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DEA-87, PHASE II
PROGRESS REPORT NO. 4

By:

F. Sabins, T. Edwards, & K. Stringer

Westport Technology Center International
6700 Portwest Drive
Houston, Texas 77024
(713) 560-4666
(713) 864-9357 (Fax)
www.westport1.com

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Approved by:
D. B. Young

DEA 87 PHASE 2
PROGRESS REPORT NO. 4

OBJECTIVE

The objective of this project is to test and compare Blast Furnace Slag Cements with Portland Cement in two testing scenarios. These tests were performed: gas migration tests and annular sealing tests. The dimensional stability tests were not performed for this report. This report summarizes the initial data conducted on the cement and slags.

SECTION I - GAS MIGRATION TESTS

This section will outline the gas migration testing results obtained on the PHPA Slag Cements. The gas migration test cell used in the testing is shown in schematic 1. The results for tests conducted so far as shown in plots 1a, b through 4a, b in the Appendix. In order for the data to be analyzed easier each test result was plotted into two plots. The first plot (plot a) shows the data in the first 1000 to 1500 minutes. The next plot (plot b) shows the data collected during the entire test time (over 7 days in most cases).

Testing Procedures for Seven Day Tests:

Testing conditions were as follows:
BHCT = 126°F
BHST = 152°F
8000 Ft Casing Job with 0.9°F/100 ft Gradient

The mud compositions used in the testing was as follows:

Nondispersed System (PHPA)
Sea Water
10.0 ppb PH Bentonite
1.5 ppb PHPA
2.0 ppb CMS
0.5 ppb PAC-L
NaOH to pH 9.5
Barite to 12.5 ppg
30.0 ppb Rev Dust
Density = 12.5 #/gal

The Final Cementing Density was 15.6 #/gal for all compositions.

The cement composition tested was the following:

- Portland Class H cement + 1.0% Fluid Loss Additive + Bentonite + Dispersant at a Density of 15.6 #/gal

Bentonite was used to meet design criteria for the cement slurry.

The test procedures for conducting the gas migration tests were as follows:

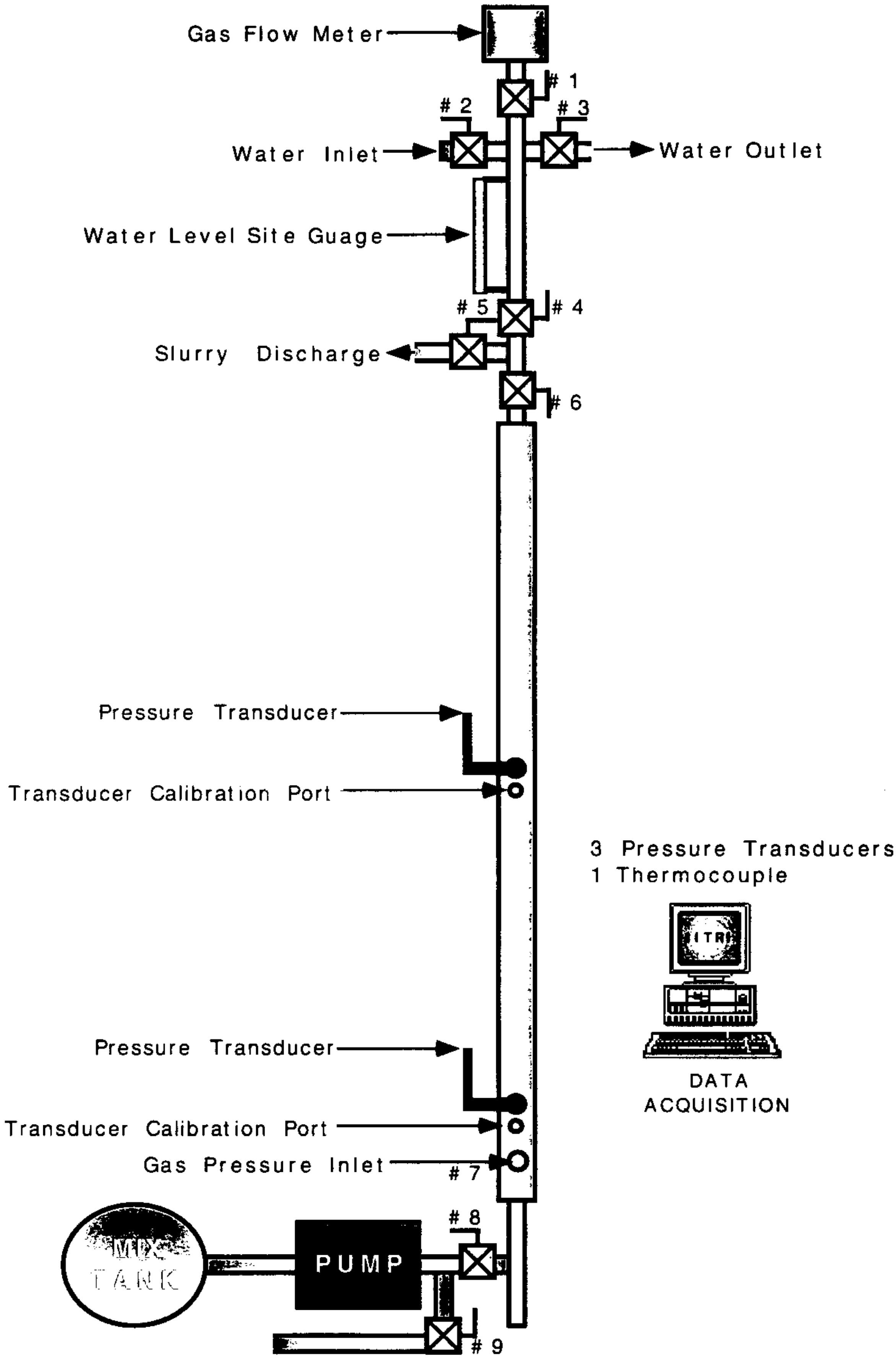
1. Fill the model up with water and heat it to the BHCT.
2. Mix approximately 4 gal of the test slurry in a 5 gal bucket.
3. Heat the slurry up to the BHCT while continuously stirring the slurry under low shear.
4. Condition the slurries for one hour.
5. Pump the slurry into the model until good returns from the top of the model are observed.
6. Open valves for water column on top of the cement and gas pressure.
7. Maintain 1.7 psi differential between hydrostatic pressure and the gas pressure.
8. Increase Temperature of the model from BHCT to BHST.
9. Maintain the BHST for the entire testing time.

10. Record the following data:
    a. Temperature of the Model
    b. Pore pressure at several locations in the model (one at the gas entry point, and one at 6 feet from the bottom).
    c. Amount of Gas entering the model (first 48 hours).
    d. Amount of Gas flowing out of the model
11. At the end of the testing period evaluate the path of gas flow

Schematic 1

DEA-87 PHASE II

GAS MIGRATION MODEL



Laboratory Test Results

The laboratory design test results on each of the slurries tested for the PHPA systems is shown in Table 1.

All the slurries had similar properties. The data for the Portland Cement system is shown for comparison purposes only.

Table 1
Slurry Test Data

Slurry	1 Portland	6 PHPA 4/0	7 PHPA 4/4	8 PHPA 4/8	9 PHPA 4/12
Thick Time Hrs:min	2:11	2:41	3:35	3:34	3:03
Free Water cc's	0	0	0	0	0
UCA 50 psi 500 psi 24 hrs	 5:04 6:36 2820	 3:03 4:04 1100	 3:35 3:55 1400	 3:42 3:53 1530	 2:43 2:55 1696
Rheology 600 300 10':10"	 300+ 164 5:17	 300+ 150 4:7	 300+ 100 5:11	 300+ 141 5:14	 235 119 5:14

Seven Day Gas Migration Test Results:

Below is the summary of the tests conducted and a description of the data generated for each test. All of the plots are in the Appendix at the end of this report.

- Test/Slurry No. 6 - plot #1a,b

  Composition: PHPA Mud diluted from 12.5 ppg to 10.5 ppg, 4 ppb Sodium Hydroxide, 0 ppb Sodium Carbonate, 3 ppb Dispersant (Unical), 362 ppb Blast Furnace Slag, Final Density of 15.6 ppg.

  Test Comments: From plot 1a the gas entry started about 1100 minutes and the gas out of the model was observed shortly thereafter. The gas rate in and the gas rate out continued for the entire 7 day testing period. Plot 2b shows that a total of about 5500 cc of gas was observed throughout the testing period.

- Test/Slurry No. 7- plot #2a,b

  Slurry No. 3

  PHPA Mud diluted from 12.5 ppg to 10.5 ppg, 4 ppb Sodium Hydroxide, 4 ppb Sodium Carbonate, 3.5 ppb Dispersant (Unical), 354 ppb Blast Furnace Slag, Final Density of 15.6 ppg.

  Test Comments: Plot 2a shows that the gas entry was much quicker with the 4/4 slurry than the 4/0 slurry. Gas into the model started about 400 minutes and gas was observed shortly after. Plot 2b shows that a total of about 50 liters of gas was measured coming out of the model during the entire 7 day testing program.

- Test/Slurry No. 8 - plot #3a,b

  Slurry No. 4

  PHPA Mud diluted from 12.5 ppg to 10.5 ppg, 4 ppb Sodium Hydroxide, 8 ppb Sodium Carbonate, 3.5 ppb Dispersant (Unical), 346 ppb Blast Furnace Slag, Final Density of 15.6 ppg.

Test Comments: In this case, plot 3a shows that the gas entry into the model was about 350 minutes and the gas out shortly after. Plot 4b indicates that 110 liters of gas was measured out of the model during the entire testing period.

- Test/Slurry No. 9 - plot #4a,b
  Slurry No. 5
  PHPA Mud diluted from 12.5 ppg to 10.5 ppg, 4 ppb Sodium Hydroxide, 12 ppb Sodium Carbonate, 3.5 ppb Dispersant (Unical), 343.76 ppb Blast Furnace Slag, Final Density of 15.6 ppg.

  Test Comments: This slurry allowed gas to enter the model in about 200 minutes. This is the shortest time observed in all of PHPA testing (see plot 5a). The total amount of gas that was measured through the model was over 400 liters (see plot 5b)

Permeability Measurements:

Tables 2, 3, 4 and 5 summarizes the bulk permeability to gas that was observed and calculated in each of the tests. Bulk Permeability were calculated from Cutting the Model. Once the test models were through the seven day testing, they were then cut up into one foot sections. A special adapter was made to capture the cross-sectional flow of gas through the model. Equation 1 was used to calculate the bulk permeability.

Equation 1:

$k = (q_{sc} P_{sg} T Z \mu L) \backslash (3.164 T_{sg} A (P_1^2 - P_2^2))$

where:

k = Permeability, darcy

q_{sc} = Volumetric Flow rate of Gas, SCF/Day

P_{sg} = Standard Pressure, psia

T = Temperature , °R

Z = Z factor

μ = Viscosity, cp

L = Length, ft

T_{sg} = Standard Temperature, °R
A = Flowing Area, ft^2
P_1 = High pressure, psi
P_2 = Low pressure, psi

The flow rate q is taken from the inlet gas volumetric flow rate and then adjusted to standard temperature and pressure. These measurements were taken with the model at the test temperature at 5 minute intervals up to 15 minutes.

Table 2
Summary of Bulk Permeability to Gas
4/0 PHPA

Pressure (psi)	Length from Gas Inlet (ft)	Perm (m)
8.6	10	8.2
	9	6.9
	8	--
	7	--
	6	--
	5	12.5
	4	13.6
	3	21.1
	2	23.7
	1	18.8

Table 3
Summary of Bulk Permeability to Gas
PHPA 4/4

Pressure (psi)	Length from Gas Inlet (ft)	Perm (md)
8.6	10	215
	9	286
	8	294
	7	315
	6	355
	5	334
	4	323
	3	426
	2	421
	1	658

Table 4
Summary of Bulk Permeability to Gas
PHPA 4/8

Pressure (psi)	Length from Gas Inlet (ft)	Perm (md)
8.6	10	382
	9	654
	8	605
	7	769
	6	1270
	5	1427
	4	1452
	3	1421
	2	1269
	1	3288

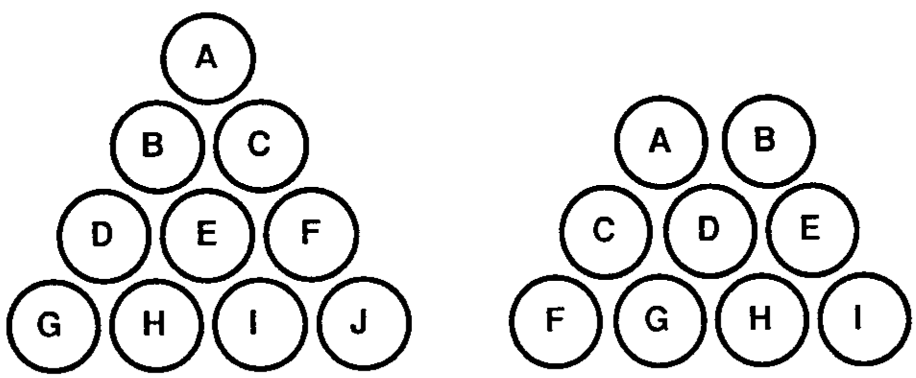
Table 5
Summary of Bulk Permeability to Gas
PHPA 4/12

Pressure (psi)	Length from Gas Inlet (ft)	Perm (md)
8.6	10	776
	9	2724
	8	2980
	7	3149
	6	4300
	5	6311
	4	7609
	3	9955
	2	20610
	1	13491

Mapping Gas Flow Channels in Models

The model was cut in one foot intervals from the top down. Photos of the cuts of each gas migration tests are shown in figures 1 through 4 in the Appendix. The top cut is identified as Cut A down through Cut I on the bottom. The nitrogen pressure applied to the bottom of the model throughout the gas migration test was continuously maintained through out the cutting process. The temperature on the model was maintained at 152°F BHST through out the cutting process. Immediately after the cut had been made the exposed facial surface was wetted with soapy water. Any gas through the model was identified by the formation of bubbles. If the gas was from between the inner pipe wall and the outer cement surface the area was marked with a grease pen enclosing the area of bubbles. If the gas was coming through the matrix of cement the area was circled.

The group photo is laid out in either of the following patterns. Orientation of each piece is in a straight line.



SECTION 2 - DIMENSIONAL STABILITY

OBJECTIVE

The objective of this portion of Phase II is to measure the plastic state shrinkage, total volume reduction and the "gas tightness" of BFS and Portland cement systems by way of the Cement Hydration Analyzer. No slurries were tested in this section. It is recommended that due to the limited data obtained with this testing that no future work should be performed.

SECTION 3 - ANNULAR SEALING TEST

OBJECTIVE

The objective of this portion of the project is to test the ability of various BFS systems, and Portland Cement systems, to seal gas in an annular configuration. Well conditions simulating high stress will be modeled. The flow rate of dry gas will be measured in a full scale annular model containing several different slurries for periods up to 28 days. Additionally, the same model will investigate the ability of the systems to seal gas flow in the annulus under high stress conditions.

The slurries tested in this section will be the same ones used in section 2 and 3.

Test Models

The test models are a 2 3/8" pipe (1.90" inside diameter) inside a 5" pipe (4" inside diameter) 2 1/2' long (see schematic 2). Three different slurries were tested for a pressure stress test only.

Test Procedures

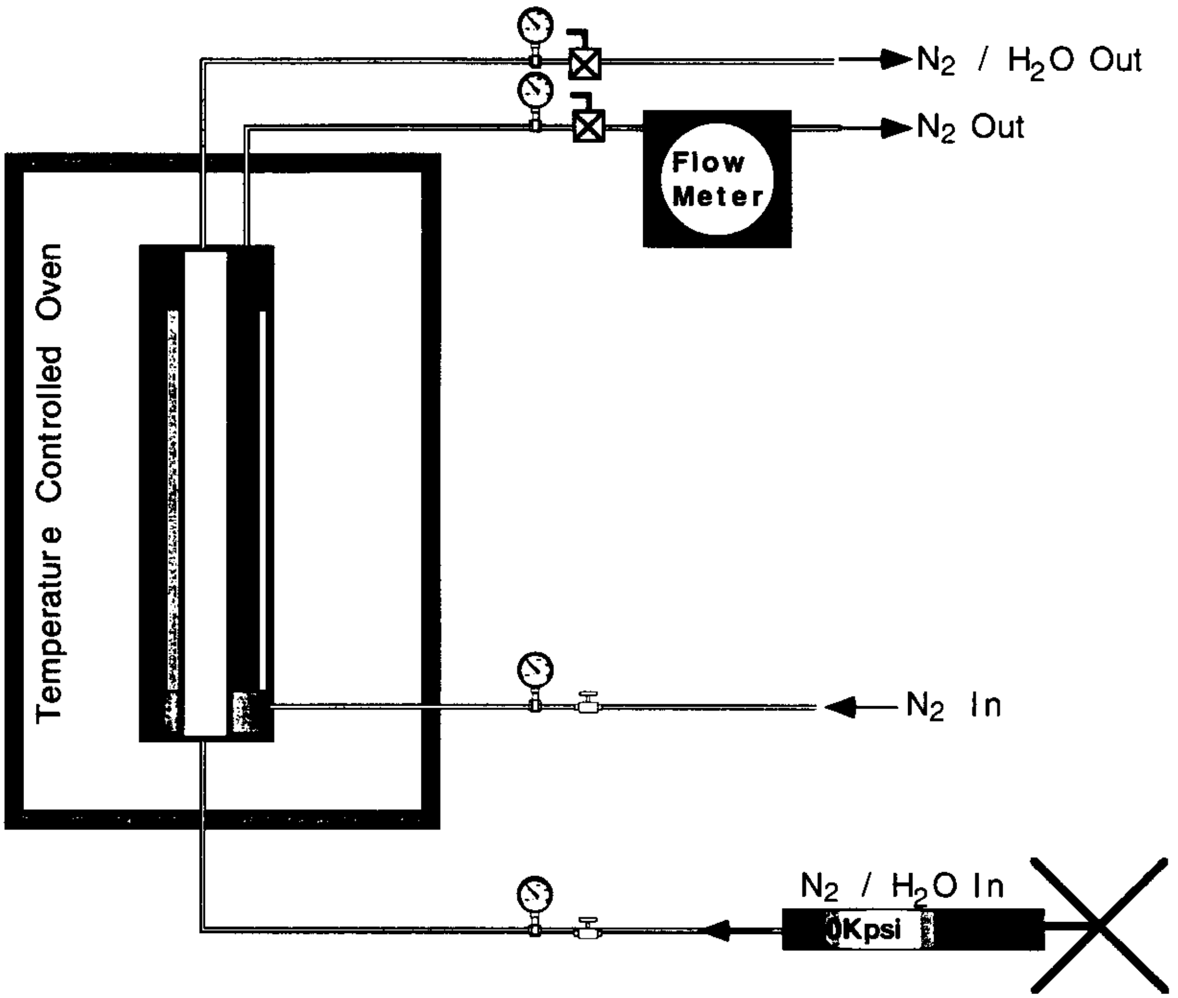
1. The slurries will be mixed in a one gallon mixer at room temperature.
2. The models will be filled with slurry and placed in an oven and heated to BHST.
3. After curing for a period of over 72 hours the pressure stress test will be conducted.
   a. Stress inside of casing to preset value for 5 minutes
   b. Release the pressure inside the casing and measure the flow rate of gas through the model with 50 psi gas pressure for 5 minutes.
   c. Increase the pressure inside the casing and repeat steps a and b.
   d. Repeat steps c up to safety pressure limit of inside casing.
4. After curing for a period of over 72 hours the temperature stress test was to be conducted. These tests however were not conducted on the samples. The procedure was to do the following:
   a. Circulated room temperature water inside the 2 3/8 " casing for 5 minutes.

b. Continually measure the flow rate of gas through the annulus with 50 psi pressure.
c. Increase temperature to 175 °F and repeat steps a and b.
d. Increase temperature to 200 °F and repeat steps a and b.

