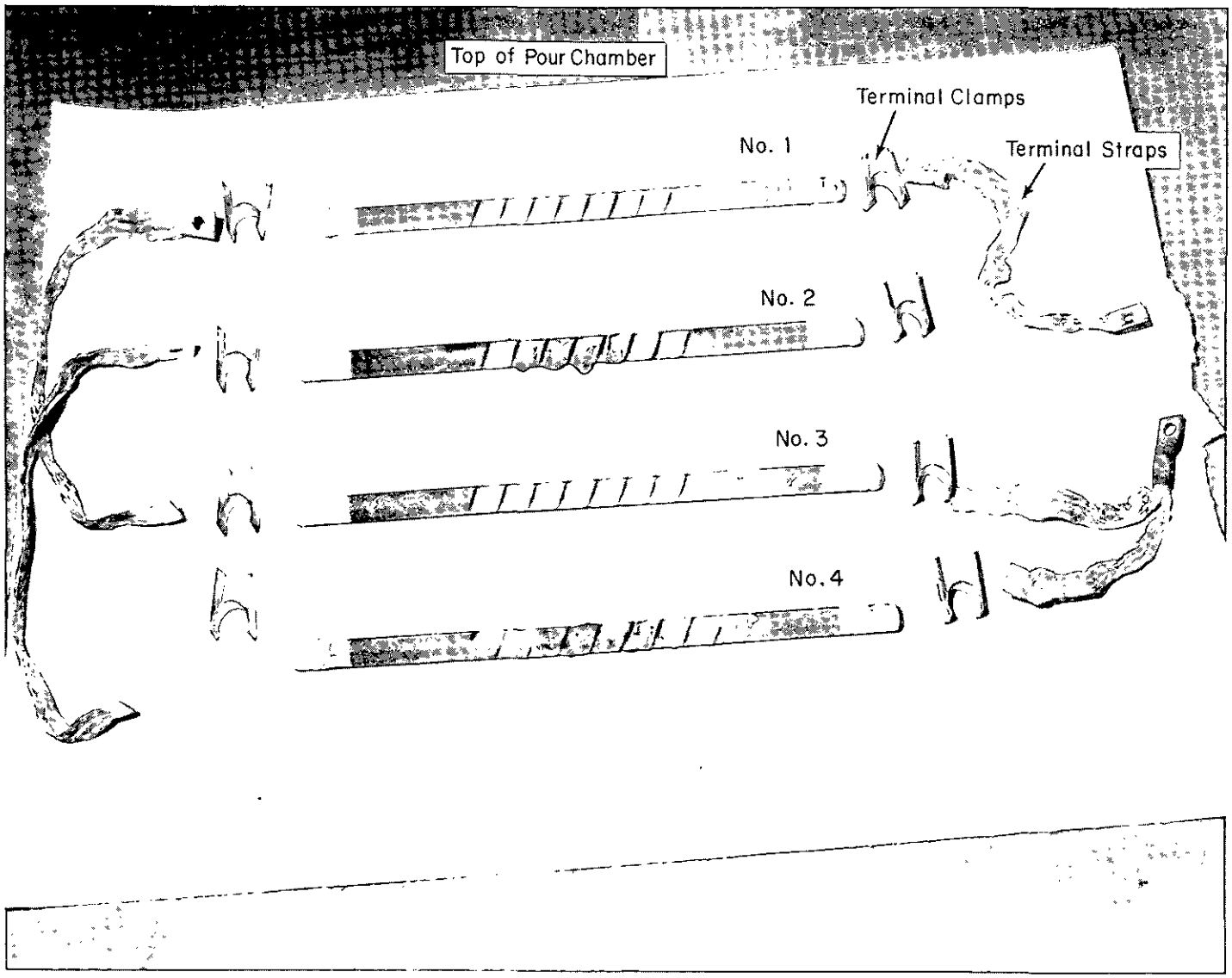

FIGURE 50. Pour Chamber Heaters at the End of the Third Campaign

Since heaters 1 and 3 were wired in series, they were both replaced when heater 1 failed in order to balance their relative power generation.* They then remained in survive until the end of Campaign 3.

Heaters 2 and 4 were in service throughout all three melter campaigns (786 days). Some glassy deposits are evident on them (Figure 50) as a result of the probing just mentioned, but they still appear to be in reasonably good shape. The terminal straps (aluminum braid) and clamps used to bring electrical power to the heaters are also shown in Figure 50. Although some of the straps were beginning to show signs of embrittlement, no failures occurred throughout the three melter campaigns. One failure of silastic electrical cable at the junction of the cable and the aluminum terminal strap did occur and it was subsequently repaired.

Thermocouple Performance

All themocouples (TC's) used in the SCM in all three campaigns were Type K (chromel-alumel) thermocouples sheathed with Inconel® 600. Approximately 40 TC's were required to monitor various data of interest. TC's inserted directly into the glass pool generally lasted from several weeks to a month for 1/4-inch diameter TC's, and from a few days to a few weeks for 1/8-inch diameter TC's. As the TC's aged, their temperature signal would slowly drift upward or downward until the TC actually registered an open circuit. Thus it was necessary to measure critical temperatures, e.g. melt pool, with multiple TC's to maintain credible control of the electrical power input.

To increase TC lifetime, thermowells made from Inconel® 690 pipe were inserted into the melt pool with 1/8-inch diameter TC's inside them to monitor the glass temperature. These TCs typically lasted 1 to 3 months.

TC's were also embedded in the melter itself during construction; they were used to monitor temperatures wherever two different construction materials interfaced. Most of these 1/8-inch diameter TC's that were 8 inches or more away from the glass pool survived all three melter campaigns.

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* With heaters in series, both draw the same electrical current. As the heaters age however, their resistance increases. Thus an old heater in series with a new heater tends to overheat.

Tilt Mechanism Performance

Glass was poured from the melter in all three campaigns by tilting the entire vessel about +5° from level with the use of an electrical screwjack* mounted on the bottom rear (north end) of the melt vessel. The maximum tilt angle that could be achieved was +15°. This maximum angle was used frequently to aid to dumping and flushing of the SCM when difficulties were encountered with floor deposits during Campaign 3.

Throughout all three campaigns, no maintenance was ever required on the screwjack, and not a single mechanical or electrical difficulty was encountered.

The reference pour technique for the DWPF melter is termed differential pressure pouring.

Melter Drain Techniques

The drain valve in the bottom of the SCM did not perform as intended at the end of Campaign 1. This was due to insufficient power to the valve plus viscous deposits inside the valve itself. The heaters around the valve were replaced at the end of Campaign 1 and the valve was tested again at the end of Campaign 2. Again the valve failed to perform as intended, even though it was heated to >1100°C. Viscous deposits in the valve prevented glass from flowing.

In view of the difficulties with floor deposits encountered during Campaign 3, no attempts were made to use the drain valve during or at the end of this campaign. Evacuated canisters were used to drain the SCM once during Campaign 3 in order to obtain samples of the floor deposits, and again at the end of the campaign to facilitate final inspection of the melter. The use of an evacuated canister as a melter drain technique is the most simple and reliable technique tested to date, but the development of other drain techniques is underway.

Feed Devices and Feed Systems

During the first, second, and part of the third campaigns, the SCM was powder fed. This was not a DWPF reference method of feeding so no development work was conducted on the equipment used for this method.

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* Product of the Limitorque Corp.

The first slurry feed device used in the SCM (April 1981) was made from 1/2 inch OD x 0.035 inch wall tubing (Type 304L SS) which was cooled by an annular jacket (Figure 51). Slurry was fed through the device in short pulses controlled by a suitable valve and timer placed on a recirculating slurry loop. This device was susceptible to internal pluggages because of drying of the slurry between pulses. No reasonable combination of slurry-pulse frequency and pulse width alleviated the problem.

In the second slurry feed device (Figure 52), the diameter of the inner pipe through which the slurry flowed was reduced by use of 1/8-inch schedule 80-S pipe (Type 304L SS). The intent was to increase the slurry velocity as it passed through the feed device and thus reduce its temperature at the discharge point. Insulation was added around the water-cooled annulus on the device to reduce radiant energy losses from the plenum (800 to 1000°C) to the cold surface of the water annulus (30 to 40°C) because these losses were significant. Slurry was fed to this device in a pulsed fashion, but again it dried in the interior of the device between pulses and it also built up at the discharge point.

Difficulties in the control of the recirculating slurry loop led to the abandonment of both the recirculating loop and the pulsed slurry concept. They were replaced with a simple, peristaltic pump which was used to meter slurry feed on a continuous basis by control of the pump speed.

The pump method sharply reduced pluggages in the feed device while feeding was in progress. However, failure to flush the feed device before and after initiation of slurrying feeding still led to pluggage. Pluggage also occurred when slurry >47 wt % solids was fed.

The second feed device was eventually replaced with a third device in which the lower tip was modified, since this was the region in which most of the plugs were forming (Figure 53). The intent was to prevent slurry droplets from hanging on the lower tip and drying before they fell off. This modification appeared helpful, but did not eliminate the problem of plug formation at the discharge point. The third slurry feed device was used until Campaign 3 ended.

