DRILL STRING FAILURE ANALYSES

DISCLAIMER

THE COVER PICTURE

The fatigue crack (shown in 300X magnification) has originated at the exterior surface of the drill pipe and has propagated to a depth of .017 inch. Fatigue cracks, in combination with the ever present corrosion problem, have been the major cause of failure of the drill pipe during the history of the Deep Sea Drilling Project.

TECHNICAL REPORT NO. 14

DRILL STRING FAILURE ANALYSES

Prepared for the
NATIONAL SCIENCE FOUNDATION
National Ocean Sediment Coring Program
Under Contract C-482

by the

UNIVERSITY OF CALIFORNIA
Scripps Institution of Oceanography
Prime Contractor for the Project

November 1983

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INTRODUCTION

The Deep Sea Drilling Project (DSDP) became operational in August 1968 with the successful sea trials of the drillship GLOMAR CHALLENGER. The vessel's mission was to recover cores of sediments and basement rock from the deep ocean for scientific study. During the 15 years of exploration, a total penetration of 1,032,707 feet was accummulated in the course of drilling and coring 1072 holes at 614 sites. The deepest penetration beneath the sea floor was 5712 feet and the maximum penetration into basaltic crust was 3,543 feet. Wireline coring operations were undertaken with drill string lengths to 23,111 feet.

For this demanding work, the project employed drill strings of 5-inch, 19.5 lbs/ft, S-135 drill pipe with a minimum yield strength of 135,000 psi. A 4-inch minimum bore provided for high speed wireline coring and high loads could be carried within the drill pipe's 712,000 pound minimum yield load. Normal design loads were at 90% of minimum load.

During the 15 years of deep water operation, the high drill string loads, vessel positioning losses, hard seafloors and a corrosive environment have all contributed to a number of major drill string losses. Technical Report No. 14 is a summary and analysis of these drill string and bottom hole assembly failures. Operating practices and means of failure reduction are also discussed. Copies of formal metallurgical failure analyses by U. S. Steel Research and Battelle Houston Operations are included in the appendix.

ACKNOWLEDGEMENTS

Technical Report No. 14 contains analyses of major drill string failures incurred during 15 years of Deep Sea Drilling Project (DSDP) wireline coring operations. Operating experience and means to reduce such losses is also described. This operational experience and failure analyses should be of interest to other operators in designing for similar deep water work.

The Project acknowledges the prompt and thorough failure analyses provided, under contract, by U. S. Steel Research and Battelle Houston Operations.

This report was prepared by Mr. Don Bellows, Senior Design Engineer with the Project's Development Engineering Department.

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I. OPERATING CONDITIONS

Figure 1 shows, schematically, the configuration of a typical drill string used in the Deep Sea Drilling Project (DSDP). The string varies in length dependent upon water depth and depth drilled below the sea floor. The longest 5-inch drill string deployed thus far has reached 23,111 feet. The drill pipe material is S-135 steel. Some mechanical and chemical properties of this steel are given in Table I.

The most highly stressed region in the string is at the upper end. The weight of the string, as much as 450,000 pounds in water, produces a high static axial stress. The heave motion of the ship produces a dynamic axial stress, which usually is relatively low, but which near resonance of the string can reach three times its normal value. A bending load, caused by the pitch and roll of the ship, is imposed on the drill string as it passes thru the guide shoe. A typical bending stress pattern, as obtained from a strain gaged section of drill pipe, is shown in Figure 2. The envelope of the record corresponds to the pitch or roll of the ship, whereas the individual cycles correspond to the rotation of the drill string as it is lowered thru the guide shoe. The periods of zero stress represent the time when the pipe is not bent, but is swinging from one side of the guide shoe to the other. While the drill string is being rotated, the torsion is closely monitored to prevent a twist-off of the pipe.

For a 21,000 foot long, 5-inch drill string, the static axial stress is on the order of 80,000 psi. The dynamic axial stress is about 8,000 psi and the bending stress is approximately 25,000 psi. The total load is monitored during drilling operations to insure that the load does not continuously exceed the design limit of 90% of the yield strength. Stress levels are increased when re-entry cones or casing is lowered on the drill string. The submerged re-entry cone becomes a large intertial mass responding to vessel heave motion during lowering. Drill string stresses are also increased when drill pipe is used to lower long casing strings into boreholes. The additional static loads due to casing have reached 80,000 pounds during such operations. This load is equivalent to the weight of 4,300 feet of 5 1/2-inch drill pipe.

Normally the point of highest stress and vulnerability is at the top of the drill string. However, under certain conditions, the bottom of the string can also be severely stressed. The bottom hole assembly (BHA) or drill pipe can be buckled during attempts to start hole on a hard bottom without lateral support. During drilling, the drill pipe immediately above the drill collars can be buckled if the drill pipe is not kept in tension, or if there is insufficient bumper sub stroke to compensate for drill string vertical oscillation. Losses of dynamic positioning during drilling pose an additional risk to drill pipe. With dynamic

positioning lost, even for a brief period, the vessel can drift off location, bending the drill string at the sea bottom. The conditions described above have resulted in losses of drill pipe and bottom hole assemblies.

Corrosion is also a factor which has a bearing on the magnitude of stress in the drill pipe. While drilling into the ocean bottom, seawater is pumped down the string and out of the bit to flush cuttings out of the hole. This flow of water in the string erodes the inner diameter of the pipe. Also, since the water is taken from the surface, it is rich in oxygen which sets up the conditions for oxygen concentration cells on the inside surface of the pipe. The effects of corrosion and fatigue "feed on each other". A corrosion pit is frequently the initiation point for a fatigue crack. Then corrosion proceeds into the crack, further weakening that area and causing the crack to propagate at a faster rate than it would without the corrosive seawater environment. Many of the failures have resulted from fatigue cracks which have originated at erosion/corrosion pits on the inside of the pipe. Figure 3 shows a typical case of corrosion on the interior surface of the pipe. In 1977, an independent inspection was conducted by a corrosion consultant on approximately 12 joints of the drill pipe which had been coated internally with an inorganic zinc compound and had been in service for 12 months. The inspection showed the internally coated pipe to have significantly lower corrosion as compared to uncoated pipe. Based upon these findings, the 1978 purchase of drill pipe included coating on both the interior and exterior surfaces with inorganic zinc. Previous to this, only the exterior of the pipe had been coated with the zinc.

II   DRILL PIPE FAILURE MODES

The failures of the 5-inch drill pipe are summarized below.

Leg	Point of Failure	Cause of Failure	Losses Drill Pipe & BHA (m)
4	5-in drill pipe box at elevator.	Lifting bails engaged on one side of elevator only, elevator tilted on lift.	4541
36	2 joints from top	Pipe bent at keel, excessive roll in current and 17 foot swell.	3558
48	Pup joint thread	Corrosion fatigue	5056
53	23 joints above BHA	Corrosion fatigue	210
83	39 joints above BHA	Corrosion fatigue	357
84	18 joints from top	Mill inclusion defect in new pipe.	5765
93	Top of drill string (Kelly Cock sub)	Brittle fracture, low toughness.	6219

Table A-1 in Appendix A lists the major drill pipe failures that have occurred during the course of the Project. Details of the seven pipe failures and the results of the failure analyses are described on the following pages. Complete reports, including metallurgical analyses, for the failures on Legs 48, 53, 83, 84, and 93, are contained in Appendices B-1 through B-5, respectively. A formal report is also included for a bottom hole assembly loss on one Leg 88 (Appendix C).

Specification RP-7G of the American Petroleum Institute (API) states the conditions for inspection and classification of drill pipe. Some of the items mentioned are wear, fatigue cracks, cuts, gouges, and corrosion on the exterior and corrosive pitting, erosion, wear, and fatigue cracks on the interior. From the experience to date on the Project it appears that the exterior condition of the pipe is seldom the cause of a failure, except in the case of material defects. The principal cause of failure of the drill pipe has been corrosion fatigue which originates on the interior and propagates through the pipe wall.

Failure Statistics

Date of Failure:	2/8/69
Water Depth (m):	5149
Total Depth (m):	above mud line
Failure Depth (m):	at the derrick floor
Equipment Lost:	4541 m of drill pipe + BHA

Results of Analysis

1. One of the bails on the travelling block failed to fully engage in position in the elevator during a trip out of the hole. As a result, the other bail took the full weight of the string breaking the pipe in the elevator.

Corrective Action Taken

1. Insure full elevator/bail engagement before picking up pipe.

LEG 36 — HOLE 326

Failure Statistics

Date of Failure: 4/6/74
Water Depth (m):   3822
Total Depth (m):   3831
Failure Depth (m):   18
Equipment Lost: 3558 m drill pipe + BHA

Results of Analysis

1. The drill pipe failure was caused by the sharp bending of the drill string beyond the limits of the restraining member (guide shoe) as the ship rolled in response to the severe weather conditions in the Antarctic.

Corrective Action Taken

Established the following operational limits:

1. Drill pipe shall not be run when anticipated sea conditions will cause the ship to pitch and/or roll in excess of 7 degrees single amplitude.*

2. Drilling operations, including running of drill pipe, may continue on the basis of a maximum pitch and/or roll of 7 degrees single amplitude.*

3. The drill string shall be pulled if occasional pitch and/or roll exceeds 9 degrees single amplitude.

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*Limitation is 5 degrees for drill strings in excess of 6860 m. A more complete description of severe weather operational limits and procedures is contained in Appendix E.

Failure Statistics

Date of Failure: 6/3/76
Water Depth (m):   4399
Total Depth (m):   5176
Failure Depth (m):   above rig floor in pup joint
Equipment Lost: 5056 m drill pipe + BHA

Results of Failure Analysis by U.S. Steel

1. Fracture was initiated by corrosion fatigue in root of pup joint thread.

2. Chemical composition of failed pup joint corresponded to that specified for AISI 4150 steel.

3. Mechanical properties of failed joint were within those specified for AISI 4150 steel.

Corrective Action Taken

1. Procedure was set up for frequent inspections of pup joint threads using flourescent magnetic particle examination. Any joints showing cracks in threads are removed from service.

LEG 53 - HOLE 418A

Failure Statistics

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Date of Failure:    4/6/77
Water Depth (m):    5519
Total Depth (m):    5816
Failure Depth (m):  5519
Equipment Lost:     210 m drill pipe + BHA
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Results of Failure Analysis by U. S. Steel

1. Fracture was result of corrosion fatigue initiated
    on external surface of pipe.

2. Chemical composition of failed pipe corresponded to
    that given in API Specification 5AX.

3. Mechanical properties of failed pipe were within those
    given in API Specification 5AX.

Corrective Action Taken

1. A policy was established whereby only premium class
    drill pipe was to be used in any further drilling
    operations. The Project has followed this policy.

2. The interval for periodic inspection of the drill pipe
    was set at 4 to 6 months.

LEG 83 - HOLE 504B

Failure Statistics

Date of Failure:	11/29/81
Water Depth (m):	3473
Total Depth (m):	4535, 4763
Failure Depth (m):	4033, 4543
Equipment Lost:	357 m drill pipe + BHA (first failure)
	100 m drill pipe + BHA (second failure)

Results of Failure Analysis by Battelle

1. Failure was due to corrosion fatigue.

2. Fatigue cracks originated at deep broad corrosion pits on inside surface of pipe.

3. Mechanical properties of drill pipe met API Specification 5AX.

4. Chemical composition of drill pipe met API Specification 5AX.

5. Basic cause of failures was inability of internal inspection system to detect advanced corrosion damage on interior surface of drill pipe.

Corrective Action Taken

1. All suspect pipe (588 joints) was removed from ship and inspected by External Sonoscope and ultrasonic wall thickness measuring instruments.

LEG 84 - HOLE 567A

Failure Statistics

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Date of Failure:     2/7/82
Water Depth (m):     5529
Total Depth (m):     6030
Failure Depth (m):   165
Equipment Lost:      5765 m drill pipe + BHA
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Results of Failure Analysis by Battelle

1. Lap defect, at fracture point, probably produced during tube rolling operation, and which was rejectable according to API Specification 5AX.

2. Yield strength of 170,800 psi was higher than that allowed (165,000 psi) in API Specification 5AX.

3. Hydrogen embrittlement was contributing factor in failure, especially since yield strength was higher than allowed.

Corrective Action Taken

1. Hardness of Rc 38.5 corresponds to yield strength of 165,000 psi. Joints of pipe with hardness in excess of Rc 38 were removed from service.

LEG 93 - HOLE 603B

Failure Statistics

Date of Failure:	6/1/83
Water of Depth (m)	4644
Total Depth (m):	6229
Failure Depth (m):	at rig floor
Equipment Lost:	6219 m drill pipe + BHA

Results of Failure Analysis by Battelle

1. Kelly Cock sub failed by brittle fracture initiated at fatigue cracks which began at corrosion pits in the root of the last engaged thread.

2. Thoughness of Kelly Cock sub was low due to presence of mixed microstructure.

Corrective Action Taken

1. Recommendation from Battelle is to specify a tougher material such as quenched and tempered 4340 steel for replacement subs. Also, there should be a programmed replacement of the sub, say every five years.

III. BOTTOM HOLE ASSEMBLY FAILURE MODES

A schematic representation of a typical bottom hole assembly (BHA) is shown in Figure 4. A detailed listing of the failures in, or near, the BHA is given in Table A-2 of Appendix A. Comparison with Table A-1 reveals that the vast majority of the failures have occurred at the BHA. Although the top of the drill string is the most highly stressed region during normal operations, the bottom of the string is also vulnerable to damage since the driller must be guided only by the weight indicator reading which fluctuates irregularly by 50,000 to 100,000 pounds. The drill string must always be kept in tension--if it goes into compression it is susceptible to buckling which can produce damaging stresses. The driller must carefully monitor the weight on bottom to insure that buckling does not take place. This becomes especially critical when spudding in (starting a hole) on a hard bottom where the sediment cover is not thick enough to give lateral support to the 400-foot long BHA.

Once the drill string has been deployed and drilling into the bottom has started, the ship must maintain position over the site until the string is pulled out of the hole. The ship's dynamic positioning system is computer controlled and can maintain a watch circle of 50-60 feet diameter when operating in water depths up to 20,000 feet. If the ship loses dynamic positioning capability and drifts off site while the drill string is in the hole, the string may be subjected to excessive bending stresses at the mudline. Table A-2 indicates that this has happened several times resulting in the loss of part or all of the BHA.

The bumper subs are heave compensating telescoping joints interspersed among the drill collars in the BHA. They prevent the heave motion of the ship from being transmitted to the drill bit. Without the bumper subs (or some other heave compensating device) the bit would be alternately lifted off the bottom of the hole, then slammed into the bottom. Figure 5 shows a fully stroked out bumper sub which is slightly bent as a result of overstressing. The drill collars are thick wall weight members--therefore, the bumper subs are the weak link in the BHA. This is evident from the number of bumper sub failures listed in Table A-2.

During the early years of the Project, failures in the BHA were quite common. However, as experience was gained and improvements made, the frequency of BHA failures decreased. One such improvement was a transition from 6-5/8 API regular threads to 6-5/8 API full hole modified threads.

IV FAILURE PREVENTION - INSPECTION AND OPERATIONAL PRACTICE

Various methods are used to inspect the drill pipe and determine its suitability for continued service. Visual inspection of the exterior will detect any obvious problems such as cuts, gouges, and corrosion pitting. A visual inspection of the interior must be done with a borescope, an optical device which can be passed through the bore. Wall thickness and uniformity are measured with an ultrasonic thickness gage which passes sound waves through the wall of the pipe and measures the time interval for the waves to be reflected from the interior steel-air interface. Cracks caused by fatigue or overstressing, even though imperceptible to the unaided eye, may be revealed by magnetic flux leakage inspection. It is the practice of DSDP to perform a complete pipe inspection using these methods at intervals of four months. The BHA is inspected at intervals of two months. Tool joints are inspected at four month intervals. The shoulder diameter is measured with a micrometer gage. Gages are also used to determine the swell of the box (female threaded section) and the stretch of the pin (male threaded section). Profile gages show any discrepancy in the thread profile.

API specification RP-7G provides the criteria for classifying the drill pipe as a result of an inspection. The classes starting with the best are:

Class 1	New
Premium Class	80% wall
Class 2	65% wall
Class 3	=55% wall
Class 4	<55% wall

At the present time DSDP normally uses nothing lower than premium class drill pipe in its operations. The inspection of the drill pipe on board the ship is usually conducted with the pipe in the mechanized racker. Consideration should be given to an annual inspection where the pipe is racked out on the dock for a more complete inspection.

Analytical and computer studies have been made which indicate that various options may be used to obtain long drill strings and maintain stresses within a safe level. One option is to use a tapered drill string, i.e., made up of larger diameter pipe at the top tapering to smaller diameter pipe at the bottom. Another option is a mixed string using pipe of different materials, e.g., steel and aluminum.

As previously stated, the drill pipe experiences bending stresses due to pitch and roll of the ship while rotating the drill string. One way of restricting the severity of the bending is the use of rubber spacers installed at intervals along the drill string. This lowers the bending stress from about 100,000 psi to approximately 25,000 psi for a 20,000 foot, 5-inch diameter steel

string. Another way of reducing stress in the critical guide shoe area is the use of heavy wall drill pipe. The pipe is 5.5-inch diameter with 7-3/4 inch diameter knobs at intervals of about 5-feet machined integrally as part of the pipe. Operating procedures call for the use of these "knobbies" under certain conditions of drill string length, rate of penetration, and pitch and roll angle of the ship (see Appendix D). The knobbie is used in the guide shoe. The knobs produce the same effect as the rubber spacers on the regular drill pipe, i.e., they cause a reduction of the bending stress. The larger cross sectional area associated with the 5.5 inch diameter produces a decrease in the static stress.

It is important that the drill string components be inspected after regular intervals of use. It is equally important that new pipe be inspected to determine if it is adequate for service. New pipe is inspected by the quality control group at the manufacturer's plant. The Project also conducts its own inspection of new pipe before taking delivery. The items that are considered in this type of non-destructive inspection are:

1) Seams, overlaps
2) Rolled-in slugs (or pits resulting from same)
3) Cracks
4) Eccentricity
5) Hardness and hardness variations
6) Threads - gaging for fit, checking for cracks
7) Wall thickness spot testing
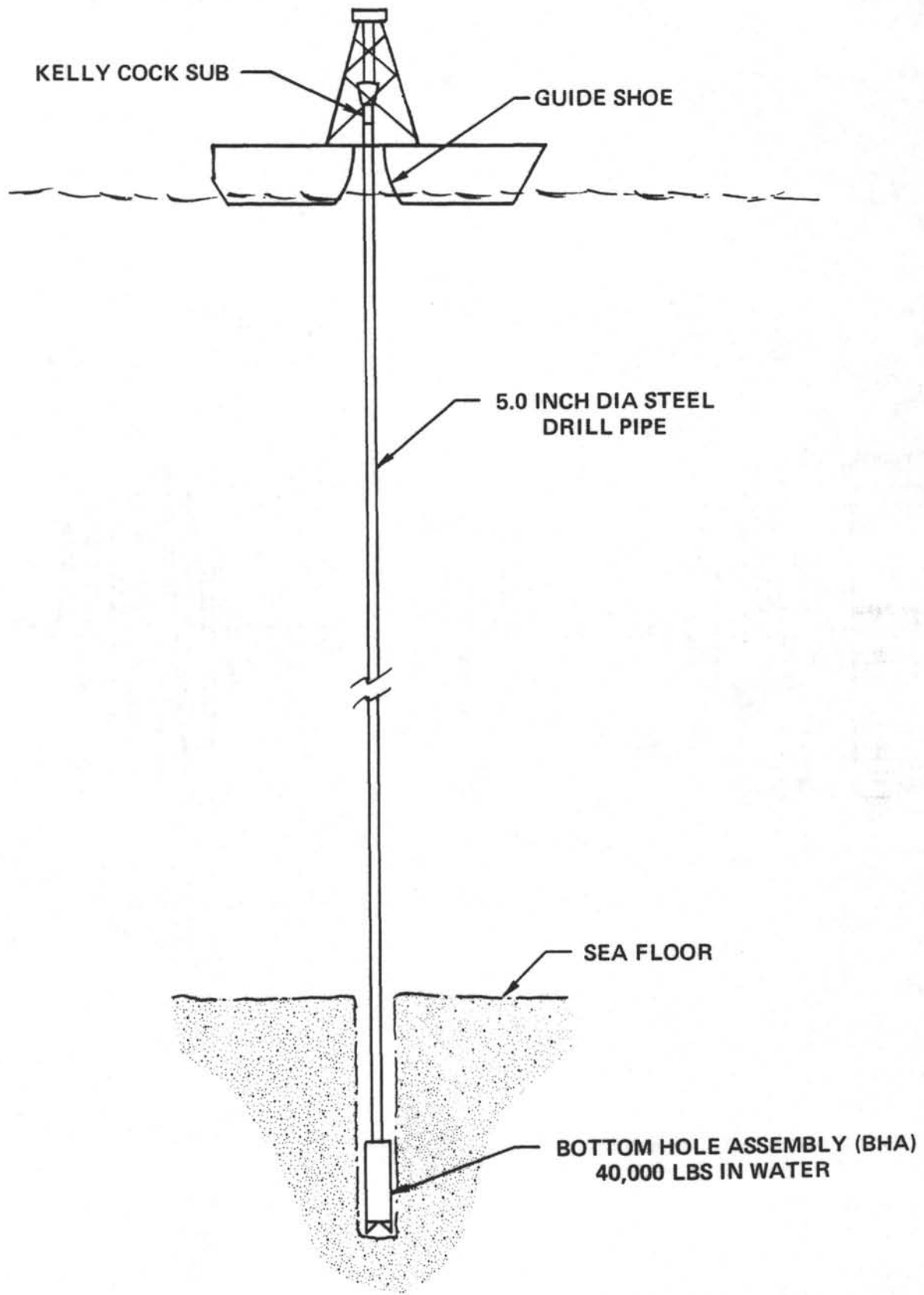8) Drifting to check bore

The same methods as mentioned for inspection of used pipe are also utilized to inspect new pipe. Appendix E is a report by Battelle giving complete mechanical and metallurgical properties of the most recent order of new pipe which was put on board in September of 1982.
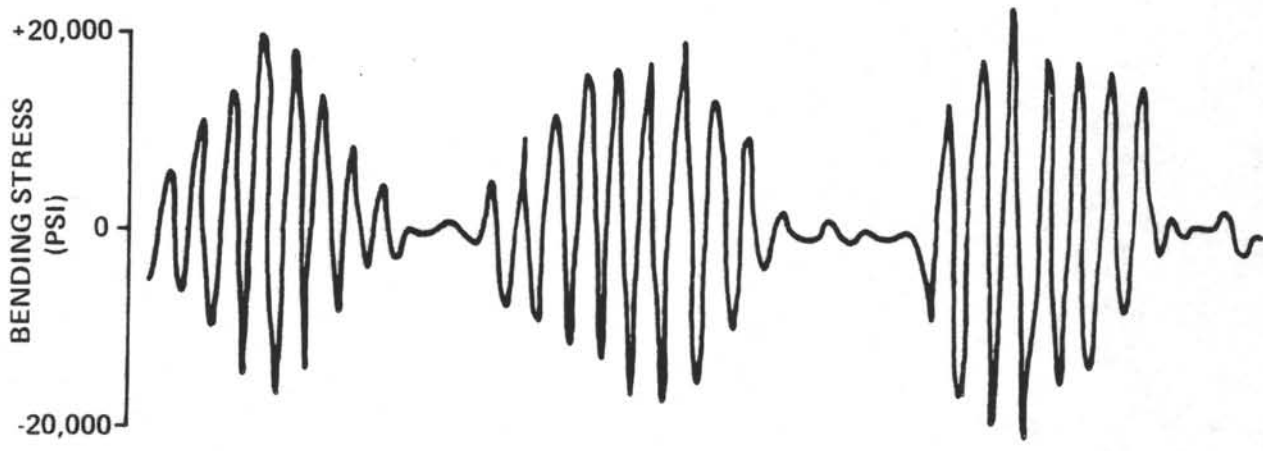
V. CONCLUSION

Coring operations in deep oceanic basins may present increased risk of drill string loss due to high stresses coupled with adverse weather, current, and drilling conditions. The risk of failure can be reduced through operational and inspection procedures. DSDP precautions against loss include the following:

1. The use of special 5-1/2 inch heavy wall drilling joints at the top of the string. The joints are used when drilling rates are less than 16 feet per hour or for very long drill string deployments. Integral 7-3/4 inch O.D. hubs at 5-foot spacing insure a smooth radius as the drilling joint bears against the 350-foot radius bending restraint during the vessel's roll/pitch motion.

2. Programmed replacement of heavy wall drilling joints and pup joints at the upper end of the drill string.

3. A minimum of 100 meters of soft sediment is normally required for lateral support of the bottom hole assembly.

4. Vessel roll/pitch motion limits have been set to prevent excessive pipe bending in the moon pool area.

5. Normally, only premium grade pipe is to be in the drill string (Class 2 pipe is used lower in the string if insufficient premium pipe is aboard).

6. All drill collars and subs that make up the BHA are to be inspected by magnetic particle methods at two month intervals. The top pup joint is to be magnafluxed at least once each month and pin connection recut after six months. After an additional six months, the top pup joint is retired.

7. The drill pipe is to be inspected at four month intervals using an internal sonde magnetic flux leakage device, borescope, and ultrasonic methods.

8. In addition to the vendor's mill inspection of new pipe, the Project will also have a third party inspection made prior to acceptance.
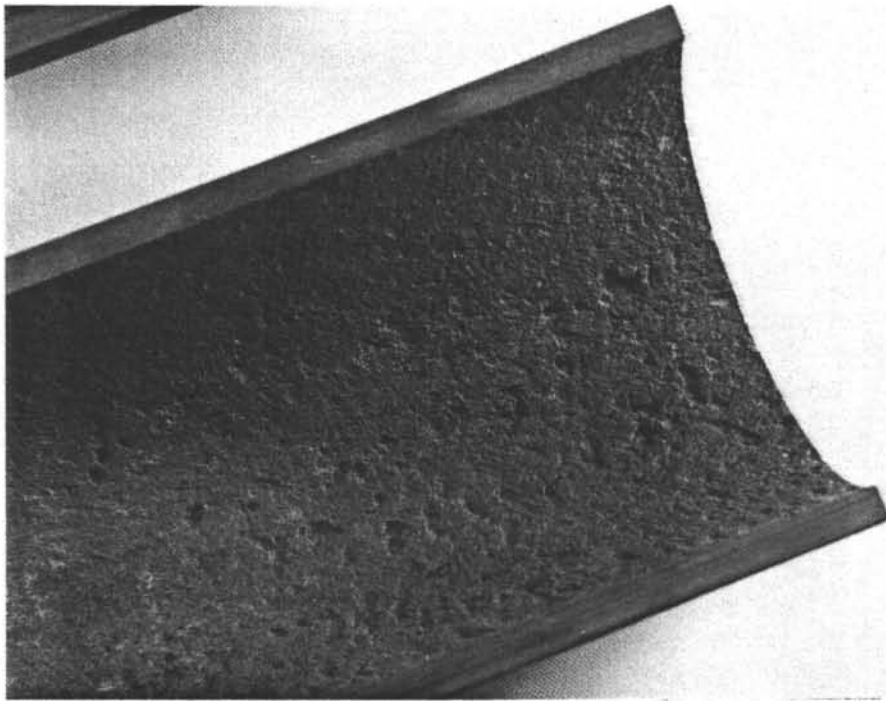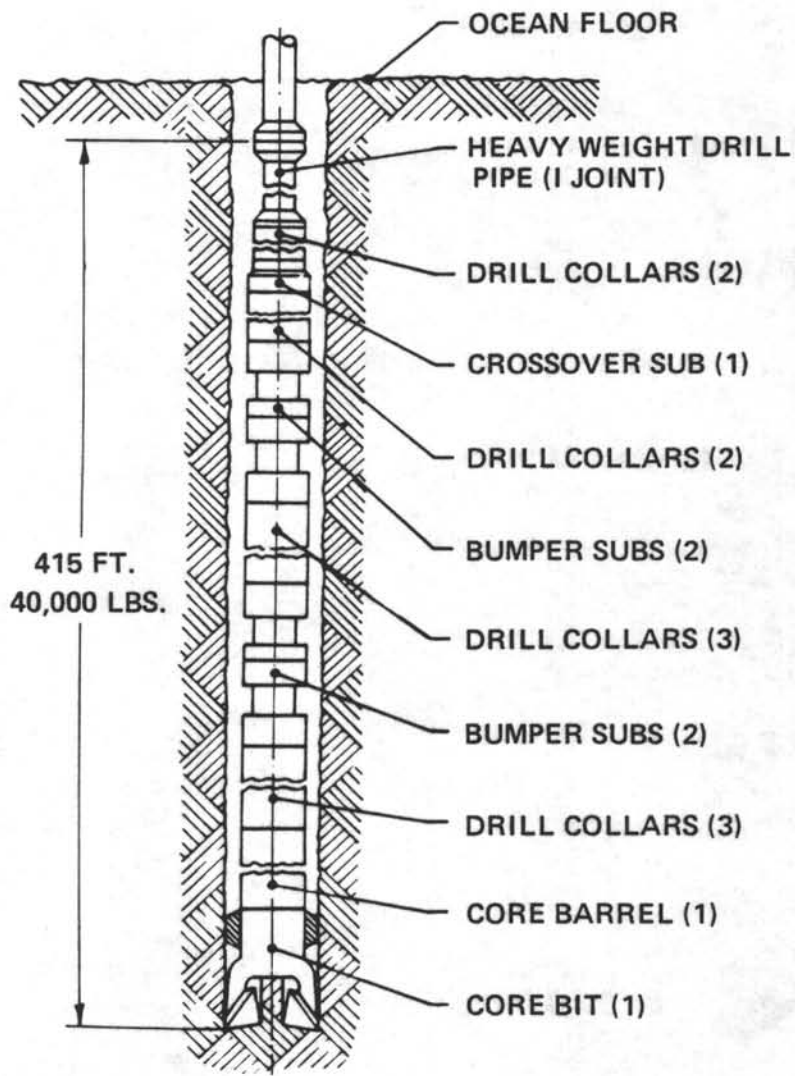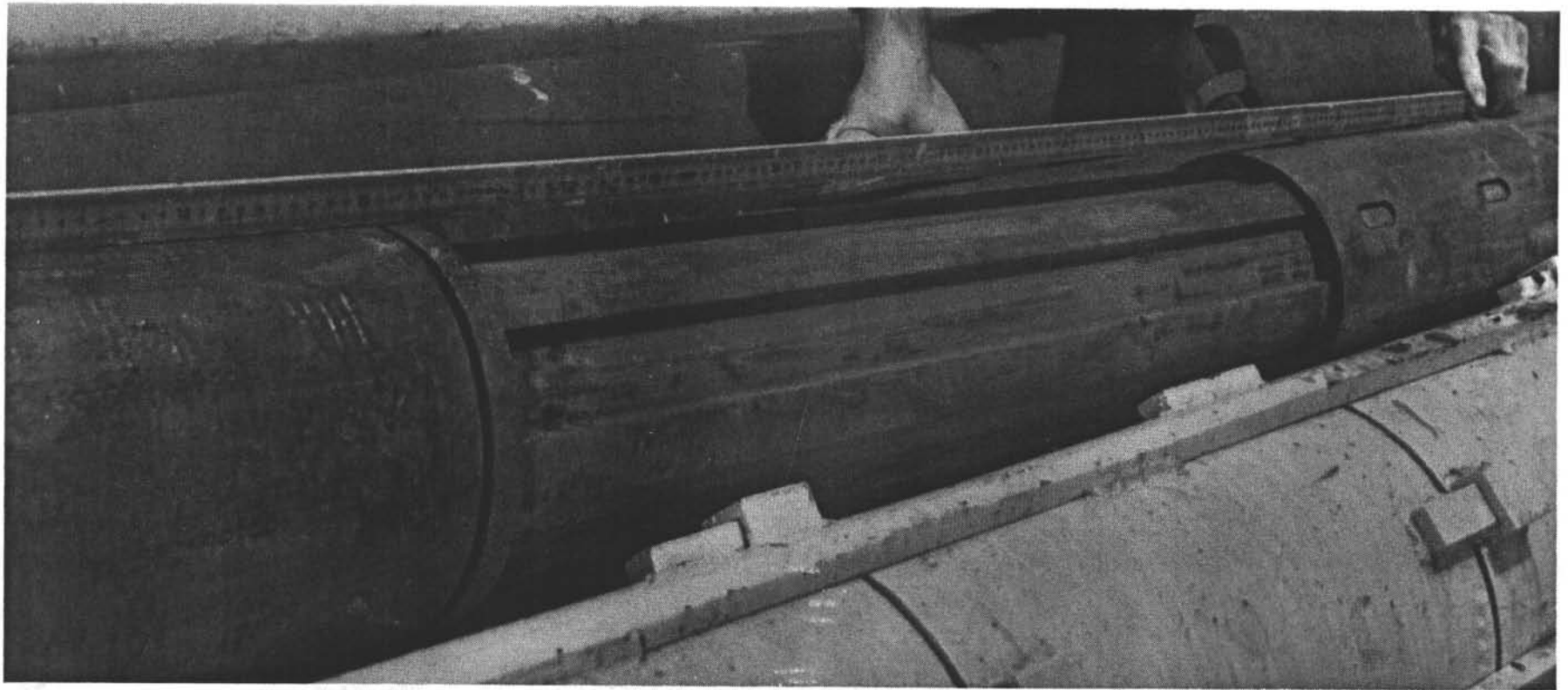
KELLY COCK SUB

GUIDE SHOE

5.0 INCH DIA STEEL
DRILL PIPE

SEA FLOOR

BOTTOM HOLE ASSEMBLY (BHA)
40,000 LBS IN WATER

CONFIGURATION OF DRILL STRING

FIGURE 1

15

BENDING STRESS IN DRILL PIPE
FIGURE 2

CORROSION ON INTERIOR SURFACE OF DRILL PIPE
FIGURE 3

OCEAN FLOOR

HEAVY WEIGHT DRILL
PIPE (I JOINT)

DRILL COLLARS (2)

CROSSOVER SUB (1)

DRILL COLLARS (2)

BUMPER SUBS (2)

DRILL COLLARS (3)

BUMPER SUBS (2)

DRILL COLLARS (3)

CORE BARREL (1)

CORE BIT (1)

415 FT.
40,000 LBS.

TYPICAL BOTTOM HOLE ASSEMBLY (BHA)
FIGURE 4

BUMPER SUB IN FULLY STROKED OUT CONDITION
FIGURE 5

TABLE I - PROPERTIES OF S-135 STEEL

Ultimate Strength (psi)	150,000
Yield Strength (psi)	135,000
Hardness (Rc)	38
Charpy Impact (ft-lb)	
73 F	40
32 F	30
Carbon (%)	.25
Manganese (%)	1.50
Silicon (%)	.25
Molybdenum (%)	.55

APPENDIX A

FAILURES OF DRILL PIPE AND BOTTOM HOLE ASSEMBLIES

TABLE A-1 MAJOR DRILL PIPE FAILURES

Leg	Site	Hole	Water Depth (m)	BSF (m)	Total Depth (m)	Location of Failure	Remarks
4	24	24	5149	0	4541	Box at Elevator	Lost 496 Jts + BHA
36	326	326	3822	9	3831	2 jts from top	Lost 389 jts + BHA
48	400	400A	4399	777	5176	Pup Joint	Lost 553 jts + BHA
53	418	418A	5519	297	5816	23 jts above BHA	Lost 23 jts + BHA
83	504	504B	3473	226	4535	5" D.P.	Lost 39 jts + BHA
83	504	504B	3473	451	4763	5" D.P.	Lost 11 jts + BHA
84	567	567A	5529	501	6030	18 jts from top	Lost 630 jts + BHA
93	603	603B	4644	1585	6229	Kelly Cock	Lost 680 jts + BHA

BSF   -   Below Sea Floor
D.P.   -   Drill Pipe
Jts   -   Joints (30 feet long)
BHA   -   Bottom Hole Assembly
Kelly Cock -   Valve at upper end of drill string

TABLE A-2 FAILURES IN BOTTOM HOLE ASSEMBLIES

Leg	Site	Hole	Date	Water Depth (m)	BSF (m)	Total Depth (m)	Location of Failure	Remarks
2	12	12	12/18/68	4555	35	4590	D.C.Tool Jt	Lost Posit-ioning
3	20	20	01/12/69	4500	44	4544	Top Sub-B.S.	
4	24	24A	02/08/69	5175	559	5734	Top Sub-B.S.	
4	25	25A	02/11/69	1939	66	2005	Top Sub-B.S.	
4	26	26	02/15/69	5198	9	5207	D.C.Tool Jt.	
5	35	35	05/03/69	3283	390	3673	B.S.Tool Jt.	
6	44	44	06/14/69	1483	82	1565	D.C.Tool Jt.	
6	45	45	06/19/69	5522	31	5553	B.S.Tool Jt.	
6	45	45A	06/22/69	5522	104	5626	Just above BHA	No.B.S.in string
6	46	46	06/25/69	5783	21	5804	D.C.Tool Jt.	
8	68	68	10/11/69	5481	24	5505	D.C.Tool Jt.	Little sedi-ment cover
9	76	76	12/09/69	4601	27	4628	D.C.Tool Jt.	Little sedi-ment cover
10	93	93	03/02/70	973	6	679	B.S.Tool Jt.	
10	93	93	03/20/70	973	6	979	B.S.Tool Jt.	
10	93	93A	03/21/70	969	2	971	B.S.Tool Jt.	
11	100	100	04/24/70	5331	335	5666	B.S.Tool Jt.	
14	143	143C	11/22/70	3517	43	3560	D.C.Tool Jt.	
17	168	168	05/07/71	5430	75	5505	B.S.	B.S.backed off
18	176	176	06/22/71	197	36	233	B.S.Tool Jt.	Ship 150' off site
18	177	177A	06/22/71	2013	467	2480	B.S.	Lock nut backed off bottom
23	226	226	04/18/72	2208	14	2222	B.S.Tool Jt.	
25	244	244	07/29/72	3847	27	3874	BHA	
29	275	275	03/07/73	2837	62	2899	B.S.	
29	280	280	03/27/73	4191	42	4233	BHA	D.C.Backoff
30	285	285	04/30/73	4674	102	4776	B.S.	
31	298	298A	07/23/73	4628	129	4757	D.C.Tool Jt	Ship 2500' off site
32	309	309	09/18/73	1470	12	1482	B.S.	
32	311	311	09/25/73	5280	46	5326	B.S.Tool Jt.	
33	315	315	11/14/73	4164	85	4249	B.S.	
34	321	321	01/30/74	4827	134	4961	Just above BHA	
45	395	395A	12/19/75	4485	0	4485	B.S.	Ran into bottom
51B	417	417C	12/29/26	5489	26	5515	B.S.Tool Jt.	
52	417	417D	03/05/77	5489	176	5665	Just above BHA	
55	431	431	08/06/77	1714	19	1733	B.S.	

