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CORROSIVE-WEAR OF BUOY CHAIN

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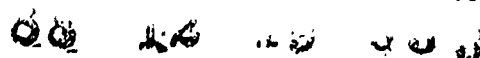
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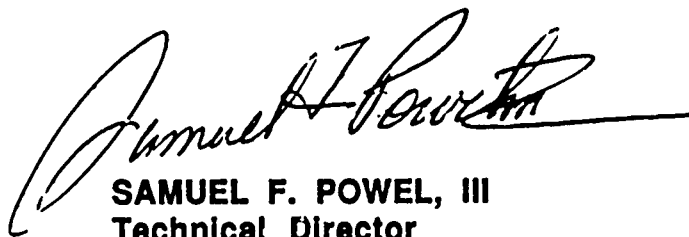


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16. Abstract Five alloy steel chains were exposed to a service environment as buoy chains to determine the best candidate to replace the 1022 steel currently used. The best combination of resistance to material loss, strength and pitting corrosion resistance was shown by the 4340 quenched and tempered steel. In the chafe section the 4340 steel displayed the best resistance to wear even though it was located in rocks and sand. The 1022 steel performed the best in terms of overall weight loss; however, the chain was positioned on a sandy location and showed greater wear in the chafe section. These results suggest that the 4340 steel may be an alternative to the 1022 steel in areas where the chain moorings experience rapid corrosive wear. However, the availability and weldability of the 4340 steel make it unsuitable as a buoy chain material at the present time. (FF)					
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (WEIGHT)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (EXACT)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price \$2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.01	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (WEIGHT)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³

TEMPERATURE (EXACT)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
-40	-40°		-40°	-40°
-20	-20°		-4°	-23°
0	0°		32°	32°
20	20°		68°	68°
40	40°		104°	104°
60	60°		140°	140°
80	80°		176°	176°
100	100°		212°	212°

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INTRODUCTION

This report summarizes the data collected over a two-year period on five different alloy steel buoy chains. The chains were field tested by employing them as mooring chains for buoys placed one mile off the coast at Charlestown, RI, shown in Figure 1. During the two-year period from August 1985 to August 1987, quarterly inspections by divers ensured the condition of the chains were adequate to continue the testing. A previous program by the Canadian Coast Guard, Reference (1), failed when buoys broke their mooring chain after six months. The inspections were aimed at forewarning and avoidance of any similar problem.

The two-year testing of the mooring chains reported in this research followed to a great extent the guidelines suggested in Reference (1):

"First of all the chain should have good corrosion resistance and especially it should have good resistance to pitting corrosion, because it is the deep pits which shorten the life of a chain, not the overall weight loss. Secondly, the chain should have good wear resistance. This encompasses both resistance to inter-link wear and barrel wear, i.e., abrasion of the sides of the chain links against a rocky bottom or on a coarse sandy bottom."

