LIGO-C962452-00-V

PROCESS SYSTEMS INTERNATIONAL, INC.
20 Walkup Drive, Westborough, MA 01581

November 7, 1996
V049-PL-314

Fax No.: (818) 304-9834

Mr. Allen Sibley c/0 Ms. Linda Turner
CALIFORNIA INSTITUTE OF TECHNOLOGY
LIGO Project
102-33 East Bridge Laboratory
Pasadena, CA 91125

Subject: **Prototype BSC Data Review Package - CDRL No. 11**

Dear Alan:

Attached please find the prototype BSC data review package - CDRL No. 10 (2 copies and 1 camera ready copy).

This package is submitted for LIGO approval.

Please call if you have any questions (508/898-0211).

Sincerely,

for Lynne Long
Richard Bagley
LIGO Project Manager

REB/lml

cc: J. Worden - WA Site (1 book)
M. Zucker - MIT (1 book)
LIGO File PL-314

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LIGO - C962452 - 00 - V

PROTOTYPE VESSEL DATA REVIEW PACKAGE

CONTRACT NO: **PC 175730**
PSI DOCUMENT NO: **V049-1-119**
PROGRAM I.D. **LIGO VACUUM EQUIPMENT**
ISSUE DATE: **OCTOBER 30, 1996**
CDRL NO: **11**
APPROVAL STATUS: **A**

SUBMITTED TO:

California Institute Of Technology
391 South Holliston Avenue
Pasadena, CA 91125

SUBMITTED BY:

Process Systems International, Inc.
20 Walkup Drive
Westborough, MA 01581

cc: Allen Sibley

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96:PVDR.LIGO/Oct

PSI

PROCESS SYSTEMS INTERNATIONAL, INC.

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Process Systems International, Inc.
20 Walkup Drive
Westborough, MA 01581

Technical Director: D.O. McWilliams
David McWilliams

Project Manager: Richard Bagley
Richard Bagley, P.E.

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95:RB:001

PROCESS SYSTEMS INTERNATIONAL, INC.

CDRL No. 11
PROTOTYPE VESSEL DATA REVIEW PACKAGE

TABLE OF CONTENTS

I. BSC PROTOTYPE MECHANICAL FABRICATION

1.0 INTRODUCTION AND SUMMARY

Introduction

As part of the proposal for the LIGO Vacuum Equipment, PSI included a prototype BSC vessel program to validate fabrication and testing techniques.

The BSC prototype was built in conjunction with Ranor, Inc. which provided the heat treating and machining to complete the vessel. During the fabrication, fixtures were designed and optimized to control distortion and interface dimensions.

The BSC was then returned to PSI, inspected, cleaned, baked out and tested.

Next a first article LN_2 80K pump reservoir was fabricated and installed inside the prototype BSC (used for the vacuum vessel). The 80K pump was instrumented with vibration sensors and run with LN_2 and a heat load. The resulting vibration spectrum was recorded and analyzed.

The results of the inspections and testing are contained in this report.

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Summary

The prototype BSC was mechanically completed in July 1996 and tested during Aug/Sept/Oct 1996.

The prototype fabrication phase was completed with minor rework to refine fabrication techniques. The prototype fabrication provided valuable insight into building the complex LIGO vessels. This knowledge has been incorporated into the production design of all the LIGO vessels.

After fabrication, the critical dimensions of the BSC vessel were measured. In general, the vessel fabrication was a success. Minor deviations to the design drawings were noted and methods were modified for the production units. (See Section I (2), and I (4) for additional details).

During vacuum testing of the prototype BSC, vacuum wall deflection was measured at a high stress point. The deflection measured was consistent with the BSC finite element stress model developed by PSI (see Section I (3) for additional details).

FIG. I-1

FIG. I-1

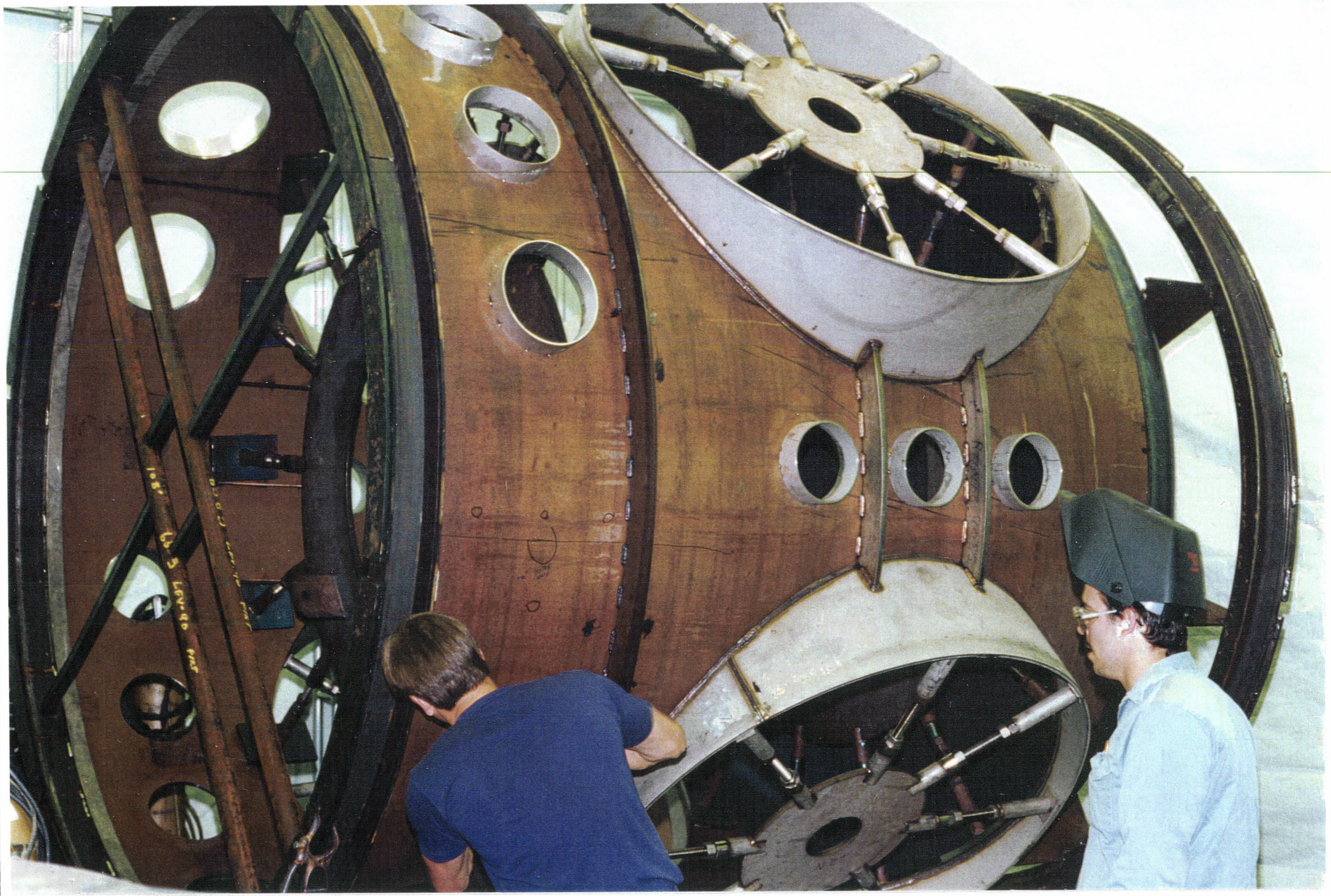

FIG. I-2

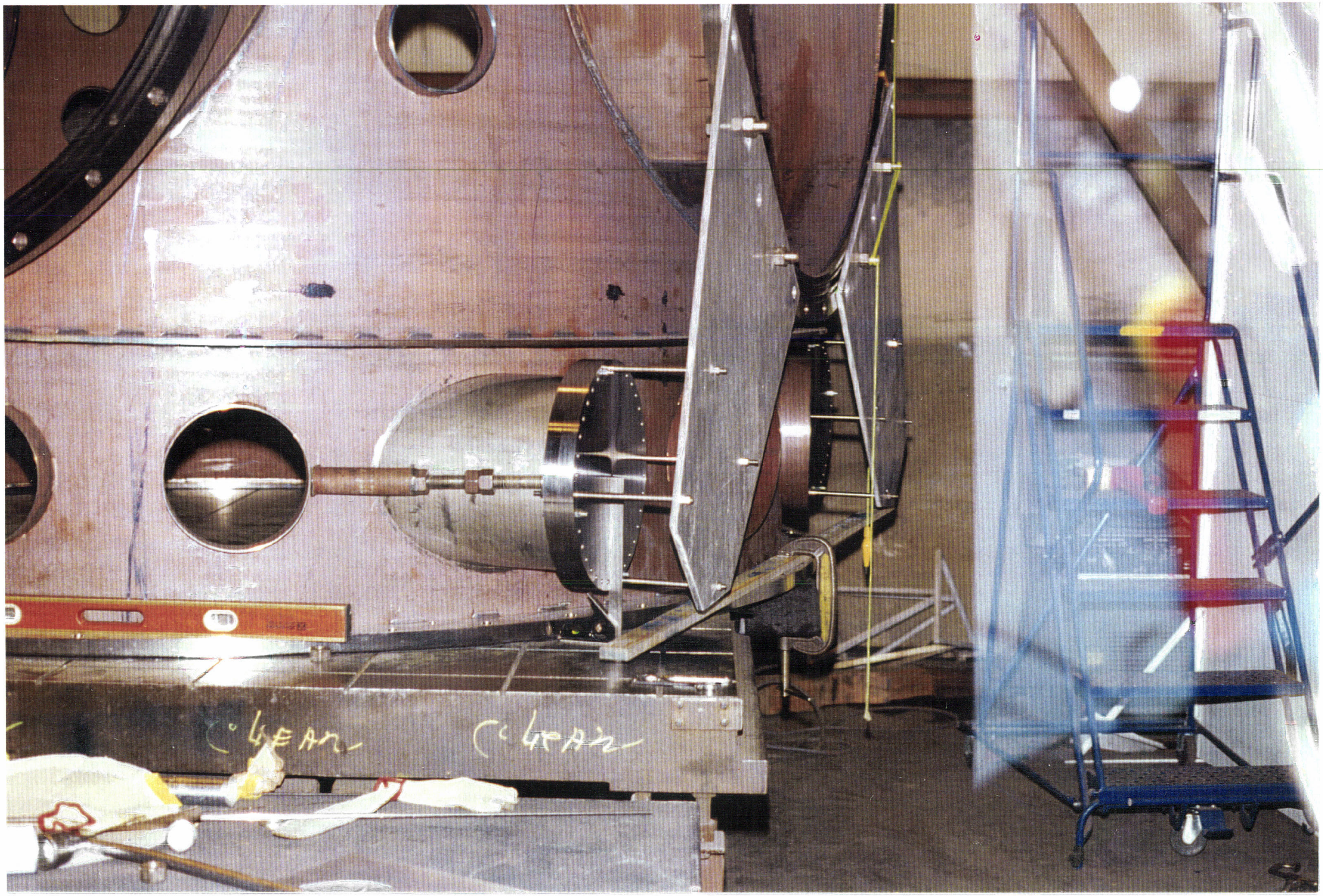

FIG. I-3

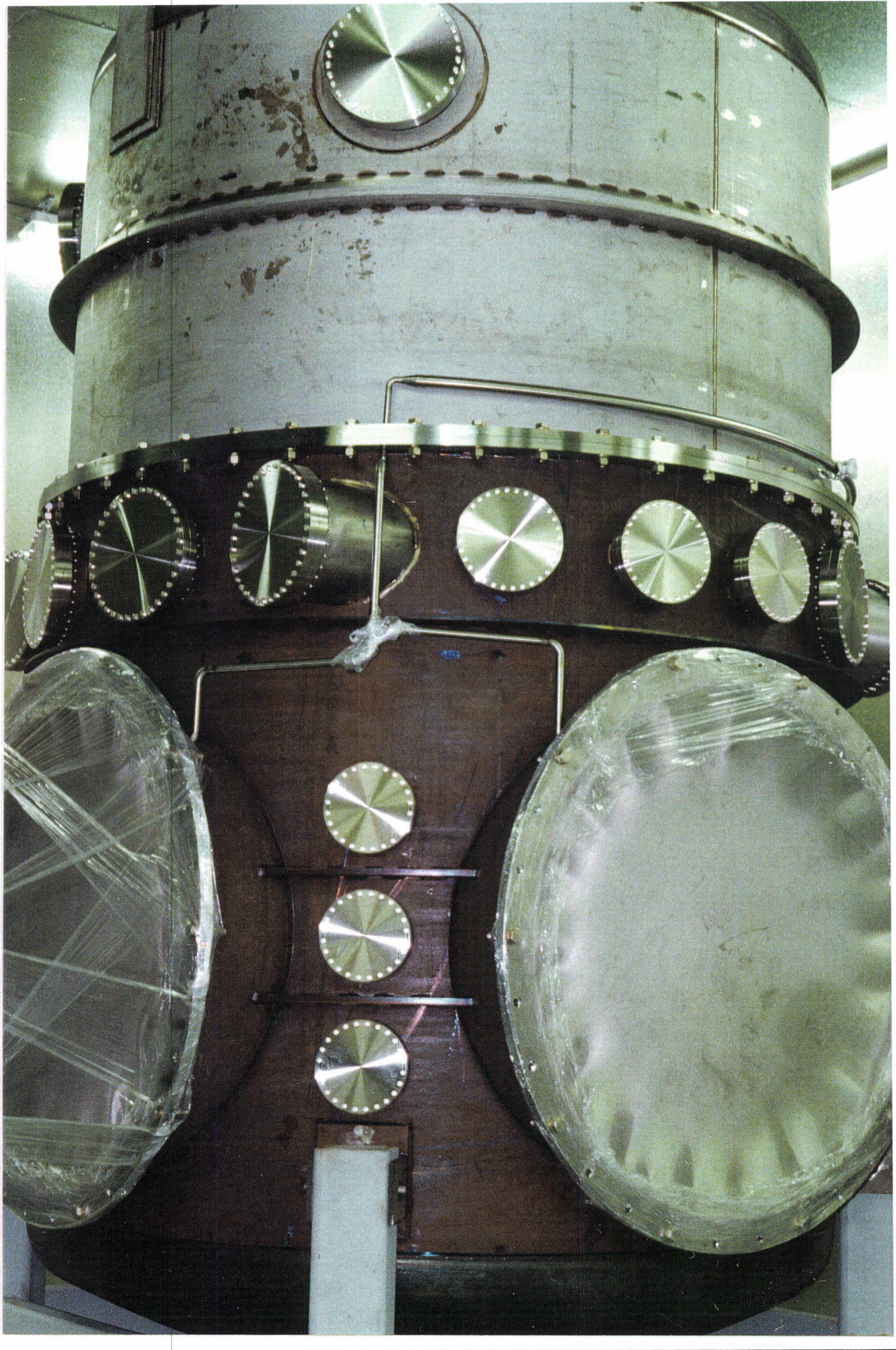

FIG. I-4

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SECTION I

FABRICATION RESULTS

Summary

The BSC prototype was inspected and measured at various stages of it's fabrication, after fabrication was complete (at Ranor) and after it was transported to PSI Westborough, MA.

This section contains the results of the various inspections. The target dimensions (from fabrication prints) are shown in boxes for reference.

PROTOTYPE WELDMENT INSPECTION DURING FABRICATION (AT RANOR)

Summary

The prototype weldment I.D. (target 104.5 in.) at various stages of fabrication was shown in the following chart.

The measurements were taken as follows:

Step	Condition
1.	60.5 In. Nozzles Tacked On (Not Welded)
2.	60.5 In. Nozzles With Only A Root Pass
3.	60.5 In. Nozzles First Plasma Pass
4.	60.5 In. Nozzles Second Plasma Pass
5.	Before Last Heat Treatment (1000^0F)
6.	Before Flange Fitup (Spider Relaxed)

BSC 104 INCH SHELL STUDY
(TARGET I.D. = 104.5 IN.)

Step	*60.5 In. Nozzle Weld Passes*	*A-C 0*	*A-C 90*	*A-C 180*	*A-C 270*	*B-D 270*	*B-D 90*	*B-D 180*	*B-D 270*
1.	**Tacked Only**	104 5/8	104 5/8	104 1/2	104 3/8	104 5/8	104 7/16	104 7/16	104 5/16
2.	**Root Pass**	104 9/16	104 7/16	104 7/16	104 9/16	104 5/8	104 7/16	104 9/16	104 7/16
3.	**First Plasma**	104 3/8	104 5/8	104 3/8	104 5/8	104 5/8	104 7/16	104 7/16	104 3/8
4.	**Second Plasma**	104 1/2	104 1/2	104 3/16	104 5/16	104 7/16	104 5/16	104 1/4	104 3/16
5.	**Before Last Heat Treat**	104 5/16	104 1/2	104 5/16	104 1/4	104 7/16	104 3/8	104 5/16	104 1/4
6.	**Before Flange Fit**	104 1/4	104 7/16	104 3/16	104 5/16	104 5/16	104 5/16	104 1/4	104 3/16
	(Note 1)								

Note 1 When spider was relaxed.

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PROTOTYPE BSC INSPECTION AT RANOR

Summary

The BSC bottom half was placed on the inspection table. The inspection table base was used as a reference to measure the relative locations of the BSC nozzle faces and centerline dimensions.

INSPECTION TABLE MEASUREMENTS (AT RANOR)

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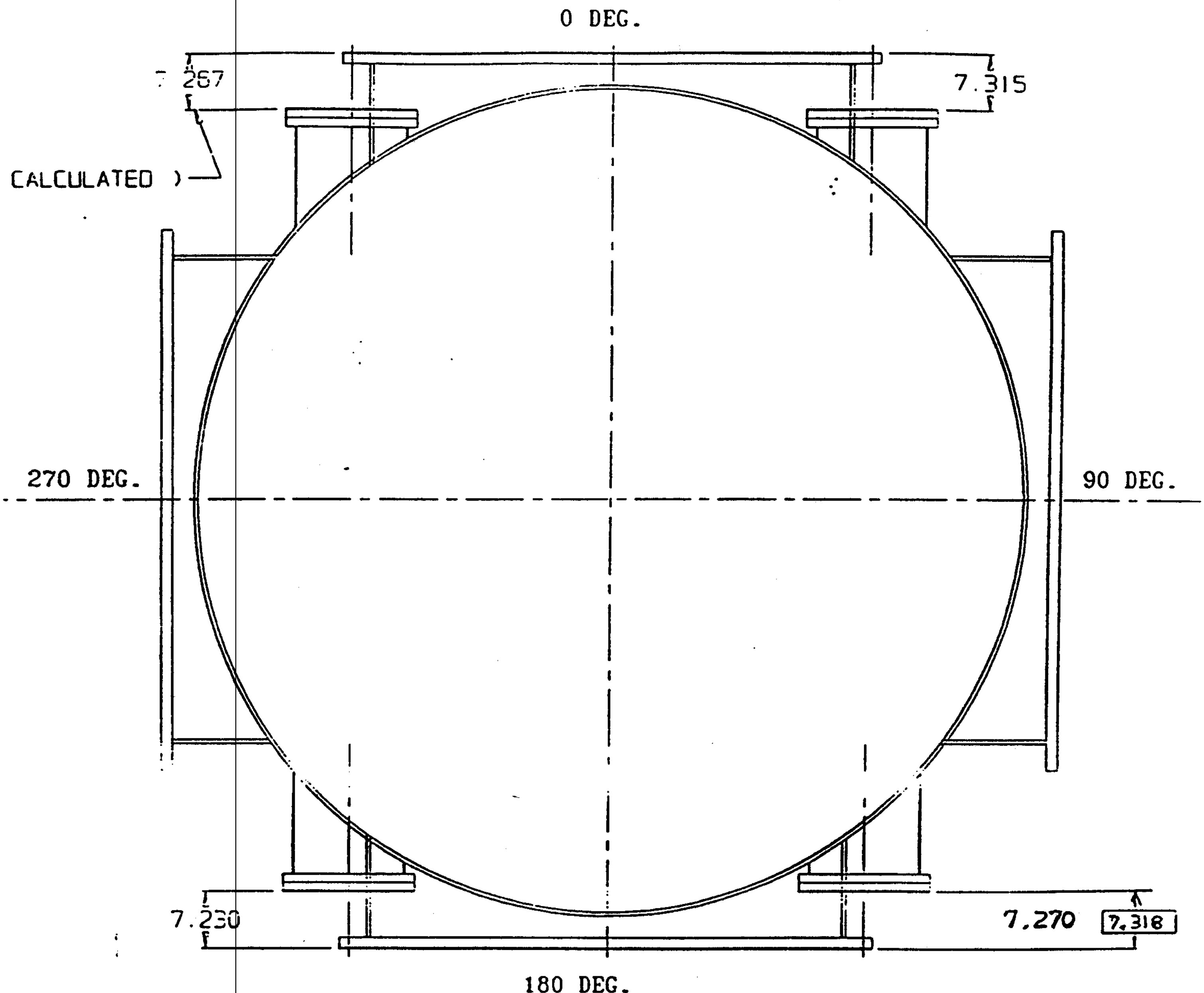


INSPECTION DATE ON THE LOWER SHELL
PERFORMED ON A 3 POINT SET-UP, USING A LAYOUT ARM.

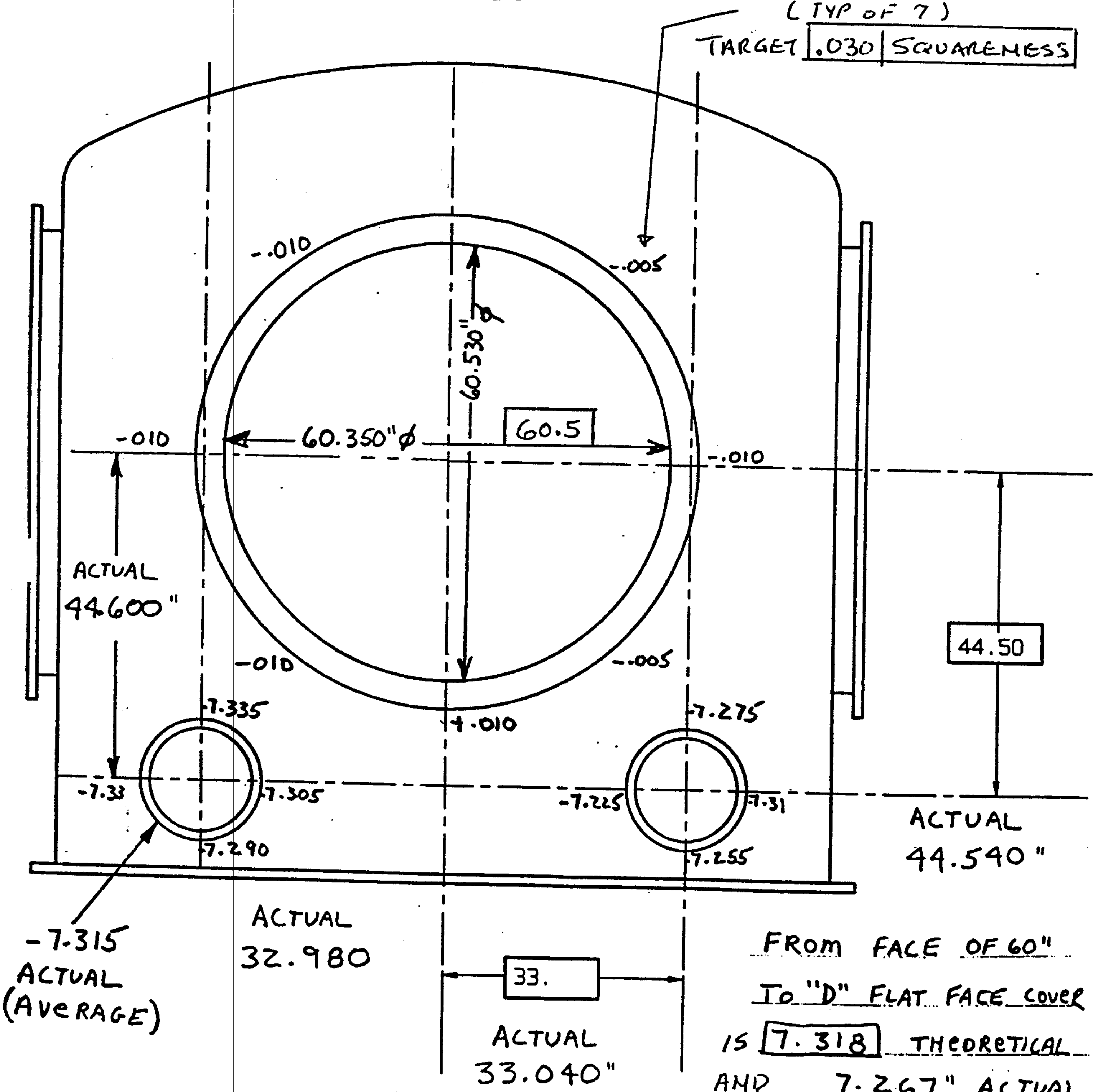
PART WAS LEVELED, & BALLANCED TO THE LAYOUT GRID WITHIN .010"

ALL RAW DATA (SHEETS 1 THRU 7) ARE RELATIVE NUMBERS
DATUMS ESTABLISHED FROM BEST BALLANCE OF THE 60 " NOZZLE FLANGES.

INSPECTION TABLE MEASUREMENTS (AT RANOR)

PROCESS SYSTEMS INTERNATIONAL, INC.

0 DEG

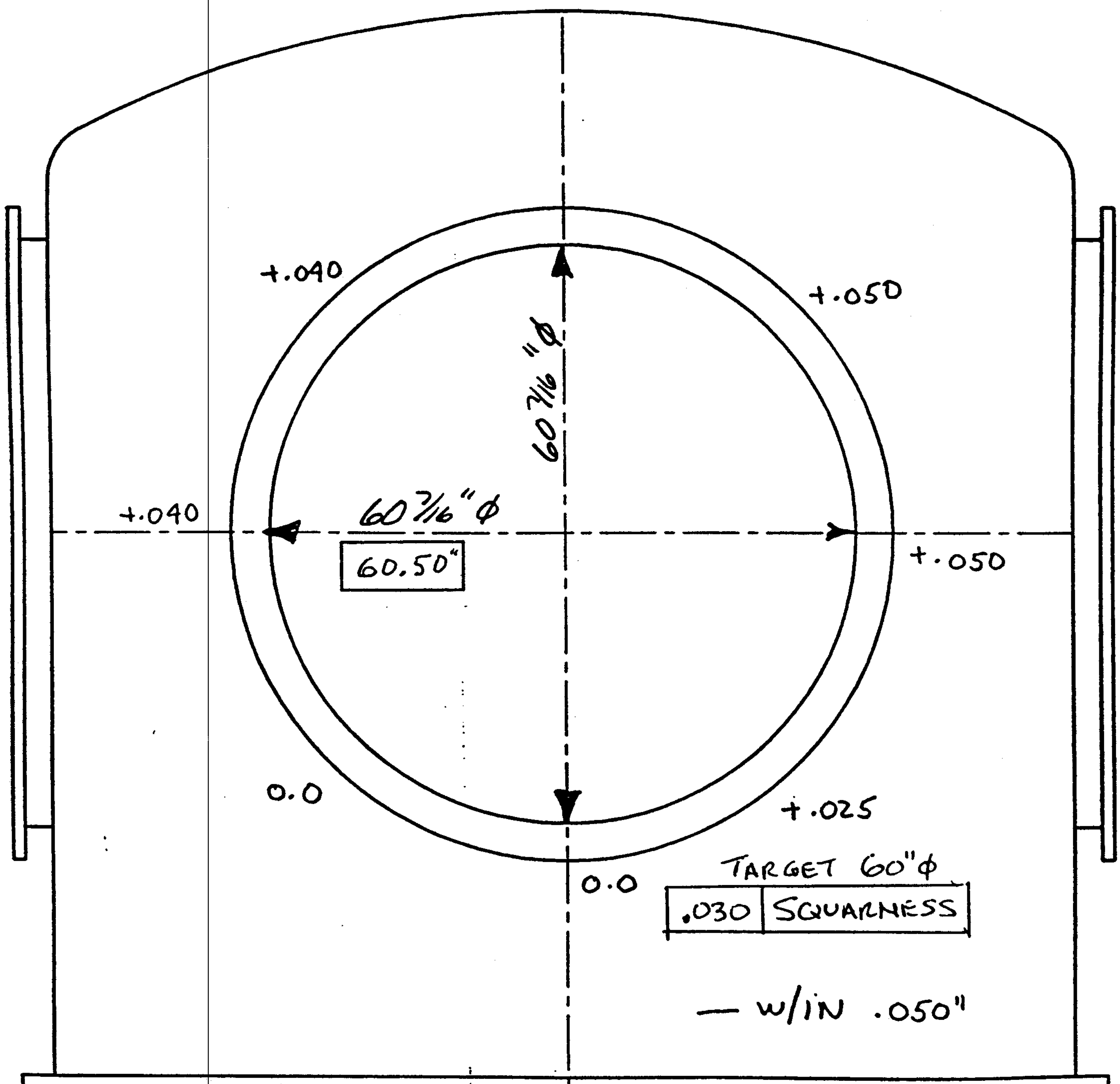


FROM FACE OF 60"
TO "D" FLAT FACE COVER
IS 7.318 THEORETICAL
AND 7.267" ACTUAL
"D" NOZ. TARGET .075 SQUARENESS

INSPECTION TABLE MEASUREMENTS (AT RANOR)

PROCESS SYSTEMS INTERNATIONAL, INC.

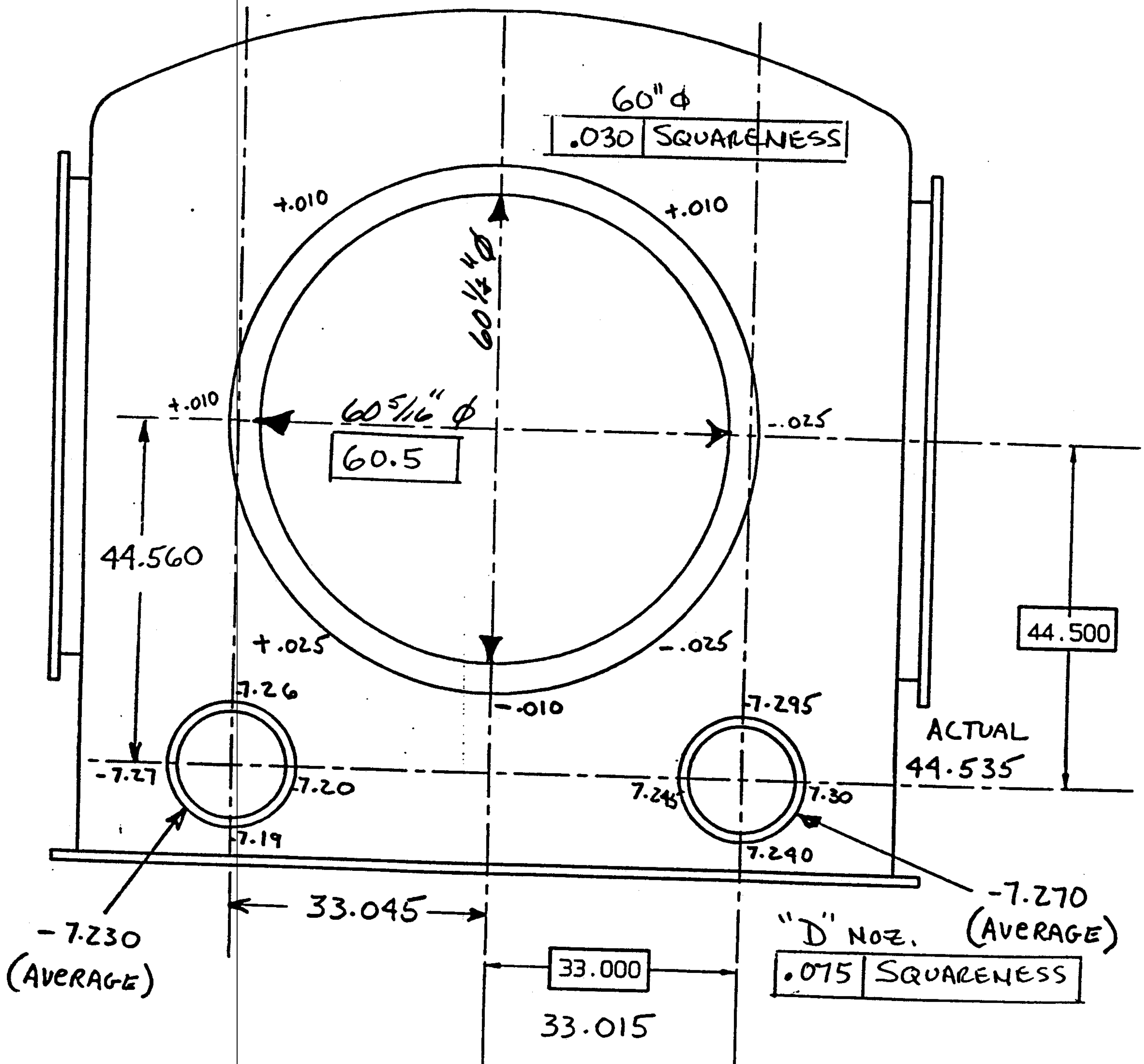
90 DEG.



INSPECTION TABLE MEASUREMENTS (AT RANOR)

PROCESS SYSTEMS INTERNATIONAL, INC.

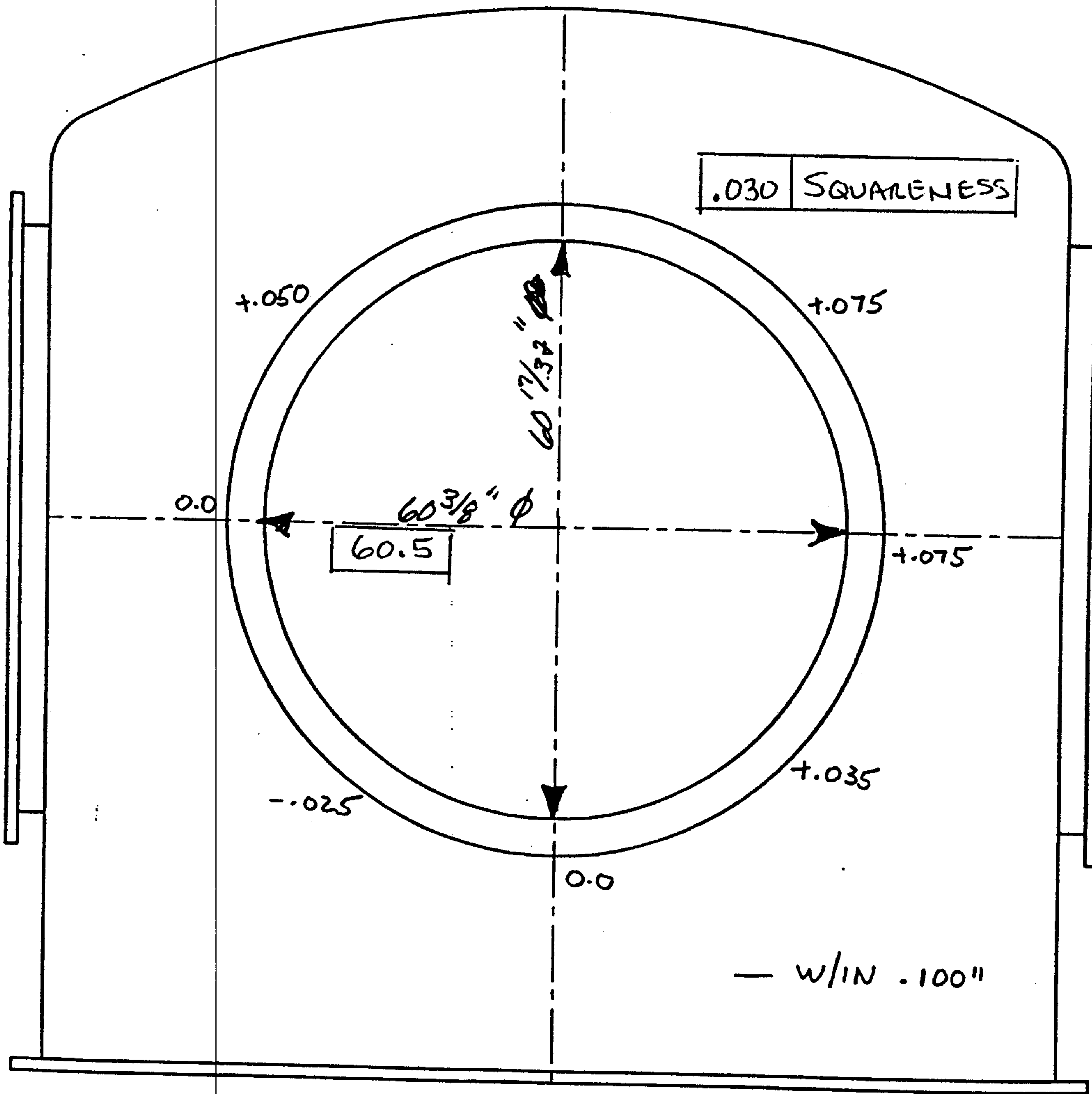
180 DEG.



INSPECTION TABLE MEASUREMENTS (AT RANOR)

PROCESS SYSTEMS INTERNATIONAL, INC.

270 DEG.



SECTION ONE

2.0 FABRICATION RESULTS

60.5 in. flange to flange measurements before and after transporting to PSI Westborough

C-C		Facing 90
	Before	After Transportation
0-0	113 11/16	113 11/16
270-90	113 11/16	113 11/16
180-180	113 3/4	113 3/4
90-270	113 3/4	113 3/4

B-B		Facing 180
	Before	After Transportation
0-0	113 7/8	113 13/16
270-90	113 3/4	113 3/4
180-180	113 13/16	113 13/16
90-270	113 13/16	113 13/16

60.5 in. Flange To Flange Measurements

(Target is 113.750 in.)

SECTION ONE

2.0 FABRICATION RESULTS

60.5 inch nozzle measurements at PSI

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PROTOTYPE BSC 60.5" ID NOZZLE MEASUREMENTS

TERMINOLOGY

References to vertical, horizontal, up, down, etc. are used with reference to the vessel in operating position.

Orientation of nozzles is clockwise from top (0, 90, 180, 270).

Orientation of face nozzles is clockwise from top as viewed looking toward the nozzle from outside.

APPROACH

60 inch nozzles were measured across in both the horizontal and vertical axes. Straight through and diagonal measurements were made between opposite 60 inch nozzles. (Attachment A)

Centerline measurements were made to determine vertical displacement of nozzle pairs.

External straight edges were used to establish dimensions of the four sides and diagonals of the quadrilateral in the horizontal plane formed by the nozzle faces.

Measurements for the D nozzles were taken from the corresponding 60 inch flange.
(Attachment A)

TECHNIQUE 60 INCH NOZZLES

Measurements for diameters were made using a 72 inch scale and a vernier.

Bars were bolted to the flanges with holes located at the nozzle centerpoints. Fish line was pulled between opposite nozzles. Feeler gauges indicated that the axis of the 90-270 nozzles was .032 above the axis of the 0-180 nozzles.

Straight through measurements were made using a single bar for all measurements and a vernier. Diagonal measurements were made using a fixture to establish a difference between diagonal dimensions.

