Awwa Research Foundation
Advancing the Science of Water®

EPA

Failure of Prestressed Concrete Cylinder Pipe

Subject Area:
Infrastructure Reliability

Failure of Prestressed Concrete Cylinder Pipe

Awwa Research Foundation

About the Awwa Research Foundation

The Awwa Research Foundation (AwwaRF) is a member-supported, international, nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

The Foundation's mission is to advance the science of water to improve the quality of life. To achieve this mission, the Foundation sponsors studies on all aspects of drinking water, including supply and resources, treatment, monitoring and analysis, distribution, management, and health effects. Funding for research is provided primarily by subscription payments from approximately 1,000 utilities, consulting firms, and manufacturers in North America and abroad. Additional funding comes from collaborative partnerships with other national and international organizations, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated. Government funding serves as a third source of research dollars.

From its headquarters in Denver, Colorado, the Foundation's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

The results of research are disseminated through a number of channels, including reports, the Web site, conferences, and periodicals.

For subscribers, the Foundation serves as a cooperative program in which water suppliers unite to pool their resources. By applying Foundation research findings, these water suppliers can save substantial costs and stay on the leading edge of drinking water science and technology. Since its inception, AwwaRF has supplied the water community with more than $300 million in applied research.

More information about the Foundation and how to become a subscriber is available on the Web at **www.awwarf.org.**

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FOREWORD

The Awwa Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation (USBR), and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

BACKGROUND

The report of water pipelines failing can be sensational, particularly where the resulting flood damage provides spectacular footage for the 10 o'clock news. These failures, some of which are prestressed concrete cylinder pipe (PCCP), also cost significant sums for repair and eventual pipeline replacement. These failures can wash out parallel sanitary sewers, which present a public health problem due to the possible contamination of the drinking water supply, and can also destroy private property (Henry, Miller, and Do 2005; Ortega, Henry, and Hovsepian 2005). Corroded or damaged PCCP pipelines have explosively failed during rapid changes in pipeline operation.

PCCP tends to be of large diameter, making failures of this type of pipe relatively catastrophic and costly. To date, most research has been focused on PCCP inspection technologies and performance prediction in order to minimize the risk to utilities from failures. The performance of PCCP has been an item of interest to water utilities for a long time. Fifteen years ago, Awwa Research Foundation (AwwaRF) and the Bureau of Reclamation initiated a study, "Performance of Prestressed Concrete Pipe" that was unfortunately never published (summary statistics were separately published by the Bureau of Reclamation). This study is intended to disseminate some of the answers that were to be provided by that study and to provide more complete data useful for the prediction of PCCP service life.

RESEARCH OBJECTIVES

This report presents data collected from this study, as well as expands upon previous studies on PCCP failures. The project began with a survey of a selected group of water utilities with a fair amount of PCCP in their systems, selected carefully to represent the range of conditions and variables that affect PCCP performance across North America. The survey results, combined with a database of 592 PCCP failures, were statistically projected over the installed PCCP base of North America and provide a surprising indicator of failures and failure rate of PCCP.

A timeline was developed to determine when PCCP was made, when it failed, and what events (such as changes to design and material standards) may have affected its performance. This timeline was statistically analyzed against the failure data.

SIGNIFICANCE TO WATER UTILITIES

PCCP users know that they have a potential problem. Every pipe has a story to tell. Central to the cause of problems in waterworks are incomplete data, which would otherwise allow rational decision-making. The problem is that the data are dispersed and diffuse. Thus, a primary goal of this study was to collect the data and put it into place at one time.

APPROACH

A survey and workshop were conducted, including water utilities with a fair amount of PCCP in their systems. The objective was to make this a utility/user-driven project, utilizing the following approach:

- Define and find the failures, however and wherever possible.
- Solicit, collect, and review all possible information about PCCP design, operation, and failures.
- Scrutinize and summarize what is "known."
- Understand and state what is "not known."
- Report what was concluded by others.
- Take a critical look at the conclusions in light of the increasing knowledge base.
- Use statistical tests to determine important factors and begin predictive modeling.

CAUSES AND MODES OF FAILURE

Similar to the human population, each individual pipe section has a birth (manufacturing) to death cycle that is affected by its heredity (design, manufacturer, materials, etc.), birth defects (construction, installation), and lifestyle (operations and maintenance, etc.). For the purposes of this study, failure has been defined as the loss of use of a pipe section or reduction in confidence in that pipe section to remain in service, after discovery of a pipe section deficiency. This includes repair, replacement, or reduction in operating pressure.

Three categories or models of PCCP failure were defined:

1. Catastrophic ruptures and leaks (Category 1)
2. Significant deterioration or structural weakness discerned by inspection (Category 2) by
    - Visual, sounding, and accidental discovery
    - Electronic inspections
3. Loss of service (Category 3)
    - Time out of service
    - Full or partial replacement

The reasons cited by PCCP owners for the failures that they experienced are many. They included:

- Rupture or break – broken wires found after the failure – many causes
- Leaking at joints – many causes including out-of-roundness of joint and construction damage
- Cracks in core – many causes including alkali-silica reactivity of the aggregate
- Low quality of core – poor concrete strength
- H_2S (force mains) – unlined
- Dented cylinder – fabrication and construction
- Cracks in cylinder welds – poor cylinder fit-up

- Low quality of wires – not just Type IV
- Overwrapping of wire – inadequate total prestress
- Wire spliced and restressed – inadequate total prestress
- Low quality of mortar – low density, low thickness, and low cement content
- High chlorides in soil – corrosive/aggressive soil inappropriate for mortar-coated pipe
- Inadequate joint restraint – pipe moved exposing joint to environment
- Construction damage – coatings damaged and not repaired
- Coating delamination – many causes
- Hydrogen embrittlement of wire – excessive cathodic protection applied to susceptible wire
- Inadequate prestress – wires broken and spliced without retensioning resulting in low core compression
- Cantilever (bending or broken back) – many causes including poor bedding
- Settlement – general and at structures
- Poor bedding – not corresponding to design assumption
- Surge – unanticipated and above design value
- Looped gasket – joint fit-up
- Wrong pipe class – pipe laid out of order
- Cracks in joint welds – poor/no field inspection
- Hydrotest pressure in excess of design pressure
- Excess external load – greater than design assumption
- Missing joint coating

FAILURE DATABASE

The failure database has a total of 592 independent entries representing a diverse collection of Category 1, 2, and 3 failures across all data partitions and across 35 states and the District of Columbia.

To be included in the database, every entry represented one pipeline that had recorded at least one failure and a corresponding known location. No other lack of information precluded the entry from the database.

Of the 592 independent entries, the database includes 435 Category 1 failures, or 61.1 percent of the entries. There were 35,662 Categories 2 and 3 failures, or 45.3 percent of the entries. Thirty-eight of the entries, or 6.5 percent, specified both a Category 1 and a Categories 2 and 3 failure. Of all the entries, 98.3 percent of the entries had a diameter specified, 97.8 percent had a pipe type (embedded, lined, etc.) specified or assumed based on the diameter, and 92.9 percent had a wire type (Class I, II, III, or IV) specified or assumed based on the installation year. In totality, 95.9 percent had the installation date specified and 92.0 percent had a fail date specified. With these, a total of 85.6 percent of the entries had both the installation date and the fail date, such that a pipe age could be calculated.

Breaking the database into the partitions in a meaningful manner required the pipeline age. This left sample populations for further analysis grouped by ranges of dates of different versions of the AWWA PCCP standards as previously described:

DATA PARTITIONS

PCCP has had a long and diverse history with many changes in standards and materials. To account for these changes and any impact they might have had on failure rates, the failure data was analyzed in groups of years that shared similar standards and materials. These groups were:

- Pre-1955 (presumably as manufactured to AWWA 7B.2-T [1949])
- 1955–63 (presumably as manufactured to AWWA C301-55 or C301-58)
- 1964–67 (presumably as manufactured to AWWA C301-64)
- 1968–71 (presumably as manufactured to AWWA C301-64)
- 1972–78 (presumably as manufactured to AWWA C301-72)
- 1979–91 (presumably as manufactured to AWWA C301-79 or C301-84)
- 1992–2007 (presumably as manufactured to AWWA C301-92, although the Principal Investigators are aware of at least one project specified to AWWA C301-84 in 1994)

HISTOGRAMS AND SIMPLE STATISTICAL ANALYSIS

Using the sample populations, lifespan histograms were produced. When comparing all failures, it was concluded that the mode, or value that occurs most frequently, of Category 1 failures occurs in 6 to 10 years, while Categories 2 and 3 failures peak at the 26- to 30-year group. The Categories 2 and 3 failure distribution generally lags the Category 1 failure distribution by 20 years. The means were 13.95 and 16.75 years for Category 1 and Categories 2 and 3 failures, respectively.

With a total of 4,979,837 pipe produced between 1940 and 2006, the average failure rates for Category 1 and Categories 2 and 3 were 7.89×10^{-5} and 4.98×10^{-3} failures per pipe produced, respectively. This indicates statistically that within 50 years of being installed, one rupture and 66 other failures occurred for every 13,200 pipes (~50 miles of pipe).

Other histograms examine those failed pipelines that were installed within eras represented by the date of manufacture grouped by effective date of the AWWA standard. The most interesting histograms are for PCCP pipe installed in 1972–78. This timeframe represents an era when a loophole was used to use a higher wire class, Class IV, while still adhering to the standard. Over three times as many Category 1 failures occurred from this time period than from the other manufacturing eras.

Another histogram examines failures as a function of wire class. It was observed that the highest frequency of Category 1 failures occurred with Class IV wire. The second highest frequency of failures occurred with Class II wire. For Categories 2 and 3 failures, the highest occurrence of failures also occurred with Class IV wire. The second highest frequency of failures occurred with Class III wire. The least number of Categories 2 and 3 failures were reported for Class II wire.

PREDICTING SERVICE LIFE

Histograms and simple statistical analyses examined failures that had already occurred. Histograms visualize the existing data. The next progression was to utilize these failure data to forecast future occurrences by cumulative frequency distributions, expressed graphically in a line

graph called an ogive. Ogive uses historical data to make predictions based only on what failed (no credit given for the population that is still in service). The ogive plots cumulative frequency versus the upper boundary of a class. The cumulative frequency of PCCP failures were plotted for each sample population as a function of age.

In order to predict future failure rates, Weibull probability distributions were developed for the sample populations. Weibull gives credit for population still in service and allows prediction of failure probability as a function of age. Weibulls are expressed graphically as unreliability, or probability of failure, versus time on a log-log graph—a graph with logarithmic scales on both axes. Then probabilities were determined for select populations for failures 10 and 100 years of age.

ASSESSMENT MATRICES

A full-day workshop was held with participating utilities on January 31, 2007 at the Underground Technology Conference, Houston, Texas. Representatives of 15 utilities participated in the review of the project goals, definitions, and the draft utility assessment protocol. Those participating represent approximately 6 percent of the PCCP installed (by linear feet).

In the workshop, the participating utilities were asked, in their opinions, what were the most important factors related to PCCP failures experienced within their systems. Their responses were:

- Owner's risk factors (for material): Wire class and size (No. 1), manufacturer (No. 2), slurry under wire (No. 3). Also cited were lining cast vs. sprayed, cylinder thickness, age or date of manufacture (birth), presence of electrical bonding, quality of external coating, plant vs. site manufactured pipe, and core quality.
- Owner's inspection and installation factors: inspection and records (No. 1), contractor (No. 2), pressure class, quality of backfill, handling/transportation, joint mortaring/diapering, and electrical continuity. Also cited was the presence of physical preloading (or tension in the wire) actually present in the wire.
- Environmental/operations factors: Surge (No. 1), soil (No. 2), cathodic protection/interference, fluctuating groundwater, surcharging (right-of-way) management, appurtenance maintenance, ground movement, internal corrosion of core, and underground to aboveground transition (aerials).
- Maintenance factors: Postconstruction inspection and monitoring (No. 1), data analysis/study, life extension (rehabilitation/repair), design reanalysis.

The participants stressed that in many instances, although it was clear that many factors influence the longevity of PCCP, there is limited information available for many pipelines. Poor recordkeeping is the norm, and reconstructing the information even when available is time-consuming. The participants requested that a two-tier approach be developed, one quickly determined assessment, and another more extensive initial assessment based upon acquisition and review of available data. The intent is to be able to determine what, if anything, needs to be evaluated for any particular pipeline constructed of PCCP. The methodology is equally applicable to lined-cylinder type PCCP (LC-PCCP) and embedded-cylinder type PCCP (EC-PCCP).

The short form assessment matrix that was developed addresses the top five factors that are both likely to be known about a PCCP pipeline and which have a significant effect on the pipeline. The longer form assessment matrix addresses many of the factors that are both likely to be known (or can be discovered with examination of records) about a PCCP pipeline and which have a significant effect on the pipeline.

The final assessment forms were utilized to evaluate 22 pipelines. Examining the scores of the long-form assessments it became clear that those that scored below zero had multiple problems. What was most curious about those with high scores that still experienced failures was that the common thread was excessive surge pressures. Examination of the contract documents of those also revealed little evidence of design consideration for the surge or the hydrostatic test as design conditions. Those two items are red flags waving. Clearly, a PCCP pipeline can have one or two negatives against it and fail, for the weight of the positives may not override the weaknesses in the system.

The checklists are thus not intended to be a definitive failure predictor, rather, part of a multiphased approach. The intent is to provide a tool to the PCCP-owning utility to do a preliminary self-assessment of its pipelines (using the short form) followed if indicated by a more refined self-assessment. It was not uncommon for utilities to include with their assessments comments similar to “One thing this showed us is that we don't have nearly as much info as we should.” Carefully completed, it is intended that the assessment checklists, both long and short form, will be useful as pipe inspection and maintenance prioritization tools and possible input to risk assessment of PCCP pipelines.

CONCLUSIONS

The initial design basis for manufacture of PCCP appeared to be conservative, and as experience was gained and competitiveness with other pipe materials increased, changes were made in the standard to reduce the unit cost of manufacture. Those changes tended to increase the stress level in the pipe at working pressures and reduced the margin for error. The result was a significantly increased rate of failure for pipe installed between 1971 and 1979. Fully 50 percent of the catastrophic leaks and breaks recorded were manufactured or installed between those years.

The trend toward reduced conservatism of the product through revisions in the standard began to reverse course in 1984 with the issuance of AWWA C301-84. That year saw the allowable additions of fly ash and other pozzolans in an attempt to increase the density of the concrete coating and core, the incorporation of ASTM C33 for concrete and mortar aggregate requirements, the slurry placement under the wire, and the minimum coating thickness increased to 3/4 inch. Significant revisions to the standard in 1992 and adoption of the very detailed design standard C304-92 appear to have resulted in much improved performance of as-installed PCCP. The statistics are summarized in the following table:

Summary statistics

	Failures by Age										Failures by Install Date	
	All 1942-2007	pre-1955	1955–63	1964–67	1968–71	All 1972–78	Interpace 1972–78	Unknown & non-Interpace 1972–78	1979–91	1992–2007	Failures	Normalized failures
Category 1												
Sample pop. (ruptures)	393	32	40	31	60	194	152	42	35	1	403	403
Total pop. (sticks)	4,979,837	476,458	1,051,498	594,367	551,345	856,323	468,296	856,323	1,067,552	382,295		
Failure rate (failures/sticks made)	7.89E-05	6.72E-05	3.80E-05	5.22E-05	1.09E-04	2.27E-04	3.25E-04	4.90E-05	3.28E-05	2.62E-06		
Mean (years)	13.95	23.32	23.78	15.13	11.07	12.16	10.38	17.90	7.47	12.00	6.20	6.09E-05
Standard Dev (years)	8.95	6.92	10.21	6.71	6.01	7.70	6.47	8.56	6.37	N/A	10.23	9.17E-05
25th percentile (years)	6.7	19.0	18.0	10.9	6.2	6.1	5.5	9.3	2.9	11.3		
50th percentile (years)	11.5	23.5	23.6	12.9	8.4	9.9	9.1	16.9	6.1	12.5		
75th percentile (years)	18.8	28.6	40.6	14.8	11.5	16.9	14.7	24.2	10.4	13.8		
Category 2/3												
Sample pop. (sticks)	24,822	10	2,381	63	46	15,158	4,349	10,809	5,864	1,299	27,805	27,805
Sample pop. (database entries)	217	7	19	30	30	98	64	34	32	1	256	256
Total pop. (sticks)	4,979,837	476,458	1,051,498	594,367	551,345	856,323	468,296	856,323	1,067,552	382,295		
Failure rate (failures/sticks made)	4.98E-03	2.10E-05	2.26E-03	1.06E-04	8.34E-05	1.77E-02	9.29E-03	1.26E-02	5.49E-03	3.40E-03		
Mean (years)	16.75	24.86	29.79	16.90	13.47	15.97	12.44	22.62	12.72	12.00	428	4.01E-03
Standard Dev (years)	10.24	5.96	10.26	10.06	8.14	9.75	8.45	8.56	7.77	N/A	1194	1.12E-02
25th percentile (years)	22.1	21.3	22.2	11.6	8.4	25.1	21.4	26.4	21.3	11.3		
50th percentile (years)	26.3	23.3	24.5	17.7	12.5	27.6	23.7	28.6	24.0	12.5		
75th percentile (years)	29.4	26.3	41.5	30.1	26.3	30.2	26.9	31.2	26.9	13.8		

Database Percentages	Pop.	% Interpace	% Other	% Unknown
Category 1 failures	435	41.84%	8.97%	49.20%
Category 2/3 failures	35,662	60.73%	2.69%	36.58%
Production (sticks)	4,979,837	52.25%	47.75%	-

Failures by Wire Class	Total pop.	Class I	Class II	Class III	Class IV
Category 1 failures	397	63	117	38	179
Category 2/3 failures	25,809	7,162	395	8,853	9,398

Failures by Pipe Type	Sample pop.	Production	Mean failure rate
LCP Category 1 failures	228	13,458	0.0126
ECP Category 1 failures	159	5,405	0.0188
LCP Category 2/3 failures	3,972	13,458	0.254
ECP Category 2/3 failures	20,428	5,405	2.65

CHAPTER 1
INTRODUCTION

LITERATURE SEARCH

Research to Identify PCCP with High Likelihood of Failure

Early failures of PCCP pipelines prompted visual inspections of many miles of pipelines. Those inspections often revealed cracks on the interior, leading to further investigations. Interior cracks sometimes indicated disbondment of the concrete core from the steel cylinder, and it was soon discovered that tapping on the interior (called “sounding”) was an effective means for identifying those areas. These internal inspections were often supplemented with ultrasonic examination to infer the condition of the core (Lewis and Fisk 2005). An AwwaRF study (Jackson, Pitt, and Skabo 1992) reviewed the available nondestructive evaluation technology for waterlines, some of which are applicable to PCCP. But these do not provide any significant indication of the structural integrity of the prestressing wires.

An alternative inspection methodology was made commercially available in 1997, by utilizing the wires within the pipe as a radio-frequency measurable coil antenna (Mergalas, Atherton, and Kong 2001b). Because that technique promised to identify the number and location of wire breaks in each pipe length inspected, the PCCP owning utilities were interested in its development to the extent that AwwaRF funded a study (Mergalas and Kong 2001a).

Acoustic monitoring of in-service EC-PCCP pipelines has also been utilized to identify actively breaking wires (Diaz, Campbell, and Holley 2005; Worthington and DiMarco 1996). Another real-time technique reported to be successful is inductive scan imaging (Almughery et al. 2005), a technique that to date has been used only on the exterior of PCCP. Methods developed to determine the number of wire breaks in EC-PCCP have recently been extended to LC-PCCP (Kong and Mergalas 2005; Mergalas, Kong, and Balliew 2005). These methods have widely been promoted to determine the condition of PCCP pipelines, yet their accuracy has not been as yet demonstrated sufficient to rely entirely thereon (Galleher, Bell, and Romer 2005; Bambei and Lewis 2005; Parks, Drager, and Ojdrovic 2001). Water utilities, desperate for concrete answers, continue to fund research (Bengtsson et al. 2005).

It is clear that the time to more actively manage the remaining service life of PCCP pipelines is at hand. Evaluation and management of PCCP pipelines by utilities has been approached on the basis of evaluating existing information (Bichler 2005), and a risk-based approach has been presented (Romer and Bell 2004). A typical PCCP pipeline assessment approach begins with data collection and analysis (Bell, Kendall, and Mulligan 2001):

- Data collection, design, and shop drawings
- Complete system surge analysis
- System operation modifications
- Corrosion survey and alignment corrosivity analysis
- Nondestructive investigations
- Detailed structural integrity evaluation

Crucial data for analyses are often lacking, even at a utility with comprehensive records (Galleher et al. 2001). Models have been developed to estimate failure risk using fuzzy Markov techniques (Marshall et al. 2005; Kleiner, Sadiq, and Rajani 2004), when data are scarce or unreliable. It is not clear that the additional effort provides any greater level of confidence to the utility, because so little data generally exist.

Remote field-eddy current inspection was initially reviewed in an AwwaRF study (Jackson, Pitt, and Skabo 1992). This type of inspection, however, is only a component of risk management (Mergalas et al. 2001c).

AwwaRF has funded a workshop (Lillie et al. 2004), which summarized the devices available to utilities for inspection of water transmission mains. In that study, the economics of condition assessment were evaluated against the deferral of capital (replacement of the pipeline) and operating expenses (repair/rehabilitation). An equally recent AwwaRF study (Reed, Robinson, and Smart 2004) addressed means of continuous monitoring of the structural capacity of transmission mains.

Perhaps the most effective, on an individual pipe basis, is analysis of the structural integrity of the pipe, using the best available data. Those analyses can be as complicated as finite-element models (Lofti, Oesterle, and Roller 2005, Diab and Bonierbale 2001) or analysis using the best-available analytic methods at the time the pipeline in question was originally designed (Lewis and Fisk 2005). Some finite-element models possess a complexity far in excess of the original pipe design (Gomez et al. 2004).

Alleviating PCCP Failures

Initial steps beyond inspection and analyses at alleviating failure of PCCP included application of cathodic protection to the prestressing wires (Zarghamee, Ojdrovic, Fongemie 1998), assuming that cathodic protection could reduce the rate of corrosion for corrosion-based failures. Uncontrolled or unidentified stray currents can cause rapid deterioration of PCCP pipelines due to hydrogen embrittlement (HE). Even cathodic protection as applied to PCCP in an effort to control corrosion has been attributed as the cause of failures (Marshall 1998). Methodologies to identify sources of and isolation of pipelines from stray currents and electric utility grounding issues were identified in two AwwaRF studies (Duranceau, Schiff, and Bell 1996; Romer and Bell 2004). Others have proposed pulsed cathodic protection (Doniguian, Kips, and Barnes 1998).

Clearly, there is a significant interest in the preservation and the extension of useful life of water mains and, in particular, PCCP. Utilities have taken steps in advance of failure to reline (Fiori, Kendall, and Mulligan 2001), utilizing carbon fiber (Moncreif et al. 2001) and steel cylinders (Suydam et al. 2001) and replacement with new steel pipe subsequent to failure. However, even these relined pipelines have been known to fail (McCaffrey, Kendall, and Mulligan 2006).

Cost of Failures

An accurate method of estimating the tangible and intangible cost of transmission and distribution water mains failures was introduced in an AwwaRF study (Cromwell et al. 2002). In that study, electric, transportation, natural gas, and emergency planning industry methods for estimating “customer outage costs” were extrapolated to the waterworks industry.

The cost of replacement of the nation's inventory of PCCP has been estimated at over $40 billion (Megalas 1998). The cost of maintenance of a PCCP pipeline can also be high (Marshall, Meza, and Swinnea 2002). AwwaRF has funded studies that focus on the rehabilitation of distribution mains (Deb et al. 1990; O'Day et al. 1986) wherein the cost of rehabilitation of small-diameter mains approaches the cost of new pipelines. The economics has not changed significantly in the 16 years since publication of those reports.

Relining PCCP in-place has been generally completed with steel cylinders, starting with the Bureau of Reclamation's Jordan Aqueduct in 1984. Many large aqueducts have been rehabilitated, at great cost, in this manner (Stine and Stift 1998, Khondiker and Mitchell 1998) with sometimes significant reduction of flow capacity (and as noted previously, at least one catastrophic failure).

Survey of Utilities to Supplement Existing Database

Probably more important than simply identifying PCCP leaks and breaks was to establish if there are patterns of leaks and breaks in PCCP. The Water:\Stats database contains a tremendous amount of data, but because it lacks information regarding the age, wire type, and manufacturing characteristics of PCCP, it is not very useful for this study. A more useful set of data was compiled for AwwaRF (von Fay and Peabody 1994). The PCCP failure rate at that time was not significantly greater than other pipeline materials, based upon survey results from 114 utilities.

Table 1.1 includes all the PCCP failure data collected since that unpublished study. It includes information on 583 PCCP failures but omits the cases where data are missing or incomplete. Figure 1.1 shows the geographic distribution of the lined-cylinder type failures, and Figure 1.2 shows the geographic distribution of the reported failures of embedded-cylinder type PCCP. These data represent the most complete body of PCCP failures to the year 2006 extant. The sources of the data were:

- Openaka's database
- Records accumulated by the Principal Investigators
- Previous reports
- Published papers
- Newspaper and trade press
- Manufacturer's literature
- Interviews
- Unpublished information (from participating utilities)

Predicting Failures

The inference of future performance of PCCP based upon analysis of failure rates has been addressed from an industry perspective (Prosser 1996) and by comparison with other pipeline materials (von Fay and Peabody 1994). The determination of the remaining useful life of pipelines, not just PCCP pipelines, has been reported utilizing probabilistic or statistical methods to estimate a survival function on the basis of past behavior (Nelson 2005). Assignment of a pipe criticality index included web-based data in a very large PCCP system (Essamin et al. 2005) for EC-PCCP. Artificial neural networks (Najafi and Kulandaivel 2005) have been utilized

to predict behavior of systems based upon past behavior. Because of the high numbers of PCCP pipelines manufactured by Interpace and with Class IV wire, one utility used linear extrapolation to estimate time of failure (Bradish, Cronin, and Lewis 1995).

The remaining service life has even been estimated on its actuarial value (Baik Shik, Abraham, and Gipson 2004), although it is understood that utilities would like to believe that their underground assets have an indefinite useful life. The mathematics proposed (Kleiner, Rajani, and Sadiq 2005) for managing the risk inherent with PCCP pipes may be significantly daunting to management, whose eyes roll at the thought of manipulating fuzzy-based Markov techniques, even when aided by computer programs. What is necessary is a risk assessment system whose results are readily understandable by water utility management.

The Principal Investigators struggled with the comparison of the effect of PCCP pipeline failures by “valuation.” The Principal Investigators do not know the sizes for much of the production (only LC vs. EC), so comparison by inch-diameter is not possible. The Principal Investigators do not know how much was the selling price, so the Principal Investigators do not know the relative worth of each.

And the Principal Investigators really do not know if mostly EC-PCCP or LC-PCCP fails, only what has been well publicized, that EC-PCCP failures are big enough to be publicized or subject to lawsuits.