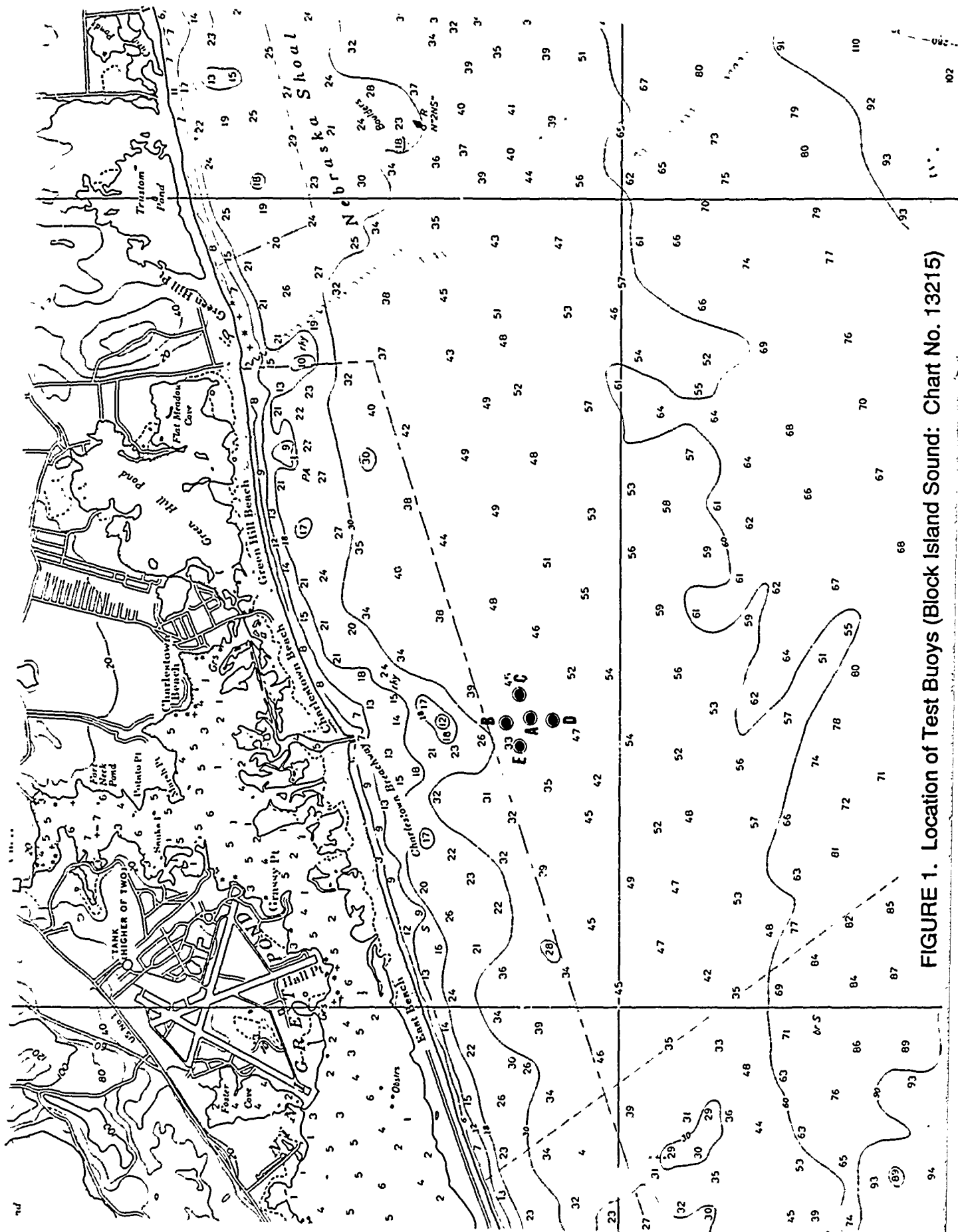


FIGURE 1. Location of Test Buoys (Block Island Sound: Chart No. 13215)

The content of this report includes:

- o The types of steels tested
- o Precautions taken to ensure premature failure of the chains
- o Types of corrosion observed from tested chain
- o Data on chain wear from the field tests
- o Comparison with the laboratory data

OBJECTIVE

The main objective of the research was to determine whether an improvement can be achieved in the service life of chain moorings through the use of alloy steels. Laboratory testing was conducted to simulate the mechanisms involved in the corrosive-wear of steel chain so that the effects of the steel's composition, hardness, and microstructure on their degradation could be determined in a controlled environment. Field testing of the different steel chains provided more realistic data for comparing their performance.

MATERIALS

Five different steel alloy chains were employed as mooring chains for the buoys. The composition of the steels are shown in Table 1 along with their respective hardness values. The

TABLE 1
STEEL COMPOSITION

<u>Steel</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	Hardness (Rc)
1022	0.18-0.23	0.7-1.0	0.04	0.05					8
4140	0.38-0.43	0.75-1.0	0.035	0.04	0.15-0.35		0.8-1.0	0.15-0.25	28
4340	0.38-0.43	0.65-0.85	0.035	0.04	0.15-0.35	1.65-2.0	0.7-0.9	0.2-0.3	27
8740	0.38-0.43	0.75-1.0	0.035	0.04	0.15-0.35	0.4-0.7	0.4-0.6	0.2-0.3	25
8620	0.18-0.23	0.70-0.9	0.035	0.04	0.15-0.35	0.4-0.7	0.4-0.6	0.15-0.25	30

variations examined were basically chromium, nickel and molybdenum contents. The 4340 steel has the largest total of these alloying additions with the 8740, 8610 then 4140 steels decreasing in their alloying additions. The conventional steel chain used by the Coast Guard contain none of these alloying additions. The purposes of the alloying additions are:

- o Improving the hardenability of the steel
- o Strengthening of the steel by the presence of the additions in the ferrite
- o Enhancement of uniform corrosion protection by modifying the surface layers of the steel

However, by increasing the alloy content and strength, the stress corrosion cracking (SCC) resistance decreases. The alloy steels therefore require a temper to approximately Rc30 or less to avoid premature failure in them by SCC in the marine environment. As evident in Table 1, the alloy steels in this research program were tempered to Rc30 or less to avoid SCC failure. In addition, tempering produces a microstructure in the alloy steels of fine carbides in a ductile body-centered cubic ferrite matrix. The microstructures of the alloy steels are shown in Figures 2 to 5. In Figure 6 the 1022 steel microstructure of large ferrite grains with fine areas of pearlite at the grain boundaries is shown in contrast with the alloy structures.

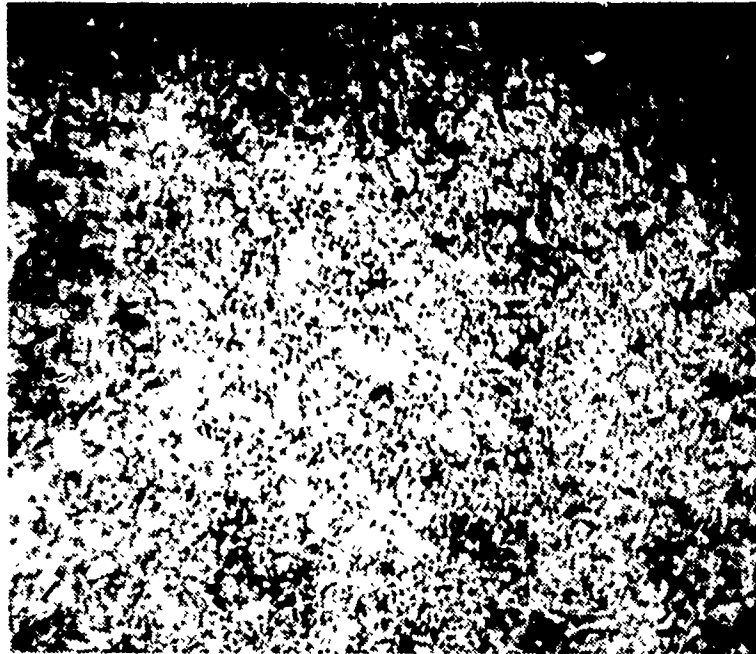


FIGURE 2. Quenched and tempered structure of 4140 steel.