Leg	Site	Hole	Date	Water Depth (m)	BSF (m)	Total Depth (m)	Location of Failure	Remarks
55	431	431A	08/07/77	1713	26	.1739	B.S.	
55	432	432	08/08/77	1320	15	1335	B.S.	
55	432	432A	08/09/77	1320	74	1394	B.S.Tool Jt.	Working stuck pipe
60	452	452	03/25/78	5838	28	5866	D.C.Tool Jt.	Ran into bottom
65	483	483B	03/02/79	3084	267	3351	Pin-Head Sub	
65	484	484A	03/04/79	2906	62	2968	Top-Head Subs	Backed off
77	535	535	01/07/81	3455	714	4169	Just above BHA	
78A	541	541	02/14/81	4961	0	4961	Top-Head Subs	
87A	582	582	06/29/82	4892	39	4931	Top-Head Subs	Ship 900' off site
88	581	581A	08/25/82	5490	380	5870	Just above BHA	
93	603	6038	05/20/83	4644	616	5260	B.S.	Wash Pipe broke loose
94	606	606B	07/05/83	3024	164	3188	B.S.	Mandrel pin parted

BSF — Below Seafloor
D.C. — Drill Collar
B.S. — Bumper Sub
BHA — Bottom Hole Assembly

APPENDIX B-1

FAILURE ANALYSIS OF
DRILL PIPE TOOL JOINTS
(LEG 48)

Bulletin

Research
United States Steel Corporation
Monroeville, Pennsylvania
December 29, 1976

Failure Analysis of Drill Pipe Tool Joints

Summary

Scripps Institute of Oceanography contracted with
U. S. Steel Research to conduct a failure analysis on two
sections of drill pipe that failed during service in the Scripps
Deep Sea Drilling Project. The results of the investigation
showed that fracture occurred in the pin end of the AISI 4150
steel tool joints causing the loss of several thousands of feet
of pipe string. Fractographic and metallographic examination
showed that the failure was a result of corrosion fatigue. It
is believed that fracture occurred a short time (relative to
the total life time of the components) after the cracks initiated
at the root of the threads. Thus, the useful life of the com-
ponent was governed primarily by the initiation of cracks rather
than by their propagation to failure. Frequent inspection of
tool joint pins is suggested to serve as a basis for replacing
cracked joints.

(Discussion attached)

FAILURE ANALYSIS OF
DRILL PIPE TOOL JOINTS   December 29, 1976

Discussion

Introduction

Recently the Scripps Institute of Oceanography (University
of California) experienced failure of a drill pipe used in the
Deep Sea Drilling Project being conducted for the National
Science Foundation. The failure occurred in the pin end threads
of a tool joint in the uppermost length of pipe (pup joint) in
the derrick. Because of its location, this joint is not immersed
in seawater. The pipe was placed on board the drill ship GLOMAR
CHALLENGER on May 1, 1972, and the pin end fractured in May 1976
thereby sending the remaining 16,300 feet of drill pipe to the
ocean floor.

According to information provided by Scripps, two pup
joints were alternated in the drill string during four years of
service. The total rotating time of both joints was 3930 hours,
and although the rotating time for each joint is not known, it is
assumed that each joint was exposed to about one half of the total
rotating hours. The average rotation speed was 60 revolutions per
minute, corresponding to about 7×10^6 revolutions for each joint.
During the drilling operation the joints are subjected to tension
loads only (due to the weight of about 350,000 pounds of pipe in
seawater) for about 90 percent of the time and to additional bending
loads for about 10 percent of the time while the joint is in the
guide horn of the ship. (The guide horn located below the derrick
provides a radius of 350 feet for support of the drill string when
the ship is rolling to prevent bending the pipe against a sharp edge.
This arrangement is schematically represented in Figure 1.)

After the failure of the pin in one of the two tool joints,
the failed section with the adjacent pipe as well as the pin end
of the other joint were submitted for examination.

Visual Examination

Of the two received sections, shown in Figure 2, one was
not fractured although some threads were severely scored; the
other (tool joint B, Figure 2) had fractured in the third thread
course, which is considered to be an area of highest stress con-
centration in threads. Figure 3 shows a close-up of the broken
section. There was essentially no rust on the outside surface,
on the threads, and on the fracture surface. However, the inside
surface of both pipe sections which was exposed to aerated seawater

Discussion (Continued)

during the drilling operation was covered with a heavy layer of rust. The appearance of the inside surface seen in Figure 3 is typical of both pipes.

The fracture surface which extended from the root of the third thread course consisted of two distinct zones: an outer flat fracture zone and an inner slanted fracture zone, illustrated in Figures 3 and 4. The two zones were essentially equal in area; and although they were not concentric with the pipe, the flat zone extended along the entire perimeter in the thread root. The deepest penetration of the flat zone was 0.40 inch, comprising about 73 percent of the wall thickness (0.55 inch) in that area. Figure 4 also shows that the flat zone contains markings roughly concentric with the pipe (called beach marks) indicating periodic crack propagation.

Magnetic Particle Examination

The pins of the tool joints were examined by a fluorescent magnetic particle technique, and typical areas were photographed with ultraviolet illumination. The nonfractured pipe (tool joint A, Figure 2) showed many disconnected cracks in the thread roots of the four thread courses adjacent to the shoulder. Two typical areas are shown in Figure 5. This type of cracking was found on more than one half of the circumference. Figure 6 shows schematically the distribution of the cracks. In this schematic only the first five thread courses are shown; there were no cracks in the other threads. Many short cracks were also present in the remaining threads of the fractured pin (tool joint B, Figure 2), and typical cracked areas are shown in Figure 7. This type of cracking was present in essentially all the remaining threads. Figure 8 shows schematically the distribution of the cracks.

Chemical Composition, Mechanical Properties, and Stress Considerations

Specimens for the determination of chemical composition and mechanical properties were removed from the tool joints at areas immediately adjacent to the threaded pin. The chemical composition of the two tool joints, given in Table I, correspond to that for AISI 4150 steel.

Discussion (Continued)

The mechanical properties are summarized in Table II. The yield strength of tool joint A was somewhat lower than that of tool joint B, although the tensile strength, elongation, and reduction of area were essentially the same for both joints.

The stress at the critical cross section (fracture area) was estimated based on the weight of the drill string, the bending in the guide horn, and the torquing effects from the makeup of the threaded joint. The greatest contribution to the total longitudinal stress came from the weight of the string (42 ksi), and the bending moment contributed about 18 ksi. The resultant maximum combined tension stress was 64 ksi, disregarding the stress concentrating effect of the thread-root curvature. Although a comprehensive stress analysis was not conducted, this elementary approach showed that, assuming a stress-concentrating factor of 2.5,[1]* a stress of 160 ksi could occur at the thread root if the material were elastic up to that stress. Since this value exceeds the yield strength of the tool joint, localized yielding in the thread root is expected to have occurred whenever the joint was bent in conformance with the contour of the guide horn.

Fractography

The fracture face of tool joint B was examined in several areas by using a scanning electron microscope. Figure 9 shows a magnified view of the flat fracture in Area A, Figure 4, which was chosen for examination because it was expected that it would be relatively protected from accidental damage by the adjacent raised slanted fracture zone. The examination showed that the elevated portions of the fracture were flattened, as shown in Figure 10, probably as a result of alternate opening and closing of the crack. The depressed portions were filled with corrosion product. A similar appearance was observed in all other areas examined. The partial flattening of the fracture surface resulted in a smoothed appearance as indicated in Figure 11, which also shows the beach marks mentioned previously. This view also reveals "racheting" (areas of different elevation) in the area of the thread root indicating that cracking initiated from many small areas in the thread root. These cracks then joined up as the crack propagated toward the interior of the pipe. The beach marks on the fracture

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*See References

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Discussion (Continued)

surface are usually caused by periodic crack propagation under different stress-fluctuation conditions.

Metallography

Examination of the cracks in cross section at several locations of the two tool joints showed that the length of the cracks that had not propagated to failure varied from about 0.001 to 0.02 inch. Generally, the cracks were filled with corrosion product and in many instances were associated with small corrosion pits, as shown in Figure 12. Multiple crack initiation shown in Figure 13 was also observed. The cracks progressed along a jagged path and showed short side branches, illustrated in Figures 12, 14, and 15. This evidence, together with the mode of loading, indicates corrosion fatigue as the mode of **fracture initiation**. The microstructure of the steel was that of tempered martensite, normal for AISI 4150 quenched and tempered steel, as shown in Figure 15.

Discussion and Summary

The above-presented evidence indicates that the failure of the threaded pipe (fracture of one pin and cracking of the other pin) occurred as a result of corrosion fatigue. The exact nature of **the corrosive environment at the mating surface of the threaded joint is not known; however, it seems certain that seawater was involved.** The environment produced corrosion pits on the thread surface which acted as initiation sites for fatigue cracks. Furthermore, the presence of the environment probably increased the crack propagation rate.

Based on the design information provided by Scripps and the air-fatigue data for this type of steel,[2] it is estimated that the tool joints were stressed at or below the fatigue limit in air; thus in the absence of a corrosion environment a long service life would be expected. Technical literature[3,4,5] and prior experience indicate that at stress levels below the fatigue limit in air most of the total corrosion fatigue life is spent in initiating cracks, and that complete fracture occurs a short time thereafter. The references cited do not, however, provide specific information which would permit any estimate of the relative time for initiation of cracks to an inspectable size as compared with the time for propagation to failure. To make such an estimate, crack propagation rates would have to be obtained on AISI 4150 steel of the tool joints stressed at the rotation speed of the drill string (60 cycles/

Discussion (Continued)

minute) in an environment simulating the service condition. An
alternate empirical approach would be to inspect the pins of pup
joints at relatively frequent intervals to detect crack initia-
tion (and also to serve as a basis for replacing any cracked
joint).

References

1. R. E. Peterson, "Stress Concentration Factors," John Wiley &
    Sons, 1974, p 42, Figure 23.

2. S. T. Rolfe and J. M. Barsom, Fracture and Fatigue Control in
    Structures—Applications of Fracture Mechanics, Prentice-Hall, Inc.,
    Englewood Cliff, N. J., 1976.

3. D. W. Hoeppner, "Corrosion Fatigue Considerations in Materials
    Selection and Engineering Design," Corrosion Fatigue, National
    Association of Corrosion Engineers, 1972, pp 3-11.

4. W. E. Krupp, D. W. Hoeppner, E. K. Walker, "Crack Propagation
    of Aluminum Alloys in Corrosive Environments," Corrosion Fatigue,
    National Association of Corrosion Engineers, 1972, pp 468-483.

5. V. Rollins, B. Arnold, E. Lardner, "Corrosion Fatigue in High
    Carbon Steel," British Corrosion Journal, Vol. 5, 1970, pp 33-40.

Table I

Chemical Composition of Tool Joints, percent

Tool Joint	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al (total)
A	0.49	0.96	0.023	0.019	0.29	0.03	0.03	1.01	0.21	0.08
B	0.50	0.99	0.028	0.019	0.27	0.03	0.03	1.04	0.21	0.07

Table II

Mechanical Properties of Tool Joints

Tool Joint	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 inch, percent	Reduction in Area, percent
A	113.8	152.7	20.3	56.8
B	125.2	152.0	19.5	55.2

U. S. Steel Corporation, Research, Monroeville, Pennsylvania

DERRICK

350 FT RADIUS

GUIDE HORN

DRILL STRING
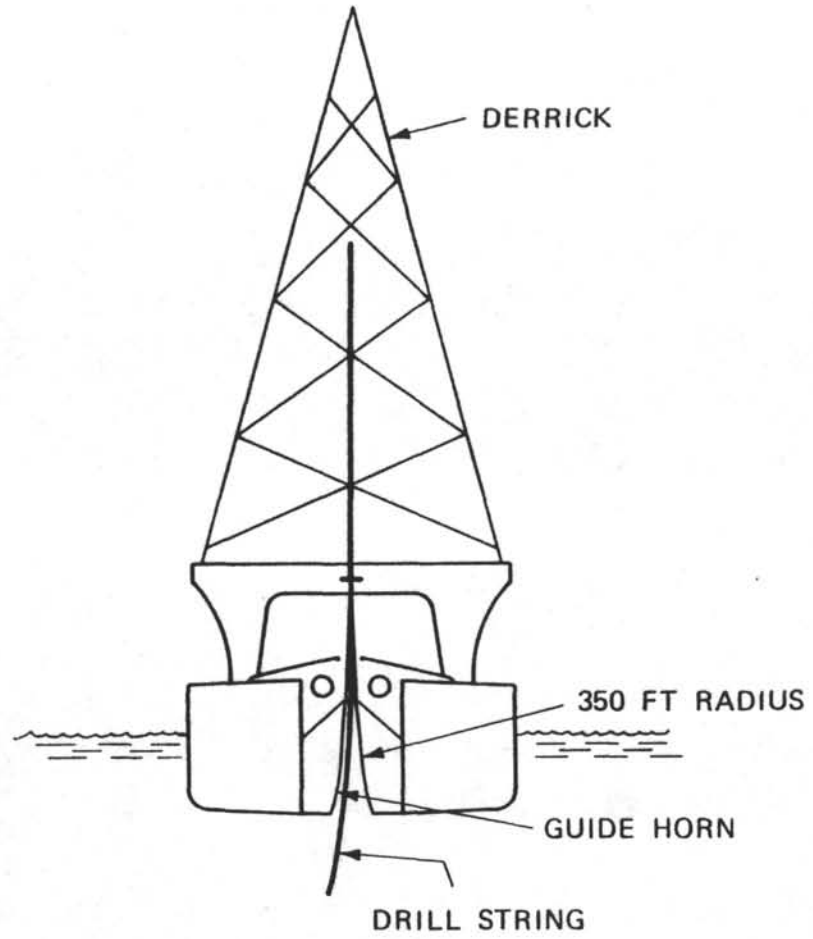
TRANSVERSE SECTION OF DRILL SHIP SHOWING
DRILL PIPE GUIDE HORN
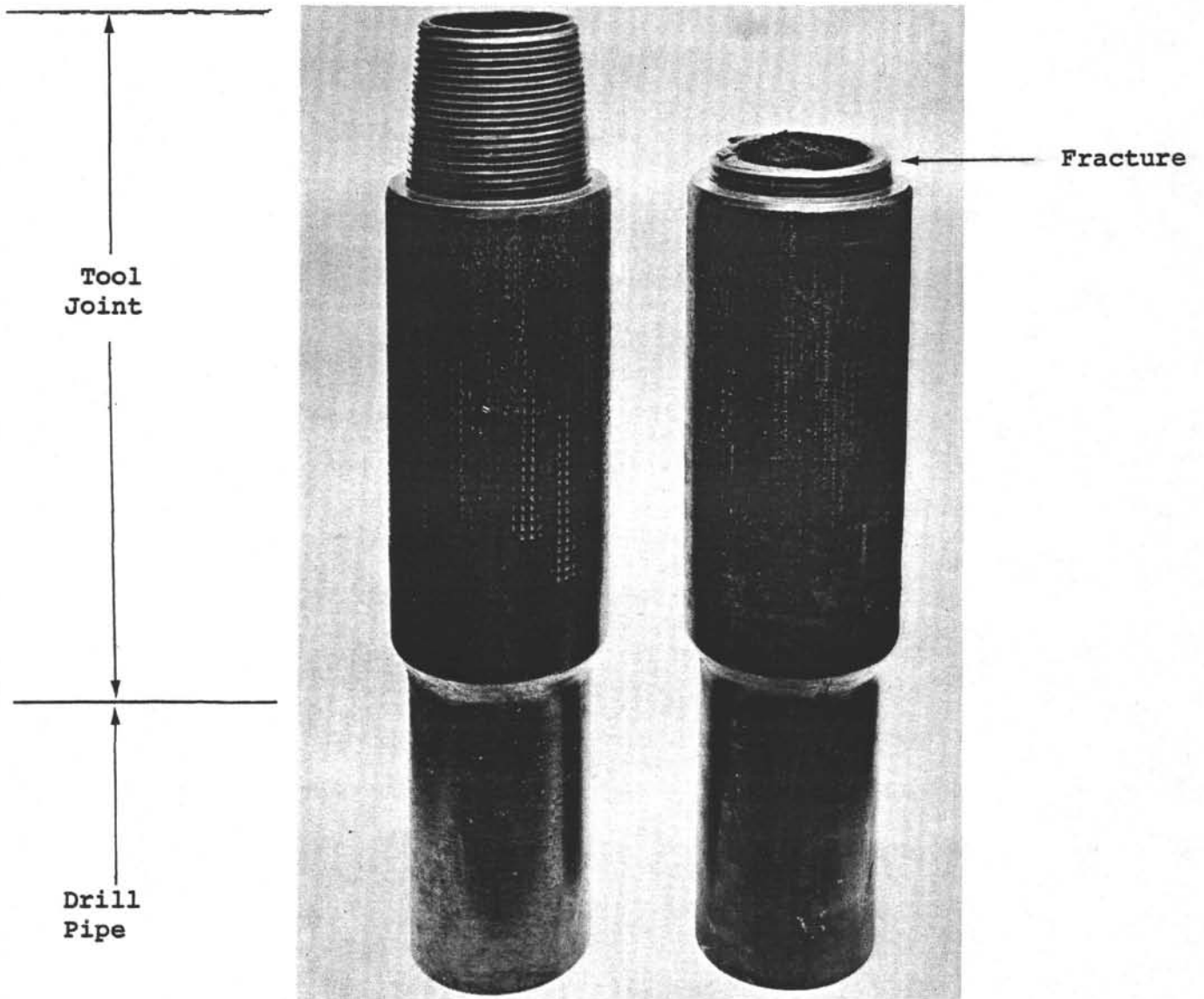
Figure 1

Tool joints A (left) and B (right) submitted for
examination after four years service. About 1/5
actual size.

Tool
Joint

Drill
Pipe
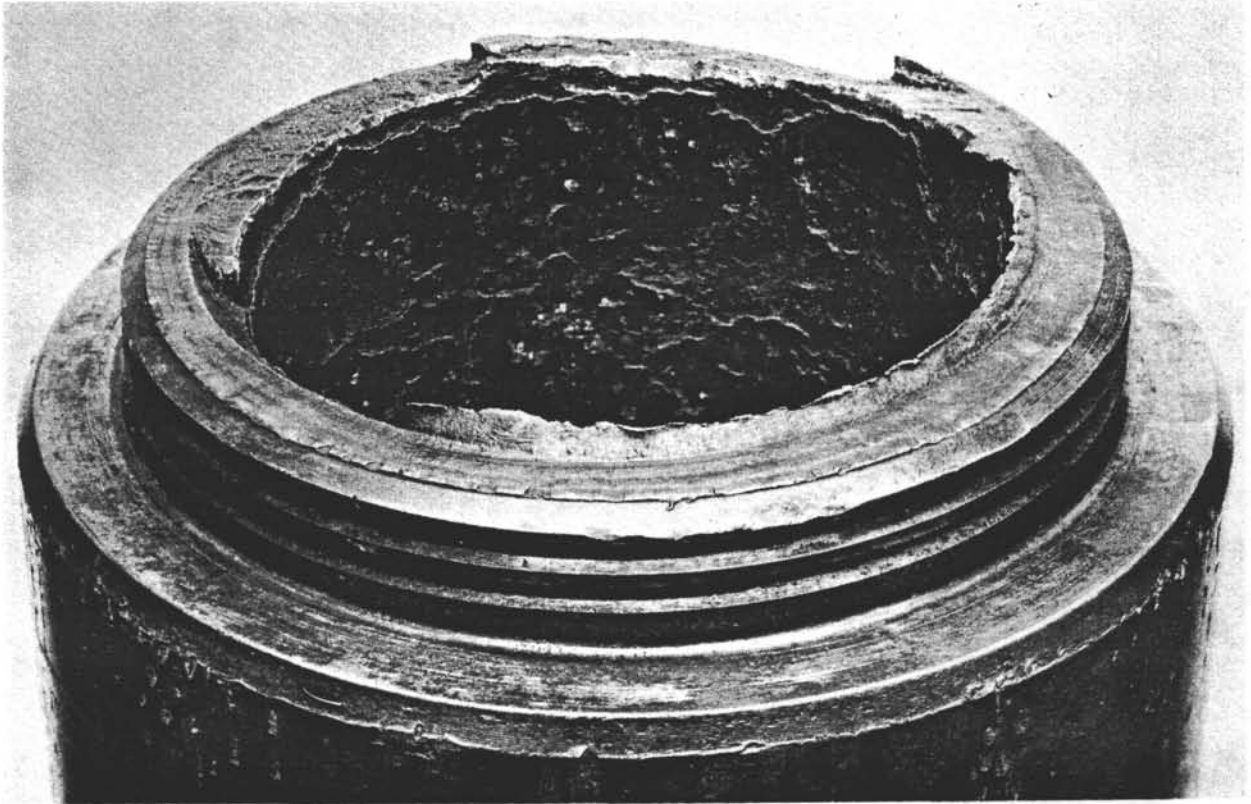
Fracture

Figure 2

Tool joint B (Figure 2) that had fractured in the
threads. Note the heavy layer of rust on the inside
surface. Approximately actual size.
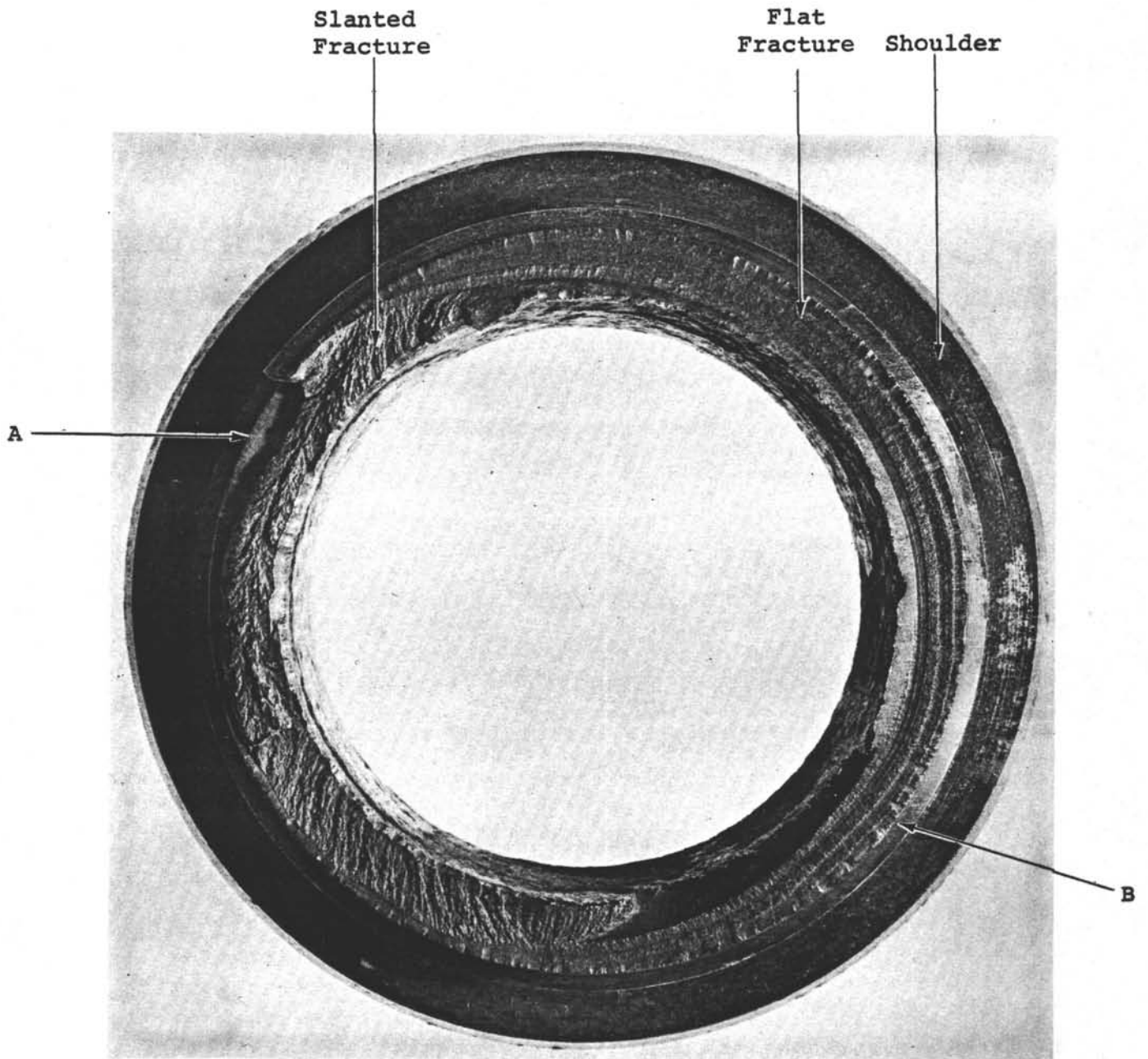
Figure 3

Fracture surface of tool joint B. Approximately actual size.
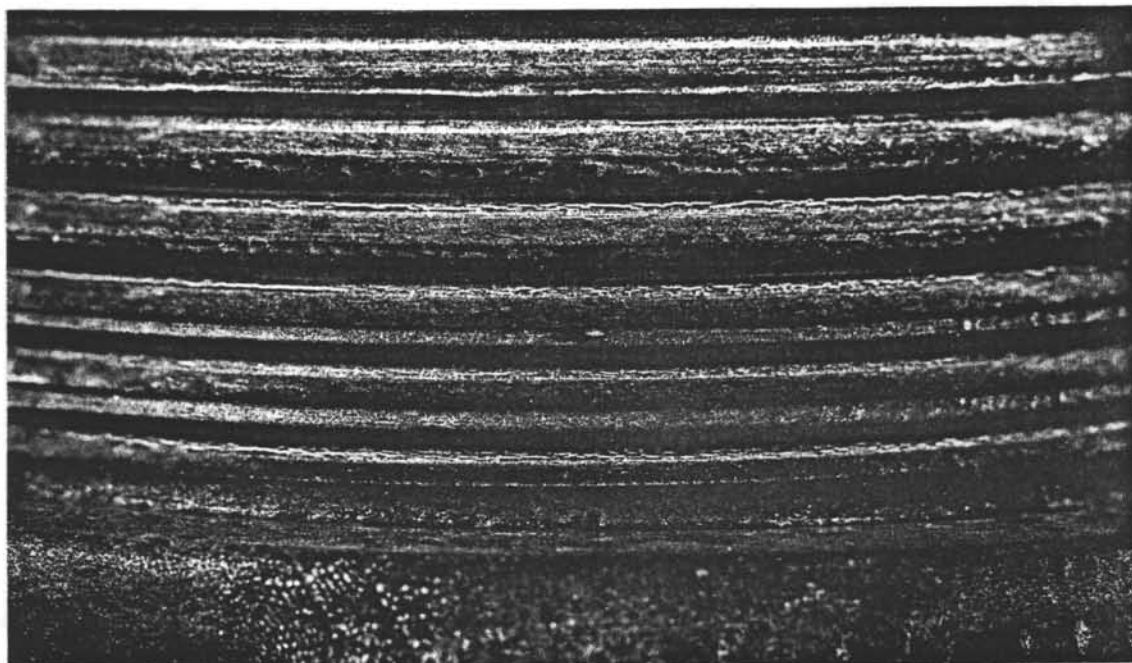
Figure 4

Shoulder →

Shoulder →

Cracks in thread roots of tool joint A (as indicated
by disconnected white lines in thread roots). Cracks
were revealed by fluorescent magnetic particle tech-
nique with ultraviolet illumination. X2.

Neg. Nos.
P-6136B-5
P-6136B-7

Figure 5
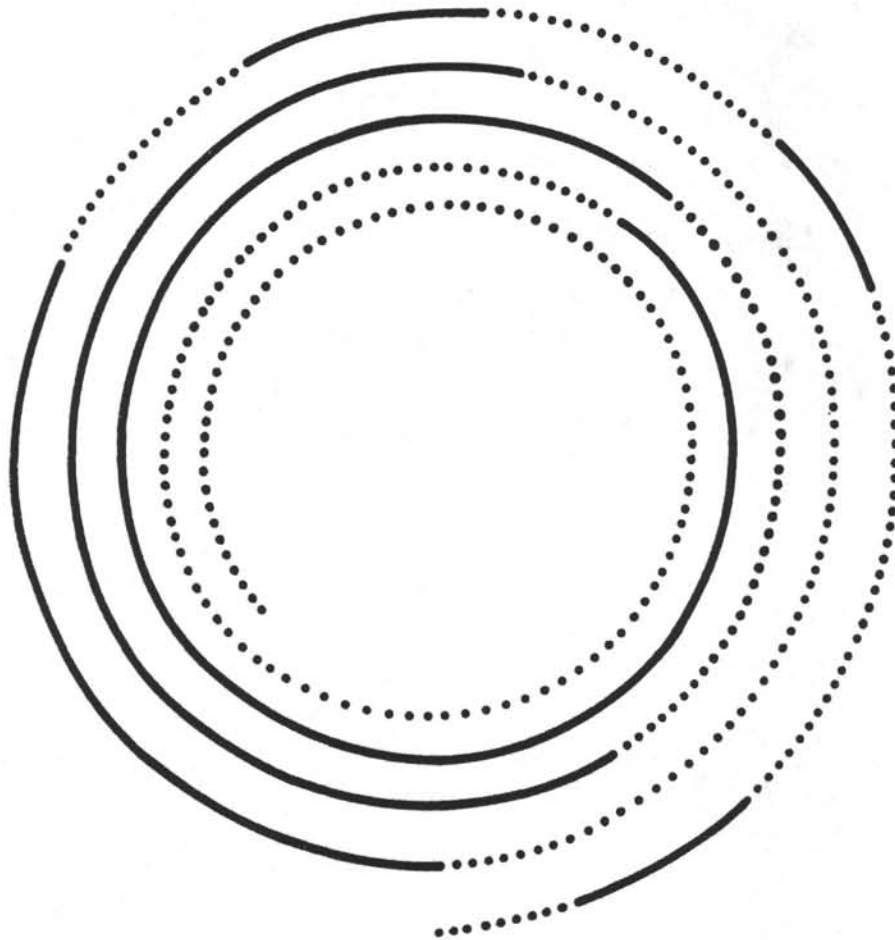
43

CRACKED

NOT CRACKED

SCHEMATIC REPRESENTATION OF CRACK DISTRIBUTION IN THREAD
ROOTS OF TOOL JOINT A. THE DRAWING SHOWS THREAD ROOTS
AS A PROJECTION OF AN EXPANDED CONE.

