GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No./(Center No.) E-25-630 (R6333-0A0) GTRC/~~GIT~~ DATE 7 / 9 / 87

Project Director: Dr. Jorn Larsen-Basse School/~~Lab~~ Mechanical Engineering

Sponsor: University of Hawaii
Hawaii Natural Energy Institute

Agreement No.: Contract No. CH-6934

Award Period: From 4/1/87 To 12 ~~10~~/31/87 (Performance) 12/31/87 Reports

Sponsor Amount:

	New With This Change	Total to Date
Contract Value:	$ 30,000	$ 30,000
Funded:	$ 30,000	$ 30,000

Cost Sharing No./(Center No.) N/A Cost Sharing: $ N/A

Title: Tribology Research Services in Support of Abrasion-Corrosion Studies for HDWC, Phase II-C

ADMINISTRATIVE DATA OCA Contact Earnestine P. Smith x. 4820

) Sponsor Technical Contact:

2) Sponsor Issuing Office:
University of Hawaii at Manoa
Hawaii Natural Energy Institute
Holmes Hall 246
Honolulu, Hawaii 96822
Attn: Lois Nagahara (808) 948-8890

litary Security Classification: N/A ONR Resident Rep. is ACO: ______ Yes X No

r) Company/Industrial Proprietary: N/A Defense Priority Rating: N/A

STRICTIONS

Attached N/A Supplemental Information Sheet for Additional Requirements.

vel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

uipment: Title vests with GIT. None proposed.

MMENTS:

Subcontracts and consulting Agreements require sponsor approval.

JUL 1987 RECEIVED SUPPORT SERVICE OCA

ES TO: SPONSOR'S I.D. NO. 02.400.071.87.001

ct Director	Procurement/GTRI Supply Services	GTRC
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unting	Research Communications	

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 2/24/88

Project No. E-25-630 School/~~Lab~~ ME

Includes Subproject No.(s) n/a

Project Director(s) J. ~~Larson~~ Larsen-Basse GTRC/~~GIT~~

Sponsor Univ. of Hawaii/Natural Energy Institute

Title Tribology Research Services in Support of Abrasion-Corrosion Studies ~~inHDWC~~ for HDWC, Phase II-C

Effective Completion Date: 12/31/87 (Performance) 12/31/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Copy of Last Invoice Serving as Final
- [x] Release and Assignment
- [x] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [x]
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. Continued by Project No.

COPIES TO:

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Monthly Progress Report

to

Hawaii Natural Energy Laboratory
University of Hawaii
2540 Dole St.
Honolulu, HI 96822
Under Contract No. CH6934

TRIBOLOGY RESEARCH SERVICES IN SUPPORT OF ABRASION-CORROSION STUDIES FOR HDWC, PHASE II-C

Jorn Larsen-Basse
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

GTRC Project# E-25-630

Period: July 1987
Date: July 31, 1987

Summary of Activities

A visit was made to Hawaii June 26-July 2, 1987, including laboratory work at NELH on June 29 and 30. Purpose of the trip was to review data and test methods of the abrasion tests being performed at UH and to retrieve the warm water cable test sample at NELH. Previously obtained corrosion potential data were retrieved and analyzed.

Results

Abrasion test: testing at UH is proceeding essentially according to schedule. It is possible that wear rates are somewhat lower than should be expected in actual operation because the laboratory test use the smooth rock surfaces which are produced by cutting. This was discussed and comparison tests are in progress with rock surfaces, which have been sandblasted rough after cutting.

Corrosion tests: two sets of corrosion potential measurements are discussed in the attachment. Previously reported data obtained at NELH for corrosion coupons were evaluated in more detail; and the data for a cable test speciment were collected.

The cable specimen was a three conductor cable, 106.9 mm in outer diameter and weighing 20.4 kg/m (13.7 lb/ft). Details of this cable, which was obtained from Pirelli are given in the attached letter from Pirelli to Georgia Krasnick.

The cable section was cut into four pieces, each approximately 45 cm (18") long. One sample was retained for comparison, the other three were used for exposure tests at NELH. Before immersion the cut ends were covered with epoxy and "duct" tape. For each of the two samples exposed in troughs on shore at the NELH facility, insulated copper lead wires were soldered to four different armor wires. The attachment sites were covered with epoxy.

One sample was deployed off shore on November 22, 1985. It is located at approximately 13.7 m (45 ft.) depth on top of the cold water supply pipeline to the laboratory, about 1.5 m (5 ft) above the ocean floor. This is a point with significant water movement due to swells and currents. It is also the location for the Hawaii portion of the on-going ASTM round-robin test of seawater corrosivity.

Two samples were inserted in the covered cold and warm seawater troughs at NELH on October 31, 1985. Water flow rates through the troughs were approximately 1.5 l/m for the cold water and 0.5 l/m for the warm. Temperatures were quite constant, falling in the range 8-12°C for the cold water and 25-29°C for the warm. It became necessary to remove the warm water sample on June 28, 1987 because of a planned temporary shut down of the warm water supply.

Periodic measurements were made of the armor wire potentials vs. Ag/AgCl reference electrode. Potential data for the warm water sample are discussed in the attached.

This sample was dissected after removal and the various components evaluated for corrosion and deterioration. Very little damage had occurred, as will be reported by Mr. Tadjvar in the near future.

Examination of the attachment sites of the lead wires to the armor wires was not completely conclusive. It appears that corrosion took place around the attachment sites for wires #1 and #2. This could mean that the joint was incompletely protected and the potential measured, consequently is the corrosion potential of a copper-zinc couple or of copper-steel.

Data for wires #0 and #4 show that the zinc coating was protective during the full six hundred days. This is confirmed by the corrosion data, to be reported later.

Future Plans

The abrasion test data and past corrosion data are being analyzed in some detail in order to arrive at estimates for expected cable life under worst-case scenarios. Analysis of possible cable movement is being performed in order to determine reasonable test variables for the corrosion and abrasion test analyses.

The two remaining cable samples will be removed in late August/early September.

PIRELLI
CABLE CORPORATION
800 RAHWAY AVENUE · UNION, NEW JERSEY 07083 · (201) 687-0250

September 5, 1985

Parsons Hawaii
567 South King Street
Suite 105
Honolulu, Hawaii 96813

RECEIVED
SEP 10 1985
PARSONS

Attention: Mr. G. Krasnick

Subject: Hawaii Deep Water Cable Program
Subcontract No. 6-SC-6547-1
HDWC-O-580L

Dear Mr. Krasnick:

Pursuant to your request, the following is a detailed description of the two 6-foot long cable samples that were sent to the Hawaii Natural Energy Laboratory and the Western Gear Machinery Co.

Cable Construction

Conductor - compact stranded tinned copper, 3x150 sq.mm.
Conductor shield - Ethylene propylene rubber (EPR) semiconducting compound
Insulation - EPR insulating compound
Insulation Shield - EPR semiconducting compound
Metallic screen - annealed tinned copper tape

The three cores are layed up with polypropylene fillers and bound with a rubberized fabric core tape.

Bedding - armor - serving layers consisting of:
- bedding of polypropylene yarn having a nominal thickness of 2.0 mm (0.079 in) with a nominal diameter of 88.9 mm (3.5 in)
- 45 galvanized steel wires each having a diameter of 6 mm (0.236 in). The armor is applied with a left hand lay at a nominal lay angle of 13° 18'. The nominal diameter is 100.9 mm (3.972 in).
- layer of bitumen
- serving consisting of a layer of polypropylene yarn having a nominal thickness of 3.0 mm (0.118 in) and a nominal diameter (which is the overall cable diameter) of 106.9 mm (4.209 in).
- Total net weight of the cable is 20.4 Kg/m (13.7 lb/ft).

Chemical & Physical Properties of Polypropylene Yarn

Bedding - Yarn count is TEX 4600 i.e. 4.6 Kg/Km ± 10%
Tensile strength 800 N ± 10%.
Note - This material is different than that which will be used on the HDWC cable.

Serving - Yarn count TEX 3x1500 i.e. 3x1.5 Kg/km ± 10%
Tensile strength 850 N (min).
Elongation at rupture 20% (min)
Note - This material is identical to that which will be used on the HDWC cable.

Chemical & Physical Properties of Galvanized Steel Wires

Chemical composition - carbon 0.25 ± 0.05%
phosphorous 0.065 % max.
sulphur 0.075% max.

1025
$\rho = 7.8\ g/cm^3$

Tensile strength, N/mm^2 373 min.
490 max.

I trust that this detailed description meets your needs. If you have any further questions please call me.

Very truly yours,

PIRELLI CABLE CORPORATION

Leonard M. Bonacorsa

LMB:jma

POTENTIAL MEASUREMENTS

A. Test Coupons

Test data for a number of common materials exposed in coupon form in the troughs at NELH were obtained previously by Mr. Park and were reported in his M.S. thesis and in our 1986 report. These data have been evaluated more closely and are plotted in Fig. 1. Steady state comparison data from the literature (INCO) are also shown. It is seen that except for the lead, the NELH values are in line with commonly reported literature data. For the galvanized steel samples the potentials seem to fluctuate between a pure steel potential and a potential of about -0.85 V, corresponding to the corrosion potential of a steel-zinc couple where the steel is cathodically protected.

B. Cable Specimen in Warm Water

The cable specimen exposed in the warm water trough was removed on June 28, 1987 after 604 days of exposure. Potentials of four different armor wires measured during this period are listed in Table 1 and plotted in Fig. 2. While the data may be somewhat affected by differences in observer and instrument the general patterns are quite clear. Wire 0 and wire 3 both are in the steel corrosion regime in the early stage and then become galvanically protected by the zinc after 150-180 days, establishing steady state potentials in the range -0.8 to -0.95 V. Wires 1 and 2, on the other hand, are in the steel corrosion regime for the whole period, except for some brief excursions during the first 200 days to the cathodically protected potential.

The reason for the two different types of behaviors is not clear at this stage. It may be related to the method used to fasten the electrical lead to the wire and the amount of zinc coating removed during this process. Hopefully, this will become apparent when the wires are examined after specimen disassembly.

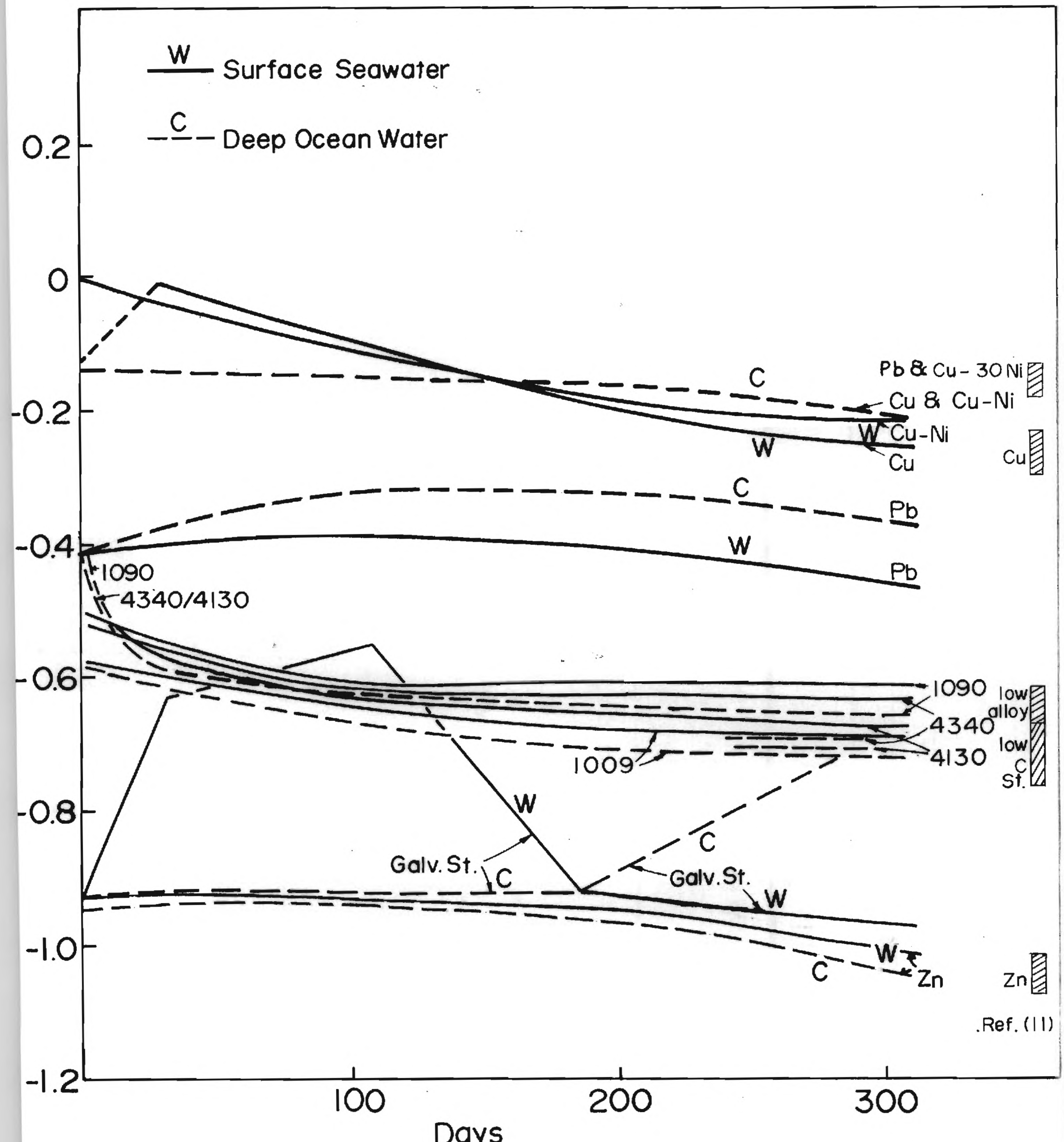


Fig. 1 Corrosion potentials, volts vs. Ag/AgCl for samples exposed in cold and warm water troughs at NELH (after Park). Comparison literature data for long-term exposures from the La Que Corrosion Center in North Carolina

Table 1

Potential, volts vs. Ag/AgCl, of four different armor wires in cable section exposed in warm water trough at NELH.

DATE	10/31 85	12/4 85	1/20 86	2/14 86	4/1 86	4/30 86	5/28 86	4/14 87	6/28 87
DAY	0	34	81	106	152	181	209	530	604
WIRE 0	--	-0.50	-0.53	-0.54	-0.40	-0.81	-1.02	-0.81	-0.80
WIRE 1	--	-1.04	-0.89	-0.41	-0.39	-0.81	-1.02	-0.35	-0.34
WIRE 2	--	-0.50	-0.89	-0.42	-0.40	-0.81	-1.02	-0.35	-0.34
WIRE 3	--	-0.49	-0.88	-0.51	-0.81	-0.82	-1.03	-0.96	-0.94
TEMP.,°C	--		25.0		27.5	26.0			
INSTRUMENT*	--	HP.	MM	MM	MM	MM	HP.	EM	EM
OBSERVER**	--	P	L-B	L-B	L-B	L-B	P	T	T

* **HP**-3478 multimeter; **MM**-portable multimeter; **EM**-electrometer

** **P**: Young-Ho Park; **L-B**: Jorn Larsen-Basse; **T**: Ahmad Tadjvar

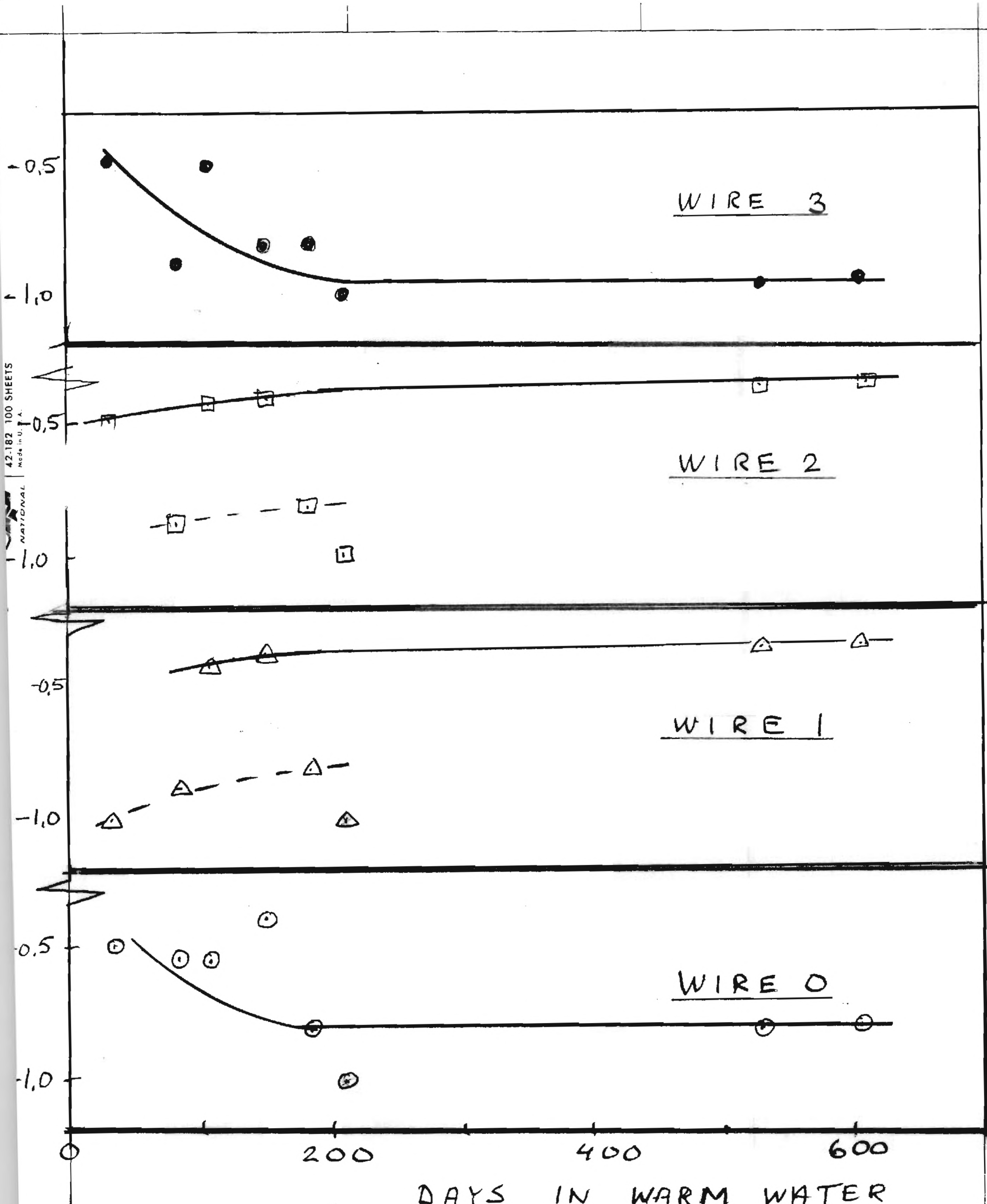


Fig. 2 Potentials, V vs. Ag/AgCl, of 4 different armor wires in cable specimen, wires are cold drawn, galvanized AISI 1025 steel.

E-25-630

Monthly Progress Report

to

Hawaii Natural Energy Laboratory
University of Hawaii
2540 Dole St.
Honolulu, HI 96822
Under Contract No. CH6934

TRIBOLOGY RESEARCH SERVICES IN SUPPORT OF ABRASION-CORROSION STUDIES FOR HDWC, PHASE II-C

Jorn Larsen-Basse
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

GTRC Project# E-25-630

Period: August 1987
Date: August 31, 1987

Summary of Activities

The UH abrasion test data are being evaluated in detail. The results are appended for abrasion by SiC abrasive papers using fresh tracks. It is concluded that there is no significant effect of specimen orientation relative to the drawing directions on wear rate.

Evaluation of the data for repeated sliding over SiC abrasive papers is currently on hold as the friction data obtained are in obvious error by almost an order of magnitude.

A paper was presented (by proxy) at the Second International Conference on Wear of Machines by Hard Particles in Prague, Czechoslovalia, June 1987. Title of the paper was "Preliminary Estimate of the Role of Abrasion in Determining the Service Life of the Hawaiian Deepsea Power Cable." A copy of the brief abstract is attached. The proceedings are on microfilm which I will try to have copied for my next report.

Future Plans

Analysis of the previously obtained corrosion data will be completed shortly. One of the goals is to establish both short-term and long-term corrosion rates in the deep sea for the major cable materials.

Evaluation of the abrasion data will continue and some tests with pillow basalt are being planned.

ABRASION TESTS

Several different types of abrasion tests were utilized, ranging from sliding against dry abrasive papers to repeated sliding against pillow lava rocks immersed in seawater.

A. Abrasion by SiC Abrasive Paper

In order to determine the possible effects of wire orientation on abrasive wear rates scoping tests were carried out using 120 grit silicon carbide abrasive paper, which has a mean grit size of 120 micrometers. Since the armor wire has rectangular cross section and is heavily cold drawn the mechanical properties may vary with direction. There are six possible orientations of interest, as shown in Figure 1. The ASTM notation system for fracture mechanics has been adapted for use here. The arrows indicate direction of sliding, i.e., direction of the abrasion grooves.

The tests were all conducted dry at a sliding velocity of 3.0 cm/s on a track length of 1.42 m. Some tests were conducted with repeated sliding in the same track, while others utilized fresh paper for each pass. Specimen size was 34 x 10 x 3 mm and both galvanized and bare samples were tested. The wear was calculated as mm^3 of steel lost from weight loss measurements. The cutting force was averaged over each pass and the coefficient of friction was calculated.

A.1. Tests with Fresh Tracks

These tests were conducted with galvanized samples, except for one test with a base sample (zinc removed). The results are listed in Table 1 and plotted in Figure 2.

The coefficient of friction stayed essentially constant for each test and only the average values have been listed. These range between 0.59 and 0.72, showing no clear correlation with specimen direction being abraded. An overall average value of 0.66 appears to be reasonable.

Since the tests were conducted with galvanized samples, some of the behavior seen is due to abrasion of the zinc in the early stages of testing. With 75 micrometers of zinc coating, the face corresponding to T-S has 25.5 mm^3 of zinc, S-T and L-T have 7.65 mm^3, while S-L has no zinc on the front face. Recalculated as mm^3 steel these numbers become 25.5, 7.65 and zero. With the long specimen size selected it is probable that complete contact was not achieved for the T-S and possibly the S-T directions, i.e., a combination of zinc and steel wear may be seen. Since the zinc is soft it will have little resistance to abrasive wear.

The curves for galvanized T-S and S-T show initial rapid wear, probably corresponding to zinc removal, followed by linear relations after 5m of sliding. The other directions show wear proportional to sliding distance, as is generally expected. Slopes of the lines are:

T-S	0.36	mm^3/m
T-S, bare	0.27	
S-T (1)	0.23	
S-T (2)	0.21	
S-L	0.20	
L-T	0.19	

Of these, the T-S value is discarded because of the contribution of the zinc, as discussed above. The chosen geometry and dimensions of the test specimens do not permit a direct, rigorous comparison of the data. If the wear rates are plotted vs. specimen length in the direction of sliding, see Figure 3, a slightly increasing trend is seen. This is not unexpected from the mechanics of abrasion alone and indicates that there are no significant differences in abrasion properties between these three directions. The wear rate for the T-S direction is somewhat greater. This can be attributed to the greater width and lower contact pressure for this configuration. Again, the data does not indicate any significant variation in abrasion resistance with specimen orientation. This is seen more clearly in Figure 4, where wear rates have been plotted against contact area. The value for the very short dimension, L-T, lies below the general correlation here. Values for the galvanized samples have been adjusted to account for the 6% of the wear rate which is due to removal of zinc around the perimeter of the contact area.

The work expended in removing unit volume can be calculated from

$$CW = \frac{P.\mu}{\dot{\omega}}$$

Where CW is the cutting work (J/mm^3), P is the applied load (N), μ is the coefficient of friction and $\dot{\omega}$ is the wear rate (mm^3/m). The calculated values are

S-T (1)	36.41	N/mm^3
S-T (2)	40.26	
L-T	43.48	
S-L	37.63	

These values are also plotted in Figure 3. The cutting work drops rapidly as sample length increases to about 10 mm and then essentially levels off.

These experiments have shown that there are no significant differences in abrasion resistance between the various orientations of the armor wire and that a coefficient of friction of 0.66 and a max. wear of around 0.275 mm^3/m can be expected for the conditions used.

Table 1

Abrasive wear by 120 grit SiC paper using fresh track. Load 11.91 N.

	Wear, Calculated as mm^3 Steel					
Total Distance m	Galvanized					Bare
	S-T	S-T	L-T	S-L	T-S	T-S
1.42	0.615	0.603	0.269	0.180	1.218	0.423
4.27	1.526	1.513	0.833	0.756	3.295	1.192
8.53	2.577	2.410	1.603	1.551	4.692	2.154
14.22	3.808	3.577	2.769	3.000	6.705	3.756
21.33	5.372	4.859	4.154	4.346	9.487	5.680
Coeff. Friction	0.661	0.667	0.652	0.594	0.719	----

