APPENDIX B

GPU Nuclear

TECHNICAL DATA REPORT

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BUDGET ACTIVITY NO. 123125	**PAGE** 1 **OF** 50	
DEPARTMENT/SECTION Engineering & Design Materials Engrg/Failure Anal.		
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PROJECT: TMI-1 OTSG REPAIRS

DOCUMENT TITLE: Evaluation of Eddy Current Indications Detected During the 1984 Tech. Spec. Inspection

ORIGINATOR SIGNATURE	DATE	APPROVAL(S) SIGNATURE	DATE
F. S. Giacobbe for [signature]	10/21/85	F. S. Giacobbe [signature]	10/21/85
		D. K. Croneberger [signature]	10-30-85
		APPROVAL FOR EXTERNAL DISTRIBUTION	**DATE**
		R. F. Wilson [signature]	10/31/85

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*** DISTRIBUTION**

R. O. Barley
D. D. Bowman
G. R. Capodanno
J. J. Colitz
D. K. Croneberger
B. D. Elam
N. C. Kazanas
R. J. McGoey
R. F. Wilson
T. G. Broughton

ABSTRACT:

In order to identify the cause of the eddy current indications detected during the TMI-1 OTSG tube examination beginning in November 1984, Materials Engineering/Failure Analysis performed an in-depth review of the eddy current results and plant operating/chemistry history since the OTSG's were first filled after the kinetic expansion repairs.

Two possible causes for the eddy current indications were evaluated: corrosion, either continuing or newly initiated, and enhanced eddy current detectability of existing intergranular attack (IGA or intergranular stress assisted cracks (IGSAC). During unit layup, GPUN Layup specifications were followed. Some out of specification periods did occur; however. they were promptly corrected and were not of sufficient magnitude to have caused corrosion. Additional corrosion-preventive conditions were also maintained during layup.

During hot operations, system chemistry conditions were maintained within specifications that industry experience and TMI-1 tube testing have shown are non-corrosive.

The most likely reason for having eddy current indications at this time was enhanced detectability of pre-existing areas of IGA/IGSAC. As a result of thermally induced strains and hydraulic forces during hot functional testing, grains could fall out or grain boundaries could separate within pre-existing IGA, resulting in greater local disturbance of the eddy currents and a correspondingly higher signal to noise ratio.

Additional plant data from leak rate observations and the fiberscope examination of a sample of tubes also support the mechanical damage scenario. No leaks have been identified in the tube free span since 1983. In the region of 1984 eddy current indications, patch-like indications suggestive of IGA were seen by the fiberscope examination.

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REV	SUMMARY OF CHANGE	APPROVAL	DATE
1	Abstract: Changed IGA to IGA/IGSAC Changed larger eddy current signal to higher signal to noise ratio	FFS	10/21/85
1	Page 7: Changed IGA to IGSAC	FFS	10/21/85
1	Page 23: Deleted Para. 4	FFS	10/21/85
1	Page 23: Added under item 1: ... in the LTCT LTCT (Ref. 8). This could produce a crack like indication, etc.	FFS	10/21/85
1	Page 25: Revisions made to entire page	FFS	10/21/85
1	Page 27: Added Table 7	FFS	10/21/85
		[signature]	10-30-85

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Introduction

In accordance with the requirements of Technical Specification 4.19, eddy current testing of the OTSG tubing at TMI-1 was begun in November 1984. Initial testing with the 0.540" high gain standard differential probe method revealed previously unreported indications in the unexpanded portions of the OTSG tubes between the tube sheets.

Two possible causes for the eddy current indications were identified and evaluated; first, whether corrosion of the OTSG tubes caused either new defects or growth of existing defects and second, whether straining of existing defects caused them to become more detectable by eddy current. Since the original 100% baseline inspection of the OTSG tubes in 1982, the tubes have been subjected to mechanical loading during the kinetic expansion and thermal and hydraulic loads during the two hot functional tests.

In order to attempt to determine the cause of these indications, the Materials Engineering/Failure Analysis group reviewed 1) the historical eddy current data and 2) plant operational and chemistry data since the OTSG's were filled after the kinetic expansion repair of the tubes.

Based on the results of this review, the cause of the indications is discussed. Data supporting the conclusion are also included.

Background

As defined by Technical Specification 4.19, GPUN conducted eddy current examinations of both steam generators at TMI Unit 1. Performance of this examination ultimately resulted in 100% of the tubes in A-OTSG and all tubes in the outer 16 tube periphery of the B-OTSG being examined.

The B-OTSG had only a limited number of indications with an indicated through-wall extent greater than 40%. Due to the limited number of B-OTSG indications, statistically-based analysis is not feasible. All these indications, however, are located near the outer periphery of the B-OTSG.

The following generalizations about the EC indications can be drawn from the A-OTSG results:

1. They are primarily located in the upper tube sheet and 16th tube span area.
2. They are concentrated in the outer periphery, but some indications occur across the entire OTSG.
3. Approximately 78% of the indications are less than 50% through wall.
4. They generally exhibit voltages in the 0.5-2 v. range.
5. Except for two indications, the number of 8 X 1 absolute eddy current coils producing a signal from a defect is 2 or less, indicating a small circumferential extent.

Evaluation of Eddy Current Results

Note: This section uses the eddy current data base as of Jan. 3, 1985.

GPUN conducted a qualified full-length, eddy current examination program on all tubes from both generators during July to November 1982. The purpose of this program was to screen out all relevant indications and establish a 6" qualified length in the kinetically expanded zone immediately above the new transition zone which was essentially indication free. It was further established that small defects below the threshold of detection could exist. Reference 1 identifies the maximum size of these small defects which could possibly go undetected.

Prior to the expansion, a 100-tube sample of tubes in each generator was eddy current tested periodically to check for indication changes. These tests were performed on seven occasions over a 7 month period. No growth was observed.

Post-Baseline Growth Studies

In-Process Testing

During and following the kinetic expansion repair, a total of 437 tubes were inspected in both the A and B generators (Ref 2, 3). A total of 15 tubes (3.5%) with indications were found that had not been detected by our ECT inspection program prior to the repair. An evaluation was performed on why these indications were not identified previously (Ref. 3). It was concluded that:

1) The recent indications were not initiated by the kinetic expansion process nor was there any evidence of ductile propagation of existing indications.

2) The defects were small (threshold) type indications that had been either masked by the high background noise levels in the upper tube regions or were sufficiently tight that the volume of lost metal was not detectable. Kinetic expansion may have altered these areas of IGA/IGSAC to make them more detectable by causing additional grain boundary separation.

Confirmation on the small size of the indications was established by the visual examination using fiber-optics. Some of the indications appeared to be small pits.

Additional confirmation was obtained that kinetic expansion would not cause ductile tearing by using test mock-ups and metallurgical examination (Ref. 2). Small intergranular stress assisted (IGSAC) cracks were examined using eddy current techniques before and after kinetic expansions. Expansion caused the cracks to become non-detectable by .540" S.D. techniques. However, the cracks remained visible to the 8 X 1 absolute technique with essentially no change in signal. These specimen tubes were subsequently removed from the test block and metallurgical examination did not reveal ductile tearing or generation of new indications.

ISI Indications

During OTSG repairs, a subset of tubes (28 in A-OTSG, 56 in B-OTSG) was identified as having eddy current indications that did not require plugging. That is, the indications were less than 40% through wall, not in the lane/lane wedge area, and below the 15th tube support plate. This group of tubes (designated as "ISI" tubes by GPUN) was fully characterized and listed for eddy current inspection in the future as a distinct subset.

The "ISI" tubes were re-examined in April/May 1983. No growth of the existing indications was detected.

As part of the eddy current campaign which started in October 1984, all 84 of the "ISI" tubes have been retested. No growth in the ISI subset was detected. (Growth is identified as a substantial increase in the through wall percentage, combined with an increase in voltage and/or circumferential extent.)

June 1984 Testing

During June 1984, 67 tubes in B-OTSG and 3 tubes in A-OTSG were eddy current tested. This set of tubes was retested in November 1984 - no new indications were detected for the two retests performed.

100 Tube Sample November 1984

Since discovery of the additional indications in November 1984, a second 100 tube sample with indications has been re-examined at approximate two week intervals. As of December 18, 1984, no growth and no new indications have been detected for the two retests performed.

1984 Technical Specification Required Testing

In November 1984, eddy current testing required by TMI-1 Technical Specification 4.19 was conducted as specified. 3% of the tubes in each generator were initially examined. This examination included tubes randomly selected across the entire generator plus a concentrated examination in the periphery of each generator. The more extensive examination in the periphery was performed because this was the region of highest previous (1981) damage .

As a result of this initial examination, OTSG A was classified as category "C-3" per technical specification and OTSG B was classified as category "C-2". Subsequently the entire A-OTSG was inspected while the B-OTSG inspection was complete after the entire 16-tube periphery, approximately 6500 tubes, had been examined.

The number of indications is much higher in A-OTSG than B-OTSG. In A-OTSG, 2.0% of the tubes (299 out of approximately 14589) have indications greater than 40% through wall, while in B-OTSG, 0.5% (33 out of approximately 6576) have such indications.

Spatial Distribution

The indications with greater than 40% through wall depth are concentrated toward the outer periphery and top of A-OTSG. In the outer periphery, the percentage of tubes with greater than 40% through wall indications is higher than the 2.0% average, while inside the outer support rods the percentage of indications is below 1%. 71% of the indications are located above the 15th tube support plate (TSP).

Characterization of Indications

To understand the nature of the defects better, we characterized the indications reported back in the 1981-1982 time frame and compared them to the indications discovered today.

The axial and radial locations of indications in A-OTSG are essentially the same in 1984 as in 1982, if one does not consider the 1982 indications in the kinetically expanded region in the 1984 evaluation.

Table 1 characterizes the 1982 and 1984 eddy current signals. The 1984 eddy current indications exhibit a similar type of signal response as the previous test program. Details of the differences in responses are noted below:

1) Reported voltages are essentially the same. This indicates that the 1984 indications present a similar volume for the eddy current probe to detect as the 1982 IGSAC.

2) Both through wall penetration and number of coils is significantly lower in 1984. Thus, the 1984 indications extend a shorter distance both into and around the OTSG tube.

Statistical analysis of the eddy current data reveals that 78% of the observed indications are less than 50% through wall and 90% are .194" or less in circumferential extent.

Degraded Tubes

Per GPUN procedure, tubes with indications reported between 20 and 40% through wall were not required to be plugged if the tubes were not in the lane or lane wedge and the indication was below the 15th tube support plate. At the completion of the 1982 kinetic expansion repairs, a total of 15 A-OTSG tubes and 51 B-OTSG tubes were classified as "degraded" and were included in the ISI group. As of January 4, 1985, 347 additional A-OTSG tubes and 98 additional B-OTSG tubes are classed as degraded.

Table 1

Comparison of 1982 and 1984 Eddy Current Data

a) Reported Voltage - % of indications reported

	A-OTSG		B-OTSG	
Voltage	1982	1984	1982	1984
< 1	34	40	24	27
1	44	35	30	21
2	16	20	25	29
3	4	4	10	12
> 3	2	1	11	11

b) Reported through wall penetration - % of indications

	A-OTSG		B-OTSG	
% T.W.	1982	1984	1982	1984
< 20	< 1	< 1	12	
20-40	3	61	28	75
40-60	21	25	24	18
60-80	17	10	15	5
> 80	59	4	21	2

c) Number of coils on 8 x 1 examination - % of calls

	A-OTSG		B-OTSG	
Coils	1982	1984	1982	1984
1	20	90	18	80
2	26	10	24	20
3	16	< 1	15	< 1
> 3	38	< 1	43	< 1

NOTE: 1982 data includes inspection of original tube roll transition area. The 1984 data does not include inspection from the top of tube sheet to the bottom of the kinetically expanded region. See TDR 652 for complete summary of eddy current indications (Ref. 17).

Chemistry Specifications

Corrosion Experience with Inconel 600

Three types of primary-side initiated attack have been identified in Inconel 600. In recirculating steam generators using mill-annealed tubes that have not been stress-relieved after U-bending, stress corrosion cracking (SCC) has initiated from the primary side in the highly stressed bend areas. Also in mill-annealed tubes in recirculating steam generators, SCC has been found to initiate from the primary side at highly stressed transition areas in the lower tubesheet. Laboratory studies have shown that the stress relieved Inconel tubing used in OTSG's is significantly more resistant to SCC than the mill annealed type.

The other primary side attack of Inconel 600 that has occurred in steam generators is the intergranular stress assisted cracking (IGSAC) caused by reduced sulfur species on sensitized OTSG tubing. This is the mechanism which caused the TMI-1 OTSG leakage in 1981. This mechanism requires sensitized tubing, low temperatures, oxygen, and significant levels of reduced sulfur species.

Corrosion Test Results

As part of the overall program to evaluate the most recent eddy current testing results, we have reviewed the results of corrosion tests performed as part of the original failure analysis and OTSG requalification programs. These data provided a partial basis upon which we could evaluate the layup and test conditions to which the steam generators had been subjected.

Long Term Corrosion Test (LTCT)

The primary purpose of the long term corrosion tests was to verify that the proposed operating chemistry specifications are satisfactory to prevent corrosive attack of the OTSG tubes. To this end, chemistry conditions for the testing were established at the maximum allowable values consistent with the upgraded TMI-1 operating specification (Ref. 4). The LTCT was conducted using actual TMI-1 tubing. Temperatures, tube loads, and heatup and cooldown rates were representative of actual plant operating conditions.