Raw data for diameters, straight through measurements, and difference of diagonal lengths were recorded. (Attachment C)

Computational techniques were applied to the data (diameters-n1 n2, delta of diagonals-d1 d2, straight through measurements-11 12) to produce centerline length and angle of flange face to centerline (c1 length angle a angle b). (Attachment D). Results (Attachment E & F)

TECHNIQUE EXTERNAL STRAIGHT EDGES AND DIAGONALS

Straight edges off the nozzle were used to establish vertices from which, using a bar and vernier, differences of diagonal lengths could be measured in the horizontal plane of the nozzle centerlines. Also dimensions from straight edges to nozzle outside diameters were taken. Data from processed per Attachment D to produce dimensions and representation.
(Attachments G & H)

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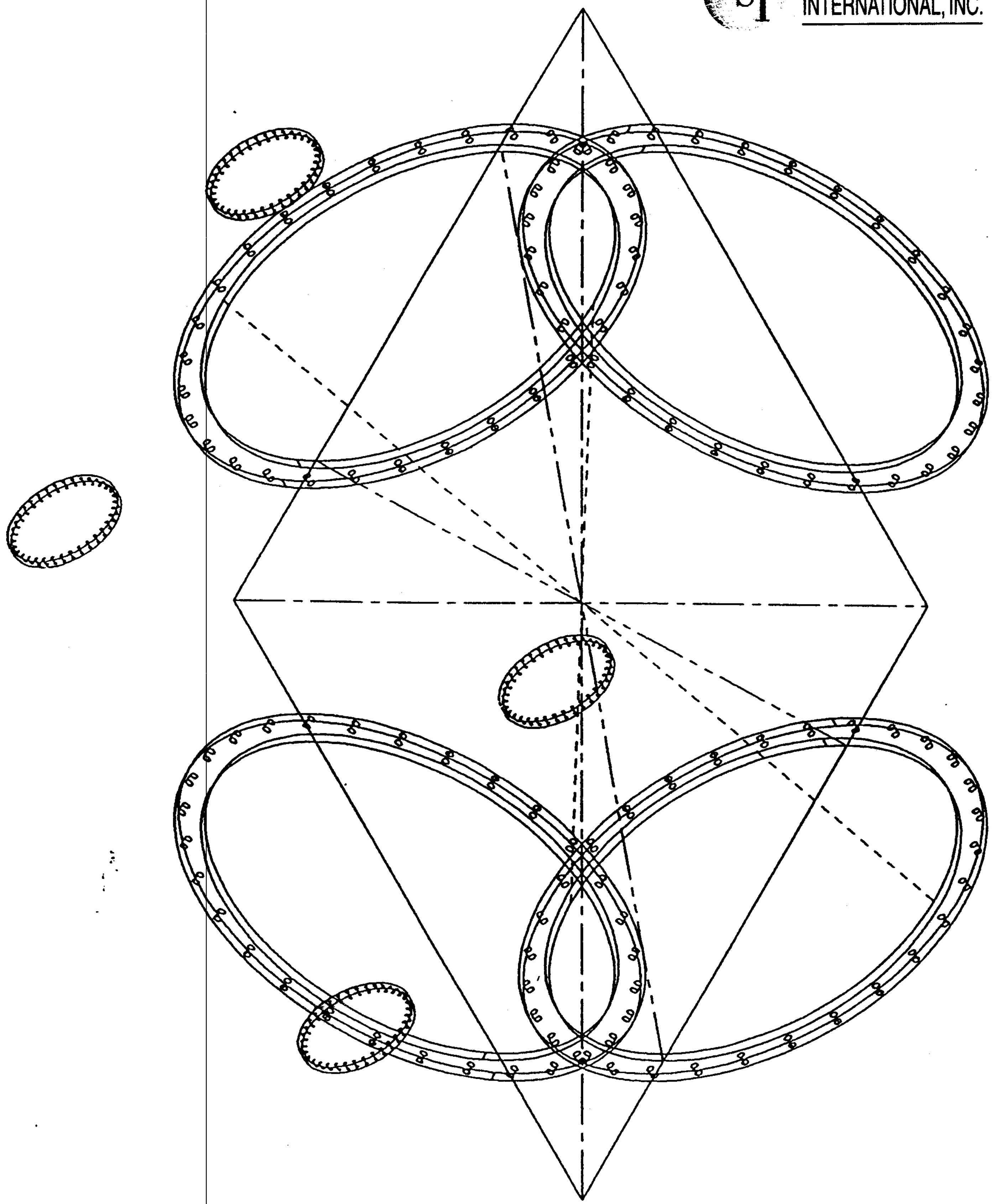

FIGURE A
BSC VESSEL

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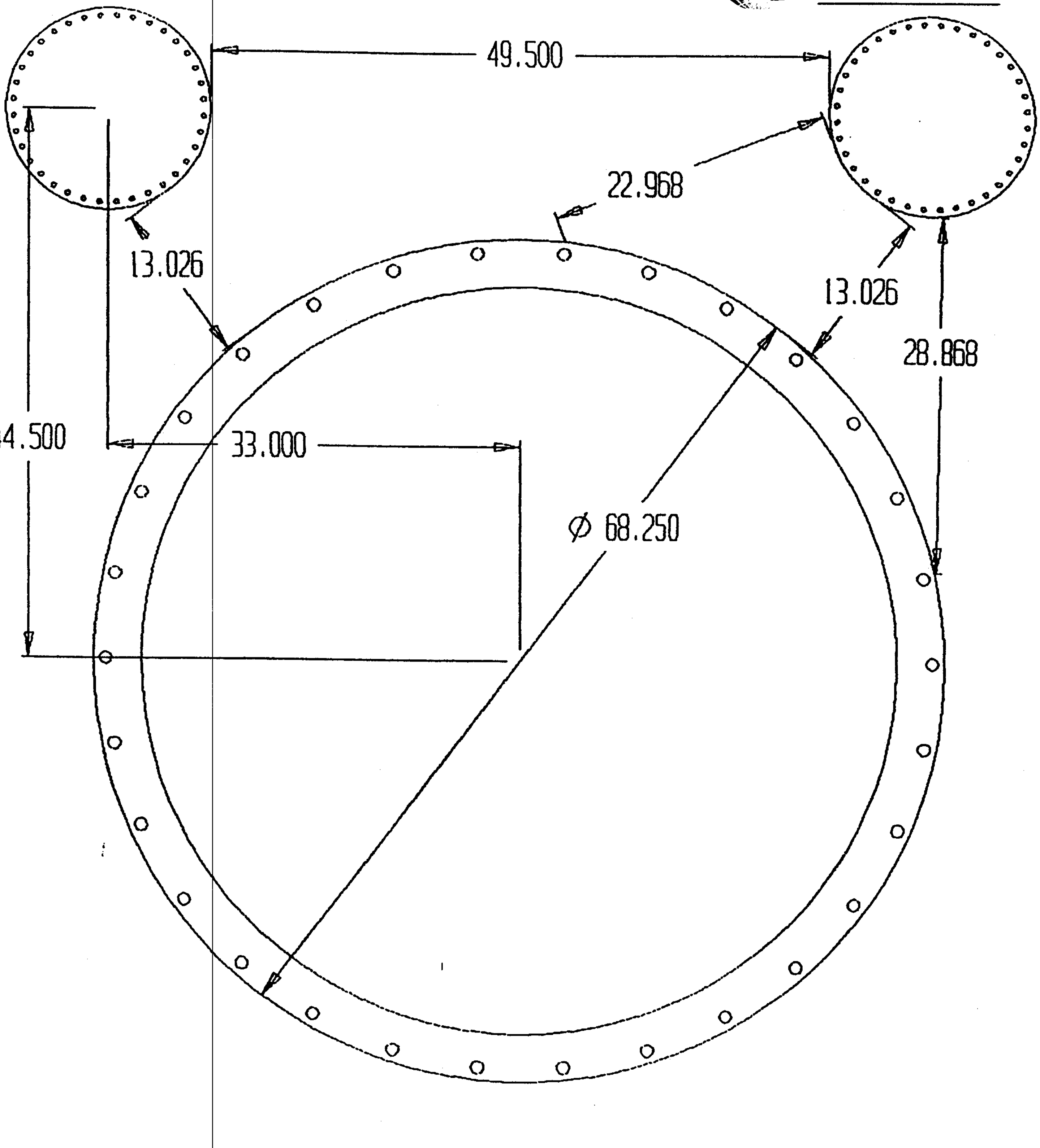

FIGURE B
60.5 INCH NOZZLE DIMENSIONAL REQUIREMENTS

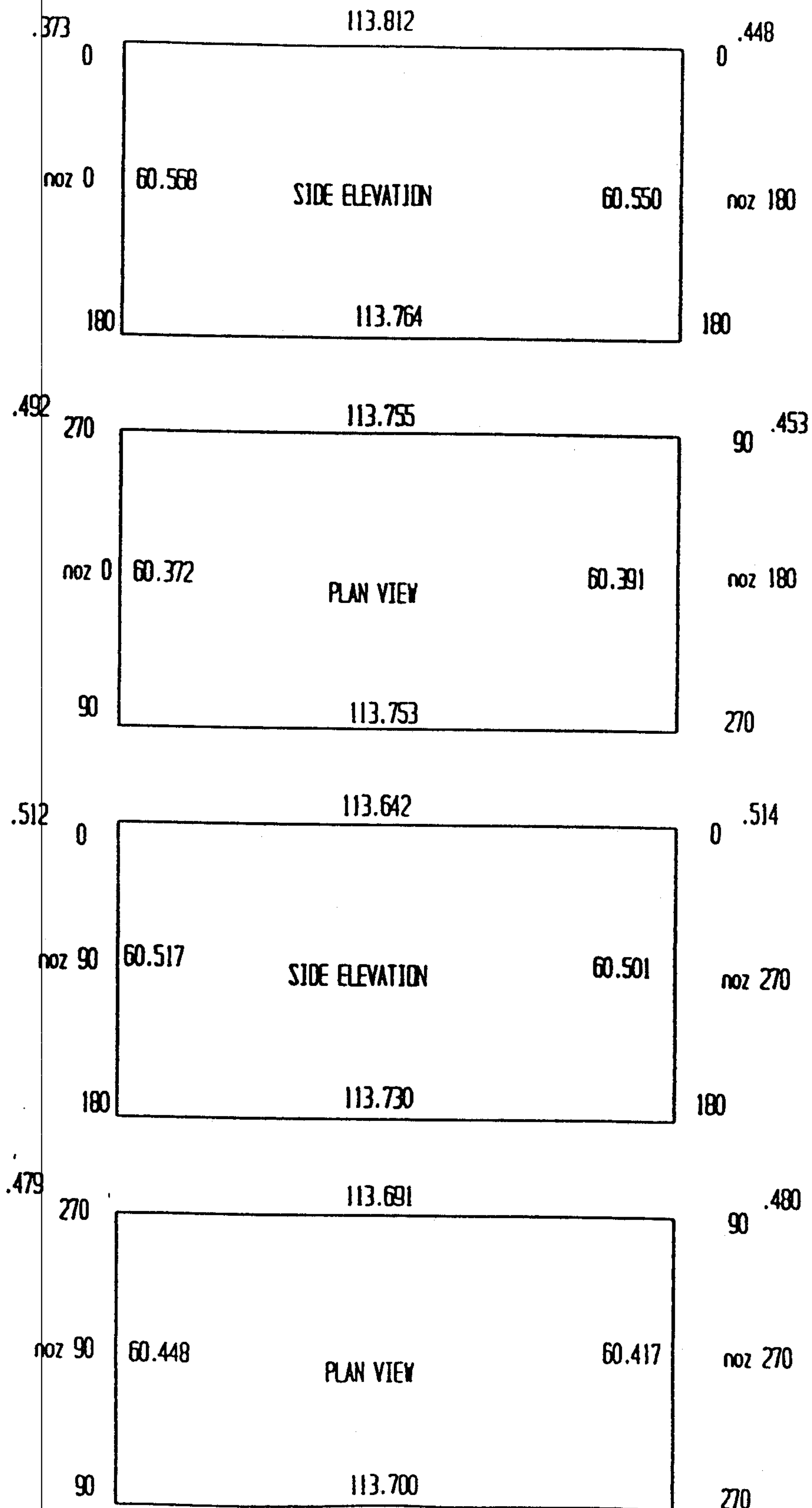

FIGURE C
BSC 60.5 INCH MEASUREMENT

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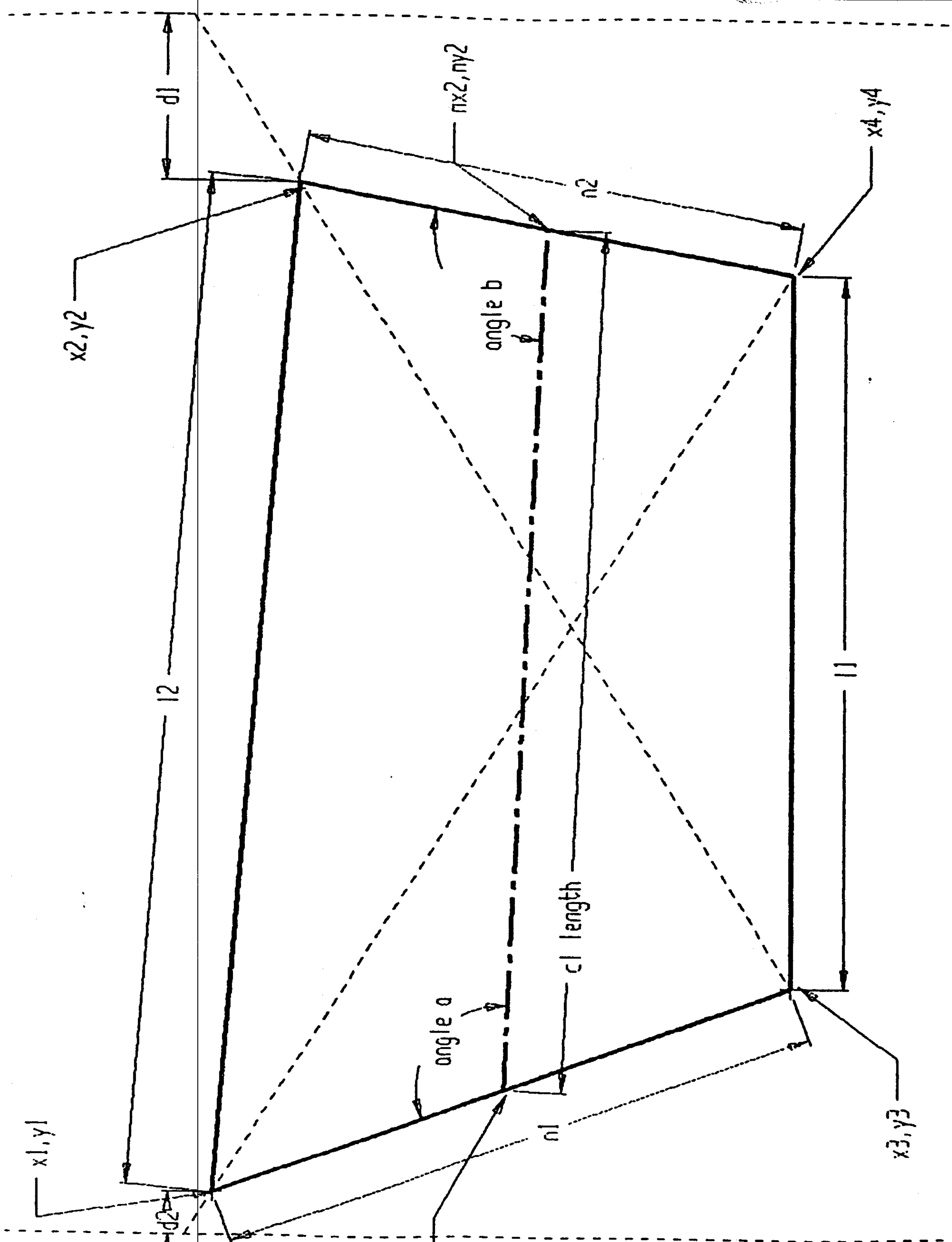

FIGURE D
BSC VARIABLES

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SID0180

19961028 all angles in degrees

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n1= 60.568
n2= 60.55
~~d1= .448~~
d2= .373
l1= 113.764
~~l2= 113.812~~

cl length= 113.788
~~angle a= 90.068251~~
angle b= 89.977149

~~a linear misalignment from center= -3.6074405e-2~~
b linear misalignment from center= 1.2074401e-2

~~a angular misalignment from center= -6.8250946e-2~~
b angular misalignment from center= 2.2850941e-2

sid90270

·9960804 all angles in degrees

= 60.517
-= 60.501
d1= .514
d2= .512
l1= 113.73
l2= 113.642

cl length= 113.686
angle a= 89.959535
angle b= 89.957138

a linear misalignment from center= 2.1369878e-2
b linear misalignment from center= 2.2630127e-2

a angular misalignment from center= 4.0464793e-2
b angular misalignment from center= 4.2862461e-2

pln90270

960804 all angles in degrees

= 60.448
n2= 60.417
d1= .48
d2= .479
l1= 113.7
l2= 113.691

cl length= 113.6955
angle a= 89.996301
angle b= 89.995166

a linear misalignment from center= 1.9512901e-3
b linear misalignment from center= 2.5487063e-3

a angular misalignment from center= 3.6990698e-3
b angular misalignment from center= 4.8340737e-3

FIGURE F
BSC RESULTS

BSCOUTDM

19961028 all angles in degrees

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```
n1= 113.75
n2= 113.843
d1= 0
d2= .064
l1= 113.732
l2= 113.774

cl length=  113.75299
angle a=  89.978333
angle b=  90.042788

a linear misalignment from center=  .02150816
b linear misalignment from center= -4.2508158e-2