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
143	ALTOONA, PA	24	LCP	1955	1980	25	I		1		RUPTURED	
19	ARLINGTON, TX	20	LCP		1972				1		RUPTURED	
534	ARLINGTON, VA	60	ECP	1972-78	2007		IV			105	REPLACEMENT	Replacement of approximately 2100 linear feet of PCCP (project 7000) -BC added manufacturer and install date per wire class (C301-72, A648, Interpace practice)
535	ARLINGTON, VA	48		1972-78	2007		IV			525	REDUNDANT LINE	Creation of redundant line prior to inspection and rehabilitation -BC added manufacturer and install date per wire class (C301-72, A648, Interpace practice)
404	ATLANTA, GA			1969			II		1		RUPTURED	CORROSION
323	AUGUSTA, GA	42	LCP	1974	1989	15	IV	8	1		RUPTURED	
342	AUGUSTA, GA	42	LCP	1974	1991	17	IV	8	1		RUPTURED	
366	AUGUSTA, GA	42	LCP	1974	1995	21	IV	8	2		RUPTURED	AT SPIGOT
391	AUGUSTA, GA	42	LCP	1974	1998	24	IV	8		1	INCIPIENT FAILURE; INTERNAL INSPECTION	PROBABLE SURGE DAMAGE
394	AUGUSTA, GA	42	LCP	1974	1999	25	IV	8	1		RUPTURED	EXCAVATION DAMAGE AND ENVIRON. CORROSION

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
533	AURORA, CO	54	ECP	1980	2000	20	III	8		2	REPAIR	Repair severely distressed pipes 959 (52 wire breaks) and 958 after PPIC inspection -BC added wire class/size per install year (C301-79, A648)
65	BALTIMORE, MD	108	ECP	1963	1977	14	I			1	LEAKING	APPARENT DAMAGE DURING INSTALLATION
90	BALTIMORE, MD	72	ECP	1972	1978	6	IV			1	LEAKING	IN TIMBER CRADLE; LINE SHIFTING LATERALLY
113	BALTIMORE, MD	30	LCP	1950	1979	29	I		2		RUPTURED	SEWER FORCE MAIN; H2S, H2SO4
144	BALTIMORE, MD	30	LCP	1966	1980	14	II	6	1		RUPTURED	COATING DAMAGED TOP OF PIPE; WIRES CORRODED
207	BALTIMORE, MD	72	ECP	1975	1982	7	IV	6		1	LEAKING	EXCESSIVE JOINT OPENING; MOVEMENT
208	BALTIMORE, MD	30	LCP	1980	1982	2	IV			1	LEAKING	CANTILEVER BENDING FAILURE
297	BALTIMORE, MD	36	LCP DW		1985				1		RUPTURED	
350	BALTIMORE, MD	72	ECP	1975	1992	17	IV	6	1		RUPTURED	
351	BALTIMORE, MD	72	ECP	1975	1992	17	IV	6		1	LINING DISTRESS,	INTERNAL INSPECTION
558	BALTIMORE, MD	72	ECP		2002				1	2	RUPTURED, REPAIRED	20-foot ruptured segment, cracking in two adjacent pieces repaired
564	BALTIMORE, MD	36	LCP		2004				1		RUPTURE	Break March 17, 2004
565	BALTIMORE, MD	36	LCP		2004				1		RUPTURE	Break January 17, 2004
566	BALTIMORE, MD	36	LCP		2004				1		RUPTURE	Break March 26, 2004
484	BALTIMORE, MD	54	ECP		2005				3	228		

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
28	BATON ROUGE, LA	48	LCP	1963	1973	10	I		1	2	RUPTURED	three pipes total - sewage force main
556	BEULAH, ND	42	ECP, LCP	1979	2005	26	III	8		2,348	REPLACEMENT	Replace with 42" cement-lined and tape-coated steel pipe -BC added install date per BOYLE data, added wire class & size per install date (C301-79, A648)
66	BOCA RATON, FL	24	LCP	1971	1977	6	II		1	2	LEAKING	SEWER FORCE MAIN H2S TAIL OFF
2	BOSTON,MA	24	LCP	1949	1957	8	I	1/8	1		RUPTURED	MBOT
209	BRANDON SHORES, MD	78	ECP	1980	1982	2	IV	6	1		RUPTURED	SETTLEMENT AND GRADE E STEEL
301	BRANDON SHORES, MD	102	ECP	1980	1986	7	IV	6	1		RUPTURED	
330	BRANDON SHORES, MD	102	ECP	1980	1990	10	IV	6		7	INCIPIENT FAILURE; INTERNAL INSPECTION	
343	BRANDON SHORES, MD	102	ECP	1980	1991	11	IV	6		8	INCIPIENT FAILURE; INTERNAL INSPECTION	
352	BRANDON SHORES, MD	102	ECP	1980	1992	12	IV	6		13	INCIPIENT FAILURE; INTERNAL INSPECTION	
359	BRANDON SHORES, MD	102	ECP	1980	1993	13	IV	6		3	INCIPIENT FAILURE; INTERNAL INSPECTION	
367	BRANDON SHORES, MD	102	ECP	1980	1995	15	IV	6		2	INCIPIENT FAILURE; INTERNAL INSPECTION	
375	BRANDON SHORES, MD	102	ECP	1980	1996	16	IV	6		3	INCIPIENT FAILURE; INTERNAL INSPECTION	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
382	BRANDON SHORES, MD	102	ECP	1980	1997	17	IV	6		8	INCIPIENT FAILURE; INTERNAL INSPECTION	
383	BRANDON SHORES, MD	78	ECP	1980	1997	17	IV	6		1	INCIPIENT FAILURE; INTERNAL INSPECTION	
392	BRANDON SHORES, MD	102	ECP	1980	1998	18	IV	6		5	INCIPIENT FAILURE; INTERNAL INSPECTION	
395	BRANDON SHORES, MD	102	ECP	1980	1999	19	IV	6		17	INCIPIENT FAILURE; INTERNAL INSPECTION	
396	BRANDON SHORES, MD	102	ECP	1980	1999	19	IV	6	1		RUPTURED	ENVIRONMENTAL CORROSION AND SURGE EVENTS
256	BRECKENRIDGE,MN	16	LCP	1955	1983	28	I	6		1	LEAKING	LOOPED GASKET
9	BRIDGEPORT, CT	24	LCP	1954	1968	14	I			1	LEAKING	COATING & PIPE DAMAGED DURING INSTALLATION
210	BROADVIEW, IL	24	LCP	1966	1982	16	II			1	LEAKING	EXCESS JOINT OPENING
12	BROCKTON, MA	30	LCP	1966	1971	5	II		1		RUPTURED	LOOPED GASKET ERODED MORTAR AND STEEL
173	BUCKS CO. PA	48	ECP	1969	1981	12	II		1		RUPTURED BARREL, BROKEN WIRES	APPEARS TO BE BY CONTRACTOR
33	BURNSVILLE, MN	36	LCP	1970	1974	4	II		1		RUPTURED	DEFECTIVE WIRE
174	BURNSVILLE, MN	36	LCP	1971	1981	10	II			1	LEAKING	FLEX TIED JOINT SEPERATED; UNSTABLE BEDDING
211	BURNSVILLE, MN	36	LCP	1968	1982	14	II			1	BROKEN WIRES	CATHODIC INTERFERENCE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
427	CALABASAS, CA	54	ECP	1975			II	8 - 1/4		14		14 pipe sections with breaks; the maximum number of wire breaks in any single section is 15.
469	CALLEGUAS, CA	51	ECP	1962	1988	26	II	6	1		RUPTURE	1988 Leak & Pipe Replacement
448	CALLEGUAS, CA	48	ECP	1962	1999	37	II	6		5	Wire breaks: very low number of breaks per pipe	partial RECT/TC
449	CALLEGUAS, CA	78	ECP	1971	2001	30	II	8, 6, 1/4		1	Wire breaks: brittle wires from impressed current	RECT/TC
450	CALLEGUAS, CA	78	ECP	1975	2001	26	III	6		2	Wire breaks: brittle wires from impressed current	RECT/TC
451	CALLEGUAS, CA	66	ECP	1980	2001	21	III	8, 6		8	Wire breaks: brittle wires from impressed current	RECT/TC
447	CALLEGUAS, CA	51	ECP	1962	2002	40	II	6		1	Wire breaks: very low number of breaks per pipe	partial RECT/TC
470	CALLEGUAS, CA	51	ECP	1962	2002	40	II	6		165	REPLACEMENT	2002 Steel Liner Project
536	CALLEGUAS, CA	51	ECP	1962	2005	43	II	6	7		RUPTURE	The steel liner had failed along the longitudinal seam for approximately 42.7 linear meters (140 linear feet)
468	CALLEGUAS, CA	51	ECP	1962	2007	45	II	6	1		RUPTURE	Failure at Yosemite, January 2007
471	CALLEGUAS, CA	51	ECP	1962	2007	45	II	6	1		RUPTURE	Failure west of Stearns St., February 2007

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
114	CALVERT CITY, KY	24	LCP	1952	1979	27	I		1		RUPTURED	PIPELINE UNDER A SALT PILE
428	CASTAIC, CA	201	ECP	1968			II	8 - 1/4		3		Moderately good condition; 3 pipes with 20+ breaks
50	CENTER, ND	30	LCP	1974	1976	2	IV	8	2	1	LEAKING	COOLING H2O MAKEUP PIPE 1.5 YEARS OLD
466	CENTER, ND	30	LCP	1974	1977	3	IV	8		340	REPLACED	6800' replaced in 1977
91	CENTER, ND	30	LCP	1976	1978	2	IV	8	1		RUPTURED	SHEARED AT FACE OF CONCRETE THRUST BLOCK
34	CHESTER, PA	42	LCP	1968	1974	6	II			1	LEAKING	COATING DAMAGED DURING INSTALLATION
212	CHESTER, PA	42	LCP	1968	1982	14	II		1		RUPTURED	CHEMICAL PROBLEM .. IN CORN FIELD
257	CHESTER, PA	66	ECP	1974	1983	9	IV		1		RUPTURED	
453	CHICAGO, IL	30	LCP	1954	1959	5	MB OT		1		RUPTURED	Lewiston Pipe (non-cylinder) Possible external load fromm mfooter
285	CHICAGO, IL	42	LCP	1972	1984	12	IV		1		RUPTURED	CORROSION
454	CHICAGO, IL	42	LCP	1972	1984	12	IV		1		RUPTURED	CORROSION
13	CLEVELAND, OH	48	LCP	1964-67	1971		II		1		RUPTURED	-BC added install date per wire class (C301-64, A227)
14	CLEVELAND, OH	48	ECP	1956	1971	15	I	6	1		RUPTURED	CHOLRIDE ION CONTAMINATION
40	CLEVELAND, OH	30	LCP	1955	1975	20	I	6	1		RUPTURED	AGGRESSIVE GROUND WATER, CHLORIDE IONS
213	CLEVELAND, OH	30	LCP	1956	1982	26	I	6		1	LEAKING	CHOLRIDE IONS

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
384	CLEVELAND, OH	36	LCP	1968	1997	29	II	6	1		RUPTURED	DENTED CYLINDER
51	CLOQUET, MN	36	LCP	1968	1976	16	II	6		1	LEAKING	CHUNK OF CONCRETE DROPPED AGAINST COATING
67	CLOQUET, MN	36	LCP	1968	1977	9	II	6		1	LEAKING	COATING APPARENTLY DAMAGED WHEN INSTALLED
68	CLOQUET, MN	36	ECP	1968	1977	9	II	6	1		RUPTURED	PUMP STATION CONTROLS MALFUNCTIONED
92	CLOQUET, MN	36	LCP	1976	1978	2	IV	6	2		RUPTURED	CORROSION
115	CLOQUET, MN	36	ECP	1968	1979	11	II	6	1		RUPTURED	FLEX TIED WELDED JT. FAILED DUE TO SURGE
214	CLOQUET, MN	36	LCP	1968	1982	14	II	6		1	LEAKING	CORRODED WIRES; INSTALLATION RELATED
215	CLOQUET, MN	36	ECP	1968	1982	14	II	6		1	LEAKING; BROKEN WIRES	SURGE; UNSTABLE SOIL
216	CLOQUET, MN	36	LCP	1968	1982	14	II	6		1	LEAKING, BROKEN WIRES	CONTRACTOR FAULTY WELDING
217	CLOQUET, MN	36	LCP	1968	1982	14	II	6		1	BROKEN WIRE	CONTRACTOR DAMAGED; BEDDING OUT OF SPEC.
6	COBB CO., GA	30	LCP	1951	1967	16	I	6	1		RUPTURED	
7	COBB CO., GA	30	LCP	1952	1967	15	I	6	1		RUPTURED	DAMAGED DURING INSTALLATION
20	COBB CO., GA	30	LCP	1951	1972	21	I	6	1		RUPTURED	
21	COBB CO., GA	30	LCP	1952	1972	20	I	6	1		RUPTURED	WATER HAMMER FOLLOWING POWER SURGE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
29	COBB CO., GA	36	ECP	1969	1973	4	II	8	1		RUPTURED	
35	COBB CO., GA	36	ECP	1969	1974	5	II	8	1		RUPTURED	2ND PIPE FROM PREVIOUS FAILURE
36	COBB CO., GA	36	ECP	1969	1974	5	II	8	1		RUPTURED	
41	COBB CO., GA	30	LCP	1951	1975	24	I	6	1		RUPTURED	
42	COBB CO., GA	30	LCP	1952	1975	23	I	6	1		RUPTURED	SURGE AND CORROSION
52	COBB CO., GA	30	LCP	1951	1976	25	I	6	1		RUPTURED	
53	COBB CO., GA	30	LCP	1951	1976	25	I	6	1		RUPTURED	
54	COBB CO., GA	30	LCP	1952	1976	24	I	6	1	2	LEAKING	CORROSION
55	COBB CO., GA	36	ECP	1969	1976	7	II	8	1	2	BROKEN WIRES	100 FT APART
69	COBB CO., GA	36	ECP	1969	1977	8	II	8	3	2	BROKEN WIRES	ABOUT 3 MOS. APART; SAME AREA
70	COBB CO., GA	36	ECP	1969	1977	8	II	8	1		RUPTURED	
71	COBB CO., GA	36	ECP	1969	1977	8	II	8	1		RUPTURED	
72	COBB CO., GA	36	ECP	1969	1977	8	II	8	1		RUPTURED	1 DAY AFTER PREVIOUS ONE; MOVED VERTICALLY
73	COBB CO., GA	36	ECP	1969	1977	8	II	8	1		RUPTURED	200 FT FROM PREVIOUS FAILURES
74	COBB CO., GA	36	ECP	1969	1977	8	II	8		2	BROKEN WIRES	SURGES
93	COBB CO., GA	36	LCP	1966	1978	12	II	6	1		RUPTURED	
94	COBB CO., GA	36	LCP	1967	1978	11	II	6		1	BROKEN WIRES	FOUND UNCOVERED FOR PRESSURE TEST
95	COBB CO., GA	36	ECP	1969	1978	9	II	8	1		RUPTURED	
116	COBB CO., GA	36	ECP	1969	1979	10	II	8	1		RUPTURED	CORRODED WIRE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
117	COBB CO., GA	36	ECP	1969	1979	10	II	8	1		RUPTURED	COATING GOUGED AND POSSIBLY PATCHED
118	COBB CO., GA	36	LCP	1973	1979	6	IV	8	3	3	1 LEAKING; 2 WITH BROKEN WIRES	CORRODED WIRE
119	COBB CO., GA	36	LCP	1974	1979	5	IV	8		2	1 LEAKING; 1 WITH BROKEN WIRE	LOOPED GASKET; POOR COATING
145	COBB CO., GA	36	ECP	1969	1980	11	II	8	1	1	BROKEN WIRES	RIVER CONN. BALLOONED; CTG. OFF FOR 1 FOOT
146	COBB CO., GA	48	ECP	1973	1980	7	IV	8	1	1	BROKEN WIRES	HEALED ALONG CRACKS IN RUPTURED PIPE
147	COBB CO., GA	48	ECP	1975	1980	5	IV	8	1		RUPTURED	BROKEN WIRE
175	COBB CO., GA	36	LCP	1969	1981	12	II	8		1	LEAKING	CONTRACTOR DAMAGED COATING
176	COBB CO., GA	36	ECP	1970	1981	11	II	8	1		RUPTURED	CORRODED WIRE
177	COBB CO., GA	36	LCP	1973	1981	8	IV	8	1		RUPTURED	THIN COATING AND WRONG CLASS OF PIPE
178	COBB CO., GA	36	LCP	1973	1981	8	IV	8		1	LEAKING WITH BROKEN WIRES	THIN COATING; CEMENT CONTENT; WIRE BRIDGING
179	COBB CO., GA	36	LCP	1973	1981	8	IV	8		1	LEAKING	THIN CTG.; CEMENT CONTENT; WIRE BRIDGING
180	COBB CO., GA	36	LCP	1973	1981	8	IV	8		1	LEAKING	THIN CTG.; CEMENT CONTENT; WIRES; POSS. SURGE
181	COBB CO., GA	48	ECP	1974	1981	7	IV	8	1		RUPTURED	CORRODED WIRE
182	COBB CO., GA	48	ECP	1974	1981	7	IV	8	1		RUPTURED	CORRODED WIRE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
183	COBB CO., GA	36	LCP	1975	1981	6	IV	8	1		RUPTURED	WIRE FRACTURE
184	COBB CO., GA	36	LCP	1975	1981	6	IV	8	1		RUPTURED	OUT-OF-ROUND SPIGOT; CRACKED COATING
218	COBB CO., GA	30	LCP	1951	1982	31	I	6	1		RUPTURED	SURGES
219	COBB CO., GA	30	LCP	1951	1982	31	I	6	1		RUPTURED	SURGE
220	COBB CO., GA	36	ECP	1969	1982	13	II	8	1		RUPTURED	BAD WELD
221	COBB CO., GA	48	ECP	1973	1982	9	IV	8	1		RUPTURED	MANY FACTORS
258	COBB CO., GA	36	ECP	1970	1983	13	II	8	1		RUPTURED	ONE DAY AFTER PREVIOUS RUPTURE
259	COBB CO., GA	36	ECP	1970	1983	13	II	8	1		RUPTURED	POSSIBLE HOLLOW COAT
260	COBB CO., GA	36	ECP	1970	1983	13	II	8	1		RUPTURED	POSSIBLE HOLLOW COAT
261	COBB CO., GA	36	ECP	1970	1983	13	II	8	1		RUPTURED	
262	COBB CO., GA	36	LCP	1974	1983	9	IV	8	1		RUPTURED	5TH FAILURE IN THIS AREA
263	COBB CO., GA	48	ECP	1974	1983	9	IV	8	1		RUPTURED	7 TH FAILURE IN THIS AREA
264	COBB CO., GA	48	ECP	1978	1983	5	IV	8	1		RUPTURED	6TH FAILURE IN THIS AREA
265	COLORADO SPRINGS, CO.	36	LCP	1981	1983	2	IV	8	1		RUPTURED	POOR DESIGN
222	CORAL GABLES, FL	48	LCP	1949	1982	33	I		1		RUPTURED	wires cut by trencher 2 weeks prior -BC added wire class/size per install date
1	CORPUS CHRISTI, TX	24	LCP		1955		I		1		RUPTURED	
455	COSTA MESA, CA	40	LCP		1975				1			

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
120	DALTON, GA	30	LCP	1953	1979	26	I		1		RUPTURED	DAMAGED COATING
223	DeKALB, GA	48	LCP	1961	1982	21	I	6	1		RUPTURED	CONTRACTOR DAMAGE OR TIGHT JOINT (1983 per PBC list 4/7/86)
385	DENVER, CO	66	ECP	1977	1997	20	IV	1/4	1		RUPTURED	
393	DENVER, CO	48	LCP	1972	1998	26	IV	8	1		RUPTURED	
397	DENVER, CO	48	LCP	1972	1999	27	IV	8		10	INCIPIENT FAILURE; INTERNAL INSPECTION	CATHODIC PROTECTION/INTERFERENCE
407	DENVER, CO	36	LCP	1952				6		42	REPLACED	Most replaced - all but approx 125' remains
408	DENVER, CO	36	LCP	1962				6		15	REPLACED	Almost all replaced
409	DENVER, CO	48	LCP	1964				6		90	REPLACED	Replaced
410	DENVER, CO	48	LCP	1974			IV	8		326	REPLACED	Replaced
411	DENVER, CO	48	LCP	1974			IV	8		195	REPLACED	Replaced
412	DENVER, CO	48	LCP	1974			IV	8		281	REPLACED	Replaced
413	DENVER, CO	72	ECP	1974			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
414	DENVER, CO	72	ECP	1974			IV	8		40	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
415	DENVER, CO	72	ECP	1974			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
416	DENVER, CO	72	ECP	1974			IV	6		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
417	DENVER, CO	60	ECP	1974			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
418	DENVER, CO	66	ECP	1977			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
419	DENVER, CO	66	ECP	1977			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
420	DENVER, CO	66	ECP	1977			IV	8		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
421	DENVER, CO	66	ECP	1977			IV	6		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
422	DENVER, CO	66	ECP	1977			IV	6		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
423	DENVER, CO	66	ECP	1977			IV	6		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
424	DENVER, CO	66	ECP	1977			IV	1/4		1	REPLACED	Some sections of Conduit No. 94 replaced - need to determine which.
121	DETROIT, MI	48	ECP	1972	1979	7	III	6		1	LEAKING	LOOPED GASKET
224	DETROIT, MI	42	ECP	1972	1982	10	III	6	1		RUPTURED	SLAG INCLUSION ALLOWED WIRE TO FAIL
148	DULUTH, MN	42	LCP	1971	1980	9	II		1		RUPTURED	
149	DULUTH, MN	42	LCP	1974	1980	6	IV	8	2		RUPTURED	SURGE WHEN SHIFTING PUMPS
185	DULUTH, MN	42	LCP	1975	1981	6	IV	8	1		RUPTURED	SURGES
225	DULUTH, MN	42	LCP	1975	1982	7	IV	8	1		RUPTURED	SURGE
150	DURHAM, NC	30	LCP	1974	1980	6	IV		1		RUPTURED	LOOPED GASKET

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
56	EAST ORANGE, NJ	24	LCP	1965	1976	11	II			1	LEAKING	LARGE ROCK AGAINST COATING IN BACK FILL
96	EAST ORANGE, NJ	24	LCP	1965	1978	13	II			1	LEAKING	HOLE PUNCHED THROUGH WALL
75	EDISON, NJ	20	LCP	1974	1977	3	IV			1	LEAKING	DAMAGED DURING INSTALLATION
76	EDISON, NJ	20	LCP	1974	1977	3	IV			1	LEAKING	SEWER FORCE MAIN DAMAGED AT INSTALLATION
97	EDISON, NJ	20	LCP	1974	1978	4	IV			1	LEAKING	DAMAGE TO COATING AFTER INSTALLATION
286	EL PASO, TX	60	ECP	1977	1984	7	III	6	1		RUPTURED	PBC list 4/7/86 indicates inst. range 1972-78
287	EL PASO, TX	60	ECP	1977	1984	7	III	6	1		RUPTURED	
288	EL PASO, TX	60	ECP	1977	1984	7	III	6	1	6	BROKEN WIRES, EXTERNAL INSPECTION	POROUS COATING; BROKEN WIRES
289	EL PASO, TX	54	ECP	1979	1984	5	III	6	1		RUPTURED	CATHODIC INTERFERENCE
317	EL PASO, TX	54	ECP	1979	1988	9	III	6	1	13	BROKEN WIRES, EXTERNAL INSPECTION	POROUS COATING; BROKEN WIRES
344	EL PASO, TX	60	ECP	1976	1991	15	III	6	1		RUPTURED	CYLINDER LEAK
403	EL PASO, TX	54	ECP	1979	1992	13	III	6		5	LINING DISTRESS, INTERNAL INSPECTION	POROUS COATING; BROKEN WIRES

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
361	EL PASO, TX	54	ECP	1979	1994	15	III	6		7	LINING DISTRESS, INTERNAL INSPECTION	POROUS COATING; BROKEN WIRES
368	EL PASO, TX	54	ECP	1979	1995	16	III	6		5	LINING DISTRESS, INTERNAL INSPECTION	
527	EL PASO, TX	60, 54, 42	ECP, LCP	1977	2003	26		6	1		FAILURE	
526	EL PASO, TX	48	ECP	1955-63	2005		I	6		1		AWWA C301. -BC added wire class and install date per wire size (C301-55 or C301-58, A227)
43	ERIE CO, PA	42	ECP	1971	1975	4	II			1	LEAKING	WELD FAILURE BETWEEN JOINT RING & CYLINDER
226	FAIRFAX CITY, VA	24	LCP	1960	1982	22	I		1		RUPTURED	
22	FAIRFAX CO. VA		LCP	1962	1972	10	I		1		RUPTURED	LOOPED GASKET; ERODED MORTAR AND STEEL
44	FAIRFAX CO. VA	30	LCP	1960	1975	15	I	6	1		RUPTURED	
57	FAIRFAX CO. VA	24	LCP	1959	1976	17	I	6	1		RUPTURED	
58	FAIRFAX CO. VA	30	LCP	1947	1976	29	I		1	1	BROKEN WIRES	IN SECTION OF LINE RELAID IN 1964
77	FAIRFAX CO. VA	30	LCP	1947	1977	30	I		1		RUPTURED	IN SECTION OF LINE RELAID IN 1964
98	FAIRFAX CO. VA	30	LCP	1947	1978	31	I		1		RUPTURED	
99	FAIRFAX CO. VA	36	LCP	1975	1978	3	IV	8	1		RUPTURED	
122	FAIRFAX CO. VA	30	LCP	1965	1979	14	II		1		RUPTURED	

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
123	FAIRFAX CO. VA	36	LCP	1975	1979	5	IV	8	1	1	BROKEN WIRES	
456	FAIRFAX CO. VA		LCP	1976	1979				3		RUPTURED	PBC list 4/7/86 indicates failure. range 1979-80. It's not clear that these are in the above listed.
186	FAIRFAX CO. VA	36	LCP	1975	1981	6	IV	8	1	1	LEAKING	COATING CRACK
187	FAIRFAX CO. VA	30	LCP	1975	1981	6	IV	8	1	2	LEAKING	BELL BOLT JOINT; GRADE E CYLINDER
227	FAIRFAX CO. VA	36	LCP	1975	1982	7	IV	8	1		RUPTURED	
298	FAIRFAX CO. VA	36	LCP	1975	1985	10	IV		1		RUPTURED	
299	FAIRFAX CO. VA	36	LCP	1975	1985	10	IV	8	1		RUPTURED	
302	FAIRFAX CO. VA	36	LCP	1975	1986	11	IV	8	1		RUPTURED	
331	FAIRFAX CO. VA	36	LCP	1975	1990	15	IV	8	1		RUPTURED	TORN CYLINDER
332	FAIRFAX CO. VA	36	LCP	1975	1990	15	IV	8	1		RUPTURED	
369	FAIRFAX CO. VA	36	LCP	1975	1995	20	IV	8	1		RUPTURED	
386	FAIRFAX CO. VA	36	LCP	1975	1997	22	IV	8	1		RUPTURED	
530	FAIRFAX CO. VA	36	LCP		2001					1,000	REPLACEMENT	
531	FAIRFAX CO. VA	36	LCP		2002					400	REPLACEMENT	
228	FAYETTEVILLE, NC	48	LCP	1968	1982	14	II		1		RUPTURED	THRUST PROBLEM; WIRE SPACING TOO CLOSE 4/7/86 PBC lists 1 yr. newer, 1 year earlier failure.
387	FAYETTEVILLE, NC	42	LCP	1969	1997	28	IV	8	1		RUPTURED	
229	GAFFNEY, SC			1982	1982	0	III	6	1		CYLINDER WELD FAILURE	