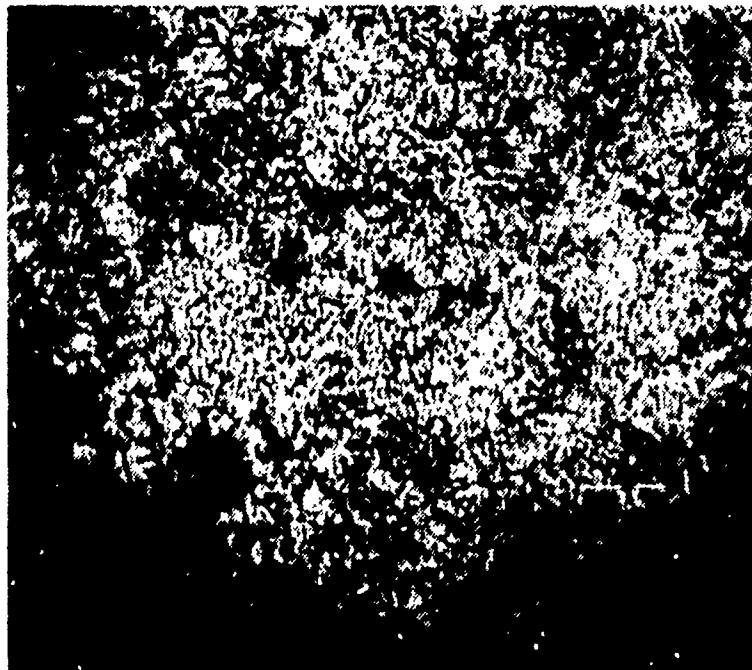


FIGURE 3. Quenched and tempered structure of 4340 steel.

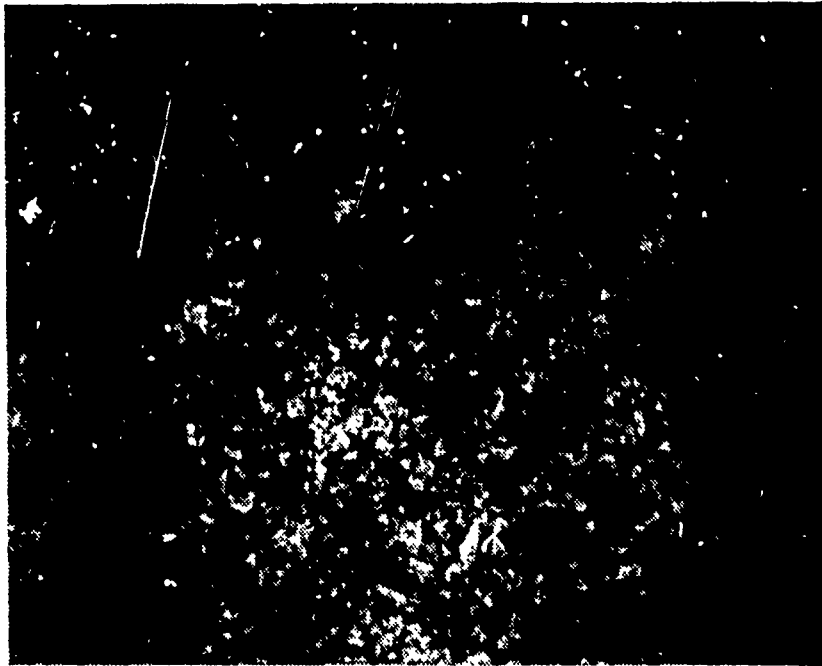


FIGURE 4. Quenched and tempered structure of 8740 steel.