In addition, as the LTCT was actually performed, specific factors which parallel actual plant layup conditions were experienced. The tubes were held in a cold, aerated condition for several days after the completion of each operating cycle. Aeration was done after cooldown. Before heatups, or while waiting for other autoclaves in the test program to be ready for operation, the test loops were operated in a cold, deaerated, circulating mode. Because eddy current examinations were done after each test cycle, the tubes had to be removed from the autoclaves and drained. Thus, drained aerated layup conditions were also included.

Table 2 summarizes LTCT operational times in each mode. All loops spent significant time under drained, cold deaerated, and aerated conditions.

Review of the chemistry history of the LTCT's revealed that the conditions were comparable to the plant's experience. The LTCT specification (Ref 5) for sulfate and chlorides was 0.100 ppm $\pm$ .050 ppm. Actual analysis results (Ref. 6, 7, 8) revealed that the concentrations of these species were maintained at or slightly above the .150 ppm upper limit. The actual values measured in these tests bound any of the contaminant "spikes" reported in the Chemistry and Operational History Review.

C-ring tube samples from archive tubing (tubing never installed in the TMI-1 OTSG's, which was included as a control sample) showed no evidence of cracking, pitting or general corrosion both before and after the LTCT.

Data presented from the LTCT show that of a total of 54 "C" ring samples tested and evaluated, 46 had no visible defects, 3 had very short circumferential cracks when strained severely, 3 had IGA patches greater than 20% but less than 40% through wall (Table 7) and 2 had IGA patches less than 20% through wall.

Five full tube samples were examined after the LTCT. In addition to previously reported defects, four samples exhibited scattered, shallow cracking or IGA which were not sized metallographically and therefore a determination could not be made as to their detectability by eddy current testing.

IGA which was metallographically evaluated was consistent in size and shape with IGA that had been seen during the failure analysis (Ref. 9). Therefore, the observed IGA on these four tubes was judged to have been present at the start of the LTCT. And as stated above, the control samples showed no IGA/IGSAC.

Results of metallographic examination of the LTCT samples (Ref. 8) confirmed that normal operations would not cause corrosion of TMI-1 OTSG tubing.

Short Term Test Results

Several sets of tests were previously run on Inconel 600 tubing to establish corrosion resistance under various conditions representative of TMI-1 service. Those results which apply to the period of this review are summarized below:

1) Screening work on actual TMI-1 removed tubes and archive tubes (Ref. 10) identified that at oxidizing potentials, 1 ppm of thiosulfate was required to cause IGSAC. Sulfate levels as high as 10 ppm did not cause IGSAC.

2) Simulation of hot functional testing and cooldown (Ref. 11) utilizing thiosulfate contamination and actual operating temperatures and times revealed that 1 ppm of thiosulfate caused IGSAC.

These short term tests thus confirmed that in the absence of thiosulfate contamination, no short term attack of OTSG tubes is expected.

Bulk vs. Surface Effects

The above corrosion tests were performed using actual TMI-1 OTSG tubing. The surface film condition was therefore representative of that in the plant. Chemistry control in both corrosion testing and actual operation is done by the measurement and control of species of interest in the bulk fluid.

Since both surface conditions and chemistry control were identical between the laboratory tests and plant operations, the results of the corrosion tests can be directly applied to the plant environment, and, conversely, plant bulk chemistry data can be used to evaluate the propensity for corrosion.

TMI-1 Chemistry Guidelines

Hot Operations

After sulfur was identified as the causative agent of the 1981 IGSAC, hot operational guidelines (Ref. 4) were reviewed to ensure that adequate corrosion protection was maintained. As a result of this review, two changes were made to provide increased margins against corrosive attack.

First, a requirement was added that primary system sulfate be maintained below 0.100 ppm. Sulfate at this level does not cause corrosive attack of Inconel 600 in primary coolant, and maintaining sulfate below this level provided assurance that intermediate sulfur species could not exist at harmful concentrations.

Second, the lower limit on lithium concentration was increased to 1.0 ppm, to take advantages of lithium's inhibiting effect on sulfur-induced IGSAC in Inconel 600 (Ref. 12).

The net result of these changes is to ensure that total sulfur species concentrations are a factor of 10 below the level at which corrosive attack might occur. At the same time, the minimum Li/S ratio will be 30 (or Li/SO4 of 10), which is a factor of 3 over the recommended (Ref. 12) ratio of 10 for inhibition of IGSAC initiation.

Layup

For cold layup conditions, guidelines have been established to maintain as many protective conditions as feasible. The individual protective conditions that are feasible for the TMI-1 RCS are:

1) Elevated pH - during layup, pH has been elevated, using ammonia, to at least 7.2. The normal pH without ammonia is 5.6 - 6.5.

2) Control of contaminants - The primary water contaminants of concern are chlorides and sulfates. Chlorides have traditionally been limited to less than 0.100 ppm during operation; we have maintained this level as a general guideline during layup. The sulfate level of less than 0.100 ppm used during hot operation also applies to layup.

3) Control of oxygen level - When the system is filled and able to be pressurized, the oxygen level is to be maintained below 0.1 ppm. For cases where the primary system is open and oxygen cannot be excluded, air saturated conditions are specified as this is more protective than some intermediate oxygen level.

4) Control of OTSG level - One of the contributing factors to the 1981 IGSAC incident was the existence of a water line on the primary side of the OTSG tubes. For layup of the OTSG's, wherever possible, no static waterline shall be allowed to exist in the OTSG tubes. Either the water level should be above the upper tubesheet or the OTSG primary side should be fully drained.

5) Inventory Turnover - Periodic replenishing of the OTSG contents will assure that local buildup of contaminants will not occur. Layup guidelines have included provisions for periodically turning over the water inventory on the OTSG primary side to meet this objective.

TABLE 2

Summary of Operations for Long Term Corrosion Tests

	Operating Days				
		Cold Circulating		Drained	
Loop	Hot	Deaerated	Aerated	Layup (Note 1)	Comments
1	348	52	28	132	
2	308	69	27	157	Thiosulfate loop
3	241	42	23	58	
4	242	40	22	61	

Notes

1. Does not include drained layup between completion of operational cycles and start of metallographic examination.

Chemistry and Operating History Review

Data Base

The chemistry and operating history data were obtained from two sources. First, the on-site Plant Analysis group reviewed operational records to identify plant conditions during this time period (Ref. 13). Then, we retrieved the primary plant chemistry parameters of interest from the GPUN computerized chemistry data base.

The major plant activities that occurred between May 1983 and October 1984 are listed in Table 3. Within each of these periods, we identified different plant conditions of RCS level, temperature, pressure, circulation, and pH. Then, we reviewed the chemistry data for each time period.

Chemistry data selected to be of interest with respect to corrosion were pH, oxygen, lithium, sulfate and chloride. As an additional check on the effectiveness of chemistry controls, we calculated the lithium to sulfur ratio for each operating period. In cases where simultaneous analyses for lithium and sulfate exist, we calculated the Li/S ratio for each data point.

The data from the operational and chemistry investigations are plotted as a function of time in Appendix A.

Results of Operational/Chemistry Review

During both hot shutdown and cold layup conditions, TMI-1 has maintained conditions within chemistry guidelines for about 95% of the time. For short time periods, some deviations have occurred which are discussed in the balance of this section.

Chloride and Sulfate

There have been short time periods where chlorides and/or sulfates have exceeded specified limits. In all instances chemistry data reflect that corrective actions were appropriately and promptly taken to return the concentrations of these species to specified levels. Collectively, these out-of-specification periods can best be described as normal chemistry "spikes".

Oxygen

In preparation for both the September 1983 and May 1984 hot functional tests, it was necessary for the RCS to be taken from a layup to an operating mode. During this transition, oxygen levels were higher than desired for optimum protection, but other factors made it very unlikely that corrosion occurred. First, chloride and sulfate concentrations were controlled to acceptably low levels. Second, the lithium level was maintained such that the minimum lithium to sulfur ratio was 66; the recommended minimum value for protection against IGSAC is 10 (Ref. 12). Chemistry control during these periods is summarized in Table 4.

Other Operational Considerations

During the Integrated Leak Rate Test (ILRT) in April 1984, the primary side water level was maintained at about the 12th tube support plate for 8 days. This condition was both preceded and followed by drained layup with elevated pH, aerated water. Both sulfate and chloride levels remained within specification. Therefore, no OTSG tube corrosion was expected.

In August 1983 and May 1984 oxygenated water was injected into deoxygenated RCS during HPI testing. Most of these tests were conducted prior to the high temperature portion of the hot functional tests, and the oxygen introduced would have been consumed by hydrazine and/or hydrogen added for that purpose. One test was conducted on May 26, 1984, at the end of HFT and may be postulated to have injected 5000-6000 gallons of oxygen-saturated water. During this time period, however, the lithium to sulfur ratio was greater than 30 which was more than adequate to inhibit corrosion during this test.

TABLE 3

Major Plant Evolutions, 5/83 to 10/24

Event	Duration
Fill & Bubble Test	June 1983
Peroxide Clean	July 1983
Hot Functional Test	Aug - Oct 1983
Circulating Wet Layup	Oct - Nov 1983
DH-V1 Repair	Nov 1983
Circulating Wet Layup	Nov 1983 - Jan 1984
RC-P1B Repair	Feb - April 1984
Integrated Leak Rate Test	April 1984
Hot Functional Test	May 1984
Non-Circulating Wet Layup	May - June 1984
Tube Plug Rerolling and Bubble Testing	June - Oct 1984

TABLE 4

Chemistry Summary Before Hot Functional Testing

Period	Days	Oxygen, ppm	Li, ppm	SO_4, ppm	Cl ppm	Li/S Ratio
8/83	29	0.3	.82-1.96	.047-.079	.05-.156	66-123
5/84	19	.075-2.2	1.06-2.17	.02-.047	.05-.110	127-240

In-Plant Observations

Leak Testing

Since completion of the kinetic expansion repairs, several leak tests have been performed to measure primary-to-secondary leakrates and identify individual leaking tubes. These tests are summarized in Table 5.

No pattern of tube leakage can be seen. After the cooldown tests included in hot functional testing some increase in leakage was seen. Further investigation showed that this leakage was the result of leaks through a small number of tubes. These leaks were located in the expanded region within the upper tube sheet and were repaired by mechanically rolling a portion of the expanded area.

Of greatest significance is that since 1983 no tube which is in service has had a leak in an unexpanded portion of the tube. All leaks have either been due to bypass leaks in the expanded area or leaking plugs.

Fiberscope Inspection of Selected Tubes

A fiberscope inspection was performed (Ref. 14) of six A-OTSG tubes which exhibited typical eddy current indications. During the inspection features were observed on 4 out of 6 tubes at the same elevation as the eddy current indications.

The visual features were "patchlike" rounded areas having an outer ring which was darker than the general tube surface and slightly reflective components in the interior. The patches were between 0.020 and 0.060" in diameter.

The patches appeared similar to surface deposits seen during the initial tube failure analysis. These earlier deposits were found to be associated with partial through wall intergranular attack.

TABLE 5

Leak Tests in OTSG's Since 5/01/83

Month/Year	Test Type	Reason For Test	Results	Repairs
May 1983	Drip	Test of Kinetic Expansion	2 Leaking Tubes, 8 Leaking Rolled Plugs 10 Leaking Explosive Plugs	Plugs Installed/Rerolled
June 1983	Bubble/Drip	Final Test of Kinetic Expansion	Small Number of Slightly Leaking Tubes and Plugs in A OTSG - 1 Leaking welded plug	Repaired welded plug
Sept 1983	Kr-85 Tracer	Establish Baseline Leak Rate	Baseline Leak Rate 1 gph	None Required
May 1984		Measure Baseline Leak Rate	Slight Increase in Leak Rate	None Required
June 1984	Bubble/Drip	Identify Leaking Tube(s)	4-5 Leaking Tubes in B-OTSG	Plug 3 tubes w/welded plugs
			6 Rolled Plugs Missing	Reroll all W plugs Replugged tubes.
Oct. 1984	Bubble/Drip	Test Rolled Repairs	Small Number of Leaking Tubes, one welded plug	Roll 8 Tubes Reweld Plug

Note: No leaks seen in final October 1984 Bubble Test, after tube rolling.

Discussion

General

Removal of sodium thiosulfate from the TMI-1 site and tighter operational chemistry controls implemented since 1981 have made it highly unlikely that the conditions to cause sulfur-induced IGA/IGSAC could be recreated. The steam generator layup guidelines are specifically designed to protect the steam generators from additional corrosion and are more stringent than B&W's generic recommendations, particularly in the areas of contaminant control and the use of elevated pH during cold layup. Industry experience on B&W PWR's also does not reveal any other primary-side initiated attack mechanisms on Inconel OTSG tubing.

TMI-1 compliance with operating and layup specifications has been excellent. Transient out-of-specification conditions, which were identified during plant operation, have been infrequent and corrected promptly by the plant operators. Plant conditions have always been bounded by those which were evaluated during corrosion testing and found to be satisfactory.

The only period of possible vulnerability to corrosion would have existed during the time when the OTSG's were drained for the kinetic expansion repair. During this period sulfur would have remained in the oxide film on the tube surfaces as peroxide cleaning had not yet been performed. During this time, however, eddy current testing done on the 100 tube surveillance sample did not reveal any growth of existing indications or any new indications. Thus, while the oxide film may have contained sulfur during this time, there is no evidence that corrosion continued.

