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Richmond, Virginia 23212

Telephone 804-788-8200

B B & T Building
P. O. Box 109
Raleigh, North Carolina 27602
919-828-9371

First Virginia Bank Tower
P. O. Box 3889
Norfolk, Virginia 23514
804-625-5501

1919 Pennsylvania Avenue, N. W.
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October 3, 1983

Lawrence Brenner, Esq.
Administrative Judge
Atomic Safety and Licensing Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dr. Peter A. Morris
Administrative Judge
Atomic Safety and Licensing Board
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dr. George A. Ferguson
Administrative Judge
Atomic Safety and Licensing Board
School of Engineering
Howard University
2300 6th Street, N.W.
Washington, D.C. 20059

Diesel Generator 102 Crankshaft

Dear Judges Brenner, Morris and Ferguson:

For your information, enclosed is a copy of the "Preliminary Metallurgical Evaluation of Failed Crankshaft From DG 102" produced for LILCO by Failure Analysis Associates.

Sincerely,

Anthony F. Earley, Jr.

Anthony F. Earley, Jr.

221/765
Enclosure

cc: All Parties

DS03

PRELIMINARY METALLURGICAL EVALUATION OF FAILED CRANKSHAFT FROM DG102

PRELIMINARY INFORMATION GENERATED IN CONTEMPLATION OF LITIGATION

SUMMARY

The fracture occurred by fatigue. The fatigue fracture originated at a machining mark on the machined surface of the fillet radius.

The microstructure, hardness, tensile properties, chemical composition, and forging flow pattern were normal. No metallurgical anomalies or substandard characteristics have been found to date.

INTRODUCTION

A metallurgical failure analysis is being performed on the broken crankshaft from the emergency diesel generator (DG102) that failed on August 12, 1983 at the Shoreham Nuclear Power Station. The analysis is intended to assess the nature of the fracture and to identify any metallurgical characteristics of the crankshaft that may have influenced the fracture process. This report describes the work done to-date. A formal, detailed metallurgical account will be included in the DG102 Failure Cause Report.

Prior to any laboratory testing, a plan of action was agreed upon by representatives of Long Island Lighting Company, Stone & Webster Engineering Corporation, Transamerica Delaval, Inc., and Failure Analysis Associates. The protocol outlining the work to be carried out is attached. This includes schematics showing cuts that were subsequently made and identification of the cut pieces by code letter.

The failed crankshaft had fractured into two pieces at the crank pin journal of cylinder number 7. The fracture occurred mostly through the web

connecting the number 7 crank pin journal to the number 9 main bearing journal. The section examined was saw-cut from the crankshaft; cuts were made through the number 8 and 9 main bearing journals. This two piece section, containing the fracture, was shipped to Palo Alto, California for laboratory examination. Both pieces of the fractured section were examined visually, then the metallurgical failure analysis was performed on the piece nearest to the number 9 main bearing. The other, mating fracture surface has been preserved for any additional examination that may become appropriate in the future.

Residual stress measurements by x-ray diffraction are in progress, but results from these tests are not yet available. FaAA originally proposed measuring residual stresses in the machined fillet radius. In the September 9, 1983 memo, we proposed to use strain gage and hole-drilling or trepanning techniques. We were unable to perform either technique due to the crankshaft geometry and fillet radius curvature. Instead, near-surface residual stresses will be measured using an x-ray diffraction and electrochemical machining technique. The final DG102 Failure Cause Report will include the x-ray residual stress measurements.

VISUAL INSPECTION

The fracture surface exhibited an obvious, unmistakable fatigue crack pattern. Concentric beach marks showed that the fatigue crack started at the surface of the machined fillet radius where the crank pin journal blends into the web. The fatigue crack had progressed through the thickness of the web, and it extended over more than one-third of the web cross section when final separation occurred.

