POLYESTER MOORINGS RELIABILITY AND DATA UNCERTAINTY ASSESSMENT

Report of a Joint Industry Project Prepared for:

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GLOSSARY

Abbreviation

NBS	Nominal Break Strength
BS	Break Strength
JIP	Joint Industry Project
Y-O-Y	Yarn-On-Yarn
HMPE	High-Modulus Polyethylene
LCAP	Liquid Crystal Aromatic Polyester
OCIMF	Oil Companies' International Marine Forum
WRC	Wire Rope Construction
PSC	Parallel Strand Construction
MNS	Manufacture Nominal Strength
BL	Breaking Load
OTC	Offshore Technology Conference

EXECUTIVE SUMMARY

EQE International, Inc., as contractor for a Joint Industry Project, was tasked to investigate the reliability of polyester moorings based on available data and mechanistic understanding. The project compiled a database of all known tensile fatigue, static break load and elongation data for polyester rope, and used this data set to formulate a tension fatigue life curve.

Background

Due to the promising economic potential for polyester mooring systems, a number of E&P operators are considering the use of polyester moorings in deepwater. Demonstrated confidence in predicted reliability is required for these systems to be employed. In this Joint Industry Project, EQE International was tasked with a threefold objective:

- Integrate all relevant data, including actual, in-service data and test data of various forms, into a single coherent data set.
- Combine this data with the best available physical understanding of degradation to determine a rational basis for collecting future data with the most information.
- Develop best estimates of polyester rope reliability

Approach and Results

Several different approaches were attempted in this project and modified as data analysis results were obtained. Early on, the data were explored using nonlinear, multivariate algorithms to formulate a life prediction model. It was concluded that the variance in the data (and all logical subsets of the data) exhibited variances too great to explain with all hypothesized models. In conclusion, a simple, tension fatigue life model was proposed, fitted, and explored for use in satisfying project objectives.

Conclusions and Recommendations

1. Failure Mechanisms

A comprehensive review of failure mechanisms was performed and the state of knowledge regarding polyester is captured in the table below. This JIP focused on tension fatigue.

Mechanism	State of Knowledge
Abrasion at Termination	Design – protection
Abrasion due to Sediment within Rope Body	Operational (Installation) Issue
Axial Compression Fatigue	Further Study
Creep Rupture	Include
Fishbite Damage	Further Study
Heat Build-up	Design Issue
Hydrolysis	Further Study
Installation Damage	Operational Issue
Material or Fiber Fatigue	Include
Splice Slippage at Termination	Design – limiting strength
Ultraviolet Light Exposure	Design – no exposure

2. ***Polyester Database*** From review of all the data made available to EQE by participating JIP sponsors, a database was developed that compiled results from tension fatigue tests, static break load tests and load extension tests together in a single comparable format. As much of the data used to assemble this database was generated for specific purposes and not necessarily to employ in life prediction models, it was expected that there would be significant variance in model predictions.

3. ***Recommendations for Future Testing***. A number of recommendations regarding future testing, from the viewpoint of the reliability engineer, were concluded from this study:
   - Documentation of the complete rope specimen test history (including recovery periods between tests) is crucial for polyester ropes.
   - Estimate and record the uncertainty associated with each rope test measurement
   - As often is practical, test polyester rope specimens to failure
   - Provide abrasion protection at the eye termination of all rope specimens
   - Accurately document rope specimen length
   - Measure and document the bedding-in process
   - Develop standardized procedures and guidelines for rope specimen bedding-in
   - Test specimens that have terminations that are similar to those expected to be used in field.

4. ***Strain-to-Failure Model.*** A Strain-to-failure model was postulated in this work that appears to have some merit based upon data analysis results. Further investigation into the physical and mechanistic plausibility of such a theory should be undertaken. The predictive task of this project culminated in a simple fatigue life model, using a collection of data collected under dissimilar conditions and for different purposes. Being dependent upon this database, the predictive model is accompanied by substantial (much greater than steel mooring systems) uncertainty in fatigue life estimates. Any use of this model and the associated parameter estimates should be used with due consideration to the application-specific features of the user.

5. ***Regression Issues.*** In developing simple regression fits to the TN curve for polyester, it was discovered that a substantial amount of analogous work has been published for wire rope treating the stress range as the random variable, which is incorrect. Fatigue life (cycles) should be the random variable in analyzing this type of data. For relatively large detests that could be characterized as having moderate variance, improper regression of S on N (i.e. treating S as random) does not introduce a large error. However, for this database of polyester rope test data, there is a significant difference between the results obtained by treating S random vs. treating N random.

6. ***Sample Size Sensitivity.*** In addition to the regression issue, this data set for polyester rope also exhibited an increasing (non-constant) variance with increasing N. This was modeled using standard techniques and generated more accurate confidence intervals than the typical constant variance approach. The data set began with 62 data points, and after removal of inconsistent data (from an engineering point of view), resulted in only 17 points. Concern over the uncertainty in predictions based upon this small sample size motivated sensitivity testing on number of observations. Predictions of confidence intervals were made using a hundred times the number of data points, yet with the same coordinates. Only insignificant changes in the upper and lower bounds result from the increase of the number of points, which indicated that the scatter in the data is the main factor controlling the uncertainty in predicting fatigue life.

7. ***Addressing Runouts.*** Three of the high cycle data points were runouts. The sensitivity of predicted results to the mathematical treatment of these runout points was investigated in two ways.

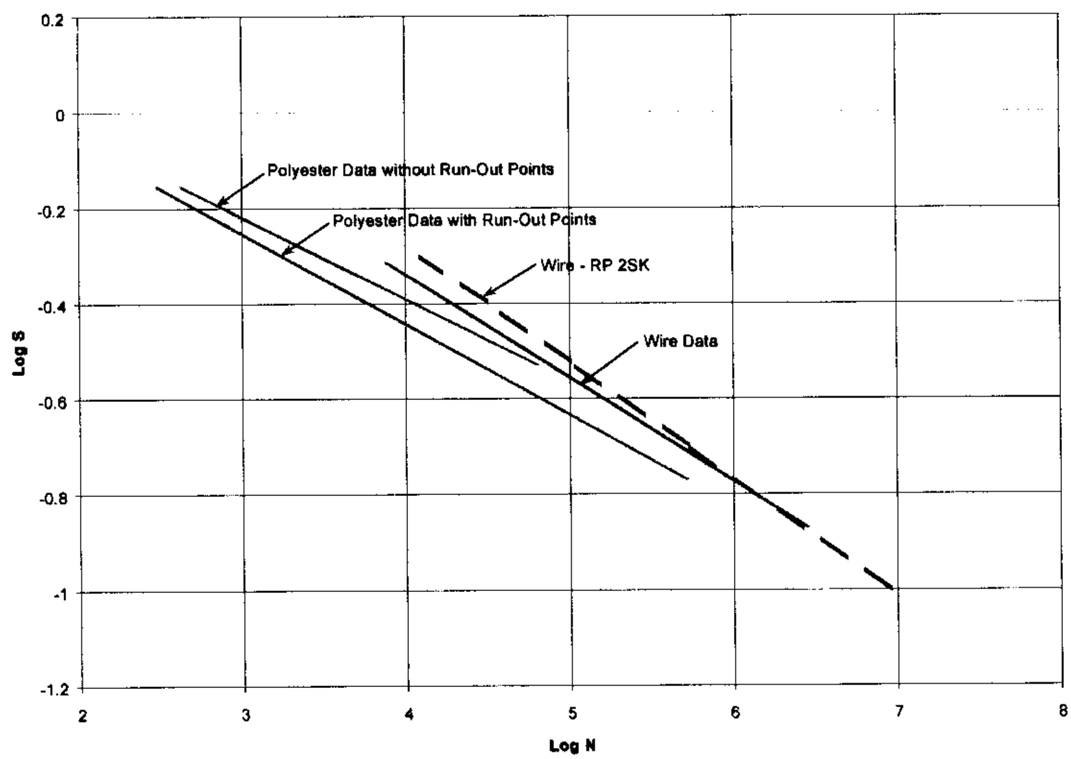
   - First, the N coordinate (life) of the run-out data points was increased by an order of magnitude. This resulted in an increase in predicted fatigue life of more than a factor of five at one million cycles.

- Second, the run-out points were removed altogether. The resulting effect of removal of the runouts was a further increase of the lower bound line from the original calculation by an additional factor of five over the extension of the runouts, of ten times the original lower bound.

This clearly implies that the low stress—high cycle fatigue experiments are not behaving in the same manner as the high stress low cycle data. The effect of including them in the same data set is to predict decreasing fatigue life with lower stress ranges.

8. ***Comparison to Wire Rope.*** Polyester rope fatigue life was compared to wire rope as shown in Figure ES.1. Polyester results are shown for lines obtained with and without run-out points.

Figure ES.1– Wire vs. Polyester S-N curve – Variable Variation



The following observations may be drawn from the above figure:

- Polyester rope is predicted to have lower fatigue life than the wire rope over the range of the curve fit (range of data).

- When removing the polyester run-out data points, an S-N curve predicting higher fatigue life is obtained.

- Comparing the polyester curve with run outs to the RP 2SK design curve, there is a factor of from 7x at high stress range / low cycle fatigue to 5x at low stress range / high cycle fatigue. Although it must be noted that practical polyester mooring systems will not be designed to experience high stress range loading.

- It is ***not*** recommended to extrapolate the fatigue life curves far beyond the range of data used to obtain them. The curves shown in Figure 5.2 are plotted to represent these limits.

Upon first view of the resulting polyester vs. steel fatigue characteristics, it appears that the fatigue life of polyester will always be less than steel wire rope. This is true for the case of like stress ranges. However, since the modulus (EA) of polyester is much greater than the modulus of steel, the motion-induced stresses in a polyester rope in deepwater taut mooring applications will be lower than that for steel and polyester could take on superior performance to a similar steel system.

1.0 Introduction

1.1 Background and Objectives

Due to the promising economic potential for polyester mooring systems, a number of E&P operators are considering the use of polyester moorings in deepwater. One fundamental concern that offsets the performance of the polyester mooring is there is inadequate field experience on the polyester lines in this type of application.

Johnson and Hooker of Marlow Ropes stated the issue succinctly in a recent paper[1]: "The key word is confidence. The industry must gain **confidence** in the **reliability** of synthetic fibre moorings. There must be confidence in the **predicted** behavior of these mooring systems. *[Emphasis added]"*

Selected experience has been collected and shared among the deepwater offshore community[2,3]. However, the development of this knowledge can be characterized as stepwise, test-and-install advancements. The process lacks any formal estimation of risk, and furthermore, there is no overall framework for systematic data collection to support long term life predictions and associated uncertainties.

Many large E&P operators are willing to participate in, and conduct specific field tests. The question is; *what testing is most crucial to gaining confidence in long term reliability?* Answering this question, prior to conducting the testing, necessitates an innovative modeling approach. This proposal addresses the two emphasized points in Hooker and Johnson's comment – gaining ***confidence*** in the ***reliability*** synthetic moorings

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[1] Hooker, J. and C. M. Johnson. 1997. "The Specification, Manufacture and Testing of Synthetic Fibre Tethers for Offshore Mooring Applications," Second Annual Two Day Conference on Continuous Advances in Mooring & Anchoring, Aberdeen, Scotland, UK, June 2-3.

[2] DelVecchio, C. 1997. "Mooring Systems – Recent Developments in Brazil," Second Annual Two Day Conference on Continuous Advances in Mooring & Anchoring, Aberdeen, Scotland, UK, June 2-3.

[3] Dove, P.G. S., T. M. Fulton, and P. V. Devlin, 1997. "Installation of DeepStar's Polyester Taut Leg Mooring," OTC 8522, Proceedings of the 29th Annual Offshore Technology Conference, May 5-8, Houston TX.

1.2 Scope of Work

This Joint Industry Project Goal is threefold:

- Integrate all relevant data, including actual, in-service data and test data of various forms, into a single coherent data set.
- Combine this data with the best available physical understanding of degradation to determine a rational basis for collecting future data with the most information.
- Develop best estimates of polyester rope reliability

2.0 POLYESTER ROPE FAILURE MECHANISMS

One of the first steps in the data gathering stage of the project was to identify failure mechanisms of a polyester mooring line. The failure mechanisms were derived during JIP participant meetings and from available documents and test data. The identified failure mechanisms are discussed below. Many of these failure mechanisms were excluded from the rope life prediction models because they were associated with random events or could be eliminated by a proper mooring design.

2.1 Hydrolysis

Polyester is nearly hydrophobic, but there is evidence that polyester will loss some strength over time when immersed in water due to hydrolysis. Hydrolysis is the process of decomposition involving the splitting of a bond and the addition of the water hydrogen. This type of decomposition causes the polyester fibers to slowly become more brittle and thus causes a reduction in rope strength. The effects of hydrolysis on polyester fibers are shown in Table 2.1 [27].

Table 2.1 - Hydrolysis Effects on Polyester Fibers

Temp.	Time for Strength to Fall to:		
deg C	90% BL	70% BL	50% BL
0	6310 years	25119 years	63096 years
20	200 years	794 years	1995 years
40	10 years	50 years	100 years
60	290 days	3 years	9 years
80	29 days	145 days	258 days
100	3 days	18 days	46 days

It should be noticed that the strength loss due to hydrolysis under anticipated mooring line temperatures is expected to be minimal. Therefore, it was decided that this failure mechanism would not be included in the proposed rope life models.

2.2 Creep Rupture

Creep is a phenomenon in which a material develops additional strains over a period of time. Creep rupture occurs when the material fails due to continued elongation or accumulated strain. The amount of creep in a material is dependent upon applied load and temperature. For polyester ropes, this type of failure has generally been considered a factor at high cyclic load ranges and high mean tensions (usually above 60% - 70% of nominal break strength) [6]. Such high tensions are not usually expected in a typical taut leg polyester mooring design. If a safety factor of 2.0 against rope failure were assumed during the extreme environmental condition, the maximum tension would only be 50% of the nominal break strength. This is below the tensions usually associated with this type of failure.

Based on some of the literature and the expected maximum tension loads, it might seem that this type of failure mechanism could be disregarded. However, some of the available test data indicate indirectly that this mechanism may be a concern at lower load ranges (40 - 50% NBS) in the termination regions where the rope tends to heat up internally due to fiber-to-fiber abrasion and externally due to pin-to-rope abrasion at the eye. Additionally at the terminations, jackets are usually present which are meant to protect the rope, but they may also reduce the rate of heat loss. This heating combined with the moderately high-tension loads may increase the risk of creep rupture.

Because of this and the fact that much of the available test data (primarily fatigue tests) are run at high tension ranges which cause this type of failure, creep rupture was accepted as a mode of failure that should be included in any proposed rope life models.

2.3 Splice Slippage at Termination

Splice slippage is a concern, especially with the latest rope constructions, where new state-of-the-art splices are being developed. Splice slippage was observed during many of the polyester rope fatigue and strength tests conducted in the Fibre Tethers 2000 JIP and in the Norsk Hydro JIP. In some cases the rope actually failed due to the slippage of the splice.

This type of failure, although a concern, was not included as a failure mechanism in the rope life models. Generally, splice slippage problems are attributed to design flaws in the splice. Most of the splice slippage problems in the two JIPs were attributed to the problems with the rope manufacture's splices. Although it is assumed that this problem can be overcome by proper design and installation and the fact that it cannot be modeled accurately at this time, it was not included as a failure mechanism in any proposed rope life models.

2.4 Abrasion at Termination

Typically, failure due to external abrasion (i.e., abrasion between the eye and the pin) should not occur if adequate protection has been provided at the termination. This type of failure can be overcome by ensuring the termination design provides ample protection against external abrasion.

In spite of the fact that abrasion damage is dependent on the design, this type of failure still persists to be problem, as shown in the Fibre Tether 2000 JIP. Of the 14 tension-to-tension fatigue tests conducted on 5 and 120 tonne polyester ropes with looped and spliced termination 9 failed at the termination. This means that most of the fatigue test results were not measuring the fatigue characteristics of the rope, but rather the abrasion resistance at the terminations. Tests using other types of terminations (e.g., resin sockets and barrel and spliced) exhibited even higher end failures rates.

Since this type of failure mechanism is associated with the termination design and the abrasion protection between the eye and pin, it was not included as a failure mechanism in the rope life models. However, it should be noted that any life prediction models developed using the available polyester rope fatigue test data, like the Fiber Tether 2000 tests, will inevitably be influenced by this mode of failure.

2.5 Abrasion Fatigue Due to Sediment within Rope Body

During the installation of a standard steel catenary mooring, much of the line length will come in contact with the seabed. Conversely, it is not recommended that a polyester rope come in contact with the seafloor at any time. If the polyester rope is allowed to rest on the seabed small abrasive particles may enter into the rope body. This is especially a concern during installation when the ropes are under little or no tension.

These abrasive particles may wear down or create cracks in the polyester fibers, and thus overtime reduce the life of the rope. Yarn-on-yarn (Y-O-Y) abrasion tests with the presence of sediment have been conducted on polyester fibers. The test results show a dramatic reduction in life [25]. The Norsk Hydro JIP conducted yarn abrasion tests on specimens that were exposed to different size salt, silica, and sediment. The results of the tests showed that when compared to the control sample all of the abrasive material gave about the same order of magnitude reduction in Y-O-Y abrasion life when tested under the same concentration. This infers that the type of abrasion media may not be the key property in determining abrasion life, since there is a large difference in mechanical properties between the tested particles. These tests also indicated that the smaller particles tended to cause more damage, but this may be due to the smaller particles being able to penetrate deeper into the yarn.

These tests show that abrasion due to ingress of particles is a concern and should be addressed in the mooring design and installation procedures. This type of degradation can be avoided by proper mooring design and installation procedures, which prevent the rope from getting in contact with the seabed and from drying after Emerson in seawater), it was not included in any of the proposed rope life models.

2.6 Ultraviolet Light Exposure

This type of degradation is a concern for all synthetic ropes (HMPEs, polyesters, aramids, etc), but it is only a factor when the rope is above the water surface for an extended period of time. For a polyester mooring design, a typical leg will generally consist of chain or steel wire at the fairlead (near the surface) and at the touch down point (at the mudline) with the polyester rope between these steel sections.

Based on this, it is safe to assume the mooring leg will be designed such that the polyester rope will never touch the seabed or come in contact with the fairlead. Based on these assumptions, the polyester section of the mooring line would never be above the water surface and thus will not be exposed to UV rays. Therefore, this type of degradation was not included in any of the proposed rope life models.

2.7 Installation Damage

This type of failure is very difficult to account for in a rope life model. This is particularly true since there are few statistics on damage to synthetic mooring lines occurring during installation, primarily because there are very few mooring systems currently in operation that use synthetic ropes. The likelihood of this type of failure occurring is dependent on the rope handling procedures, and thus cannot be accounted for in a rope life model. Obviously, care must be taken to assure no damage is sustained during the installation procedure, plus adequate checks and inspections must be conducted during and after installation to assure no rope damage occurred.