Under mechanical loadings induced by kinetic expansion or cooldown, areas of IGA/IGSAC could become more detectable by eddy current through several mechanisms:

1) creation of a linear grain boundary separation within the IGA islands as was seen in the LTCT (Ref. 8). This could produce a crack-like indication, or increase the overall grain boundary volume of the IGA patch. In addition, mechanical working can also produce increased grain boundary separation of IGSAC.

2) disconnected grains dropping out and leaving pits.

Two additional pieces of data from Ref. 16 lend support to the mechanical scenario. First, peripheral tubes consistently see higher loads than core tubes. Therefore, in the periphery, the highest stresses would also act on this IGA/IGSAC. Second, the A-OTSG cooled down more quickly than the B unit. The peak load during the most rapid cooldown (Ref. 16) was 200 lb. in the A-OTSG, 12% higher than in B-OTSG. Figure 1 is a representation of how the A-OTSG would have had significantly more tubes carrying loads high enough to cause IGA/IGSAC to become more detectable.

A previous study (Ref. 15) on crack opening displacement of archive tubes with approximately .5" long through-wall cracks found that loads between 1500 and 2000 lbs. would induce permanent displacements in the vicinity of the cracks. Loads less than this would induce only elastic displacements with a load of 1000 lbs. producing an elastic displacement of approximately .002". Although tubes with cracks of this size are no longer in-service with the steam generators, this study does point out that one can expect local straining in the vicinity of smaller defects, but that it would be of proportionately lesser magnitude.

During the 1983 HFT, the most rapid cooldown was calculated to have induced loads in the tubing of between 1600 and 1700 lbs. (Ref. 16). It is such loads acting on the regions of IGA/IGSAC which we believe leads to grain dropping or grain boundary separation.

Detectability of Indications by Eddy Current

It should be noted that the primary defects of concern for OTSG tube integrity (i.e. tube rupture) are circumferential cracks. The production of 0.540" standard differential eddy current technique is optimized and qualified for this type of defect. However, it can also be used for detecting different defect geometries as discussed below.

The 1984 tube ID indications as detected by eddy current and as seen during the fiberscope inspection had significantly different characteristics than the IGSAC responsible for the 1981 tube leakage. The 1981 IGSAC consisted of tight, circumferential cracks that penetrated completely through the wall. The 1984 IGA as observed by fiberscopic examination appears rounded and does not completely penetrate the tube wall.

The different geometry will have a direct effect on detectability. The current .540" S.D. eddy current technique was optimized for the IGSAC geometry; therefore, a different geometry will have a different detectability. The balance of this section of this report will discuss changes in sensitivity due to changes in indication geometry.

Figure 2 (Figure 2 from Reference 2) shows the measured sensitivity of the .540" S.D. technique in the range of short circumferentially oriented defects. The shaded region in Fig. 2 identifies the range based on eddy current indication sizing in which 90% of the 1984 indications fall. It can be seen that the eddy current calls span the 0.3 volt detectability limit. (NOTE: Circumferential length is based on the number of 8X1 coils giving a signal and not an actual defect measurement.) Thus only slight changes in indication geometry could cause a particular indication to become detectable assuming the defects lie close to the detectability line.

In Figure 3a and 3b, we have taken the eddy current data and visual observations from the fiberscope inspection (shown in Table 6) and indicated where the indications would be in relationship to the calibration curves. The tubes for fibrescope inspection were chosen to be representative of the types of indications being found in 1984. All of the below-UTS indications (Figure 3b) are close to the 0.3 v detectability limits; the within-UTS indications (Figure 3a) do not fall into the detectable range. Therefore, it is reasonable that before mechanical loading these indications may not have been detectable. Mechanical loading, as discussed in the previous section, can alter IGA/IGSAC geometry.

The large increase in the number of degraded tubes in A-OTSG and B-OTSG is also consistent with the scenario of pre-existing IGA/IGSAC becoming more detectable. IGA/IGSAC of 20-40% through wall extent could be estimated to have a length of about .015-.030 inches; this is below the 300 mV sensitivity for free-span detection (Figure 2). The inability to detect these small regions of IGA/IGSAC below the level of detectability was further confirmed by evaluations which took place during the Long Term Corrosion Test Program. This program identified four patches of IGA which also were not detected (Table 7) by eddy current examination.

Table 6 - Comparison of Preliminary Eddy Current Data and Fiberscope Results

"A" - OTSG			EC Results				
			.540 S.D.		8 X 1		
Row	Tube	Elevation	% T.W.	Volts	Volts	Coils	Visual Observations
89	124	US+5.4	98	1.6	1.6	2	
		US+4					Rounded indications - possible IGA
		US+5.8					Axial alignment of 3 rounded indications
76	119	US+2.4	97	2.1	0.8	2	
		US+5.5					Small dark spot when scanning w/90° head
66	129	15+27.6	62	2.8	1.3	2	
		15+24.5					Rounded indications - possible IGA
61	123	15+21.8	59	2.3	1.1	2	
		15+26					Small dark spot - no detail visible
		15+24.7	28	1.7	0.5	1	
57	128	US-2.6	92	1.3	0.3	1-2	
		US-1.5					Axially oriented rounded indications
60	126	15-14.2/15-6.5	20/31	1/1.0	NDD		Small single rounded indication

TABLE 7

IGA 20% T.W. in Samples Removed From the LTCT
Not Detected by Eddy Current

Tube	Section	IGA Location With Respect to Top of Upper Tubesheet	IGA Size Circum.	IGA Size Depth	Type Sample
A-24-94	25 7/16" - 30 13/16"	28"	.030"	.010"	C-ring (1)
A-24-94	19 5/16" - 25 7/16"	26"	.035"	.009"	C-ring (1)
A-24-94	19 5/16" - 25 7/16"	27"	.006"	.008"	C-ring (2)
A-13-63	11" - 18 15/16"	12.5"	.020"	.013"	Tube (1)

Note (1): These samples were exposed to thiosulfate contaminant during the LTCT.

(2): This sample was exposed to sulfate contaminant during the LTCT.

Figure 1 - TMI-1 OTSG Testing 3rd Cooldown (10-2-83)

Tube Load Distribution as a Function of Tube Location at the Peak Applied Load for "A" and "B" OTSGs