a angular misalignment from center=  2.1667285e-2
b angular misalignment from center= -4.2787668e-2
```

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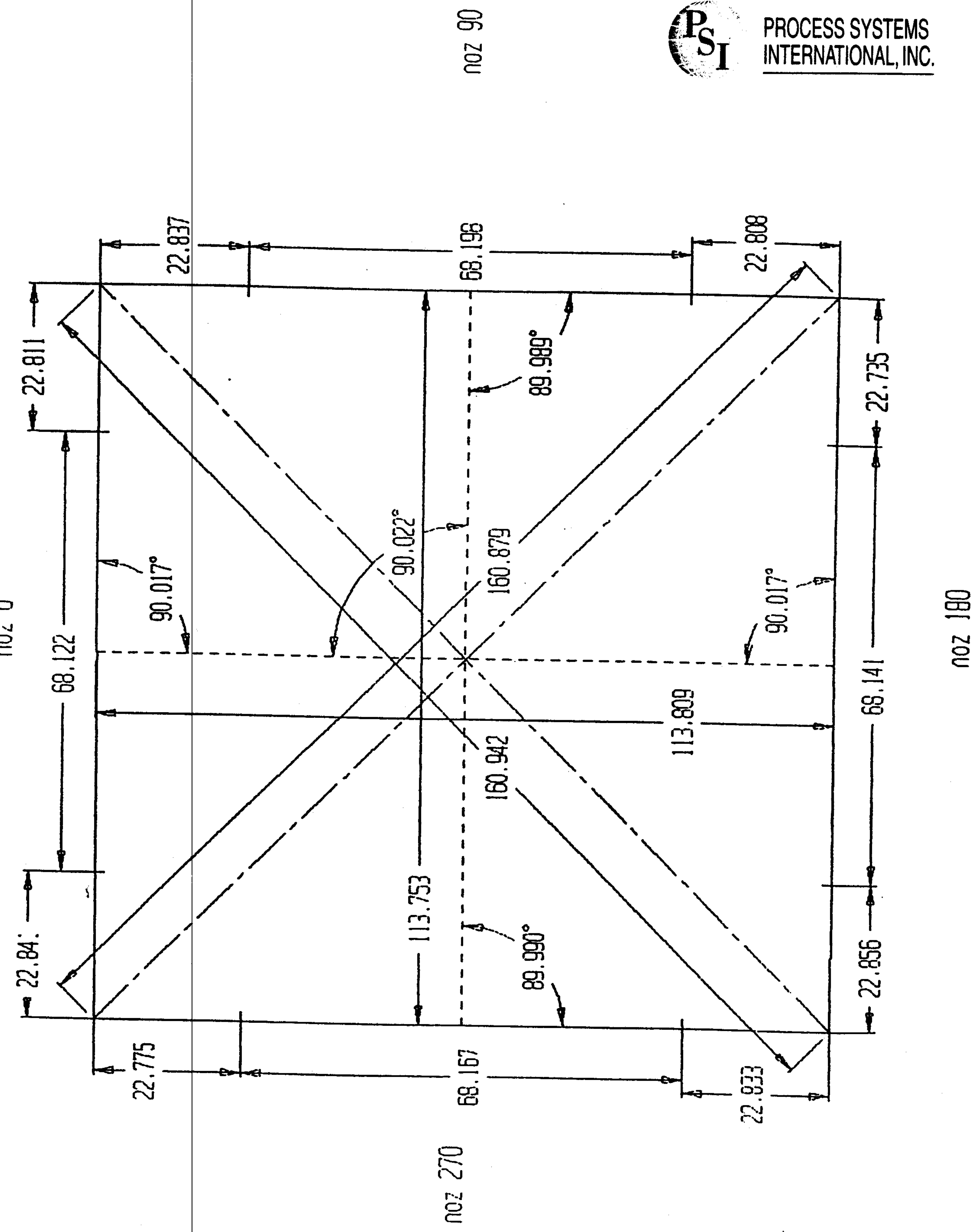

FIGURE H
BSC FLANGE/CENTERLINE RESULTS

3.0 Mechanical Deflection Predictions and Results

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The prototype BSC was pumped down to -14.7 psig. Measurements of the radial deflection were taken at the lower stiffener between G-nozzles on the 104.5 ID shell using a dial gage. This is the area of maximum deflection as predicted by the finite element analysis. As shown in Fig.III-1, the dial gauge was mounted on the support bracket that is below the area where the measurement was taken. Hence, the measurement gave the relative deflection of this support point and the stiffener.

Figure III-2 shows the displacement contour plot taken from the finite element results for the y-axis displacements. Due to symmetry of the quarter model, the z displacements are similar. From this plot, the maximum radial displacement at the lower stiffener is

$$\Delta = (0.106^2 + 0.106^2)^{1/2}$$

$$\Delta = 0.15 \text{ in}$$

Similarly, at the area of the support bracket connection the radial deflection is

$$\Delta = (0.0562^2 + 0.0562^2)^{1/2}$$

$$\Delta = 0.08 \text{ in}$$

Therefore, the relative deflection predicted by the FE analysis is

$$0.15 - 0.08 = 0.07 \text{ in}$$

A plot of the measured deflection versus the BSC internal pressure is shown in Figure III-3. The maximum reading of radial deflection at -14.7 psig was 0.061 in which compares to the predicted deflection of 0.07 in. Hence, there is good correlation between the predicted and measured deflections.

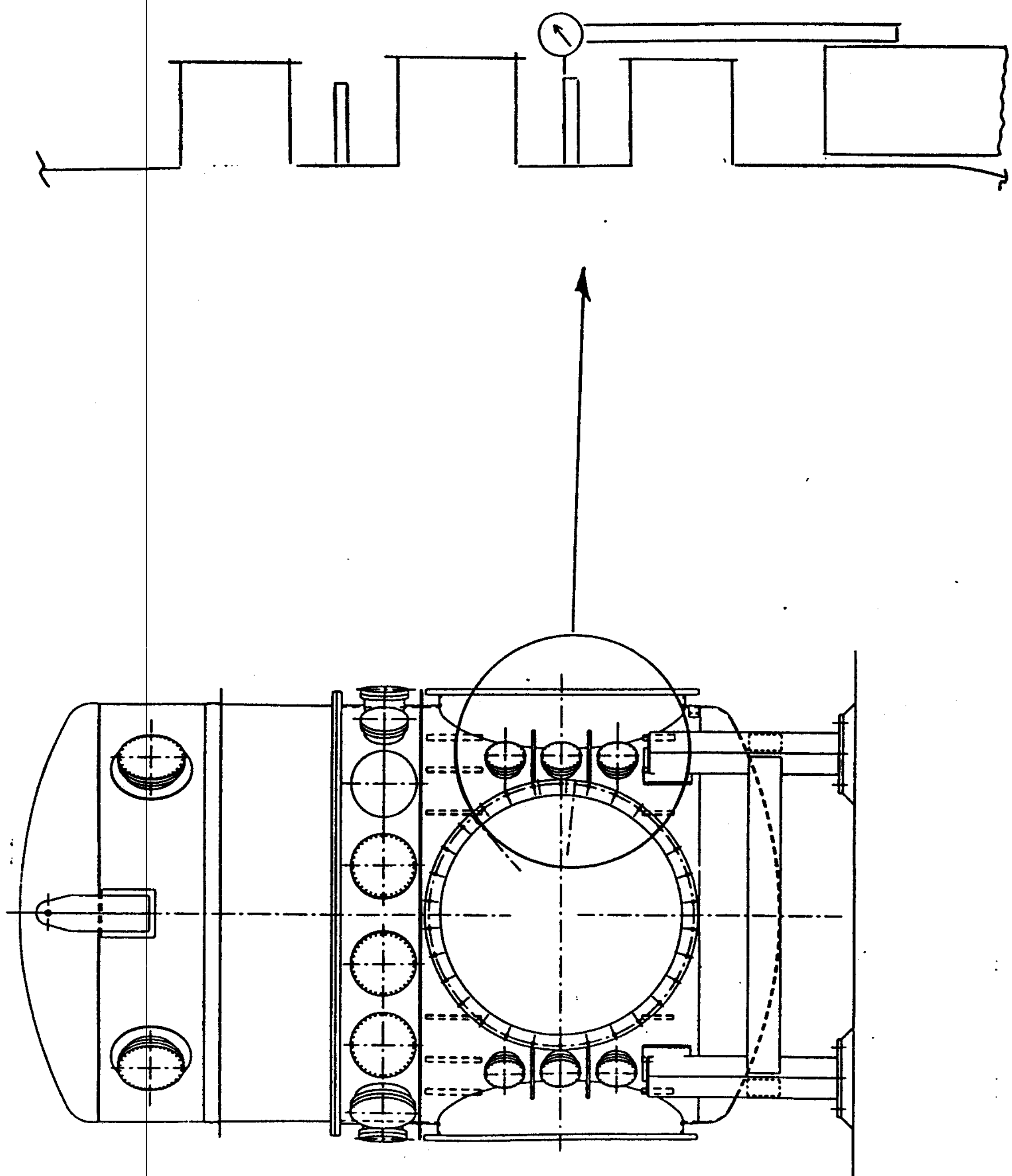

Figure III-1 BSC Deflection Measurement Setup

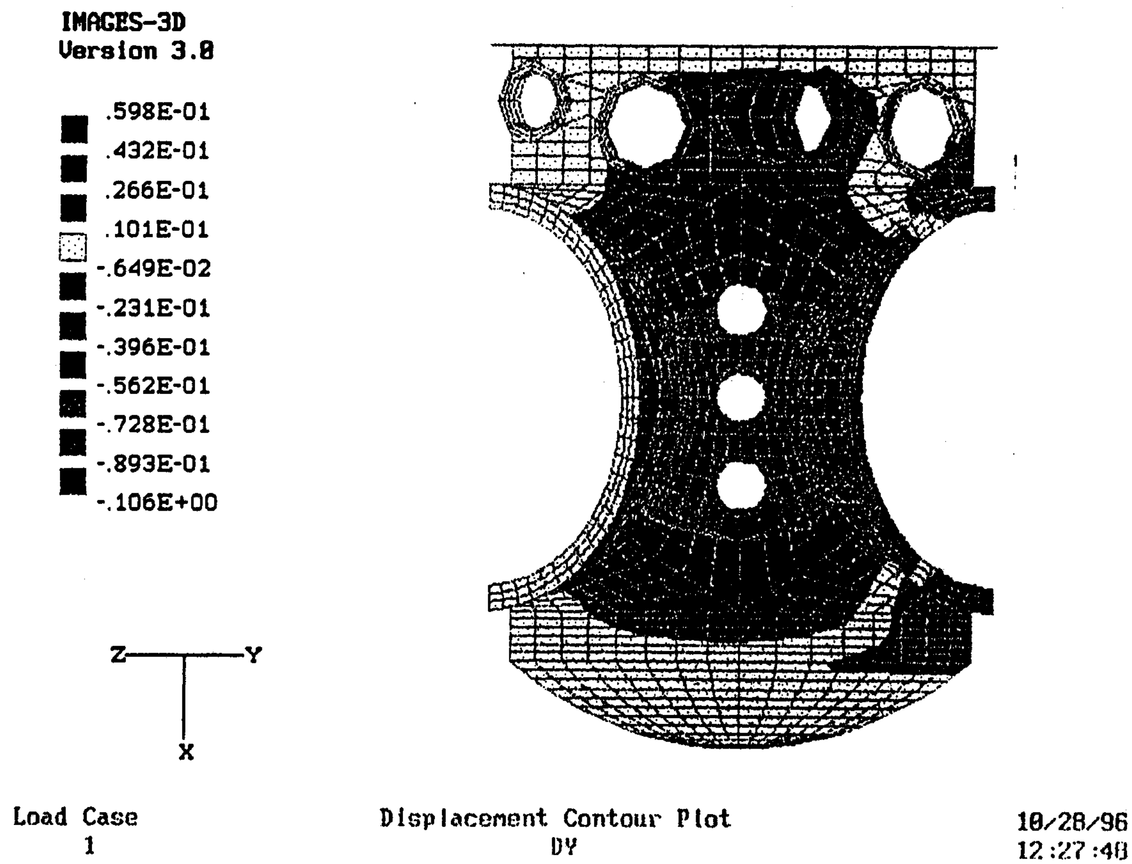

Figure III-2 Predicted Deflections

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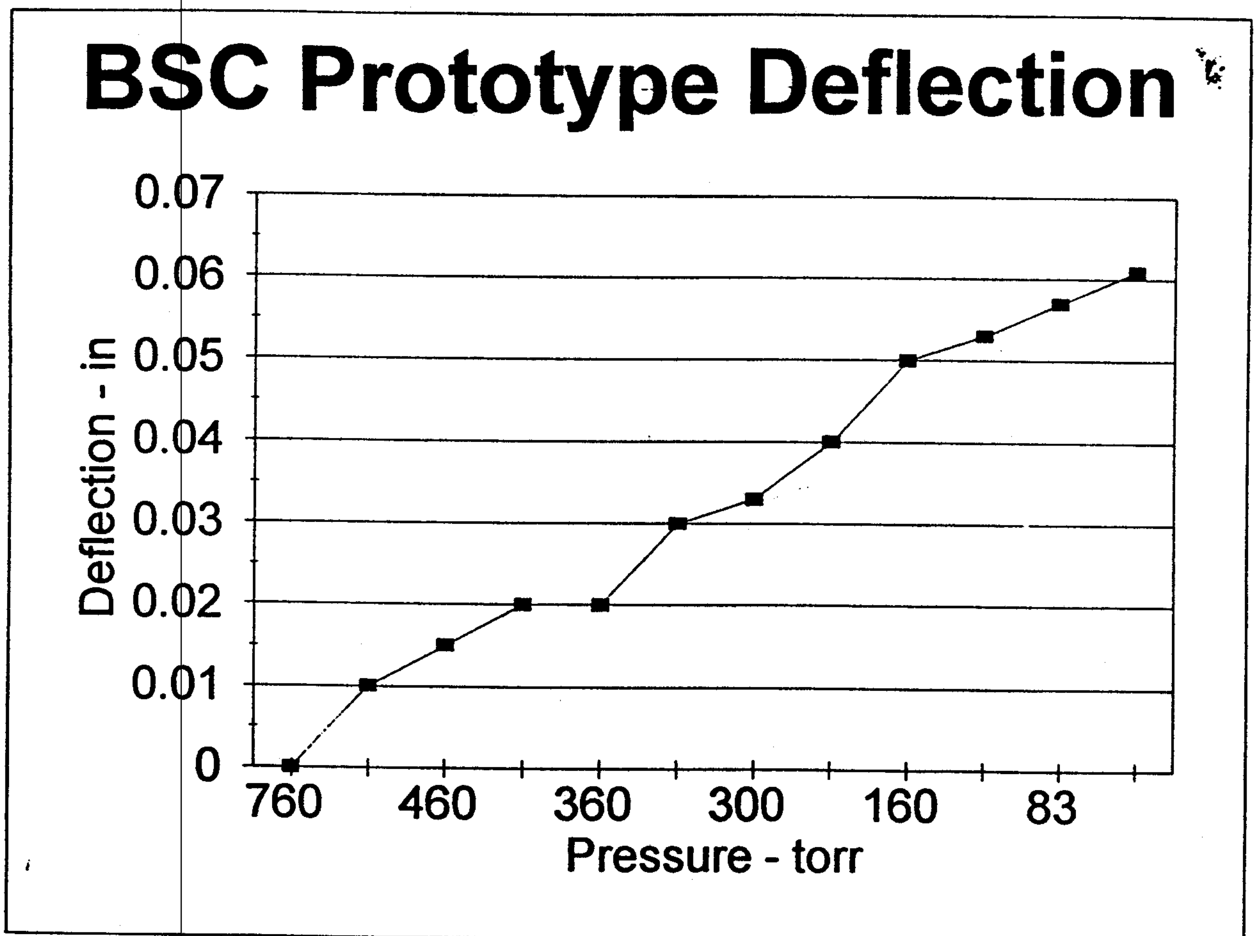

Figure III-3 Measured Deflections

SECTION I

4.0 FABRICATION TECHNIQUES ANALYSIS

As a result of the prototype BSC vessel program, various fabrication techniques have been modified to improve dimensional control and manufacturability for the production units.

The following is a list of significant items that were incorporated into the production units designs:

- All nozzle welds were reduced in size to minimize distortion of the nozzle (i.e. full penetration 60" nozzle welds reduced to a fillet vacuum weld on the inside and stitch welding on the outside).
- All conflat flanges will be purchased with nipples welded on (special lengths) by the conflat vendors.
- For large door assemblies (60"/84"), the head will be welded to the flange before final machining of the flange sealing surfaces.
- New stronger fixtures will be used during machining to prevent vessel vibration.
- A special flange assemble fixture will be used at PSI to accurately install all spool and cryopump flanges.
- Heat treating will be used on the BSC and HAM vessels prior to machining and flange installation.
- Fixtures will be used to install critical vessel nozzles (BSC - "D"/HAM - "E").
- Plasma welding will be used on critical nozzles and seams to minimize heat distortion.
- CO_2 cleaning will be used prior to all vacuum boundary welds.
- Internal bars have small continuous welds vs. stitch to avoid dirt traps.
- Revised angle of o-ring groove to improve machineability.
- Lifting lugs on door covers revised, now 4 per door instead of one; this will aid all future lifting of covers.

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SECTION II

BSC PROTOTYPE VACUUM PERFORMANCE

1. 0 Introduction and Summary

1.1 Introduction

The prototype BSC was assembled, cleaned and tested in accordance project procedures. It was then baked under vacuum for 48 hours at 150^0C using the prototype bakeout system and allowed to cool to ambient temperature. Partial and total pressures were measured after cool down.

The BSC was then back filled to atmospheric pressure and soaked for 24 hours with nitrogen generated from LN_2 boiloff. The vessel was than repumped and the pressures measured after 100 hours.

The outgassing rates were calculated, and the resulting rates used to project the probable partial pressures achievable in an isolatable volume. The measured outgassing rates are compared with the design outgassing rates.

Additional testing was done on the 10" chamber to establish 100 hour outgassing rates for an all metal configuration, and for an o-ring configuration. Outgassing rates were determined for various reexposure conditions.

Detailed results are found in the body of the report along with calibration procedures.

1.2 Summary

1.2.1 Hydrogen Outgassing

The measured hydrogen outgassing rate varied considerably depending on the test method. Rates range from the high 10^{-12} to the low 10^{-11} torr-l/s-cm^2. The most credible data was measured when pumping with the turbo pump. The hydrogen outgassing for this case is in the high 10^{-12} torr-l/s-cm^2 which is less than the design outgassing rate of $1x10^{-11}$ torr-l/s-cm^2. See Table 4.1-3 in section 4.1 for details. (Note: This is only a sample of 1 lot out of 30-40 mill runs of stainless steel.)

1.2.2 Cleaning and Baking

The cleaning and baking procedures were very effective. There was little evidence of hydrocarbon contamination after the bakeout. Partial pressures of hydrocarbons heavier than methane were 3 to 4 orders of magnitude less than hydrogen. See RGA scan cycle 2 in section 3.0.

1.2.3 Gas Loads after Reexposure

The principal gas loads after the 24 hour nitrogen soak are hydrogen, water and nitrogen. The pressures are of approximately equal magnitude. While the gas loads for hydrogen and water are consistent with the design basis, the 100 hour gas load for nitrogen after a 24 hour nitrogen soak exceeds the LIGO goals by a factor of 10. The rate is sufficiently high that although the total pressure goal of less than $2x10^{-8}$ torr after 100 hours of pumping may be achieved, the results of this test indicate that there is very little design margin.

Additional testing performed on the 10" chamber has identified the viton o-rings as the source of the nitrogen. The nitrogen outgassing rates and decay exponents for viton have been determined for reexposure times of 1 hour and 24 hours. The viton outgassing rate depends on the reexposure time. By limiting the reexposure time to 1 hour, a decade improvement in outgassing rate can be achieved.

Table 3.4-1 in section 3.4 shows the predicted partial pressures in the largest isolatable volume after 100 hours when re exposed to nitrogen for 1 hour and 24 hours, and compares these values to the LIGO partial pressure goals.

1.2.4 Predicted Partial Pressures Vs LIGO Design Goals

Section 4.3 of the LIGO specification requires that each vacuum section shall attain a total pressure of less than $2x10^{-8}$ torr after 100 hours of pumping. If the hydrogen content of the steel prevents attainment of this value than the total pressure of all gases other than hydrogen and water shall not exceed $6x10^{-9}$ torr. The LIGO specification also states that the partial pressure goals shall be adjusted to be consistent with the prototype test results and the design margins required for consistent implementation.

Since many stainless steel mill runs will be used in the fabrication, the hydrogen outgassing will vary from batch to batch and attainment of the total pressure may not be achieved. In this case the secondary requirement of achieving $6x10^{-9}$ torr for the other gases will apply.

The partial pressure goal of $6x10^{-9}$ torr for all gases other than hydrogen and water was established during contract negotiations and provided a design margin of approximately 3 over the expected pressures as determined by calculation for outgassing rates taken from the literature.

To maintain this design margin to be consistent with the BSC prototype test results and as supplemented by additional data obtained from the 10" chamber for a 1 hour nitrogen reexposure, the goal for the sum of the partial pressures for the other gases should be adjusted to 1.7×10^{-8} torr.

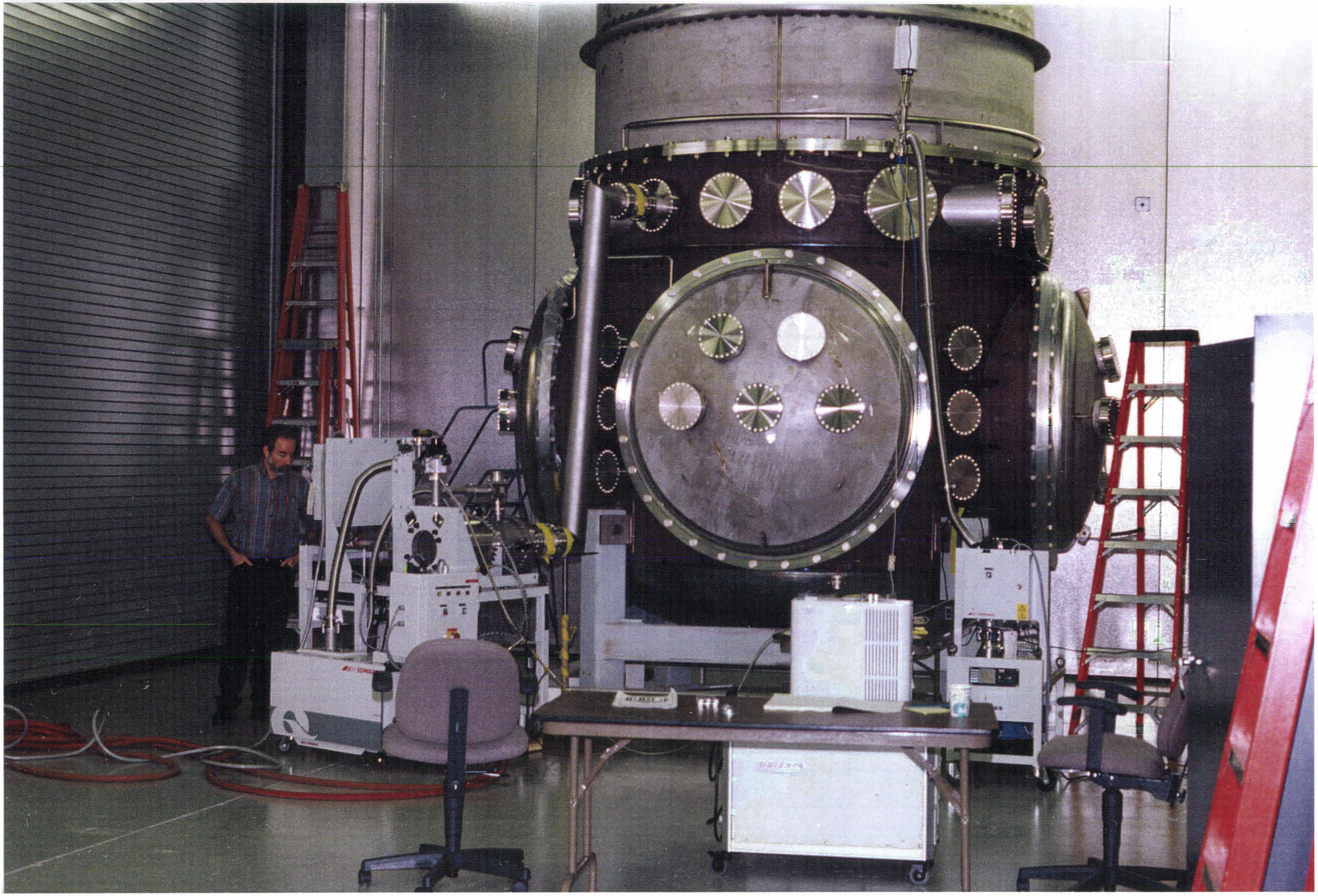

FIG. II-1

2.0 BSC Bakeout

The chamber was baked under vacuum to 150°C and soaked for 48 hours at 150°C. Cool down occurred over a period of 2 days. The main turbomolecular pump was used to pump on the chamber during the bake. Figure 2.1 shows the test setup for the bakeout.

The temperatures measured for the zones were between 127°C to 152°C. Figure 2.2 shows the location of the temperature zones. Low temperatures occurred where the blankets fit poorly.

ZONE	TEMPERATURE °C	ZONE	TEMPERATURE °C	ZONE	TEMPERATURE °C
1	152	17	144	40	145
2	147	18	133	41	127
3	144	19	142	42	137
4	150	20	147	43	142
5	147	21	131	44	154
6	149	22	138	45	148
7	152	23	130	46	149
8	148	32	143	47	148
9	147	33	133	48	138
10	145	34	147	49	147
11	148	35	148	50	
12	148	36		51	138
13	145	37	131		
14	146	38	136		
15	139	39	135		
16	149				

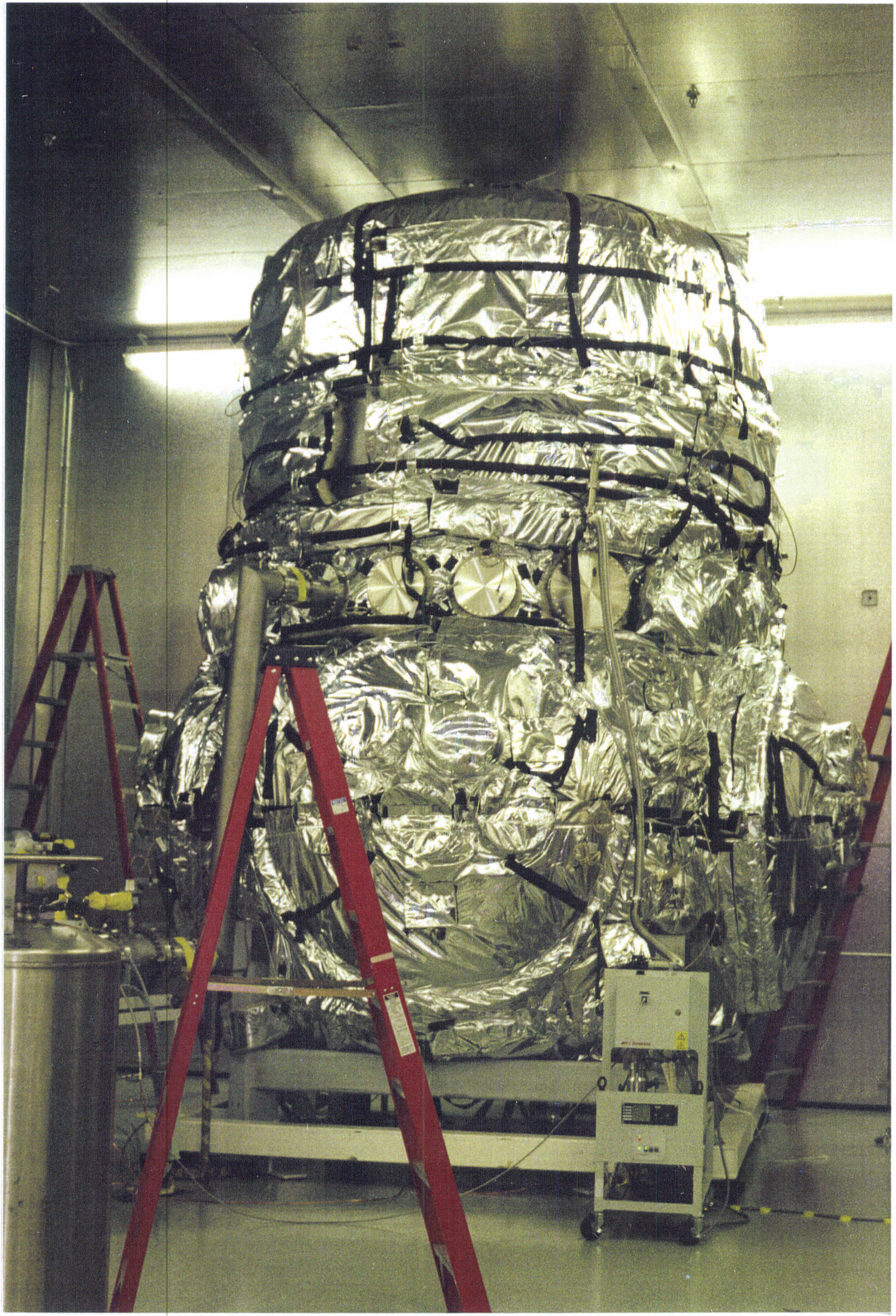

FIG. II-2

BLANKET ZONE MAP

PROCESS SYSTEMS INTERNATIONAL, INC

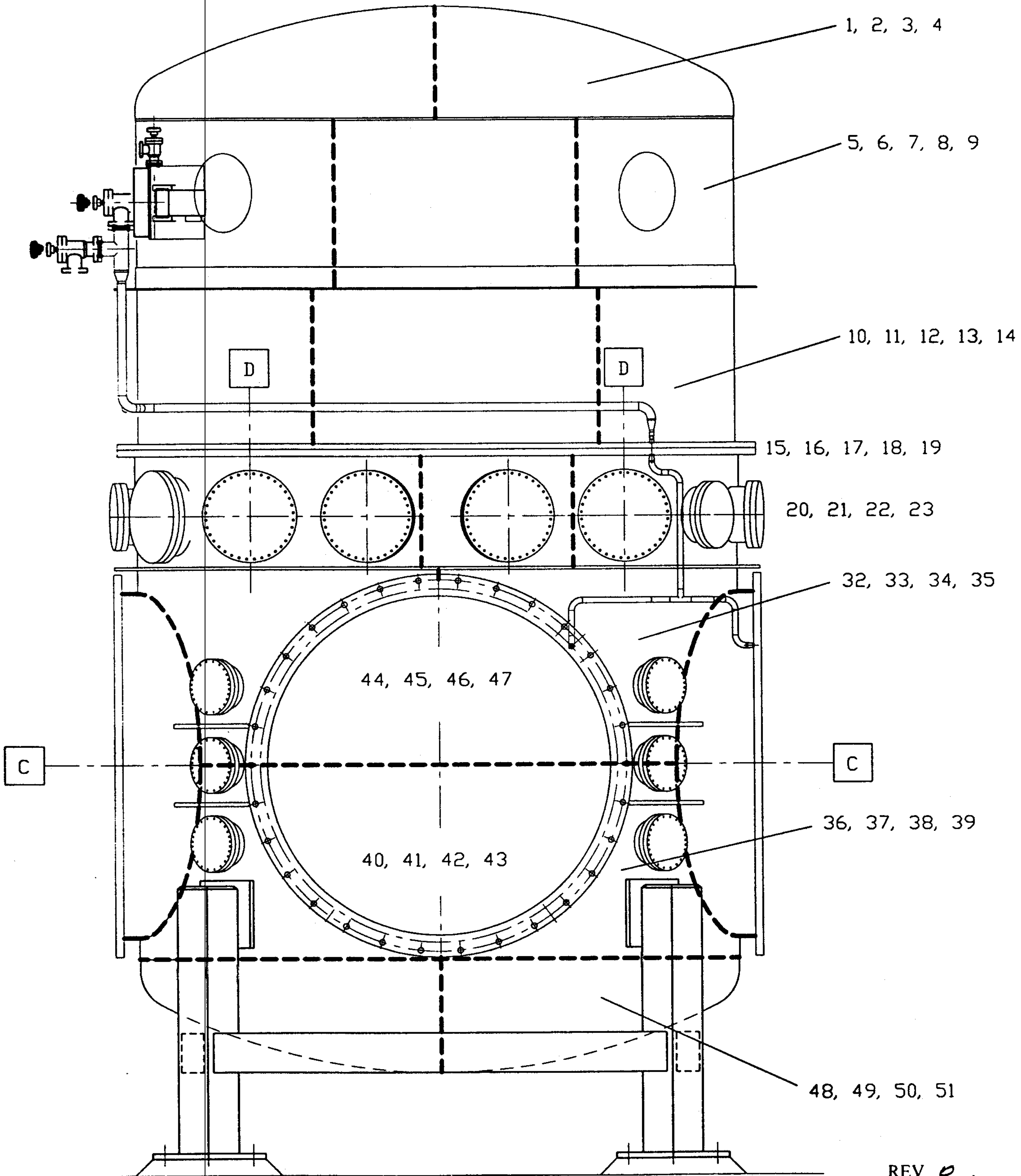

FIG 2-1

PROCESS SYSTEMS INTERNATIONAL, INC.

3.0 BSC Vacuum Measurements

3.1 Vacuum Measurements After Bakeout Prior to Reexposure

The dominant gas species at the end of cool down was hydrogen. The total pressure indicated on the ion gauge was about $7X10^{-9}$ Torr.

Based on the calculated ion pump speed and ion gauge reading the total gas load was estimated at $1X10^{-5}$ Torr-liter/sec, or $2X10^{-11}$ Torr-liter/sec-cm^2

Based on the calibrated hydrogen leak sensitivity determined after the 100 test, the gas load is estimated to be $1.6X10^{-11}$ Torr-liter/sec-cm^2.

3.1.1 Table 3.1-1 After Bake Data

Table 3.1-1 gives the RGA ion current data for the most dominant peaks. The 2nd column contains the RGA data. The 3rd column contains the total current for the mass indicated by matching intensities based on cracking patterns obtained from the RGA sensitivity calibration against the ion gauge. For those species that do not have a calibrated pattern, the manufacturer's theoretical values were used.

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TABLE 3.1-1
RGA DATA DOMINANT PEAKS
BAKED AND COOL

	DATA	TOTAL	H2	CH4	CO	N2	H2O	O2	CO2	Ar	25	26	27	30	41
		Sensitivity	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp
		Sensitivity	11.8	33.6	28.5	28.5	18.2	28.5	47.4	43.0	28.5	28.5	28.5	28.5	28.5
	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr	Pres Torr
CORRECTED by 1.3 factor ion gauge															
N2 EQ.	9.1E-09	1.12E-08	9.88E-09	2.24E-10	3.705E-11	1.85E-10	2.03E-10	0	6.04E-10	1.45E-11	5.56E-12	2.59E-11	2.22E-11	1.26E-11	1.59E-11
TRUE		2.26E-08	2.15E-08	1.4E-10	3.705E-11	1.85E-10	2.03E-10	0	4.31E-10	1.12E-11	5.56E-12	2.59E-11	2.22E-11	1.26E-11	1.59E-11
ACTUAL															
N2 EQ.	7.00E-09	8.64E-09	7.60E-09	1.72E-10	2.85E-11	1.43E-10	1.57E-10	0	4.65E-10	1.12E-11	4.28E-12	2E-11	1.71E-11	9.69E-12	1.23E-11
TRUE		*1.74E-08*	*1.65E-08*	*1.08E-10*	*2.85E-11*	*1.43E-10*	*1.57E-10*	*0*	*3.32E-10*	*8.6E-12*	*4.28E-12*	*2E-11*	*1.71E-11*	*9.69E-12*	*1.23E-11*
MASS	DATA	TOTAL	H2	CH4	CO	N2	H2O	O2	CO2	Ar	25	26	27	30	41
amu	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp
1		1.55E-10	1.54E-10				6.88E-13								
2	1.40E-09	1.40E-09	1.40E-09	2.37E-12											
3															
4															
5															
6															
7															
8															
9															
10															
11															
12	6.00E-13	6.75E-13			4.5E-14				6.3E-13						
13															
14	1.00E-12	9.05E-13		4.99E-13	6E-15	4E-13									
15	4.00E-12	2.72E-12		2.72E-12											
16	5.40E-12	4.52E-12		3.20E-12	9E-15		9.46E-14	0	1.22E-12						
17	3.00E-12	1.98E-12					1.98E-12								
18	8.60E-12	8.60E-12					8.60E-12								
19															
20		6.18E-14					2.58E-14			3.6E-14					
21															
22	0.00E+00	1.54E-13							1.54E-13						
23															
24	0.00E+00	0.00E+00													
25	1.50E-13	1.50E-13									1.50E-13				
26	7.00E-13	7.00E-13										7.00E-13			
27	6.00E-13	6.00E-13											6.00E-13		
28	7.00E-12	6.80E-12			1.00E-12	5.00E-12			7.98E-13						
29		1.10E-14			1.1E-14										
30	3.40E-13	3.40E-13												3.40E-13	
31															
32	0.00E+00	0.00E+00						0.00E+00							
33															
34															
35															
36															
37															
38															
39	2.70E-13	0.00E+00													
40	2.30E-13	2.00E-13								2.00E-13					
41	4.30E-13	4.30E-13													4.30E-13
42															
43	2.30E-13	0.00E+00													
44	7.10E-12	7.00E-12							7.00E-12						
45															

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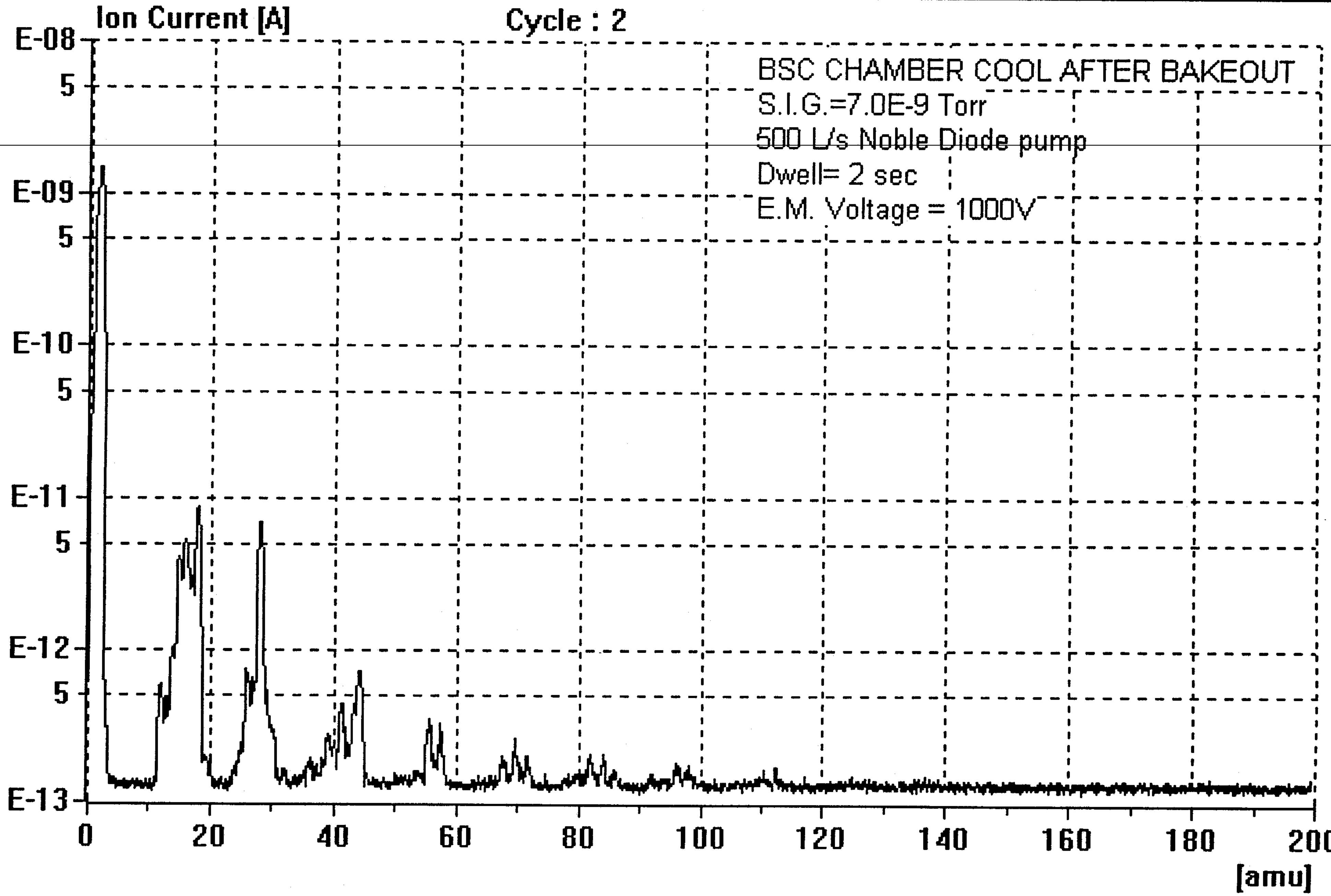
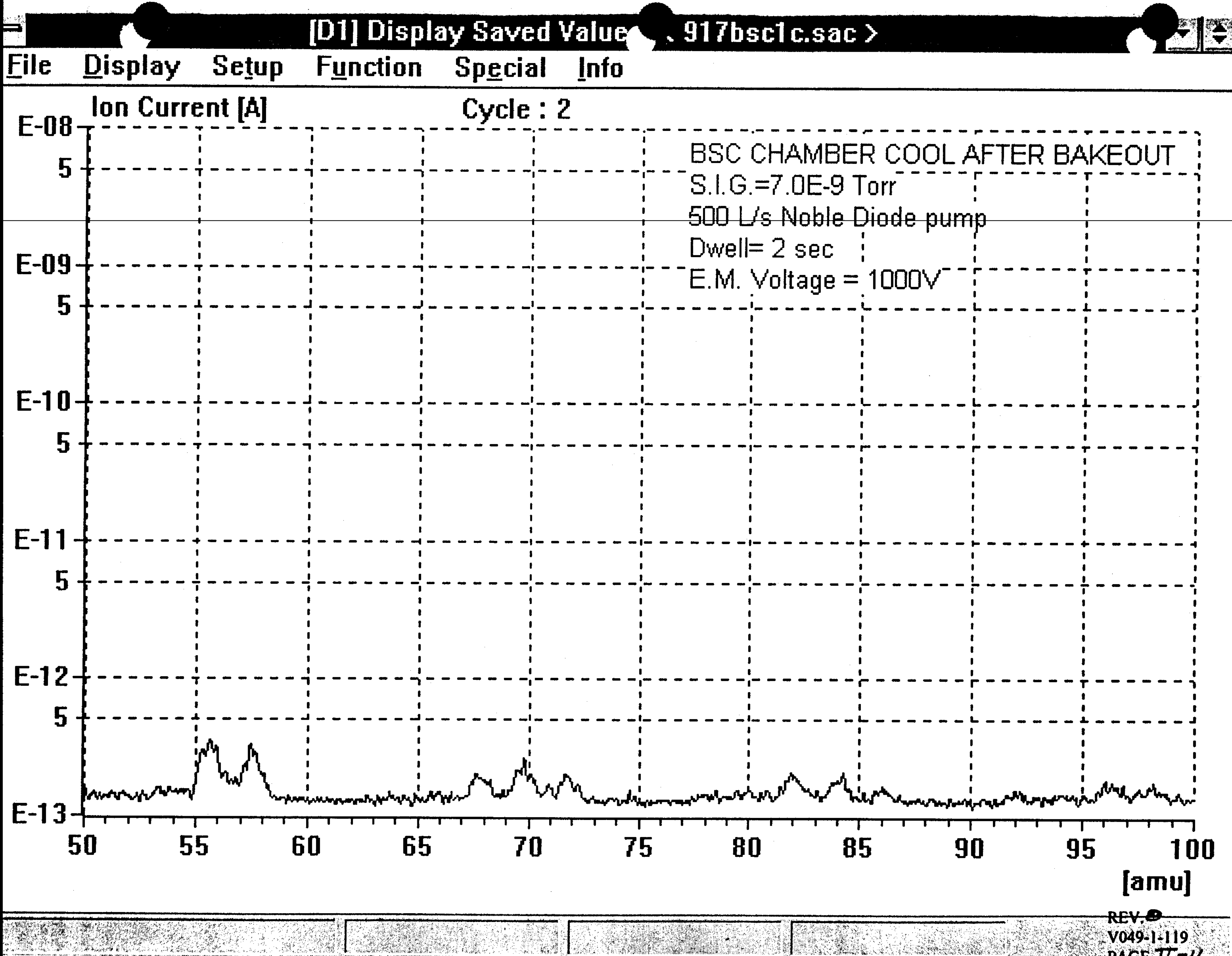
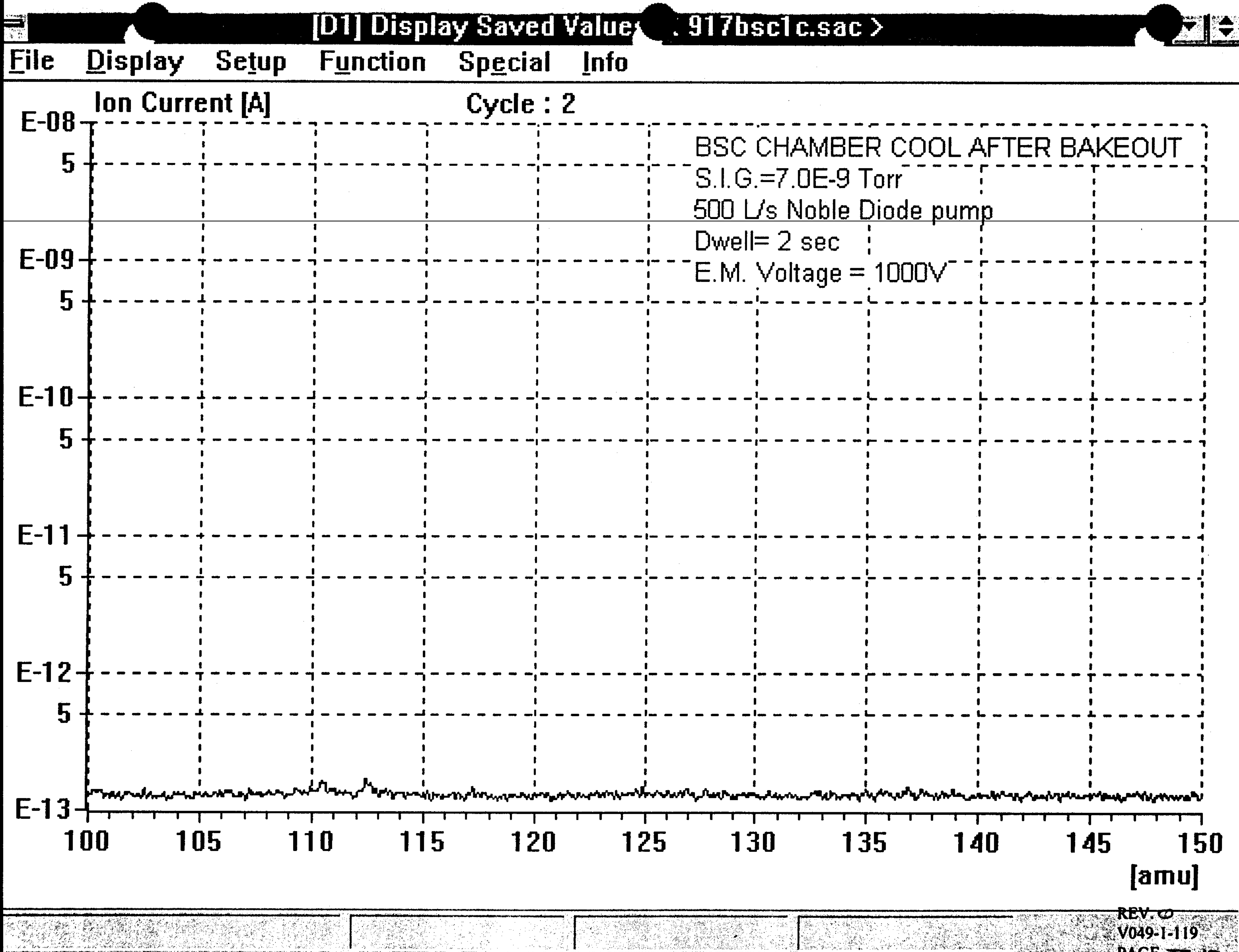


REV. 0
V049-1-119
PAGE C-10



REV. 0
V049-1-119
PAGE II-11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File Display Setup Function Special Info
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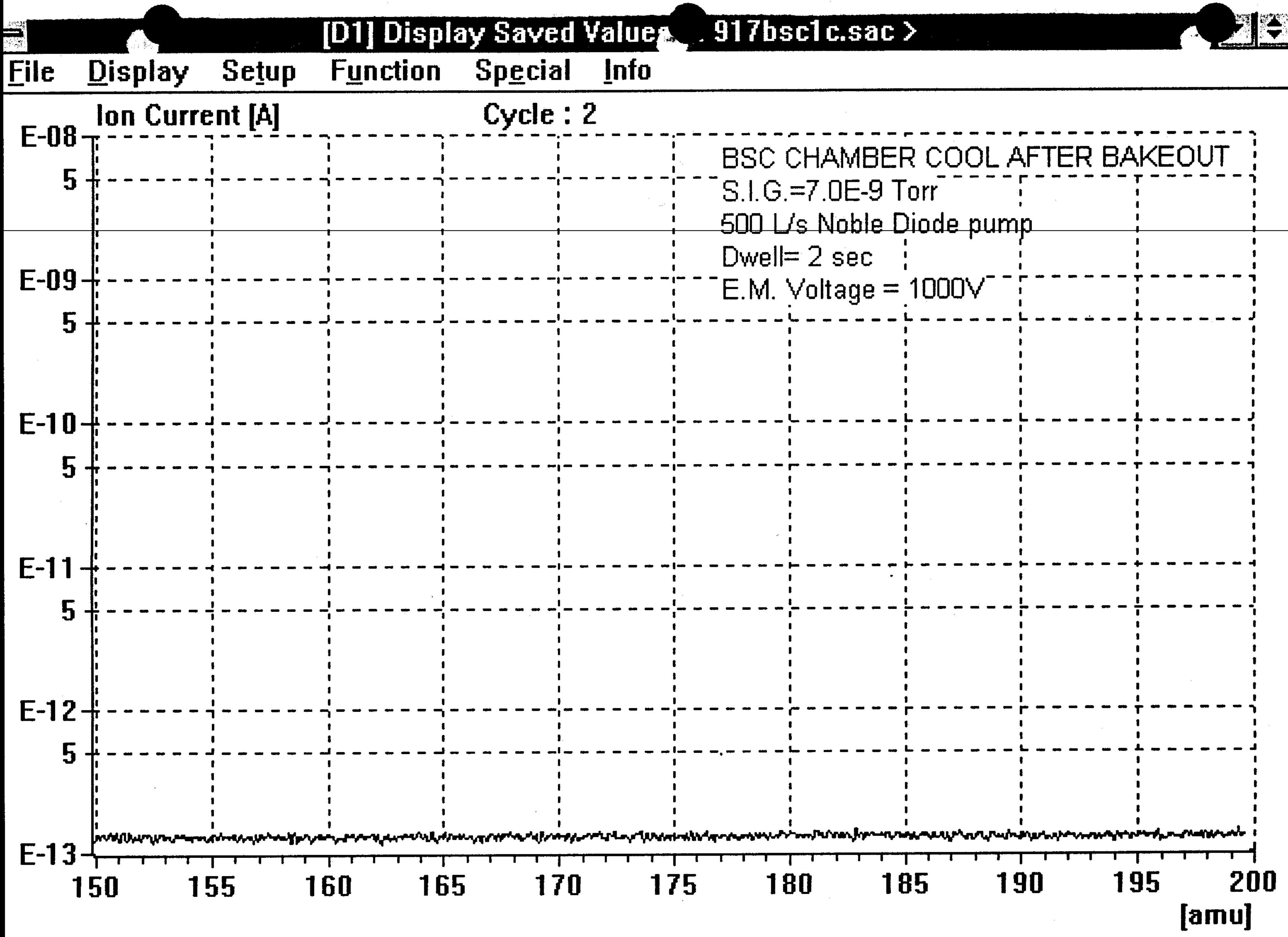
Cycle : 2
BSC CHAMBER COOL AFTER BAKEOUT
S.I.G.=7.0E-9 Torr
500 L/s Noble Diode pump
Dwell= 2 sec
E.M. Voltage = 1000V
E-08
5
E-09
5
E-10
5
E-11
5
E-12
5
E-13
100
105
110
115
120
125
130
135
140
145
150
[amu]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File Display Setup Function Special Info
Ion Current [A]
Cycle : 2
BSC CHAMBER COOL AFTER BAKEOUT
S.I.G.=7.0E-9 Torr
500 L/s Noble Diode pump
Dwell= 2 sec
E.M. Voltage = 1000V
E-08
5
E-09
5
E-10
5
E-11
5
E-12
5
E-13
150
155
160
165
170
175
180
185
190
195
200
[amu]

3.2 Vacuum Measurements After Reexposure and 100 Hours of Pumping

Table 3.2-1 shows a log of the test activities after completion of the bakeout. Figure 3.2-1 shows the pumpdown curve after reexposure.

TABLE 3.2-1

DATE	TIME	ACTIVITY
9/17/96	9/17/96 12:00 PM	The BSC was back filled to 1 atmosphere with nitrogen gas from a liquid nitrogen dewar.
9/17/96	1:00 PM	The BSC was then soaked for 24 hours in this dry nitrogen.
9/18/96	1:00 p.m.	The chamber was then evacuated using the QDP80 to a pressure of 0.5 Torr.
9/18/96	5:00 p.m.	The turbo pump was started and allowed to pump for the next 20 hours.