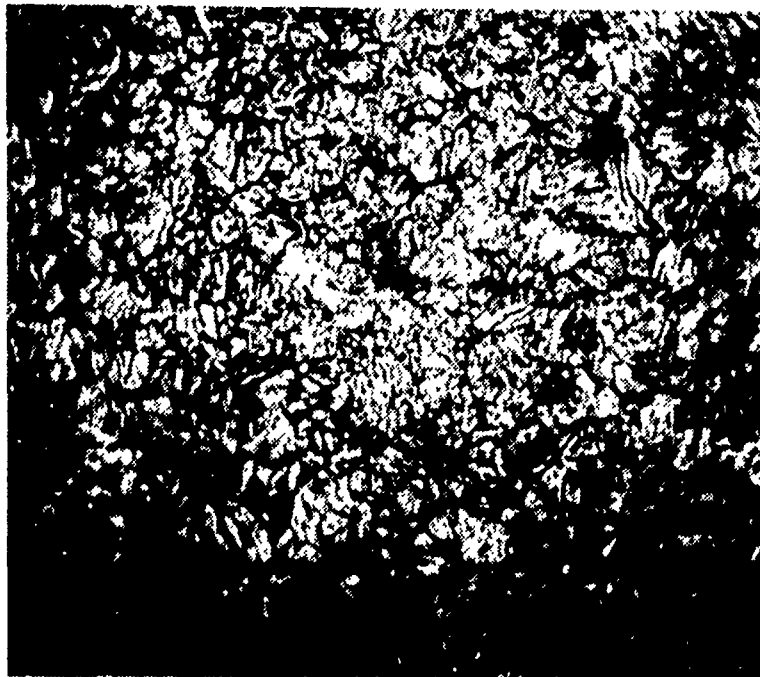


FIGURE 5. Quenched and tempered structure of 8620 steel

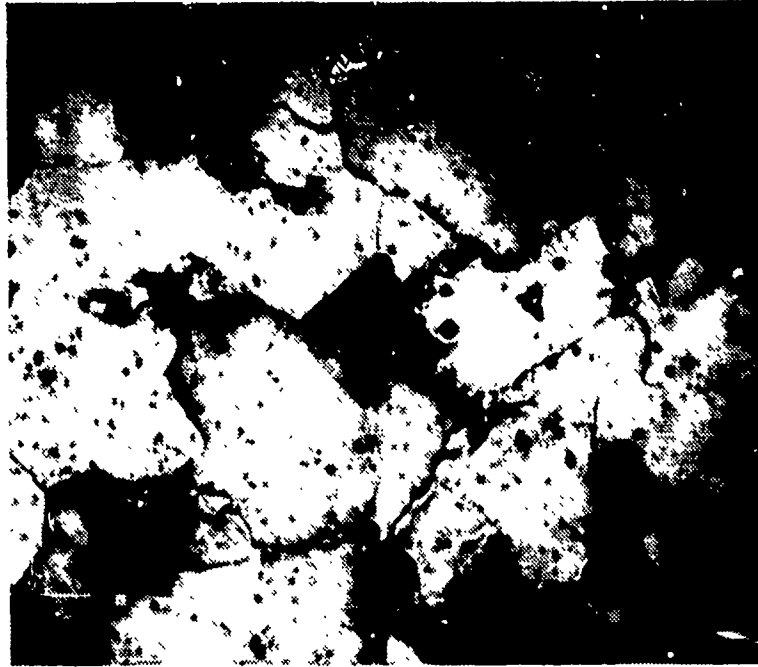


FIGURE 6. Ferrite and pearlite structure of 1022 steel.

DESCRIPTION OF MOORING SYSTEM

The mooring system used for the field testing, shown in Figure 7, consisted of the following components:

- o Fourth class can buoy
- o One shot (90 ft) of chain
- o 2000 lb. concrete sinker

The buoys were constructed of sheetmetal filled with closed-cell foam and weighed approximately 465 lbs.

The location of the buoys, shown in Figure 1, was selected for several reasons. The most important of these is that the buoys could be monitored at frequent intervals. Secondly, the environment was semi-exposed. A wave height average of 24 feet and a current of less than one knot were observed. Lastly, a water depth of 35 feet with a rough floor was required.

PROCEDURE

The alloy steel chains were weighed initially with a spring scale. The 1022 steel chain was weighed using a calibrated load cell since the chain wasn't available to be weighed with the others. Both instruments were accurate to within one pound. Three readings were taken for each chain and the average of these was used for the initial weights.