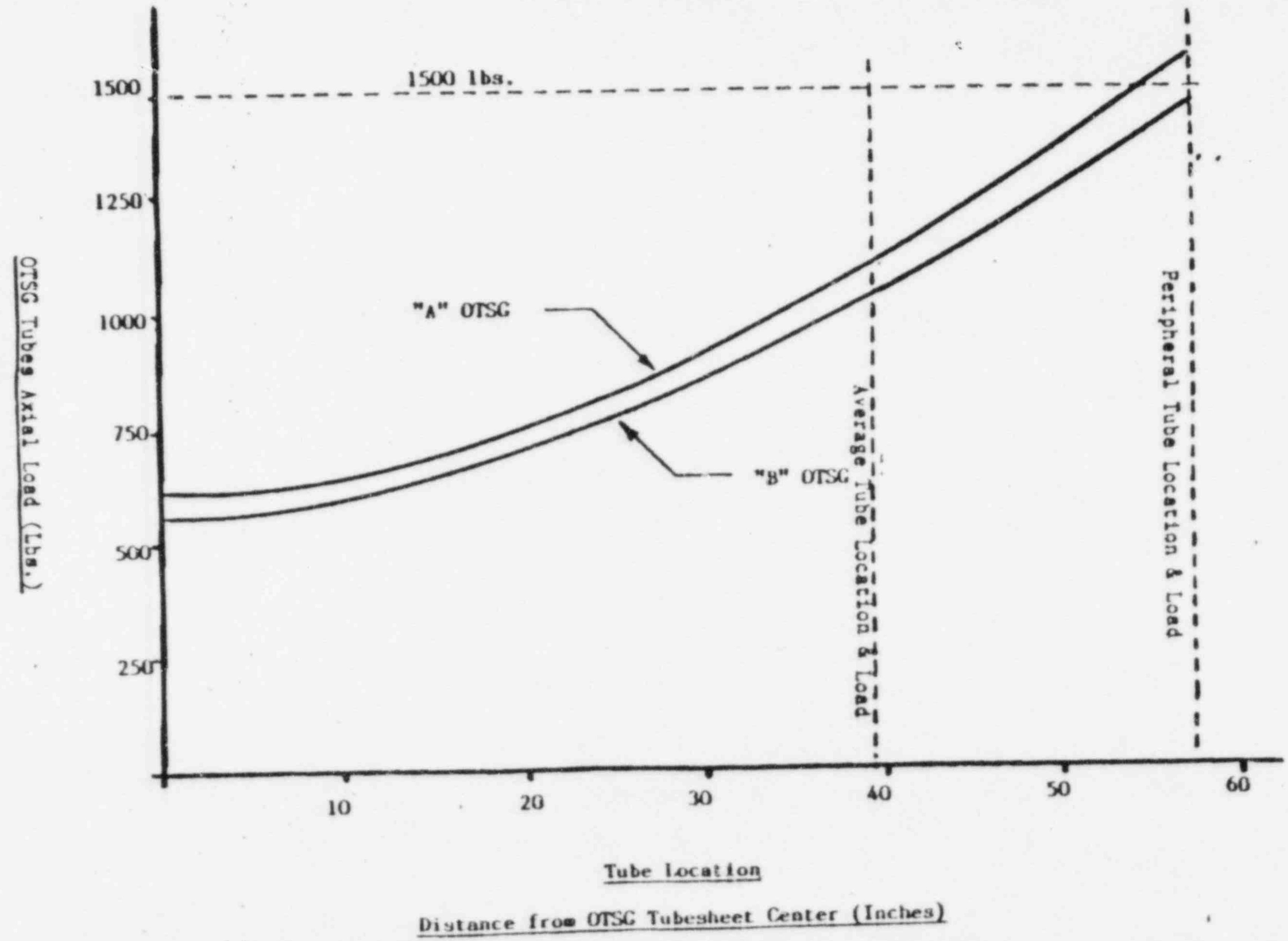


Figure 2 - 1984 Eddy Current Date

Compared to Detectability Limits

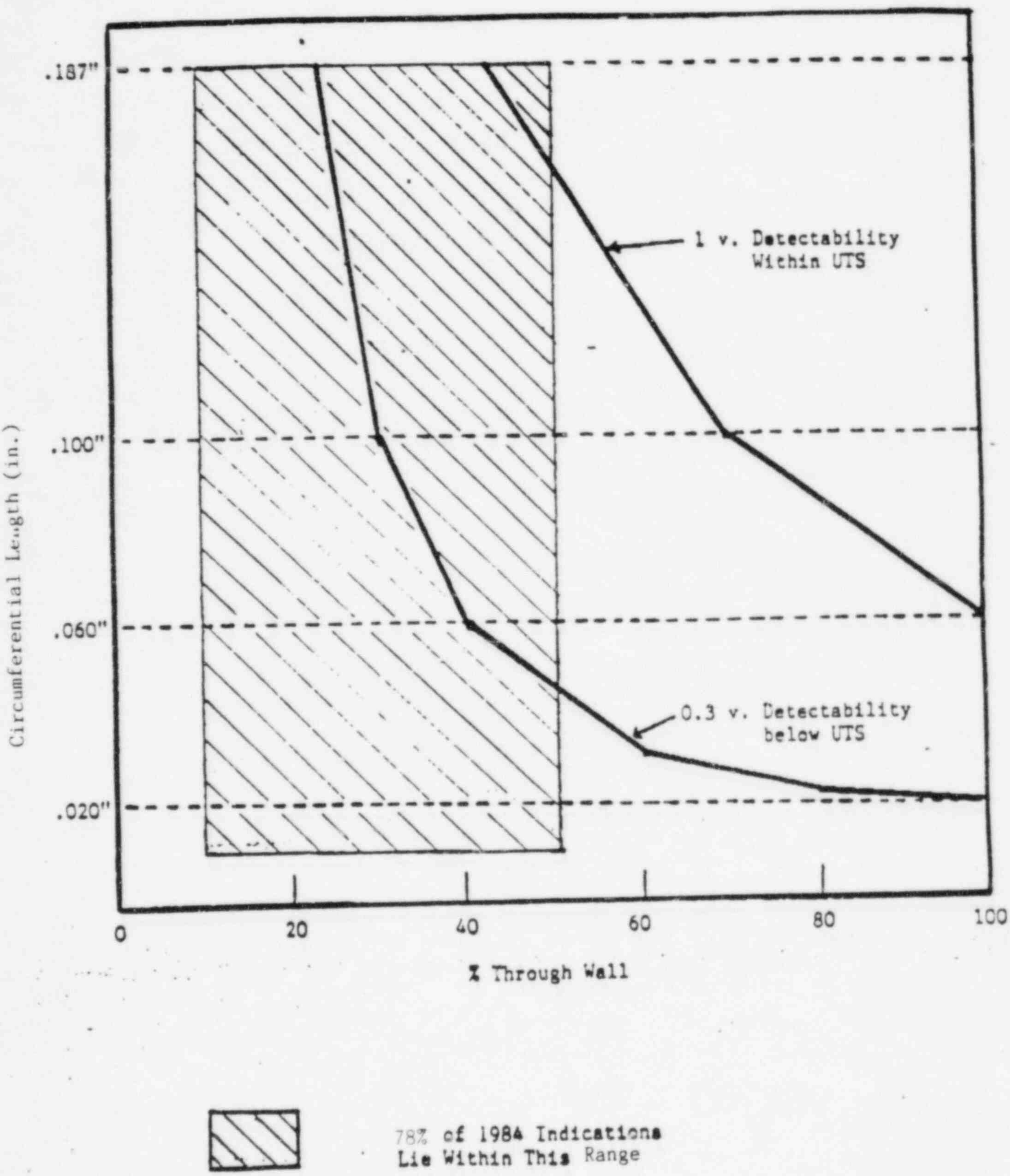
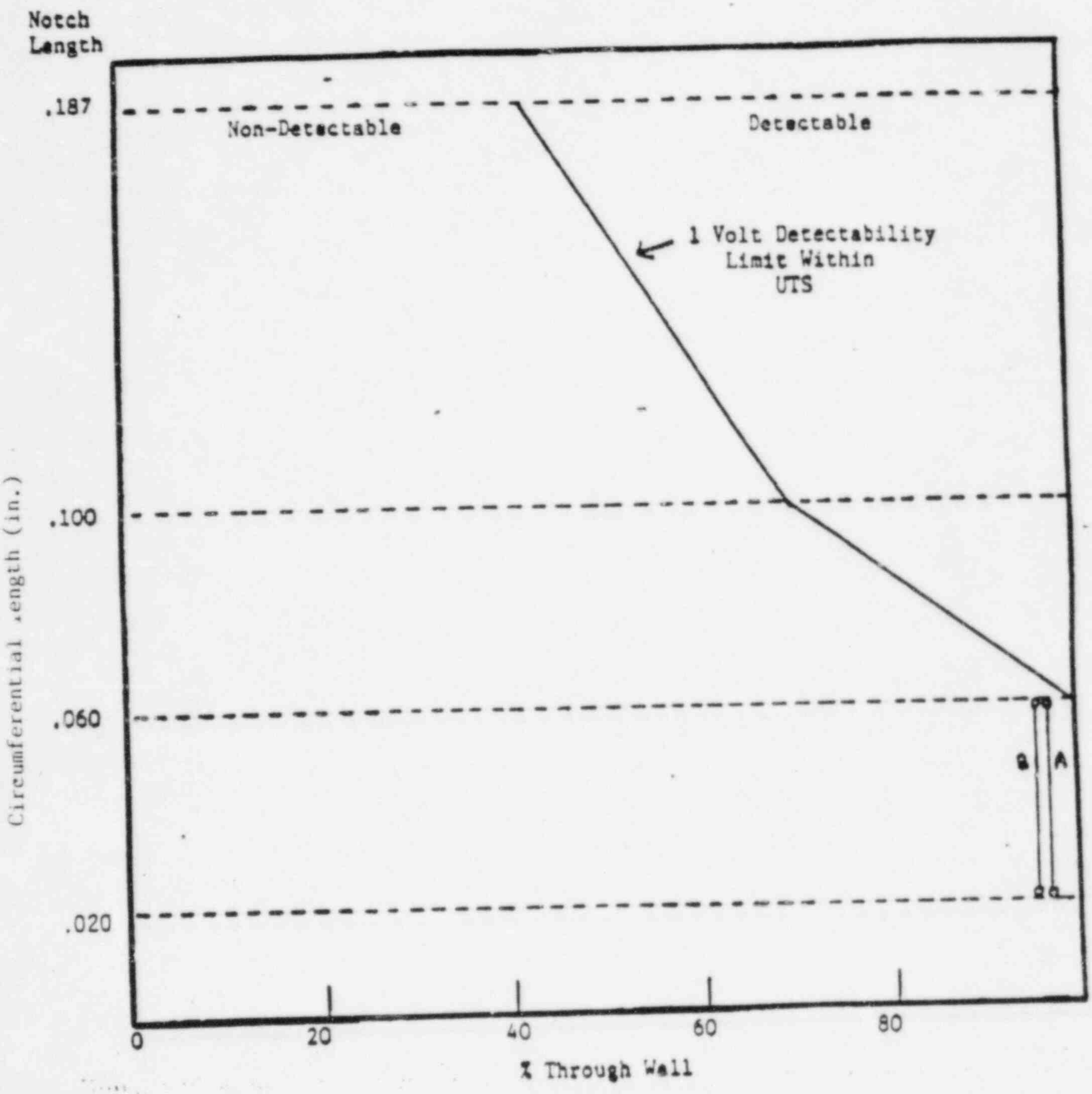


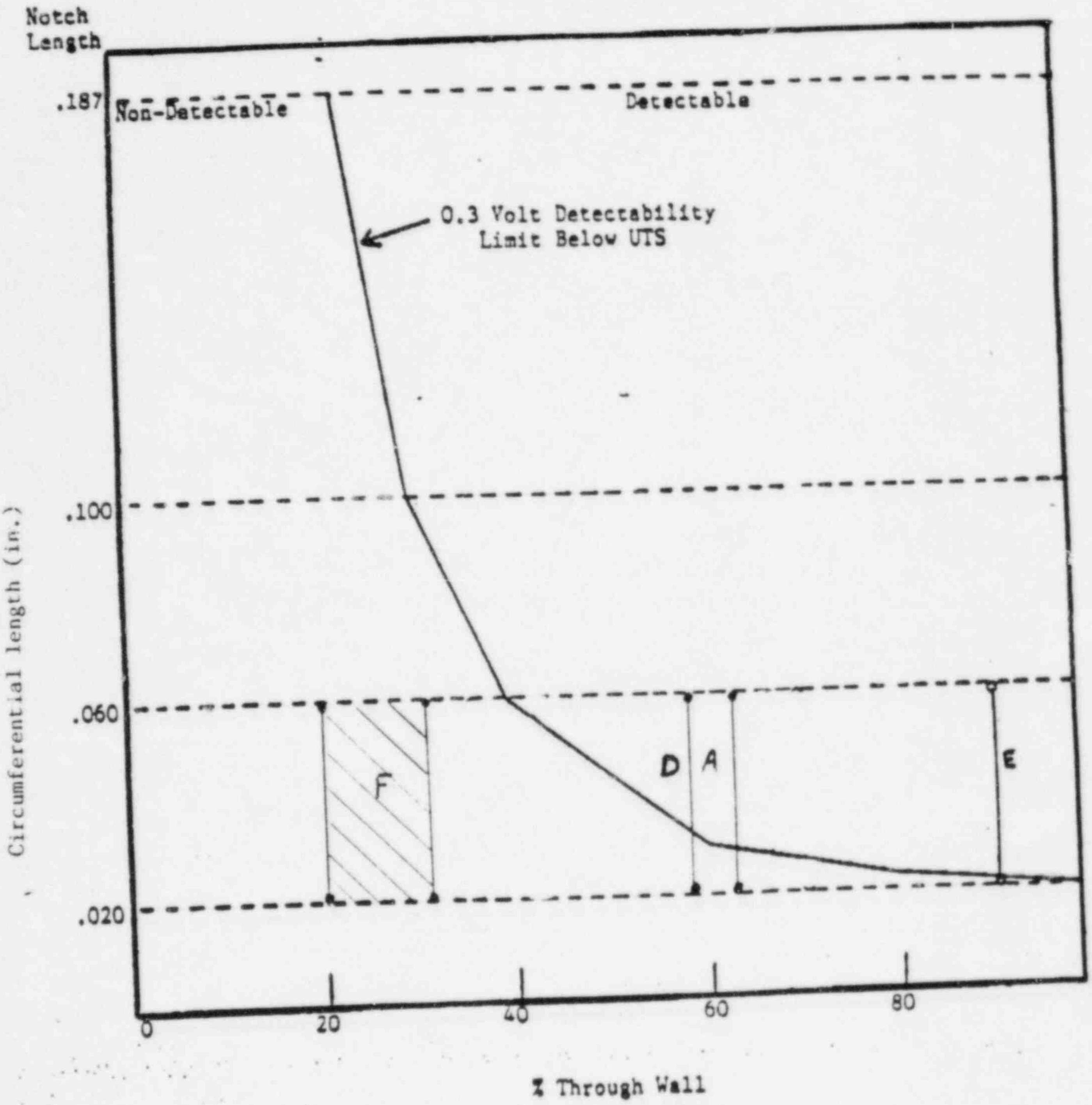
Figure 3a - Within - Tubesheet
Fiberscope Indications
Compared to Detectability Limit



Tube Identification

A A-89-124
B A-76-119

Figure 3b - Below - Tubesheet Fiberscope Indications Compared to Detectability Limit



Tube Identification

C	A-66-129
D	A-61-123
E	A-57-128
F	A-60-126

Conclusions

1. The TMI-1 layup guidelines are adequate to prevent any identified mechanisms for primary side initiated corrosion of Inconel 600 OTSG tubes.

2. The TMI-1 layup guidelines have been adhered to since completion of the kinetic expansion repair. Minor deviations have been corrected promptly.

3. Vulnerability to corrosion may have existed during the period when the OTSG's were drained for repair prior to peroxide cleaning. However, eddy current data and the absence of OTSG leakage during thi~ time period do not show evidence of corrosion of OTSG tubes.

4. Results of both GPUN-sponsored and industry corrosion test programs confirm that corrosion would not be expected during TMI-1 operations since May 1983.

5. Results of eddy current tests since 1982 do not indicate any trends of indication growth of pre-existing indications.

6. Leak rate testing and OTSG bubble testing do not indicate any increases in leakage or new leaks in the tube free span.

7. The eddy current data and visual observations are consistent with a mechanism where previously existing areas of IGA/IGSAC are made more detectable by mechanical loading during kinetic expansion and thermal and hydraulic loading during cooldown from HFT.

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2. G. E. Rhedrick, "Task IV Report on Eddy Current Indications Found Subsequent to Kinetic Expansion of TMI-1 Steam Generator Tubes," GPUN Technical Data Report 401, Rev. 0, April 1983.

3. T. M. Moran, "Assessment of TMI-1 Plant Safety for Return to Service After Steam Generator Repair," GPUN Topical Report 008, Rev. 3, August 19, 1983.

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6. "Long Term Corrosion Test Program of Nuclear Steam Generator Tubing Samples from Three Mile Island Unit 1 - First Interim Report," Westinghouse Electric Corp. Report No. 0914c/0127c/010684:5, October 1983.

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APPENDIX A

TMI-1 CHEMISTRY DATA

MAY 1, 1983 to OCTOBER 26, 1984

Contents

Table A1

CHEMISTRY GUIDELINES APPLIED TO TMI-1

5/1/83 to 10/26/84

Operating Mode	Wet Layup	Drained Layup	Hot Shutdown (Hot Functional Testing)	Peroxide Cleaning
OTSG Primary Level	Full	Drained	Full	Full
Maximum Chloride, ppm	0.1	0.1	0.1	0.2
Maximum Sulfate, ppm	0.1	0.1	0.1	Note 2
Maximum Oxygen, ppm	0.1	N/A	0.1	Note 2
pH	greater than 7.2	4.6-8.5	4.6-8.5	8.0-8.5
Li, ppm	1.0-2.0	1.0-2.0	1.0-2.0	1.8-2.5
Minimum Li/S ratio	10	10	10	N/A

Notes:
1. Limits are for bulk RCS - no water in OTSG's at this time.