9/19/96	1:00 p.m.	The 500 liters/sec ion pump was started at a pressure of about $5X10^{-7}$ Torr. The turbo pump was isolated.
9/20/96	8:44 am	Close calibrated nitrogen leak
9/22/96	4:00 p.m. 5:10 p.m. 6:15 p.m.	End of pumpdown test Shut ion pump and do rate of rise for 70 minutes Re pump with ion pump to base pressure Open calibrated nitrogen leak
9/23/96	9:00 p.m.	Take RGA data with calibrated N2 leak Do rate of rise test with calibrated nitrogen leak
9/23/96	11:00 p.m.	Close nitrogen leak and re pump. Take RGA data.
9/23/96		RGA gas species sensitivity calibration
9/24/96		PV expansion into BSC to check ion gauge
9/25/96	7:50 am 8:35 am	Take RGA data Open leak Take RGA data with calibrated N2 leak
9/26/96		BSC Volume calibration
9/27/96		Take system data with Calibrated hydrogen leak.

3.2.1 Table 3.2.1-1 100 hr pumpdown test

Table 3.2-11 gives the RGA ion current data for the most dominant peaks. The 2nd column contains the RGA data. The 3rd column contains the total current for the mass indicated by matching intensities based on cracking patterns obtained from the RGA sensitivity calibration against the ion gauge. For those species that do not have a calibrated pattern, the manufacturer's theoretical values were used.

FIGURE 3.2-1

BSC 100 HR PUMPDOWN TEST

TOTAL PRESSURE STABIL ION GAUGE

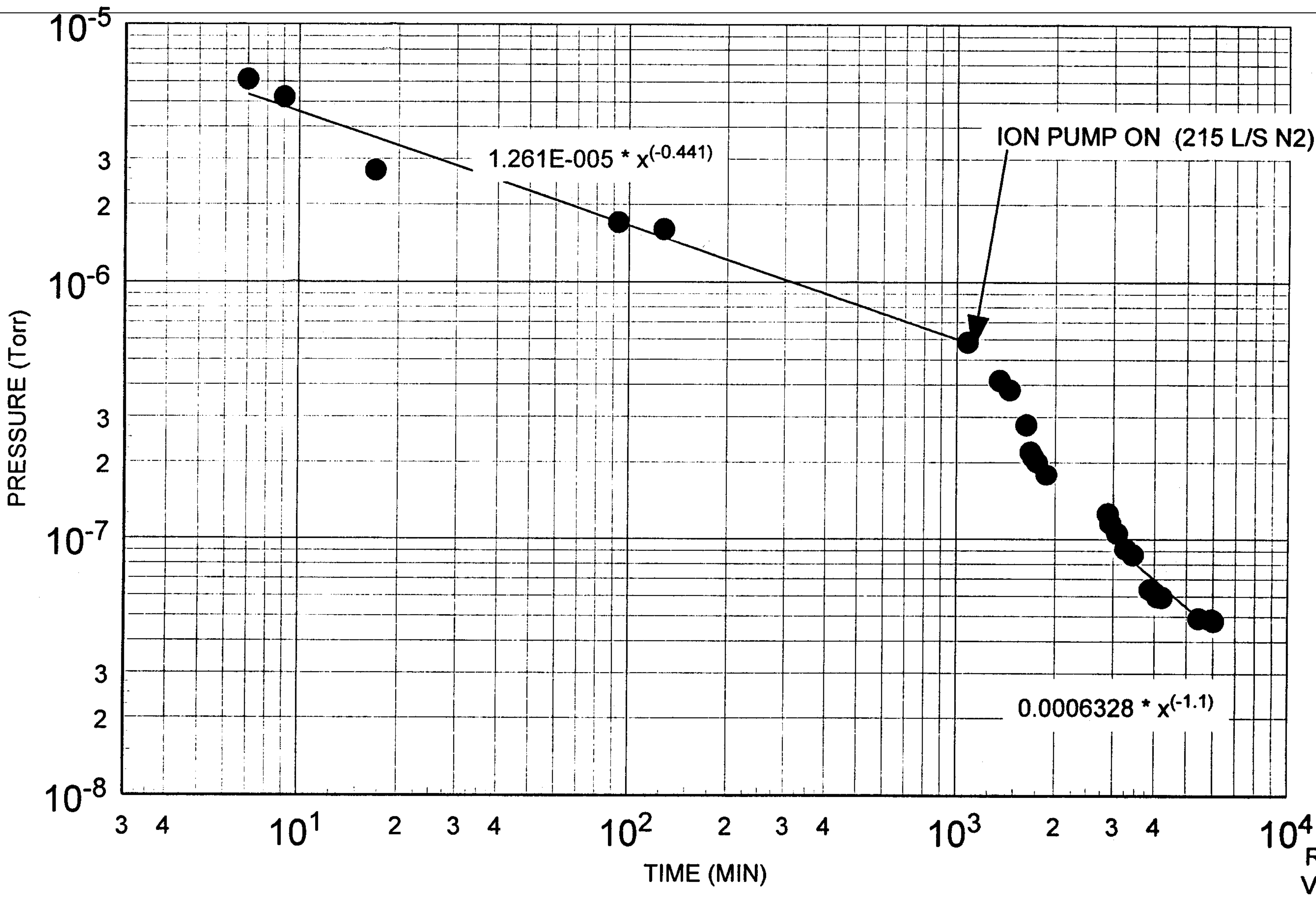
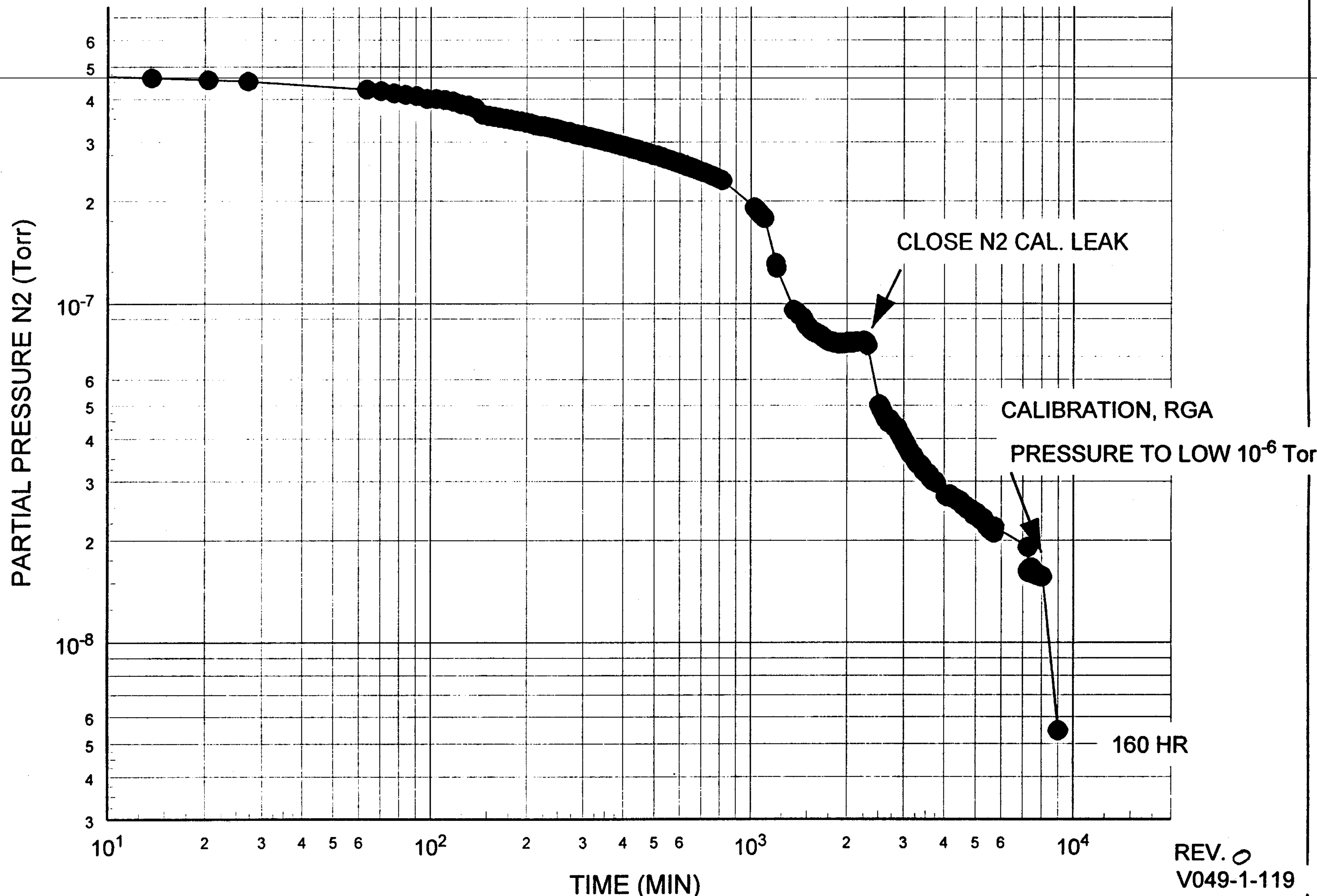


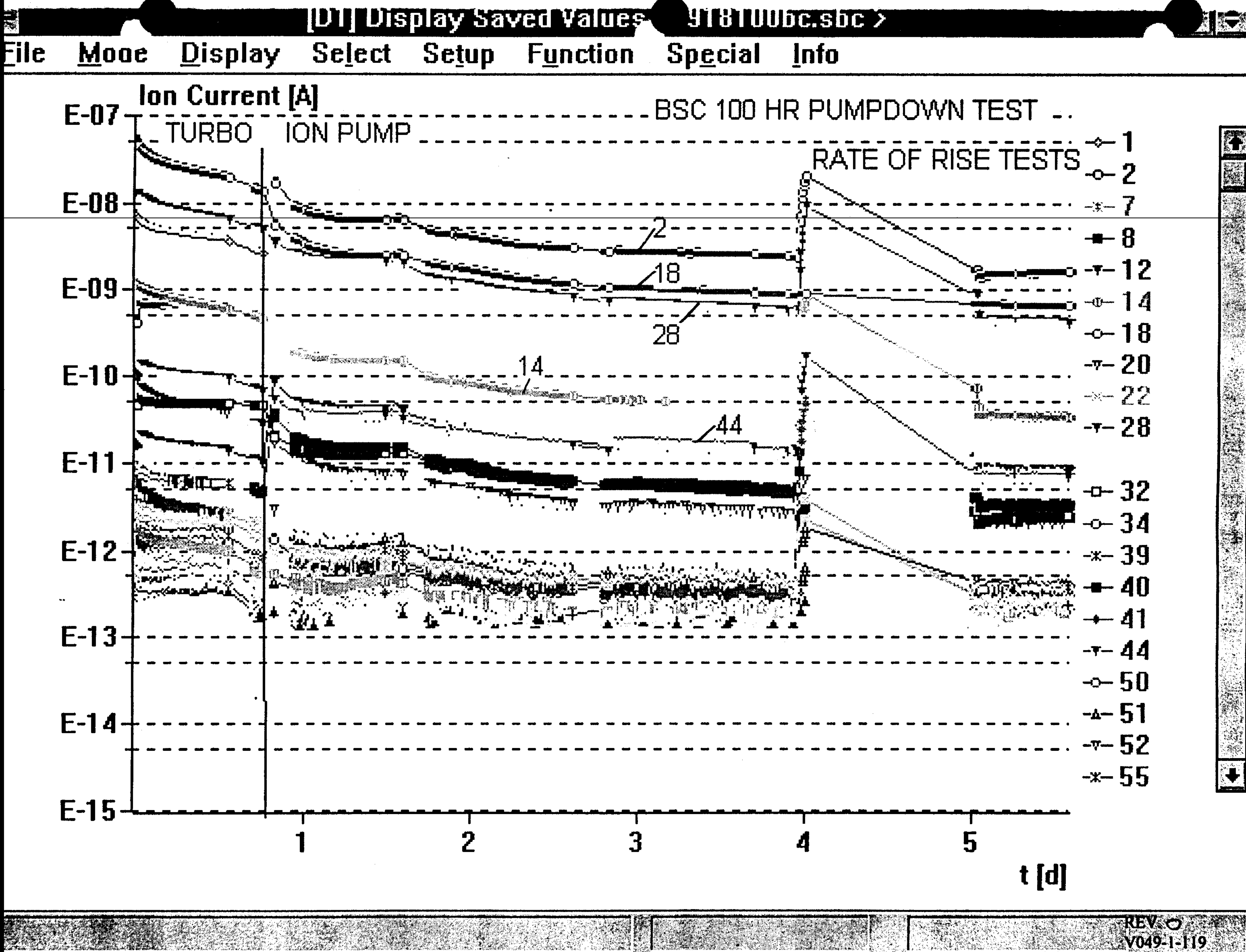
TABLE 3.2.1-1
RGA DATA DOMINANT PEAKS
100 HR PUMPDOWN

		TOTAL	H2	CH4	CO	N2	H2O	O2	CO2	Ar	25	26	27	30	41
		Sensitivity	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp	Torr/amp
	DATA	Sensitivity	11.8	33.6	28.5	28.5	18.2	28.5	47.4	43.0	28.5	28.5	28.5	28.5	28.5
		TOTAL													
	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres	Pres
	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr	Torr
CORRECTED by 1.3 factor ion gauge															
N2 EQ.	6.24E-08	6.81E-08	1.76E-08	2.1E-09	7.41E-09	1.48E-08	2.13E-08	1.964E-10	1.484E-09	3.63E-10	1.41E-10	7.04E-10	1.19E-09	6.3E-10	1.48E-10
TRUE		*8.75E-08*	*3.84E-08*	*1.31E-09*	*7.41E-09*	*1.48E-08*	*2.13E-08*	*1.964E-10*	*1.06E-09*	*2.8E-10*	*1.41E-10*	*7.04E-10*	*1.19E-09*	*6.3E-10*	*1.48E-10*
ACTUAL															
N2 EQ.	4.80E-08	5.24E-08	1.36E-08	1.61E-09	5.7E-09	1.14E-08	1.64E-08	1.511E-10	1.141E-09	2.8E-10	1.08E-10	5.42E-10	9.12E-10	4.85E-10	1.14E-10
TRUE		*6.73E-08*	*2.96E-08*	*1.01E-09*	*5.7E-09*	*1.14E-08*	*1.64E-08*	*1.511E-10*	*8.15E-10*	*2.15E-10*	*1.08E-10*	*5.42E-10*	*9.12E-10*	*4.85E-10*	*1.14E-10*
MASS	DATA	TOTAL	H2	CH4	CO	N2	H2O	O2	CO2	Ar	25	26	27	30	41
amu	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp
1	2.00E-10	3.47E-10	2.75E-10				7.2E-11								
2	2.55E-09	2.52E-09	2.50E-09	2.22E-11											
3															
4															
5															
6															
7															
8															
9															
10															
11															
12	1.40E-11	1.05E-11			9E-12				1.548E-12						
13															
14	4.30E-11	3.79E-11		4.68E-12	1.2E-12	3.2E-11									
15	2.36E-11	2.55E-11		2.55E-11											
16	9.90E-11	4.50E-11		3.00E-11	1.8E-12		9.9E-12	2.65E-13	2.993E-12						
17	3.00E-10	2.07E-10					2.07E-10								
18	9.00E-10	9.00E-10					9.00E-10								
19															
20	3.20E-12	3.60E-12					2.7E-12			9E-13					
21															
22	5.90E-13	3.78E-13							3.784E-13						
23															
24	1.30E-12	0.00E+00													
25	3.80E-12	3.80E-12									3.80E-12				
26	1.90E-11	1.90E-11										1.90E-11			
27	3.20E-11	3.20E-11											3.20E-11		
28	6.00E-10	6.02E-10			2.00E-10	4.00E-10			1.961E-12						
29		2.20E-12			2.2E-12										
30	1.70E-11	1.70E-11												1.70E-11	
31															
32	5.30E-12	5.30E-12						5.30E-12							
33															
34															
35															
36	3.00E-13	0.00E+00													
37	5.00E-13	0.00E+00													
38	1.00E-12	0.00E+00													
39	1.90E-12	0.00E+00													
40	5.00E-12	5.00E-12								5.00E-12					
41	4.00E-12	4.00E-12													4.00E-12
42		0.00E+00													
43	1.10E-12	0.00E+00													
44	1.72E-11	1.72E-11							1.72E-11						
45															

FIGURE 3.2-2

PARTIAL PRESSURE MASS 28 BSC 100 HR TEST, 24 HR SOAK

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TURBO
ION PUMP
BSC 100 HR PUMPDOWN TEST
RATE OF RISE TESTS
E-07
E-08
E-09
E-10
E-11
E-12
E-13
E-14
E-15
1
2
3
4
5
t [d]
2
18
28
14
44
1
2
7
8
12
14
18
20
22
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32
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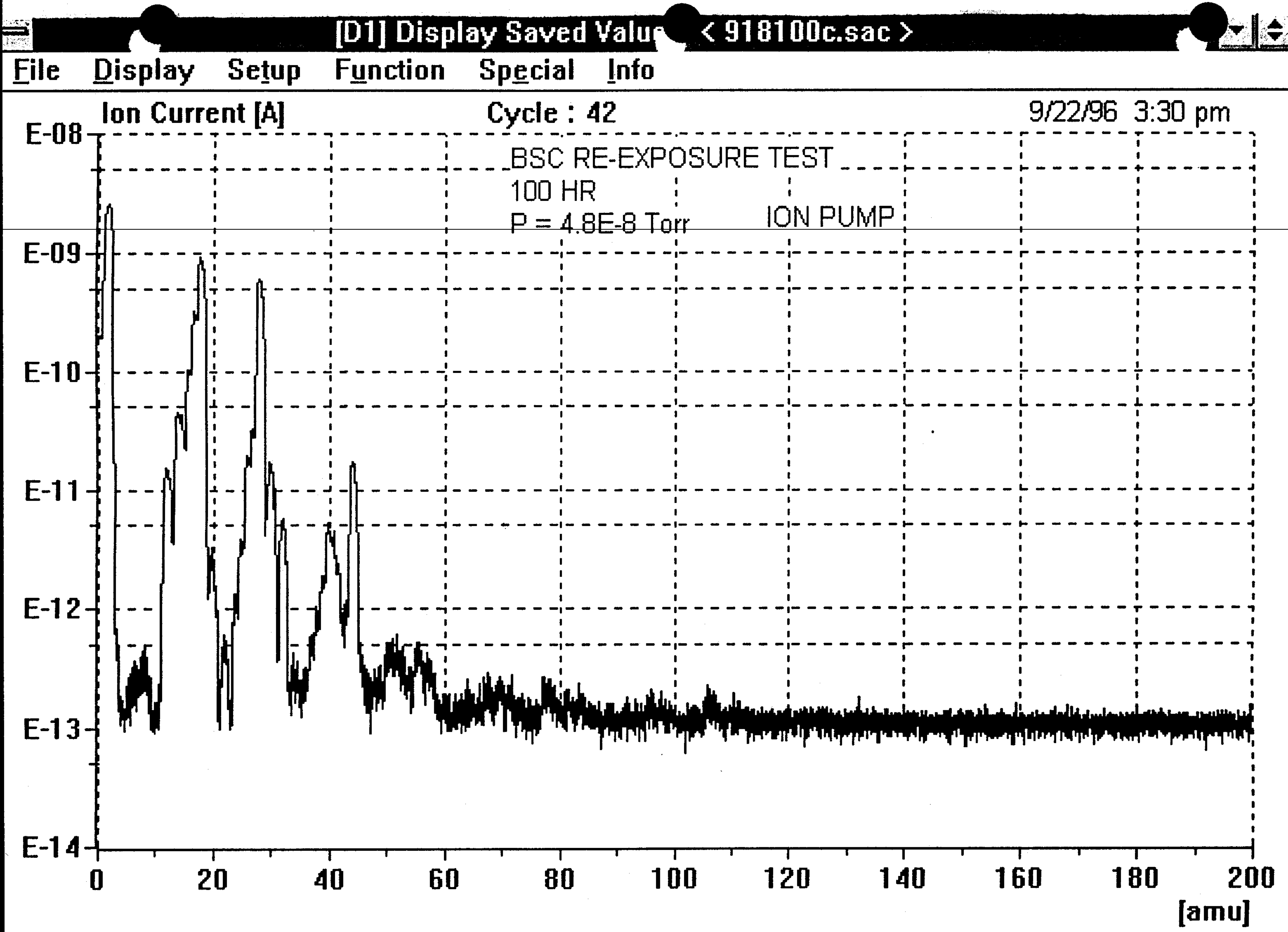
40
41
44
50
51
52
55



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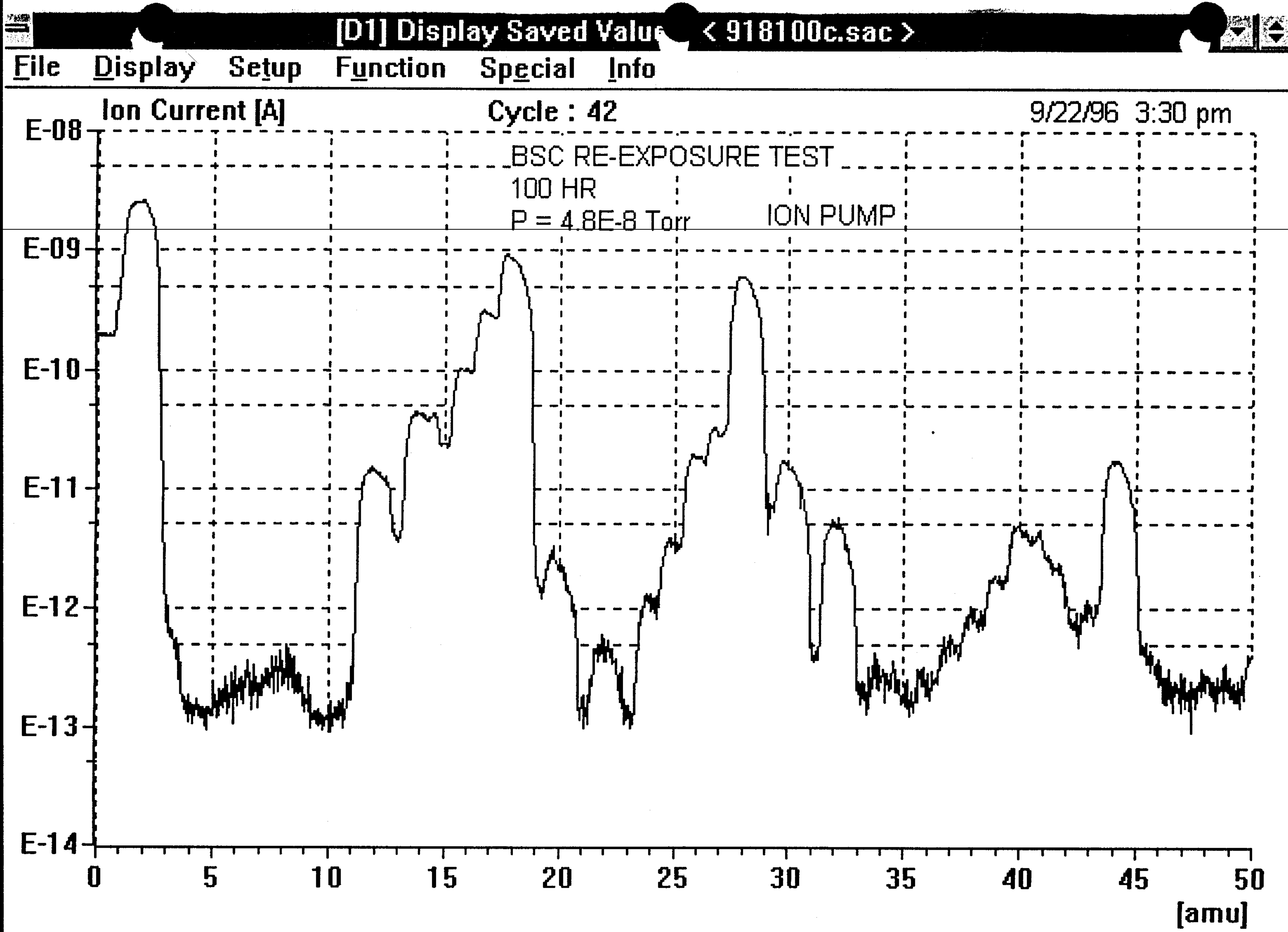
9/22/96 3:30 pm
BSC RE-EXPOSURE TEST
100 HR
P = 4.8E-8 Torr
ION PUMP
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
20
40
60
80
100
120
140
160
180
200
[amu]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9/22/96 3:30 pm
BSC RE-EXPOSURE TEST
100 HR
P = 4.8E-8 Torr
ION PUMP
E-08
E-09
E-10
E-11
E-12
E-13
E-14
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5
10
15
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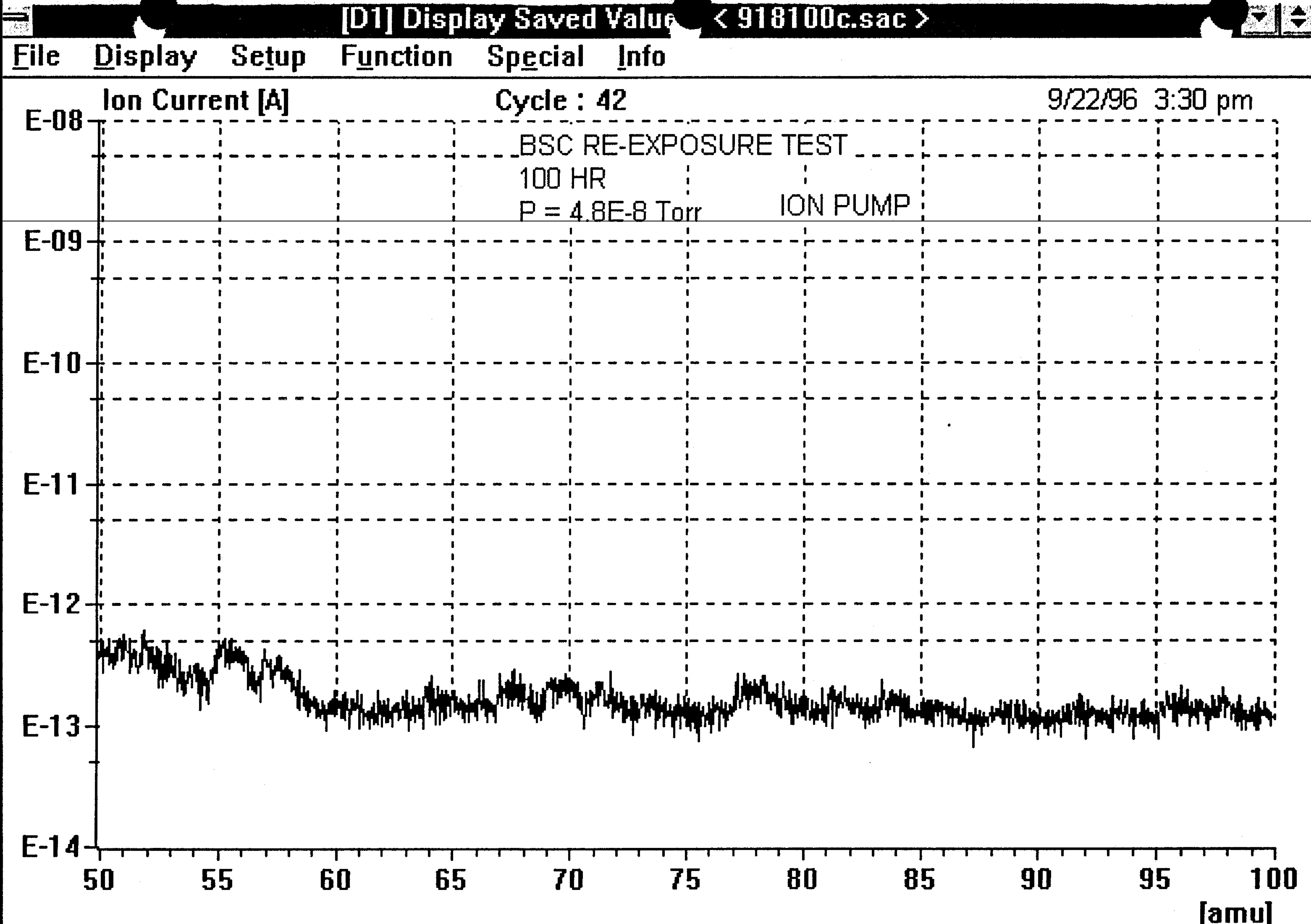
25
30
35
40
45
50
[amu]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9/22/96 3:30 pm
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100 HR
P = 4.8E-8 Torr
ION PUMP
E-08
E-09
E-10
E-11
E-12
E-13
E-14
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55
60
65
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75
80
85
90
95
100
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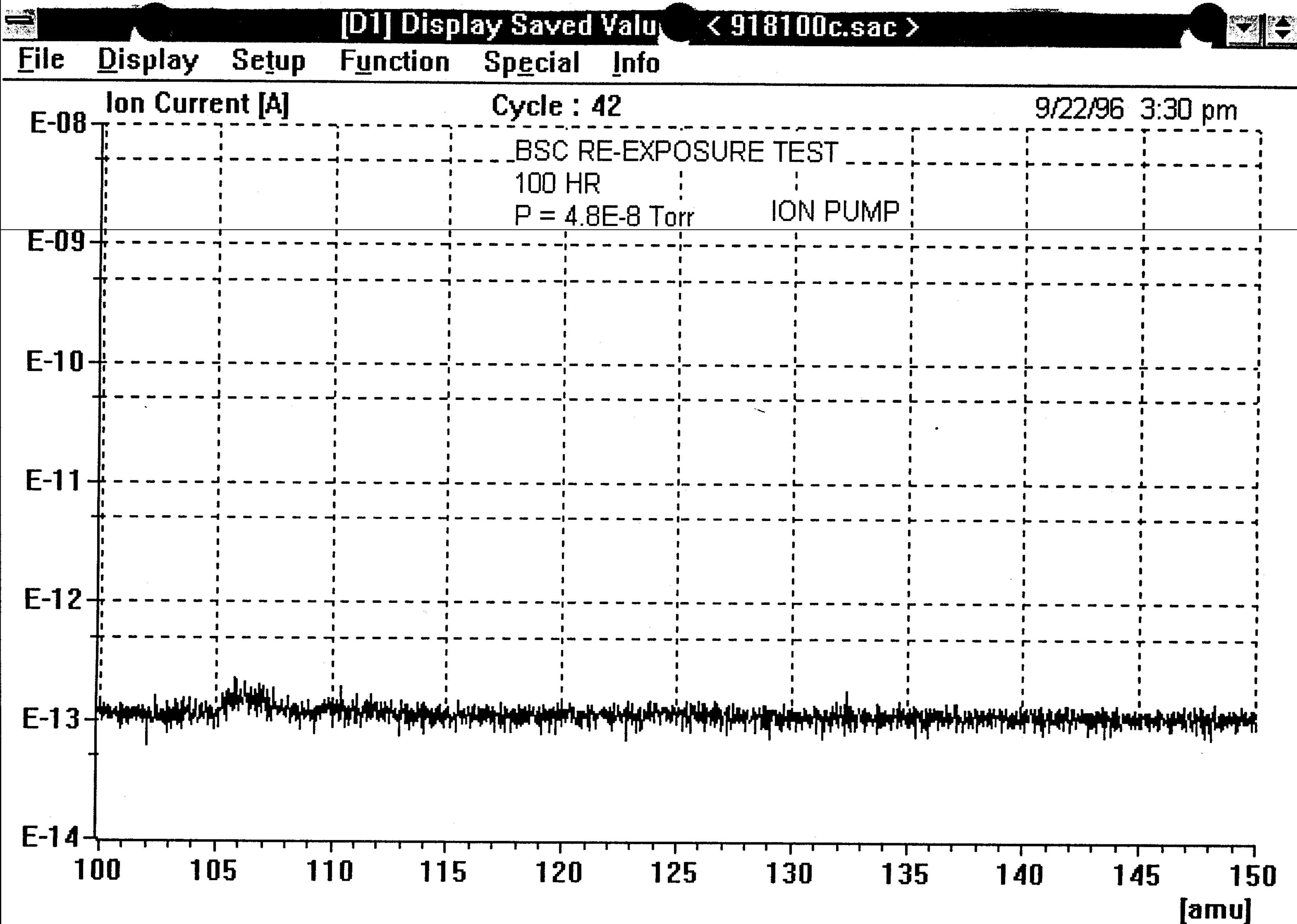
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9/22/96 3:30 pm
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100 HR
P = 4.8E-8 Torr
ION PUMP
E-08
E-09
E-10
E-11
E-12
E-13
E-14
100
105
110
115
120
125
130
135
140
145
150
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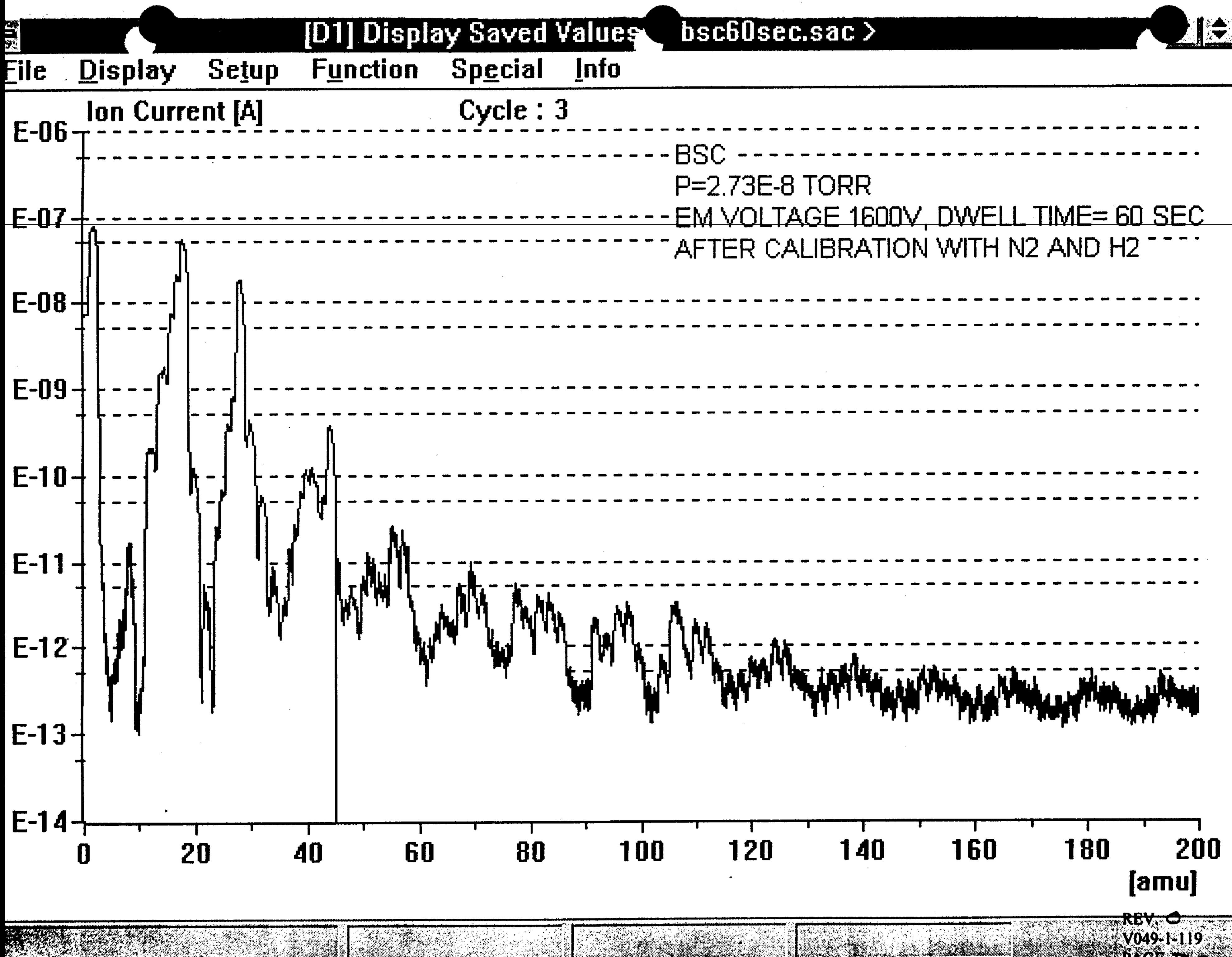
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AFTER CALIBRATION WITH N2 AND H2
E-06
E-07
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
20
40
60
80
100
120
140
160
180
200
[amu]

3.3 Additional 10" Chamber Test Results

The 10" chamber was tested in an all metal configuration and with a 10" o-ring placed loosely in the chamber. The following tests were run to establish the characteristics of the viton.

- All metal, 24 hour reexposure and soak with 0 grade nitrogen. Re pump for 100 hours.
- All metal, 24 hour reexposure and soak with cryotrapped 0 grade nitrogen. Re pump for 100 hours.
- Loose viton, 24 hour reexposure and soak with cryotrapped 0 grade nitrogen. Re pump for 100 hours.
- Loose viton, 1 hour reexposure and soak with cryotrapped 0 grade nitrogen. Re pump for 100 hours.

Figure 3.3-1 shows the relative performance for the various cases. Note that the viton with 1 hour reexposure is approximately midway between the 24 hour case and the all metal case.

Figure 3.3-2 shows the decay exponent for the viton with 1 hour and 24 hour reexposure.

Table 3.3.1 shows the 100 hour outgassing data for four cases in tabular format.

RGA scans for the four cases are also included.

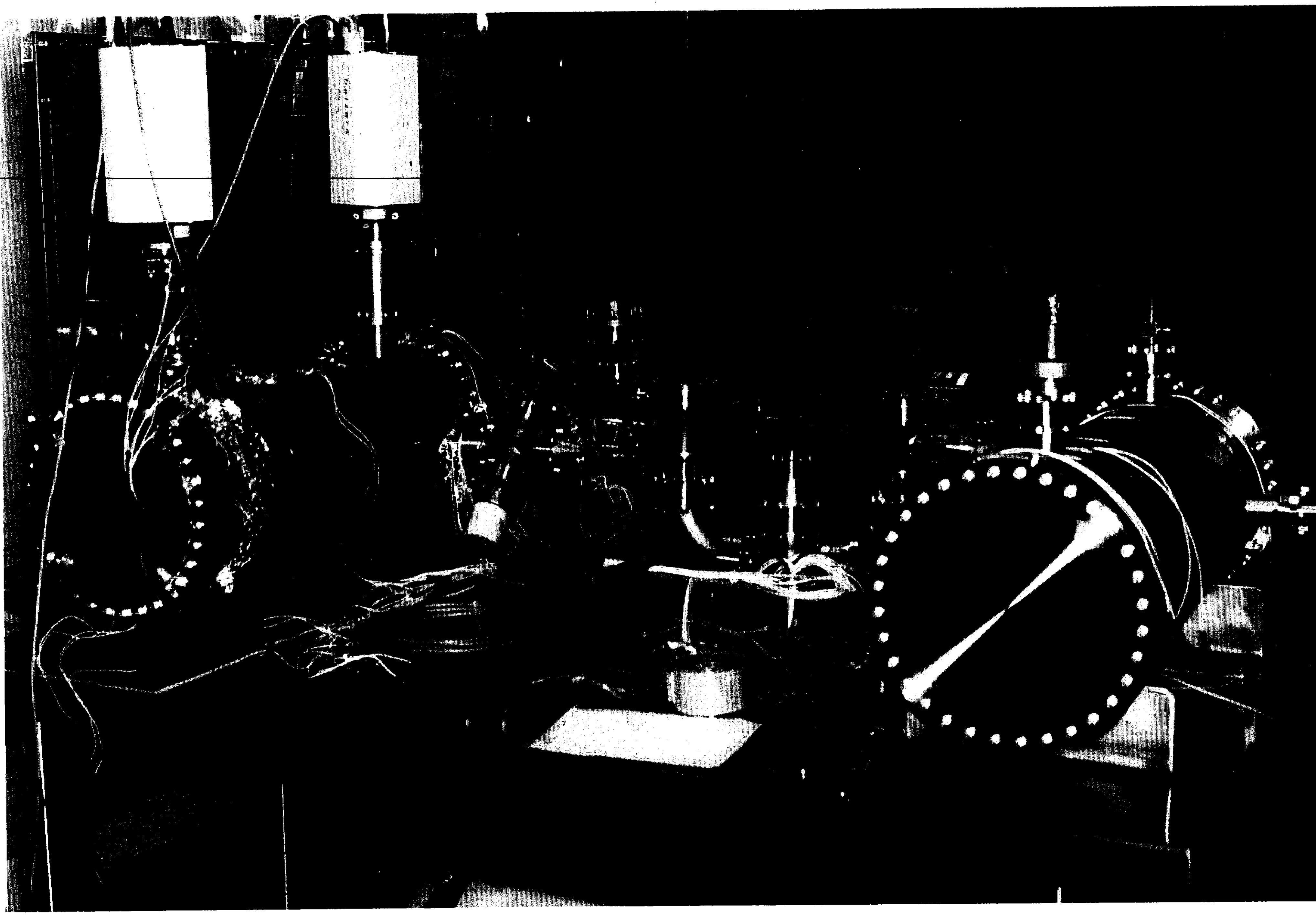


FIG II-3

FIGURE 3.3-1
10 INCH CHAMBER TEST DATA

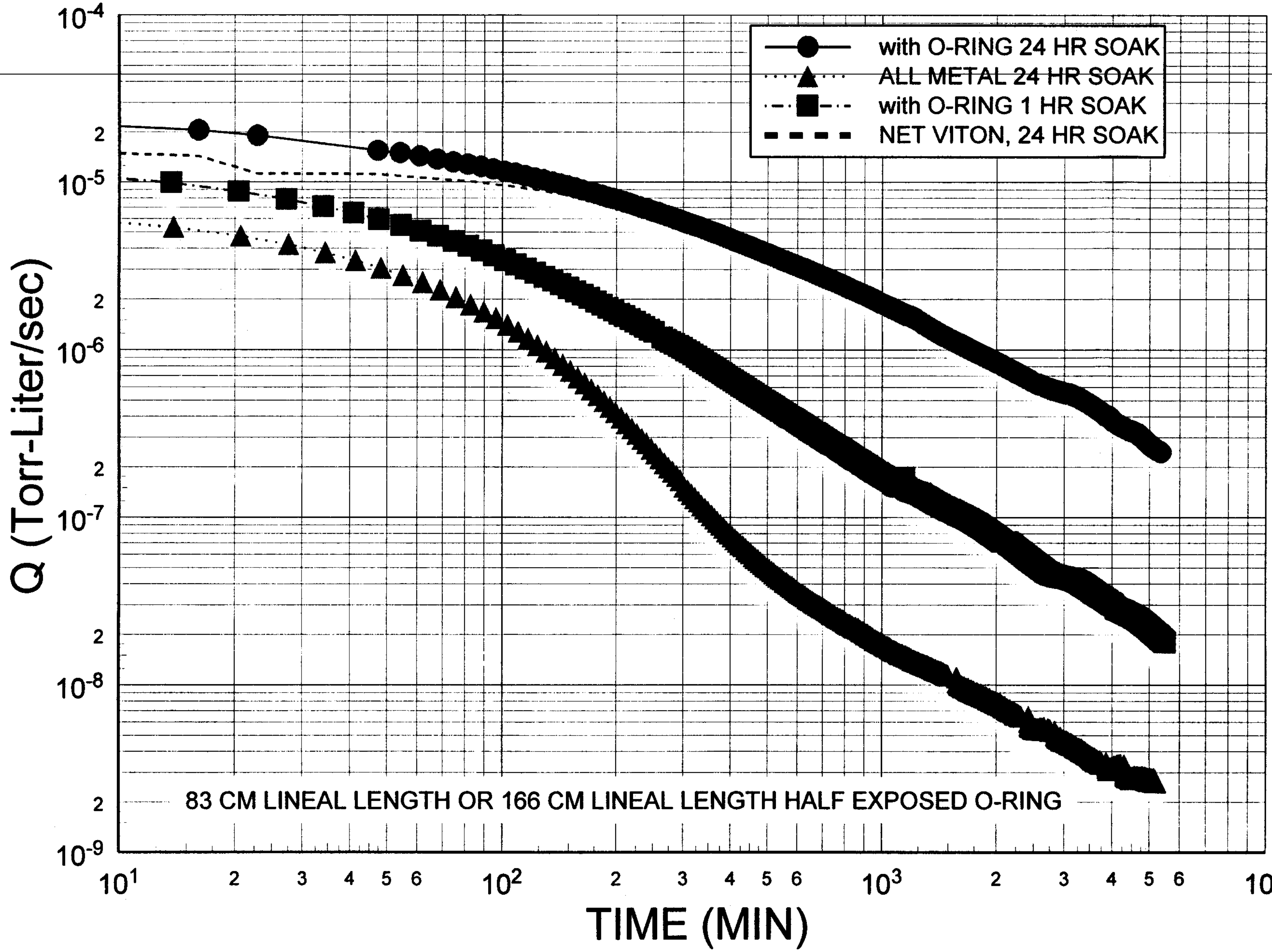
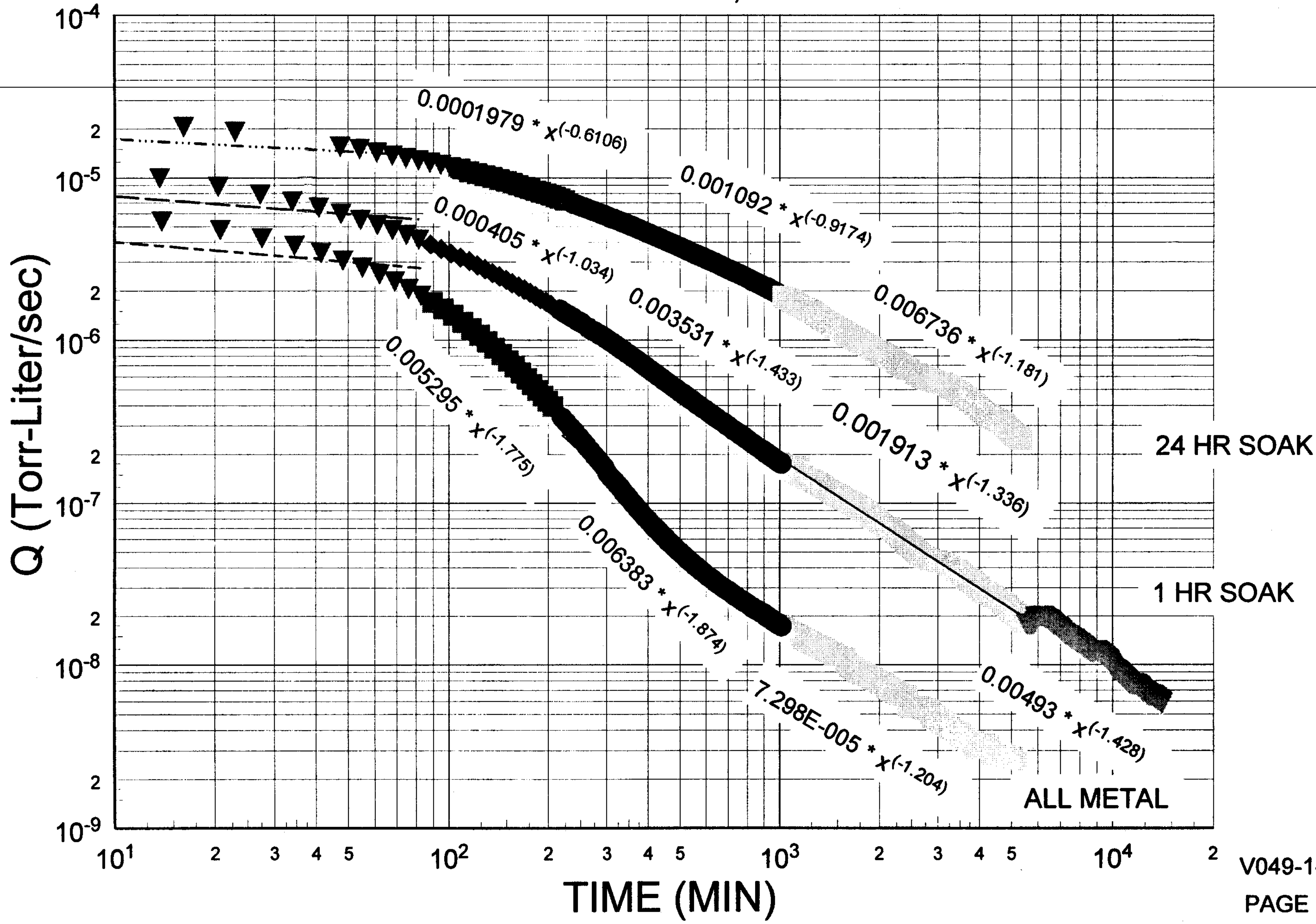
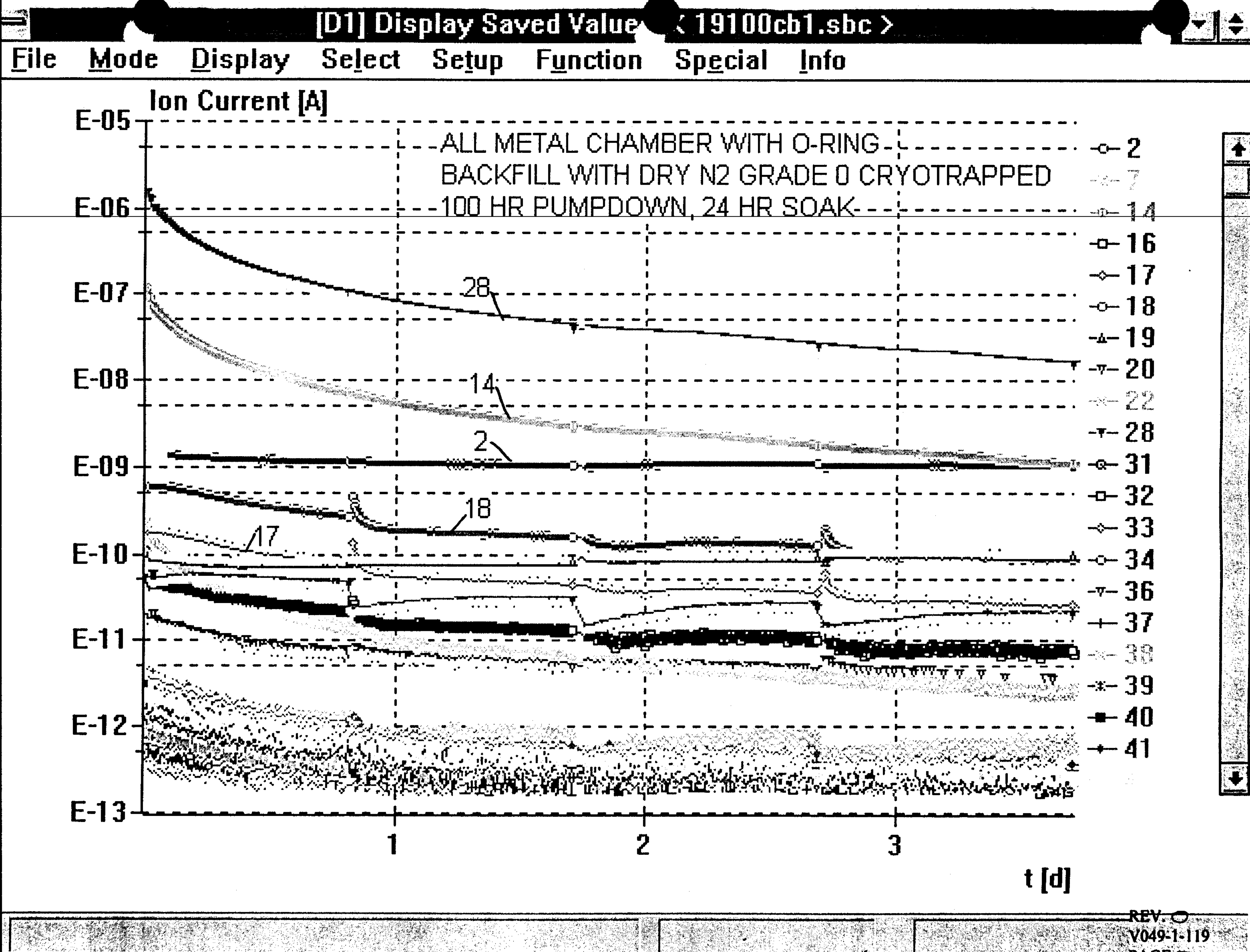


FIGURE 3.3-2

10 INCH CHAMBER TEST DATA, DECAY CURVE-FIT



V049-1-119



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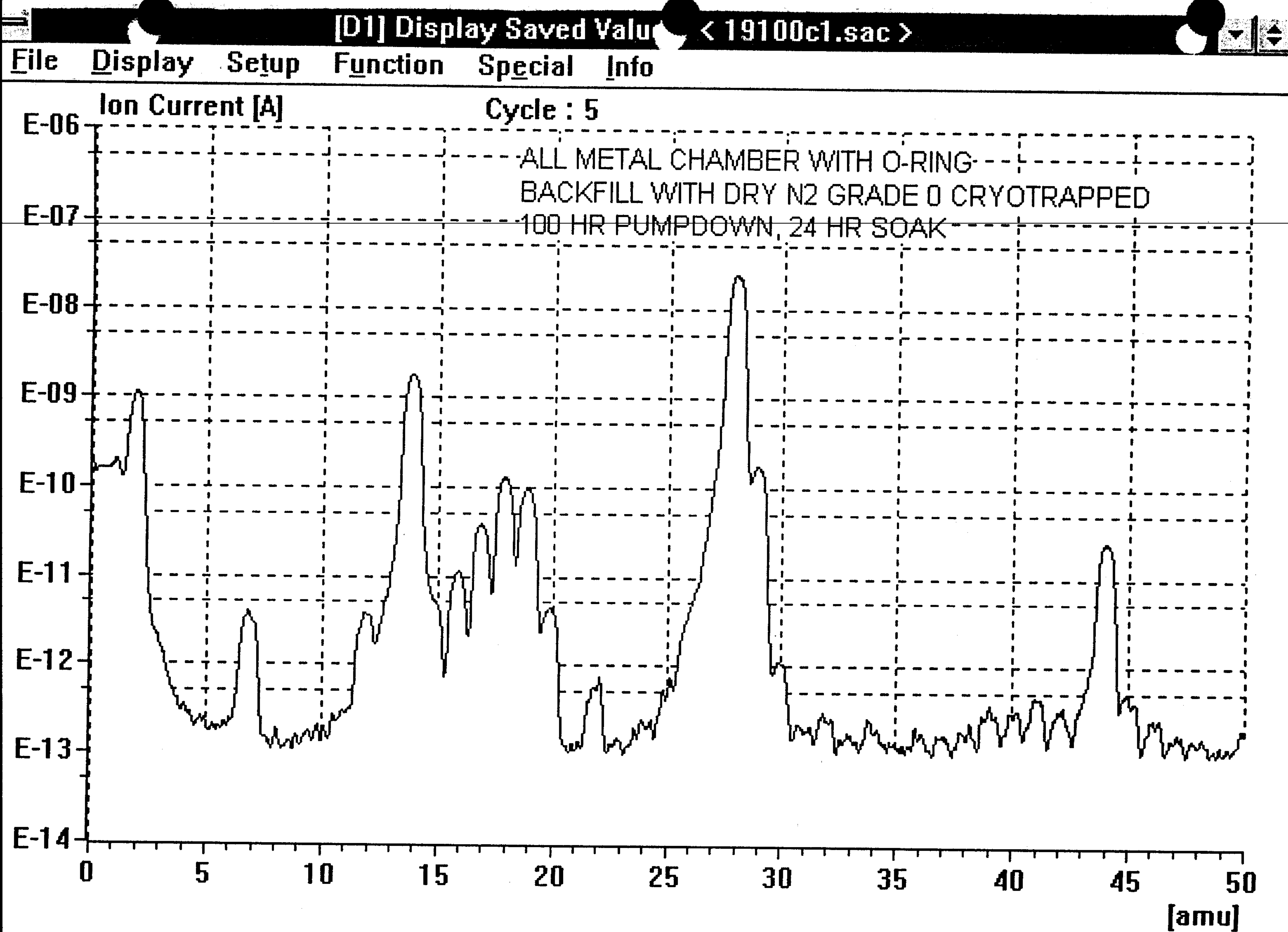
E-06
E-07
E-08
E-09
E-10
E-11
E-12
E-13
ALL METAL CHAMBER WITH O-RING
BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED
100 HR PUMPDOWN, 24 HR SOAK
28
14
2
18
17
1
2
3
t [d]
2
7
14
16
17
18
19
20
22
28
31
32
33
34
36
37
38
39
40
41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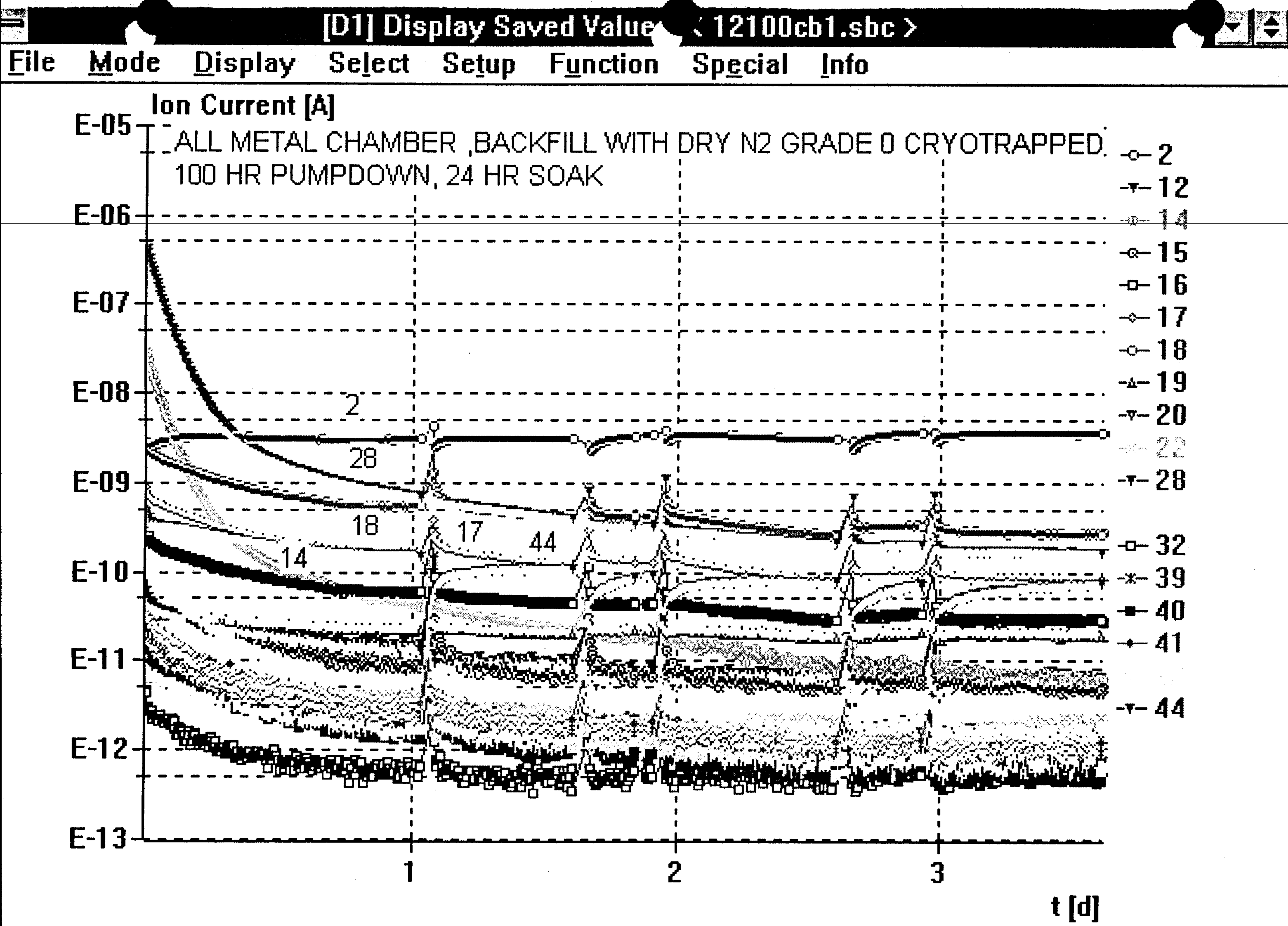
File Display Setup Function Special Info
Ion Current [A]
Cycle : 5
ALL METAL CHAMBER WITH O-RING
BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED
100 HR PUMPDOWN, 24 HR SOAK
E-06
E-07
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
5
10
15
20
25
30
35
40
45
50
[amu]



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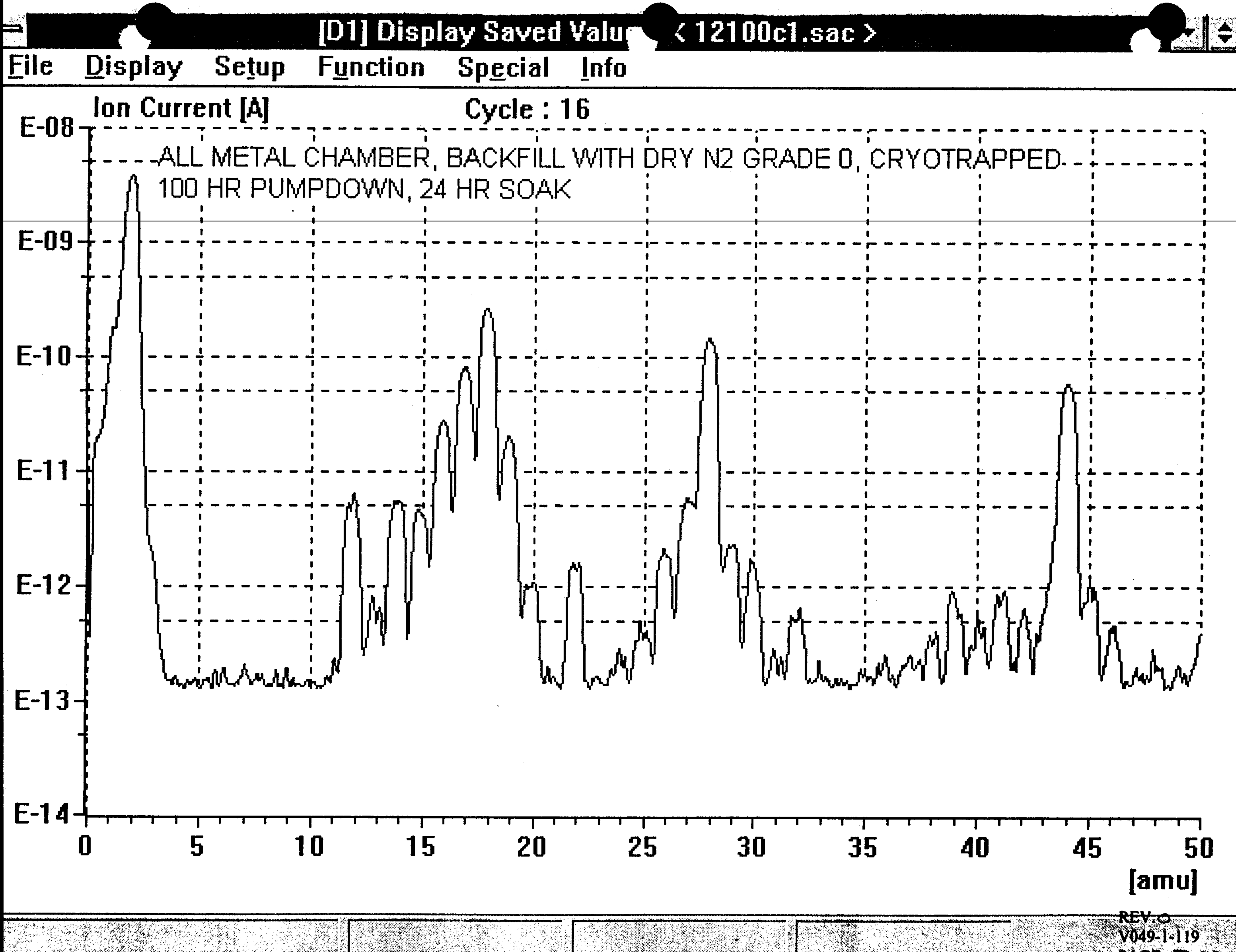
Ion Current [A]
ALL METAL CHAMBER ,BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED.
100 HR PUMPDOWN, 24 HR SOAK
E-05
E-06
E-07
E-08
E-09
E-10
E-11
E-12
E-13
2
28
18
17
44
14
1
2
3
t [d]
2
12
14
15
16
17
18
19
20
22
28
32
39
40
41
44



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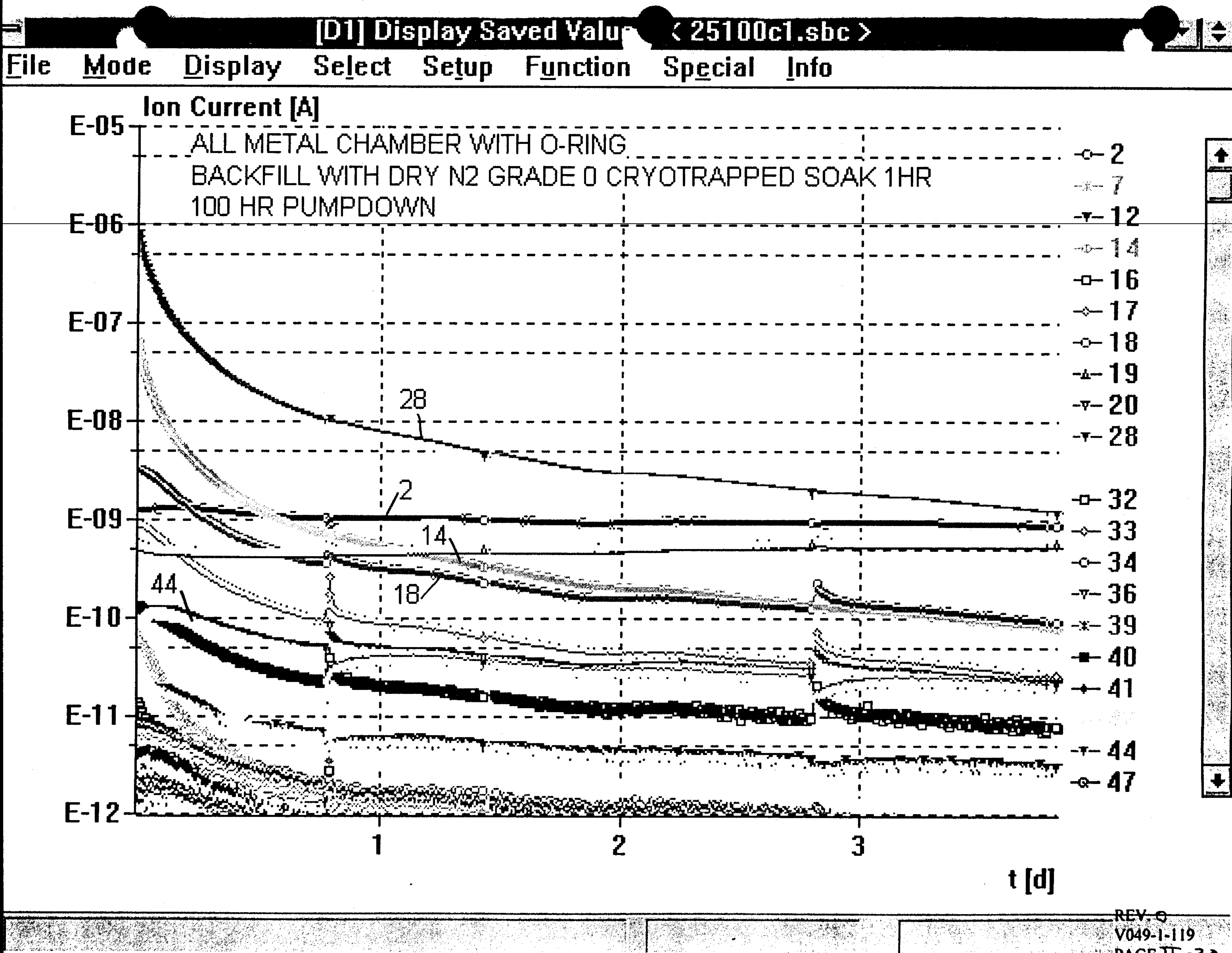
< 12100c1.sac >
File Display Setup Function Special Info
Ion Current [A]
Cycle : 16
ALL METAL CHAMBER, BACKFILL WITH DRY N2 GRADE 0, CRYOTRAPPED.
100 HR PUMPDOWN, 24 HR SOAK
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
5
10
15
20
25
30
35
40
45
50
[amu]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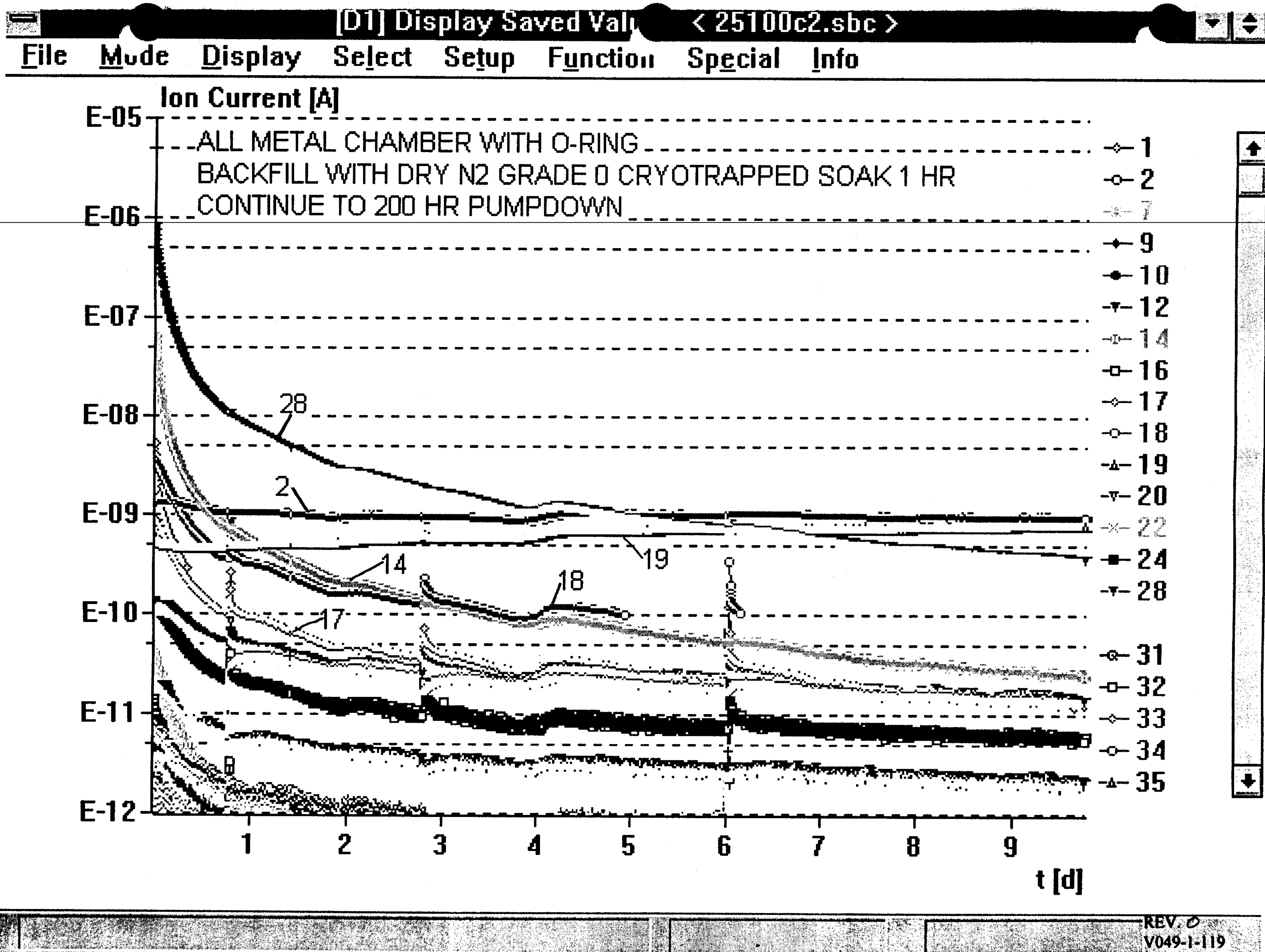
File Mode Display Select Setup Function Special Info
Ion Current [A]
ALL METAL CHAMBER WITH O-RING
BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED SOAK 1HR
100 HR PUMPDOWN
E-05
E-06
E-07
E-08
E-09
E-10
E-11
E-12
28
2
14
18
44
1
2
3
t [d]
2
7
12
14
16
17
18
19
20
28
32
33
34
36
39
40
41
44
47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File Mode Display Select Setup Function Special Info
Ion Current [A]
ALL METAL CHAMBER WITH O-RING
BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED SOAK 1 HR
CONTINUE TO 200 HR PUMPDOWN
E-05
E-06
E-07
E-08
E-09
E-10
E-11
E-12
28
2
19
14
18
17
1 2 3 4 5 6 7 8 9
t [d]
1
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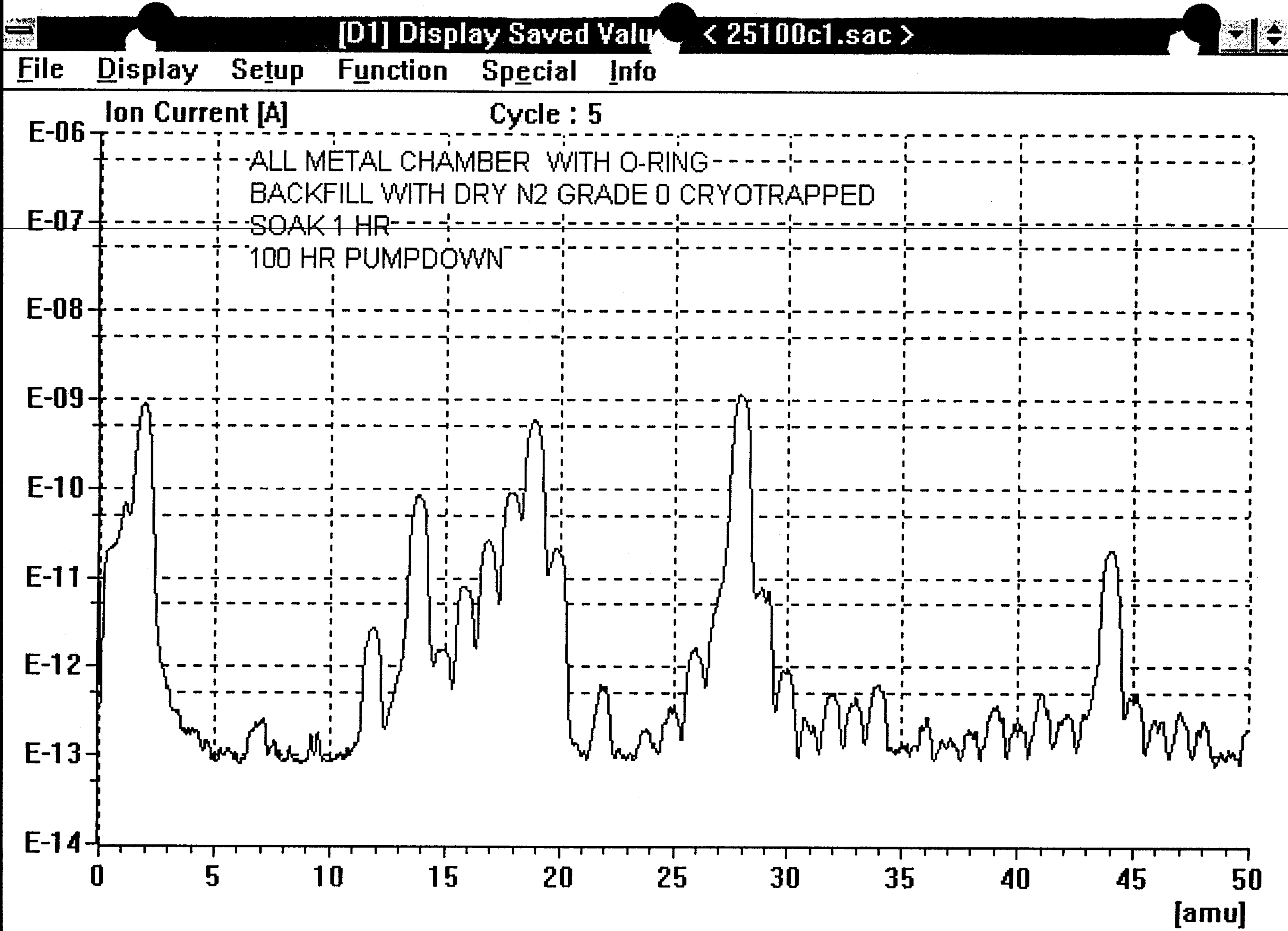
31
32
33
34
35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File Display Setup Function Special Info
Ion Current [A]
Cycle : 5
ALL METAL CHAMBER WITH O-RING
BACKFILL WITH DRY N2 GRADE 0 CRYOTRAPPED
SOAK 1 HR
100 HR PUMPDOWN
E-06
E-07
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
5
10
15
20
25
30
35
40
45
50
[amu]

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3.4 Projected System Pressures

Table 3.4-1 give the predicted partial pressures after 100 hours of pumping for the largest isolatable section based on the BSC data and on 1 hour reexposure data from the 10" chamber.

TABLE 3.4-1
ISOLATABLE SECTION ULTIMATE PRESSURES @ 100 HRS, PREDICTED
VERTEX + BEAM MANIFOLD

	LIGO	Predicted	Predicted
	Pressure	Pressure	Pressure
	Goals	24 hr exposure	1 hr exposure
Species	Torr	Torr	Torr
H2	5.0E-09	4.0E-09	4.0E-09
H2O	5.0E-09	2.4E-09	2.4E-09
N2	5.0E-10	**7.2E-09**	**7.0E-10**
CO	5.0E-10	3.0E-09	3.0E-09
CO2	2.0E-10	3.0E-10	3.0E-10
CH4	2.0E-10	9.0E-10	9.0E-10
OTHER	5.0E-10	6.6E-10	6.6E-10
TOTAL EXCLUDING H2O, H2	1.9E-09	1.2E-08	5.5E-09
TOTAL	**1.2E-08**	**1.8E-08**	**1.2E-08**

TABLE 3.4-2
ISOLATABLE SECTION ULTIMATE PRESSURES @ 100 HRS, PREDICTED
VERTEX + BEAM MANIFOLD

VERTEX + MANIFOLD FROM 10 INCH DATA 24 HR SOAK				
LINEAL LENGTH VITON (CM)	37639	CM		
AREA (M^2)	478	M^2		
VITON LIN. LEN. /SS_AREA	78.74	CM/M^2		
	RATE	SPEED	Pressure	Pressure
				GOALS
	Torr-L/s-cm^2	L/S	Torr	Torr
H2	1.00E-11	12000	4.0E-09	5.0E-09
H2O	1.00E-11	20000	2.4E-09	5.0E-09
N2	3.00E-13	8000	1.8E-10	5.0E-10
CO	5.00E-12	8000	3.0E-09	5.0E-10
CO2	5.00E-13	8000	3.0E-10	2.0E-10
CH4	1.50E-12	8000	9.0E-10	2.0E-10
OTHER	1.10E-12	8000	6.6E-10	5.0E-10
N2 FROM VITON Torr-L/s-cm	*1.50E-09*	8000	*7.1E-09*	5.0E-10
TOTAL			**1.8E-08**	**1.2E-08**
VERTEX + MANIFOLD FROM 10 INCH DATA 1 HR SOAK				
LINEAL LENGTH VITON (CM)	37639	CM		
AREA (M^2)	478	M^2		
VITON LIN. LEN. /SS_AREA	78.74	CM/M^2		
	RATE	SPEED	Pressure	Pressure
				GOALS
	Torr-L/s-cm^2	L/S	Torr	Torr
H2	1.00E-11	12000	4.0E-09	5.0E-09
H2O	1.00E-11	20000	2.4E-09	5.0E-09
N2	3.00E-13	8000	1.8E-10	5.0E-10
CO	5.00E-12	8000	3.0E-09	5.0E-10
CO2	5.00E-13	8000	3.0E-10	2.0E-10
CH4	1.50E-12	8000	9.0E-10	2.0E-10
OTHER	1.10E-12	8000	6.6E-10	5.0E-10
N2 FROM VITON Torr-L/s-cm	*1.10E-10*	8000	*5.2E-10*	
TOTAL			**1.2E-08**	**1.2E-08**

TABLE 3.4-3
10 INCH TEST DATA

	DRY ALL METAL					**ULTRA ALL METAL**				
MASS	A	Torr	Torr-L/s-A	Torr-L/s	Torr-L/s-cm^2	A	Torr	Torr-L/s-A	Torr-L/s	Torr-L/s-cm^2
H2	1.00E-09	9.01E-09	20	2E-08	2.66667E-12	*3.70E-09*	3.33E-08	20	7.4E-08	9.86667E-12
CH4	5.00E-11	1.04E-09	10	5E-10	6.66667E-14	3.00E-11	6.25E-10	10	3E-10	4E-14
H2O	3.50E-09	7.29E-08	10	3.5E-08	4.66667E-12	2.50E-10	5.21E-09	10	2.5E-09	3.33333E-13
CO	1.30E-10	3.47E-09	16	2.08E-09	2.77333E-13	7.00E-11	1.87E-09	16	1.12E-09	1.49333E-13
N2	1.00E-10	2.67E-09	16	1.6E-09	2.13333E-13	8.00E-11	2.13E-09	16	1.28E-09	1.70667E-13
CO2	2.70E-10	1.13E-08	25	6.75E-09	9E-13	5.80E-11	2.42E-09	25	1.45E-09	1.93333E-13
	5.05E-09	**1E-07**					**4.56E-08**		8.07E-08	
	ULTRA DRY WITH O-RING 24 HR SOAK					**ULTRA DRY WITH O-RING 1 HR SOAK**				
	O-RING	83 cm lineal length X 2 SIDES				O-RING	83 cm lineal length X 2 SIDES			
MASS	A	Torr	Torr-L/s-A	Torr-L/s	Torr-L/s-cm lineal lenght	A	Torr	Torr-L/s-A	Torr-L/s	Torr-L/s-cm lineal lenght
H2	1.00E-09	9.01E-09	20	2E-08		8.70E-10	7.84E-09	20	1.74E-08	
CH4	1.50E-11	3.13E-10	10	1.5E-10		8.00E-12	1.67E-10	10	8E-11	
H2O	1.10E-10	2.29E-09	10	1.1E-09		8.90E-11	1.85E-09	10	8.9E-10	
CO	1.50E-10	4E-09	16	2.4E-09		7.00E-11	1.87E-09	16	1.12E-09	
N2	1.50E-08	4E-07	16	2.4E-07	1.44578E-09	1.10E-09	2.93E-08	16	1.76E-08	1.06024E-10
CO2	2.00E-11	8.33E-10	25	5E-10		2.00E-11	8.33E-10	25	5E-10	
	1.63E-08	**4.16E-07**		2.64E-07		2.16E-09	**4.19E-08**		3.76E-08	
PREDICTED N2 GASLOAD FOR BSC										
LINEAL LENGHT VITON			2650	CM						
Specific gas load at 100 hr			1.50E-09	Torr-L/s-cm^2						
Total gas load from 10 inch data			3.98E-06	Torr-L/s						
BSC 100 hr test data reduced			5.50E-06	Torr-L/s						

4.0 Calibration Data

The RGA and the ion gauge were calibrated after the 100 hour pumpdown for both hydrogen and nitrogen.

4.1 Calibrated N2 Leak and H2 Leak Date Reduction

4.1.1 Nitrogen Data (See TABLE 4.1.1)

A 3.8×10^{-6} Torr-liter/sec calibrated nitrogen leak was used to calibrate the systems nitrogen gas load.

TABLE 4.1-1

CASE	DESCRIPTION
N1	Calibrated nitrogen leak test 1. The nitrogen leak was introduced and the change in current intensity at mass 28 was used to determine gas load sensitivity. The system gas load was computed from using the ion current at T=100hr.
N2	Calibrated nitrogen leak test 2. The test was repeated about 2 days later. The nitrogen leak was introduced and the change in current intensity at mass 28 was used to determine gas load sensitivity. The system gas load was computed from using the ion current at T=100hr.