ILLUSTRATIONS

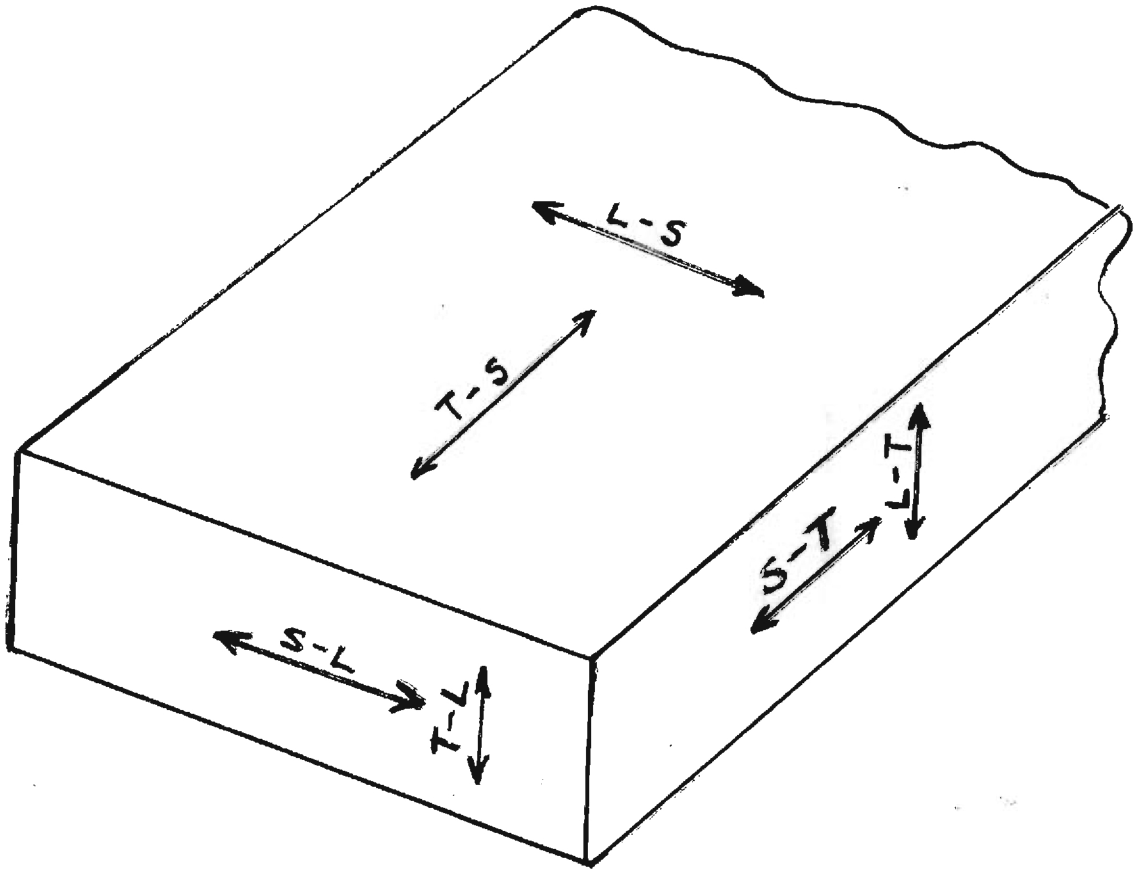
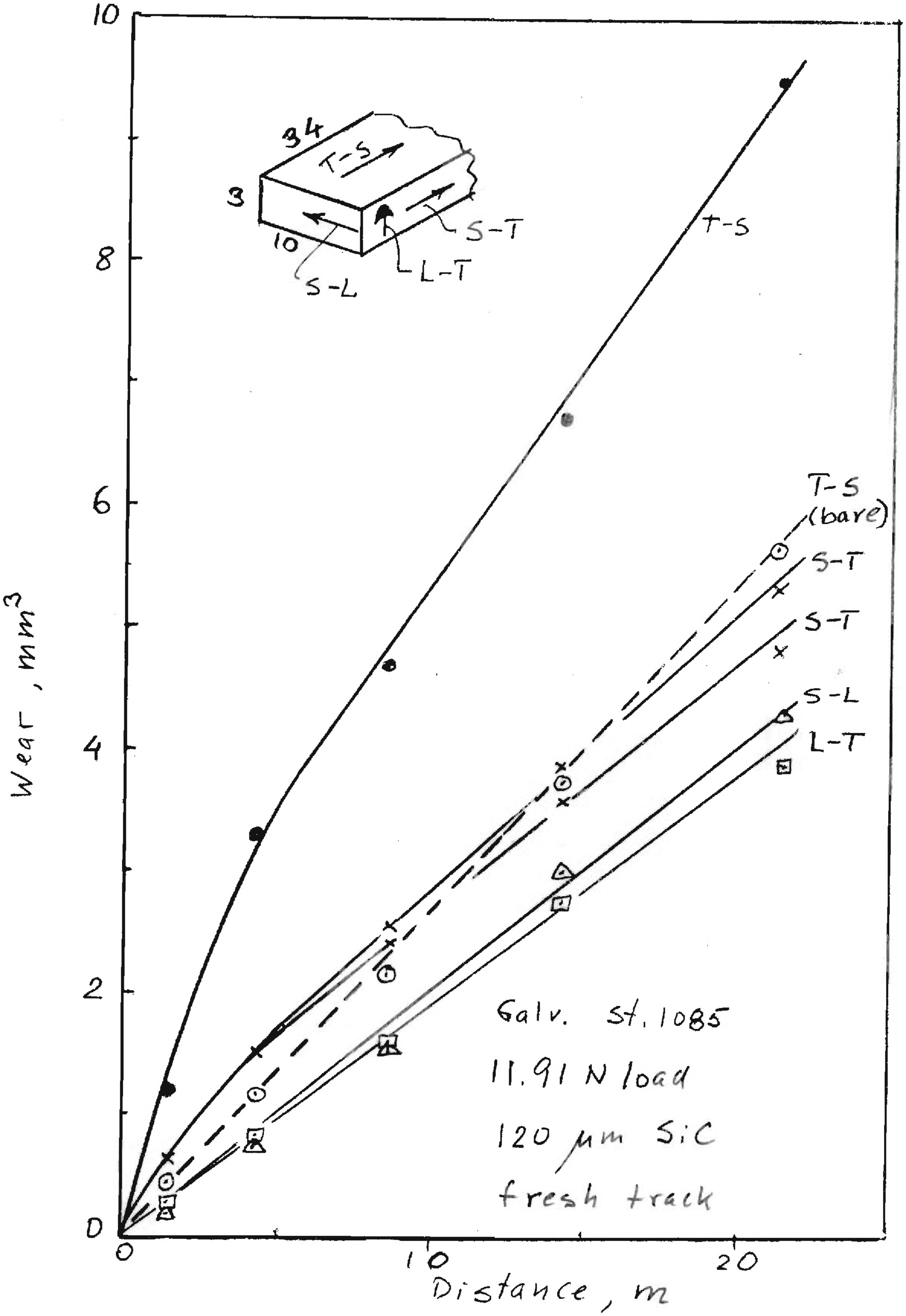
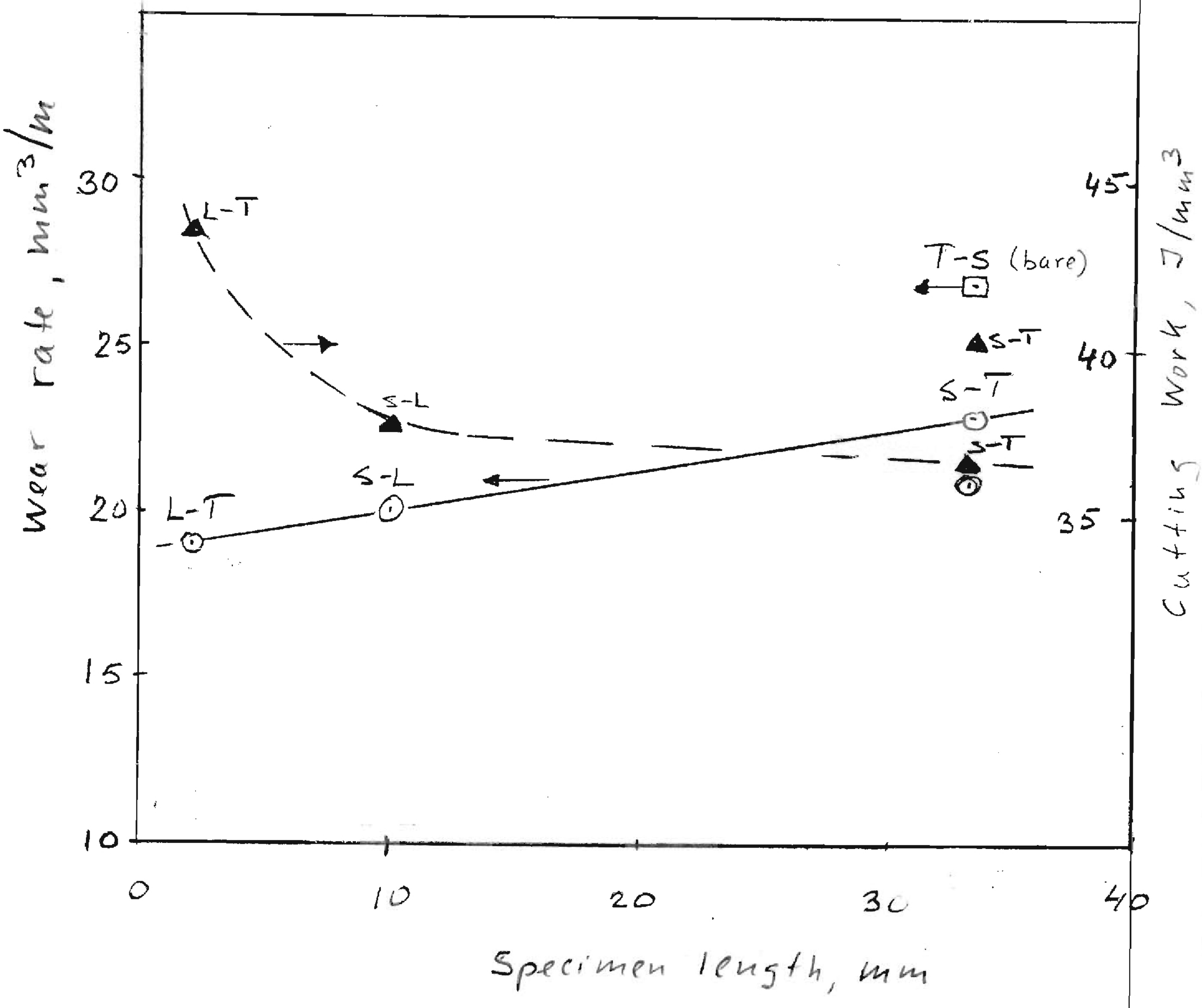


Fig. 1



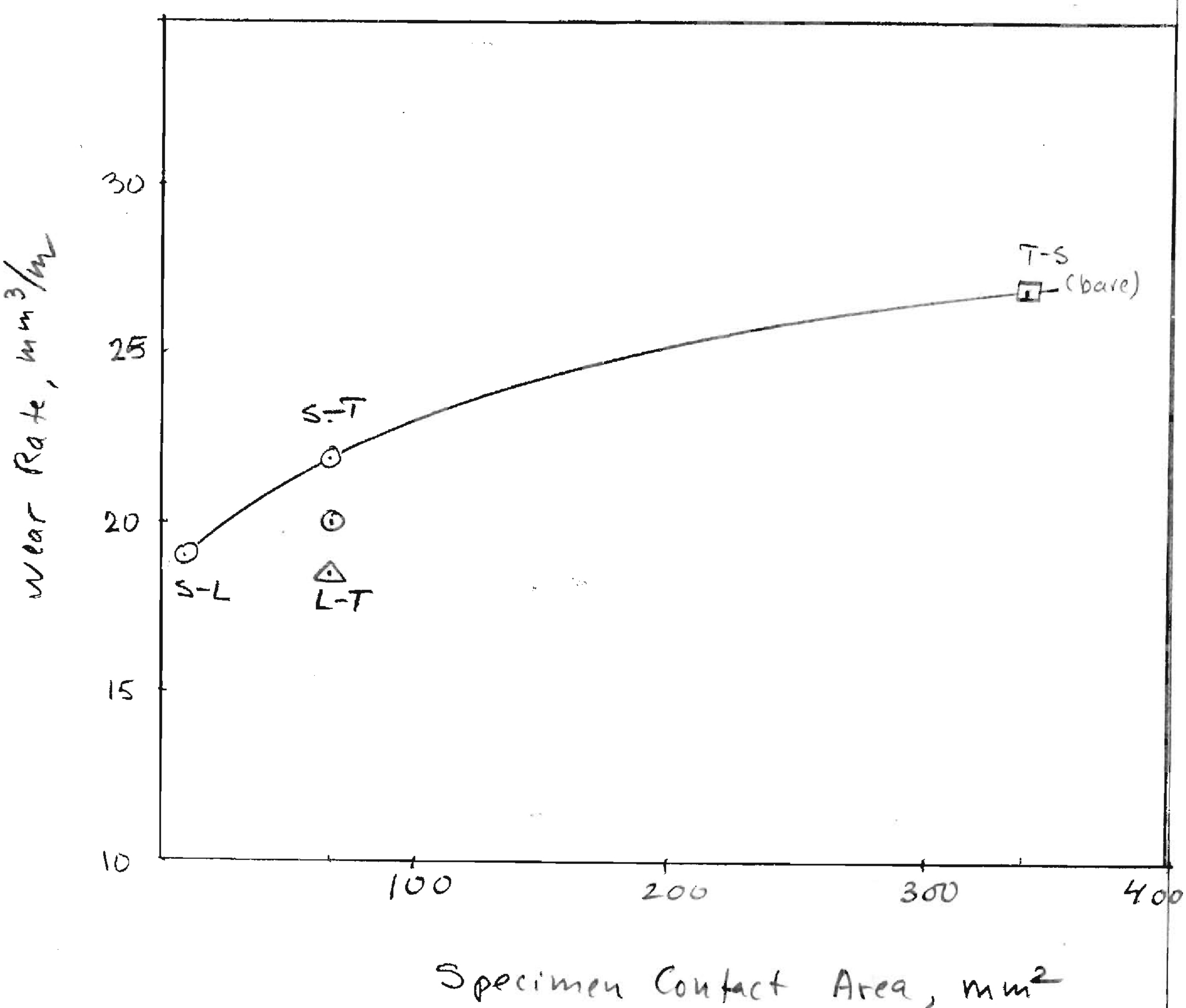
34
T-S
3
10
S-T
L-T
S-L
T-S
T-S
(bare)
S-T
S-T
S-L
L-T
Galv. st. 1085
11.91 N load
120 μm SiC
fresh track
Wear, mm^3
Distance, m
0
2
4
6
8
10
0
10
20

Fig. 2



Wear rate, mm³/m
Cutting work, J/mm³
30
25
20
15
10
45
40
35
0
10
20
30
40
Specimen length, mm
L-T
S-L
S-T
T-S (bare)

Fig. 3



Wear Rate, mm³/m
30
25
20
15
10
T-S
(bare)
S-T
S-L
L-T
100
200
300
400
Specimen Contact Area, mm²

Fig. 4

ČESKOSLOVENSKÁ VĚDECKOTECHNICKÁ SPOLEČNOST
ЧЕХОСЛОВАЦКОЕ НАУЧНО-ТЕХНИЧЕСКОЕ ОБЩЕСТВО
TSCHECHOSLOWAKISCHE WISSENSCHAFTLICH-TECHNISCHE GESELLSCHAFT
CZECHOSLOVAK SCIENTIFIC AND TECHNICAL SOCIETY

OPOTŘEBENÍ STROJŮ ČÁSTICEMI
ИЗНОС МАШИН ЧАСТИЦАМИ
VERSCHLEISS DER MASCHINEN DURCH PARTIKELN
WEAR OF MACHINES BY HARD PARTICLES
II.

RESUMÉ - РЕЗЮМЕ

ČSSR - PRAHA - 1987
ЧССР - ПРАГА - 1987

2. PRELIMINARY ESTIMATE OF THE ROLE OF ABRASION IN DETERMINING THE SERVICE LIFE OF THE HAWAIIAN DEEPSEA POWER CABLE

- J. Larsen - Basse, U.S.A.

The contribution deals with influence of abrasion on the service life of deepsea power cable connecting the geothermal power source with the consumption point in the Hawaiian Islands.

It was shown that abrasive cable wear plays a limiting role from the service life point of view: the cable surface has a contact with abrasive elements on the sea bottom during relative movements caused by deep sea currents.

In this paper the available laboratory data are used to make a preliminary assessment of the probable time to failure of this cable due to straight abrasion as well as abrasion-enhanced corrosion. It is shown that failure by these mechanisms is distinctly possible.

2. VORLÄUFIGE BEWERTUNG DER ABRASIONSROLLE BEI DER FESTLEGUNG DER LEBENSDAUER VON UNTERSEEISCHEN KRAFTKABELN

- J. Larsen - Basse, USA

Der Beitrag betrifft das Abrasionproblem im Zusammenhang mit der Lebensdauer von Untersee-Kabeln, welche die geothermale Energiequelle mit dem Ort des Energieverbrauchs auf den Hawaischen Inseln verbinden.

Es wurde nachgewiesen, dass der Kabelverschleiss infolge von Abrasion die Lebensdauer begrenzt, da die Kabeloberfläche infolge der, durch Strömungen und Stromschnellen hervorgerufenen Bewegungen, unter abrasivem Verschleiss im Kontakt mit dem Meeresboden, leidet.

Im Beitrag werden die Ergebnisse der Laborversuche und auch die vorläufige Einschätzung der, bis zum Entstehen von Kabeldefekten durch Abrasion, ggf. Korrrosion des Kabels verlaufenden Zeit, behandelt.

2. ПРЕДВАРИТЕЛЬНАЯ ОЦЕНКА РОЛИ АБРАЗИИ ПРИ ОПРЕДЕЛЕНИИ СРОКА СЛУЖБЫ МОРСКОГО ЭНЕРГЕТИЧЕСКОГО КАБЕЛЯ

- Дж. Ларсен - Вассе, США

В работе рассмотрена проблема абразии и ее влияние на долговечность морского силового электрокабеля, соединяющег геотермальный источник энергии с местом потребления на Гавайских островах.

Доказано, что абразивный износ кабеля играет лимитирующую роль в отношении долговечности вследствие контакта поверхности кабеля с абразивной средой на морском дне при относительном движении, вызванном морскими течениями во врем приливов и отливов.

В работе даны результаты лабораторных опытов, а на и основе и предварительный расчет времени до возникновения с каза кабеля вследствие абразии, или коррозии кабеля, вызва ной абразивным эффектом.

2. PŘEDBĚŽNÉ HODNOCENÍ ÚLOHY ABRAZE PŘI STANOVENÍ ŽIVOTNOSTI PODMOŘSKÉHO ENERGETICKÉHO KABELU

J. Larsen - Basse, USA

Příspěvek se týká vlivu abraze na životnost podmořského silového elektrického kabelu spojujícího geotermální zdroj energie s místem spotřeby na Havajských ostrovech.

Bylo prokázáno, že abrazívní opotřebení kabelu hraje limitující roli z hlediska životnosti při kontaktu povrchu kabelu s abrazívním prostředím na mořském dně při relativním pohybu vyvolaném mořskými proudy v důsledku slapového působení.

V příspěvku jsou uvedeny výsledky laboratorních pokusů a na jejich základě i předběžný odhad času do vzniku poruchy kabelu abrazí, eventuálně korozí kabelu iniciovanou abrazívním účinkem.

E-25-630

Monthly Progress Report

to

Hawaii Natural Energy Laboratory
University of Hawaii
2540 Dole Street
Honolulu, HI 96822
Under Contract No. CH6934

TRIBOLOGY RESEARCH SERVICES IN SUPPORT OF ABRASION-CORROSION STUDIES FOR HDWC, PHASE II-C

Jorn Larsen Basse
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

GTRC Project # E-25-630

Period: September 1987
Date: October 1, 1987

Summary of Activities

The general corrosion data from NELH, which were obtained as part of Phase II-B and reported in our final report from that phase, were further analyzed in preparation of a paper for CORROSION '88. This conference will be held in St. Louis during March 21-25, 1988. The abstract, the conclusions and some of the major graphs are attached hereto. The complete preprint will be submitted after the manuscript has been reviewed and printed.

Briefly, it was found:

(1) that the cold water is less aggressive than the warm, except for pH-sensitive materials such as Zn and aluminum,

(2) that the cold water data compare very well with long-term data from actual in-situ deep ocean tests reported in the literature, and

(3) that the carbon steels in cold water appear to follow a relation

$$x = x_o \, t^{1/3} \tag{1}$$

where x is thickness of material lost in μm, t is days of exposure, and x_o = 5.1 μm for AISI 1090 in the annealed state.

If equation (1) holds for the short exposure times anticipated between corrosion film removal due to abrasion in worst-case scenario, and if the film is completely removed each time, then corrosion-erosion can obviously be a serious danger. Removal rates of 12.9 μm/day for 4 passes/day at 1/4 day intervals or 5.1 μm/day for 1 pass each day can readily be calculated; they indicate early failure.

Evaluation of some recent short-term tests from UH is in progress to confirm or refute the validity of the above extrapolation and of these estimates.

Initial wear testing is underway to determine the relative wear of rock and armor wire at various contact pressures, and stroke lengths, and for various load cycles. The test is intended to determine whether an abrasive rock contacting point would wear down and lose it abrasive properties. More detail will be provided next month.

Future Plans

Analysis of the UH corrosion data and the recent NELH corrosion data will be completed and the results compared with the data discussed above.

The initial abrasion-deterioration tests with heavily loaded contacts will be developed into a complete test series.

Initial attempts will be made to combine the results of the various tests into a coherent knowledge base which allows estimation of cable life for various scenarios.

CORROSION IN SLOWLY FLOWING OTEC SEAWATER: A ONE-YEAR STUDY

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Atlanta, Georgia 30332-0405

and

Young-Ho Park
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ABSTRACT

A number of common alloys were exposed in parallel in slowly flowing Hawaiian surface seawater and cold deep seawater pumped from 590 m depth for periods of 1 - 10 months. The cold water has relatively low pH and oxygen content and was found to be much more aggressive than the warm surface water towards zinc, copper, lead and galvanized steel and much less aggressive towards carbon, low alloy, and stainless steels.

The cold water corrosion rates compare quite closely with data for tests conducted in situ at various depths in the Pacific Ocean off Port Hueneme in Southern California, showing the possibility of conducting future tests with pumped water in convenient on-shore locations.

All samples, except aluminum in cold water show corrosion rates which decrease rapidly with time during the early stage of exposure. For the warm water the decrease is more rapid than reported from other sites, possibly because these locations were not similarly sheltered from the actions of waves, currents, and macrobiofouling. After 1-3 years most data from around the world trend towards similar values for individual alloys.

CONCLUSIONS

This study has shown that the Hawaii data from on-shore tests are quite similar to results reported in the literature from at-sea exposures. Minor differences are shown in the early stages of exposure of copper alloys and steels in surface ocean water where the corrosion rates of the sample from the protected on-shore tests drop more rapidly than the rates found in off-shore tests. In the latter samples are exposed to wave and current action and to macrobiofouling and this most probably accounts for the difference. After exposure of 1-4 years the samples from the different test sites reach quite similar corrosion rates. These long-term corrosion rates have been summarized in Table 6. It is realized that steady state conditions may never be fully established and that the listed values may overestimate corrosion rate for very long periods of time, thus being conservative values from an engineering design point of view.

Results from tests conducted in the cold deep seawater pumped to the laboratory compares closely with the deep ocean tests conducted in situ in the Pacific ocean off Port Hueneme in Southern California. This means that it should be possible to obtain meaningful data for other materials and test periods by conducting the exposure tests in the convenient on-shore location.

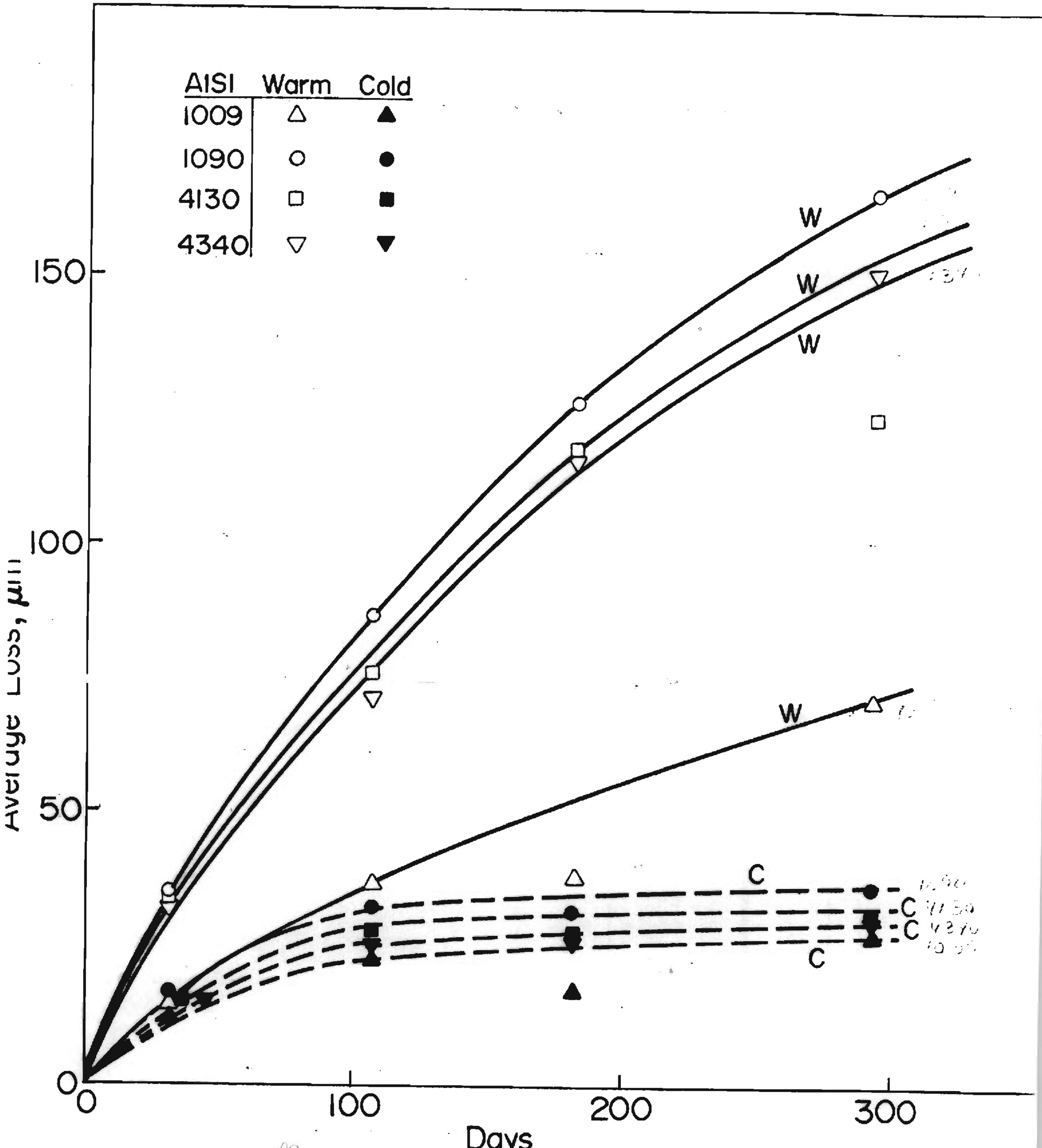
The cold water is much more aggressive than the warm for aluminum, slightly more for zinc, lead and copper, and much less aggressive against carbon, low alloy, and stainless steels.

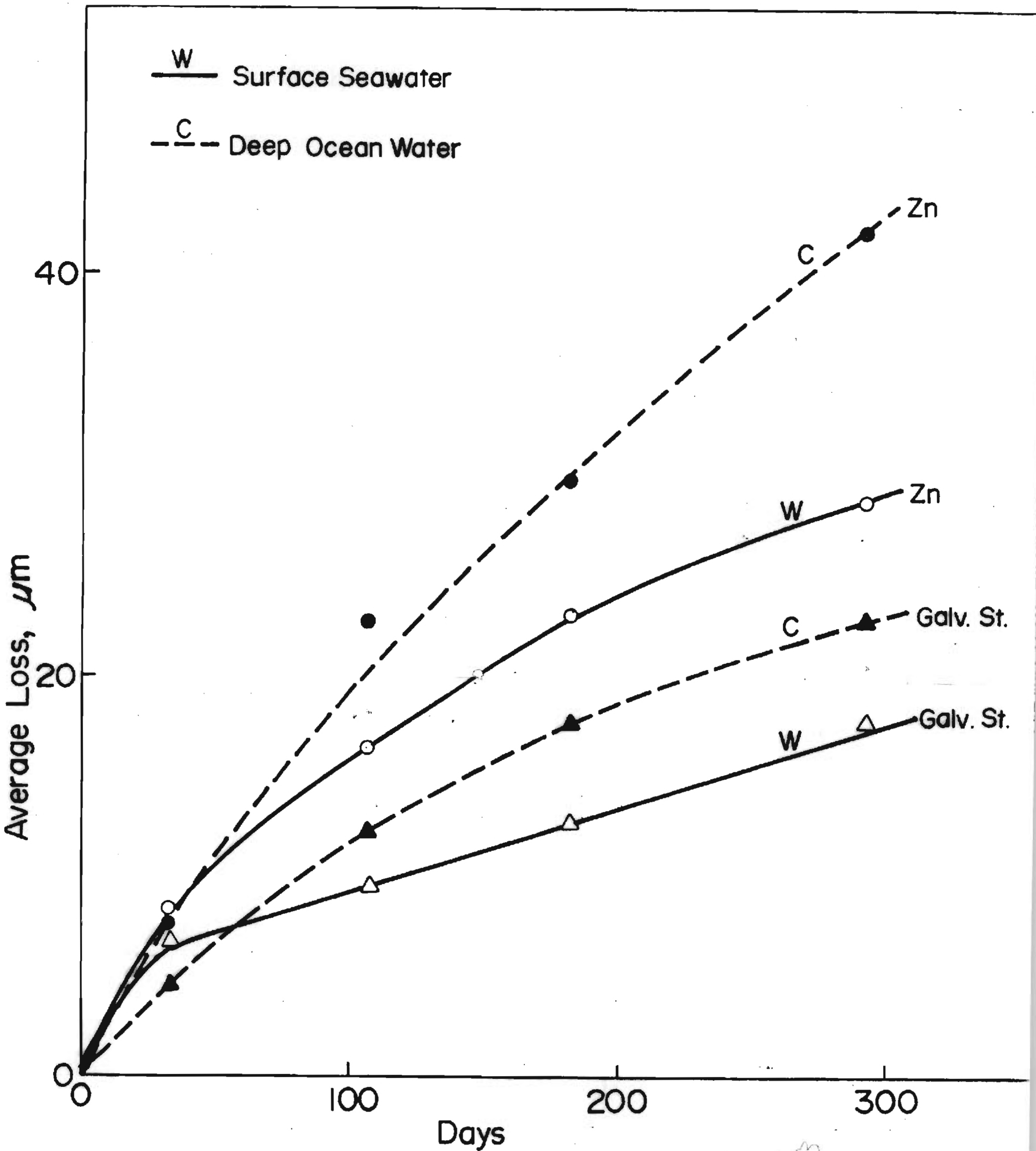
Table 6

Estimated Long Term Corrosion Rates and Time of Exposure to Establish Near-Steady State Data from This Study Combined With Literature Results.