2. Sulfate and oxygen were monitored but no limit was applied.

CHEMISTRY DATA
FILL AND BUBBLE TEST PERIOD
May – July 1983

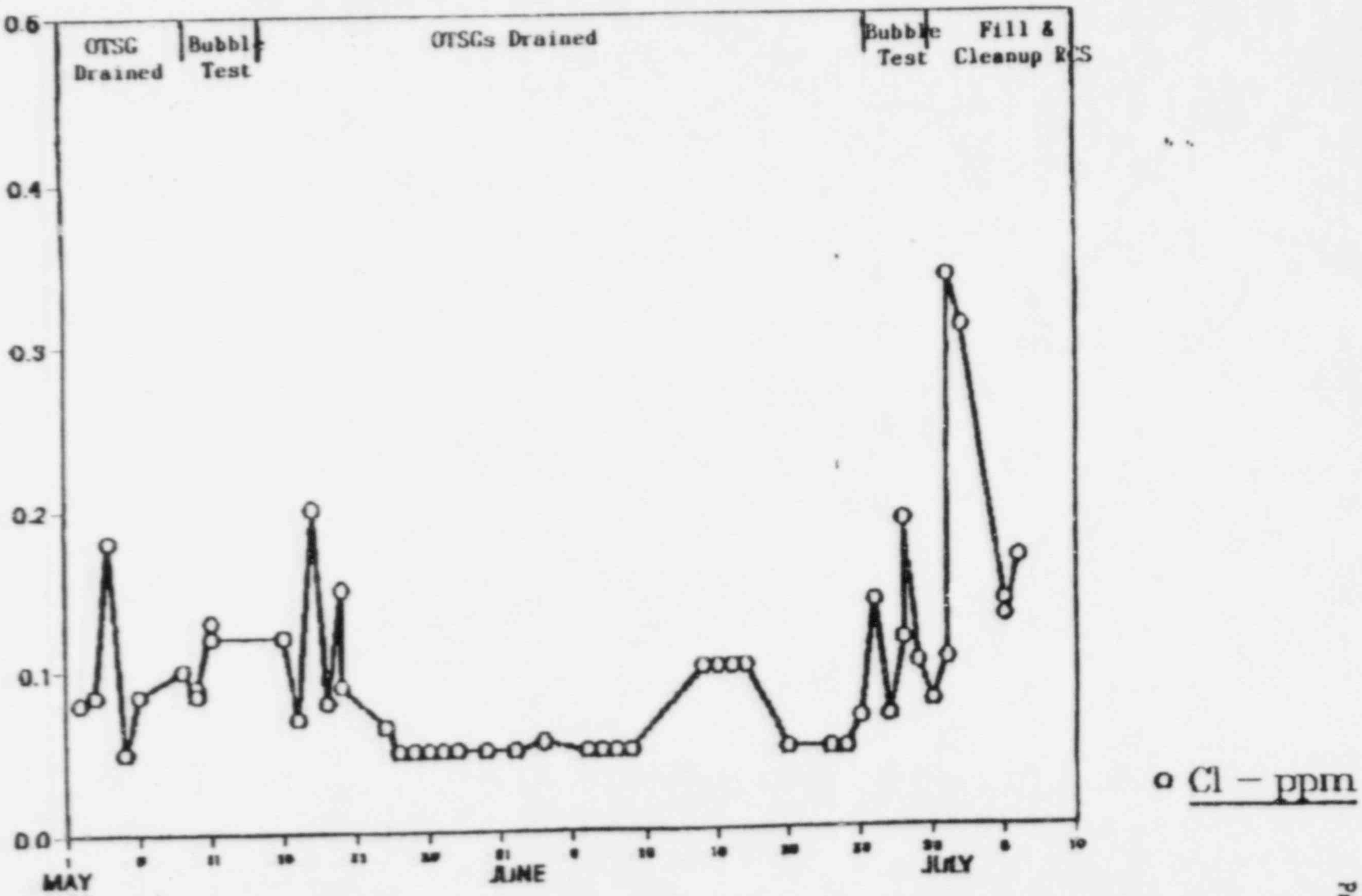

Figure A1-1a

CHEMISTRY DATA
FILL AND BUBBLE TEST PERIOD
May – July 1983

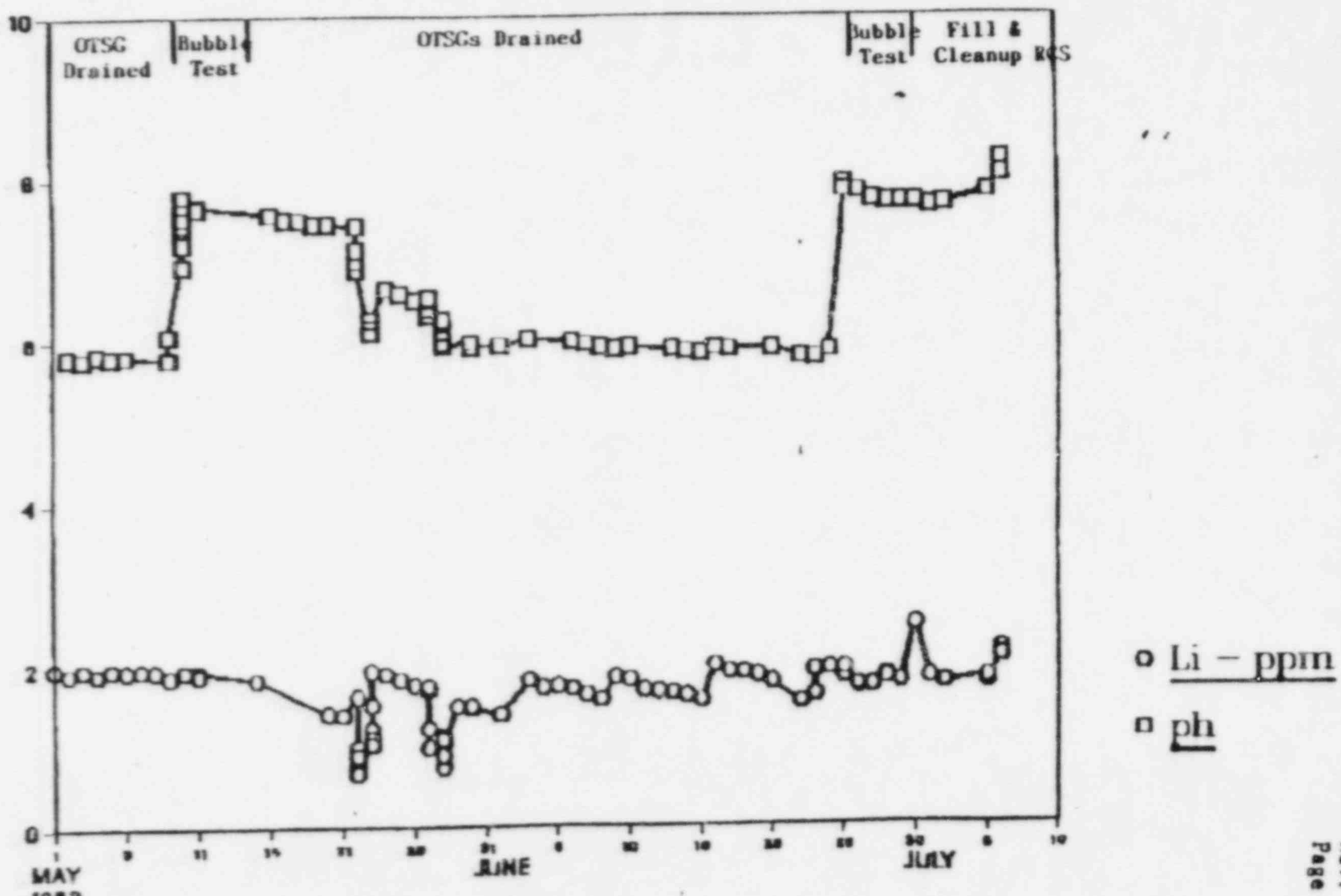

Figure A1-1b

CHEMISTRY DATA
PEROXIDE CLEANING AND PREPARATIONS FOR HFT
July – August 1983

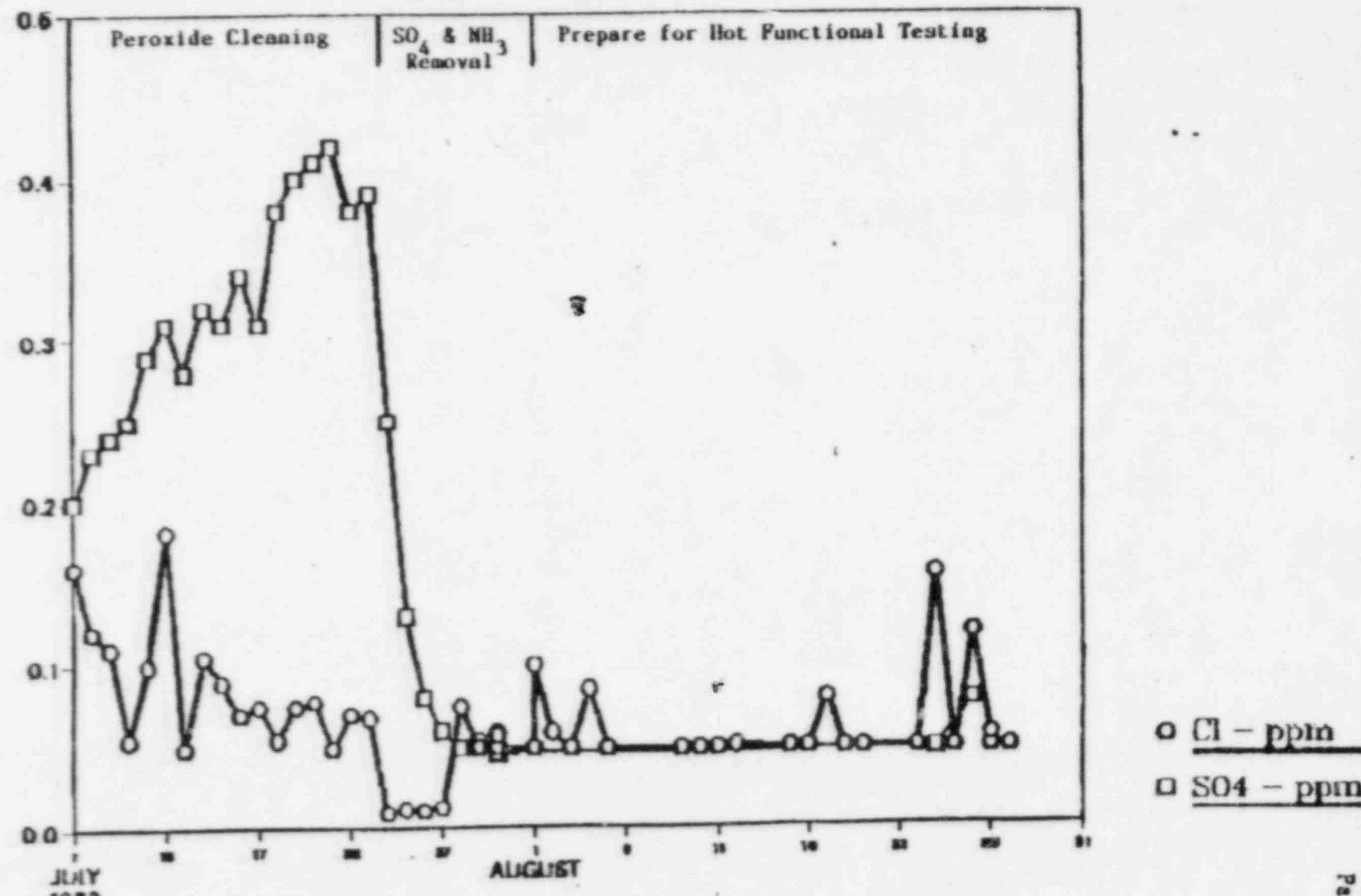