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
188	GAINESVILLE, FL	36	LCP	1968	1981	13	II			1	LEAKING	JOINT RING
266	GAINESVILLE, FL	48	LCP	1969	1983	14	I	6		1	LEAKING	
151	GRAHAM, NC	30	LCP	1974	1980	6	IV		1		RUPTURED	LEAKING IN SEAM WELD
78	GRAND FORKS, ND	30	LCP	1960	1977	17	I			1	LEAKING	H2S
230	GRAND FORKS, ND	30	LCP	1959	1982	23	I			1	LEAKING	FAULTY AIR RELEASE VALUE OPERATION
457	GRAND JUNCTION, CO	24	LCP	1964	1979		II	8	1			Corrosion -BC added wire class/size per install date (C301-64, A227)
529	GRAND VALLEY, CO	42, 36, 24	LCP	early 1960s	2001		I	6		4,884	REPLACEMENT	The pipeline is presently subject to frequent breaks due to deteriorated pipe condition, and is unreliable due to its location within geologic hazards and stream erosion areas.
189	GRANITE CITY, IL	24	LCP	1958	1981	23	I		2		RUPTURED	STEEL PLANT - RUPTURED IN AREA OF JOINT
190	GREENVILLE, SC	30	LCP		1981				1		RUPTURED	
541	GREENVILLE, SC	48		1976	1988	12	IV		6		RUPTURES	
539	GREENVILLE, SC	42, 48	LCP	1974	1990	16	IV		1		RUPTURE	
540	GREENVILLE, SC	42, 48	LCP	1974	1994	20	IV		2		RUPTURES	
537	GREENVILLE, SC	48		1974	1997	23	IV			370	REPLACEMENT	Remove and replace 7,400 feet of 48" PCCP with 48" CIP (contract 85)

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
538	GREENVILLE, SC	20, 24	LCP	1973	1997	24	IV		3		RUPTURES	
542	GREENVILLE, SC	72	ECP	1979	1997	18	IV		2		RUPTURES	Failures occurred near creek crossings. Appeared to be due to hydrogen embrittlement
543	GREENVILLE, SC	72	ECP	1979	1999	20	IV		1		RUPTURE	Failures occurred near creek crossings. Appeared to be due to hydrogen embrittlement
544	GREENVILLE, SC	72	ECP	1979	2000	21	IV			2,785	PARALLEL MAIN	Parallel transmission main installed due to diminished reliablity of existing 72-inch main. Contracts 87, 91, 93 made redundant 55,700 feet of PCCP
549	GREENVILLE, SC	24	LCP	1973	2001	28	IV	8		490	PARALLEL MAIN	Parallel transmission main installed due to diminished reliablity of existing 24-inch main. Contracts 92 made redundant 9,800 feet of PCCP - BC added wire size per install date (C301-72, A648)
545	GREENVILLE, SC	48		1974	2004	30	IV			685	REPLACEMENT	Remove and replace 13,700 feet of 48" PCCP, some slipplined (contract 95)
546	GREENVILLE, SC	42	LCP	1974	2005	31	IV			60	REPLACEMENT	Remove and replace 1,200 feet of 42" PCCP with 42" DIP (contract 99)
547	GREENVILLE, SC	42	LCP	1974	2006	32	IV			275	REPLACEMENT	Remove and replace 5,500 feet of 42" PCCP with 42" DIP (contract 100)
548	GREENVILLE, SC	36	LCP	1971			III	8	2		RUPTURES	BC added wire class/size per year installed (C301-64, A227)
100	GWINETT CO, GA	48	LCP	1975	1978	3	IV	8	1		RUPTURED	250 FT DOWN SLOPE FROM EARLIER ONE

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
101	GWINETT CO, GA	48	LCP	1975	1978	3	IV	8	1	2	BROKEN WIRES	SURGE - 100FT DROP BETWEEN AIR VALVES
152	GWINETT CO, GA	48	LCP	1975	1980	5	IV	8	2		RUPTURED	BETWEEN 2 IN 1978
153	GWINETT CO, GA	48	LCP	1975	1980	5	IV	8	1		RUPTURED	1500 FT FROM EARLIER BREAKS AND CLOSE TO END
154	GWINETT CO, GA	48	LCP	1975	1980	5	IV	8	1		RUPTURED	2300 FT FROM EARLIER BREAK NEAR END OF LINE
155	GWINETT CO, GA	48	LCP	1975	1980	5	IV	8	1		RUPTURED	NEAR PREVIOUS ONE; 2300 FT FROM 1978 RUPTURE
191	GWINETT CO, GA	48	LCP	1975	1981	6	IV	8	1		RUPTURED	OVERWRAPING
192	GWINETT CO, GA	48	LCP	1975	1981	6	IV	8	1		RUPTURED	OVERWRAPPING
193	GWINETT CO, GA	48	LCP	1975	1981	6	IV	8	1		RUPTURED	PIPE OVERWRAPPING
194	GWINETT CO, GA	48	LCP	1975	1981	6	IV	8	1		RUPTURED	OVERWRAPPING
195	GWINETT CO, GA	48	LCP	1980	1981	1	IV	8	1		RUPTURED	DESIGN CONSIDERATIONS
303	GWINETT CO, GA	48	LCP	1976	1986	10	IV	8	1		RUPTURED	4/7/86 PBC list indicates 14 failures between 1978 & 1981
307	GWINETT CO, GA	48	LCP	1976	1987	11	IV	8	2	1	RUPTURED	
318	GWINETT CO, GA	48	LCP	1976	1988	12	IV	8	1		RUPTURED	
324	GWINETT CO, GA	48	LCP	1976	1989	13	IV	8	1		RUPTURED	
333	GWINETT CO, GA	48	LCP	1976	1990	14	IV	8	1	1	RUPTURED	
345	GWINETT CO, GA	48	LCP	1976	1991	15	IV	8		1		

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
353	GWINETT CO, GA	48	LCP	1976	1992	16	IV	8	1		RUPTURED	
362	GWINETT CO, GA	48	LCP	1976	1994	18	IV	8	4	3	RUPTURED	
370	GWINETT CO, GA	48	LCP	1976	1995	19	IV	8	3	9	RUPTURED	
376	GWINETT CO, GA	48	LCP	1976	1996	20	IV	8				
156	HACKENSACK, NJ	48	LCP	1968	1980	12	II			1	LEAKING	THRUST BLOCK AT ELBOW REMOVED
102	HADDON HEIGHTS, NJ	16	LCP	1964	1978	14	II			1	LEAKING AT TAP	
458	HENDERSON, NC				1976				1			4/7/86 PBC list indicates 1 failure
467	HESPERIA, CA	132	ECP	1971	1988	17	II	8, 6, 4	1		RUPTURE	High Ground Water, Electrically shorted to water services and reinforcing steel in "Y" vault. Corrosion Pipe Failure in 1988, 132in pipe abandoned in place
103	HINCKLEY, ME	36	LCP	1975	1978	3	IV			1	LEAKING	LAID CANTILEVERED ON ROCK LEDGE-CRUSHED
354	HOPE CREEK, NJ	144	ECP	1976	1992	16	IV	1/4		4	FOUND DURING EXTERNAL INSPECTION	WIRES SPLICED AND RESTRESSED
388	HOPE CREEK, NJ	144	ECP	1976	1997	21	IV	1/4		4	FOUND DURING EXTERNAL INSPECTION	WIRES SPLICED AND RESTRESSED
30	HOT SPRINGS, AK	24	LCP	1968	1973	5	II		1		RUPTURED	LAID ON ROCK
45	HOT SPRINGS, AK	24	LCP	1968	1975	7	II		1		RUPTURED	LAID ON ROCK
79	HOT SPRINGS, AK	24	LCP	1968	1977	9	II		1		RUPTURED	MAY HAVE BEEN WRONG CLASS

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
551	HOUSTON, TX	108	ECP	1972	1990	18	IV	8	1		RUPTURE	"Renovation of three 108-inch PCCP water pipelines" by Ralph T Rundle, John M Olden. Hydrogen Embrittlement from CP. -BC added wire size per install date (C301-72, A648)
552	HOUSTON, TX	108	ECP	1972	1991	19	IV	8	1		RUPTURE	"Renovation of three 108-inch PCCP water pipelines" by Ralph T Rundle, John M Olden. Hydrogen Embrittlement from CP. -BC added wire size per install date (C301-72, A648)
474	HOUSTON, TX	60	ECP	1976	2002	26			1	99	prestressed wires failed due to hydrogen embrittlement	
475	HOUSTON, TX	42	LCP	1992	2004	12	III	0.192	1	1,299	corrosion coinciding with cracks in the mortar linings	sliplined with 36-inch HDPE pipe. Lockwood, Andrews & Newnam, Inc. (LAN) assisted in the failure assessment. -BC added wire class and size per install date (C301-92, A648)
124	HOWARD CO., MD	36	LCP	1976	1979	3	IV	8		1	LEAKING	MANIFOLD PIPE W/24 OUTLET; TEAR IN CYLINDER
490	HOWARD CO., MD	30, 36	LCP	1972-78	1979		IV	8	1		CATASTROPHIC BURST	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
231	HOWARD CO., MD	36	LCP	1974	1982	8	IV	8	1		RUPTURED	THIN COATING; LEAN COATINGS
232	HOWARD CO., MD	36	LCP	1975	1982	7	IV	8	1		RUPTURED	UNKNOWN
491	HOWARD CO., MD	30, 36	LCP	1972-78	1982		IV	8	1		CATASTROPHIC BURST	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
492	HOWARD CO., MD	30, 36	LCP	1972-78	1982		IV	8	1		CATASTROPHIC BURST	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
319	HOWARD CO., MD	36	LCP	1974	1988	14	IV	8	1		RUPTURED	DELAMINATED BELL COATING; DENTED CYLINDER
493	HOWARD CO., MD	30, 36	LCP	1972-78	1988		IV	8	1		CATASTROPHIC BURST	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
325	HOWARD CO., MD	36	LCP	1974	1989	15	IV	8		1	LEAKING	COLLAPSED ON EXCAVATION
494	HOWARD CO., MD	30, 36	LCP	1972-78	1989		IV	8	1		LEAK, PIPE COLLAPSED UPON EXCAVATION	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
334	HOWARD CO., MD	36	LCP	1974	1990	16	IV	8		3	LINING DISTRESS, INTERNAL INSPECTION	LONGITUDINALLY CRACKED LININGS
495	HOWARD CO., MD	30, 36	LCP	1972-78	1990		IV	8	1		CATASTROPHIC BURST	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
346	HOWARD CO., MD	36	LCP	1974	1991	17	IV	8		1	JOINT LEAK	LOOPED GASKET
496	HOWARD CO., MD	30, 36	LCP	1972-78	1991		IV	8	1		JOINT LEAK	-BC added install date, wire size, and manufacturer per wire class (C301-72, A648, Interpace practice)
355	HOWARD CO., MD	36	LCP	1974	1992	18	IV	8	1		RUPTURED	

(continued)

Table 1.1
Reported failures of prestressed concrete cylinder pipe

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
360	HOWARD CO., MD	42	LCP	1974	1993	19	IV	8	1		RUPTURED	
489	HOWARD CO., MD	42	LCP	1974	1993	19			2			
497	HOWARD CO., MD	30, 36	LCP	1972-78	1996		IV	8		710	COMPLETELY REPLACED	PURE investigated. Under Capital Project W-8169, the Elkridge Transmission was replaced in 1996. -BC added install date, wire size, and manufacturer per wire class (C301
488	HOWARD CO., MD	42	LCP	1974	2000	26				4		Accoustically monitored by PURE, detected numerous wire breaks between Sta.49+62 and Sta.50+20. Eighty linear feet PCCP replaced.
488	HOWARD CO., MD	42	LCP	1974	2002	28				385		Howard County's Bureau of Engineering initiated a new capital project for fiscal year 2002 to repalce the entire 7,700 linear feet of 42-inch PCCP
233	JAMESTOWN, ND	20	LCP	1953	1982	29	I			1	LEAKING	STRUCK WITH BACK HOE
234	JEFFERSON CO, CO	27	LCP	1976	1982	6	IV			1	LEAKING	SULFATE OR CYLINDER DEFECTS
235	JEFFERSON CO, CO	27	LCP	1976	1982	6	IV		1		RUPTURED	CORROSION
267	JUNCTION CITY, KS	20	LCP	1978	1983	5	IV	8	1		RUPTURED	THRUST BLOCK MOVED
236	KANSAS CITY, MO	72	ECP	1981	1982	1	IV			1	LEAKING	COATING CRACKS
405	KANSAS CITY, MO	48	LCP	1947			MB OT		1		RUPTURED	
157	KNOXVILLE, TN	48	LCP	1971	1980	9	II	8	13		RUPTURED	CORROSION OF PRESTRESS WIRES

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
196	KNOXVILLE, TN	48	LCP	1972	1981	9	II	8	2		RUPTURED	CORROSION OF WIRES; FAILURES 100 FT. APART
197	KNOXVILLE, TN	48	LCP	1972	1981	9	II	8	1		RUPTURED	
237	LAKEHURST, CO	27	LCP	1975	1982	7	IV			1	LEAKING	AGGRESSIVE SOIL
158	LASALLE CO, ILL	54	ECP	1974	1980	6	IV	8	1		RUPTURED	DAMAGED; CHLORIDE CONTAMINATION
15	LITTLE ROCK, AR	16	LCP	1953	1971	18	I		1		RUPTURED	COATING DAMAGED DURING INSTALLATION
125	LITTLE ROCK, AR	24	LCP	1965	1979	14	II		1		LEAKING	LOOPED GASKET
238	LITTLE ROCK, AR	48	ECP	1956	1982	26	I		1		RUPTURED	ROCK UNDER PIPE; CONTRACTOR
239	LITTLE ROCK, AR	72	ECP	1980	1982	2	IV	8	1		RUPTURED	
240	LITTLE ROCK, AR	48	LCP	1980	1982	2	IV	8	1		RUPTURED	
591	LIVONIA, MI	48		1972	2003	31			1		RUPTURED	Ruptured near Inkster Road
590	LIVONIA, MI	48		1972	2007	35			1		RUPTURED	Ruptured July 12, 2007
435	LOS ANGELES, CA	84	ECP	1967			II	6 - 5/16		1		Moderate condition; many possible 5-wire breaks, several 10+ breaks
436	LOS ANGELES, CA	78	ECP	1967			II	5/16 - 3/8		1		Moderately good condition; some possible 5-wire breaks and a few 10-wire breaks
437	LOS ANGELES, CA	78	ECP	1967			II	1/4 - 5/16		1		Moderate condition; many possible 5-wire breaks, several 10+ breaks
438	LOS ANGELES, CA	78	ECP	1967			II	8 - 1/4		1		Moderate condition; many possible 5-wire breaks, several 10+ breaks

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
439	LOS ANGELES, CA	150	ECP	1970			II	8		1		Moderately good condition; some possible 5-wire breaks and a few 10-wire breaks
440	LOS ANGELES, CA	96	ECP	1970			II	1/4 - 5/16		1		Moderately good condition; some possible 5-wire breaks and a few 10+-wire breaks
441	LOS ANGELES, CA	96	ECP	1970			II	1/4		1		Moderately good condition; some possible 5-wire breaks and one 10-wire breaks
442	LOS ANGELES, CA	96	ECP	1970			II	6 - 5/16		1		Good condition; one possible 5-wire break
443	LOS ANGELES, CA	96	ECP	1970			II	6 - 5/16		1		Moderately good condition; several possible 5-wire breaks
444	LOS ANGELES, CA	84	ECP	1970			II	1/4 - 5/16		1		Moderately good condition; several possible 5-wire breaks and one 10-wire breaks
59	LOUISVILLE, KY	60	ECP	1975	1976	1	IV		1		RUPTURED	failure at shop welded joint
241	MAMARONECK, NY	30	LCP	1958	1982	24	I			1	BROKEN WIRES	SETTLEMENT OF CONCRETE
60	MANDEN, ND	24	LCP	1975	1976	1	IV			1	LEAKING	LINE WAS BEING TESTED
242	MANDEN, ND	30	LCP	1975	1982	7	IV			1	LEAKING	EXCESSIVE JOINT OPENING
243	MANDEN, ND	30	LCP	1975	1982	7	IV			1	LEAKING	CONTRACTOR; IMPROPER INSTALLATION
244	MARTINS CREEK, PA	108	ECP	1973	1982	9	IV		1		RUPTURED	CONTRACTOR HIT PIPE WITH BACKHOE
104	McGEHEE, AR	30	LCP	1975	1978	3	IV		1		RUPTURED	SURGE DUE TO SUDDEN VALVE CLOSURE
105	McGEHEE, AR	30	LCP	1975	1978	3	IV		1		RUPTURED	HOLE PUNCHED BY SUPPORT BUILT ON PIPE
80	MIAMI, FL	30	LCP	1967	1977	10	II			1	LEAKING	H2S

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
23	MIDDLESEX CO., NJ	48	ECP	1969	1972	3	II		1		RUPTURED	CRACKED COATING
198	MIDDLESEX CO., NJ	102	ECP	1977	1981	4	III	8		1		TURNBUCKLE JOINTS; ROTATION FAILURE -BC added wire class/size per install date (C301-79, A648)
268	MIDDLESEX CO., NJ	102	ECP	1977	1983	6	IV	6	1		RUPTURED	COLUMN SEPARATION; SURGE
335	MIDDLESEX CO., NJ	48	LCP	1967	1990	23	II	8		1	LEAKING	DENTED CYLINDER
356	MIDDLESEX CO., NJ	48	LCP	1967	1992	25	II			1	LEAKING	CYLINDER WELD FAILURE
473	MIDDLESEX COUNTY, NJ	102	ECP	1977	1983	6	IV	6, 1/4		1		due to hydraulic surges exceeding the design strength of the pipe caused by power loss to the pumping station
472	MIDDLESEX COUNTY, NJ	102	ECP	1977	2003	26	IV	6, 1/4	1		RUPTURE	the first PCCP failure in the MCUA system attributable to environmental degradation of the pipeline
126	MIDLAND, MI	48	LCP	1947	1979	32	I		1		RUPTURED	
37	MINOT, ND	24	LCP	1961	1974	13	I	6	1		RUPTURED	HIGH H2S LEVELS - BC added wire size per C301-58
106	MORRIS CO, NJ	24	LCP	1972	1978	6	IV		1		RUPTURED	SURGES CRACKED COATING
24	MORRISTOWN WTR. CO., NJ	16	LCP	1965	1972	7	II		1		RUPTURED	COATING DAMAGED DURING INSTALLATION
81	MT LEBANON, PA	48	ECP	1958	1977	19	I		1		RUPTURED	POSSIBLE HIGH SULFATE LEVEL
159	MT LEBANON, PA	48	ECP	1958	1980	22	I		1		RUPTURED	AGGRESSIVE SOIL
520	MUSKEGON COUNTY, MI	66	ECP	1972	1983	11			1		RUPTURE	Sewer line breaks under Eastern Avenue near downtown Muskegon.

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
521	MUSKEGON COUNTY, MI	66	ECP	1972	1988	16			1		RUPTURE	Line breaks northwest of Marquette Avenue and Getty Street.
522	MUSKEGON COUNTY, MI	66	ECP	1972	1999	27			1		RUPTURE	Line breaks under Yuba Street
523	MUSKEGON COUNTY, MI	66	ECP	1972	2001	29			1		RUPTURE	Line breaks for a fourth time, under Sumner Avenue west of Wood Street.
524	MUSKEGON COUNTY, MI	66	ECP	1972	2001	29				528	REPLACEMENT	Muskegon County replaces a two-mile section of 66-inch sewer main, between downtown Muskegon and Muskegon Township, near U.S. 31.
525	MUSKEGON COUNTY, MI	66	ECP	1972	2007	35			1		RUPTURE	A section of 66-inch diameter sewer main, previously thought to be structurally sound, breaks on MacArthur Street.
107	NAGUABO, PR	30	LCP	1967	1978	11	II		7		RUPTURED	SURGES-7TH BREAK-IN FIRST 800' FROM PUMP
127	NAGUABO, PR	30	LCP	1967	1979	12	II		1		RUPTURED	SURGE-8TH BREAK
269	NASHVILLE, TN	60	ECP	1974	1983	9	IV	8		1	LEAKING	POOR FIELD WELD
16	NEW BERN, NC	30	LCP	1967	1971	4	II	8		1	LEAKING	CORROSION
25	NEW BERN, NC	30	LCP	1967	1972	5	II	8		1	LEAKING	BRITTLE FRACTURE OF WIRE
26	NEW BERN, NC	30	LCP	1967	1972	5	II	8		1	LEAKING	COATING DAMAGED; CORE CRACKED
46	NEW BERN, NC	30	LCP	1967	1975	8	II	8		1	LEAKING	BRITTLE BREAKS IN WIRE
61	NEW BERN, NC	30	LCP	1967	1976	9	II	8		1	LEAKING	WIRES CORRODED
62	NEW BERN, NC	30	LCP	1968	1976	8	II	8		1	LEAKING	SEVERAL PIN HOLES & SPLIT IN CYLINDER
63	NEW BERN, NC	30	LCP	1968	1976	8	II	8		1	LEAKING	CORRODED WIRE; BAD DIAPER

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Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
108	NEW BERN, NC	30	LCP	1967	1978	11	II	8		1	LEAKING	
128	NEW BERN, NC	30	LCP	1967	1979	12	II	8		1	LEAKING	
129	NEW BERN, NC	30	LCP	1967	1979	12	II	8		1	LEAKING	
130	NEW BERN, NC	30	LCP	1967	1979	12	II	8		1	LEAKING	
131	NEW BERN, NC	30	LCP	1967	1979	12	II	8		1	LEAKING	1100 FT SECTION
160	NEW BERN, NC	30	LCP	1967	1980	13	II	8		1	BROKEN WIRES	COATING CRUMBLED AND WIRES CORRODED
199	NEW BERN, NC	30	LCP	1969	1981	12	II	8		3	BROKEN WIRES; EXTERNAL INSPECTION	LONGITUDINAL COATING CRACKS; CORROSION
270	NEW BERN, NC	30	LCP	1967	1983	16	II	8		13	BROKEN WIRES; EXTERNAL INSPECTION	
320	NEW JERSEY WATER SUPPLY	108	ECP	1974	1988	14	IV	6	1		RUPTURED	CORROSION AND BREAKAGE OF PRESTRESSED WIRE
326	NEW JERSEY WATER SUPPLY	108	ECP	1974	1989	15	IV	6		3	LINING DISTRESS, INTERNAL INSPECTION	LONGITUDINAL LINING RACKS
336	NEW JERSEY WATER SUPPLY	108	ECP	1974	1990	16	IV	6		7	LINING DISTRESS, INTERNAL INSPECTION	
245	NEW YORK CITY, NY	16	LCP	1974	1982	8	IV		1		RUPTURED	BEAM PROBLEM
109	NEWARK AIRPORT, NJ	16	LCP	1969	1978	9	II		1		RUPTURED	ELECTROLYSIS; C.P. INTERFERENCE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
461	NORTH ANDOVER, MA	72	ECP	1974	2005	31	IV	6		14		140 pipe sections, 14 were found to have wire breaks. 4 pipe sections >50 wire breaks. In 2005, post tensioning tendons installed on one pipe section. Being acoustically monitored.
445	NORTH ANDOVER, MA	72	ECP	1974			IV	6		1	REPAIRED	same pipeline as above. In 2005, we installed post tensioning tendons on one pipe section
161	NORTH GLENN, CO	48	LCP	1980	1980	0	IV		1		RUPTURED	BELL BOLT JT.; CYL. FAILED ADJ. TO HELICAL WELD
82	NOVI, MI	24	LCP	1975	1977	2	IV		1		LEAKING	LOOPED GASKET
459	OAKLAND, CA								1			4/7/86/ PBC list
162	OKLAHOMA CITY, OK	60	ECP	1973	1980	7	IV	8	1	3	BROKEN WIRES	LOOPED GASKET OR JOINT LEAK
200	OKLAHOMA CITY, OK	60	ECP	1973	1981	8	IV	8	1		RUPTURED	SURGED
246	OKLAHOMA CITY, OK	60	ECP	1973	1982	9	IV	8	1		RUPTURED	SURGES
271	OKLAHOMA CITY, OK	60	ECP	1973	1983	10	IV	8	1		RUPTURED	SURGED
272	OKLAHOMA CITY, OK	60	ECP	1973	1983	10	IV	8		1	BROKEN WIRES	SURGED
273	OKLAHOMA CITY, OK	60	ECP	1973	1983	10	IV	8	1		RUPTURED	SURGED
290	OKLAHOMA CITY, OK	60	ECP	1973	1984	11	IV	8	1		RUPTURED	
291	OKLAHOMA CITY, OK	60	ECP	1973	1984	9	IV	8	1		RUPTURED	
308	OKLAHOMA CITY, OK	60	ECP	1974	1987	13	IV	8	1		RUPTURED	STEEL CYLINDER RUPTURED

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Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
309	OKLAHOMA CITY, OK	60	ECP	1974	1987	13	IV	8		3	LINING DISTRESS, INTERNAL INSPECTION	LEAKING CYLINDER
563	OKLAHOMA CITY, OK	60	ECP	1974	2004	30	IV	8	1		RUPTURED	
528	OKLAHOMA CITY, OK	72	ECP		2006				3		RUPTURES	
83	OMAHA, NE	36	LCP	1974	1977	3	IV		1		RUPTURED	TORN ALONG HELICAL; BELL BOLT JTS. 45 ELBOW
110	OMAHA, NE	36	LCP	1974	1978	4	IV		2		RUPTURED	TORN ALONG HELICAL; BELL BOLT JTS. 45 ELBOW
163	OMAHA, NE	48	LCP	1974	1980	6	IV		1		RUPTURED	SHORT BETWEEN TWO ELBOWS W/BELL BOLT JT.
164	OMAHA, NE	48	LCP	1974	1980	6	IV		1	1	LINING DISTRESS, INTERNAL INSPECTION	
3	ONONDAGA CO., NY	30	LCP	1947	1960	23		1/8	1		CRACKED COATING	CHEMICAL WASTES
84	ONONDAGA, NY	30	LCP	1976	1977	1	IV		2		RUPTURED	SEAM RUPTURE DURING TESTING; PIPE ON ROCK
327	ORADELL, NJ	60	ECP	1988	1989	1	III			1	LEAKING	WELDED RESTRAINED JOINT PARTED
554	ORLANDO, FL	36, 42		1984	2004	20	III	8	1	2	RUPTURE	Failed several times. Replaced with BA04-89, BR04-289, Project No. 2729 -BC added wire class & size per year installed (C301-79 or 84, A648)
132	PALM BEACH, FL	20	LCP	1956	1979	23	I		1	2	BROKEN WIRES	H2S; H2S04

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Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
476	PHOENIX, AZ	252	ECP	1978	1990	12	III	1/2		91	REPAIR	corrosion monitoring indicated several pipes along all six siphons corroding. OF the 223 pipe units excavated to springline, 91 (41%) exhibited external distress which required additional repairs
477	PHOENIX, AZ	252	ECP	1978	1990	12	III	1/2		35	REPAIR	Relining the first 700 ft of siphon under Interstate 10 with steel
478	PHOENIX, AZ	252	ECP	1978	1990	12	III	1/2		25	REPAIR	Relining 500 ft of siphon with steel
480	PHOENIX, AZ	252	ECP	1978	1993	15	III	1/2		425	REPLACEMENT	replacing the existing siphon with parallel cast-in-place concrete or steel pipelines (8,492 linear feet)
481	PHOENIX, AZ	252	ECP	1978	1993	15	III	1/2		278	REPLACEMENT	replacing the existing siphon with parallel cast-in-place concrete or steel pipelines (5,544 linear feet)
363	PHOENIX, AZ	66	ECP	1978	1994	16	II		1		RUPTURED	
389	PHOENIX, AZ	66	ECP	1978	1997	19	II		1		RUPTURED	
390	PHOENIX, AZ	96	ECP	1978	1997	19	II		1		RUPTURED	
485	PHOENIX, AZ	72-108	ECP	1973	2003	30				3,696		The City of Phoenix initiated a multi-year rehabilitation program to slipline all but one mile of the pipeline using steel pipe.
452	PHOENIX, AZ	60	ECP	1978	2006	28	III	8	1		Failure in October 2006 (the failure was in the section as-built in 1978)	
479	PHOENIX, AZ	252	ECP	1978			III	1/2		492	REPLACEMENT	replacing the existing siphon with parallel cast-in-place concrete or steel pipelines (9,840 linear feet)
133	PINELLAS CO ,FL	60	ECP	1977	1979	2	IV	8	1		RUPTURED	COATING AND CORE DAMAGED PBC list indicates 1978 construction