44

Figure 6
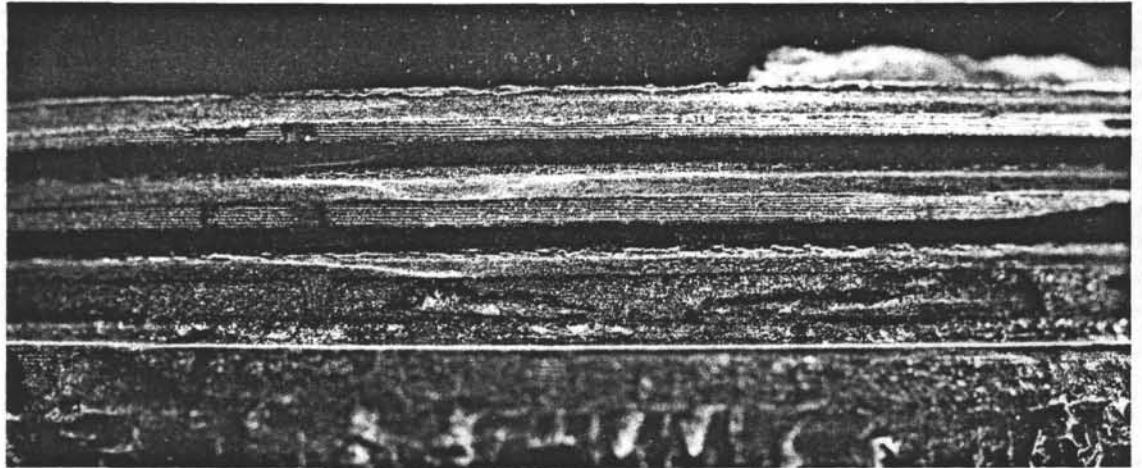
Fracture →
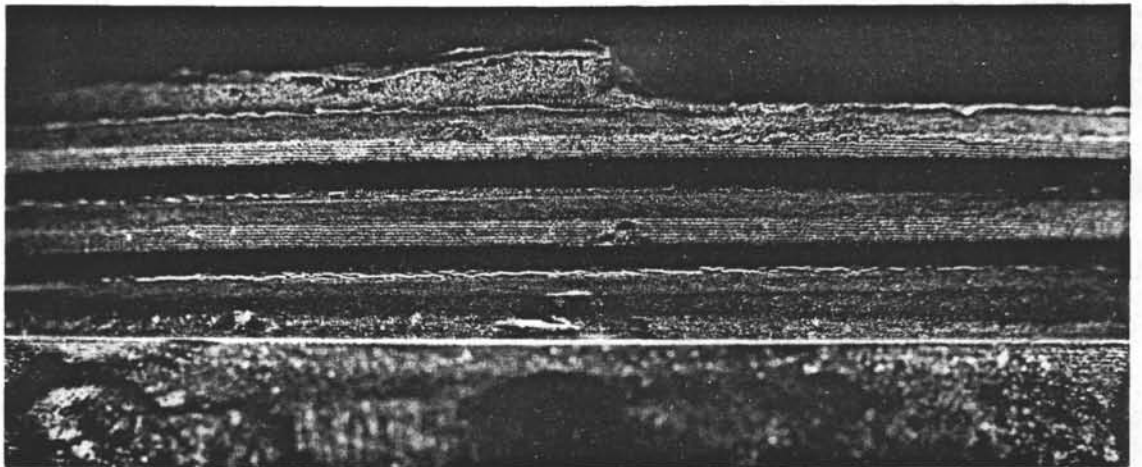
Shoulder →

Fracture →

Shoulder →

Fracture →
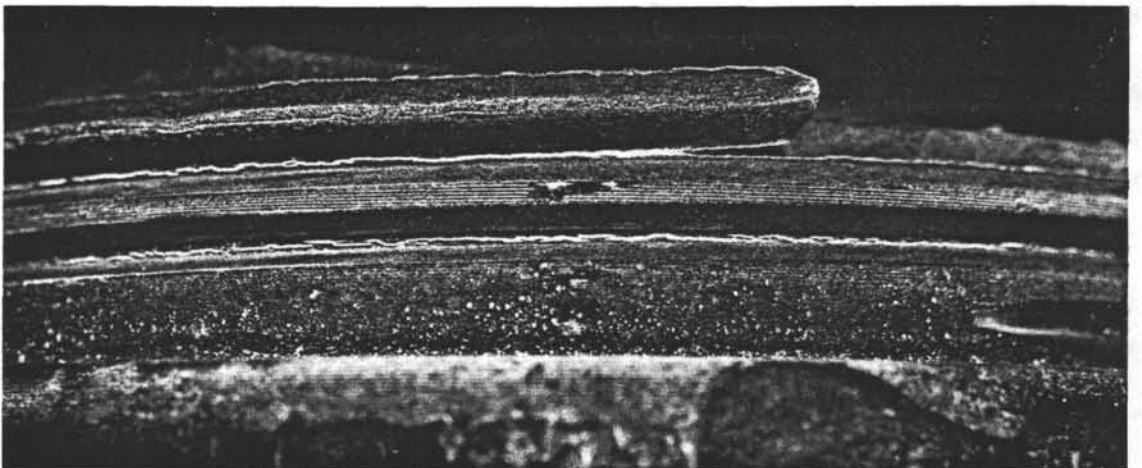
Shoulder →

Cracks in thread roots of tool joint B (as indicated
by disconnected white lines in thread roots). Cracks
were revealed by fluorescent magnetic particle tech-
nique with ultraviolet illumination. X2.

Figure 7

FRACTURE
CRACKED
NOT CRACKED

SCHEMATIC REPRESENTATION OF CRACK DISTRIBUTION IN THREAD
ROOTS OF TOOL JOINT B. THE DRAWING SHOWS THREAD ROOTS
AS A PROJECTION OF AN EXPANDED CONE.

Thread

Flat
fracture

Slanted
fracture

A-1
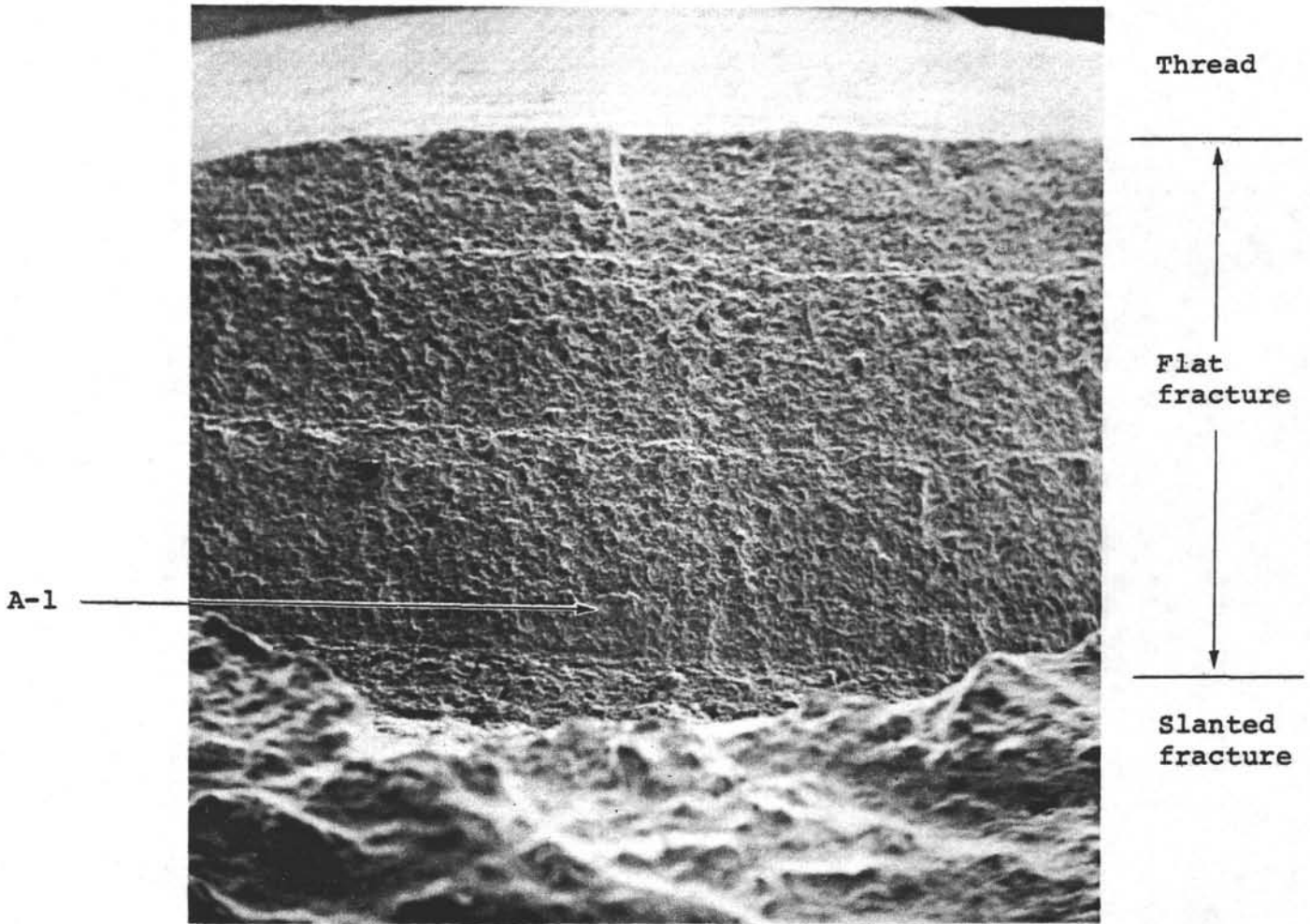
Surface of flat fracture zone in Area A, Figure 4.   X25.

Figure 9

47
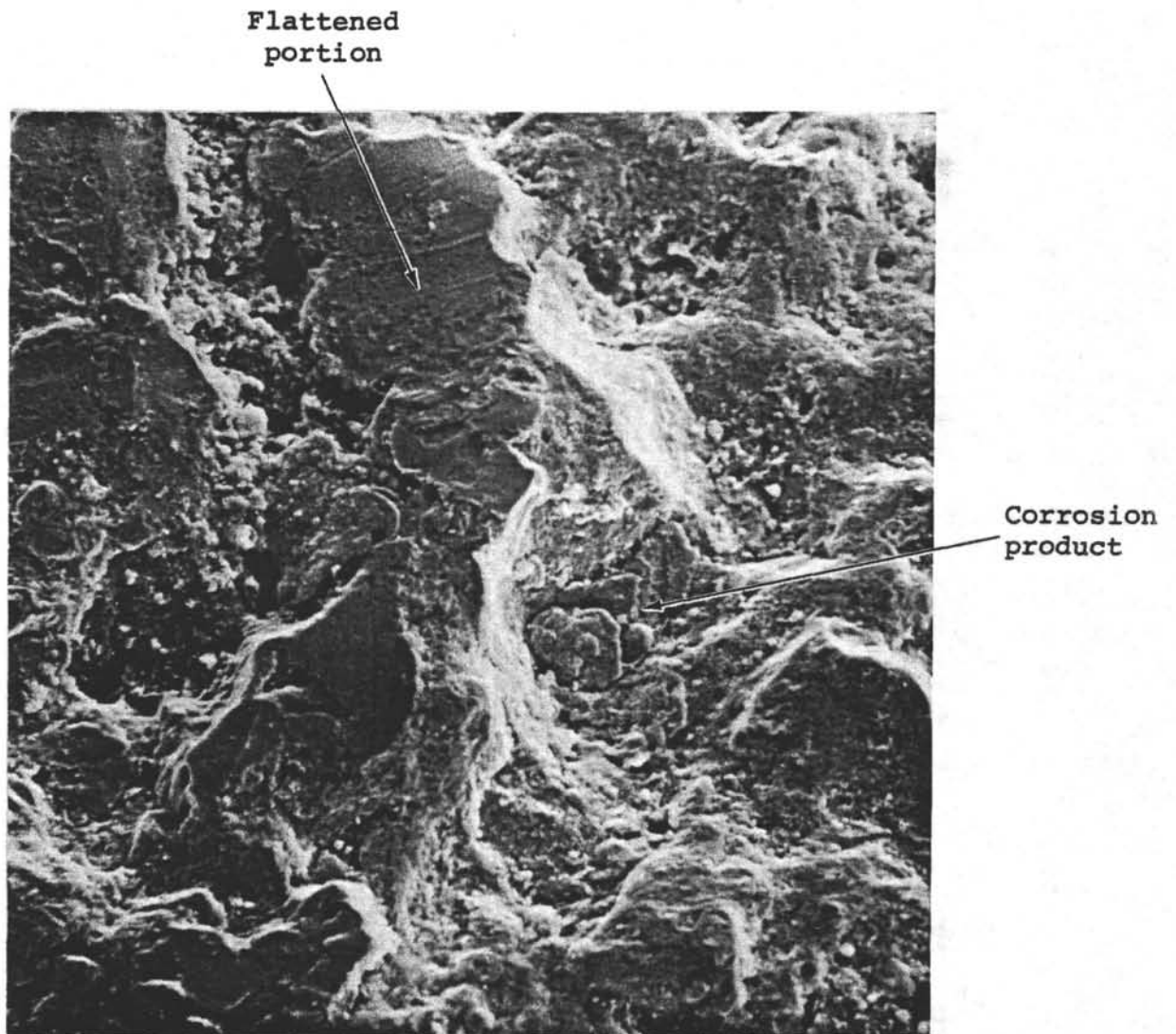
Surface of flat fracture zone in Area A-1, Figure 9, showing
flattened raised portions and corrosion product in low
portions.   X1000.

Figure 10

48
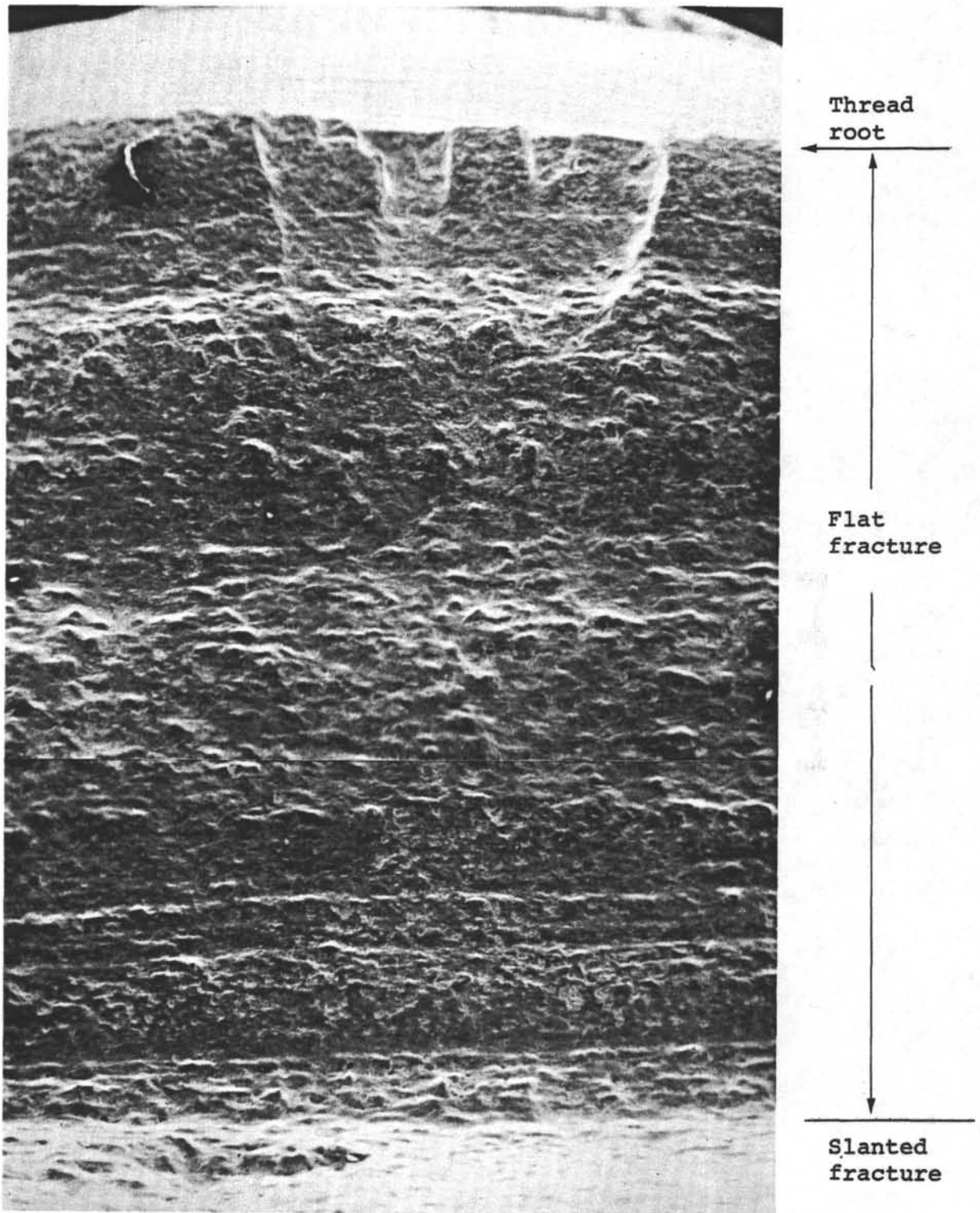
Surface of flat fracture zone in Area B, Figure 4.   X25.
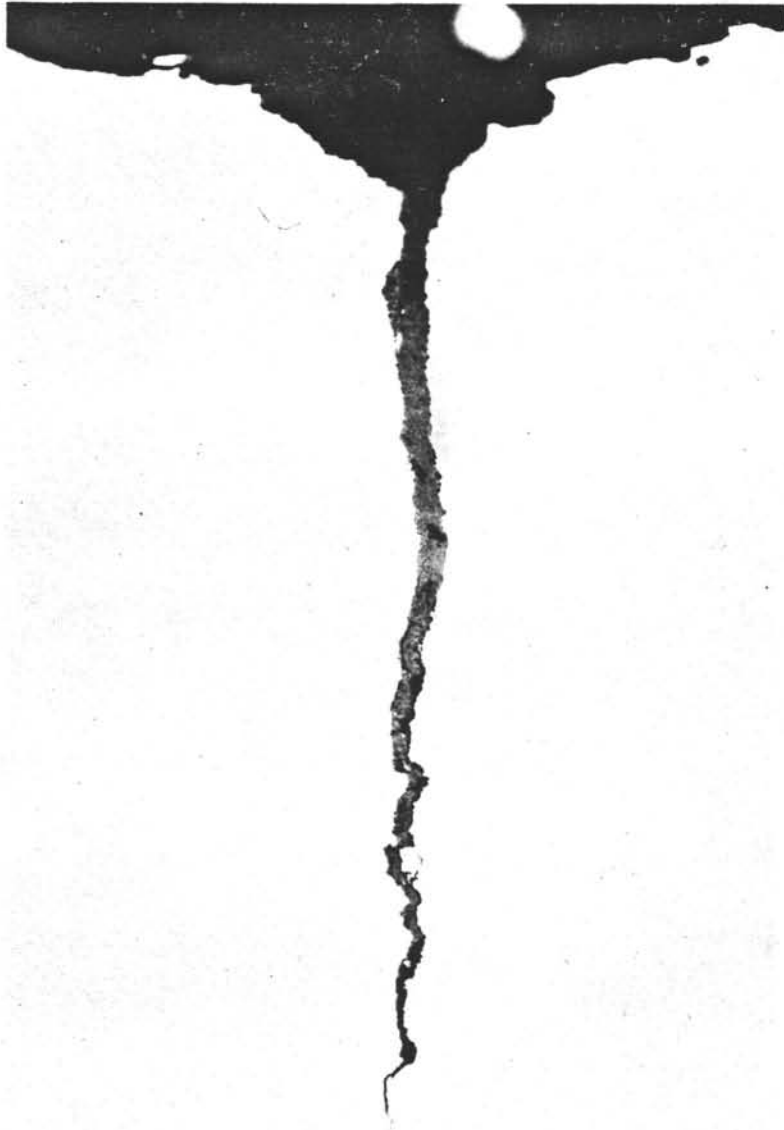
Figure 11

Crack emanating from a corrosion pit in the thread
root of tool joint B. Unetched. X500.

Figure 12

50
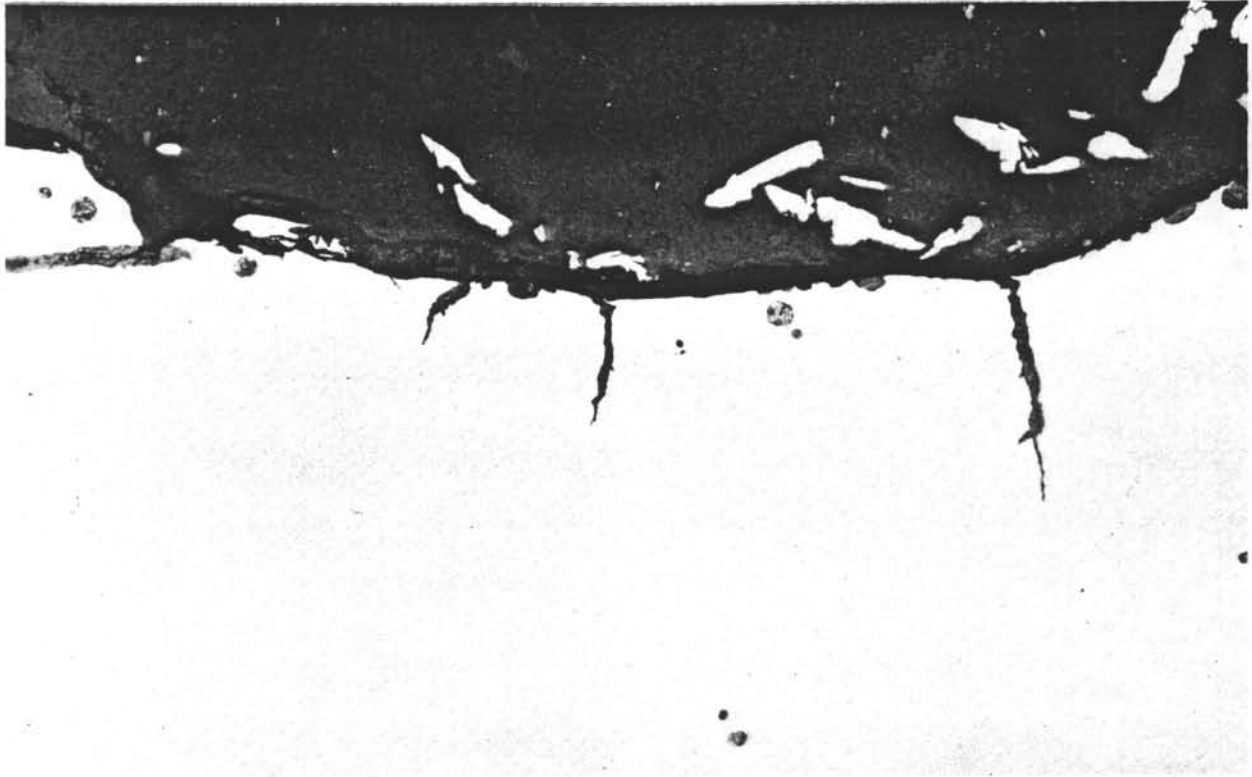
Multiple crack initiation in a thread root of tool
joint A. Unetched. X250.

Typical crack in tool joint B. Unetched. X500.

Figure 14
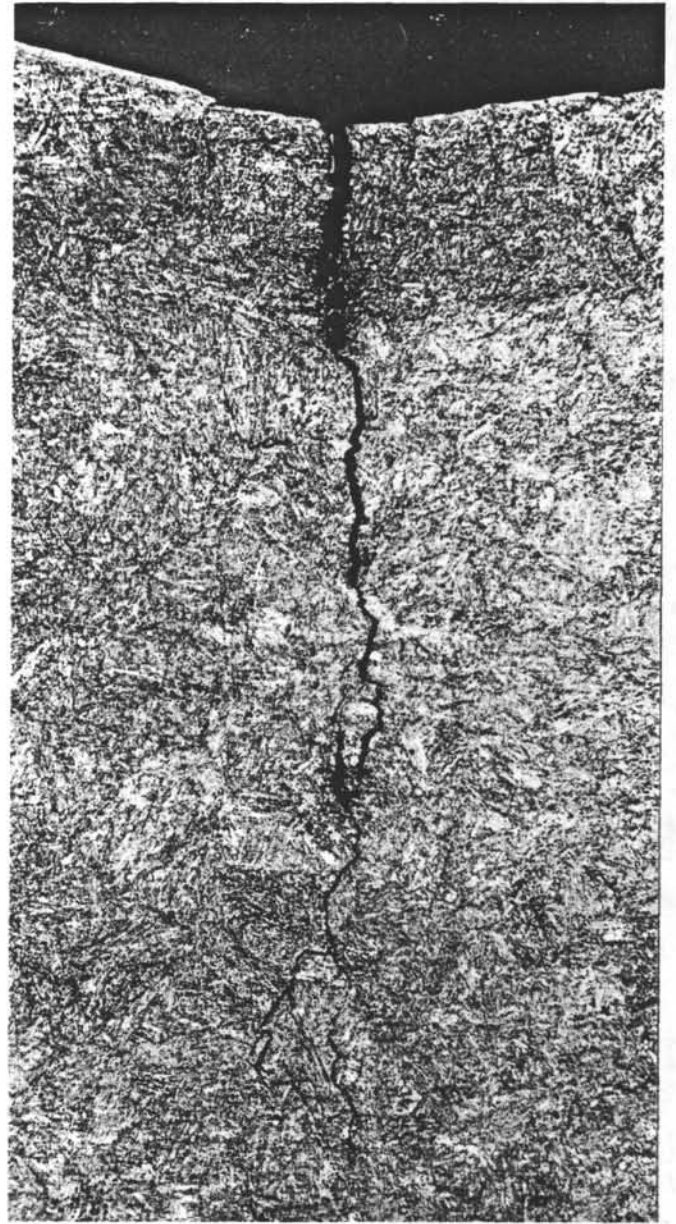
Unetched   Etched in picral

Crack path and microstructure in tool joint B.   X500.

Figure 15

APPENDIX B-2

FAILURE ANALYSIS OF S-135 DRILL PIPE
USED IN DEEP SEA DRILLING
(LEG 53)

BULLETIN

Research
United States Steel Corporation
Monroeville, Pennsylvania
November 8, 1977

FAILURE ANALYSIS OF S-135 DRILL PIPE
USED IN DEEP SEA DRILLING

Summary

Scripps Institution of Oceanography contracted with
U. S. Steel Research to analyze failures of three sections of
API Specification 5AX Grade S-135 drill pipe. The drill pipes
fractured during drilling operations in seawater at considerable
depths.

The study confirmed that the chemical composition,
mechanical properties, and microstructure are typical for S-135
drill pipe. Fractographic and metallographic examinations
showed that the failures occurred as a result of corrosion fatigue
initiating on the external surface of the drill pipe. Corrosion
pitting on the fracture surfaces of cracks that progressed
partially through the pipe wall suggests that the corrosion fatigue
cracks progressed relatively slowly permitting sufficient time for
corrosion pits to grow on the newly exposed crack surfaces. How-
ever, specific information was not available to permit an estimate
of the time-to-failure after crack initiation.

(Discussion attached)

FAILURE ANALYSIS OF
S-135 DRILL PIPE USED
IN DEEP SEA DRILLING   November 8, 1977

Discussion

Introduction

Scripps Institution of Oceanography (University of California) experienced failure of a drill pipe (API Specification 5AX Grade S-135) used in the Deep Sea Drilling Project being conducted for the National Science Foundation. During service, the drill pipe is immersed in seawater to a considerable depth and aerated seawater is pumped through the pipe.

Three samples of failed pipes were submitted for examination. The chemical composition and mechanical properties, shown in Tables I and II, respectively, and the microstructure are typical for S-135 drill pipe. One sample received in April 1977 without identification will be referred to as Sample A. Two other samples received in July 1977 were identified as 53418A. One of these came in two pieces (2A and 2B) representing mating faces of a fracture; this pipe will be referred to as Sample B. The other pipe sample (53418A1) received in July contained a threaded tool joint and will be referred to as Sample C.

Sample A

This pipe sample (5.5-inch OD, 0.42-inch wall) had a fracture on one of its ends consisting of a flat portion that extended for about one third of the circumference and of an irregular portion. Figure 1 shows a portion of the pipe containing the fracture face, and Figure 2 shows the relative positions of the flat and irregular fractures. The flat portion, extending essentially normal to the pipe axis, indicates that the initial fracture was caused by a predominantly axial load. After the initial flat fracture extended to critical size, the remaining portion failed by overload in an irregular manner. The inside surface was more severely corroded than the outside and contained many irregularly shaped pits, as is illustrated in Figure 3. No secondary cracks were observed on the inside surface. The higher corrosion rate on the inside is believed to be the result of high oxygen concentration from some air entrapment and of high flow rate.

The outside surface was corroded to an appreciably lesser extent than the inside surface, the corrosion was more general in nature, and pitting was shallow and infrequent. In addition, many

Discussion (Continued)

small cracks were present on the outside surface immediately
adjacent to the flat fracture. Typical cracks are shown in
Figure 4. Considerable lateral corrosion also occurred in some
of the cracks as depicted in Figure 5.

The fracture surface was severely corroded, thereby obscur-
ing the original features of the fracture face. Removal of corro-
sion products*) from the flat fracture section revealed small, deep
pits and cracks essentially perpendicular to the fracture surface,
as illustrated in Figure 6.

Sample B

Sample B represents two matching sections of a pipe
(5-inch OD, 0.35-inch wall) that had fractured. The fractured ends
of the pipe are shown in Figure 7. Similar to Sample A, this pipe
sample also contained a flat portion in its fracture surface
extending about one third of the circumference, the remainder of the
fracture being irregular. Fluorescent magnetic particle examination
revealed longitudinal bands of circumferential cracks adjacent to
the flat fracture, as schematically indicated in Figure 7. A
detailed view of one cracked zone is shown in Figure 8.

Metallographic examination showed that these cracks, about
0.01 inch deep, were filled with corrosion product as is illustrated
in Figure 9. Considerable corrosion was also present on the frac-
ture face indicating that the pipe was exposed to seawater for an
appreciable time after the fracture occurred. In addition to
general corrosion, deep narrow pits were present on the fracture
surface, Figures 10 and 11. The fracture surface adjoining the
outside diameter of the pipe revealed "ratcheting" (areas of dif-
ferent elevation) illustrated in Figure 12. This configuration
indicates that the flat fracture initiated from many small cracks
on the outside surface, such as those shown in Figure 8, which then
joined up as the crack propagated. Branch cracks were also seen
on the fracture surface, as is illustrated in Figures 13 and 14,
for areas at the outside and inside pipe surfaces, respectively.

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*) The corrosion products were removed ultrasonically in an
   18 percent HCl solution inhibited by 5 g/l of 1,3-D-n-butyl-2
   thiourea. This solution does not attack steel, but it removes
   rust and exposed sulfide inclusions.

Discussion (Continued)

Sample C

This sample, shown in Figure 15, consisted of a 5-inch OD, 0.35-inch wall pipe section attached to a tool joint. About 24 inches from the pin end, the pipe contained a rather straight circumferential crack about 1.5 inches long; Figure 15 shows the location of the crack. The outside pipe surface in the vicinity of the crack was ground off before receipt of the sample. A metallographic section at about midlength of the crack showed that the crack was very straight. Although in this section the crack had not propagated through the pipe wall, in an adjacent area the crack did penetrate the crack wall. Figure 16 shows that the crack initiated on the outside surface, and that pitting corrosion occurred laterally from the crack, indicating that the crack propagated relatively slowly. The straightness of the crack is typical of fatigue cracks. The tip of the crack follows a slightly branched, predominantly transgranular path, as illustrated in Figure 17. Although the crack initiation area could be identified, as shown in Figure 18, the grinding of the outside surface precluded linking the exact initiation site with metallographic or corrosion features.

Discussion and Summary

Examination of three sections of API Grade S-135 drill pipe that failed during drilling operations in seawater revealed several features which indicate that the fractures occurred as a result of corrosion fatigue. Multiple crack initiation occurred on the outside surface, the cracks propagated rather slowly, and the cracks were filled with corrosion product. The flatness of the fracture being essentially normal to the pipe axis indicates that the load was predominantly axial. The remainder of the fracture, which was irregular, was caused by overload after the fatigue crack had progressed to a critical size.

Although the inside surface of the pipe contained appreciably more and deeper corrosion pits than the outside, the corrosion fatigue cracks started from the outside surface. Lateral pitting corrosion on the fracture surfaces of cracks that progressed partially through the pipe wall indicates that the cracks progressed relatively slowly permitting sufficient time for corrosion pits to grow on the newly exposed crack surfaces. However, specific information was not available that would permit an estimate of the time-to-failure after crack initiation.

Table I

### Chemical Composition of Drill Pipe, percent

Sample	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al (total)	V
A	0.32	1.93	0.004	0.026	0.25	0.02	0.01	0.02	0.49	0.002	0.009
B	0.29	1.87	0.018	0.018	0.23	0.01	0.01	<0.003	0.41	0.003	0.013
C	0.33	1.87	0.017	0.021	0.20	0.01	0.01	<0.003	0.41	0.001	0.013

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United States Steel Corporation, Research, Monroeville, Pennsylvania

Table II

Mechanical Properties of Drill Pipe

Sample	Yield Strength, (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 inch, percent	Reduction in Area, percent
A	149.0	163.5	17.3	58.0
B	140.6	154.6	18.1	59.7
C	146.1	160.6	18.0	57.0

United States Steel Corporation, Research, Monroeville, Pa.

Fractured end of Sample A. Note flat portion
at bottom of photograph. About 0.6 actual size.

Figure 1
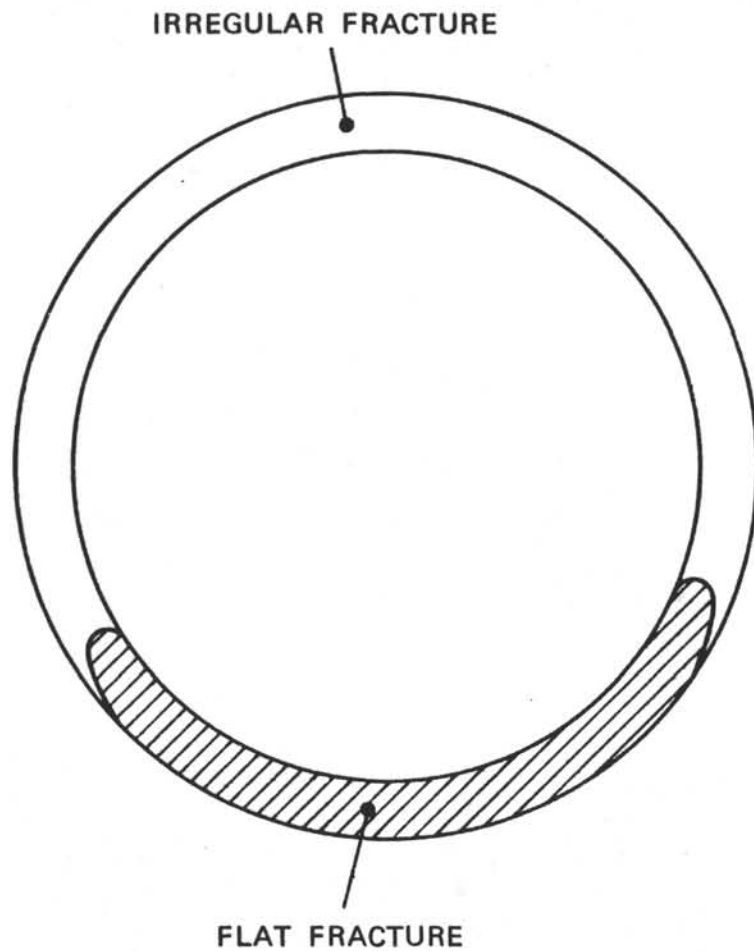
FRACTURE SURFACE OF SAMPLE A.   ABOUT 0.7 ACTUAL SIZE.

64

77-H-052(001)

Figure 2
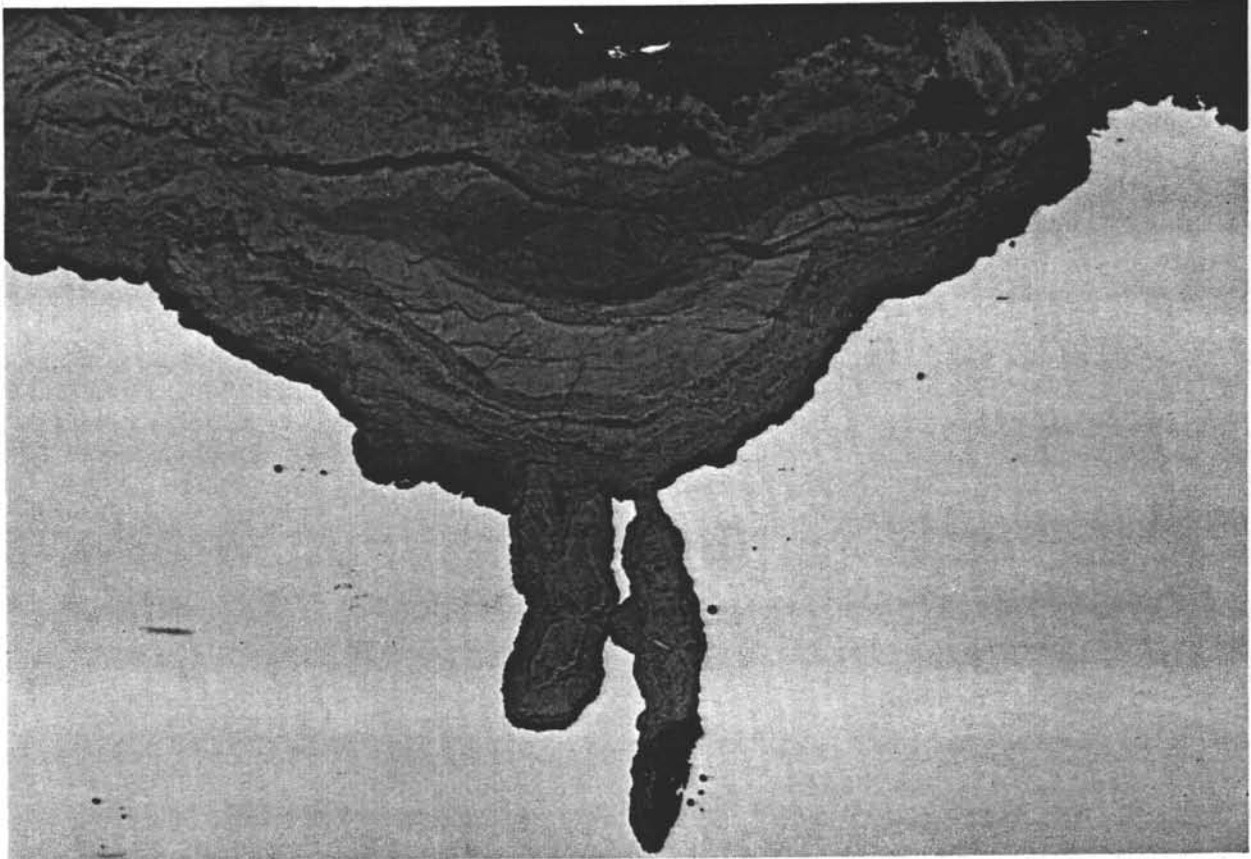
Irregularly-shaped corrosion pit on the inside
surface of Sample A. Not etched. X300.