Off-Gas System

No rigorous program for characterization of melter off-gases and equipment performance was in effect during any of the three melter campaigns. The off-gas system for slurry feeding during Campaign 3 consisted of only a shower type scrubber and exhauster (Figure 54). Only two off-gas line plugs occurred during

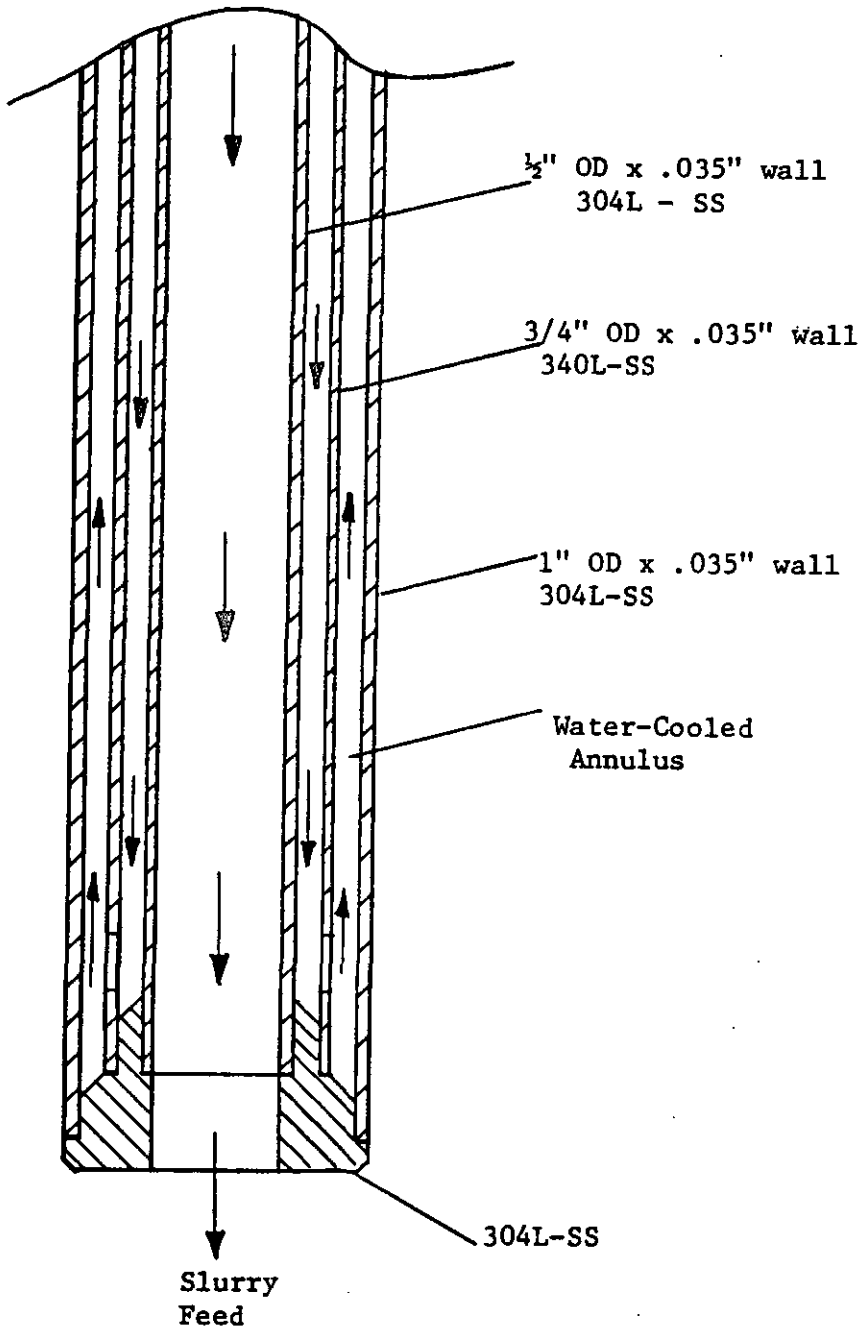

FIGURE 51. First Slurry Feed Device Used in the SCM

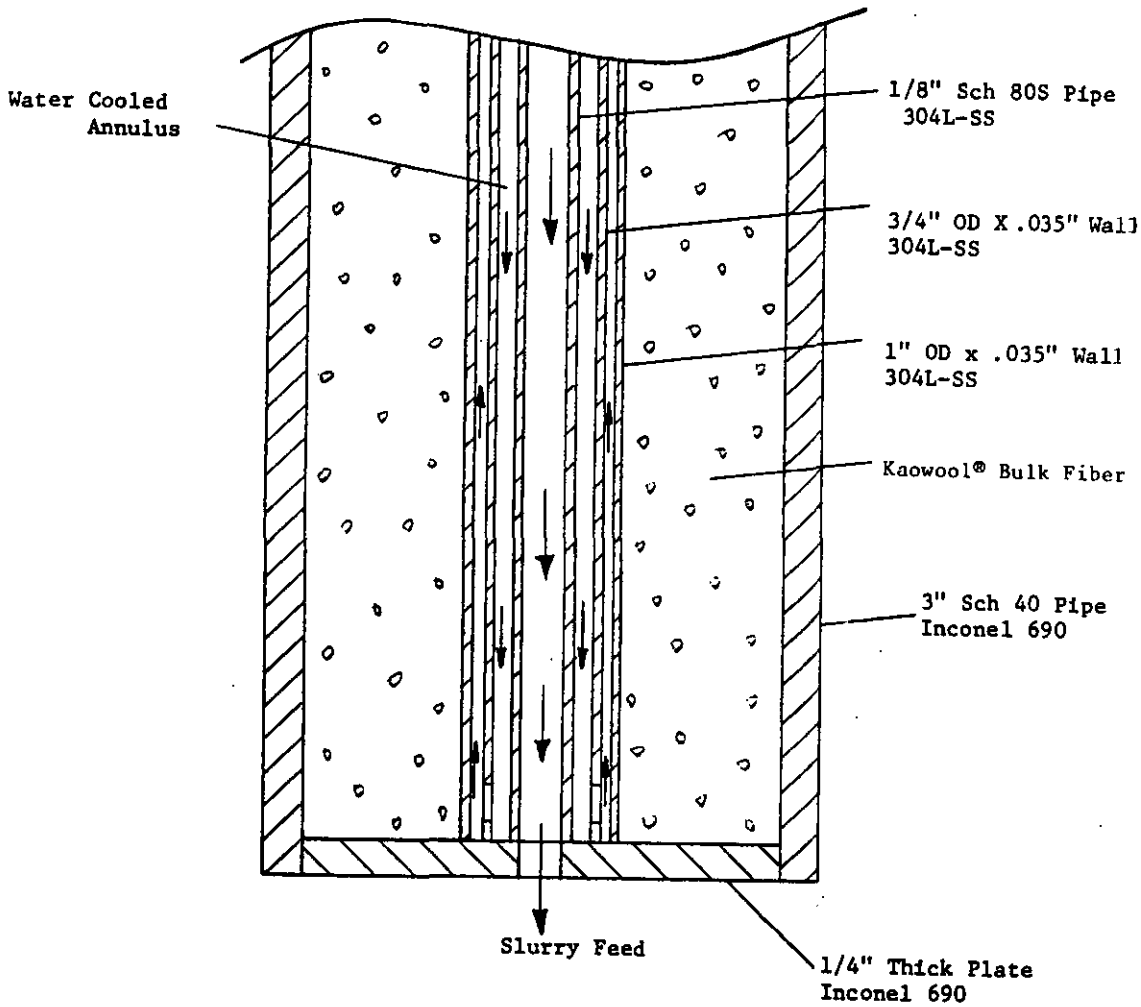

FIGURE 52. Second Slurry Feed Device Used in the SCM

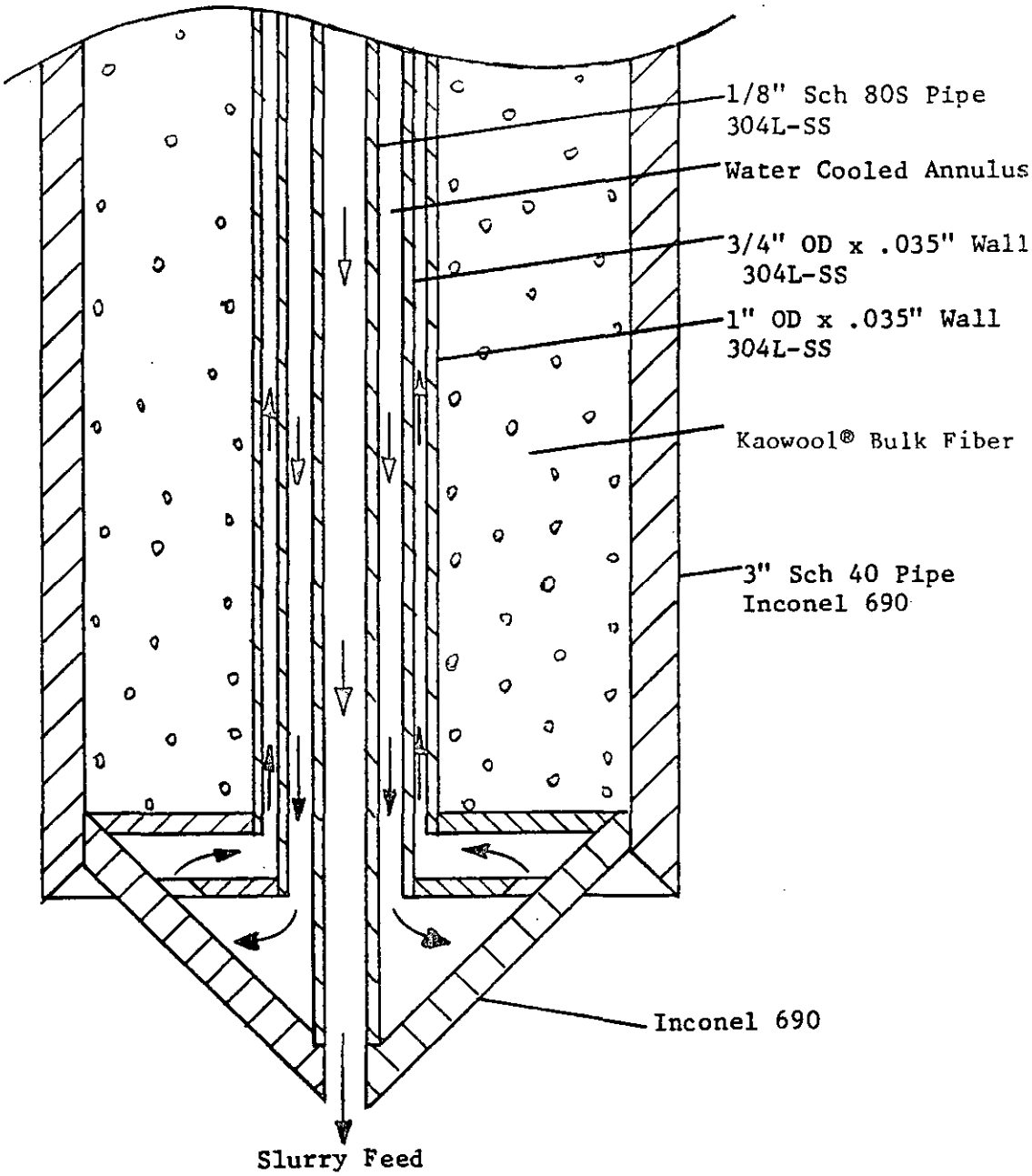

FIGURE 53. Third Slurry Feed Device Used in the SCM

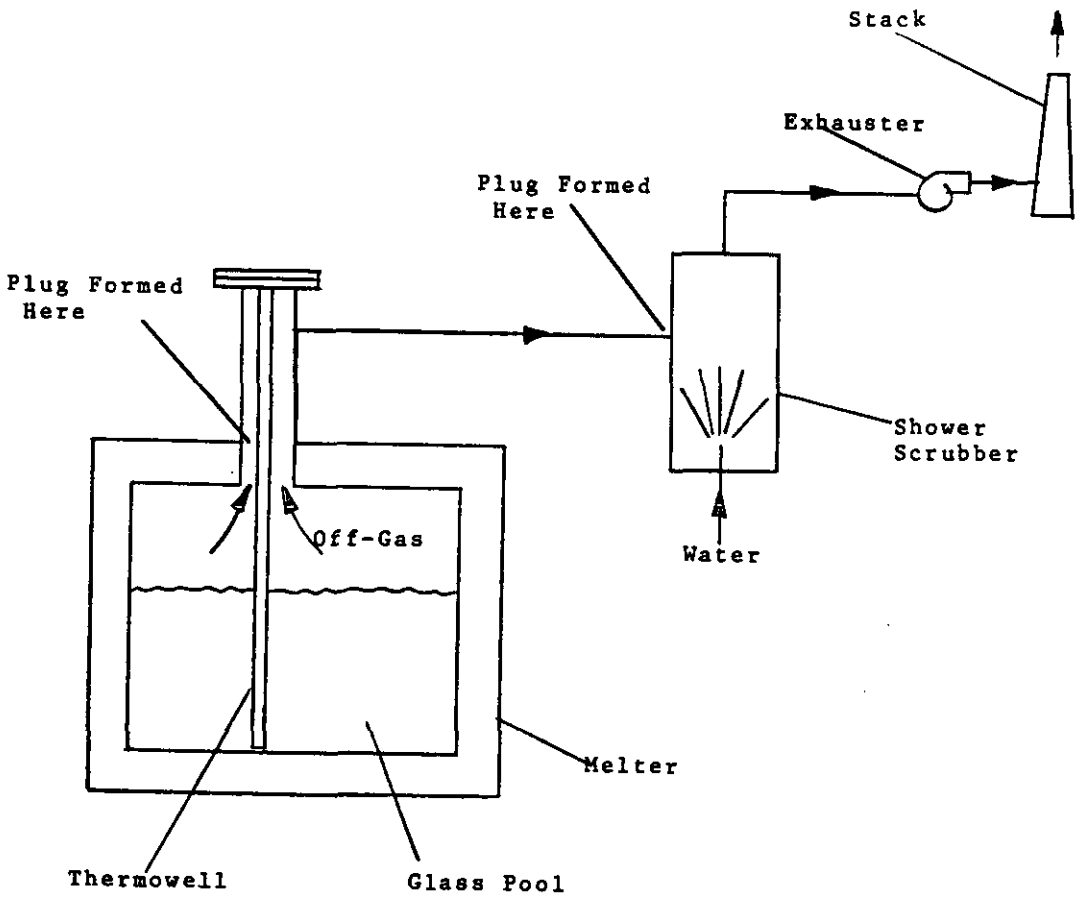

FIGURE 54. Off-Gas System for Slurry Feeding During Campaign 3

Campaign 3: one between the thermowell and the inside of the off-gas line, and a second at the entrance to the scrubber. The second plug apparently occurred because water spray from the scrubber entered the off-gas line.

No problems with the off-gas system were reported during powder feeding of the SCM.

Television Camera Performance

Visual observation of the melter interior is a valuable means of interpreting melter behavior, especially during unusual conditions. Initial experiments with closed circuit television monitoring of the interior of the SCM were performed with a color TV camera. However the large amount of electromagnetic radiation in the red, orange, and yellow frequency bands made it difficult to see clearly. Subsequent experiments with a simple black and white TV camera provided a much better picture and the color TV camera program was abandoned.

The TV camera mounting arrangement used during a large part of Campaign 3 is shown in Figure 55. In general, the performance of the TV camera was good although the percentage of the melt surface that could be viewed was small due to the geometry of the mounting arrangement.

Ports for injecting air were provided just below the pyrex glass used at the top of the viewport. Air injection was necessary to keep splatter and condensible vapors from depositing on the glass at the top of the viewport.

Refractory Disassembly

Following shutdown of the SCM at the end of Campaign 3, the melter refractories were disassembled for inspection. Figure 56 shows the north side of the melter after the Type 304L SS inner liner was cut off exposing the cold side of the Ram Cement™ (product of Carborundum Co.). This material is a high alumina, castable refractory (Table 14) which was used to fill in behind the Monofrax™ K3 brick (Figure 30). Considerable cracking of the Ram Cement™ is evident in Figure 56, and some of it fell out of place when the inner liner was removed. There was no indication that glass penetrated the Ram Cement™ at any point.

Figure 57 shows the cold side of the 8-inch-thick Monofrax™ K3* after the Ram Cement™ was removed. The Monofrax™ K3 appears

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* Two 4-inch layers of Monofrax™ K3 were used in the sidewalls.