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
165	PINELLAS CO ,FL	60	ECP	1977	1980	3	IV	8	1		RUPTURED	BEING REFILLED FOR STATIC TESTING; SURGE PBC list indicates 1978 construction
406	PINELLAS CO ,FL	60	ECP	1977			IV	8	2		RUPTURED	
482	PINELLAS COUNTY, FL	48			2001						No rupture	Accoustically monitored by PURE, found several problematic areas. Jason Consultants recommended sliplining.
85	PITTSBURGH, PA	48	LCP		1977		I	6	1		RUPTURED	COATING DETERIORATION
166	PITTSBURGH, PA	48	LCP		1980		I	6	1		RUPTURED	COATING DETERIORATION; SULFATES
274	PITTSBURGH, PA	48	LCP		1983		I	6		1	LEAKING	
292	PITTSBURGH, PA	36	LCP	1960	1984	24	I		1		RUPTURED	AT JOINT
300	PITTSBURGH, PA	36	LCP	1960	1985	25	I		1		RUPTURED	MID-PIPE AT BOTTOM
275	PLEASANT PRAIRE, WI	30	LCP	1978	1983	5	IV	8	1		RUPTURED	
402	PLEASANT PRAIRE, WI	30	LCP	1978	1983/5	6	IV	8	4		RUPTURED	2ND PROBLEM; 5 FAILURES BY 1985
377	PROVIDENCE, RI	102	LCP	1970	1996	26	III	8	1	1	RUPTURED	ALSO ADJACENT PIPE REPLACED -BC added wire class & size per installed year (AWWA C301-64, A227)
557	PROVIDENCE, RI	102	LCP	1970	2000	30	III	8		11	REPAIRED	-BC added wire class & size per installed year (AWWA C301-64, A227)
86	PUERTO RICO	60	ECP		1977				1		RUPTURED	
276	RALEIGH, NC	36	LCP	1974	1983	9	IV	8		1	LEAKING	INSTALLED ON POOR FOUNDATION

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
201	RIALTO, CA			1970	1981	11	III	8	1		RUPTURED	-BC added wire class/size per install date (C301-64, A227)
429	RIALTO, CA	96	ECP	1972	2004	32	III	8 - 5/16		3	REPAIRED	Moderate condition; several break locations
430	RIALTO, CA	120	ECP	1972			III	6 - 5/16		1		Moderate condition; several 5-wire break locations
277	RICHMOND, VA	36	LCP	1982	1983	1	IV			1	LOOSE COATING	10 PIPE REPAIRED
310	RICHMOND, VA	36	LCP	1979	1987	8	IV	6	1		RUPTURED	WIRE NOT AS SPECIFIED
321	RICHMOND, VA	36	LCP	1979	1988	9	IV	6	1		RUPTURED	WIRE NOT AS SPECIFIED
426	RIVERSIDE, CA	96	ECP	1976			III	6 - 8		1		No broken wires; however, several "broken backs"
27	ROCHESTER, NY	20	LCP	1960	1972	12	I		1		RUPTURED	SFM DAMAGED DURING INSTALLATION
134	ROCK HILL, SC	30	LCP	1972	1979	7	IV			1	LEAKING	TEAR IN WELD AT JT. RING; PIPE REPAIRED
87	S.E. OAKLAND CO., MI	20	LCP	1970	1977	7	II			1	LEAKING	STORM SEWER FLUSHING LINE W/4 12" OUTLETS
88	S.E. OAKLAND CO., MI	20	LCP	1975	1977	2	IV			1	LEAKING	STORM SEWER FLUSHING LINE W/4 12" OUTLETS
204	S.E. OAKLAND CO., MI	20	LCP	1970	1981	11	II			1	LEAKING	SPLIT WELD
460	SACRAMENTO, CA								1			4/7/86 PBC list indicates 1 failure
135	SAGINAW, MI	48	LCP	1948	1979	31	I		1		RUPTURED	
293	SALT LAKE CITY, UT	66	ECP	1981	1984	3	III	8	1	1	RUPTURED	BROKEN WIRES, CATHODIC PROTECTION - Two units of pipe (failed No. 797 and neighbor 798) were replaced

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Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
553	SALT LAKE CITY, UT	66	ECP	1981	1990	3	III	8		607	RELINED	All 2.3 miles were rehabilitated by lining with steel
5	SAN DIEGO CO. CA	24	LCP		1962		I		1		RUPTURED	
136	SAN DIEGO CO. CA	66-69	ECP	1960	1979	19	I		1		RUPTURED	FAILURE OF 66-69 INCH PIPE. Rupture Feb 23, 1979
248	SAN DIEGO CO. CA	72	ECP	1972	1979	7	III		1		RUPTURED	Broken back at structure (date approximate)
567	SAN DIEGO CO. CA	66, 69	ECP	1960	1980	20	I	6	1		RELINED	Rupture Dec 31, 1980. BC added wire class/size per install year (C301-58, A227)
462	SAN DIEGO CO. CA	66	ECP	1960	1982	22	I	6		1,322	RELINED	Relined 1982-84. BC added wire class/size per install year (C301-58, A227)
568	SAN DIEGO CO. CA	66, 69	ECP	1960	1982	22	I	6	1		RELINED	Rupture May 28, 1982. BC added wire class/size per install year (C301-58, A227)
251	SAN DIEGO CO. CA	72	ECP	1972	1982	10	III		1		RUPTURED	9/18/82 BROKEN WIRES; CORROSION
278	SAN DIEGO CO. CA	72	ECP	1973	1983	10	III		1		RUPTURED	BROKEN WIRES/ CORROSION
249	SAN DIEGO CO. CA	72	ECP	1972	1987	15	III		1	7	RUPTURED	8/3/87 replaced 8 sections
247	SAN DIEGO CO. CA	72	ECP	1959	1988	29	III		1		RUPTURED	January - 1 pipe replaced
250	SAN DIEGO CO. CA	72	ECP	1972	1990	18	III		1		RUPTURED	replaced 1 section
337	SAN DIEGO CO. CA	84	ECP	1974	1990	16	III	8	1	1	RUPTURE, EXTERNAL INSPECTION	Rupture October 1990. External inspection found severe corrosion on pipe 547
569	SAN DIEGO CO. CA	84	ECP	1974	1991	17	III	8		6	LINING DISTRESS, INTERNAL INSPECTION	BROKEN WIRES/ CORROSION

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
570	SAN DIEGO CO. CA	96	ECP	1972	1992	20				1	LINING DISTRESS, INTERNAL INSPECTION	BROKEN WIRES/ CORROSION
571	SAN DIEGO CO. CA	66	ECP	1972	1992	20				2	LINING DISTRESS, P4EI INSTALLATION	BROKEN WIRES/ CORROSION
572	SAN DIEGO CO. CA	96	ECP	1972	1993	21			1	1	RUPTURE, EXTERNAL INSPECTION	BROKEN WIRES/ CORROSION. Rupture Nov. 1993
573	SAN DIEGO CO. CA	66	ECP	1960	1994	34	I	6		5	INTERNAL INSPECTION	BROKEN WIRES/ CORROSION. BC added wire class/size per install year (C301-58, A227)
574	SAN DIEGO CO. CA	69	ECP	1959	1997	38	I	6		1	INTERNAL INSPECTION	MANUFACTURING DEFECT. BC added wire class/size per install year (C301-58, A227)
575	SAN DIEGO CO. CA	72	ECP	1977	1997	20				1	INTERNAL INSPECTION	Internal corrosion, cracked can, leaking water
576	SAN DIEGO CO. CA	66	ECP	1964	1999	35	II	8		5	CONCRETE ENCASED	BC added wire class/size per install year (C301-64, A227)
577	SAN DIEGO CO. CA	69	ECP	1959	1999	40	I	6		5	INTERNAL INSPECTION	BROKEN WIRES/ CORROSION. Relined. BC added wire class/size per install year (C301-58, A227)
578	SAN DIEGO CO. CA	84	ECP	1974	2003	29	III	8		3	LINING DISTRESS, INTERNAL INSPECTION	BROKEN WIRES/ CORROSION from RFEC/TC
584	SAN DIEGO CO. CA	69	ECP	1959	2003	44	I	6		851	RELINED	Relined. BC added wire class/size per install year (C301-58, A227)

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
579	SAN DIEGO CO. CA	96	ECP	1972	2004	32				6	INTERNAL INSPECTION	BROKEN WIRES/ CORROSION from RFEC/TC
585	SAN DIEGO CO. CA	96	ECP	1972	2004	32				835	RELINED	Relined 2003-2004
580	SAN DIEGO CO. CA	69	ECP	1959	2004	45	I	6		11	INTERNAL INSPECTION	BROKEN WIRES/ CORROSION. PPIC RFEC/TC. Concrete encased. BC added wire class/size per install year (C301-58, A227)
586	SAN DIEGO CO. CA	96	ECP	1972	2004	32				1,325	RELINED	Relined 2004-2005
587	SAN DIEGO CO. CA	96	ECP	1972	2004	32				1,071	RELINED	Relined 2004-2005
581	SAN DIEGO CO. CA	90	ECP	1969	2005	36	III	8		1	INTERNAL INSPECTION	BROKEN WIRES/ CORROSION. BC added wire class/size per install year (C301-64, A227)
582	SAN DIEGO CO. CA	33	LCP	1978	2005	27				1	INTERNAL INSPECTION	LONGITUDINAL COATING CRACKS; CORROSION
588	SAN DIEGO CO. CA	96	ECP	1972	2005	33				266	RELINED	Relined 2005-2006
463	SAN DIEGO CO. CA	66	ECP	1959	2006	47	I	6	2		RUPTURE	Failure 5-16-06 on Mission Trails -BC added wire class/size per install year (C301-58, A227)
465	SAN DIEGO CO. CA	96	ECP	1981	2006	25	III	8		2	REPAIRED	Pieces 234 & 240 repaired with Carbon Fiber June 2006 after eddy current testing -BC added wire class/size per install year (C301-79, A648
464	SAN DIEGO CO. CA	96	ECP	1981	2007	26	III	8		2	REPAIRED	Pieces 1225 & 2196 repaired with Carbon Fiber March 2007 after eddy current testing -BC added wire class/size per install year (C301-79, A648
583	SAN DIEGO CO. CA	33, 42	LCP	1978	2007	29				3	INTERNAL INSPECTION	Leak detected after moisture surfaced.

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
425	SAN DIEGO CO. CA	96	ECP	1985			III	6		1	REPAIRED	Pipe includes longitudinal shorting strap under wires. Only one break area caused by mechanical damage, otherwise in good condition
432	SAN DIEGO CO. CA	99	ECP	1970			II	8 - 5/16		1		Moderate good condition; a few 5-wire breaks
433	SAN DIEGO CO. CA	96	ECP	1981			III	8 - 5/16		1		Good condition; one 10-wire break
338	SAN FRANCISCO, CA	66	ECP	1980	1990	10	III	8	1	1	LINING DISTRESS, INTERNAL INSPECTION	Failure @ 153+40. Investigated by CERCO (No.9015). Hydrogen Embrittlement suggested as cause.
347	SAN FRANCISCO, CA	84	ECP	1985	1991	6	II	8		1	LINING DISTRESS, INTERNAL INSPECTION	CARBONATED COATING
532	SAN FRANCISCO, CA	96	ECP	1966	2004	38	II	8		1	REPAIR	Repair four brittle fractures in pipe 749 after PPIC inspection -BC added wire class/size per install year (C301-64, A227)
434	SAN JACINTO, CA	96	ECP	1975			III	8		1		Only one break area caused by mechanical damage, otherwise in good condition
47	SANFORD, NC	24	LCP	1971	1975	4	II			1	LEAKING	DAMAGED
202	SANFORD, NC	24	LCP	1971	1981	10	II		1		RUPTURED	LARGE BOULDER; CONTRACTOR DAMAGE
203	SANFORD, NC	24	LCP	1981	1981	0	IV		1		RUPTURED	ELECTROLYSIS
446	SANTA CLARA, CA	96	ECP	1985			III	6, 1/4, 5/16			About 10% inspected (eddy current) and found to be in excellent condition (Fall 2003)	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
279	SAYERVILLE,NJ	102	ECP	1980	1983	3	IV	6	1		BROKEN WIRES	POSSIBLE WIRE BRIDGING AND FAULTY INSTALLATION
31	SOUTH PITTSBURGH,PA	24	LCP	1952	1973	21	I		1		RUPTURED	WRONG CLASS PIPE USED; HIGH PRESSURE
280	SOUTH PITTSBURGH,PA	48	ECP	1958	1983	25	I	6	1		LEAKING	PIPE SETTLED
17	ST. LOUIS CO., MO	36	LCP	1952	1971	19	I		1		LEAKING	MANUFACTURING DEFICIENCIES
18	ST. LOUIS CO., MO	36	LCP	1952	1971	19	I		1		LEAKING	MANUFACTURING DEFICIENCIES
38	ST. LOUIS CO., MO		LCP	1950	1974	24	I		1		RUPTURED	MANUFACTURE DEFECT
39	ST. LOUIS CO., MO	36	LCP	1952	1974	22	I			2	1 LEAKING; 1 WITH BROKEN WIRES	
64	ST. LOUIS CO., MO	36	LCP	1952	1976	24	I			2	1 LEAKING; 1 WITH BROKEN WIRES	
137	ST. LOUIS CO., MO	36	LCP	1953	1979	26	I		1		RUPTURED	
550	ST. PAUL, MN	48		1972-78			IV	8			REPLACEMENT	exhibited cracks in the protective cement mortar coating, delaminated protective cement mortar coating, and corroded and broken prestressed wires. -BC added install date & wire size per wire class/manufacturer (C301-72, A648, Interpace practice)
281	STAMFORD, CT	24	LCP	1969	1983	14	II	6	1		RUPTURED	STRAY CURRENT; SEVERAL FAILURES
4	SYRACUSE, NY	30	LCP		1961		I		1		RUPTURED	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
498	TAMPA, FL	66	ECP	1975	1987	12	IV	8	1		RUPTURE	A pipeline investigation was conducted between February 1990 and April 1992 by PURE. Soils and groundwater chemistry were generally benign. -BC added wire class and size per install date (C301-72, A648, Interpace practice)
499	TAMPA, FL	84	ECP	1975	1990	15	IV	8	1		RUPTURE	-BC added wire class and size per install date (C301-72, A648, Interpace practice)
357	TAMPA, FL	90	ECP	1975	1992	17	IV	8		1	EXTERNAL INSPECTION; BROKEN WIRES	
500	TAMPA, FL	84	ECP	1975	1997	22	III	8	1		RUPTURE	Rupture October 30, 1997 in an area intermixed with Interpace pipe -BC added wire class and size per install date (C301-72, A648)
561	TAMPA, FL	84	ECP	1975	1998	23	IV	8	1		RUPTURE	Rupture September 23, 1998 -BC added wire class and size per install date (C301-72, A648, Interpace practice)
562	TAMPA, FL	84	ECP	1975	1999	24	IV	8	1		RUPTURE	Rupture April 22, 1999 -BC added wire class and size per install date (C301-72, A648, Interpace practice)
502	TAMPA, FL	84	ECP	1975	1999	24	III	8		2		Conclusion from acoustic monitoring: Sta. 673+55 & 683+35 were repaired/replaced. -BC added wire class and size per install date (C301-72, A648)
501	TAMPA, FL	84	ECP	1975	2000	25	IV	8		2,000	REPLACEMENT	Conclusion from internal inspection: the Interpace piping should be immediately replaced. 40,000 feet replaced with Price Brothers PCCP in fall of 2000 -BC added wire class and size per install date (C301-72, A648, Interpace practice)

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
559	TAMPA, FL	84	ECP	1975	2003	28	III	8	1	3	RUPTURE	Second rupture of Price Brother's pipe on March 20, 2003. Three additional pieces removed. -BC added wire class and size per install date (C301-72, A648)
560	TAMPA, FL	84	ECP	1975	2003	28	III	8		1,628	REPLACEMENT	After second rupture, Board boted to replace the remaining 5.5 mile segment -BC added wire class and size per install date (C301-72, A648)
555	TAMPA, FL	84	ECP	1975	2005		III	8		1,450	PARALLEL MAIN	The new main parallels and will replace the final section of a failing 84" main. -BC added wire class & size per install date (C301-72, A648)
504	TARRANT COUNTY, TX	72, 84	ECP	1972	1981	9	II	6, 8, 1/4	1		RUPTURE	Corrosion failure
505	TARRANT COUNTY, TX	72, 84	ECP	1972	1983	11	II	6, 8, 1/4	1		RUPTURE, REPAIRED	Corrosion failure
506	TARRANT COUNTY, TX	72, 84	ECP	1972	1988	16	II	6, 8, 1/4	1		RUPTURE, REPAIRED	Corrosion failure
511	TARRANT COUNTY, TX	90, 108	ECP	1988	1988	0	III	6, 1/4		2		Thrust failures during hydrostatic testing and first pump test
507	TARRANT COUNTY, TX	72, 84	ECP	1972	1989	17	II	6, 8, 1/4	1		RUPTURE, REPAIRED	Corrosion failure
508	TARRANT COUNTY, TX	72, 84	ECP	1972	1990	18	II	6, 8, 1/4	1		RUPTURE, REPAIRED	Corrosion failure
509	TARRANT COUNTY, TX	72, 84	ECP	1972	1991	19	II	6, 8, 1/4	2		RUPTURE, REPAIRED	Corrosion failures

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
512	TARRANT COUNTY, TX	90, 108	ECP	1988	1992	4	III	6, 1/4	1		RUPTURE	Corrosion failure
513	TARRANT COUNTY, TX	90, 108	ECP	1988	1993	5	III	6, 1/4	1		RUPTURE	Thrust restraint failure
514	TARRANT COUNTY, TX	90, 108	ECP	1988	1995	7	III	6, 1/4	1		RUPTURE	Thrust restraint failure
510	TARRANT COUNTY, TX	72, 84	ECP	1972	1996	24	II	6, 8, 1/4	1		RUPTURE, REPAIRED	Hydrogen embrittlement failure
515	TARRANT COUNTY, TX	90, 108	ECP	1988	1996	8	III	6, 1/4	2		RUPTURE	Corrosion failure and hydrogen embrittlement failure
516	TARRANT COUNTY, TX	90, 108	ECP	1988	1997	9	III	6, 1/4	1		RUPTURE	Corrosion failure
517	TARRANT COUNTY, TX	90, 108	ECP	1988	1998	10	III	6, 1/4	2		RUPTURE	Corrosion failure and hydrogen embrittlement failure
518	TARRANT COUNTY, TX	90, 108	ECP	1988	1999	11	III	6, 1/4	1		RUPTURE	Corrosion failure
592	TARRANT COUNTY, TX	72	ECP	1972	2004	32	II	6	1		RUPTURE, REPAIRED	Failed January 2004
519	TARRANT COUNTY, TX	72, 84, 90, 108	ECP	1972	2005	33	III	6, 1/4		70	REPAIR/REPLACEMENT	Results of the PPIC inspections revealed that of the 37148 segments inspected, 818 segments have wire breaks. Repairs were made choosing pipes with 50 or more broken wires.
431	TEMECULA, CA	162	ECP	1971			II	1/4 - 5/16		8		Moderate condition; several break locations

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
252	TROY, MI	16	LCP	1974	1982	8	IV			1	LEAKING	ROLLED GASKET; CONTRACTOR
398	TUCSON, AZ	96	ECP	1988	1999	11	III	6	1		RUPTURED	
483	TUCSON, AZ	96	ECP		1999				1		RUPTURE, corrosive soil	
205	URBANA, IL	30	LCP	1964	1981	17	II		1		RUPTURED	CLASS 90 SURCHARGE LOAD
89	UTE, CO	18	LCP	1964	1977	13	II		1	2	LEAKING	
111	UTE, CO	18	LCP	1964	1978	14	II		2		LEAKING	
138	UTE, CO	24	NCP	1964	1979	15	II		1		LEAKING	LOOPED GASKET
139	UTE, CO	24	NCP	1964	1979	15	II		1		RUPTURED	MORTAR COATING DETERIORATION
8	UTICA, NY	30	LCP	1954	1967	13	I		1		RUPTURED	OPEN JOINT OR LOOPED GASKET
253	WALWORTH CO, WI	20	LCP	1981	1982	1	IV		1		LEAKING	CONTRACTOR LEFT 1" JOINT SEPARATION
10	WASHINGTON DC	30	LCP	1962	1969	7	I		1		LEAKING	
254	WAYNE, NJ			1981	1982	1	IV		1		RUPTURED	CONTRACTOR; COLLAPSED CORE
311	WEST COAST REGIONAL, FL	84	ECP	1974	1987	13	IV	6	1		RUPTURED	CORRODED WIRES; POROUS COATING
348	WEST COAST REGIONAL, FL	84	ECP	1974	1991	17	IV	6		1	BROKEN WIRES	OTL SURVEY
349	WEST COAST REGIONAL, FL	84	ECP	1974	1991	17	IV	6	1		RUPTURED	WIRE CORROSION
167	WEST ORANGE, NJ	27	LCP	1965	1980	15	II		1		RUPTURED	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
503	WESTFIELD, NJ	60	ECP	1977	2002	25	IV	8	1	1	RUPTURE	Investigation of the leak determined that the cause was corrosion of the steel cylinder where the concrete lining had been cut back to weld the joint and the lining had not been repaired. External inspection found one additional prob. pipe
255	WESTMORELAND, PA	20	LCP	1956	1982	26	I		1		LEAKING	ACID ATTACK
282	WHEATLAND, WY	24	LCP	1978	1983	5	IV	6	1		RUPTURED	GRADE E SHEET; EXCESS LOAD
140	WILMINGTON, DE	24	LCP	1970	1979	9	II		1		RUPTURED	H2S; H2SO4
141	WILMINGTON, NC	24	LCP	1970	1979	9	II		1		RUPTURED	H2S; H2SO4
32	WINSTON-SALEM, NC	36	LCP	1949	1973	24	I		1		RUPTURED	SURGES
486	WINTERSBERG, AZ	114, 96, 66	ECP	1982	1994	12	III	8	1		RUPTURE	-BC added wire class and size per install date (C301-79, A648)
487	WINTERSBERG, AZ	114, 96, 66	ECP	1982	1995	13	III	8		2		Accoustically monitored by PURE, found five pipe sections with acoustic events. Two of the pipe sections had indications of intermediate to advanced distress and were repaired. -BC added wire class and size per install date (C301-79, A648)
11	WSSC, MD	16	LCP	1965	1970	5	II		1	6	3 LEAKING; 3 W/BROKEN WIRES	CATHODIC INTERFERENCE
48	WSSC, MD	30	LCP	1943	1975	32	I			1	LEAKING	ERODED CORE
49	WSSC, MD	96	ECP	1970	1975	5	II	6	1		RUPTURED	CORRODED WIRE; PRIOR DAMAGE TO COATING

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
112	WSSC, MD	84	ECP	1974	1978	4	IV	6	1		RUPTURED	DAMAGED COATING AND CORRODED WIRES
142	WSSC, MD	42	LCP	1974	1979	5	IV	6	1		RUPTURED	BROKEN CYL.; DAMAGED AT MANUFACTURE
168	WSSC, MD	60	ECP	1967	1980	13	II	6	1		RUPTURED	BROKEN WIRE; POSSIBLE SURGE
169	WSSC, MD	60	ECP	1967	1980	13	II	6	1		RUPTURED	BROKEN WIRE; POSSIBLE SURGE
170	WSSC, MD	72	ECP	1974	1980	6	IV	6	1		RUPTURED	COATING DAMAGED ON ONE SIDE
171	WSSC, MD	84	ECP	1974	1980	4	IV	6	1		RUPTURED	
172	WSSC, MD	72	ECP	1976	1980	4	V	6	1		RUPTURED	CYLINDER AND PRESTRESS WIRES CORRODED
206	WSSC, MD	42	LCP	1971	1981	10	II	8	1		LEAKING; BROKEN WIRES	MANUFACTURER-DENTED CYLINDER; SPLIT
283	WSSC, MD	42	LCP	1974	1983	9	IV	6	1		RUPTURED	BELL JOINT RING OUT-OF-ROUND
284	WSSC, MD	42	LCP	1974	1983	9	IV	8		3	2 WITH BROKEN WIRES; 1 ROLLED GASKET	
294	WSSC, MD	60	ECP	1967	1984	7	II	6	1		RUPTURED	DISRUPTED COATING
295	WSSC, MD	84	ECP	1974	1984	10	IV	6	1		RUPTURED	LEAKING CYLINDER
296	WSSC, MD	72	ECP	1974	1984	10	IV	6	1	5	BROKEN WIRES, EXTENSIVE CORROSION	LEAKING CYLINDER
304	WSSC, MD	60	ECP	1967	1986	19	II	6	1		RUPTURED	LEAKING JOINT RING WELD
305	WSSC, MD	84	ECP	1975	1986	11	IV	1/4	1		RUPTURED	CORROSION; WIRE BREAKAGE

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
306	WSSC, MD	42	LCP	1975	1986	11	IV	8	1		RUPTURED	WIRE BREAKAGE DUE TO DENTED CYLINDER
312	WSSC, MD	60	ECP	1967	1987	20	II	6	1		RUPTURED	CORROSION; BROKEN WIRE; WIRE EXPOSED
313	WSSC, MD	48	ECP	1970	1987	17	II	8	1		RUPTURED	LEAKING THROUGH WELDING IMPERFECTIONS
314	WSSC, MD	42	LCP	1975	1987	12	IV	6	1		RUPTURED	SPIGOT END LEAKING RESULTED IN BURST
315	WSSC, MD	42	LCP	1975	1987	12	IV	8	2		RUPTURED	DENTED CYLINDER
316	WSSC, MD	30	LCP	1975	1987	12	IV	8	1		RUPTURED	CYLINDER SPLIT AT SPIGOT END
322	WSSC, MD	24	LCP	1966	1988	22	II	6	1		RUPTURED	DISRUPTED MORTAR COATING
328	WSSC, MD	96	ECP	1966	1989	23	II	6		1	LINING DISTRESS, INTERNAL INSPECTION	
329	WSSC, MD	60	ECP	1967	1989	22	II	6		5	LINING DISTRESS, INTERNAL INSPECTION	INTERNAL LONGITUDINAL CRACKS; BROKEN WIRES
339	WSSC, MD	42	LCP	1959	1990	31	I	6		4	1 LEAKING; 3 W/BROKEN WIRES	
340	WSSC, MD	48	LCP	1960	1990	30	II	6	1	2	EXTERNAL INSPECTION	BROKEN WIRES
341	WSSC, MD	24	LCP	1972	1990	18	IV	8	1		RUPTURED	
358	WSSC, MD	42	LCP	1974	1992	18	IV	8	1		RUPTURED	
364	WSSC, MD	42	LCP	1974	1994	20	IV	8	1		RUPTURED	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
365	WSSC, MD	108	ECP	1977	1994	18	IV	6		4	LINING DISTRESS, INTERNAL INSPECTION	BROKEN WIRES
371	WSSC, MD	60	ECP	1960	1995	35	II	6	1		RUPTURED	AT SPIGOT HAUNCH; HALF BEVEL
372	WSSC, MD	60	ECP	1967	1995	28	II	6	1		RUPTURED	CYLINDER SPLIT AT BEVEL SADDLE WELD
373	WSSC, MD	36	LCP	1967	1995	28	II	8	1		RUPTURED	
374	WSSC, MD	108	ECP	1977	1995	18	IV	6		6	LINING DISTRESS, INTERNAL INSPECTION	
378	WSSC, MD	60	ECP	1967	1996	29	II	6		1	LINING DISTRESS, INTERNAL INSPECTION	INTERNAL LONGITUDINAL CRACKS; BROKEN WIRES
379	WSSC, MD	96	ECP	1970	1996	26	II	6	1		RUPTURED	LEAKING CYLINDER
380	WSSC, MD	96	ECP	1970	1996	26	II	1/4		1	LINING DISTRESS, INTERNAL INSPECTION	CORROSION; WIRE BREAKAGE
381	WSSC, MD	24	LCP	1966	1996	30	II	6	1		RUPTURED	DISRUPTED COATING; AUGER DAMAGED
399	WSSC, MD	54	ECP	1967	1999	32	II	8		1	INCIPIENT FAILURE; INTERNAL INSPECTION	
400	WSSC, MD	54	ECP	1965	1999	34	II	6		5	INCIPIENT FAILURE; INTERNAL INSPECTION	
401	WSSC, MD	54	ECP	1965	1999	34	II	6		4	INCIPIENT FAILURE; INTERNAL INSPECTION	

