GL00601

FAILURE INVESTIGATION OF WELL CASING FROM THE SALTON SEA SCIENTIFIC DRILLING PROJECT (SSSDP)

by

D. van Rooyen and J. R. Weeks
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

In August 1986, the piping which served as the well casing for the Salton Sea Drilling Project was found to be broken off at the 10th junction. Samples of the well casing and collar were cut from the pipes at each of the three junctions and sent to BNL for investigation as part of our continuing program "Metallic Materials for Geothermal Systems." This investigation consisted of the following activities:

1. cataloging and photographing the samples as received;
2. visual and, as necessary, dye penetrant inspection to determine the locations of any of the cracks in the components received;
3. metallographic examination of the cracked components;
4. determination of the mechanical properties of the collar and the casing pipe as well as an estimate of their chemical composition.

BACKGROUND INFORMATION ON LINER FAILURE ON SSSDP

BACKGROUND

We include this background section so received from Bechtel National, Inc., since these details are pertinent to the environment and history of the failed casing.

The original criteria for the well stated that the well would only have to stay open for six months after completion. Based on this and on casing costs, it was felt that the N-80, round thread, 29 lb/ft LTC casing would be adequate since N-80 is recommended for H_2S environments above 150°F.

(5.0)

Another decision made just prior to the installation of the liner was that the liner guide shoe would be drilled out and a 6 1/8-in. hole would be drilled below the existing 8 1/2-in. hole at 10,475 ft to ensure a connection with a suspected lower flow zone. To ensure that the uncemented liner would not back off during drilling operation, the casing makeup torque was increased above the optimum 5,970 ft lb. However, it was kept below the maximum recommended torque of 7,460 ft lb.

HISTORY

On March 16, 1986 the 7-in. liner was installed after repeated attempts were made to deepen the 8 1/2-in. hole below 10,475 ft. These attempts failed due to loss of circulation problems encountered at the bottom of the hole. The liner was run and set from 5,735 ft to 10,136 ft without incident. As mentioned previously, the casing was made up to higher than optimum torque values to minimize chances of a backoff during drilling operations to deepen the hole.

On March 17, 1986 the 7-in. guide shoe was drilled out and a 6 1/8-in. hole was drilled from 10,475 ft to 10,564 ft without circulation (blind).

On March 20, 1986 the second flow test was initiated. The well flowed for approximately 38 hours producing 1.1 million gallons of brine. Estimates of downhole temperatures and pressures at 10,440 were 667°F and 4,287 psi, respectively, which were based on the Kuster tool runs. Flow rates ranged from 300,000 to 500,000 lb/hr with a maximum of 700,000 lb/hr. The highest well head flowing temperature and pressure were 486°F and 500 psi, respectively. Surface analysis for H_2S indicated from 7-7.4 ppm. Reservoir H_2S was estimated by one observer at 50-70 ppm. However, no confirmation of this is presently available.

Production was assumed to come from all the major loss zones behind the liner as well as below the liner. These zones were indicated as temperature reversals on the USGS temperature logs. The zone at 6,119-6,133 ft was associated with the first flow test and is adjacent to the area where the liner initially parted.

From March 26-27, 1986 the brine was reinjected into the well. This contained oxygen to the extent it could be absorbed from the air during the few days it sat in the ponds. However, no measurements of oxygen level were made. The final brine injected was displaced with 500 bbl of fresh water containing an oxygen scavenging agent. During the 4 days between the flow test and reinjection, logging and fluid sampling operations were performed. Logging was conducted for four days after the reinjection.

On April 1, 1986 USGS ran the final temperature survey for the beginning of the shut-in and temperature buildup period.

On April 22, 1986 the third temperature log was run without incident. This was 38 days after installing the liner.

On May 28, 1986, approximately 74 days after running the liner, another temperature log was attempted. The tool would go no deeper than 6,380 ft going in and hung up at 6,195 ft coming out of the hole; thus suggesting that the liner had parted at 6,195 ft. The temperature tool was safely removed later in the day.

From June 24-26, 1986 diagnostic logs were run which indicated the casing had parted at a coupling at 6,181 ft and an open hole existed below this point to 6,422 ft. The logs also showed that there was little or no corrosion of the existing liner and that nine joints of casing were still in place below the hanger.

On August 7-12, 1986 the drill rig was mobilized for remedial work to repair the damaged liner. The objective was to remove the liner hanger and attached liner, replace it with a new hanger and liner sufficient to reach and tie into the lower string of original liner. This was intended to reestablish continuity to the bottom of the liner permitting measurement of the bottom hole temperature.

On August 13, 1986 the liner hanger was speared into and jarred loose. The jars were required to unseat the liner. While pulling the liner hanger through the expansion spool, the slip segment lodged in the expansion spool and jammed.

On August 14, 1986 a cement plug was pumped downhole and allowed to set up before disassembling the expansion spool and removing the slip segments. Only four joints of the casing were recovered. The coupling on the bottom of the fourth joint (Junction 2) was badly cracked. The jarring action to recover the liner evidently dislodged the bottom five joints of casing.

On August 15, 1986 the BOPE was reassembled, the cement plug was drilled out, and the remaining five joints of liner were fished from the hole.

On August 16, 1986 a 6 1/8-in. tapered mill was run to 8,000 ft where an obstruction was encountered. Efforts to mill through the spot were unsuccessful.

On August 17, 1986 the top of the lower section of liner was dressed off with a pilot mill and a piggyback liner was installed. The new liner was L-80 buttress thread 29 lb/ft LTC.

OBSERVATIONS:

Observations of the liner at the jobsite after the liner was recovered are as follows:

- The liner hanger showed signs of erosion on the outside body indicating the seals had leaked. Examination of the seals showed that they were all in place but badly charred. The slip segments had come off the drag springs because the Allen bolts holding the slips to the drag springs had completely corroded. Although the liner hanger was designed for geothermal, the fasteners for the segments apparently were not. Inspection of the polished bore receptable (PBR) showed a high degree of pitting on the inside bore.
- Visual cracks were noted in the couplings with extreme cracking in the coupling on the bottom of the fourth joint (Junction 2 in this BNL Report).
- No cracks were observed in any of the recovered casing, confirming the subsequent BNL finding that there were no cracks observed in the sections of casing that were received.

- Both the collars and the casing showed signs of corrosion.

ADDITIONAL FACTS:

1) The well path was not always vertical. Well surveys were made. The well was noted to have about a 5° dogleg near the location of the initial separation. This is expected to have increased the stress level in the liner joints.

2) Temperature surveys were made as noted above. These indicate temperature following the injection of the fluid.

3) The geothermal brine is a high temperature saturated brine. It is in the order of 300,000 ppm with about 180,000 ppm being chlorides.

4) Jars were used to remove the nine joints of liner (see August 14). Jars caused an impact force. How much of the cracking noted on Junction 2 can be attributed to this is not certain.

RECOMMENDATIONS:

Bechtel talked with tubing suppliers. Several recommendations have been made on ways to minimize the problem. Some of the suggested solutions are:

1) Use buttress thread casing
2) Use lower torques on the casing
3) In zones of high doglegs, heavier weight casing and couplings should be considered.
4) Use L-80 grade casing, which is recommended for use in H_2S environments at all temperatures. It also has a maximum hardness of R_c23, which falls within the recommended NACE standard for H_2S usage.
5) Consider using a premium joint connection such as Hydril which seals the threads from exposure to corrosion.

All these recommendations should be considered in light of the criteria stated in the background, i.e., six months life.

EXAMINATION OF THE PIECES RECEIVED AT BNL

The specimens sent to BNL as identified by the sender (Bechtel) are listed in Appendix A. The piping received as 7-in. diameter, 29 #N-80 LT&C R3 seamless steel casing. Photographs of the sections of the pipe and collars, as received at BNL, are shown in Figures 1 through 4 (Junction numbers 1, 2, and 3, together with specimen 4 which is from a jaw assembly located above items 1, 2, and 3. As can been seen, the extent of general corrosion on 1, 2, and 3 appears to increase with depth. Note, however, that specimen number 4 was also severely corroded. A major branched crack is also visible in the crack in the collar of section 2.

VISUAL AND DYE PENETRANT EXAMINATION OF THE SPECIMENS

In addition to the through wall crack shown on the collar on specimen two, a second (and possibly third) crack is visible on the photograph (Figure 2). Dye penetrant examination also revealed a short, longitudinal crack on the outer surface of the collar on the first junction. No cracking was seen on any of the casing pipe specimens received. No collar was received on specimen 3. The second major failure appears to have occurred on the second collar, the first being the collar from section 3, which was the original problem since the liner parted at this collar. The smaller crack in junction number 2 and the part through-wall crack from junction number 1 were selected for further metallographic examination.

The Crack in Collar Number 2

The cross sections of the secondary crack from collar number 2 are shown in Figures 2 through 7. The surface of the main crack is seen to be heavily corroded and a number of secondary cracks emitting from the primary crack are evident. The structure of the alloy is heavily martensitic, with no tendency for the crack to follow any of the martensite grain boundaries. Attempts to etch the specimens to try to bring out the original austenitic grain boundaries were unsuccessful. However, the micrographs of these cracks in the unetched condition show some of the martensitic grain structure in the vicinity of the cracks, suggesting that some penetration along the martensite grains may have occurred. Figures 8 and 9 show the fracture surface (in scanning electron micrographs) of two of these cracks after they were opened up in the laboratory. On the first, a through wall crack, one can see deposited crystals which from the EDS charts appear to be high in silicon, suggesting these crystals grew from the brine solution either during evaporation of the brine or as it flowed through the crack. An EDS spectrum of the second crack showed significant amounts of calcium and silicon present on the crack surface. There is no strong evidence of an intergranular type cracking phenomenon, however, or of any ductile rupture occurring in these cracks.

COMPARISON OF THE COLLAR AND CASING MATERIALS

The microstructure of the casing and collar materials are shown in Figure 10 at 400 x magnification; by comparison with the coarse-grained acicular structure of the collar, the casing is seen to be finer grained, but still martensitic. The slight rounding of the particles, however, suggests that some tempering of the martensitic had occurred.

Specimens according to ASTM specifications were cut from both the casing and the collar materials for mechanical property tests. The results are shown in Table 1. The yield strength of the collar material that we tested is higher than that of the specimens cut from the casing itself (91,500 vs. 82,500 psi approximate values). This is believed quite significant because the oil industry prefers to use material below 90,000 psi yield and Rc22 to help resist hydrogen cracking in sour oil wells, although these values are not absolute thresholds. The observed difference is consistent with the untempered state of the martensite in the collar. Both numbers, however, are probably within the usual scatterband of N80. The hardness measurements appear to correspond with the tensile properties. Significantly, several readings obtained from the collar (outside surface especially) were >Rc22, while none from the casing were as high. The collar material is also slightly less ductile, and both are less ductile and somewhat lower strength than the mill test report for the casing steel, also shown in Table 1.