Figure A1-2a

CHEMISTRY DATA
PEROXIDE CLEANING AND PREPARATIONS FOR HFT
July – August 1983

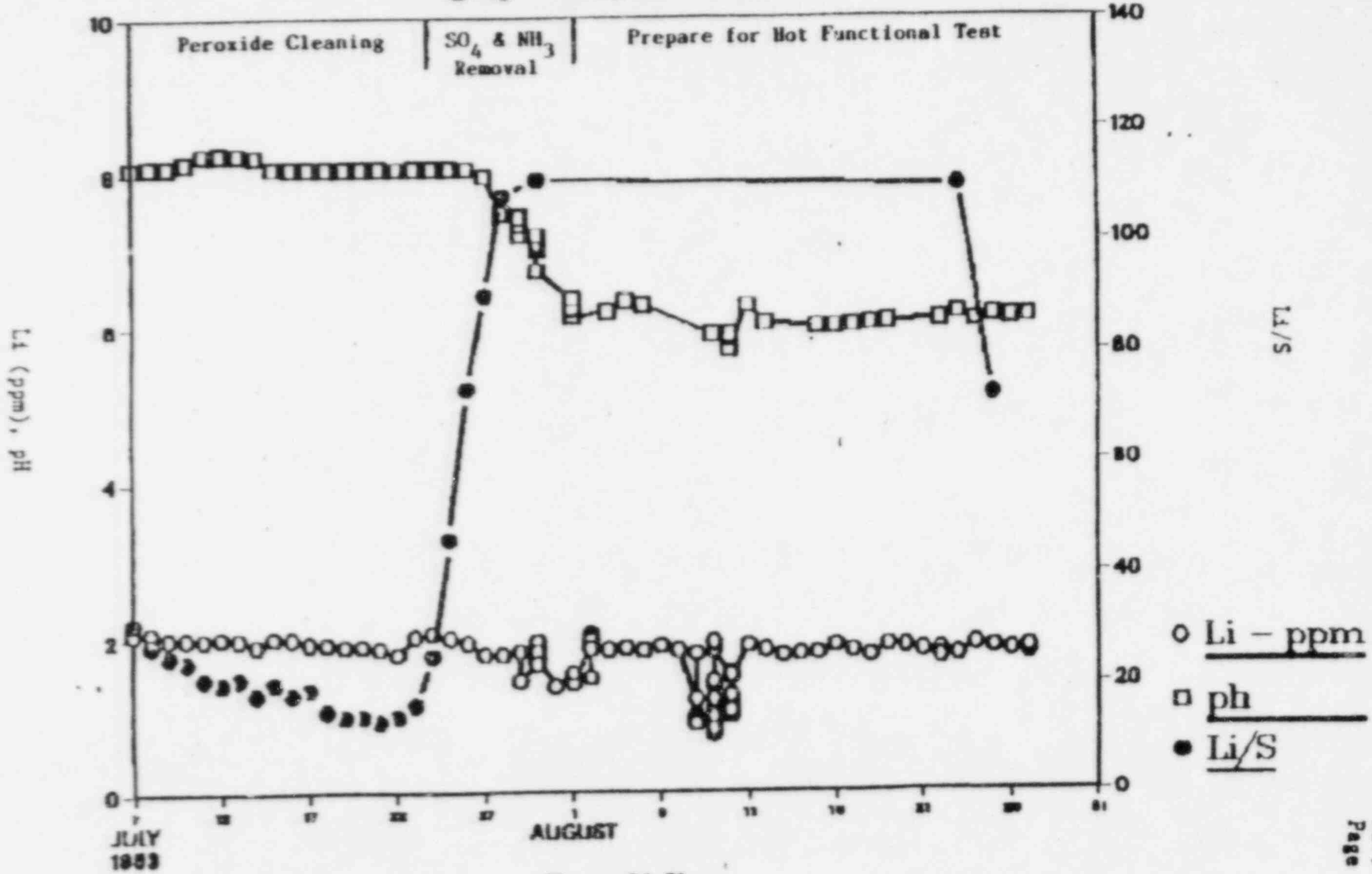

Figure A1-2b

CHEMISTRY DATA
HOT FUNCTIONAL TESTING AND WET LAYUP
August – November 1983

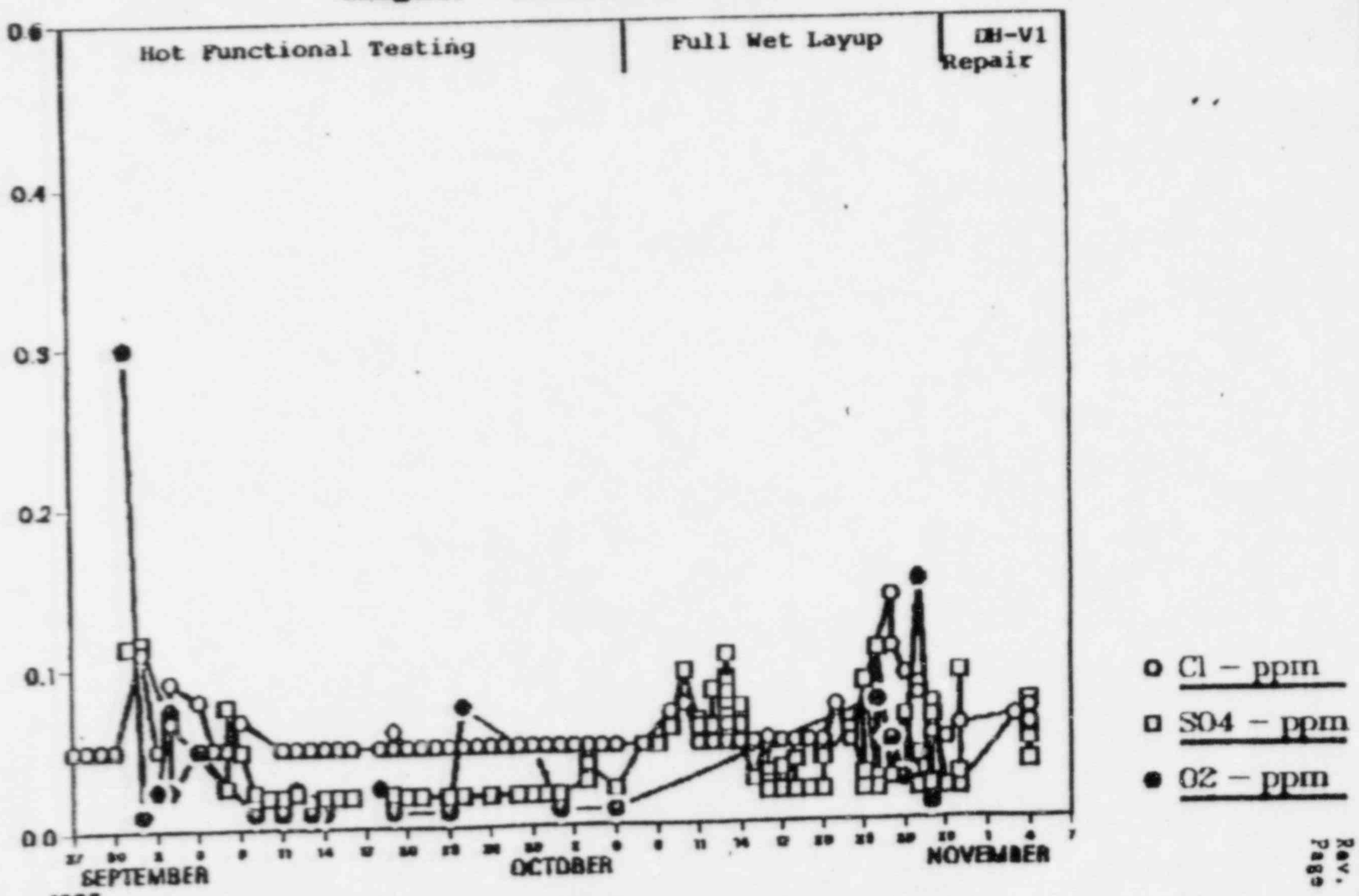

Figure A1-3a

CHEMISTRY DATA
HOT FUNCTIONAL TESTING AND WET LAYUP
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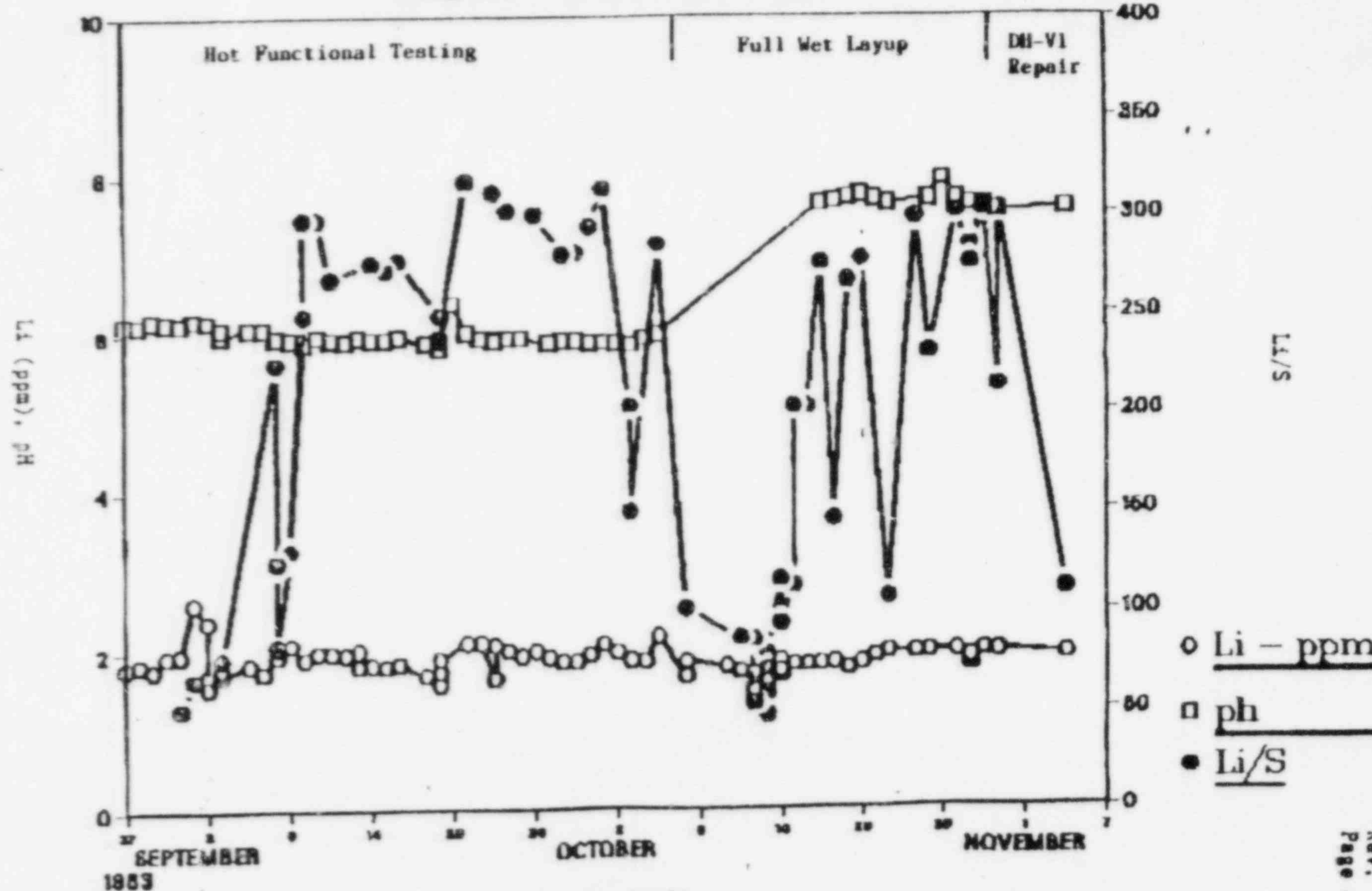