(continued)

Table 1.1 continued

ID	Location	Dia. (in.)	Pipe type	Install date	Fail date	Age yrs.	Wire class	Wire size	No. of ruptures	Other failures	Failure/condition	Comment by investigator
589	YORBA LINDA, CA	69	ECP	1979	1999	20	III	1/4	1		RUPTURED	Ruptured December 13, 1999 near station 187+80. Brittle wire.
			LCP = LINED CYLINDER PIPE					NCP = NON-CYLINDER PIPE			MBOT = MILD BRIGHT OIL TEMPERED WIRE	RFEC/TC*: Remote Eddy Current/Transformer Coupling
592	TOTAL		ECP = EMBEDDED CYLINDER PIPE					DW = DOUBLE WRAPPED			FAC = Fly Ash Cement	

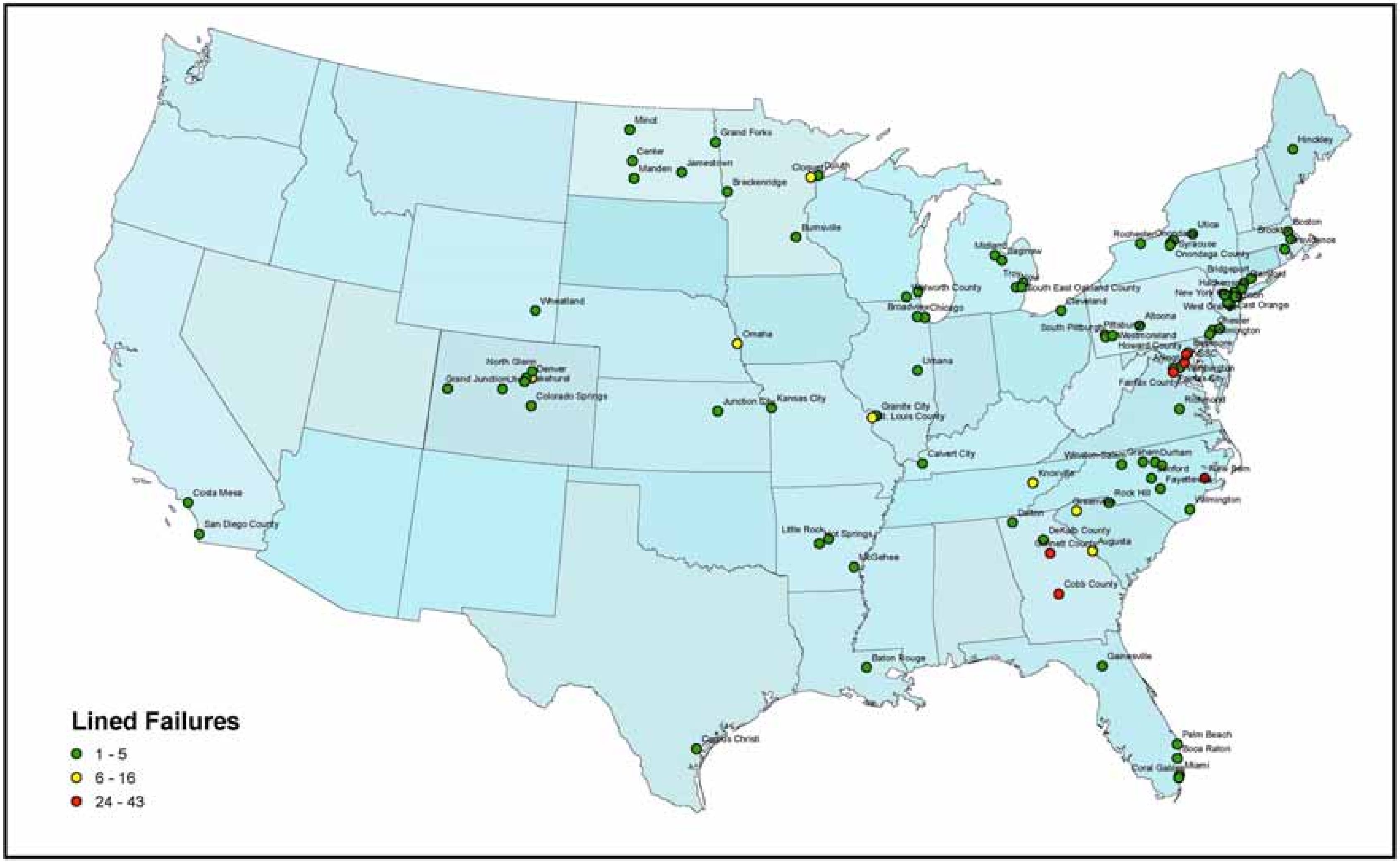

Figure 1.1 Location of failures – LC-PCCP

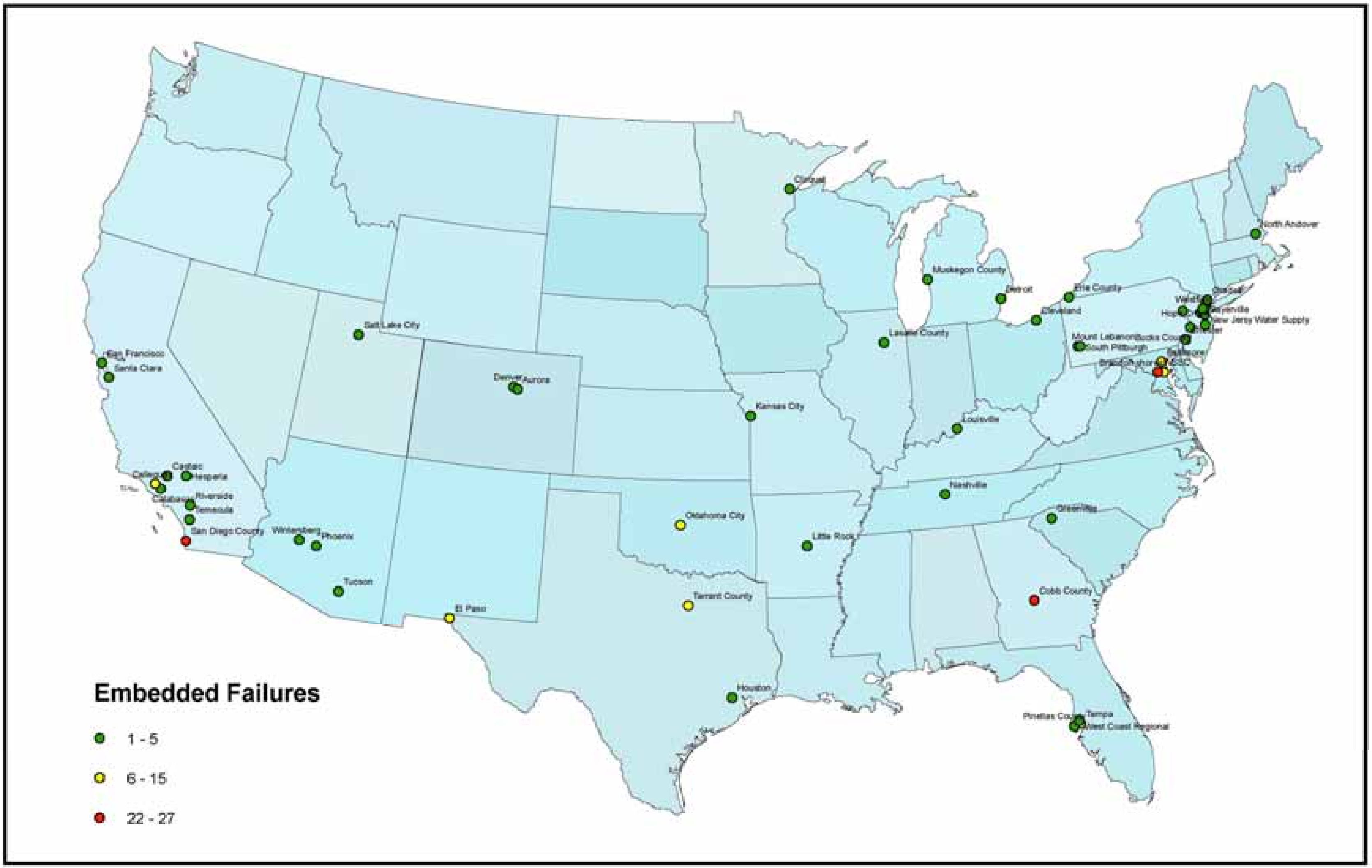

Figure 1.2 Location of failures – EC-PCCP

CHAPTER 2
HISTORY OF PCCP

PRODUCTION DATA

Early reinforced concrete pressure pipe was an extension of concrete culvert pipe, with addition of a steel cylinder for water retention. Spirally wound reinforcement has been reported as early as 1929 (Lynch, Wilson, and Gunther 2004) for concrete pressure pipe. In response to the high demand for steel in the war years, the emerging technology of prestressing concrete was applied to water pipelines. The earliest application in the U.S. was in 1942 (AWWA C301-99 Foreword). That pipe, which is now known as LC-PCCP consists of a steel cylinder with cast concrete core, over-wrapped with steel wire. Continuing scarcity of steel, coupled with successful application to smaller pipe, led to the introduction of EC-PCCP in 1953 (AWWA C301-99 Foreword). Site-manufactured EC-PCCP has been constructed as large as 256 inches in diameter.

Significant differences in the manufacture of LC-PCCP and EC-PCCP not only exist, but the configuration of each type has changed significantly throughout the years of manufacture. Table 2.1 lists some of the major differences in the pipe, and Table 2.2 lists some of the significant changes in the products. Those changes are described in more detail below.

Table 2.1
Differences between lined and embedded type PCCP

Feature	LC-PCCP	EC-PCCP
Diameter range	16 through 60 inches	30 through 256 inches
Construction	Steel cylinder lined with a cast concrete core	Steel cylinder embedded in a concrete core
Prestressing wire	Wrapped over steel cylinder	Wrapped over concrete core

Table 2.2
PCCP significant changes with time

Date/Event	Revision
1942	First installation of LC-PCCP in U.S.
1949	First edition of AWWA C301-“Tentative”, allowable wire stress approximately 45% of ultimate strength and minimum mortar coating thickness 7/8 inch.
1952	First edition of AWWA C301.
1953	First installation of EC-PCCP in U.S.
1955	“Tentative” standard. Included minimum design basis.
1958	Second edition of AWWA C301, allowable wire stress 70% of ultimate strength and minimum mortar coating thickness 5/8 inch.
1964	Third edition of AWWA C301, combined loading design procedure added; allowable wire stress 75% of ultimate strength.
1972	AWWA C301 revised.
1979	AWWA C301 revised.
1979	Manual M9, first edition.
1984	AWWA C301 revised, minimum mortar coating increased to 3/4 inch; cast concrete coating deleted.
	(continued)

Table 2.2 (continued)

Date/Event	Revision
1992	AWWA C301 revised, design appendices deleted, minimum wire size increased to 0.192 inch, minimum cylinder thickness increased to 16 gauge. First edition of AWWA C304.
1995	Manual M9, second edition.
1999	AWWA C301 revised.
2007	AWWA C301 revised.
2007	Manual M9, third edition.

PCCP was first produced and installed in the U.S. in 1942. Since that time, more than 100,000,000 feet of pipe have been produced. In order to characterize the population of PCCP production on an annual basis and allow evaluation of the effects of changes in production, records were solicited. Production data for Ameron Concrete Pipe Group were furnished by Henry Bandalgian. Production data for Cretex & Price Brothers were furnished by Armand Tremblay. Mr. Tremblay also provided production data from Lockjoint and its successors Interpace and GHA-Lockjoint. Production data from Hanson Pipe & Precast were furnished by Sam Arnaout. Production data for United Concrete Pipe were determined from records furnished by Bob Card and Jim Davenport. Those data are listed in Table 2.3 and illustrated in Figures 2.1 and 2.2.

Production data for Hyprescon, Inc., and Vianini were not made available to the project. Hydro Conduit Corp. constructed a plant in Corona, California in 1968 to manufacture EC-PCCP for western water utilities. According to Joe Zaccarro, Hydro Conduit chief engineer, the manufacturing records have been lost due to two relocations of the engineering department. Hydro Conduit's production ended in the mid-1970s when the equipment was sold. Some PCCP made by LaFarge was also installed in the U.S.

Total production by year of both ECP and LCP is compared in Figure 2.3. Production of EC-PCCP began in 1951. The low in production occurred the following year, with only 950 linear feet manufactured. The peak year production was 1984, with 1,936,970 linear feet manufactured. Total production of ECP by manufacturer is illustrated in Figure 2.4. Production of LC-PCCP continues today. From a low of 21,000 linear feet of pipe produced in 1942 to a high of 2,433,523 feet in 1971, there has been at least 71,638,359 feet produced, or about 72 percent of all PCCP production. Total production of LCP by manufacturer is illustrated in Figure 2.5. Peak production for both types of PCCP occurred in 1971 with 3,563,327 feet produced.

Please note that because of the differences in reporting and recording production data, pipe could have been "booked" as a sale one year, manufactured in the following year, and installed the next year. Only analysis of more complete data from the utility could refine the numbers and is unlikely to result in statistically different information.

CHANGES IN PIPE STANDARDS

The first PCCP was manufactured by LockJoint in 1942 to its own design for the Naval Oil Depot in Virginia. Production continued under the manufacturer's standard until 1949 when the first AWWA Consensus Standard 7B.2-T was tentatively adopted on November 21, 1949. That was followed in 1952 by adoption of the first edition of AWWA C301. Revisions to AWWA C301 were adopted in 1955, 1958, 1964, 1972, 1979, 1984, 1992, and 1999. A revision in 2007 is anticipated. Those standards were compared in an attempt to determine what effect, if any, the changes in the standards may have had on the number and frequency of PCCP failures.

Table 2.3
Production of prestressed concrete cylinder pipe

	PCCP Production (lin. ft.)			Production by Manufacturer by Year											
Year	Total	LCP Total	ECP Total	Ameron		CRETEX		Hanson		LockJoint / Interpace / GHA-LockJoint		Price Brothers		United Concrete Pipe	
				LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP
1940															
1942	21,000	21,000	0							21,000					
1943	226,675	226,675	0							167,680		58,995			
1945	200,366	200,366	0							200,366					
1946	1,305,314	1,305,314	0	1,900						1,303,414					
1947	447,685	447,685	0							304,616		143,069			
1948	893,852	893,852	0					19,800		859,148		14,904			
1949	725,410	725,410	0	26,909				39,263		517,834		141,404			
1950	805,070	805,070	0	6,601				20,407		700,923		77,139			
1951	925,834	914,918	10,916					22,885		752,356		139,677	10,916		
1952	931,188	930,238	950					44,832		692,576		192,830	950		
1953	1,294,097	1,254,119	39,978	38,548				56,290	18,666	898,913		260,368	21,312		
1954	1,752,670	1,482,035	270,635					58,721	26,312	997,117	243,473	426,197	850		
1955	1,991,826	1,437,237	554,589					15,080	5,520	1,167,829	535,933	254,328	13,136		
1956	2,284,547	1,860,798	423,749					46,312	31,785	1,422,345	348,321	392,141	43,643		
1957	2,182,540	1,797,252	385,288	25,355				88,446	23,637	1,196,023	348,253	487,428	13,398		
1958	2,056,495	1,497,426	559,069	67,976				27,741	15,531	1,037,485	445,186	364,224	19,552		78,800
1959	2,179,924	1,576,372	603,552		56,066			56,559	46,187	1,101,059	381,306	418,754	31,433		88,560
1960	2,278,095	1,804,354	473,741	15,725				35,737	22,535	1,338,091	323,365	414,801	8,341		119,500
1961	2,862,046	1,710,406	1,151,640		40,674			20,191	248,590	1,163,154	846,389	527,061	15,987		

Table 2.3 Continued

Year	PCCP Production (lin. ft.)			Production by Manufacturer by Year											
	Total	LCP Total	ECP Total	Ameron		CRETEX		Hanson		LockJoint / Interpace / GHA-LockJoint		Price Brothers		United Concrete Pipe	
				LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP
1962	2,515,046	1,375,402	1,139,644	17,680	336,533			27,176	3,918	981,273	760,643	349,273	38,550		
1963	2,679,433	1,639,768	1,039,665	40,672	86,995			58,580	10,422	977,661	848,924	562,855	88,624		4,700
1964	3,170,979	1,915,776	1,255,203		76,381			97,187	48,452	1,211,747	853,728	606,842	226,642		50,000
1965	3,023,743	1,418,063	1,605,680	12,551	67,790			55,803	80,013	1,221,923	694,707	127,786	742,363		20,807
1966	2,877,632	1,779,514	1,098,118		81,186			90,117	39,727	1,211,712	674,073	477,685	210,832		92,300
1967	2,814,977	2,159,074	655,903	35,655	85,355			99,238	112,550	1,352,079	342,828	672,102	38,970		76,200
1968	2,621,965	1,922,658	699,307		87,090			234,275	29,860	1,166,508	460,684	521,875	32,728		88,945
1969	2,392,680	1,586,247	806,433		57,766			104,506	77,466	936,319	447,598	545,422	48,999		174,604
1970	2,448,931	1,734,379	714,552		134,385			140,157	142,975	999,987	324,402	594,235	61,921		50,869
1971	3,563,327	2,433,523	1,129,804		101,931			228,738	260,740	1,688,326	639,822	516,459	87,410		39,901
1972	2,244,698	1,564,241	680,457		73,490			111,722	198,665	977,752	332,757	474,767	40,891		34,654
1973	2,757,025	2,072,785	684,240	25,377	125,117			302,625	25,279	1,224,409	377,599	520,374	84,738		71,507
1974	2,723,351	1,965,691	757,660	13,789	71,353			193,879	162,055	1,238,944	423,782	519,079	100,470		
1975	2,363,548	1,692,189	671,359	45,827	111,726			302,330	63,222	730,856	443,537	613,176	32,363		20,511
1976	1,860,150	1,301,514	558,636		70,573			101,959	196,295	619,320	187,056	545,755	100,303	34,480	4,409
1977	2,576,568	1,763,398	813,170	31,725	219,057			258,942	53,716	924,227	482,007	514,791	58,390	33,713	
1978	2,601,117	2,017,024	584,093	5,345	76,152			158,169	77,253	1,075,802	327,880	658,947	75,583	118,761	27,225
1979	1,802,973	1,246,353	556,620	19,026	13,822			155,033	169,162	668,366	268,272	361,373	91,094	42,555	14,270
1980	2,482,482	1,653,428	829,054	22,650	133,473			482,039	174,810	515,873	440,501	541,831	68,022	91,035	12,248
1981	1,921,147	1,426,200	494,947	46,402	34,981			239,585	42,552	662,033	240,765	468,462	127,830	9,718	48,819
1982	1,358,447	939,746	418,701	20,400	98,210			105,838	38,966	562,156	165,148	251,352	87,377		29,000
1983	1,871,979	1,548,688	323,291	113,31	34,643			245,971	45,820	469,506	205,532	719,892	37,296		

Table 2.3 Continued

Year	PCCP Production (lin. ft.)			Production by Manufacturer by Year											
	Total	LCP Total	ECP Total	Ameron		CRETEX		Hanson		LockJoint / Interpace / GHA-LockJoint		Price Brothers		United Concrete Pipe	
				LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP
				9											
1984	1,774,748	1,179,707	595,041	14,931	117,556			150,000	151,849	401,170	216,943	554,689	108,693	58,917	
1985	1,557,419	1,017,591	539,828		128,335			188,611	143,305	293,920	77,373	418,115	168,515	116,945	22,300
1986	1,789,172	1,186,724	602,448		152,305	44,283	3,352	302,567	224,846	313,077	66,429	526,797	155,516		
1987	1,597,626	1,019,775	577,851		88,788	120,976	115,262	221,738	183,405			677,061	190,396		
1988	1,471,808	912,607	559,201		53,070	141,488	74,515	119,232	231,873			651,887	199,743		
1989	1,689,087	1,168,307	520,780		137,175	233,941	28,756	115,480	61,011			818,886	293,838		
1990	1,143,370	838,233	305,137	650	87,143	215,968	54,630	145,246	38,798			476,369	124,566		
1991	890,779	719,261	171,518	3,452	2,838	37,234	30,799	194,032	48,227			484,543	89,654		
1992	937,130	750,103	187,027	8,246	4,362	177,671	75,982	111,521	5,200			452,665	101,483		
1993	519,931	316,326	203,605		152	25,048	3,927	23,664	100,323			267,614	99,203		
1994	680,547	428,525	252,022	947	12,274	42,771	43,979	63,147	28,516			321,660	167,253		
1995	829,756	445,457	384,299		2,817	55,547	26,910	16,871	71,323			373,039	283,249		
1996	501,878	414,210	87,668	783	2,354	114,574	17,028	22,262	5,109			276,591	63,177		
1997	393,734	249,260	144,474	300	17,317	3,770	47,536	11,267	21,993			233,923	57,628		
1998	502,632	237,256	265,376	10,500	19,350	49,086	59,232	39,936	48,036			137,734	138,758		
1999	723,965	551,866	172,099	4,100	44,906	184,528	30,590	79,521	32,522			283,717	64,081		
2000	671,838	430,295	241,543	38,089	10,680	64,005	22,555	56,674	70,984			271,527	137,324		
2001	423,576	261,934	161,642		20,473			39,067	12,193			222,867	128,976		
2002	402,363	194,951	207,412	1,096	66,900			31,682	68,209			162,173	72,303		
2003	365,653	228,036	137,617		28,000			19,619	7,017			208,417	102,600		

Table 2.3 Continued

	PCCP Production (lin. ft.)			Production by Manufacturer by Year											
Year	Total	LCP Total	ECP Total	Ameron		CRETEX		Hanson		LockJoint / Interpace / GHA-LockJoint		Price Brothers		United Concrete Pipe	
				LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP	LCP	ECP
2004	446,423	344,658	101,765					18,481	56,128			326,177	45,637		
2005	201,947	105,949	95,998	200	500			12,355	22,744			93,394	72,754		
2006	44,535	9,687	34,848					9,687	34,848						
	99,596,74	71,056,90	28,539,84	716,72	3,272,04	1,510,89	635,05	6,338,79	4,161,14			23,717,49	5,526,26	506,12	1,170,12
Sums	9	6	3	6	4	0	3	3	0	38,266,875	13,775,216	8	1	4	9

Analyses described within this study have been grouped as "families" of production, by the standard in effect at the time of reported manufacture. It is understood that there are exceptions to this that were not determinable without examination of individual project construction documents. For example, pipe could have been made conforming to a pending standard but could also have been specified to an earlier standard. It is assumed that most pipe was manufactured at least nominally to the standard in effect at time of production.

Design basis, as noted above, was originally established by the pioneers of PCCP. Beginning with the tentative AWWA 7B.2-T standard, the design basis was addressed within the body of the standard.

In 1964, two design bases were incorporated as Appendices A and B. Those are addressed later in this study. In 1992, the appendices were deleted and an entirely new design basis was adopted as a separate standard, AWWA C304-92.

The principal revisions to these standards are summarized in Table 2.4 and discussed below.

Size Range

Size range was initially 16 to 48 inches in 1949. That upper limit was increased to 54 inches in 1952 and reduced to 48 inches (for LC-PCCP) in 1955. In 1979, the upper limit for LC-PCCP was increased to 60 inches in diameter, where it remains today.

The size of EC-PCCP was initially limited between 24 and 72 inches in 1955. The size limit was increased to 96 inches in the 1964 revision, with a note allowing larger diameters subject to the approval of the engineer. The 1972 standard increased the maximum size to 144 inches, and in the 1979 standard, a note recognized that larger sizes had been manufactured. The largest EC-PCCP pipe manufactured to date is 252 inches (21 feet) for siphons on the Central Arizona Project. Although seemingly innocuous, the furnishing of pipe sized beyond the limits of the standard may be relevant to manufacturing pipe with other features beyond those standards' limits.

Design Basis

The 1949 tentative AWWA standard and, presumably, the manufacturer's standards' design was based upon both the steel cylinder and the wire to simultaneously reach their elastic limit at 2-1/4 times the working pressure. On the surface, that implies a factor of safety on yield (or restated as design working stress of those elements at 0.45 Fy). But because the wire exhibits no elastic limit, this is not correct. What is the elastic limit of the steel wire? The answer is found in ASTM A82-34, which was in effect and unchanged until 1952. The wire was required to meet a tensile strength of 80,000 psi and a yield point of 80 percent of that value. Paragraph 4(c) of that standard stated, "The yield point shall be determined by the drop of the beam or halt in the gauge of the testing machine. In case of no definite drop of the beam or halt in the gauge is observed until final rupture occurs, the test shall be construed as meeting the requirement for yield point…." In other words, the ductility requirement of 20 percent was specifically waived. In practice then it is assumed that the design of PCCP to meet "...their respective elastic limits..." was based upon 80 percent of the tensile strength of the wire.