A sample from each alloy was examined in the EDAX. The patterns received are shown in Figure 11 A and B. It is apparent these EDAX scans are essentially identical and indicate no major differences in alloying constituents between the collar and casing materials.

Neither the collar nor the casing material showed any significant number of inclusions; both were clean, good-quality alloys as judged by microstructure.

EXAMINATION OF CRACK FROM COLLAR AT JOINT NUMBER 1

As noted above, during dye penetrant examination, a small, longitudinal, part through-wall crack was identified in collar number 1. A portion of this collar including the crack was examined metallographically. The results are shown in Figure 12 A and B. It can be seen that this is a shallow crack that propagated at an acute angle to the surface and not in a direction in which it would have tended to penetrate the piping. The appearance of this crack is entirely consistent with "hydrogen blistering" although whether it was actually due to this phenomenon or to another stress corrosion phenomenon cannot be determined at present.

DISCUSSION

In our opinion, all the evidence obtained in this investigation suggests that the cracking/failures were due to a stress corrosion and/or hydrogen embrittlement phenomenon, accentuated by the presence of hydrogen sulfide in the water and the relatively high yield strength, and relatively low ductility, of the collar alloy. The increased tensile load on the collars from tightening them would also have contributed to the environmentally assisted cracking, although it is only through an increased stress and not direct mechanical damage during tightening, since we found no evidence of this type of failure. DOE advised us that the pipe not only has been used to withdraw hot geothermal brine from the subsurface reservoir but also to recharge brine that had been stored on the surface (in the air), to the reservoir at a later date. Consequently, not only was hydrogen sulfide present in the brine, but oxygen was also present during reinjection; whether this can account for all the corrosion damage is not totally certain, because this was only for a few days. The increase in general corrosion with depth from the surface could be due to an increase in temperature as this oxygenated brine flowed back into the geothermal reservoir. The fact that the reinjection process lowered the temperature considerably suggests also that any hydrogen damage to the collar steel would have been greatest during this period, combined with an increase in corrosion due to the composition of the cold brine.

It was not possible to tell whether the cracks in the collar number 2 originated from the inner or outer surface of the collar. The crack on the first collar, however, was definitely shallow and only on the exterior surface. The nature of this crack is quite suggestive of that for hydrogen blistering as described by others, as cited above. It is interesting to note that the highest hardness was consistently observed on the outer surface of the collar and that it consistently exceeded the (nominal) borderline (Rc22) associated with oil industry applications.

Embrittlement due to hydrogen or hydrogen blistering tends to peak below 100°C. The temperature of these junctions are believed to have been higher than that during flow tests, but, as also stated above, must have been lowered during recharge so that it can be speculated that the cracks have formed during the latter stage. At that time, the lowest temperatures would be expected closer to the surface, and oxygen (increased corrosion) was also introduced as dissolved in the reinjected liquid.

CONCLUSIONS (See also earlier recommendations provided by Bechtel)

The collars probably failed by a stress corrosion/hydrogen embrittlement mechanism caused by the susceptibility of a martensitic structure at a marginal strength level and, the high hardness, especially on the outside surface to stress corrosion and/or hydrogen embrittlement. The cracking resulted from a combination of this susceptibility with high tightening tensile stress, and the presence of H_2S in the environment as well as the introduction of O_2 and the lowering of temperature during reinjection of brine. Tempering the martensitic collar material to increase its ductility and decrease its hardness and yield strength would be expected to substantially reduce the tendency of this material to crack in the environment to which it is exposed. There appears to be no significant difference in the materials used for the piping and the collars in terms of chemical composition, number of inclusions, or microstructure other than that brought about by the difference in heat treatments of the two. Both appear to be good quality material. The significant differences are believed to be the higher strength of the collar steel, and cracking susceptibility is believed to have been enhanced by tightening during assembly as well as some untempered martensite in the collar steel. However, it should be noted that we found no evidence of overtightening in the sense of actual mechanical damage to the pieces we examined.

REFERENCES

1. R.N. Parkins "Environmental Aspects of Stress Corrosion Cracking in Low Strength Ferritic Steels" in Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, NACE-5.

2. R.H. Wallace (DOE) Telecon 10/31/86.

TABLE 1

Mechanical Properties of Collar and Casing Aloys Cut from Joint #2

Collar	0.2% offset Yield stress, psi	Hardness (Rc)	%Elongation
Sample 1	91,200	20.5, 24.5	15.0
Sample 2	91,650	19.5, 20.5	–
Casing			
Sample 3	82,400	34, 35, 36 35, 35, 35	19.3
Sample 4	82,700	–	18.15
Casing steel test report, N-80, quench and tempered condition (duplicate specimens)	94,940 93,140	– –	23.0 23.5

Figure 1. Junction 1, as received at BNL.

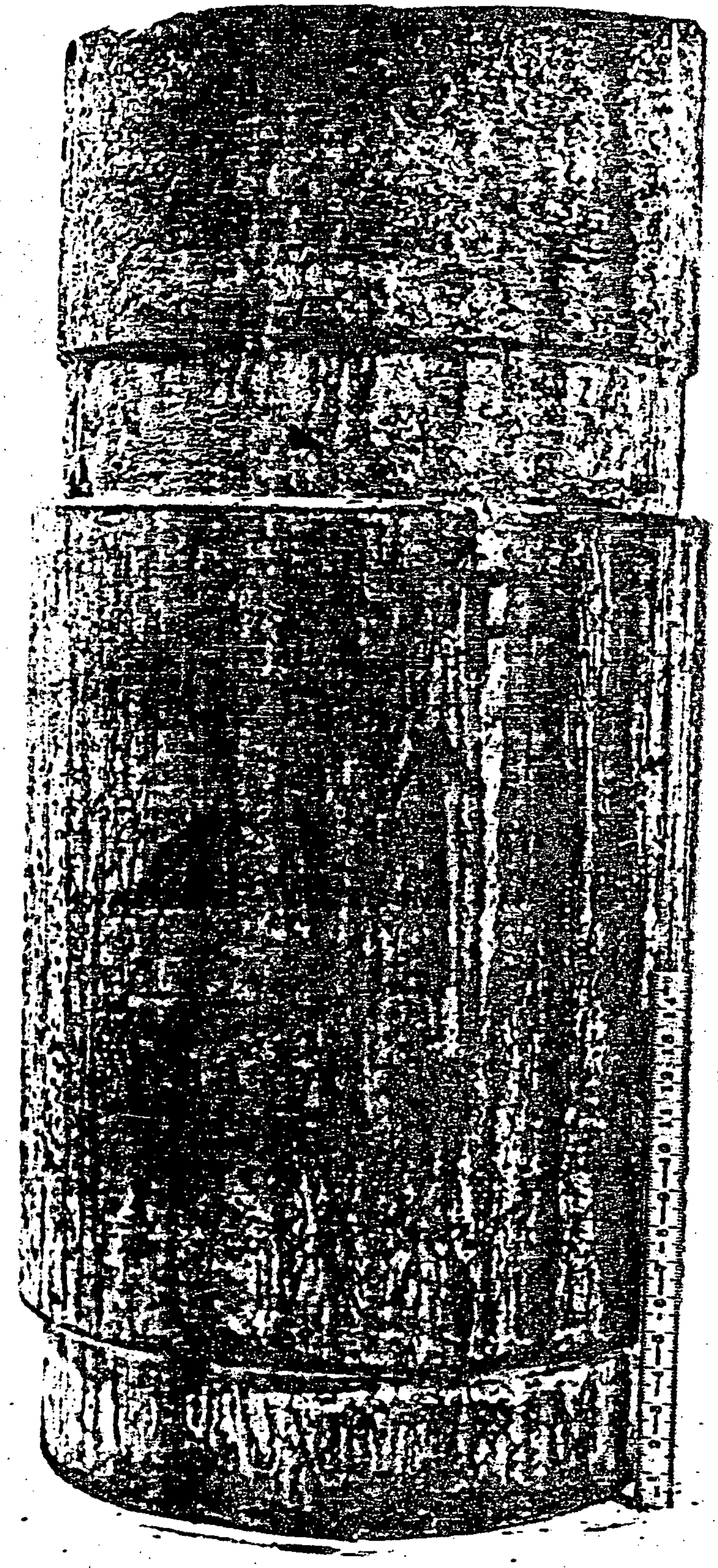


Figure 1a. Junction 1, as received at BNL.

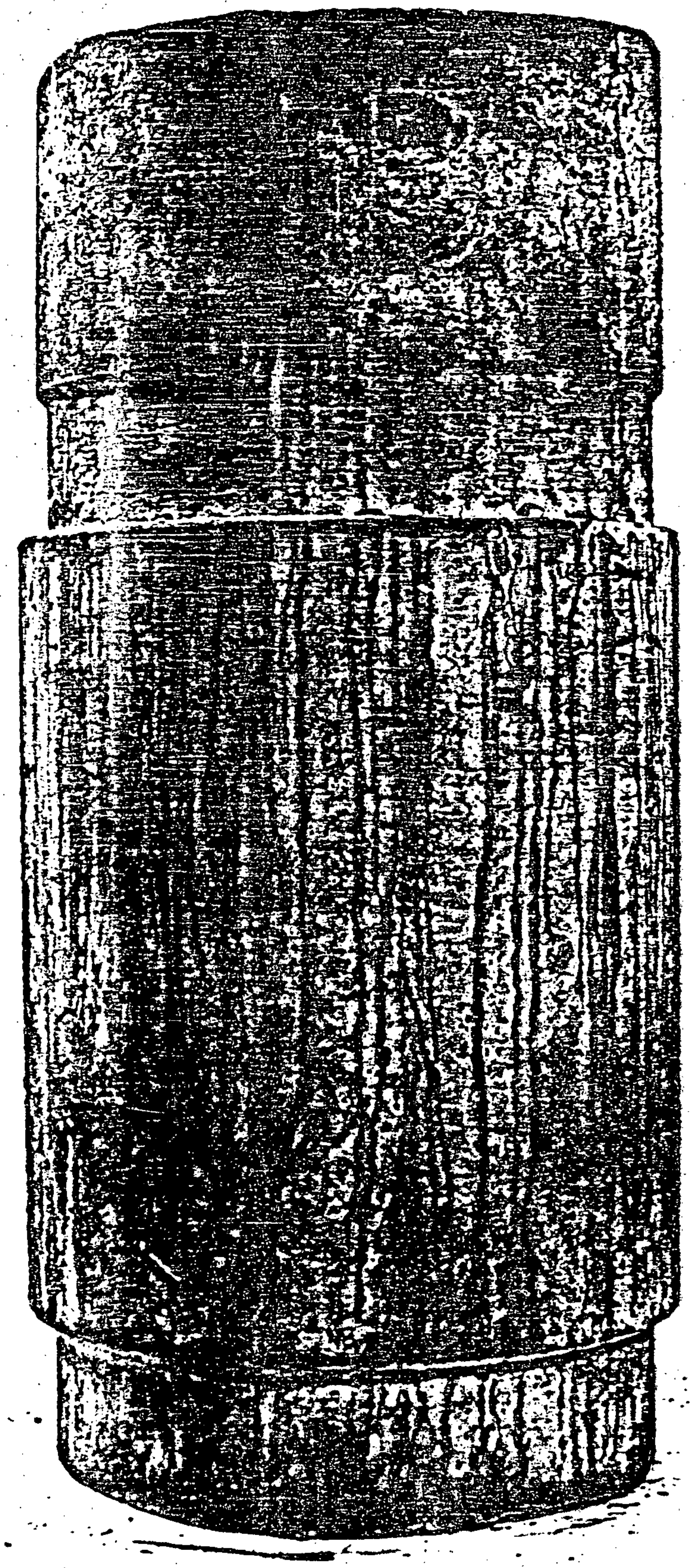


Figure 1b. Junction 1, as received at BNL.