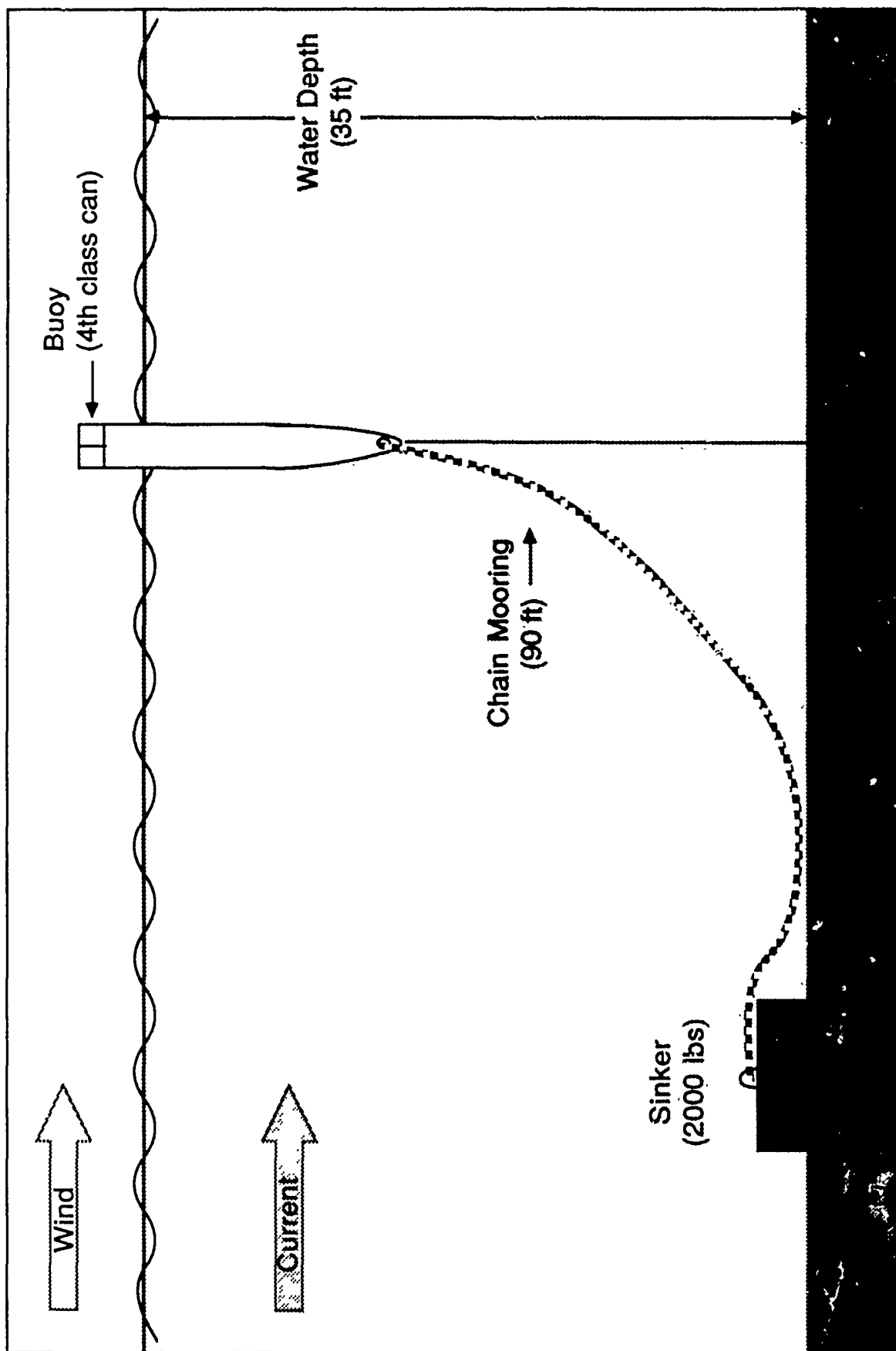


FIGURE 7. Buoy and Mooring

Link diameter measurements were obtained for all the chains using a caliper micrometer. The accuracy of this instrument was to within (.001 in). The measurements were taken at two positions on the link, shown as dimensions "A" and "H" in Figure 8. Measurements were acquired on ten links at various locations along each chain and the averages were calculated to yield the initial diameters for each position.

The mooring chains were placed in service on 29 August 1985. The moorings were inspected quarterly to ensure they were in good condition and weren't wrapped around their sinkers. The buoys were exposed to several severe storms including Hurricane Gloria on 27 September 1985. One of the buoys was reported sinking during the deployment period due to a corroded plug. The buoy was repaired before it could sink completely. An interim inspection was accomplished on 23 October 1986. The inspection consisted of pulling the chains up to short stay which allowed for examination of the ends of the chafe section and link diameter measurement at position "A" with the caliper micrometer for some of the chains. In addition, a diver obtained photographic documentation of the bottom conditions. The buoys and chain moorings were removed from service on 15 July 1987.

At the conclusion of the field testing the final weights of all the chains were obtained using the calibrated load cell. As with the initial weights, three readings were taken

for each chain and the average weight calculated. Although each chain experienced some marine growth, this was assumed to be equal for all chains and would not change the results significantly.

Link diameter measurements were also collected at the same positions on the links, "A" and "H" in Figure 8, using the caliper micrometer. The measurements were obtained from the links closest to the sinker, where high wear rates were observed.

RESULTS

Initial weights of the chain prior to marine exposure are shown in Table 2 along with the weights after two years of exposure. The general condition of the chains during weighing is shown in Figure 9. Also shown in Table 2 is the general condition of the ocean floor surrounding the sinker. The two ocean floor types, namely sandy and rocky, are shown in Figures 10 and 11. The weight loss of chains was largely influenced by the ocean floor rather than the chain type. Both steels exposed to a sandy floor lost the least weight while a rocky floor resulted in maximum weight loss. It was unfortunate that the ocean floor varied so rapidly in such a short distance.

All the link diameter measurements recorded using the caliper micrometer are listed in Table 3. The average initial

TABLE 2
CHAIN WEIGHT DATA

<u>Steel</u>	Initial Weight <u>(lbs)</u>	Final Weight <u>(lbs)</u>	Change <u>(lbs)</u>	<u>Floor</u>
1022	410	371	-39	Sand
4140	413	376	-37	Sand
4340	409	363	-46	Sand+Rock
8740	407	356	-51	Rock
8620	406	353	-53	Sand