Table 6, 7 and 8 summarizes the data for the slurries tested.

Schematic 2

ANNULAR SEALING TEST SCHEMATIC



Measurement of Bulk Permeability

The bulk permeability of the models were calculated from the flow data using Equation 1. Table 6 and Table 7 indicates that the Portland cement and the 4/0 PHPA system maintained a tight seal to gas even when pressures of 10,000 psi was placed on the inside of the casing. Table 8 however, indicated that the 4/12 PHPA BFS system allowed a substantial amount of gas to flow even before any stress was placed inside the casing. The calculated bulk permeability however did not change much with increasing stress on the inside casing.

A cut of each of the models is shown in figures 5 ,6 and 7 in the Appendix.

Table 6
Portland Cement System

Pressure of Gas (psi)	Time (days)	Pressure inside casing (psi)	Flow rate (1/5 min)	Perm (md)
50	3	0	0	0
50	3	1000	0	0
50	3	2000	2	0.11
50	3	3000	2	0.11
50	3	4000	2	0.11
50	3	5000	2	0.11
50	3	6000	2.6	0.14
50	3	7000	2.2	0.14
50	3	8000	14	0.74
50	3	9000	20	1.06
50	3	10000	30	1.59
50	14	0	12	0.64
50	14	10000	72	3.81
50	21	0	12	0.64
50	21	10000	42	2.22
50	28	0	10	0.53
50	28	10000	39	2.06

Table 7
BFS System (4/0)

Pressure of Gas (psi)	Time (days)	Pressure inside casing (psi)	Flow rate (l/min)	Perm (md)
50	3	0	0	0
50	3	1000	2	0.11
50	3	2000	2	0.11
50	3	3000	4	0.21
50	3	4000	4	0.21
50	3	5000	2	0.11
50	3	6000	11	0.58
50	3	7000	13.4	0.71
50	3	8000	20	1.06
50	3	9000	26	1.38
50	3	10000	40	2.12
50	14	0	152	8.04
50	14	10000	173	9.16
50	21	0	194	10.27
50	21	10000	230	12.2
50	28	0	88	4.66
50	28	10000	222	11.75

Table 8
BFS System (4/12)

Pressure of Gas (psi)	Time (days)	Pressure inside casing (psi)	Flow rate (l/min)	Perm (md)
50	3	0	7.16	379
50	3	1000	10.4	550
50	3	2000	12.68	671
50	3	3000	14.3	757
50	3	4000	15.66	829
50	3	5000	16.6	879
50	3	6000	17.2	910
50	3	7000	17.56	929
50	3	8000	15.6	826
50	3	9000	16.0	847
50	3	10000	16.8	889
50	14	0	17.0	900
50	14	10000	18.54	981
50	21	0	18.98	1004
50	21	10000	20.58	1089
50	28	0	19.0	1005
50	28	10000	18.2	963

Appendix

Plot 1 a - Gas Migration Test With 4/0 BFS System (Short Time)
Plot 1 b - Gas Migration Test With 4/0 BFS System (Entire Test Time)

Plot 2 a - Gas Migration Test With 4/4 BFS System (Short Time)
Plot 2 b - Gas Migration Test With 4/4 BFS System (Entire Test Time)

Plot 3 a - Gas Migration Test With 4/8 BFS System (Short Time)
Plot 3 b - Gas Migration Test With 4/8 BFS System (Entire Test Time)

Plot 4 a - Gas Migration Test With 4/12 BFS System (Short Time)
Plot 4 b - Gas Migration Test With 4/12 BFS System (Entire Test Time)

Figure 1a-j: Cross Section Cuts Of Gas Migration Model (4/0 BFS System)

Figure 2a-j: Cross Section Cuts Of Gas Migration Model (4/4 BFS System)

Figure 3a-j: Cross Section Cuts Of Gas Migration Model (4/8 BFS System)

Figure 4a-j: Cross Section Cuts Of Gas Migration Model (4/12 BFS System)

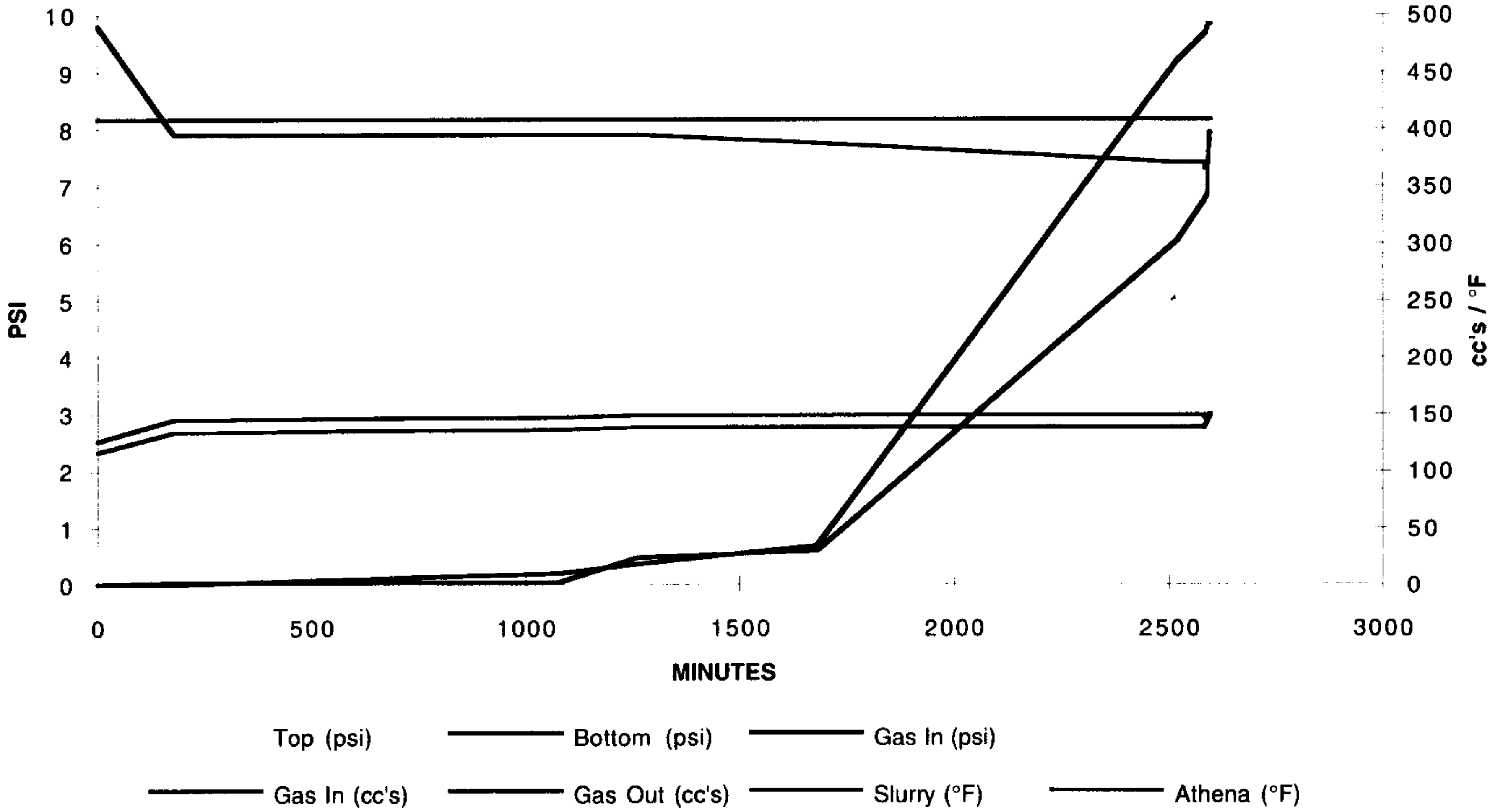
Figure 5 - Cross Section Cut Of Annular Sealing Model (Portland Cement)

Figure 6 - Cross Section Cut Of Annular Sealing Model (4/0 BFS System)

Figure 7 - Cross Section Cut Of Annular Sealing Model (4/12 BFS System)