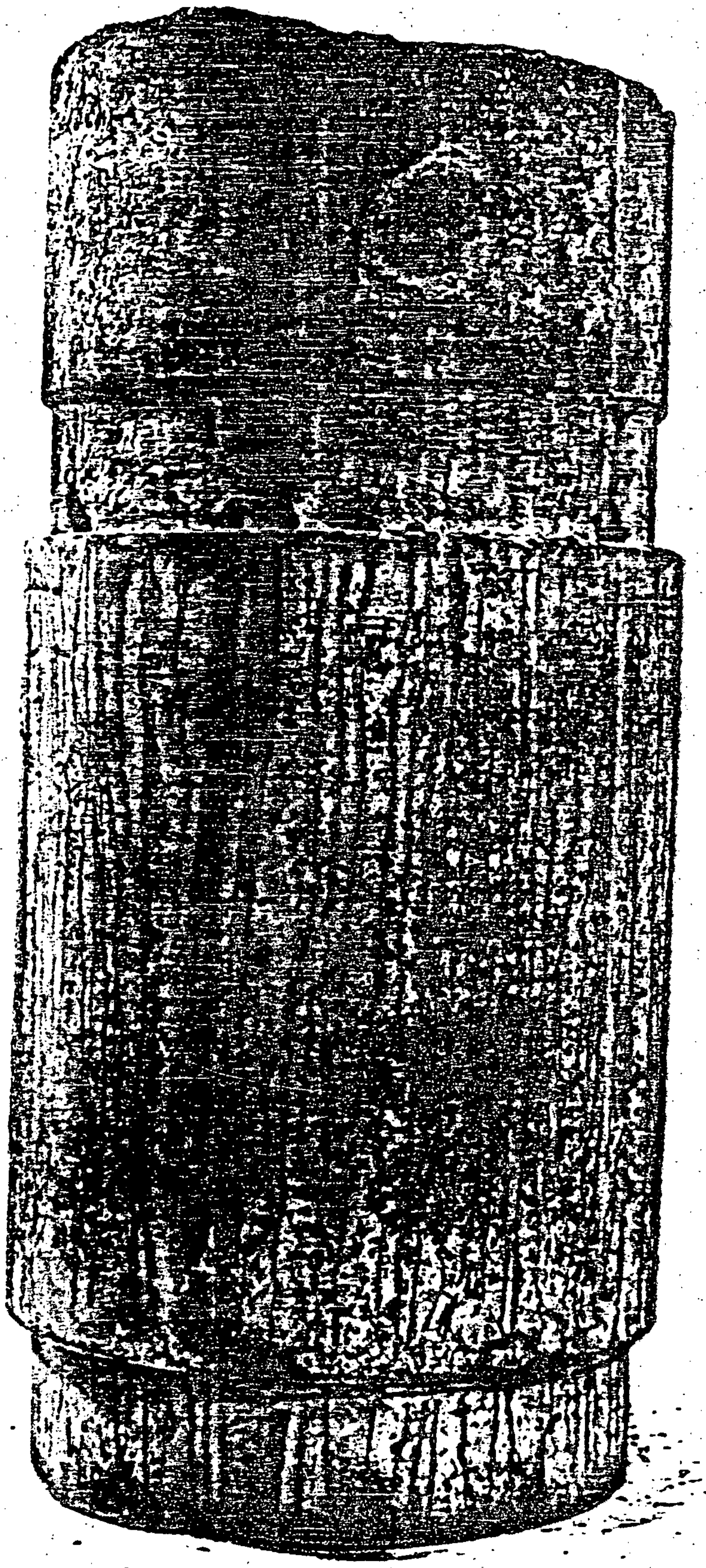


Figure 1c. Junction 1, as received at BNL.

Figure 2. Junction 2, as received at BNL.

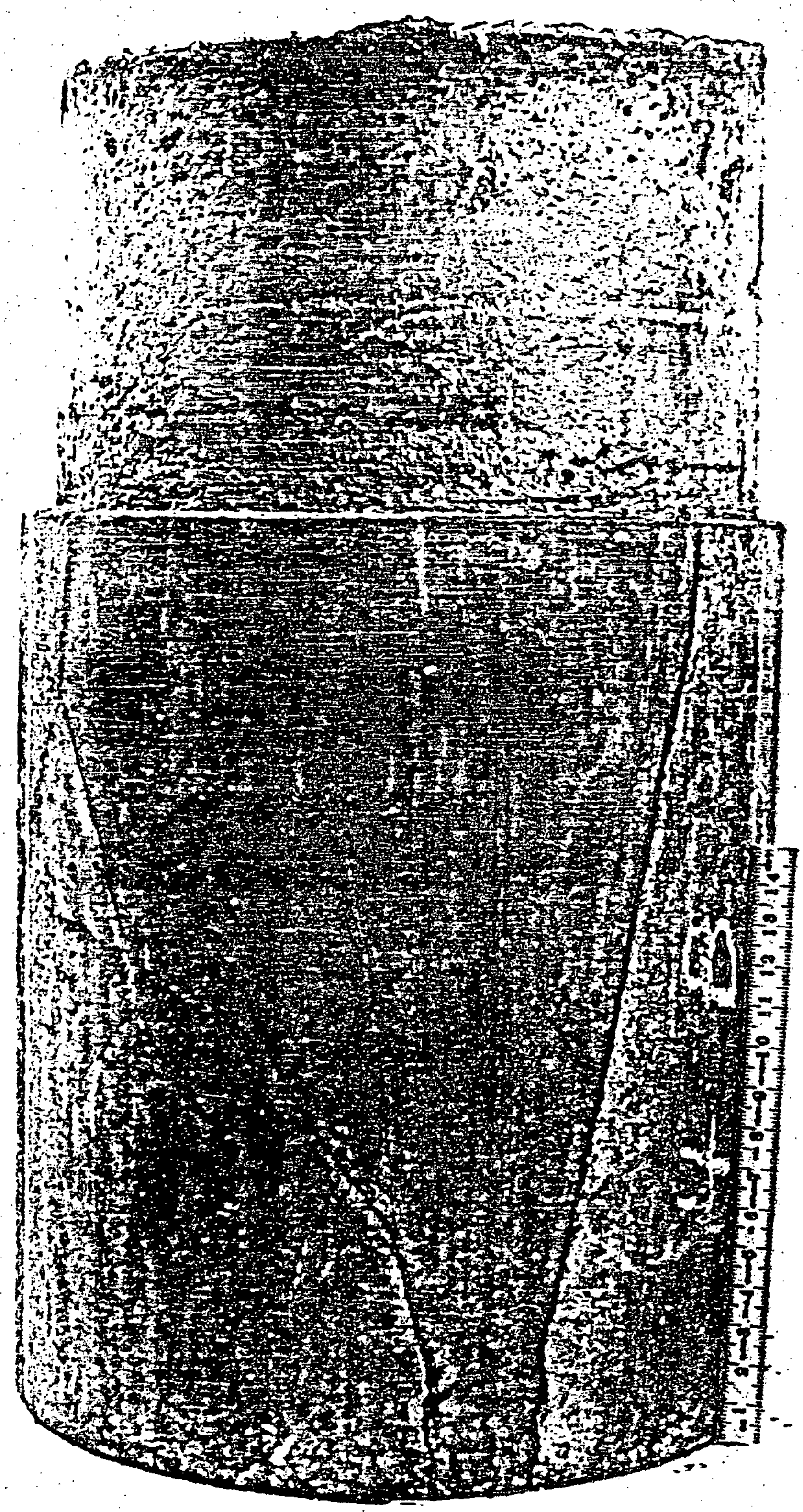


Figure 2a. Junction 2, as received at BNL.