Table 2.4
AWWA C301 prestressed concrete cylinder pipe timeline

Standard	7B.2-T	C301	C301	C301	C301	C301	C301	C301	C301	C301	C301
Year	1949	1952	1955	1958	1964	1972	1979	1984	1992	1999	2007
Approval date	21-Nov-49	13-Jun-52	17-Jun-55	26-Jan-58	27-Jan-64	31-Jan-72	28-Nov-79	30-Jan-84	22-Jun-92	24-Jan-99	pending
Status	Tentative	First Ed.	Tentative	2nd. Ed. (a)	3rd. Ed. (a)	Standard	Standard	Standard	Standard	Standard	
Effective date									1-Apr-93	1-Sep-99	
Size range Lined Cylinder type	16-48 in.	16-54 in.	16-48 in.	16-48 in.	16-48 in. (i)	16-48 in.	16-60 in.	16-60 in.	16-60 in.	16-60 in.	16-60 in.
Size range Embedded Cylinder type			24-72 in.	24-72 in.	24-96 in. (i)	24-144 in.	24-144 in. (l)	24-144 in. (l)	24-144 in. (l)	24-144 in. (l)	24-144 in. (l)
Pressure range	100 to 600 ft.	100 to 600 ft.	50 to 350 psi.	50 to 350 psi.			note n				
Design basis	note b	note s	note d	note d	Appendix A or B	Appendix A or B	Appendix A or B	Appendix A or B (r)	AWWA C304	AWWA C304	AWWA C304
Design calculations			submit if required	submit if required	submit if required	submit if required	submit if required	submit if required	submit "verification of the design"	submit "verification of the design"	submit "verification of the design"
Design pressure minimum					40 psi	40 psi	40 psi	40 psi	AWWA C304	AWWA C304	AWWA C304
Design surge allowance			50 psi (e)	50 psi (e)	40%	40%	40%	40%			
Design earth load minimum			6 ft. cover & ordinary trench, 3 ft AASHO "crushing strength"	6 ft. cover & ordinary trench, 3 ft AASHO "crushing strength"	6 ft. cover & ordinary trench, AASHO H-20 live load	6 ft. cover & ordinary trench, AASHO H20 live load	6 ft. cover & ordinary trench, AASHTO H20 live load	6 ft. cover & ordinary trench, AASHTO H20 live load			
Supply of pipe	No pipe manufactured until drawings approved	No pipe manufactured until drawings approved	No pipe manufactured until drawings approved	No pipe manufactured until drawings approved	No pipe manufactured until drawings approved	supply from inventory OK	supply from inventory OK	supply from inventory OK	supply from inventory OK	supply from inventory OK	supply from inventory OK
Cement (ASTM C150)	Type II	Type I or II	Type I or II	Type I or II	Type I or II	Type I or II	Type I or II	Type I or II, and fly ash, pozzolans up to 20% substitution for cement	Type I or II, and fly ash, pozzolans between 10% & 20% substitution for cement	Type I or II, and silica fume, fly ash, pozzolans between 10% & 20% substitution for cement	Type I or II. Fly ash, pozzolans up to 20% substitution for cement, silica fume up to 10%
Fine aggregate organics/impurities	Fig 2, ASTM C40-33	Fig 2, ASTM C40	"no darker than ref. std." in ASTM C40	"no darker than ref. std." in ASTM C40	"no darker than ref. std." in ASTM C40	ASTM C33-71a Sec. 4.2	ASTM C33-77 Sec. 5	ASTM C33	ASTM C33 except for sections 7.2 & 7.3	ASTM C33	ASTM C33
Fine aggregate quality	equal to Ottawa sand	equal to Ottawa sand	equal to Ottawa sand	equal to Ottawa sand	equal to Ottawa sand	gradation in Table 1					
Fine aggregate gradation, % passing No. 200	5	5	5	5	5	5	ASTM C33-71a Sec. 4.2				
Fineness Modulus variation	+/- 0.20	+/- 0.20	+/- 0.20	+/- 0.20	+/- 0.20	+/- 0.20	+/- 0.20				
Coarse aggregate gradation	note c	note c	note c	note c	note g	note g	note g	ASTM C33	ASTM C33	ASTM C33	ASTM C33
Coarse aggregate deleterious substances, max %	5	5	5	5	5	5	ASTM C33 Table 3 class 4S exc. soundness test		ASTM C33, Class 3S, 3M, or 1N in Table 3, Fig 1.	ASTM C33, Class 3S, 3M, or 1N in Table 3, Fig 1.	ASTM C33, Class 3S, 3M, or 1N in Table 3, Fig 1.
Admixtures						ASTM C494	ASTM C494	ASTM C494	ASTM C494	ASTM C494	ASTM C494
Steel Cylinders	ASTM A245-48T	ASTM A245, gr. B or C	ASTM A245, gr. B or C	ASTM A245 gr. B or C	ASTM A415, max c 0.25%, Fy = 27 ksi min.	ASTM A570 gr. B or C, or ASTM A569, max c 0.25%, Fy = 27 ksi min.	ASTM A570, or ASTM A569, max c 0.25%, Fy = 27 ksi min., or ASTM A611, gr. B, C, D, or E (m)	Fy = 30 ksi min. ASTM A570, ASTM A611 gr. B, C, or D, AISI G10120 through G10200, or ASTM A569, max c 0.25%,	Fy = 33 ksi min. ASTM A569, ASTM A570, ASTM A611 gr. C, or D, AISI Manual 1214	Fy = 33 ksi min. ASTM A569, ASTM A570, ASTM A611 gr. C, or D, ASTM A635 gr. 1012 through 1020, ASTM A659, or ASTM A907	ASTM A1011 SS, ASTM A635, ASTM A569, or ASTM A1018 SS
Cylinder thickness minimum	16 ga.	16 ga.	none (f)	none (f)	none (f)	18 ga. ≤ 48in., 16 ga ≤ 54 in	18 ga. ≤ 60 in., 16 ga ≤ 60 in	18 ga. ≤ 36 in., 16 ga > 36 in.	0.0598 in. (16 ga.)	0.0598 in. (16 ga.)	0.0598 in. (16 ga.)
Mill tests of steel	submit in advance of mfr	submit in advance of mfr	submit in advance of mfr	submit in advance of mfr	made available	made available	mill tests or plant tests at mfr's option made available	mill tests or plant tests at mfr's option made available	mill tests or plant tests at mfr's option made available	mill tests or plant tests at mfr's option made available	mill tests or plant tests at mfr's option made available
Hydrostatic test w/ joint rings attached	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max.	20 ksi min, 25 ksi max. (p)	20 ksi min, 25 ksi max. (p)	20 ksi min, 25 ksi max. (p)	20 ksi min, 25 ksi max. (p)	20 ksi min, 25 ksi max. (p)
Bend and tensile tests of cylinder	per AWWA 7A.3-1940	per AWWA C201	per AWWA C201	per AWWA C201	none						
Wire reinforcement	ASTM A229-41, ASTM A227-47T, or ASTM A82-34	ASTM A227, or ASTM A82	ASTM A227	ASTM A227	ASTM A227 (h)	ASTM A227 (h)	ASTM A648 (h)	ASTM A648	ASTM A648	ASTM A648	ASTM A648 including the supplementary requirements
Wire size minimum	1/8 in. dia.	1/8 in. dia.	6 gauge	6 gauge (0.192")	8 gauge (0.162")	0.162"	0.162"	0.162"	0.192 in. (6 ga.)	nominal 0.192" (6 ga.)	nominal 0.192" (6 ga.)
Wire anchorage strength	"equivalent to strength of wire"	"equivalent to strength of wire"	"equivalent to strength of wire"	"equivalent to strength of wire"	"minimum ultimate tensile strength of wire"	75% Fu	75% Fu	75% Fu	75% Fu	75% Fu	75% Fu
Wire wrapping stress		0.7Fu	0.7Fu	0.7Fu	0.75Fu	0.75Fu	0.75Fu	0.75Fu	0.75Fu	0.75Fu	0.75Fu
Maximum wire spacing	1 in.	1.0", except for no. 6 & larger, 1.5" if ≤ 100psi	1.5" for no. 6 wire, 1.0" for larger wire	1.5" for no. 6 wire, 1.0" for larger wire	1.5"; 1" for LC with > No. 6 wire (j)	1.5"; 1" for LC with wire > 0.192"	1.5"; 1" for LC with wire > 0.192"	1.5"; 1" for LC with wire ≥ 0.250"	1.5"; 1" for LC with wire ≥ 0.250"	1.5"; 1" for LC with wire ≥ 0.250"	1.5"; 1" for LC with wire ≥ 0.250"
Minimum wire spacing	0.3 in.	0.3 in.	3/16 in. clear	3/16 in. clear	3/16 in. clear	3/16 in. clear	3/16 in. clear	3/16 in. clear	2.75 wire dia. for LC & 2.0 wire dia.for EC	2.75 wire dia. for LC & 2.0 wire dia.for EC	2.75 wire dia. for LC & 2.0 wire dia.for EC
Min. core thickness	Table 3	Table 3	Table 3	Table 3a	Table 3	1/16 ID	1/16 ID	1/16 ID	1/16 ID	1/16 ID	1/16 ID
Core out of roundness	"round and true"	"round and true"	"round and true"	"round and true"	"round and true"	"round and true"	1% of average	1% of average	0.7% for LC, 0.5% for EC	greater of 3/16" or 0.7% for < 48 in. dia., 1/2" or 0.5% for pipe > 4in.	greater of 3/16" or 0.7% for < 48 in. dia., 1/2" or 0.5% for pipe > 4in.

(continued)

Table 2.4 (Continued)

Standard	7B.2-T	C301	C301	C301	C301	C301	C301	C301	C301	C301	C301
Core ID tolerance	1/4 in.	1/4" for ≤ 36", 3/8" for 42 & larger	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54"	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54"	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.	1/4" for ≤ 36", 3/8" for 42 & 48", 1/2" for ≥ 54", and 3/4" for ≥ 84 in.
Core thickness tolerance	+/- 1/8 in.	+/- 1/8 in.	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for ≥ 54"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for ≥ 54"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"	1/8" for ≤ 36", 3/16" for 42 & 48", 1/4" for 54" to 72" & 3/8" for > 72"
Joint rings - min. thickness of	3/16 in.	3/16 in.	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger	3/16 in. for ≤ 36", 1/4" for larger
Joint ring tolerance	1/32 in.	1/32 in.	1/32 in.	1/32 in.	3/16 in.	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)	3/16 in. for gaskets 21/32 in. dia. or less, and 1/4" for greater dia.(k)
Rubber gaskets	65% natural rubber	50% natural or synthetic	50% natural or synthetic	50% natural or synthetic	50% natural or synthetic	50% natural or synthetic	50% natural or synthetic	50% natural or synthetic	50% synthetic polyisoprene or other synthetic rubbers	50% synthetic polyisoprene or other synthetic rubbers	50% synthetic polyisoprene or other synthetic rubbers
Gasket diametral tolerance						+/- 1/64 in.	+/- 1/64 in.	+/- 1/64 in.	+/- 1/64 in.	+/- 1/64 in.	+/- 1/64 in.
Core cement content/cu. yd.	7 sacks	7 bags	7.0 bags	7 sacks	6 sacks	6 bags	560 lb	560 lb	560 lb	560 lb	560 lb
Core water/cement ratio	"to meet strength"	"to meet strength"	"to meet strength"	"to meet strength"	"to meet strength"	"to meet strength"	0.6 max.	0.6 max.	0.5 max.	0.5 for pipe centrifigal cast, 0.45 for vert. cast or radial compaction.	0.5 for pipe centrifigal cast, 0.45 for vert. cast or radial compaction.
7 day compressive strength	2,600 psi, min.	2,600 psi, min.	2,600 psi, min.	2,600 psi, min.	3,000 psi, min.	3,000 psi, min.	3,000 psi, min.	3,000 psi, min.			
28 day compressive strength	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.
Wire wrap core after placing	7 days	7 days	core reaches 7 day strength	core reaches 7 day strength	core reaches 7 day strength	core reaches 7 day strength	core reaches 7 day strength	core reaches 3,000 psi	core reaches 3,000 psi	core reaches 3,000 psi	core reaches 3,000 psi
Core stress induced at time of wrap	0.40 fcw	0.40 fcw	0.40 fcw	0.40 fcw	0.55 fcw	0.55 fcw	0.55 fcw	0.55 fcw	0.55 fcw	0.55 fcw	0.55 fcw
Slurry under wire								1 sack/10 gal. water	94 lbs./10 gal. water	94 lbs./10 gal. water	94 lbs./10 gal. water
Steam or water curing	36 hr. min.	36 hr. min.	32 hr. min.	32 hr. min.	32 hr. min.	24 hr. min.steam, 32 hr. min. water	steam: note q, water: 12 hr. min.	steam: note q, water: 12 hr. min.	steam: note q, water: 12 hr. min.	steam: note t, water: 12 hr. min.	steam: note t, water: 12 hr. min.
Mortar coating mix	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand	1 cement to 3 sand
Soluble chloride content							0.06%, max.	0.06%, max.	0.06%, max.	0.06%, max.	0.06%, max.
Mortar coating thickness	3/4 in. min.	3/4 in. min.	7/8 in.	7/8" nom., 3/4 in. min.	5/8" min. over wire	5/8" min. over wire	5/8" min. over wire	3/4" min. over wire	3/4" min. over wire	3/4" min. over wire	3/4" min. over wire
Mortar strength (cubes, ASTM C109)									5,500 psi. min.	5,500 psi. min.	5,500 psi. min.
Concrete coating mix	1 cement to 4 aggregate	1 cement to 4 aggregate	7 bags	7 bags	7 bags	7 bags	660 lbs.	deleted			
Soluble chloride content - conc. ctg.							0.06%, max.				
Concrete coating thickness	1 in. min.	1 in. min.	1 1/2 in.	1.5" nom., 1" min.	1.5" nom., 1" min. over core	1.5" nom., 1" min. over core	1.5" nom., 1" min. over core				
Coating compressive strength, 7 day	2,600 psi, min.	2,600 psi, min.	2,600 psi, min.	2,600 psi, min.	3,000 psi, min.	3,000 psi, min.	3,000 psi, min.				
Coating compressive strength, 28 day	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.	4,500 psi, min.				
Coating steam cure	12 hr. min.	12 hr. min.	12 hr. min.	12 hr. min.	12 hr. min.	12 hr. min.	note q, 12 hr. min, after 6 hr. water cure OK	note q, 12 hr. min, after 6 hr. water cure OK	12 hr. min.	12 hr. min.	12 hr. min.
Coating water cure	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.	4 days min.
Seal coat					AWWA C104 if ordered	AWWA C104 if ordered					
Openings allowed in pipe wall								Sec. 4.4	Sec. 4.4	Sec. 4.7.4	Sec. 4.7.4

Notes

Red indicates a change from previous version of the standard.

(a) All printings of the previous edition are obsolete.

(b) "…the steel cylinder and wire shall reach their respective elastic limits simultaneously at a pressure equivalent to at least 2 1/4 times the normal water pressure…"

(c) Subject to the approval of the engineer.

(d) "At a pressure equal to twice the design pressure, the stress shall not exceed its original gross wrapping stress." Combination dead & live load < 110% incipient cracking of core.

(e) "…not a specific water hammer allownace…but results fromn the conservative factors used in the design…"

(f) No minimum stated, only implied 16 ga. based upon section 3.2.

(g) "...well graded subject to approval of the engineer…"

(h) "…except that wire with higher tensile strengths [exceeding class {II}[III]] may be used if it meets the other requirements of ASTM A227."

(i) Note below table 3 indicates "For embedded cylinder pipe larger than 96 in. diameter, dimensions and details of design shall be subject to approval…"

(j) Note no maximum spacing for No. 8 wire.

(k) Also, out of roundness ≤ 0.5% of average ID.

(l) "Larger sizes have been manufactured…"

(m) "Alternatively, hot-and cold-rolled steel sheets ansd strips having a minimum yield strength of 27,000 psi and conforming to AISI 1012 through 1020 specifications shall be acceptable."

(n) For minimum core & cylinder, 250 psi for 16-20 in. LC, 200 psi for 24-36" LC, 175psi for 42" pipe, & 100 psi for 54 & 60" pipe. EC is unlimited.

(p) Cylinders > 10 ga. shall be tested to same pressure as 10 ga.

(q) "…sufficient to produce the concrete strengths specified…"

(r) Advisory included in foreword stating that the standard "…does not contain all of the information needed…" and also recommends use of AWWA Manual M9 to supplement the standard.

(s) "…such that the core will be sufficiently compressed to withstand an internal hydrostatic pressure equal to at least 1.25 times the designed pressure without tensile stress being induced in the core."

(t) "…concrete curing compound suitable …" allowed, then "…sufficient to produce the concrete strengths specified…"

Also, the tentative standard did not include a limit on the decompression stress of the concrete core. That was rectified in the 1952 standard with the requirement "…that the core will be sufficiently compressed to withstand an internal hydrostatic pressure equal to at least 1.25 times the design pressure without tensile stress being introduced in the core." On the surface, that would imply an increased factor of safety, but the allowable stress at water pressure was also increased to 70 percent of ultimate. The overall result was a lowering of the ultimate safety factor for the affected components.

The 1955 standard incorporated a minimum 50-psi design allowance for surge pressures and also addressed submittal of the design if required by the project specifications.

The 1964 revision, as indicated previously, moved the design basis to the appendices. Design according to Method A used a semi-empirical approach based on *Wo*, which is nine-tenths of the three-edge bearing test load that causes incipient cracking and the theoretical internal pressure (*Po*) that relieved the calculated residual compression in the concrete core due to prestressing exclusive of external load. The allowable combinations of three-edge bearing load and internal pressure were determined by a cubic parabola, passing through *Wo* and *Po*, which defined the limit of such combinations. The three-edge bearing loads used in Method A were converted to earth loads and transient external loads using bedding factors such as described in AWWA Manual M9, *Concrete Pressure Pipe* (1979) and ACPA, *Concrete Pipe Design Manual* (1988). That procedure also allowed a 20 percent increase on the external load and 40 percent increase on the core decompression load for short-duration (i.e., surge) events.

Appendix B was similar to Appendix A except its axes would be determined by analysis and the intercepts determined as straight lines. The Method B procedure limited the maximum combined net tensile concrete stress in pipe under static external load and internal pressure to a value equal to $7.5\sqrt{f'c}$, where f'c equals the 28-day compressive strength of core concrete in psi. Coefficients for moments and thrusts to determine stresses were to be per Paris (1921) or Olander (1950).

Both design methods limited the working pressure for embedded-cylinder pipe to *Po* and to 0.8*Po* for lined-cylinder pipe. Under transient conditions, such as those produced by surge pressures and live loads, both methods permitted the above-noted increased allowable internal pressure and external load.

The 1964 revision also included a minimum design pressure of 40 psi.

No substantial revision occurred to the design basis (other than wire stresses discussed separately) until the 1992 elimination of the design appendices and the adoption of the design standard AWWA C304. The 1992 design standard was a significant change in design approach to a strength and serviceability basis. The development of that design standard is described in the foreword to the standard and elsewhere (Heger, Zarghamee, and Dana 1990; Zarghamee 1990a; Zarghamee and Fok 1990b; Zarghamee, Fok, and Sikiotis 1990c; Zarghamee and Dana 1991).

Concrete Quality

The 1949 tentative standard only included Type II cement. In 1952, Type I was allowed and it stayed that way until fly ash and other pozzolans were allowed as a substitute for up to 20 percent of the cement in 1984. That substitution was revised in 1992 to between 10 and 20 percent. In 1999, silica fume was allowed on equal basis with fly ash and other pozzolans but was limited in the pending 2007 revision to 10 percent. The effect of fly ash, silica fume, and

pozzolans is to increase the density and reduce the permeability of the concrete. Admixtures as described in ASTM C494 have been allowed since the 1972 standard.

Aggregate quality, as defined by the impurities allowed in the fine and coarse aggregate, size, and gradation, has varied with each standard revision. Since the 1972 edition, some modification or outright adoption of ASTM C33 has occurred. For more details, refer to Table 2.4. There were no statistically significant data to indicate that these changes in specified materials affected the performance of PCCP. The forensic examination of individual specimens may ultimately indicate otherwise. The effects of creep, shrinkage, and temperature on concrete are a result of the quality of the concrete, which were addressed in the new design standard, AWWA C304-92. In order to accommodate the new design standard, for the purpose of qualifying a source of aggregate to be used in the manufacture of pipe, the apparent specific gravity of fine aggregate was required to be sampled in accordance with ASTM D75 and measured in accordance with ASTM C128 when not less than 2.6. Specific gravity measurements and all other mandatory tests listed in ASTM C33 also had to be made at six-month intervals or whenever the source of fine aggregate is changed. Sieve analysis of fine aggregate also was required to be performed in accordance with ASTM C33 on a weekly basis (Section 2.2).

For the purpose of qualifying a source of coarse aggregate to be used in the manufacture of pipe, the 1992 standard also required the apparent specific gravity of coarse aggregate, when sampled in accordance with ASTM D75 and measured in accordance with ASTM C127, to be not less than 2.6. Specific gravity measurements and all other mandatory tests listed in ASTM C33 had to be made at six-month intervals or whenever the source of coarse aggregate is changed. Sieve analysis of coarse aggregate also was required to be performed in accordance with ASTM C33 on a weekly basis. Never before had deleterious materials been addressed, but the 1992 standard also required coarse aggregate to meet the deleterious substances requirements for Class 3S, 3M, or 1N shown in Table 3 of ASTM C33 in the severe, moderate, and negligible weathering regions, respectively, shown in Figure 1 of ASTM C33.

Steel for Cylinders

Many different ASTM standards have been referenced in the PCCP standards, likely because of changes to material availability and changing ASTM standards. There were no statistically significant data to indicate that these changes materially affected PCCP performance. For more details, refer to Table 2.4.

Steel Cylinder Thickness

The requirements for steel cylinder thickness changed significantly since the original development of PCCP. They are illustrated in Figure 2.6. The original design basis was for 16-gauge (0.060-inch thick) steel, and that was incorporated in the (tentative) 1949 and 1952 standards. The 1955, 1958, and 1964 standards did not address minimum cylinder thickness. Rather, it was implied in Section 3.2, “Maximum design pressures for the various core thicknesses and 16-gauge cylinders shall be those indicated in Tables 3a and 3b” (1955 and 1958) and “These values are predicated on the use of 16-gauge cylinders and the concrete strength specified in Sec. 3.6” (1964). The 1972 standard allowed 18-gauge (0.048-inch thick) steel for PCCP ≤48 inches and 16 gauge for 54 inches and greater. The 1979 standard increased

the diameter for which 18-gauge cylinders were allowed to 60 inches but that was reduced to 36 inches in the 1984 standard. The 1992 standard and subsequent revisions have required 16-gauge minimum for all sizes.

Steel Cylinder Weld Tests

The 1949 through 1958 standards required bend and tensile tests to be conducted on the cylinder weld seams. These requirements were omitted from later standards. Those test requirements referenced the comparable AWWA steel pipe weld seam tests. It is probable that these tests were omitted because of the difficulty in getting lap seams (how many of the pipe cylinders were made) to pass bend tests. Currently, the only test of those welds is the hydrostatic shop test of the cylinder with joint rings attached.

Wire Reinforcement

The type of wire used in PCCP varied widely. It is discussed separately below.

The minimum size (diameter) of reinforcement changed significantly with each standard revision. The variation with time in the minimum wire size is illustrated on Figure 2.7. Initially, 1/8 inch (0.125 inch) in the 1949 and 1952 standards, the minimum size was increased 235 percent by volume to 6 gauge (0.192 inch) in the 1955 standard then reduced to 8 gauge (0.162 inch) in the 1964 standard. The 1992 standard increased the minimum again to 6 gauge (0.192 inch) where it remains today. The use of 8-gauge wire reinforcement (±1964 to 1984) may be the most problematic change in PCCP manufacture. This is discussed separately below.

Wire Wrapping Stress

Research of records to date has not revealed conclusive evidence of what stress the wire reinforcement was wrapped on the cylinder (for LC-PCCP) or concrete core (for EC-PCCP), prior to the 1952 standard. In that year, the allowable wire stress was 70 percent of ultimate tensile wire strength (0.7 Fy). In the 1964 standard the wire stress allowable was increased to 75 percent of ultimate strength (0.75 Fy) where it remains today. The anchorage of the wire was initially required to have strength “equivalent to the strength of the wire,” but the 1992 standard reduced that to the same strength value as the wire at wrap. That also is unchanged today.

Wire Reinforcement Spacing

Wire reinforcement spacing varied from standard revision to standard revision. The interested reader is referred to the timeline table for more details, but what is important is the minimum clear distance between wires so as to provide adequate room for placement of the cement mortar coating. Table 2.5 shows the minimum wire clearance for the minimum wire size. Most significant is the 66 percent increase in minimum wire clearance in the 1984 standard, providing adequate clearance for mortar to fully protect the wire.

Table 2.5
Minimum wire clearance for minimum wire size

	Minimum Clearance		Maximum Clearance	
Standard (years)	LC-PCCP (inches)	EC-PCCP (inches)	LC-PCCP (inches)	EC-PCCP (inches)
1949	0.175	—	0.875	—
1952	0.175	—	1.375[(1)]	—
1955	0.188	0.188	1.308	1.308
1958	0.188	0.188	1.308	1.308
1964	0.188	0.188	1.338[(2)]	1.338
1972	0.188	0.188	1.338	1.338
1979	0.188	0.188	1.338	1.338
1984	0.188	0.188	1.338[(3)]	1.338
1992	0.336	0.192	1.308[(3)]	1.308
1999	0.336	0.192	1.308	1.308
2007 Pending	0.336	0.192	1.308	1.308

(1)If ≤100 psi design working pressure.

(2)0.838 inch for LC with No. 6 wire or more.

(3)0.750 inch for LC with 1/4-inch wire or more.

It is curious that the maximum wire spacing is reduced with larger sized wire reinforcement.

Concrete Core Manufacturing Tolerances

Until the 1979 standard, the core was required to be "round and true." In the 1979 standard, the out-of-roundness was allowed to be 1 percent of the measured difference between the maximum and minimum diameters. That large tolerance coupled with the joint ring tolerances discussed below may have had a significant effect on PCCP performance. Other tolerances in the core dimensions (internal diameter and thickness) may not have individually affected the PCCP performance but tolerances are cumulative. See the timeline (Table 2.4) for more details.

Joint Ring Tolerances

Until the 1958 standard, joint rings had to meet a tolerance of 1/32 inch (0.031 inch) on the design clearance. That meant that the nominal space between a round and true bell-and-spigot would be zero. In actual practice, the cumulative tolerances for a 42-inch LC-PCCP made to the standard tolerances could have joint dimensions as shown in Table 2.6.

Table 2.6
Joint dimensions

	Tolerance		Note
	+	—	
Nominal ID	42.0	42.0	Round and true
Core ID	42.375	41.625	
Core thickness at spigot	42.563	41.437	
Difference: worst case within tolerance	1.126 inches		
Tolerance on diameter not on ovality	0.031 inch		1/32 inch
Worst-case interference	1.095 inches		

In actual practice, of course, the joint rings were separately made, so that based upon circumference, the nominal fit was likely to meet the 1/32-inch clearance tolerance. But also in actual practice, the joint rings were cast within the cores made to the tolerances of the standard. Because there is no ovality tolerance, the mismatch of joints is likely the cause of many joint leaks.

Strength of Concrete

Factors that affect the strength of concrete include the amount of cement per unit volume and the water-cement ratio. The minimum seven-day strength in the standard up until the 1964 standard was 2,600 psi, when it was increased to 3,000 psi. The 1992 standard and subsequent standards do not address minimum strength at seven days. All the standards require 4,500-psi minimum at 28 days.

The amount of cement in the core required per cubic yard was seven 94-pound sacks until 1964, when six 94-pound sacks were required. It is curious that this decrease in required cement content accompanied an increase in required early strength. The 1979 and subsequent standards slightly reduced the minimum cement content to 560 pounds per cubic yard.

From 1949 until the 1979 standard, the only prescription regarding water-cement ratio was "…to assure that the concrete will meet the strength requirements." But in 1979 and 1984, the standard put a limit of 0.6 on the water-cement ratio. In 1992, that was further reduced to 0.5 and in 1999, for vertically cast or radially compacted cores, that was further reduced to 0.45.

Core Prestressing Limits

Limitations on when the core could be wrapped and the stresses induced by wrapping have been addressed in each of the standards. The intent is to avoid cracking the core as it is squeezed at one end during wrapping and unstressed at the other. Another intent of these limits is to avoid crushing of the core. To that extent then the 1949 and 1952 standards limited winding of wire around the core "…until at least seven days after the concrete lining is placed…."

In 1955, that absolute time was negated by a performance level "…or until the concrete has reached the minimum seven-day compressive strength specified…." The net effect was to speed up pipe production.

Those time limits were coupled with a limit on the design stress induced in the core of 40 percent of the compressive strength at the time of wrap. In other words, a concrete core at seven

days age meeting the minimum 2,600-psi compressive strength could only be wrapped such that the compressive stress induced would not exceed 1,040 psi (0.4 x 2,600 psi).

The 1964 standard increased the compressive stress allowable to 55 percent of the core concrete strength at time of wrap (f'cw). That minimum strength was also increased to 3,000 psi in 1964, so the induced compressive stress could be as much as 1,650 psi at the minimum specified compressive stress. There was (and is) no upper limit in the standards on the design core concrete compressive strength, although practical limits exist.