A thin layer of aluminum had been deposited over much of both mating fracture surfaces. The crank pin journal bearing was the source of this aluminum. Small fragments of the damaged bearing appear to have been carried by lubricating oil in between the mating fracture surfaces where they were deposited by rubbing contact between the fracture surfaces.

The appearance of both fracture surfaces was documented photographically.

SCANNING ELECTRON MICROSCOPY

The microscopic features of the fracture surface (Piece F, see attachment) were examined by scanning electron microscopy (SEM) after careful stripping with cellulose acetate tape to remove the aluminum deposited on the fracture. The rubbing contact between the mating fracture surfaces had eliminated any possibility of identifying fatigue striations near the origin. All of the fatigue fracture surface examined had been rubbed, a characteristic of many fatigue fractures, and it had many irregular, short scratch marks, probably caused by debris from the bearing.

A unique point of origin of the fatigue crack was found at the edge of the fracture surface at the surface of the machined fillet radius. The origin was indicated by the tear line pattern on the fracture surface which showed that the crack started in a machining mark that is deeper than adjacent machining marks. The machined surface of the fillet was also examined by SEM to show the machining mark at the point of fatigue crack origin as well as the machined surface nearby.

The details made apparent by SEM on the fracture surface and on the machined surface of the fillet groove were photographed.

METALLOGRAPHY

After the SEM examination was completed and documented photographically, the sample containing the origin of the fracture was diamond-sawed to expose a cross section through the point of origin. This specimen was polished and etched to reveal the microstructure of the steel at the crack origin and surrounding areas.

The microstructure consists of pearlite and ferrite in approximately equal proportions. From the pearlite/ferrite microstructure, the prior austenite grain size was seen to vary from ASTM 4 to ASTM 8. A few nonmetallic inclusions were found, a normal expectation. The few fine inclusions to be seen did not warrant the statistical sampling required to give an ASTM inclusion rating to this clean steel.

The microstructure at the point of crack origin was the same as elsewhere. There was nothing unusual or noteworthy; e.g., we observed no large inclusion in the microstructure at the origin. The polished cross section did show the same machining mark which had been previously identified by SEM as the fatigue crack origin. The pearlite/ferrite microstructure at the surface adjacent to the machining mark appeared locally disturbed showing that the steel had been deformed slightly when the machining mark was made.

Photomicrographs were taken to depict the microstructure in the vicinity of the fracture origin and elsewhere.

TENSILE TESTS

Mechanical properties of the forged crank were determined for transverse, longitudinal, and radial orientations. Strength and ductility parameters were determined following the ASTM A370 specification; the measured properties meet or exceed those set forth by the ABS Grade 3 specification. A summary of the mechanical test results is presented in Table 1.

CHEMICAL ANALYSES

Material from Section D (see attachment) was submitted for standard chemical analyses. Except for the carbon and sulfur, which were determined by a combustion gas analysis method, the chemical analyses were obtained by an inductively-coupled plasma technique. These results are given in Table 2. Comparison of these chemistry results with the mill chemistry shows that the steel meets the ASTM A235-67 Class E original specifications.

TABLE 1

Summary of Tensile Tests

Specimen Number	Yield Stress (ksi) Upper	Yield Stress (ksi) Lower	Ultimate Strength (ksi)	Elongation (%)	Reduction in Area (%)
R1	46.6	45.0	89.0	25.4	42.0
R2	45.3	44.9	89.4	30.0	45.1
T1	47.1	45.9	87.6	37.1	49.1
T2	46.9	46.9	88.2	39.0	47.6
L1	47.3	45.9	89.5	25.1	35.3
L2	47.4	44.8	89.1	23.0	30.6