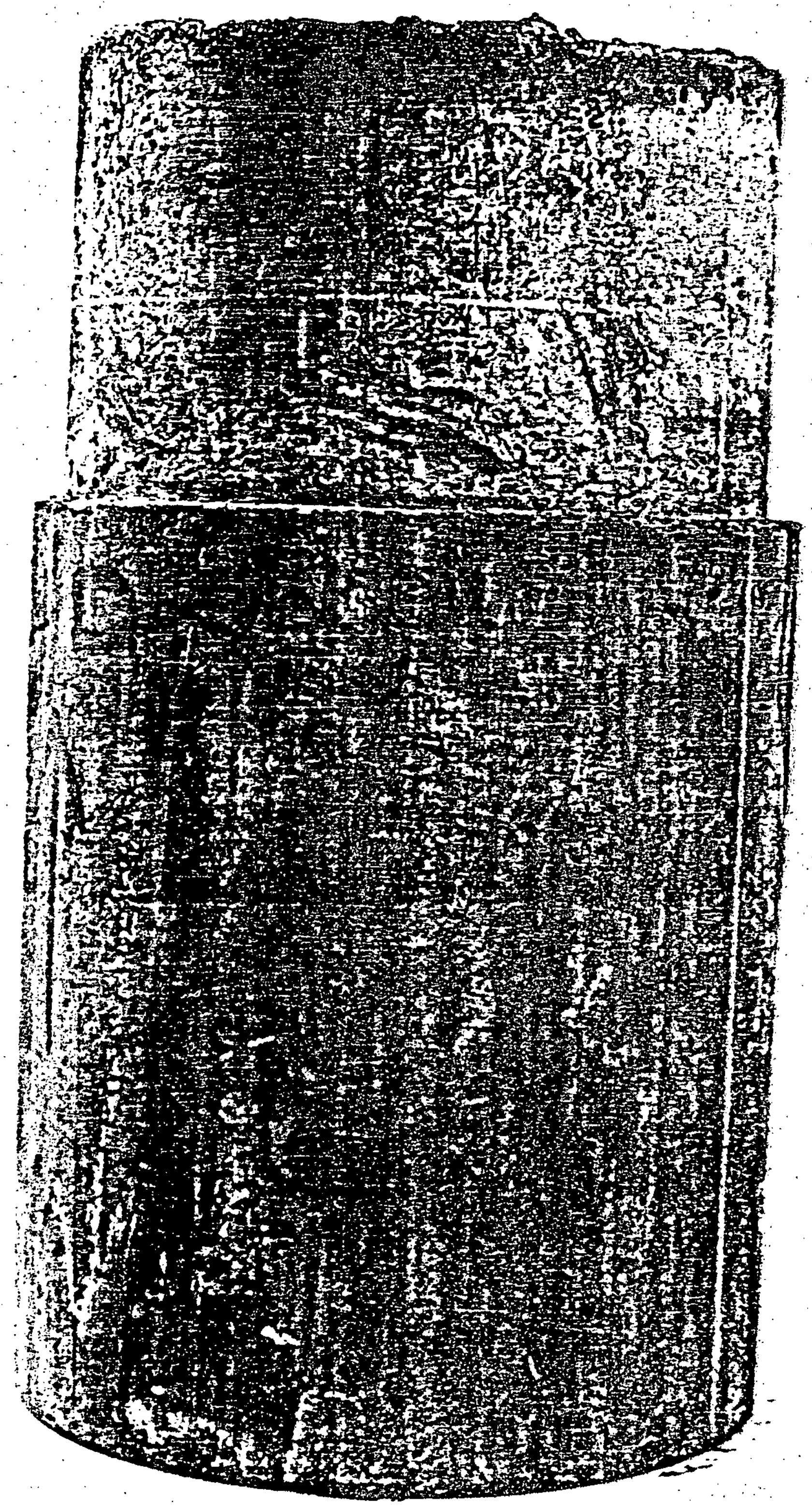


Figure 2b. Junction 2, as received at BNL.

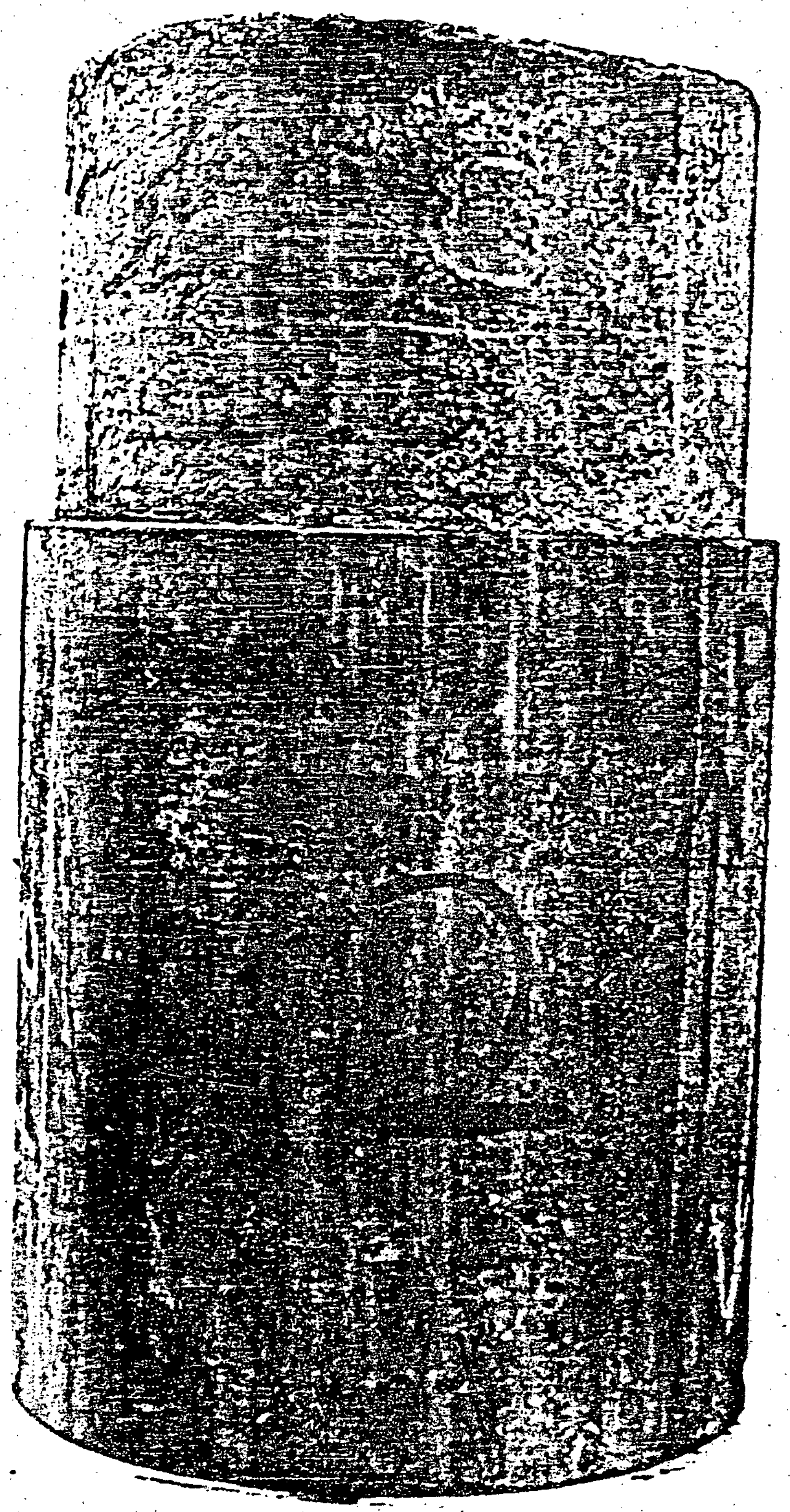


Figure 2c. Junction 2, as received at BNL.

Figure 3. Junction 3, as received at BNL. Casing only - no collar. Bottom end damaged by falling 330 feet and impacting 7" liner at the bottom of the hole.

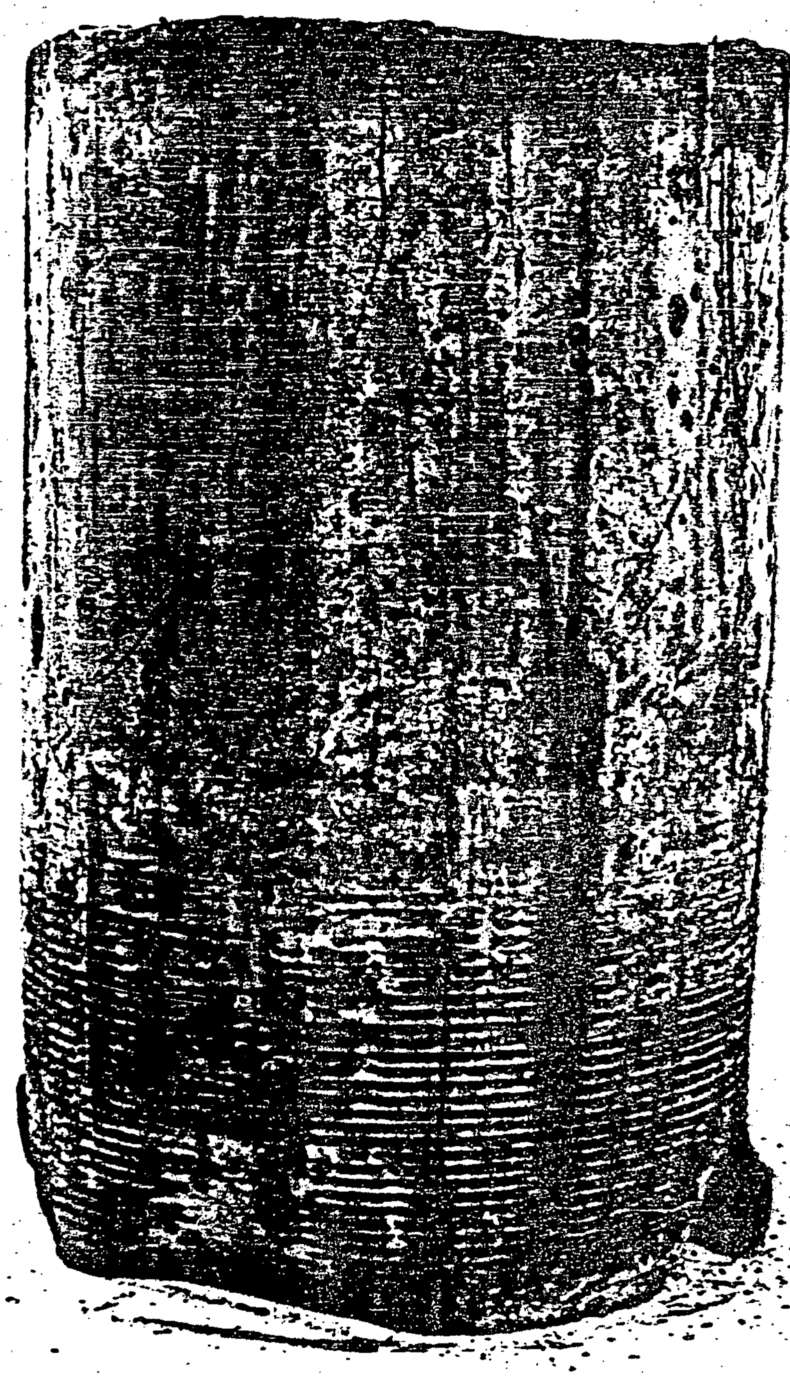


Figure 3a. Junction 3, as received at BNL. Casing only - no collar. Bottom end damaged by falling 330 feet and impacting 7" liner at the bottom of the hole.

Figure 3b. Junction 3, as received at BNL. Casing only - no collar. Bottom end damaged by falling 330 feet and impacting 7" liner at the bottom of the hole.