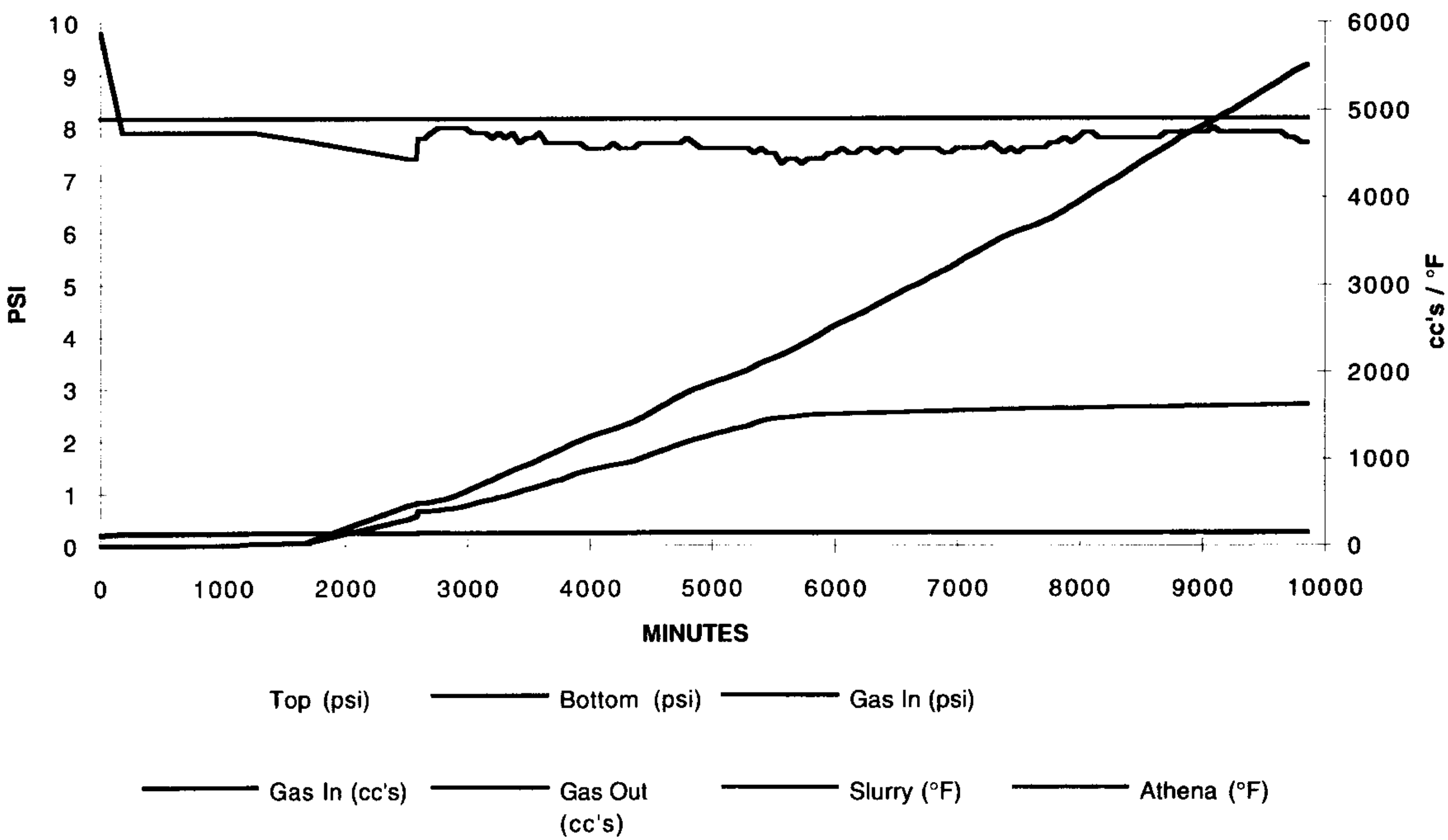
Plot 1a

PHPA 4 / 0



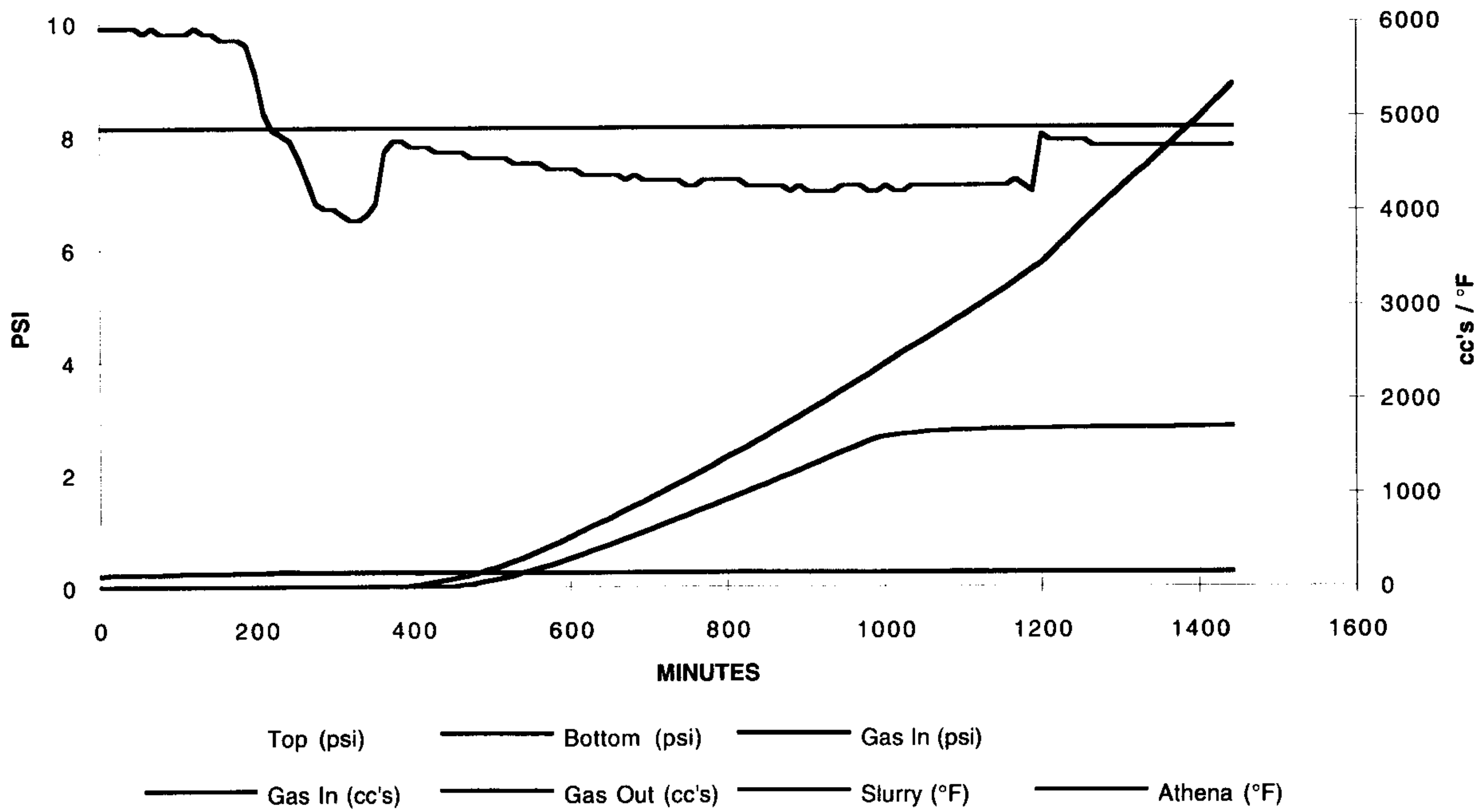
Plot 1b

PHPA 4 / 0



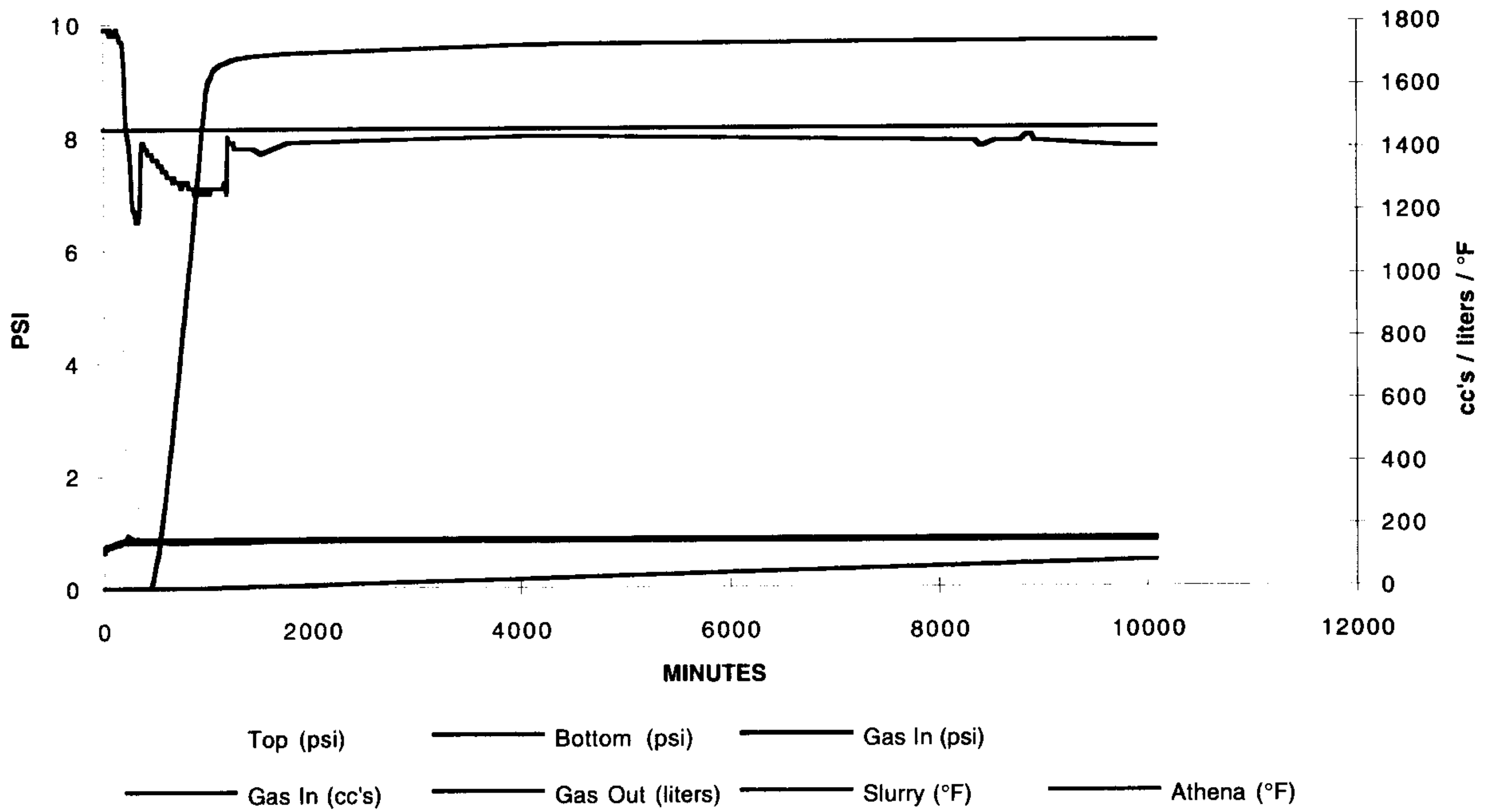
Plot 2a

PHPA 4 / 4



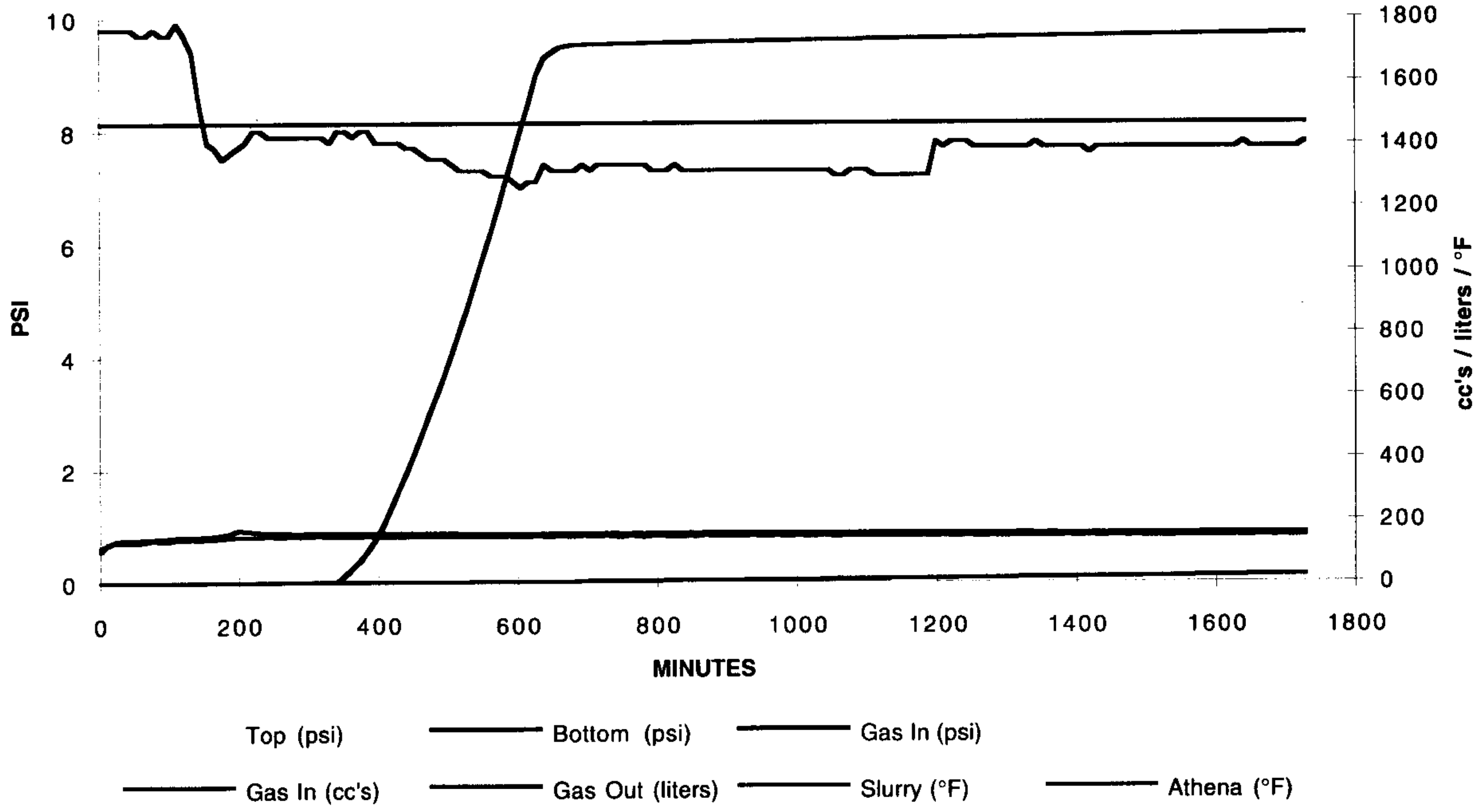
Plot 2b

PHPA 4 / 4



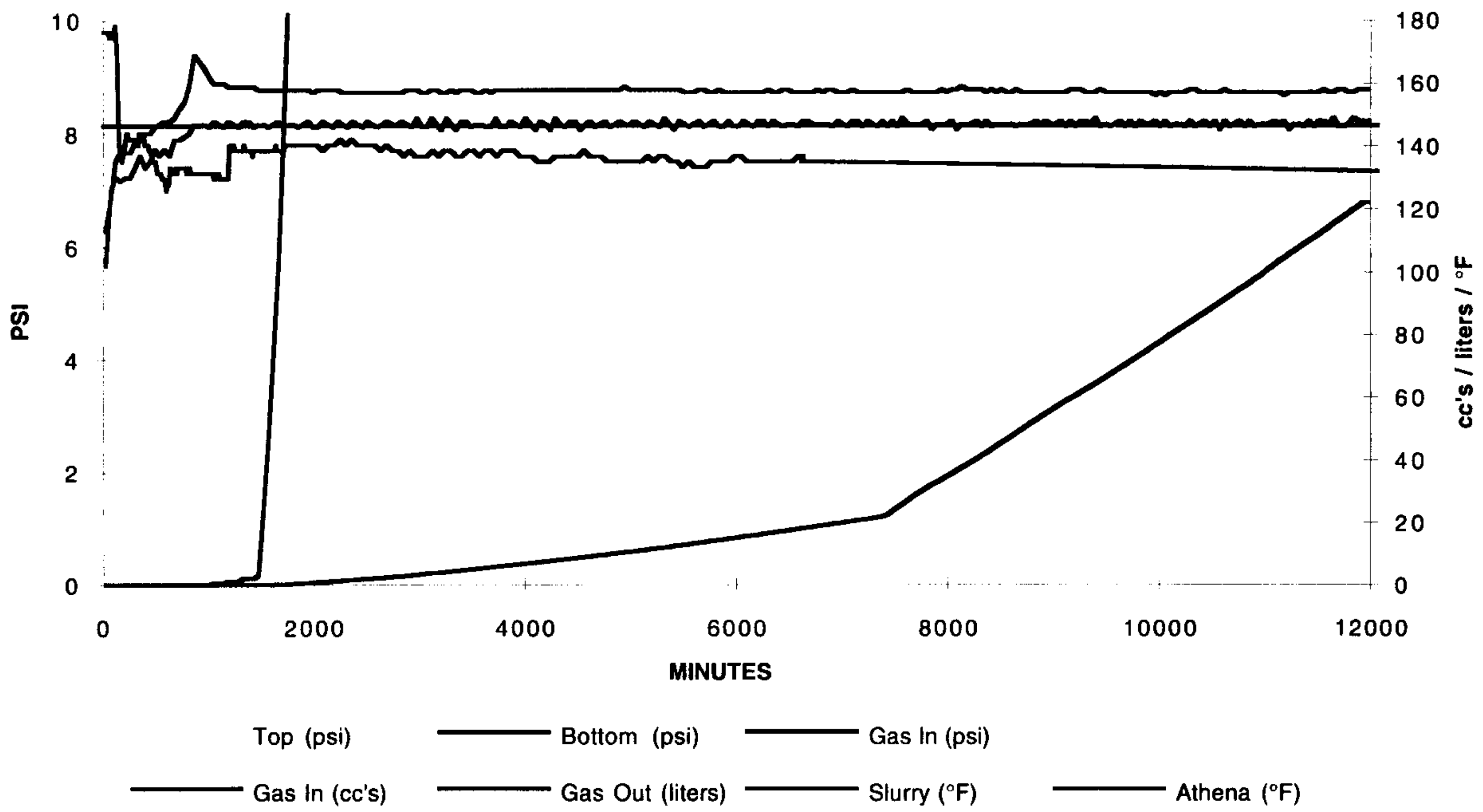
Plot 3a

PHPA 4 / 8



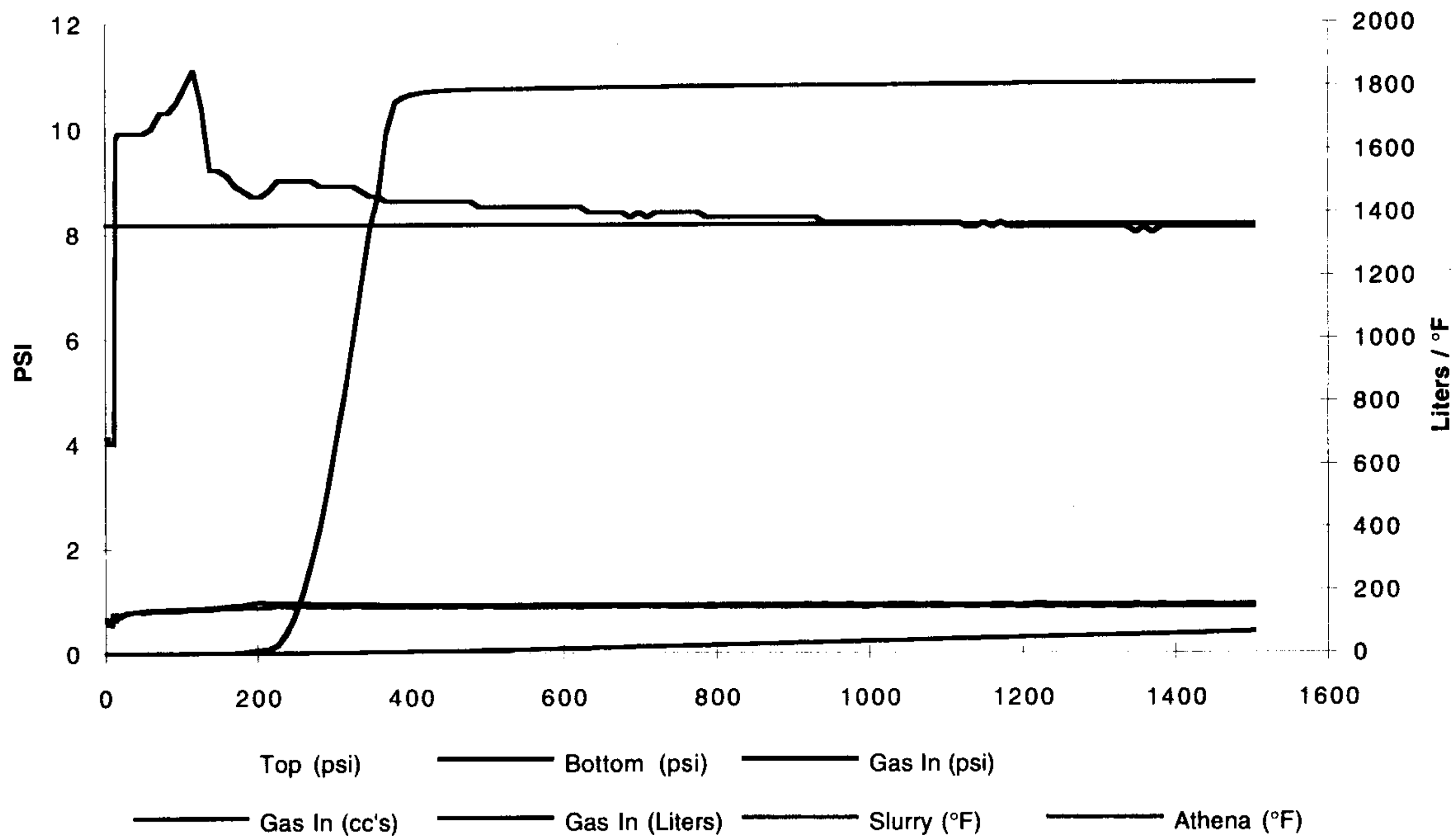
Plot 3b

PHPA 4 / 8



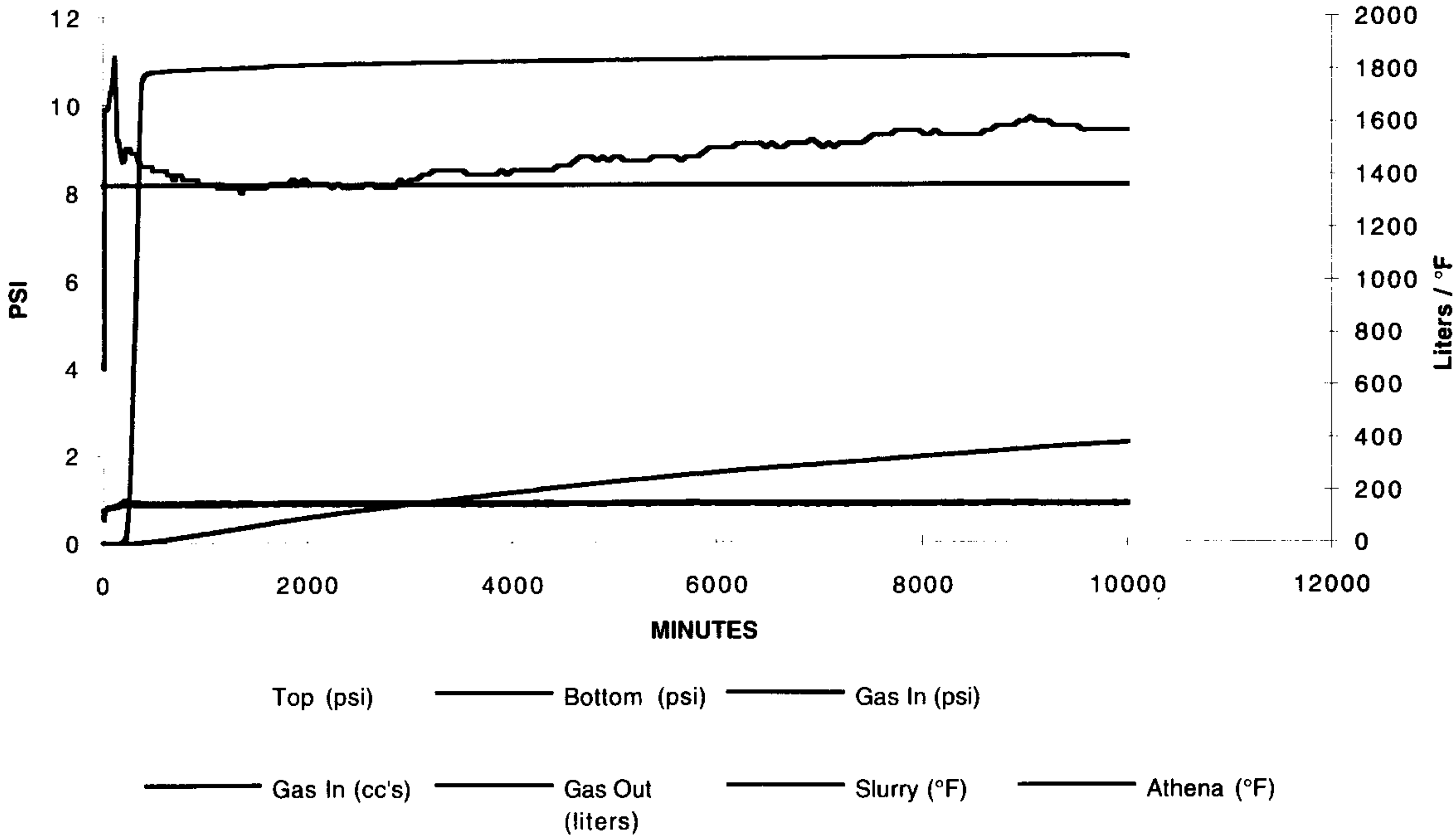
Plot 4a

PHPA 4 / 12



Plot 4b

PHPA 4 /12



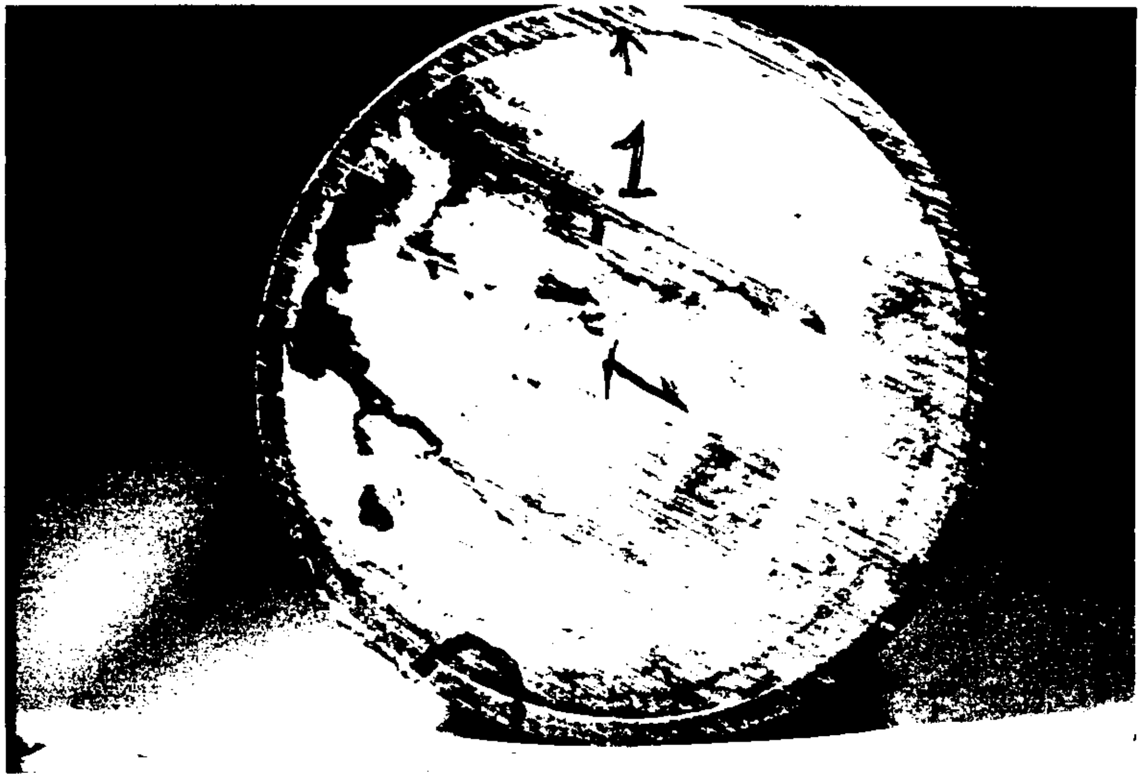


Figure 1a: PHPA 4 / 0 BFS - Cut A

Figure 1b: PHPA 4 / 0 BFS - Cut B