Figure A1-3b

CHEMISTRY DATA
FULL WET LAYUP
November – December 1983

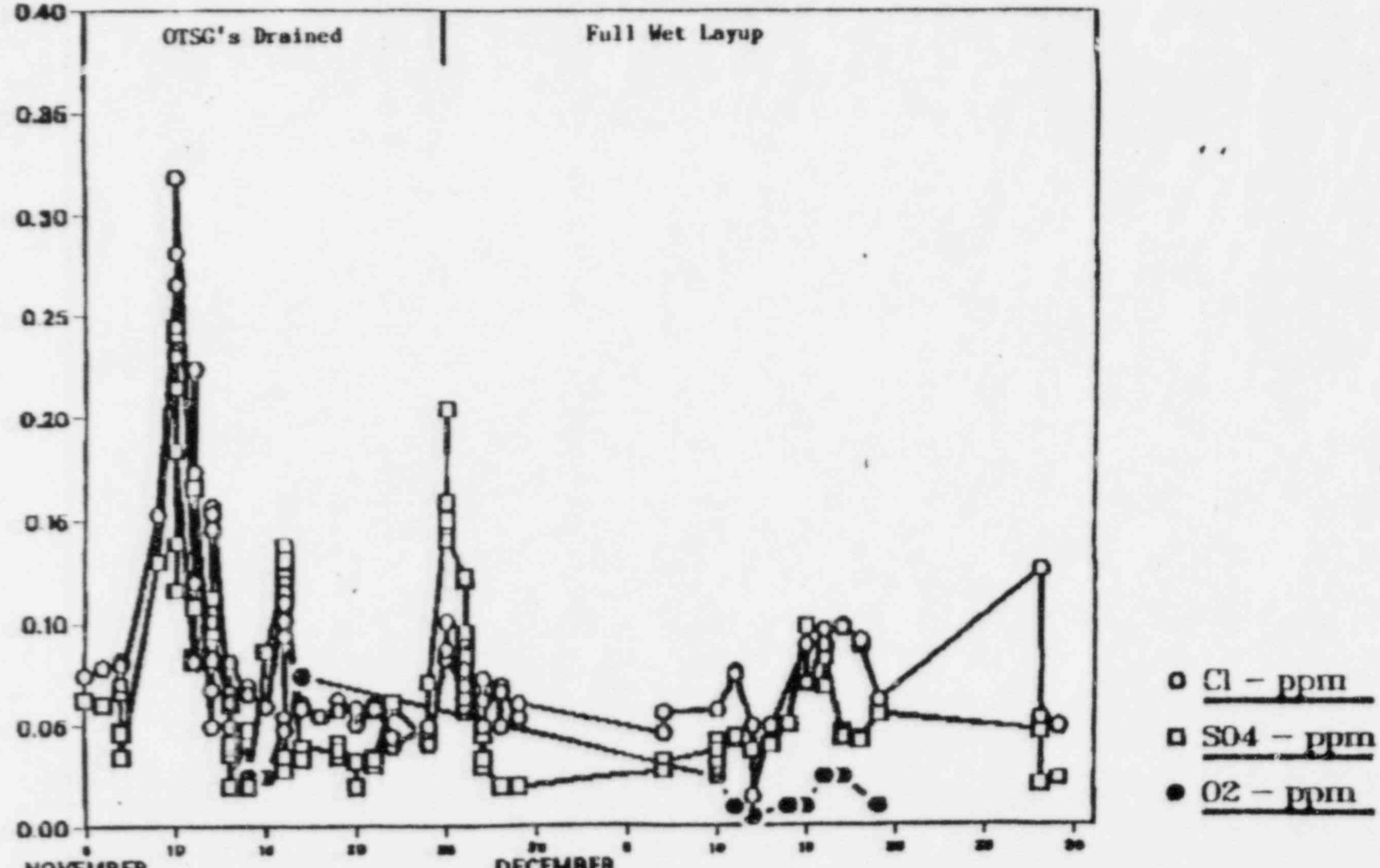

Figure A1-4a

CHEMISTRY DATA
FULL WET LAYUP
November – December 1983

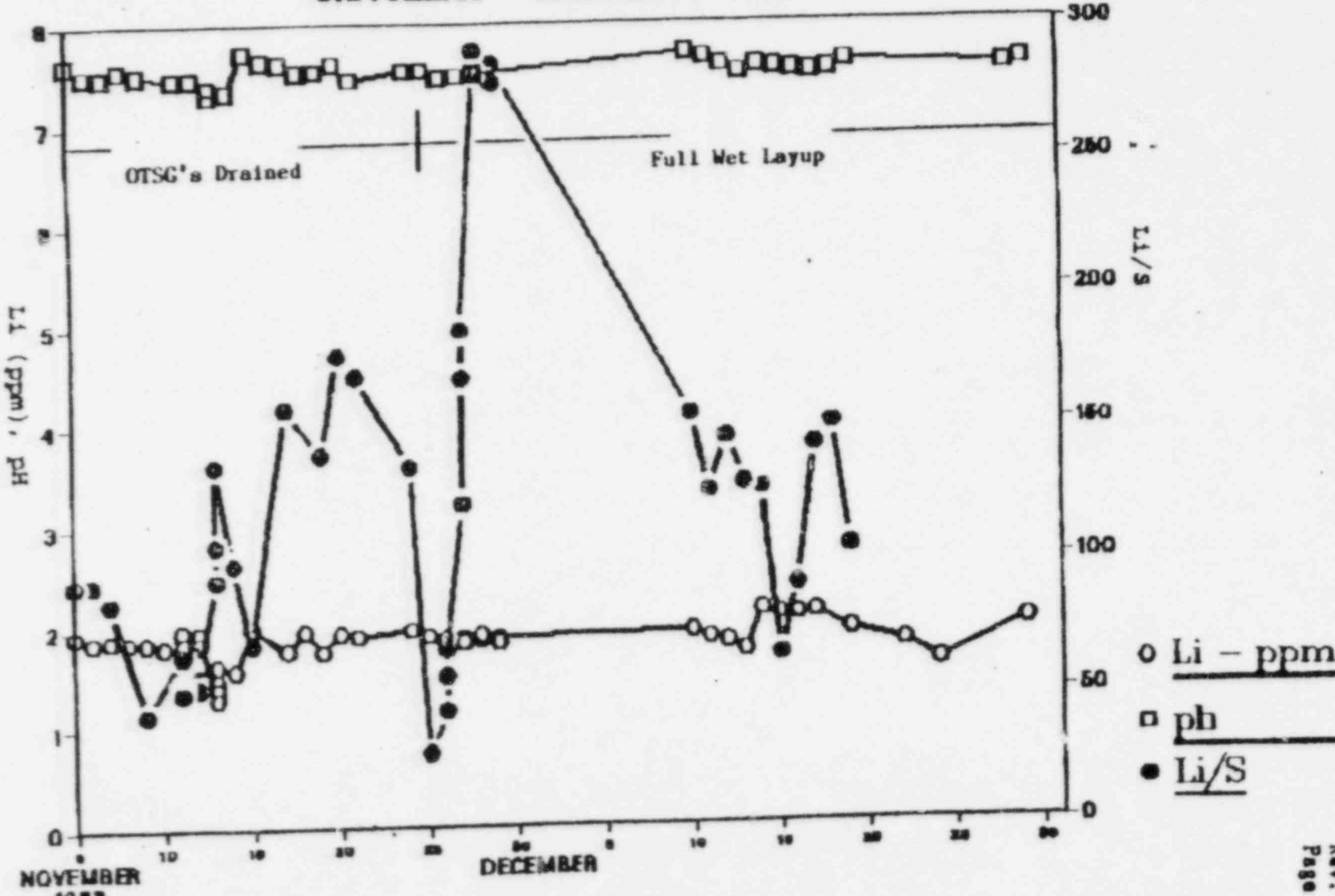

Figure A1-4b

CHEMISTRY DATA
FULL WET LAYUP AND RC-P1B TESTING
January – April 1984

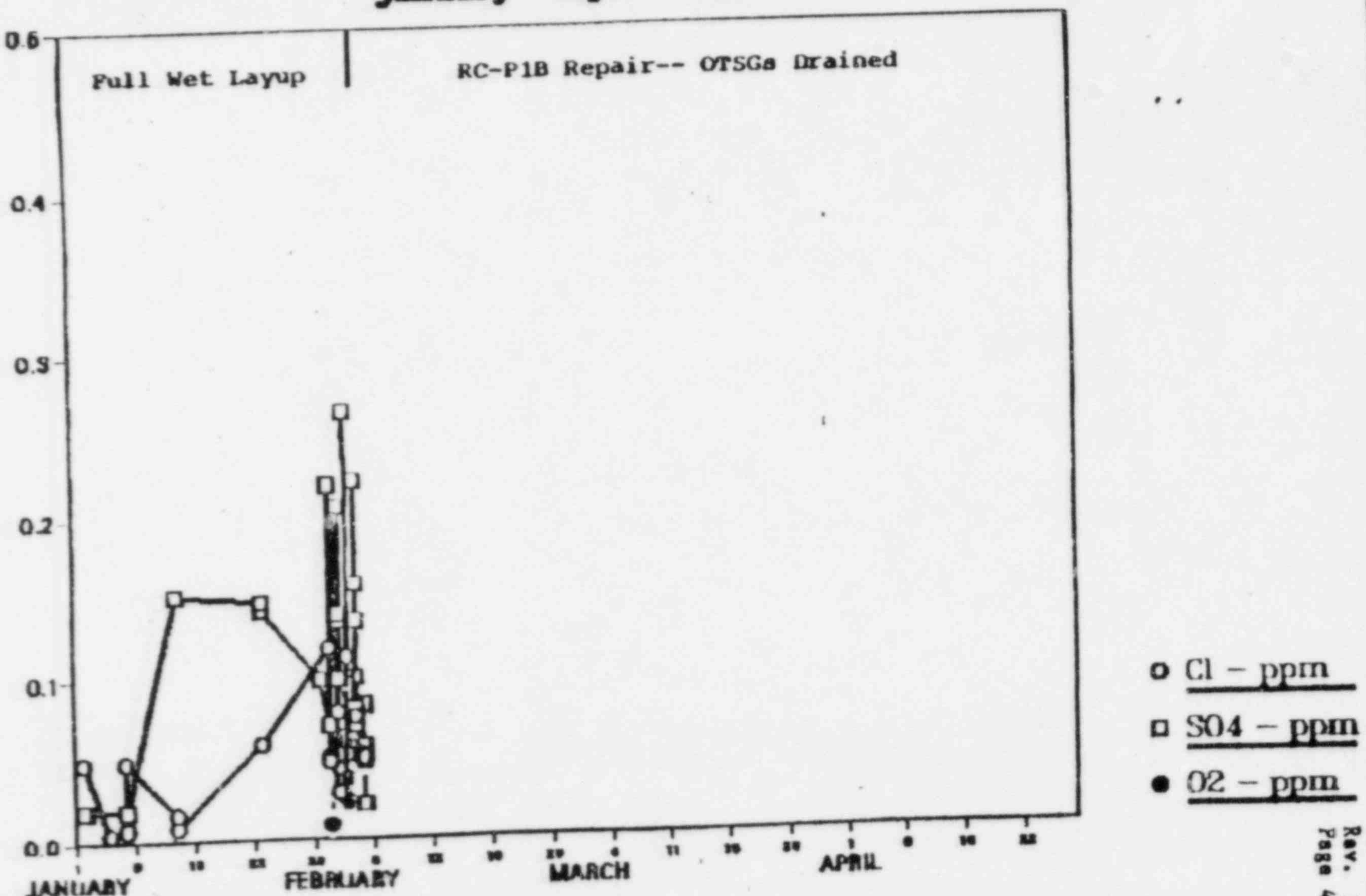

Figure A1-5a

CHEMISTRY DATA
FULL WET LAYUP AND RC-P1B REPAIR
January - April 1984

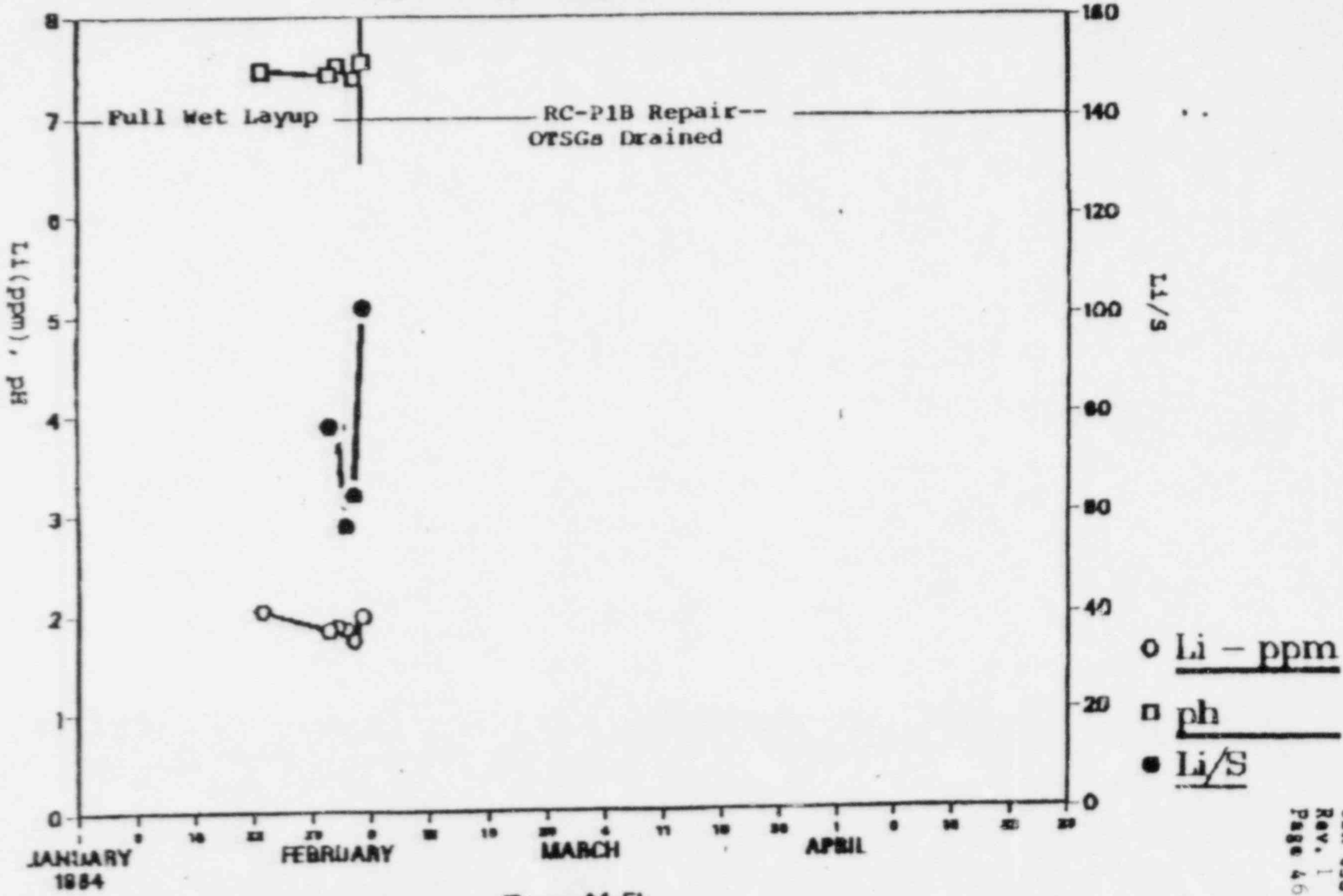

Figure A1-6b