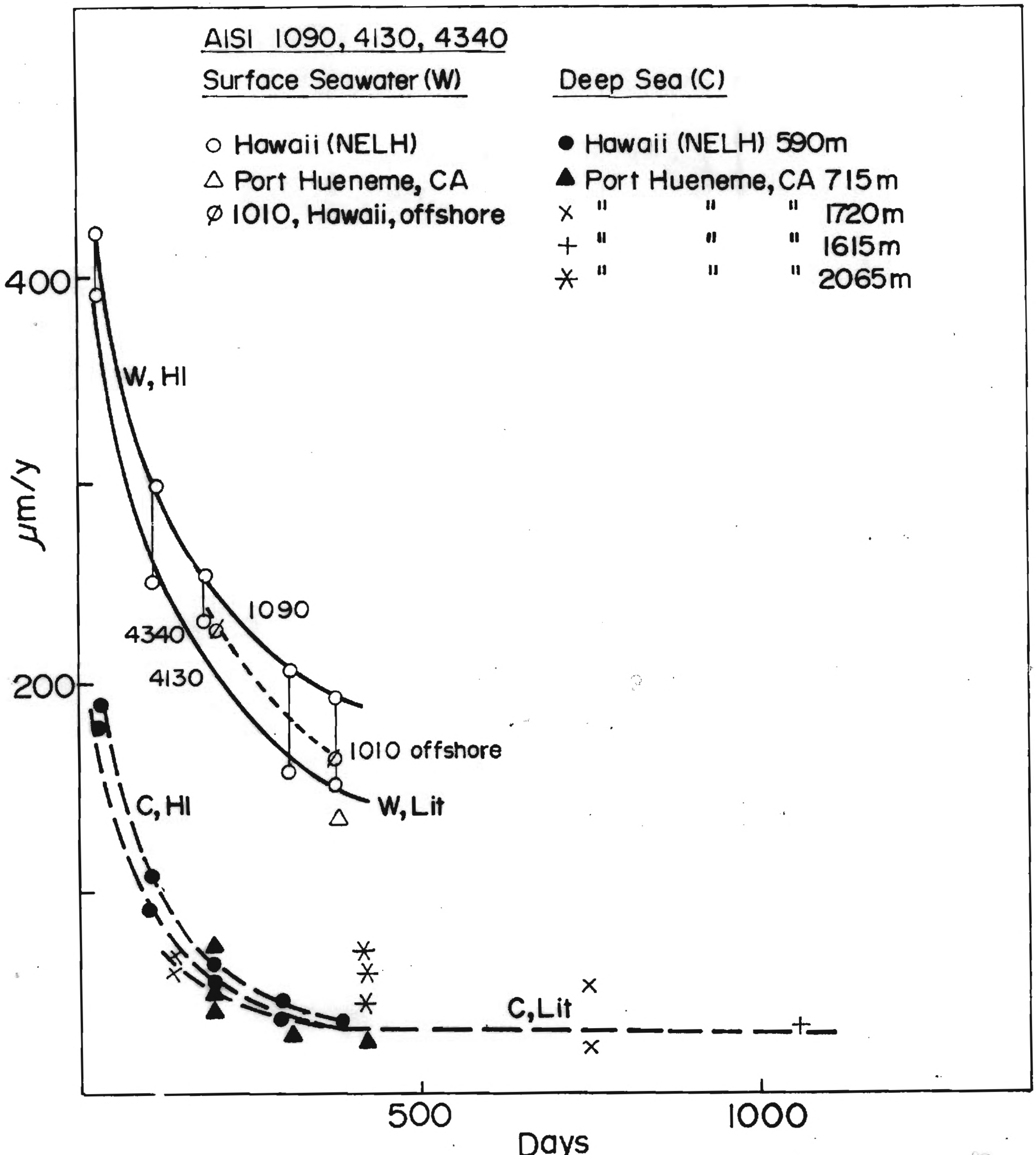
	Surface seawater		Deep Ocean Water	
Alloy	Rate, μm/y	Years to establish	Rate, μm/y	Years to establish
Cu*	5	2.5	5	2.5
Cu-30Ni	2	2.5	2	2
Pb	3(12)**	2(3)**	2	2
AISI 1009	50-75 (50)**	1.5-2.5(3.5)**	40	1
AISI 1090				
AISI 4130	[70]+	[3]+	30	1
AISI 4340				
Zn*	20	2.5	30(40)**	2.5(5)
Galv. Steel	20	2	20	2

*Shallow pitting
**Literature Values at Variance with Data from this Study
+Highly Uncertain Data

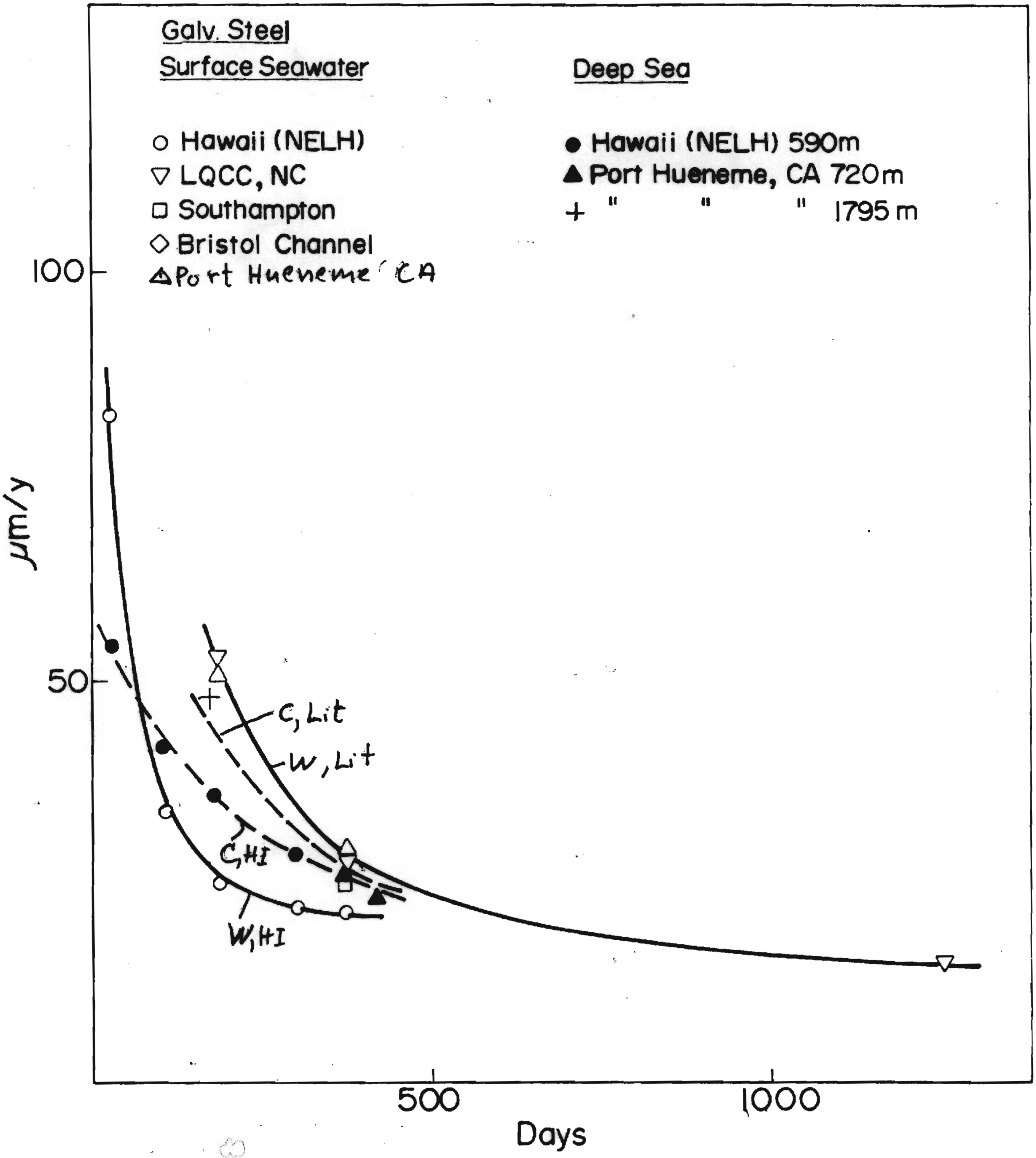

AISI Warm Cold
1009
1090
4130
4340
W
W
W
W
C
C
C
C
Average Loss, μm
Days
0
50
100
150
0
100
200
300



W Surface Seawater
C Deep Ocean Water
Zn
C
Zn
W
Galv. St.
C
Galv. St.
W
40
20
0
Average Loss, μm
0
100
200
300
Days



AISI 1090, 4130, 4340
Surface Seawater (W)
Deep Sea (C)
○ Hawaii (NELH)
△ Port Hueneme, CA
ø 1010, Hawaii, offshore
● Hawaii (NELH) 590m
▲ Port Hueneme, CA 715m
× " " " 1720m
+ " " " 1615m
✳ " " " 2065m
400
200
μm/y
W, HI
1090
4340
4130
1010 offshore
W, Lit
C, HI
C, Lit
500
1000
Days



Galv. Steel
Surface Seawater
Hawaii (NELH)
LQCC, NC
Southampton
Bristol Channel
Port Hueneme CA
Deep Sea
Hawaii (NELH) 590m
Port Hueneme, CA 720m
" " " 1795 m
100
50
μm/y
C, Lit
W, Lit
C, HI
W, HI
500
1000
Days

E-25-630

Monthly Progress Report

to

Hawaii Natural Energy Laboratory
University of Hawaii
2540 Dole Street
Honolulu, HI 96822
Under Contract No. CH6934

TRIBOLOGY RESEARCH SERVICES IN SUPPORT OF ABRASION-CORROSION STUDIES FOR HDWC, PHASE II-C

Jorn Larsen Basse
George W. Woodruff School of Mechanical Engineering
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Atlanta, GA 30332-0405

GTRC Project # E-25-630

Period: October 1987
Date: November 9, 1987

Summary of Activities

II. Laboratory studies to measure wear of both rock and armor wire under high contact stresses are under way. The purpose is to determine whether lava rock becomes more abrasive, or less abrasive, as it is worn by armor wire steel under loads which are sufficient to cause slight surface crushing. The extent of the damage is being measured, as are the cutting, or friction forces since they determine the potential distance of abrasive sliding in each tidal cycle. The results will complement the wear data from U.H.

We have encountered a number of unanticipated start-up problems and delays but still expect to complete the work during November. Initial results compare very well with the U.H. data. They show for the fine grained rock, which was dredged from the Alerumihaha Channel,

a) that the coefficient of friction is quite low, compared to abrasive wear in general, and

b) that the rate of abrasive damage, inflicted by this fine-grained, non-porous rock on the hard steel, is fairly low; the porous and coarse grained surface rocks give significantly greater wear.

II. I attended the Fall Meeting of the Metallurgical Society and the American Society for Metals in Cincinnati, Ohio. The purpose was to follow several sessions on wear and corrosion and to present one paper in each area:

"Effect of Hardness and Fracture Toughness on abrasive Wear of WC-Co Alloys" - by J. Larsen-Basse

and

"Acid Rain to the Max - Atmospheric Corrosion at a Hawaiian Geothermal Site" - by S. Quazi, J. Larsen-Basse, and B. E. Liebert.

III. In a previous report I referred to a paper presented (by proxy) at a meeting in Prague. In this short paper a first attempt is made to estimate the potential for damage to the cable by abrasion and corrosion in combination, based on the data available at the time. While some of the input data now are changed due to our current efforts, and while some minor corrections need to be made, the approach still appears to be valid and will be used in the final analysis.

A copy is appended of

J. Larsen-Basse, "Preliminary Estimate of the Role of Abrasion in Determining the Service Life of the Hawaiian Deepsea Power Cable," Int. Conf. on Wear of Machines by Hard Particles, Prague, June 1987, Czechoslovak Scientific and Technical Society, paper #2, 11 pp. (microfiche).

PRELIMINARY ESTIMATE OF THE ROLE OF ABRASION IN DETERMINING THE SERVICE LIFE OF THE HAWAIIAN DEEPSEA POWER CABLE

- J. Larsen-Basse, U.S.A.

1. Introduction

In the Hawaiian Islands a large geothermal resource has been proven on the island of Hawaii, or the Big Island. To fully develop this resource it is necessary to transport the electricity to Honolulu, on the island of Oahu, where most of the state's population resides.

The most feasible way of transporting the electricity at the present time is by means of a submarine power cable. This cable must cross a channel where depths of up to 2100 m are encountered. Total length of the cable is expected to be some 280 km. These conditions require extension of the current technology of high voltage direct current (HVDC) cables in that they are substantially beyond any previously encountered submarine cable conditions /1/.

The subject of abrasive wear takes on importance because it could conceivably be a life-limiting factor. The ocean bottom exhibits many rock outcroppings from fairly recent submarine volcanic eruptions, which contains abrasive mineral grains, such as olivine.

During deployment of the cable, it is expected that sections of it inevitably will become suspended between rock ledges or outcroppings, as shown in Fig. 1. The strong tidal currents in the channel will swing the suspended cable section back and forth twice a day, and this may cause abrasive wear where the cable comes into contact with rocks.

The selected final design is shown in Fig. 2. The materials selection was based on many factors but a major

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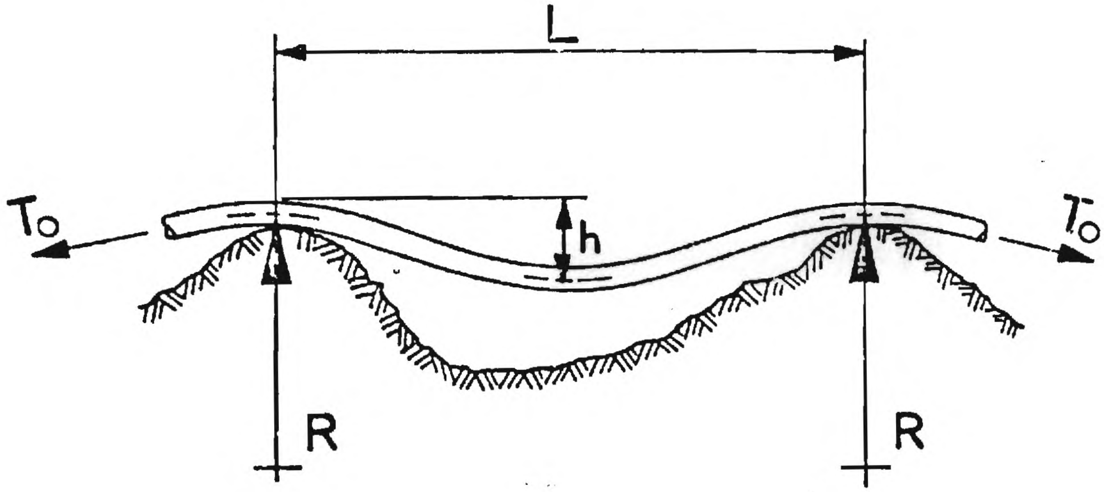

Fig. 1 Configuration of cable suspended on two outcrops of the same height

one was the strength to weight ratio, in order to make cable laying feasible at the depths encountered. It has been estimated /2/ that the cable will fail immediately due to lead sheath fracture, if the span length in Fig. 1 exceeds 60 m; and that the cable will fail by lead sheath fatigue in less than the desired 30-year life, if the span exceeds 40 m. The question to eventually be answered by the wear tests is if abrasion alone or in combination with corrosion can cause failure sooner than will fatigue.

The cable is a so-called self-contained oil filled cable for 300 kV dc current, with aluminium conductors. It is a complex design with a total of 22 different layers. The outermost layers, which are of interest in this connection, are listed in Table 1.

The purpose of this study was to make a preliminary estimate of the potential of failure due to abrasion, in order that suitable design or protection countermeasures can be taken before final manufacture of the cable.

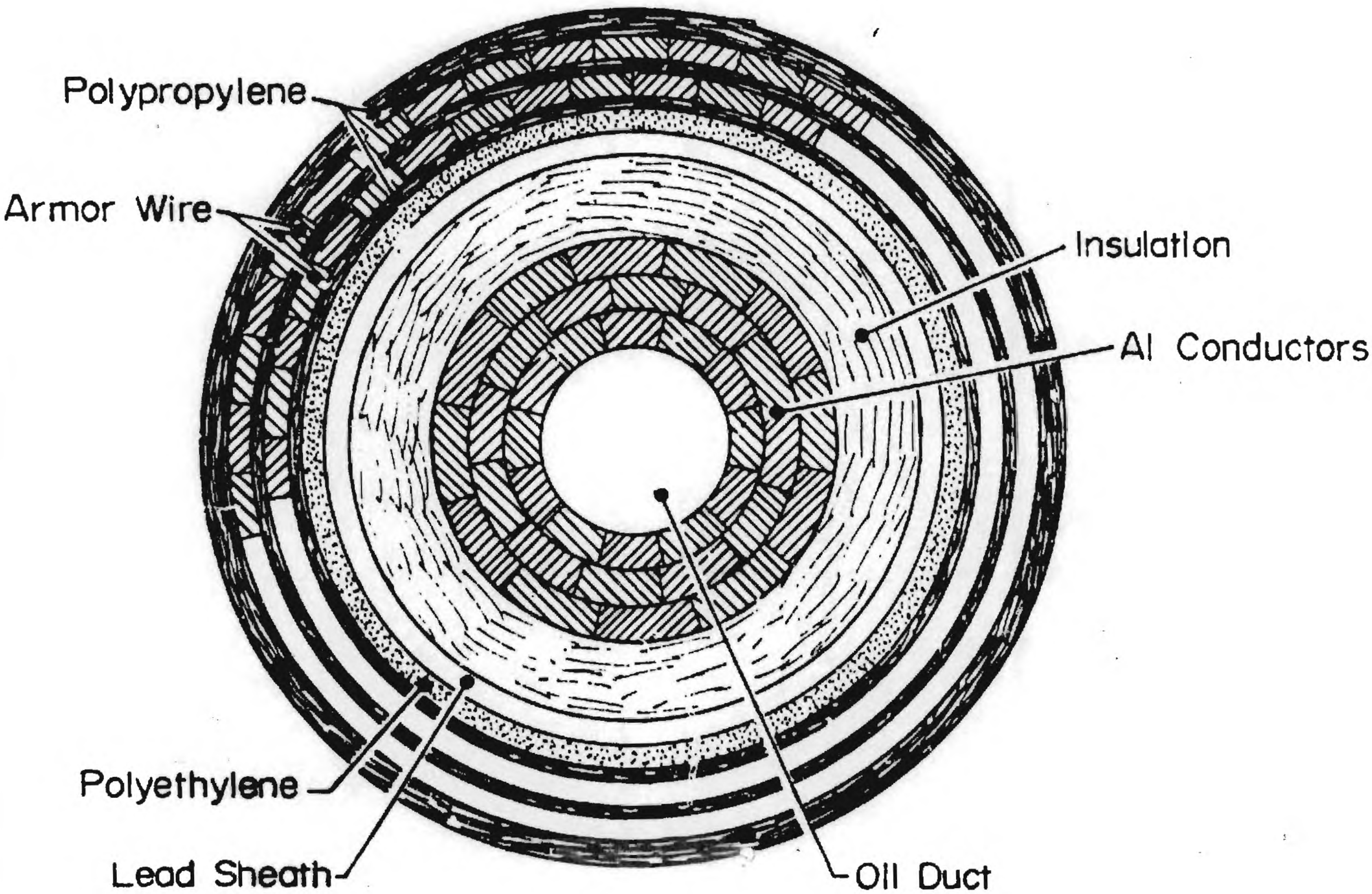

Fig. 2 Cross section of the final cable design. Cable is 300 kV d.c., self-contained oil filled. Weight in air: 37 kg/m. Weight in water 27 kg/m. Only the major components are indicated

TABLE 1

Major Outer Layers in Final Cable Design

	Thickness mm	Outer Dia. mm
Polypropylene yarn serving	3.3	118.4
Outer steel[x] armor, 31 wires	3.0	111.8
Polypropylene yarn bedding	1.6	105.8
Inner steel[x] armor, 29 wires	3.0	102.6
Polypropylene yarn bedding	1.1	96.6
Polyethylene jacket	4.0	93.5
Bronze Tape	0.6	84.6
Lead Sheath	3.3	82.6

x Steel wires are 3 mm x 10 mm, cold drawn galvanized AISI 1085 (0.85 % C).

2. Available Information

Abrasive Surface

The submarine lavas of the cable route are expected to be very similar to the lavas currently being produced by the Kilaue volcano, and the lava used in tests reported in /4/ was collected there from a recent (1976) flow. The most abundant minerals in lava are Pyroxene, Feldspar, and Olivine. A typical lava contains some 48 % Pyroxene, 33 % Feldspar, 8-10 % glassy phase, and 3-6 % Olivine /3/. All of these minerals are hard enough to abrade polymers and annealed steel but only the olivine is harder than cold drawn 0.85 % C steel.

Wear Data

Abrasion tests of various polymers in slurries of sea-water and crushed coral and crushed lava have been reported /4/. They showed that lava was 1.5 to 3 times more abrasive to the polymer than the coral. Tests on metals have shown even greater differentiation, as shown in Fig. 3. For the steel, the lava gives 20 times greater wear than the coral. There is little difference in wear rate between the two test geometries. Abrasion on the cylinder end gives linear wear time curves, while the curve for wear on the perimeter shows slight deviation at longer times. This is thought to be caused by deterioration of the abrasive due to the repeated sliding. For abrasion by coral the line for abrasion on the perimeter is parallel to the line for abrasion on the cylinder end, but located above it a distance which corresponds to removal of the zinc coating during the early stages of abrasion.

Abrasion in seawater slurry with coral is about twice as rapid as abrasion in a slurry based on fresh water. No such difference was found in the tests on polymers /4/; it is thought to be due to corrosion of the zinc. Actual corrosion data for medium-term exposures in Hawaiian surface and deep ocean seawater are shown in Fig. 4. The data can be used for a rough estimation of the effect of corrosion-erosion.

Wear Cycles

The wear is caused when the cable moves in response to the very significant tidal currents. The average current at the surface is 1 m/s. At the bottom it is expected to be 0.4 m/s, which exerts a drag on suspended sections of cable of 70 N/m /2/. There will be four passes per day at about 6 h intervals.

Excursion

For the selected value of bottom tension (T_0 in Fig. 1) of 30 000 N, the calculated drag force of 70 N/m, and the maximum span length of 40 m, it can readily be shown that the cable will not slide at the span supports due to tidal current forces. The abrasion will take place where the suspended cable swings in contact with a rock located between

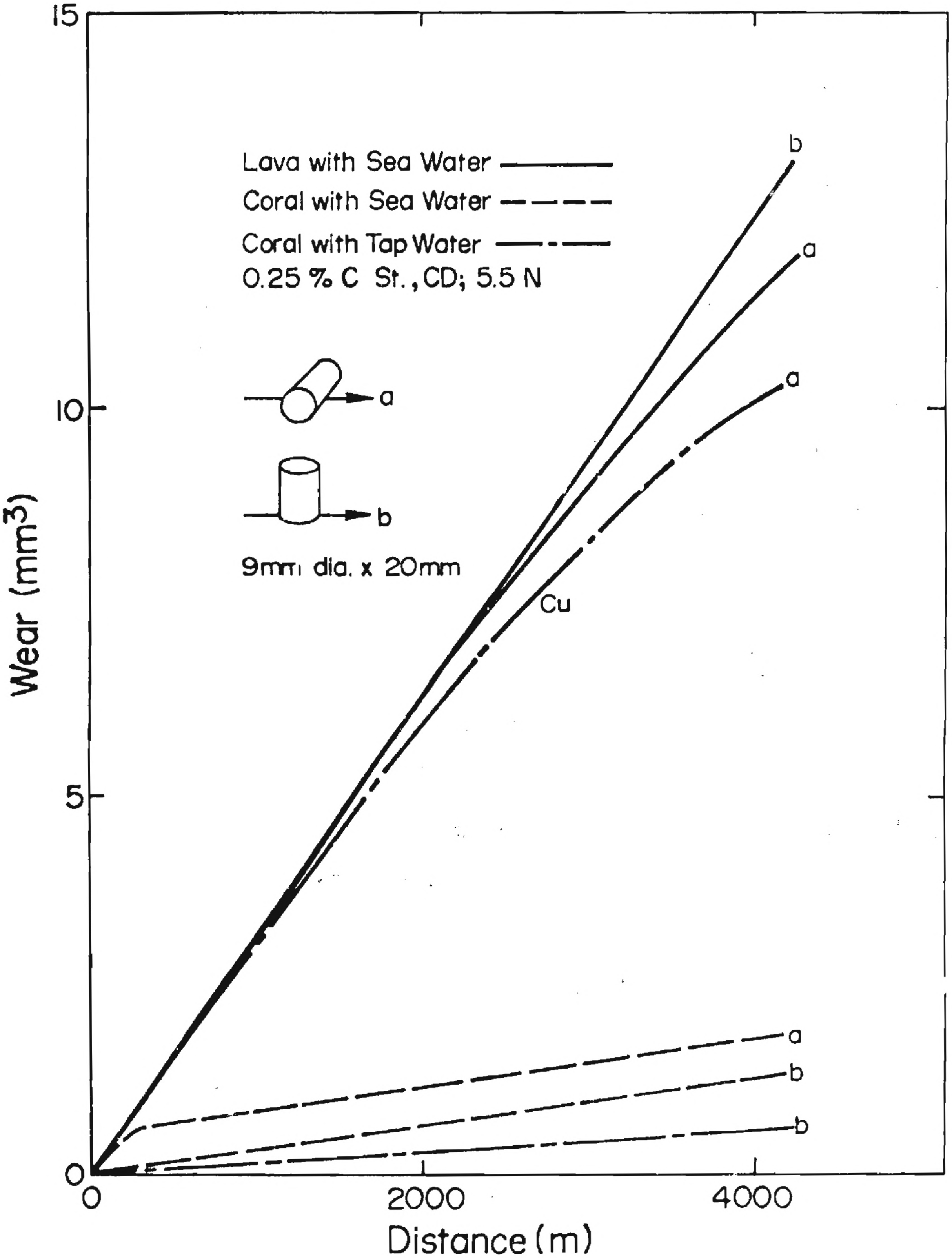

Fig. 3 Slurry abrasion data for copper and armor wire steel (cold drawn 0.25 %) in slurries of 250-400 [illegible] crushed coral or lava with tap water or seawater. 4000 m sliding corresponds to 8.5 h of testing and to 7,160 to-and-fro strokes /5/

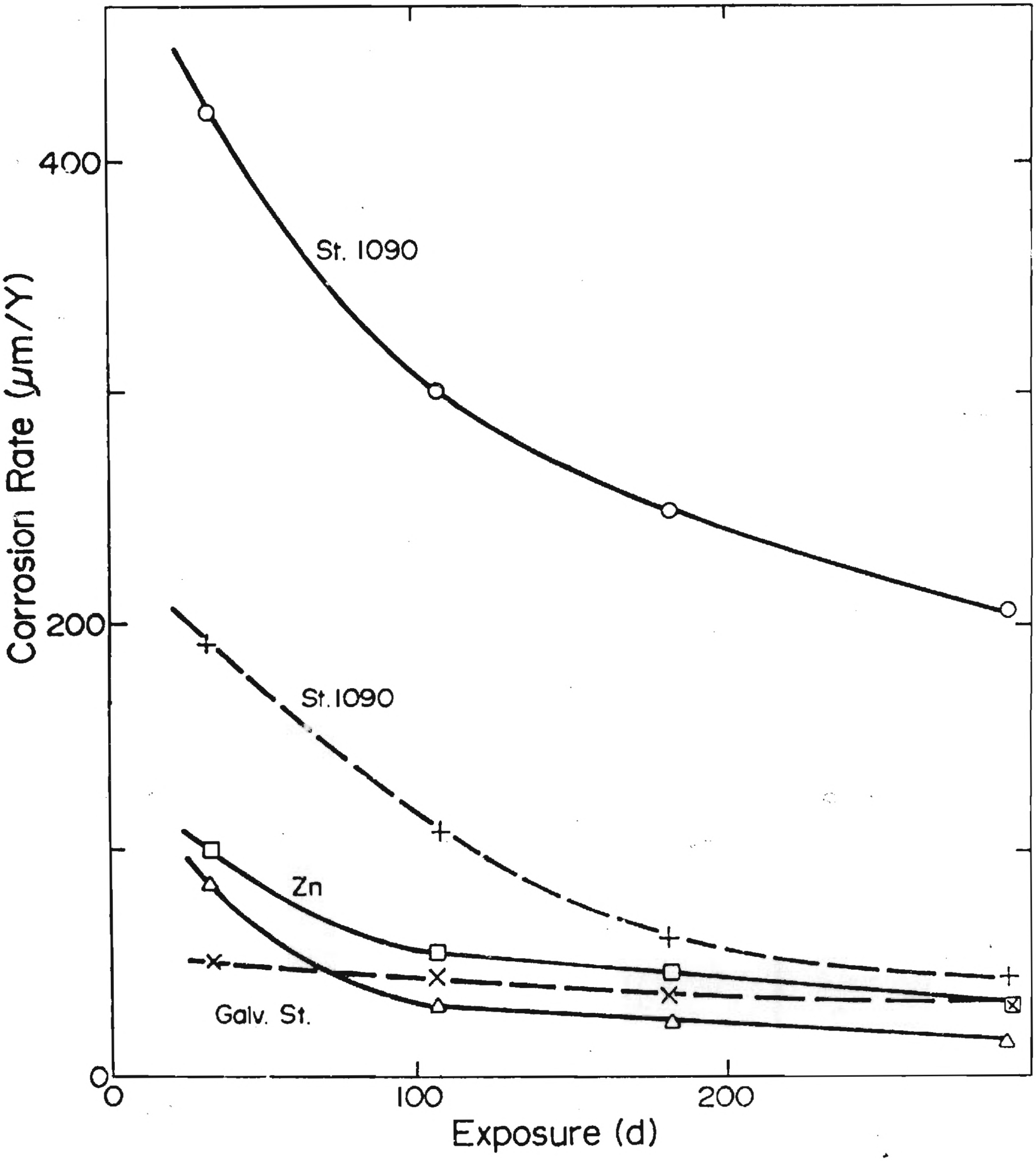

Fig. 4 Corrosion data for 0.9 % carbon steel, pure zinc, and galvanized steel exposed in slowly flowing Hawaiian surface seawater (25-28 °C, full lines) and cold (7-9 °C, dashed lines) deep ocean water pumped from 600 m depth /6/

the two main supports of a span. The excursion at midpoint is $\pm$ 1.83 m for an unrestrained catenary. The wear path may range from this value at zero load to zero at maximum load, if suitable rocks happen to be present at mid-point.

Contact Load and Pressure

The contacting load will vary from zero to a maximum determined by the slope of the rock face, the coefficient of friction, and the length of cable supported by the rock. The load is roughly estimated from the horizontal force required to force a catenary from the maximum excursion permitted to a lower value, $g\ell$. Resolution of this force parallel to the bottom surface set at the maximum angle which will allow the excursion ($\sim 15^{\circ}$) yields a friction force. Division of this force by a suitable coefficient of friction yields a normal contact load for use in the abrasion calculations. This load decreases linearly to zero at 1.83 m from 2400 N at ℓ = 0.2 m and μ = 0.75 and from 1200 N at ℓ = 0.2 m and μ = 1.5.

This load is expected to be supported by an area of at least 2 x 4 cm, taking the size of the cable and of typical sharp rock edges into account. Corresponding contact pressures range from zero to 2.25 MPa.