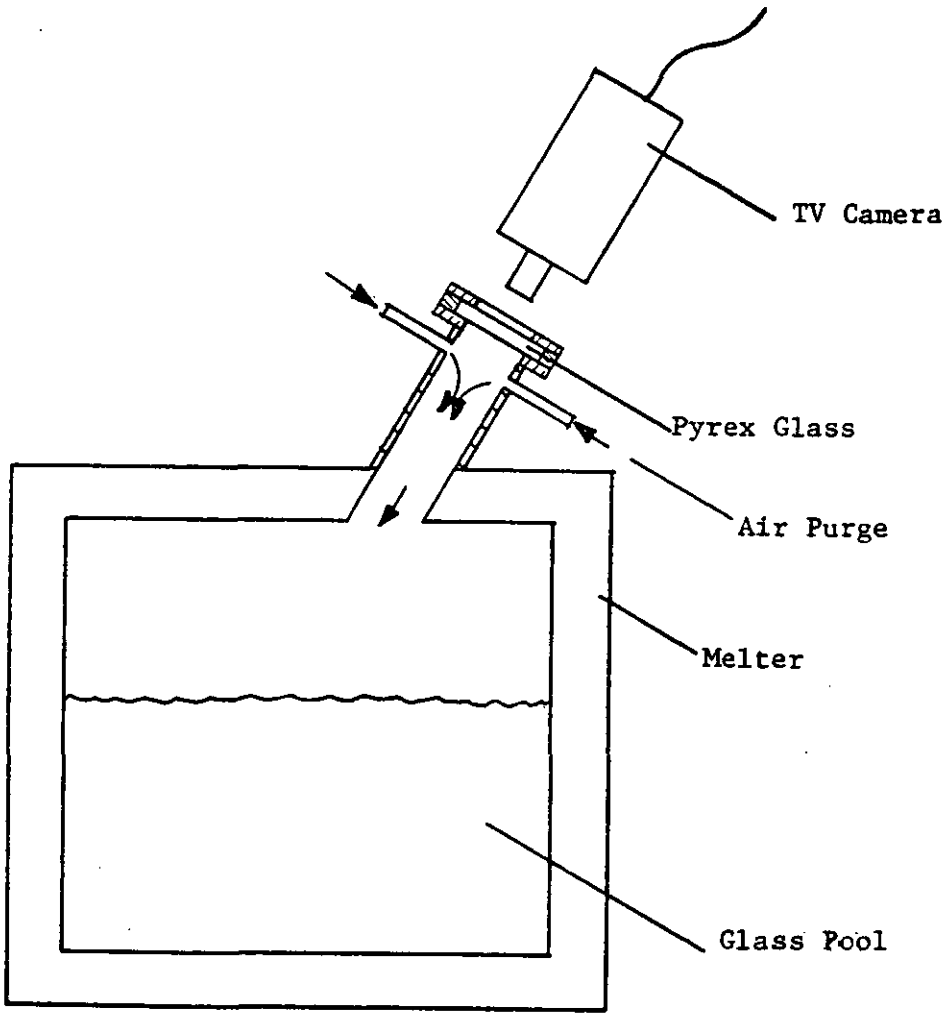

FIGURE 55. TV Camera and Viewport Arrangement

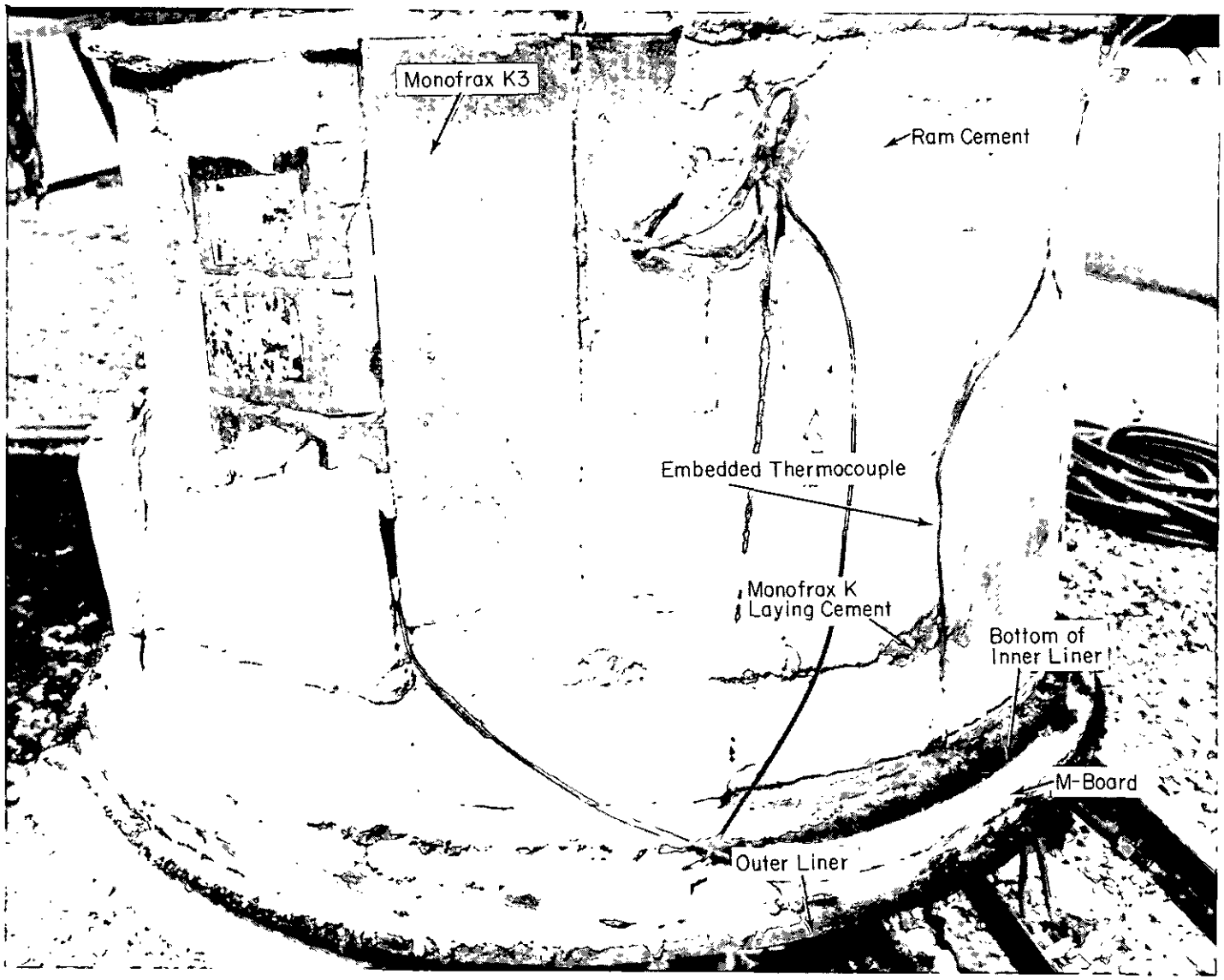

FIGURE 56. Inner Liner Removed (North Side)

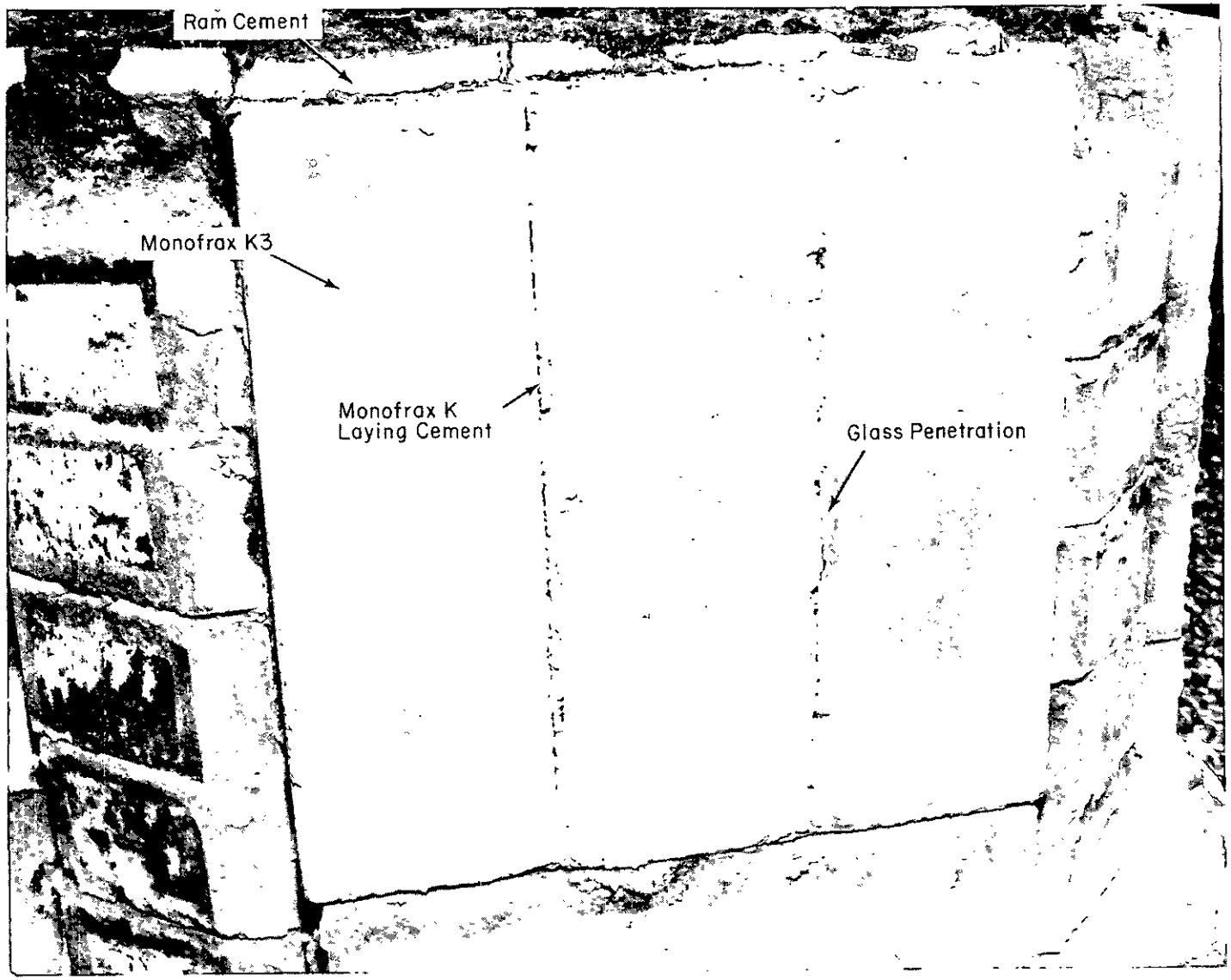

FIGURE 57. Ram Cement™ Removed (North Side)