TABLE 2

Chemical Analysis* of Shoreham Crankshaft

	1st Piece	2nd Piece	Ellwood City Mill Chemistry	ASTM A235-67 Class E
C	0.47	-	0.47	0.4-0.47
Mn	0.6	0.65	0.83	0.9 max
Si	0.12	0.12	0.18	-
S	0.014	-	0.010	0.05 max
P	0.01	0.01	0.006	0.05 max
Cr	0.30	0.39	-	-
Ni	0.054	0.055	-	-
Mo	0.03	0.03	-	-
V	0.04	0.04	-	-
Cu	0.04	0.04	-	-
Al	0.004	0.004	-	-
Ti	-	0.03	-	-

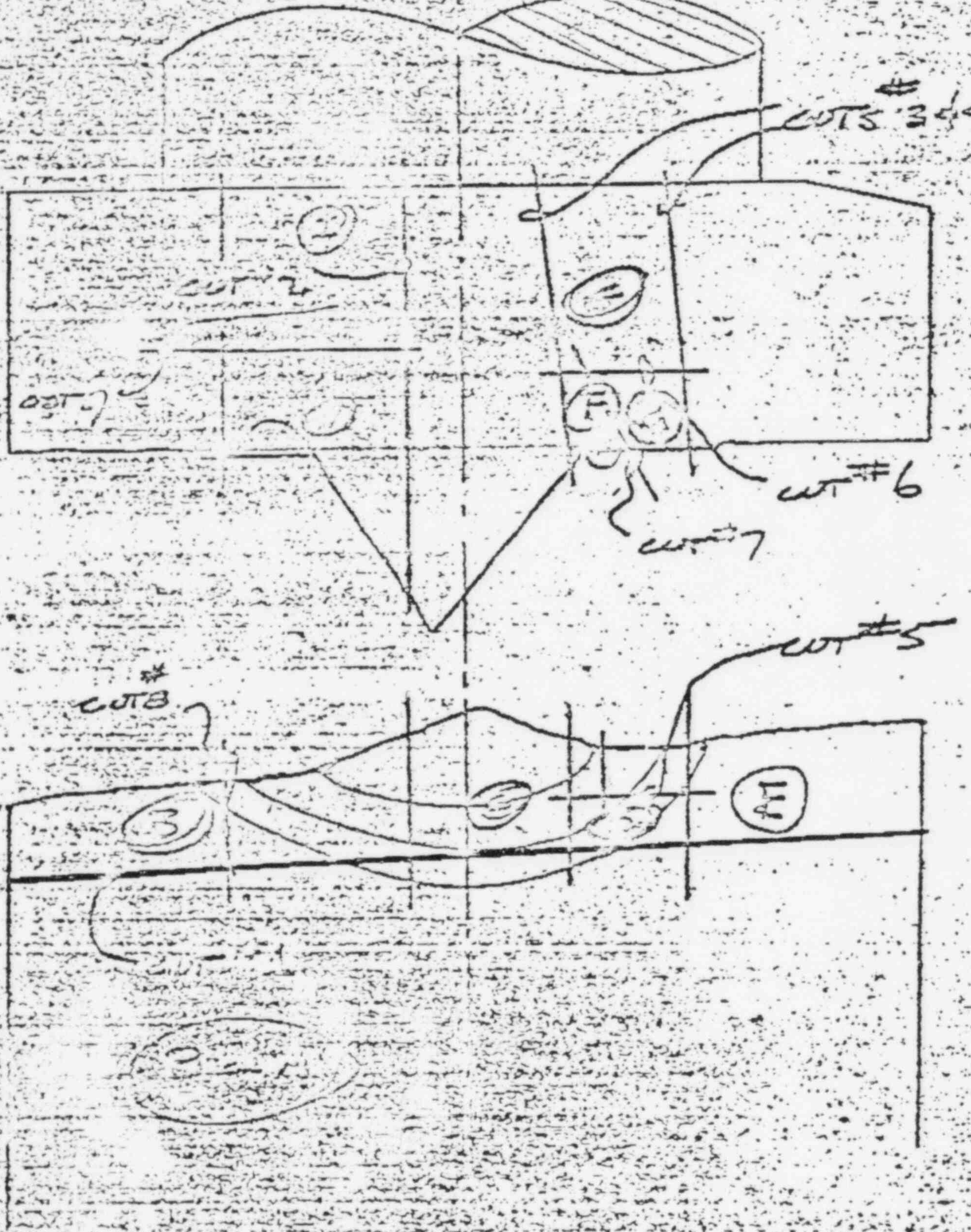
*All elements are reported in weight percent.