99

Etched in picral.   X300.
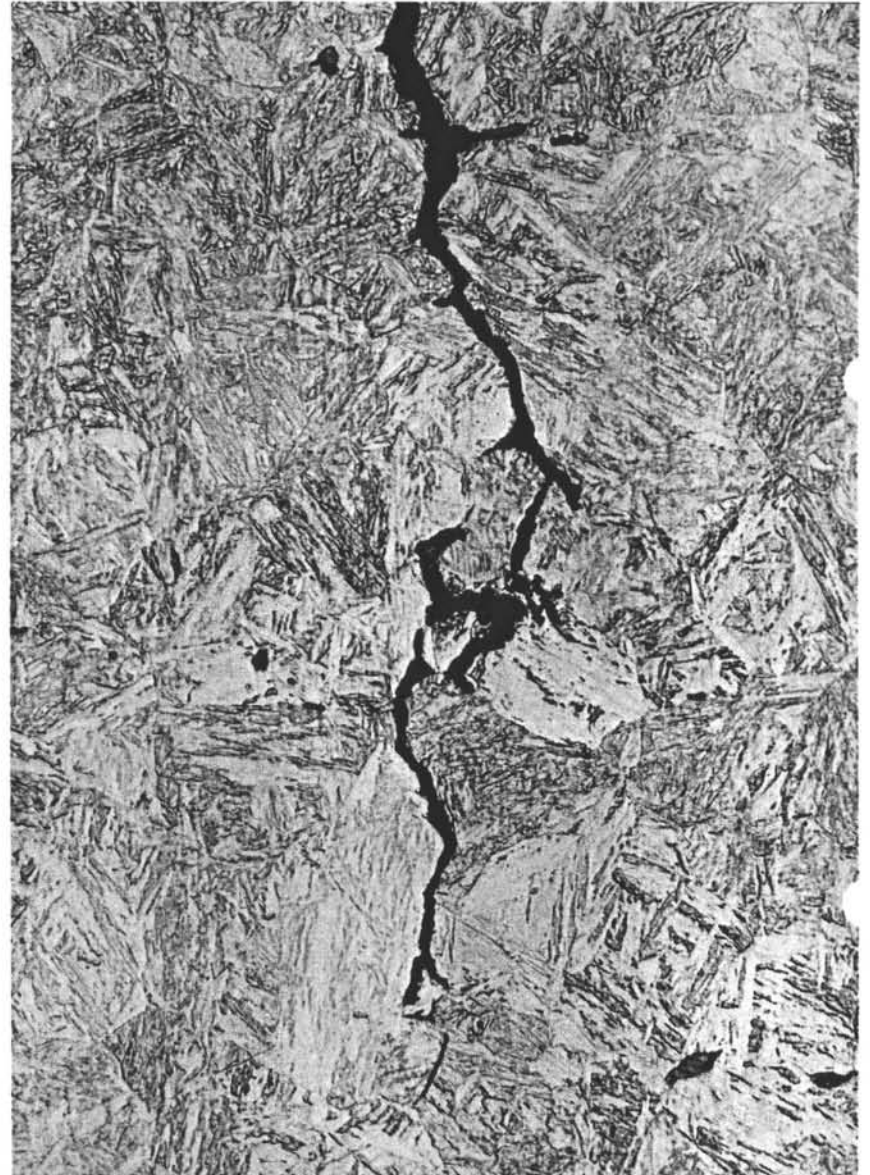
Etched in Vilella's Reagent.   X750.

Cracks emanating from the outside surface of Sample A.

1M-1834-A-5
1M-1834-A-8

Figure 4

Irregular corrosion on the outside surface of
Sample A. Etched in picral. X200.
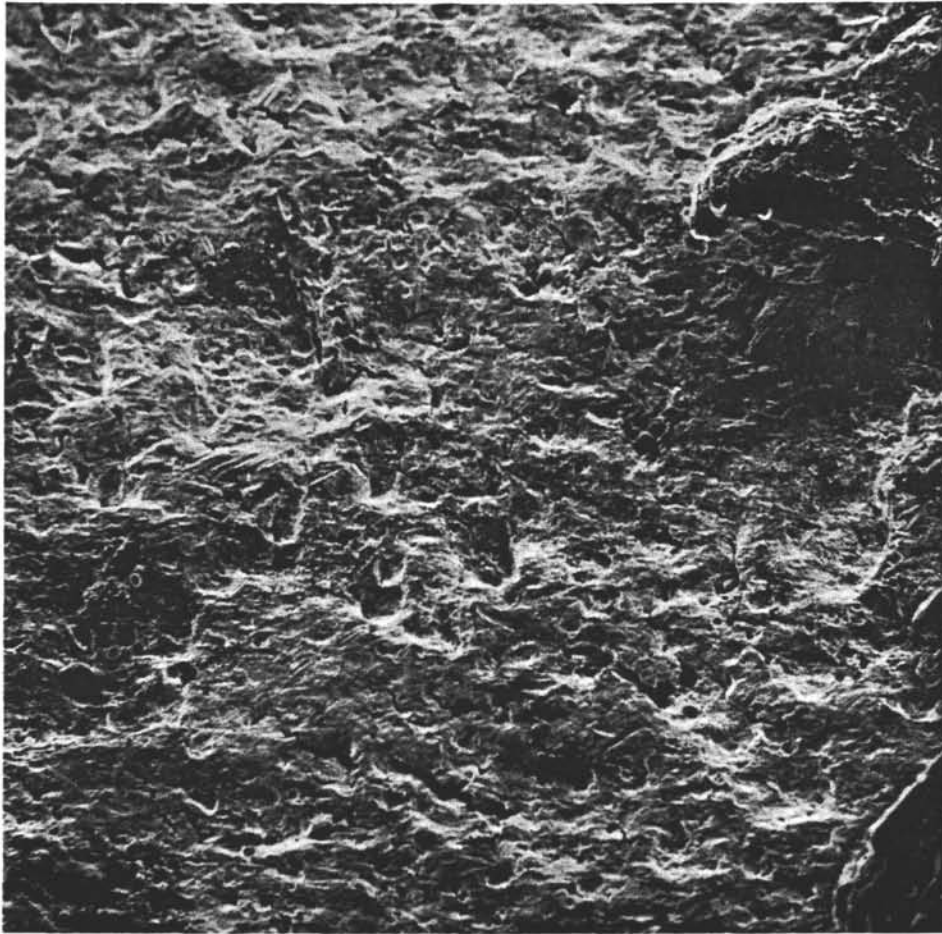
Flat fracture surface of Sample A after removal
of corrosion product. Note corrosion pits and
secondary cracks. X100.

2S-10289

Figure 6

68

CRACKED
ZONES
(SEE
FIGURE 8)

FLAT
FRACTURE
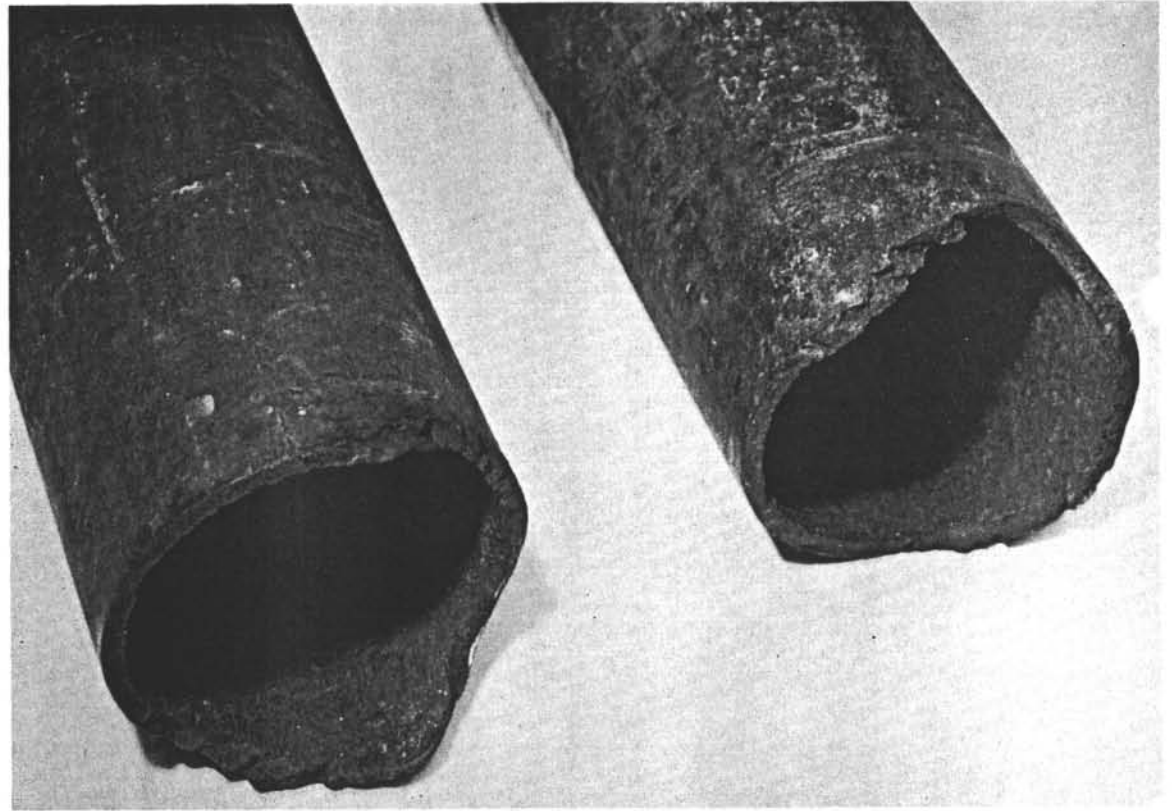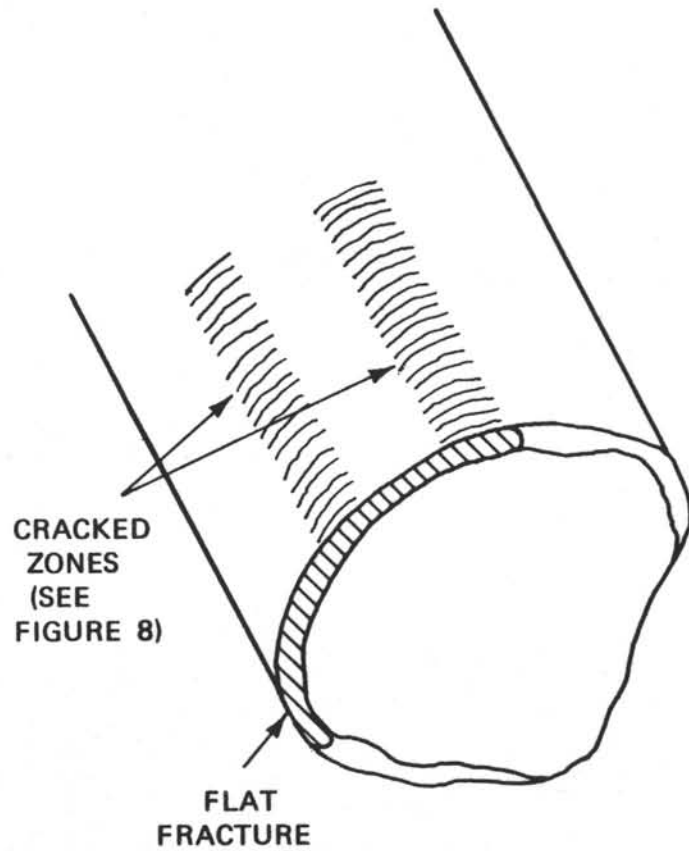
MATCHED FRACTURE FACES OF SAMPLE B.
ABOUT 0.5 ACTUAL SIZE.

69

Pipe Axis
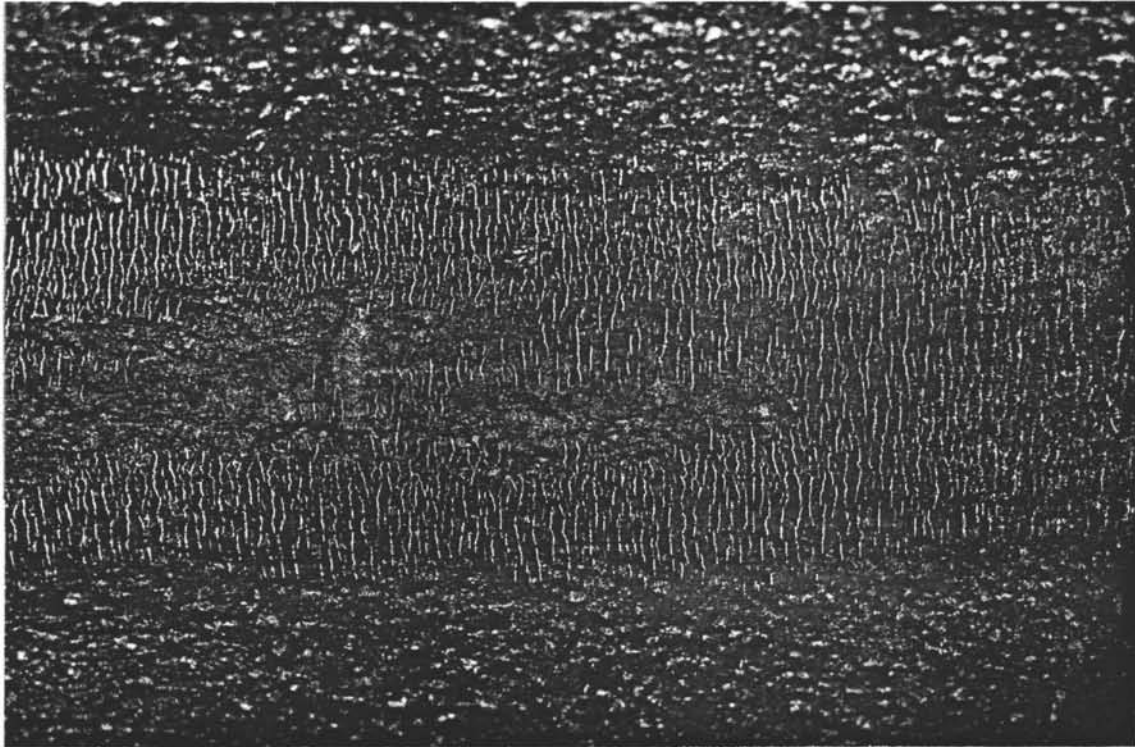
Cracked zone on the outside surface of Sample B.
The cracks were revealed by fluorescent magnetic
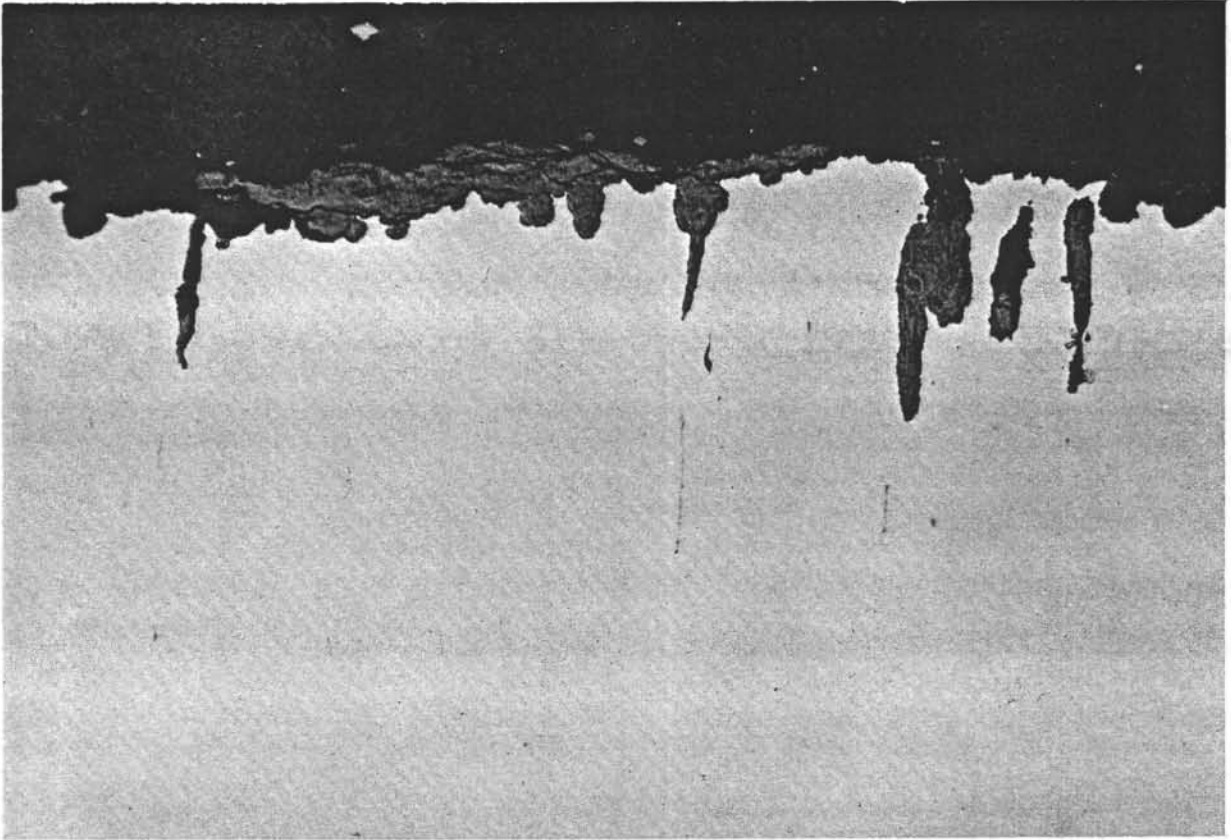particle technique with ultraviolet illumination.
X1.3.
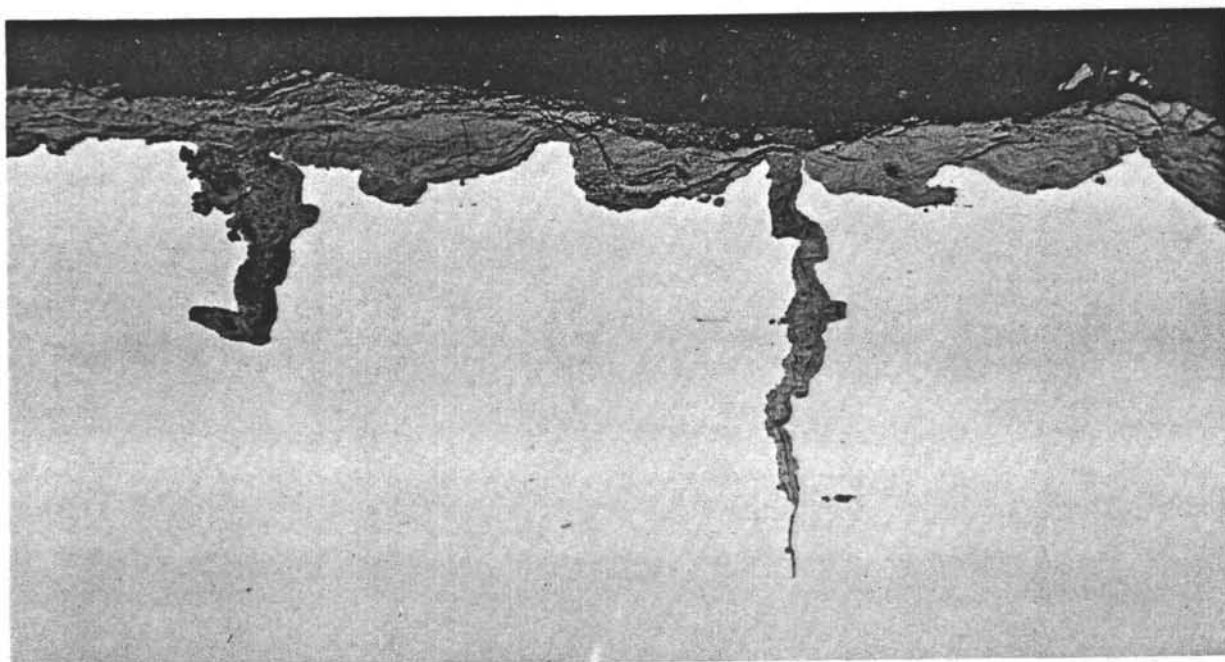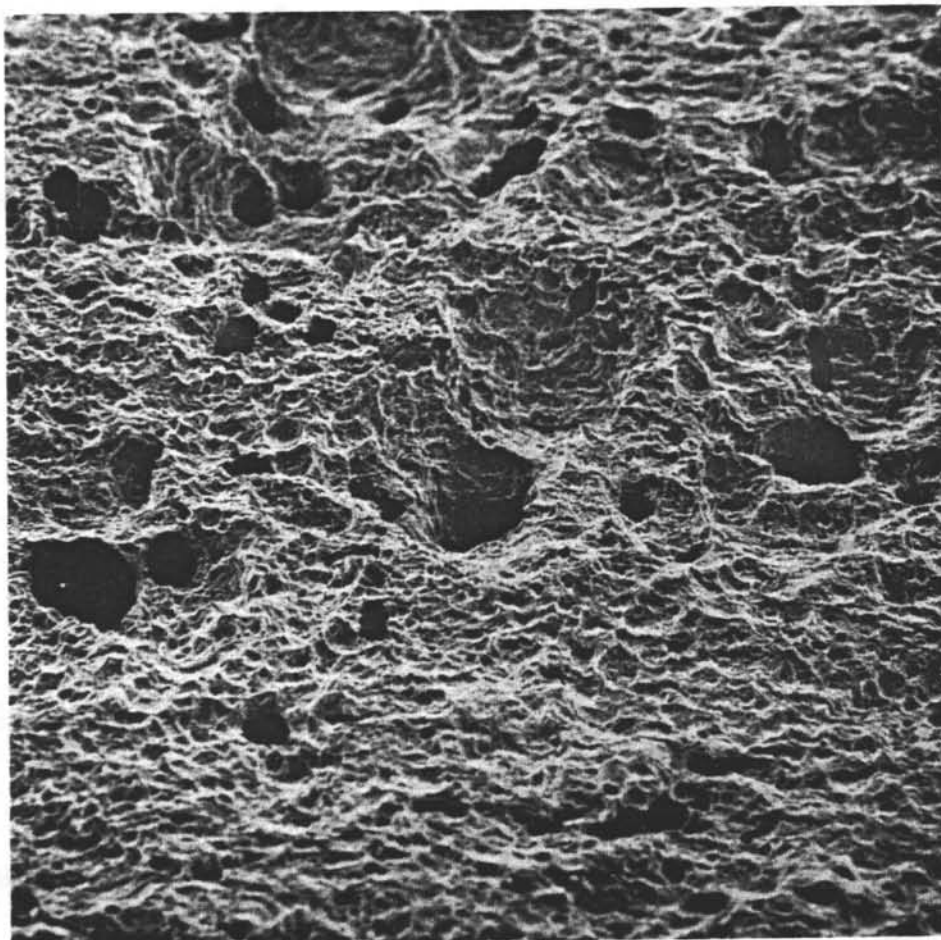
Not etched
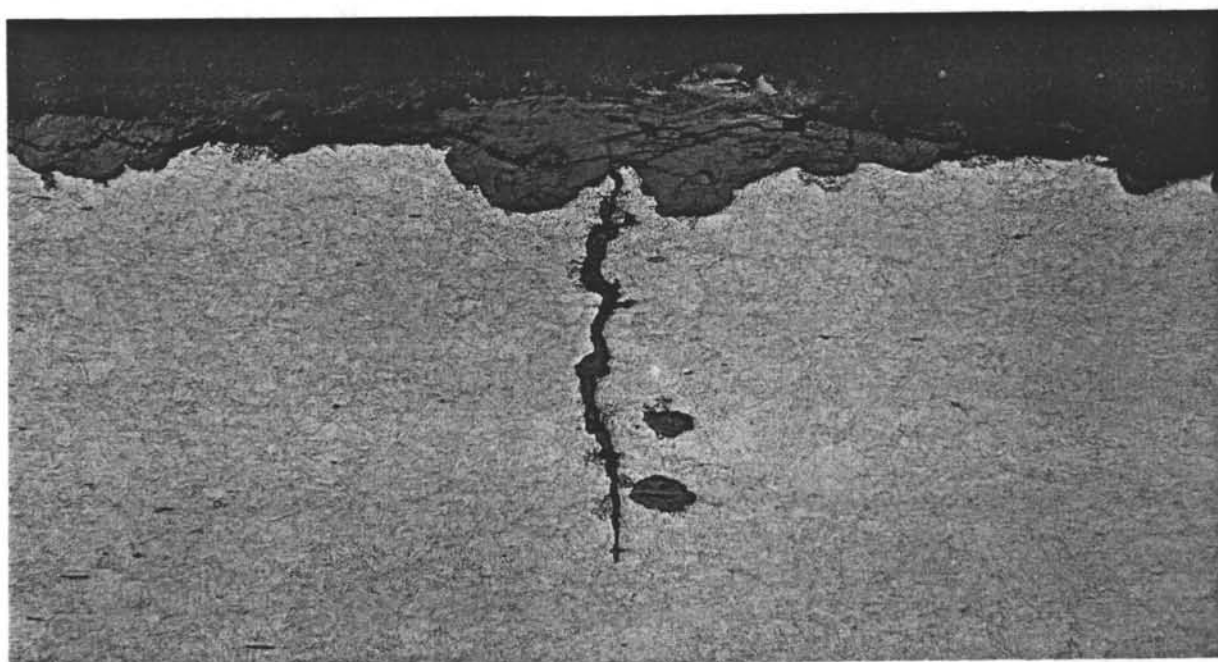
Etched in picral

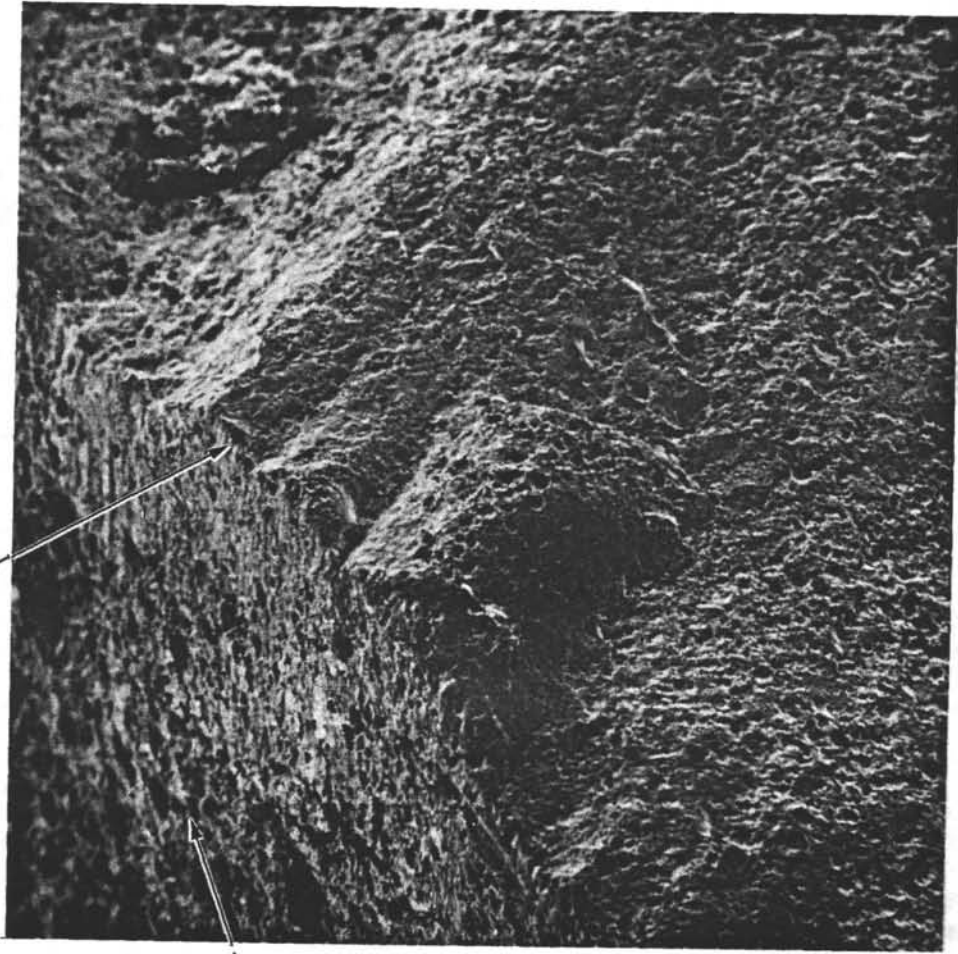Cracks on the outside surface of Sample B.   X200.

Figure 9

General corrosion and pitting on the flat fracture
surface of Sample B. Not etched. X250.

Figure 10

Flat fracture surface of Sample B after removal
of corrosion product. X250.
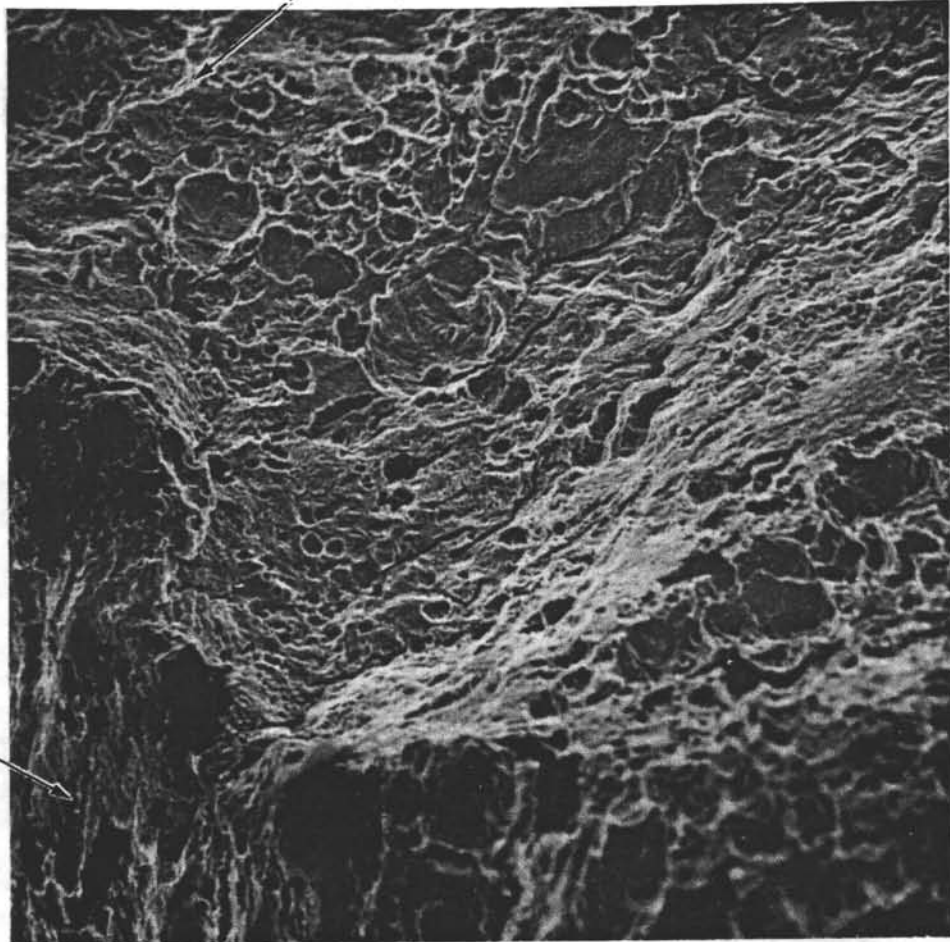
Figure 11

Area A

Outside surface

Edge of the flat fracture at the outside diameter showing ratcheting. X50.
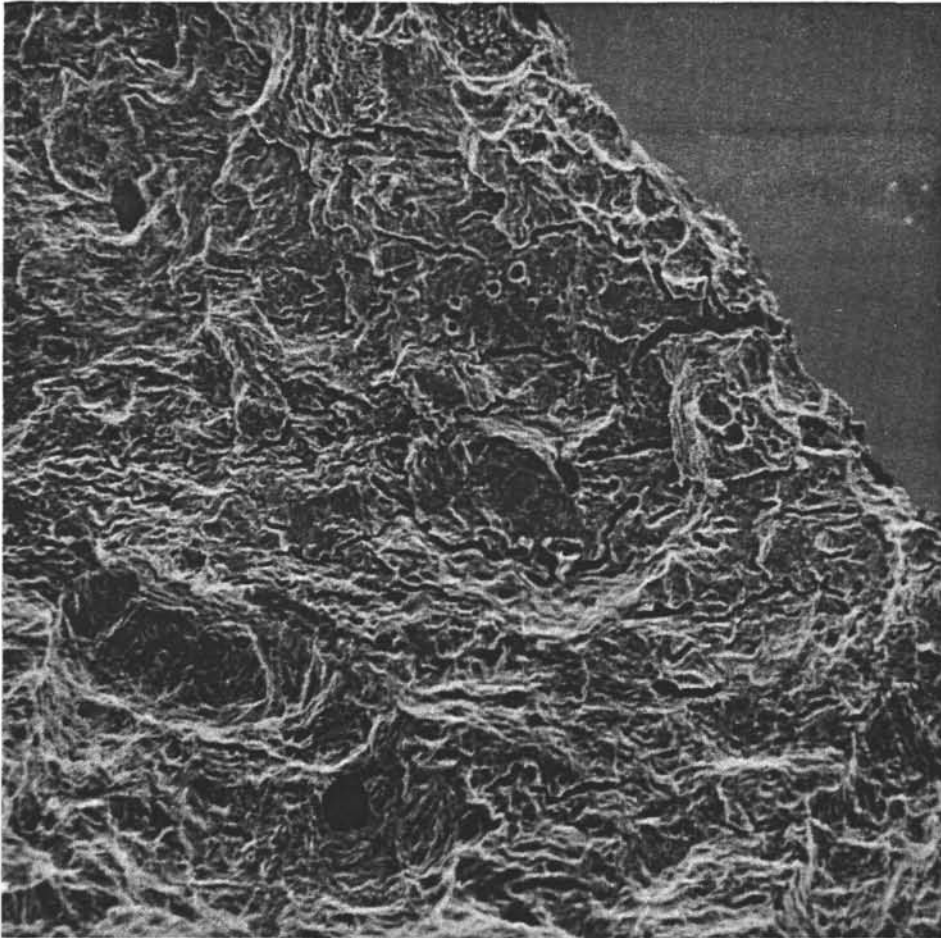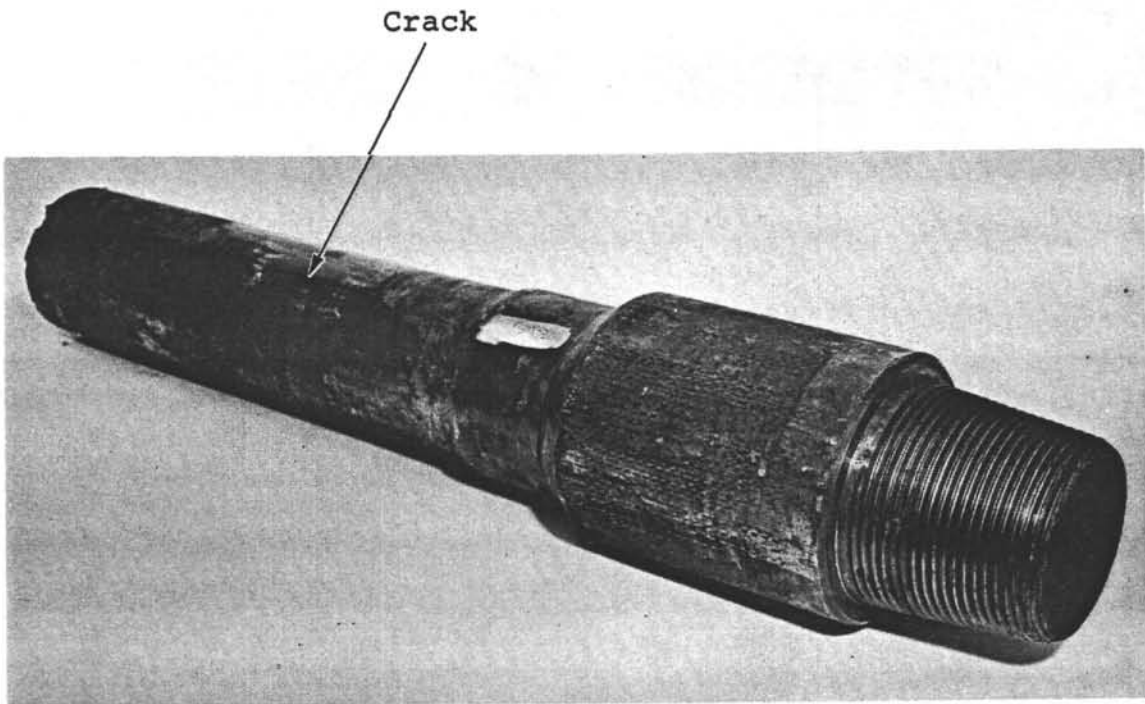
Fracture surface

Outside
surface
(OD)

Branch cracks on flat fracture surface of Sample B.
Area A in Figure 12.   X500.