Estimated Life

For a worst-case situation the wear will be proportional to the slurry abrasion values, adjusted for distance, load, and hardness. The wear shown in Fig. 3 was 12 mm^3 in 4000 m of sliding, less 0.6 mm^3 considered to be due to corrosion. The area was 63.6 mm^2 and the wear corresponds to removal of 0.0448 $\mu m/m$ at a pressure of 86.5 kPa. The steel used had a hardness of about 75 % of the steel to be used in the final design. Thus, the expected maximum wear per day can be determined from

$$d_{max} = 0.0448 \;.\; 0.75 \;.\; \frac{p}{0.0865} \;.\; 8 . \ell \qquad (1)$$

where d is the maximum depth of wear (μm), P is the calculated maximum contact pressure and 8ℓ is the total distance traveled per day. Calculated values are shown in Fig. 5. It is seen that very substantial wear rates may

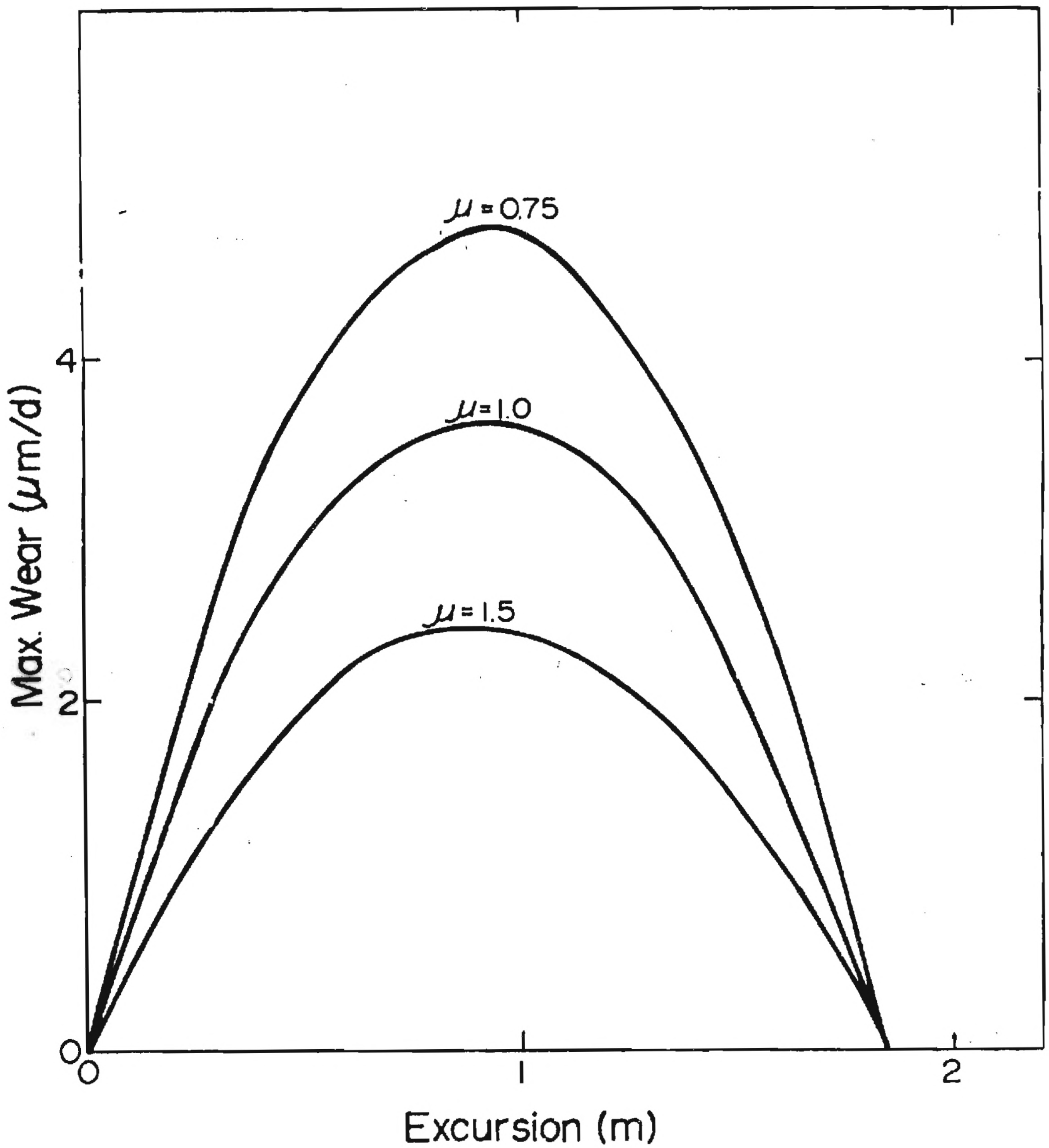

Fig. 5 Calculated maximum wear rates for assumed values of friction and excursion per cycle

be encountered in the extreme case. Setting the maximum rate at 4 μm/day and using a corrosion rate for the freshly abraded surface in cold seawater at 0.75μm/day (275 μm/y) the maximum loss is 4.75 μm/day. At this rate the first penetration of the armor wire will occur after 640 days (630 days for the steel and 10 days for the outer polypropylene yarn). Penetration of the second layer of armor wire will occur after 4.4 years. Penetration of the lead sheath with consequent catastrophic failure will occur after 10.3 years.

Under actual conditions it is expected that the contacting rock will wear also and thus lose much of its abrasiveness. However, no data is available at this point to quantify this phenomenon. This factor, as well as the probability of encountering the severe conditions assumed in this preliminary study must be taken into account before a more detailed assessment can be made. Also needed is a more detailed criterion for failure of the cable.

Clearly, however, abrasion and abrasion-erosion can be very significant life-limiting factors for the cable.

3. Conclusions

It has been shown that under severe conditions the cable can be expected to fail due to abrasive wear and abrasion-enhanced corrosion in a period of 4-10 years. The abrasion of the armor wire may amount to 4μm/d and the corrosion to 0.75μm/d. While the abrasion may decrease with time due to wear and dulling of the rock, the corrosion contribution is expected to continue for as long as the cable slides over the rock on a daily basis.

4. Acknowledgements

This work was supported in part by the State of Hawaii through Hawaiian Electric Industries, Inc. (HEI) via a subcontract from Parsons, Hawaii, contract administrators for HEI.

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/3/ MACDONALD, G.A. and ABBOTT, A.T.:"Volcanoes in the Sea," University of Hawaii Press, 1970.

/4/ LARSEN-BASSE, J. and TADJVAR, A.: "Behavior of Some Polymers Subjected to Slurry Abrasion Under Simulated Submarine Condition," in preparation.

/5/ TADJVAR, A.: "Abrasion of Some Polymers in Slurries," MSME Thesis, University of Hawaii, 1986.

/6/ PARK, Y.-H.:"Corrosion Tests in Hawaiian OTEC Works," MSME Thesis, University of Hawaii, 1986.

E-25-630

Monthly Progress Report

to

Hawaii Natural Energy Laboratory
University of Hawaii
2540 Dole Street
Honolulu, HI 96822
Under Contract No. CH6934

TRIBOLOGY RESEARCH SERVICES IN SUPPORT OF ABRASION-CORROSION STUDIES FOR HDWC, PHASE II-C

Jorn Larsen-Basse
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

GTRC Project # E-25-630

Period: November 1987
Date: December 8, 1987

Summary of Activities

Abrasion tests have been run under length contact loads between samples of the armor wire and sections of lava rock. The rock used was a piece from the deep dredge #6 in the HIG study. It is a very fine grained rock with only small pores. The location is one of the steep scarps on the Haleakala side of the Alenuihaha channel, at about 1500 m depth. It is a site where cable damage by abrasion is a definite possibility.

High contact pressures were obtained by pressing the edge of the armor wire against a 90-degree edge cut on the rock. Samples were slid back and forth in a 2 cm path under loads from 6 to 13 lbs. Both friction and wear was measured.

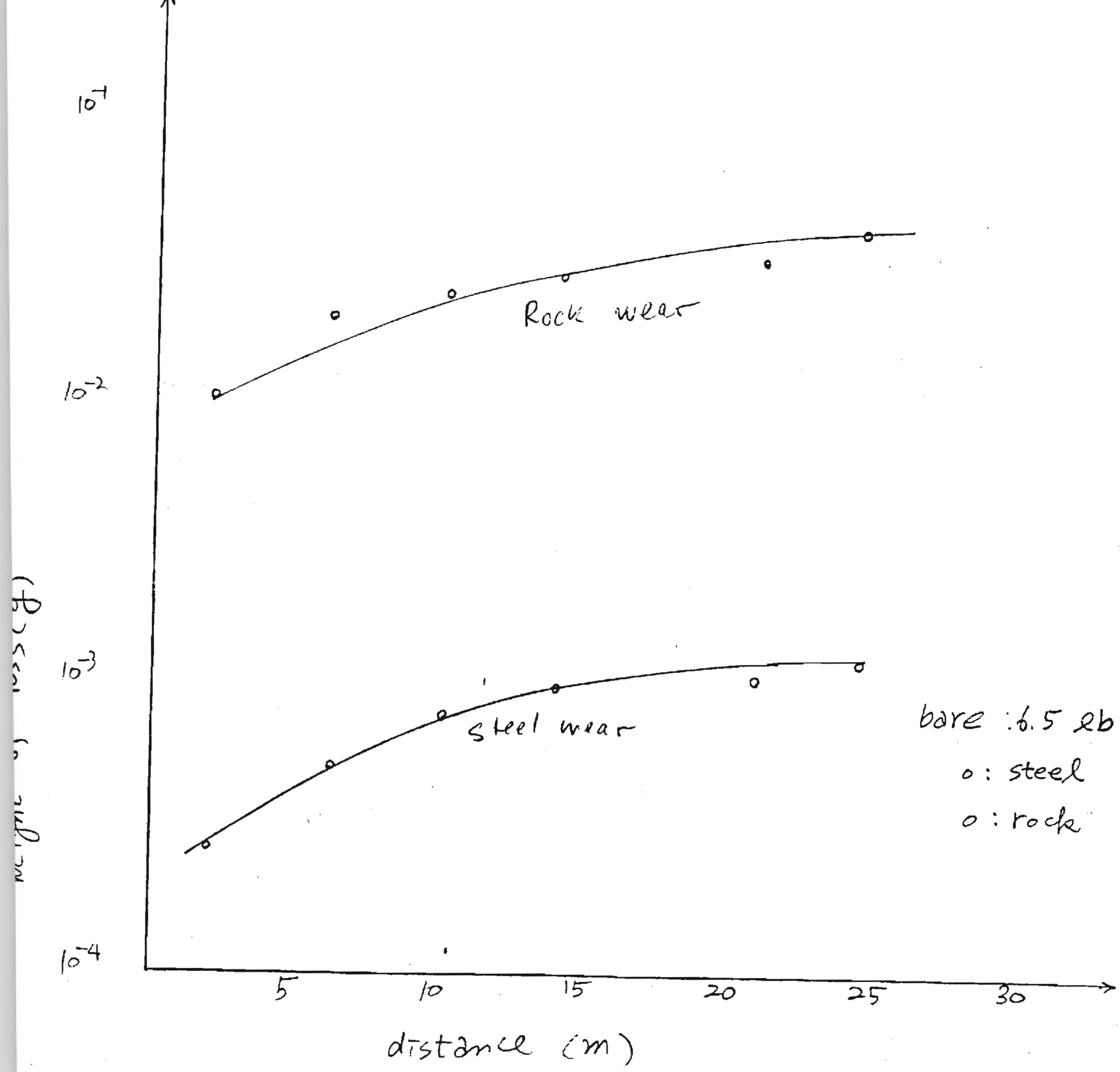
Some typical results are shown in the attached graphs. Both rock and steel show a rapidly declining wear rate, to the point where the material loss on both sides becomes negligible. At the same time, the coefficient of friction drops from around 0.45 to 0.35.

Tests are in progress with a rock collected near shore. This rock has larger pores and greater hardness than the deep sea rock and appears to be more abrasive.

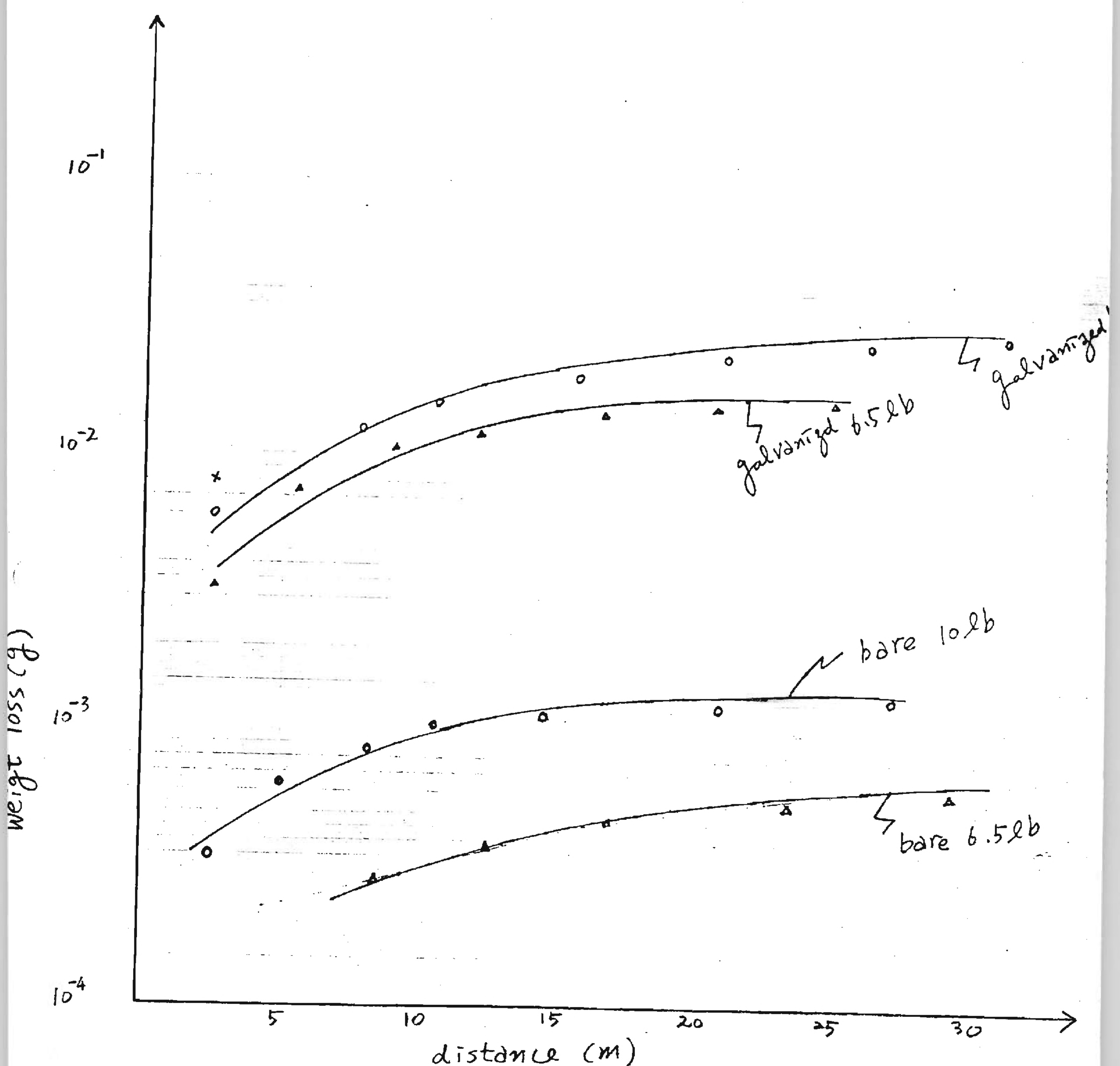
Future Plans:

A trip will be made to Hawaii in early December to discuss details of the final report. In preparation for that, all data are being re-evaluated.

Smooth rock, #6



Porous rock



10^-1
10^-2
10^-3
10^-4
weigt loss (g)
galvanized
galvanized 6.5 lb
bare 10 lb
bare 6.5 lb
5
10
15
20
25
30
distance (m)

E-25-630

Final Report

ABRASION-CORROSION STUDIES FOR THE HAWAII DEEP WATER CABLE PROGRAM PHASE II-C

Prepared For:

Hawaii Natural Energy Institute
University of Hawaii
2540 Dole Street
Honolulu, HI 96822
Under Contract NO. CH 6934

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December 31, 1987

GEORGIA INSTITUTE OF TECHNOLOGY

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332

1987

ABRASION-CORROSION STUDIES FOR THE HAWAII DEEP WATER CABLE PROGRAM PHASE II-C

Final Report
to
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2540 Dole Street
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December 31, 1987

CONTENTS

FOREWORD

This Final Report is the combined report for two separate, but closely coordinated research efforts, one conducted at Georgia Institute of Technology and the other at the University of Hawaii. During the course of data evaluation it became apparent that combination of the results was both desirable and necessary, thus the combined report.

I. EXECUTIVE SUMMARY

An assessment is presented of the possibility that the Hawaii Deep Water Cable may be damaged due to abrasion or abrasion-enhanced corrosion. The sites of potential damage are the several steep scarps in the deep water section of the Alenuihaha Channel. It is anticipated that during deployment the cable may become suspended between ledges and moved back and forth by the daily tidal currents.

It has been shown that the cable will fail by fatigue in less than the 30-year design life if the catenary span exceeds 40 m. We therefore set out to determine if abrasion and corrosion, jointly or separately, could result in failure in 30 years of a 40 m or shorter span.

Previously reported corrosion tests in warm and cold seawater at the Natural Energy Laboratory of Hawaii (NELH) were re-examined, additional tests were conducted, and literature data were evaluated. It was found that the cold drawn AISI 1085 armor wire does not crack in seawater by stress corrosion cracking or hydrogen embrittlement; that freely exposed galvanized coatings corrode at a long-term rate of 15-20 μm/y and bare armor wire at about 75 μm/y in surface seawater, 30 μm/y in cold deep ocean water; that the corrosion rate of the zinc increases drastically when it is protecting bare areas of steel; and that for actual cable specimens the polypropylene serving and the bitumen bedding provide excellent protection which slows the rate of corrosion of the zinc coating to about 30% the rate of freely exposed coupons.

Abrasion tests were conducted on lava rocks from shore and pillow basalt rocks dredged from one of the scarps of interest. Wear was measured as functions of applied pressure and distance of travel. Tests at very high contact stresses were made also to determine the wear of the rock when in contact with the steel. Coefficients of friction fall in the range 0.35-0.45 and this determines the relationship between the maximum excursion due to current drag and the contact load against any abrading rock surface at mid-span. These values vary linearly from zero excursion at 540 kg load to 0.47 m at zero load.

Corrosion-erosion tests against rock showed that corrosion in seawater of the surface freshly formed by abrasion contributes significantly to the loss, at least 0.05 μm per pass.

Combining the various damage mechanism we find a worst-case damage at a contact load of 100 kg, a corresponding excursion of 0.38 m and a 30-year travel of 33 km. Here, the wear is 7 mm, general corrosion is 2 mm, and corrosion erosion 2-2.5 mm, for a total of about 11.5 mm. The radial distance from the outer wire diameter to the outer lead sheath diameter is 14.6 mm. Given these numbers, and given the fact that there is very low probability that the worst case scenario of span length, rock contact length, and daily excursions will appear in actuality, it appears reasonable to expect that the cable will survive damage by abrasion.

II. INTRODUCTION

Stimulated by the oil embargo exploration for geothermal energy was initiated on the island of Hawaii, or the Big Island, in the Hawaiian chain. It resulted in drilling of a successful well which struck a very hot geothermal fluid. A 3 MW pilot plant has been operated for now well over five years on this reservoir. Additional wells have since been completed and it appears that the resource is very large.

A major obstacle in the way of further development of this important energy resource is the distance to market. About 80% of Hawaii's ~ 1 M inhabitants live in and around Honolulu, on the island of Oahu, some 240 km from the Big Island. All of Oahu's 1000 MW power consumption is supplied by imported oil and this island is therefore the obvious market for the electricity generated at the geothermal fields of the Big Island.

The most feasible way of transporting the electricity at the present time is by means of a submarine power cable. This cable must cross the Alenuihaha Channel between the Big Island and the island of Maui, where depths of up to 2,100 m are encountered. Total length of the cable is expected to be some 280 km. One of the possible routes is shown in Fig. 1 for illustration purposes. These conditions require extension of the current technology of high voltage direct current (HVDC) cables in that they are beyond any previously encountered submarine cable conditions. Present HVDC cable technology has been developed to the extent that the deepest and longest cables deployed and in operation are the Skagerak cables, between Norway and Denmark. These cables are deployed at depths of up to 550 m over a distance of 125 km. Recent cable projects approaching the Skagerak cable depth include a project

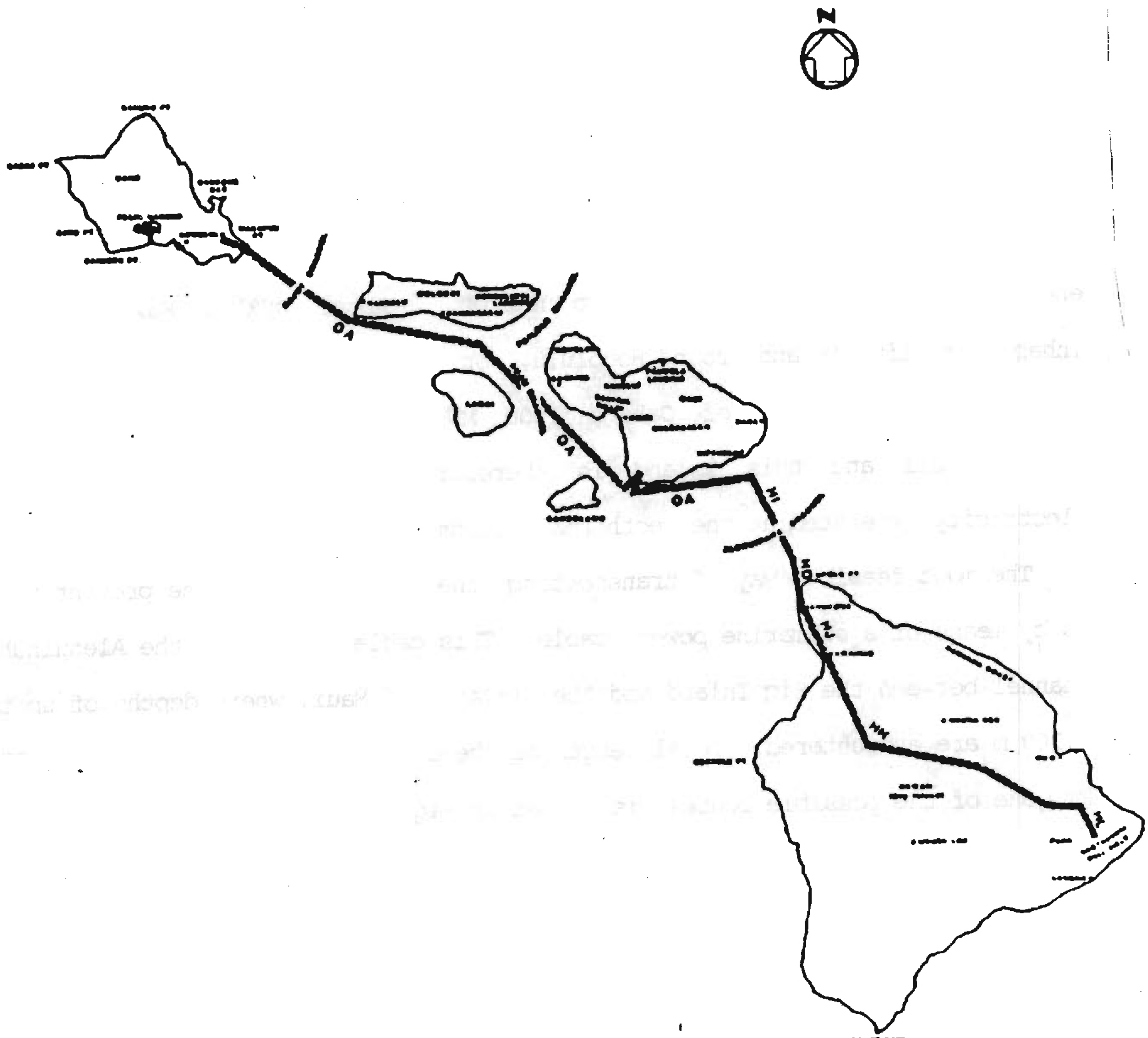

Fig. 1 One of the possible cable routes (1).

in Vancouver, British Columbia and one in the Messina Strait between Italy and Sicily (2). These cables are at depths of 400 and 305 m, respectively.

For the Hawaii cable the subject of abrasive wear takes on importance because it could conceivably be a life-limiting factor. The Alenuihaha Channel is not only the deepest section of the cable route, it is also the most recent, geologically speaking. The bottom is not completely covered with a thick layer of sediment, as is usually the case in the ocean, but exhibits many rock ledges and rock outcroppings from fairly recent submarine volcanic eruptions. Some coral ledges are found also but most ledges are of pillow basalt which contains abrasive mineral grains, such as olivine.

During deployment of the cable, it is expected that sections of it inevitably will become suspended between rock ledges or outcroppings. The substantial tidal currents in the channel will swing the suspended cable section back and forth twice a day, and this may cause abrasive wear against rocks in the vicinity.

It has been estimated (3) that the selected final cable design will fail immediately due to lead sheath fracture, if the span length exceeds 60 m; and that the cable will fail by lead sheath fatigue in less than the desired 30-year life, if the span exceeds 40 m. The question to be answered by these wear tests is if abrasion alone or in combination with corrosion can cause failure sooner than will fatigue.

These concerns were the focus of the present study.

III. RELEVANT OPERATIONAL PARAMETERS

In order to select reasonable test variables it is useful to briefly review the information at hand regarding cable design and environmental as well as operating conditions.

III a. Cable Design

The cable is a so-called self-contained oil filled cable for 350 kV dc current, with aluminum conductors. It is a complex design with a total of 22 different layers. The outermost layers, which are of interest in this connection, are listed in Table 1. The outer diameter is 118.5 mm and the weight is 37 kg/m in air and 27 kg/m in water.

The selected final design is shown in Fig. 2. The materials selection was based on many factors but a major one was the strength to weight ratio, in order to make cable laying feasible at the depths encountered.

TABLE 1
Major Outer Layers in Final Cable Design

	Thickness mm	Outer Dia. mm
Polypropylene yarn serving	3.3	118.4
Outer steel* armor, 31 wires	3.0	111.8
Polypropylene yarn bedding	1.6	105.8
Inner steel* armor, 29 wires	3.0	102.6
Polypropylene yarn bedding	1.1	96.6
Polyethylene jacket	4.0	93.5
Bronze Tape	0.6	84.6
Lead Sheath	3.3	82.6

*Steel wires are 3 mm x 10 mm, cold drawn galvanized AISI 1085.

III b. Failure Criteria

Abrasion damage can lead to cable failure in two general ways

1) due to water infiltration when the damage penetrates the lead sheath, indicated by line A-A in Fig. 2, or

2) due to mechanical overload after significant corrosion and abrasion has taken place and while a deep water section of the cable is being retrieved for repair of other damage.

It would appear that condition (1) above is the more commonly expected of the two. It will be used as the failure criterion in this study. For illustration the level of requisite damage is indicated by the line in Fig. 2.

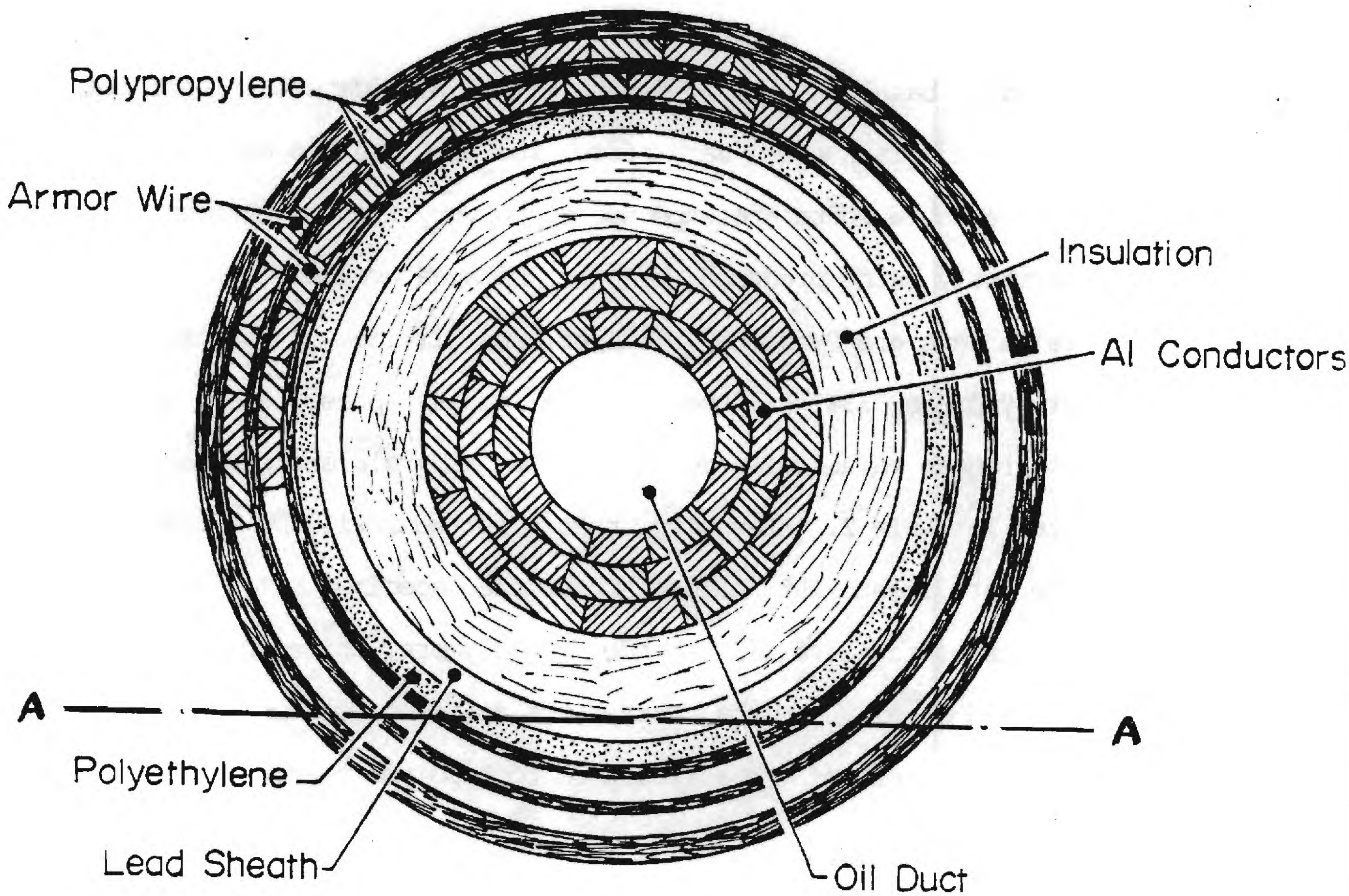

Fig. 2 Cross section of the final cable design. Only the major components are indicated.