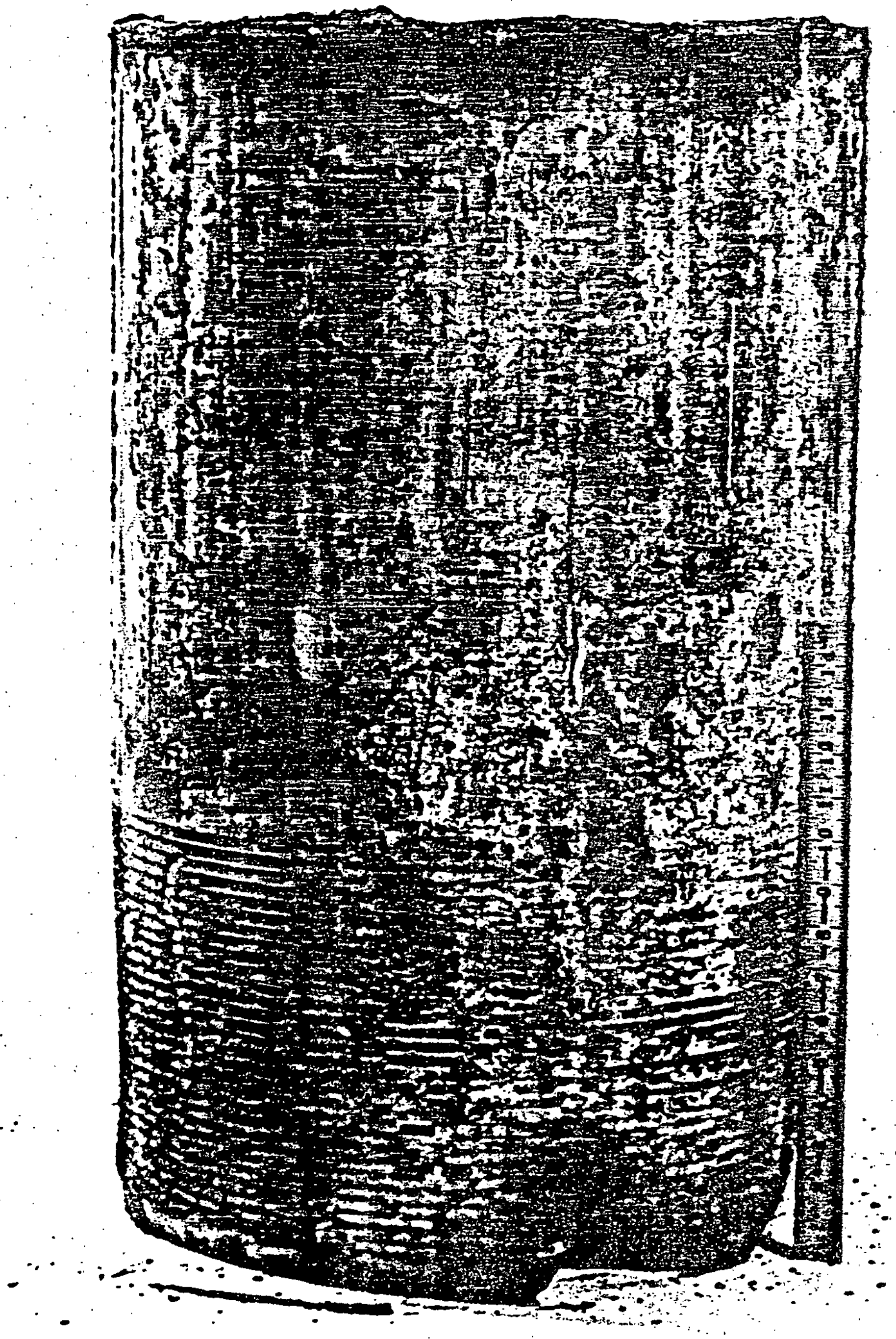


Figure 3c. Junction 3, as received at BNL. Casing only - no collar. Bottom end damaged by falling 330 feet and impacting 7" liner at the bottom of the hole.

Figure 4. Junction 4, two segments of the casing pipe.

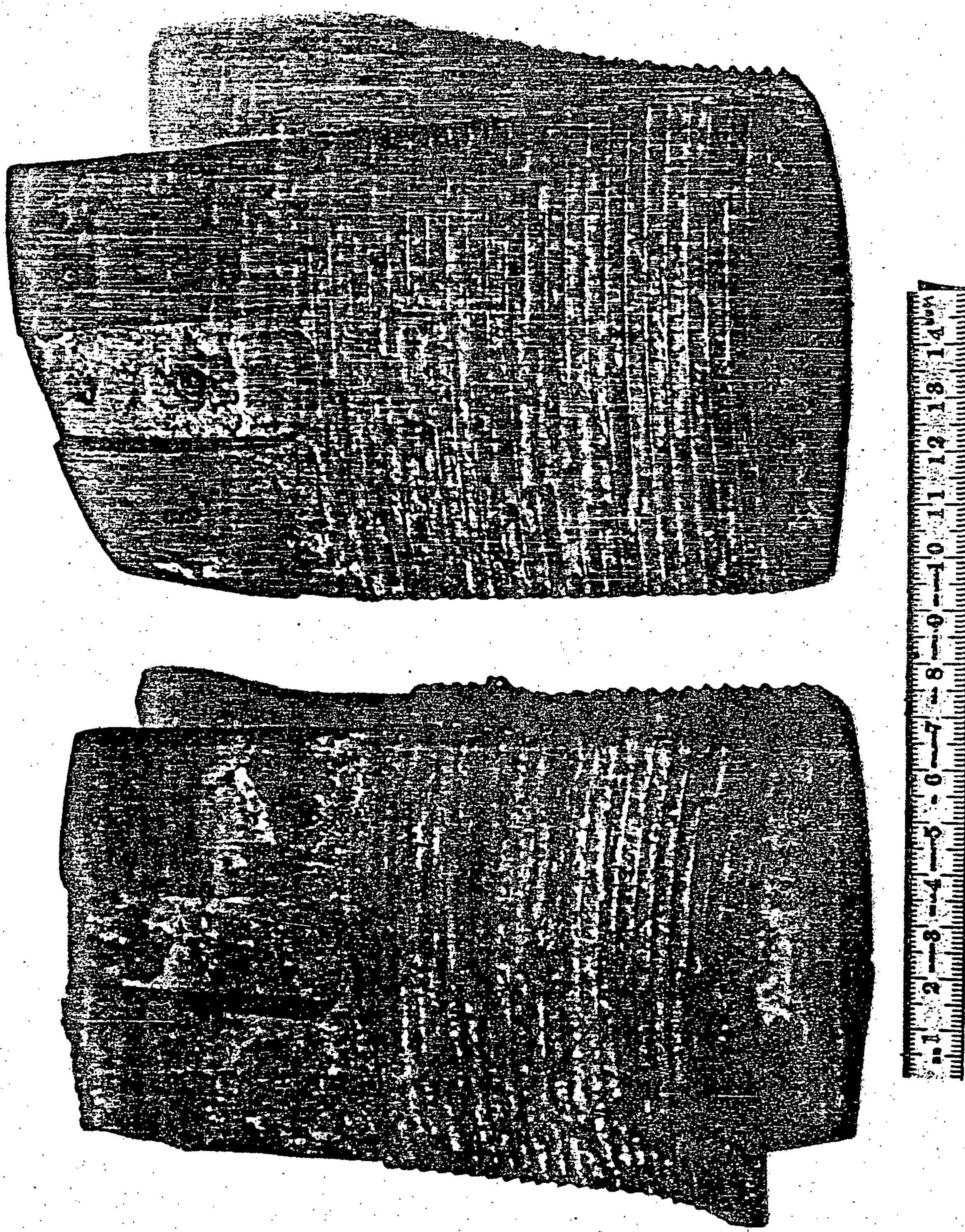


Figure 4a. Junction 4, two segments of the casing pipe outer surface.

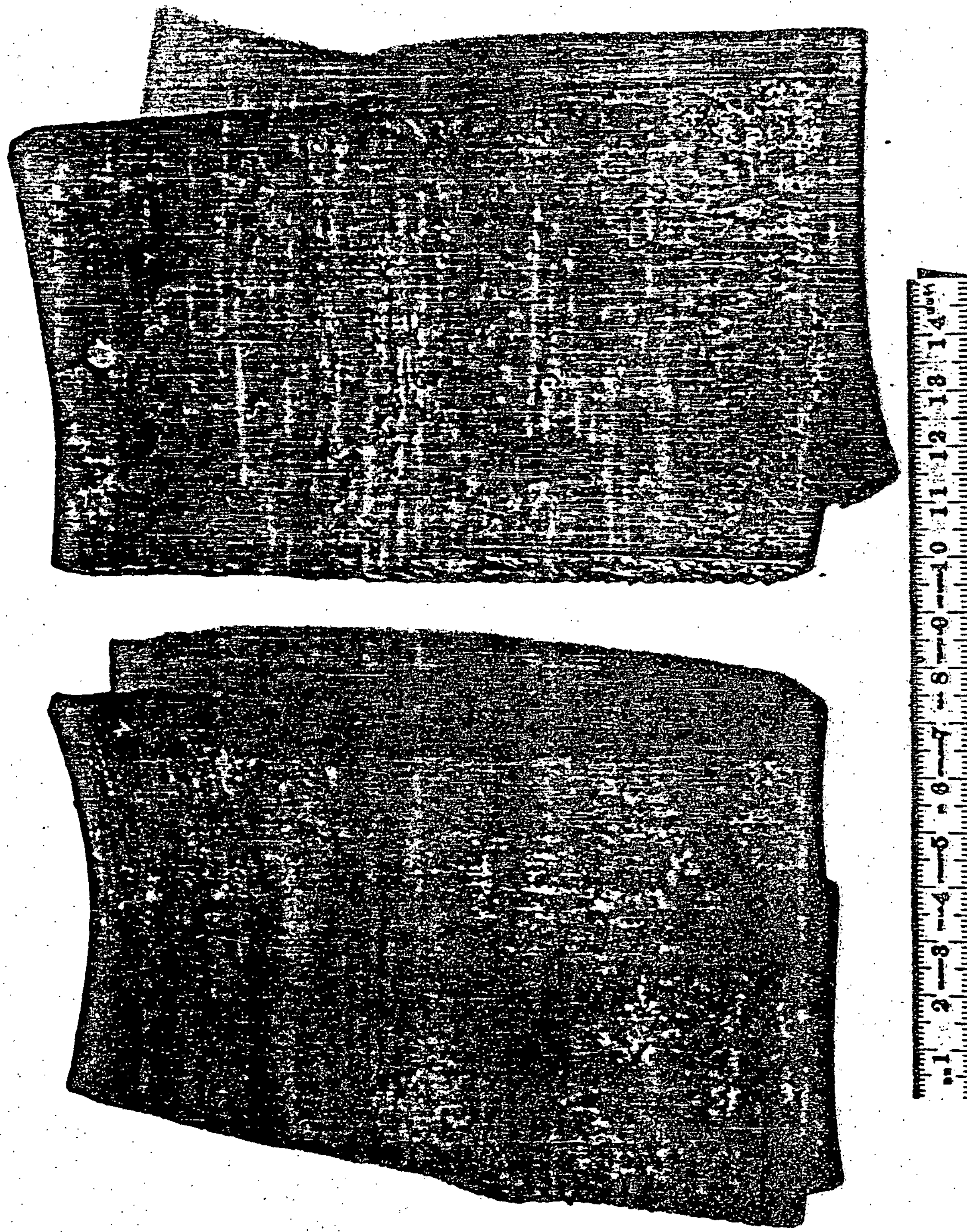


Figure 4b. Junction 4, two segments of the casing pipe inner surface.