N3	Using the calculated pumping speed for the ion pump and partial pressure of mass 28 for the current intensity at T=100 hr (converted with the calibrated RGA sensitivity), the system gas load was determined from this information.

4.1.2 Hydrogen Data

TABLE 4.1-2

CASE	DESCRIPTION
H1	Calibrated hydrogen leak test. The current intensity is lower compared to the value at T=100 hr. This could only be explained by an increased in hydrogen pumping speed that occurred after the rate of rise tests. Due to operation at higher pressures the pump was able to clean itself up. The system H2 gas load was computed using the ion current at T=100hr.
H2	Using the same system H2 gas load sensitivity in case H1 but the system gas load was computed using the current intensity measured during the calibrated leak test. This assumes that the hydrogen outgassing rate remain almost constant over time.
H3	Using the calculated pumping speed for the ion pump and partial pressure of mass 2 for the current intensity measured during the leak test (converted with the calibrated RGA sensitivity) the system H2 gas load was determined from this information.
H4	Using the calculated pumping speed for the ion pump and partial pressure of mass 2 for the current intensity measured T=100hr (converted with the calibrated RGA sensitivity) the system H2 gas load was determined from this information.
H5	Data after baking before re-exposure. Using the calculated pumping speed for the ion pump and partial pressure of mass 2 for the current intensity measured after bake (converted with the calibrated RGA sensitivity) the system H2 gas load was determined from this information.
H6	Turbo pump data. Data taken during pumpdown. Using the calculated pumping speed for the turbo pump and partial pressure of mass 2 for the current intensity measured during the pumpdown (converted with the calibrated RGA sensitivity) the system H2 gas load was determined from this information. The ion current was practically constant during the turbo pump operation.

Calibrated Leak

The leak was adjusted to give an intensity on the RGA that was about three times larger than the BSC base hydrogen intensity to be able to measure a current difference with minimum error. The hydrogen leak was calibrated by doing a rate of rise of the hydrogen leak into a small calibrated volume using the Baratron 698 to measure the pressure in the small calibrated volume.

The measured intensity difference due to the leak was 2.75×10^{-9} ampere.

The leak was measured at 1.7×10^{-5} Torr-liter/sec.

The hydrogen intensity without the leak was 8×10^{-10} ampere this would give a hydrogen gas load of about 5×10^{-6} Torr-liter/sec.

TABLE 4.1-3
N2 AND H2 DATA SUMMARY

CASE	N2 DATA	Gasload sensitvity	PUMP SPEED	Current	Current 100 hr	Partial Pressure	Gasload	Specific Rate
		Torr-L/sec-amp	L/S	A	A	Torr	Torr-L/s	Torr-L/s-cm^2
N1	CALIBRATED LEAK TEST 1	**10080**		5.23E-10	**5.90E-10**		**5.95E-06**	**1.08E-11**
N2	CALIBRATED LEAK TEST 2	**14620**		1.50E-10	**5.90E-10**		**8.63E-06**	**1.57E-11**
N3	RGA +ION GAUGE 100 HR		**237**		5.90E-10	**1.70E-08**	**4.03E-06**	**7.33E-12**
	H2 DATA							
	ION PUMP DATA							
	CALIBRATED LEAK TEST							
H1	using current at Time = 100hr	**6286**		7.50E-10	**2.40E-09**		**1.51E-05**	**2.74E-11**
H2	using current at test time	**6286**		7.50E-10	**7.50E-10**		**4.71E-06**	**8.57E-12**
H3	RGA +ION GAUGE *		***535***		7.50E-10	**8.90E-09**	**4.76E-06**	**8.66E-12**
H4	RGA +ION GAUGE 100 HR		***535***		2.40E-09	**2.80E-08**	**1.5E-05**	**2.72E-11**
	BAKED							
H5	RGA +ION GAUGE		***535***	1.40E-09		**1.50E-08**	**8.03E-06**	**1.46E-11**
	TURBO PUMP DATA							
H6	RGA +ION GAUGE		**398**	7.20E-10		**1.10E-08**	**4.38E-06**	**7.96E-12**
	535 L/s: Hydrogen speed is uncertain							
	* After the rate of rise test hydrogen current dropped which indicates ion pump for H2 increased							
	RGA + ION GAUGE: RGA Sensitivity used to obtain partial pressure from calibration against ion gauge, corrected by 1.3 factor							
	Bold: Information used to compute gasload							

4.2 Ion Gauge Calibration

The hot ionization gauge used was a factory calibrated Series 360 Granville-Phillips Stabil-Ion Gauge. The hot ion gauge was checked by expanding a known amount of mass into the BSC. The amount of gas was measured by filling a calibrated volume (0.994 liter) with nitrogen in the range from 0.01 Torr to 0.05 Torr using a 0.1 Torr range high accuracy capacitance manometer (MKS 698 Baratron) to measure the pressure. The known mass was then expanded into the BSC and allowed to equilibrate. No surface temperature measurements were made of the BSC's wall. The environmental control was operating and the room temperature was between 18^0C to 24^0C. Temperature difference between the calibrated volume and the BSC should be minimal.

The PV expansion pressure over ion gauge reading gives a ratio of 1.3. The Ion gauge appears to read a bit low in this pressure range against the PV expansion values.

<u>BSC volume calibration</u>

To determine the pressure in the BSC accurately the volume of the chamber needs to be measured. This was done by filling the BSC chamber with nitrogen. Mass input was measured using a mass flow meter and elapsed time. The pressure was measured using the capacitance manometer. The measured volume was about 25000 liters ±1700 liters.

<u>Ion gauge check against the high accuracy capacitance manometer.</u>

The ion gauge was also checked against the Baratron between the pressure of $2X10^{-4}$ Torr and $8X10^{-4}$.

The Baratron pressure over ion gauge pressure was about 1.12 in this pressure range.

4.3 RGA Gas Species Sensitivity Calibration

The RGA used in the test was a Balzers Prisma QMS200. The RGA's sensitivity for various gasses was determined against the Granville-Phillips Stabil ion gauge with the pump on and by bleeding in gas in through the variable leak valve.

The flow was changed to obtain data over a pressure range from low 10^{-7} Torr to low 10^{-6} Torr.

The RGA and ion gauge were mounted on a 10 inch diameter by 18 inch long spool piece mounted on one of the BSC 10 inch nozzles. The RGA was mounted at 90 degree angle from the ion gauge. The gauges were not in line of sight of each other. The gauges were located about 5 inches from the entrance to the BSC nozzle.

The leak was introduced at the far end of the 10 inch spool piece.

Net Pumping Speed Calculations

NET PUMPING SPEED
TURBO AND ION PUMP

TURBO PUMP

$R := 8314.8 \cdot \frac{m^2}{sec^2 \cdot K}$ $\quad T := 293. \cdot K$ $\quad D_{10in} := 0.248 \cdot m$ $\quad D_{6in} := .148 \cdot m$

$M_{N2} := 28.$ $\quad M_{H2} := 2.$ $\quad L_{10in} := .228 \cdot m$ $\quad L_{6in} := 2.5 \cdot m$

$V_{N2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{N2}}}$ $\quad V_{N2} = 117.677 \cdot m \cdot sec^{-1}$ $\quad V_{H2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{H2}}}$ $\quad V_{H2} = 440.306 \cdot m \cdot sec^{-1}$

$A_{10in} := \frac{\pi}{4.} \cdot D_{10in}^2$ $\quad A_{10in} = 0.048 \cdot m^2$ $\quad A_{6in} := \frac{\pi}{4.} \cdot D_{6in}^2$ $\quad A_{6in} = 0.017 \cdot m^2$

$P_{10in} := \left(1 + 0.375 \cdot \frac{L_{10in}}{0.5 \cdot D_{10in}}\right)^{-1}$ $\quad P_{6in} := \left(1 + 0.375 \cdot \frac{L_{6in}}{0.5 \cdot D_{6in}}\right)^{-1}$

$C_{H2\_10in} := P_{10in} \cdot V_{H2} \cdot A_{10in}$ $\quad C_{H2\_6in} := P_{6in} \cdot V_{H2} \cdot A_{6in}$

$C_{N2\_10in} := P_{10in} \cdot V_{N2} \cdot A_{10in}$ $\quad C_{N2\_6in} := P_{6in} \cdot V_{N2} \cdot A_{6in}$

$C_{N2\_10in} = 3.365 \cdot 10^3 \cdot \frac{liter}{sec}$ $\quad C_{H2\_6in} = 554.158 \cdot \frac{liter}{sec}$

$C_{H2\_10in} = 1.259 \cdot 10^4 \cdot \frac{liter}{sec}$ $\quad C_{N2\_6in} = 148.105 \cdot \frac{liter}{sec}$

$S_{N2pump} := 2000 \cdot \frac{liter}{sec}$ $\quad S_{H2pump} := 1600 \cdot \frac{liter}{sec}$

$$Snet_{N2} := \frac{1.}{\left(\frac{1}{S_{N2pump}} + \frac{1}{C_{N2\_10in}} + \frac{1}{C_{N2\_6in}}\right)} \qquad Snet_{N2} = 132.465 \cdot \frac{liter}{sec}$$

$$Snet_{H2} := \frac{1.}{\left(\frac{1}{S_{H2pump}} + \frac{1}{C_{H2\_10in}} + \frac{1}{C_{H2\_6in}}\right)} \qquad Snet_{H2} = 398.569 \cdot \frac{liter}{sec}$$

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NET PUMPING SPEED
TURBO AND ION PUMP

500 L/S NOBLE DIODE ION PUMP

$R := 8314.8 \cdot \frac{m^2}{sec^2 \cdot K}$ $T := 293. \cdot K$ $M_{N2} := 28.$ $M_{H2} := 2.$ $D_{6in} := .148 \cdot m$ $L_{6in} := 0.55 \cdot m$

$V_{N2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{N2}}}$ $V_{N2} = 117.677 \cdot m \cdot sec^{-1}$ $V_{H2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{H2}}}$ $V_{H2} = 440.306 \cdot m \cdot sec^{-1}$

$A_{6in} := \frac{\pi}{4.} \cdot D_{6in}^2$ $A_{6in} = 0.017 \cdot m^2$ $P_{6in} := \left(1 + 0.375 \cdot \frac{L_{6in}}{0.5 \cdot D_{6in}}\right)^{-1}$

$C_{N2\_6in} := P_{6in} \cdot V_{N2} \cdot A_{6in}$ $C_{H2\_6in} := P_{6in} \cdot V_{H2} \cdot A_{6in}$

$C_{N2\_6in} = 534.552 \cdot \frac{liter}{sec}$ $C_{H2\_6in} = 2 \cdot 10^3 \cdot \frac{liter}{sec}$

$S_{N2pump} := 425 \cdot \frac{liter}{sec}$ **at 1x10^{-7} Torr** $S_{H2pump} := 730 \cdot \frac{liter}{sec}$ **at 1x10^{-7} Torr**

$Snet_{N2} := \frac{1.}{\left(\frac{1}{S_{N2pump}} + \frac{1}{C_{N2\_6in}}\right)}$ $Snet_{N2} = 236.761 \cdot \frac{liter}{sec}$

$Snet_{H2} := \frac{1.}{\left(\frac{1}{S_{H2pump}} + \frac{1}{C_{H2\_6in}}\right)}$ $Snet_{H2} = 534.807 \cdot \frac{liter}{sec}$

Calibrated N2 and H2 Leak Data Reduction

NET PUMPING SPEED
TURBO AND ION PUMP

TURBO PUMP

$R := 8314.8 \cdot \frac{m^2}{sec^2 \cdot K}$ $\quad T := 293. \cdot K$ $\quad D_{10in} := 0.248 \cdot m$ $\quad D_{6in} := .148 \cdot m$

$M_{N2} := 28.$ $\quad L_{10in} := .228 \cdot m$ $\quad L_{6in} := 2.5 \cdot m$

$M_{H2} := 2.$

$V_{N2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{N2}}}$ $\quad V_{N2} = 117.677 \cdot m \cdot sec^{-1}$ $\quad V_{H2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{H2}}}$ $\quad V_{H2} = 440.306 \cdot m \cdot sec^{-1}$

$A_{10in} := \frac{\pi}{4.} \cdot D_{10in}^2$ $\quad A_{10in} = 0.048 \cdot m^2$ $\quad A_{6in} := \frac{\pi}{4.} \cdot D_{6in}^2$ $\quad A_{6in} = 0.017 \cdot m^2$

$P_{10in} := \left(1 + 0.375 \cdot \frac{L_{10in}}{0.5 \cdot D_{10in}}\right)^{-1}$ $\quad P_{6in} := \left(1 + 0.375 \cdot \frac{L_{6in}}{0.5 \cdot D_{6in}}\right)^{-1}$

$C_{H2\_10in} := P_{10in} \cdot V_{H2} \cdot A_{10in}$ $\quad C_{H2\_6in} := P_{6in} \cdot V_{H2} \cdot A_{6in}$

$C_{N2\_10in} := P_{10in} \cdot V_{N2} \cdot A_{10in}$ $\quad C_{N2\_6in} := P_{6in} \cdot V_{N2} \cdot A_{6in}$

$C_{N2\_10in} = 3.365 \cdot 10^3 \cdot \frac{liter}{sec}$ $\quad C_{H2\_6in} = 554.158 \cdot \frac{liter}{sec}$

$C_{H2\_10in} = 1.259 \cdot 10^4 \cdot \frac{liter}{sec}$ $\quad C_{N2\_6in} = 148.105 \cdot \frac{liter}{sec}$

$S_{N2pump} := 2000 \cdot \frac{liter}{sec}$ $\quad S_{H2pump} := 1600 \cdot \frac{liter}{sec}$

$Snet_{N2} := \frac{1.}{\left(\frac{1}{S_{N2pump}} + \frac{1}{C_{N2\_10in}} + \frac{1}{C_{N2\_6in}}\right)}$ $\quad Snet_{N2} = 132.465 \cdot \frac{liter}{sec}$

$Snet_{H2} := \frac{1.}{\left(\frac{1}{S_{H2pump}} + \frac{1}{C_{H2\_10in}} + \frac{1}{C_{H2\_6in}}\right)}$ $\quad Snet_{H2} = 398.569 \cdot \frac{liter}{sec}$

NET PUMPING SPEED
TURBO AND ION PUMP

500 L/S NOBLE DIODE ION PUMP

$R := 8314.8 \cdot \frac{m^2}{sec^2 \cdot K}$ $T := 293. \cdot K$ $M_{N2} := 28.$ $M_{H2} := 2.$ $D_{6in} := .148 \cdot m$

$L_{6in} := 0.55 \cdot m$

$V_{N2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{N2}}}$ $V_{N2} = 117.677 \cdot m \cdot sec^{-1}$ $V_{H2} := \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M_{H2}}}$ $V_{H2} = 440.306 \cdot m \cdot sec^{-1}$

$A_{6in} := \frac{\pi}{4.} \cdot D_{6in}^{2}$ $A_{6in} = 0.017 \cdot m^2$ $P_{6in} := \left(1 + 0.375 \cdot \frac{L_{6in}}{0.5 \cdot D_{6in}}\right)^{-1}$

$C_{N2\_6in} := P_{6in} \cdot V_{N2} \cdot A_{6in}$ $C_{H2\_6in} := P_{6in} \cdot V_{H2} \cdot A_{6in}$

$C_{N2\_6in} = 534.552 \cdot \frac{liter}{sec}$ $C_{H2\_6in} = 2 \cdot 10^{3} \cdot \frac{liter}{sec}$

$S_{N2pump} := 425 \cdot \frac{liter}{sec}$ **at 1x10^{-7} Torr** $S_{H2pump} := 730 \cdot \frac{liter}{sec}$ **at 1x10^{-7} Torr**

$Snet_{N2} := \frac{1.}{\left(\frac{1}{S_{N2pump}} + \frac{1}{C_{N2\_6in}}\right)}$ $Snet_{N2} = 236.761 \cdot \frac{liter}{sec}$

$Snet_{H2} := \frac{1.}{\left(\frac{1}{S_{H2pump}} + \frac{1}{C_{H2\_6in}}\right)}$ $Snet_{H2} = 534.807 \cdot \frac{liter}{sec}$

NITROGEN GAS LOAD

CASE N1: TEST 1 CALIBRATED N2 LEAK

$I_{withleak} := 9.0 \cdot 10^{-10} \cdot amp$ $I_{noleak} := 5.23 \cdot 10^{-10} \cdot amp$ $Q_{leakN2} := 3.8 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$

$P_{iongaugewithleak} := 4.92 \cdot 10^{-8} \cdot torr$ $P_{iongaugenoleak} := 3.87 \cdot 10^{-8} \cdot torr$

$S_{leakN2} := \frac{Q_{leakN2}}{(I_{withleak} - I_{noleak})}$ $S_{iongauge} := \frac{Q_{leakN2}}{(P_{iongaugewithleak} - P_{iongaugenoleak})}$

$S_{leakN2} = 1.008 \cdot 10^{4} \cdot torr \cdot \frac{liter}{sec \cdot amp}$ $S_{iongauge} = 361.905 \cdot \frac{liter}{sec}$ **torr N2/torr ion gauge**

If all current at M28 is N2

$Q_{N2} := I_{noleak} \cdot S_{leakN2}$ $Q_{N2} = 5.272 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$

$I_{N2\_100hr} := 5.9 \cdot 10^{-10} \cdot amp$

$Area_{BSC} := 55. \cdot 10^{4} \cdot cm^{2}$

$Q_{N2\_100hr} := I_{N2\_100hr} \cdot S_{leakN2}$ $Q_{N2\_100hr} = 5.947 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$ **at 100 hr** $q_{N2\_100hr} := \frac{Q_{N2\_100hr}}{Area_{BSC}}$ $q_{N2\_100hr} = 1.081 \cdot 10^{-11} \cdot torr \cdot \frac{liter}{sec \cdot cm^{2}}$

CASE N2: **TEST 2 CALIBRATED N2 LEAK**

$I_{withleak} := 4.1\cdot10^{-10}\cdot amp$ $I_{noleak} := 1.5\cdot10^{-10}\cdot amp$ $Q_{leakN2} := 3.8\cdot10^{-6}\cdot torr\cdot\frac{liter}{sec}$

$P_{iongaugewithleak} := 3.68\cdot10^{-8}\cdot torr$ $P_{iongaugenoleak} := 2.73\cdot10^{-8}\cdot torr$

$S_{leakN2} := \frac{Q_{leakN2}}{(I_{withleak} - I_{noleak})}$ $S_{iongauge} := \frac{Q_{leakN2}}{(P_{iongaugewithleak} - P_{iongaugenoleak})}$

$S_{leakN2} = 1.462\cdot10^{4}\cdot torr\cdot\frac{liter}{sec\cdot amp}$ $S_{iongauge} = 400\cdot\frac{liter}{sec}$ **torr N2/torr ion gauge**

If all current at M28 is N2

$Area_{BSC} := 55.\cdot10^{4}\cdot cm^{2}$