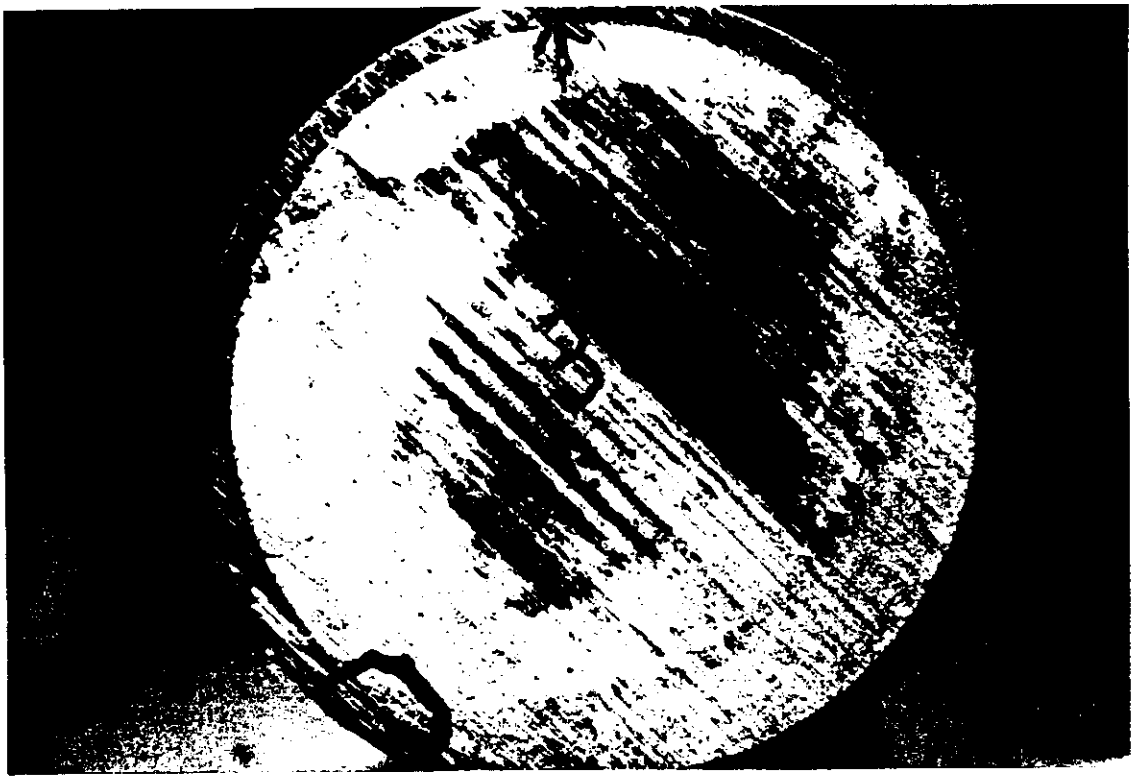


Figure 1c: PHPA 4 / 0 BFS - Cut C

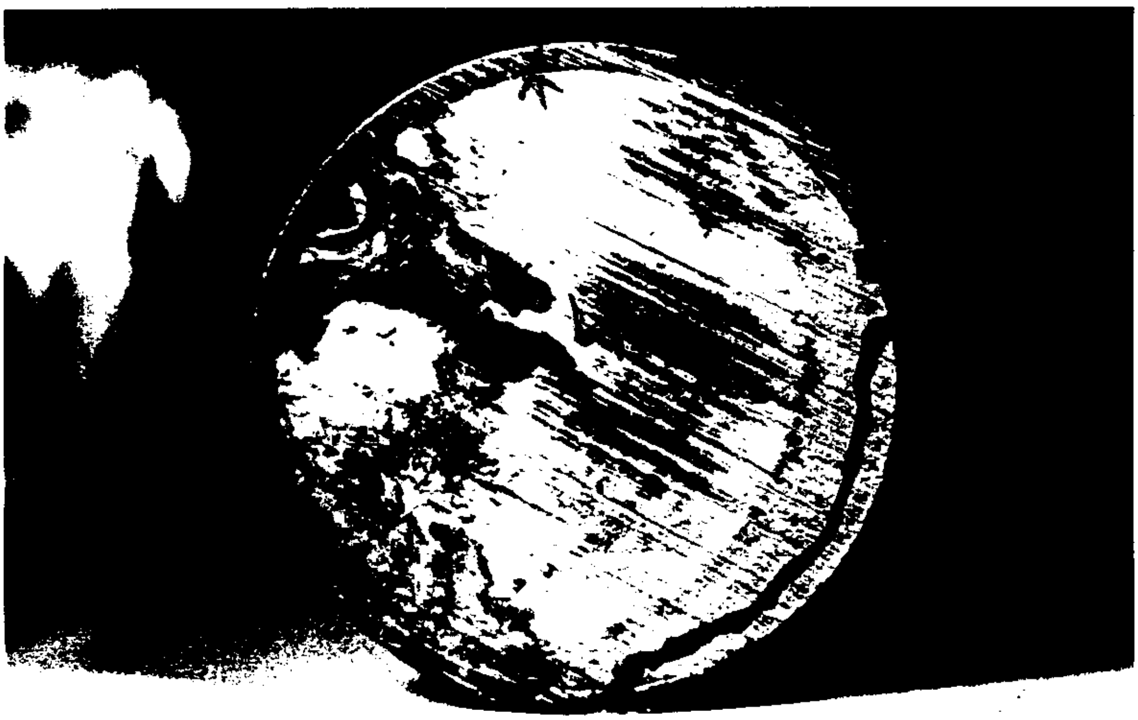


Figure 1d: PHPA 4 / 0 BFS - Cut D

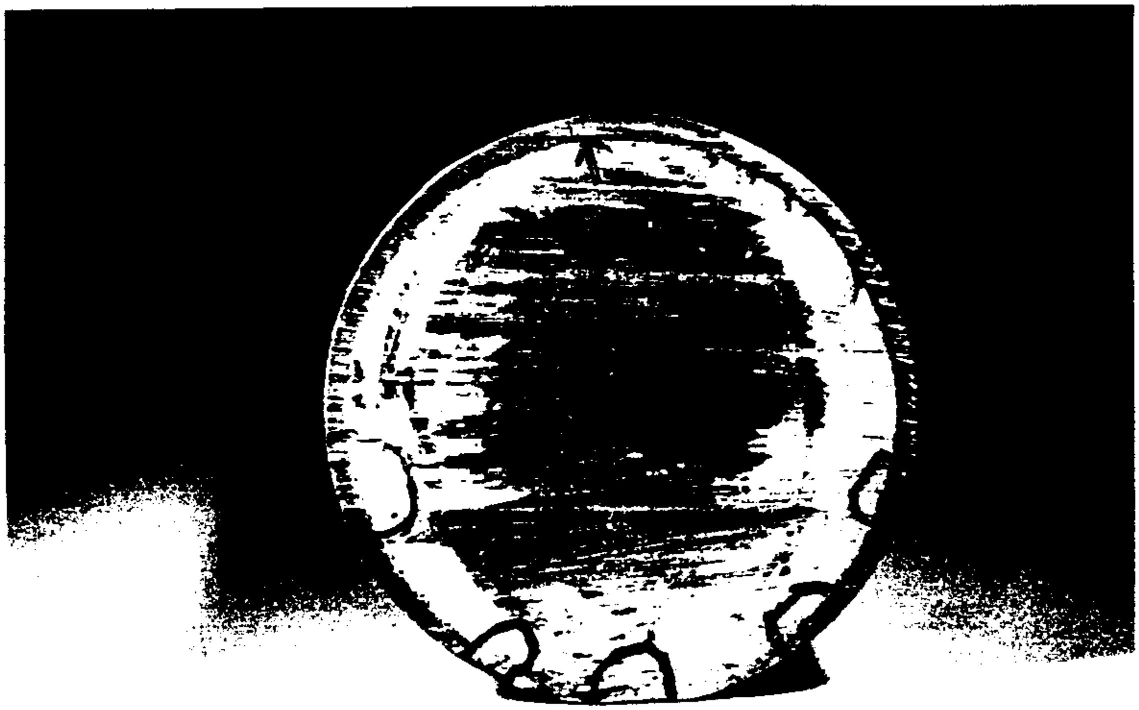


Figure 1e: PHPA 4 / 0 BFS - Cut E

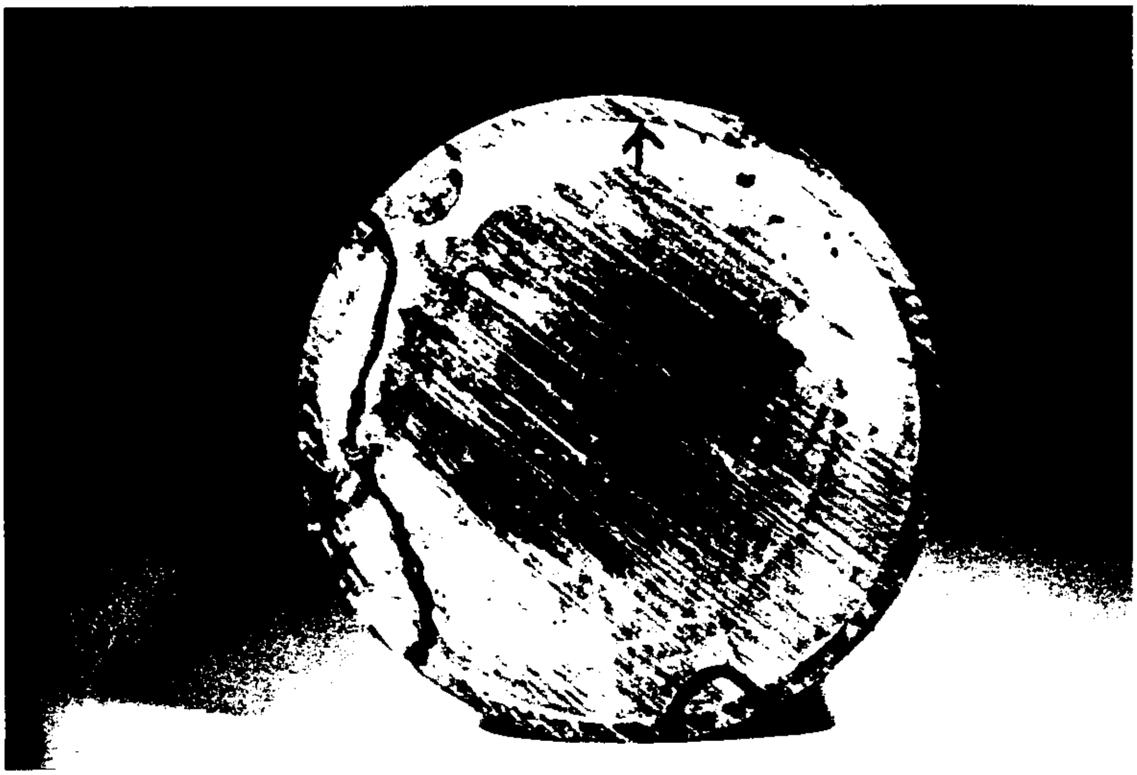


Figure 1f: PHPA 4 / 0 BFS - Cut F

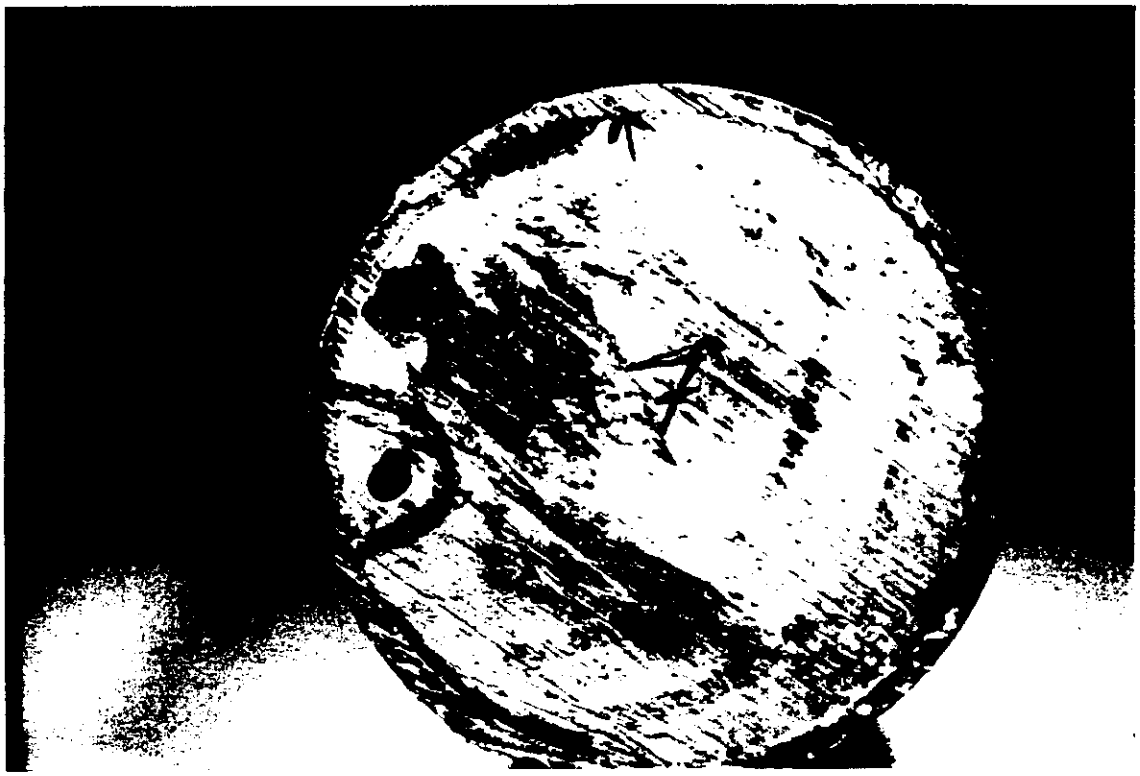


Figure 1g: PHPA 4 / 0 BFS - Cut G

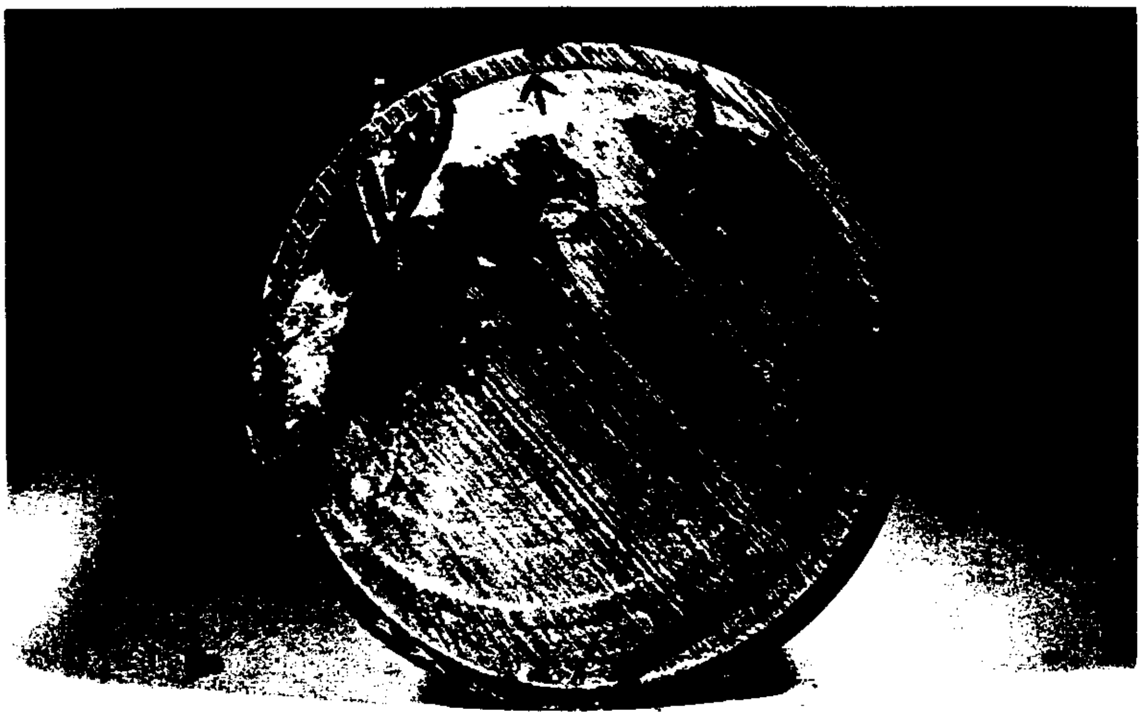


Figure 1h: PHPA 4 / 0 BFS - Cut H

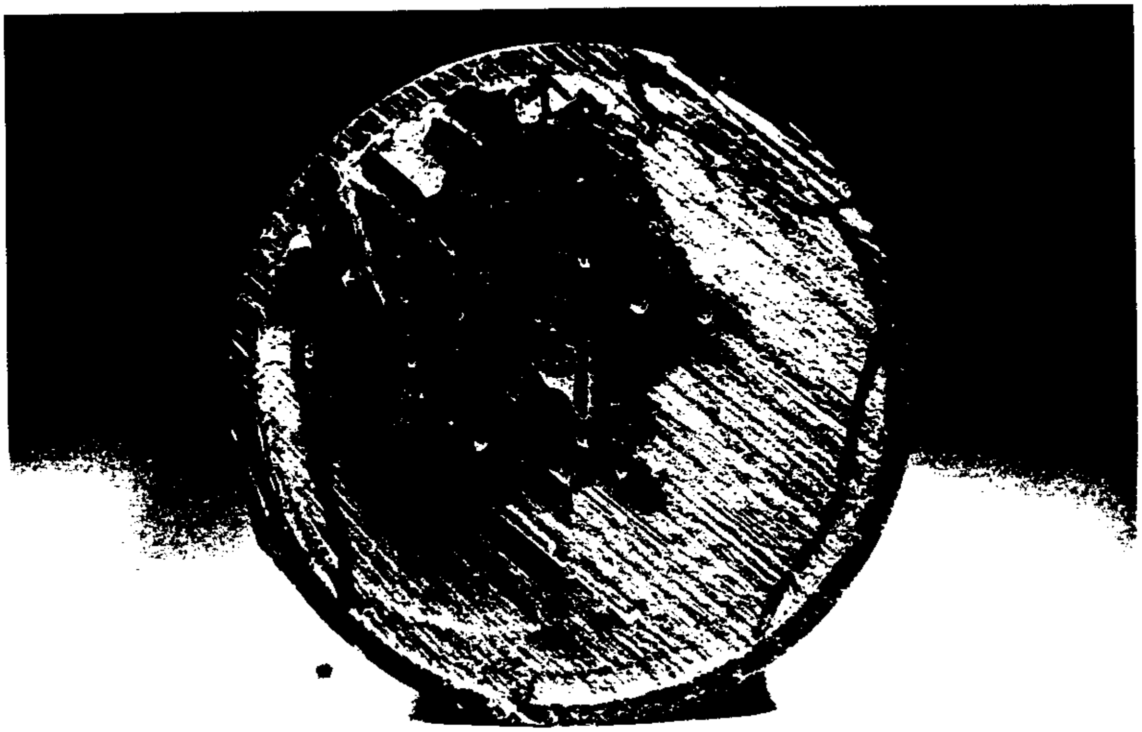


Figure 1i: PHPA 4 / 0 BFS - Cut I

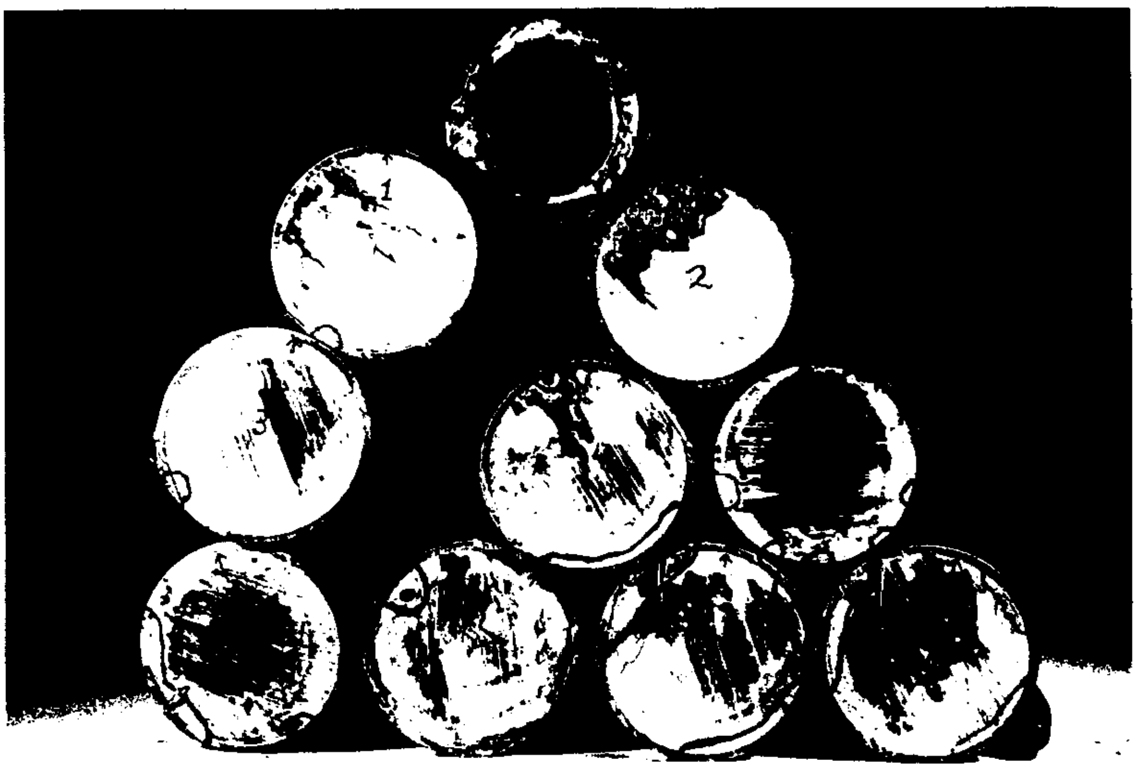