The seven-day compressive strength requirement was deleted from the standard in 1992. The effect of this deletion was to allow wrapping of wire on cores younger than seven days which had reached the 3,000-psi minimum core strength. The imposed core stress at time of wrapping remained at 0.50 x f'cw.

An improvement added to the 1984 standard was the requirement that a thin cement slurry be placed immediately prior to wrapping the wire. That was intended to ensure complete encapsulation of the wire in the high pH portland cement environment. Some applications have been discovered to have left a void beneath one quadrant of the wire, rather than all of the wire resting on a "bed" of mortar.

Concrete Coating

Initial concrete coating was cast around the wire-wrapped core, likely using the same forms used for other concrete pipe products. The minimum cast coating thickness over the core has varied from 1 inch minimum in 1949 to 1.5 inches in the 1955 standard to 1.5 inches nominal and 1 inch minimum in 1958. That is illustrated on Figure 2.8. (The minimum wire size is also graphically represented.) The 1964 standard reduced that cover to 1 inch over the core so that the minimum cover over the wire could have been 5/8 inch using 3/8-inch wire. The cast coating was deleted in 1984.

Sprayed, shotcrete-type mortar coating was allowed in the 1949 standard at minimum thickness of 3/4 inch. The thickness was increased to 7/8 inch in the 1955 standard. In 1958, the 7/8-inch thickness became nominal with a 3/4-inch minimum standard. In 1964, the minimum coating was reduced further to 5/8 inch. That proved to be inadequate and the 3/4-inch coating was restored in the 1984 standard.

Summary

It can be seen in examining Table 2.4 and Figure 2.2 that the initial design basis for manufacture of PCCP appeared to be conservative, and as experience was gained and competitiveness with other pipe materials increased, that changes were made to reduce the unit cost of manufacture. In sum, those changes tended to increase the stress level in the pipe at working pressures and reduced the margin for error.

The most negatively influential year in terms of changes to the standard was 1964 because:

- Design Appendices A and B were adopted, moving the design criteria from the body of the standard to an appendix.
- No minimum cylinder thickness (since 1955 edition) was included.
- 18.5 percent reduction in minimum wire size occurred.

- The standard allowed a 37.5 percent increase in concrete core stress at time wire is wrapped.
- The standard allowed a 16.7 percent reduction in the minimum amount of portland cement in the core.
- The standard allowed a 20 percent reduction in the minimum coating thickness.

The trend toward reducing conservatism of the product through revisions in the standard began to reverse course in 1984 with the issuance of AWWA C301-84. That year saw the allowable additions of fly ash and other pozzolans in an attempt to increase the density of the concrete coating and core, the incorporation of ASTM C33 for concrete and mortar aggregate requirements, the slurry placement under the wire, and the minimum coating thickness increased to 3/4 inch. Significant revisions to the standard in 1992 and adoption of the very detailed design standard C304-92 appear to have resulted in much improved performance of as-installed PCCP.

CHANGES IN MATERIAL STANDARDS

By far the most influential material item in the performance of PCCP pipe is the wire. The wire is the means of effecting the prestress, and without it maintaining the core in compression, the pipe's service life is compromised. In order to examine the effect of changing standards in the wire and its use within the AWWA PCCP standards, a separate timeline was prepared listing the ASTM standards and comparing some of the important requirements within those standards. Table 2.7 compares chemical and mechanical requirements, for the cited standards in effect at the time they were referenced.

Table 2.7
Timeline of wire standards for PCCP

Item	ASTM A82-34	ASTM A229-41	ASTM A227-47	ASTM A227-63
Incorporated in ASTM Book of Standards	1934	1941	1941, rev. 1947	1964
Carbon, per cent		0.55 to 0.75	0.65 to 0.75 (a)	0.45 to 0.75 (a)
Carbon, per cent, Class I				
Carbon, per cent, Class II				
Carbon, per cent, Class III				
Manganese, percent		0.8 to 1.2 (n)	0.6 to 1.20 (b)	0.6 to 1.20 (b)
Manganese, per cent, Class I				
Manganese, per cent, Class II				
Manganese, per cent, Class III				
Phosphorous, maximum, per cent		0.045	0.045	0.040
Sulfur, maximum, per cent		0.05	0.05	0.050
Silicon, per cent		0.10 to 0.30	0.10 to 0.30	0.10 to 0.30
Nitrogen, maximum, percent				
Wrap test, 0.162" & smaller		1 diameter	1 diameter	1 diameter
Wrap test, 0.02" ≤ 0.162" & smaller, Class I				
Wrap test, 0.02" ≤ 0.162" & smaller, Class II				
Wrap test, ≤ 0.312" (0.3 in. in ASTM A 82-34)	1 diameter	2 diameters	2 diameters	2 diameters
Wrap test, 0.162" ≤ 0.312", Class I				
Wrap test, 0.162" ≤ 0.312", Class II				*(continued)*

Table 2.7 (continued)

Item	ASTM A82-34	ASTM A229-41	ASTM A227-47	ASTM A227-63
Wrap test, 0.162" ≤ 0.312", Class III				
Wrap test, 0.162" ≤ 0.250", Class III				
Wrap test, 0.312", Class III				
Wrap test, > 0.312" (0.3 in. in ASTM A 82-34)	2 diameters	not addressed	not addressed	"not applicable"
Reduction of area test (ASTM A370, Sup. IV)				
Reduction of area test, 0.192" wire				
Item	ASTM A82-34	ASTM A229-41	ASTM A227-47	ASTM A227-63
Reduction of area test, > 0.192" wire				
Relaxation Test (ASTM E328)				
Torsion test				
Splitting Test				
Tensile strength, ksi, 8 gauge (0.162")	80 min.	200 min, 230 max.	200 min, 230 max.	200 min, 230 max.
Tensile strength, ksi, 8 gauge, Class I				
Tensile strength, ksi, 8 gauge, Class II				
Tensile strength, ksi, 8 gauge, Class III				
Tensile strength, ksi, 6 gauge (0.192")	80 min.	192 min, 220 max.	192 min, 221 max.	192 min, 221 max.
Tensile strength, ksi, 6 gauge , Class I				
Tensile strength, ksi, 6 gauge, Class II				
Tensile strength, ksi, 6 gauge, Class III				
Hydrogen embrittlement test (ASTM A1032)				
Item	ASTM A227-64	ASTM A227-68	ASTM A227-71	ASTM A648-72
Incorporated in ASTM Book of Standards	1965	1971	1972	1973
Carbon, per cent				
Carbon, per cent, Class I	0.45 to 0.75 (a)	0.45 to 0.85 (c)	0.45 to 0.85 (c)	0.45 to 0.75 (c)
Carbon, per cent, Class II	0.60 to 1.20 (a)	0.45 to 0.85 (c)	0.45 to 0.85 (c)	0.50 to 0.85 (c)
Carbon, per cent, Class III				0.55 to 0.93 (c)
Manganese, percent				
Manganese, per cent, Class I	0.6 to 1.20 (b)	0.6 to 1.20 (b)	0.6 to 1.30 (b)	0.60 to 1.10 (b)
Manganese, per cent, Class II	0.6 to 1.30 (b)	0.6 to 1.30 (b)	0.6 to 1.30 (b)	0.60 to 1.10 (b)
Manganese, per cent, Class III				0.60 to 1.10 (b)
Phosphorous, maximum, per cent	0.040	0.040	0.040	0.040
Sulfur, maximum, per cent	0.050	0.050	0.050	0.050
Silicon, per cent	0.10 to 0.30	0.10 to 0.30	0.10 to 0.30	0.10 to 0.35
Nitrogen, maximum, percent				
Wrap test, 0.162" & smaller				
Wrap test, 0.02" ≤ 0.162" & smaller, Class I	1 diameter	1 diameter	1 diameter	
Wrap test, 0.02" ≤ 0.162" & smaller, Class II	2 diameters	2 diameters	2 diameters	
Wrap test, ≤ 0.312" (0.3 in. in ASTM A 82-34)				
Wrap test, 0.162" ≤ 0.312", Class I	2 diameters	2 diameters	2 diameters	2 diameters
Wrap test, 0.162" ≤ 0.312", Class II	4 diameters	4 diameters	4 diameters	3 diameters
Wrap test, 0.162" ≤ 0.312", Class III				4 diameters
Wrap test, 0.162" ≤ 0.250", Class III				
Wrap test, 0.312", Class III				*(continued)*

Table 2.7 (continued)

Item	ASTM A227-64	ASTM A227-68	ASTM A227-71	ASTM A648-72
Wrap test, > 0.312" (0.3 in. in ASTM A 82-34)	"not applicable"	"not applicable"	alternative test (d)	alternative test (d)
Reduction of area test (ASTM A370, Sup. IV)				
Reduction of area test, 0.192" wire				
Reduction of area test, > 0.192" wire				
Relaxation Test (ASTM E328)				
Torsion test				
Splitting Test				
Tensile strength, ksi, 8 gauge (0.162")				
Item	ASTM A227-64	ASTM A227-68	ASTM A227-71	ASTM A648-72
Tensile strength, ksi, 8 gauge, Class I	200 min, 230 max.	200 min, 230 max.	200 min, 230 max.	200 min.
Tensile strength, ksi, 8 gauge, Class II	231 min, 261 max.	231 min, 261 max.	231 min, 261 max.	231 min.
Tensile strength, ksi, 8 gauge, Class III				262 min.
Tensile strength, ksi, 6 gauge (0.192")				
Tensile strength, ksi, 6 gauge , Class I	192 min, 221 max.	192 min, 221 max.	192 min, 221 max.	192 min.
Tensile strength, ksi, 6 gauge, Class II	222 min, 251 max.	222 min, 251 max.	222 min, 251 max.	222 min.
Tensile strength, ksi, 6 gauge, Class III				252 min.
Hydrogen embrittlement test (ASTM A1032)				

Item	ASTM A648-84	ASTM A648-86a	ASTM A648-88a	ASTM A648-88b
Incorporated in ASTM Book of Standards	1985	1987	1989	1990 (h)
Carbon, per cent				
Carbon, per cent, Class I	0.45 to 0.75 (c)	0.45 to 0.75 (c)		
Carbon, per cent, Class II	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)
Carbon, per cent, Class III	0.55 to 0.88 (c)	0.55 to 0.88 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)
Manganese, percent				
Manganese, per cent, Class I	0.60 to 1.10 (b)	0.60 to 1.10 (b)		
Manganese, per cent, Class II	0.60 to 1.10 (b)	0.60 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)
Manganese, per cent, Class III	0.60 to 1.10 (b)	0.60 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)
Phosphorous, maximum, per cent	0.040	0.040	0.030	0.030
Sulfur, maximum, per cent	0.050	0.050	0.035	0.035
Silicon, per cent	0.10 to 0.35	0.10 to 0.35	0.10 to 0.35	0.10 to 0.35
Nitrogen, maximum, percent				
Wrap test, 0.162" & smaller				
Wrap test, 0.02" ≤ 0.162" & smaller, Class I				
Wrap test, 0.02" ≤ 0.162" & smaller, Class II				
Wrap test, ≤ 0.312" (0.3 in. in ASTM A 82-34)				
Wrap test, 0.162" ≤ 0.312", Class I	2 diameters	2 diameters		
Wrap test, 0.162" ≤ 0.312", Class II	2 diameters	2 diameters		
Wrap test, 0.162" ≤ 0.312", Class III				
Wrap test, 0.162" ≤ 0.250", Class III	2 diameters	2 diameters		
Wrap test, 0.312", Class III	3 diameters	3 diameters		
Wrap test, > 0.312" (0.3 in. in ASTM A 82-34)				
Reduction of area test (ASTM A370, Sup. IV)	30% min.	30% min.		*(continued)*

Table 2.7 (continued)

Item	ASTM A648-84	ASTM A648-86a	ASTM A648-88a	ASTM A648-88b
Reduction of area test, 0.192" wire			35% min.	35% min.
Reduction of area test, > 0.192" wire			30% min.	30% min.
Relaxation Test (ASTM E328)				
Torsion test			6/4/3 turns (e)	6/4/3 turns (e)
Splitting Test		pass/fail (g)	pass/fail	pass/fail
Tensile strength, ksi, 8 gauge (0.162")				
Tensile strength, ksi, 8 gauge, Class I	200 min, 230 max	200 min, 230 max		
Tensile strength, ksi, 8 gauge, Class II	231 min, 261 max	231 min, 261 max		
Tensile strength, ksi, 8 gauge, Class III	262 min, 297 max	262 min, 297 max		
Tensile strength, ksi, 6 gauge (0.192")				
Tensile strength, ksi, 6 gauge , Class I	192 min, 222 max	192 min, 222 max		
Item	ASTM A648-84	ASTM A648-86a	ASTM A648-88a	ASTM A648-88b
Tensile strength, ksi, 6 gauge, Class II	222 min, 252 max	222 min, 252 max	222 min, 252 max (f)	222 min, 252 max (f)
Tensile strength, ksi, 6 gauge, Class III	252 min, 290 max	252 min, 290 max	252 min, 282 max (f)	252 min, 282 max (f)
Hydrogen embrittlement test (ASTM A1032)				

Item	ASTM A648-90a	ASTM A648-94	ASTM A648-95	ASTM A648-04a
Incorporated in ASTM Book of Standards	1994 (h)	1995 (j)	1998 (i) (k)	2004
Carbon, per cent				
Carbon, per cent, Class I				
Carbon, per cent, Class II	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)
Carbon, per cent, Class III	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)	0.50 to 0.85 (c)
Manganese, percent				
Manganese, per cent, Class I				
Manganese, per cent, Class II	0.50 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)
Manganese, per cent, Class III	0.50 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)	0.50 to 1.10 (b)
Phosphorous, maximum, per cent	0.030	0.030	0.030	0.030
Sulfur, maximum, per cent	0.035	0.035	0.035	0.035
Silicon, per cent	0.10 to 0.35	0.10 to 0.35	0.10 to 0.35	0.10 to 0.35
Nitrogen, maximum, percent				0.007 (m)
Wrap test, 0.162" & smaller				
Wrap test, 0.02" ≤ 0.162" & smaller, Class I				
Wrap test, 0.02" ≤ 0.162" & smaller, Class II				
Wrap test, ≤ 0.312" (0.3 in. in ASTM A 82-34)				
Wrap test, 0.162" ≤ 0.312", Class I				
Wrap test, 0.162" ≤ 0.312", Class II				
Wrap test, 0.162" ≤ 0.312", Class III				
Wrap test, 0.162" ≤ 0.250", Class III				
Wrap test, 0.312", Class III				
Wrap test, > 0.312" (0.3 in. in ASTM A 82-34)				
Reduction of area test (ASTM A370, Sup. IV)				
Reduction of area test, 0.192" wire	35% min.	35% min.	35% min.	35% min.
				(continued)

Table 2.7 (continued)

Reduction of area test, > 0.192" wire	30% min.	30% min.	30% min.	30% min.
Relaxation Test (ASTM E328)			results reported	results reported
Torsion test	6/4/3 turns (e)	6/4/3 turns (e)	8/6/5 turns (e)(l)	10/8/7 turns (e) (l)
Splitting Test	pass/fail	pass/fail		
Tensile strength, ksi, 8 gauge (0.162")				
Tensile strength, ksi, 8 gauge, Class I				
Tensile strength, ksi, 8 gauge, Class II				
Tensile strength, ksi, 8 gauge, Class III				
Tensile strength, ksi, 6 gauge (0.192")				
Tensile strength, ksi, 6 gauge , Class I				
Tensile strength, ksi, 6 gauge, Class II	222 min, 252 max (f)	222 min, 252 max (f)	222 min, 252 max (f)	222 min, 252 max (f)
Tensile strength, ksi, 6 gauge, Class III	252 min, 282 max (f)	252 min, 282 max (f)	252 min, 282 max (f)	252 min, 282 max (f)
Item	ASTM A648-90a	ASTM A648-94	ASTM A648-95	ASTM A648-04a
Hydrogen embrittlement test (ASTM A1032)				Time to failure > 75 hrs. (g)

Notes
(a) Carbon in any one lot shall not vary more than 0.20 percent.
(b) Manganese in any one lot shall not vary more than 0.30 percent.
(c) Carbon in any one lot shall not vary more than 0.13 percent.
(d) " … an alternative test procedure may be agreed upon …"
(e) Varies by size (6, 1/4, 5/16) See Table 3. Value in parenthesis is equivalent tensile max on that basis.
(g) Supplementary requirement (S1.) applicable only when specified.
(h) This appears to include formatting and scope caveat revisions only.
(i) Reapproved 2000 and printed in 2001 standards.
(k) Added reference standards including AWWA C304.

Changing References to ASTM Wire Standards

AWWA Standard 7B.2-T (tentative) allowed wire manufactured to ASTM A229-41, ASTM A227-47T, or ASTM A82-34. ASTM A82-34 (re-adopted through the 1952 edition) was for "Cold-Drawn Steel Wire for Concrete Reinforcement." The minimum tensile strength was 80,000 psi. The yield point of the wire was allowed to be established at 80 percent of the tensile strength of the "final rupture" strength. ASTM A229-41 was for "Oil Tempered Steel Spring Wire". No yield strength was specified, rather a range of minimum and maximum tensile strengths. ASTM A227-47T, for "Hard Drawn Steel Spring Wire" also specified only a range of tensile strength. Comparing the last two standards, the minimum strength of ASTM A227-47 in size 0.1192-inch wire was 192,000 psi, versus 190,000 psi for the oil tempered wire in ASTM A229.

AWWA C301-52 allowed wire manufactured to ASTM A227 or ASTM A82.

AWWA C301-55 and AWWA C301-58 allowed wire manufactured to ASTM A227, deleting ASTM A82 wire in the 1955 standard.

AWWA C301-64 and AWWA C301-72 allowed wire manufactured to ASTM A227 and included "…except that wire with higher tensile strengths may be used if it meets the other requirements of ASTM A227." In the ASTM A227-63T, effective at the time of adoption of AWWA C301-64, there was only one range of tensile requirements (maximum to minimum.)

In ASTM A227-65, two strength classes were adopted. Those Class I and Class II tensile requirements carried over to the ASTM A227-68, which was effective at the time of adoption of AWWA C301-72.

AWWA C301-79 allowed wire manufactured to ASTM A648, a standard developed exclusively for “Steel Wire, Hard Drawing for Prestressing Concrete Pipe.” The standard included “Wire with specified minimum tensile strengths exceeding those in A648, Class III may be used if it meets the other requirements of ASTM A648, Class III.” ASTM A648-72 includes a footnote: “Prior to the issuance of this specification it was common practice in the prestress concrete pipe industry to refer to the requirements of Specification A 227, Hard Drawn Steel Mechanical Spring Wire.” ASTM A648-72 includes requirements nearly identical to ASTM A227, except that a third tensile strength range, Class III was added.

AWWA C301-84 allowed wire manufactured to ASTM A648, but the exception allowing higher strength wire was deleted. All subsequent standards incorporate ASTM A648. In ASTM A648-88a, adopted in 1989, Class I wire, which was essentially the same as ASTM A227, was dropped.

The 1992 standard revision addressed additional wire requirements above ASTM A648, including a requirement for the wire manufacturer to audit the surface temperature of the wire throughout the length of the wire-drawing process or “take similar dependable precautions to provide assurance that the maximum wire surface temperature does not exceed 360°F (182°C) during drawing.” Not specified was what constituted “similar dependable precautions.”

The minimum number of turns to failure in the torsion test was now specified to not be less than 8 for 0.192-inch (4.88-mm) wire, 6 for 0.250-inch (6.35-mm) wire, and 5 for 0.312-inch (7.92-mm) wire per 8 inches (203 mm) of test sample length. Torsion test specimens were required to have cross section of the primary break showing “approximately three-fourths or more of the failure area” as coplanar shear perpendicular to the wire axis. However, any coil for which the failure torsion test sample has a radial, spiral (that is, longitudinal) split extending the full length of the sample between the torsion machine jaws was allowed to be retested instead of rejected.

In addition, relaxation-loss data were required to be provided as a means of qualifying each manufacturer of wire to be used in the manufacture of pipe. Wire-relaxation-loss quality assurance tests were also required in AWWA C304-92, Section 6.7.3.

Changes Within the ASTM Wire Standards

The differences between standard revisions were principally derived from the apparent desire of the purchasers of that wire (the PCCP manufacturers) to minimize the amount of steel necessary to prestress. Fundamentally, the higher the strength available from the wire, the less wire needed to be included in the pipe and its economic advantage increased. How was the increased strength achieved? It was achieved through advances in chemistry and mechanics.

Refer to Table 2.7. The upper limit on carbon was 0.75 percent up until 1964. ASTM A227-64 included a new tensile strength range for each size of wire, and the new Class II wire was allowed a range from 0.60 to 1.20 percent carbon. The upper limit on manganese was also increased to 1.30 percent from 1.20 percent. ASTM A227-68 increased the upper limit on carbon for the Class III, but decreased both the lower limit (to 0.45 percent) and the upper limit

(to 0.85 percent.) In ASTM A227-68, the carbon limit ranges for both classes of wire were from 0.45 to 0.85 percent. The major change in ASTM A227-71 was the increase in upper limit of manganese for Class II to 1.30 percent.

With the development of ASTM A648-72, the new Class III wire was restricted to a carbon range of between 0.55 and 0.93 percent. The lower bound of Class II carbon was increased to 0.5 percent and the upper bound of Class I was reduced to 0.75 percent. With the upper bound reduced slightly to 0.88 percent for Class III in ASTM A648-84 and further reduced to 0.85 percent in ASTM A648-88a, the carbon limits have remained constant.

ASTM A648-84 contained significant changes to the standard. Including the carbon limit revision and deletion of Class I, testing requirements were changed, and the minimum strengths were expressed as minimum breaking strength in pounds, instead of calculated stress. Also, the maximum amount of sulfur was reduced from 0.040 to 0.030 percent, and the maximum silicon was reduced from 0.050 to 0.035 percent. Those limits are substantially unchanged to date. Among the most important testing changes were the wire splitting test and torsion test.

Commercial Changes Beyond the ASTM Wire Standards

It has been previously noted that AWWA C301-64 and AWWA C301-72 allowed wire manufactured to ASTM A227 and included "…except that wire with higher tensile strengths may be used if it meets the other requirements of ASTM A227." And when ASTM A648-72 was adopted by AWWA C301-79, the standard included "Wire with specified minimum tensile strengths exceeding those in A648, Class III may be used if it meets the other requirements of ASTM A648, Class III." The net effect of this was for the wire manufacturers to try and achieve higher tensile strength wire.

In particular, wire was manufactured by Interpace Corporation in its Solon, Ohio plant and marketed as Class IV wire. There were even projects engineered to use Class III 1/2 wire, somehow expected to be between the limits of the ASTM standards and the marketed Class IV wire. In order to achieve these high strength levels, the wire was drawn through dies at a great rate of speed, creating temperatures in excess of 400°F. That proved to be detrimental to the wire, both serving to induce longitudinal cracks and to make the wire particularly susceptible to hydrogen embrittlement.