MACROETCH ANALYSIS

Slabs (A1A, A1B, and A1C) having radial, longitudinal, and transverse cross sections were removed from section A. Macroetching was performed using hot hydrochloric acid; we used this procedure to reveal forging flow lines and possible macrosegregation. These sections exhibited smooth forging contours with no evidence of macroscopic ingot segregation.

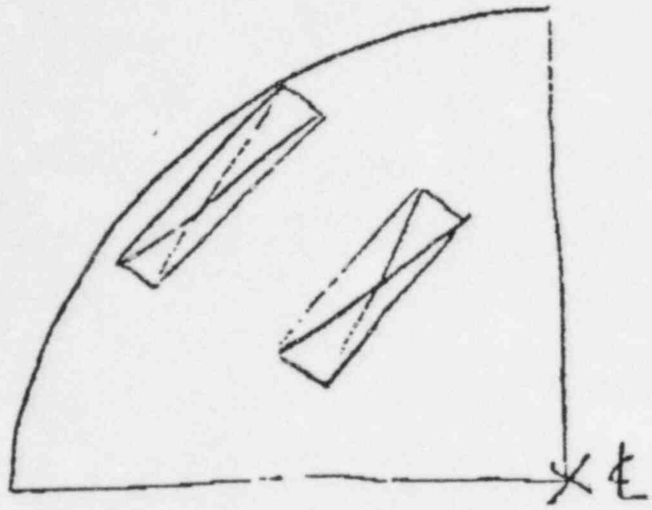
HARDNESS TESTING

Both macro- and micro-hardness tests were performed on various metallurgical cross sections. Bulk hardnesses, as measured on the Rockwell B scale, ranged between 80 and 89 HRB; the average hardness value was 85 HRB. In order to obtain hardness measurements immediately adjacent to the point of fatigue fracture origin and very near to the machined surface of the fillet radius, Knoop microhardness traverses were made parallel and perpendicular to the machined fillet surface. In both cases the average hardness was approximately 94 HRB; the individual readings ranged between 83 and 100 HRB. Both the bulk and microhardness values reflect the metallurgical soundness of the forging. These hardness values are in the range typically observed in forgings of this type.