CHEMISTRY DATA
HOT FUNCTIONAL TESTING AND WET LAYUP
April – June 1984

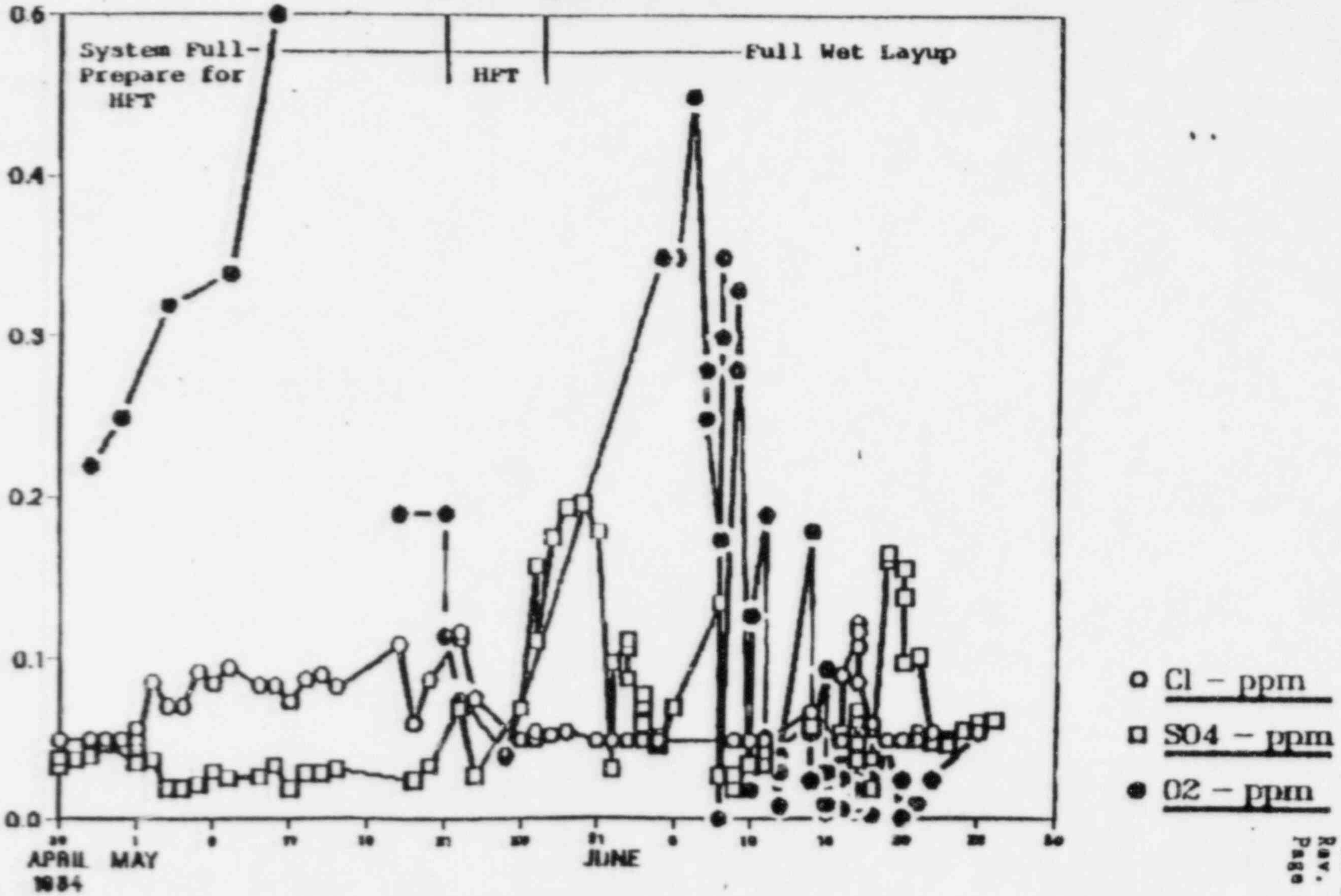

Figure A1-6a

CHEMISTRY DATA
HOT FUNCTIONAL TESTING AND WET LAYUP
April – June 1984

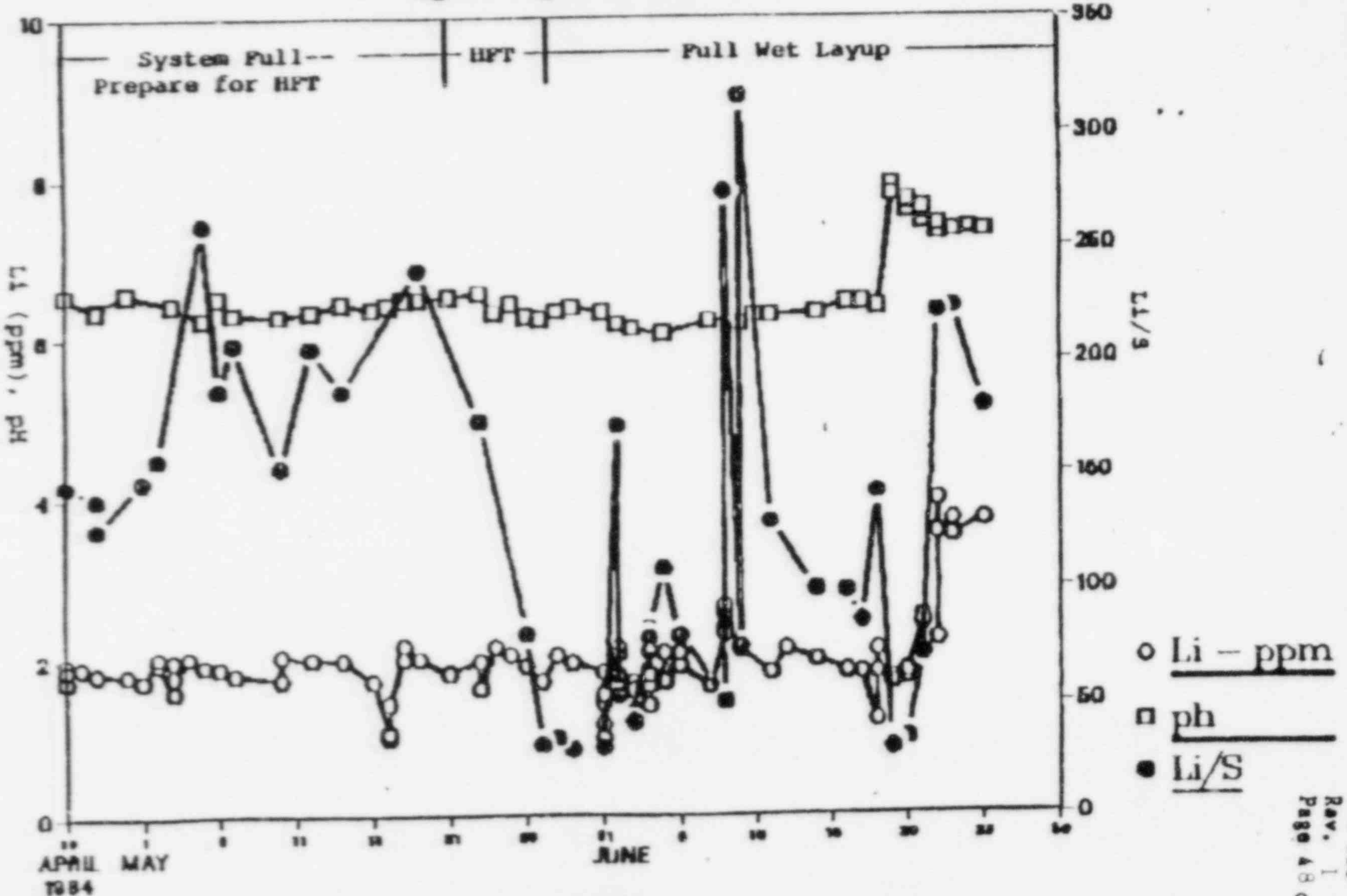

Figure A1-6b

CHEMISTRY DATA
PLUG REROLLING AND BUBBLE TESTING
June – October 1984

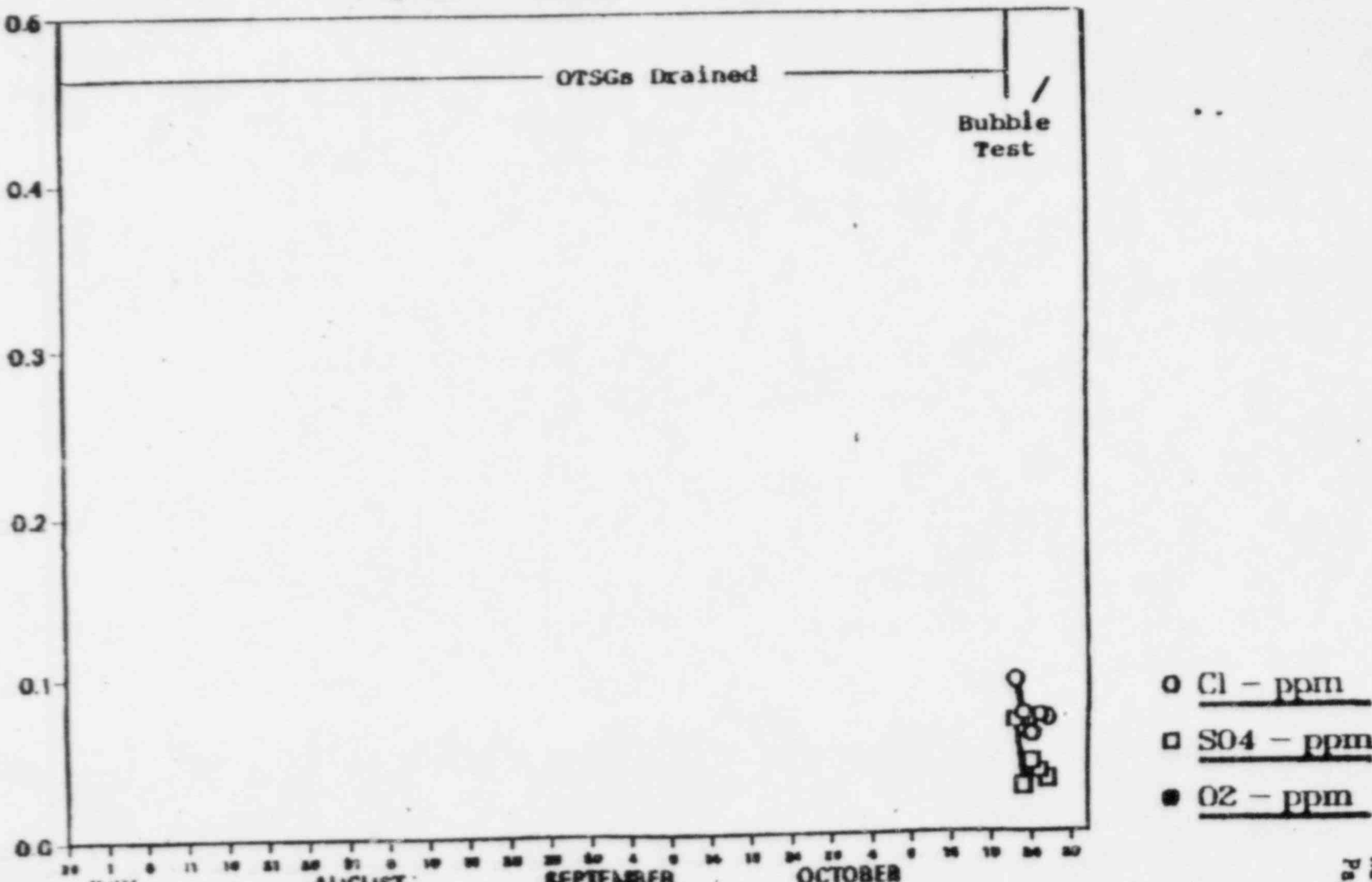

Figure A1-7a

CHEMISTRY DATA
PLUG REROLLING AND BUBBLE TESTING
June – October 1984

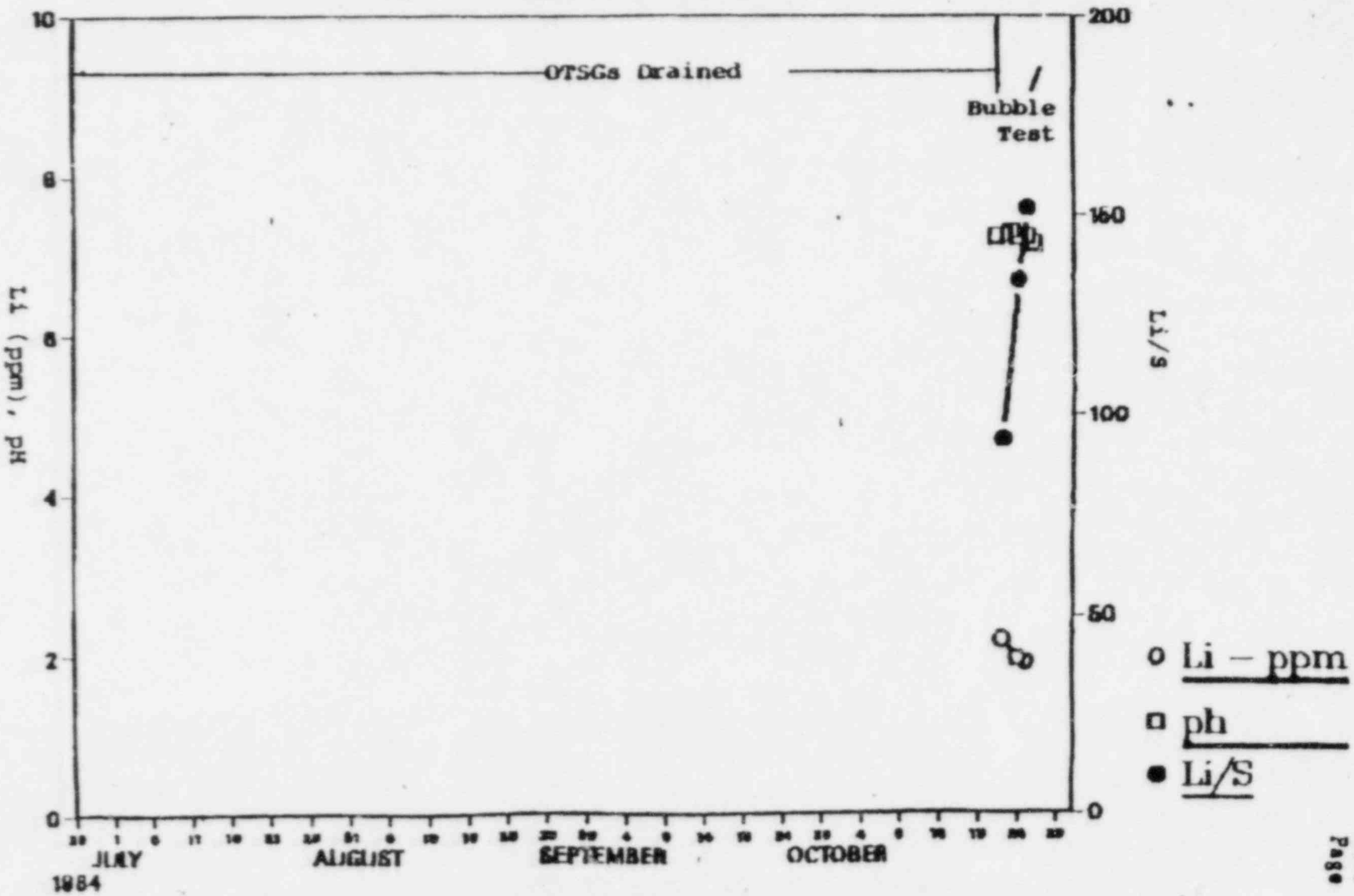

Figure A1-7b