Figure 5. Branching cracks departing from main crack, collar #2 (on left).

Figure 5a. Branching cracks departing from main crack, collar #2 (on left). 50 X, unetched.

Figure 5b. Branching cracks departing from main crack, collar #2 (on left). 100 X, unetched.

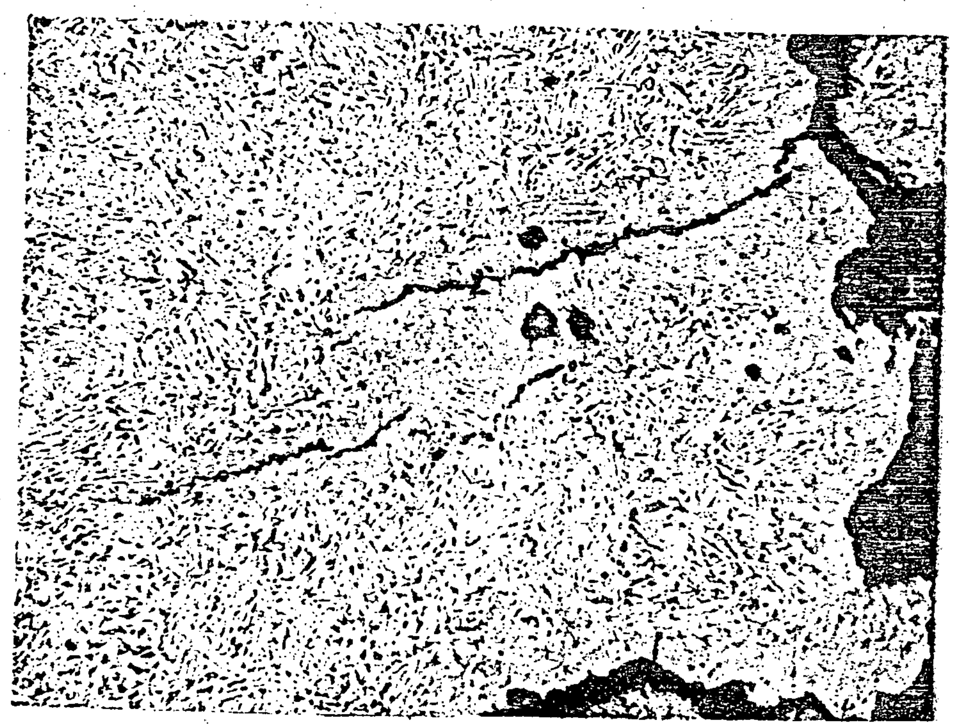


Figure 6. Cracks shown in Figure 5b, 100 X, etched.

Figure 7. Crack tip, 200 X, unetched.

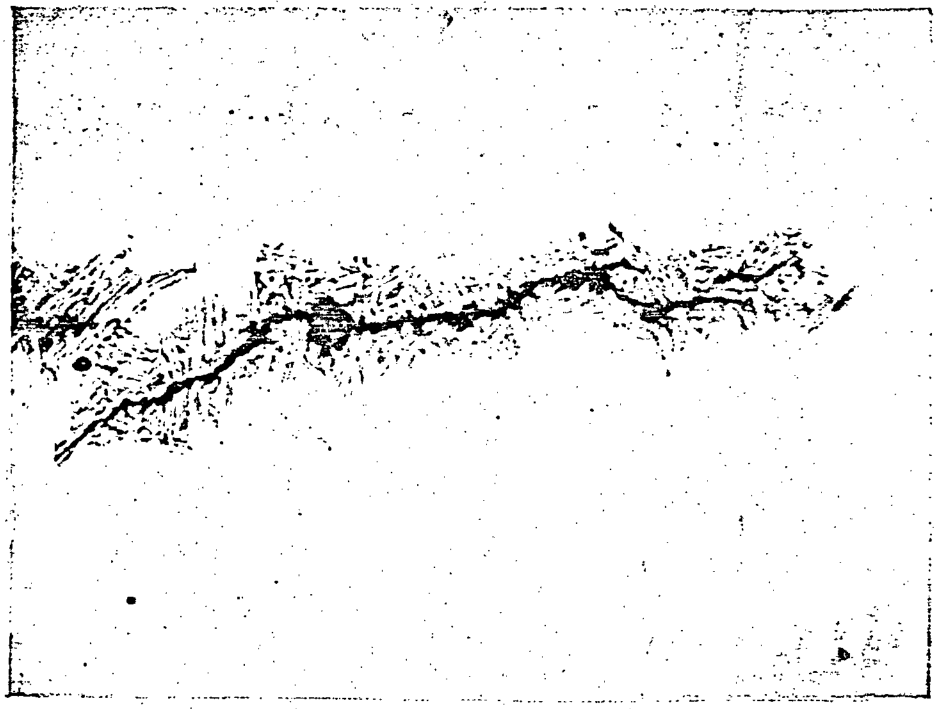


Figure 7a. Crack tip, 200 X, unetched.

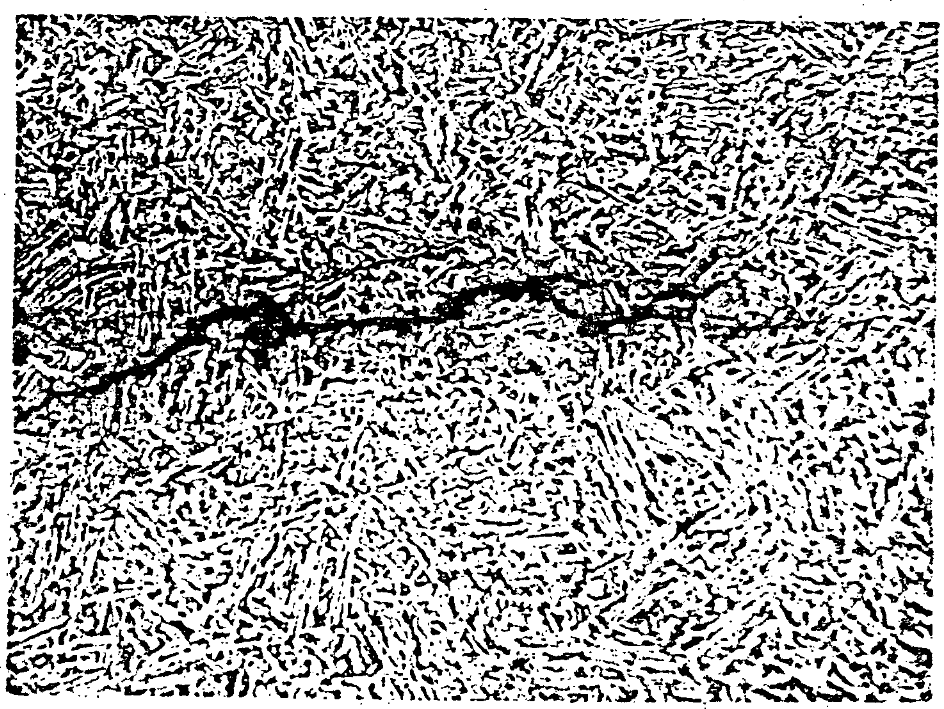


Figure 7b. Crack tip, 200 X, etched.

Figure 8. SEM picture of crack surface, showing crystals grown from geothermal brine.

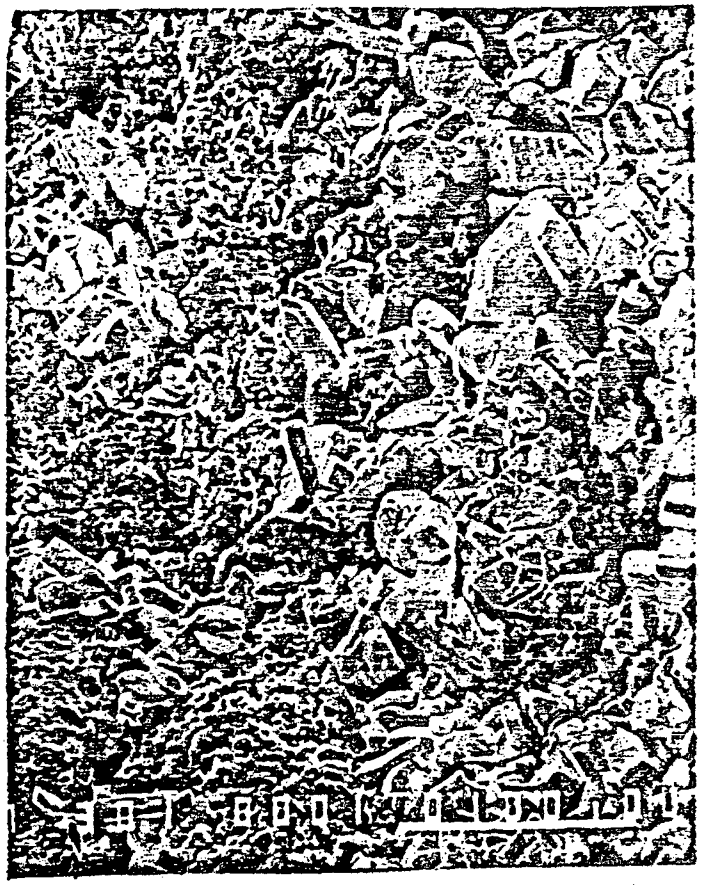


Figure 8a. SEM picture of crack surface, showing crystals grown from geothermal brine.

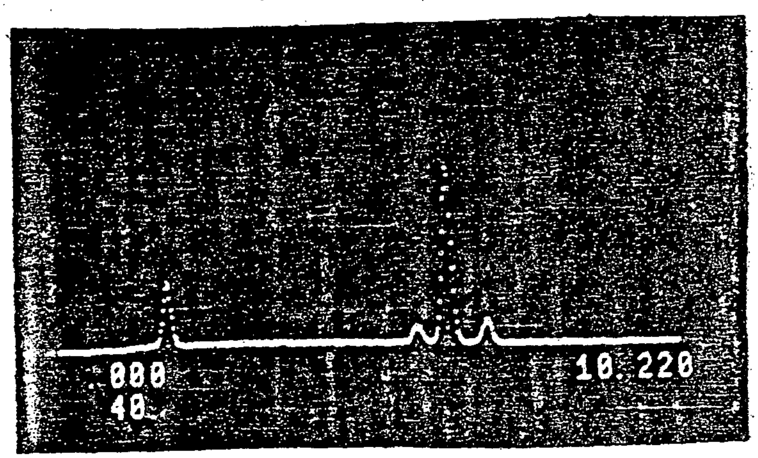


Figure 8b. EDAX of crystals.

Figure 9. SEM picture of fracture surface of secondary crack.