Figure 1j: PHPA 4 / 0 BFS - Cuts A through I

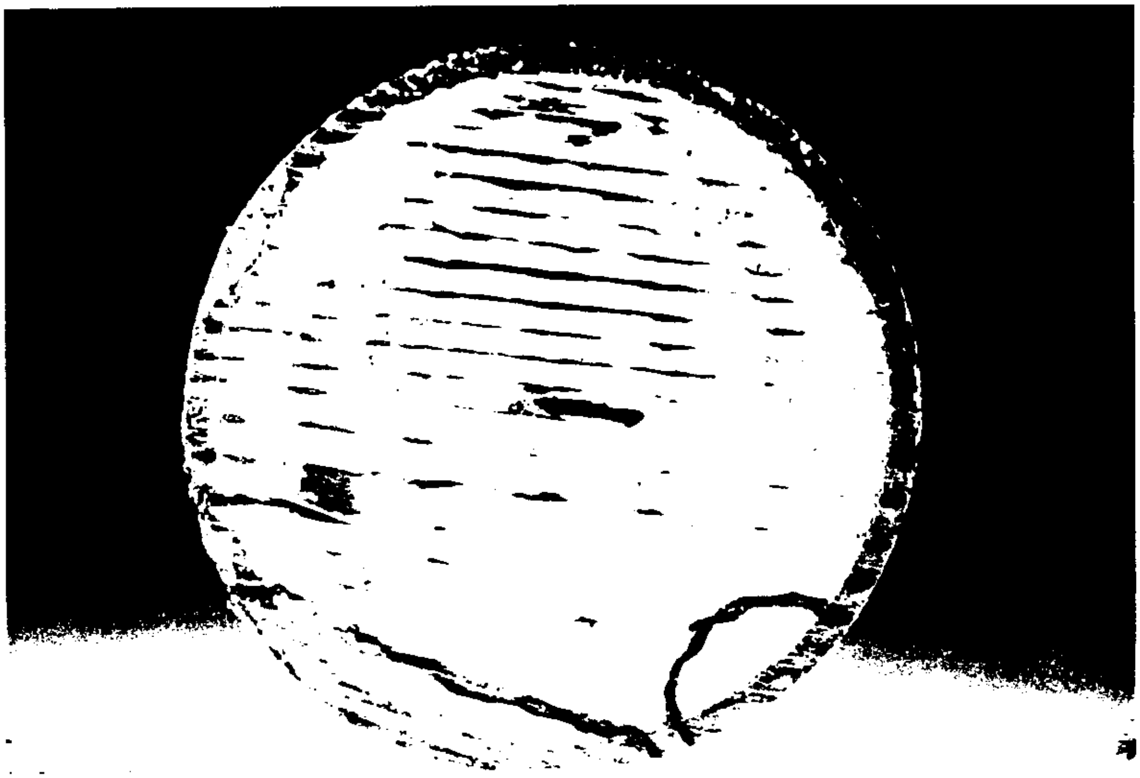


Figure 2a: PHPA 4 / 4 BFS - Cut A

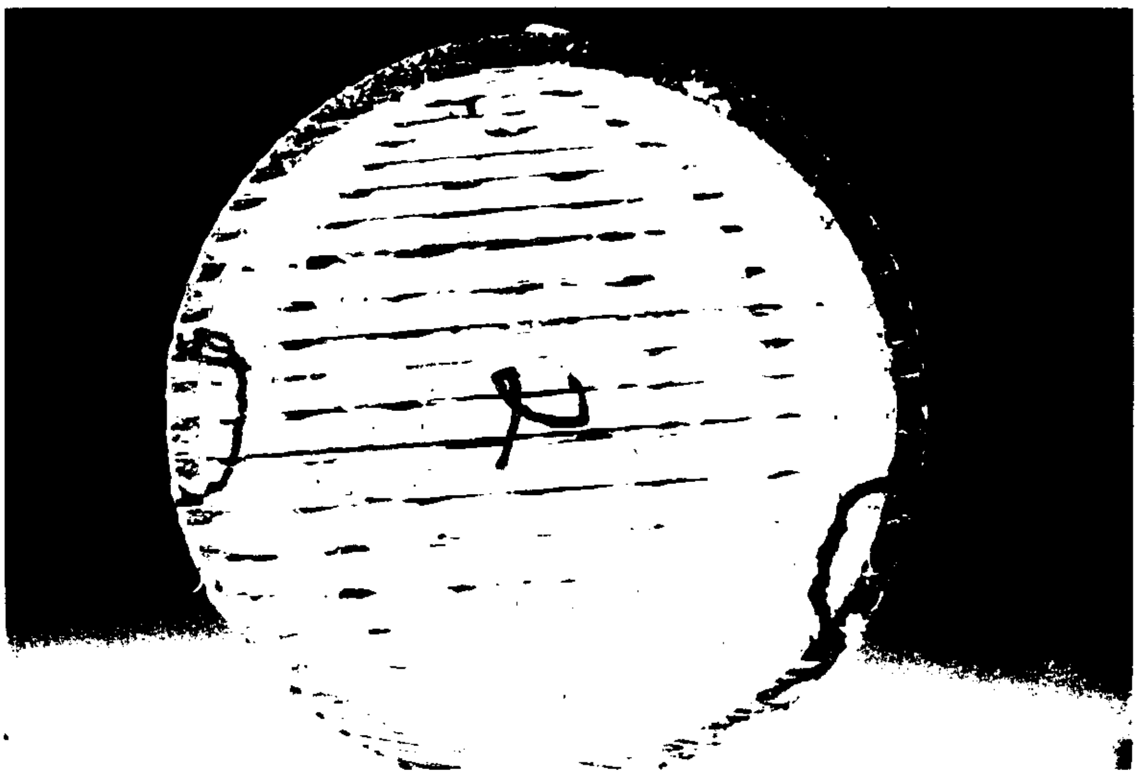


Figure 2b: PHPA 4 / 4 BFS - Cut B

Figure 2c: PHPA 4 / 4 BFS - Cut C

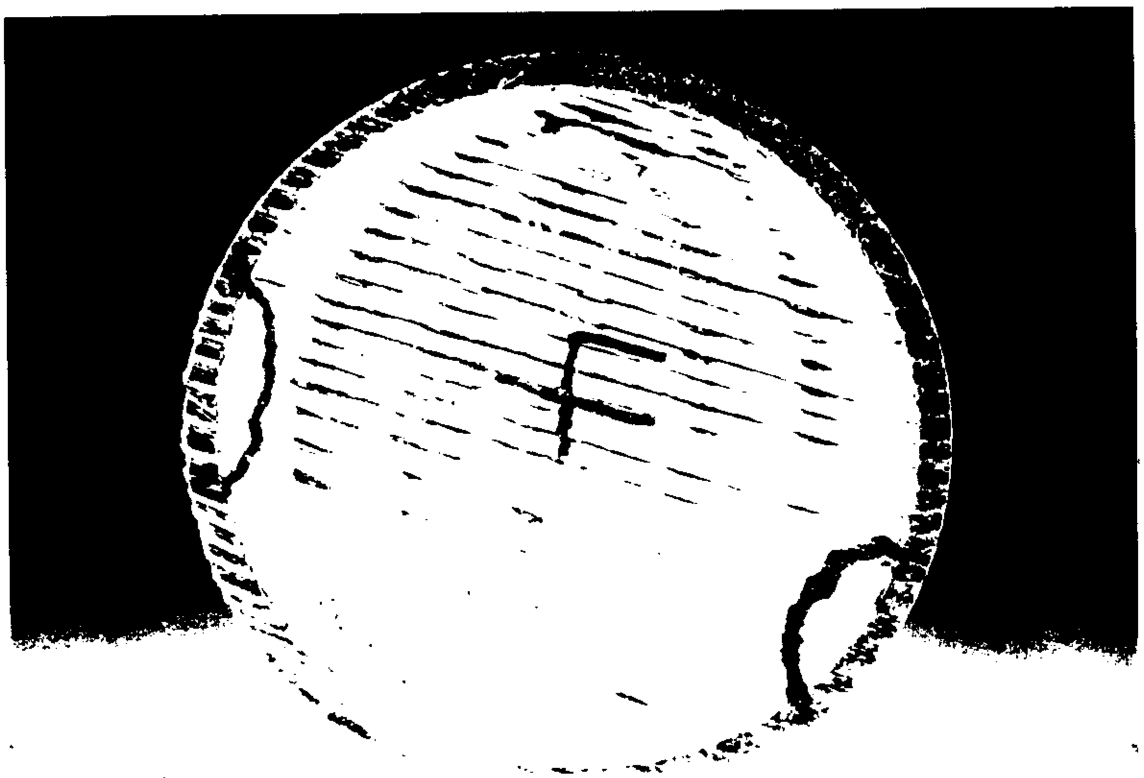


Figure 2d: PHPA 4 / 4 BFS - Cut D

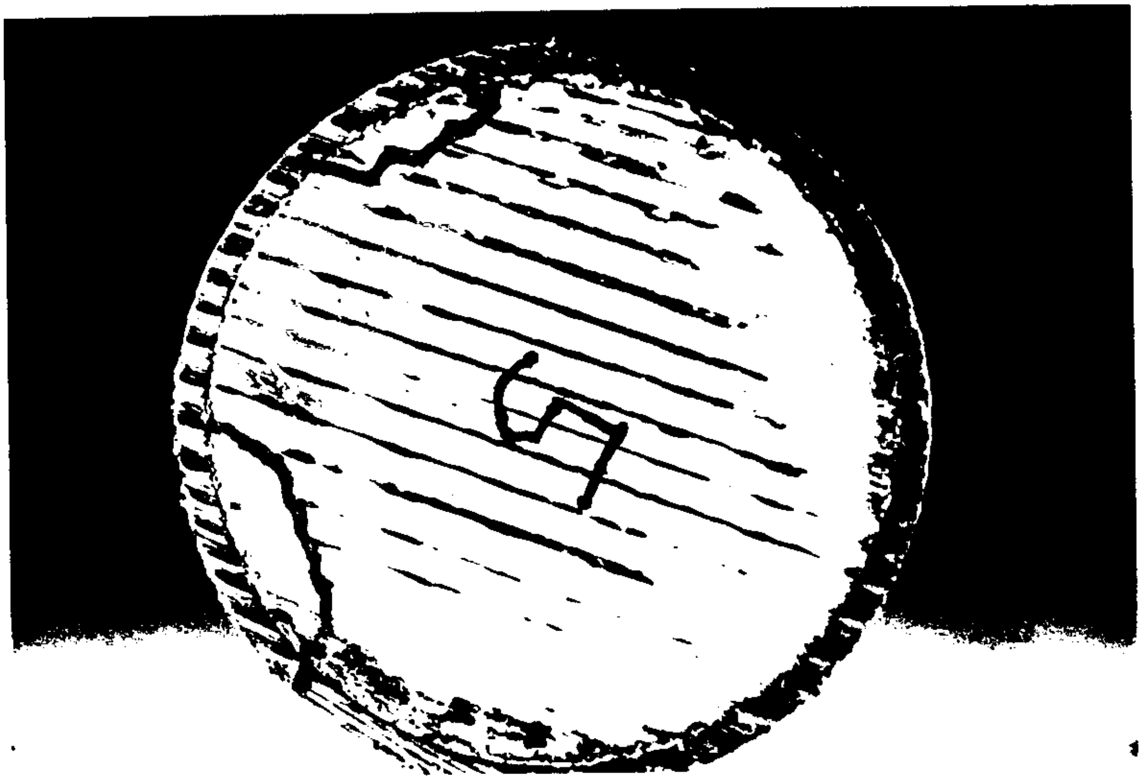


Figure 2e: PHPA 4 / 4 BFS - Cut E

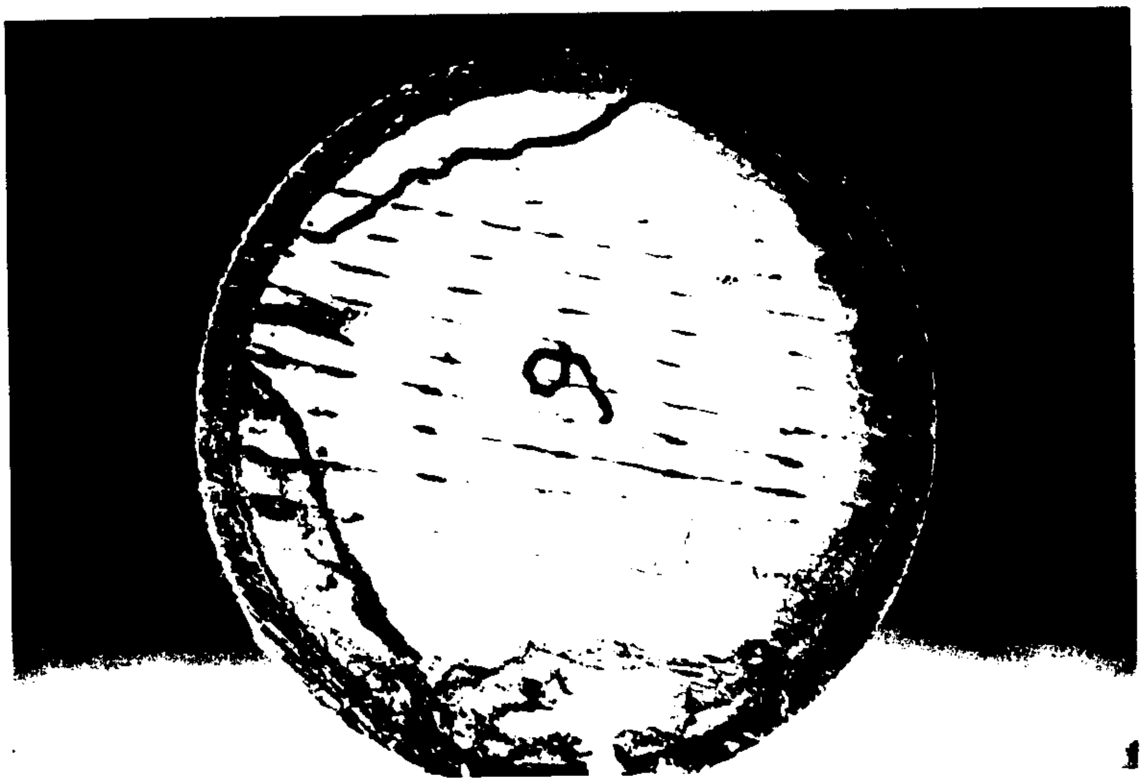


Figure 2f: PHPA 4 / 4 BFS - Cut F

Figure 2g: PHPA 4 / 4 BFS - Cut G

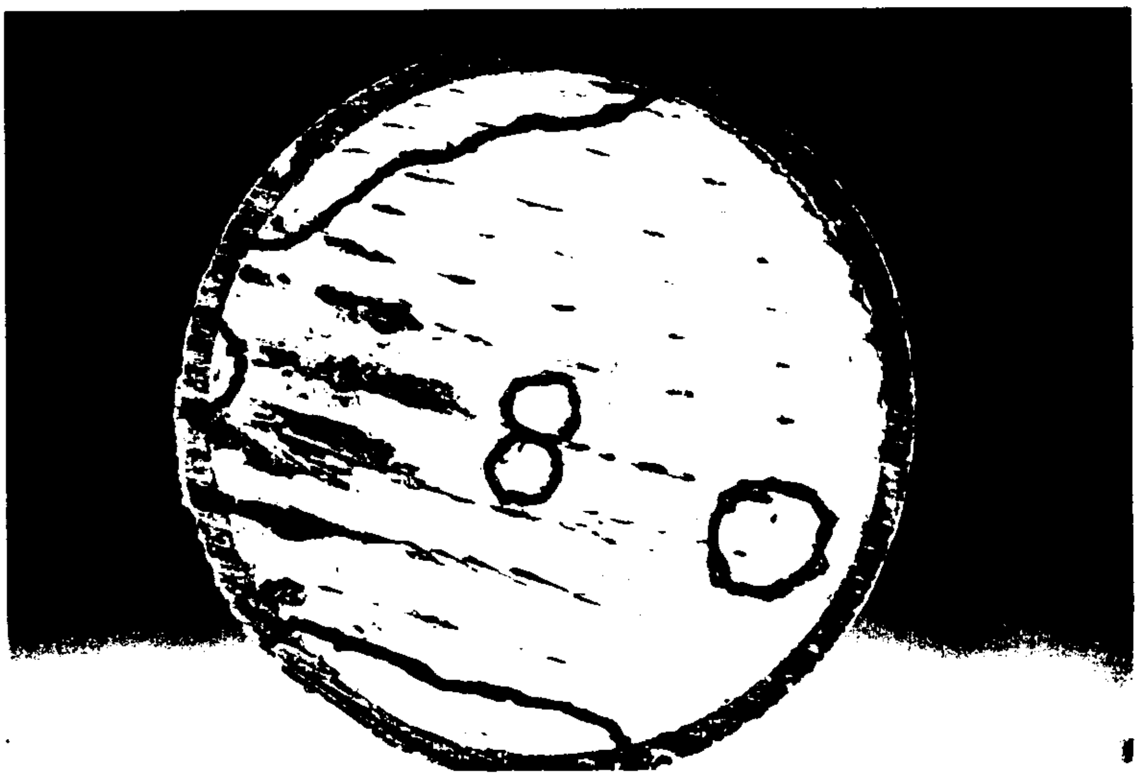