2.8 Fishbite Damage

There is a surprising amount of literature on these types of failures. One notable reference is the Woods Hole Oceanographic Institute (WHOI) report entitled "Deep Sea Mooring Fishbite Handbook" [28]. This document summarizes their experience with fishbite failures of deepwater moorings used to deploy oceanographic instruments. Typically, these moorings are located in water depths greater than 2000 meters and consist of small diameter ropes (around ¾" to 1-½" diameter). The National Data Buoy Center (NDBC) also has published literature that documents their experience with fishbite occurrence in the Gulf of Mexico [2]. NDBC have three buoys in the Gulf of Mexico in about 10000 feet of water. The diameter of these synthetic-mooring lines is approximately 1-¾". They have had 5 failures attributed the fishbites at these three sites, averaging a 12 percent annual probability of this type of failure.

Although, this data tends to indicate that this type of failure may be a concern for a permanent polyester mooring system, there is no supporting data that indicates this is the case for larger diameter ropes (e.g. 6" to 10" diameter). For example, Shell has deployed a 4" diameter polyester supply boat mooring in 1000 feet of water and there has not been any evidence of this type of damage since it's installation in May 1992. Due to the lack of any evidence indicating that this type of failure is a concern for large diameter ropes, it was decided that fishbite damage would not be included in any proposed rope life model.

2.9 Axial-Compression Fatigue

Axial-compression fatigue or buckling fatigue is a failure mechanism that occurs when rope fibers are subjected to repetitive compression-tension loads. This type of fatigue is very severe since the rope fibers buckle and bend under the compressive loads. In some cases the fibers become tangled and twisted (e.g. birds nest) greatly reducing the rope's capacity to carry tension loads.

In the Fiber Tethers 2000 JIP, buckling fatigue tests were conducted on Aramid, HMPE, and polyester yarns. In this study, the polyester yarns outperformed all other synthetic fibers with a retain strength of no lower than 89% MNS for 11000 compression cycles. The HMPE fibers were a close second with a retained strength no lower than 81% MNS for up to 11000 compression cycles, and the aramid yarn samples were last with a retained break strength as low as 19% MNS for 11000 compression cycles.

This data shows polyester yarns tend to be more robust under compression or buckling loads than other synthetic rope fibers, but there is limited data on the performance of full-scale ropes under these conditions. Furthermore, it is well known that compression loads are not good for any type of steel or synthetic rope system, and thus the mooring systems are usually designed so that no compression will occur during the life of the system. Therefore, this type of fatigue failure was excluded for the proposed life model.

2.10 Heat Build-Up

For this mode of failure, the rope is assumed to heat up enough to cause some of the fibers to melt. As these fibers melt, the tension loads are shed to other fibers in the cross-section and the rope eventually fails. This mode of failure becomes a greater concern as the rope size increases.

The ability of the rope to dissipate heat increases proportionately to the radius, while the capacity to generate heat increases proportionally to the radius squared. Additionally, other modes of failure may also influence rope life at elevated temperatures. These include hydrolysis and creep rupture, both of which are very sensitive to temperature, as mention in the previous sections.

Unfortunately, there is only limited data available on heat build-up in full-scale ropes, and most of this data comes from the Norsk Hydro JIP tests. These tests measured temperature increases within polyester and aramid ropes at key locations (i.e., at the back of the eye, within the splice, at the tail of the splice, and in the mid-length). Some of the key observations from this study included the following:

- Construction dependence on heat build-up is contingent on whether or not water is allowed to penetrate the rope. The parallel strand construction rope generally allows more water penetration that wire rope construction and thus tends to have lower heat build-up.
- Less heat is generated in the splice region than the clear rope. This is particularly noticeable as the strain rate (load range) is increased.
- Temperatures at the eye of the rope tend to be the highest. This may be due to the fact that the rope becomes effectively dry due to the contact pressures between the pin and rope.
- Under high strain amplitudes and sine wave loading the eye temperatures are very high, but under stochastic loading conditions (more realistic loading conditions) temperature in this region does not seem to be a problem.

Based on these results, heat build-up may be a cause of rope failure especially under high load ranges. Since much of the available fatigue test data is run under extreme cyclic conditions (i.e. sine wave loading at high load ranges) this type of failure mechanism should be included in any proposed life model if the model is to be developed using available test data.

2.11 Material or Fiber Fatigue

This type of failure is common in steel wire systems and is also a concern with all of the synthetic fibers. Testing conducted on polyester ropes, such as axial compression tests (See section 2.9) and tension-to-tension fatigue tests, show the material to be very robust and quite forgiving under very severe loading conditions. For most of the available fatigue tests on polyester ropes that have been cycled to failure there has been little evidence indicating that the mode of failure was due to material fatigue. However, this may be because most of the fatigue tests were subjected to very severe loading conditions due to time and money constraints. At these severe loading conditions (i.e. high load range, high mean tension, and high frequency), polyester rope failures are usually due to other modes of failure, such as creep rupture, abrasion at the terminations, or internal heat build-up. Under more mild loading conditions, material fatigue may be the mode of failure over the life of the rope. Because of this material fatigue should be included in any proposed life prediction models.

3.0 DATA BASE DEVELOPMENT

The second task in developing life prediction models and the associated uncertainty is to gather all available test data on polyester ropes. During this task, it became evident there were only limited data available. Table 3.1 summarizes the available test data. In reviewing this table, it should be noted that most of the tests were structured for material screening. As a result, most of the tests procedures included not only polyester, but also aramids, HMPE's, LCAP's, etc. Since the focus of most of these tests was not solely on polyester ropes, but rather on all available synthetic fiber ropes that may be used in marine applications, the data on polyester ropes was not always complete or easy to use for purposes related to this study. In many cases, only the variables that were deemed important in comparing different synthetic rope performances were measured. An example of this would be measuring only the applied cyclic load range and the corresponding number of cycles to failure, but taking no elongation or stiffness measurements during the test.

All of the documents reviewed for this study have been provided in Section 8.0 - References. These documents vary greatly in content, providing information on test data, proposed rope life models, mooring feasibility studies, and actual case studies. For this JIP, only key documents that contained actual test data were used to develop life-prediction models for polyester ropes. These documents are discussed in the following sections.

3.1 Fibre Tethers 2000 Joint Industry Project

This study's key objective was to develop selection procedures for synthetic fiber ropes and begin the development of tension-tension endurance data for the different synthetic materials, construction, and terminations. The materials, investigated in this study, included ropes constructed of Aramid, HMPE, Polyethylene, Polyester, LCAP, and Carbon Fiber. The rope construction types included PSC, WRC, parallel yarn, carbon strand, and braid-on-braid. Three termination types were also used in the study. They included resin sockets, barrel and spike, and looped and spliced. All of the tests were run on wet ropes.

Table 3.1 - Available Polyester Rope Test Data

SOURCE OF DATA	TESTS CONDUCTED	MEASURED VARIABLES	TESTING OBJECTIVES
Fibre Tethers 2000 JIP	cyclic tension-tension fatigue tests on 5 and 120 tonne ropes	number of cycles to failure, load range, frequency, mean tension, pin-to-pin elongation (select tests), pin-to-pin stiffness (select tests)	1) Begin to develop endurance curves for various types of synthetic ropes. 2) Determine if scaling effect due to rope sizes. 3) Compare performance of termination types. 4) Compare performance of different types of synthetic ropes.
	break strength tests on 5 and 120 tonne ropes	pin-to-pin elongation (select tests), pin-to-pin stiffness (select tests)	1) Compare actual break strength to manufactures nominal break strength values. 2) Compare performance of termination types. 3) Compare performance of different types of synthetic ropes.
	yarn creep tests	applied load, elongation, time to failure	Compare creep performances of different types of synthetic yarns.
	yarn buckling fatigue tests	number of cycles to failure	Compare axial compression performances of different types of synthetic yarns.
	yarn-on-yarn abrasion tests	number of cycles to failure	Compare internal abrasion performances of different types of synthetic yarns.
	external abrasion tests on yarn	number of cycles to failure	Compare external abrasion performances of different types of synthetic yarns.
Norsk Hydro JIP (Phase 1)	cyclic tension-tension tests on 250 tonne polyester ropes	rope temperature, load range (strain amplitude), mean tension, frequency, stiffness (pin-to-pin and rope), elongation (pin-to-pin and rope)	1) Investigate rope core heat build-up. 2) Investigate influence of frequency, load range, and mean load on rope stiffness. 3) Investigate influence of frequency, load range, and mean load on rope elongation.
	retained break strength tests on 250 tonne polyester ropes	pin-to-pin load/elongation	Investigate retained break strength of cycled ropes to manufactures nominal break strength values.

SOURCE OF DATA	TESTS CONDUCTED	MEASURED VARIABLES	TESTING OBJECTIVES
	yarn-on-yarn abrasion tests w/particle intrusion	number of cycles to failure, sediment particle size, sediment particle types	Investigate fatigue life of polyester yarns with particle intrusion
Norsk Hydro JIP (Phase 2)	cyclic tension-tension tests on 7500 and 15000 tonne polyester ropes	rope temperature, load range (strain amplitude), mean tension, frequency, stiffness (pin-to-pin and rope), elongation (pin-to-pin and rope)	1) Investigate rope core heat build-up. 2) Investigate influence of frequency, load range, and mean load on rope stiffness. 3) Investigate influence of frequency, load range, and mean load on rope elongation.
	break strength tests of cycled and new 7500 and 15000 tonne polyester ropes	pin-to-pin load/elongation	Investigate retained break strength of cycled ropes and compare to new rope break strength values.
O.C.I.M.F. Hawser Standards Development Program - Trial Prototype Rope Tests	Cyclic load tests on 80 to 100 kip synthetic ropes (approx. 2" dia.)	number of cycles to failure, load range	Compare performance of different types of synthetic ropes and rope constructions.
	wet and dry break strength tests on 80 to 100 kip break strength synthetic ropes	break strength, load/extension to 50% break strength	1) Compare wet and dry break strength values. 2) Compare break strength performance of different types of synthetic ropes and constructions.
	external abrasion tests on ropes	retained break strength	Comparison of external abrasion performances for different types of synthetic ropes.
National Engineering Laboratory (NEL) - Cyclic Testing of Continuously Wetted Synthetic Fiber Ropes	Cyclic tension-tension fatigue tests on 10 and 100 tonne synthetic ropes	number of cycles to failure, load range, frequency, mean tension, abrasion at termination	1) Develop endurance curves for various types of synthetic ropes. 2) Compare abrasion performance at eye termination for different types of synthetic ropes. 3) Compare abrasion performance at eye termination for different types of cloth protection.

SOURCE OF DATA	TESTS CONDUCTED	MEASURED VARIABLES	TESTING OBJECTIVES
Enka Research Institute - Dynamic Behavior of Synthetic Ropes	Cyclic tension-tension fatigue tests on 5 tonne synthetic ropes	number of cycles to failure, load range, fiber finishes	1) Develop endurance curves for various types of synthetic ropes. 2) Investigated fiber affect of fibers finishes on synthetic rope fatigue
	wet and dry break strength tests on 5 tonne synthetic ropes	break strength, retained break strength, elongation	1) Compare wet and dry break strength values. 2) Compare break strength performance of different types of synthetic ropes and constructions. 3) Investigated retained break strength of cycled ropes.
Naval Civil Engineering Laboratory (NCEL) - Tension and Bending Fatigue Test Results of Synthetic Ropes	Cyclic tension-tension fatigue tests on 120 kip synthetic ropes	number of cycles to failure, load range, mean tension, frequency, pin-to-pin elongation	1) Develop endurance curves for polyester and kevlar ropes. 2) Compare performance of different types of synthetic ropes.
	break strength tests of cycled and new 120 kip polyester ropes	break strength, retained break strength, elongation	1) Investigate break strength performance of different types of synthetic ropes and constructions. 2) Investigated retained break strength of cycled ropes.
	bending fatigue tests on 120 kip synthetic ropes	number of cycles to failure, rope diameter to sheave diameter	1) Compare bending fatigue endurance for polyester and kevlar ropes. 2) Investigate influence of sheave diameter on fatigue endurance.

In addition to the testing, the study also ran analysis on two case studies, an FPS and a TLP, for both harsh and mild environments. The objective of the analyses was to determine the feasibility of the synthetic fibers being investigated in this project for these marine applications.

The final report for this study was issued in February 1995 and documented over 4 years of testing. The report was to remain confidential to the JIP participants for a period of 2 years from this date.

3.1.1 Tests Conducted in the Study

This study set out a very aggressive testing program with rope specimens for 44 different combinations of materials, construction, and terminations tested at the 5 tonne scale. Each of rope specimen combinations included both break strength and tension-tension fatigue tests.

For the 120 tonne scale tests, three rope specimen sets were manufactured and tested. These tests were primarily conducted to assess the influence of rope size on rope properties.

In addition to the rope tests, yarn tests were conducted. The yarn tests investigated creep, buckling, Y-O-Y abrasion, and external abrasion of all of the marine fibers chosen for the study. These tests are summarized in Table 3.1.

3.1.2 Polyester Rope Tests

For the polyester ropes, a total of 41 tension-tension fatigue tests were conducted on the 5 tonne ropes. Of these 41 fatigue tests, 17 were conducted on ropes with resin socket terminations, 10 were conducted on ropes with barrel and splice terminations and 14 were conducted on ropes with looped and splice terminations.

The ropes were cycled at a frequency varying between 1 to 2 hertz. The peak-to-peak load ranges were varied between 30% to 70% MNS, and for all tests the mean load was 40% MNS. For all of these tests the rope was cycled to failure or 940,000 cycles, which was considered run-out. The overall length of the polyester samples was 2.2 meters.

Six tension-tension fatigue tests were also conducted on 120 tonne samples. All of these samples had looped and splice terminations. These ropes were tested at frequencies between 0.1 and 0.3

hertz. The peak-to-peak load ranges varied between 20% MNS and 70% MNS with a mean of 40% MNS for all but one of the runs. For all of these tests the ropes were cycled to failure or to run-out (940,000 cycles). The overall length of the samples was 5.8 meters.

In addition to the fatigue tests, break strength tests were conducted on new ropes. A set of three break tests was carried out for each construction/termination combination that was run in the fatigue tests. There were a total of nine different rope construction/ termination combinations run in the 5 tonne fatigue tests. For each of these combinations three break strength tests were conducted giving a total of 27 polyester break tests. Three break strength tests were also conducted on the 120 tonne ropes.

In addition to the rope tests, creep, buckling fatigue, external abrasion, and Y-O-Y abrasion tests were run on polyester yarn samples.

3.1.3 Measurements Taken on Polyester Ropes

Prior to running the fatigue and break strength tests all samples were loaded once up to 60% MNS. During this single bedding-in cycle no elongation measurements were taken.

For the 5 tonne fatigue tests, the frequency and mean tensions were the same for all runs. The key objective of the fatigue runs was to measure the effect of load range on the number of cycles to failure. Generally, four to six runs were conducted for each rope construction/termination combination with each run set at a different load range. The results from these fatigue runs were used to generate endurance curves for each combination. This in turn was used to compare endurance performance between the nine different rope construction/termination combinations. No elongation measurements were taken during any of the 5 tonne rope fatigue tests.

The 120 tonne rope fatigue tests were conducted in the same manner as the 5 tonne, with the only exception being that elongation measurements were taken for three of the fatigue tests.

For the 5 tonne break strength tests only the break strengths were reported. The elongation for these tests was not shown due to the splice slippage problems that occurred during these tests. The 120 tonne rope load/elongation curves were also not documented in the final report, but at Shell's request, TTI provided these data. Splice slippage was observed in all of these break tests.

3.1.4 Key Findings and Observations

Some of the key findings from the study are summarized below.

- Resin Socket terminations tended to have longer fatigue life than looped and spliced or barrel and spike, but this may be because the looped and splice specimens did not have adequate abrasion protection between the eye and pin (based on 5 tonne tests).
- Parallel yarn and parallel strain rope construction had slightly better fatigue life than wire rope construction (based on 5 tonne tests).
- The break strength tests showed little difference in the strength performance between the three rope constructions, parallel yarn, parallel strain, and wire rope (based on 5 tonne tests).
- The best over all terminations are provided by looped and splice terminations. This type of termination gives superior strength and comparable fatigue life relative to the resin socket and barrel and spike terminations (based on 5 tonne tests).
- Fatigue lives appear to be higher for polyester ropes than for comparable steel wire ropes. Most importantly, the 95% lower bound fatigue lives of the polyester ropes with looped and splice terminations tested during this study exceed that of steel wire ropes of comparable strength.
- The FPS case studies found the polyester ropes to be well suited for both the harsh and mild environments. For the TLP study, polyester ropes did not appear to be suitable for use in the vertical mooring tethers due to the materials low specific stiffness.
- Polyester, when compared to aramid, HMPE, or LCAP fibers, was found to be superior in axial compression or bending fatigue. Thus polyester tends to be a more forgiving and robust material for many of the predicted marine applications.

3.2 Norsk Hydro Joint Industry Project - Phases 1 and 2

The study was initiated because of the general lack of data and knowledge on characteristics and behavior of full size synthetic rope under offshore conditions. Many questions regarding heat build-up and residual rope properties for large diameter rope had not been answered during previous test programs. Therefore, in an attempt to gain knowledge on full-scale rope behavior the study conducted a series of tests on medium to large-scale diameter ropes. During all of the tension-tension cyclic tests, measurements were taken on heat build-up, axial rope stiffness, elongation. All of the tests were conducted on wet ropes submerged in ASTM seawater.

The project lasted three years and was broken into two phases. The first phase involved tests on medium size ropes (250 tonne MNS) and the second phase tested large ropes ranging from 7500 kN to 15000 kN MNS. The final report was completed in December 1996 and is confidential to JIP participants.

3.2.1 Polyester Rope Tests

This study focused mainly on the large-scale polyester ropes. During phase 1, a total of four 250 tonne (approximately 4" diameter) polyester ropes were tested. Two of the ropes were WRC construction and other two PSC. Both constructions had looped and spliced terminations. The four samples were cycled for a given period of time under numerous load ranges, frequencies, and mean loads. During this testing none of the specimens were cycled to failure. The cyclic test matrix included:

- Mean loads of 20%, 25%, and 30% of MNS, with a few additional runs at 44% and 55%.
- Strain amplitudes of 0.25%, 0.50%, and 0.90%, which correspond approximately to peak-to-peak load ranges of 14%, 27%, and 41% MNS, respectively. These amplitudes were chosen because they relate to the high frequency wave-induced tangential motion of the mooring line.
- Frequencies of 0.077, 0.1, and 0.1428 Hz. These frequencies correspond to wave periods of 13, 10, and 7 seconds.

All of the load cases in the test matrix were run under sinusoidal loading conditions with a few extra runs under stochastic loading conditions. Following the cyclic loading tests, three of the samples were break tested to determine the residual strength.