$Q_{N2} := I_{noleak}\cdot S_{leakN2}$ $Q_{N2} = 2.192\cdot10^{-6}\cdot torr\cdot\frac{liter}{sec}$ **at 160 hr** $q_{N2} := \frac{Q_{N2}}{Area_{BSC}}$ $q_{N2} = 3.986\cdot10^{-12}\cdot torr\cdot\frac{liter}{sec\cdot cm^{2}}$

$I_{N2\_100hr} := 5.9\cdot10^{-10}\cdot amp$

$Q_{N2\_100hr} := I_{N2\_100hr}\cdot S_{leakN2}$ $Q_{N2\_100hr} = 8.623\cdot10^{-6}\cdot torr\cdot\frac{liter}{sec}$ **at 100 hr** $q_{N2\_100hr} := \frac{Q_{N2\_100hr}}{Area_{BSC}}$ $q_{N2\_100hr} = 1.568\cdot10^{-11}\cdot torr\cdot\frac{liter}{sec\cdot cm^{2}}$

CASE N3: AGAINST RGA SENSITIVITY WITH ION GAUGE AND CALCULATED PUMP SPEED

$S_{PUMPN2} := 237 \cdot \frac{liter}{sec}$ $S_{N2RGA} := 28 \cdot \frac{torr}{amp}$

$P_{N2} := S_{N2RGA} \cdot I_{N2\_100hr}$ $P_{N2} = 1.652 \cdot 10^{-8} \cdot torr$

$Q_{N2\_100hr} := P_{N2} \cdot S_{PUMPN2}$ $Q_{N2\_100hr} = 3.915 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$

$Q_{N2\_100hr\_correct} := Q_{N2\_100hr} \cdot 1.3$ **correct for ion gauge 1.3 factor**

$Q_{N2\_100hr\_correct} = 5.09 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$

$q_{N2\_100hr} := \frac{Q_{N2\_100hr}}{Area_{BSC}}$ $q_{N2\_100hr} = 7.119 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

$q_{N2\_100hr\_correct} := \frac{Q_{N2\_100hr\_correct}}{Area_{BSC}}$ $q_{N2\_100hr\_correct} = 9.254 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

HYDROGEN GAS LOAD

CASE H2 : CALIBRATED H2 LEAK

$V_{calibrated} := 0.994 \cdot liter$ $\quad P_{baratron} := 0.05236 \cdot torr$ $\quad Time := 3000 \cdot sec$

$Q_{leakH2} := V_{calibrated} \cdot \frac{P_{baratron}}{Time}$ $\quad Q_{leakH2} = 1.735 \cdot 10^{-5} \cdot torr \cdot \frac{liter}{sec}$

$I_{withleak} := 3.51 \cdot 10^{-9} \cdot amp$ $\quad I_{noleak} := 7.5 \cdot 10^{-10} \cdot amp$

$S_{leakH2} := \frac{Q_{leakH2}}{(I_{withleak} - I_{noleak})}$

$S_{leakH2} = 6.286 \cdot 10^{3} \cdot torr \cdot \frac{liter}{sec \cdot amp}$ **gasload sensitivity per ampere at mass 2**

$Area_{BSC} := 55 \cdot 10^{4} \cdot cm^2$

$Q_{H2} := I_{noleak} \cdot S_{leakH2}$ $\quad Q_{H2} = 4.714 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$ $\quad q_{H2} := \frac{Q_{H2}}{Area_{BSC}}$ $\quad q_{H2} = 8.571 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

CASE H1: USING ION CURRENT AT T=100 HR

$I_{H2100hr} := 2.4 \cdot 10^{-9} \cdot amp$ **(if pumping remained the same, using the ion current at Time=100 hr)**

$Q_{H2\_100hr} := I_{H2100hr} \cdot S_{leakH2}$ $\quad Q_{H2\_100hr} = 1.509 \cdot 10^{-5} \cdot torr \cdot \frac{liter}{sec}$ $\quad q_{H2} := \frac{Q_{H2\_100hr}}{Area_{BSC}}$ $\quad q_{H2} = 2.743 \cdot 10^{-11} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

CASE H5: H2, AFTER BAKE

$I_{H2\_afterbake} := 1.4 \cdot 10^{-9} \cdot amp$ $\quad$ $P_{iongauge} := 7.0 \cdot 10^{-9} \cdot torr$

USING ION GAUGE READING AND CALCULATED PUMPING SPEED

$F_{ion\_H2} := 0.46$ $\quad$ **ionization efficiency**

$P_{H2} := \dfrac{P_{iongauge}}{F_{ion\_H2}}$ $\quad$ $P_{H2} = 1.522 \cdot 10^{-8} \cdot torr$ $\quad$ $S_{PUMPH2} := 535 \cdot \dfrac{liter}{sec}$ $\quad$ $Area_{BSC} := 55 \cdot 10^{4} \cdot cm^{2}$

$Q_{H2\_afterbake} := P_{H2} \cdot S_{PUMPH2}$ $\quad$ $Q_{H2\_afterbake} = 8.141 \cdot 10^{-6} \cdot torr \cdot \dfrac{liter}{sec}$

$q_{H2\_afterbake} := \dfrac{Q_{H2\_afterbake}}{Area_{BSC}}$ $\quad$ $q_{H2\_afterbake} = 1.48 \cdot 10^{-11} \cdot torr \cdot \dfrac{liter}{sec \cdot cm^{2}}$

correct for ion gauge by factor of 1.3

$Q_{H2\_afterbake} := P_{H2} \cdot S_{PUMPH2} \cdot 1.3$ $\quad$ $Q_{H2\_afterbake} = 1.058 \cdot 10^{-5} \cdot torr \cdot \dfrac{liter}{sec}$

$q_{H2\_afterbake} := \dfrac{Q_{H2\_afterbake}}{Area_{BSC}}$ $\quad$ $q_{H2\_afterbake} = 1.924 \cdot 10^{-11} \cdot torr \cdot \dfrac{liter}{sec \cdot cm^{2}}$

CASE H6: USING DATA WITH TURBO PUMP AND RGA SENSITIVITY WITH ION GAUGE

$I_{H2\_turbo} := 7.2 \cdot 10^{-10} \cdot amp$ $\qquad S_{TURBO\_H2} := 398 \cdot \frac{liter}{sec}$

$P_{H2} := S_{H2RGA} \cdot I_{H2\_turbo}$ $\qquad P_{H2} = 8.496 \cdot 10^{-9} \cdot torr$

$Q_{H2\_TURBO} := P_{H2} \cdot S_{TURBO\_H2}$ $\qquad Q_{H2\_TURBO} = 3.381 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$ $\qquad q_{H2} := \frac{Q_{H2\_TURBO}}{Area_{BSC}}$ $\qquad q_{H2} = 6.148 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

$q_{H2\_correct} := q_{H2} \cdot 1.3$ $\qquad q_{H2\_correct} = 7.992 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$ $\qquad$ **corrected for ion gauge by 1.3 factor**

CASE H4: AGAINST RGA SENSITIVITY WITH ION GAUGE AND CALCULATED PUMP SPEED

USING ION CURRENT AT 100 HR

$S_{PUMPH2} := 535 \cdot \frac{liter}{sec}$ $\quad S_{H2RGA} := 11.8 \cdot \frac{torr}{amp}$ $\quad I_{H2\_100hr} := 2.4 \cdot 10^{-9} \cdot amp$

$P_{H2} := S_{H2RGA} \cdot I_{H2\_100hr}$ $\quad P_{H2} = 2.832 \cdot 10^{-8} \cdot torr$

$Q_{H2\_100hr} := P_{H2} \cdot S_{PUMPH2}$ $\quad Q_{H2\_100hr} = 1.515 \cdot 10^{-5} \cdot torr \cdot \frac{liter}{sec}$ $\quad q_{H2} := \frac{Q_{H2\_100hr}}{Area_{BSC}}$ $\quad q_{H2} = 2.755 \cdot 10^{-11} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

CASE H3: USING ION CURRENT at time =160 hr

$I_{H2\_160hr} := 7.5 \cdot 10^{-10} \cdot amp$

$P_{H2} := S_{H2RGA} \cdot I_{H2\_160hr}$ $\quad P_{H2} = 8.85 \cdot 10^{-9} \cdot torr$

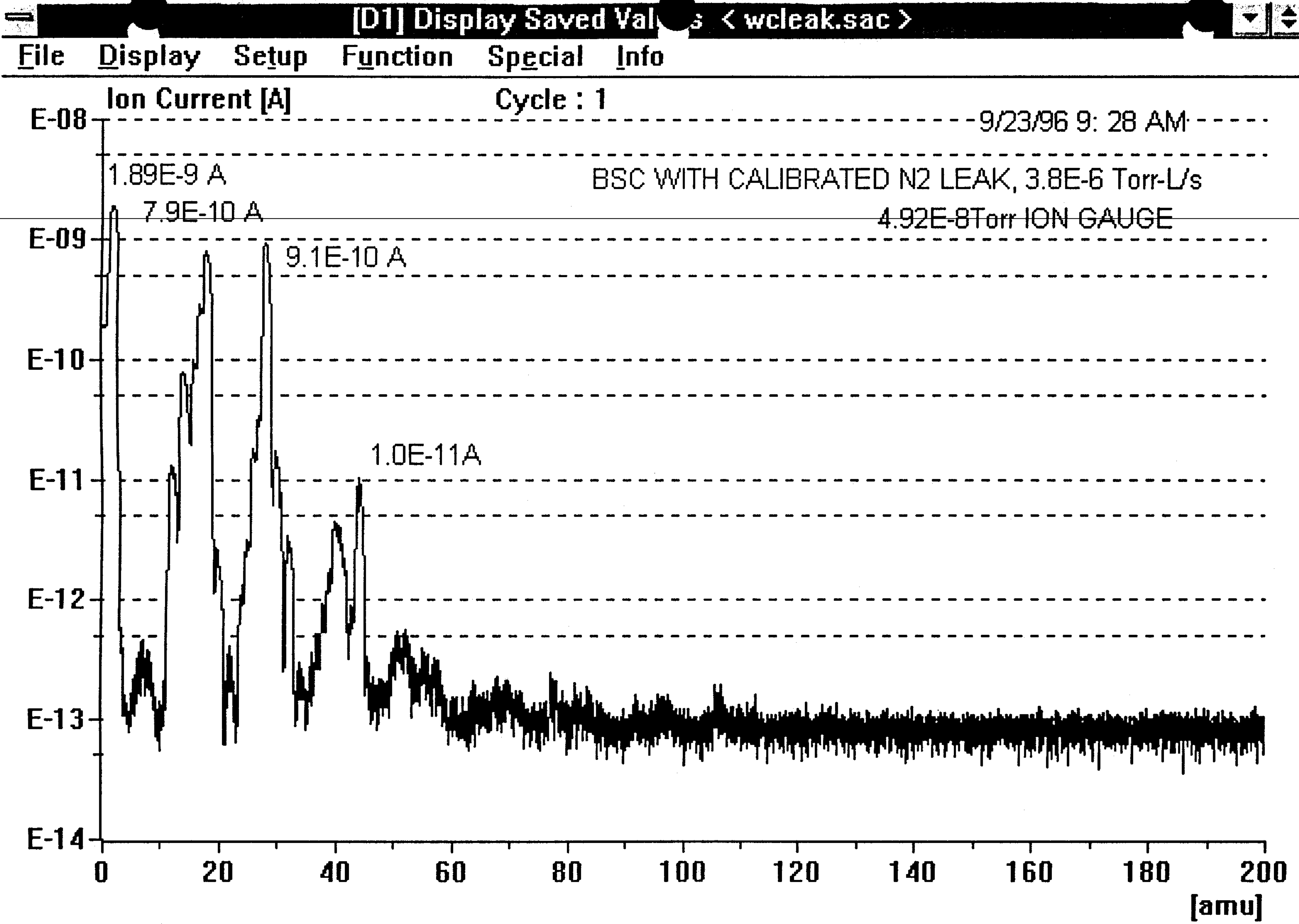
$Q_{H2\_100hr} := P_{H2} \cdot S_{PUMPH2}$ $\quad Q_{H2\_100hr} = 4.735 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$ $\quad q_{H2} := \frac{Q_{H2\_100hr}}{Area_{BSC}}$ $\quad q_{H2} = 8.609 \cdot 10^{-12} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

$Q_{H2\_100hr\_correct} := Q_{H2\_100hr} \cdot 1.3$ $\quad Q_{H2\_100hr\_correct} = 6.155 \cdot 10^{-6} \cdot torr \cdot \frac{liter}{sec}$ **correct for ion gauge with 1.3 factor**

$q_{H2\_correct} := \frac{Q_{H2\_100hr\_correct}}{Area_{BSC}}$ $\quad q_{H2\_correct} = 1.119 \cdot 10^{-11} \cdot torr \cdot \frac{liter}{sec \cdot cm^2}$

HYDROGEN LEAK CALIBRATION

Time	Pressure	Volume	Leakrate
min	Torr	liter	Torr-L/s
1	0.00131	0.994	2.17E-05
2	0.00248	0.994	2.05E-05
3	0.00366	0.994	2.02E-05
4	0.0048	0.994	1.99E-05
5	0.00595	0.994	1.97E-05
6	0.00707	0.994	1.95E-05
7	0.0082	0.994	1.94E-05
8	0.0093	0.994	1.93E-05
9	0.01041	0.994	1.92E-05
10	0.01151	0.994	1.91E-05
11	0.01259	0.994	1.90E-05
12	0.01368	0.994	1.89E-05
13	0.0148	0.994	1.89E-05
14	0.01585	0.994	1.88E-05
15	0.01692	0.994	1.87E-05
16	0.01798	0.994	1.86E-05
17	0.01904	0.994	1.86E-05
18	0.02009	0.994	1.85E-05
19	0.02114	0.994	1.84E-05
20	0.02217	0.994	1.84E-05
21	0.02321	0.994	1.83E-05
22	0.02426	0.994	1.83E-05
23	0.02528	0.994	1.82E-05
24	0.02632	0.994	1.82E-05
25	0.02738	0.994	1.81E-05
26	0.02838	0.994	1.81E-05
27	0.0294	0.994	1.80E-05
28	0.03043	0.994	1.80E-05
29	0.03144	0.994	1.80E-05
30	0.03246	0.994	1.79E-05
35	0.03752	0.994	1.78E-05
40	0.04253	0.994	1.76E-05
46	0.04847	0.994	1.75E-05
50	0.05236	0.994	1.73E-05
65	0.06672	0.994	1.70E-05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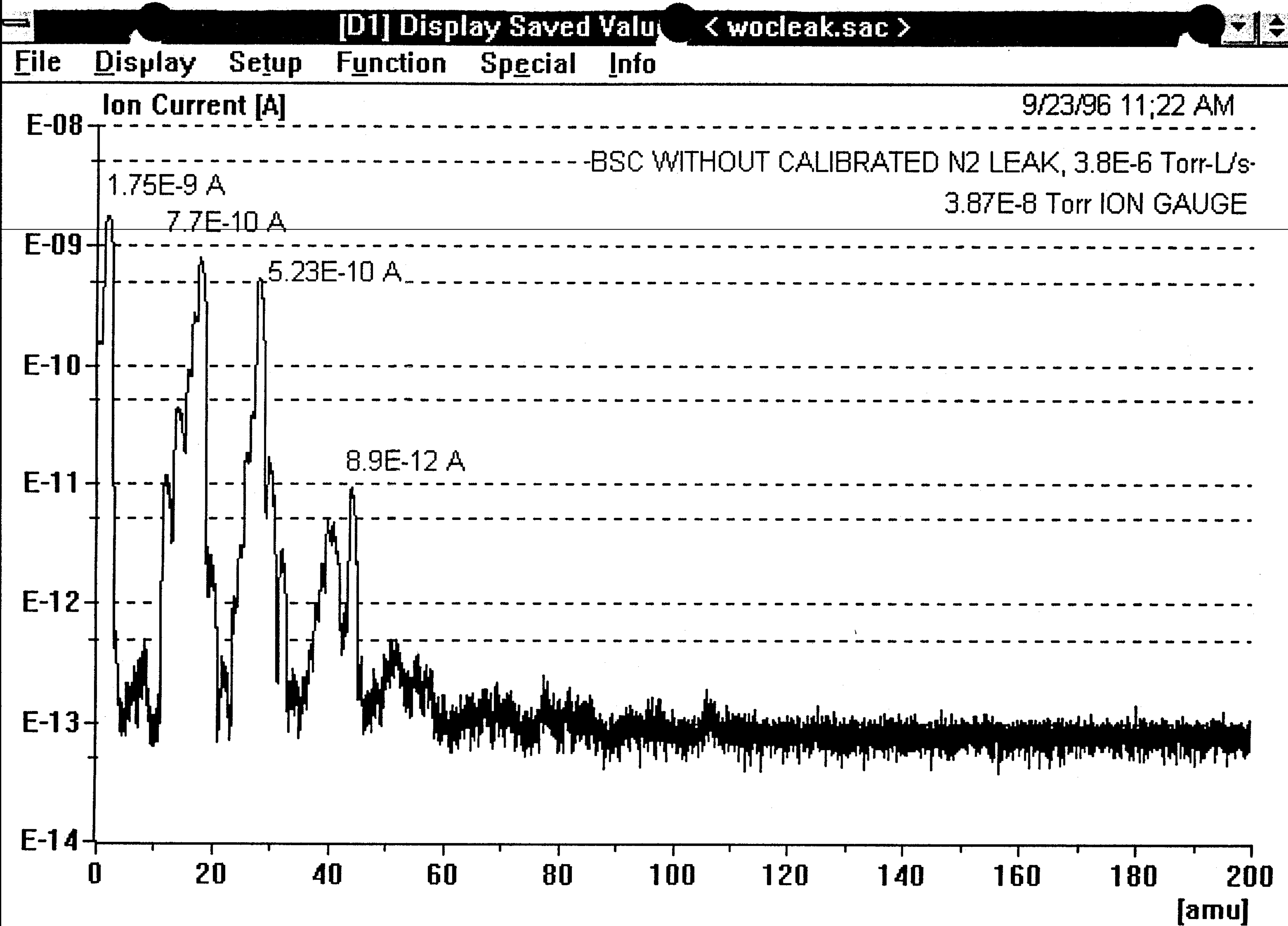
File Display Setup Function Special Info
Ion Current [A]
Cycle : 1
9/23/96 9: 28 AM
BSC WITH CALIBRATED N2 LEAK, 3.8E-6 Torr-L/s
4.92E-8Torr ION GAUGE
1.89E-9 A
7.9E-10 A
9.1E-10 A
1.0E-11A
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
20
40
60
80
100
120
140
160
180
200
[amu]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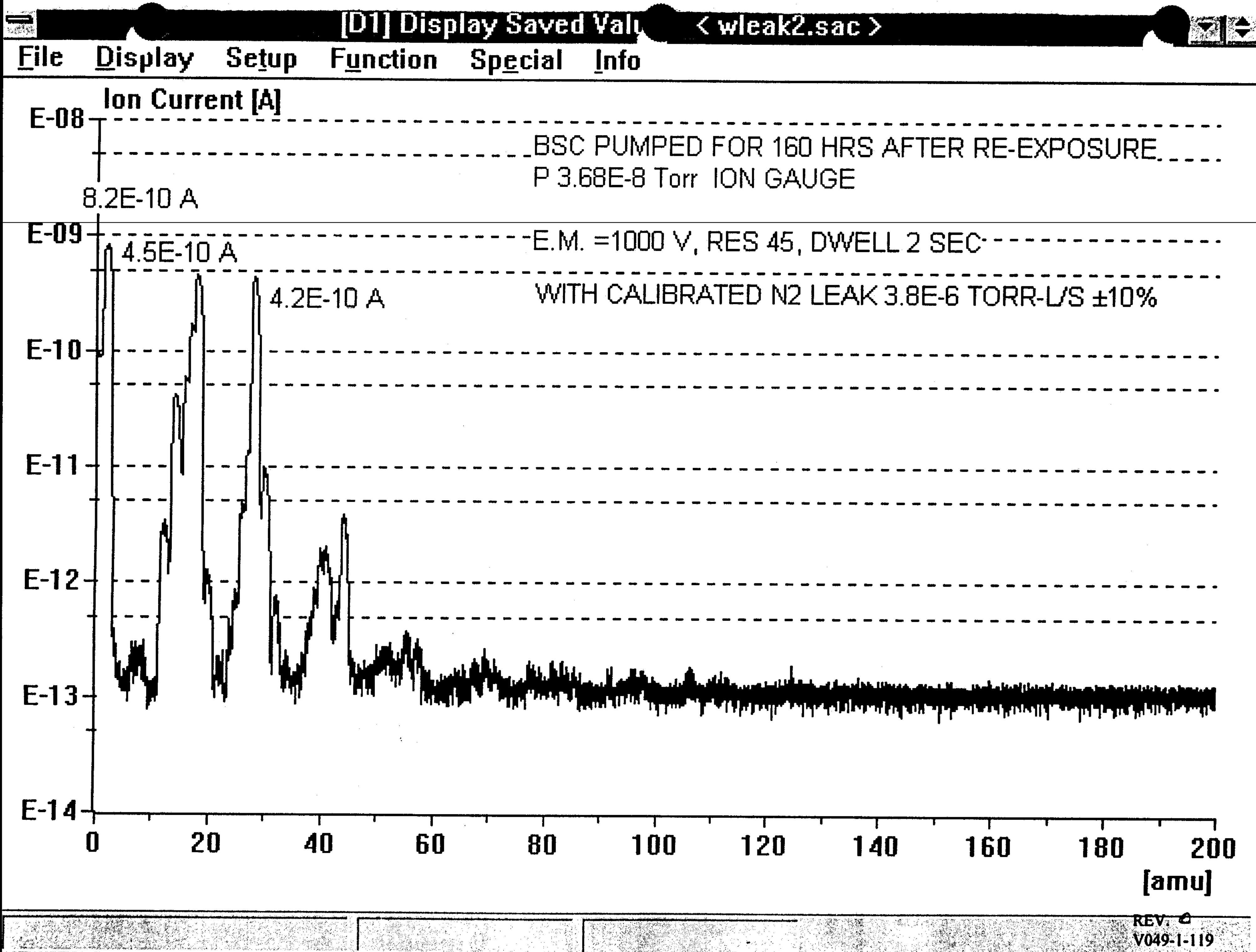
File Display Setup Function Special Info
Ion Current [A]
9/23/96 11;22 AM
-BSC WITHOUT CALIBRATED N2 LEAK, 3.8E-6 Torr-L/s-
3.87E-8 Torr ION GAUGE
1.75E-9 A
7.7E-10 A
5.23E-10 A
8.9E-12 A
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
20
40
60
80
100
120
140
160
180
200
[amu]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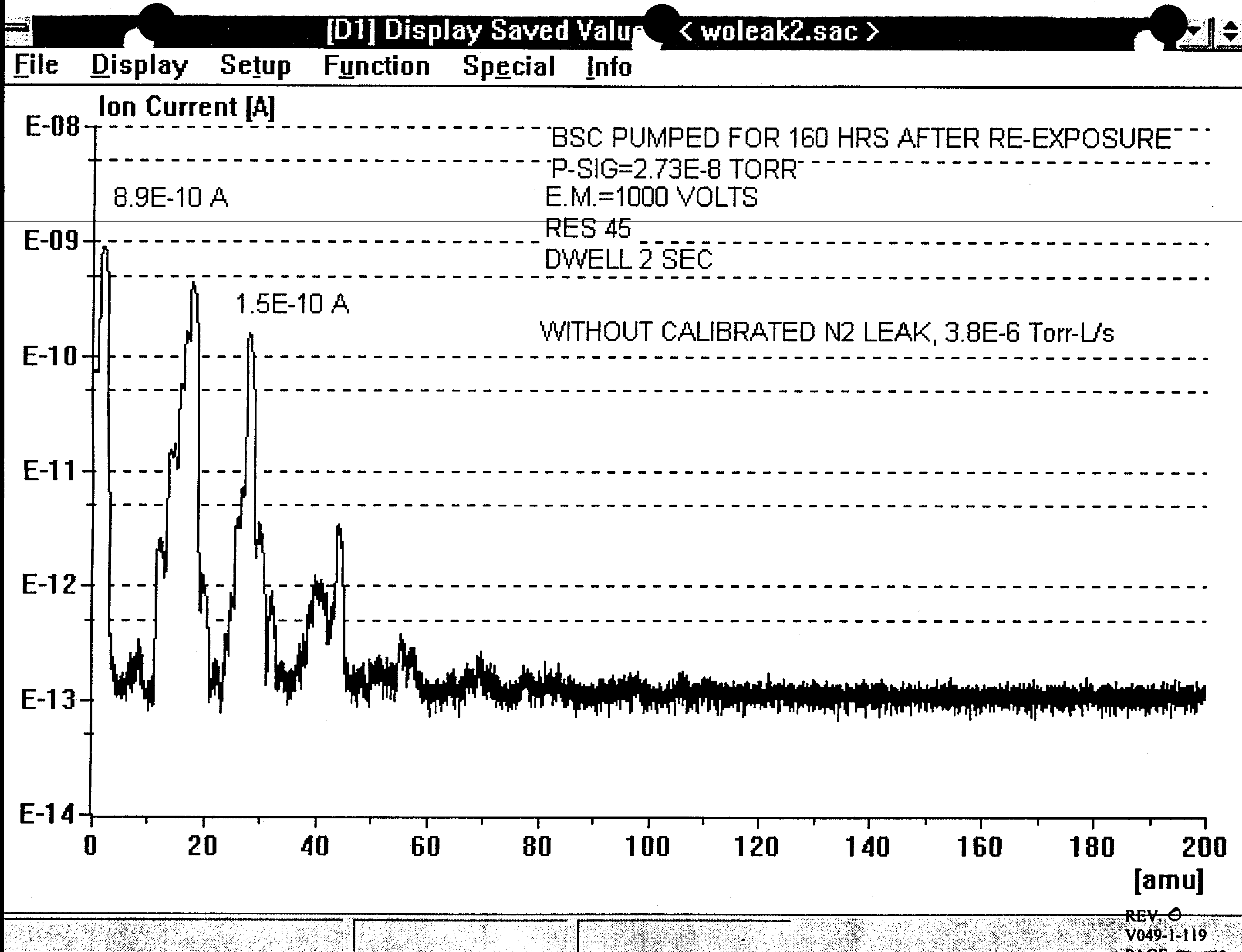
File Display Setup Function Special Info
Ion Current [A]
E-08
E-09
E-10
E-11
E-12
E-13
E-14
8.2E-10 A
4.5E-10 A
4.2E-10 A
BSC PUMPED FOR 160 HRS AFTER RE-EXPOSURE
P 3.68E-8 Torr ION GAUGE
E.M. =1000 V, RES 45, DWELL 2 SEC
WITH CALIBRATED N2 LEAK 3.8E-6 TORR-L/S ±10%
0
20
40
60
80
100
120
140
160
180
200
[amu]



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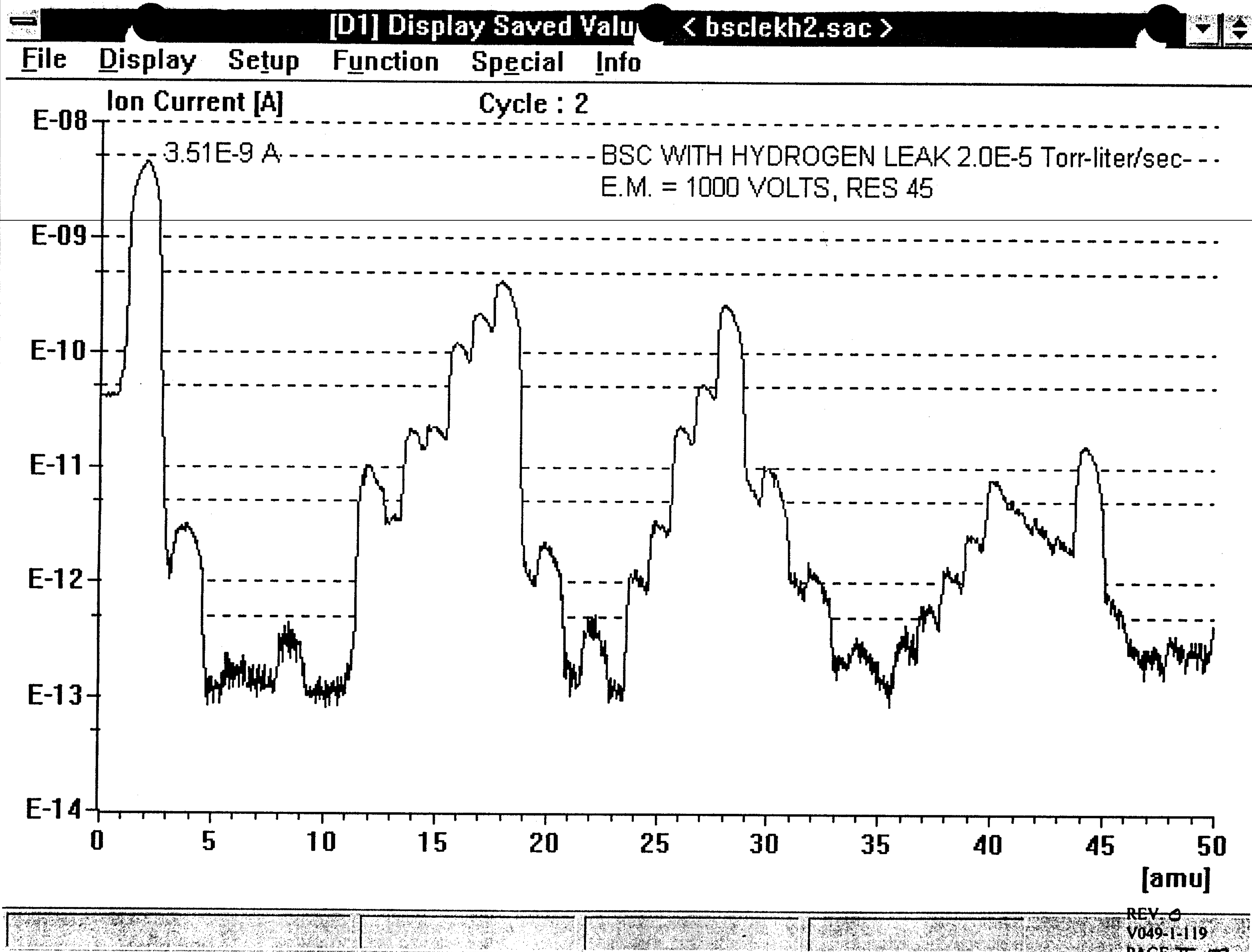
File Display Setup Function Special Info
Ion Current [A]
E-08
E-09
E-10
E-11
E-12
E-13
E-14
8.9E-10 A
1.5E-10 A
BSC PUMPED FOR 160 HRS AFTER RE-EXPOSURE
P-SIG=2.73E-8 TORR
E.M.=1000 VOLTS
RES 45
DWELL 2 SEC
WITHOUT CALIBRATED N2 LEAK, 3.8E-6 Torr-L/s
0
20
40
60
80
100
120
140
160
180
200
[amu]



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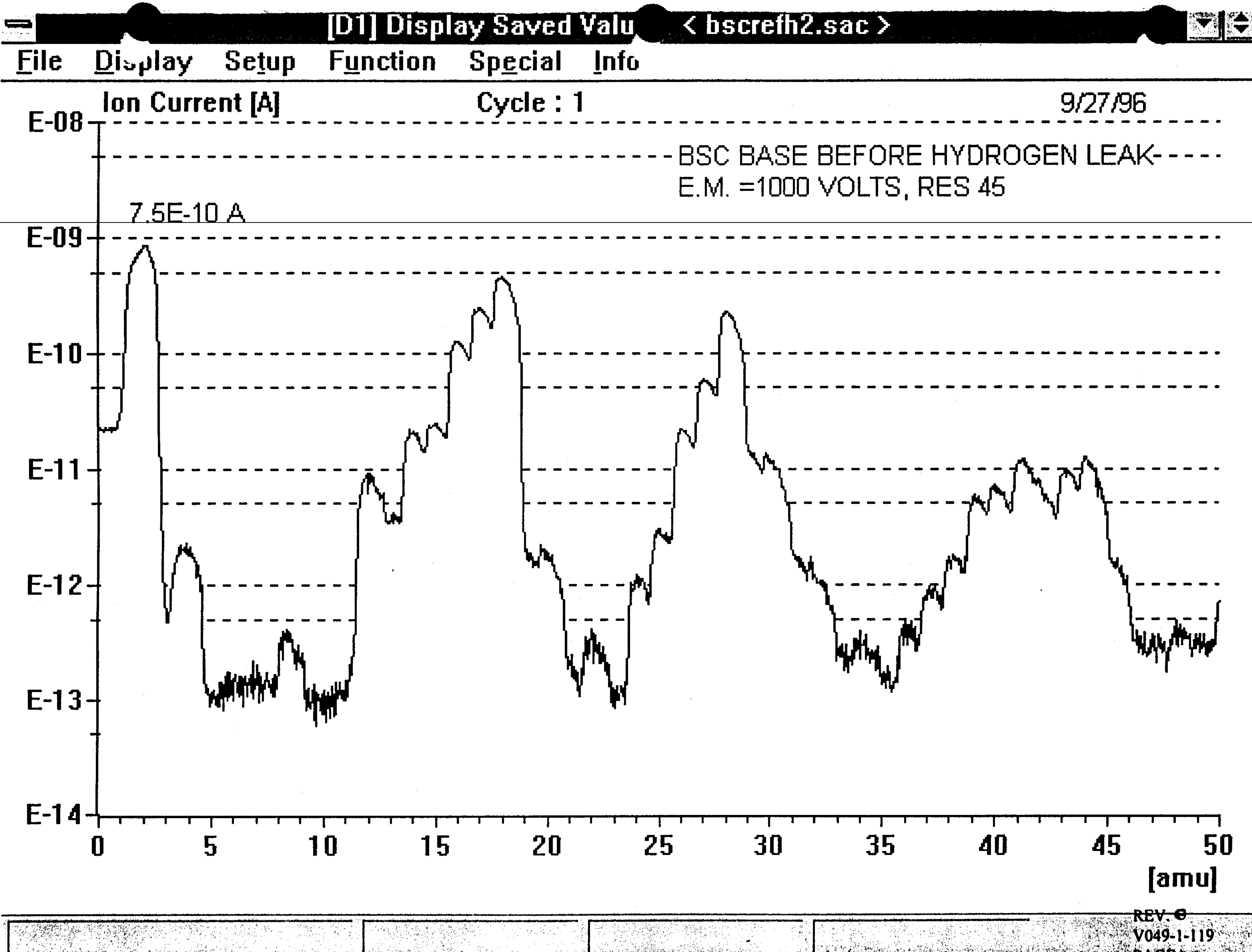
V049-1-119
PAGE VI-59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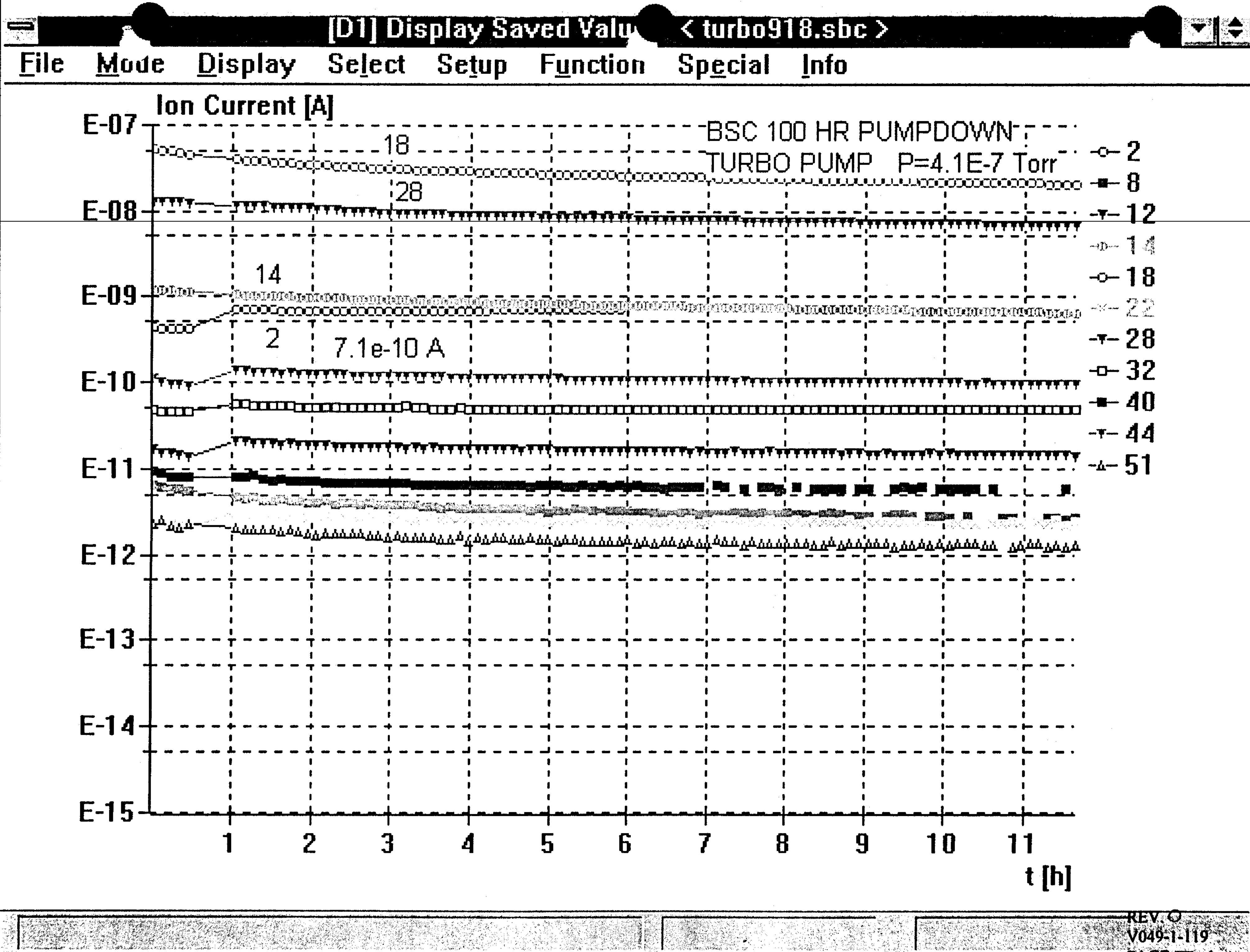
Ion Current [A]
Cycle : 1
9/27/96
BSC BASE BEFORE HYDROGEN LEAK
E.M. =1000 VOLTS, RES 45
7.5E-10 A
E-08
E-09
E-10
E-11
E-12
E-13
E-14
0
5
10
15
20
25
30
35
40
45
50
[amu]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Ion Current [A]
E-07
E-08
E-09
E-10
E-11
E-12
E-13
E-14
E-15
BSC 100 HR PUMPDOWN
TURBO PUMP P=4.1E-7 Torr
18
28
14
2
7.1e-10 A
1 2 3 4 5 6 7 8 9 10 11
t [h]
2
8
12
14
18
22
28
32
40
44
51

Ion gauge Calibration by P*V expansion

BSC VOLUME CALIBRATION

FLOWRATE										
FLOW	ERR	ERR	TIME	ERR	ERR	PRES	ERR	TOTAL	VOLUME	ERR
sccm	sccm	%	min	min	%	Torr	%	%	liters	liters
1000	50	5.00%	2.5	0.0333	1.33%	0.0766	0.12%	8.45%	24804	2,096
2000	50	2.50%	1.5	0.0333	2.22%	0.0905	0.12%	5.95%	25193	1,499
1500	50	3.33%	2	0.0333	1.67%	0.09125	0.12%	6.78%	24986	1,695
									24995	**1763**

EXPANSION #5

ION GAUGE CHECK AGAINST EXPANSION OF KNOWN PV INTO BSC

calibrated volume		0.89	liter		
angle valves		0.094	liter		
1/4" tube		0.01	liter		
		0.994	liter		
Pbaratron	0.00975	Torr			
PV =	0.0096915	Torr-liter			
BSC Volume	25000	liters			
BSC Vol err	1763	liters			
Pcalc	3.88E-07				
P err	2.73E-08				
Perr %	7%				
	Time	P-SIG	R.O.R.	Background	
	min	Torr	Torr	Torr	
	0	5.00E-08	0.00E+00	5.00E-08	
	0.5	1.82E-07	1.67E-09	5.00E-08	
	1	2.30E-07	3.33E-09	5.00E-08	
	1.5	2.61E-07	5.00E-09	5.00E-08	
	2	2.90E-07	6.66E-09	5.00E-08	
	2.5	3.10E-07	8.33E-09	5.00E-08	
	3	3.28E-07	9.99E-09	5.00E-08	
	4	3.51E-07	1.33E-08	5.00E-08	
	5	3.62E-07	1.67E-08	5.00E-08	
	6	3.67E-07	2.00E-08	5.00E-08	
	7	3.72E-07	2.33E-08	5.00E-08	**2.99E-07**
			PEXP/PSIG		**1.30**

EXPANSION #6
ION GAUGE CHECK AGAINST EXPANSION OF KNOWN PV INTO BSC

calibrated volume		0.89	liter		
angle valves		0.094	liter		
1/4" tube		0.01	liter		
		0.994	liter		
Pbaratron	0.02003	Torr			
PV =	0.01990982	Torr-liter			
BSC Volume	25000	liters			
BSC Vol err	1763	liters			
Pcalc	**7.96E-07**				
P err	5.62E-08				
Perr %	7%				
	Time	P-SIG	R.O.R.	Background	
	min	Torr	Torr	Torr	
	0	3.55E-08	0.00E+00	5.00E-08	
	0.5	2.56E-07	1.67E-09	5.00E-08	
	1	3.56E-07	3.33E-09	5.00E-08	
	1.5	4.36E-07	5.00E-09	5.00E-08	
	2	4.97E-07	6.66E-09	5.00E-08	
	2.5	5.45E-07	8.33E-09	5.00E-08	
	3	5.80E-07	9.99E-09	5.00E-08	
	3.5	6.10E-07	1.17E-08	5.00E-08	
	4	6.32E-07	1.33E-08	5.00E-08	
	5	6.63E-07	1.67E-08	5.00E-08	
	6	3.72E-07	2.00E-08	5.00E-08	
	7	6.91E-07	2.33E-08	5.00E-08	
	8	6.94E-07	2.66E-08	5.00E-08	
	10	7.01E-07	3.33E-08	5.00E-08	**6.18E-07**
			PEXP/PSIG		**1.29**

EXPANSION #7

ION GAUGE CHECK AGAINST EXPANSION OF KNOWN PV INTO BSC

calibrated volume		0.89	liter		
angle valves		0.094	liter		
1/4" tube		0.01	liter		
		0.994	liter		
Pbaratron	0.05065	Torr			
PV =	0.0503461	Torr-liter			
BSC Volume	25000	liters			
BSC Vol err	1763	liters			
Pcalc	**2.01E-06**				
P err	1.42E-07				
Perr %	7%				
	Time	P-SIG	R.O.R.	Background	
	min	Torr	Torr	Torr	
	0	5.00E-08	0.00E+00	5.00E-08	
	0.75	6.09E-07	2.50E-09	5.00E-08	
	1	7.69E-07	3.33E-09	5.00E-08	
	1.5	9.70E-07	5.00E-09	5.00E-08	
	2	1.10E-06	6.66E-09	5.00E-08	
	2.5	1.25E-06	8.33E-09	5.00E-08	
	3	1.35E-06	9.99E-09	5.00E-08	
	3.5	1.42E-06	1.17E-08	5.00E-08	
	4	1.52E-06	1.33E-08	5.00E-08	
	5	1.56E-06	1.67E-08	5.00E-08	
	5.5	1.58E-06	1.83E-08	5.00E-08	
	6.5	1.62E-06	2.16E-08	5.00E-08	
	8	1.65E-06	2.66E-08	5.00E-08	
	10	1.65E-06	3.33E-08	5.00E-08	**1.57E-06**
			PEXP/PSIG		**1.29**

EXPANSION #8
ION GAUGE CHECK AGAINST EXPANSION OF KNOWN PV INTO BSC

calibrated volume		0.89	liter		
angle valves		0.094	liter		
1/4" tube		0.01	liter		
		0.994	liter		
Pbaratron	0.03168	Torr			
PV =	0.03148992	Torr-liter			
BSC Volume	25000	liters			
BSC Vol err	1763	liters			
Pcalc	**1.26E-06**				
P err	8.88E-08				
Perr %	7%				
	Time	P-SIG	R.O.R.	Background	
	min	Torr	Torr	Torr	
	0	5.00E-08	0.00E+00	5.00E-08	
	0.5	4.16E-07	1.67E-09	5.00E-08	
	1	5.76E-07	3.33E-09	5.00E-08	
	1.5	6.93E-07	5.00E-09	5.00E-08	
	2	7.79E-07	6.66E-09	5.00E-08	
	2.5	8.44E-07	8.33E-09	5.00E-08	
	3	8.95E-07	9.99E-09	5.00E-08	
	3.5	9.36E-07	1.17E-08	5.00E-08	
	4	9.67E-07	1.33E-08	5.00E-08	
	5	1.01E-06	1.67E-08	5.00E-08	
	5.5	1.02E-06	1.83E-08	5.00E-08	
	6.5	1.04E-06	2.16E-08	5.00E-08	
	8	1.07E-06	2.66E-08	5.00E-08	
	10	1.08E-06	3.33E-08	5.00E-08	**9.97E-07**
			PEXP/PSIG		**1.26**

EXPANSION #9
ION GAUGE CHECK AGAINST EXPANSION OF KNOWN PV INTO BSC

calibrated volume		0.89	liter		
angle valves		0.094	liter		
1/4" tube		0.01	liter		
		0.994	liter		
Pbaratron	0.01522	Torr			
PV =	0.01512868	Torr-liter			
BSC Volume	25000	liters			
BSC Vol err	1763	liters			
Pcalc	**6.05E-07**				
P err	4.27E-08				
Perr %	7%				
	Time	P-SIG	R.O.R.	Background	
	min	Torr	Torr	Torr	
	0	5.00E-08	0.00E+00	5.00E-08	
	0.5	2.25E-07	1.67E-09	5.00E-08	
	1	2.96E-07	3.33E-09	5.00E-08	
	1.5	3.50E-07	5.00E-09	5.00E-08	
	2	3.95E-07	6.66E-09	5.00E-08	
	2.5	4.33E-07	8.33E-09	5.00E-08	
	3	4.57E-07	9.99E-09	5.00E-08	
	3.5	4.78E-07	1.17E-08	5.00E-08	
	4	4.95E-07	1.33E-08	5.00E-08	
	5	5.17E-07	1.67E-08	5.00E-08	
	5.5	5.26E-07	1.83E-08	5.00E-08	
	6.5	5.40E-07	2.16E-08	5.00E-08	
	8	5.52E-07	2.66E-08	5.00E-08	
	10	5.61E-07	3.33E-08	5.00E-08	**4.78E-07**
			PEXP/PSIG		**1.27**

STABIL ION GAUGE VS BARATRON

BARATRON	S.I.G.	P-I.G./P-BARA	P-BARA/P-I.G.
Torr	Torr		
7.90E-04	6.84E-04	0.866	1.15
7.70E-04	6.65E-04	0.864	1.16
6.70E-04	5.90E-04	0.881	1.14
6.60E-04	5.80E-04	0.879	1.14
6.30E-04	5.60E-04	0.889	1.13
4.40E-04	4.00E-04	0.909	1.10
3.26E-04	2.92E-04	0.896	1.12
3.11E-04	2.79E-04	0.897	1.11
3.00E-04	2.70E-04	0.900	1.11
2.07E-04	1.86E-04	0.899	1.11
		0.888	**1.127**

RGA Gas Species Sensitivities Calibration Against Ion Gauge

RGA H2 SENSITIVITY CALIBRATION

P-IG	PIG-backg	2	1	S	Ion Efficiency	S	1/2
Torr	Torr	A	A	Torr N2/amp	w.r.t.N2	Torr/amp	%
2.64E-07	2.14E-07	5.25E-08	5.80E-09	4.08	0.46	8.86	11.05%