Inside
surface

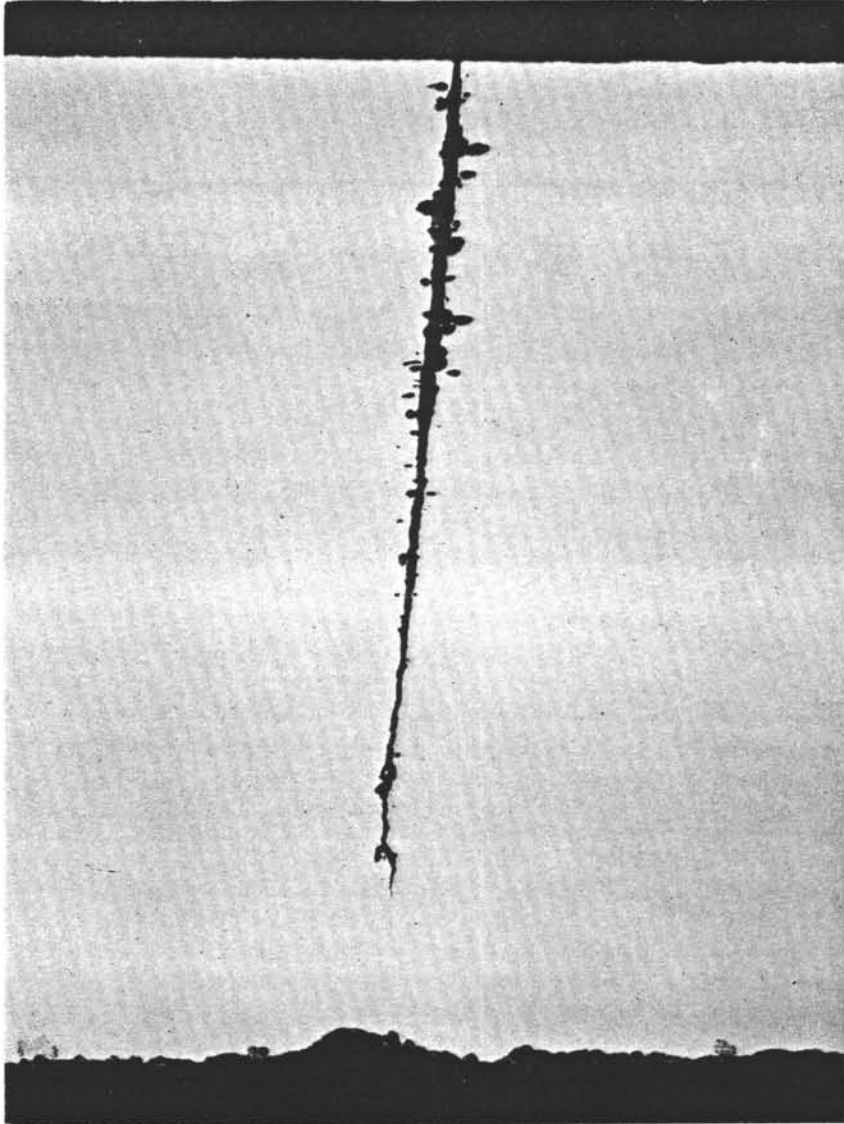Branch cracks on flat fracture surface of Sample B.
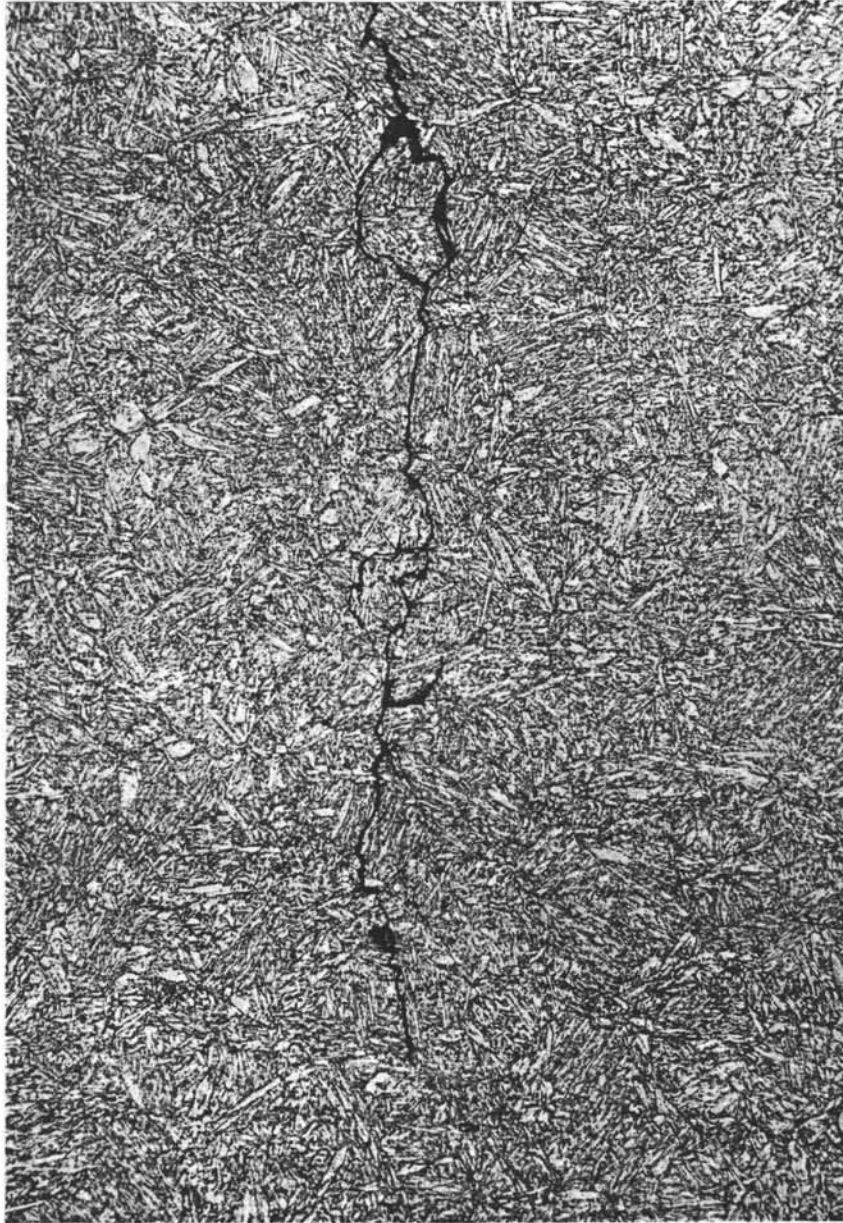X500.

Figure 14

Crack

Sample C showing location of crack in relation to the pin end.

Outside surface

Inside surface

Crack in Sample C showing lateral pitting
corrosion. Not etched. X15.

Figure 16

Tip of the crack shown in Figure 16. Etched in
super picral. X500.

Crack initiation area

Outside
surface
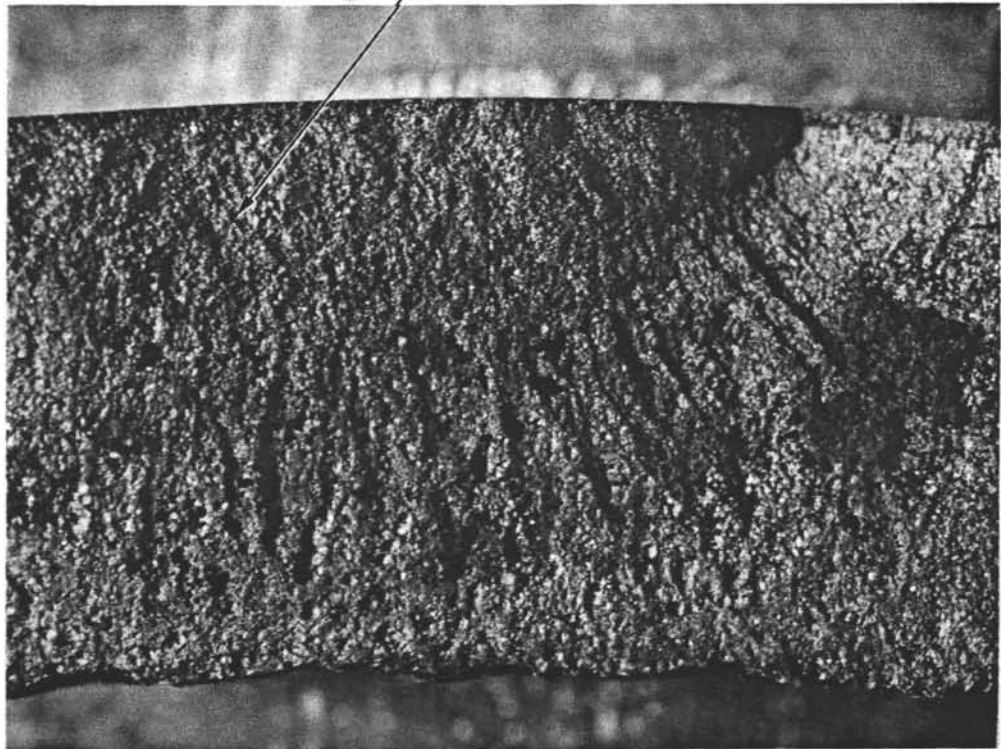
Inside
surface

Fracture surface at crack initiation site after
removal of corrosion product from Sample C. Sec-
tions shown in Figures 16 and 17 were taken at an
area adjacent to the right edge of this picture.
About 9X.

LM-1870-C4-1

Figure 18

APPENDIX B-3

DOCKSIDE PRELIMINARY EXAMINATION OF
FAILED S-135 STEEL DRILL PIPE FROM
D/V GLOMAR CHALLENGER AND ASSOCIATED
METALLURGICAL FAILURE ANALYSIS OF
FRACTURED DRILL PIPE, LEG 83, HOLE 504B

REPORT

on

DOCKSIDE PRELIMINARY EXAMINATION OF
FAILED S-135 STEEL DRILL PIPE FROM
D. V.V. GLOMAR CHALLENGER AND ASSOCIATED
METALLURGICAL FAILURE ANALYSIS OF
FRACTURED DRILL PIPE
LEG 83, HOLE 504B

Contract No G 12696-3058

to

DEEP SEA DRILLING PROJECT

March 30, 1982

by

D. R. McIntyre

BATTELLE
Houston Operations
2223 West Loop South
Houston, Texas

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(continued)

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SUMMARY

Deep internal corrosion pitting led to fatigue cracks in four pieces of 5 inch
I.D. S-135 drill pipe used for the Deep Sea Drilling Project (DSDP) on the
D.S. GLOMAR CHALLENGER. Two of these pieces fractured during leg 83 of the
DSDP. H_2S did not accelerate crack initiation or propagation. The mechanical
properties, chemistry and microstructure of the drill pipe itself were normal
and within API specification 5AX. The external inorganic zinc coating was
effective in preventing corrosion on the outside surface.

The root cause of these failures is the inability of the internal magnetic
flux leakage inspection unit to pick up the severe general corrosion pitting
and cracking present on these pieces. The drill string was inspected four
months before failure; these pieces should have been retired at that time. A
different inspection method which gives a more positive, quantitative measure
of wall thinning, such as mechanical caliper surveys, should be used on the
drill string in future.

INTRODUCTION

The Deep Sea Drilling Project analyzes geological core samples collected by
the drilling ship Glomar Challenger. On November 30, 1981, the D.S. Glomar
Challenger was drilling between Panama and the Galapagos Islands on DSDP Hole
No. 504B in 3473 meters of water. While drilling at a bottom hole depth of
4535 meters, the drill string parted at 4048 meters. (Figure 1)

·The broken section of drill pipe was fished from the hole. Drilling continued
until December 14, 1981, when the drill string parted again at a depth of 4543
meters. The bottom hole depth at the second failure was 4761 meters. When
the broken string was pulled back onboard ship, water was observed leaking
from three other sections of cracked pipe. The power sub, to which the string
is attached at the swivel head, was also cracked.

At the time of the failure, the D.V.S. Glomar Challenger was coring through basalt under the following conditions:

Torque:	1250-1300 Foot Pounds
R.P.M.:	45-60
Drilling Fluid:	Surface Seawater

Drill String

Outside diameter:	5 inches
Nominal wall Thickness:	.362 inches
Weight/Foot:	19.5 Pounds
Total Weight:	F1 = 430,000 Pounds
	F2 = 630,000 Pounds
Weight at Point of Failure:	F1 = 75,000 Pounds
	F2 = 45,000 Pounds
Grade:	S-135
Age:	≈ Seven Years
Coatings:	o.d. = Dimetcote D-4
	Inorganic Zinc
	i.d. = None

Surface seawater is pumped down the hole as a coolant and drilling fluid. Bentonite mud is used to flush the cuttings between cores.

Bottom samples of seawater returning up the outside of the drill string showed 0.5 ppm - 0.7 ppm H_2S. This suggests H_2S concentrations in the formation on the order of less than or equal to 2 ppm (0.01 psia). The H_2S would have been in contact only with the outside of the drill string, since surface seawater is pumped in through the inside.

After the second failure, the coring operation was abandoned and the drill string brought back onboard. As the string was being disassembled, water was observed leaking from three more joints of pipe, indicating cracks in these joints. The exact depth and location of these cracked joints was not recorded before the string was disassembled and racked.

Visual Examination

The two broken joints were labeled F1 (first fracture) and F2 (second fracture). (Figure 2) Both fractures propagated perpendicular to the

longitudinal axis of the pipe over approximately 25 percent of the circumference of the pipe with no noticeable plastic deformation. The final fracture was in shear on both joints, with the fracture surface running at approximately 45 degrees to the longitudinal axis of the pipe.

Corrosion and mechanical damage had smoothed and obscured much of the surface on both fractures. However, "rachet marks" or radial marks, were still present indicating a series of fracture initiation sites at deep, broad corrosion pits on the inside surfaces (Figures 3 and 4). At the bottom of the deepest pit on F1, the remaining wall thickness was 0.266 in. At the bottom of the deepest pit on F2, the remaining wall thickness was 0.249 in.

The three cracked joints were labelled A, B, and C. The crack in Sample A was detected in two out of three trials during the on board inspection with the internal magnetic flux leakage unit. The cracks in joints B and C could not be detected with the magnetic flux leakage unit. Areas which appeared to be cracked were cut out and sent in for analysis. The three samples are shown in Figure 5.

The through-wall cracks in joints A and B were found with dye penetrant and broken open to expose the fracture surfaces. Figures 6 and 7 show the surface of the crack in joint A. Figures 8 and 9 show the fracture surface from joint B.

Both fractures showed essentially the same features as F1 and F2. The surfaces were heavily encrusted with corrosion products, but ratchet marks indicated a series of fracture initiation sites at the bottom of pits on the inside surface. At the thickest point the wall thickness of joint A was 0.330 inches; at the base of the pit which formed the fracture initiation site the remaining wall thickness was 0.232 inches. On Sample B, the thickest remaining area was also 0.330 inches. At the fracture origin, at the base of the pits, the remaining wall thickness was 0.240 inches.

On Sample C, dye penetrant testing revealed no cracks, even in the area with heavy slip marks. The damaged area was quartered, and each quarter was bent

on a tensile machine to open up any cracks present. However, no cracks were found. Apparently the cracked part of the joint was not in the section sent in for examination.

Scanning Electron Microscope Fractography

The fracture surfaces from the four cracked samples were examined with scanning electron microscope. All of the fractures were covered with corrosion products. After cleaning with an alkaline ultrasonic cleaner and replicating tape, the corrosion products were removed. After cleaning the fracture surfaces were relatively flat and featureless. No intergranular facets or fatigue striations were observed during observation at 50 to 5000x. From the examination it was determined that the microscopic surface features on these fractures had been obliterated by corrosion. However, SEM examination confirmed that all the fractures initiated along the inside surface of the pipe.

Metallographic Examination

Metallographic examination was performed on sections taken through fracture initiation sites on samples F1, F2, A and B. Figures 10 and 11 show the fracture profile at an initiation site from Sample F1. Heavy corrosion damage was observed along the inside edge of the pipe. The fracture profile was relatively straight, transgranular and non-branching. Figures 12 and 13 show the fracture profile from Sample A, which had a through-crack that had not separated. The crack in Sample A was similar to that shown in Figures 11 and 12 in that it initiates in a corrosion pit, propagates transgranularly, is relatively straight and non-branching.

The microstructure of the base metal on all the metallographic samples showed essentially the same features: tempered martensite of medium grain size, with no significant concentrations of anomalies which might have affected crack initiation or propagation.

Mechanical Properties Tests

Two specimens were removed from each of the joints of drill pipe for
mechanical properties tests. Table 1 presents the results. All the joints
met the API 5AX specification with regard to strength. One of the tensile
specimens from Sample B could not be analyzed because it broke through an
undetected secondary fatigue crack on the inside surface of the pipe.

Chemical Composition

Each of the pipe joints was analyzed for chemical composition using wet
chemistry. Table 2 presents the results. API specification 5AX requires
limits only on phosphorous and sulfur, which all the joints met.

Discussion

All the fracture initiation sites on the cracked pipe joints were on the
inside surface, the side which had suffered seawater corrosion damage.

The seawater used as drilling fluid is pumped from the surface down the pipe,
then up around the pipe O.D. to dissipate on the sea floor. Consequently the
environment at the crack tip would be exclusively aerated seawater. The H_2S
encountered in the formation would have had no effect on these fractures.

This is borne out by the fracture profiles of all the cracks. The fracture
profiles are exclusively transgranular, relatively straight and non-
branching. These characteristics indicate failure by corrosion fatigue.
Corrosion fatigue, of course, is the most likely fracture mode for drill pipe
because of the cyclic stress environment. By contrast, sulfide stress
cracking in high-strength steels is normally intergranular, with considerable
crack branching.

The deep, broad pits at the fracture origins had reduced the wall thickness at
the points of origin to approximately 64 percent of the original.
Consequently, the stresses at these points could be expected to be at least 37
percent higher than on a new piece of pipe. The stress concentration factor

from the pit geometry would make the effective stresses higher still.

The mechanical properties of the drill pipe met the appropriate API specifications in all respects. Yield strength, tensile strength and ductility were well beyond the specified minimums on all specimens except one from Sample B. This specimen had several service related secondary fatigue cracks which went undetected during the machining of the tensile specimen. On loading in the tensile test machine these cracks caused failure at uncharacteristically low load and elongation. However, these secondary cracks, which were not more than 0.07 inch deep, added another confirmation that the failure was due to corrosion fatigue starting on the inside surface of the pipe.

Chemistry requirements in API specification 5AX are largely left to the manufacturer's discretion with the exception of phosphorous and sulfur. On all specimens tested, these elements were well below the specification maximums. The carbon, chromium, nickel and molybdenum contents of these specimens indicate that this drill pipe was made of Carbon-manganese- 0.5 molybdenum steel.

Relatively little corrosion took place on the outside surfaces of the drill pipe. The outside surfaces had been coated with Dimetcote D-4 inorganic zinc coating. The zinc-rich coating provides cathodic protection to the steel during immersion or storage, preventing the corrosion damage that terminated the life of the fractured samples. In 1974, when this pipe was purchased, the technology for applying inorganic zinc coatings to the inside of small-diameter pipe was not well developed. The replacement load of drill pipe has been zinc-coated both inside and out, which should effectively eliminate the corrosion pitting that caused these failures.

The deep pitting and general corrosion on these drill pipe joints accumulated over several years. Although all the drill pipe on the Challenger was inspected four months prior to the failure, these pitted and corroded joints were not rejected. At dockside, the 3-inch long through-wall crack in Sample A was detected twice in three trials with the magnetic flux leakage unit. The through-wall cracks in Samples B and C were not detected during the dockside

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examination, nor were any of the numerous secondary cracks in Sample B found with the magnetic flux leakage unit.

Magnetic flux leakage inspection has inherent limitations in that it cannot measure remaining wall thickness. In addition, the internal inspection unit used on the Challenger generates a relatively small magnetic field compared to the external inspection units in more general commercial use. Consequently the resolution can be expected to be lower. Accurate, quantitative inspection data are crucial for making timely retirement decisions. Consequently an upgraded inspection system would definitely be a benefit.

The requirements for an inspection system for this particular application are as follows:

1. ability to inspect the pipe on board ship, in the racked, horizontal position

2. ability to quantify remaining wall thickness

3. ability to detect corrosion pitting and quantify pit depth

4. ability to locate corrosion fatigue cracks in their early stages.

Requirement one, on-board inspection, effectively prevents the use of any external inspection system since the close spacing of the pipe racks on the Challenger and the rubber drilling collars limit access to the outside surface of the pipe. However, no single internal inspection system can fulfill requirements 2, 3 and 4. Mechanical caliper surveys probably come closest in that wall thickness and pit depth can be obtained. However, mechanical calipers cannot detect corrosion fatigue cracks. An ultrasonic inspection system could be designed with a ring of multiple transducers for both angle-beam crack detection and straight-beam wall thickness measurement. However, such systems would have to be custom-built since they are not commercially available. A compromise may be necessary, using an on-board mechanical caliper survey and yearly or bi-annual dockside inspection with an external magnetic flux leakage system.

Conclusions

1. Failure of the drill string on Leg 83 was due to corrosion fatigue.

2. The fatigue cracks initiated at deep, broad corrosion pits on the inside surface of the pipe.

3. The H_2S encountered in the formation had no effect on these failures.

4. The mechanical properties of the drill pipe met API specification 5AX.

5. The chemical composition of the drill pipe met API specification 5AX.

6. The root cause of these fractures was the failure of the internal inspection system to detect the advanced corrosion damage on the inside surface of the drill pipe.

7. The inorganic zinc coating on the exterior of the drill pipe was effective in preventing corrosion and consequently should extend the useful service life of pipe internally coated with inorganic zinc.

TABLE 1
MECHANICAL PROPERTIES OF CRACKED DRILL PIPE
(AVERAGE OF TWO SPECIMENS)

Sample	Yield Strength, ksi	Ultimate Tensile Strength, ksi	Percent Elongation
F1	144.1	157.7	15.5
F2	147.8	149.7	18.0
A	151.8	163.0	14.5
B*	154.4	164.1	15.0
C	145.6	158.2	15.0
API Specification 5AX	135-165	145 min	9.5 - 10.5 +

* Value From One Specimen. The second specimen broke at a secondary fatigue crack.

+ Specified minimum percent elongation is calculated from the specimen cross-sectional area using the formula:

$$e_1 min = 625.000 \; \frac{A^{0.2}}{U^{0.9}}$$

where A - specimen area, in^2 and u = specified minimum UTS, psi.

TABLE 2
CHEMICAL COMPOSITION OF FAILED DRILL PIPE

ELEMENT	F1	F2	A	B	C	API SPECIFICATION 5AX
C	0.32	0.32	0.30	0.30	0.30	n.s.*
Mn	1.80	1.90	1.47	1.84	1.52	n.s.*
P	0.026	0.012	0.021	0.015	0.014	.040 max
S	0.012	0.012	0.011	0.013	0.007	.060 max
Si	0.14	0.22	0.05	0.09	0.16	n.s.
Ni	<0.02	<0.02	<0.02	<0.02	0.02	n.s.
Cr	<0.02	<0.02	<0.02	<0.02	0.05	n.s.
Mo	0.45	0.47	0.40	0.48	0.39	

n.s. - not specified

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MUDLINE — 3473 METERS

BASEMENT CONTACT — 3743 METERS

WATER SAMPLE: 80 C + H_2S — 3948 METERS

TOP FISH #1 — 4048 METERS

WATER SAMPLE: 115 C + H_2S — 4263 METERS

487 METERS

OLD HOLE TO 4307 METERS

4335 METERS

4399 METERS

TOTAL DEPTH FISH #1 — 4535 METERS

TOP FISH #2 — 4543 METERS

218 METERS

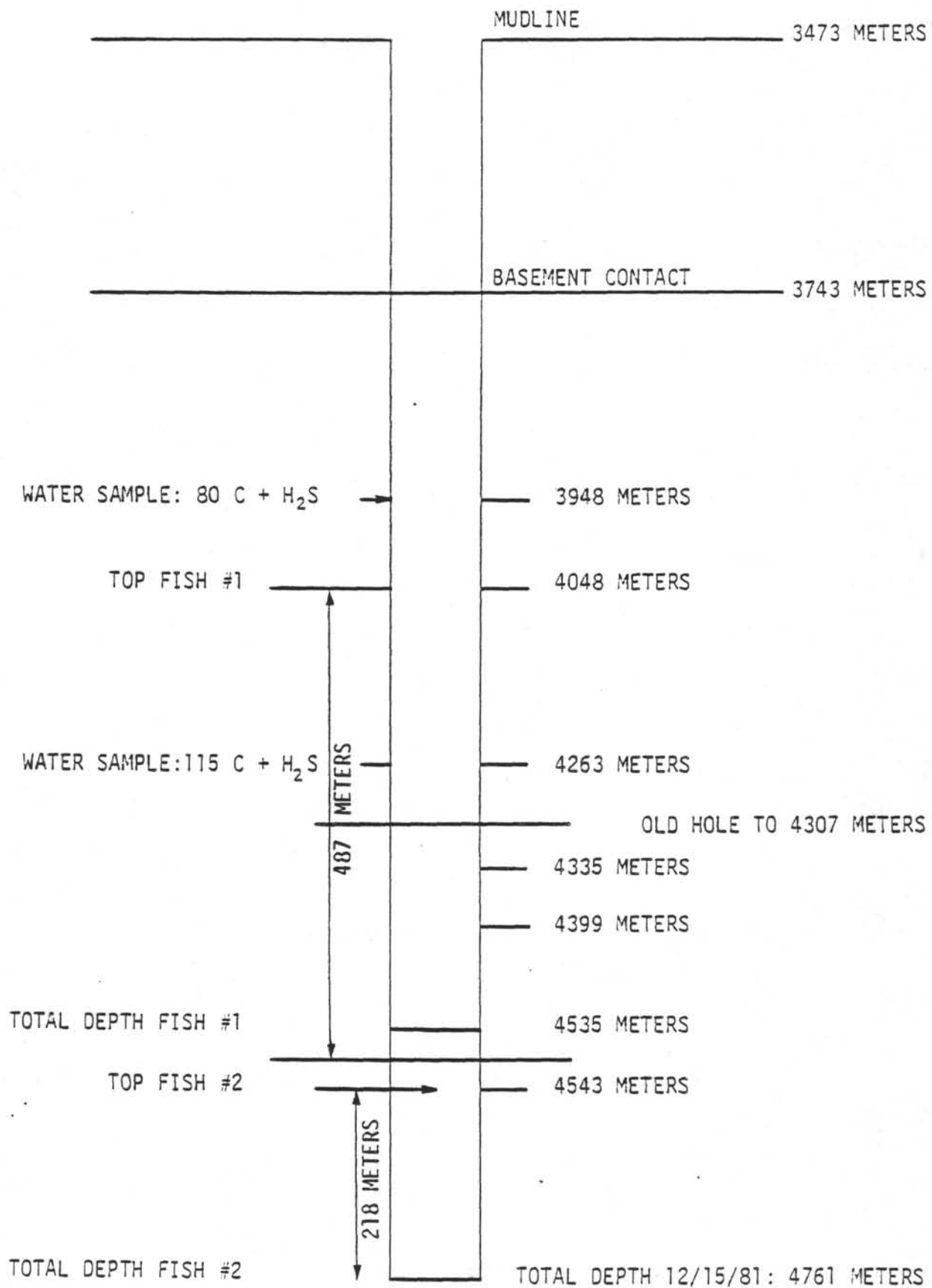TOTAL DEPTH FISH #2 — TOTAL DEPTH 12/15/81: 4761 METERS
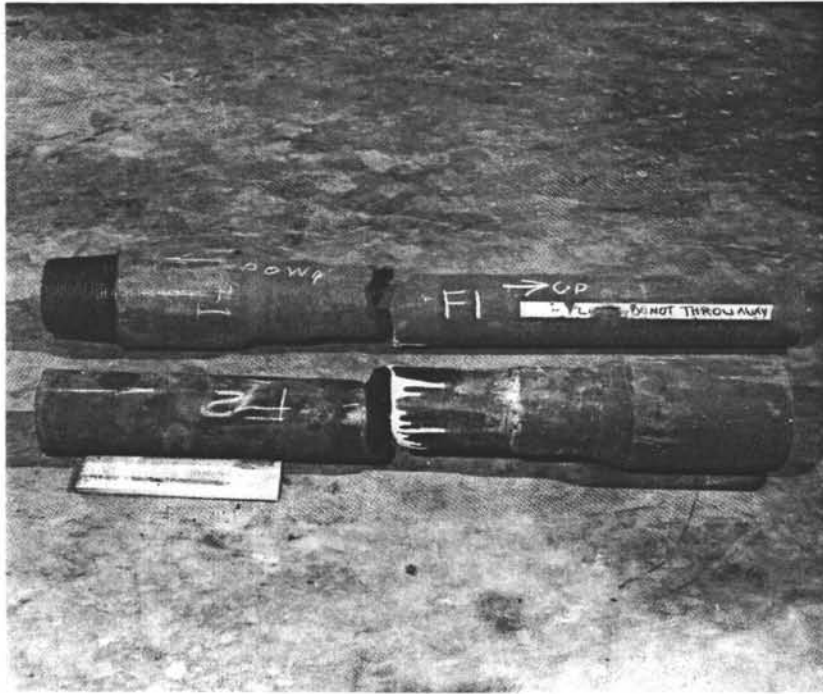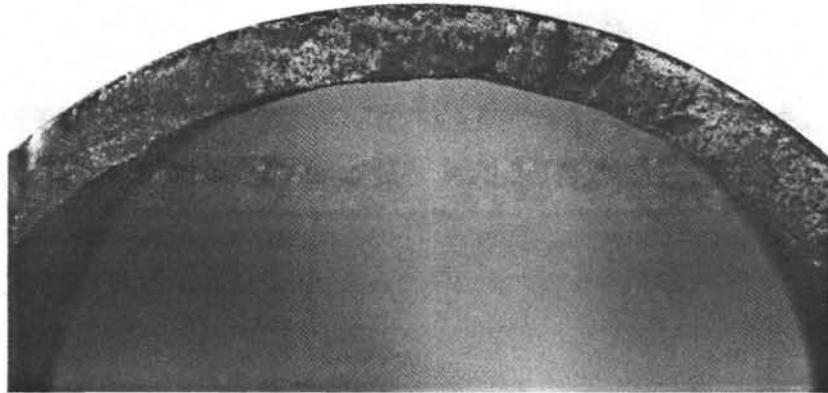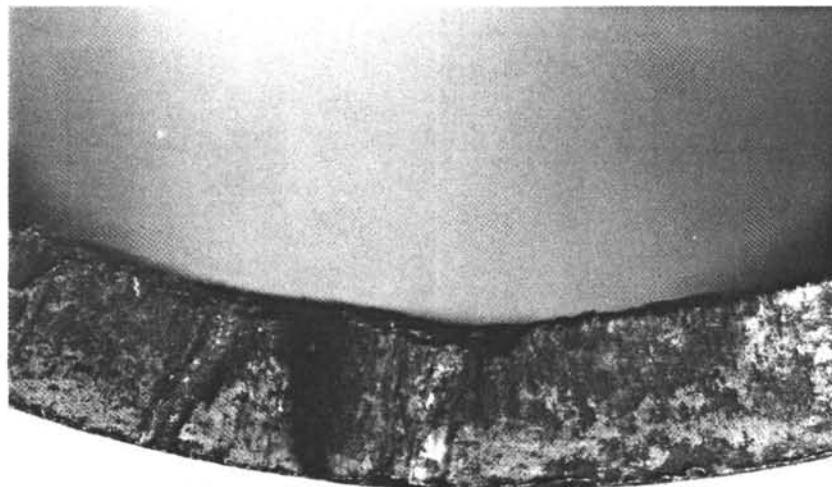
FIGURE 1. Schematic of DSDP Hole 504B.

BHO 1444-1

FIGURE 2. FRACTURED PIECES OF DRILL PIPE. (NOTE:
WHITE SUBSTANCE ON F-2 BOX END FRACTURE
IS SILICONE RUBBER FOR PROTECTING THE
FRACTURE SURFACE)

BHO 142 2

FIGURE 3.   FRACTURE SURFACE OF F 1.
        ≈ 1x
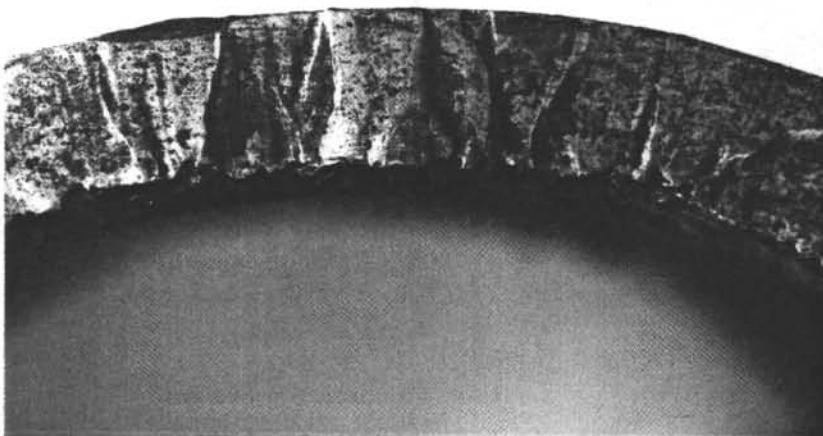

BHO 142 1

FIGURE 3A.   CLOSE-UP OF FRACTURE FROM F 1.   RATCHET
        MARKS INDICATE ORIGINS ON I.D. SURFACE.
        ≈ 3x

BHO 1424

FIGURE 4.   FRACTURE SURFACE OF F2.
             ≈1x

BHO 1423

FIGURE 4A.   CLOSE-UP OF FRACTURE FROM F2.   RATCHET MARKS
              INDICATE ORIGINS AT PITS ON I.D. SURFACE.
              ≈3x
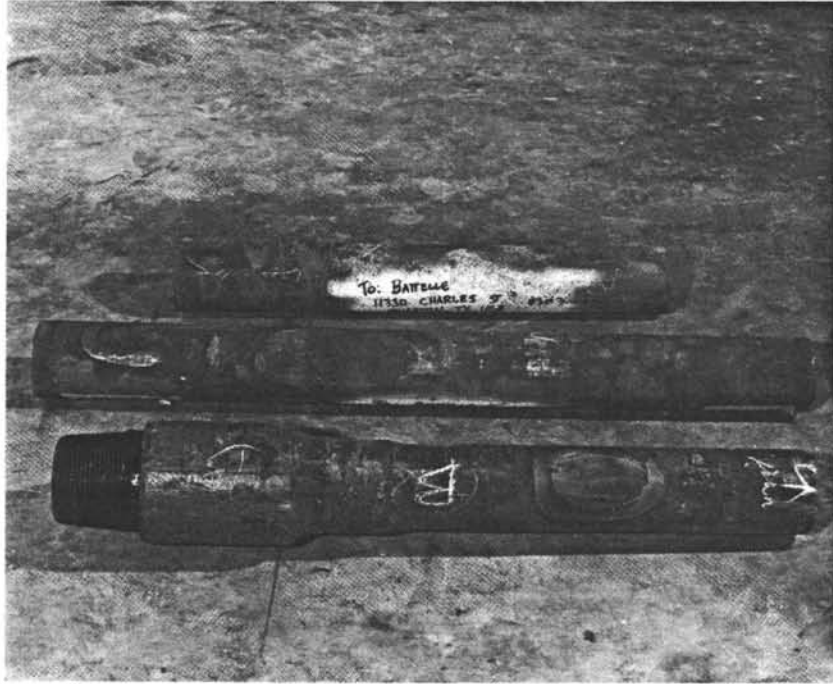
BHO 1444-5

FIGURE 5. CRACKED PIPE JOINTS.