TABLE 14

Properties of Ram Cement™

Typical Chemical Analysis

Al_2O_3	86.95%
SiO_3	10.76
Fe_2O_3	0.34
CaO	Trace
MgO	0.07
TiO_2	0.23
Alkalis	1.57

Typical Physical Properties

Density (installed)	157 lbs/ft^3
Shrinkage (fired at 2550°F)	3.0%
Modulus of Rupture (fired at 2550°F)	1500 psi
Thermal Conductivity	7 - 9 Btu $in/hr\text{-}ft^2\text{-}°F$

to be in excellent condition with no evidence of cracking. Some glass did penetrate to the back of the Monofrax™ K3, however.

Figure 58 shows the cold side of the 4-inch-thick Monofrax™ K3 bricks on the north side of the melter. These bricks were in direct contact with the glass pool on their hot face (Figure 3). Some evidence of glass penetration through the bricks is again apparent.

Figures 59 to 61 show the cold side of the Ram Cement™, the cold side of the 8-inch-thick Monofrax™ K3, and the cold side of the Monofrax™ K3 with 4 inches of brick removed, all on the east side of the melter. Cracking but no glass penetration of the Ram Cement™ occurred (Figure 59) which is similar to what was seen on the north side. Some glass penetration at a brick joint is seen in Figure 60. The glass penetration shown in Figure 61 appeared to have oozed through the brick itself rather than migrated along a brick joint. This may have resulted from high brick porosity due to a manufacturing defect.

FIGURE 58. Four Inches of Monofrax™ K3 Removed (North Side)

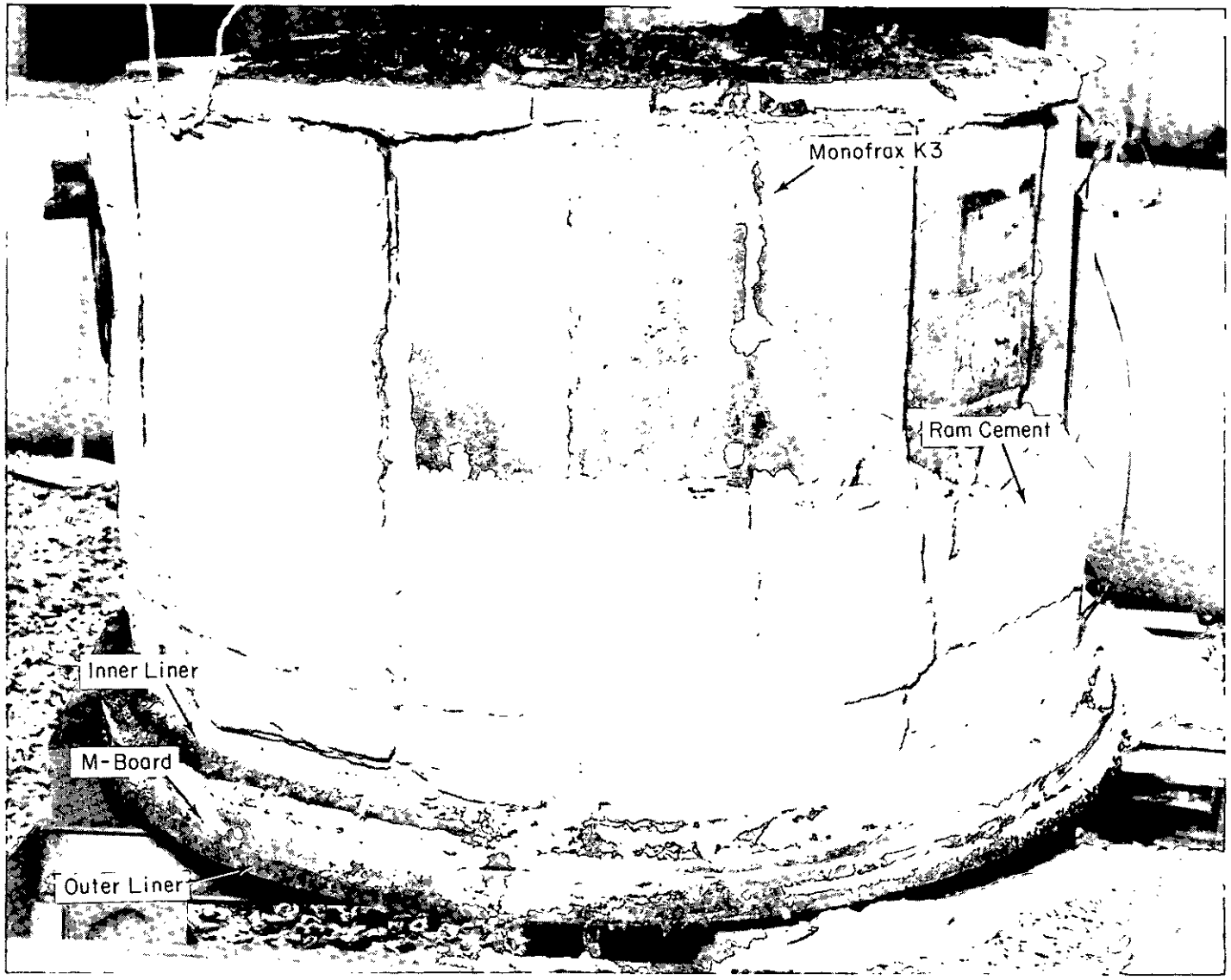

FIGURE 59. Inner Liner Removed (East Side)

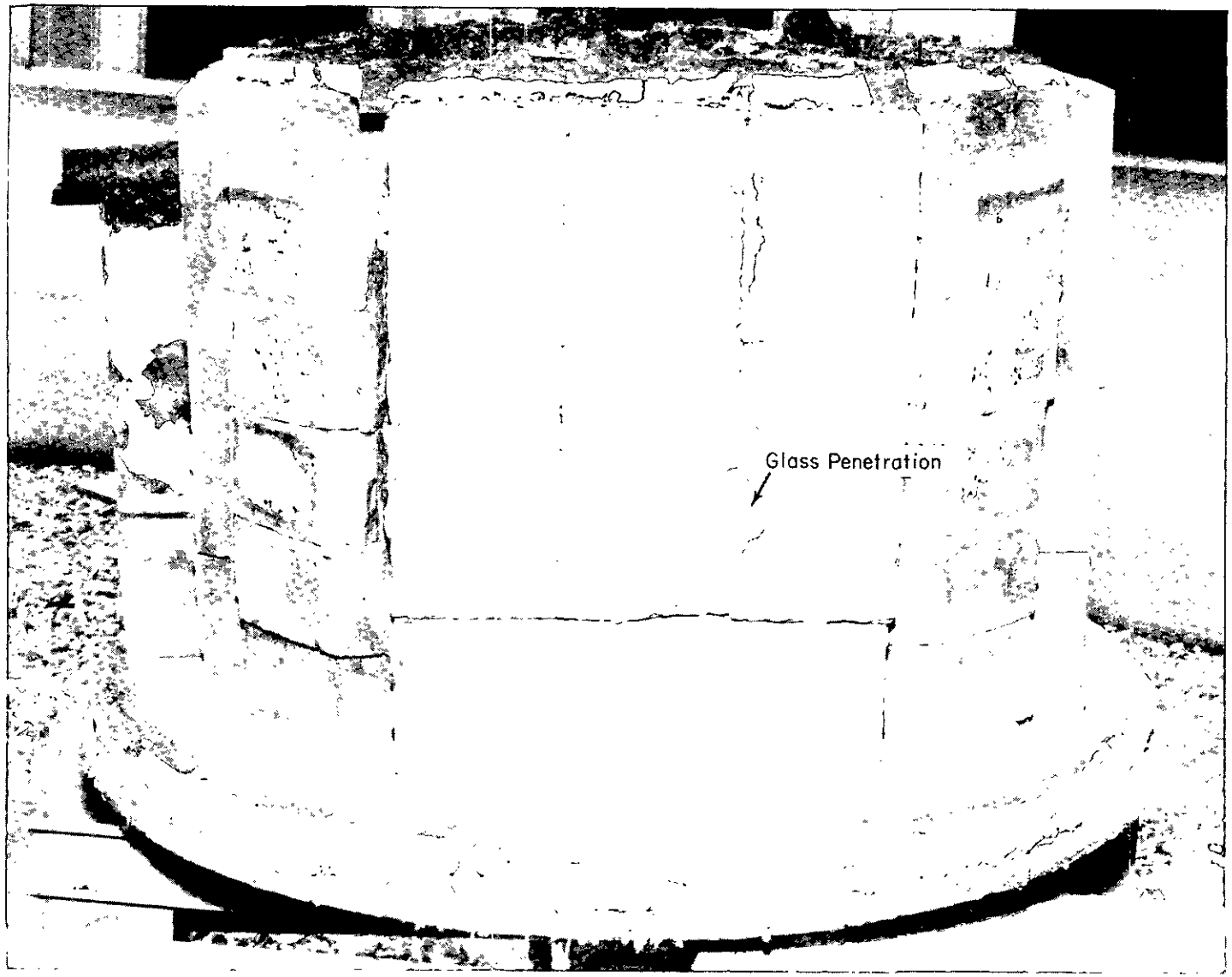

FIGURE 60. Ram Cement™ Removed (East Side)