Phase 2 of the study was conducted using the same test matrix and test procedures as Phase 1. The ropes tested in Phase 2 included two 7500 kN polyester ropes (approximately 6" diameter), four 15000 kN polyester ropes (between 8" to 9" diameter), and one 10000 kN kevlar rope. The two 7500 kN ropes and two of the 15000 kN ropes were PSC. The other two 15000 kN ropes were WRC. All of the ropes tested in this phase had looped and spliced terminations with a fabric jacket at the eye to protect the rope from external abrasion.

Prior to initiating the cyclic runs all ropes were run through a bedding-in process which included runs at a mean of 20% MNS and strain amplitudes between 0.1 and 0.6% at a frequency of 0.077 Hz for a duration of 3 days. For the break tests on new ropes, the ropes were cycled 10 times up to 50% MNS.

3.2.2 Measurements Taken on Polyester Ropes

During all of the cyclic tests heat build-up was measured along the rope length at key locations (i.e., free length, splice, eye, etc). The heat build-up was measured using thermocouples located within the rope core. The heat build-up was monitored for each run along with the pin-to-pin elongation and extensometer elongation. After each run, the rope was unloaded during which time the test machine and equipment were set up to make the next run at a different mean load, frequency, or load range. The recovery in the rope during these rest periods was not monitored, and the elongation measurements for each run were started at null.

Although the study did use only a few polyester rope samples, it generated a large quantity of useful data on full-scale ropes. Much of the collected data on frequency, mean tension and load range effects on rope stiffness and heat build-up had not been investigated in detail on full scale ropes prior to this study.

In addition to the cyclic tests, residual break tests were also conducted on most of the polyester rope samples. This was done for both phases of the study.

3.2.3 Key Findings and Observations

Some of the key findings from the study are summarized below.

- Heat build-up was a function of strain amplitude (load range) under cyclic loading. The greater the strain amplitude the higher the recorded temperature in the polyester ropes. There was also some evidence that frequency affects heat build-up, but this effect was not as pronounced as strain amplitude. Increase in frequency gives a rise in heat-build up.

- Hysteresis loss increases with strain amplitude (load range) and reduces with increasing mean load.

- Heat build-up in the 15000 kN WRC polyester rope was a problem at the high strain amplitude (0.9%) under sinusoidal loading, but there is evidence that the sinusoidal loading was too severe a testing regime and thus not representative of service conditions. This was evident when stochastic runs, peaking at 0.5% strain amplitude, were conducted on the 15000 kN rope. When this stochastic run was compared to the 0.25% strain amplitude run under sinusoidal loading, the rope heat build-up in the sinusoidal run was found to be higher even though the peak strain amplitude was half that of the stochastic run. Therefore, heat build-up in the 15000 kN rope may not be a problem under more realistic loading conditions.

- The splice region was found to generate less heat than the clear rope.

- Eye temperature does not appear to be a problem under stochastic loading conditions.

- Modulus was found to be dependent on strain amplitude (load range). The modulus reduced as strain amplitude was increased.

- Modulus was found to be dependent on mean load. The modulus increased as the mean load increased.

- There was a marginal effect of frequency observed on modulus. The rope modulus tended to increase slightly as the frequency is increased.

- Evidence of rope recovery was observed. The rope recovery occurred during test runs when a lower mean load than the previous run was used. This recovery was manifested by the slight reduction in rope length during the lower mean load run.

- The break strength tests on all of the polyester ropes for phases 1 and 2 were higher than the manufactures nominal strength (MNS) for both the new and "used" ropes. The "used" ropes were the ones that had been used in the cyclic tests.

3.3 O.C.I.M.F Hawser Standards Development Program - Prototype Rope Tests

This program's objective was to develop standards for the purchase, production, inspection, and testing of synthetic rope for marine hawsers. The actual testing was conducted to help develop standardized test methods and assure their practicality. Four types of materials were investigated in this study. They included ropes constructed of nylon, polyethylene, polyester, and polypropylene. The rope construction types included three-strand, six-strand, eight-strand, and double-braid. Most of the ropes tested in the program were between 1 to 2 inches in diameter.

The final report for the prototype rope tests was issued in October 1983.

3.3.1 Tests Conducted in the Study

The prototype test program involved break-tests (both wet and dry), cyclic fatigue tests, and rope abrasion tests. For the break tests the specimens were cycled 10 times up to 50% MNS and then loaded until failure. The procedure for the cyclic fatigue tests included running the rope at a load range of 50% MNS for 1000 tension-tension cycles. If the rope does not fail, the load range is increased to 60% MNS and cycled again for 1000 cycles. This was repeated until the rope failed. These load levels were called thousand cycle load levels or TCLL. These TCLL's were used to gauge the cyclic performance of the rope. The report also presents equations that can be used to extrapolate the number of cycles that rope will fail at for a given load range.

Abrasion tests were also conducted on the rope samples. This testing consisted of mounting ropes through a system of wheels. One of the wheels (the abrasion wheel) was rotated 100 revolutions. The rope was than removed and break tested to determine the residual strength.

3.3.2 Polyester Rope Tests

During this test program 10 polyester rope specimens were subjected to the break, cyclic fatigue, and abrasion tests.

3.3.3 Measurements Taken on Polyester Ropes

For the cyclic fatigue tests only the TCLL value for each rope was determined. No elongation or stiffness measurements were taken during this type of testing. These measurements were also not taken during the wet and dry break tests. Rope elongation curves were only developed for the first and tenth cycles of the bedding-in process. These generally showed the polyester ropes becoming stiffer from the first cycle to the tenth cycle.

3.3.4 Key Findings and Observations

Some of the key findings from the test program are summarized below.

- The quality of the yarn used to make ropes has a major influence on the rope strength.
- Polyester rope had an average TCLL value greater than 70%. Nylon, polypropylene, and polyethylene ropes generally had TCLL values less than 60%. Thus, polyester ropes have better cyclic loading performance than the other materials

Since the primary focus of this testing program was to develop practical testing standards for synthetic ropes used in marine applications, it did not provide much specific data in regards to the behavior of polyester ropes. However, the testing program does help provide guidance on rope bedding-in procedures and a means of generating data that is useful in rating the overall performance of a synthetic ropes.

3.4 National Engineering Laboratory (NEL) - Cyclic Testing of Continuously Wetted Synthetic Fiber Ropes

The objective of this program was to study the cyclic load endurance properties of various synthetic rope materials and constructions. The data collected from the study provided comparative performance data on rope material and forms of construction. The three materials included polyamides (nylon), polyester, and polypropylene. Three rope construction types were also investigated in the study. They included braid-on-braid, eight-strand, and parallel lay. Most of the ropes tested in the program were between 1 to 2-1/2 inches in diameter. All of the ropes were continuously sprayed with fresh water during the cyclic testing.

The National Engineering Laboratory (NEL) conducted this testing program. NEL was commissioned by the UK Department of Energy in 1977 to conduct the rope tests to investigate the feasibility of these synthetic ropes for possible use in future mooring and anchoring systems.

The test program lasted 5 years and is summarized in OTC paper 4635, which was published in May 1983.

3.4.1 Tests Conducted in the Study

The test program included only cyclic tension-tension fatigue tests of ropes with looped and spliced terminations. Most of the ropes tested had no sheathing or thimble protection at the eyes. This was intentionally done to compare endurance results of terminations with no protection to terminations with protection. Because of this, the most endurance results reflected the abrasion resistance of the rope and not the true fatigue characteristics. A total of 88 tension-tension fatigue tests were conducted on the various ropes, and all the ropes were cycled to failure.

3.4.2 Polyester Rope Tests

During this test program, 6 polyester rope constructions were investigated. Of these, two were approximately 2.5 inches in diameter and the remaining four were approximately 1 inch in diameter. Three to six fatigue tests were conducted for each rope construction. The results of these fatigue tests are summarized in Table 3.2. It should be noted that only one of rope constructions had abrasion protection at the eye.

Table 3.2 - Polyester Fatigue Test Results from NEL Study

Test No.	Mean Load (%MNS)	Load Range (%MNS)	No. of Cycles to Failure	Position of Failure
Eight Strand Polyester Rope (MNS = 269 kN)				
1	41	79	1791	Back of eye
2	36	69	4080	Back of eye
3	33	64	12091	Back of eye
4	31	59	38029	Back of eye
Eight Strand Polyester Rope (MNS = 1010 kN)				
1	30	59	5926	Back of eye
2	28	54	6853	Back of eye
3	25	49	19218	Back of eye
4	23	44	31784	Back of eye
Braid-on-braid Polyester Rope (MNS = 622 kN)				
1	41	64	1517	Back of eye
2	36	56	3973	Back of eye
3	31	48	5659	Back of eye
4	26	40	31843	Back of eye
5	21	31	163738	Back of eye
Braid-on-braid Polyester Rope (MNS = 100 kN)				
1	35	70	2531	Back of eye
3	25	50	5200	Back of eye
2	30	60	5461	Back of eye
5	20	40	20304	Back of eye
4	25	50	24710	Back of eye
6	20	40	25066	Back of eye
Braid-on-braid Polyester Rope w/Abrasion Protection (MNS = 100 kN)				
1	26	50	58177	Crotch of Splice
2	21	40	338096	Back of eye
3	16	30	446654	Back of eye

* One set of fatigue tests (5 runs) was not included in this table. These test sets tested rope finishes at the eye. All runs were run at the same load range.

3.4.3 Measurements Taken on Polyester Ropes

For the cyclic fatigue tests, only the number of cycles to failure was recorded for the given peak-to-peak load range. Elongation was monitored during select fatigue tests. These were presented in the form of extension/endurance curves. There was no documentation on the bedding-in procedure and the associated rope elongation. Additionally, stiffness calculations were not made during the testing. Most of the ropes were cycled at very long periods (between 40 to 160 seconds per cycle). This was due to the limitations of the testing machines and it points out why it took five years to complete the test program.

3.4.4 Key Findings and Observations

Some of the key findings from the test program are summarized below.

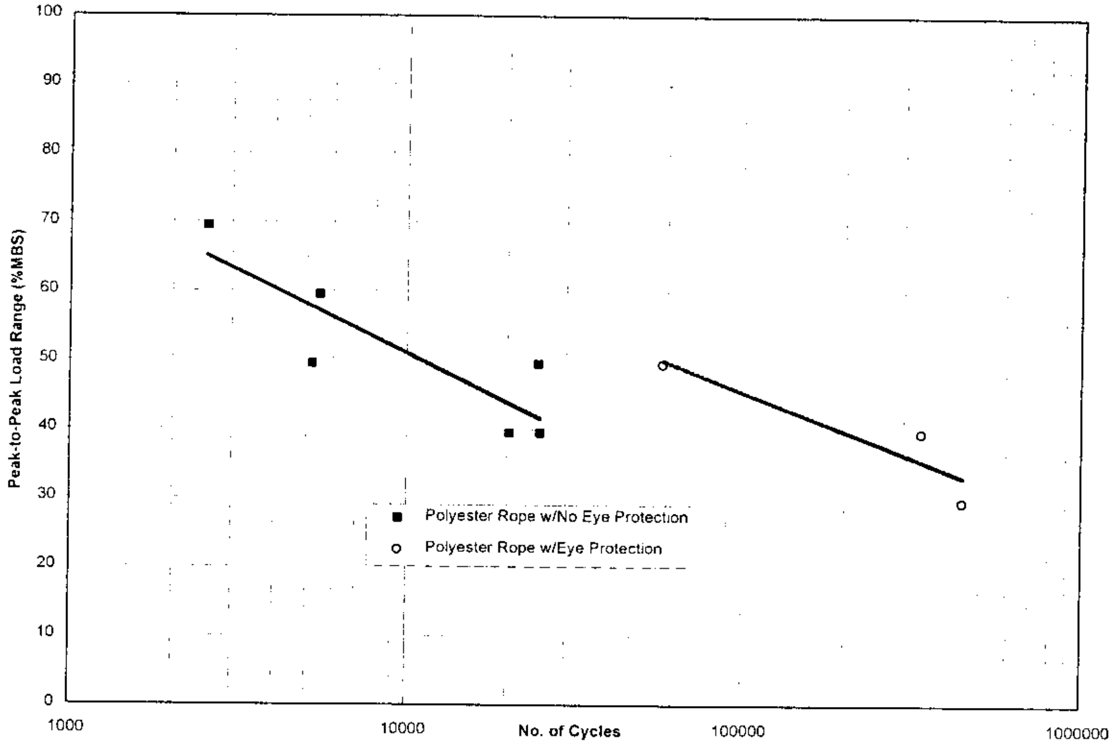
- When compared to nylon, unprotected polyester ropes have better endurance performance.

- The shorter the rope helix or lay of the rope, the more rapid the rate of wear. This was observed in the nylon ropes, but was not conclusive for the polyester ropes. This behavior may be caused by the lack of protection at the eyes. The longer laid ropes will tend to flatten or form around the pin, giving more contact area at the pin and less localized abrasion effects. The shorter laid ropes do not flatten as much at the pin and localized abrasion will be more pronounced.

- Polyester cloth protection was successful in overcoming abrasion failures at the eye and showed a five to six fold improvement in endurance. Load endurance curves showing an unprotected rope versus a protected rope are shown in Figure 3.1.

Like the O.C.I.M.F test program, this testing program focused primarily on the performance of different synthetic materials. The difference between the two programs was that this test program cycled the ropes to failure at a constant load range. Because of this, the data can be used to develop lower-bound endurance curves or S-N curves for polyester ropes. The curves are considered lower bound because most of the rope failures occurred at the eye due to the absence of abrasion protection (See Table 3.2). Higher fatigue lives can be expected if there is adequate protection between the eyes and pins.

Figure 3.1 - Influence of Abrasion Protection at Eye on Fatigue Life



3.5 Enka Research Institute - Dynamic Behavior of Synthetic Ropes

The objective of this program was to study the cyclic load endurance and residual break strength properties of various synthetic rope materials and constructions. The data collected from the study provided comparative performance data on rope material and forms of construction. In addition to the material type and construction, the effect of fiber lubrication was also studied. The materials included polyamides (nylon), polyester, polypropylene, and aramids. Three rope construction types were also investigated in the study. They included braid-on-braid, three-strand, and wire rope construction. Most of the ropes tested in the program were between 10 to 18 mm (0.4 to 0.7 inches) in diameter. All of the cyclic tests were run on wet ropes.

This testing program was conducted by Enka Research Institute, and tests are summarized in OTC paper 4003, published in May 1981.

3.5.1 Tests Conducted in the Study

The test program investigated about 200 rope samples. These tests include both fatigue and residual break strength tests. The ropes were tested dry and wet. All of the ropes tested had sheathing or thimble protection at the eyes. All ropes had looped and spliced terminations.

3.5.2 Polyester Rope Tests

During this test program, four tests were conducted on polyester ropes. These ropes varied in construction. Three of the tests were conducted on ropes with no fiber lubricant and one with lubricant. All of the cyclic fatigue tests were run at a frequency of 0.5 Hz. Details on the exact number of fatigue tests run on the polyester ropes were not presented in the paper.

3.5.3 Key Findings and Observations

Some of the key findings from the test program are summarized below.

- Based on the residual break tests conducted on ropes cycled between 10000 and 250,000 times, residual break strength was found to be no lower than 80, indicating that residual break strength is a hard criteria for judging tension-tension fatigue history.
- The above observation also tends to indicate that internal abrasion within the rope is not a mode of failure, since residual break strength would fall as the rope is cycled.

3.6 Naval Civil Engineering Laboratory (NCEL) - Testing and Bending Fatigue Test Results of Synthetic Ropes

The test program had two objectives. The first was to establish long-term fatigue life of synthetic ropes under low-tension cyclic loading; the second was to identify the effects of rope material, construction, and rope diameter-to-sheave diameter relationships on bending fatigue. Two rope materials were investigated in the study. They included aramid and polyester. For the fatigue tests only parallel strand ropes were investigated. For the bending fatigue tests various rope constructions were tested. For the tension-tension fatigue tests 2-1/2 inch diameter ropes were used. For the bending fatigue tests the ropes varied in size from 1 to 4-inch diameter. All of the tension-tension cyclic tests were run on wet ropes.

The Naval Civil Engineering Laboratory (NCEL) conducted this testing program for the U.S. Navy. The navy conducted these tests to investigate the use of these synthetic ropes for long-term (20 years or more) moorings and ocean lift operations. The test procedures and results are summarized in OTC paper 5720, published in May 1988.

3.6.1 Tests Conducted in the Study

For the tension-tension fatigue tests, three tests were run at different load ranges on the two-rope material, for a total of 6 tension-tension fatigue tests. The tension-tension tests were run at a high range (8 tests - 70 % MNS), medium range (8 tests - 50% MNS), and at a low range (8 tests - 25% MNS). The cyclic period was 10-11 seconds for the high and medium load ranges and 5 seconds for the low load range.

In addition to the fatigue tests the specimens that were cycled at the lower range were break tested after 2 million cycles (run-out). This residual break test was compared to a break test conducted on a new or uncycled specimen. The medium and high load range runs were all cycled to failure. All ropes had looped and spliced terminations.

For the bending fatigue tests, various rope materials and constructions were cycled over sheaves of different diameter. Most of the ropes were cycled to failure.

3.6.2 Measurements Taken on Polyester Ropes

Load range, frequency, mean load, number of cycles to failure, and elongation were all monitored during the tension-tension fatigue tests, but there was no documentation on the bedding-in procedure prior to the testing. Additionally, stiffness calculations were not made during the testing.

3.6.3 Key Findings and Observations

Some of the key findings from the test program are summarized below.

- After 2 million cycles the retained break strength was found to be 93% of the new strength. This finding supports the findings from the Enka tests, and further indicates that residual break strength is not a good indicator for judging tension-tension fatigue history.

- Pin-to-pin elongation for the polyester rope samples cycled to failure were the same (13.7%) even though they were cycled at different load ranges.
- Elongation at failure during the static break test (12.4%) was very close to the elongation of the ropes that were cycled to failure, thus possible indicating that there may be an ultimate strain that the polyester rope will fail at, regardless of the rope's load history.

4.0 MULTIVARIABLE FAILURE MODEL DEVELOPMENT

4.1 Setting up the prediction problem.

The requirement is to determine the reliability (probability of failure) of a given mooring line with specified design features that is subject to known loadings and motions. Based on the literature review of available data and technical literature (Chapter 3), failure mechanisms were reviewed, evaluated and selected to be included in the rope failure model by the JIP steering Committee. The decision rational is documented in Table 4.1, below.

Design issues were eliminated from the modeling activity, as these were thought to be better addressed by modification of the system design itself and not a fundamental reliability issue.

Operational issues were eliminated from modeling activity, as these were the subject of other industry initiatives (e.g. DeepStar-98). Any attempts at the development of predictive methods to treat such failure mechanisms were expected to change discretely and dramatically with the growth of the collective experience of the industry (e.g. each time an incident occurs).