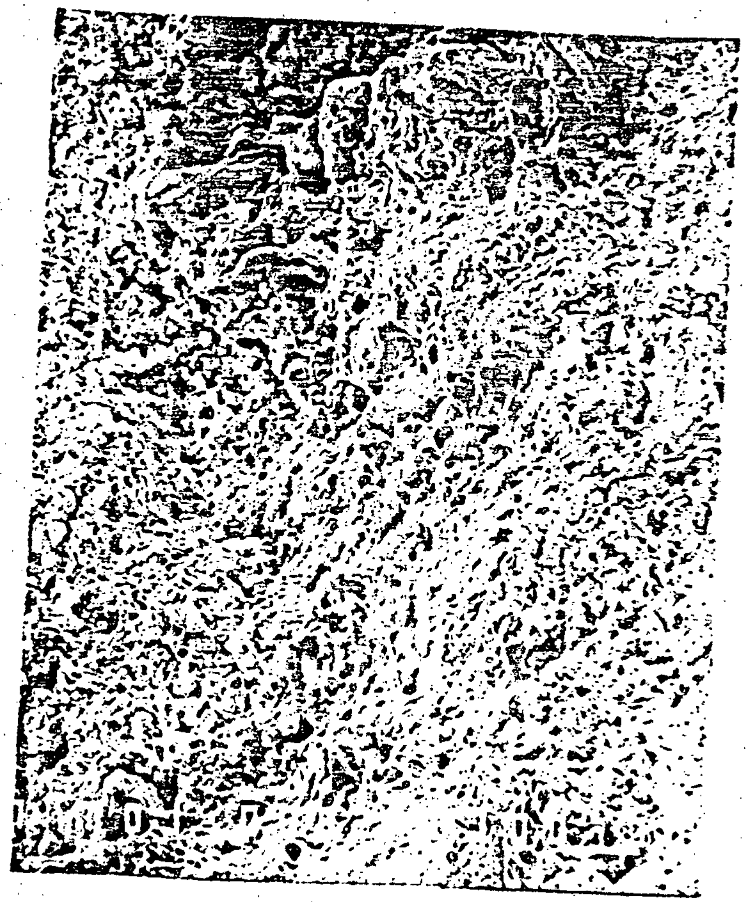


Figure 9a. SEM picture of fracture surface of secondary crack.

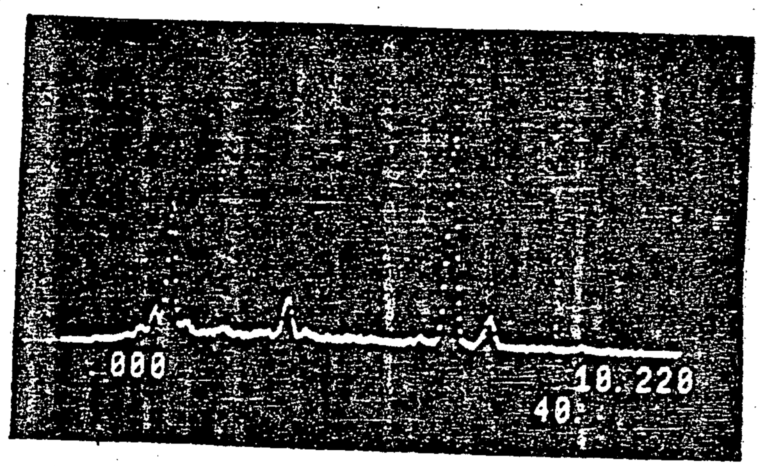


Figure 9b. EDAX of corrosion product.

Figure 10. Casing material

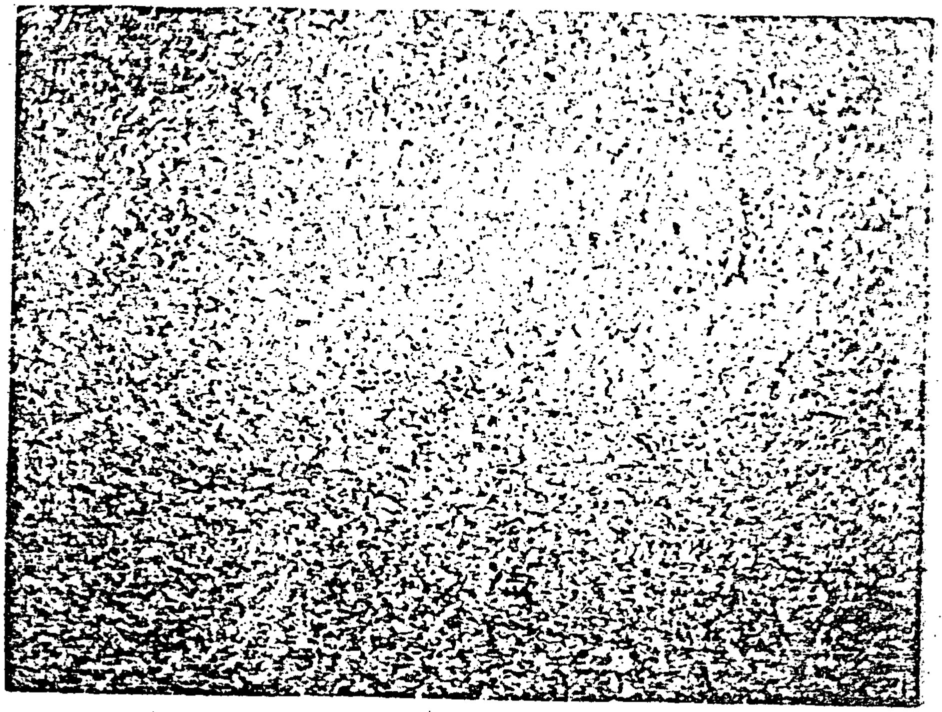


Figure 10a. Casing material 400 X 5% nital etched.

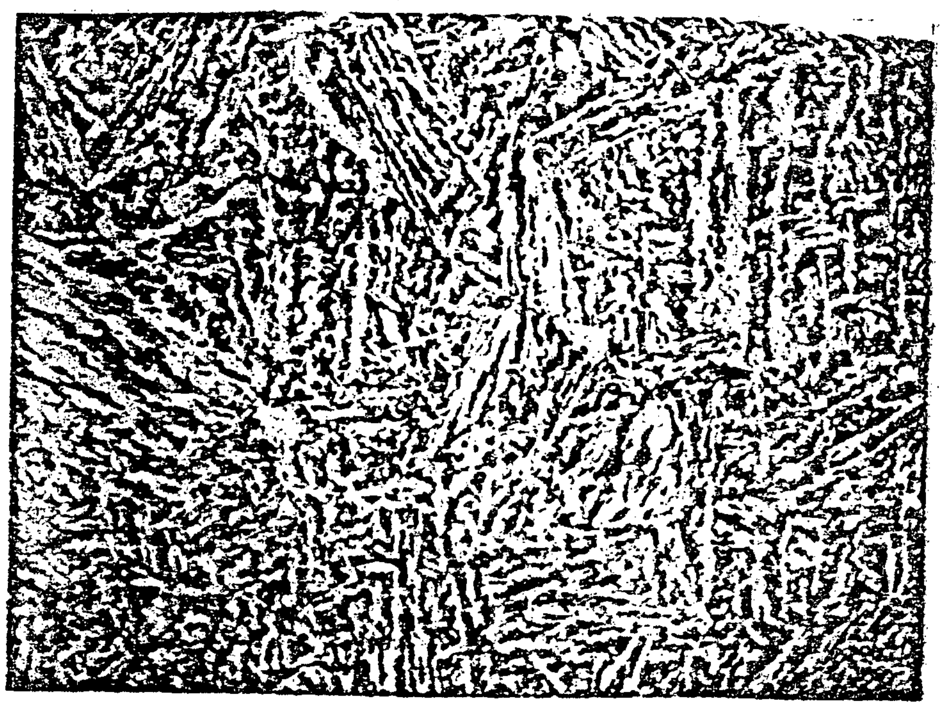


Figure 10b. Collar material 400 X 2% nital etched.

Figure 11. EDAX scan of casing alloy.

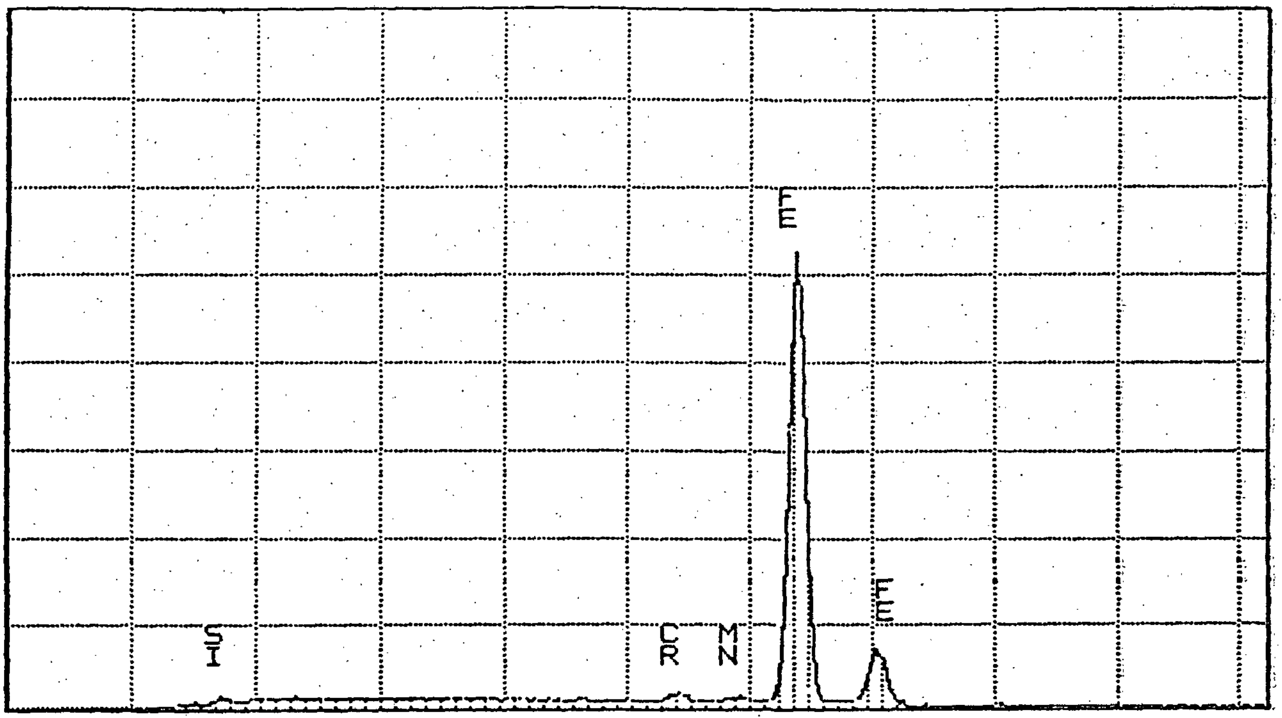


Figure 11a. EDAX scan of casing alloy.