FIGURE 61. Four Inches of Monofrax™ K3 Removed (East Side)

Figures 62 and 63 show the disassembly of the south side of the SCM where the throat, riser, and trough were located. The Ram Cement™ on this side (Figure 62) appeared to have experienced much less cracking than on the north and east sides (Figures 56 and 59). Glass penetrated through the Monofrax™ K3 near the trough (Figure 62) but was stopped by the presence of the Type 304L SS inner liner which was electrically isolated from the outer liner. In fact, glass leakage to the inner liner was expected (by design) at this point since the Inconel® 690 pour lip (Figure 3) was welded to the inner liner at the top of the trough block. Glass leakage in this region was not nearly as extensive as anticipated.

Cracks in the trough block are evident in Figure 63. This block set directly south of the throat and riser block (Figure 3), which also experienced significant cracking (Figure 10). The other Monofrax™ K3 bricks at the back of the 8-inch-thick layer of Monofrax™ K3 on the south side of the SCM appeared to be in excellent condition (Figure 63), which is similar to the appearance of that on the north and east sides. Removal of the outer 4 inches of Monofrax™ K3 brick on the south wall resulted in extensive breakup of the brick. Thus there is no direct photographic comparison with Figures 58 and 61.

Figures 64 to 66 show the disassembly of the west side of the SCM. The Ram Cement™ appears similar to that on the south side with respect to cracking, and dissimilar to that on the north and east sides. Some glass penetration is again apparent on the cold side of the 8-inch layer of Monofrax™ K3 (Figure 65) at a brick joint, but the bricks themselves appear to be in excellent shape. Extensive glass penetration is apparent in Figure 66 after the outer 4 inches of Monofrax™ K3 has been removed. This glass appears to have penetrated near the right side of Figure 66 and then moved from the right to the left behind the first 4 inches of the Monofrax™ K3 bricks.

The presence of the inner liner in the melter floor effectively blocked penetration of glass to the underlying M-Board (Figure 3). No castable refractory was used between the Monofrax™ K3 and the inner liner.

CONCLUSION

- Campaign 3 was the longest campaign conducted in the SCM (518 days). 38,369 lb of glass were produced (219 melt volumes) in this campaign at an average melt flux of 2.41 lb/hr-ft^2 using both powder feed and slurry feed materials.

- Moderate cracking of the Monofrax™ K3 refractory sidewalls occurred on the hot surfaces in contact with molten glass.

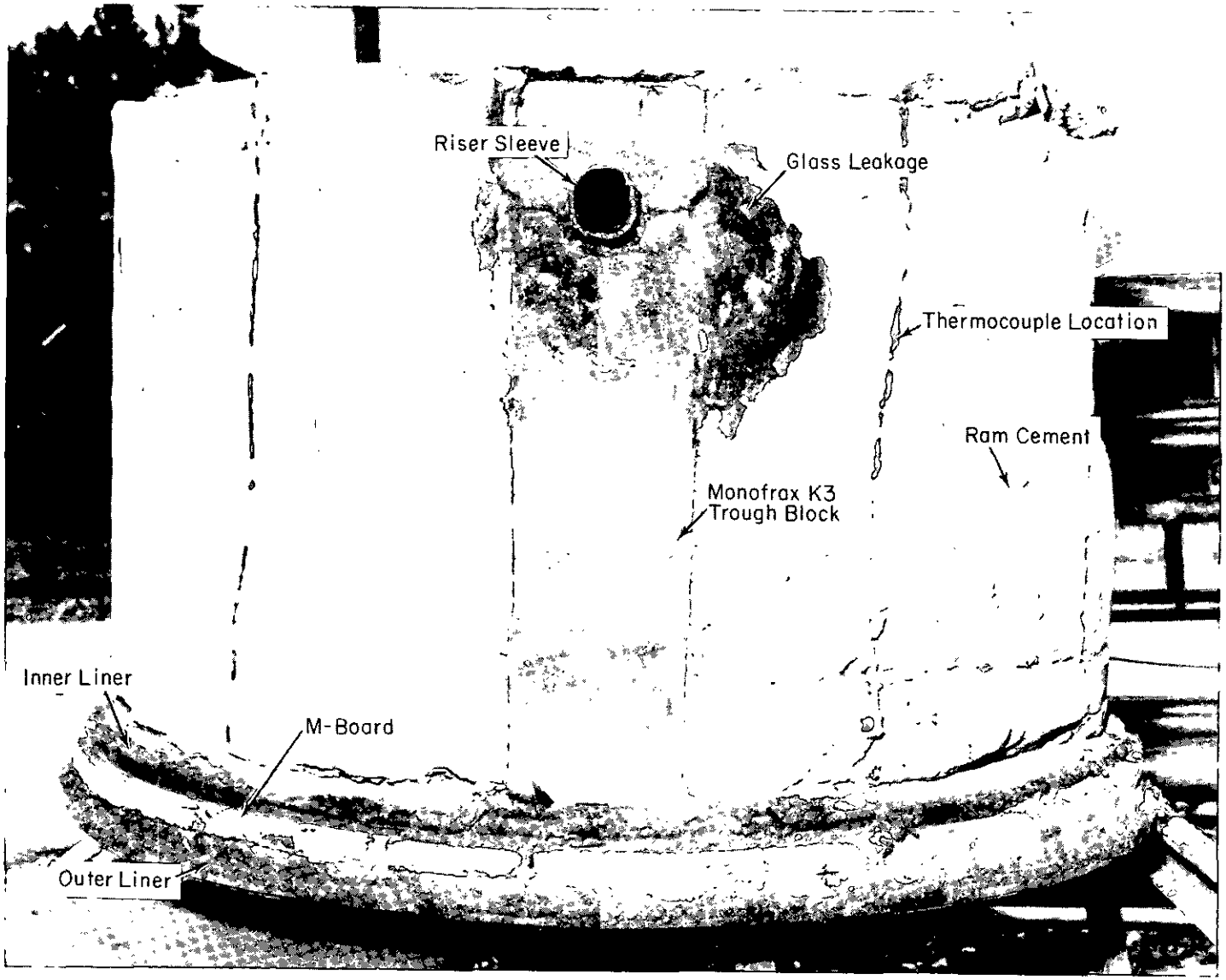

FIGURE 62. Inner Liner Removed (South Side)