Finally, areas in which fundamental physical understanding was lacking were relegated to *further study*. These areas required more fundamental research and development to represent in a physical or statistical model.

Table 4.1 State of Knowledge of Failure Mechanisms

Mechanism	State of Knowledge
Abrasion at Termination	Design – protection
Abrasion due to Sediment within Rope Body	Operational (Installation) Issue
Axial Compression Fatigue	Further Study
Creep Rupture	Include
Fishbite Damage	Further Study
Heat Build-up	Design Issue
Hydrolysis	Further Study
Installation Damage	Operational Issue
Material or Fiber Fatigue	Include
Splice Slippage at Termination	Design – limiting strength
Ultraviolet Light Exposure	Design – no exposure

Having limited the failure mechanisms of interest to tension fatigue and creep rupture, a database was constructed that compiled tension-tension fatigue data and load extension data and associated variables to explore for their dependence in the failure model:

Fatigue Database

- Rope Construction
- Tested to Failure? (Y or N)
- Nominal Break Strength
- Mean load
- Number of cycles on test
- Load Range
- Position of failure (if failure)

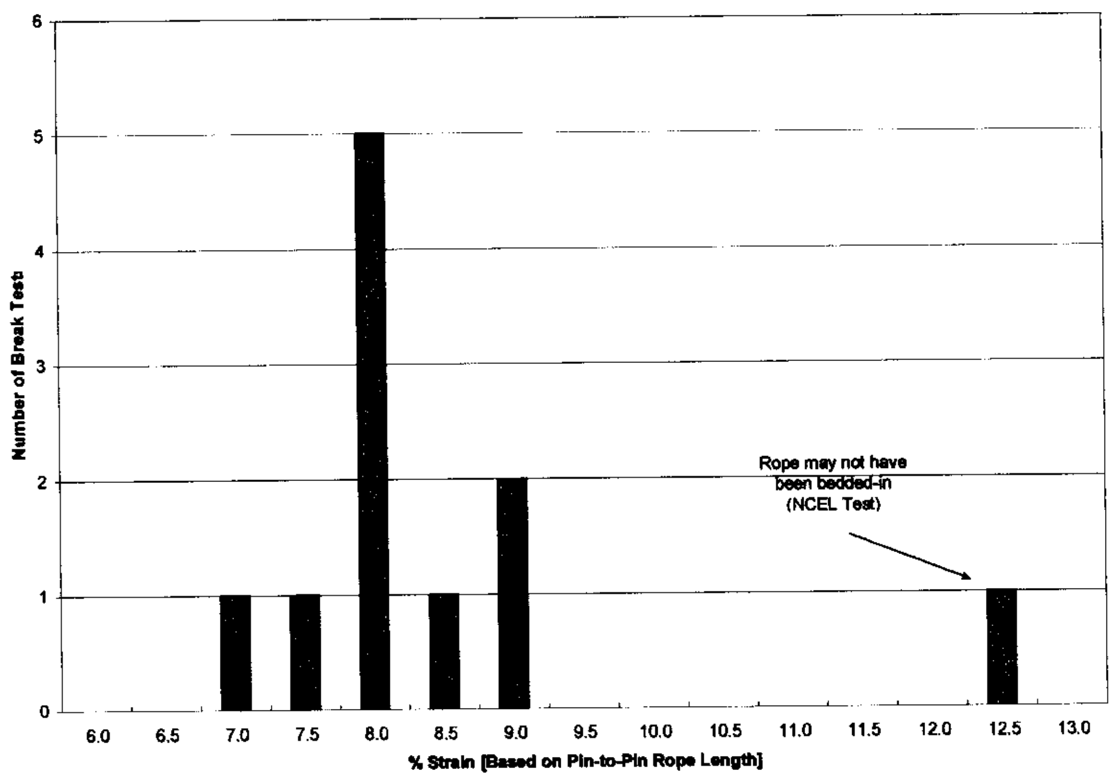
Load Extension Database

- Rope Construction
- Nominal Break Strength

4.2.1 Strain-to-Failure Model

In exploring the data for another variable to represent degradation, it was observed that the small subset of rope specimen failures (11 break tests) exhibited a correlation of *strain* at failure (centered at approximately 8%). This behavior is shown in Figure 4.1. Various mechanistic algorithms relating to stain at failure were investigated using a multivariable nonlinear regression approach as listed in Table 4.2.

Figure 4.1 Strain-to-Failure Test Results



- Mean Load
- Strain at given number of cycles (typically end of testing)
- Number of Cycles on Test
- Load Range
- Frequency
- Elongation
- Specimen Length
- Strain Rate

4.2 Developing Mechanistic Algorithms

It was readily identified from the data set that our interest in establishing mechanistic failure algorithms would be limited by several constraints:

- None of the fatigue tests tested the rope specimens to failure. And only a small fraction of the specimens (4 out of 53) were loaded statically to failure ***after*** cyclic fatigue loading had taken place.

- Rope specimens were used in a number of fatigue loading tests, and the history between tests for a given specimen was unavailable to EQE, thus the complete load history and recovery was not characterized.

- The subset of the fatigue test database that related load range to number of cycles did not contain sufficient associated variables (e.g. frequency, temperature, and extension) with which to model the variance.

These constraints forced abandonment of the use of a classic Miners Rule accumulated damage formulation, as was originally intended.

Table 4.2 Strain–to-Failure Hypotheses

Set	Form	Results
1	$\varepsilon = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(f) + b_4\ln(Num) + b_5\ln(NBS)$	No convergence, some error reduction after appx. 70 iterations. These forms were thought to be aphysical, try a term representing time at load
2	$\varepsilon = b_1 ML + b_2 LR + b_3 f + b_4\ln(Num)$	
3	$\varepsilon = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(f) + b_4\ln(Num)$	
4	$\varepsilon = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(f)$	
5	$\varepsilon = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(\mathrm{Num}/f)$	No convergence, no error reduction after appx. 1000 iterations. Data far too noisy
6	$\varepsilon = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(\mathrm{Num}/f) + b_4\ln(f)$	
7	$\partial\varepsilon/\partial t = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(\mathrm{Num}/f)$	
8	$\partial\varepsilon/\partial t = b_1\ln(ML) + b_2\ln(LR) + b_3\ln(\mathrm{Num}/f) + b_4\ln(f)$	

Where:

ε = Strain

ML = Mean Load

LR = Load Range

Num = Number of Cycles

f = frequency

Although the strain-to-failure approach appeared to have some validity from exploratory data analysis, none of the hypothesized algorithms were able to fit the data with sufficient accuracy. As indicated in Table 4.2, none of the model forms were able to converge, and those functional forms that best represented our mechanistic understanding of the damage process (i.e. total time at load) demonstrated the poorest explanation of the data set variance. Several reasons are postulated for this lack of convergence in the Strain-to-Failure formulation:

- *Invalid Hypothesis – Strain-to-Failure.* The hypothesis was made that a cumulative permanent strain could be related to the test (and in-service) conditions (e.g. mean load, load range, number of cycles/frequency). A further, related assumption was made that a cumulative strain-to-failure existed and could be characterized with these data. The current lack of convergence is associated with the first assumption. If the hypothesis were invalid, we would have observed difficulty in fitting the parameters.

- *Invalid Hypothesis – Treatment of History.* At the outset, we assumed no effect of history on these ropes. That is, in our data individual rope specimens were tested multiple times. We assumed that the second and subsequent tests, rope specimens behaved as new rope specimens. Permanent elongation this was accounted for in subsequent elongation datum. Ideally, we could investigate this history-dependence, however data did not exist that documented rest cycles and recovery phenomena on individual rope specimens between tests. Without data there was little or nothing that could be done about this issue.

- *Inconsistent Bed-in Processes.* We do not know the bed-in process for all data groups in our database. For some, the bed in process within a group was consistent, but varied from group to group. In other cases it is simply not known. This unknown can affect the validity of both hypotheses. It can introduce variations in the multivariate model, but these should not be greater than an order of magnitude. It can also introduce bias in the strain to failure distribution. Unless measurements of elongation and load conditions on the bed-in process can be obtained, the multivariate model cannot account for the differences in bed-in. Assumptions can be made on 1) whether rope specimens were bedded-in (if not explicitly stated) and we can apply gross but analogous bed-in elongation from known specimen data to those undocumented data points. This can be done parametrically, to "shift" groups of test data in the strain-to-failure distribution.

For these reasons the Strain-to-Failure model was not further developed.

4.2.2 Simplified Fatigue Life Model

After review of the available polyester test data, a relatively simple approach to modeling rope life was proposed. This approach was developed according to the methodology used to determine the fatigue life of typical steel wire and chain mooring systems. This approach assumes that the life of the rope can be estimated by comparing the long-term cyclic loading of a polyester mooring line with the resistance of the polyester rope to fatigue damage. The approach uses a T-N curve to determine the amount or rope damage similar to that for a steel mooring system [35]. This T-N curve gives the number of cycles to failure for a polyester rope as a function of constant load range. The T-N curve becomes the multivariable model that is developed using the available polyester test data.

Once the multivariable model is developed, the cumulative fatigue damage can be expressed using Miner's Rule. Where the damage ratio (D) is calculated by the following equation,

$$D = \sum \frac{n_i}{N_i}$$

where:

n_i = number of cycles within the tension range interval i.

N_i = number of cycles to failure at tension range i as given by the T-N curve.

Failure is defined when the cumulative damage ratio (D) exceeds unity. Generally, for design applications the in-service design life is increased by a prescribed factor of safety. For steel mooring systems, API recommends a factor of safety of 3.0.

The fundamental assumption associated with this model is that the polyester rope behaves in a similar manner to a steel wire system. Specifically, it assumes that polyester rope damage is independent of the rope loading history (counter-indications of this assumption have been found in the data development for this project). It should also be noted that this model does not specifically identify failure mechanisms, such as internal abrasion, creep, or material fatigue as governing. One or all of these mechanisms may be active in the overall degradation process.

The rope model only addresses damage (rope failure) macroscopically, by expressing total fatigue damage as a function of cyclic load range.

4.2.2.1 Selection of Test Data

To develop the model all of the available cyclic tension-tension fatigue tests were gathered into a single database. The testing programs that generated cyclic fatigue test data of polyester ropes included the Fibre Tethers 2000 JIP, the NEL tests, and the NCEL tests. The Norsk Hydro JIP conducted tension-tension cyclic test on polyester ropes, but none were cycled to failure. The data collected during the Enka tests were not presented in sufficient detail in the source OTC paper, and therefore could not be used in developing the database. From the three sources mentioned above, 53 fatigue tests were run on polyester ropes. The results from these tests are presented in Figure 4.3.

The overall process for selecting the data set is shown in Figure 4.2 ad further explained in the remainder of this section.

Figure 4.2 Data Development Logic

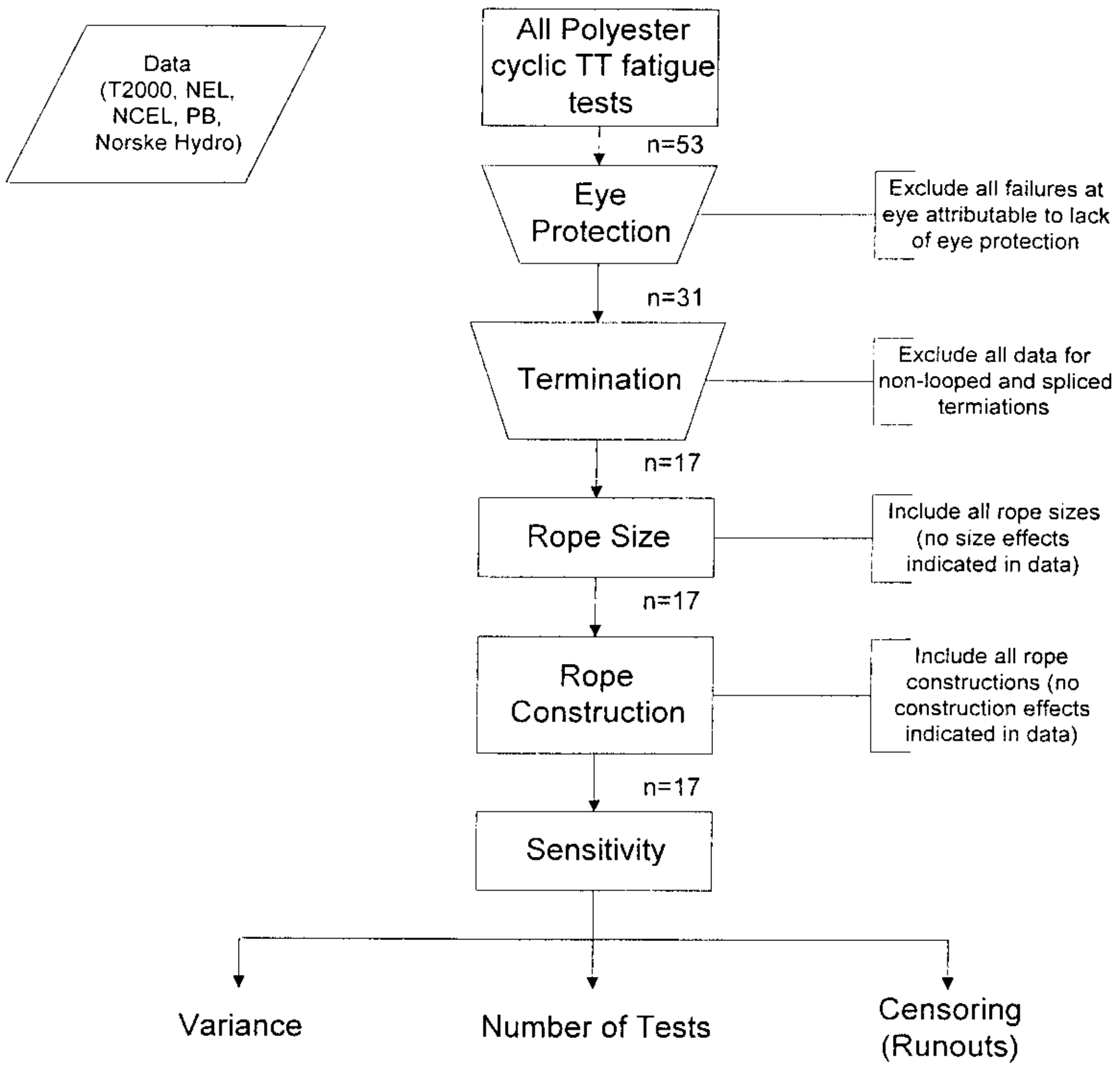
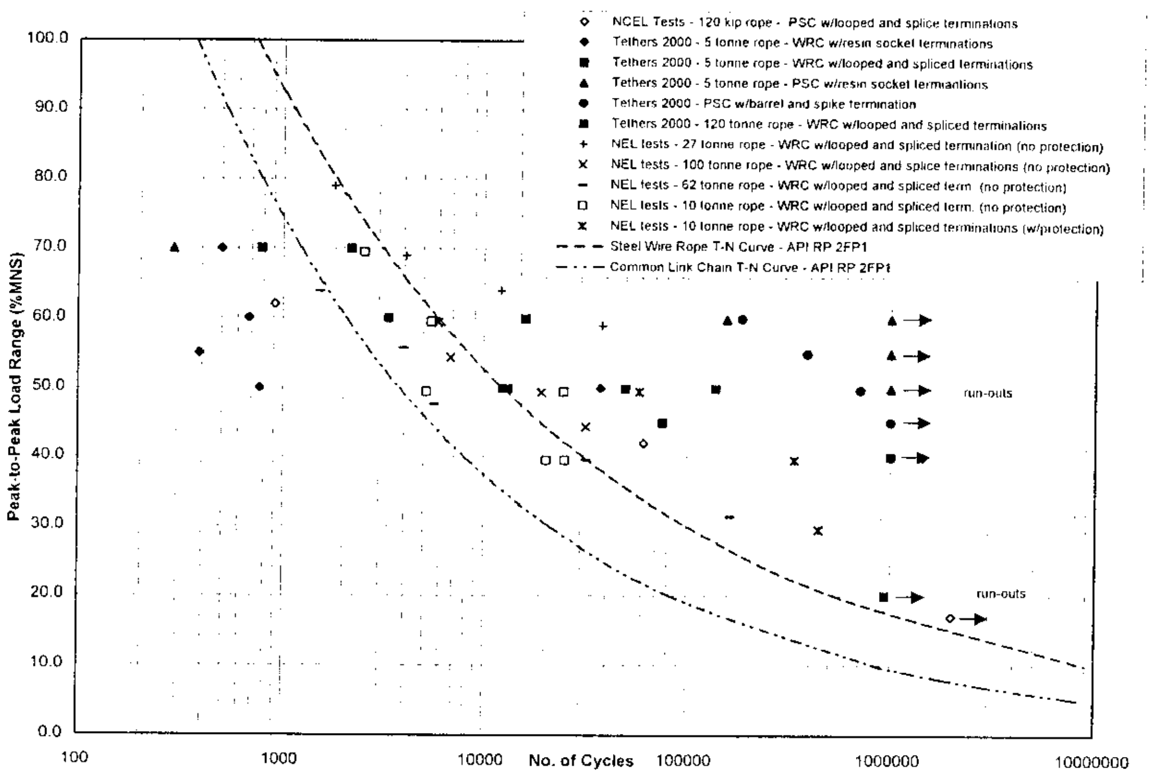
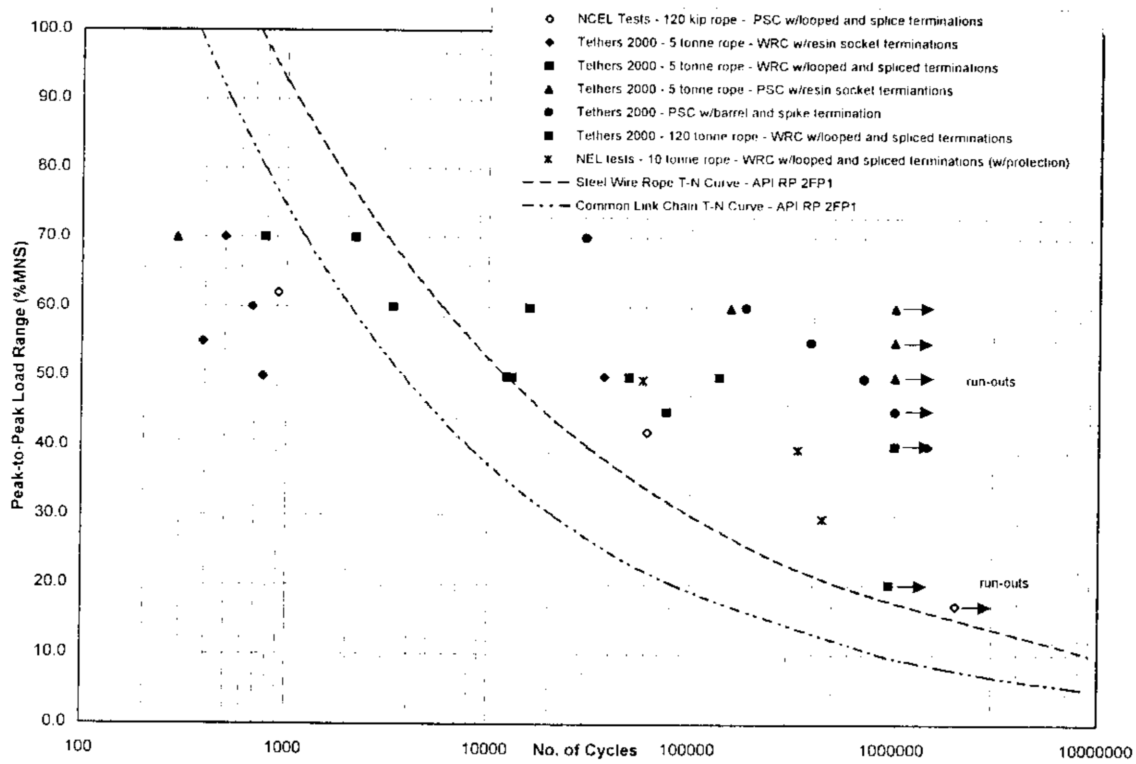


Figure 4.3 - Available Tension-Tension Fatigue Tests



When reviewing Figure 4.3, it is evident that there is large scatter in these data. It also appears that some of the polyester ropes do not perform as well as their steel counterparts; however, this is not the case. The reason why many of the polyester ropes presented in Figure 4.3 are below the steel T-N curves is because these tests were run with no protection at eye termination. These short life to failure data are the NEL tests, that were conducted in the early 1980's to investigate the abrasion performance of different synthetic ropes. Because of this the tension-tension fatigue results are skewed or biased to a lower number of cycles to failure. Since this situation does not represent a realistic in-service condition (i.e., no eye protection), these data points were eliminated from the model database. Figure 4.4 displays all of the tension-tension fatigue tests of Figure 4.3, excluding the NEL tests with no eye protection.