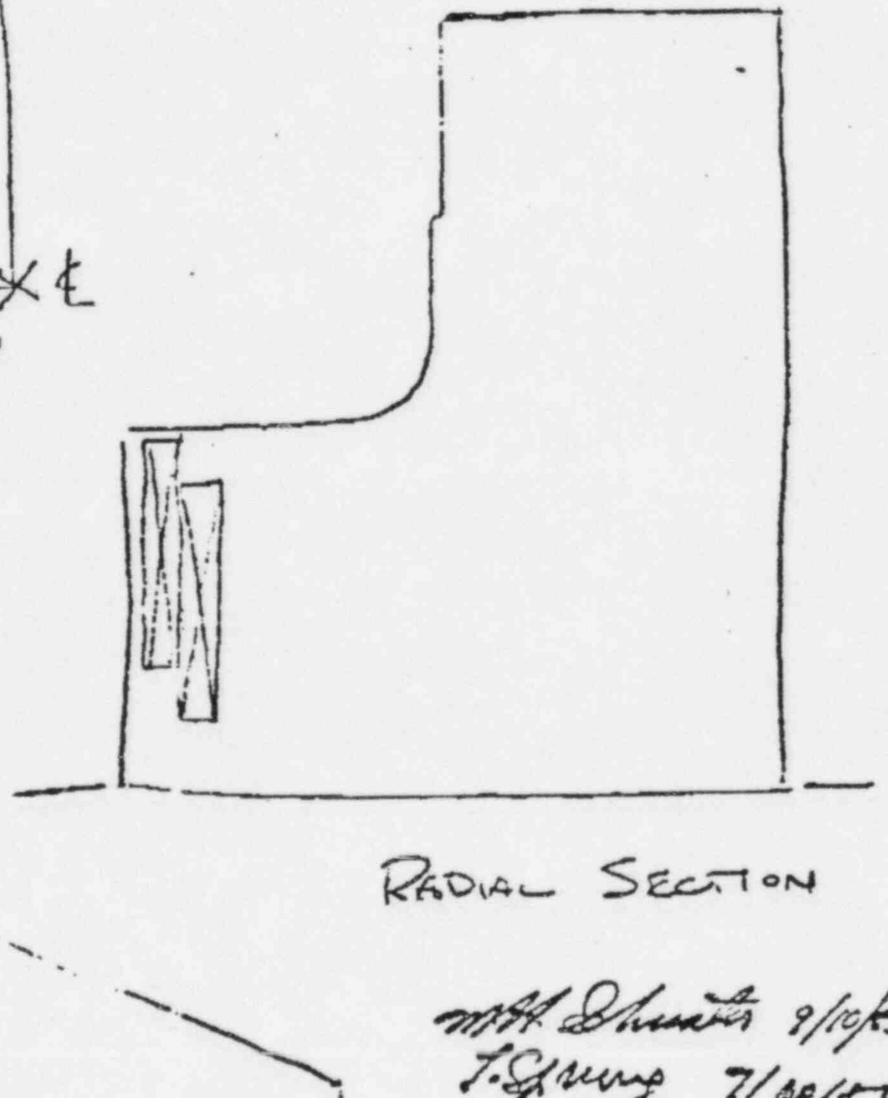


[illegible] LILCO 9/10/83
[illegible] SWEC 9/10/83
[illegible] TDI 9/10/83
[illegible] FaAA 9/10/83

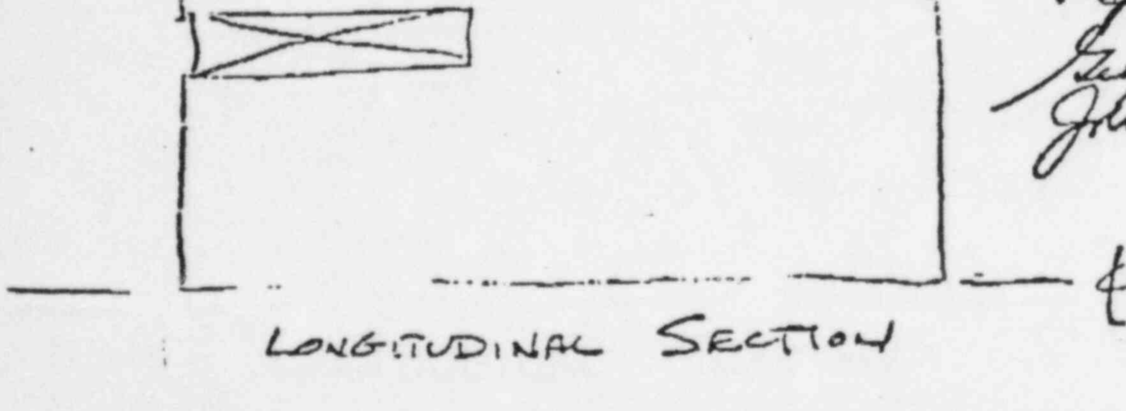
TENSILE SPECIMEN POSITION
($\frac{1}{4}$" TEST BAR)