BHO 1436

FIGURE 6.   FRACTURE SURFACE OF CRACK EXPOSED IN SAMPLE A.
             1x

BHO 1435

FIGURE 7.   CLOSE-UP OF FRACTURE SURFACE FROM SAMPLE A.
             3.8x

FIGURE 8.   FRACTURE SURFACE EXPOSED IN SAMPLE B.
            2.2x

FIGURE 9.   CLOSE-UP OF FRACTURE SURFACE FROM SAMPLE B.
            3.3x

BHO 1453

FIGURE 10. PHOTOMICROGRAPH FROM A SECTION THROUGH A
FRACTURE ORIGIN ON SAMPLE F 1.
62.5x, NITAL ETCH
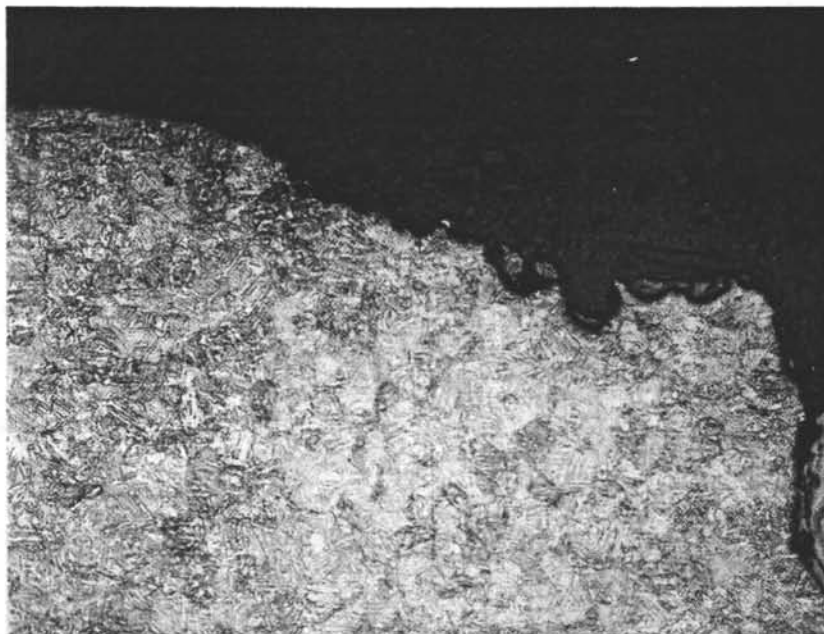
BHO 1446

FIGURE 11. HIGHER-MAGNIFICATION PHOTOMICROGRAPH OF
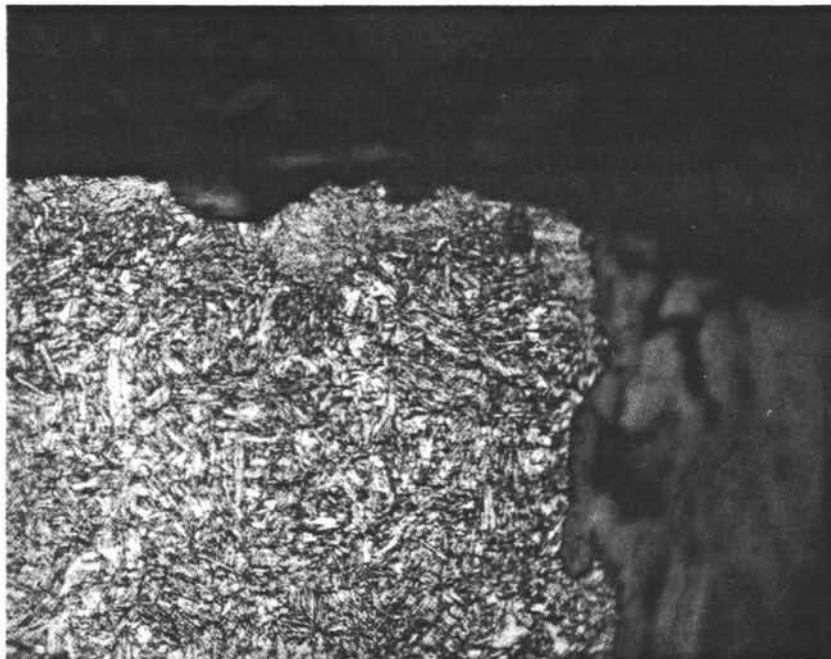ORIGIN IN FIGURE 10.
125x
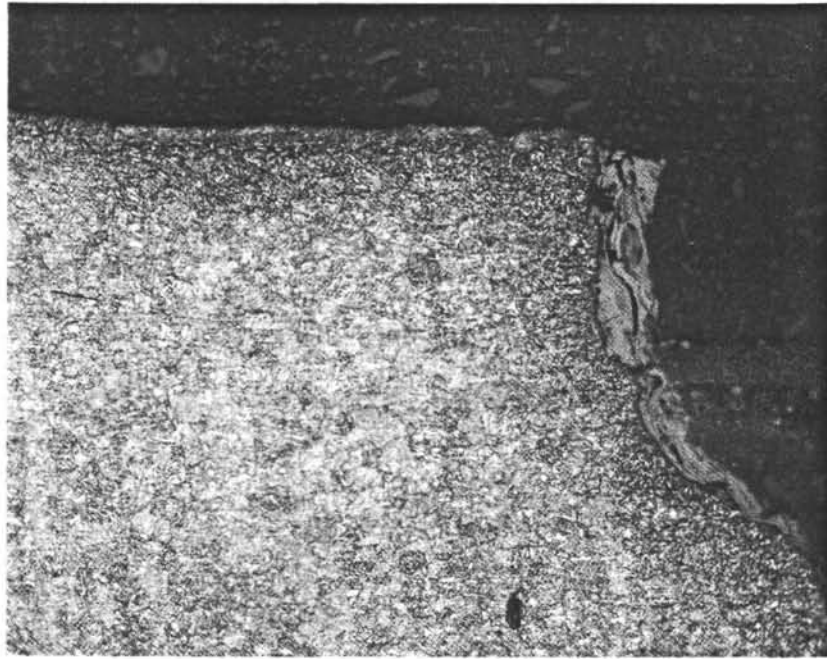
BHO 1451

FIGURE 12. PHOTOMICROGRAPH FROM A SECTION THROUGH A
FRACTURE ORIGIN ON SAMPLE A.   FRACTURE PROFILE
IS AT TOP.—
125x, NITAL ETCH

BHO 1452

FIGURE 13. HIGHER MAGNIFICATION PHOTOMICROGRAPH OF
ORIGIN IN FIGURE 12.
500x, NITAL ETCH

APPENDIX B-4

FINAL REPORT
FAILURE OF DRILL STRING
DSDP LEG 84

April 26, 1982

Re: Failure of Drill String, DSDP Leg 84 Contract No. G 12696-3058

Enclosed are five copies of Battelle's report on the failure of the drill string, DSDP Leg 84. This report constitutes fulfillment of the April 30, 1982, reporting requirement of Contract G 12696-3058.

FINAL REPORT
FAILURE OF DRILL STRING, DSDP LEG 84

SUMMARY

Excessive strength and hardness led to hydrogen embrittlement cracking of the failed joint of a 5-inch O.D., 19.5 lb/ft S-135 drill pipe (DSDP identification number DP-568-7-2-82). Crack initiation was accelerated by the presence of a 1.5 inch by 0.045 inch deep lap, a rolled-in mill defect. The hydrogen which caused the embrittlement was generated by corrosion of the pipe's sacrificial zinc coating in sea water. Any remaining joints from this order of pipe should be hardness tested. Joints with hardness exceeding R_c38 should not be used.

Deep Sea Drilling Project   April 26, 1982

BACKGROUND

On February 7, 1982, during logging operations at DSDP 567A, the drill string
parted in the 18th joint below the rig floor. The failed joint was 5-inch
O.D., 19.5 lb/ft S-135 pipe which had been internally and externally coated
with inorganic zinc. The failed piece was one of 667 30-ft joints of S-135
drill pipe made by Jones and Laughlin's Youngstown mill in two different lots
in June and September of 1977 for DSDP. Jones and Laughlin heat numbers for
this order were 26638, 24132, 27846, 25995 (June 1977) and 32549, 27168, 27170
(September, 1977). The failed joint was loaded on the GLOMAR CHALLENGER on
November 3, 1979 at Balboa, Panama. It remained in the 'tween-decks hold of
the drill ship until January 16th, 1982. The joint had spent about 8 1/2 days
deployed in the drill string with approximately 67 total rotating hours.
Weather conditions assured bending stresses had been at a minimum. String
weight at the failure was estimated to be 370,000 pounds which equates to a
tensile stress level of approximately 70,100 psi. This value is only 52
percent of the API specified minimum yield strength (SMYS) of 135,000 psi.

A four foot section of the failed pipe joint, see Figure 1, was received at
the Battelle laboratories at the end of March.

VISUAL EXAMINATION

Visual examination revealed a flat, brittle fracture which originated at a lap
and propagated approximately 90 degrees around the pipe circumference. The
fracture mode then changed to shear overload, evidenced by a 45 degree
orientation fracture face, (Figure 2-4).

Mechanical and Chemical Properties

A section of the failed pipe joint was used to determine the mechanical and
chemical properties, see Tables 1 and 2. The yield strength was found to be
higher than allowed in API Specification 5AX. Microhardness readings, which
were taken across a mounted specimen, ranged in value from Knoop hardness 100
kg number 386 to 477, see Figure 5. These numbers roughly correspond to
Rockwell hardness numbers in the R_c 40-45 range. The mechanical properties

obtained by Battelle indicate higher strength levels than the reported mill
values, see Table 1.

Chemical properties are given in Table 2. The composition of this pipe joint
meets that required in API specification 5AX.

SEM Fractography

The fracture origin was examined in the scanning electron microscope (SEM).
Region 2 (Figure 6) shows the origin at 11X; the chevron marks pointing
towards the point of fracture initiation are clearly evident. Higher
magnification of this region reveals intergranular fracture , Figure 7. The
flat, brittle part of the fracture was exclusively intergranular cracking,
with no evidence of fatigue striations. In the shear lip, the fracture mode
switched to dimpled rupture.

Optical Metallography

The fracture was next sectioned and mounted to closely examine cross-sections
of the origin and lap. Etching revealed the material microstructure was
quenched and tempered martensite, as is expected for quenched and tempered
S-135 pipe. The cross section through the origin (Section A-A) confirmed that
the fracture mode was intergranular, Figure 8. Deformation was seen in grains
near the surface, see Figure 9. This deformation was most likely caused after
the failure. There was no evidence of high-temperature oxide on the fracture
surface or in the crack branches.

The lap (Section B-B) was found to be filled with oxide. The region directly
adjacent to the lap surface was decarburized (See Figure 10). These fractures
indicate the lap was formed during the rolling process in the mill.

DISCUSSION

The drill pipe failure shows all the elements of hydrogen embrittlement-
cracking. Hydrogen embrittlement cracking is a form of stress corrosion
cracking in which corrosion-generated hydrogen diffuses into the steel and

causes embrittlement, resulting in cracking at stresses well below the tensile
yield strength.

The high strength and hardness of this joint of drill pipe rendered it
particularly susceptible to hydrogen embrittlement-cracking. High strength
low alloy steels become increasingly sensitive to hydrogen embrittlement-
cracking as the strength is increased. Practically speaking such failures are
rarely observed in sea water if the ultimate tensile strength of the material
is less than about 180 ksi. This is one reason for the 165 ksi maximum yield
strength requirement in API specification 5AX.

The lap in the surface was apparently introduced during the tube rolling
operation, since there was a thin decarburized zone on its faces. This is
typical of mill defects which occur during hot-rolling. The lap served as a
stress raiser causing locally high stresses. API 5AX specification allows
imperfections such as this lap as long as they do not exceed 12.5 percent of
the nominal wall thickness, which in this case would be 0.045 inch in depth.
The deepest measured depth of the lap was 0.045 in. Therefore, this lap was
rejectable according to API 5AX.

The source of the hydrogen was the corrosion of the sacrificial zinc coating
on the pipe. As the zinc corrodes, hydrogen is evolved at the cathode, which
in this case would be any exposed steel. Zinc-rich coatings are a standard
corrosion prevention method in sea water and marine atmospheres; earlier
strings of zinc coated S-135 (with lower hardness levels) gave up to seven
years' service on the DSDP before failing by corrosion pitting on the uncoated
inside of the pipe. However, in addition to the corrosion protection, zinc
coating also greatly increases the amount of hydrogen being absorbed into the
steel. If the pipe's hardness and strength are excessive, thus making it
susceptible to hydrogen embrittlement-cracking, a zinc coating will cause
rapid and catastrophic cracking, see Figure 11.[1,2,3]

Since other pipe joints from this same order may have the same high stregnth,
all joints from this order are suspect. Any joints left from this order
should not be used unless their strength has been tested and confirmed to fall

within the API specification range. Direct strength evaluations, however,
require destructive testing.

It is more practical to estimate the strength of drill pipe in the field by
hardness testing. Hardness correlates well with ultimate tensile strength,
and the ultimate tensile strength can be used to predict the yield strength.
Analysis of mechanical properties data from fifty samples of S-135 drill pipe
indicates that the yield strength averages 92 percent of the ultimate tensile
strength, with a range of from 86 to 94 percent. This would indicate that, at
the upper yield strength limit of 165 ksi, ultimate tensile strengths of from
175 to 191 ksi can be expected. High-strength low alloy steels with ultimate
tensile strengths of 175 ksi will have hardnesses of approximately R_c 38.5.
Therefore, any pipe joints with hardness in excess of R_c38 should be rejected.

CONCLUSIONS

1) The strength of the failed drill pipe exceeded the API 5AX
   specification, making it unusually susceptible to hydrogen
   embrittlement

2) The fracture initiated at a lap, a rolled-in mill defect which
   was rejectable by the API 5AX specification. The presence of
   the lap caused locally high stresses and therefore accelerated
   crack initiation

3) The fracture mode was intergranular, indicating failure by
   hydrogen embrittlement

4) The hydrogen which caused the cracking came from corrosion of
   the sacrificial zinc-rich coating on the pipe. However, the
   zinc-rich coating should be safe to use if the strength of the
   pipe is kept within specification

5) Any remaining pieces of drill pipe from this order should be
   tested for hardness. Any pieces whose hardness exceeds R_c38
   should be discarded to prevent a recurrence of this kind of
   failure.

Deep Sea Drilling Project   April 26, 1982

If you have any questions concerning this report, please contact us at (713) 877-8034. It was a pleasure working with DSDP again; thank you for contacting Battelle.

Very truly yours,

Beverlee G. Steinberg   *Dale R. McIntyre*

Beverlee G. Steinberg   Dale R. McIntyre
Research Scientist   Principal Research Scientist

References

1.   "Effects of Zinc Coatings on the Stress Corrosion Cracking and
      Hydrogen Embrittlement of Low-Alloy Steel," H. E. Townsend, Met.
      Trans A, vol 6A, 877-833, Apr 1975.

2.   "A New Model of Hydrogen-Assisted Cracking in High Strength Steels"
      C. D. Beachem, Met Trans A, vol 3A, Feb 1972, 437-451.

3.   "Stress Corrosion Cracking of High Strength Steels," B. F. Brown, The
      Theory of Stress Corrosion Cracking in Alloys, edited by J. C.
      Scully, North Atlantic Treaty Organization Scientific Affairs
      Division, Brussels 1971, pp 186-204.

TABLE 1. MECHANICAL PROPERTIES OF FAILED JOINT

|	Yield Strength 0.7% offset (ksi)	Tensile Strength	Percent Elongation	Hardness (Knoop)
Failed Sample	170.8	186.3	16.0	386-477
API Spec 5AX	135.0 - 165.0	145.0 min	12.5 min	
Jones-Laughlin Mill Reports	151.4 - 162.8	166.4 - 177.7	17-25	

TABLE 2. CHEMICAL PROPERTIES

|	C	Mn	P	S	Si	Cr	Mo	Ni	AR	V
Failed Sample	0.27	1.42	0.011	0.015	0.21	0.02	0.58	<0.02		
API Spec. 5AX			0.04*	0.06*						
Jones E-Laughlin Mill Report	0.25-0.27	1.48-1.57	0.009-0.018	0.02-0.026	0.25-0.27	0.06-0.08	0.51-0.61		0.046-0.065	0.038-0.041

*maximum

115
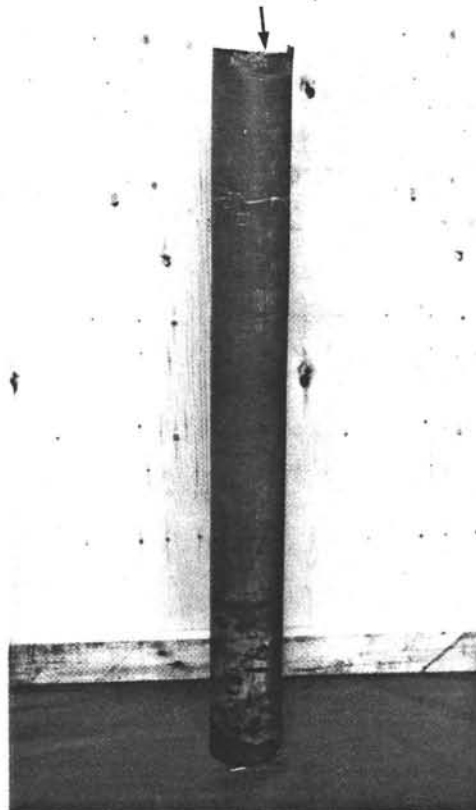
-BHO 1470

FIGURE 1. AS RECEIVED PHOTOGRAPH OF FAILED JOINT. THE
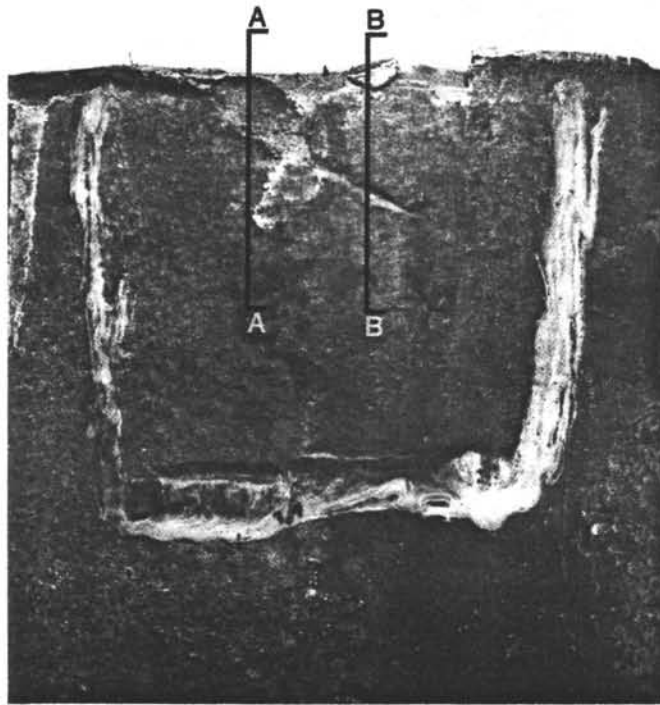ARROW POINTS TO THE FRACTURE ORIGIN AND THE
ROLLED IN LAP.
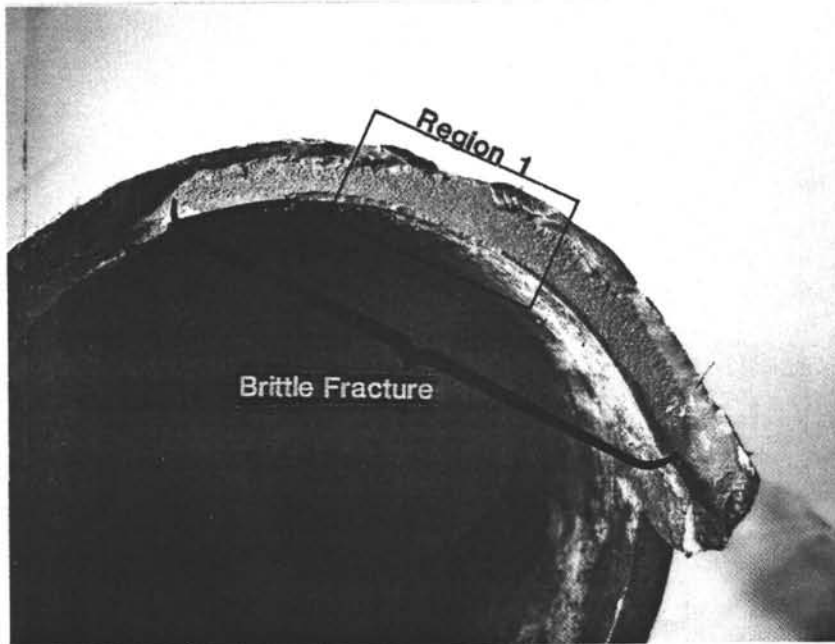
BHO 1471

FIGURE 2. THE BRITTLE FRACTURE EXTENDED APPROXIMATELY
90 DEGREES AROUND THE CIRCUMFERENCE OF THE
PIPE. THE BOXED IN AREA, REGION 1, IS SHOWN
MAGNIFIED IN FIGURE 3.
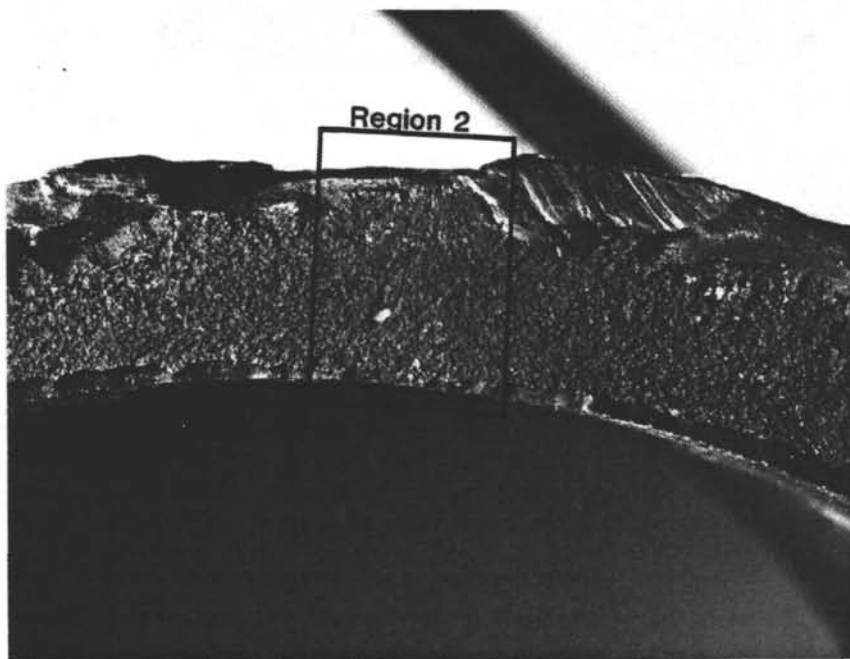
BHO 1474

FIGURE 3. A DISTINCT ORIGIN IS SEEN WITHIN THE BOXED
AREA. THIS AREA, REGION 2, IS SHOWN MAGNIFIED
IN FIGURE 6.

117

BHO 1468

FIGURE 4.   A ROLLED IN LAP IS CLEARLY SEEN IN THIS PHOTO-
GRAPH.   SECTION A-A IS AT THE ORIGIN AND DENOTES
THE LOCATION USED FOR OPTICAL METALLOGRAPHIC
STUDIES.   SECTION B-B DENOTES THE LOCATION USED
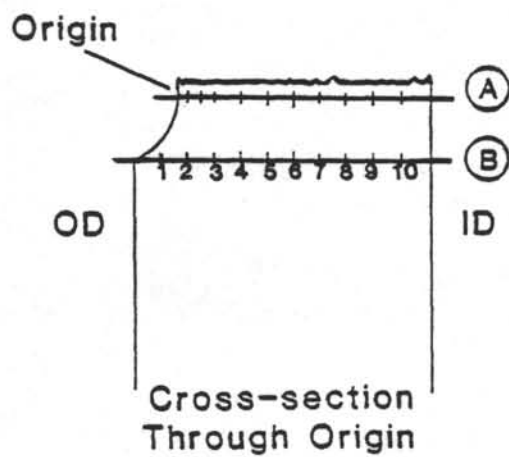FOR THE LAP METALLOGRAPHY.
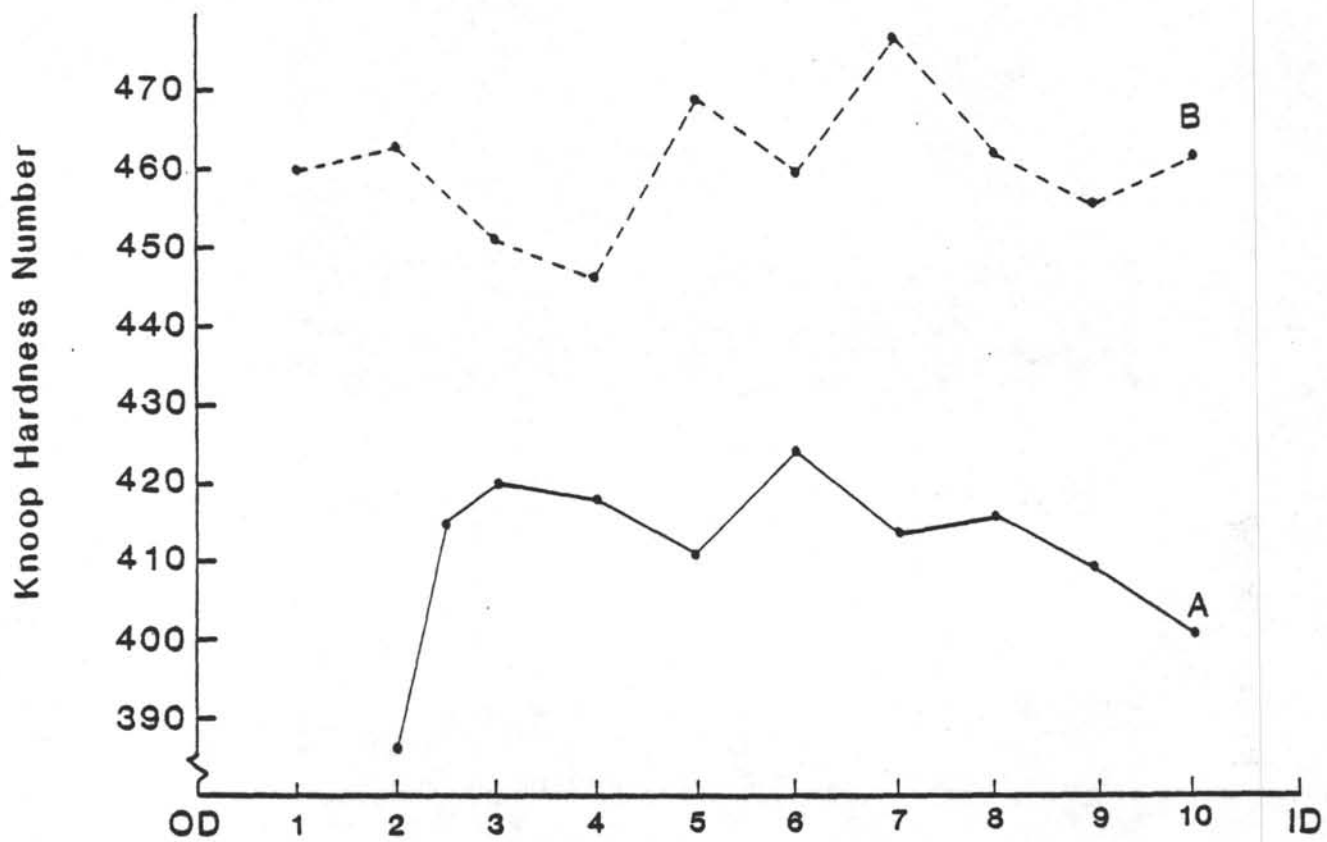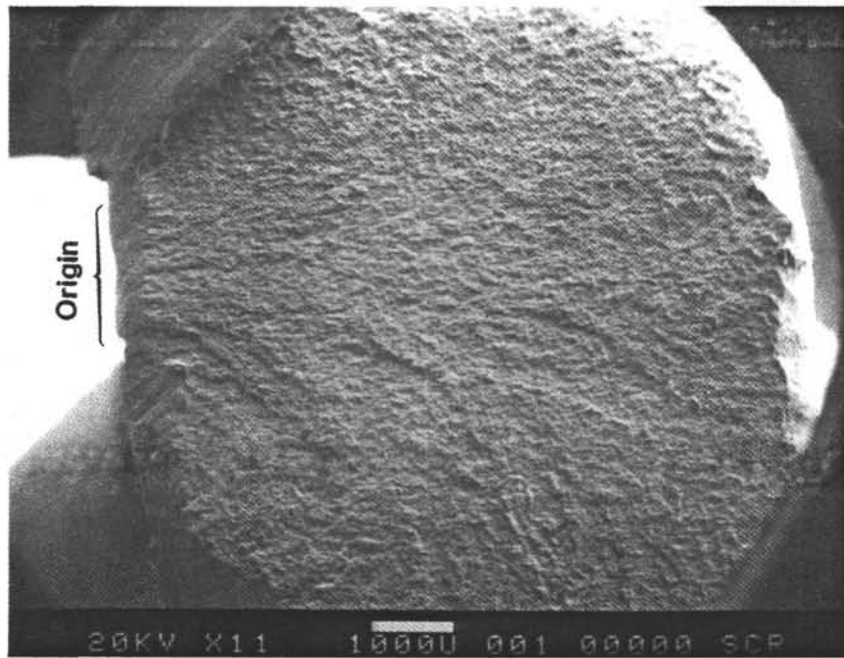
FIGURE 5. MICROHARDNESS TRANSVERSE ACROSS THE WALL THICKNESS NEAR THE ORIGIN.

BHO 1493

FIGURE 6. SEM MICROGRAPH OF REGION 2 CLEARLY SHOWS
CHEVRON MARKS POINTING TO ORIGIN (BRACKETED
REGION), 11X.
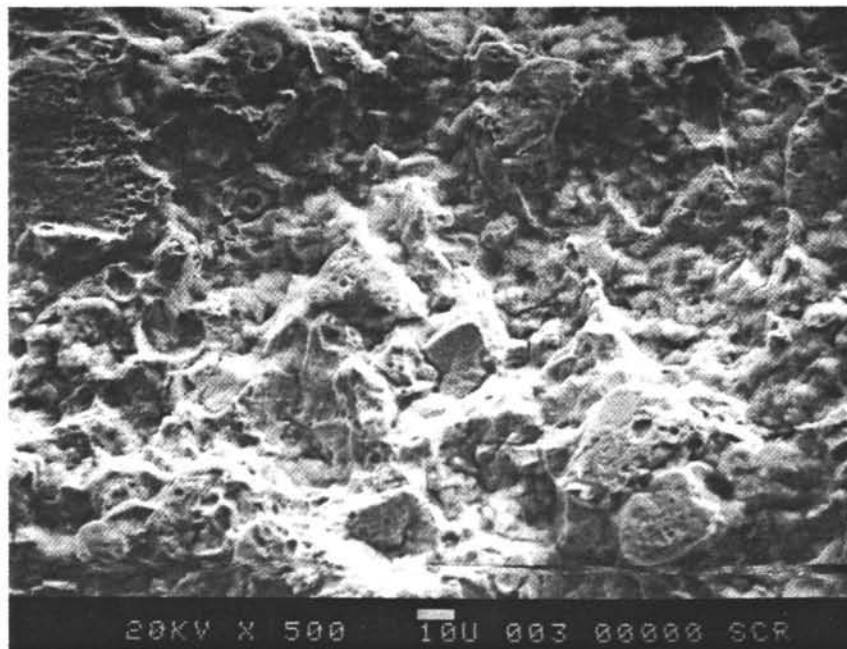
BHO 1494

FIGURE 7. A HIGH MAGNIFICATION (500X) VIEW NEAR THE ORIGIN
REVEALS AN INTERGRANULAR MODE OF FRACTURE. THIS
FRACTURE MODE IS TYPICAL OF HYDROGEN EMBRITTLE-
MENT.
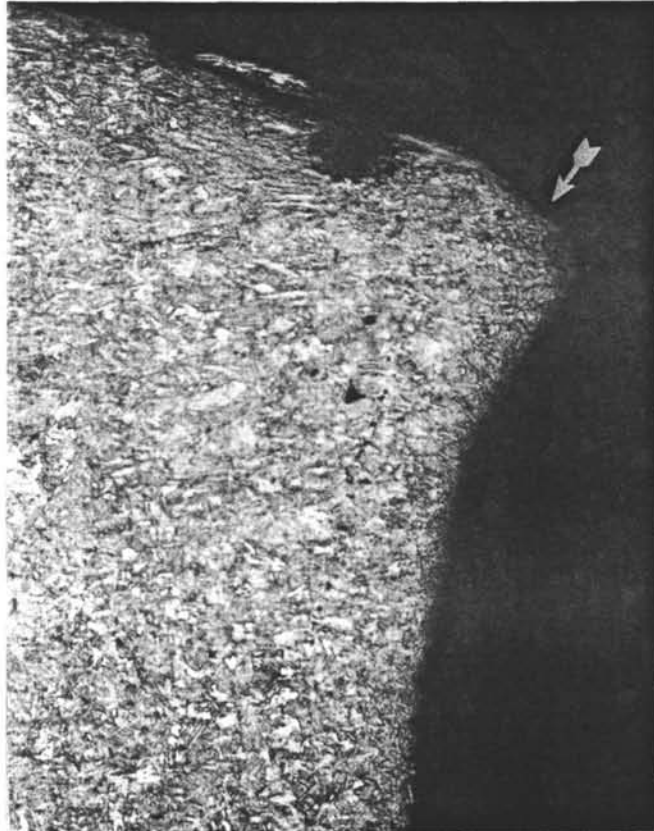
FIGURE 8. SECTION A-A THROUGH THE ORIGIN OF FAILURE. THE
TOP OF THE PHOTOGRAPH IS THE FRACTURE FACE. THE
DEFORMATION OF THE GRAINS NEAR THE FRACTURE FACE
PROBABLY OCCURRED AFTER THE FAILURE. THE ARROW
POINTS TO THE AREA OF THE ORIGIN. THE RIGHT
EDGE WAS THE LAP FACE. WHEN THE PIPE WAS RECEIVED
AT BATTELLE, THE LAP WAS BROKEN OFF HERE, SEE
FIGURE 4.