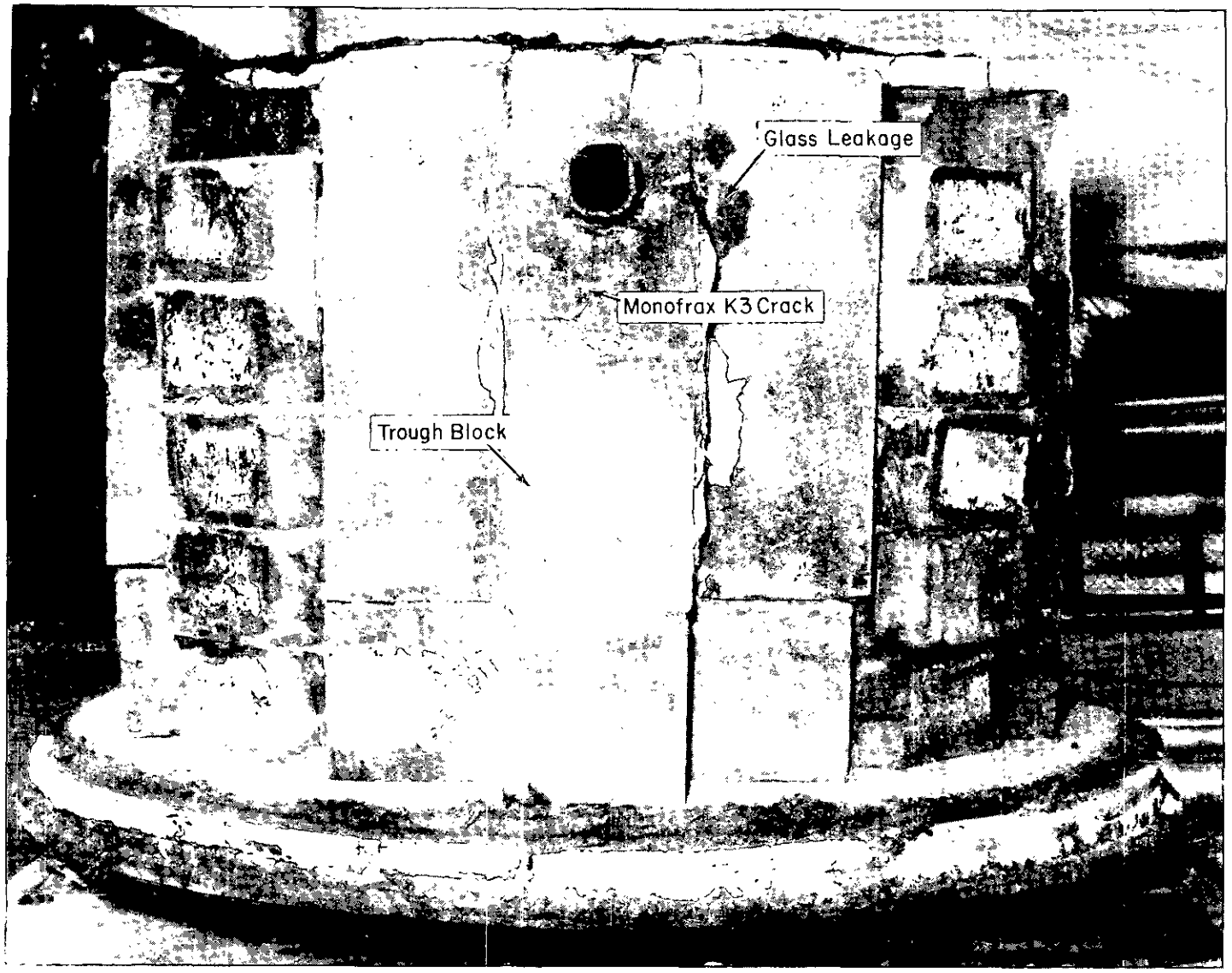

FIGURE 63. Ram Cement™ Removed (South Side)

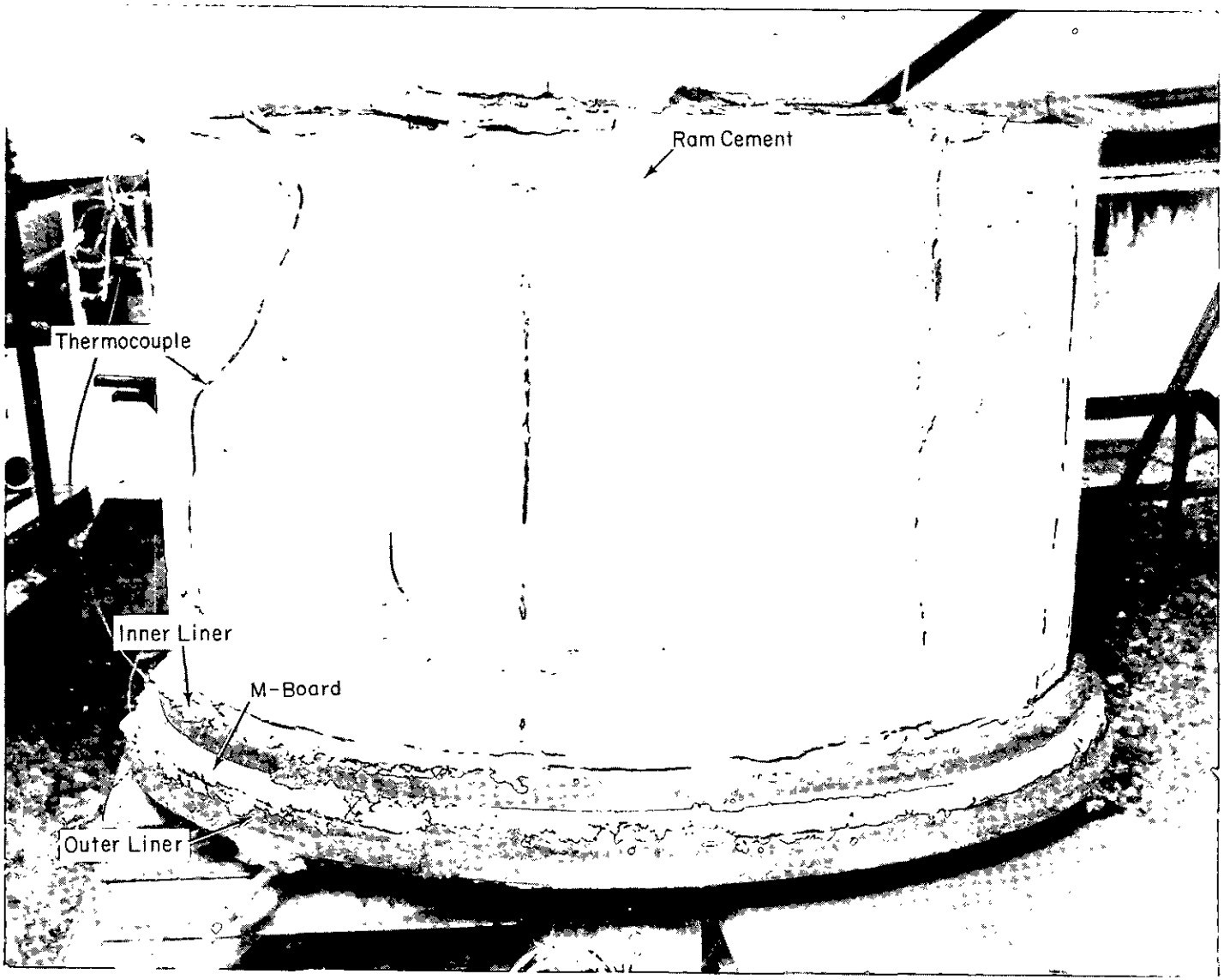

FIGURE 64. Inner Liner Removed (West Side)

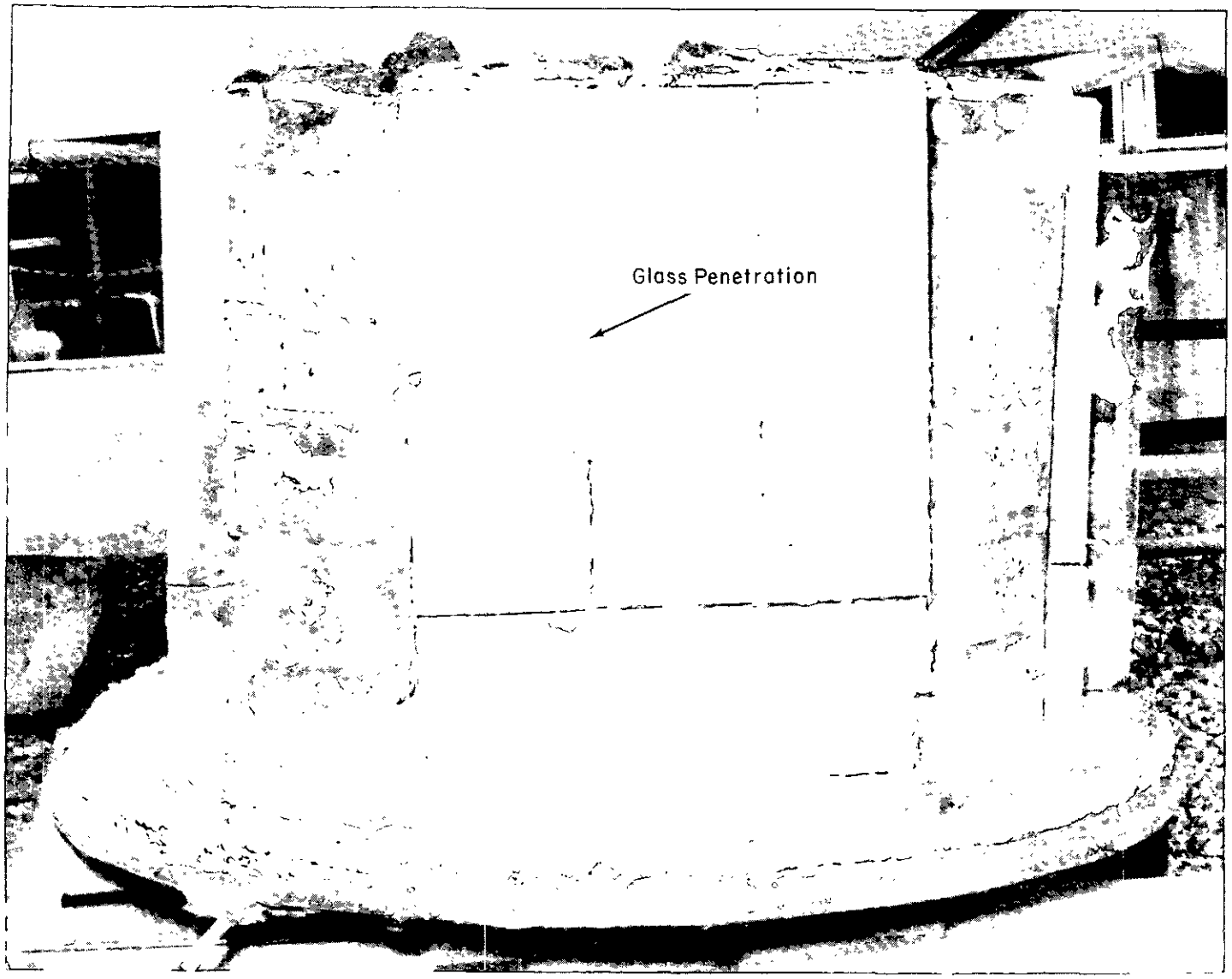

FIGURE 65. Ram Cement™ Removed (West Side)