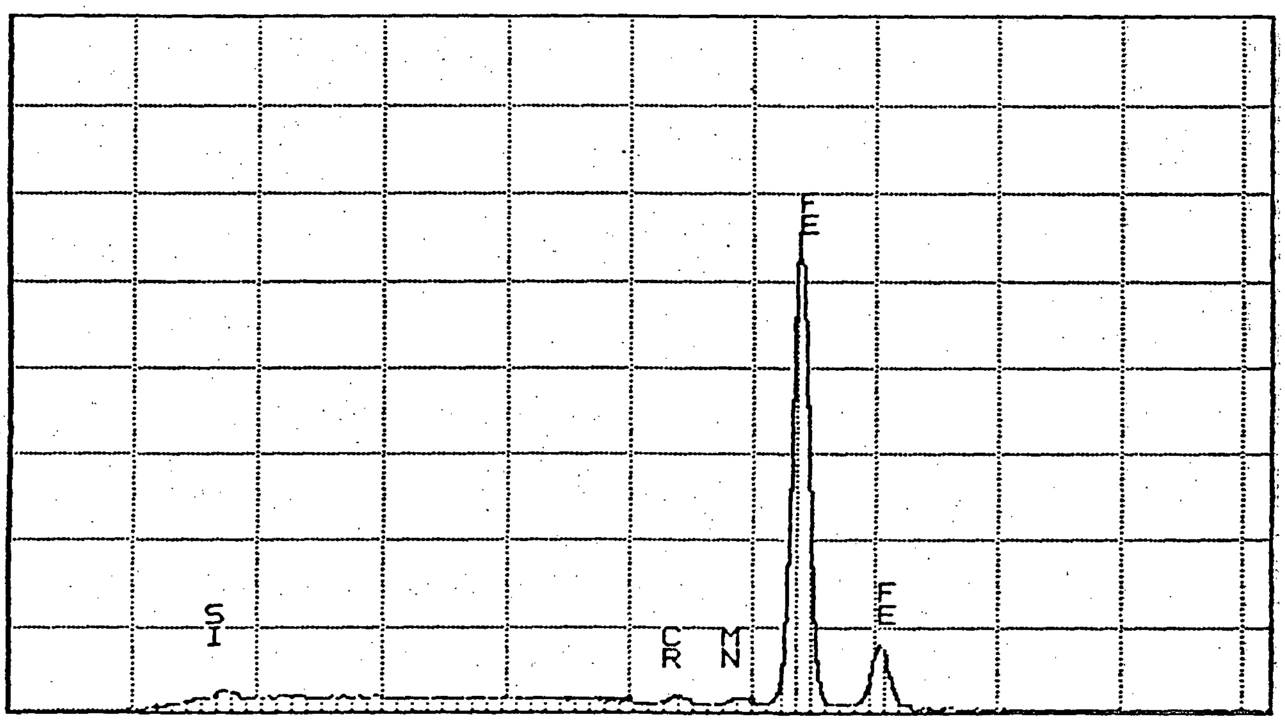


Figure 11b. EDAX scan of collar alloy.

Figure 12. Surface crack found near collar #1 or casing, 200 X, unetched.

Figure 12a. Surface crack found near collar #1 or casing, 200 X, unetched.

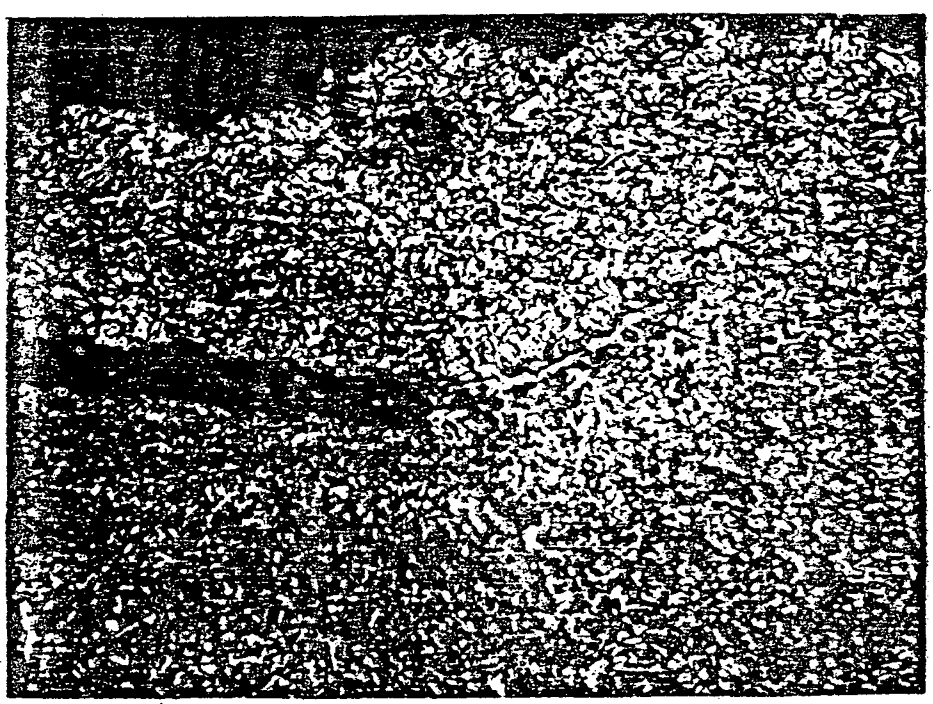


Figure 12b. Surface crack found near collar #1 or casing, 200 X, etched.

Bechtel National, Inc.
Engineers—Constructors

Fifty Beale Street
San Francisco, California
Mail Address: P.O Box 3965. San Francisco, CA 94119

25th August, 1986

Letter No. 16937-500- 287

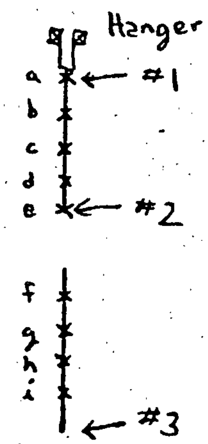
Mr. John Weeks
Building 703
Brookhaven National Laboratory
Upton, New York 11973

Subject: <u>Transmittal of 7" Collars/Pins</u>

Dear Mr. Weeks:

Information specific to the three pieces of casing transmitted to you via UPS, 8-21-86, include:

Sketch of recovered liner



X Collars

Material - 7", 29#/ft, L-80
Hanger @ approx. 5,730'
Liner separation
- collar @ #2
- pin @ #3
Damage to pin #3 was caused by falling 330' and impacting 7" liner at the bottom of the hole

Service - geothermal saline brine
Temperature - in excess of 400°F (less than 550°F)

If there are questions, please call me at (415) 768-9918.

Very truly yours,

DT Rabb

D. T. Rabb
Site Manager
Research and Development

DTR/jak

cc: C. A. Harper
H. Lechtenberg (DOE)

4123E

11565

United States Steel Corporation
01 000.0605 (REV. 10-82)

TUBULAR PRODUCTS
METALLURGICAL TEST REPORT

REQ., JOB., CONTRACT NO.	P.O. DATE	PURCHASE ORDER NO.
		S-0322460/U5

SHIPPERS NO.	MILL ORDER NO.	INVOICE NO.
	NJ 51270	

VEHICLE IDENTITY

This is to certify that the material described herein was manufactured, sampled, tested and/or inspected in accordance with the stated specification and fulfills specification requirements in such respects.

VENDOR SOLD TO: National

SHIP TO: Republic Supply Company of California

PREPARED BY THE OFFICE OF
E. L. Bartolotta, Manager
Tech. Service & Quality Assurance
National Plant
Date June 28, 1984

SPEC & INSP: Seamless Casing

Quench and Temper

7" 29# N-80 L T&C R/3

ITEM NO.	SIZE	WALL	SPECIFICATION & GRADE	MATL	HEAT/ LOT NO.	MIN. HYDRO. PSI	YIELD STR. PSI	TENSILE STR. PSI	ELONG. % IN 2"	GAGE WIDTH IN.	FLAT	BE
07	7"	.408"	API 5A 36th Edition N80 and Supp. 1	Smls.	L80994	7400	94940	113990	23.0	1½"		
					L81659	7400	93140	118630	23.5	1½"		
							END OF DATA					

ITEM NO	HEAT NO.	TYPE	C	MN	P	S	SI	CU	NI	CR	MO
	L80994	Prod	31	1 24	017	014	27				
		Prod	31	1 21	016	014	26				
		Heat	31	1 25	017	012	26				
	L81659	Prod	31	1 28	019	010	15				
		Prod	31	1 28	018	010	15				
		Heat	31	1 29	022	009	18				
				END OF	DATA						

PACIFIC INSPECTION COMPANY

INSPECTION SERVICES

p.c. x subj. Chrono reading

VENTURA
P.O. BOX 2084 ZIP 93001
(805) 643-4757

HUNTINGTON BEACH
P.O. BOX 2035 ZIP 92647
(714) 846-6133

BAKERSFIELD
P.O. BOX 9296 ZIP 93309
(805) 589-2111

1.18.9-D009
P622

INSPECTION REPORT OF TUBULAR GOODS

DATE 12-19-85

CUSTOMER Republic Supply

ORDERED BY MK Pryde

SERVICE ORDER NO. Po# 42-10510

WORK ORDER NO. 14319

LOCATION Pipeline Shafter CA.

WELL NAME & NO.

TYPE INSPECTION NEW CASING: Electrolog 4 API Thread, API Drift, Special END AREA.

INSPECTION SPECIFICATIONS

☑ As per API Standard # RP5A5 12.5% of Nominal wall thickness .051" Drift Diameter—API Standard 6.059"

☐ As per Customer Specification:

MATERIAL INSPECTED

75 Total Lengths NEW CASING " O.D. 7, 29 #, Grade N-80,

Range 3, .408" wall thickness, with L-T-C connections,

Mfg. USS

SUMMARY OF RESULTS

75 Lengths were found to be free of internal &/or external surface defects exceeding 12.5 % of nominal wall thickness.

These lengths are identified by White Paint Band and Pacific stencil near coupling or box end.

4 Defective couplings were found on above lengths. Identified by Red Paint Band.

____ Defective pins were found on above lengths. Identified by Red Paint Band.

____ Lengths were found with internal defect which could not be accurately measured. Identified by Blue Paint Band.

____ Defective couplings identified by Red Paint Band.

____ Defective pins identified by Red Paint Band.

____ Lengths contained defects exceeding 12.5 % of nominal wall thickness. Identified by Red Paint Band.

____ Defective couplings identified by Red Paint Band.

____ Defective pins identified by Red Paint Band.

____ Other Lengths

003911