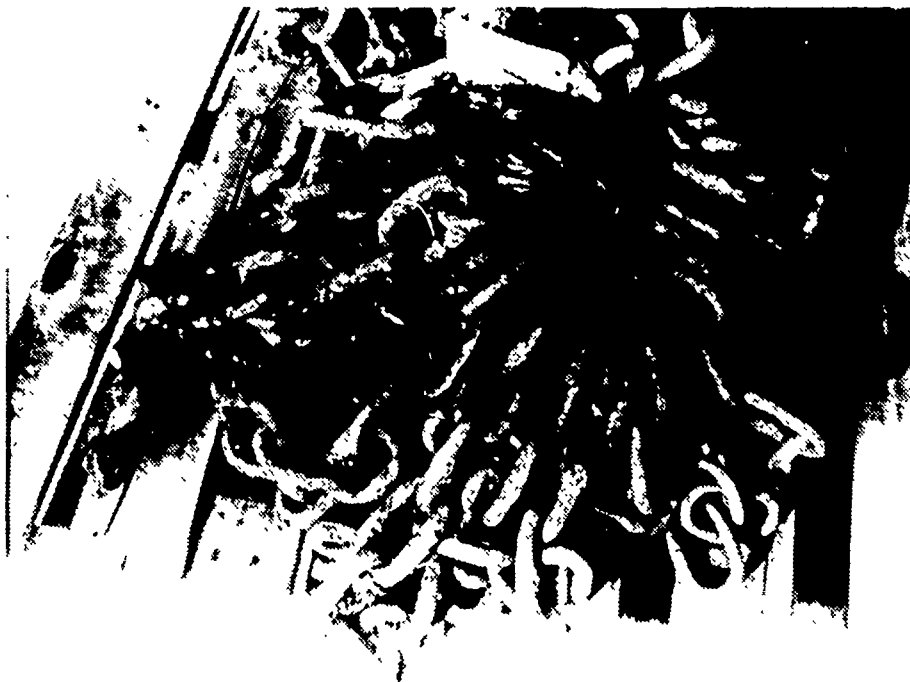


FIGURE 9. Chain appearance after two years of exposure, 1022 steel.



FIGURE 10. Sandy ocean floor. Note chain motion markings in the sand indicating lateral motion.

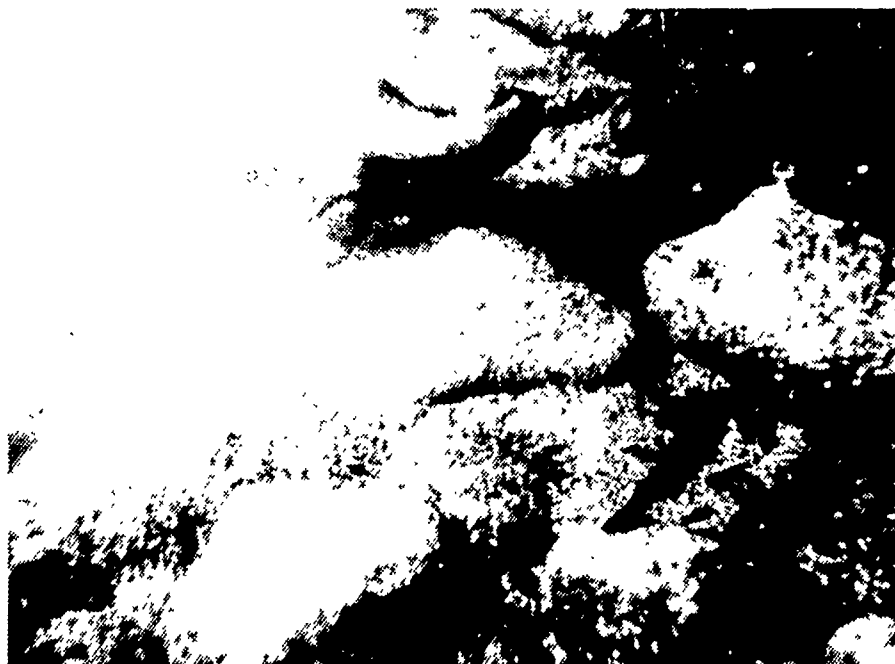


FIGURE 11. Rocky ocean floor with six to twelve-inch diameter rocks.

TABLE 3

CHAIN LINK DIAMETER DATA

Steel	Initial Link Diameter (in.)				Mid-term Link Diameter (in.)	Final Link Diameter (in.)		Material Loss	
	"A"		"H"			"A"	"H"	(in.)	(%)
1022	.776	.782	.740	.742	.701	.572	.444	0.304	41.1
	.775	.780	.755	.730		.565	.444		
	.775	.780	.731	.735		.575	.436		
	.776	.778	.730	.739		.530	.422*		
	.773	.772	.741	.744		.529	.432		
	AVE. = 0.777		AVE. = 9.739			AVE. = 0.554	AVE. = 0.435		
4140	.755	.755	.728	.726	.748	.552	.443	0.285	39.3
	.752	.754	.731	.727		.548	.437		
	.749	.752	.726	.728		.566	.443		
	.752	.752	.721	.721		.574	.451		
	.756	.758	.725	.721			.427*		
	AVE. = 0.754		AVE. = 0.725			AVE. = 0.560	AVE. = 0.440		
4340	.754	.751	.722	.736	.705	.542	.474	0.237	32.6
	.756	.751	.729	.725		.541	.487		
	.752	.753	.730	.722		.549	.497		
	.756	.758	.725	.722			.483*		
	.751	.752	.729	.727			.488		
	AVE. = 0.753		AVE. = 0.727			AVE. = 0.544	AVE. = 0.490		
8740	.754	.759	.726	.732	.654	.602	.559	Data not valid	
	.752	.757	.729	.726		.620	.564		
	.753	.750	.738	.727		.612	.563		
	.751	.752	.731	.730			.546		
	.754	.756	.730	.727			.544		
	AVE. = 0.754		AVE. = 0.730			AVE. = 0.611	AVE. = 0.555		
8620	.767	.753	.723	.741	.697	.595	.437	0.289	39.6
	.769	.750	.725	.724		.585	.440		
	.759	.752	.729	.743		.594	.434*		
	.764	.758	.738	.726		.590	.441		
	.760	.755	.727	.721		.573	.453		
	AVE. = 0.759		AVE. = 0.730			AVE. = 0.587	AVE. = 0.441		

*indicates smallest diameter link

and average final link diameters at position "H" were used to compute the loss in diameter of the chafe section for each chain since the greatest wear occurred at this position. The percentage losses were then calculated to allow for comparison between the steels. An asterisk indicates the smallest link measurement for each chain which indicates the so-called "weakest link" where failure would most likely occur.