III c. Abrasive Counterface

The rocks on the ocean floor will be either coral or pillow basalt from undersea eruptions. The coral is largely soft $CaCO_3$, which is not expected to generate much wear. However, coral rocks usually also contain remains of silica concentrating organisms in small amounts. It is expected that skeleton particles from these organisms will be responsible for most of the abrasion caused by coral.

Lavas and basalts are somewhat more complicated. Their composition, mineralogy, and grain size vary from location to location. The submarine lavas of the cable route are expected to be very similar in composition to the lavas currently being produced by the Kilauea volcano. The most abundant minerals in lava are Pyroxene, Feldspar, and Olivine. A typical lava contains some 48% Pyroxene, 33% Feldspar, 8-10% glassy phase, and 3-6% Olivine (4). Typical hardness values of some of these minerals and some common abrasives are listed in Table 2. Assuming that most wear will be caused by abrasives which are at least 10% harder than the specimen it is seen that all constituents of the lava will abrade the polymers, while only the olivine will abrade a hard steel. In the coral, the silica constituents will probably be responsible for most of the abrasion of both polymers and metals.

TABLE 2

Typical Hardness Values for Some Materials of

Interest (4, 5)

Substance	Moh's Scale	Knoop Number	% in Typical Lava	% in Typical Coral
Calcite	3	135	–	98+
Glass		530+	10	–
Pyrotene	5–6	430–560	50	–
Feldspar (orthoclase)	6	560	33	–
Olivine	6,5–7	700–820	6	–
Quartz	7	820	–	1–2
Garnet		1,360		
Alumina	9+	2,100		
Silicon Carbide		2,400		
Steel	5–8	400–750		
Copper	2–3	100–150		
Polymer	1–2	10–100		

The main differences between pillow basalt from deep sea eruptions and lava from surface flows are that the former generally are less porous, due to solidification under pressure, and fine grained due to rapid cooling. They usually have a smooth surface, also due to the rapid cooling.

At-sea surveys of the deeper parts of the Alenuihaha Channel have identified a proposed cable route across this critical section of the total deployment distance (6), see Fig. 3. The survey identified the following bottom conditions, starting from the Kohala side (see Fig. 3).

a-b, shore to coral terrace 6 km offshore at 380 m depth: not investigated,

b-c, large coral terrace, expected to be fairly smooth limestone with occasional pinnacles to 20 m in height,

c-d, 350 m to 850 m, gentle slope of about 2.5 degrees, thin sediment, probably over coral

d-e, 850-950 m, nearly flat with very little sediment

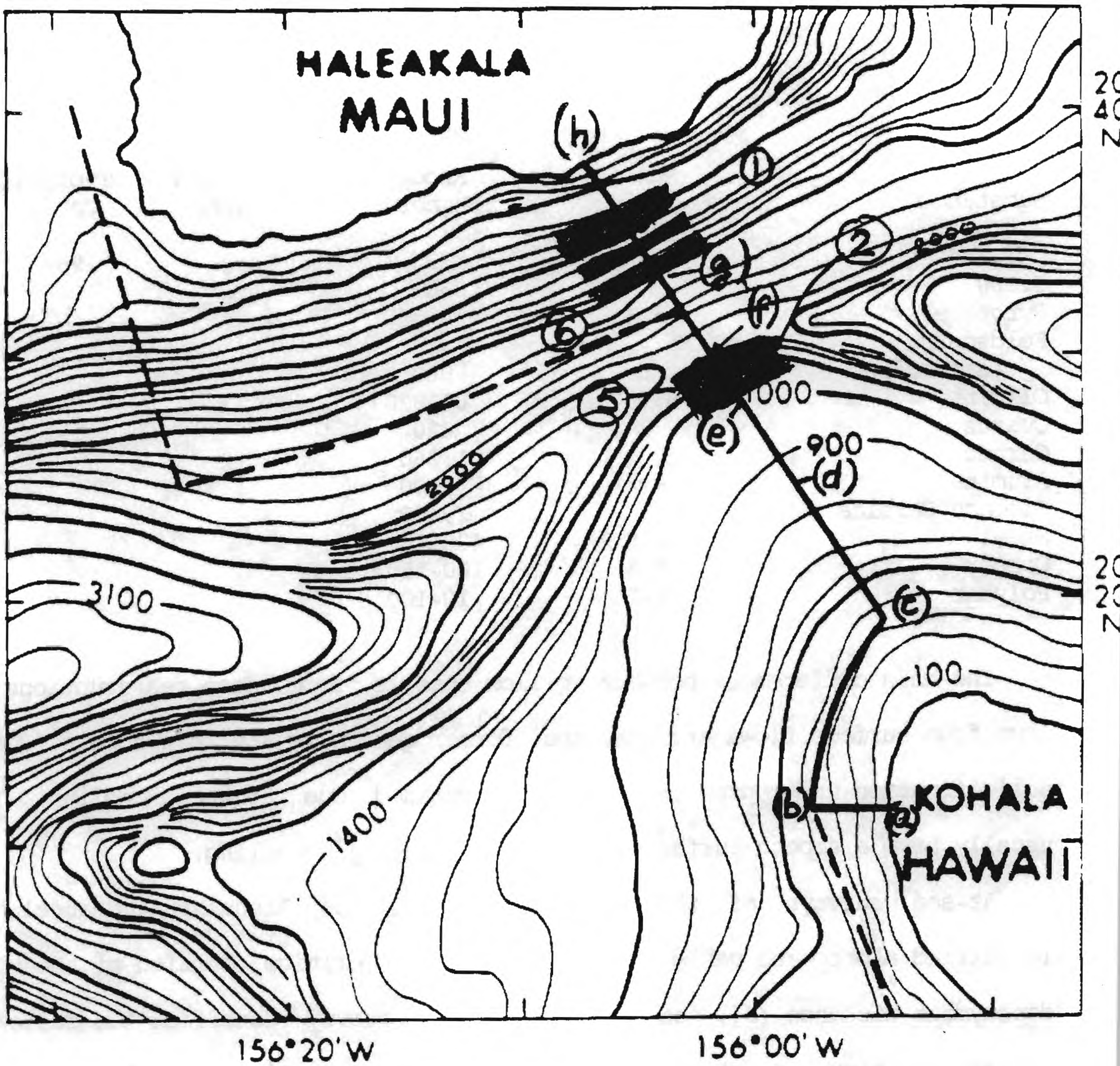

Fig. 3 Suggested route of cable across Alenuihaha channel (6). Numbers refer to dredge samples detailed in (6). Letters refer to discussion in text. Darkened areas are steep scarps where the potential for damage due to abrasion appears greatest.

e-f, 950-1900 m, steep slope of 20 degrees average, but with regions of 35 degrees or greater slope. Lava rock. This was once the shore of the Kohala Volcano. Some coral was found at the upper edge of the slope

f-g, 3-5 km of thick sediment deposits; this section includes the deepest point, which is at about 1925 m,

g-h, the slope up to the Maui coast, average 7 degrees. It consists mostly of gravity flows but has two scarps of volcanic rock at 25 degree slope, or more, at approximately 1500-1300 m and 900-650 m depth. A third such scarp may exist at about 1200 m.

It is expected that if sections of the cable do become suspended as catenaries between rock outcroppings it will most likely happen in the deeper and steeper sections of the route, i.e., at any of the three or four steep lava rock scarps. It has previously been shown (7) that coral generally is much less abrasive than lava; therefore, this study concentrated on abrasion by the types of lava most likely to be found in the scarps.

During the at-sea survey rock dredges were collected at four different points of interest here. These points are shown as numbers 1,2,5 and 6 in Fig. 3. The description of these rocks from (6) is summarized below.

On the Haleahala side

RD 1, 640-850 m depth.
Very massive, dark gray, fine to medium grained lava, probably basalt or hawaiite. Some pieces are coarsely vesicular and almost certainly formed subaerially.

RD 6, 1120-1140 m depth.
Basaltic pillow with thick glassy rind. Piece is aphyric and aphonitic with possible microphenocrysts ($\lesssim$ 1 mm) of plagioclase. Probably submarine. Samples from this dredge were used in tests described below.

On the Kohale side

RD 2, 1400-1670 m depth.
Three principal rock types - fine grained basaltic pillow, vesicular basalt, and breccia of these two rocks. The pillow fragments are olivine basalt with about 5% fresh euhedral phenocrysts up to 5 mm in size in an aphanitic ground mass. A thin (~ 1 mm) Mn coating is on the surface, which has 2-3 mm glassy rinds. The vesicular basalt has vesicules up to 5 mm in size and is richer in olivine, with

grains up to 5 mm comprising up to 20% of the modal volume. These rocks were probably erupted in shallower water.

RD 5, 1155-1615 m depth

Mostly very olivine-rich basalt (oceanite) with 15-20% olivine phenocrysts up to 15 mm long. Probably formed subaerially. Also some pieces of hyaloclastite with glassy clasts up to 2 cm in diameter. Some of the glassy clasts have olivine phenocrysts up to 4 mm.

In general, then, the rocks of interest are fine grained with occasional large grains of olivine. They have been formed under submarine or subaerial conditions, and thus will have relatively little porosity.

More porous rock with a coarse matrix of the non-olivine mineral components would be expected from surface eruptions. Such rocks may be more abrasive because of the coarser grains and the mechanical locking due to the pores. They may exist in the near-coastal section (a)-(b) and at the top edge of the scarp (e)-(f). In section (a)-(b), which was not investigated, the bottom slope is quite flat and the water depth is relatively low. Therefore, abrasive conditions are not likely to be severe and inspection of the cable laying should be easy. For section (e)-(f) the two dredge samples did not contain any rock from surface eruptions. However, considering that this scarp is the old coastline of the Kohala Volcano, such surface or near-surface rocks may exist over some parts of the scarp.

III d. Dimensions of Abrading Span

The amount of wear due to abrasion depends on the contact load and the distance of sliding. These factors will be estimated below.

In the catenary study (3) mentioned previously, it was estimated that the cable will fail due to overload in bending (radius of curvature greater than 1.5 m) if the span length is greater than 60 m or if the cable hangs over one outcrop which is more than 4 m high (Fig. 4a). And it will fail in fatigue due to tidal forces in 30 years or less if the span length exceeds 40 m (Fig. 4b). We have used these conditions as the upper limits for the case of failure due to abrasion.

For the calculations the same values as in (3) were used for bottom tension (3000 kg) and flexural modulus (500 kg • m^2, measured for the Vancouver and Messina cables). The vertical force on a span is 27 kg/m (the cable's weight in water) and the horizontal force is due to drag from the tidal currents. Using again the values from (3) this force varies from zero to an average maximum of 7 kg/m. Force balance between these two forces means that the cable can swing an angle of $\tan^{-1}$ (7/27) = 14.5°. For the condition shown in Fig. 4b the maximum excursion is at the midpoint and it amounts to 0.47m.

III e. Points of Abrasion

The cable span may conceivably abrade at two types of contact with the rock:

a) at the ends of the span, or

b) at points in between where the contact load is insufficient to provide a span? minus and the contact is of a "grazing" nature.

At the support points for the span in Fig. 4b the vertical force is 20 x 27 kg = 540 kg. The average max. horizontal force is 20 x 7 = 140 kg. Thus, for a coefficient of friction between cable and rock of less than 140/540 = 0.26, the cable will slide at the supports. This value is quite low for abrasive situations, where values of 0.6 - 0.8 are common. Thus, unless

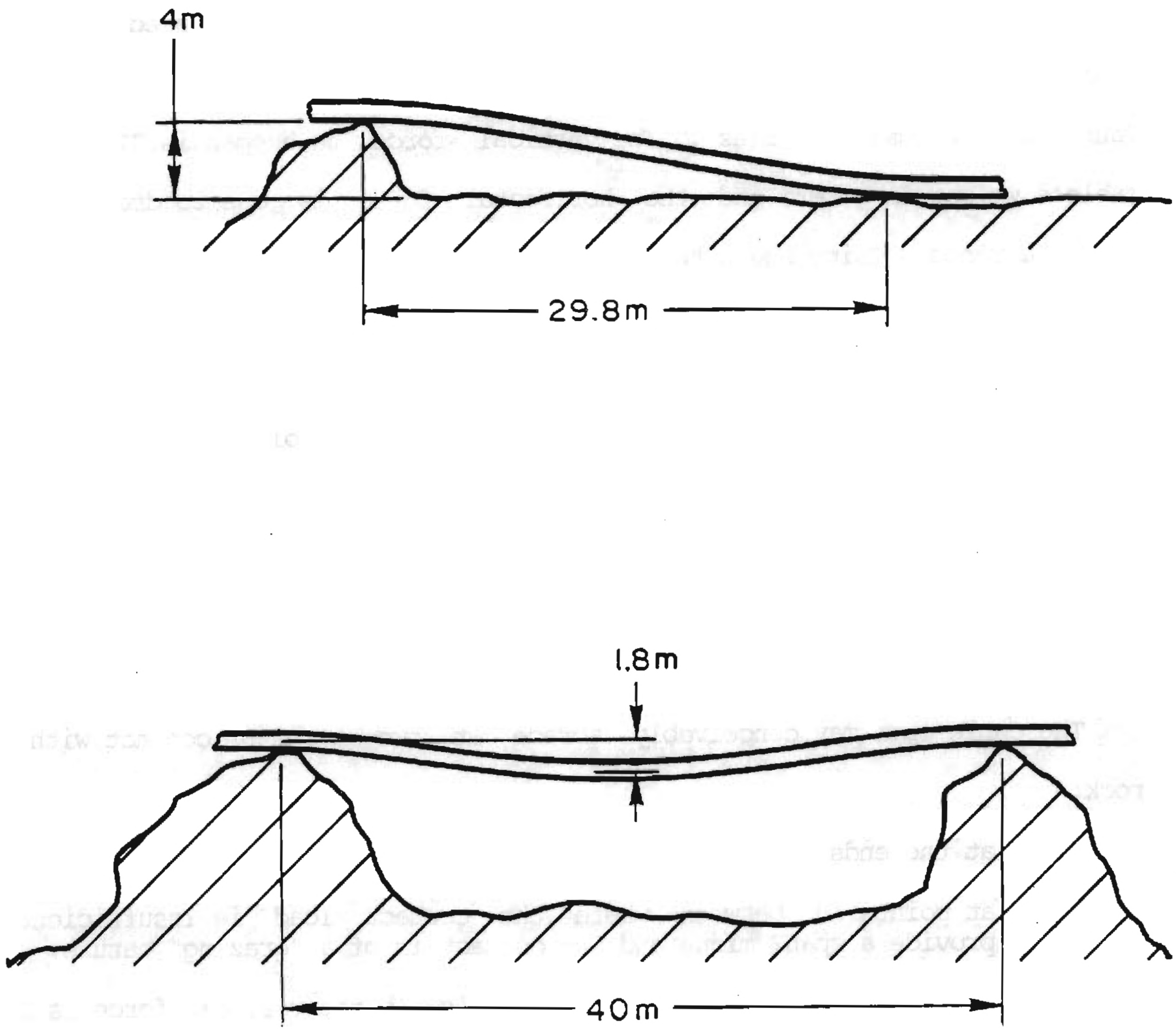

Fig. 4 Sketch of upper-limit conditions for which abrasion becomes a potential failure mechanism.

actual data show such low friction values, one should not expect the cable to undergo major sliding at the support points.

Some minor sliding could be expected at these points, however. This could occur if there is contact for some distance from the major support point, see Fig. 5b. In the horizontal plane the radius of curvature at the support joint is about 4.45 m for a drag of 7 kg/m. If the contact zone is, say, 0.5 m long, the excursion at the end of that zone is then 2.8 cm.

III f. Excursions and Loads

If abrasion takes place at a mid point of a span, then the excursion at that point depends on the contact load and the coefficient of friction, see Fig. 5a. The friction force at midpoint will counteract movement of the cable in the horizontal plane due to tidal drag. To obtain a rough estimate of the excursion as a function of the friction force the latter has been distributed on the middle 36 m of the 40 m catenary. The drag then is (7 - F/30) kg/m, where F is the friction force. The excursion at mid point then becomes

$$h \simeq \frac{wL^2}{8T_o} = \frac{(7 - F/30) \cdot 40^2}{8 \cdot 3000} \qquad (1)$$

$$h = 0.47 - F \cdot 0.0022 \qquad (2)$$

where h is in m and F in kg force, and

$$F = \mu N \qquad (3)$$

where μ is the coefficient of friction and N is the normal load ($N \lesssim 540$ kg).

It is realized that this approach is only a rough estimate. It should be sufficient to evaluate the possible abrasive conditions in a worst-case scenario. The calculated excursion-load relations for selected values of μ

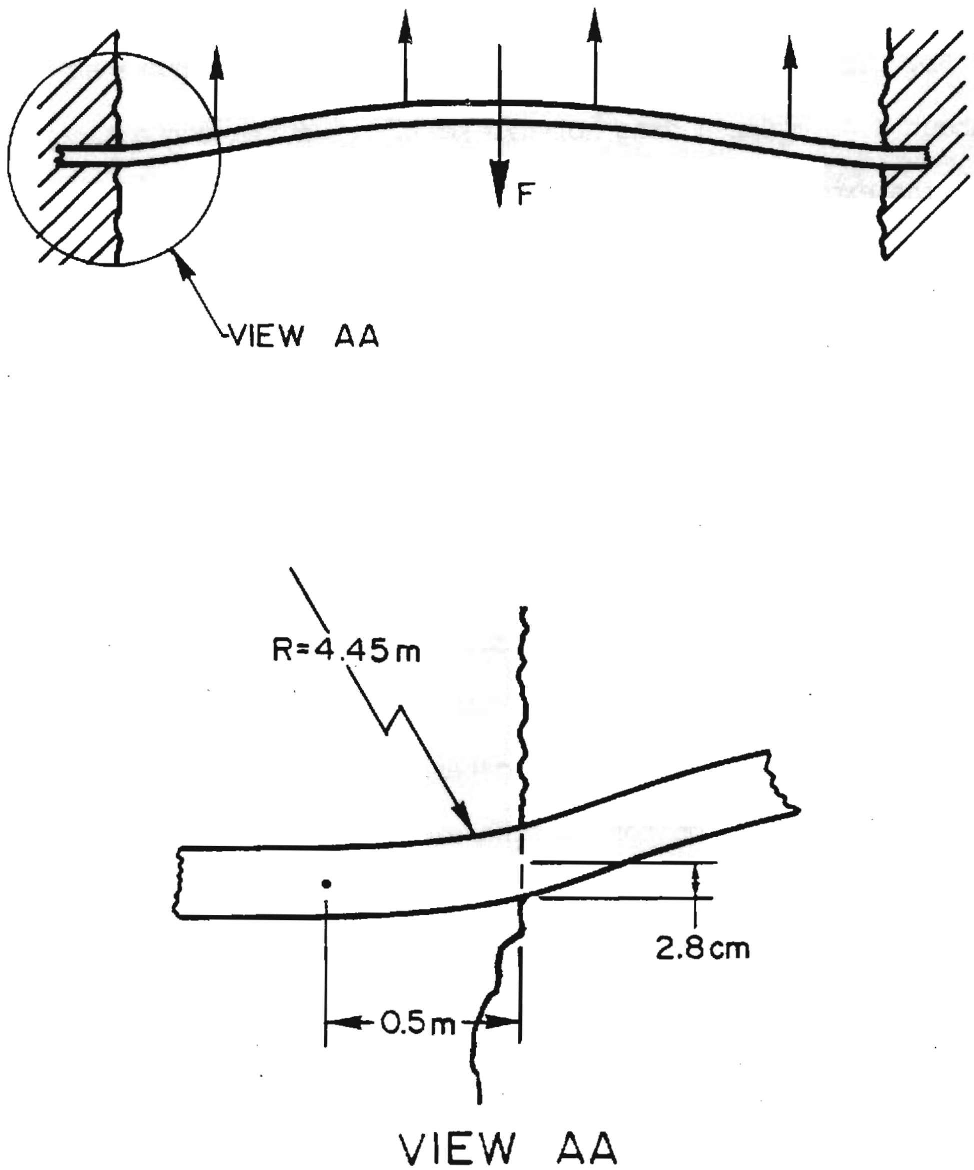

Fig. 5 Top view of catenary exposed to tidal current drag; excursion at mid-point, balance between tidal current drag and possible friction against rock; possible excursion at support point.

are shown in Fig. 6. Quite similar results, but slightly lower, are expected for the case shown in Fig. 4a, where the free span equivalent is about 30 m in length.

III g. Number of Cycles and Sliding Distance

The tidal currents give two complete load cycles per day, or a sliding distance of about 8 times the excursion values calculated above. While the magnitude of the currents varies and there is no significant bottom current for about 10% of the time (3), we have used the full value in these worst-case calculations. In 30 years the max. sliding distance becomes 87,600 x h.

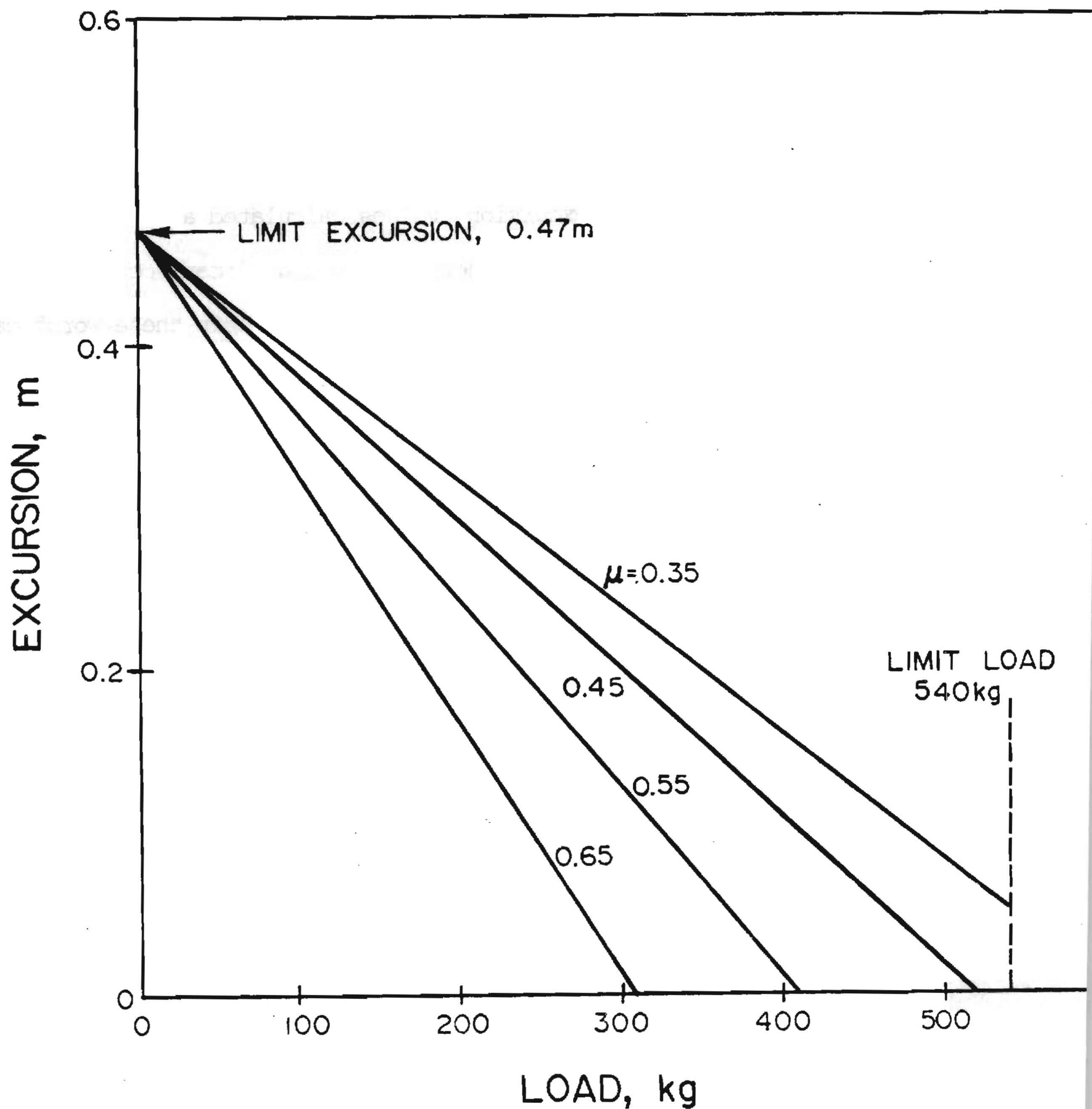

Fig. 6 Estimated mid-point excursions for various levels of contact load and friction coefficient.

IV. CORROSION TESTS

The armor wires will be subjected to corrosion by the surrounding seawater. Steels generally are especially susceptible to attack by sulfate reducing bacteria, which are quite abundant in Hawaiian waters and ocean bottom sediments.

In general, the cold deep ocean seawater is low in oxygen, pH and temperature. It is therefore generally less aggressive towards steels but may be more aggressive towards pH-sensitive metals, such as zinc and aluminum. Tests conducted at the Natural Energy Laboratory of Hawaii (NELH) have permitted a rather extensive evaluation of these effects, at least as they are manifested in relatively short-term exposures. They will be discussed below.

Cable operating temperature is expected to be around 60°C. In the current program phase it has not been possible to determine the corrosivity of deep ocean water, when heated to this temperature. Only some tentative generalizations can be made, based on tests in deep ocean water in the as-is condition, i.e, as it arrives on shore at the NELH.

IV a. Corrosion Coupon Tests

In our report for Phase II B of this project, we presented corrosion data for a number of alloys tested at NELH. Briefly, coupons were exposed in covered troughs on shore at NELH in slowly flowing water. Parallel tests were conducted in warm surface seawater and in cold, deep ocean water pumped from 600 m depth. Exposure times of up to 10 months were used.

These data have been further evaluated, combined with other results from NELH, and compared with literature results (8). The basic findings can be summarized as follows.

- The cold water corrosion rates compare quite closely with data for tests conducted in situ on the bottom at various depths in the Pacific Ocean off Port Hueneme in California.
- There is no significant difference in corrosion rate with depth between 600 and 2100 m.
- Corrosion rates for all samples decrease rapidly with time during the early stage of exposure.
- After 1-3 years most data from around the world for corrosion rates tend towards similar values for individual alloys, and
- The cold deep ocean water is more aggressive than the warm surface water towards zinc, copper, lead and galvanized steel and less aggressive towards steels. This behavior may be due to the low pH of the deep ocean water, which results in rapid attack of pH-sensitive alloys; and to the abundant presence of sulfate reducing bacteria in the surface seawater, which accelerate the corrosion of steels.

For alloys of specific interest in connection with the current effort, the results may be summarized as follows.

<u>Galvanized Steel:</u> The data followed quite closely the expression

$$x = 1.5 \bullet t^{1/2} \tag{4}$$

in the warm water and

$$x = 3.0\ t^{2/3} \tag{5}$$

in the cold. Here, x is the thickness loss, in μm, and t is the exposure time, in days. While the initial corrosion rate in the warm water was greater than in the cold, the latter soon overtook the former. After 10 months 85% of the 45 μm thick coating had disappeared in the cold water and 50-60% in the warm. At this point the remaining zinc still essentially protected the underlying steel.

Comparison with literature data is shown in Fig. 7. The limited deep ocean data indicate that a long term rate of around 20 µm/y is established after two years. The surface water data from Hawaii showed lower rates in the beginning than did other waters around the world, possibly because of the high pH. After about two years, however, a universal rate of about 15-20 µm seems to become established.

High-Carbon Steel: Annealed steel AlSl 1090 was tested. It followed a similar log-log relation as the galvanized coating, with

$$x = 3.4\ t^{2/3} \tag{6}$$

in the warm water, and

$$x = 5.1\ t^{1/3} \tag{7}$$

in the cold. Comparison with literature data is shown in Fig. 8. This graph also includes data for low alloy steels AlSl 4130 and 4340 from the troughs at NELH, as well as data for AlSl 1010 tested offshore at NELH in a round-robin ASTM test series. The cold water data coincide with the Port Hueneme deep ocean test results and show that a long-range corrosion rate of 20-40 µm/y becomes established after about one year.