Figure 2h: PHPA 4 / 4 BFS - Cut H

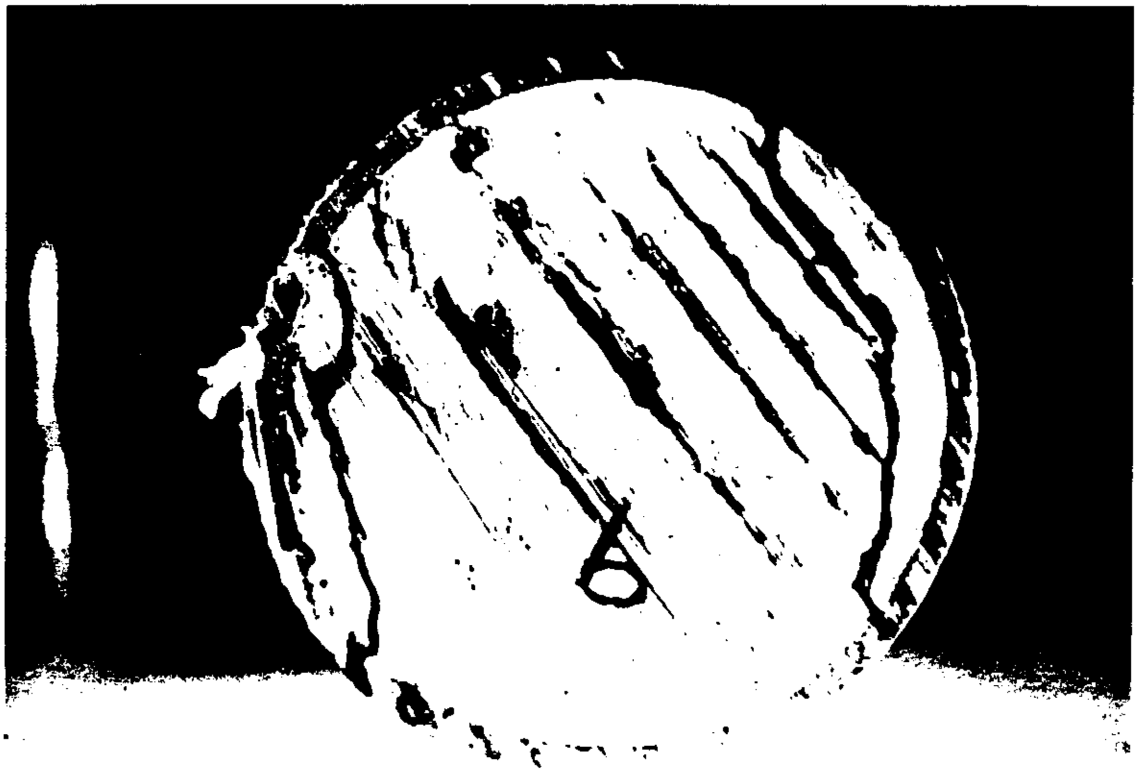


Figure 2i: PHPA 4 / 4 BFS - Cut I

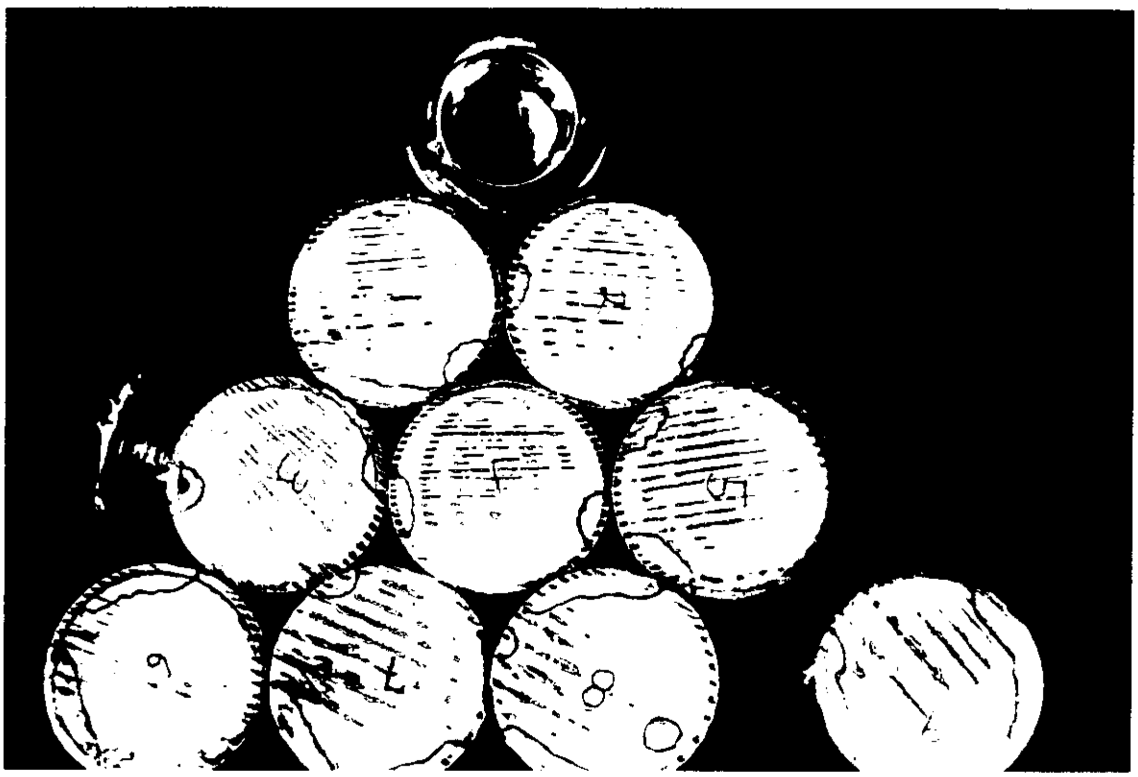


Figure 13j: PHPA 4 / 4 BFS - Cuts A through I

Figure 3a: PHPA 4 / 8 BFS - Cut A

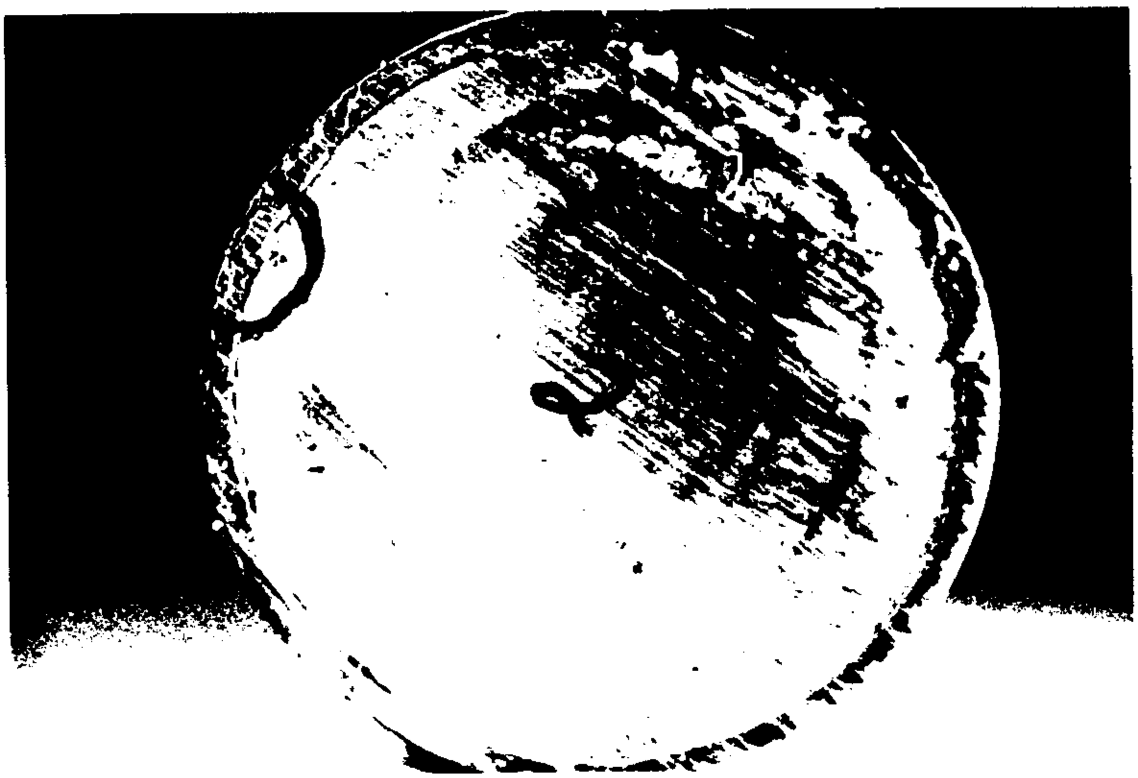


Figure 3b: PHPA 4 / 8 BFS - Cut B

Figure 3c: PHPA 4 / 8 BFS - Cut C

Figure 3d: PHPA 4 / 8 BFS - Cut D

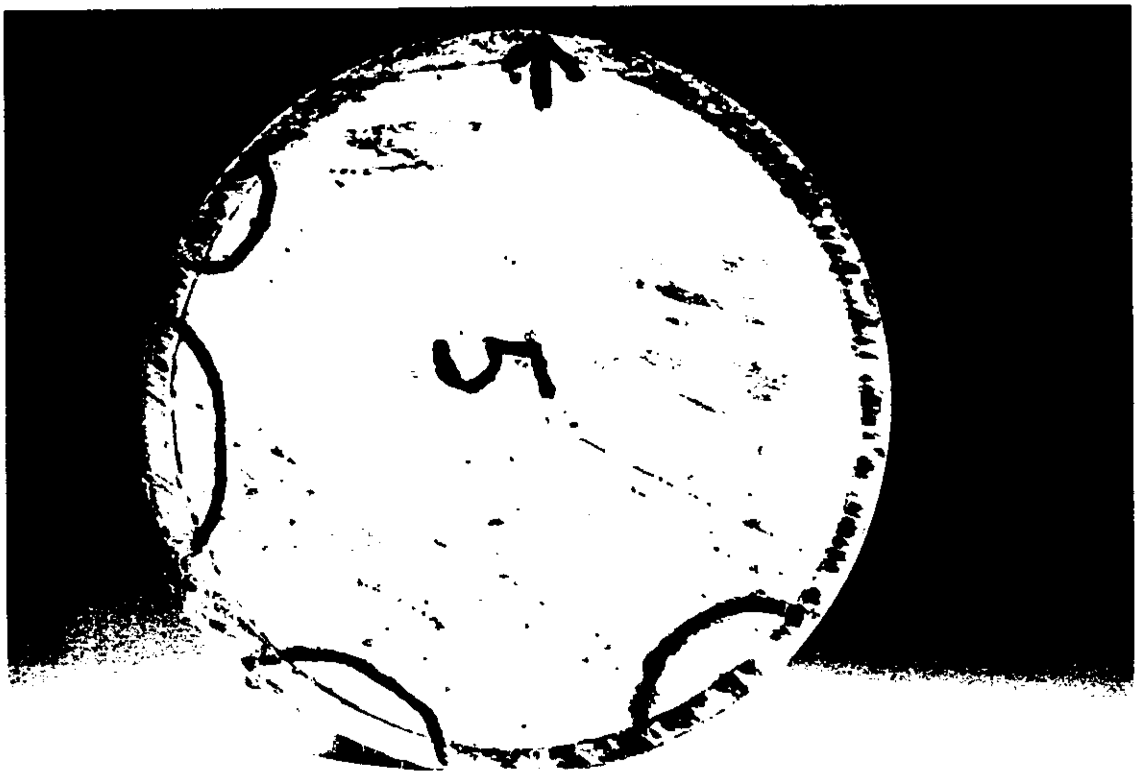


Figure 3e: PHPA 4 / 8 BFS - Cut E

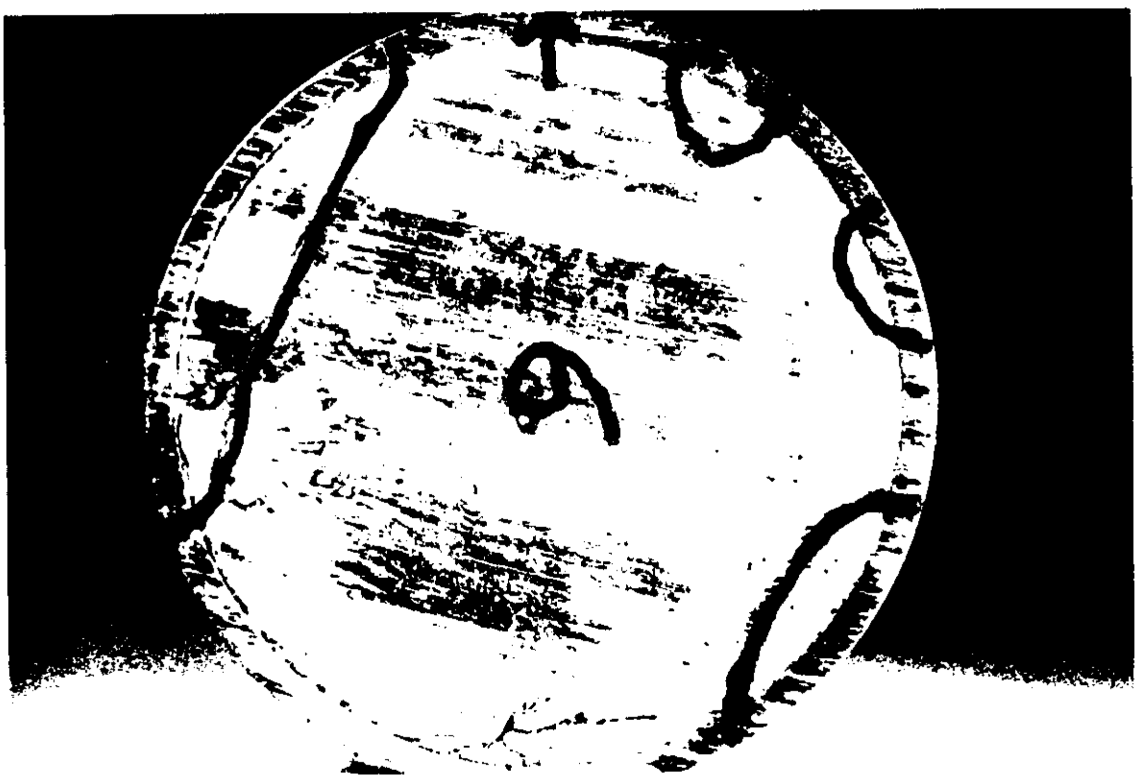


Figure 3f: PHPA 4 / 8 BFS - Cut F

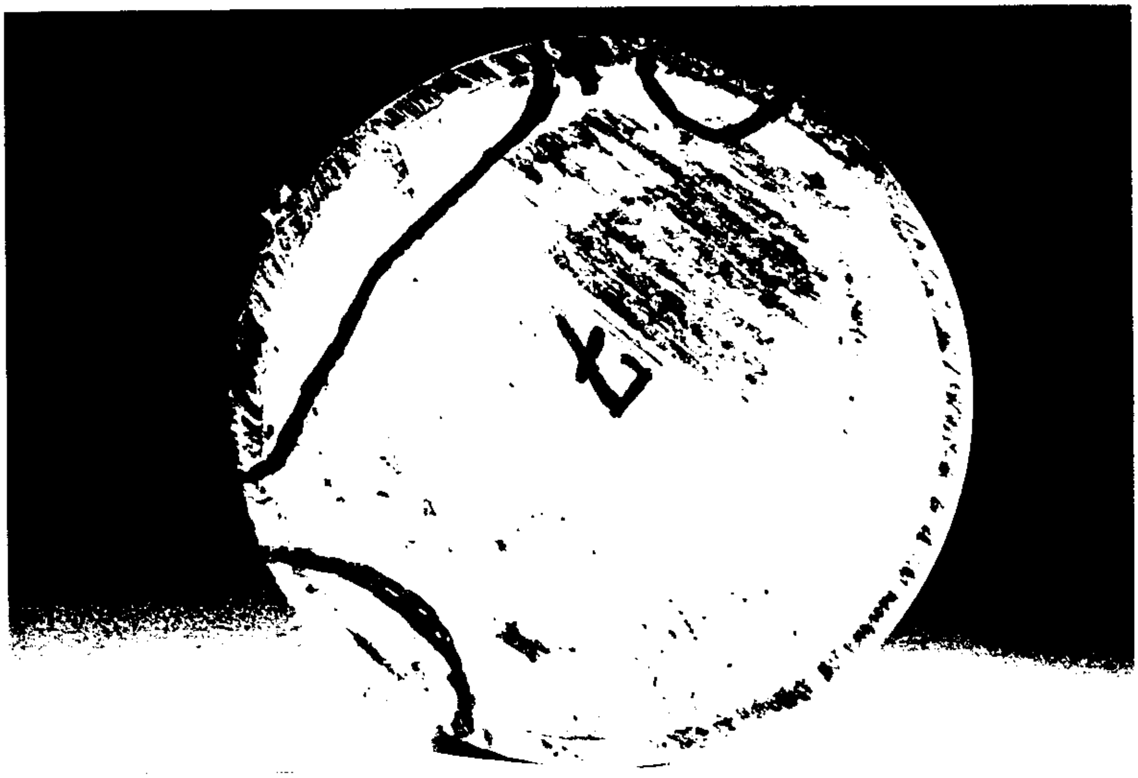