NITAL ETCH, 250X
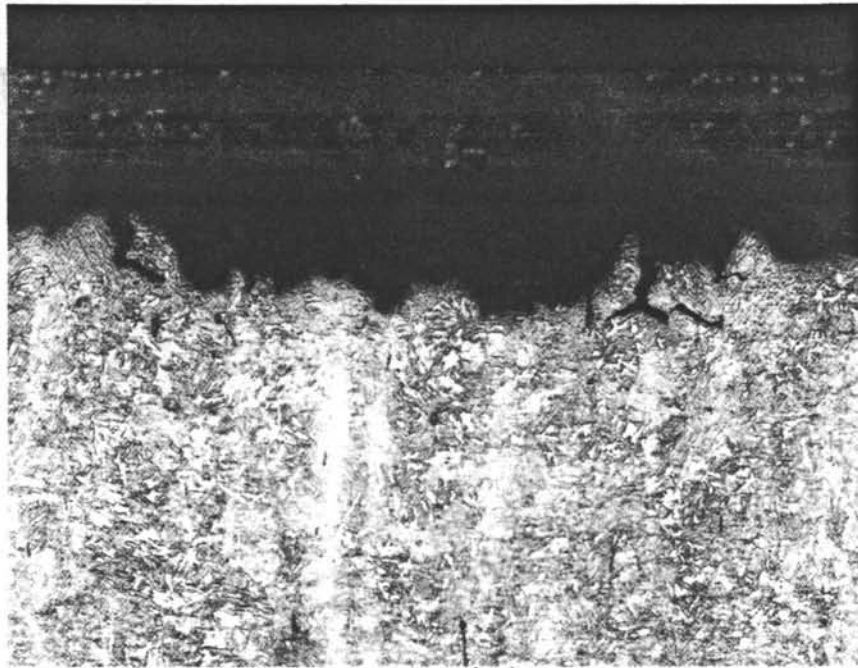
BHO

FIGURE 9. AN INTERGRANULAR CRACKING MODE OF FAILURE
CAN BE SEEN AT THE FRACTURE SURFACE.

NITAL, 250X
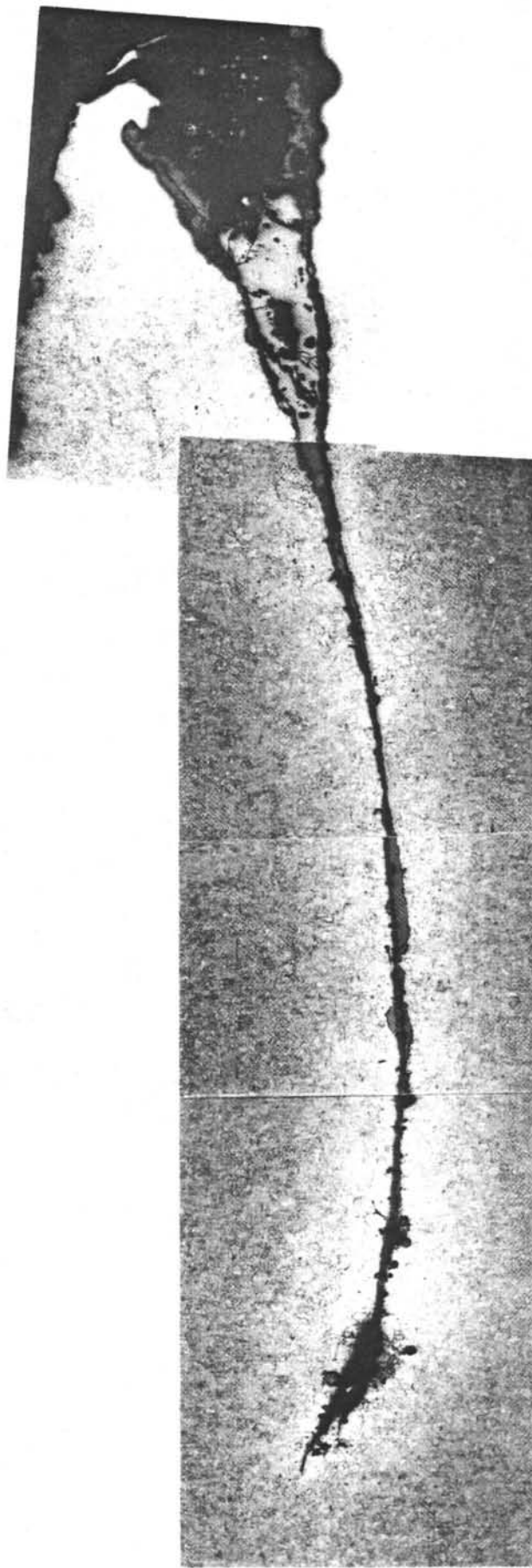
BHO 1484, 1485, 1486, 1487

FIGURE 10. SECTION B-B REVEALED A LAP WHICH WAS FILLED WITH OXIDE AND DECARBURIZED THROUGH MOST
OF ITS LENGTH. THE RIGHT SIDE OF THE PHOTOGRAPHY IS THE O.D. SURFACE.

NITAL ETCH, 125X

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FIGURE 11.   HARDNESS VERSUS CRITICAL STRESS INTENSITY FOR 4340 STEEL.

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APPENDIX B-5

FAILURE ANALYSIS OF KELLY COCK SUB
(LEG 93)

September 19, 1983

Presented herein is Battelle's report on the failure analysis of Global Marine's Kelly Cock sub from the Glomar Challenger.

SUMMARY

The Kelly Cock sub failed by brittle fracture initiating at numerous shallow fatigue cracks at the base of the last engaged thread. The fati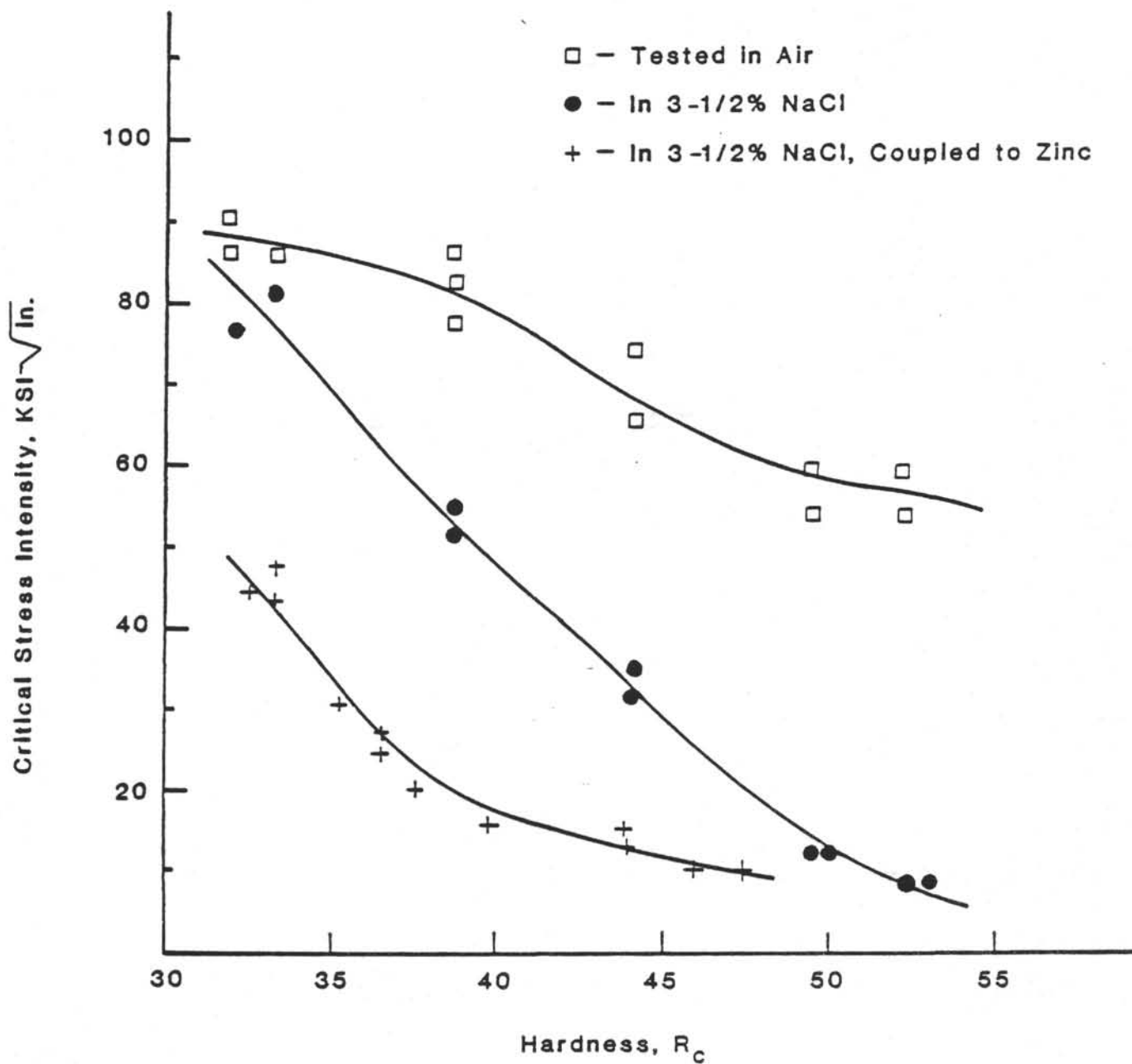gue cracks began at corrosion pits which had developed over the sub's fourteen year life. The fatigue cracks themselves appeared to be relatively recent; their number and shape suggest a recent, relatively short period of high-stress operation. The sudden and complete separation of the sub was due to brittle fracture initiating at these shallow (average 1/8th inch deep) fatigue cracks. That brittle fracture should result from such short, shallow cracks indicates that the toughness of the steel was very low. This was confirmed on metallography; the microstructure was a mixture of ferrite, pearlite and tempered martensite which would be very poor in toughness even though the hardness was only just below specification. To prevent recurrence of this catastrophic failure, replacement subs could be made of through-hardened 4340 steel for higher toughness.

INTRODUCTION

This Kelly Cock sub had seen approximately 14 years' service on the M. V. Glomar Challenger, a drill ship used for the Deep Sea Drilling Project. During June of 1983 the project was drilling an exceptionally deep hole in hard rock; three drill collars failed due to fatigue. At a total hole depth of 6219.3 meters the Kelly Cock sub fractured. At the time of failure operation and weather conditions were normal. The pipe was being raised after closing the heave compensator. The vessel roll was three degrees and the pitch two degrees. Drill string weight at fracture was 428,495 pounds.

The Kelly Cock sub is 8-7/8 inch outer diameter, with a 7-5/8 inch regular box and pin. The inside diameter is six inches. The material is AISI 4145H steel, grade S-135, heat-treated to Brinnell 285-341, with a 120 ksi minimum yield strength specification.

After torch-cutting for removal the fractured Kelly Cock sub was sent to Battelle Petroleum Technology Center in Houston for analysis.

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VISUAL EXAMINATION

The fractured Kelly Cock sub is shown in Figure 1 as received. Failure occurred in the box, in the circumferential plane, following the last engaged thread. There was no extensive plastic deformation.

Beachmarks on the fracture surface indicated a series of long, shallow fatigue zones following the root of the thread. The deepest of these fatigue zones by chance was immediately adjacent to the torch cut made during removal; at its maximum, this fatigue zone was approximately .25 inch deep (Figure 2). A number of shallower fatigue zones were observed essentially all the way around the root of the last engaged thread. These small fatigue zones averaged about 0.125 inches deep.

Chevron marks pointing back to the fatigue zones indicated that final fracture was by catastrophic brittle cleavage. Some of the chevron marks appeared to initiate on the outer surface, at deep slip marks, indicating that once final fracture began from the internal fatigue cracks, additional brittle fractures began on the outer surface and propagated inward to meet the internal cracks.

METALLOGRAPHIC EXAMINATION

Sections taken through the deepest fatigue zone and another, more typical shallow fatigue zone were polished and etched for metallographic examination. Photomicrographs from these sections are shown in Figures 3 and 4. Both cracks initiated at corrosion pits at the root of the thread; both showed the characteristic straight, transgranular path characteristic of fatigue failures.

The microstructure on both sections was mixed, showing a combination of ferrite, pearlite and tempered martensite typical of 4145H alloy quenched and tempered in thick sections.

The hardness of the sub was uniform at the root of the thread, averaging R_c28 in five measurements. This is equivalent to approximately 272 Brinnell, just below the required minimum of 285. Empirical correlations between hardness and tensile strength suggest that steel with a hardness of R_c28 would have a tensile strength of approximately 135 Ksi. If, as is typical, the ratio of yield strength to ultimate tensile strength for this item was 0.9, this would suggest a yield strength of approximately 121.5 ksi, slightly above the required minimum of 120ksi.

DISCUSSION

Items which fail in fatigue after a high number of cycles at low stresses normally show relatively few fatigue initiation sites, since cracking at one or two places relieves the stresses elsewhere. Fatigue failures produced by relatively high stresses or high stress-concentrations for relatively few cycles often show a number of fracture initiation sites around the edge of the item. This is the pattern seen on the Kelly Cock sub fracture.

For an item to develop high-stress, relatively low-cycle fatigue cracks after fourteen years in service suggests that recent operations have been relatively high-stress. Such appears to have been the case with the Kelly Cock sub, since failure of several other drill string components had recently been observed.

The sudden, catastrophic development of propagating brittle fractures from such shallow fatigue cracks indicates that the toughness of the material is low. Assuming that the Kelly Cock sub behaves like a cylindrical rod with a disc-shaped central crack of radius 3.125 (thread root diameter plus average fatigue crack depth), end loaded with 428,495 pounds and having a yield strength of 121.5 ksi, the critical plane strain fracture toughness (K_{IC}) can be calculated as

$$K_{IC} = \left[\frac{K_I}{K_o}\right] \left[2\sigma\sqrt{\frac{a}{\pi}}\right]$$

where σ = nominal applied tensile stress, a = crack radius = 3.125 inch, and the ratio K_I/K_o is taken from the graph of correction factors to K_o published by Rooke and Cartwright for plane circular cracks in cylindrical bars (from Compendium of Stress Intensity Factors, by D. P. Rooke and D. J. Cartwright, p. 249, HMSO, Uxbridge, Middlesex, UK, 1976) for the appropriate ratio of outer diameter to crack radius. For an outer diameter of 8-7/8ths, this ratio is 1.25.

The load on the sub at failure was 428,495 pounds, and its cross-sectional area was 33.6 in^2, giving a nominal tensile stress of 12,758 psi. Substituting into the equation given above indicates a critical stress intensity for brittle fracture, K_{IC} of 31,810 ksi$\sqrt{in}$.

For a steel of this hardness level such a fracture toughness can be related to Charpy impact energy using empirical correlations based on the equation

$$CVN = \frac{K_{IC}^2}{5\sigma_y} + \frac{\sigma_y}{20}$$

Substituting for the assumed values of K_{IC} and σ_y for the Kelly Cock sub gives a calculated room temperature Charpy V-notch energy of approximately 8 foot-pounds.

Such a low level of toughness is due primarily to the mixed microstructure observed on the sub. For optimum toughness a structure of tempered martensite is necessary; the mixture of ferrite, pearlite and martensite observed on the Kelly Cock sub is very much inferior to a completely tempered martensite structure. However, a mixed microstructure is inevitable on 4145 alloy steel items which exceed about one-half inch in thickness. On 4145 steel the austenite-to-ferrite reaction is so fast that even with a severe quench during heat treatment some formation of ferrite and pearlite is inevitable. For optimum toughness more highly alloyed steels such as AISI 4340H, with its slower austenite-to-ferrite reaction, are required.
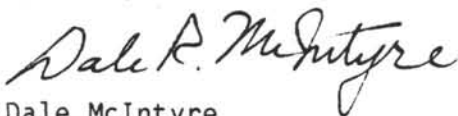
CONCLUSIONS

1) The Kelly Cock sub failed by brittle fracture initiated at fatigue cracks in the root of the last engaged thread.

2) The fatigue cracks began at corrosion pits in the thread root and were apparently associated with a recent period of relatively high-stress operation.

3) The hardness of the Kelly Cock sub was slightly below the 285 Brinell minimum required by the purchase specification. However, the yield strength is believed to be at or slightly above the specified minimum.

4) The toughness of the Kelly Cock sub, although not specified, is apparently quite low due to the presence of a mixed microstructure.

5) The low toughness caused the formation and propagation of catastrophic brittle fractures from the very shallow fatigue cracks.

6) To prevent similar brittle catastrophic failures a tougher material, such as quenched and tempered 4340 steel, will be required for replacement subs.

If there are any questions on this report, please call or write. I enjoyed working with you on this job. Thank you for calling Battelle.

Best regards,

Dale McIntyre
Principal Research Scientist

DRM:clw
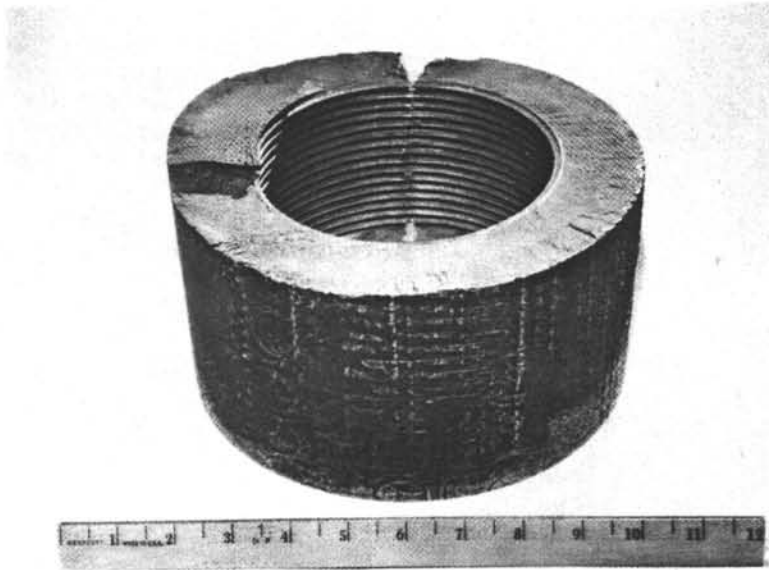
FIGURE 1. Kelly Cock sub
as received.

BHO 2671
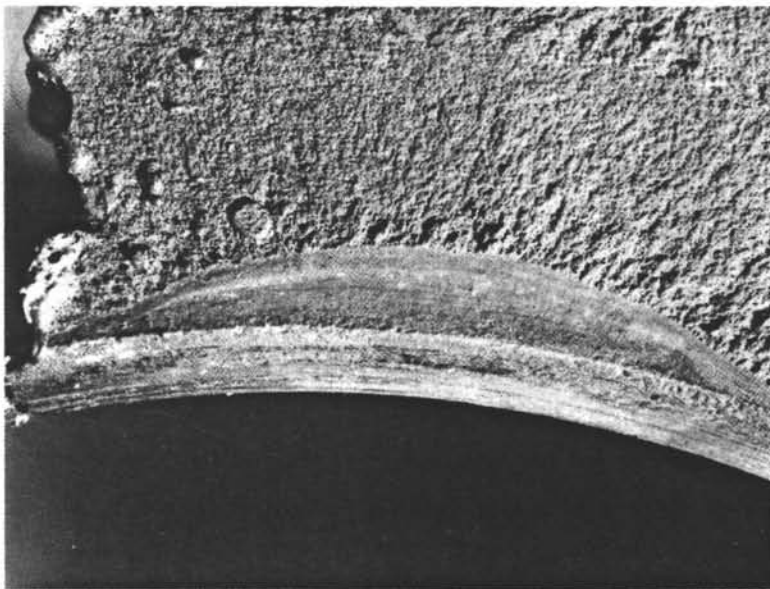
FIGURE 2. Largest fatigue
zone on the
fracture surface.
≈1.5X

BHO 2672

131
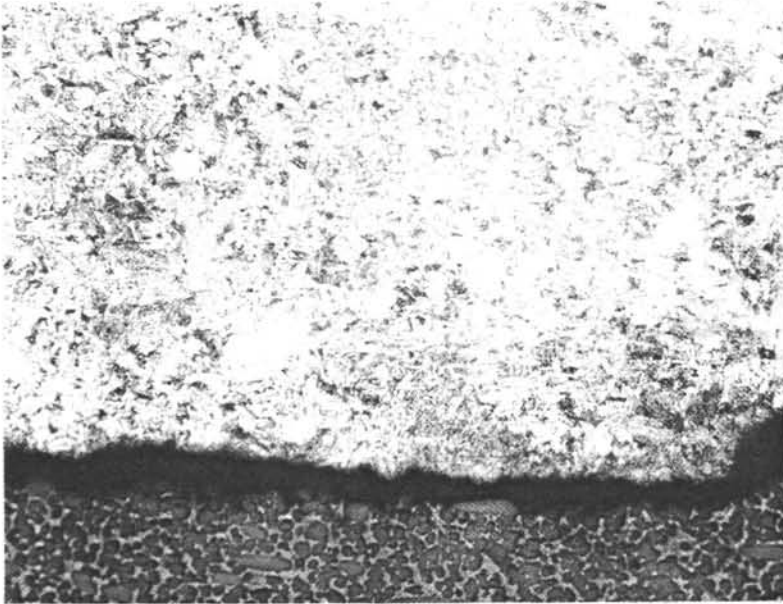
FIGURE 3. Photomicrograph of section taken through the largest fatigue origin. Note mixed microstructure. 200X Nital etchant

BHO 2709
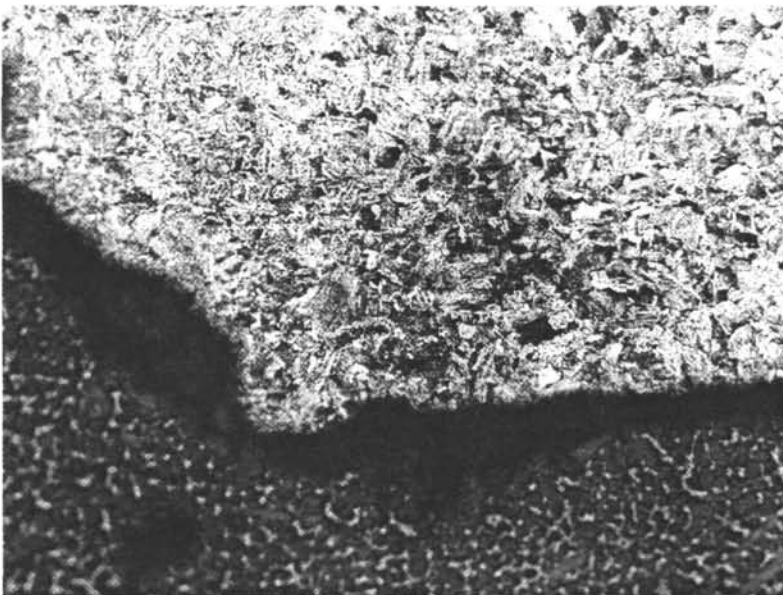
FIGURE 4. Photomicrograph of section taken through a secondary origin approximately 3 inches away from the origin in Figure 3. Note mixed microstructure, corrosion pitting at thread root. 200X Nital etch

BHO 2711

APPENDIX C

FAILURE ANALYSIS OF DRILL PIPE
FROM HOLE 581A
(LEG 88)

REPORT

on

FAILURE ANALYSIS OF DRILL PIPE FROM HOLE 581A

Contract No. G13274-3058

to

DEEP SEA DRILLING PROJECT

February 7, 1983

by

D. R. McIntyre
R. J. Olson

BATTELLE
Houston Operations
2223 West Loop South
Suite 320
Houston, Texas

REPORT

on

FAILURE ANALYSIS OF DRILL PIPE FROM HOLE 581A
CONTRACT NO.: G13274-3058

to

DEEP SEAL DRILLING PROJECT

by

Dale R. McIntyre
R.J. Olson

from

BATTELLE
Houston Operations

February 7, 1983

SUMMARY

The drill pipe in DSDP hole 581A failed due to buckling followed by fatigue
and final fracture by ductile rupture. The buckling apparently took place
some time before the drill pipe became stuck while retrieving core No. 1 and
was most likely caused by insufficient tension on the drill string. The
mechanical properties and chemical composition of the drill pipe joint met the
requirements of API 5AX in all respects.

INTRODUCTION

On August 25, 1982, The Deep Sea Drilling Project began work on hole No. 581A,
lowering a re-entry cone and 72.15 m of 16-inch casing to the sea floor in
5483 m of water on a 5 inch, 19.5 pound/ft S-135 drill pipe running string
with a 15-inch core bit.

The cone and the 16-inch casing washed in without difficulty for approximately 60 m. at which point progress slowed considerably. It was thought that the difficulties with washing in and re-entering the cone may have resulted in setting down the string either on the edge of the cone or on hard bottom at some point. With the casing shoe at 5552 m. below rig floor no further progress could be made. The cone was released from the running string at this point.

A 15-inch hole was washed and drilled to 364 m. below the sea floor, at which point continuous coring began. Torquing of up to 8000 ft-pounds, the limit set on the Bowen power swivel, was experienced during this drilling operation. While retrieving the first core sample, the drill pipe became stuck and required some 15 minutes and overpulls of 70,000 pounds (the maximum allowable under existing conditions of drill string weight) before coming free.

Torquing through the cored interval ranged consistently between 6000 and 8000 foot-pounds. The hole struck basalt some 360 meters below the mudline (5840 m). Coring was stopped 14.8 meters into basalt and a short pipe trip to the 16-inch casing shoe was made to check the hole condition before running 11 3/4 inch casing.

With the bit approximately 8 m. below the casing shoe, the travelling block was set down while the drilling line was slipped and cut. When the travelling block had been picked up again, the pipe was run back to total depth. No resistance was noted and it was assumed that the hole was thus clear. Three hundred barrels of 9.0 pound/gallon mud were displaced to fill the hole and maintain hole stability for running the 11 3/4 inch casing. When the drill pipe was recovered it was found that the joint immediately above the bottom hole assembly had fractured approximately 0.5 meters from the pin end, leaving the bottom-hole assembly in the hole. Careful examination of the drilling recorder chart revealed that the pipe had parted during the time the drilling line was being cut and slipped.

Visual Examination

Figure 1 shows the broken sample of drill pipe as received. As Figures 2, 3 and 4 show, the fractured end showed extensive plastic deformation. Around the circumference of the fracture, material at the twelve and six o-clock positions had been deformed inward while at the three and nine o'clock positions the pipe wall had bulged outward. Two longitudinal splits had occurred on opposite sides of the pipe at the two and eight o'clock positions (Figures 2 and 3). The split at the two o'clock position ran parallel to the longitudinal axis of the pipe for approximately six inches before turning ninety degrees and running perpendicular to the longitudinal axis. (Figure 4)

Virtually all of the fracture surfaces on the broken pipe end were shear fractures propagating at approximately 45 degrees to the pipe wall thickness. At the edges of the areas which had bulged outward, two small half-moon-shaped zones suggestive of fatigue were observed (Figures 5 and 6) Radial marks in these zones suggested origins on the outer surface of the pipe (arrows, Figure 7). A secondary crack under the fatigue zone at the three o'clock position also appeared to be due to fatigue.

Metallographic Examination

A section taken through the fatigue zone at the three o'clock position (Figure 7) was polished and etched for metallographic examination. Figure 8 presents a photomicrograph of the fracture origin. Although damaged by cold-work and corrosion, the fracture profile appeared to be predominantly transgranular and non-branching.

Numerous secondary cracks were observed on both the inside and outside surface of the drill pipe section. Most of these cracks were relatively blunt, transgranular and filled with corrosion products.

138
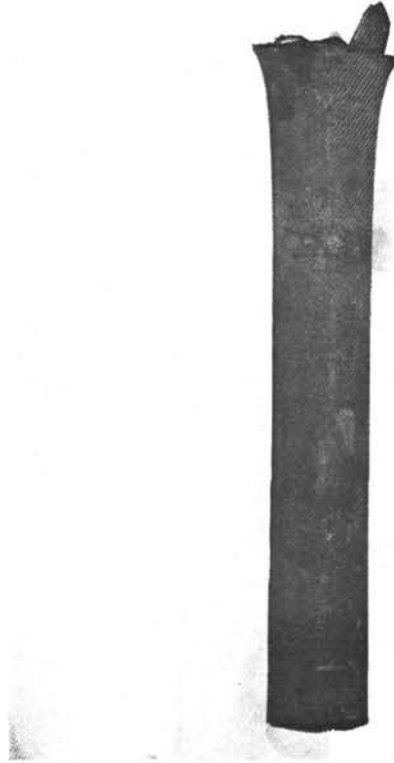
BHO 2233

FIGURE 1.   FAILED DRILL PIPE SECTION AS RECEIVED

BHO 2270

FIGURE 2.   FRACTURED DRILL PIPE END, LOOKING AT
THE CENTER OF THE BUCKLED ZONE.

BHO 2268

FIGURE 3.   SIDE VIEW OF THE BUCKLE.   NOTE THE
            LONGIGUDINAL SPLIT.

BHO 2269

FIGURE 4.   BACK VIEW OF THE BUCKLE.   THE LONGI-
TUDINAL SPLIT IN FIGURE 3 TURNS 90°
AND RUNS PERPENDICULAR TO THE LENGTH
OF THE DRILL PIPE.

143
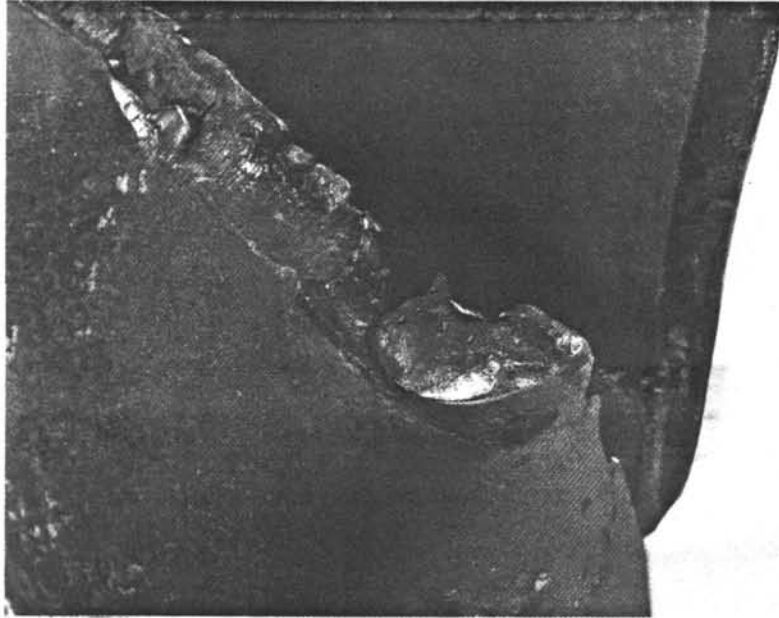
FIGURE 5. FATIGUE ZONE AT THE OUTER EDGE OF THE BUCKLE. NOTE THE SECONDARY CRACK BELOW THE FATIGUE ZONE.
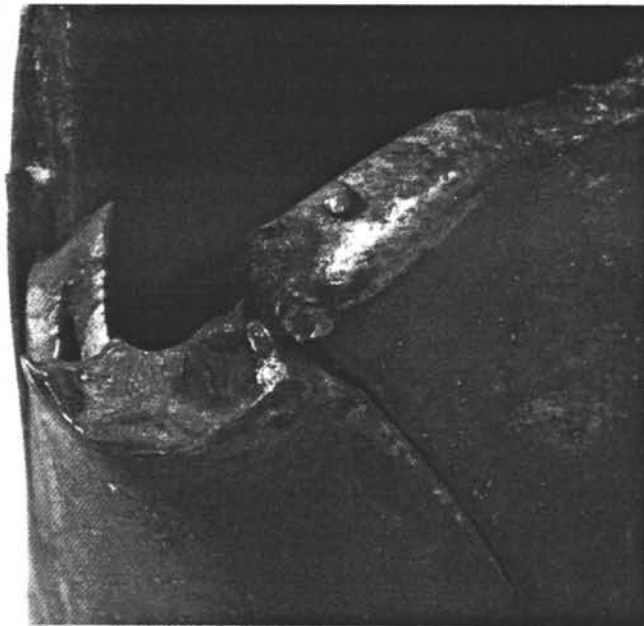
FIGURE 6. FATIGUE ZONE AT THE OUTER EDGE OF THE BUCKLE, ON THE OPPOSITE SIDE AS THAT SHOWN IN FIGURE 5.

144
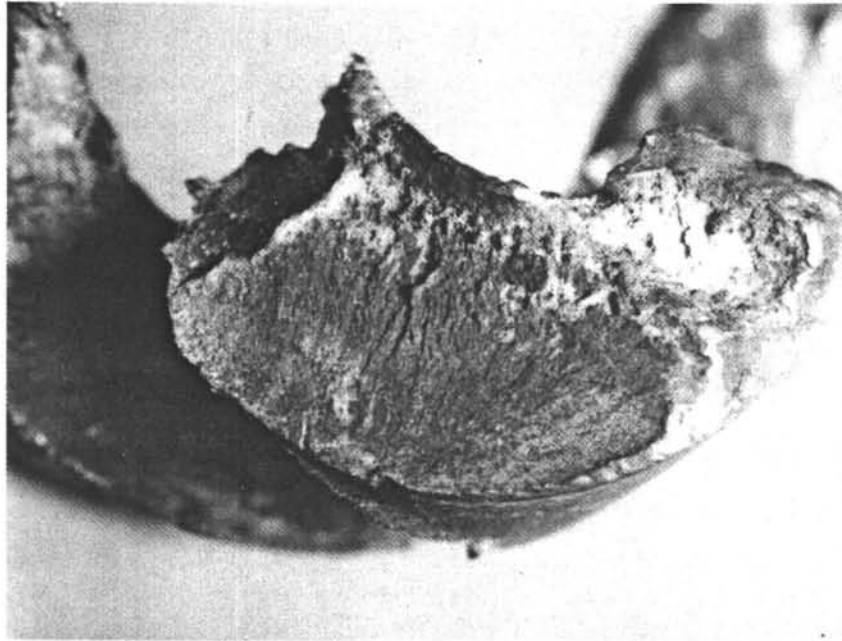
FIGURE 7.   CLOSE-UP OF FATIGUE ZONE IN FIGURE 5.   NOTE THE
RADICAL MARKS INDICATING INITIATION AT THE OUTER
EDGE.
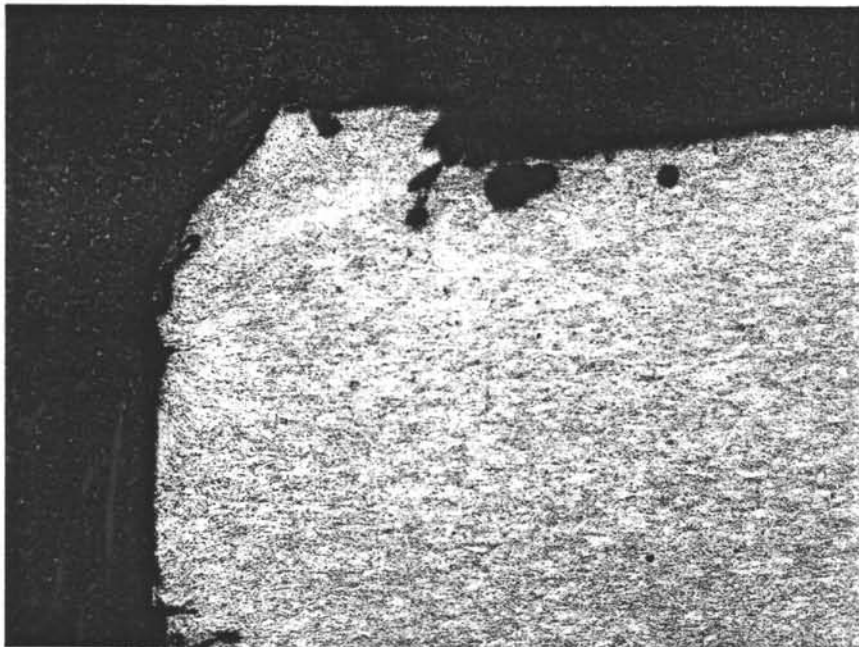
FIGURE 8.   A METALLOGRAPHIC SECTION TAKEN THROUGH THE
FATIGUE ZONE IN FIGURE 7.   THE FRACTURE SURFACE
IS AT TOP: THE PIPE OUTER SURFACE IS AT LEFT.