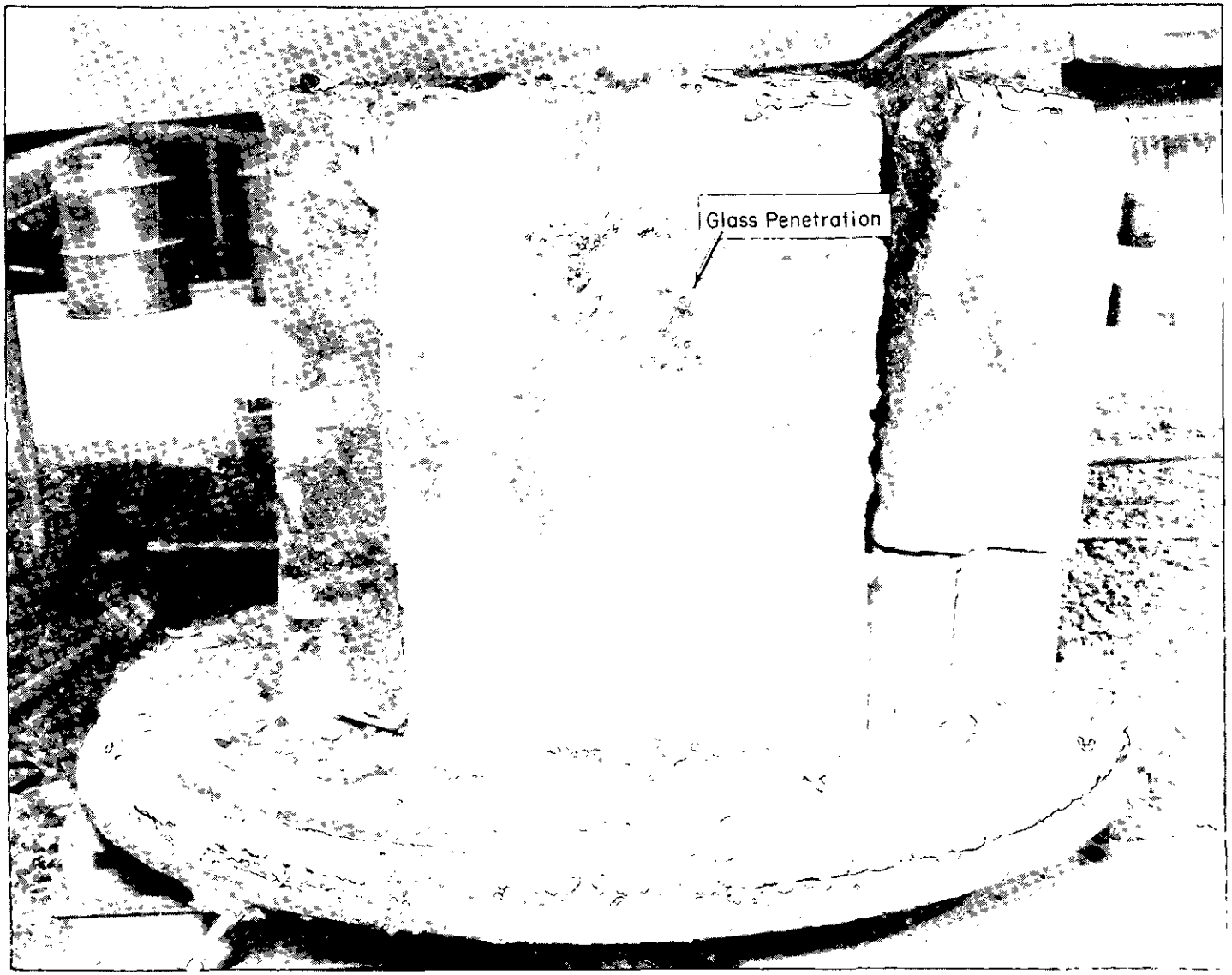

FIGURE 66. Four Inches of Monofrax™ K3 Removed (West Side)

- There was no indication that slurry feeding is more damaging to the Monofrax™ K3 refractory sidewalls than powder feeding.

- The average maximum Monofrax™ K3 refractory wear rate on the sidewalls was 1.81 mils/day and appears to be a function of melt rate and glass composition.

- Negligible wear occurred on the Monofrax™ K3 floor but this could be due to protection by overlying deposits.

- Negligible wear of the Monofrax™ K3 refractory occurrred above the melt line.

- Performance of the Inconel® 690 sleeve installed in the throat and riser region was outstanding. The use of Inconel® 690 in the throat and riser regions of future melters is strongly recommended.

- The maximum wear rate of electrodes A, B, and C occurred 1 to 3 inches below the melt line and ranged from 0.253 to 0.278 mil/day. This is a factor of 4.4 times below that which occurred in Campaign 2.

- Electrode D apparently experienced high temperature creep.

- Wear of the Inconel® 690 electrodes in the plenum ranged from 0.015 to 0.052 mil/day.

- Slurry feeding had no obviously damaging effects on the electrodes even though they penetrated the melt line.

- The use of M-Board™ (and similar products) is not recommended on exposed surfaces in the melt plenum except for short periods of time.

- The use of alumina sheaths over silicon carbide heaters in the melter plenum approximately doubled the lifetime of the heaters (from 268 days to 518+ days).

- The use of M-Board™ (and similar products) in the pour chamber is acceptable.

- Wear on the Inconel® 690 pour lip was negligible throughout the entire melter lifetime.

- Some silicon carbide heaters in the pour chamber lasted the entire melter lifetime, but contact with molten glass can significantly shorten heater lifetime.

- An excessive amount of waste in the melter feed can lead to rapid buildup of floor deposits.

- Some floor deposits are probably inevitable as a melter ages.

- The hot bottom that occurred in the SCM does not appear to have been caused by metallic deposits. Rather it appears to have been caused by highly viscous spinel deposits that could not dissipate internally generated heat by natural convection.

- The lifetime of Type K (chromel - alumel) thermocouples in direct glass contact in the SCM was a few weeks; inside a thermowell it was a few months; behind 8 inches of Monofrax™ K3 brick it was >2 years.

- An electrical screwjack is a highly reliable mechanism for use in pouring glass from a melter.

- An evacuated canister was used successfully to drain the SCM at the end of Campaign 3 in spite of excessive, viscous floor deposits.

- Pluggage of the feed device is a problem associated with slurry feeding that was insignificant when the melter was powder fed.

- Pluggage of the off-gas line was minimal in contrast to the performance of other slurry fed melters.

- The use of a television camera for observation of the melt pool was successfully demonstrated and is recommended for future melters.

- Glass penetrated to the back side of the 8-inch-thick melter sidewall constructed from Monofrax™ K3, but did not penetrate the castable refractory used behind the Monofrax™ K3 even though the refractory cracked.

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DP CATEGORY UC-70

AUTHOR(S) T L Allen, D C Iverson, M J Plodinec

TITLE History of The Small Cylindrical Melter

DIVISION

MANUSCRIPT APPROVAL
Route in turn to

	Initials	Date		Initials	Date
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SR-IC-50
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(TWX 810-771-2670, TEL 803-725-6211 WU AUGUSTA GA)</

CC: J. M. Stogner

June 5, 1985

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Patent Branch
U. S. Department of Energy
Aiken, South Carolina 29808

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Title: HISTORY OF THE SMALL CYLINDRICAL MELTER

Author(s) T. L. Allen, D. C. Iverson, and M. J. Plodinec

Contractual Origin: DE-AC09-76SR00001

Present Classification: Unclassified DP-Report

References:

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CC: J. M. Stogner

June 5, 1985

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U. S. Department of Energy
Aiken, South Carolina 29808

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Author(s) T. L. Allen, D. C. Iverson, and M. J. Plodinec

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No items were noted that, in my opinion, should be called to the attention of the DOE for patent consideration.

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