Figure 3g: PHPA 4 / 8 BFS - Cut G

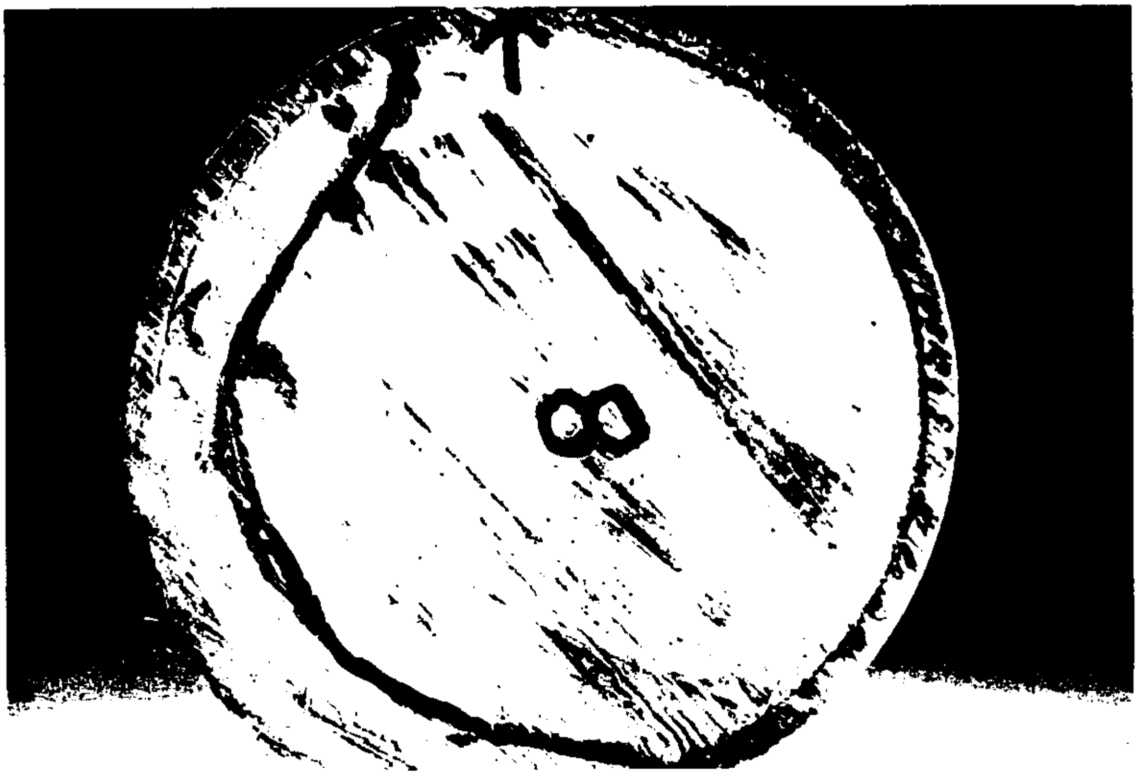


Figure 3h: PHPA 4 / 8 BFS - Cut H

Figure 3i: PHPA 4 / 8 BFS - Cut I

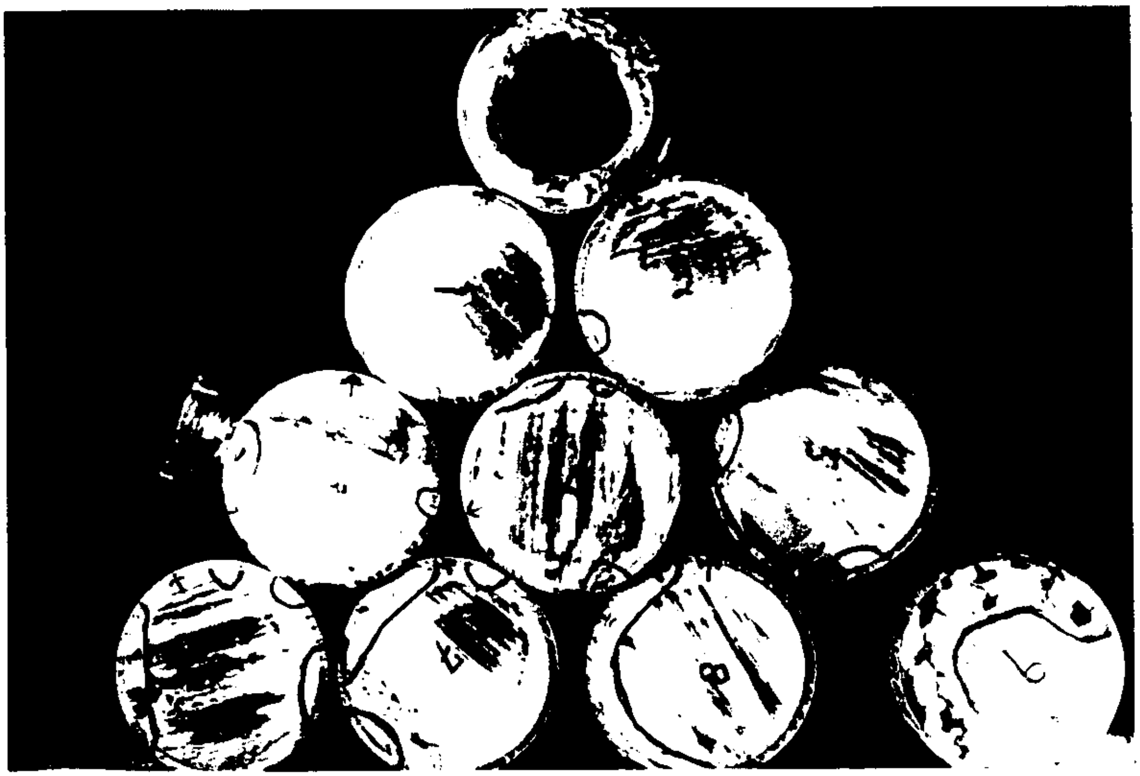


Figure 13j: PHPA 4 / 8 BFS - Cuts A through I

Figure 4a: PHPA 4 / 12 BFS - Cut A

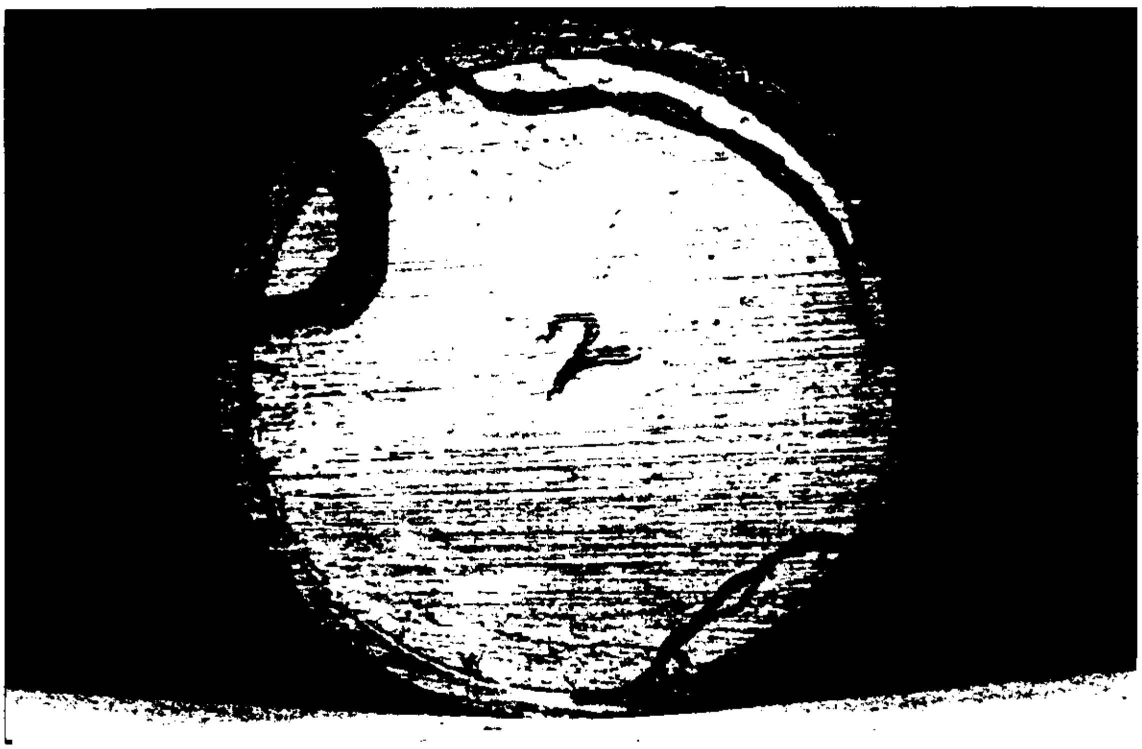


Figure 4b: PHPA 4 / 12 BFS - Cut B

Figure 4c: PHPA 4 / 12 BFS - Cut C

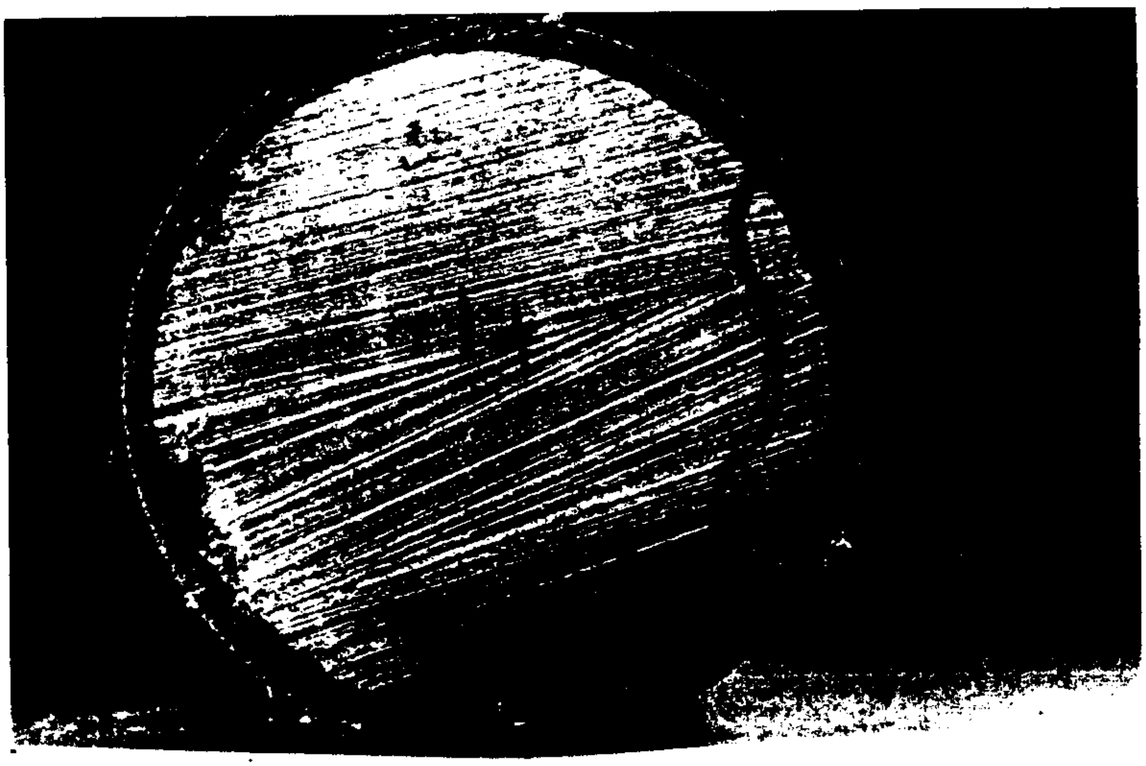


Figure 4d: PHPA 4 / 12 BFS - Cut D

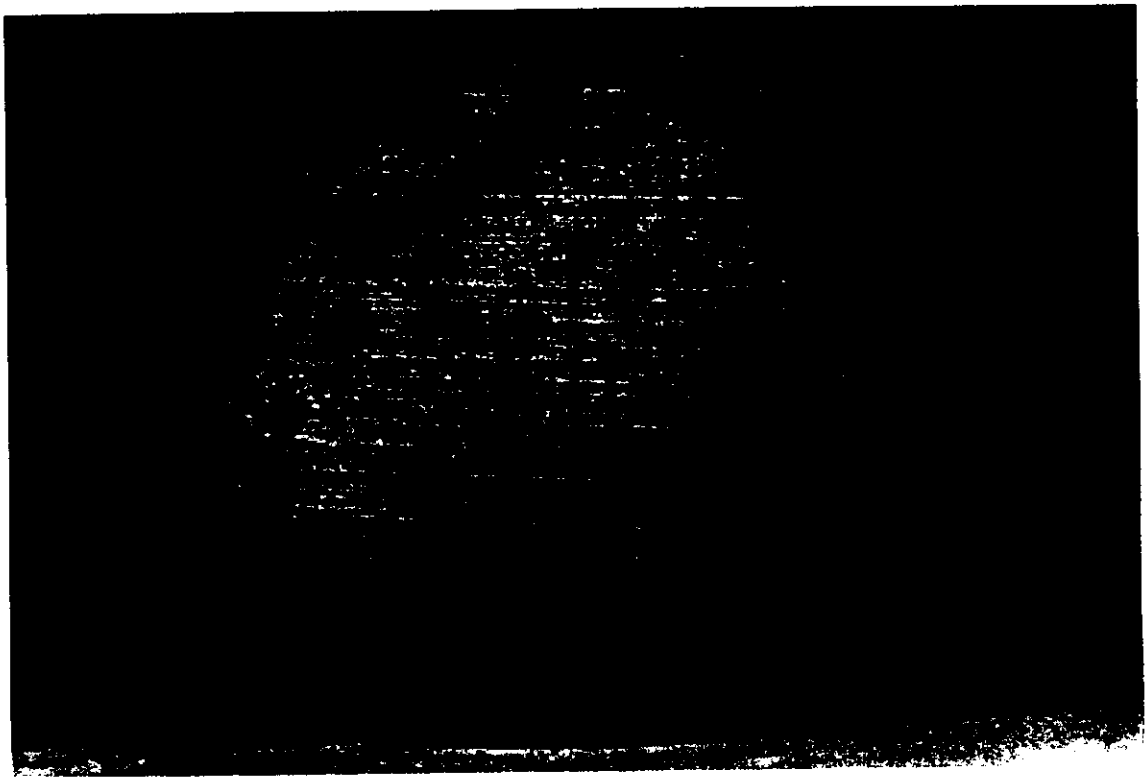


Figure 4e: PHPA 4 / 12 BFS - Cut E

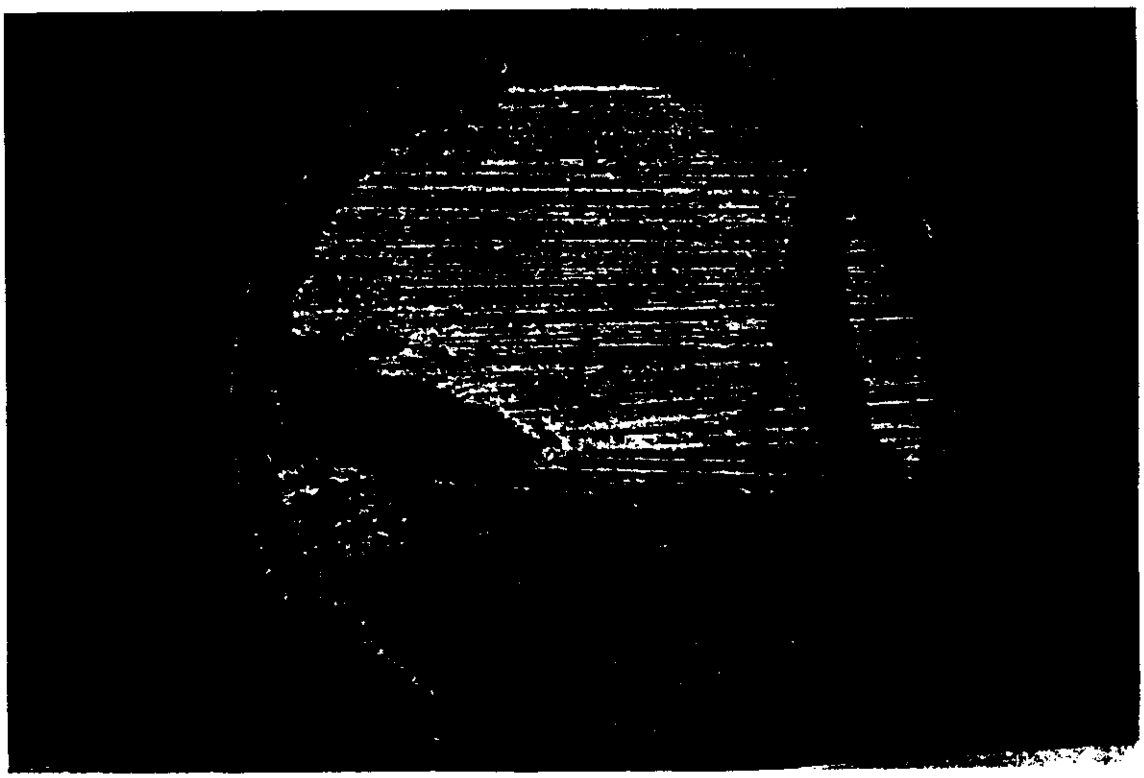