100X   NITAL

On the section through the fatigue crack, the structure was tempered martensite with some evidence of cold-work. Longitudinal and transverse sections were taken well away from the fractured end to check the structure of the base metal. (Figures 9 and 10) The base metal also showed a tempered martensite structure but with no evidence of cold-work. Microhardness tests near the fatigue zone averaged KHN_{500g} 432 (approximately R_c 42.5) while the base metal well away from the fracture averaged KHN_{500g} 388 (approximately R_c 38.5).

Mechanical Properties

Duplicate tensile specimens were taken from the broken drill pipe in an area well away from the fractured end. Average mechanical properties obtained were as follows:

	Yield Strength ksi	Ultimate Tensile Strength, ksi	Percent Elongation in 2 inches	Percent Reduction in Area
Fractured Drill Pipe	163.3	173.5	17.5	59.0
API 5AX Specification Grade S-135	135-165	145 min	12.5 min	n.s.

n.s. - not specified

Although the yield strength of the failed drill pipe is near the high end of the allowable range, the mechanical properties meet the API 5AX specification in all respects.
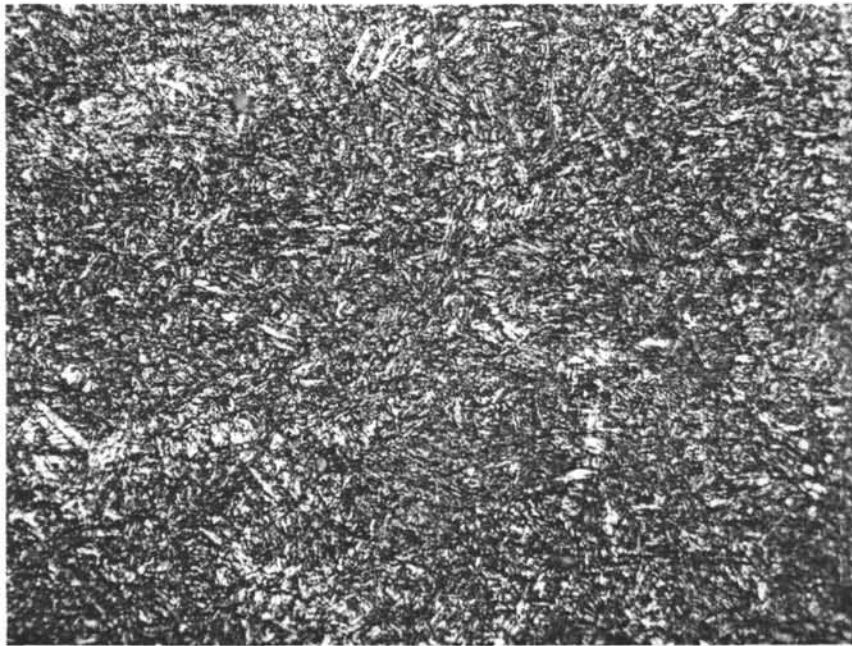
BHO 2325

FIGURE 9. TYPICAL TRANSVERSE MICROSTRUCTURE OF THE DRILL
PIPE IN THE BASE METAL, APPROXIMATELY TWO
FEET AWAY FROM THE BUCKLE.
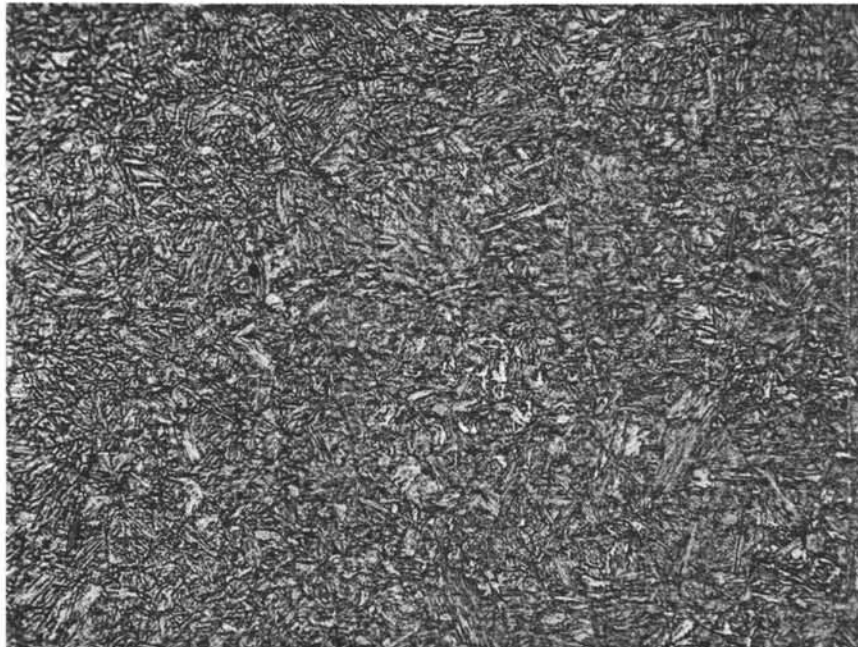
400X   NITAL ETCH

BHO 2326

FIGURE 10. TYPICAL LONGITUDINAL MICROSTRUCTURE OF THE
DRILL PIPE, TAKEN ON A SECTION APPROXIMATELY
TWO FEET AWAY FROM THE BUCKLE.

400X   NITAL ETCH

Chemical Composition

Spectrographic analysis of a sample from the failed drill pipe gave the following results:

	Failed Drill Pipe	API 5AX Specification
Carbon	0.31	n.s.
Manganese	0.96	n.s.
Phosphorus	0.011	0.04 max
Sulfur	0.015	0.06 max
Nickel	0.025	n.s.
Chromium	0.10	n.s.
Molybdenum	0.008	n.s.
Vanadium	0.055	n.s.

n.s. - not specified

The API 5AX specification is extremely non-restrictive with regard to chemistry. The failed drill pipe meets the limits for phosphorous and sulfur, the only two elements listed in the specification. However, the drill pipe is unusual in that it is essentially a plain carbon steel, with none of the elements (chromium, molybdenum or nickel) normally added to improve hardenability.

DISCUSSION

The mechanical properties of the failed drill pipe met API specification 5AX in all respects.

The failed joint was of plain carbon steel rather than low-alloy steel. Low-alloy steels are normally used for S-135 drill pipe because the alloy additions insure that the structure is transformed to martensite all the way through the pipe wall when the item is quenched during heat treating. With incomplete transformation an undesireable mixed structure forms, of martensite plus bainite or martensite plus ferrite and pearlite, which has poor toughness. However, in thin sections even plain carbon steels can be transformed completely to martensite if quenched rapidly enough. Since the failed drill pipe showed a completely tempered-martensite structure, since the failure involved considerable plastic deformation, and since the phosphorous and sulfur levels were within specification, the chemistry of the failed joint apparently had no effect on this failure.

The overall appearance of the fractured pipe is indicative of a dent or buckle - the cross-section is flattened and appears to have been creased at the failure site. As denting or buckling begins, the cross-section becomes elliptical, which in turn puts the outer wall at the ends of the major axis of the ellipse in tension. If the deformation becomes severe enough, this tension can cause longitudinal splits at the outer wall.

Three possible scenarios can be hypothesized which could cause the observed deformation of the pipe:

1. The pipe, just above the bottom hole assembly, impacts the moon pool or reentry cone causing a dent.

2. With the bottom hole assembly in the reentry cone, station keeping is lost and the vessel drifts excessivly causing the

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drill string to bend. Such bending, if large enough could cause a local buckle (collapse) of the pipe cross-section. (Figure 11)

3. While lowering the drill string, the bottom hole assembly lands on the sea floor or edge of the reentry cone causing a bifurcation buckle (column instability). (Figure 12)

Since any of these three scenarios is possible, each was considered in more detail.

Denting. The denting scenario seems very unlikely. If the pipe, just above the bottom hole assembly had impacted on the moon pool, it would have had to have been inclined at a very large angle. This probably could not occur except in extreme weather conditions. Since drilling was in progress, the weather must have been reasonably calm. Considering denting of the pipe by impact on the reentry cone, since the bottom hole assembly is over 350 feet long and the top of the cone was only 35 feet above the sea floor, it would not be possible to dent the pipe on the reentry cone.

Collapse. In order to judge the likelihood of the collapse scenario, two pieces of data were required: 1) the local bending moment at collapse of the pipe and 2) the global bending moments of the drill string when the vessel was offset. To generate these data, two computer programs COLAPS[1] a combined bending moment, tension and pressure pipe collapse program, and DWRSR[2], a marine riser analysis program, were used. Tables 1 and 2 present the salient features of the two analyses. The yield moment for the pipe is 40900 foot-pounds while the bending moment at collapse is 68850 foot-pounds. A vessel offset of 2500 feet in calm water results in a bending moment in the damaged pipe section of 8600 foot-pounds.

Column Buckling. To determine the likelihood of column buckling, a critical buckling load analysis was performed using the DWRSR marine riser analysis
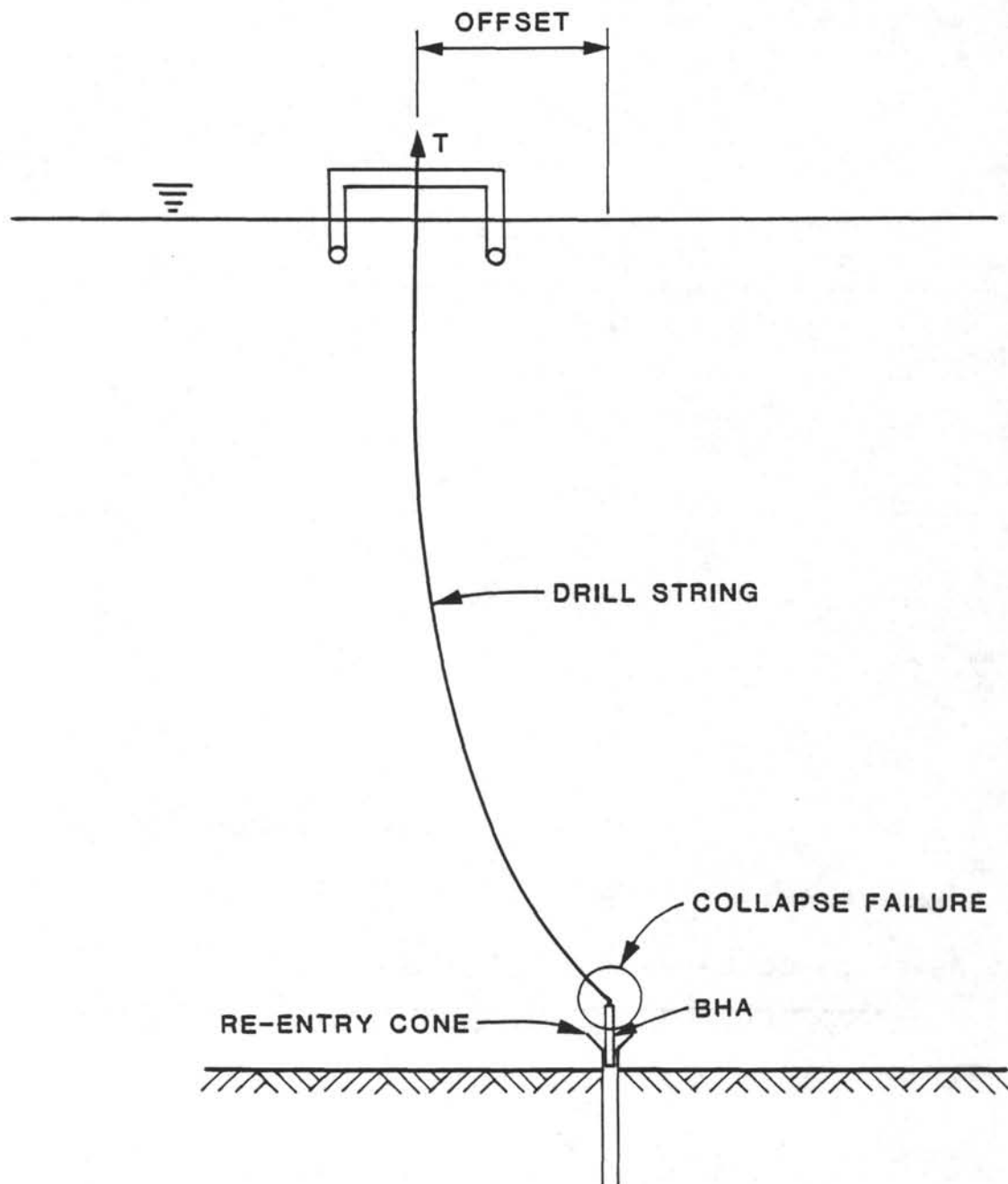
Figure 11- SCHEMATIC FOR COLLAPSE FAILURE SCENARIO

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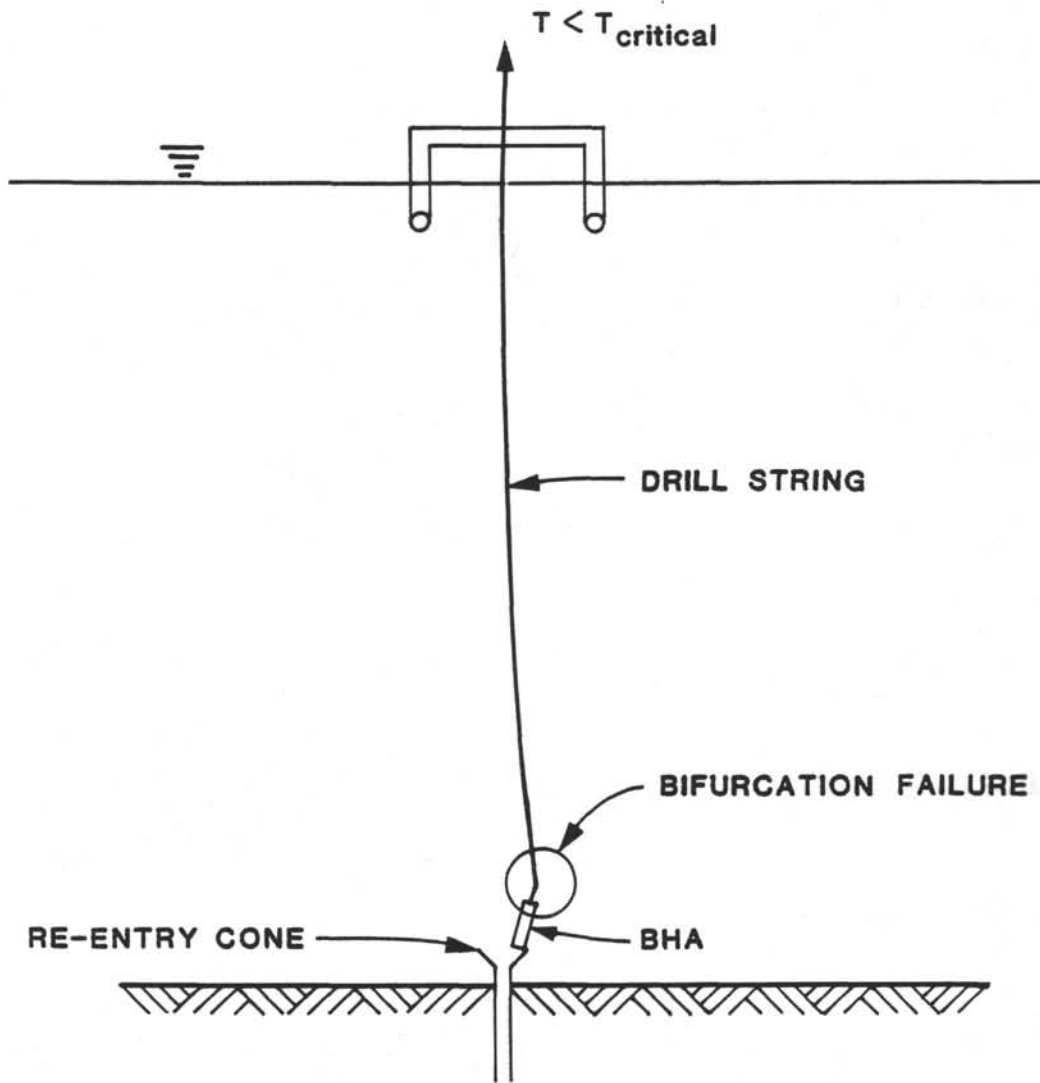
Figure 12– SCHEMATIC FOR BIFURCATION (COLUMN INSTABILITY)
FAILURE SCENARIO

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TABLE 1.   COLLAPSE ANALYSIS

Pipe:	5", 19.5 lb/ft, S-135
	1% initial out of round (assumed)
Material:	As per the measured σ - ε curves
Tension:	7700 pounds
Pressure	0 (sea Water assumed inside and out)

| Yield Moment | 40900 ft lb |
| Collapse Moment: | 68850 ft lb |

TABLE 2. VESSEL OFFSET ANALYSIS

Pipe:	5", 19.5 lb/ft, S-135
BHA:	As per BHA-01 drawing
Top Tension:	400000 lb
Offset:	2500 ft
Model:	402 tension/compression beam finite elements
	Boundary Conditions: bottom - fixed
	top - lateral roller with ball joint

Bending Moment at Collapsed Section: 8600 ft-lb

program. The relevant data for this analysis is shown in Table 3. The buckling load, 325,000 pounds is the minimum tension that must be applied to the top of the drill string to prevent buckling.

Considering all three possible causes for the initial damage to the drill pipe, column instability seems to be the most likely cause of the failure. Denting has been ruled out as physically unlikely. Collapse, while physically possible, is deemed unlikely because of the fact that to even approach the yield moment would require an offset in excess of 2500 feet. Column buckling on the other hand, seems quite reasonable - the buckling tension is very near the operating tension (400000 pounds) and the buckling mode shape results in the occurrence of the maximum moment in the drill stem at the pipe joint just above the bottom hole assembly. It should be noted that in the analyses performed, conditions have been idealized in that no waves, no current were considered and a shell approximation for collapse analysis was used. Such sea state and vessel offset data are unavailable for a more detailed analysis. The inclusion of such effects as the dynamic tension variation due to vessel heave and the influence of initial curvature due to waves and current would likely aggravate the buckling problem. In view of these analyses, the evidence strongly favors loss of tension due to drill string loads on the re-entry cone as the initial cause of the ovalization or buckling damage to the pipe.

After it buckled, the drill pipe did not part immediately. The fatigue zones on the outer edges of the buckled area suggest that after buckling, the drill pipe continued to operate for perhaps several thousand cycles. During this time at least three fatigue cracks initiated and began to grow on the outer edges of the buckled zone. The heavy overpulls necessary to free the stuck drill pipe probably caused some of the remaining ligament to part. Final fracture occurred by ductile rupture in tension when the string was lifted to be slipped and cut.

TABLE 3.   COLUMN BUCKLING ANALYSIS

Pipe:	5", 19.5 lb/ft, S-135
BHA:	As per BHA-01 drawing
Offset:	0.
Tension	Variable
Model:	402 tension/compression finite elements
	Boundary Conditions: bottom - pinned
	top - lateral roller with ball joint

Buckling Load:	325000 pounds
Max Moment in Pipe:	lower end of piece of drill pipe just above BHA

This evidence suggests that the buckle which initiated this failure occurred some time before the drill pipe became stuck while retrieving core No. 1.

CONCLUSIONS

1. The failure of the drill pipe in DSDP hole 581A was initiated by a buckling of the drill pipe.

2. Buckling apparently took place some time before the drill pipe became stuck while attempting to retrieve core No. 1. It is likely that it occurred during the setting of the 16 inch casing.

3. The buckle which initiated this failure was probably caused by insufficient tension in the drill string resulting from setting of the pipe on the sea floor or edge of the reentry cone.

4. After buckling the drill pipe did not part immediately. Several thousand cycles of rotation occurred while fatigue cracks formed at the cold-worked outer edges of the buckled zone. Final fracture occurred by ductile rupture in tension.

5. The mechanical properties of the failed drill pipe joint met the API specification 5AX in all respects.

6. The chemical composition of the drill pipe met the API 5AX specification limits for phosphorous and sulfur, the only elements required. Although the failed drill pipe joint was of plain carbon steel rather than low-alloy steel, the chemical composition apparently had no effect on this failure.

REFERENCES

1. Kingel, et al.; Summary Report on the Inelastic Collapse and Buckling of Deep Water Pipelines Under Combined Movement, Pressure, and Axial Tension; Report to Battelle's Deep Water Offshore Pipeline Group; March, 1976.

2. Olson, et al.; Applications Manual for DWRSR Riser Analysis Program; Report to Battelle's Deep Water Marine Riser Group; June, 1982.

APPENDIX D

OPERATIONS DURING SEVERE WEATHER

OPERATIONS DURING SEVERE WEATHER
(EXCERPTED FROM DSDP OPERATIONS PLAN, 8/25/82)

The following operational limits and procedures have been established to protect personnel and equipment during severe weather conditions:

1. Drill pipe shall not be run when anticipated sea conditions will cause the ship to pitch and/or roll in excess of seven degrees single amplitude.*

2. Drilling operations, including running of drill pipe, may continue on the basis of a maximum pitch and/or roll of seven degrees single amplitude.*

3. The drill string shall be pulled if occasional pitch and/or roll exceeds nine degrees single amplitude.

4. If personnel safety considerations require that pulling/ running the drill string be stopped due to weather, a minimum of three heavy drilling joints should be picked up. Then the drill string should be slowly pulled up and down over a six meter interval so that the pipe located at the keel of the vessel is moved. Avoid having a connection within 5 feet of keel.

5. Positioning, when moving the ship with drill pipe extended, bending of the drill pipe shall be held to less than seven degrees as indicated by cutouts on the horn. During such operations, the drill pipe shall be moved vertically, frequently. The ship should not be moved at a speed greater than one knot and should be moved only as far an offset from vertical as a positioning beacon permits. Sufficient time must be allowed for the drill string to resume its generally vertical position before spudding.

6. If the presence of a strong current is indicated by the handling characteristics of the ship while positioning over the beacon on a new site, time should be taken to obtain a reasonably accurate estimate of current velocity before commencing to lower the drill string. If a current in excess of three knots, or excessive drill string vibration is encountered, regardless of wind direction and speed, consideration will be given to the selection of another site.

    If wind, current, and sea forces are combined in one direction, the ship can operate in up to 15 foot swells, 40 knot winds and 3 knot currents. However, where these forces are not in the same direction (and wind or current may change direction on short notice), operations may have to be halted with much less wind and/or current.

* Limitation is five degrees for drill string in excess of 6860 meters.

APPENDIX E

MECHANICAL AND METALLURGICAL EVALUATION
OF S-135 DRILL PIPE

REPORT

on

MECHANICAL AND METALLURGICAL
EVALUATION OF S-135 DRILL PIPE

Contract No. 613068-3058

to

DEEP SEA DRILLING PROJECT

August 30, 1982

by

D. R. McIntyre

BATTELLE
Houston Operations
2223 West Loop South
Houston, Texas

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on

MECHANICAL AND METALLURGICAL EVALUATION OF S-135 DRILL PIPE
CONTRACT NO.:   613068-3058

to

DEEP SEA DRILLING PROJECT

by

Dale R. McIntyre

from

BATTELLE
Houston Operations

August 30, 1982

SUMMARY

A sample of 5 inch diameter 19.5 lb/ft S-135 drill pipe was evaluated for
toughness, alloy content, dimensional tolerance and mechanical properties.
Fracture mechanics analysis suggests that the toughness of the pipe is
adequate to fulfill the leak-before-break criterion under typical drilling
service conditions. The sample met API 5 AX specification in all respects.

INTRODUCTION

Deep Sea Drilling Project uses API 5AX, 5 inch diameter, 19.5 lb/ft grade S-
135 drill pipe for obtaining geological core samples in deep water from the
drill-ship D. V. GLOMAR CHALLENGER. DSDP has purchased a new lot of drill
pipe from Japan for future use. In the past, drill pipe failures due to
fatigue and hydrogen embrittlement have caused expensive project delays.
Battelle was requested to assess the mechanical and metallurgical condition of
samples from the new lot of pipe in the light of anticipated service

conditions. A three-foot length of drill pipe from the new lot was sent to Battelle-Houston's Charles Street laboratory for evaluation.

EXPERIMENTAL PROCEDURE

The sample was subjected to the following tests:

1. Dimensional measurements of O.D., I.D. and wall thickness using calipers at four locations on the sample.

2. Wet chemical analysis of triplicate samples for

    Carbon
    Manganese
    Phosphorous
    Silicon
    Chromium
    Molybdenum

3. Mechanical properties determination on triplicate samples at room temperature. Properties measured were:

    ultimate tensile strength
    yield strength at 0.7 percent offset
    percent elongation in two inches

4. Toughness determination on two sets of triplicate Charpy V-notch specimens tested at 32 F and room temperature.

RESULTS

Dimensional Measurements

Results of the dimensional measurements are shown presented in Table 1. The

sample received met the API 5AX specification for outer diameter tolerance, wall thickness tolerance, and ovality at all the locations tested.

Chemical Composition

Results of the wet chemical analysis on three samples from the drill pipe specimen are presented in Table 2. The API 5AX specification places limits only on phosphorous and sulfur, leaving the balance of the composition to the manufacturer's discretion. The samples analyzed easily met the required phosphorous and sulfur limits. The balance of the composition is indicative of a typical low-alloy steel roughly equivalent to AISI 4030 steel.

Mechanical Properties

Table 3 presents the results of mechanical properties tests on triplicate one-inch wide full thickness strip tensile specimens. The yield strength, ultimate tensile strength and ductility met the API 5AX specification in all respects. The ratio of yield strength to ultimate tensile strength averaged .93, which is within the range of .86 to .94 typical for S-135 drill pipe. Hardness of the pipe sample was Rc 34.

Toughness Tests

Table 4 presents the results of Charpy impact tests on triplicate three-quarter size specimens broken at room temperature and freezing temperature. There is no API specification for toughness on drill pipe. However, impact tests across the range of anticipated service temperatures can indicate whether or not brittle fracture might be a problem in service.

The toughness of the six specimens from this piece of drill pipe was good at both room temperature and freezing. The values for percent shear suggest that the ductile-to-brittle transition temperature of this material is well below freezing.

The specimens used were three-quarter size since the pipe wall thickness was too thin to permit the use of the standard ten millimeter wide Charpy specimen. The ASTM standards which allow the use of both ten-millimeter and three-quarter size Charpy specimens typically use a ratio of 0.80 for comparing the absorbed energy values of low-alloy steels. Thus 20 foot-pounds of absorbed energy in a standard ten-millimeter Charpy corresponds to 16 foot-pounds of energy in a three quarter size Charpy. [1,2] This correlation is perforce approximate and may not be valid for all materials at all yield strengths. However, using this ratio, the observed average absorbed energy values would correspond to full-size impact values of 49. 6 foot-pounds at room temperature and 37 foot-pounds at freezing temperature.

For drill pipe, there are no toughness criteria specified in API 5AX specification. However, the level of toughness required for satisfactory service can be estimated as follows:

The most desirable service requirement for drill pipe is that any fatigue cracks which form should leak before they break, allowing detection before the string parts. The leak-before-break criterion means that the pipe must be able to sustain a circumferential through-thickness crack without catastrophic brittle failure. The stress intensity generated by a circumferential through-thickness crack twice as long as the wall thickness can be approximated with the relationship:

$$K = \sigma\sqrt{T}$$

Where σ = the applied stress, T = the wall thickness, and K = the stress intensity.[3] At the specified minimum yield strength of S-135, a 2T through-thickness circumferential crack would generate

$$135000 (\pi \times 0.362)^{1/2} = 143,000 \text{ ksi } \sqrt{in}$$

of stress intensity.

The critical stress intensity a material can sustain without brittle fracture, K_{IC}, can be estimated from the Charpy impact values using Barsom, Rolfe and Novak's empirical correlations between K_{IC} and Charpy test results on the upper shelf and in the transition region between brittle and ductile behaviour.[4]

At room temperature, the calculated full-size Charpy impact value averaged 49.6 foot-pounds. Fracture was 100 percent ductile, so the upper shelf equation from Barsom, Rolf and Novak applies.

$$(\frac{K_{IC}}{\sigma})^2 = 5\ [\frac{C_v}{\sigma} - 0.05]$$

For σ = 152 ksi, C_v = 49.6 ft-lbs, the calculated K_{IC} - 179 ksi in. Therefore, the drill pipe sample could sustain a 2T through-thickness circumferential crack at any stress up to and beyond the yield strength with no danger of brittle fracture.

At freezing temperature, the calculated full-size Charpy impact values average 37 foot-pounds. Some cleavage fracture was present on the specimens, so the material is in the transition region and the following correlation between K_{IC} and CVN can be used:

$$\frac{K_{IC}^2}{E} = 2(C_v)^{3/2}$$

If C_v - 37 ft-lbs and E = 29,000,000 psi, K_{IC} = 114 ksi $\sqrt{in.}$

Therefore at freezing temperature this material could sustain a 2T through-thickness circumferential crack up to stresses of:

$$\sigma = 114,000/(\pi \times 0.362)^{1/2} = 107,000\ psi.$$

In 5 inch O.D. 19.5 lb/ft drill pipe this would be equivalent to a total string weight of 583,000 pounds. If through-thickness fatigue cracks are present at freezing temperatures with total load in excess of 583,000 pounds, then brittle fracture is possible.

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These calculations are approximate and based on two empirical correlations rather than direct measurement of the drill pipe toughness. However, they indicate that this material's toughness is entirely adequate at ambient temperatures under any elastic loading condition. At 0°C the material's toughness is adequate up to 80 percent of the specified minimum yield strength. At stresses above this level fatigue cracks might not leak before the string parts.

CONCLUSIONS

1. The drill pipe sample submitted met the API 5AX dimensional requirements in all respects.

2. The sample submitted met the chemical composition requirements of API 5AX and is typical of low-alloy steels in widespread use for this service.

3. The sample submitted met the API 5AX mechanical properties requirements in all respects.

4. The room temperature toughness of the sample submitted was sufficient to ensure leakage of any crack before brittle fracture at any load up to the specified minimum yield strength.

5. The toughness of the sample submitted was still good at 0°C, although cracks might not leak before breaking if the pipe is stressed in excess of 80 percent of the specified minimum yield strength.

REFERENCES

1. ASTM A320-80B, "Alloy Steel Bolting Material for Low-Temperature Service" American Society for Testing and Materials, <u>1981 Annual Book of ASTM Standards</u>, Part 1, p.231-240.

2. ASTM A333-79, "Seamless and Welded Steel Pipe for Low-Temperature Service" American Society for Testing and Materials, <u>1981 Annual Book of ASTM Standards</u>, Part 1, p. 241-249.

3. "Stress-Intensity Factor for a Circumferential Through-wall Crack in a Straight Pipe," Gilman, J. D. Report GEAP-5557 General Electric Co. APED, San Jose, Calif, 1968.

4. "Use of Correlations between K_{IC} and Charpy V-notch Test Results in the Transition-Temperature Range" Barsom, J. M. and Rolfe, S. T., <u>Impact Testing of Metals</u>, ASTM STP 466, American Society for Testing and Materials, 1970, pp 3-20.

TABLE 1. DIMENSIONAL MEASUREMENTS OF DRILL PIPE SAMPLE
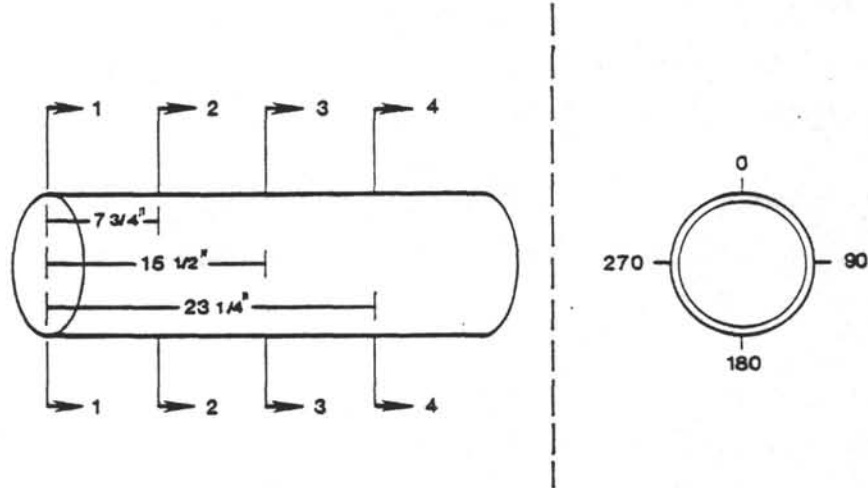
Section	Orientation	Outer Diameter in.	Inner Diameter in.	Wall Thickness in.	O.D.- Nominal, in.	Wall Thickness - Nominal, in.	Ovality $(O.D._0 - O.D._{90})$ in.
1	0	5.010	4.281	0.359	+.010	-.003	0.002
	90	5.008	4.278	0.356	+.008	-.006	
	180	*	*	0.370		+.008	
	270	*	*	0.374		+.012	
2	0	5.010	4.275	0.361	+.040 .010	-.001	0.015
	90	5.025	4.291	0.358	+.025	-.004	
	180	*	*	0.371		+.009	
	270	*	*	0.376		+.014	
3	0	5.015	4.277	0.362	+0.15 .015	0.0	0.002
	90	5.017	4.285	0.353	+.017	-.009	
	180	*	*	0.376		+.014	
	270	*	*	0.379		+.017	
4	0	5.012	4.271	0.357	+.012	-.005	0.012
	90	5.024	4.296	0.352	+0.24 .024	-.010	
	180	*	*	0.384		+.022	
	270	*	*	0.384		+.014	
API 5AX Spec.		5.0 nom.		0.362 nom.	±.0375[1]max.	-.045[2]max	0.093 max

* diameter measurements were taken from 0 to 180° and 90 to 270° so the 0° O.D. reading will be identical to the 180° reading and the 90° reading is identical to the 270° reading.

[1] ± 0.75 percent

[2] - 12.5 percent

TABLE 2. CHEMICAL ANALYSIS OF DRILL PIPE

All Values are in Weight Percent

Sample No.	1	2	3	API 5AX Specification
Carbon	0.28	0.28	0.28	n.s.
Manganese	1.37	1.38	1.38	n.s.
Phosphorus	0.020	0.020	0.021	0.040 max
Sulfur	0.010	0.009	0.010	0.060 max
Silicon	0.15	0.16	0.17	n.s.
Chromium	0.25	0.26	0.26	n.s.
Molybdenum	0.38	0.39	0.38	n.s.

* n.s. - not specified

TABLE 3. MECHANICAL PROPERTIES OF DRILL PIPE

Specimen No.	Area in^2	Yield Strength,* psi	Ultimate Tensile Strength, psi	Percent Elongation in two inches
1	.365	152,300	164,400	19.0
2	.370	151,900	162,200	20.0
3	.370	152,200	162,200	18.0
API 5AX Specification		135,000 165,000	145,000 max	11.5**

* .7% Total Extension

** API 5AX required minimum elongation varies with specimen size and is based on the formula:

$$e = 625,000 \ \frac{A^{0.2}}{U^{0.9}}$$

where:

       e = minimum elongation

       a = specimen area, in^2

       u = specified minimum tensile strength, psi

TABLE 4. TOUGHNESS OF DRILL PIPE SAMPLE.

Values are from 3/4 Size Specimens

Specimen No.	Test Temp	Impact Value (ft-lbs.)	Percent Shear
1	+73°F	38.5	100
2	+73°F	42.0	100
3	+73°F	38.5	100
4	+32°F	27.0	77
5	+32°F	30.0	79
6	+32°F	32.0	86