6.69E-07	6.19E-07	1.43E-07	1.69E-08	4.33	0.46	9.41	11.82%
7.42E-07	6.92E-07	1.50E-07	1.78E-08	4.61	0.46	10.03	11.87%
1.67E-06	1.62E-06	3.18E-07	3.78E-08	5.09	0.46	11.07	11.89%
1.87E-06	1.82E-06	3.41E-07	3.99E-08	5.34	0.46	11.60	11.70%
1.91E-06	1.86E-06	3.41E-07	3.99E-08	5.45	0.46	11.86	11.70%
1.11E-06	1.06E-06	1.74E-07	2.12E-08	6.09	0.46	13.24	12.18%
1.08E-06	1.03E-06	1.73E-07	2.06E-08	5.95	0.46	12.94	11.91%
1.00E-06	9.50E-07	1.63E-07	1.96E-08	5.83	0.46	12.67	12.02%
4.86E-07	4.36E-07	7.40E-08	8.66E-09	5.89	0.46	12.81	11.70%
4.67E-07	4.17E-07	7.18E-08	8.39E-09	5.81	0.46	12.63	11.69%
4.50E-07	4.00E-07	7.00E-08	8.17E-09	5.71	0.46	12.42	11.67%
4.38E-07	3.88E-07	6.86E-08	8.00E-09	5.66	0.46	12.30	11.66%
4.00E-07	3.50E-07	6.40E-08	7.50E-09	5.47	0.46	11.89	11.72%
3.86E-07	3.36E-07	6.28E-08	7.31E-09	5.35	0.46	11.63	11.64%
3.81E-07	3.31E-07	6.22E-08	7.23E-09	5.32	0.46	11.57	11.62%
3.76E-07	3.26E-07	6.15E-08	7.13E-09	5.30	0.46	11.52	11.59%
			AVERAGE	**5.45**		**11.85**	**12%**

RGA N2 SENSITIVITY CALIBRATION

P-IG	PIG-backg	28	14	Ion Efficiency	S	M14/M28
Torr	Torr	A	A	w.r.t.N2	Torr/amp	%
3.45E-06	3.40E-06	1.21E-07	1.05E-08	1.00	28.10	8.68%
3.37E-06	3.32E-06	1.18E-07	9.70E-09	1.00	28.14	8.22%
3.30E-06	3.25E-06	1.15E-07	9.47E-09	1.00	28.26	8.23%
3.20E-06	3.15E-06	1.11E-07	9.16E-09	1.00	28.38	8.25%
3.13E-06	3.08E-06	1.08E-07	8.90E-09	1.00	28.52	8.24%
3.08E-06	3.03E-06	1.06E-07	8.70E-09	1.00	28.58	8.21%
3.05E-06	3.00E-06	1.05E-07	8.60E-09	1.00	28.57	8.19%
2.98E-06	2.93E-06	1.02E-07	8.45E-09	1.00	28.73	8.28%
2.89E-06	2.84E-06	9.90E-08	8.10E-09	1.00	28.69	8.18%
2.80E-06	2.75E-06	9.58E-08	7.80E-09	1.00	28.71	8.14%
8.25E-07	7.75E-07	2.50E-08	1.98E-09	1.00	31.00	7.92%
9.10E-07	8.60E-07	2.92E-08	2.40E-09	1.00	29.45	8.22%
8.50E-07	8.00E-07	2.76E-08	2.30E-09	1.00	28.99	8.33%
8.06E-07	7.56E-07	2.63E-08	2.19E-09	1.00	28.75	8.33%
7.97E-07	7.47E-07	2.61E-08	2.17E-09	1.00	28.62	8.31%
7.78E-07	7.28E-07	2.56E-08	2.13E-09	1.00	28.44	8.32%
7.58E-07	7.08E-07	2.50E-08	2.10E-09	1.00	28.32	8.40%
5.50E-07	5.00E-07	1.78E-08	1.48E-09	1.00	28.09	8.31%
5.37E-07	4.87E-07	1.74E-08	1.45E-09	1.00	27.99	8.33%
4.99E-07	4.49E-07	1.62E-08	1.35E-09	1.00	27.72	8.33%
4.88E-07	4.38E-07	1.58E-08	1.32E-09	1.00	27.72	8.35%
4.42E-07	3.92E-07	1.46E-08	1.24E-09	1.00	26.85	8.49%
				AVERAGE	**28.50**	**8.27%**

RGA Argon SENSITIVITY CALIBRATION

PIG	PIG-backg	40	20	S	Ion Efficiency	S	M20/M40
Torr	Torr	A	A	Torr N2/amp	w.r.t.N2	Torr/amp	%
				40		40	
6.06E-07	5.63E-07	1.03E-08	1.88E-09	54.63	1.3	42.02	18.25%
6.27E-07	5.84E-07	1.04E-08	1.94E-09	56.13	1.3	43.17	18.65%
6.42E-07	5.99E-07	1.09E-08	1.99E-09	54.93	1.3	42.25	18.26%
1.04E-06	9.97E-07	1.83E-08	3.39E-09	54.46	1.3	41.90	18.52%
1.21E-06	1.17E-06	2.08E-08	3.87E-09	56.09	1.3	43.15	18.61%
2.52E-06	2.48E-06	4.36E-08	8.20E-09	56.81	1.3	43.70	18.81%
7.36E-06	7.32E-06	1.26E-07	2.50E-08	58.07	1.3	44.67	19.84%
					AVERAGE	**43.0**	**18.71%**

RGA CH4 SENSITIVITY CALIBRATION

PIG	PIG-backg	AMU	AMU	AMU	AMU	S	Ion Efficiency	S	M15/M16	M14/M16
Torr	Torr	16	15	14	2	Torr N2/amp	w.r.t.N2	Torr/amp		
						AMU 16	AMU 16	AMU 16	%	%
3.40E-07	3.10E-07	6.20E-09	5.25E-09	9.60E-10		50	1.6	31.25	85%	15%
3.38E-07	3.08E-07	5.95E-09	5.07E-09	9.30E-10	5.00E-09	51.76	1.6	32.35	85%	16%
7.29E-07	6.99E-07	1.35E-08	1.15E-08	1.99E-09	1.20E-08	51.78	1.6	32.36	85%	15%
7.40E-07	7.10E-07	1.35E-08	1.15E-08	1.99E-09	1.27E-08	52.59	1.6	32.87	85%	15%
2.12E-06	2.09E-06	3.33E-08	2.82E-08	4.95E-09	6.88E-08	62.76	1.6	39.23	85%	15%
						53.8		**33.6**	**85%**	**15%**

RGA CO2 SENSITIVITY CALIBRATION

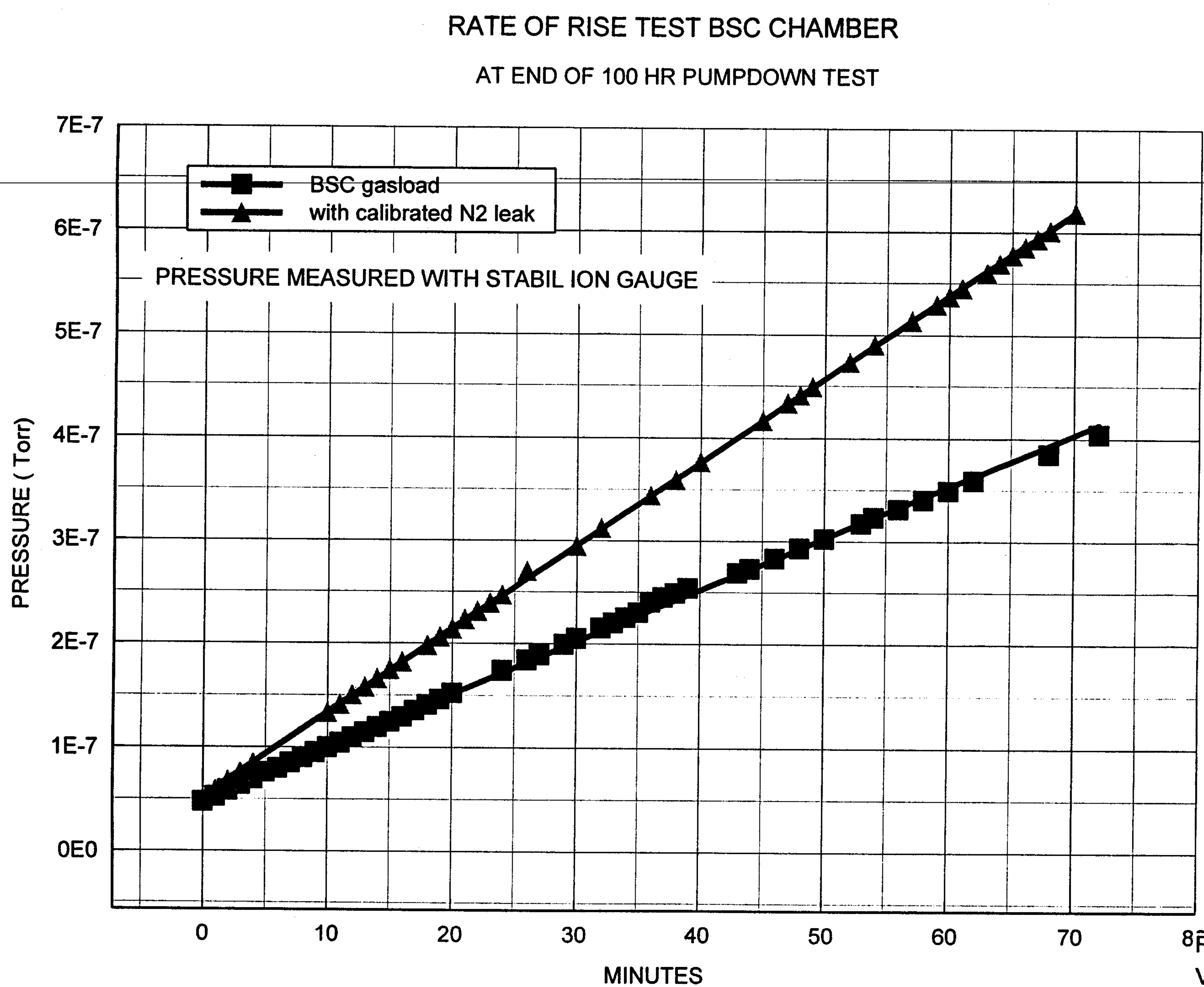
PIG	PIG-backg						S	Ion Efficiency	S	M28/M44	M22/M44	M16/M44	M12/M44
Torr	Torr	44	28	22	16	12	Torr N2/amp	w.r.t.N2	Torr/amp				
							44 amu	44 amu	44 amu				
4.88E-06	4.83E-06	7.40E-08	7.60E-09	1.58E-09	1.28E-08	6.73E-09	65.27	1.4	46.62	10.27%	2.14%	17.30%	9.09%
2.08E-06	2.03E-06	3.01E-08	3.30E-09	6.60E-10	5.15E-09	2.80E-09	67.44	1.4	48.17	10.96%	2.19%	17.11%	9.30%
1.48E-06	1.43E-06	2.10E-08	2.50E-09	4.70E-10	3.66E-09	2.00E-09	68.10	1.4	48.64	11.90%	2.24%	17.43%	9.52%
1.06E-06	1.01E-06	1.56E-08	1.89E-09	3.30E-10	2.60E-09	1.40E-09	64.74	1.4	46.25	12.12%	2.12%	16.67%	8.97%
							66.4		**47.4**	**11.31%**	**2.17%**	**17.13%**	**9.22%**

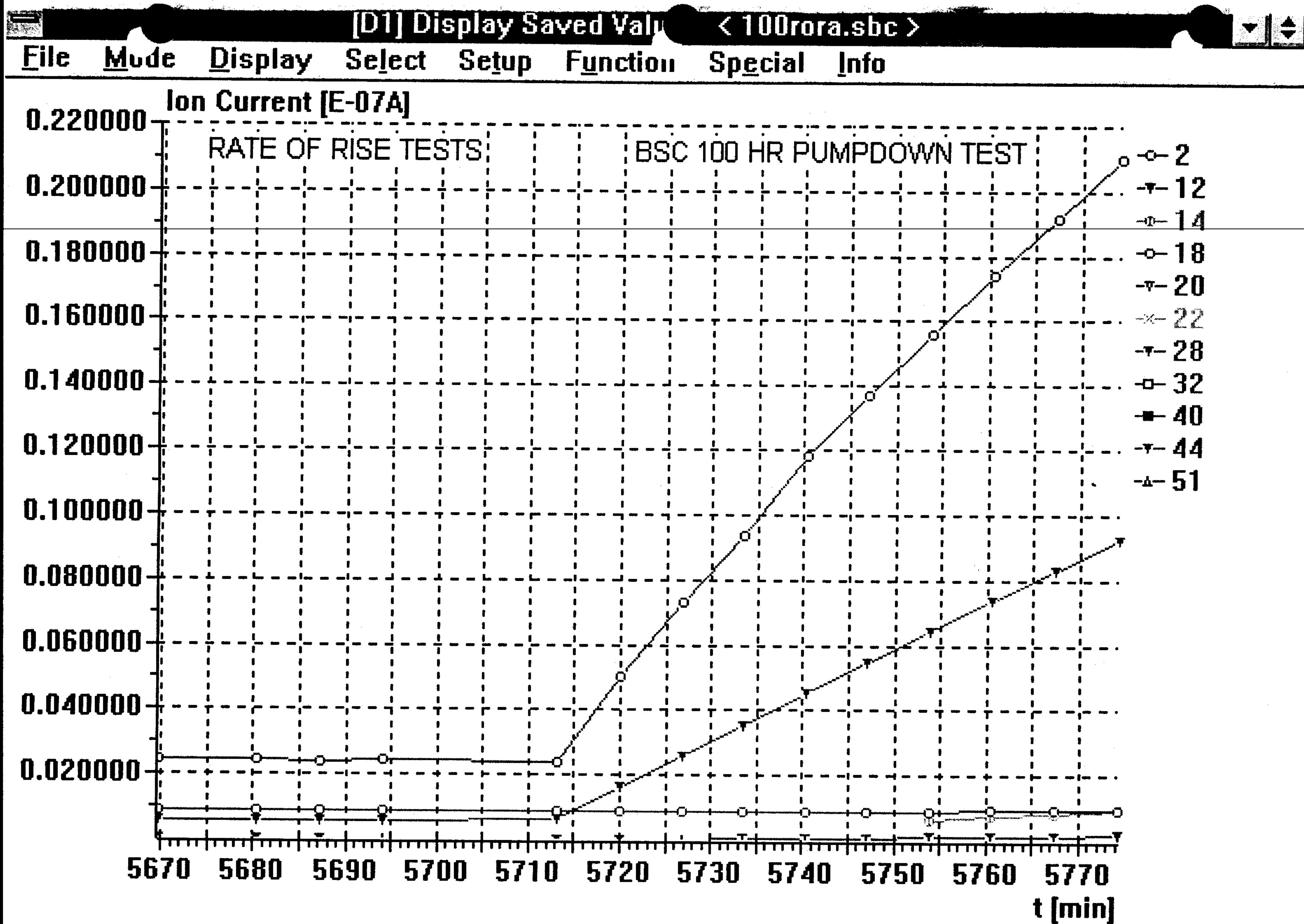
PROCESS SYSTEMS INTERNATIONAL, INC

Rate of Rise Test at End Of 100 Hr Test

RATE OF RISE
BSC 100 HR TEST

RATE OF RISE		RATE OF RISE		
NO LEAK		WITH CALIBRATED N2 LEAK		
TIME	PRES	TIME	PRES	
MIN	TORR	MIN	TORR	
0	4.76E-08	0	5.03E-08	
1	5.26E-08	1	5.83E-08	
2	5.86E-08	2	6.70E-08	
3	6.40E-08	3	7.57E-08	
4	6.96E-08	4	8.43E-08	
5	7.59E-08	10	1.33E-07	
6	7.97E-08	11	1.41E-07	
7	8.49E-08	12	1.50E-07	
8	8.98E-08	13	1.58E-07	
9	9.47E-08	14	1.66E-07	
10	9.96E-08	15	1.75E-07	
11	1.04E-07	16	1.82E-07	
12	1.09E-07	18	1.98E-07	
13	1.14E-07	19	2.06E-07	
14	1.19E-07	20	2.14E-07	
15	1.24E-07	21	2.23E-07	
16	1.29E-07	22	2.31E-07	
17	1.35E-07	23	2.39E-07	
18	1.41E-07	24	2.47E-07	
19	1.46E-07	26	2.70E-07	
20	1.52E-07	30	2.95E-07	
24	1.74E-07	32	3.12E-07	
26	1.84E-07	36	3.44E-07	
27	1.89E-07	38	3.59E-07	
29	1.99E-07	40	3.77E-07	
30	2.05E-07	45	4.16E-07	
32	2.15E-07	47	4.33E-07	
33	2.20E-07	48	4.41E-07	
34	2.25E-07	49	4.49E-07	
35	2.30E-07	52	4.73E-07	
36	2.40E-07	54	4.90E-07	
37	2.45E-07	57	5.13E-07	
38	2.49E-07	59	5.29E-07	
39	2.54E-07	60	5.37E-07	
43	2.69E-07	61	5.45E-07	
44	2.73E-07	63	5.60E-07	
46	2.83E-07	64	5.69E-07	
48	2.93E-07	65	5.77E-07	
50	3.02E-07	66	5.85E-07	
53	3.17E-07	67	5.93E-07	
54	3.23E-07	68	6.01E-07	
56	3.31E-07	70	6.18E-07	
58	3.40E-07			
60	3.49E-07			
62	3.59E-07			
68	3.85E-07			
72	4.04E-07			


RATE OF RISE TEST BSC CHAMBER
AT END OF 100 HR PUMPDOWN TEST
BSC gasload
with calibrated N2 leak
PRESSURE MEASURED WITH STABIL ION GAUGE
PRESSURE (Torr)
7E-7
6E-7
5E-7
4E-7
3E-7
2E-7
1E-7
0E0
0
10
20
30
40
50
60
70
80
MINUTES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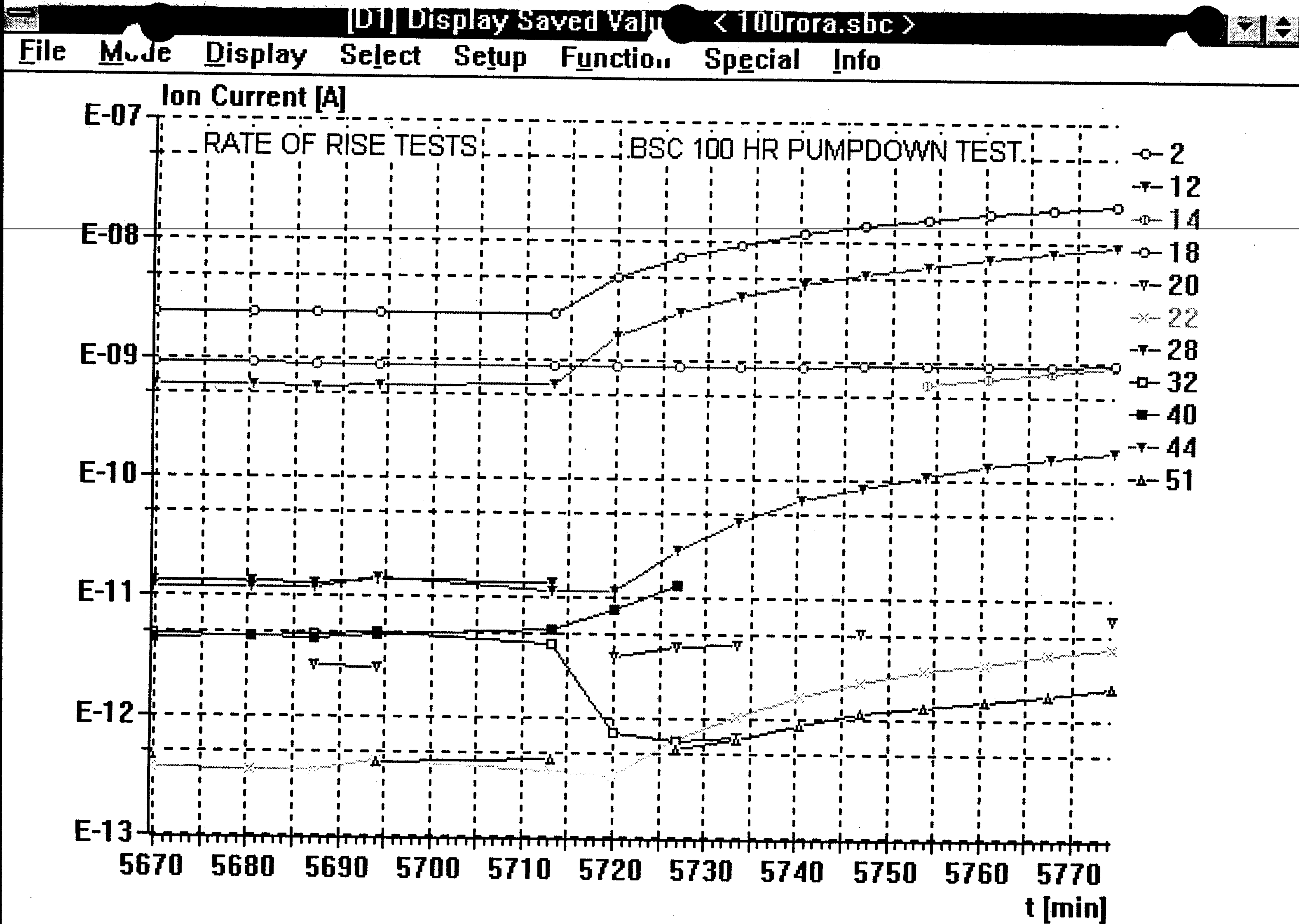
File Mode Display Select Setup Function Special Info
Ion Current [E-07A]
RATE OF RISE TESTS
BSC 100 HR PUMPDOWN TEST
0.220000
0.200000
0.180000
0.160000
0.140000
0.120000
0.100000
0.080000
0.060000
0.040000
0.020000
5670 5680 5690 5700 5710 5720 5730 5740 5750 5760 5770
t [min]
2
12
14
18
20
22
28
32
40
44
51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Ion Current [A]
RATE OF RISE TESTS
BSC 100 HR PUMPDOWN TEST.
E-07
E-08
E-09
E-10
E-11
E-12
E-13
5670
5680
5690
5700
5710
5720
5730
5740
5750
5760
5770
t [min]
2
12
14
18
20
22
28
32
40
44
51

SECTION III

80K PUMP (SHORT) LN_2 VIBRATION TEST

1.0 INTRODUCTION AND SUMMARY

One of the most critical considerations in the design of the LIGO vacuum pumping system is the degree to which vibration is transmitted to the interferometer. The 80K pumps in particular are of the utmost concern, since they operate on a continuous basis. While a great deal of attention has been paid to the pump's isolation system during the project's design phase, there has been high interest in obtaining measured data on an actual pump in a normal operation configuration. In order to obtain this data, a vibration test was conducted using the liquid nitrogen reservoir of one of the short 80K pumps, filled with a full charge of liquid nitrogen, and suspended on its isolation system.

Both the long and short pumps have isolation systems which are essentially the same. The pump is suspended on four rod hangers, each of which incorporates an extension spring approximately half way up the length of the hanger. At the warm end of each hanger is a viton isolator arrangement. The springs for the both pumps have spring rates which have been sized to produce fundamental frequencies (ignoring the viton isolators) of less than 10 hz. The pumps are restrained laterally against a postulated seismic event with a similar arrangement using softer springs.

The thermal loading on the 80K pumps vary with time, since a light frost buildup on the pumping surface will make it behave as a blackbody, and increase the liquid nitrogen boiloff rate. Given time and budgetary pressures, a vibration test simulating a "clean" pump couldn't practically be run, and so the test was configured to simulate the thermal load on a frosted short pump (approximately 560 watts). This translates into a nitrogen boiloff rate of about 4 SCFM.

2.0 TEST SETUP

The beam splitter chamber served as a vacuum space in which to hang the pump reservoir. Several of the ports on the chamber were fitted with flanges having various feedthrus for power, nitrogen, instrumentation, and a relief valve to protect the chamber. The pump reservoir was suspended on its isolation system, which in turn was supported by a test frame constructed of structural angles and pipe. Liquid nitrogen was supplied to the reservoir via a 1/2" NPS supply line, and boiloff was vented via the 1-1/2" reservoir vent line. The supply line was reasonably flexible, but contained no flex hose. (The actual design incorporates a flex hose in the supply line vacuum jacket.) The vent line did have a flex hose.

In order to simulate the heat load on the reservoir, an aluminum pipe, supported by structural angle, was placed within the resevoir vacuum space. Two 500 watt cartridge heaters attached to the pipe provided the heat source. A VARIAC power supply was used to vary the power, and therefore the heat load emitted from the heaters. During the test it was decided that due to the slow thermal response of the aluminum pipe to changing heat loads, the vacuum level in the BSC chamber could be varied to produce additional thermal loading. This allowed several vibration tests to be quickly run, with nitrogen boiloff rates ranging from approximately 2.5 SCFM to approximately 10 SCFM, thus allowing vibration to be characterized over a heat load range of about 4 to 1.

Cooldown of the pump reservoir took several hours. The temperature of the reservoir was monitored during this process by a thermocouple attached to it. The nitrogen liquid level in the reservoir was monitored by means of a photohelic gauge which mesured the differential pressure between the top and the bottom of the reservoir. The nitrogen boiloff during the test was vented to an ambient air vaporizer, and the flowrate was measured with a flowmeter downstream of the vaporizer.

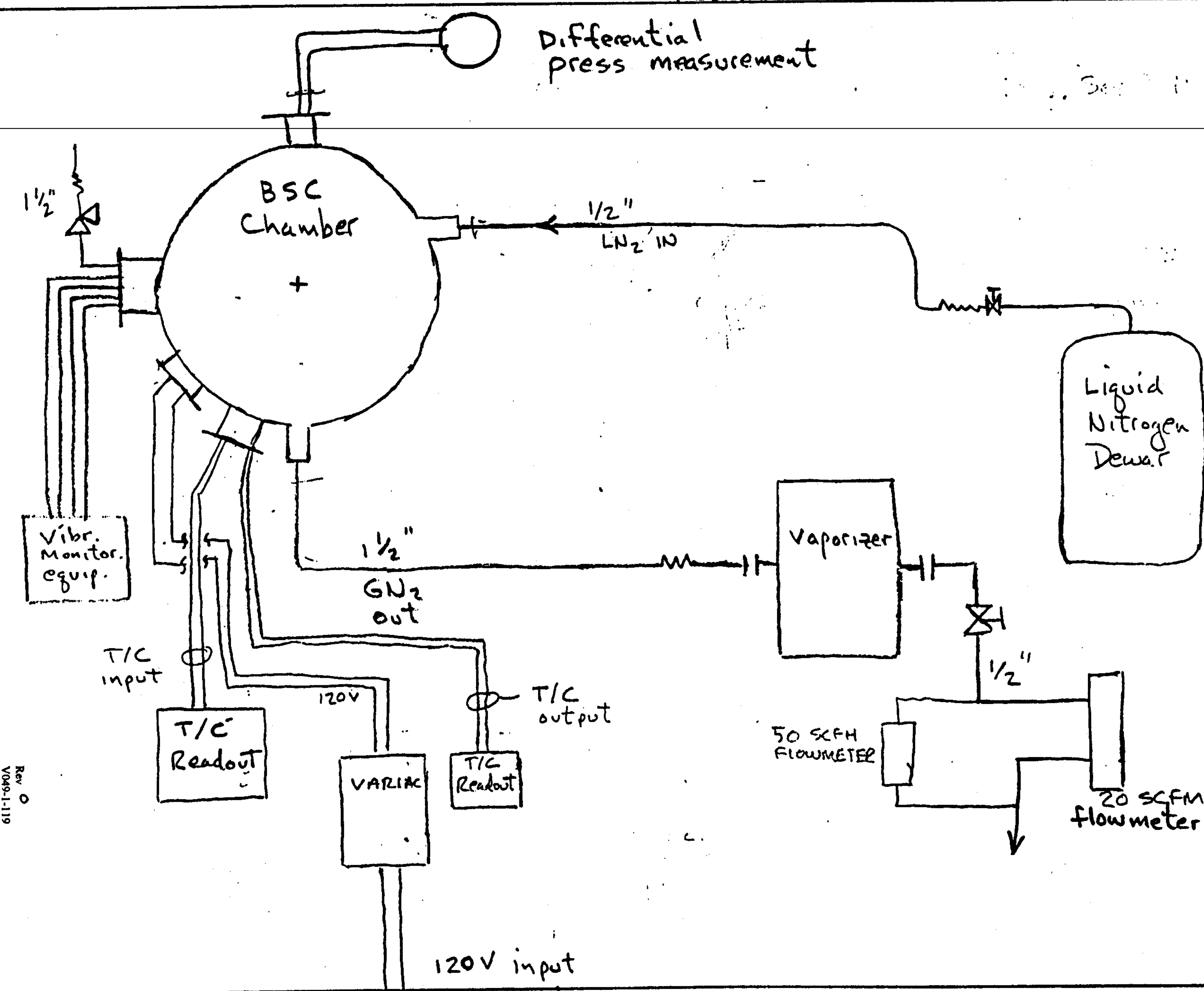
Vibration in the reservoir resulting from the boiling liquid nitrogen was measured via accelerometers attached to the supporting lugs on the shell of the reservoir. Vibration levels passing through the isolation system was measured via an accelerometer mounted on the structural angle at the warm end of one of the rod hangers. The accelerometer was placed immediately adjacent to the rod hanger termination.

A schematic diagram of the test setup is shown in the attached figure.

AMPAD 22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS

80K Pump Test

D. Moore



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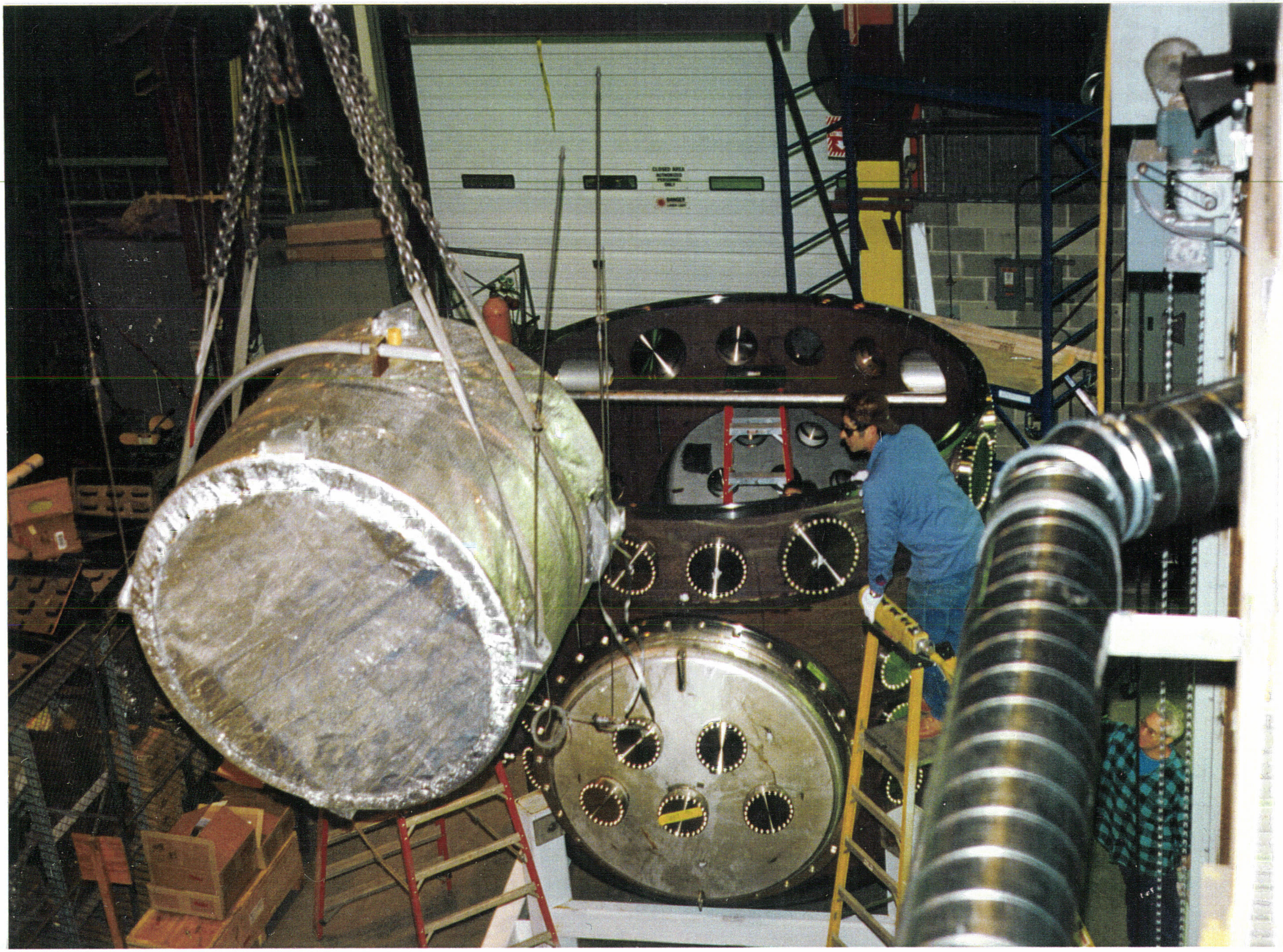

FIG. III-4

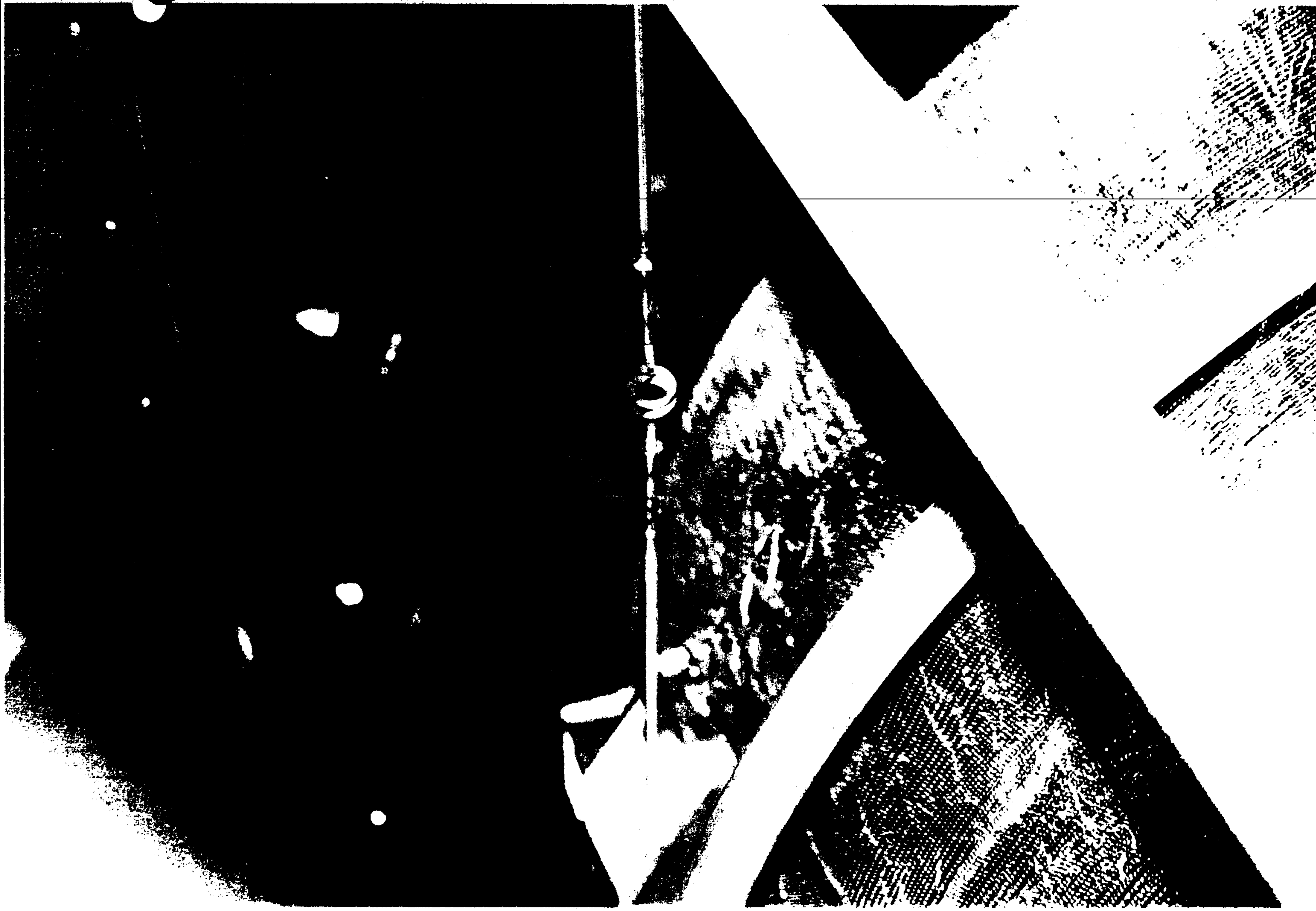

FIG III-2

SECTION III

3.0 VIBRATION RESULTS

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CONSULTING IN ACOUSTICS • NOISE & VIBRATION • STRUCTURAL & FLUID DYNAMICS
200 Boston Avenue, Suite 2500 • Medford, MA 02155-4243 • Telephone (617) 396-1421 • Fax (617) 396-1607

10 October 1996

Process Systems International, Inc.
20 Walkup Drive
Westborough, Ma 01581

Attn.: Richard Bagley

Attached are acceleration measurements of the cryopump source characterization. Accelerometers were located on the cold side of the cryopump spring support in the vertical and lateral direction and in the vertical direction on the warm side of the cryopump. There also was an accelerometer in the vertical direction at the base of the beamsplitter, the chamber for the cryopump, to evaluate ground vibration into the system. Measurements were made for various heat loads or exhaust vapor flow rate. Background measurements with the system at room temperature (not operating) were recorded. The following summarizes are conclusions:

1. The accelerometer measurements on the cold side of the spring had sufficient signal-to-noise and are assumed to be good measurements (see Fig. 1 and 2). The measurements did not show a dependency on flow rate as was anticipated. For a quick comparison, the LIGO spec. is approximately -160 dB between 10 and 1000 Hz compared to the -100 dB measured. A transfer function and coherence plot between the two cold measurements is shown in Fig. 3.

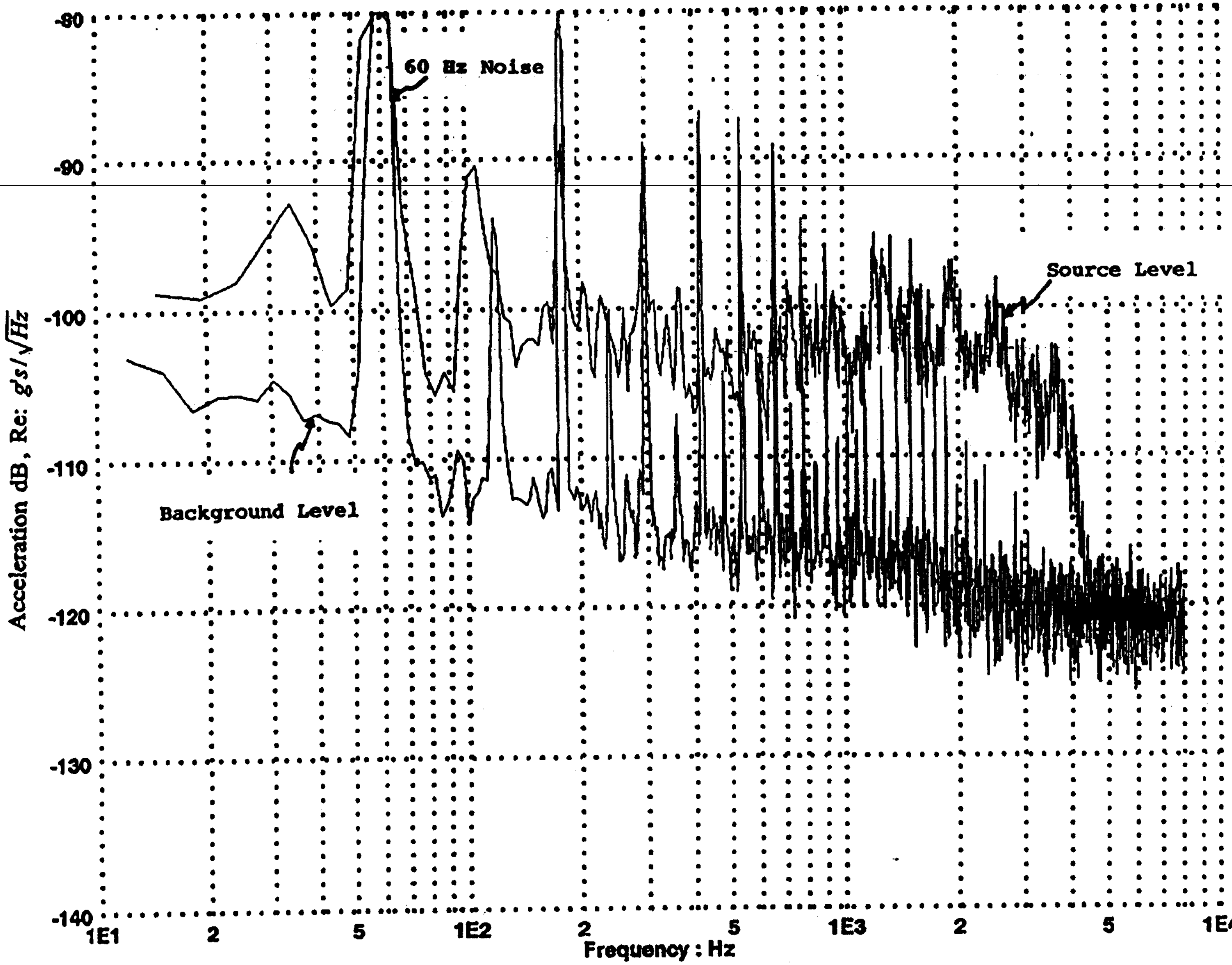
2. The accelerometer measurements on the warm side of the spring were the same in both the operating and non-operating conditions. The sensitivity of the accelerometer was not sufficient to measure the low levels. A separate test will be performed on the spring to determine its transfer function.

3. A high sensitivity accelerometer was used at the base of the beamsplitter. The vibration due to the cryopump boiling was not evident in the measurements.

Sincerely

Kyle Martini

Kyle Martini



DF: 4.88 Hz T-Lo: 0.ms T-Hi: 205.ms FFT: 4096 Wind:HANN Sm: 0.

FLOW = 4.1

Fig. 1 Cryopump cold side vertical acceleration (CAA accelerometer).

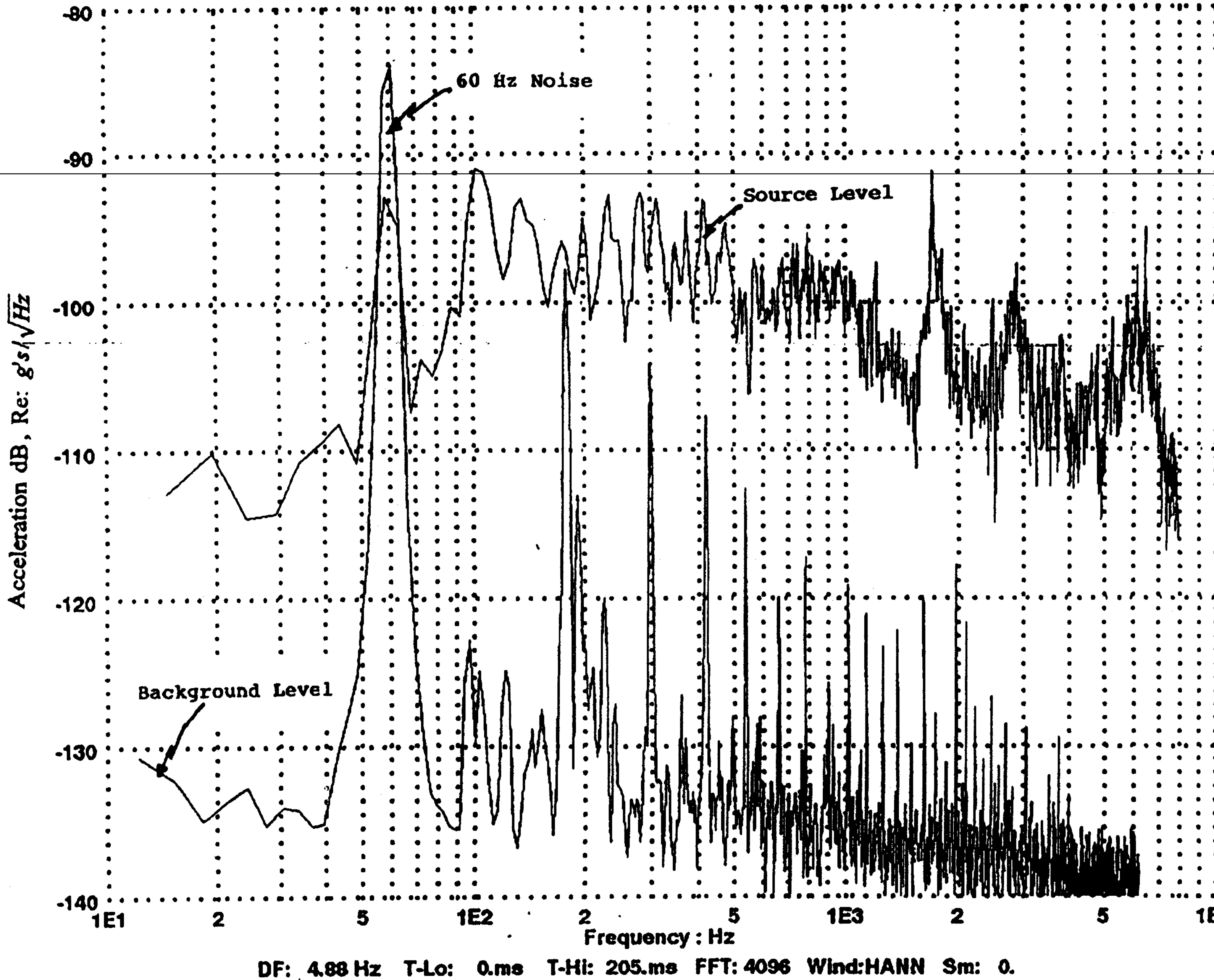


Fig. 2 Cryopump cold side lateral acceleration (MIT accelerometer).

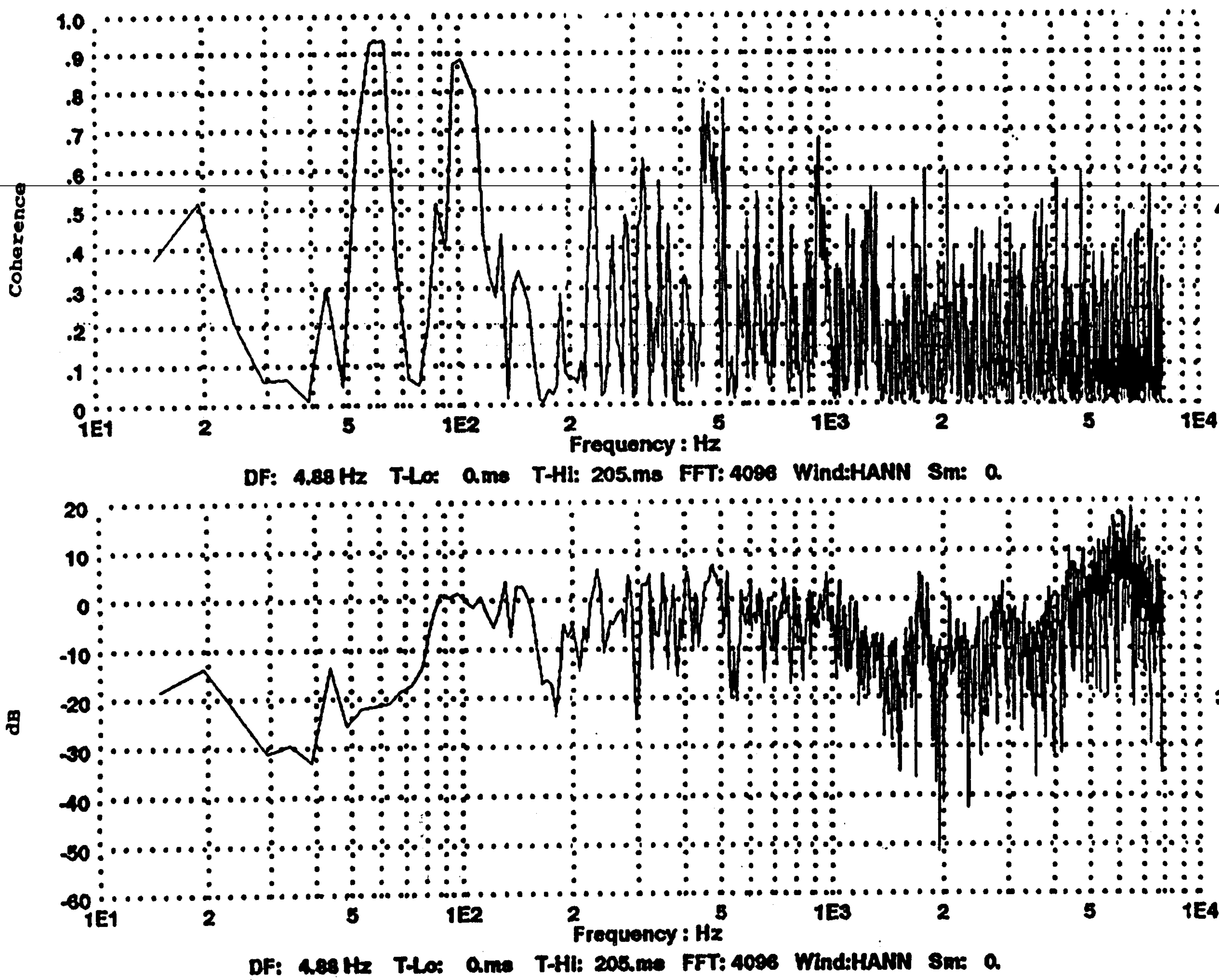
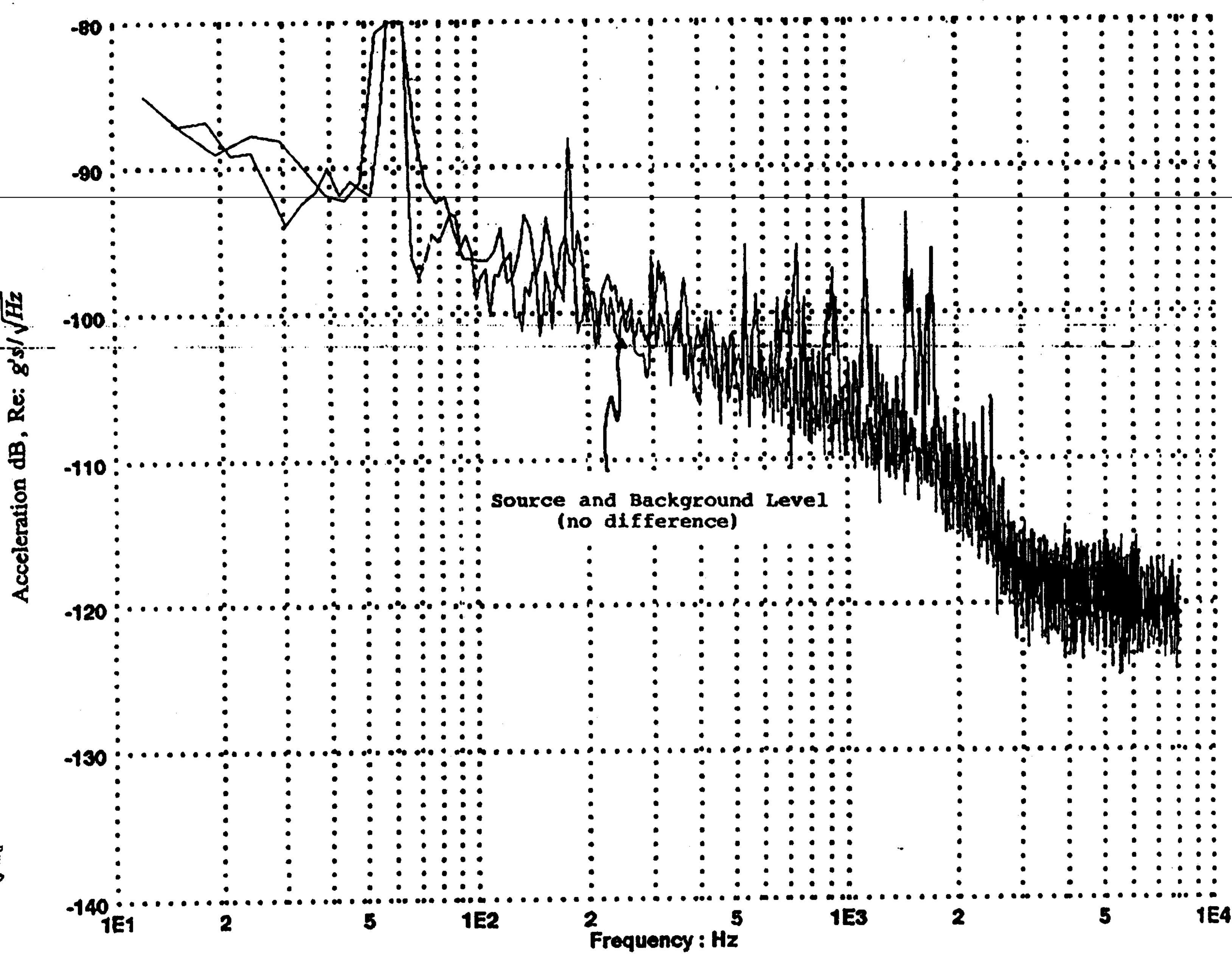


Fig. 3 Cryopump transfer function and coherence between cold side vertical and lateral acceleration.



DF: 4.88 Hz T-Lo: 0.ms T-Hi: 205.ms FFT: 4096 Wind:HANN Sm: 0.

Fig. 4 Cryopump warm side vertical acceleration (CAA accelerometer).

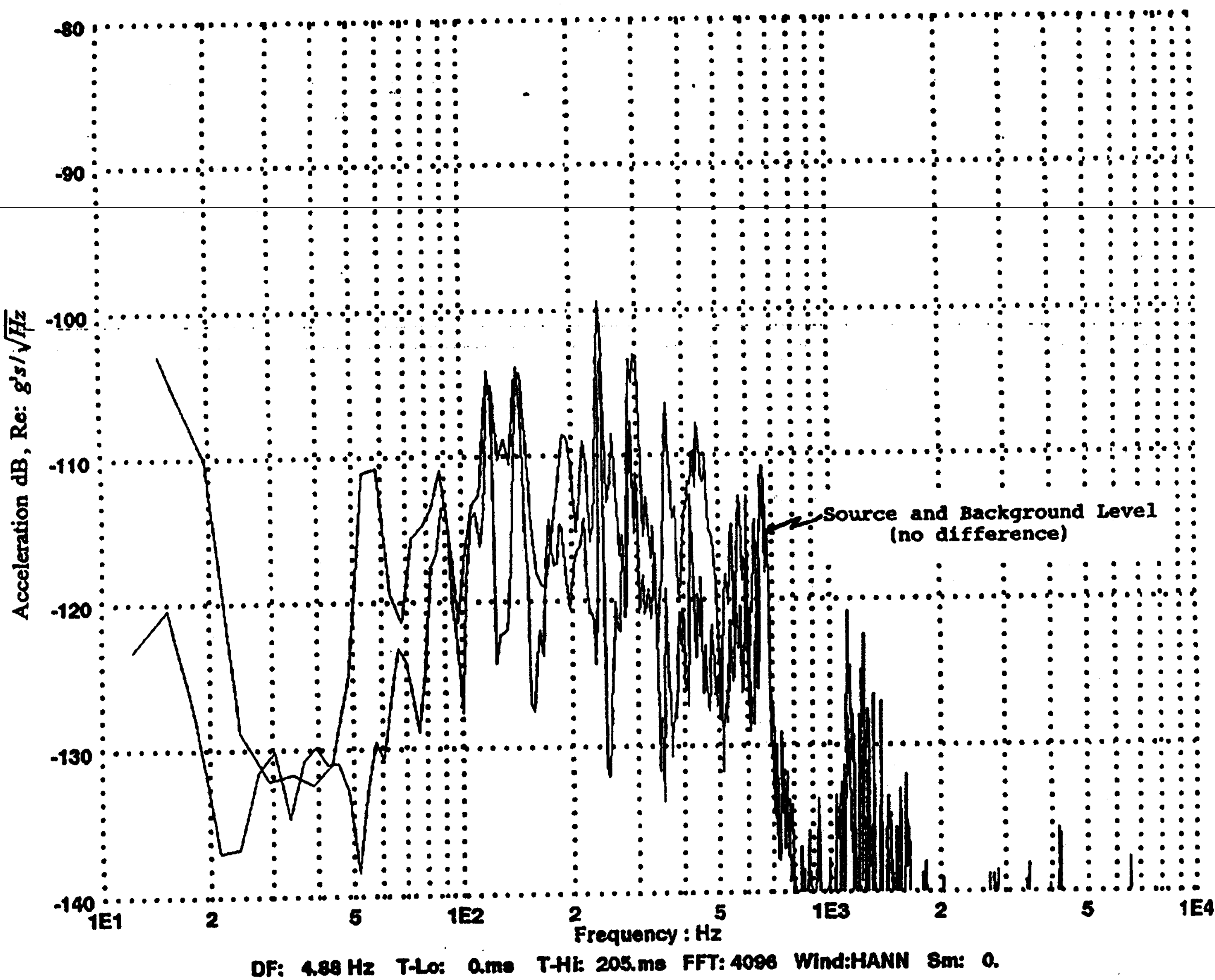


Fig. 5 Cryopump support (beamsplitter) vertical acceleration.

SECTION III

4.0 BUBBLE VIBRATION MODELING

"Bubble - Generated Forces And Resulting Structure - Borne Noise"

by M.C. Junger

Cambridge Acoustical Associates
Medford, MA

PROCESS SYSTEMS INTERNATIONAL, INC.

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200 Boston Avenue, Suite 2500 • Medford, MA 02155-4243 • Telephone (617) 396-1421 • Fax (617) 396-1607

TO: Richard Bagley, PSI

FROM: M.C. Junger

DATE: 26 August 1996

SUBJECT: BUBBLE-GENERATED FORCES AND RESULTING STRUCTURE-BORNE NOISE

TECH MEMO: TM/U-2392-2041

ABSTRACT