For the warm water the data do not allow confident estimation of long-term rates. It would appear that a rate of around 130 µm/y is established after 3 years. Comparison with results for low carbon steels suggests that the rate may drop to about 50-75 µm/y after 4-5 years.

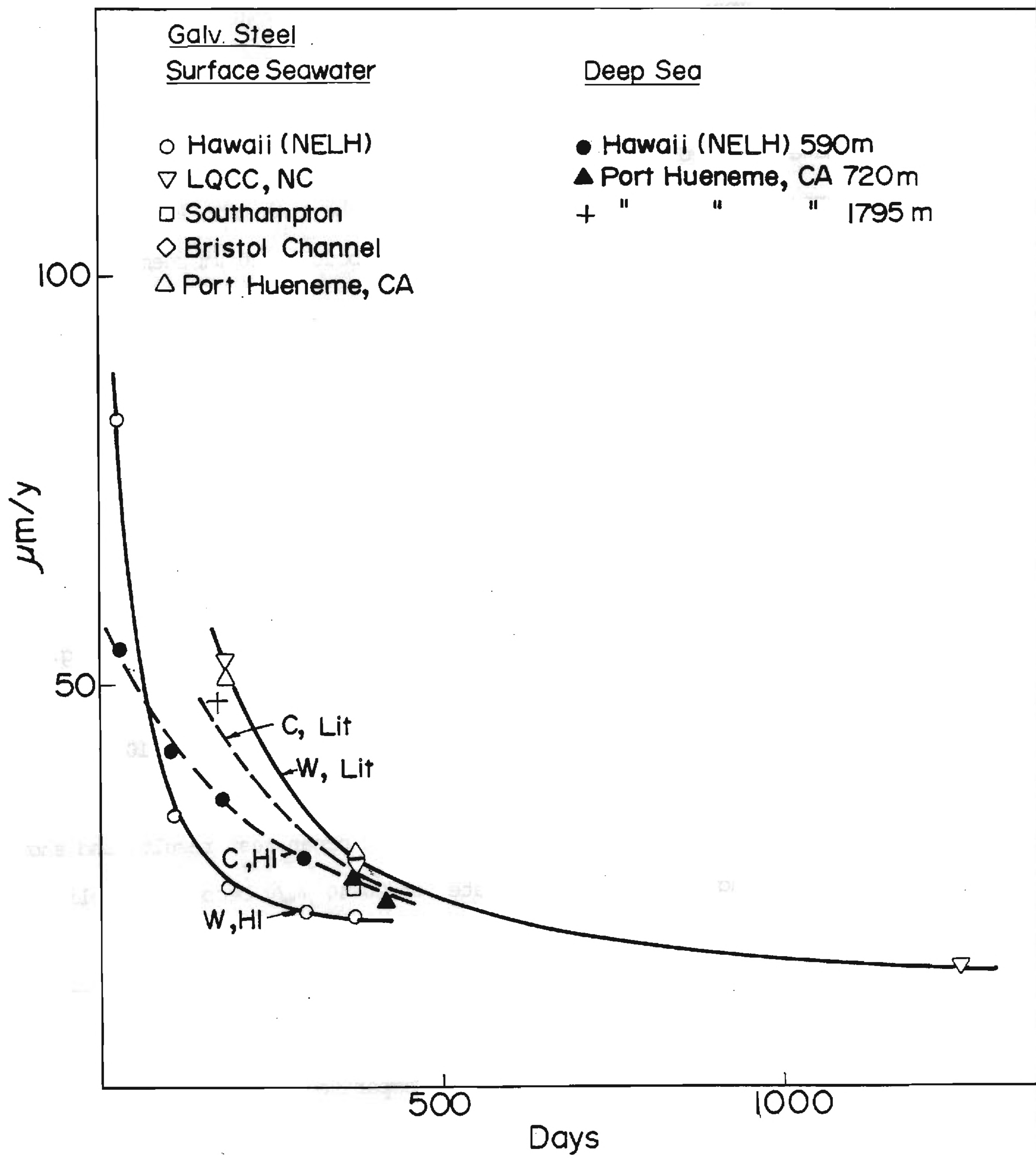

Fig. 7 Comparison of linear corrosion rate data from NELH with literature data.

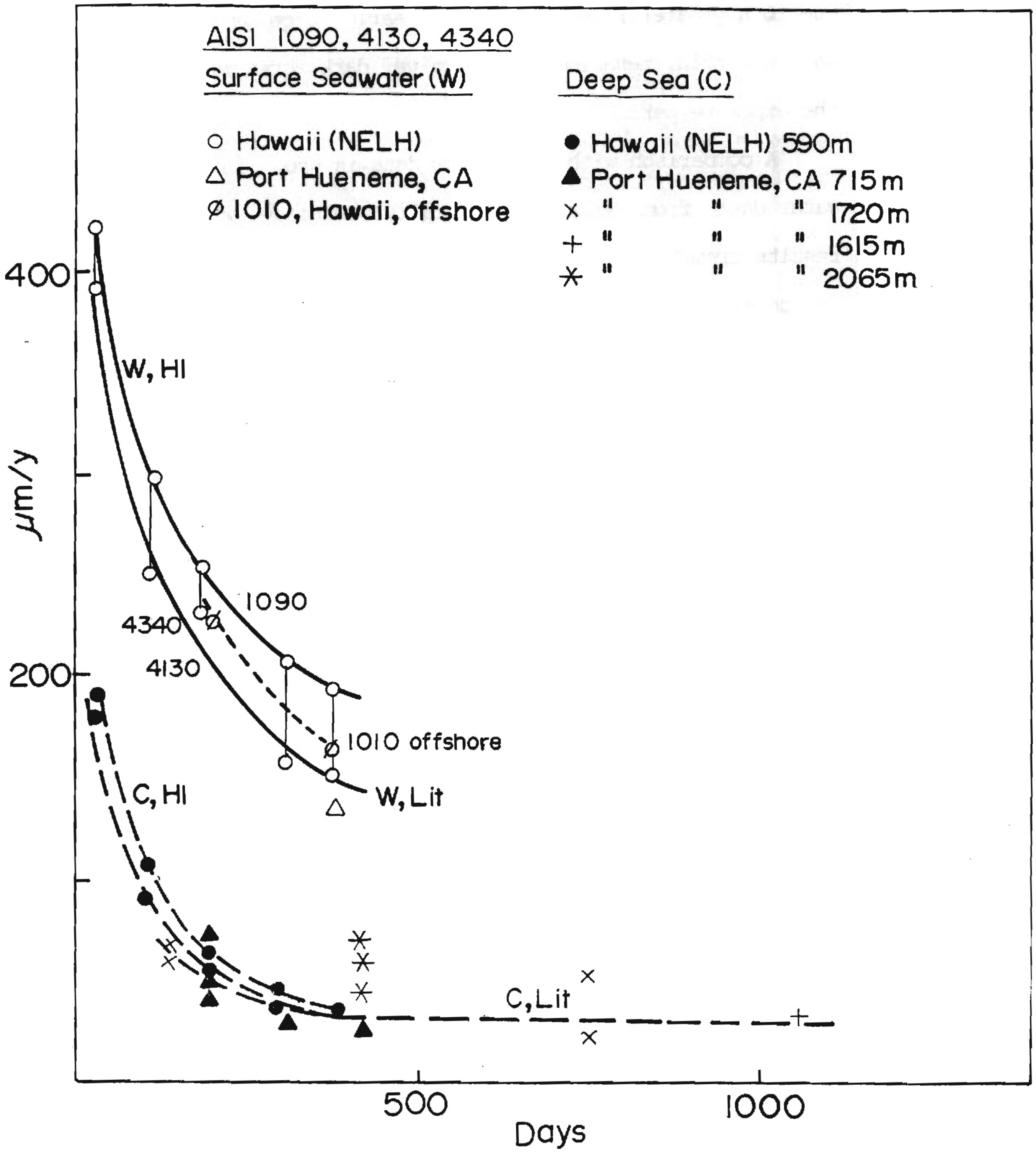

Fig. 8 Comparison of linear corrosion rate data from NELH for steels AISI 1090, 4130 and 4340 with data from Port Hueneme.

Lead: The cold water gives a slightly greater attack than the warm due to a greater rate during the early stage of exposure. In both waters a thin, tenacious, protective dark grey film forms early in the exposure period.

A comparison with literature data is shown in Fig. 9. The cold water data from Hawaii essentially coincide with the deep sea results from Port Hueneme, while the Hawaiian surface water rates are considerably lower than rates reported from other sites. It appears that a long-term rate of 2-4 µm/y is established in both Hawaiian waters after about 3 years. The same rate is obtained for the Port Hueneme deepsea exposures, while surface seawaters around the world establish a rate of 10-13 µm/y after 4 years.

In summary, long-term corrosion rates in Hawaiian surface waters are expected to be

- 15-20 µm/y for the coating on galvanized steel,
- 50-75 µm/y for the high-carbon steel, with a possibility of a higher rate, at 100-130 µm/y,
- 2-4 µm/y for lead.

In the deep ocean, the expected long-term rates are

- 20 µm/y for the coating on galvanized steel,
- 20-40 µm/y for high carbon steel, and
- 2-4 µm/y for lead.

These rates become established during the first 1-4 years of exposure.

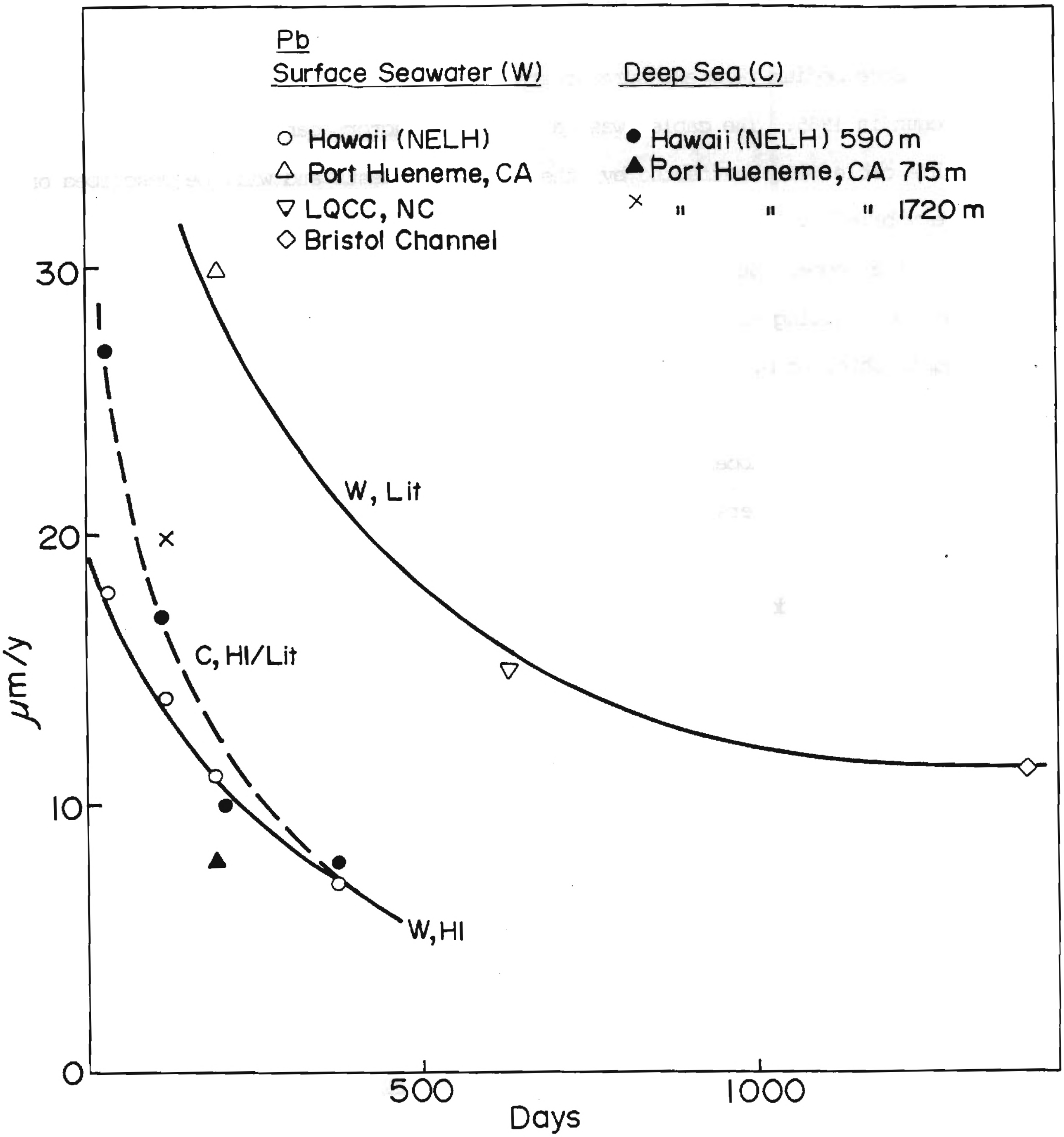

Fig. 9 Comparison of linear corrosion rate data from NELH for lead with literature data.

IV b. Tests With Cable Specimens

Some medium-term exposure tests with sections of a Pirelli cable were begun in 1985. The cable was a three-conductor cable. The inner parts of this cable were unaffected by the exposure tests and will be described only very briefly.

The copper conductors were shielded by EPR (ethylene propylene rubber) semi conducting compound, insulated by EPR insulation, and the insulation was again shielded by EPR semi conducting compound and screened by copper tape.

Three cores of the above make-up were separated by polypropylene fillers and bound with rubberized fabric tape to a diameter of 84.9 mm.

The outer layers, which are of more interest in the present context followed on top of the fabric tape:

- a bedding of 2 mm thick polypropylene yarn,
- a layer of bitumen
- a layer of 6 mm diameter galvanized armor wires of cold drawn AlSl 1025, zinc coat approximately 50 μm thick, and
- a serving of 3 mm thick polypropylene yarn, identical to the material which will be used in the HDWC cable.

The outer diameter of the cable was 106.9 mm and its weight 20.4 kg/m.

Three 0.45 m long sections were used for the exposure tests. The cut ends were covered with epoxy and duct tape. One sample was tested in the warm water trough, one in the cold water through, and one was mounted on the pipeline offshore at NELH. The latter was about 100 m from the cliff, 12 m below the surface, and 1.5 m above the bottom. The ASTM tests, mentioned earlier, were conducted at the same location. Each sample will be discussed separately below.

Sample from Warm Water Trough: this sample was exposed in slowly flowing surface seawater at 25-28°C, with a pH of 8.25 and fully saturated with oxygen. Exposure period was October 31, 1985 to June 28, 1987, or 605 days.

Upon removal the sample was dissected. Only the armor wires showed effect of the exposure, in the form of minor corrosion. The average loss of zinc coating was determined by chemical dissolution and weigh changes. It was 5 μm for an average rate of 3 μm/y. This rate is much lower than the 15-20 μm/y measured on coupons in the troughs. The difference is clearly due to the protection offered by the polypropylene serving and the bitumen layer. It is expected that almost all the loss took place on the outer 50% of the wire diameter (i.e., the area not covered with bitumen). This would give an average corrosion rate of about 6 μm/y which still is low.

Sample from Cold Water Trough: This sample was exposed in slowly flowing water pumped from about 600 m depth. The temperature was 7-10°C, pH 7.6 and the oxygen content a low 1.1 ppm. Period of exposure was October 31, 1985 through October 30, 1987, or 2 years. Upon dissection it resembled the warm water sample, discussed above, with an average zinc coating loss of 6 μm, or μm/y. Assuming attack on only one-half the surface the rate becomes 6 μm/y, which again is considerably below rates for freely exposed galvanized steel.

Off-Shore Sample: this sample was exposed for 747 days, from Nov. 23, 1985 through Dec. 10, 1987. In this case the total coating loss was 18 μm, giving distributed average rate of 8.8 μm/y and a half-area rate of 17.6 μm/y. This rate is similar to values expected for freely exposed galvanized steel. It is considerably greater than measured in the warm water trough, probably due to the strong ocean currents at the site.

IV c. Samples of Armor Wire

A number of corrosion tests were performed with pieces of the actual armor wire selected for the final HDWC design. The material is a cold drawn AlSl 1085 steel of rectangular cross section, 10 mm x 3 mm. It is galvanized to a coating thickness of 75 μm and has a Vickers hardness of 525 k_s/mm^2.

The points of interest in this study were a) the corrosion rate of this material in seawater, especially in the early stages of exposure; b) the "throwing power" of the coating, i.e., its ability to protect a break in the coating; and c) the tendency for stress corrosion cracking. Samples were exposed both in the troughs at NELH and in the Materials Engineering Laboratories at the University of Hawaii. In the latter tests stagnant surface seawater was used at room temperature in a test vessel. The water was obtained from the Waikiki Aquarium.

Tests in the Laboratory: Twenty samples of armor wire, 34 mm long, were stripped of coating by immersion in HCl and subsequently exposed in stagnant seawater at room temperature. Weight loss was determined for exposure period of 0.5 to 24 h. The calculated average thickness loss is plotted in Fig. 10. The 24 h value corresponds to an annual rate of 175 $\mu m/y$, which, in view of other data, seems reasonable for the early stage of attack. The one-hour corrosion is about 0.07 μm, which corresponds to an annual rate of 613 $\mu m/y$. The actual one-hour corrosion determined here is substantially lower than the value obtained from extrapolation of equation (6) derived from longer-term tests of AlSl 1090. That value is 0.40 μm (vs. 0.07 μm).

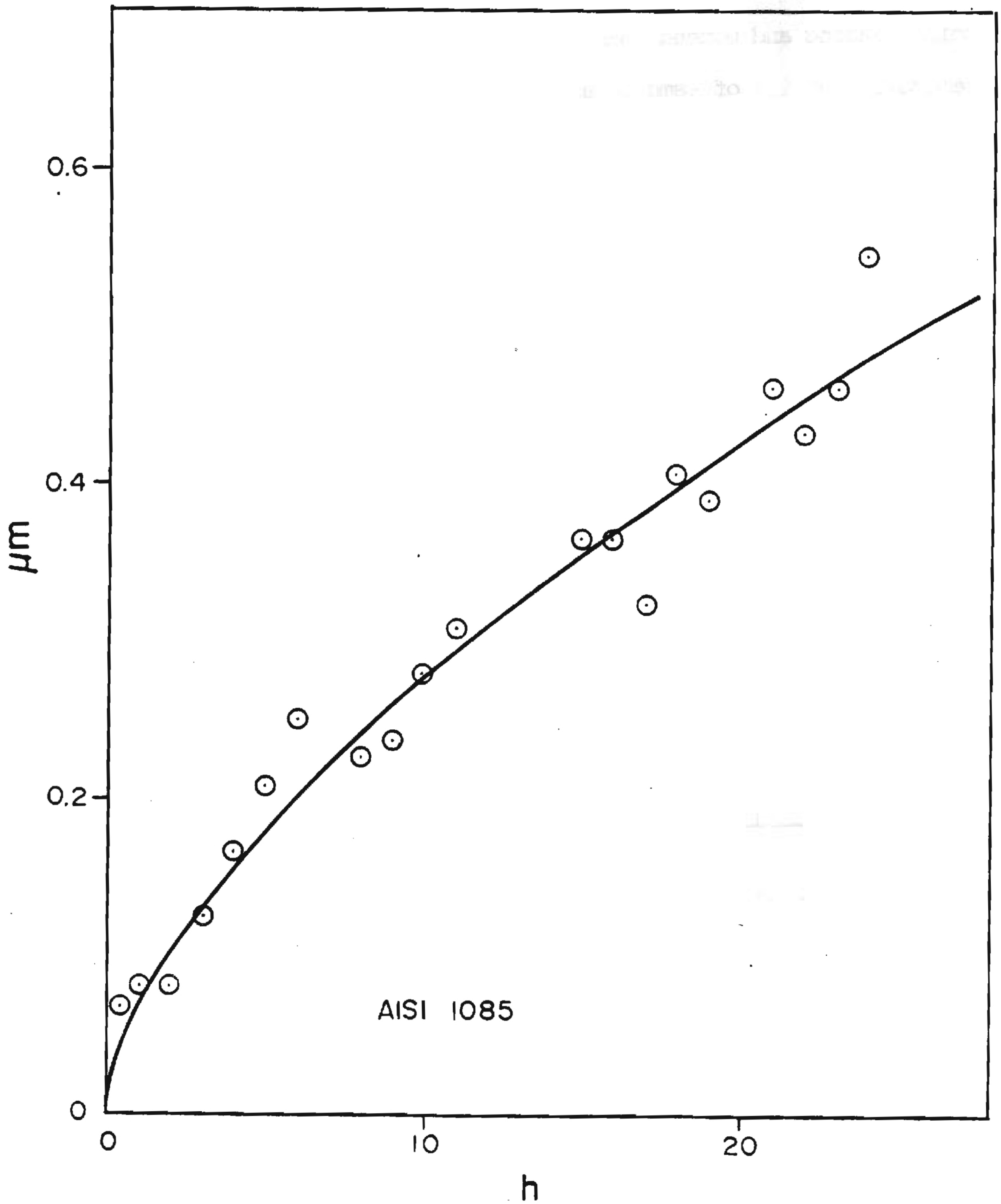

Fig. 10 Corrosion loss for armor wire exposed in stagnant seawater for short periods of time.

Tests in Warm Water at NELH: Armor wire samples were tested for their possible susceptibility to stress corrosion cracking in seawater. Both 2-point bending and U-bend samples were used with various degrees of coating removal. Details of samples and results are given in Table 3. The samples were exposed in the troughs at NELH for 202 days from 4/10/87. After removal the tension side was cleaned and examined by low power microscopy. No cracks were found.

TABLE 3
202-Day Stress Corrosion Test Samples

Type	Length mm	Max. stress psi	Zn* Removed	Coating Loss Rate, µm/y +	
				Cold Water	Warm Water
2-Point Bending (ASTM G39-70)	254.	50,000	0	41.5	36
			51 mm**	110	116.5
			full length**	121	115.5
U-bend (ASTM G30-79) R = 8.5 mm	93	125,000	0	58	22.5
			51 mm**	69.5	27
			full length**	106	33
			100%	1.3++	8.5++

* Zn removal by H Cl + 56 Cl_3 according to ASTM G90-69
** On tension side only
\+ Weight loss converted to coating loss. In reality there is some corrosion of the bare steel also.
++ Steel corrosion

Samples for general corrosion were also tested. These had various degrees of coating removal, over 30, 60 or 100% of the specimen length. They were exposed in the troughs for 67 and 189 days from 4/23/87. The results are summarized in Table 4.

TABLE 4

Tests for General Corrosion

	μm/y in Cold Water		μm/y in Warm Water	
Exposure Period	67 days	189 days	67 days	189 days
Zn corrosion				
0% removed	67.5	32	36.5	7
30% removed	113	58	25	0.5
60% removed	810	462	59	24.3
Steel Corrosion (100% Zn removed)	60	44	101.5	100

The data for both the fully galvanized and the completely bare steel in the cold water are consistent with the coupon test data discussed above, while the warm water results are somewhat lower. For the samples which have part of the coating removed, the corrosion rate of the coating is greatly accelerated in the cold water. When even a small part of the coating is removed before immersion, the remaining zinc does not fully protect the steel. This is particularly pronounced in the cold water because of reduced throwing power. When the total weight loss is calculated as thickness loss for the coating only, extremely high values result.

IV d. Summary of Corrosion Data

The corrosion tests have shown the following:

- no cracking is expected due to stress corrosion or hydrogen embrittlement at cathodic sites,
- the intact zinc coating, if freely exposed, will corrode at a long-term rate of 15-20 μm/y in the surface seawater and 20 μm/y in the deep sea,
- bare armor wire corrodes at long-term rates of about 75 μm/y in the warm water and 30 μm/y in the cold,

- when the polypropylene yarn serving and the bitumen layer on the bedding are intact the corrosion rate of the zinc is reduced by about a factor of about three,

- if the zinc coating is removed in local areas the corrosion rate increases drastically. The throwing power is less in cold water than in warm and the galvanic effect increases rapidly as the damage zone exceeds 40-50 mm in length. Even coating damage on one side only results in significant increase in galvanic corrosion and consequent rapid consumption of the zinc coating, and

- short-term corrosion rates of the bare steel in warm seawater are around 615 µm/y during the first hour and 175 µm/y during the first day.

V. ABRASION TESTS

Several different types of abrasion tests were utilized, ranging from sliding against dry abrasive papers to repeated sliding against pillow lava rocks immersed in seawater.

V. a Abrasion by SiC Abrasive Paper

In order to determine the possible effects of wire orientation on abrasive wear rates scoping tests were carried out using 120 grit silicon carbide abrasive paper, which has a mean grit size of 120 micrometers. Since the armor wire has rectangular cross section and is heavily cold drawn the mechanical properties may vary with direction. There are six possible orientations of interest, as shown in Figure 11. The ASTM notation system for fracture mechanics has been adapted for use here. The arrows indicate direction of sliding, i.e., direction of the abrasion grooves.

The tests were all conducted dry at a sliding velocity of 3.0 cm/s on a track length of 1.42 m. Some tests were conducted with repeated sliding in the same track, while others utilized fresh paper for each pass. Specimen size was 34 x 10 x 3 mm and both galvanized and bare samples were tested. The wear was calculated as mm^3 of steel lost from weight loss measurements. The cutting force was averaged over each pass and the coefficient of friction was calculated.

Tests with Fresh Tracks: These tests were conducted with galvanized samples, except for one test with a bare sample (zinc removed). The results are plotted in Figure 12.

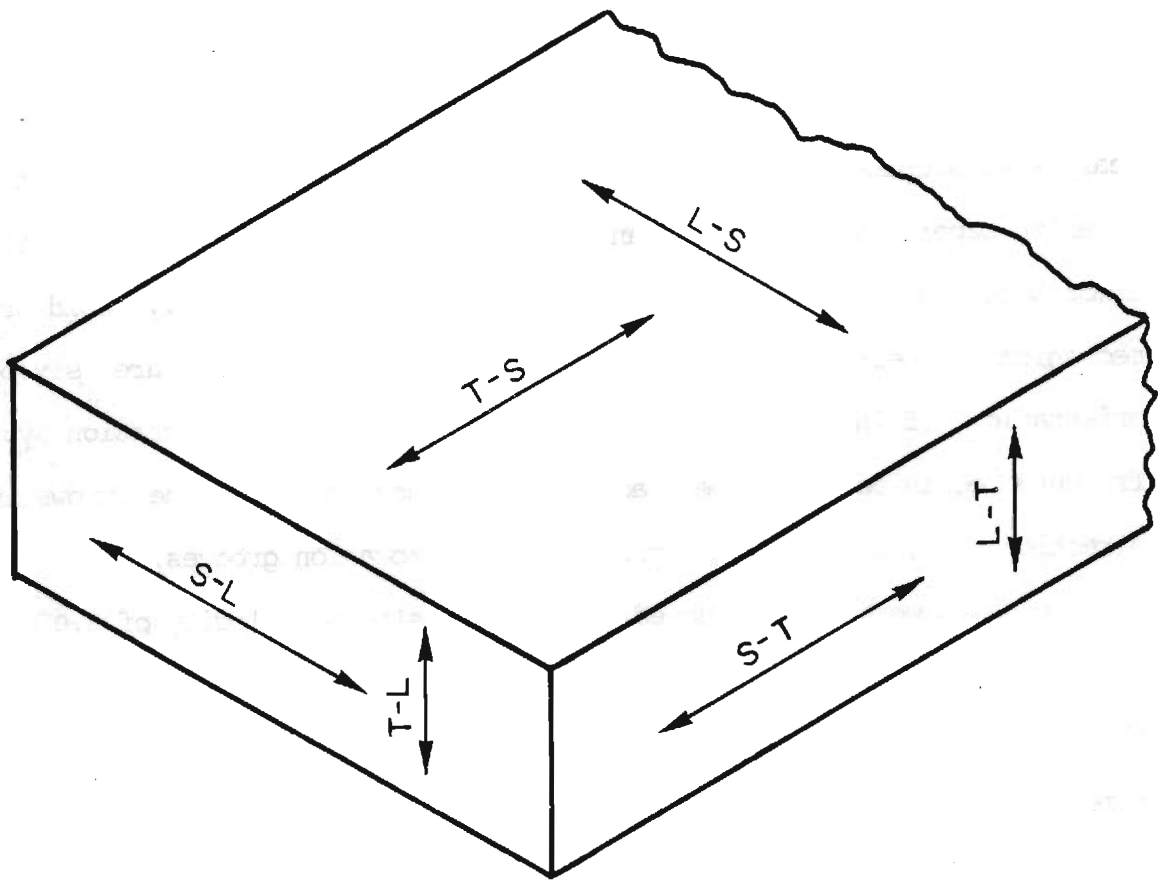

Fig. 11 Notations used to indicate sliding direction.