Figure 4.4 - Tension-Tension Fatigue Tests - Rope without Eye Protection Removed



A review of Figure 4.4 shows many of the data points that fell below the steel T-N curves have been removed. This verifies the importance of adequate abrasion protection at the eye terminations for polyester ropes. With the removal of these data, the amount of scatter is somewhat reduced; however, even with these data points removed there is still a large amount of scatter present in the database.

In trying to explain the spread in the data, there are three additional factors that may influence the tension-tension fatigue performance of the polyester ropes, and thus cause the scatter that is seen in Figure 4.4. These include termination type, size or scaling effects, and rope construction. The most influential factor is the termination type. In the tests shown in Figure 4.3 there are three types of terminations being tested. They include the resin socket, barrel and spike, and the looped and spliced terminations. All of the data on the resin socket and barrel and spike terminations were generated by the Tethers 2000 JIP. As discussed in Section 3.2, one of the main objectives of the Tethers 2000 JIP was to investigate the performance of these different terminations. The large scatter in rope fatigue data shows there are distinct, measurable performance differences among the termination types.

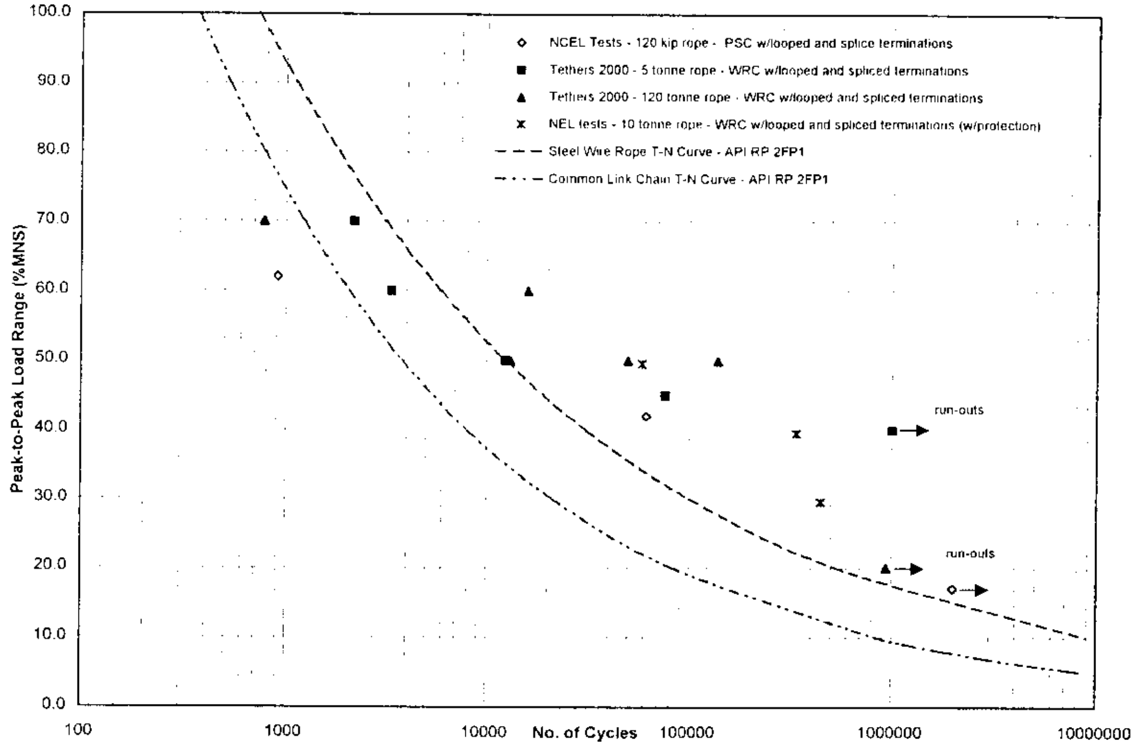
Currently, only looped and spliced terminations are used for terminating large diameter ropes. Hence, the fatigue data for the resin socket and barrel and spike terminations were excluded in the development of the model. With the removal of the dissimilar terminations data points, there are 17 data points left to be used in the development of the model, including three run-outs (the rope was not cycled to failure). These remaining data are shown in Figure 4.5. As expected, the remaining data points show reduced scatter compared to the previous two figures.

The other two factors that may have some influence on the data scatter are rope size and construction. The influence of both of these factors can be investigated by reviewing the data presented in Figure 4.5.

When reviewing the figure for scaling or size effects, no trend is evident. A comparison of the 5 and 120 tone ropes appears to show slightly increased fatigue life performance for the 120 tonne rope, but there is insufficient data to confirm the hypothesis. In the Tethers 2000 report there is some mention of a small scaling effect between the 5 and 120 tonne rope, but there are no conclusions drawn from the test data. Conversely, the 10 tonne and 120 kip ropes from the NEL and NCEL tests seem to show equal or worse fatigue performance of the larger ropes when compared to the smaller 5 tonne ropes. Based on these data, no scaling effects between the different rope sizes can be determined. Hence, it is assumed that scaling effects due to differences in rope size are negligible, and no data points presented in Figure 4.5 will be removed from the model database due to scaling effects.

Figure 4.5 - Tension-Tension Fatigue Tests –

Ropes with Looped and Splice Terminations Only



The effects of rope construction on fatigue life are also not evident in the data presented in Figure 4.5. The Tether 2000 report suggests that PSC and parallel fiber ropes generally have better fatigue performance than WRC ropes, but this does not seem to be the case when comparing the WRC ropes from Tethers 2000 to the PSC ropes from the NCEL tests. In the Tethers 2000 JIP, there are not enough like-to-like test runs that allow comparison to determine the effects of rope construction on fatigue performance. Much of the data from the Tethers 2000 JIP that was used to compare the performance of rope construction on fatigue performance was on ropes with resin socket and barrel and spike. For these types of terminations, WRC ropes do not perform well due to the twisting that occurs as the rope is tensioned. This twisting effect causes the rope to fail at the terminations. The ropes with little or no helix, such as parallel fiber, perform much better since there is little or no twisting in the rope as it is tensioned. Hence, it is possible the terminations and the lack of swivels or torque compensators used during testing cause the WRC ropes to fail at lower tensions than the PSC ropes, and not the rope construction. In general, all of the rope constructions have similar performance in regards to strength tests. Based on the available data, there is not enough evidence showing rope construction effects fatigue performance. Therefore, no rope construction effect on fatigue life was represented in the life prediction model.

4.3 Analysis of the Data

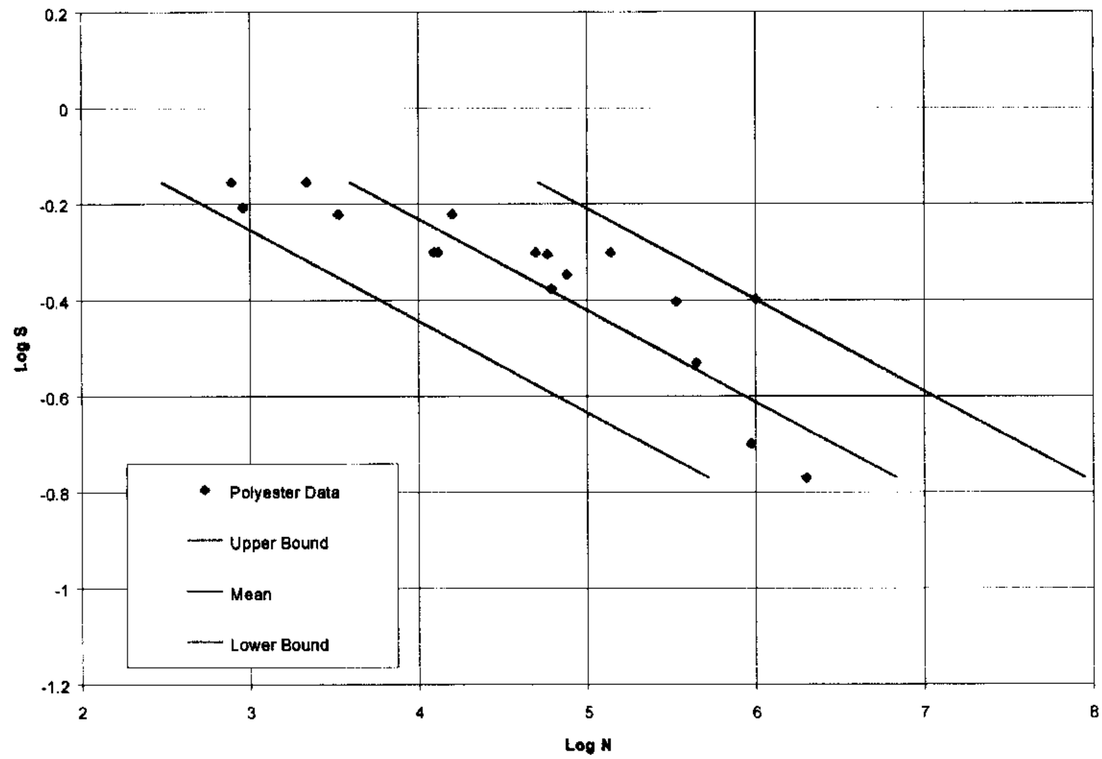
4.3.1 Treatment of the Random Variables

In the experiments conducted to generate the S-N data, S is predetermined by test equipment and specified conditions and N is measured. Under these ***testing*** conditions, N is the random variable and S is deterministic; hence N is regressed on S. There are, however, a number of references in the recent polyester rope literature in which S-N data was analyzed by regressing S on N [32, 33, 34] in error. The sections below illustrate the significant differences that can occur under the two different treatments of data.

In the experiments conducted to generate the S-N data, S is predetermined and N is measured. Therefore, N is the random variable and S is deterministic; hence N is regressed on S. EQE staff verified that N should be treated as the random variable for this assembled data set. The verification has been via numerous sources including basic statistical textbooks and discussions with experts such as Prof. Paul Worshing and Prof. Allin Cornell. It is a standard statistical treatment of the unknown (life) test variable – in this case, cycles to failure.

Figures 4.6 presents a log-log plot of the final data scatter diagram. Also shown on plot are the mean, and upper and lower 95% bounds of a linear regression analysis with constant variation. As can be seen in the figure, there is approximately a two order-of-magnitude spread (one above, and one below) the least squares (maximum likelihood) nominal fit for a given stress range, S. For a given fatigue life, N, the range is approximately exp(0.2), or a factor of 1.2.

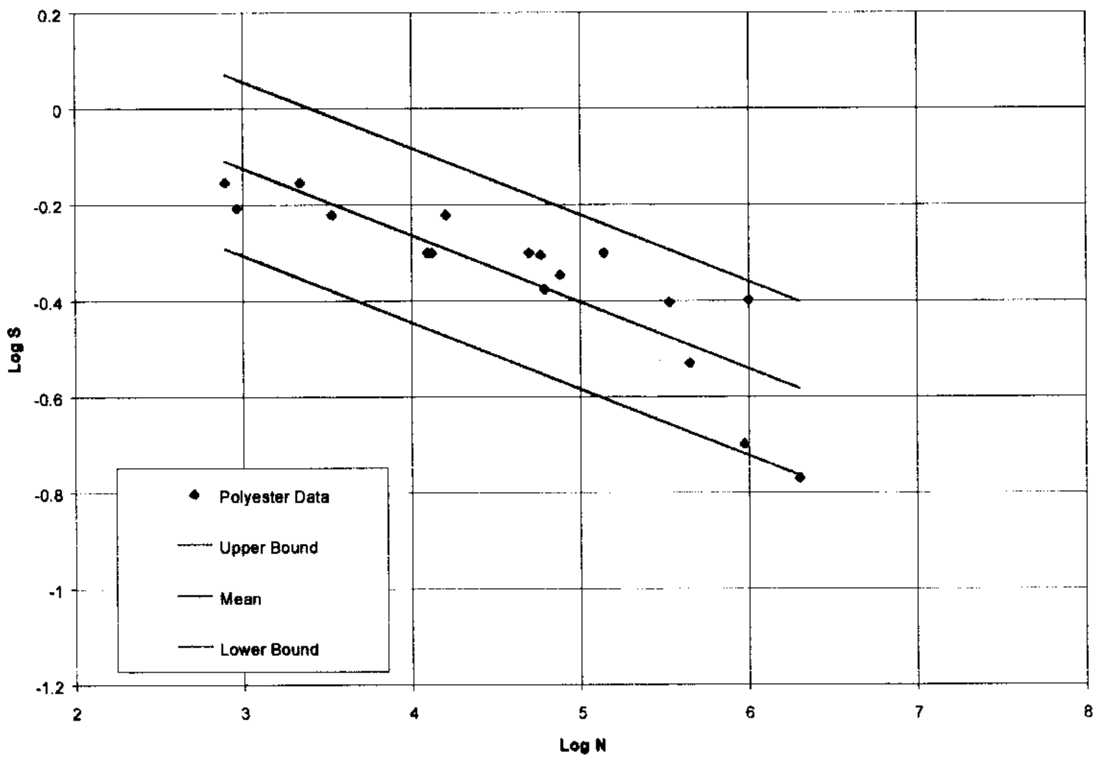
Figure 4.6 – Linear Regression with Constant Variation – N on S



In comparison, Figure 4.7 presents the same data with regression results generated by ***incorrectly*** assuming S random, i.e. by regressing S on N . As can be seen by comparing Figure 4.6 with Figure 4.7, there are significant differences between the predicted results.

- First, the confidence interval is slightly smaller in the case of S on N.
- The inverse Log-Log slope of the curves resulting from the S-Random (incorrect) regression analysis is 19.5, compared to the curves resulting from the N-Random (correct) regression analysis, which is 5.33
- At a given value of S, however, the prediction interval is approximately 3 orders of magnitude (a factor of 30 above and below the nominal) compared to the factor of 10 above.
- Most important, the slope of the predicted nominal fit and upper and lower bounds is greater for the erroneous treatment of S on N. The lower bound lines cross at approximately 10,000 cycles, N=4, above which S on N (nonconservatively) predicts greater fatigue lives than the correct treatment.

Figure 4.7 – Linear Regression with Constant Variation – S on N



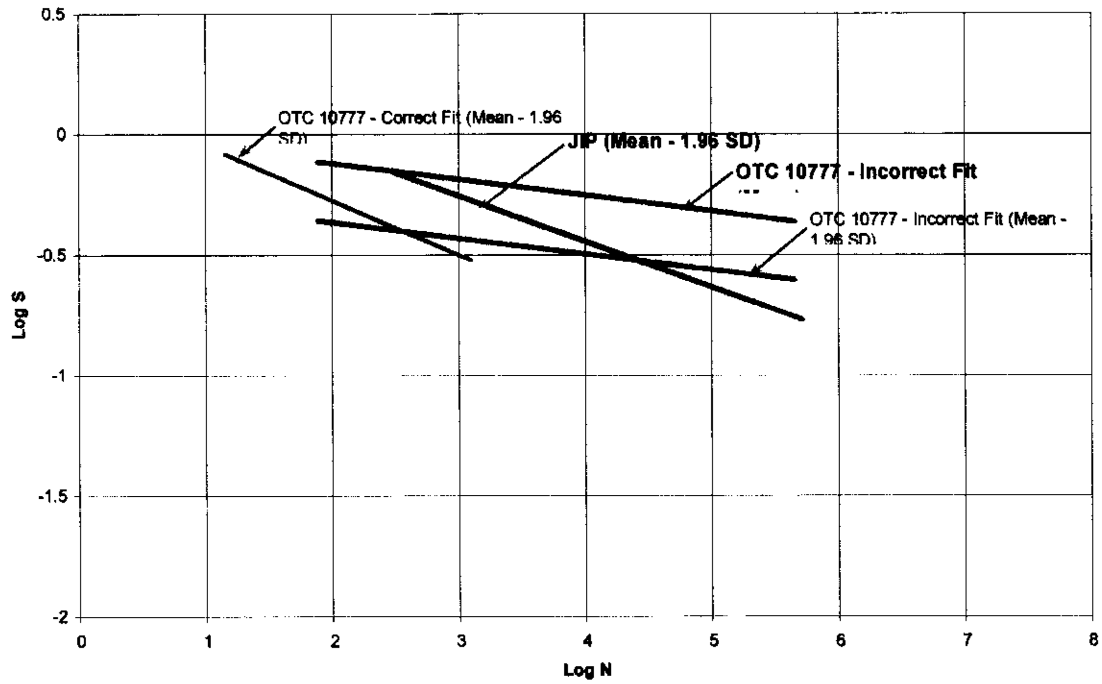
The difference between treating S or N as the random variable tends to diminish with larger data sets with lower variance. However, this sparse and noisy data set for polyester rope (17 points), clearly illustrates the differences are significant and the data analysis must be made with care to treat N as random.