A visual examination of the chains was conducted to note any damage from corrosion or other processes not involved in the wear action that may induce chain failure. On the alloy steel chains some accelerated corrosion was evident adjacent to welds. A typical example is shown in Figures 12 and 13. For the usual 1022 steel chain a much narrower attacked zone was found, Figure 14. The narrow weld attack observed was typical of the damage found on chains recovered from service. It should be noted that the narrow attack region would generally be more deleterious to stress corrosion cracking (SCC) than the wider, shallower corrosion noted on some of the alloy steel chains. Other features noted on the chain which would be deleterious to the mechanical strength of the chain were pits from localized corrosion on the chafe section of the chain.

Figures 15 to 19 show pits on the chains in the order of the best pitting resistance to the worst. In material terms the best, most pit-resistant material was the 4340 steel while the 1022, 8620, 8740 and 4140 were the decreasing order of pit



FIGURE 12. 4340 steel chain with shallow corrosion adjacent to the weld zone.



FIGURE 13. 4140 steel chain with shallow corrosion adjacent to the weld.



FIGURE 14. Weld region of 1022 steel chain. Note sharply defined corrosion at the weld..



FIGURE 15. 4340 chain in chafe section with no major pits.

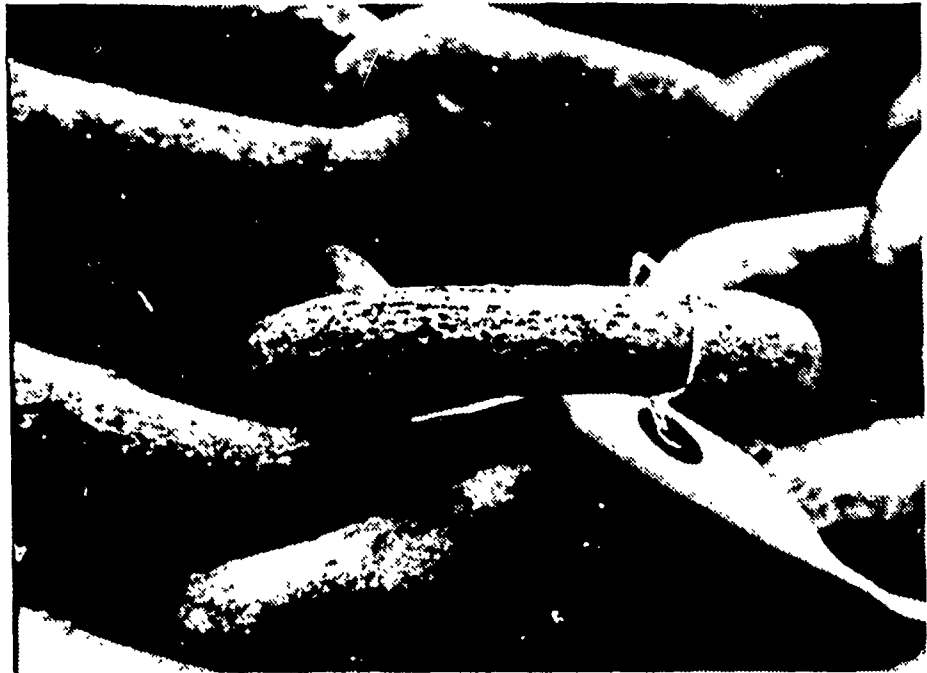


FIGURE 16. 1022 chain in chafe section with shallow elongated pits.



FIGURE 17. 8620 chain with long shallow pits in chafe section.



FIGURE 18. 8740 chain with deep pits.



FIGURE 19. 4140 chain with deep pits connecting together.

resistance. The 4340 steel chain, shown in Figure 15, shows no evidence of pitting. The pitting resistance order is the same reported previously from visual examination of chafe section at quarterly periods and reported in the annual report. The importance of these pits is that they are nucleation sites for crack initiation under SCC and effectively weaken the chain. Pit growth is highly undesirable in that detection is difficult and may lead to a premature failure of the mooring.

Microstructural examination of 4340 welds after exposure indicated no cracking in the weld zone, Figure 20. The tempered martensite structure of the 4340 was therefore reasonably stable in the marine environment.