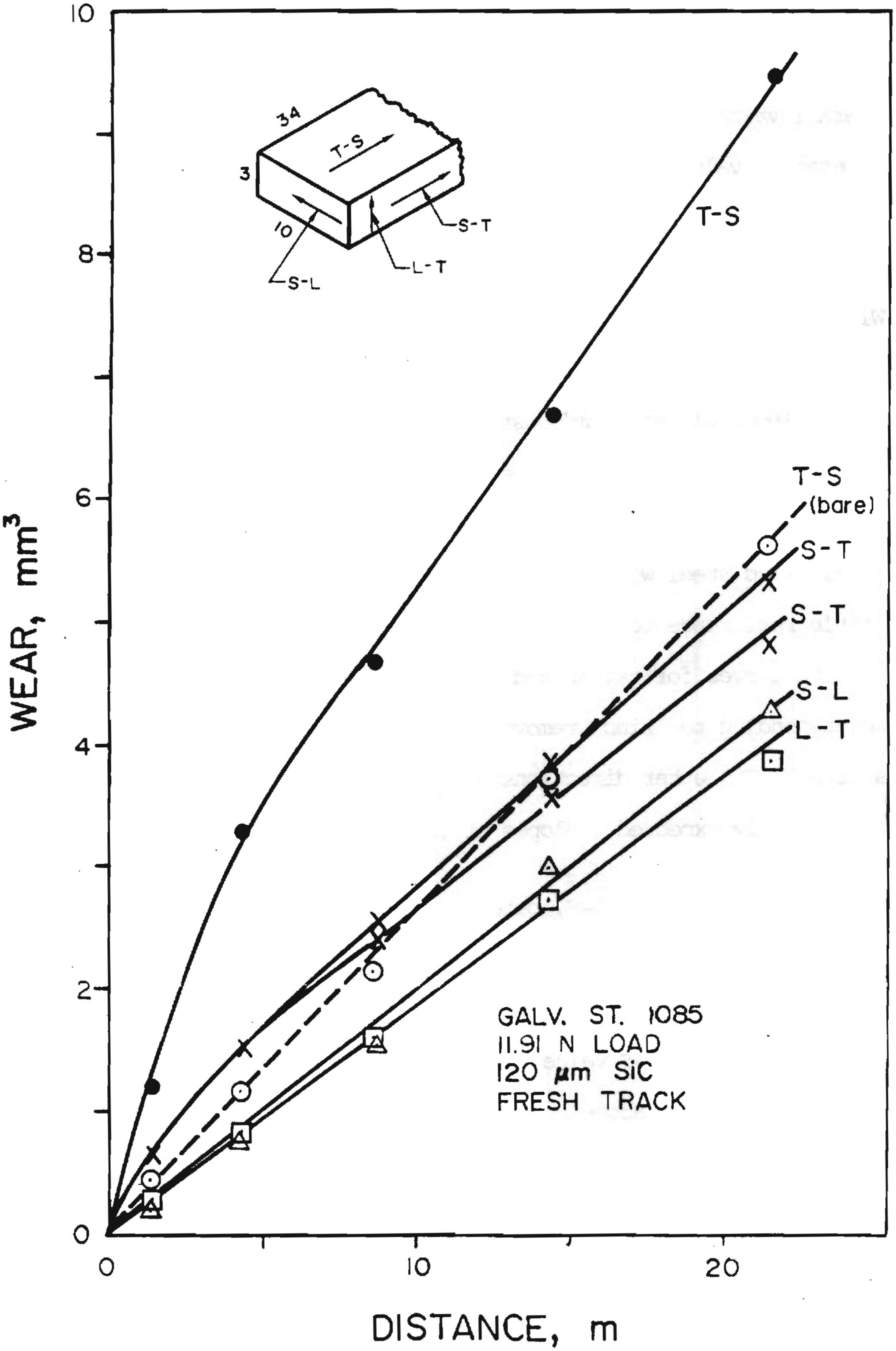

Fig. 12 Wear-distance curves for tests on fresh tracks of SiC paper for various sliding directions.

The coefficient of friction stayed essentially constant for each test and only the average values have been plotted. These range between 0.59 and 0.72, showing no clear correlation with specimen direction being abraded. An overall value of 0.66 appears to be reasonable, and is consistent with common literature values.

Since the tests were conducted with galvanized samples, some of the behavior seen is due to abrasion of the zinc in the early stages of testing. With 75 micrometers of zinc coating, the face corresponding to T-S has 25.5 mm^3 of zinc, S-T and L-T have 7.65 mm^3, while S-L has no zinc on the front face. Recalculated as mm^3 steel these numbers become 25.5, 7.65 and zero. With the long specimen size selected it is probable that complete contact was not achieved for the T-S and possibly the S-T directions, i.e., a combination of zinc and steel wear may be seen. Since the zinc is soft it will have little resistance to abrasive wear.

The curves for galvanized T-S and S-T show initial rapid wear, probably corresponding to zinc removal, followed by linear relations after 5m of sliding. The other directions show wear proportional to sliding distance, as is generally expected. Slopes of the lines are:

T-S	0.36 mm^3/m
T-S, bare	0.27
S-T (1)	0.23
S-T (2)	0.21
S-L	0.20
L-T	0.19

Of these, the T-S value is discarded because of the contribution of the zinc, as discussed above. The geometry and dimensions of the test specimens do not permit a direct, rigorous comparison of the data. If the wear rates are plotted vs. specimen length in the direction of sliding, see Figure 13, a slightly increasing trend is seen. This is not unexpected from the mechanics

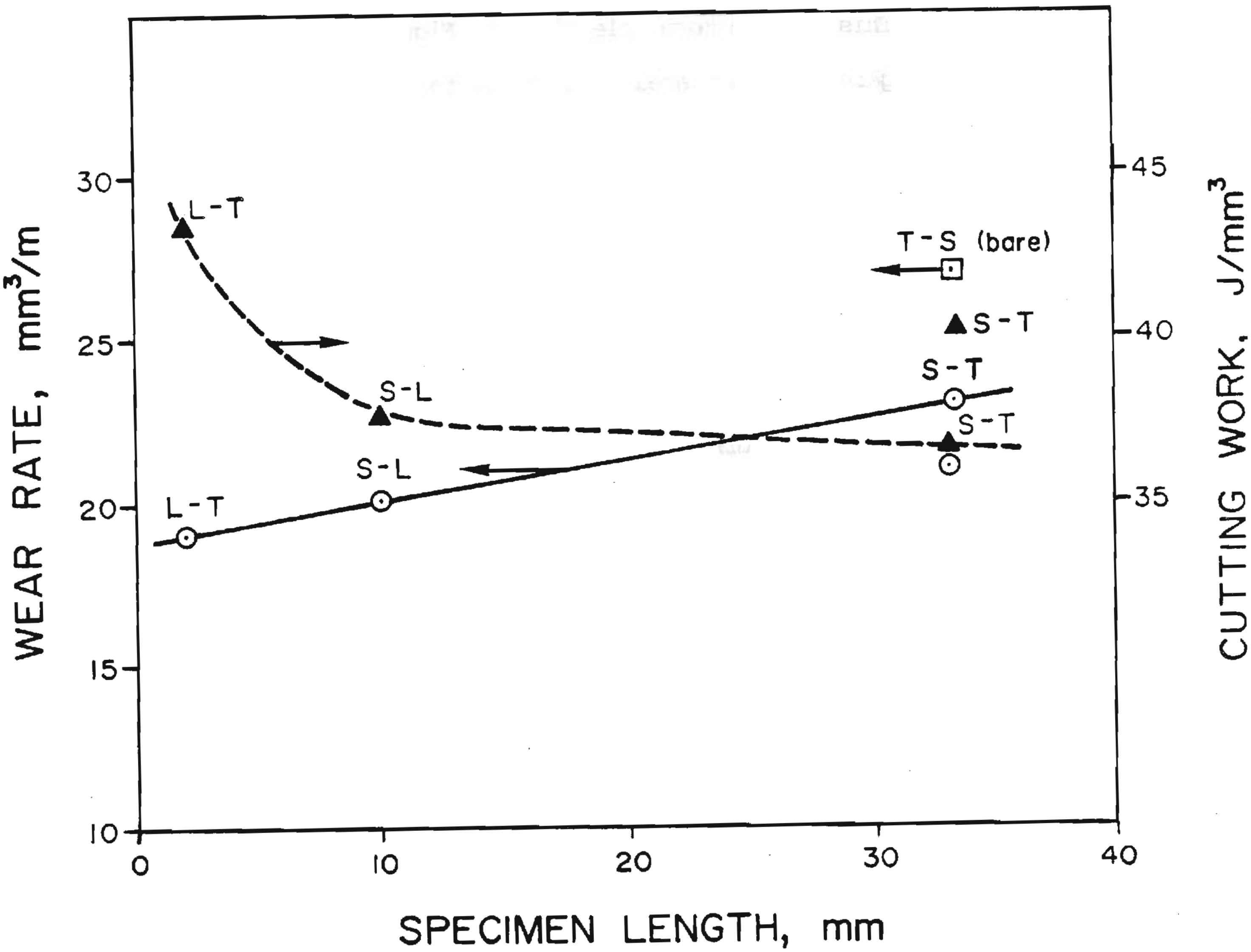

Fig. 13 Wear rate and cutting work vs. specimen length in direction of sliding, for abrasion by SiC paper.

of abrasion alone and indicates that there are no significant differences in abrasion properties between these three directions. The wear rate for the T-S direction is somewhat greater. This can be attributed to the greater width and lower contact pressure for this configuration. Again, the data do not indicate any significant variation in abrasion resistance with specimen orientation. This is seen more clearly in Figure 14, where wear rates have been plotted against contact area. The value for the very short dimension, L-T, lies below the general correlation here. Values for the galvanized samples have been adjusted to account for the 6% of the wear rate which is due to removal of zinc around the perimeter of the contact area.

The work expended in removing unit volume can be calculated from

$$CW = \frac{P \bullet \mu}{\dot{\omega}} \tag{8}$$

Where CW is the curring work (J/mm^3), P is the applied load (N), μ is the coefficient of friction and $\dot{\omega}$ is the wear rate (mm^3/m). The calculated values are

S-T (1)	36.41	N/mm^3
S-T (2)	40.26	
L-T	43.48	
S-L	37.63	

These values are also plotted in Figure 13. The cutting work drops rapidly as sample length increases to about 10 mm and then essentially levels off.

These experiments have shown that there are no significant differences in abrasion resistance between the various orientations of the armor wire and that a coefficient of friction of 0.66 and a max. wear of around 0.275 mm^3/m can be expected for abrasion by SiC abrasive papers.

Repeated Tests in Same Track: A number of tests were conducted in the same equipment but using the same track for each test. Samples were weighed

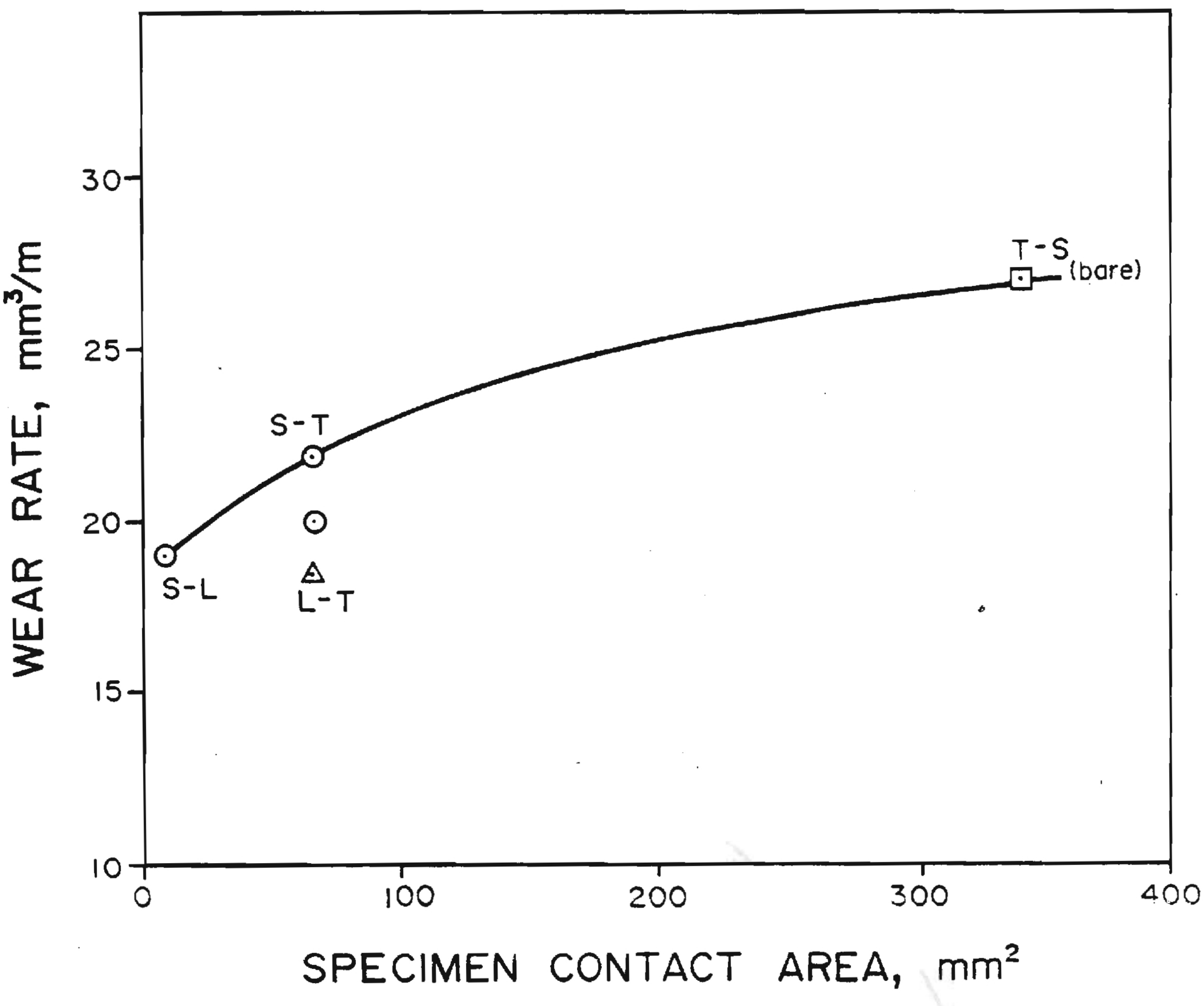

Fig. 14 Wear rate vs. contact area for abrasion by SiC paper.

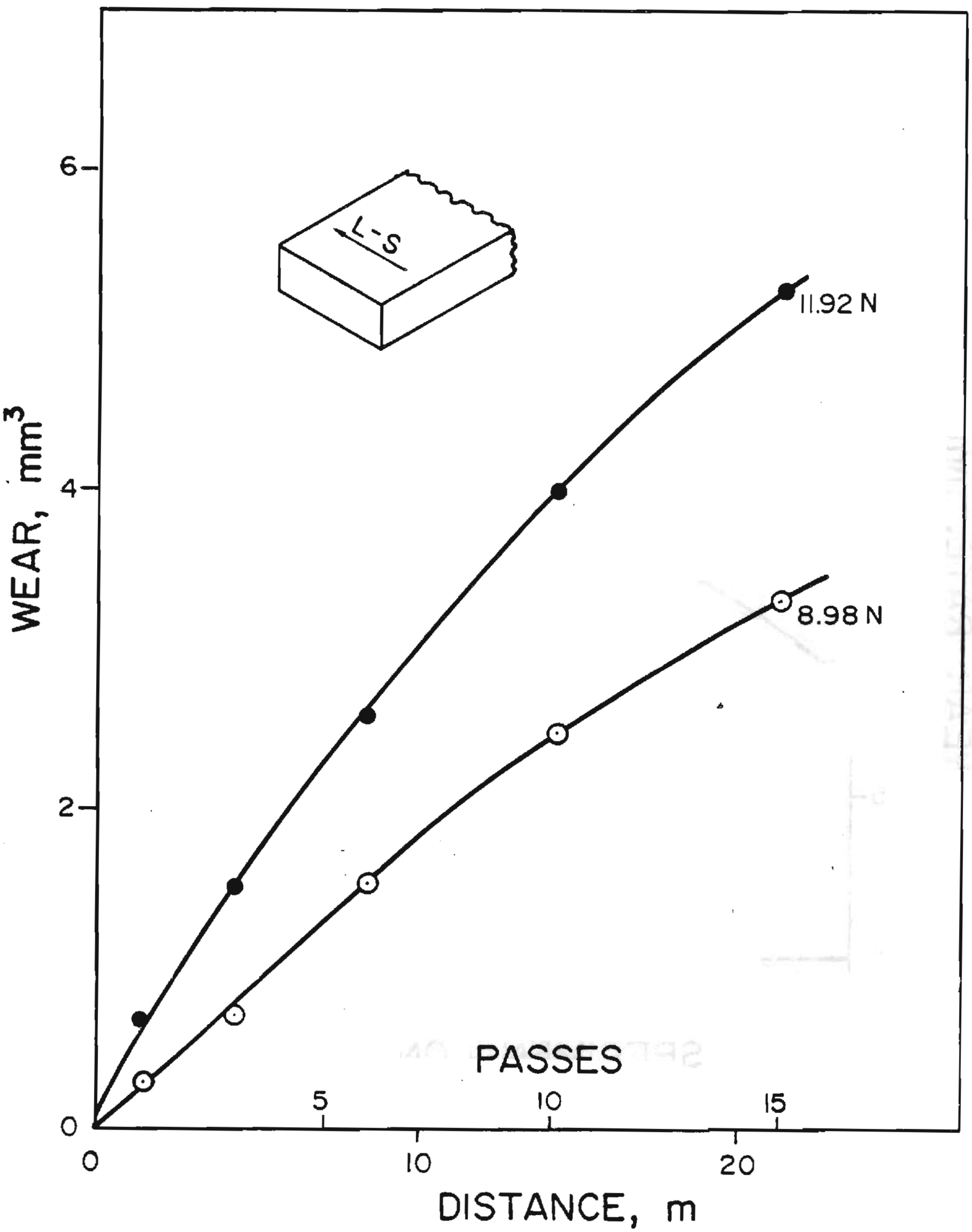

Fig. 15 Wear vs. distance of sliding in same track on SiC paper for different sample orientations.

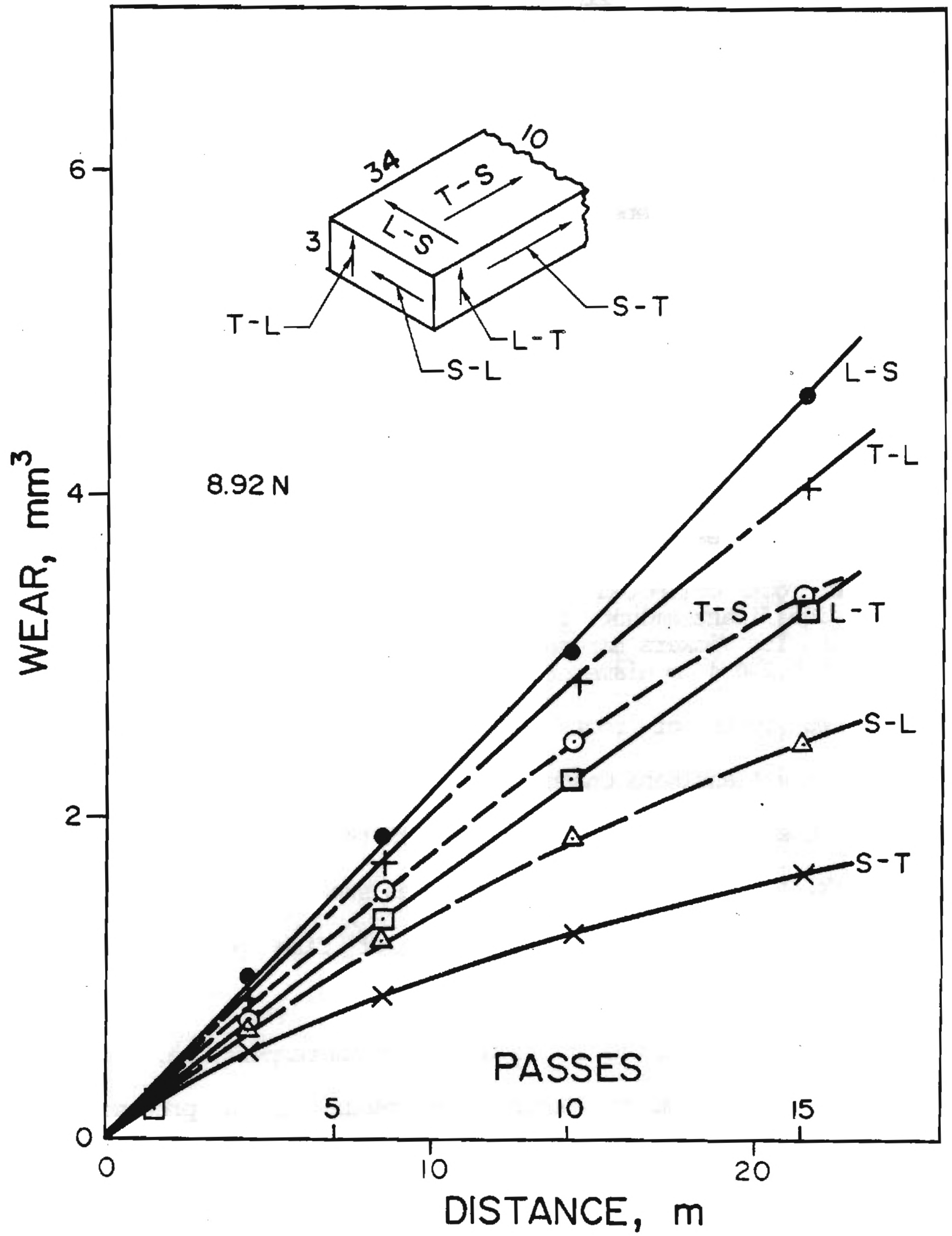

Fig. 16 Wear vs. distance of sliding in same track on SiC paper for two different loads.

after 1,3,6,10 and 15 passes in one direction over the 1.42 m long track. All samples had the zinc coating removed before test.

The wear data are plotted in Figs. 15 and 16. The results show a rather complicated interdependence of contact pressure, distance, and specimen length in the direction of sliding. Much of this behavior is due to wear of the abrasives. The data show no indication that the wire material's resistance to abrasion is in any way dependent on orientation.

V b. Abrasion of Basalt Rocks

Tests were conducted against two different types of rock:

- a deepsea channel rock from dredge #6 (see Fig. 3). This is a fine grained rock with only fine-scale porosity. Its density is 2.35 and its hardness is about 300 kg/mm^2 on the Vickers scale, and
- a rock collected from the shore at NELH. This rock has a significant amount of pores of 1-2 mm diameter. Its density is 1.96 and its Vickers hardness is about 600. It contains olivine grains of 0.2-0.4 mm diameter.

These two types of rock are thought to represent the various types expected in the Alenuihaha Channel. Since the hardness of the armor wire is 525 Vickers one might expect the shore rock to be much more abrasive than the channel rock. This was not the case, as shown below, probably because the rock hardness values hide various levels of fine porosity, which may have little effect on abrasiveness.

The tests were conducted in seawater at room temperature. This was chosen because some rocks may microfracture more readily in the presence of moisture and because it would closely resemble actual conditions.

Two samples were tested together, and a common coefficient of friction was measured. Wear was determined by weight-loss measurements at intervals of testing. The samples were slid back and forth in the same track of about 0.12 m length at a frequency of about 1200 round trip cycles/h.

Samples were tested in the galvanized condition, with the coatings removed on that 50% of the specimen which faced the rock, and bare, with all the coating removed. Removal was by chemical dissolution (HO + Sb_8Cl_3), followed by slight abrasion by 500 μm SiC paper. The 34 mm long samples of armor wire were tested in various directions relative to the direction of rolling.

In order to have a smooth run it was necessary to wear against a cut rock surface. In order to introduce a realistic surface roughness these cut surfaces were sandblasted before tests. This treatment had little effect on long-term results but was retained for all tests for purposes of reproducibility.

The initially bewildering piles of data make some sense when plotted in terms of wear as thickness of material removed as a function of contact pressure, for various values of specimen length in the direction of sliding, see Fig. 17 for low pressure levels and Fig. 18 for the high pressure range. Fig. 19 illustrates the effect of sliding distance at high pressure on the wear. The results show the following:

- shore rock is about 25% more abrasive than channel rock,
- wear increases almost linearly with distance, after an initial running-in period,
- wear increases with contact pressure, somewhat less than linearly,
- wear decreases as the specimen length is increased for the same contact pressure,
- typical wear loss at 2.7 MPa contact pressure for 3000 cycles or 720 m sliding are 220 and 140 μm vs. shore and channel rocks, respectively, and,
- coefficients of friction fall in the range 0.4 to 0.5, concentrated around 0.45.

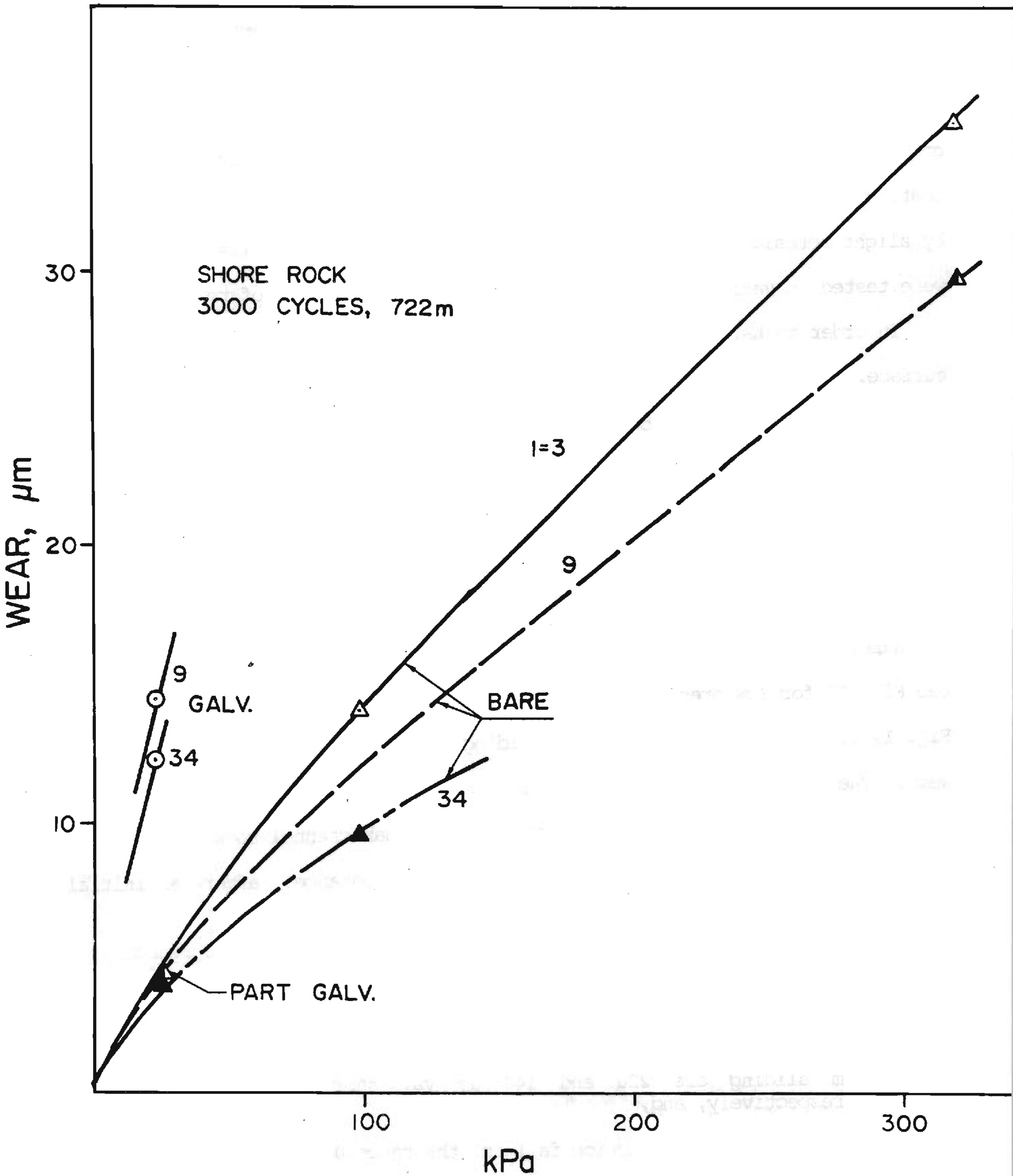

Fig. 17 Wear as thickness lost after 3,000 cycles or 722 m vs. contact pressure for different values of l, the specimen length in the direction of sliding.