TRANSVERSE SECTION



RADIAL SECTION



LONGITUDINAL SECTION

M.H. Schuster 9/10/83
T. Gruning 9/10/83
Geoff Kay 9/10/83
John Shyne 9/10/83

Addendum to memorandum from C. H. Wells to M. Mulligan, 9/9/83

M.H. Schroeder	LILCO	9/10/83
Geoff Kay	TDI	9/10/83
John Sheppard	FaAA	9/10/83
Ivan Spring	SWEC	9/10/83

Failure
Analysis
Associates

ENGINEERING AND METALLURGICAL CONSULTANTS
2225 EAST BAYSHORE ROAD
P.O. BOX 51470, PALO ALTO, CALIFORNIA 94303 (415) 856-9400

MEMORANDUM

TO: M. Milligan

FROM: C. H. Wells

DATE: September 9, 1983

SUBJECT: Schedule for Metallurgical Evaluation of Failed Crankshaft Section from DG 102 -- First Revision , with addendum

---

Friday, Sept. 9

- Removed crankshaft for bandsawing as follows:

  1. Fracture surface in one piece from remainder of web and journal.

  2. Quarter web and journal vertically and horizontally. Remove quarter section.

  3. Saw 1/2 inch thick slices from vertical, horizontal and transverse faces for macroetching, hardness impressions, chemical and physical property verification.

- Inspect second section of crankshaft and replicate fracture surface.

Saturday, Sept. 10

- 8:30 a.m. Meeting with Jack Wallace, Ivan Sprung, Mel Schuster, and John Shyne to decide how fracture surface will be sectioned for optical metallography and direct scanning electron microscopy (SEM), if needed.

Monday, Sept. 12

- Complete metallography, fracture surface evaluation.

- Measure residual stress in fillet racius as follows:

  1. Surface stress by x-ray diffraction.

  2. Near-surface stress gradient by strain gages and either hole drilling or treppaning.

  3. SEM examinationof fillet radius topography.

Review and concurrence by:

M. Schuster

Mel Schuster (LILCO)

Ivan Sprung

Ivan Sprung (SWEC)

Geoff King

Jeff King (TDI)

Failure Analysis Associates

A7) 1. ~~Subject: Schedule~~ Sectioning and metallographic and SEM Analysis.
(See the attached ~~sketches~~ Fig. 1)

- Cutting of the fracture surface ~~afterwards~~ at the web side, to be referred as W. Cuts 2, 3 and 4 will be taken perpendicular to the fracture surface. (Cut 1 is the one originally made to separate the fracture from the shaft.) Cuts 5 and 6 will be done to reduce the area to the size manageable in SEM. Cut 7 will be made through the origin area perpendicular to the fracture surface.

- Piece H will be used for the determination of surface residual stresses at the fillet. The piece will be sent to ~~Pen. State~~ Prof. C. Rudd at Pen. State for x-ray diffraction analysis.

- Specimen F will be examined in SEM. After the SEM examination the specimen will be sectioned ~~at~~ perpendicular to the fracture and the machined surfaces. The specimen, F1 that contains the origin will be polished and metallographically examined. The adjacent specimen F will be used for ~~———~~ hardness measurements.

M. H. Schuster LILCO 9/10/8
T. Spring SWEC 9/10/83
Geoff Korf TDI 9/10/8
John Sharm FaAA 9/10/83

(A-2)

B) Mechanical Testing and Macroevaluation

(see the attached Fig. 2)

•

• Surface grind and macroetch all three cross sections.

• Measure hardness on all three sections.

• Tensile tests per Fig. 2 (approximate location as shown).

• Chemical analysis will be ~~done at~~ made of this material at approximately 1/2 radius location. It will be analyzed for the following elements: C, S, P, Mn, Si, Al, Ni, Cr, Mo, Cu, V, Ti.

M.H. Schuster LILCO 9/10/83
J. Spering SWEC 9/10/83
Geoff Kief TDI 9/10/83
John Shapiro FaAA 9/10/83