A comparison was made of the results of this study to the tension-tension fatigue results for polyester found in Reference 32. The comparison is summarized in Appendix A to this report. The results presented in Reference 32 (10 test data points) regressing S on N gave an inverse log-log slope of greater than -15. Reanalysis of these same data and regressing N on S yields an inverse log-log slope of –4.4 (compared to –5.3 for this project).

4.3.2 Modeling Variance

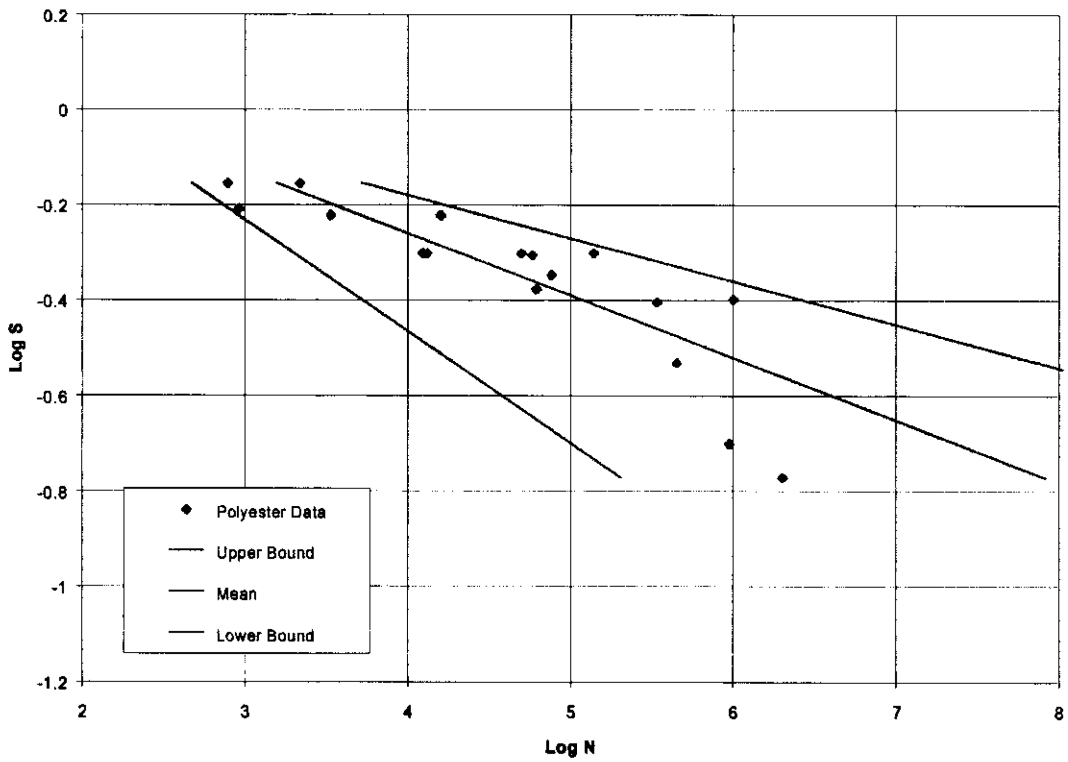
It should be noted from Figure 4.5 that the scatter in the data is higher for in the low cycle range than for higher values. Therefore, it may be useful to use a variable regression versus a constant variation. Figure 4.8 presents the results for the mean, as well as lower and upper 95% bounds of the regression analysis.

Figure 4.8 – Comparison of T-N Results to OTC 10777



The curves presented in Figure 4.8 are more descriptive of the data than those presented in Figure 4.6. Notice the larger scatter in the data in the higher cycle range, which significantly affects the lower bound. This result indicates that more data is needed at low-stress, high-cycle conditions.

Figure 4.9 – Linear Regression with Variable Variation – N on S



4.3.3 Number of Tests

The effect of the number of data points on the upper and lower 95% bounds was investigated to gain insight into the potential impacts of additional testing. The results presented in Figure 4.7 are plotted again in Figure 4.9 with two additional curves. These new curves represent the upper and lower bounds obtained when using one hundred times the number of data points, yet with the same coordinates. This allows us to explore the case in which we have generated a large data set, but the statistics (e.g. mean, variance, distribution) do not change. As can be seen from the figure, only insignificant changes in the upper and lower bounds result from the increase of the number of points. This indicates that the scatter in the data is the main factor controlling the uncertainty in predicting fatigue life.

Figure 4.9 – Linear Regression with Variable Variation – N on S

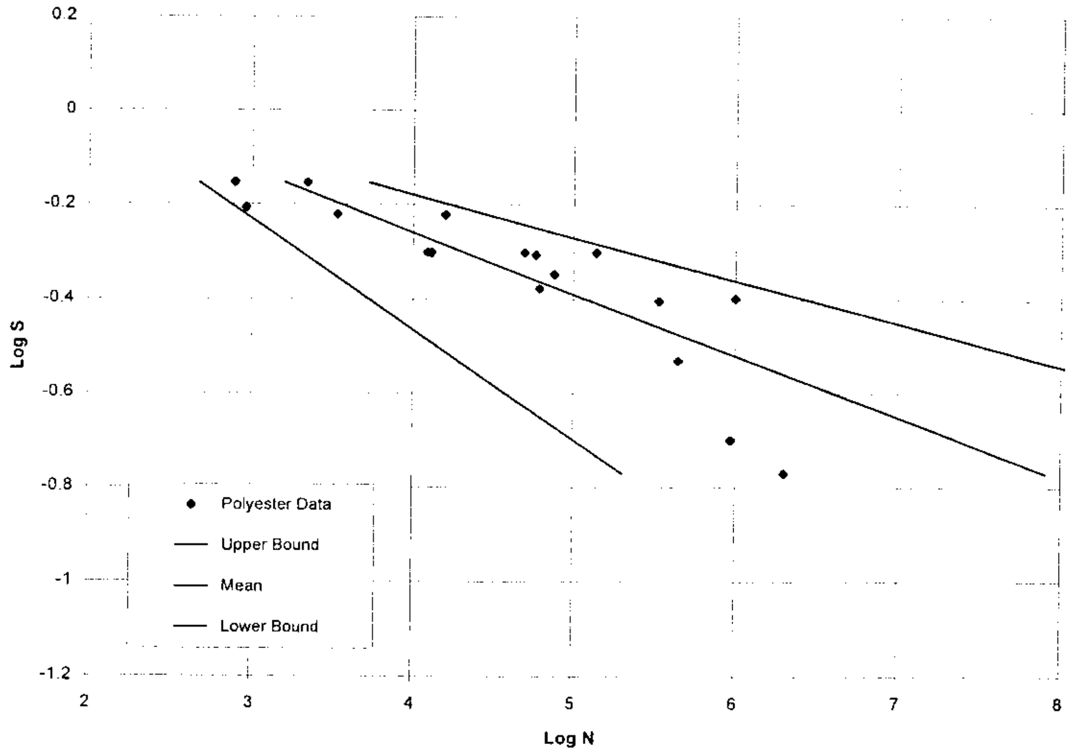


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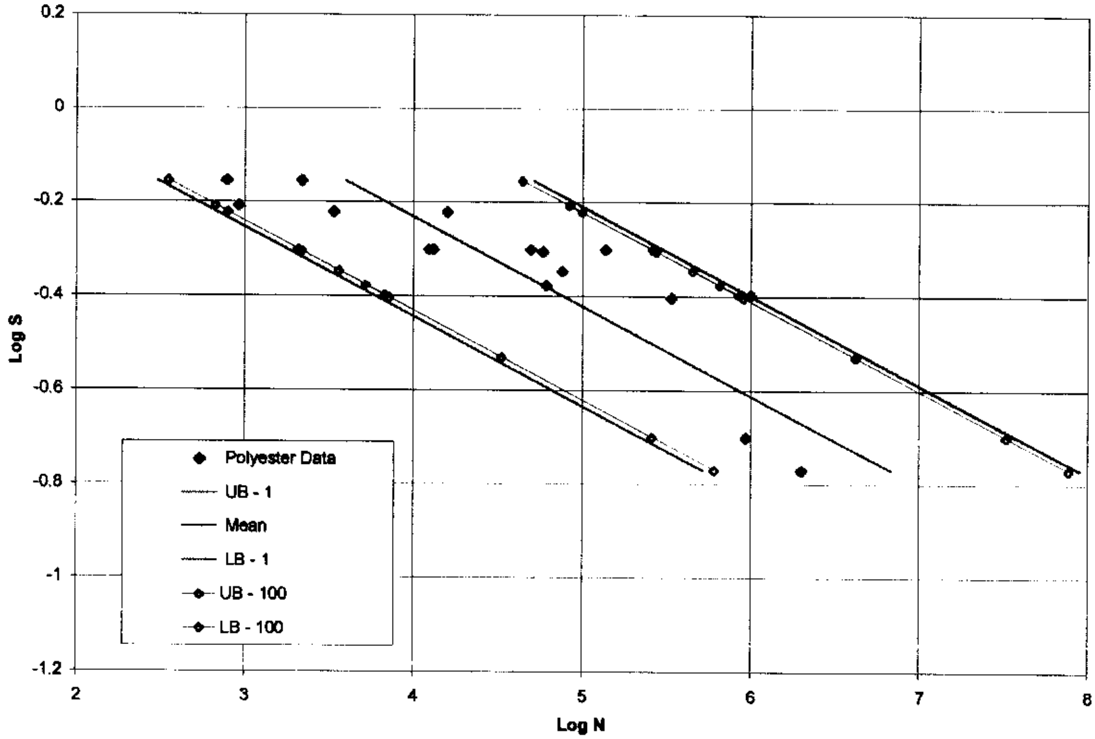
Figure 4.10 – Effect of Number of Points on Upper and Lower Bounds



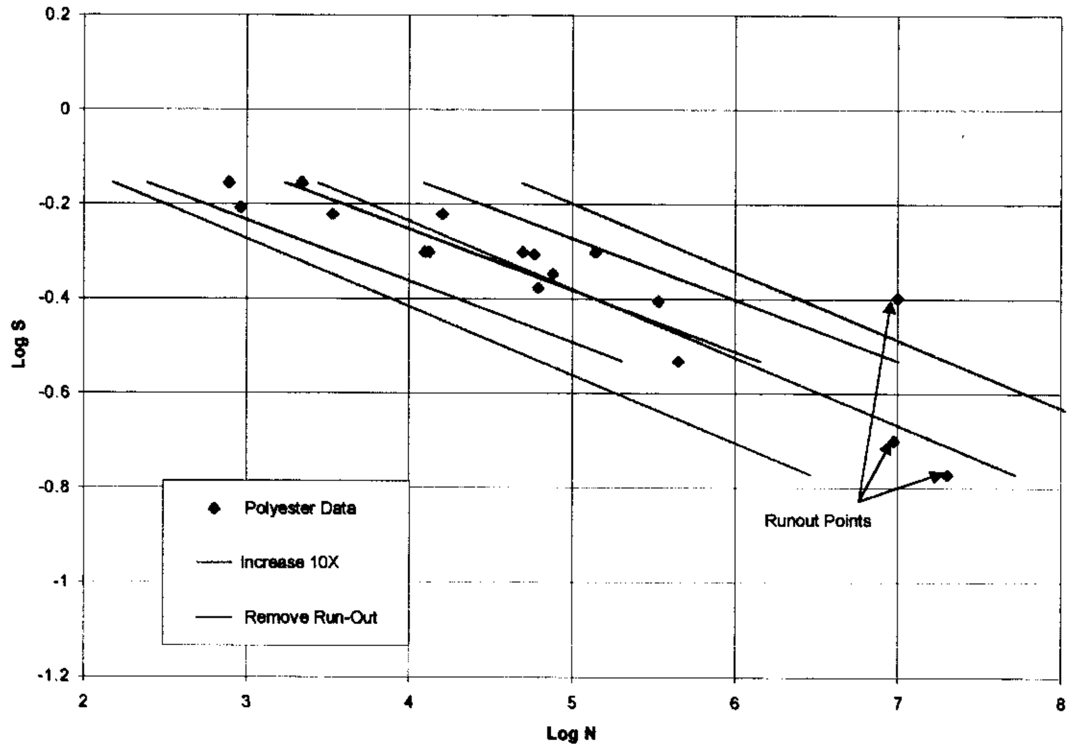
4.3.4 Effect of Censoring (Run-Out Points)

As indicated in Figure 4.5, the rightmost three data points are run-out points (tests were terminated prior to failure). Formal, mathematical methods to treat the censoring of life data in regression analysis are available [31], but require assumptions about the underlying life distribution at a given stress range. The specific distribution could be generated (theoretically) by statistical analysis of data or by relating known failure mechanisms to a particular distribution. Both of these approaches require substantially more effort in testing, or in access to subject matter experts with the appropriate phenomenological understanding of failure mechanisms.

In an attempt to gain insight into the effect of censoring, a practical, parametric approach was undertaken. Figure 4.10 presents the results of investigating the effect of different assumptions about these run-out points on the model predictions.

First, the N coordinate (life) of the run-out data points was increased by an order of magnitude to explore the impact of the hypothesis that these tests continued under identical fatigue loading to ten times the number of cycles at which the test observation was terminated. This sensitivity

Figure 4.11 – Effect of Run-Out Points

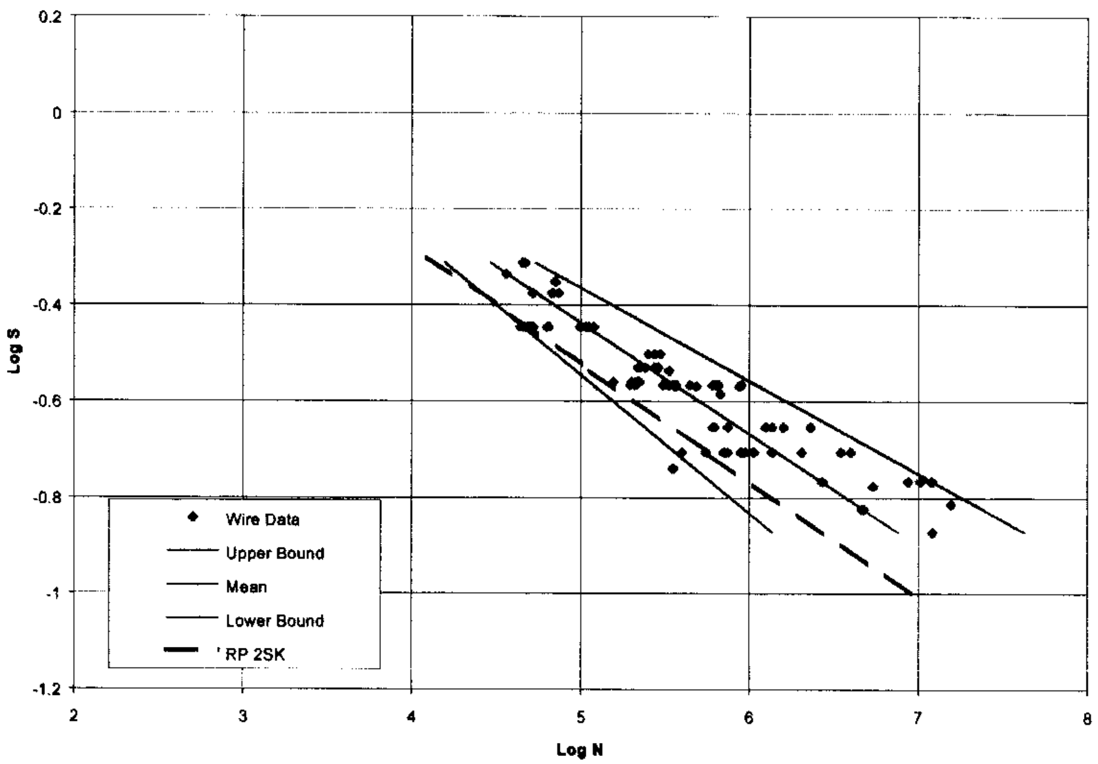


5.0 COMPARISON TO STEEL MOORINGS

5.1 Steel Data

Figure 5.1 presents a scatter diagram of the wire rope fatigue based on Noble Denton JIP [30]. The three solid lines in the plot represent the mean, and upper and lower 95% bounds of a *linear regression with variable variation* of the life, log N, on the stress, log S. Also shown in the figure is the RP 2SK S-N curve, which is represented by the dashed line.

Figure 5.1 – Wire Rope – Linear Regression with Variable Variation – N on S

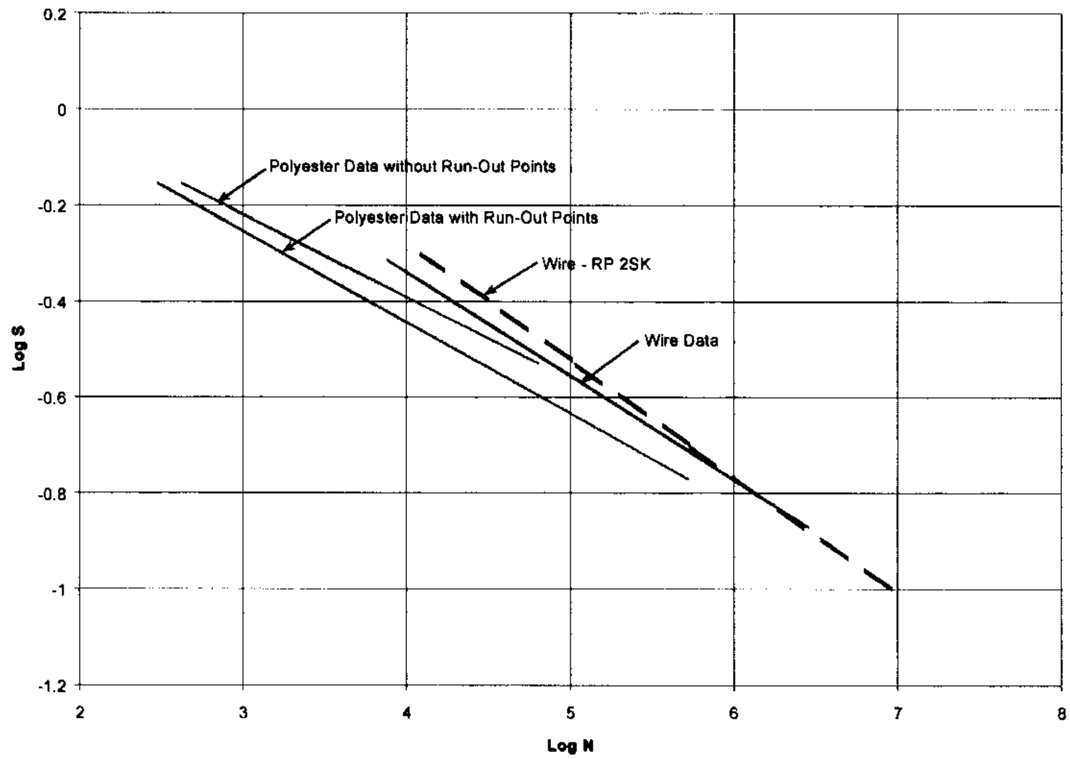


Notice the closeness of the RP 2SK curve and the lower regression analysis bound. The reason that these are not identical is a result of the fact that the data given by Chaplin [30] includes testing performed after API RP 2SK was published. Notice also the small scatter in data compared to the polyester line scatter especially in the low-stress, high-cycle range.