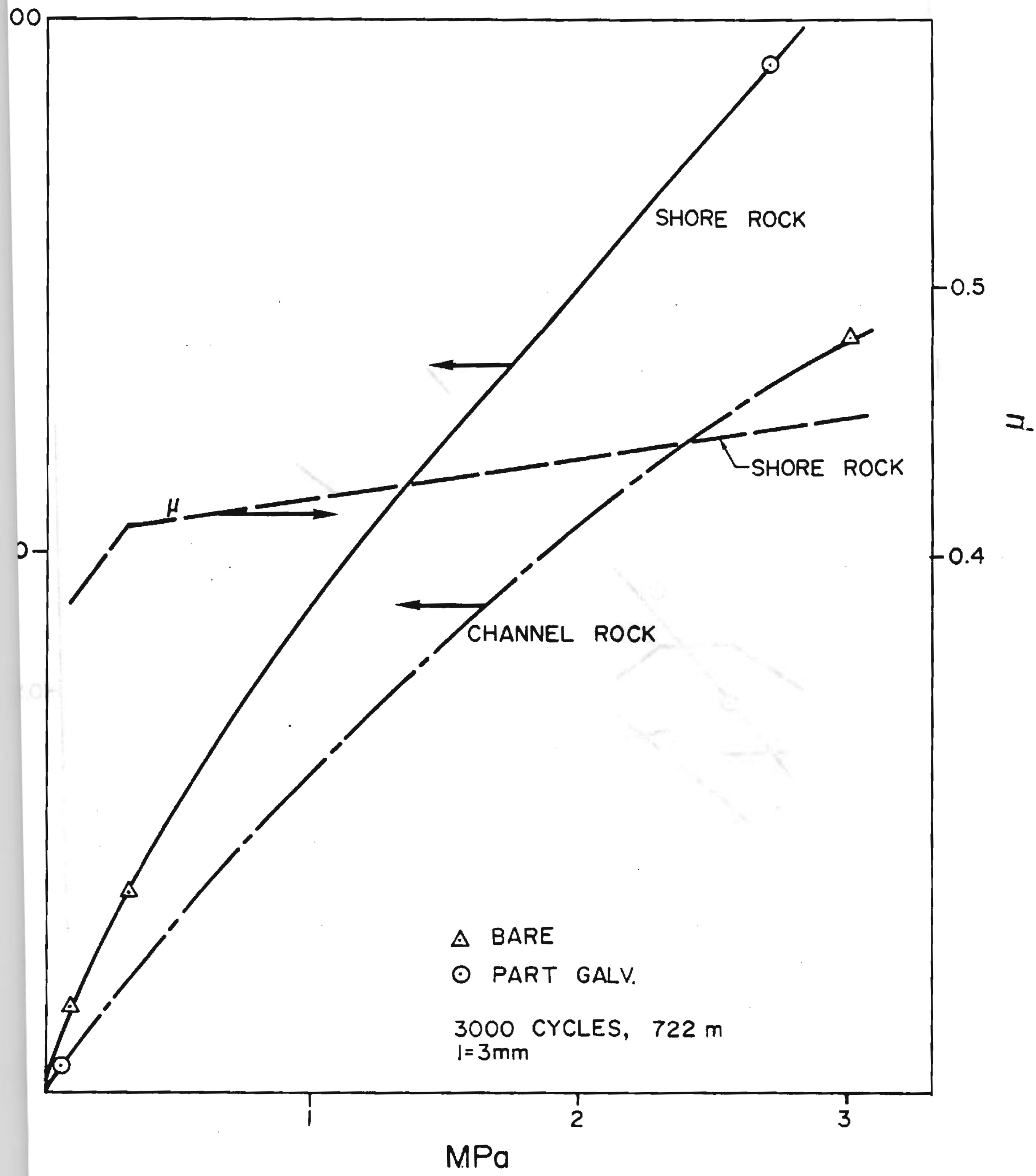

Fig. 18 Wear and coefficient of friction vs. contact pressure.

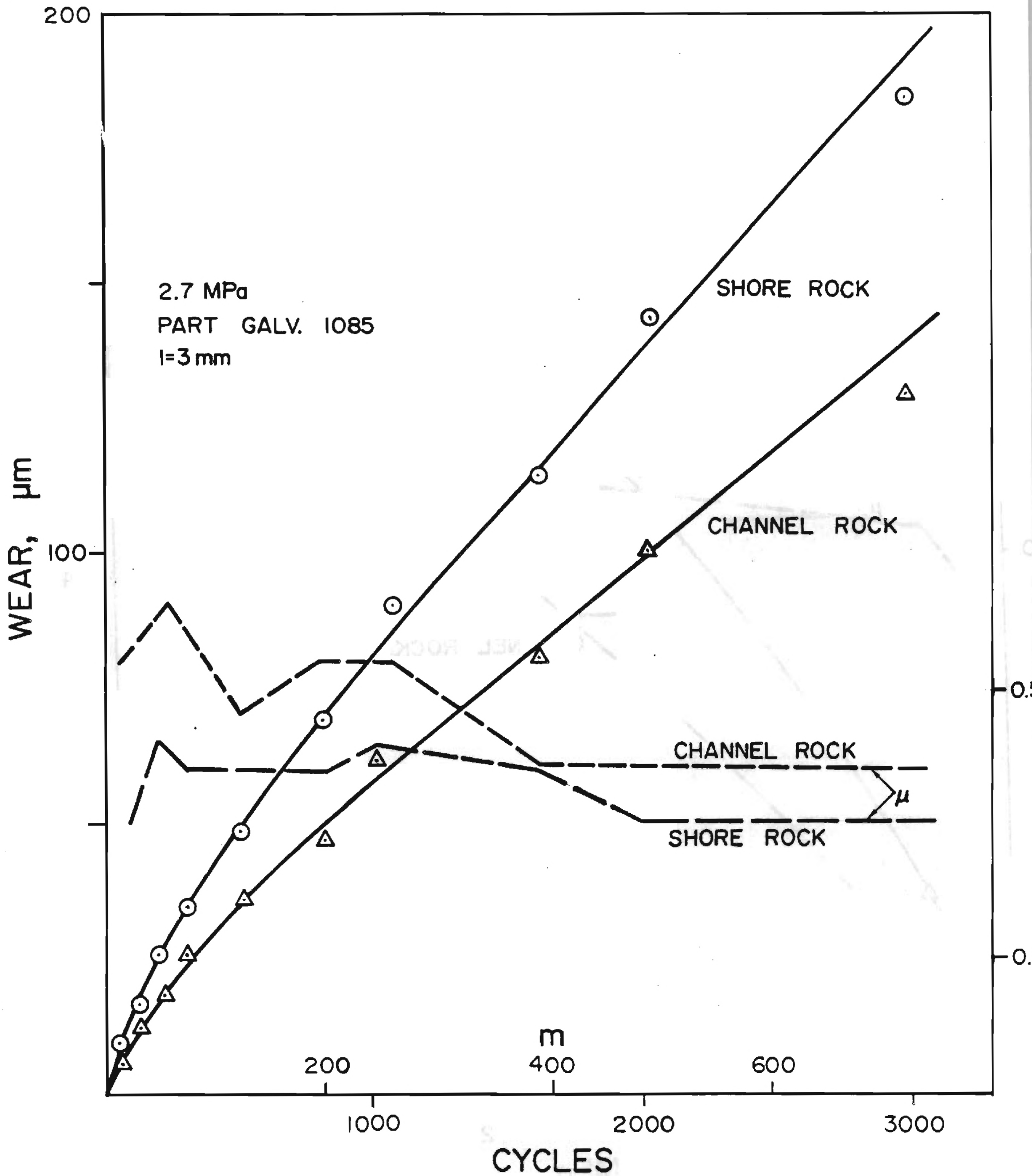

Fig. 19 Wear and coefficient of friction vs. sliding distance.

In order to obtain some information on the behavior of the armor wire-rock system under high contact stresses some tests were run with armor wires pressed against 90^{o} angle edges of rock. These tests were run dry, with stroke lengths of 0.05 m. Weight loss of both rock and steel was determined.

The results are shown in Figs. 20 and 21. There is little difference in the rate of wear caused by the two different rocks. For extended testing the channel rock both causes more steel wear and itself wears more than the shore rock. The friction values, which were measured at intervals under a reduced load of 5N, declined from 0.4-0.45 to 0.25-0.3 during the course of the test. At the end of about 800 cycles or 25 m of sliding the rock had worn to a width of about 0.8 mm, such that the contact pressure was about 3.1-3.6 MPa, which is near the top of the range used in the seawater tests described above. At that point, the wear of the steel amounted to a depth of around 25-30 μm, and the wear rates were 0.45 μm/m against the channel rock and 0.2 μm/m against the shore rock. These values are in the general range found in the previous tests, where at 3MPa and 722 m sliding the wear rates were 0.2 and 0.25 μm/m against channel and shore rocks, respectively.

Tests with galvanized wires in the same configuration showed that the zinc coating was worn through quite rapidly, in 2-3 m of sliding, or 75-100 cycles.

V c. Abrasion by Crushed Basalt Slurry

It is conceivable that debris of crushed rock may remain in the wear scar and produce abrasion as a slurry. In order to assess the possible damage in this situation some slurry abrasion tests were carried out.

Shore lava rock was crushed and sieved to a particle size of 250-500 μm. 900 grams were mixed with 1 l of seawater to produce a slurry in which samples

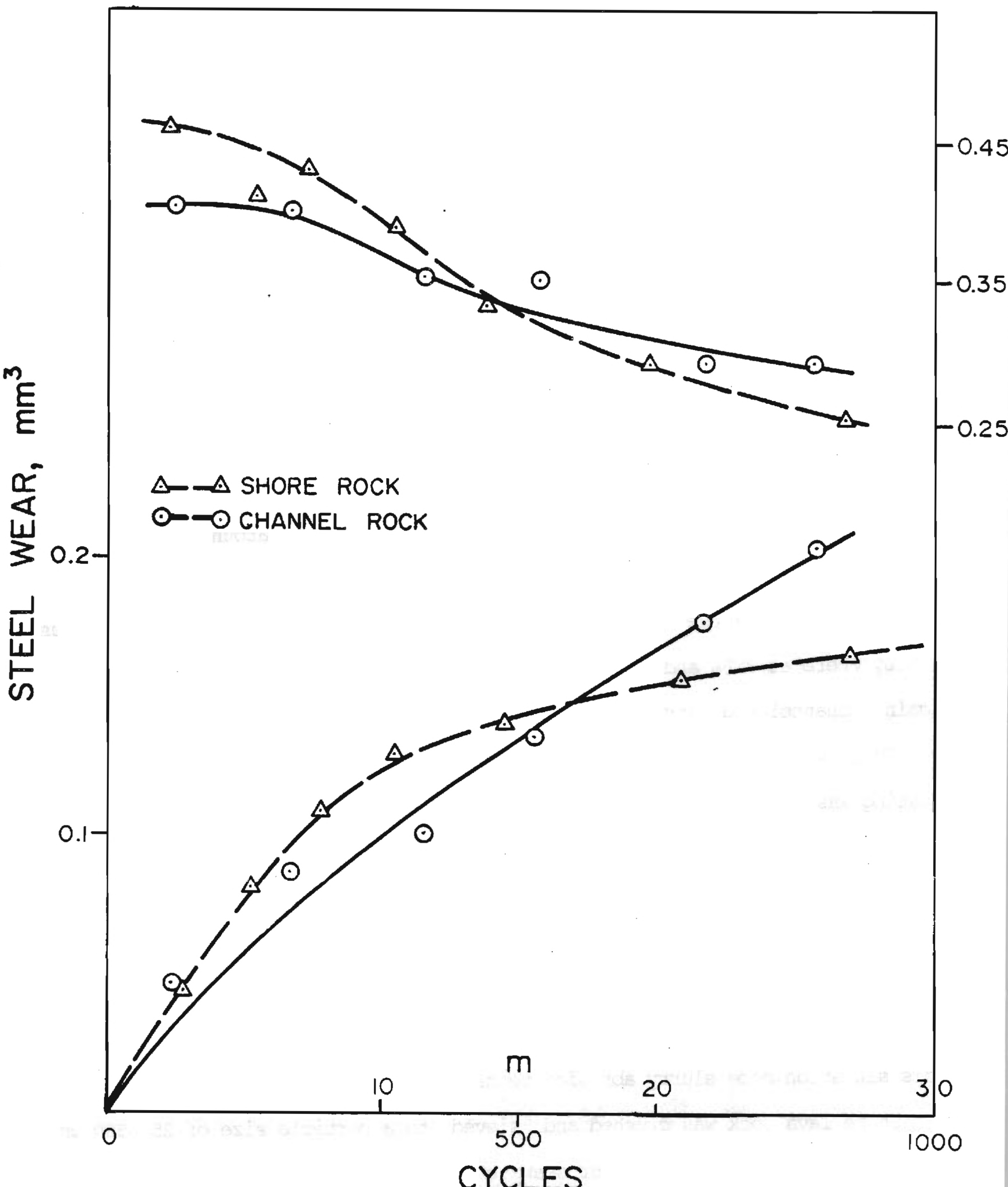

Fig. 20 Wear of bare armor wire abraded in the L-S direction against a 90° edge of rock under 46.4 N load.

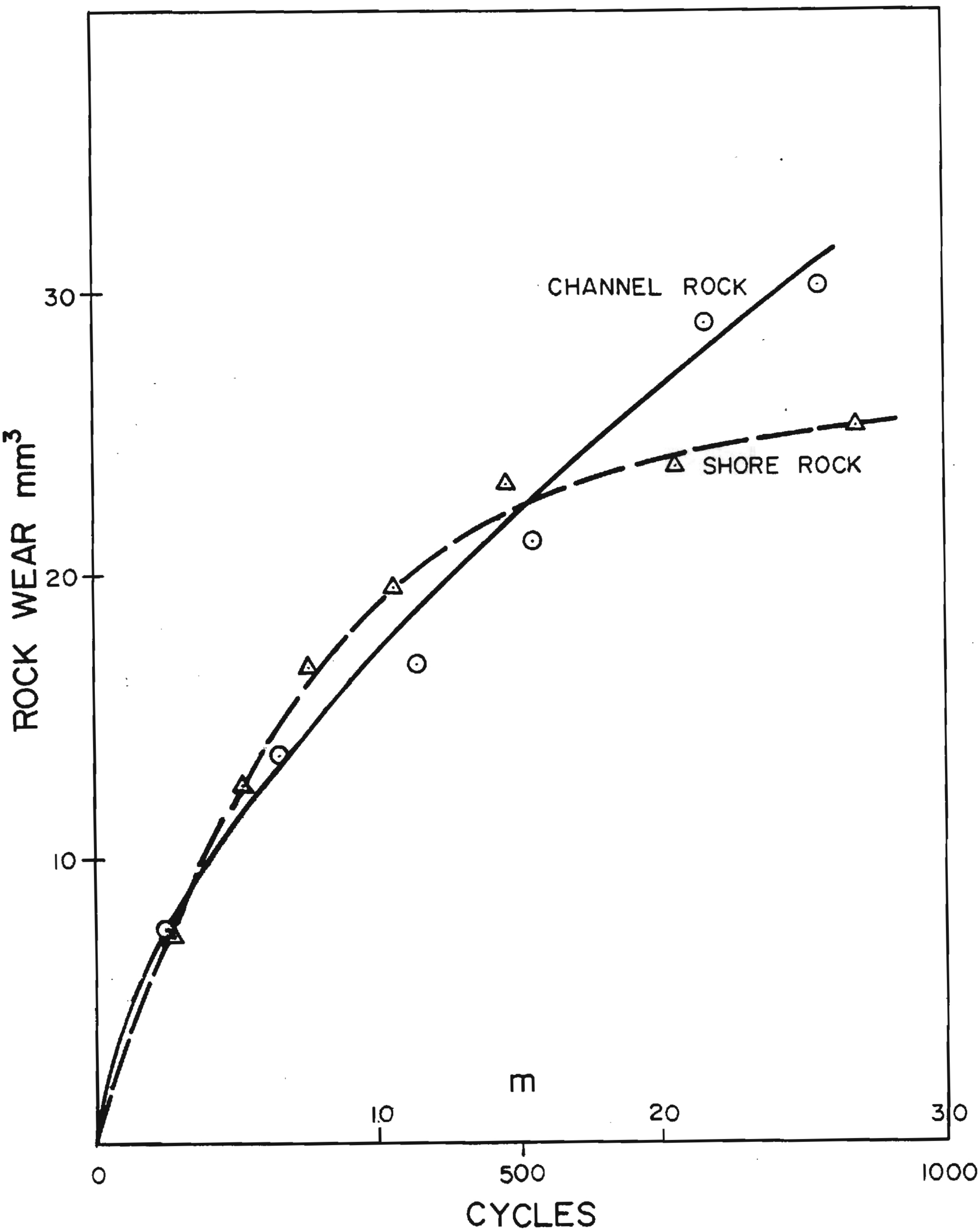

Fig. 21 Wear of rock under same conditions as in Fig. 20.

were abraded under a 9.5 N load. Details of the tester were given in our report for Phase II B. It is the same tester which was used in the seawater abrasion tests but with a different holder for the abrasives.

Results are shown in Fig. 22. Comparison with Fig. 17 shows that the slurry gives a wear rate which is about 3 times faster than abrasion by the solid rock face.

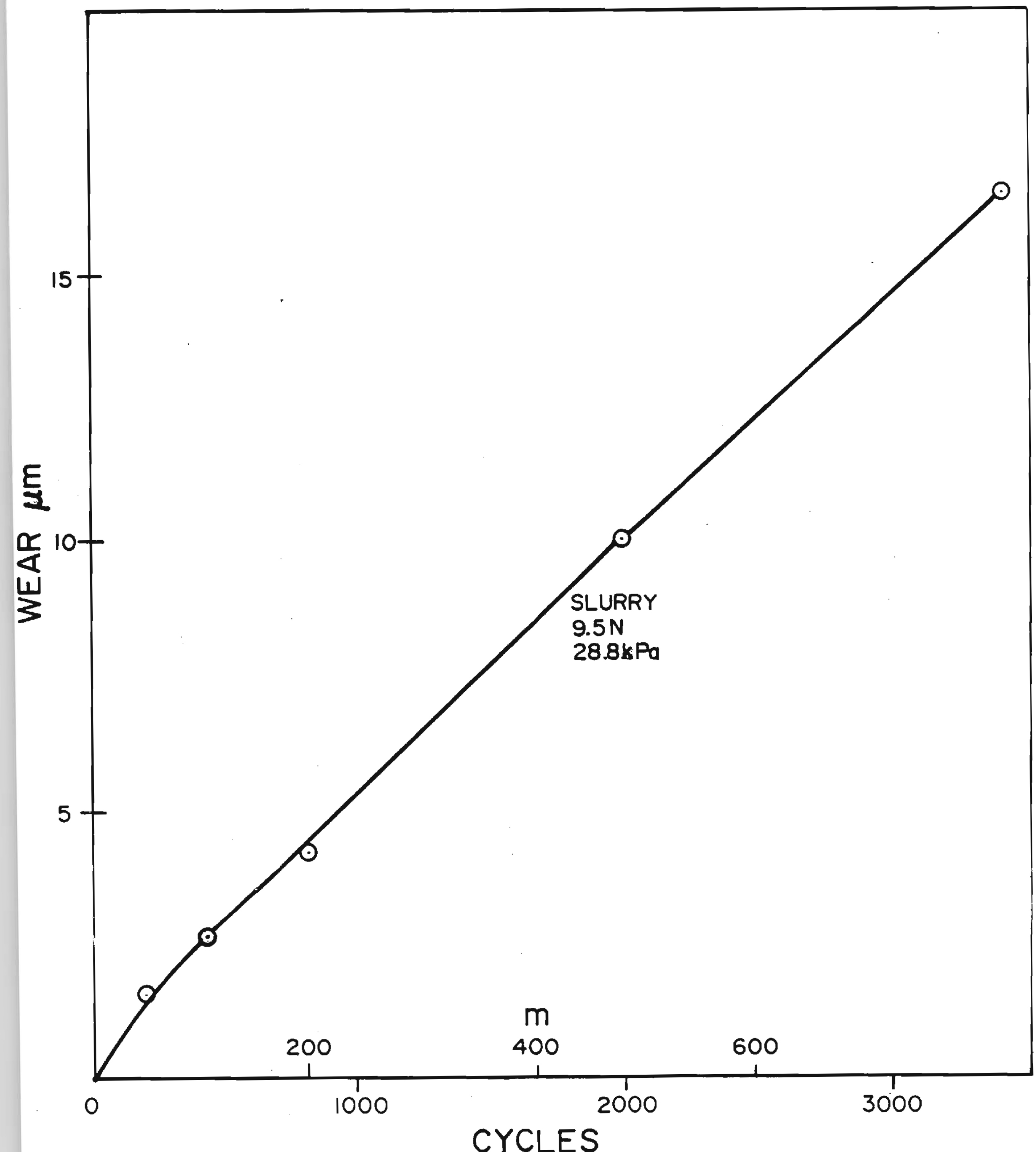

Fig. 22 Slurry abrasion of bare wire in the L-S direction at 28.8 kPa pressure.

VI. CORROSION-EROSION TESTS

If the corrosion film is allowed to build up with time it offers some protection against attack, and the corrosion rate decreases. If the film is constantly removed mechanically, there is a potential for rapid damage. The following tests were conducted in order to evaluate this possibility.

VI a. Erosion by Polyurethane Sheet

34 mm long samples of armor wire which had been completely or partially stripped of coating by chemical means as described above, followed by abrasion by 500 grit SiC paper, were used. They were exposed in stagnant seawater at room temperature in the laboratory, removed periodically and rubbed against a polyurethene sheet to dislodge the corrosion film. The results are shown in Table 5. It is seen that there is no effect of this mechanical damage on the rate of corrosion.

TABLE 5

Corrosion-Erosion by Polyurethene Sheet

Sample	Removal Interval, h	Total Exposure, h	Weight loss, ing
Bare	0.5	8	1.6
	2	8	1.6
	8	8	1.6
Part galv.	1/2	5	0.6
	5	5	0.6

VI b. Erosion by Rock

The abrasion tester used for the seawater and slurry tests was modified to be controlled by a program which switched on the motor each 15 minutes, just long enough to go through one-half abrasion cycle (0.12 m). Tests were run in stagnant seawater for up to one week. The results are shown in Fig. 23. The rocks were sandblasted before the test. The partly galvanized sample had the zinc coating removed on the bottom (contacting) 50% of the 29 mm long sample.

The results show that the nature of the rock has little effect in this case. The greater wear shown by the part galvanized sample is probably due to the direct corrosion of the zinc in the seawater. For the bare wire the wear in a week is about 75 μm. Corrosion of the non-wearing surface is responsible for about 35 μm of that number (using a weekly rate of 1 μm), which leaves 45 μm due to abrasion and corrosion of the contacting surface. Results shown in Figs. 17 and 18 for the same number of cycles and the same contact pressure (but a much shorter period of testing) gave a loss of 3-5 μm. Thus, the corrosion of renewed fresh surface during the week has contributed most of the loss, in the order of 35-40 μm, or 0.1 μm/cycle.

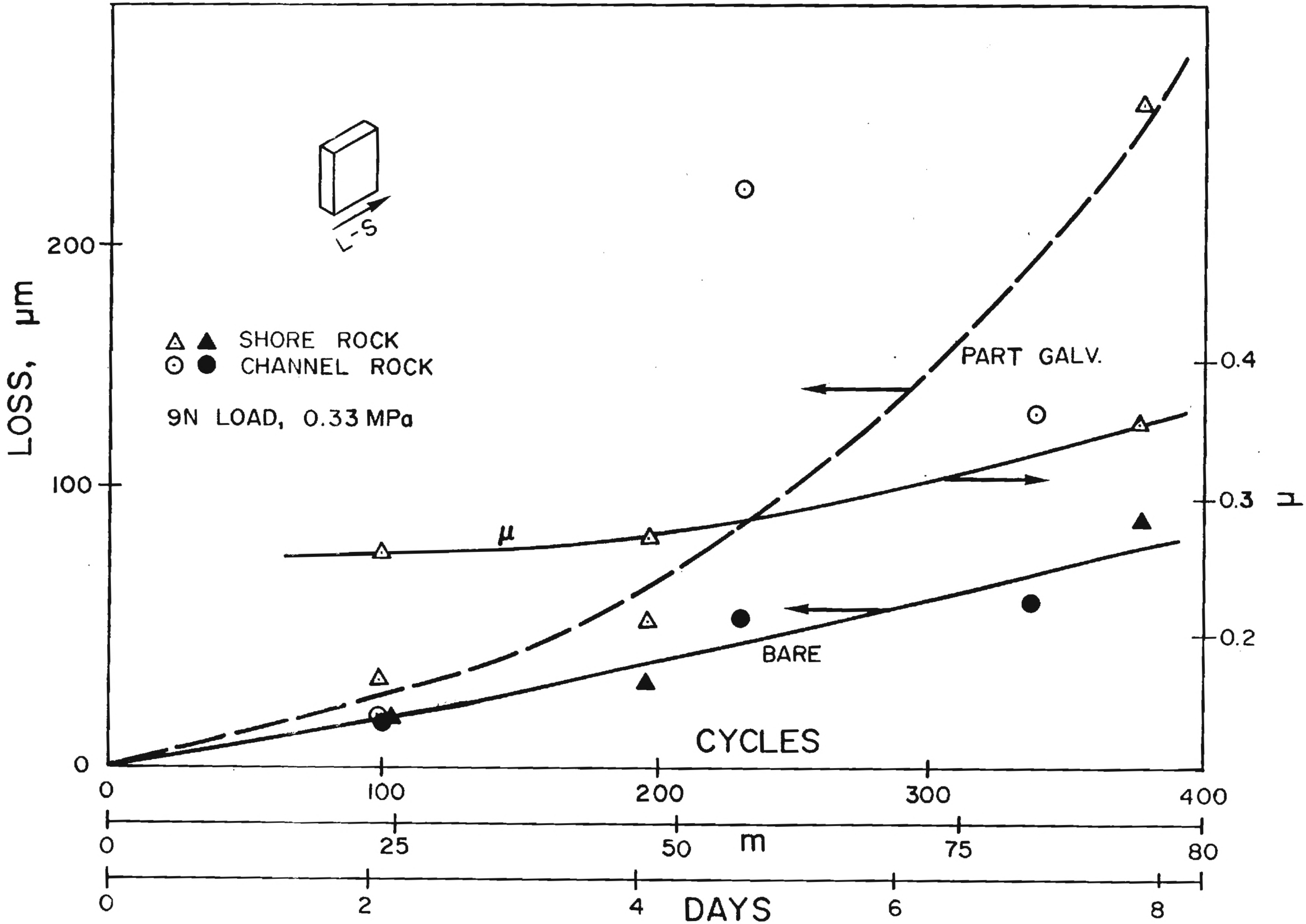

Fig. 23 Corrosion-erosion in stagnant seawater at room temperature.

VII. DAMAGE SCENARIOS

VII a. Straight Corrosion of Undamaged Cable

For an undamaged cable which has the serving and the bitumen intact the sequence of damage may be as follows:

- corrosion of the zinc coating at 6 μm/y for about 15 years,
- corrosion of the steel armor wire at about 40-50 μm/y from all sides for 30 years for complete loss of the first layer of wires. At the same time the second layer would experience some damage, but substantially less,
- even if water penetrates to the lead sheath, it has a straight corrosion life of well over a hundred years.

While the above corrosion rates are for cold water and undoubtedly will increase somewhat at the operating temperature of 60°C, there appears no reason to expect premature failure for this case.

VII b. Straight Corrosion of Damaged Cable

If the polypropylene serving is damaged during deployment the following scenario could be expected:

- corrosion of the front zinc coating at 20 μm/y for 4 years,
- galvanic corrosion of the back zinc coating at possibly 75 μm/y for 1 year,
- corrosion of the steel at 70-100 μm/y for loss of the outer layer of armor wires after about 15 more years, for a total of about 20 years.

The inner layer of armor wire would still be well protected and would corrode at the slow rate discussed in section VII a. Thus, in this case too, there is no reason to expect premature failure.

VII c. Straight Abrasion

If the cable catenary is abraded by rock, the wear will soon remove the polypropylene serving and the zinc coating in the contact zone. The coefficient of friction between armor wire and basalt in seawater is 0.35-0.45. According to Fig. 6 this means a possible combination of excursion and load at the contact point which various linearly from 0.47 m at 0 kg to 0 m at 540 kg.

$$h = 0.47 \left(1 - \frac{L}{540}\right) \tag{9}$$

where h is the excursion in m and L is the contact load in kg.

Some worst-case estimates are shown in Table 6. For three different contact loads the excursion has been calculated from equation (9), the total travel in 30 years under this load is a max. of 37,600 x h. The wear at 3 MPa is obtained from Figs. 17 and 18 as about 200 μm in 722 m for a very short sample. Reducing to 150 μm for a longer sample and using the distances calculated yields values of up to 7 mm of wear.

The contact pressure of 3 MPa was chosen as a probable steady state max. value because the rock tested soon reached that contact stress. If, on the other hand, the rock remains reasonably sharp, with a contact of 5 mm width over 40 mm of the circumference, then much greater wear values are expected, as also outlined in Table 6.

TABLE 6
ESTIMATED WORST-CASE ABRASION

Contact load, kg	500	300	100
Excursion, m	0.035	0.21	0.38
Travel in 30 y, m	3,066	18,396	33,288
Wear at 3 MPa, μm	64.4	3,863	6,990
Pressure on 40 x 5 mm Contact area, MPa	25.5	14.7	5.1
Wear for same, μm	515	19,315	11,883
General corrosion 30 x 2 x 30, μm	1,800	1,800	1,800
Corrosion-erosion 4 x 365 x 30 x 0.05 μm	2,190	2,190	2,190

VII d. Combined Effects

Generally speaking, the bottom rocks are quite smooth and rounded and significantly lower contact stresses than above will generally be expected. At 1.5 MPa for the 100 kg load the 30 year wear is 3,500 μm. To this should be added general corrosion of about 1,800 μm and corrosion-erosion of 0.05 μm per pass, or 2,200 μm. The total then is about 7,500 μm. The radial distance from the outer diameter of the armor wire to the outer diameter of the lead sheath is 14,600 μm.

It would therefore appear that the cable can survive, for its 30-year design life, the envisioned conditions of corrosion, abrasion, and corrosion-erosion.

VIII. ACKNOWLEDGMENTS

We are grateful to the staff at NELH, in particular Dr. Tom Daniel and Mr. Jan War for assistance in the on-shore and off-shore exposure tests; to Miss Tracy Kazunaga for performing many of the measurements; to Mrs. Kaye Fuller for typing the manuscript; and to our contract monitors, Mrs. Lois Nagahara at the Hawaii Natural Energy Institute and Mr. George Kraswick at Parsons Hawaii.

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