DISCUSSION

The data collection of the field testing consisted of chain weight measurements, link diameter measurements, microstructural examination, and visual observations. The link diameter measurements were the most critical part of the data in that they would determine which chain performed the best, since it is reduction in link cross section which causes failure of the mooring. However, these measurements have the highest potential for error. An example of this is evident in the final link diameter measurements of the 8740 steel chain. The link diameter of this chain is approximately 0.1 inches

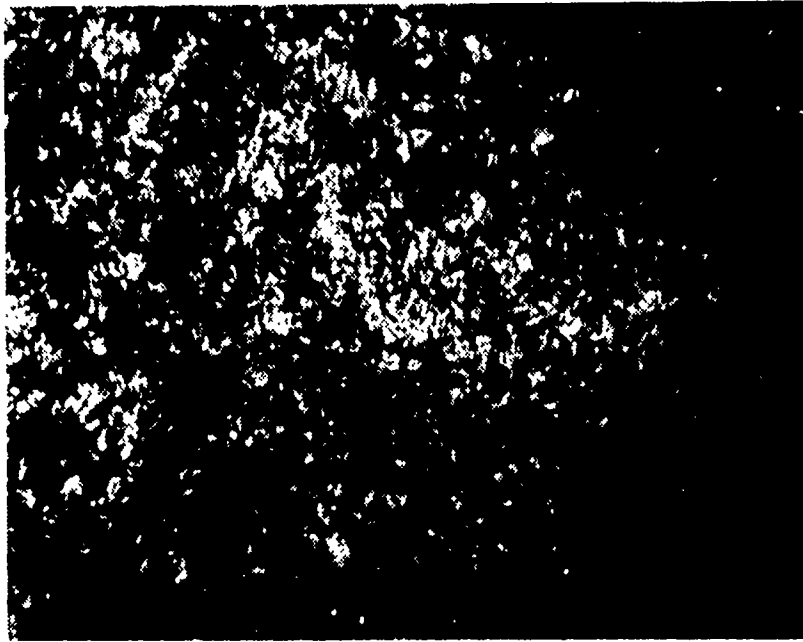


FIGURE 20. Microstructure of weld zone in 4340 steel showing no cracks after two years of exposure.

larger than all the other chains; however, the weight loss of the chain was one of the highest and the laboratory data didn't predict the chain to perform well. A reasonable explanation for this occurrence can be found in the diver inspection reports. The chain was found to be tangled in rocks in both June and October 1986. Estimating the chain to have been tangled at least six months, the reduction in wear would be accounted for by the lack of movement of the chafe section. The remainder of the chain would still undergo wear on the hard rocky bottom which would explain the overall weight loss. Therefore, the 8740 link diameter data is considered to be invalid.

A more practical method for evaluating the performance of the chains is to compare the smallest link diameter measurements. Using the weakest link data, the 4340 steel performed better than all the other steels though it was located on a semi-rocky bottom. The typical buoy chain steel, 1022, exhibited the worst performance.

A comparison of the 4140 steel chain with the 1022 steel chain shows some unexpected results. Both chains were located on the sandy ocean floor and from laboratory testing, Reference 2, the 4140 steel should have greatly outperformed the 1022 steel. However, there was little weight loss and diameter loss difference between the two steels. One possible explanation for this result is that interlink wear was a

primary mechanism of material loss. Link shape reflects the increased material loss by the curved chain portion having considerably more material loss than the remainder of the link. The 1022, 4140, and 8620 steels showed higher wear measurements at position "H" than those at position "A" which supports this theory. However, the 4340 steel showed minor difference in wear at the two positions. Barrel wear would account for the majority of the wear observed for this chain. It appears that the interlink wear is a much more damaging process than barrel wear. This conclusion is not only supported by the data but observations as well. The reason for the 1022 and 4140 steels having the same wear rate despite hardness, compositional and microstructural differences is not obvious. Clearly, the wear mechanisms for buoy chains on the ocean floor are very complex.

CONCLUSIONS

As evidenced by the field testing performed in Reference 1 and in this study, obtaining highly accurate and reliable data is difficult. The chain moorings must be exposed for long periods of time to simulate actual service conditions. The moorings may experience different conditions even though they are positioned close together. However, by combining the results of weight loss and link diameter measurements with visual observations both during and after the testing, an effective evaluation of chain mooring performance can be achieved.

From the data collected in this study, the best material choice to replace 1022 steel for buoy chain usage would be 4340 steel chain tempered to a hardness of Rc28. Previous laboratory studies on corrosive-wear of steel in a marine environment, Reference 2, indicated that 4340 steel would probably be the material of choice. Over the two-year test period the 4340 steel exhibited the least pitting of all the chains. From a weight loss perspective other chain material performed better. However, the weight loss was a function of the ocean floor condition. For the rocky ocean floor, the 4340 steel lost less weight than the 8740. Laboratory data supports the view that the 4340 will outperform 1022 steel currently in use. This was supported by the link diameter measurements in the chafe section where the 4340 steel performed the best. The 4340 steel showed the best resistance to interlink wear, which appears to account for the majority of degradation in chain integrity. Additionally, the 4340 steel is of higher strength than the 1022 steel.

The difficulty with U.S. Coast Guard usage of the 4340 steel for buoy chain is availability. Presently, there are no chain manufacturers in North America who produce this chain. Foreign manufacturers could be an alternative; however, rigorous inspection of the manufacturing process is required. Stress corrosion cracking may occur, especially in sizes greater than and including one inch diameter, if proper

welding and post heat treatment procedures are not applied. Therefore, the cost and complexity of obtaining this alloy steel chain make it unsuitable for buoy chain use at the present time.

REFERENCES

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