5.2 Comparison with Polyester

Figure 5.2 presents a comparison between the polyester and wire rope S-N curves obtained from Figures 4.8 and Figure 5.1, i.e. using a linear regression with variable variation. Polyester results are shown for lines obtained with and without run-out points (Figures 4.6 and 4.8). Again shown in dashed line is the RP 2SK curve.

Figure 5.2 – Wire vs. Polyester S-N curve – Variable Variation



The following observations may be drawn from the above figure:

- Polyester rope is predicted to have lower fatigue life than the wire rope over the range of the curve fit (range of data).
- When removing the polyester run-out data points, an S-N curve predicting higher fatigue life is obtained.
- Comparing the polyester curve with runouts to the RP 2SK design curve, there is a factor of from 7x at high stress range / low cycle fatigue to 5x at low stress range / high cycle fatigue.

Although it must be noted that practical polyester mooring systems will not be designed to experience high stress range loadings.

- It is ***not*** recommended to extrapolate the fatigue life curves far beyond the range of data used to obtain them. The curves shown in Figure 5.2 are plotted to represent these limits.

Upon first view of the resulting polyester vs. steel fatigue characteristics, it appears that the fatigue life of polyester will be less than steel wire rope. This is true for the case of like stress ranges. However, since the modulus (EA) of polyester is much greater than the modulus of steel, the motion-induced stresses in a polyester rope in deepwater taut mooring applications will be lower than that for steel and polyester could take on superior performance to a similar steel system.

6.0 GUIDELINES ON FUTURE POLYESTER ROPE DATA DEVELOPMENT

This section provides general guidelines on test procedures, primarily focusing on what measurements should be taken during a test, plus guidelines on suggested documentation during the actual tests and bedding-in procedure. These recommendations are based on findings during the data gathering stage of this project that consisted of a review of all of the available test data on polyester ropes. The available test data are discussed in Section 3.0 and summarized in Table 3.1.

Based on review of the available test data on polyester ropes, it becomes evident there is a need for additional testing. Furthermore, it becomes evident that when these future tests are conducted a more rigorous measurement and documentation procedure should be adhered to. Additionally, testing standards must be agreed upon and adhered to for all future testing. This will assure that all tests, regardless of what rope size, rope construction, or particular joint industry project the data was collected from, will be comparable.

Eight recommendations are presented below. An attempt has been made to provide these in the order of importance. Some of the recommendations provided below may seem quite simple and easily overcome by a common sense approach, but the review of the available test data indicated that there is a need for adequate control and quality assurance in these areas.

6.1 Documentation of the Complete Rope Test History

The one major difference between the behavior of polyester ropes and typical steel wire ropes is the polyester rope's dependence on loading history. Generally, this key behavior of polyester ropes is only mentioned briefly in the testing reports. In many cases the polyester rope test samples are observed showing signs of recovery during rest or down times, but no accurate measurements were taken to quantify this behavior. Also there is usually not much documentation on the bedding process of polyester ropes, and their associated elongation and stiffness changes that occur during the bedding-in process.

Knowledge on how polyester ropes behaves during and after bedding-in processes and during and after high loading conditions (i.e., storms) is critical for station keeper operators. For example, during an installation of a polyester mooring system the mooring legs were only pull-tested once to design capacity (say 50% of the rope strength). What can the station-keeping operator expect to occur over the next 2 weeks or 2 months in regards to mooring line take-in or pay-out (i.e. stiffness and elongation)? If a storm is forecasted early in the life of the system, should more line be taken-in than later in the life of the system? If the mooring lines loads continue to increase after a storm has passed, should the mooring monitor systems be checked or is this a typical recovery for a polyester mooring line? Since there is some evidence that polyester ropes are dependent on load history, many of the questions posed above will need to be answered during future testing programs. This can only be done if the complete test history of a rope sample is measured and documented.

Therefore it is recommended that during any future polyester rope tests, the complete test history of a rope sample be measured and documented. This history must also include documentation of rest periods, which may help understand the rope recovery process. In all cases, the elongation of the rope must be monitored during the entire test period, to include the bedding-in process, actual testing, and any rest periods or recovery.

6.2 Documentation of the Estimated Uncertainty Bounds

For many of the tests discussed in section 3.0 the uncertainty associated with each measurement on polyester ropes is not known. Tracking the uncertainty is very important, for it gives some measurement of confidence to the measured values (i.e., identify measurement errors and their probable effect on the results). Because the uncertainty associated with the polyester tests was not determined, it is difficult to determine the uncertainty associated with rope behavior models that are developed using these data. Therefore, it is recommended that uncertainty bounds should be estimated for all reported test data. This will help focus testers on the fidelity of the data at the time of measurement.

6.3 Loading the Rope to Failure

The most useful tests in regards to developing rope life prediction models are those that are tested under constant conditions and run until rope failure. This assures that the test will produce at least one data point that can be used in developing rope models. In many cases, the available data did not provide many data points that could be used directly in a life prediction model. Because of the lack of useful data points, assumptions had to be made to help increase the number of data points in the development of the life prediction models.

An example was the assumption that there are no load history effects in polyester ropes. This assumption was used to help increase the number of data points in the development of the Strain Method life prediction model. This assumption allowed the test data from the Norsk Hydro JIP to be used. In these tests, one rope sample was subjected to numerous runs under different load ranges, mean loads, and frequencies, and none of the tests were run to failure. Thus with this assumption that the prior loading history could be ignored, each data point (i.e. elongation for given number of cycles) could be used in the development of the model. Obviously, there are limitations in any model when such assumption must be used.

Therefore, it is recommended all tests must be loaded to failure. This may be a cyclic test with a load that causes the rope to fail or a test where the cyclic testing is ended and then break tested. In both cases, a very useful data point is developed. For a cyclic tension-to-tension fatigue test that is cycled to failure, a data point for that load range, frequency, and mean load can now be added to a database in the development of a endurance curve (e.g., S-N or T-N curve) for polyester ropes. If a cyclic test is ended after a given number of cycles, a break test should be performed. This type of testing will help in development of a database which relates the retained break strength to number of cycles at a given frequency, mean load and load range. The development of both databases is crucial in the uphill battle of gaining knowledge and industry acceptance of polyester ropes for permanent mooring applications.

It should be noted that there are types of testing that do not help in the development of the above mentioned databases, even though the testing process eventually loaded the rope to failure. An example of this type of testing was the O.C.I.M.F. Hawser testing conducted in the early 80's. For this test program, various synthetic ropes were subjected to cyclic loading at load ranges from 50% NBS to 80% NBS for one thousand cycles. If the rope did not fail, the peak-to-peak load range was increased by 10% and cycled again for one thousand cycles. This process was repeated until the rope failed. Based on these tests, the synthetic ropes were classed by the load level or range achieved during the testing. This was known as the Thousand Cycle Load Level or TCLL. This type of testing provides a cheap and efficient means of comparing the performance of various types of synthetic ropes, but it does not generate the kind of test data that is needed to develop the above mentioned databases.

6.4 Abrasion Protection at the Eye Termination

It is recommended that all break strength and fatigue tests have some type of industry accepted abrasion protection at the eye termination. This recommendation may fall into the category of common sense, but many of the tests conducted on polyester ropes with looped and spliced terminations and reported in this study had either no abrasion protection or some ad hoc protection that was added when problems were observed in previous test. Most of the cyclic fatigue tests and many of the break strength tests failed from problems related to abrasion at the eye. Thus, the external abrasion characteristics of the rope are being measured during these test rather than the fatigue or break strength of the rope.

Not only should the eye have some type of abrasion protection, it should have an abrasion protection material that is of a specific thickness, weave, and application that is accepted by the industry. Furthermore, this same type of abrasion protection should be used from test program to test program. This will assure the break strength data or fatigue data between test programs is compatible with none of the tests being skewed higher or lower due to differences in termination performance.

6.5 Documentation of Rope Specimen Length

It is recommended that for each test specimen the lengths of the splices, eyes, and rope be accurately documented. This is very important since most of the stiffness and elongation measurements are obtained using the pin-to-pin lengths which include the terminations (i.e. eyes, splices, pin diameter, etc). These stiffness and elongation measurements may need to be corrected based on the splice to free rope length ratio. Typically, one can expect a wider variance in overall length tolerances for rope test samples that have looped and spliced terminations than with other types of terminations. This is because looped and spliced terminations require the rope to be looped back and spliced into the free length of the rope. The number of tucks, types of tucks, splice length, etc., all influence the pin-to-pin length of a looped and spliced rope.

6.6 Measurement and Documentation of Bedding-in Process

It is recommended that the bedding-in process be well monitored (i.e., elongation and stiffness measurements) and be documented during all break and fatigue tests. It is also recommended that the bedding-in process be consistent for all test types, for example, cycling the rope specimen 10 times to 50% nominal break strength prior to conducting any tests.

The importance of measuring and documenting the bedding-in process is summarized in the following:

- This assures the comparison of elongation and stiffness data between ropes is accurate. For example, if the bedding-in process for one rope is different than another there may be differences in break strength load/elongation or stiffness measurements between the two samples.
- Monitoring the elongation of rope specimens throughout the entire testing, including the bedding-in process, will help in determining if there is actually a strain failure mechanism that can be used to predict the life of a polyester rope (i.e., failure will occur in the rope at a given strain regardless of load history).
- These data will help determine the required bedding-in procedures that will be needed during the mooring installation. Acquisition of these data will also help in predicting the behavior of the rope during the initial operation of the mooring system (shortly after the synthetic mooring installation).

6.7 Development of Guidelines for Rope Bedding-in

It is recommended that guidelines for rope bedding-in be developed and adhered to from test to test and JIP to JIP. This will assure that all tests (no matter what the rope size, rope construction, or particular JIP the data was collected from) will be comparable. For some of the available test data reviewed in this report, the rope bedding-in procedure consisted of 10 cycles to 50% the ropes NBS. This bedding in procedure follows the bedding procedure outlined in the O.C.I.M.F. Hawser Standards Development Program [11]. However, some of the available tests were not bedded-in this manner, nor were they documented.

6.8 Rope Terminations

It is recommended that all future rope tests be conducted using end terminations similar to those that will be used on the large-scale ropes. Typically, large scale ropes (5" diameter and greater) have looped and spliced terminations. Currently, there are no other types of terminations used on large-scale ropes. Therefore, it is recommended that all small-scale rope tests that will be used to extrapolate endurance and strength performance to large ropes should have the same type of end terminations (i.e., looped and spliced). This is very important since it has been seen that most of the rope failures that occurring under test conditions occur in the termination region. Much of the available polyester rope test data, especially in Fibre Tethers 2000, is for ropes with terminations other than looped and spliced. These data are useful in comparing performance between termination types on small diameter ropes, but they are not useful in gauging the performance of large diameter rope with looped and spliced terminations.

It should be noted that small-scale rope tests with terminations other than looped and spliced (e.g. resign socket or barrel and spike) may be useful in gathering data on actual rope stiffness and elongation. This is because these types of terminations have no splices or eyes. Therefore most of the length between the pins is the free length of the rope. Additionally, tests on polyester ropes with terminations other than looped and spliced may be useful when these type of terminations have evolved to accommodate the large diameter ropes.

7.0 CONCLUSIONS

This joint industry project depended highly upon data in existence within the offshore industry. Several different approaches to analyzing this data and using it in model predictions of reliability were accomplished.

7.1 Failure Mechanisms

A comprehensive review of failure mechanisms was performed and the state of knowledge regarding polyester is captured in Table 7.1 below. This JIP focused on tension fatigue.

Table 7.1 State of Knowledge of Failure Mechanisms

Mechanism	State of Knowledge
Abrasion at Termination	Design – protection
Abrasion due to Sediment within Rope Body	Operational (Installation) Issue
Axial Compression Fatigue	Further Study
Creep Rupture	Include
Fishbite Damage	Further Study
Heat Build-up	Design Issue
Hydrolysis	Further Study
Installation Damage	Operational Issue
Material or Fiber Fatigue	Include
Splice Slippage at Termination	Design – limiting strength
Ultraviolet Light Exposure	Design – no exposure

7.2 Polyester Database

From review of all the data made available to EQE by participating JIP sponsors, a database was developed that compiled results from tension fatigue tests, static break load tests and load extension tests together in a single comparable format. As much of the data used to assemble this database was generated for specific purposes and not necessarily to employ in life prediction models, it was expected that there would be significant variance in model predictions.

7.3 Recommendations For Future Testing

A number of recommendations regarding future testing, from the viewpoint of the reliability engineer, were concluded from this study:

- Documentation of the complete rope specimen test history (including recovery periods between tests) is curtail for polyester ropes.
- Estimate and record the uncertainty associated with each rope test measurement
- As often is practical, test polyester rope specimens to failure
- Provide abrasion protection at the eye termination of all rope specimens
- Accurately document rope specimen length
- Measure and document the bedding-in process
- Develop standardized procedures and guidelines for rope specimen bedding-in
- Test specimens that have terminations that are similar to those expected to be used in field.

7.4 Strain-to-Failure Model

A Strain-to-failure model was postulated in this work that appears to have some merit based upon data analysis results. Further investigation into the physical and mechanistic plausibility of such a theory should be undertaken.

The predictive task of this project culminated in a simple fatigue life model, using a collection of data collected under dissimilar conditions and for different purposes. Being dependent upon this database, the predictive model is accompanied by substantial (much greater than steel mooring systems) uncertainty in fatigue life estimates. Any use of this model and the associated parameter estimates should be used with due consideration to the application-specific features of the user.

7.5 Regression Issues

In developing simple regression fits to the TN curve for polyester, it was discovered that a substantial amount of analogous work has been published for wire rope treating the stress range as the random variable, which is incorrect. Fatigue life (cycles) should be the random variable in analyzing this type of data. For relatively large detests that could be characterized as having moderate variance, improper regression of S on N (i.e. treating S as random) does not introduce a large error. However, for this database of polyester rope test data, there is a significant difference between the results obtained by treating S random vs. treating N random.

7.6 Sample Size Sensitivity

In addition to the regression issue, this data set for polyester rope also exhibited an increasing (non-constant) variance with increasing N. This was modeled using standard techniques and generated more accurate confidence intervals than the typical constant variance approach.

The data set began with 62 data points, and after removal of inconsistent data (from an engineering point of view), resulted in only 17 points. Concern over the uncertainty in predictions based upon this small sample size motivated sensitivity testing on number of observations. Predictions of confidence intervals were made using a hundred times the number of data points, yet with the same coordinates. Only insignificant changes in the upper and lower bounds result from the increase of the number of points, which indicated that the scatter in the data is the main factor controlling the uncertainty in predicting fatigue life.

7.7 Addressing Runouts

Three of the high cycle data points were runouts. The sensitivity of predicted results to the mathematical treatment of these runout points was investigated in two ways.

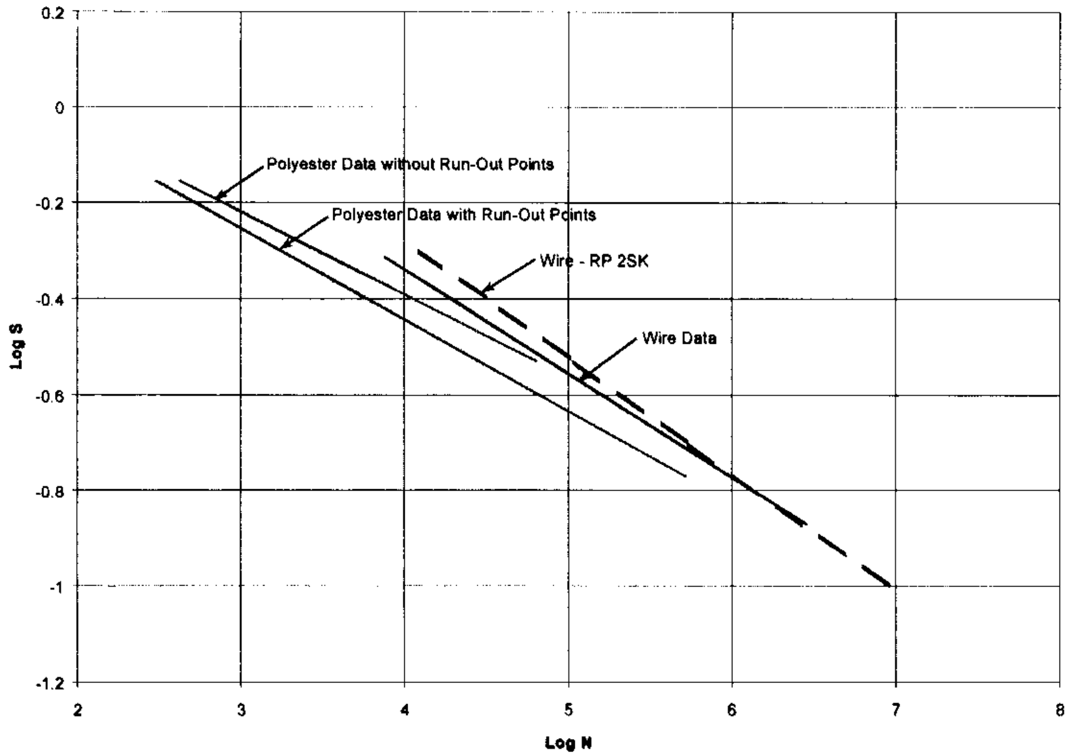
- First, the N coordinate (life) of the run-out data points was increased by an order of magnitude. This resulted in an increase in predicted fatigue life of more than a factor of five at one million cycles.
- Second, the run-out points were removed altogether. The resulting effect of removal of the runouts was a future increase of the lower bound line from the original calculation by an additional factor of five over the extension of the runouts, of ten times the original lower bound.

This clearly implies that the low stress—high cycle fatigue experiments are not behaving in the same manner as the high stress low cycle data. The effect of including them in the same data set is to predict decreasing fatigue life with lower stress ranges.

7.8 Comparison to Wire Rope

Polyester rope fatigue life was compared to wire rope as shown in Figure 7.2 (see Chapter 5). Polyester results are shown for lines obtained with and without run-out points.

Figure 7.2 – Wire vs. Polyester S-N curve – Variable Variation



The following observations may be drawn from the above figure:

- Polyester rope is predicted to have lower fatigue life than the wire rope over the range of the curve fit (range of data).
- When removing the polyester run-out data points, an S-N curve predicting higher fatigue life is obtained.
- Comparing the polyester curve with runouts to the RP 2SK design curve, there is a factor of from 7x at high stress range / low cycle fatigue to 5x at low stress range / high cycle fatigue. Although it must be noted that practical polyester mooring systems will not be designed to experience high stress range loadings.
- It is ***not*** recommended to extrapolate the fatigue life curves far beyond the range of data used to obtain them. The curves shown in Figure 5.2 are plotted to represent these limits.