The dynamics of vapor bubbles in the boiling liquid nitrogen between the two concentric cylindrical tanks and the resulting force spectrum exerted on the outer tank are formulated. Finally, the resulting acceleration spectrum level of the outer tank wall is computed.

I. BUBBLE DYNAMICS

Heat transfer across the outer tank surfaces causes the liquid nitrogen to boil. The resulting vapor bubbles rise vertically with a velocity $\dot{U}(t)$ until they collide with the surface of the inner or outer tank (Fig. 1). This analysis deals with the structure-borne noise generated by the bubbles colliding with the outer tank wall. The strongest impact force is exerted by bubbles emerging from the greatest vertical path length d, viz. a path not resulting in grazing along the inner tank wall.

A rising bubble is subjected to three forces: The buoyancy B, the inertial force $M\ddot{U}$ of the entrained mass of water, and drag $D\dot{U}$ associated with the liquid's viscosity. For the present parameter values, drag is by far the smallest of the three forces. It will be approximated by Stokes's simple expression for low-Reynolds numbers. The drag coefficient[1] is

$$D = 6\pi\nu\rho a \tag{I.1a}$$

where ν = kinematic viscosity = $1.9 \times 10^{-3} cm^2/s$ for liquid nitrogen, as compared to $10^{-2} cm^2/s$ for water at room temperature

ρ = density = $0.81 g/cm^3$

a = mean bubble radius = $3/64$ in. = 0.12 cm

Consequently,

$$D = 3.48 \times 10^{-3} \text{ dyne} \cdot \text{s/cm} \qquad (I.1b)$$

Though this expression was derived for constant flow velocity, it provides a good approximation, as drag only becomes predominant when the bubble velocity has approached its asymptotic value [Eq. I.6a below].

The mass is the entrained mass of a translating sphere small in terms of wavelengths, viz. half the displaced mass of liquid[2]:

$$M = 2\pi a^3 \rho / 3$$
$$= 2.93 \times 10^{-3} \text{ grams} \qquad (I.2)$$

The error resulting from the assumed constant bubble volume is small, because hydroacoustic pressure at shallow depth is primarily a function of the gas pressure on the liquid surface rather than of depth. The buoyant force is the weight of displaced liquid:

$$B = \frac{4\pi a^3 \rho g}{3} \qquad (I.3a)$$

where g is the acceleration of gravity, viz. 980 cm/s^2. Consequently,

$$B = 7.09 \text{ dynes} \qquad (I.3b)$$

The equation of motion therefore becomes

$$M\ddot{U} + D\dot{U} - B = 0 \ , \quad 0 < t < t_o \tag{I.4}$$

It is convenient to divide this equation by M and to express the ratios D/M and B/M explicitly:

$$\ddot{U} + \frac{9\nu}{a^2}\dot{U} - 2g = 0 \tag{I.5a}$$

At early times, the bubble rises at twice the acceleration of gravity, irrespective of its volume:

$$\left.\begin{aligned} \ddot{U} &\sim 2g \\ \dot{U} &\sim 2gt \\ &= 1960t \end{aligned}\right\} \begin{aligned} &(9\nu/a^2)\,\dot{U} \ll 2g \\ &t \ll \frac{a^2}{9\nu} = 0.84s \end{aligned} \tag{I.5b}$$

At late times, when drag predominates over the inertia force, the bubble velocity tends asymptotically to

$$\begin{aligned} \dot{U}_T &\sim \frac{2a^2g}{9\nu} \ , \quad t \gg \frac{a^2}{9\nu} \\ &= 1.65 \times 10^3 cm/s = 59.4\ km/hr \end{aligned} \tag{I.6a}$$

The solution of Eq. 1.5a is (Figs. 2a and b)

$$\dot{U} = \dot{U}_T\left[1 - \exp\left(-\frac{2gt}{\dot{U}_T}\right)\right]$$
$$\ddot{U} = 2g\exp(-2gt/\dot{U}_T) \qquad \text{(I.6b)}$$

$$U(t) = \int_0^t \dot{U}dt$$
$$= \dot{U}_T t - \frac{\dot{U}_T^2}{2g}\left[1 - \exp\left(-\frac{2gt}{\dot{U}_T}\right)\right] \qquad \text{(I.6c)}$$

For the maximum unimpeded vertical path of a rising bubble, viz. $U = d = 68.6m$, the terminal velocity and acceleration are

$$\left.\begin{aligned}\dot{U}(t_o) &= 500\ cm/s = 18\ km/hr\\ \ddot{U}(t_o) &= 1.41 \times 10^3 cm/s^2\\ &= 1.44g\end{aligned}\right\} t_o = 0.279s \qquad \text{(I.7a)}$$

Since the drag is relatively small, approximate values of rise time and velocity are

$$\left.\begin{aligned}t_o &\sim (d/g)^{1/2} = 0.26s\\ \dot{U}(t_o) &\sim 2(dg)^{1/2} = 518\ cm/s\end{aligned}\right\} D\dot{U} << M\ddot{U} \qquad \text{(I.7b)}$$

II. SPECTRUM LEVEL OF THE IMPACT FORCE EXERTED BY A BUBBLE ON THE OUTER SHELL

The bubble colliding with the outer shell exerts a time dependent vertical force

$$\left.\begin{aligned}F &= M\ddot{u}_D(t)\\ &\equiv M\ddot{U}_D\Phi(t)\ , \quad 0 < \phi(t) < 1\end{aligned}\right\} 0 < t < \tau \qquad \text{(II.1)}$$

where M is once again the entrained mass of liquid attached to the rising bubble (Eq. I.2) and $\ddot{u}_D$ is the bubble's deceleration sensed by the bubble during a time interval τ. In the absence of data or of a detailed analysis, it will be assumed that the deceleration takes place in a time interval equal to the time in which the bubble rises through a distance equal to its diameter:

$$\tau = \frac{2a}{\dot{U}(t_o)} = \frac{0.24\,cm}{500\,cm/s} = 4.8 \times 10^{-4} s \qquad \text{(II.2)}$$

where $\dot{U}(t_o)$ is the terminal bubble velocity where it reaches the shell surface (Eq. 1.7a). This velocity is cancelled as the bubble is brought to a halt. In the absence of detailed information on this process and in view of the primary interest in the low frequency portion of the spectrum where the time history is relatively unimportant, it will be assumed that the deceleration displays a semi-sinusoidal time dependence:

$$\Phi(t) = \sin\left(\frac{\pi t}{\tau}\right) \quad , \; 0 \le t \le \tau \qquad \text{(II.3)}$$

The bubble comes to a halt when

$$\dot{U}(t_o) = \ddot{U}_D \int_0^{\tau} \sin\left(\frac{\pi t}{\tau}\right) dt = \frac{2\tau}{\pi} \ddot{U}_D \qquad \text{(II.4)}$$

Solving for the deceleration amplitude,

$$\ddot{U}_D = \frac{\pi \dot{U}(t_o)}{2\tau} \quad \text{(II.5a)}$$

$$= \frac{\pi \dot{U}^2(t_o)}{4a} \quad \text{(II.5b)}$$

$$= 1.64 \times 10^6 cm/s^2$$

The force exerted by the bubble can now be expressed explicitly by substituting Eqs. I.2 and II.5b in Eq. II.1:

$$F(t) = \frac{\rho\,[\pi a \dot{U}(t_o)]^2}{6} \sin\left(\frac{\pi t}{\tau}\right) \quad , \; 0 \le t \le \tau \quad \text{(II.6)}$$

This is plotted in Figs. 3a and b.

The Fourier transform of the normalized deceleration history is[3]

$$\tilde{\phi}(\omega) = \int_0^\tau \sin\frac{\pi t}{\tau}\; e^{i\omega t}\,dt$$

$$= \frac{\pi\tau(1+e^{i\omega\tau})}{\pi^2 - \omega^2\tau^2}$$

$$= \frac{2\pi\tau\cos(\omega\tau/2)}{\pi^2 - \omega^2\tau^2}\; e^{i\omega\tau/2} \quad \text{(II.7)}$$

whose absolute value is

$$|\tilde{\phi}(\omega)| = \frac{2\pi\tau|\cos(\omega\tau/2)|}{|\pi^2 - \omega^2\tau^2|}$$

$$\left.\begin{aligned} &\approx \frac{2\tau}{\pi} \\ &= 3.1 \times 10^{-4} s \end{aligned}\right\} \quad \begin{aligned} &\left(\frac{\omega\tau}{\pi}\right)^2 << 1 \\ &(f/Hz)^2 << (4 \times 10^3)^2 \end{aligned} \qquad \text{(II.8)}$$

The force spectrum can now be computed. It is first noted that the radial force is (Fig. 1)

$$\begin{aligned} F_R &= F \sin\phi_o \\ &= F\, d/2R_o \\ &= 0.45\, F \end{aligned} \qquad \text{(II.9)}$$

Combining Eqs. I.2, II.1,2, 8 and 9, the spectrum of the radial force is formulated explicitly:

$$|\tilde{F}_R(\omega)| = \frac{M\dot{U}(t_o)d}{2R_o} \quad , \quad \omega^2\tau^2 << \pi^2 \qquad \text{(II.10a)}$$

Substituting the parameter values,

$$\begin{aligned} |\tilde{F}_R(\omega)| &= 0.66 \ \text{dyne}\cdot\text{s} \ , \quad f^2 << (4 \times 10^3 Hz)^2 \\ 20 \log|\tilde{F}_R(\omega)| &= -3.6 \ dB\, re (dyne \cdot s)^2 \end{aligned} \qquad \text{(2.10b)}$$

It is recalled that selecting the terminal velocity $\dot{U}(t_o)$ corresponding to a bubble rising from the maximum depth avoiding grazing the inner tank is one more conservative assumption.

III. ACCELERATION SPECTRUM LEVEL OF THE OUTER SHELL

The radial drive-point velocity $\dot{w}$ of a cylindrical shell driven by a radial harmonic force is formulated in terms of the shell's admittance:

$$Y_c(\omega) \equiv \frac{\dot{w}(\omega)}{\tilde{F}_R(\omega)} \qquad \text{(III.1a)}$$

corresponding to the radial acceleration

$$|\ddot{w}(\omega)| = \omega\,|Y_c(\omega)\,\tilde{F}_R(\omega)| \qquad \text{(III.1b)}$$

Y_c is the series of modal admittances which peak at the lower natural frequencies of the predominantly radial family of the three families of modes of a cylindrical shell. These resonances, identified by the circumferential wavenumber n/R_o are in the mid-frequency range (Ref. 4, p. 225, Fig. 7.6; $1 \le n \le 5$). Since even the approximate calculation of the admittance is laborious (Ref. 4, p. 226-227, Eqs. 7.99 and 7.101), an estimate of the shell acceleration will be based on the admittance vs. frequency graph in Ref. 4, p. 228, Fig. 7.7 reproduced in this report as Fig. 4. This graph is for a shell of thickness-to-radius ratio $h/R_o = 10^{-2}$ and an aspect ratio $L/2R_o = 2$, both of which fall close to the corresponding values of the present shell for which $h/R = 1.34.10^{-2}$ and $L/2R_o = 2.45$. A possibly more serious discrepancy arises from the fact that Fig.4 corresponds to simply supported boundary conditions, and to a midspan drive-point, $x_o = L/2$. For this situation, even modes are associated with their maximum generalized force, while the odd modes are not excited. These two effects partially cancel for randomly applied forces.

A major highly conservative approximation is the neglect of the radiation loading exerted by the liquid-filled annular space between the concentric shells. Unless the structure-borne noise spectrum level predicted by this simple analysis exceeds the specifications, there is no incentive to perform a more rigorous study.

In this low-frequency range, the admittance in Fig. 4 is described by the equation

$$20 \log |Y_c/Y_p| = 15 \ dB + 20 \log \Omega \ , \quad \Omega \le 0.03 \qquad \text{(III.2)}$$

where the dimensionless frequency formulated in terms of the dilatational plate velocity $c_p (= 5.4 \times 10^5 \ cm/s$ for steel and aluminum) is

$$\Omega \equiv \omega R_o / c_p$$
$$= 8.80 \times 10^{-4} \ f/Hz \qquad \text{(III.3)}$$

Y_p is the admittance of an infinite plate of the same material and thickness as the shell[5]:

$$Y_p = 3^{1/2}/4 \ \rho_s c_p h^2 \qquad \text{(III.4)}$$

where ρ_s is the density of the plate material ($= 2.8 g/cm^3$ for aluminum), and where the plate thickness $h = 3/8 \ in. = 0.95 \ cm$. Substituting these parameter values, one obtains

$$20 \ \log \ Y_p = 20 \log [3.16 \times 10^{-7} (cm/s)/\text{dyne}]$$
$$= -130.0 \ dB \ re \ (cm/s \cdot dyne)^2 \qquad \text{(III.5)}$$

The shell admittance level corresponding to Eq. III.2 finally becomes

$$20 \log |Y_c| \ dB \ re \ (cm/s \cdot \text{dyne})^2 = -176 \ dB$$
$$+ 20 \log (f/Hz) \ , \quad f \le 30 \ Hz \qquad \text{(III.6)}$$

In the low-frequency range, the simply supported shell can therefore be modelled as a spring of stiffness

$$K = \frac{\omega}{|Y_c|} = 4.0 \times 10^9 \text{ dyne}/cm \qquad \text{(III.7)}$$

It is noted that Eq. III.6 is not conservative in the resonance frequency range $30\ Hz < f < 80\ Hz$, where the error does not however exceed 7 dB for the assumed structural loss factor of $\eta_s = 0.1$. The resonance response is evaluated in the last paragraph of this section. Eq. III.6 is highly conservative at higher frequencies.

The tank's acceleration spectrum level can now be formulated in terms of the convolution theorem[6]. From Eq. III.1b the spectrum level generated by N bubbles per second colliding with the tank is

$$L_{acc}\, dB\ re\ (cm/s^2)^2/Hz = 20\ \log[2\pi\,\omega\,|\tilde{F}_R(\omega)\,Y_c(\omega\,|] + 10\ \log N \qquad \text{(III.8)}$$

Noting that

$$20\ \log(2\pi\,\omega)| = 31.9\ dB + 20\ \log(f/Hz) \qquad \text{(III.9)}$$

Substituting the numerical values from Eqs. II.10b and III.9 in Eq. III.8, the low-frequency acceleration spectrum level becomes

$$L_{acc} \left.\begin{array}{l} = -\,148\ dB\ re\ [(cm/s^2)^2/Hz] \\ = -\,88\ dB\ re\ [(\mu g)^2/Hz] \end{array}\right\} + \log f + 10\ \log N \qquad \text{(III.10a)}$$

$$= +\,15\ dB\ re\ [(\mu g)^2/Hz],\ f = 30\ Hz,\ N = 26{,}000 s^{-1} \qquad \text{(III.10b)}$$

The peak value is associated with the resonance peak in Fig. 4 at $\Omega \sim 0.058$, $f \sim 66\ Hz$, where Eq. III.6 is approximately 7 dB too low. The highest spectrum level is therefore obtained by substituting $f = 66\ Hz$ in Eq. III.10a and raising the result by 7 dB. This results in a resonance acceleration spectrum level of $36\ dB\ re\ [(\mu g)^2/Hz]$. The corresponding displacement spectrum level is obtained by subtracting $40\ \log\ dB(2\pi f) = 104\ dB$, resulting in a resonance displacement spectrum level of $-128\ dB\ re\ cm^2/Hz$.

Acknowledgement: Numerical results in Figs. 2 and 3 were generated by the author's coworker Jason Rudzinsky.

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2 Ibid., p. 124, Eq. 3.

3 B.O. Peirce, A Short Table of Integrals, 3rd ed. (Ginn, Boston 1929), p. 54, integral 414, with $a = i\omega$..

4 M.C. Junger and D. Feit, Sound, Structures, and Their Interaction, 2nd. ed. (MIT Press 1986, reprinted by Amer. Inst. of Physics 1993), p. 225-228.

5 Ibid., p. 212, Eq. 7.68.

6 A. Papoulis, The Fourier Integral and Its Applications, (Mc Graw-Hill, New York, 1962), pp. 26-28.

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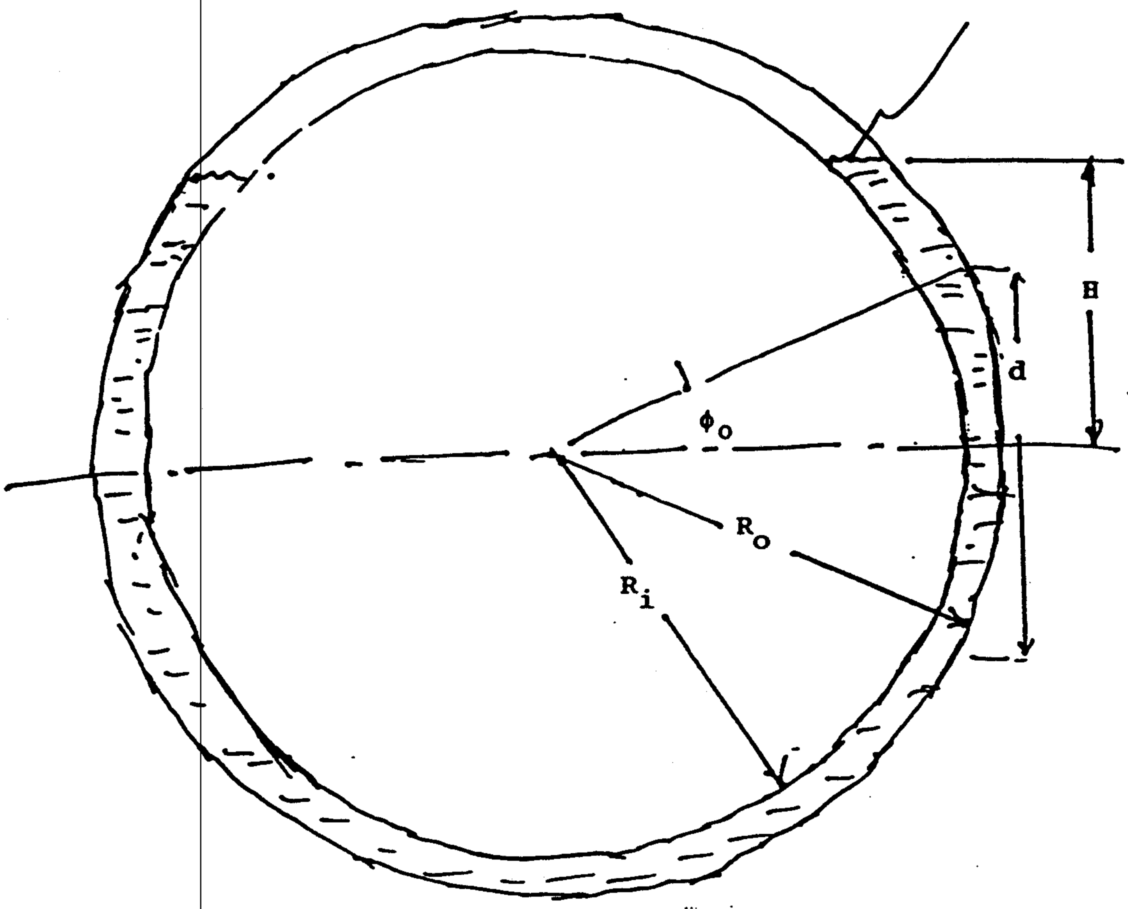

$$R_o = 29\frac{3}{4}\ in. = 75.6\,cm$$

$$R_i = 26\,\frac{1}{2}\ in. = 67.3\,cm$$

$$H = 21\ in. = 53.3\,cm$$

$$d = 2[R_o^2 - R_i^2]^{1/2} = 27\ in. = 68.7\,cm$$

$$\phi_o = \tan^{-1} d/2R_i = \sin^{-1} d/2R_o = 27°$$

Fig. 1 Configuration of concentric shells.

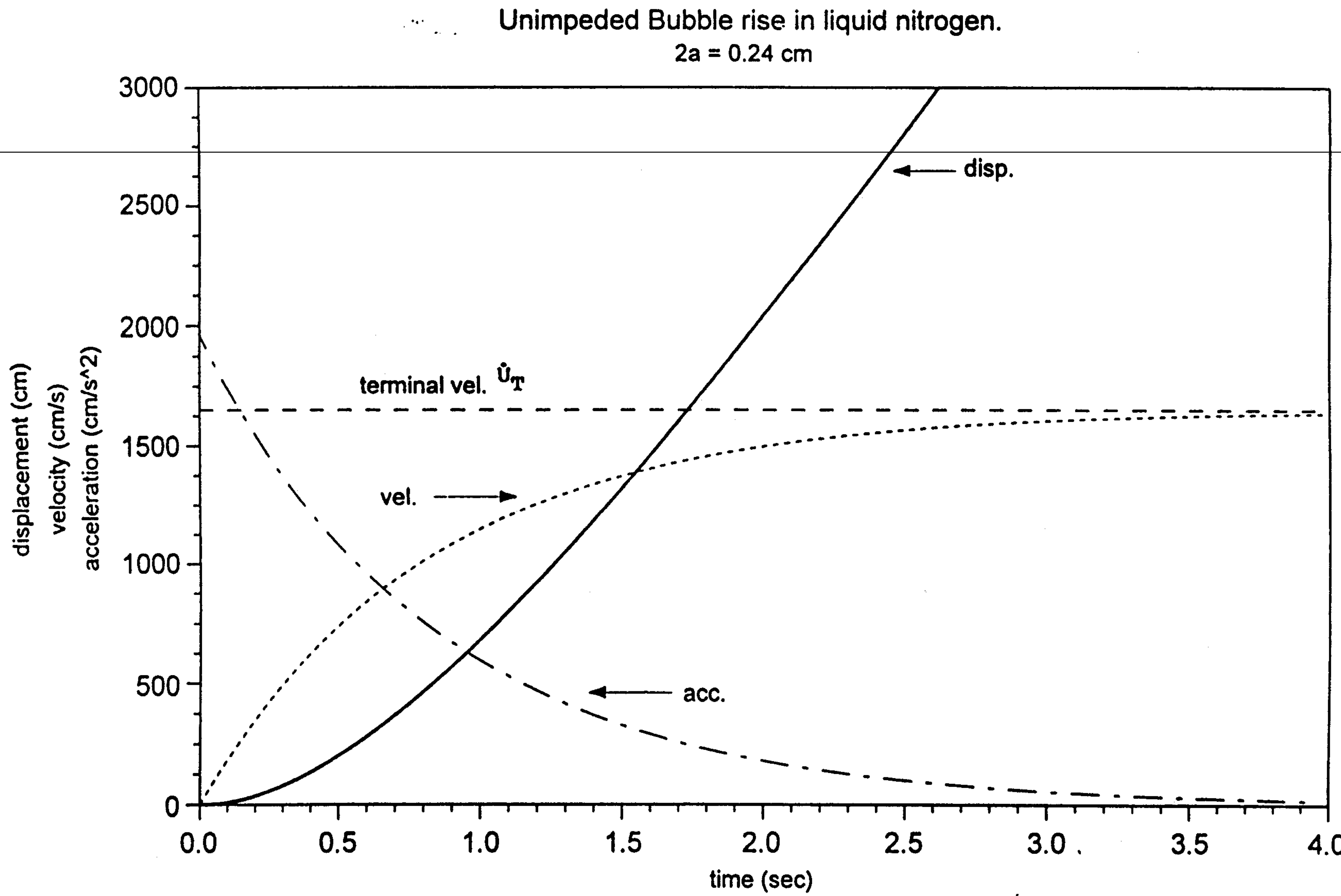

Fig. 2 Acceleration, velocity and vertical displacement of a bubble (Eqs. I.6b and c).

Fig. 2a Extended time history.

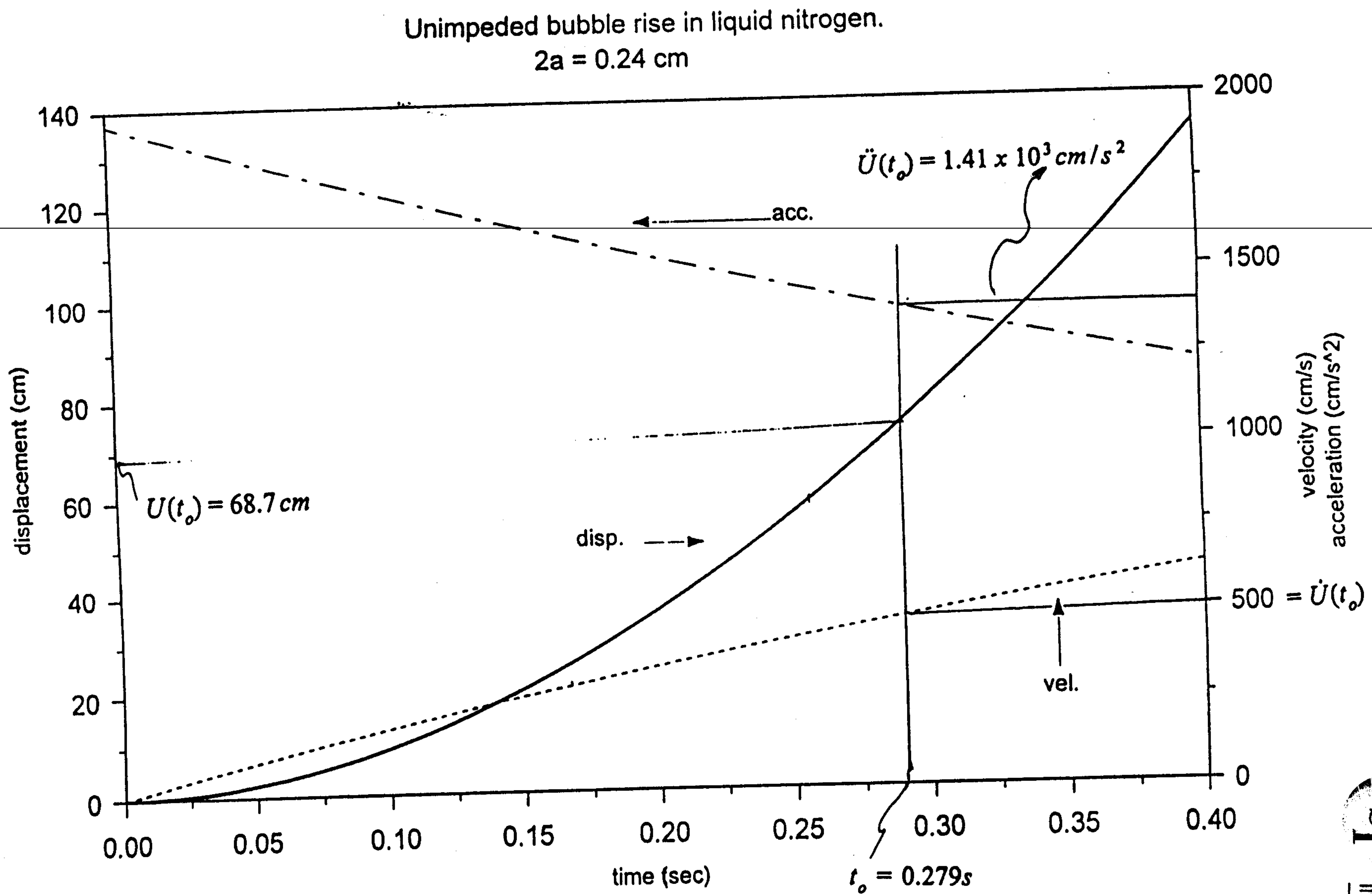

Fig.. 2b Early time history relevant to tank dimensions, (Eq. 1.7a).

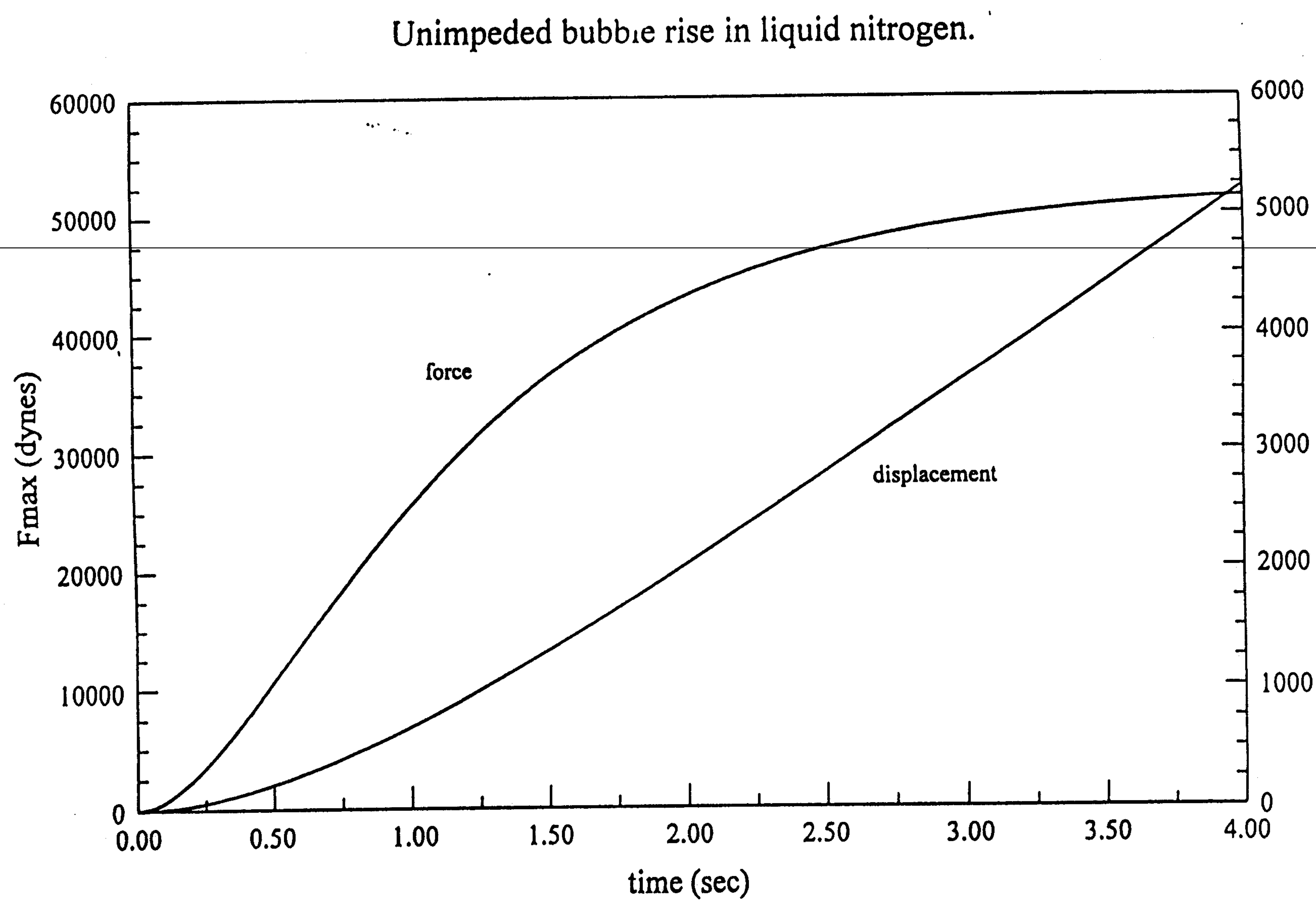

Fig. 3 Vertical force amplitude applied by the bubble colliding with shell as a function of time and of vertical distance travelled (Eq. II.6).

Fig. 3a Extended time history.

Unimpeded bubble rise in liquid nitrogen.

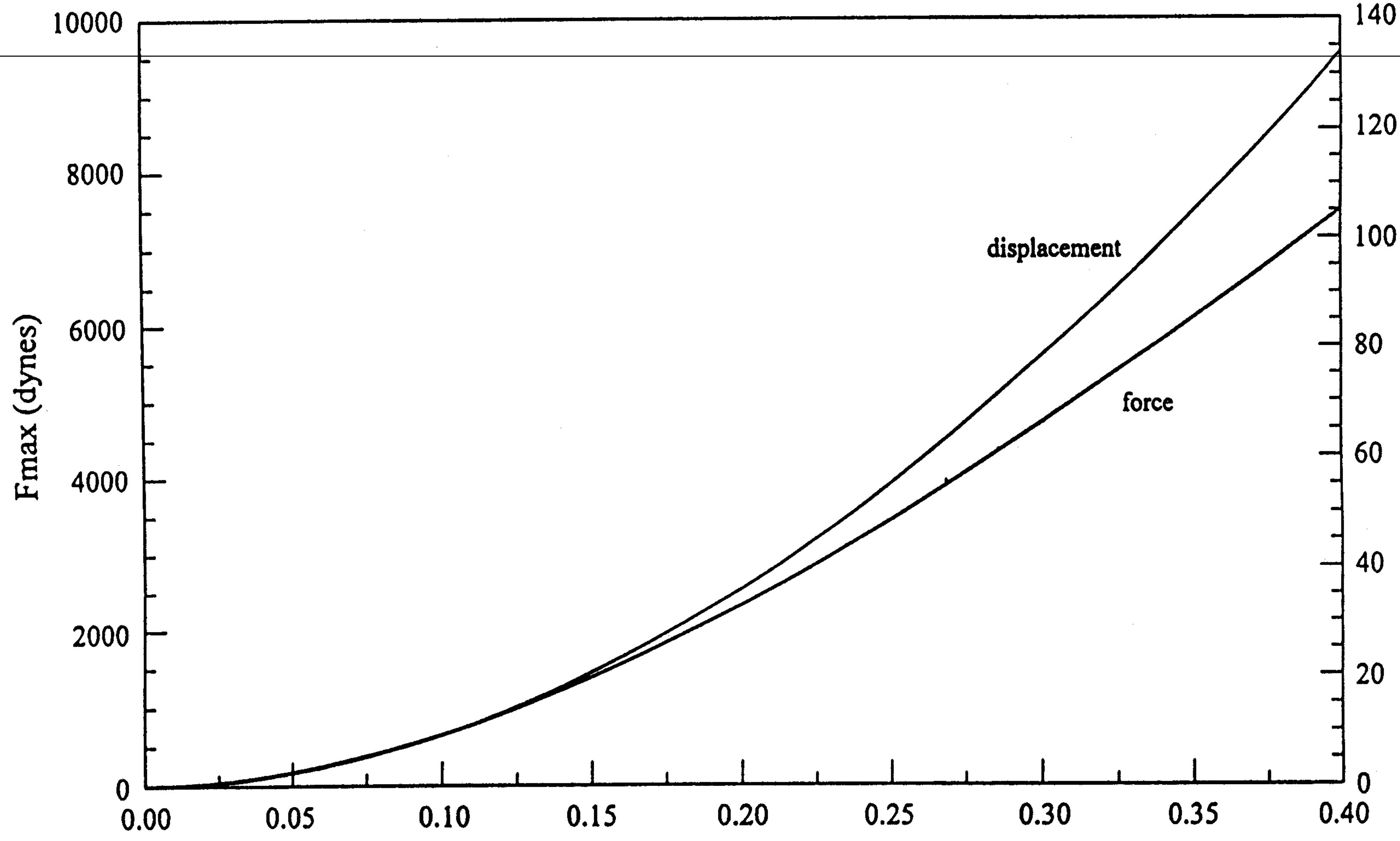

Fig. 3b Early time history relevant to tank dimensions.

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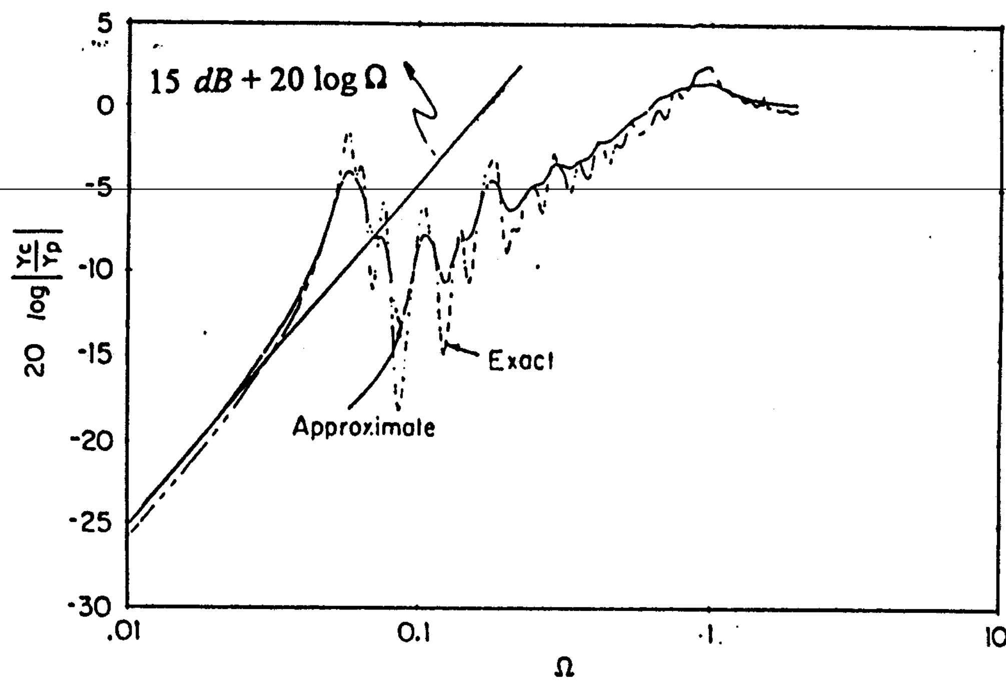

Fig. 4 Admittance of a cylindrical shell [s.s., driven at midspan, $h/a = 10^{-2}$, aspect ratio 2] normalized to the point admittance of an infinite plate of thickness h. (Reproduced from Ref. 4)