Figure 4f: PHPA 4 / 12 BFS - Cut F

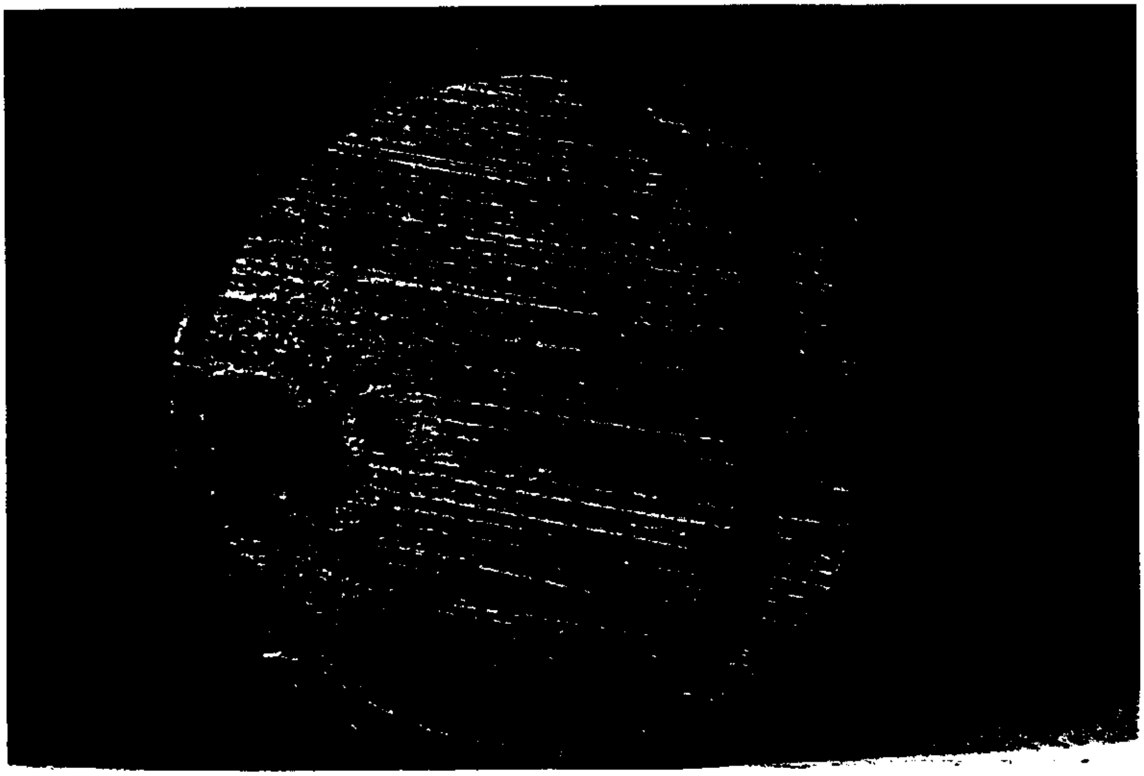


Figure 4g: PHPA 4 / 12 BFS - Cut G

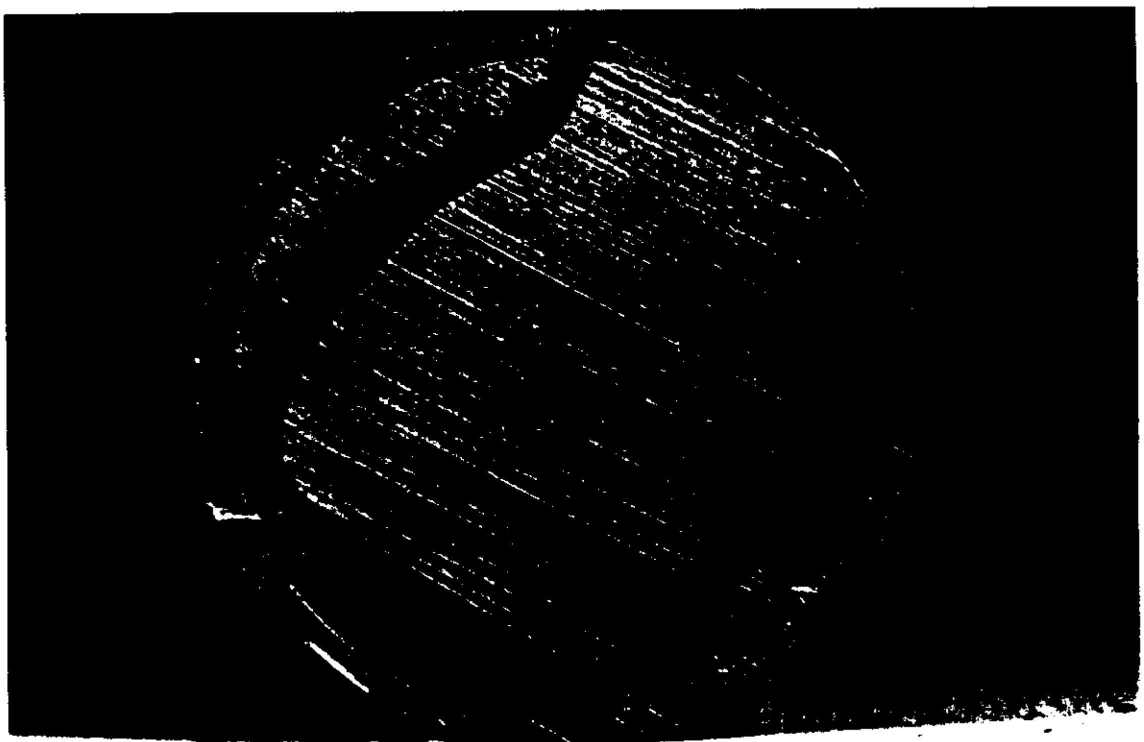


Figure 4h: PHPA 4 / 12 BFS - Cut H

Figure 4i: PHPA 4 / 12 BFS - Cut I

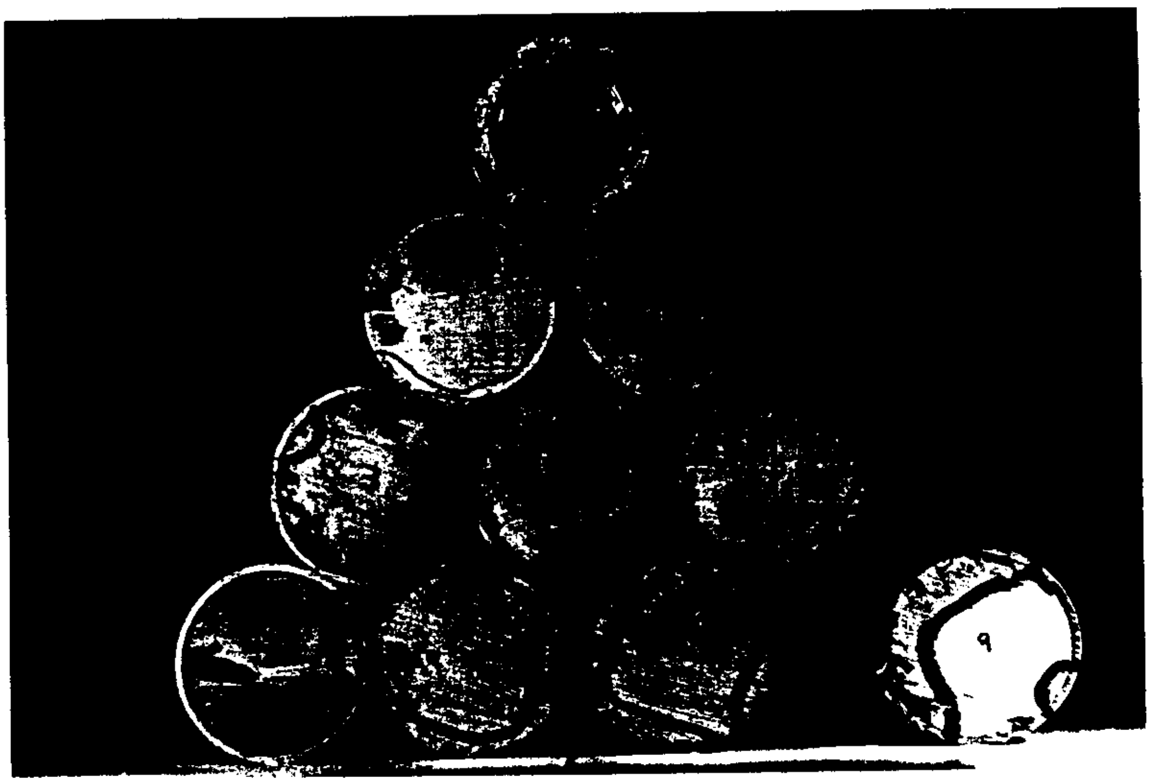


Figure 13j: PHPA 4 / 12 BFS - Cuts A through I

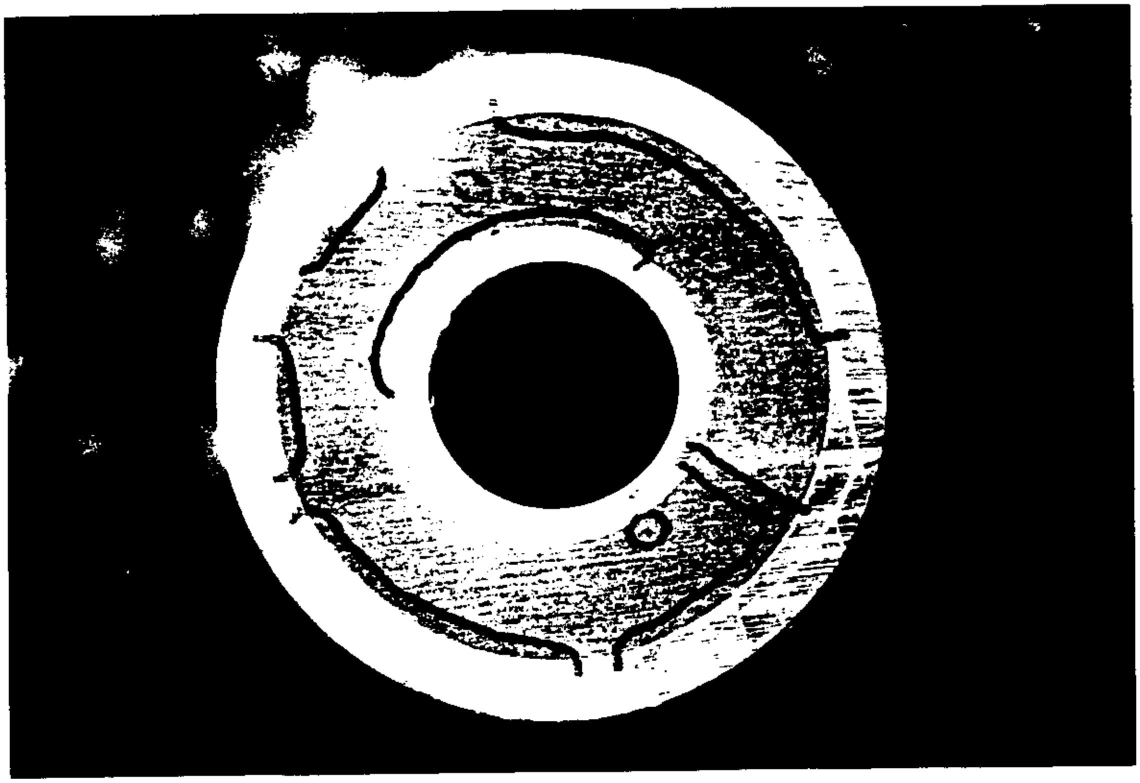


Figure 5: Portland Cement Annular Seal

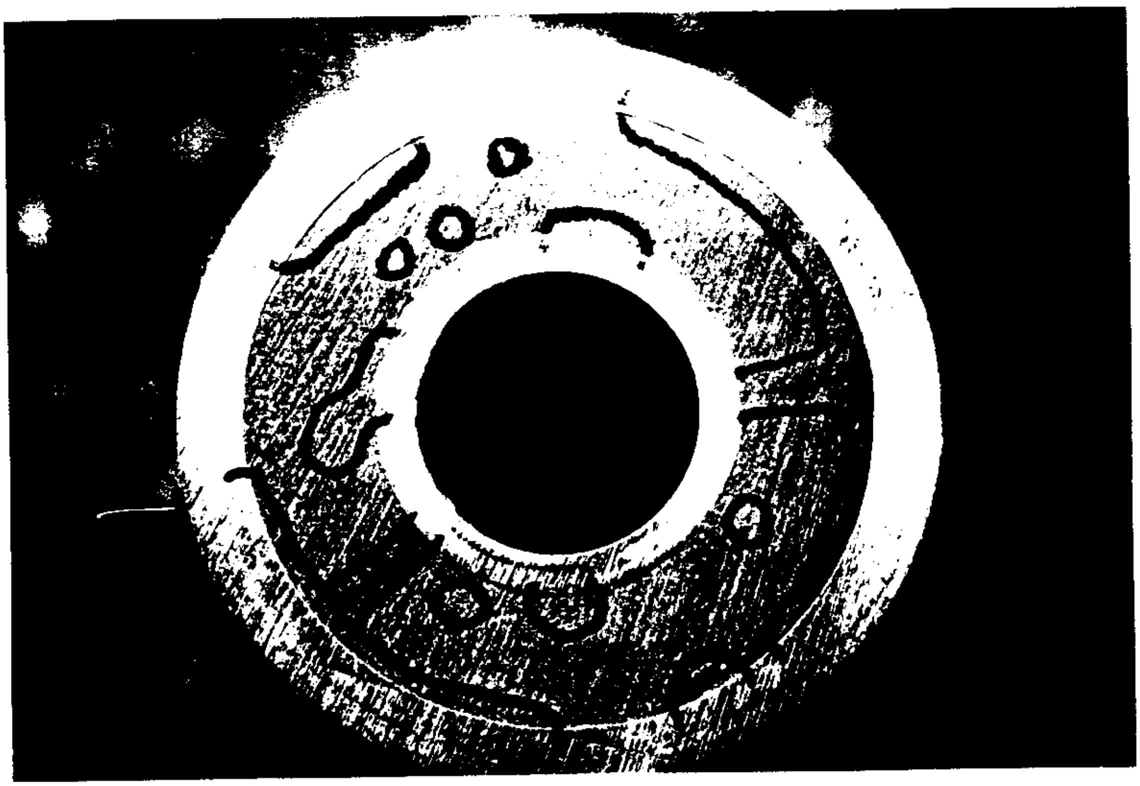


Figure 6: PHPA 4 / 0 BFS Annular Seal

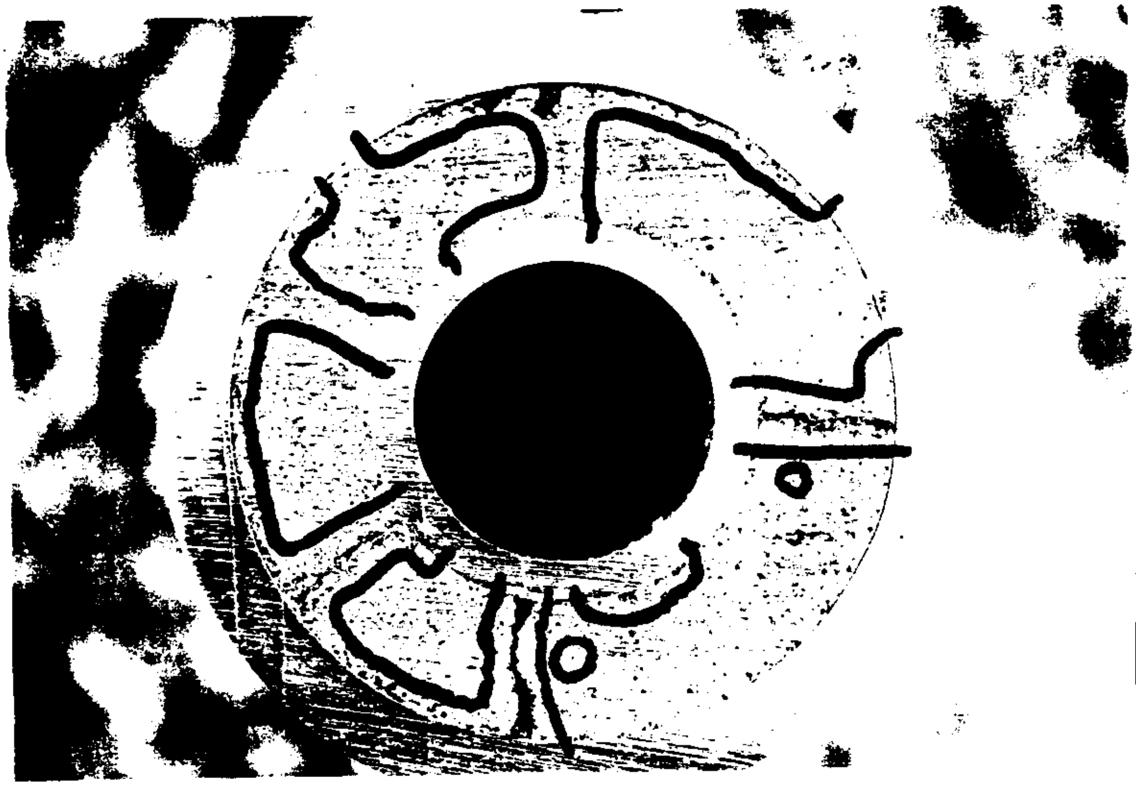


Figure 7: PHPA 4 / 12 BFS Annular Seal