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APPENDIX A

COMPARISON TO

"TENSION-TENSION FATIGUE RESULTS IN RELIABILITY OF MOORING SYSTEMS: APPLICATION TO POLYESTER MOORINGS" (OTC 10777)

December 22, 1999 Transmittal No.: AJW-99-193

To: Distribution

Subject: DATA ANALYSIS FOR POLYESTER ROPES

This letter contains a succinct summary of the most recent activities that were assigned to EQE at the May 4th JIP Steering Committee meeting of the Polyester Moorings Reliability project meeting. At that time EQE was tasked with resolving the difference in the tension – tension fatigue results in our study and that presented in *Reliability of Mooring Systems: Application to Polyester Moorings*, by Snell, et al. (OTC 10777).

The attached are a set of plots resulting from regression analysis that was performed on data available through the polyester mooring JIP, and additional data provided to EQE from BP-Amoco.

Figure 1: TTI Data –S Random
Shows the TTI data provided by BP-Amoco in June with the regression analysis performed with S treated as the random variable. Note that the ***mean*** curve in this case matches the curve published in OTC 10777. Note also that the inverse Log-Log slope of the curves resulting from this regression analysis is 19.5.

Figure 2: TTI Data –N Random
Shows the TTI data provided by BP-Amoco in June with the regression analysis performed with N as Random. Note the widening of the upper and lower confidence limits and the change in slope of these as compared to Figure 1.

EQE staff, as well as individuals withinBP-Amoco, have verified that N should be treated as the random variable. The verification has been via numerous sources including textbooks and discussions with experts such as Prof. Paul Worshing and Prof. Allin Comell. It is a standard statistical treatment of the unknown (life) test variable – in this case, cycles to failure.

Figure 3: EQE-Assembled JIP Data –N Random
Shows the JIP data with the regression analysis using N as Random. The mean curve as well as the mean +/- 2 std. dev. curves are shown. Note that the inverse Log-Log slope of the curves generated by EQE is 5.33 for the polyester mooring. This can be compared to the API X and X' curves for steel which have an inverse Log-Log slope of 4.38 and 3.74 respectively. (See API-RP2A)

Figure 4: Comparison -- TTI, JIP & Wire

The results from the above three figures are compared to the RP-2SK curve. Note the curves shown are mean and mean minus two standard deviations. This figure captures the very large shift to lower fatigue lives and much steeper slope using the TTI database and treating N as random. The TTI lower bound curve is a factor of 2 lower than the JIP at 1000 cycles, and diverges greatly toward higher cycle values.

Figure 5: Comparison -- API, JIP & Wire

EQE results (May 5, 1999) and the results presented in the August 12 Draft figure 5.2 of API RP 2SM compare exactly for regression of dataset EXCLUDING runouts.

The above does not address the quality of the data itself, only the proper analytical treatment of this data. The JIP project report addresses data quality explicitly. The above data and analyses complete EQEs required action items. I intend to issue the final JIP report by September 10, 1999. Please contact me regarding any of the information in this letter, or the May Draft. Thank you for your input and assistance in this matter.

Sincerely,
EQE International, Inc.

Andrew J. Wolford, ScD
Senior Consultant

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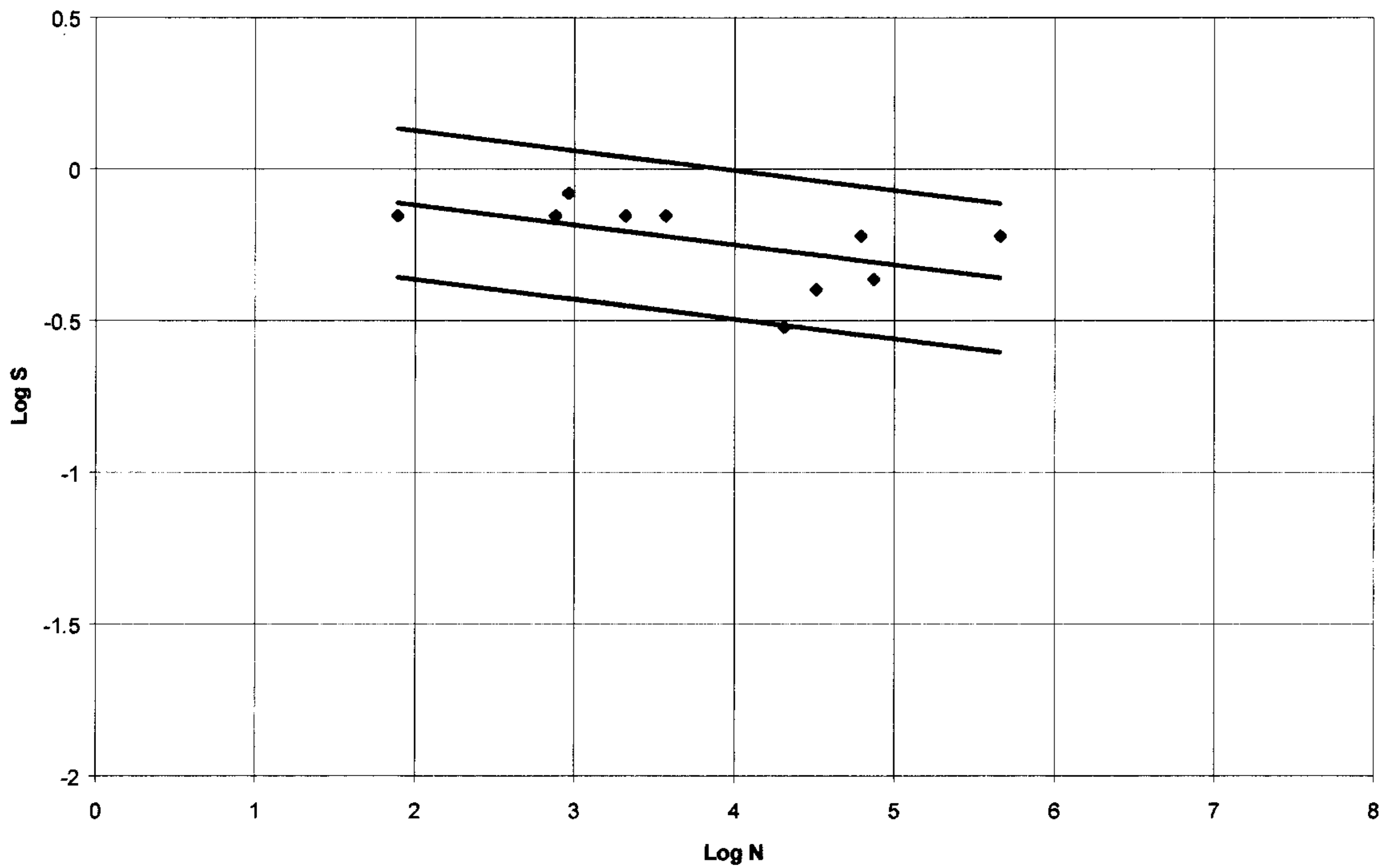
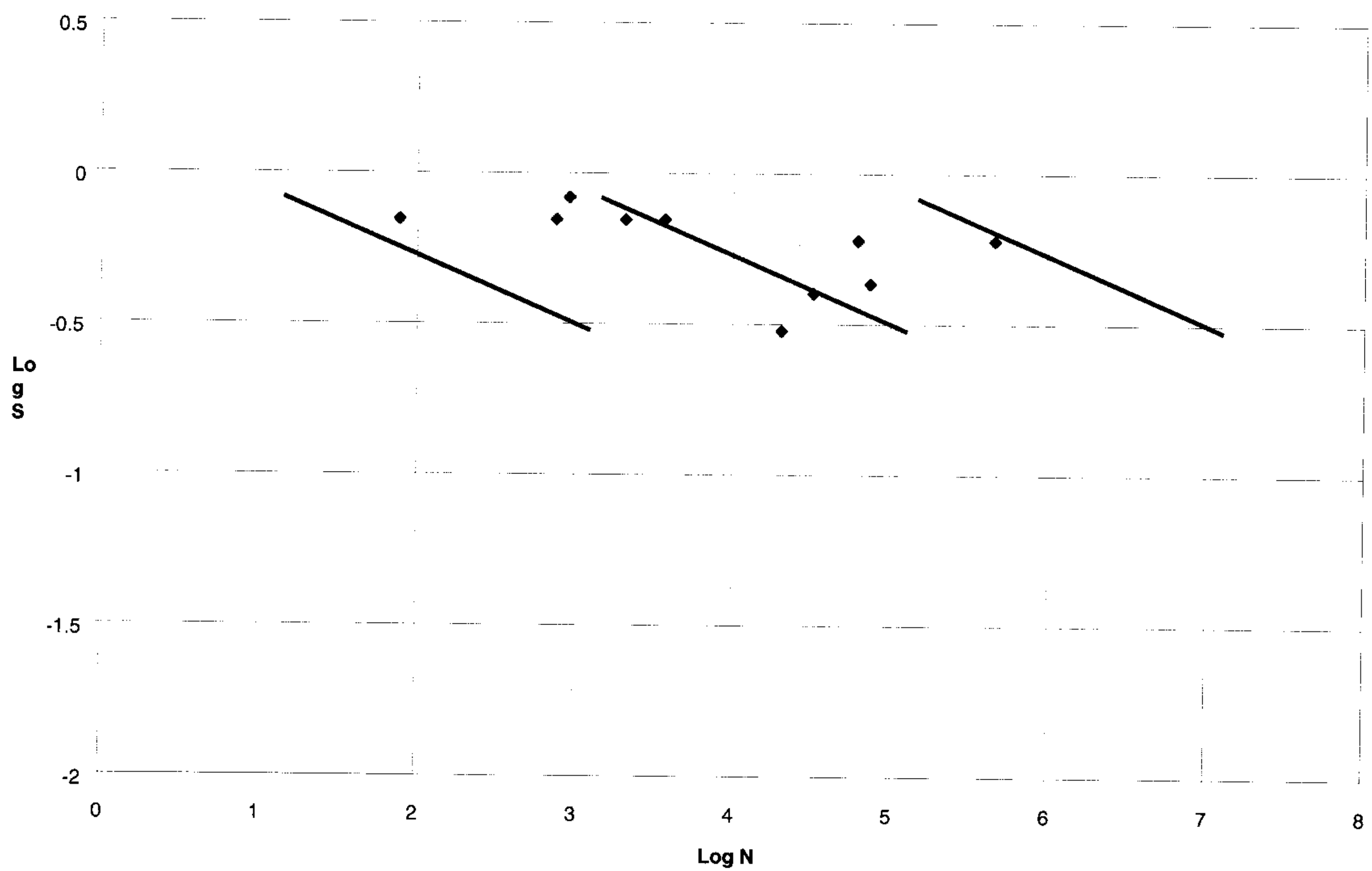
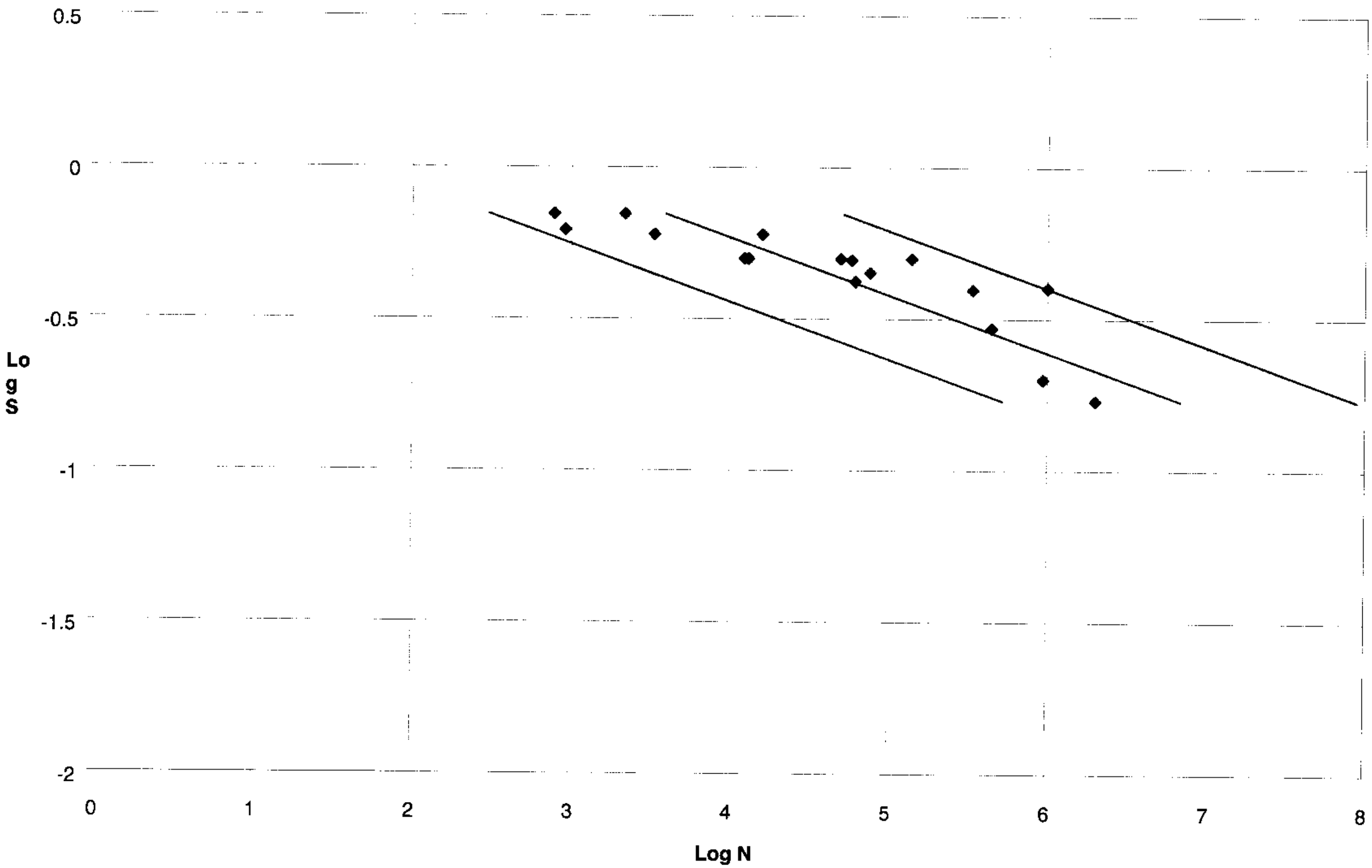
TTI Data - Incorrect Fit with S Random

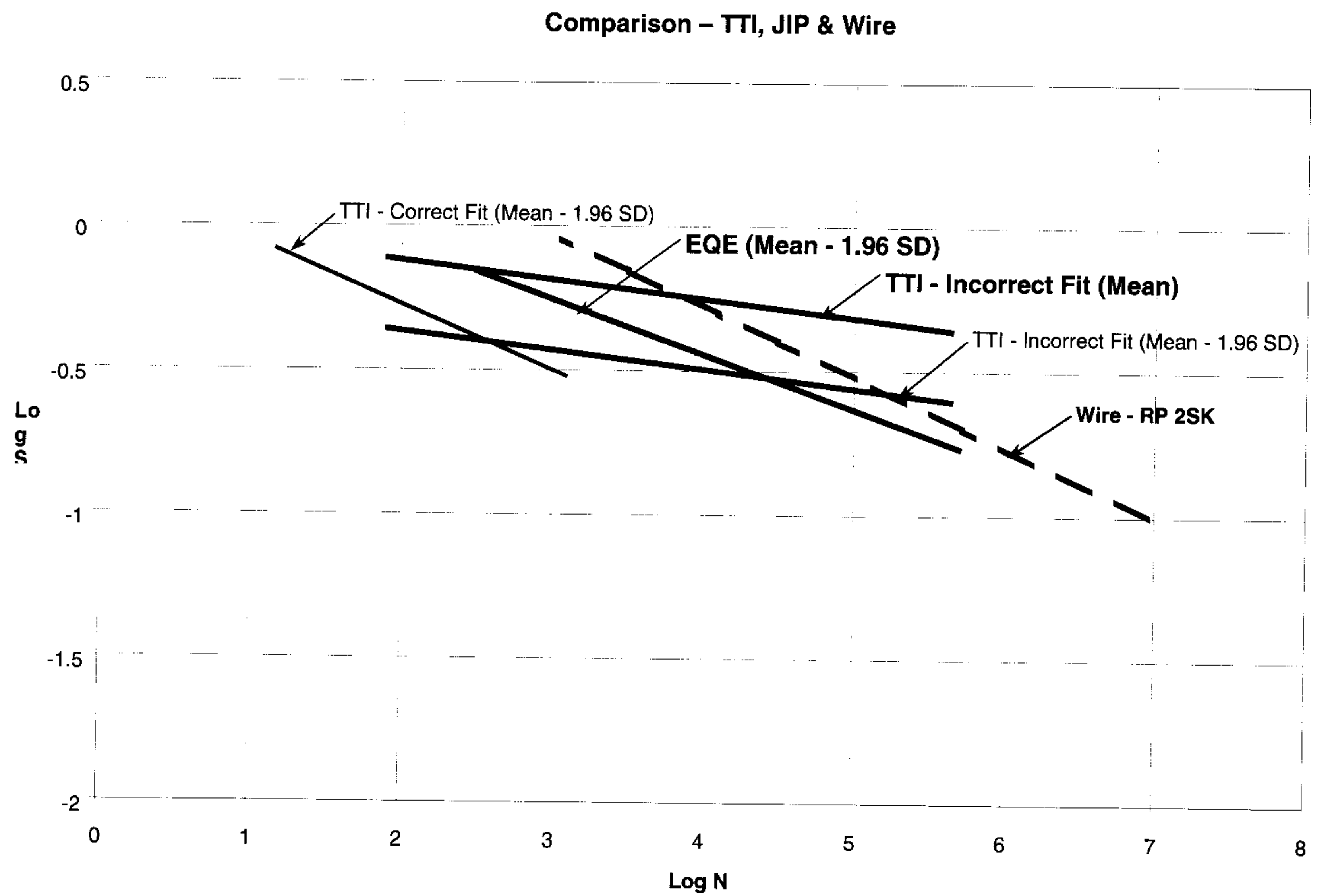


TTI Data - Correct Fit with N Random



JIP Data - Correct Fit with N Random




Comparison – TTI, JIP & Wire
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Log N
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EQE (Mean - 1.96 SD)
TTI - Incorrect Fit (Mean)
TTI - Incorrect Fit (Mean - 1.96 SD)
Wire - RP 2SK

Comparison – API, JIP & Wire