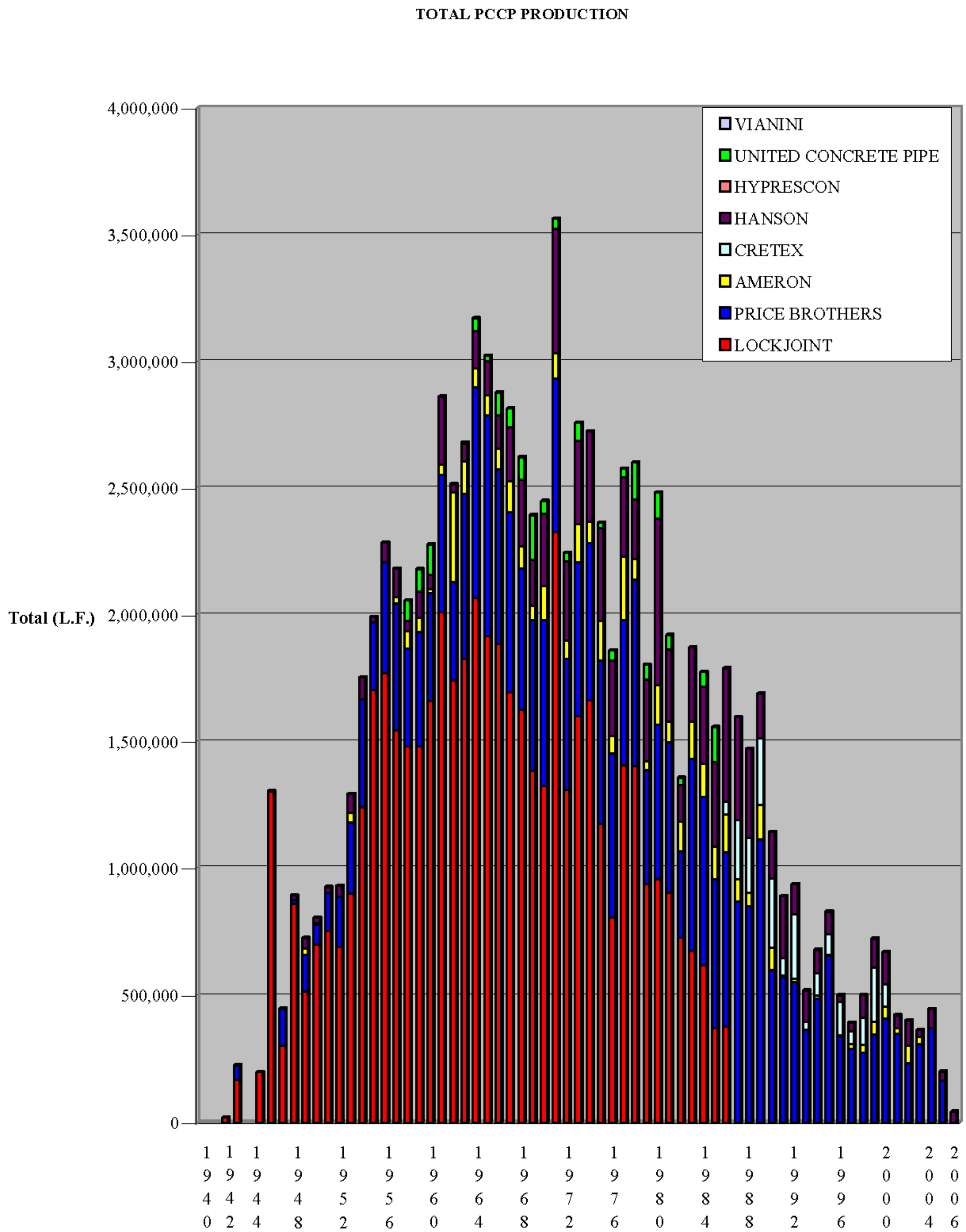

Figure 2.2 Total production – PCCP – by manufacturer

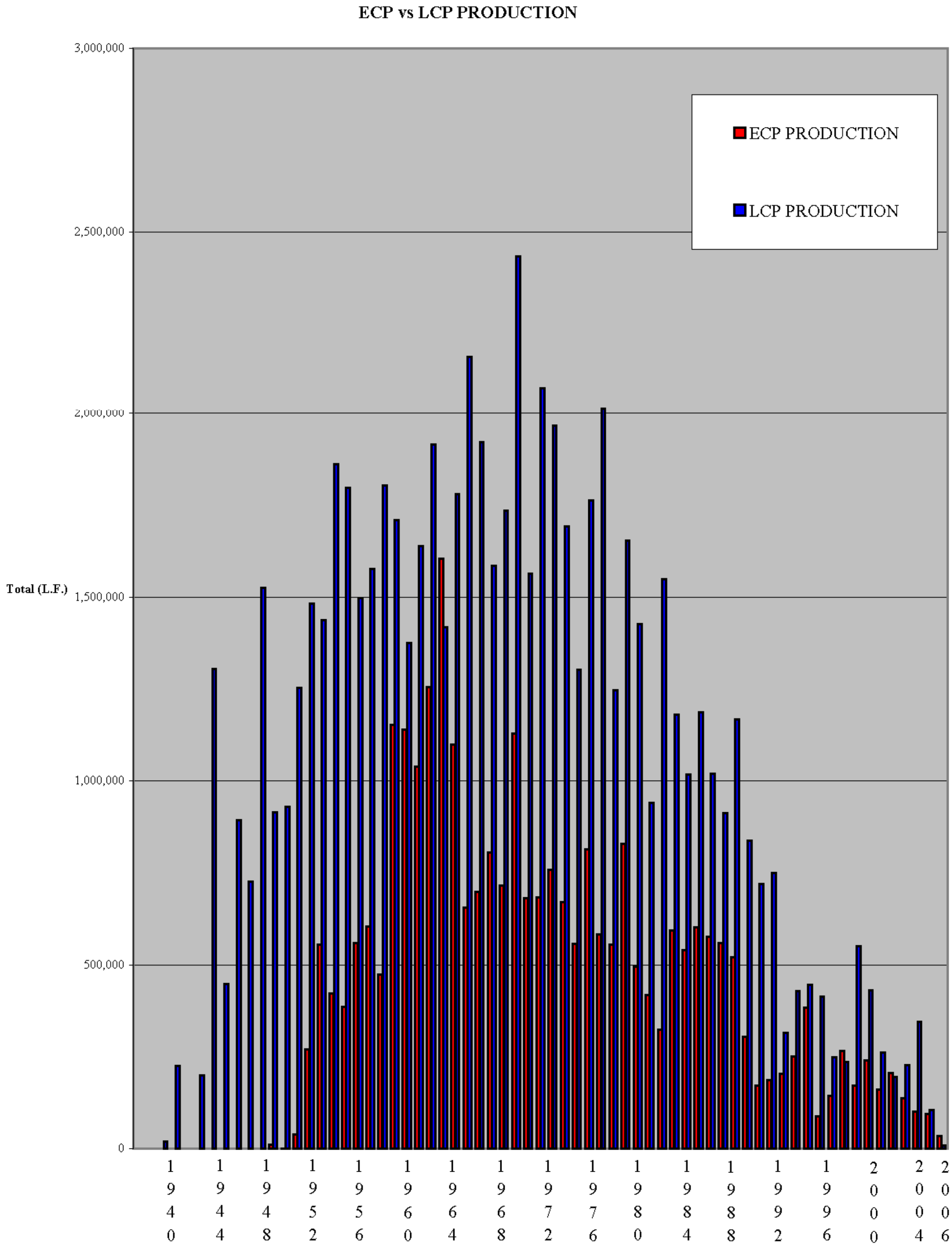

Figure 2.3 Total production – PCCP – ECP compared to LCP

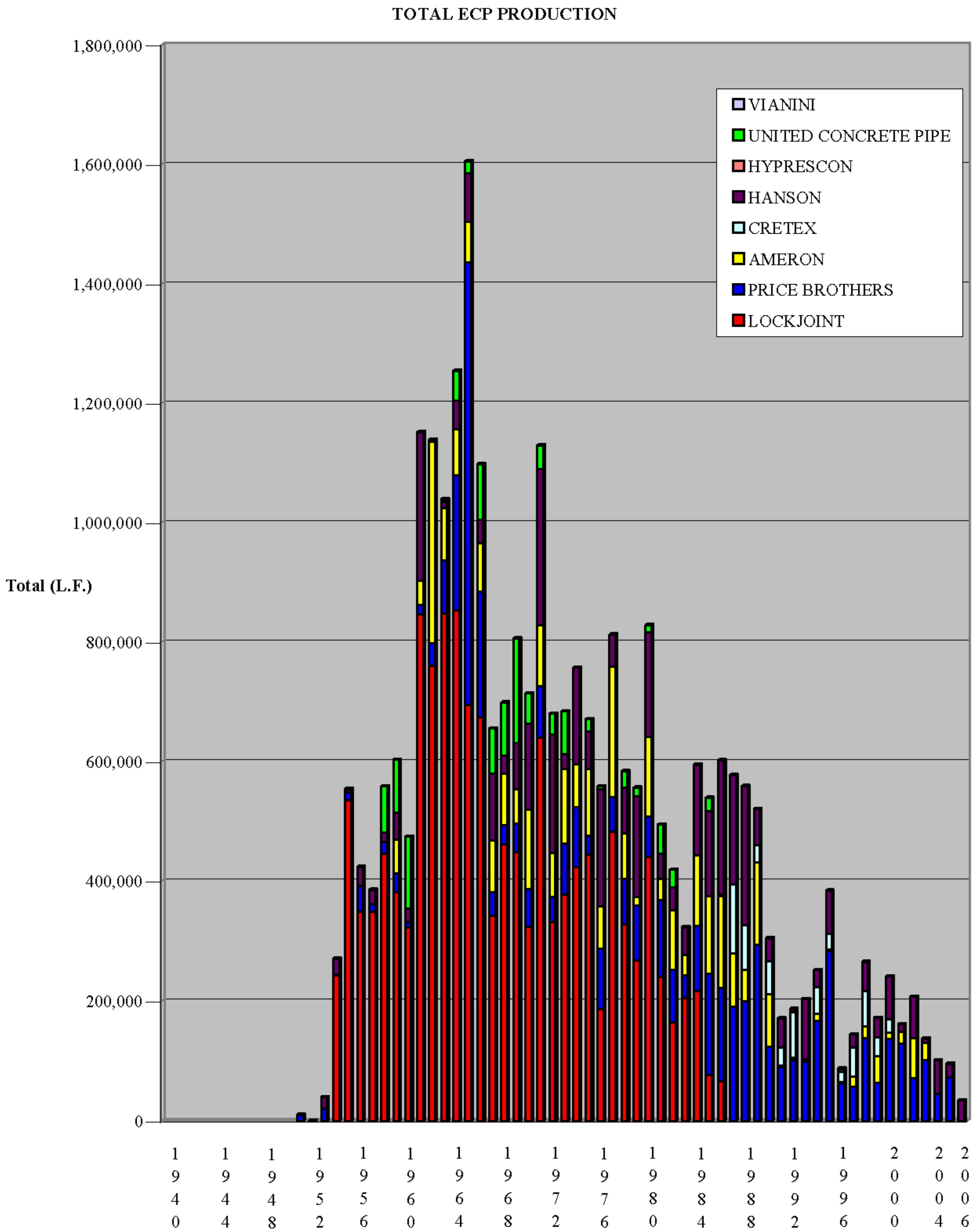

Figure 2.4 Total ECP production – by manufacturer

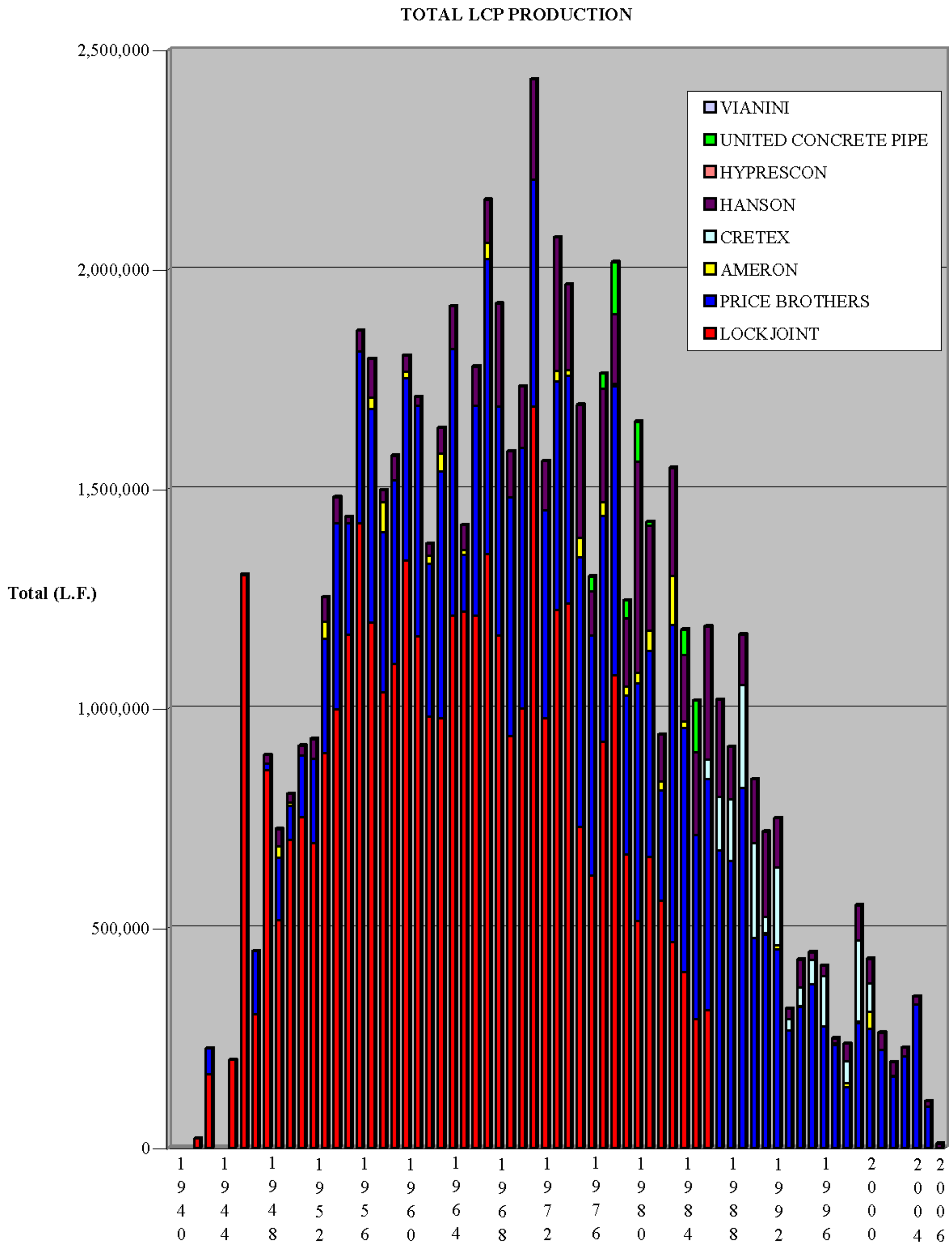

Figure 2.5 Total LCP production – by manufacturer

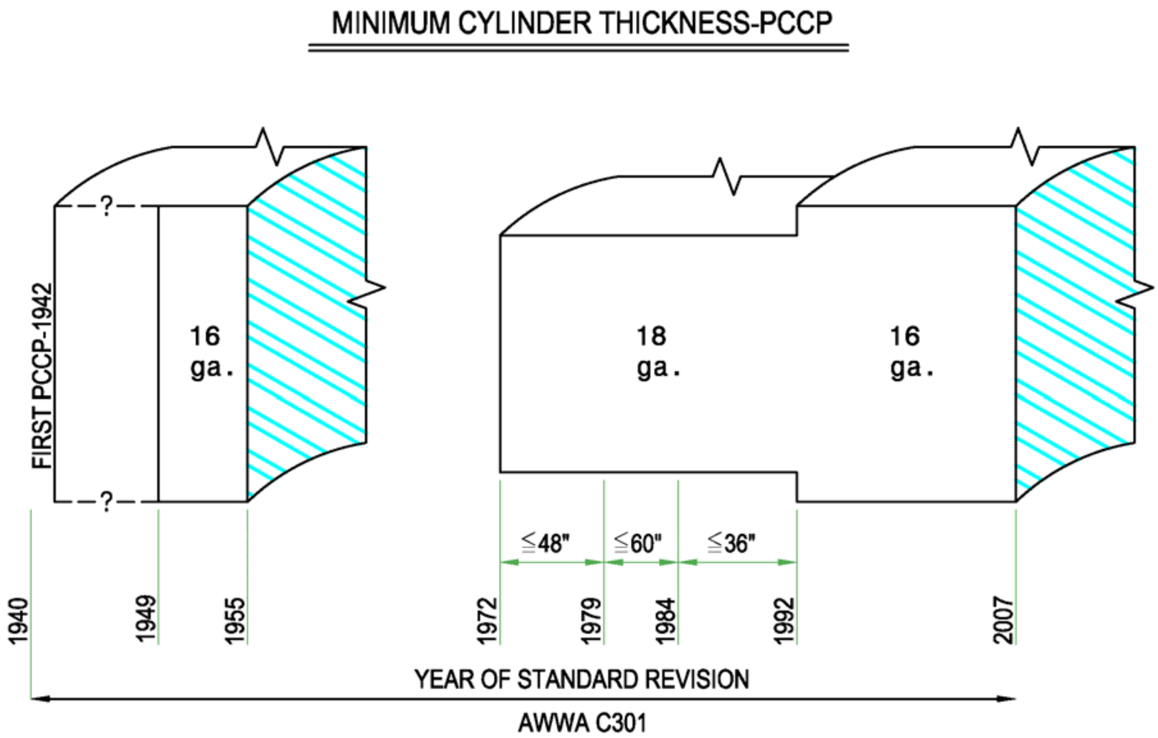

Figure 2.6 Minimum cylinder thickness – PCCP

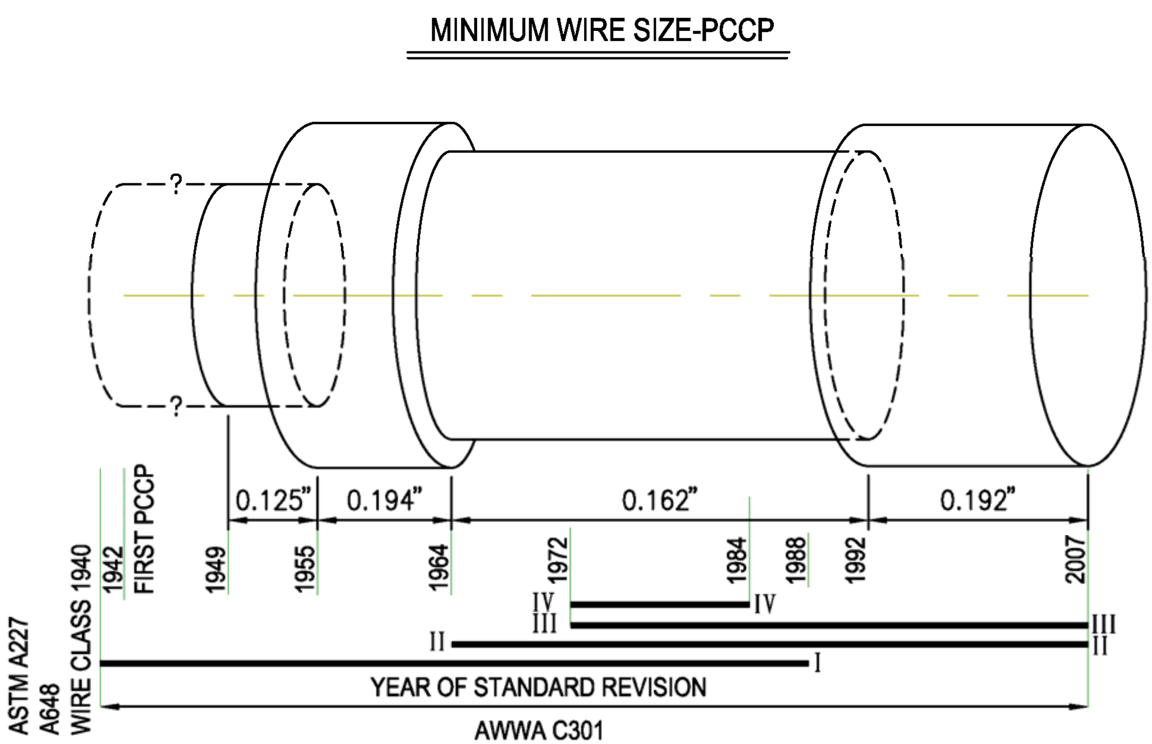

Figure 2.7 Minimum wire size – PCCP

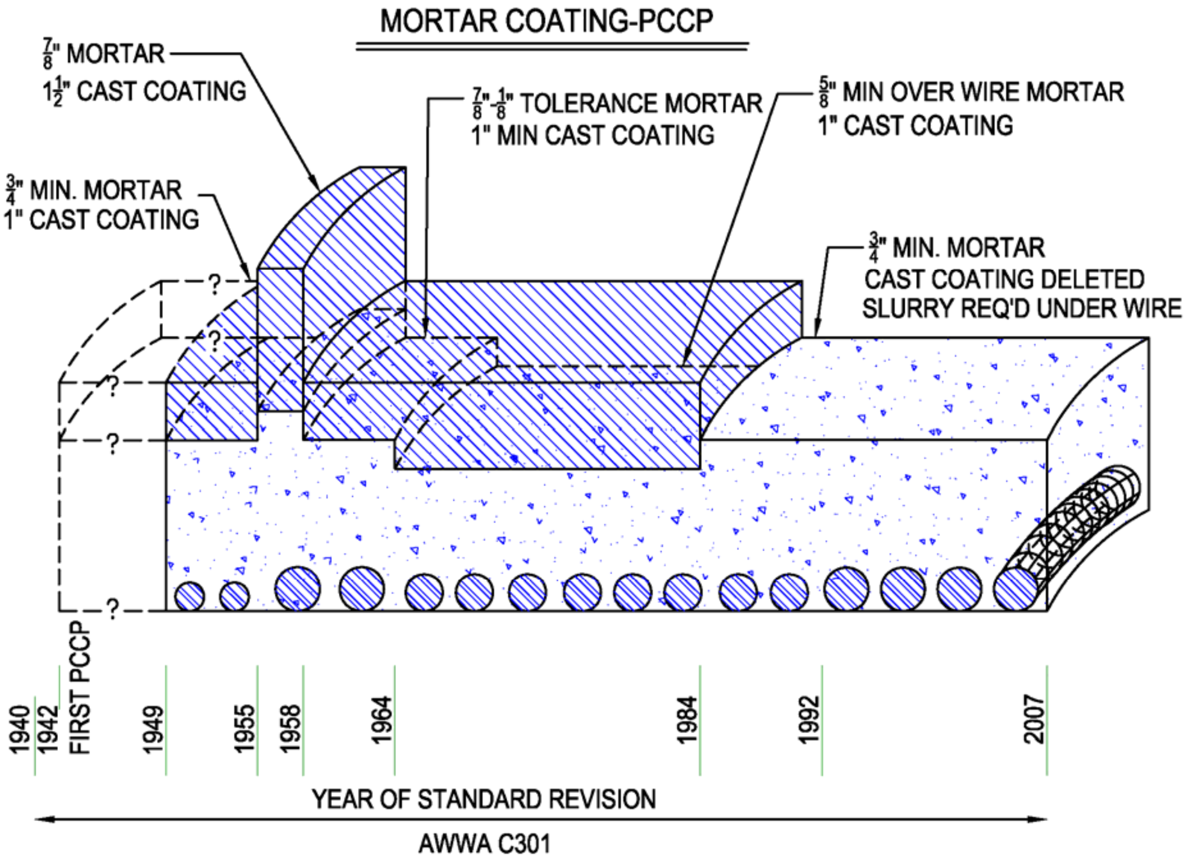

Figure 2.8 Mortar coating - PCCP

CHAPTER 3
PERFORMANCE

CAUSES AND MODES OF FAILURE

Definition of PCCP Failure

The definition of failure utilized by the USBR in its 1995 AwwaRF study was:

> "Failure was indicated as requiring action after installation to correct a pipe deficiency – repair, replacement, or both repair and replacement of the affected units" and "The term failure is synonymous with repair and replacement rate." (AwwaRF 1995)

Similar to the human population, each individual pipe section has a birth (manufacturing) to death cycle that is affected by its heredity (design, manufacturer, materials, etc.), birth defects (construction, installation), and lifestyle (operations and maintenance, etc.). For the purposes of this study, failure has been defined as the loss of use of a pipe section or reduction in confidence in that pipe section to remain service, after discovery of a pipe section deficiency. This includes repair, replacement, or reduction in operating pressure.

Common Causes of PCCP Failure

Causes of failure of PCCP are numerous. Citations in the literature include high chloride environment (Villalobos 1998), the quality of the mortar including lack of complete envelopment of the prestressing wires within the cement mortar coating (Price, Lewis, and Erlin 1998), poor quality of the reinforcing wires (Walsh and Hodge 1998, Knowles 1990), corrosive soils (Galleher and Stift 1998), inadequate thrust restraint (Ojdrovic et al. 2001), construction damage (Parks, Drager, and Ojdrovic 2001), cracks in the cylinder welds (Price 1990), and delamination of the coating (Price 1990). Details of the failure mechanism of EC-PCCP with broken prestressing wires have been published (Zarghamee and Ojdrovic 2001). Those details may be of use only in the courtroom, however, because once the pipe condition has approached the imminent failure state, it is too late.

PCCP is a rather complex engineered product which requires a good deal of attention during the design, manufacturing, inspection, operation, and maintenance in order to be successful. The following lists some of the many means that PCCP has failed, grouped by the five components of PCCP pipeline success:

1. **Design** had to have been as thorough as possible within the context of the state-of-the-art at that time and either engineered by the owner or well reviewed by the owner.

   H_2S generated in unlined force mains has resulted in sulfuric acid attack of the interior of PCCP. In retrospect, either the choice of PCCP was poor or the detailing of the pipeline to avoid air pockets was poor.

   Inadequate joint restraint has resulted in PCCP failures, particularly at the joints, because of pipe that moved, exposing the joint to the environment. Some mechanically restrained joints physically needed to move to engage the restraint

mechanism, leading to the mortared joints opening and exposing the steel joint rings to corrosive soil. Once the steel joint started to corrode, it expanded and cracked the coating, exposing the wire and cylinder to the same soil and groundwater.

Cantilever (bending or broken back) failures have occurred at structures where the pipe was encased throughout its circumference. The dissimilarity in bedding stiffness has led to differential settlement and circumferential cracks clear through the pipe section.

Hydrotest pressures have been specified in excess of the design pressure and design surge pressure, resulting in coating cracks that will never autogeneously heal.

Design of PCCP for placement in soil with chlorides >700 ppm or in soil with measured resistivities <3,000 ohm-cm without additional measures taken may have led to premature failures due to the loss of the protective environment around the prestressing wires.

The impact load of the pipe under its own weight on a rigid surface providing negligible "bedding angle" can result in high unit stresses and cracking of the core and cement mortar coating. It is still not standard practice to analyze PCCP for these loadings.

2. **Manufacturing** by a manufacturer who was committed to making each length of pipe to the highest quality level attainable, consistent with the design was and still is critical.

Low qualities of mortar such as low density, low thickness, and low cement content have all resulted in wire corrosion.

Leaking at joints may in many instances be attributable to out-of-roundness of the mating joints. Not just a misfit for undersize but cracking of the core at the joint to the cylinder when the spigot was later forced into the bell by the contractor. The significant stiffness discontinuity between the prestressed core and the unstressed spigot ring also resulted in many pipe being shipped with circumferential cracks in the thin part of the core at the junction of the cylinder and the spigot.

Alkali-silica reactivity and poor concrete strength have been cited as causes for low quality cores. The variation in compressive strength of PCCP cores vertically cast also may have affected the variation in prestress noted along the axis of some PCCP.

Wire manufacturing problems have been extensively reported. Overheating of the wire during drawing leads to dynamic strain aging. That yields poor torsion ductility and susceptibility to hydrogen embrittlement. Reports of poor quality of wire were not confined to Type IV.

Excessive core creep and shrinkage can be as a result of too high a water-cement ratio, too many fines in the aggregate, and inadequate or improper curing of the concrete core prior to prestressing. The resulting excessive wire relaxation is nothing like the design assumptions.

Excess coating shrinkage, often due to the same causes as described above, result in exposure to wire reinforcement and subsequent corrosion. The carbonated surface of the EC-PCCP core has a decreased pH of about 8.3, much

lower than the usual pH 12 of the surrounding mortar. That carbonation of the concrete core surface in contact with the wire increases crevice corrosion. Also, an uneven (layered) application of mortar results in a "flushing" of the protective alkalinity from the around the wire.

Defective cylinders have been reported. The welds to the joint rings and the lap (or "joggle") joints have been poorly made.

Rough handling of the pipes when the coating is still "green" in the manufacturer's yard and similarly rough handling in loading, transport, and unloading or placing in the trench may contribute to cracking of the coating.

3. **Inspection** by both manufacturer and owner, in the plant and during construction is important.

Loss of prestress due to core under design strength at time of prestressing has been previously noted. Loss of prestress due to wire breaks and splicing probably should have led to rejection also.

PCCP leaking at joints may possibly be due to unnoticed construction damage, missing joint coating, cracks in joint welds, a looped gasket, or poor joint fit-up, all of which point to poor or no field inspection.

Dented cylinders have been reported, likely during fabrication. Active inspection by the owner would have resulted in rejection at the plant.

Typical design bedding angle was 90 degrees. In actual practice, the shaping of bedding to achieve 90-degree bedding requires extra effort and is a requirement often times ignored. Failure to construct per the design results in excess moments and thrusts resulting in cracked lining and coating.

Pipe has been sent from the factory with no effective wire stress, as evident by examination of pipe with no residual prestress in the core. Upon removal from the ground, wire has re-coiled to the original spool diameter, indicating no permanent set. Similarly, wire removed has had as many as three splices on a single pipe, resulting in very low levels of prestress.

4. **Construction** by a contractor motivated to comply with the requirements of the construction documents is always important.

Wrong pipe class, caused by pipe laid out of order, has resulted in pipe underdesigned and understrength for the location placed. This is not a fault of the product but is indicative that each PCCP is typically designed for its specific location in a pipeline and unsuitable for placement elsewhere.

Settlement, in general and at structures, is often the result of poor compaction of bedding and backfill. Bedding not corresponding to design assumptions is not unique to PCCP, but because of its strength in the hoop direction rather than longitudinal for beam action, the correct placement of bedding is critical to its long-term performance.

Construction of a PCCP pipeline in a manner different from what was assumed may contribute to the structural distress of the pipeline. For example, the coating on the pipe may be cracked if either the trench width or height of cover exceed design assumptions.

Accidental penetration by third parties subsequent to construction and mechanical damage during construction have been documented.

5. **Operations and maintenance** (O&M) should not place the pipeline at additional risk. Rapid changes in pressure due to vagaries in operation (surge) overstresses the pipe. Transient waves smaller than design surge pressure have failed PCCP with broken wires.

   Wire is especially susceptible to hydrogen embrittlement (e.g., Class IV). This is caused by the application of excessive cathodic protection, usually well intentioned but in retrospect inappropriately, has caused many wires to break in PCCP.

   Excess external loads greater than the design assumptions and applied subsequent to construction, usually by others, have resulted in PCCP pipelines operated outside the design envelope.

How PCCP Fails

The most common failure scenario of PCCP with broken wires is hypothesized to be the result of redistribution of hoop stress in the zone of no or ineffective prestressing wires to the steel cylinder. As the core is relieved from stress when wires adjacent to the broken area break under the extra load, it begins to crack. Internal inspection can usually detect this progressing from visible longitudinal cracks. Mortar coating, if not already cracked, cracks in tension as the thin cylinder expands radially under hoop stress. The cylinder is exposed to water through the cracks, and corrosion of the cylinder progresses at a rate which is different for each pipe.

In other words, there is a cascading effect: overpressure ➔ coating cracks ➔ wires exposed to water ➔ wires corrode and break ➔ pressure is transferred to the cylinder ➔ core cracks ➔ cylinder is exposed to water ➔ cylinder corrodes and fails.

Failure mode of PCCP is usually sudden. The shear-friction of the concrete core is exceeded simultaneously as the corroded cylinder ruptures in tension. The failure pressure is lower than the ultimate bursting strength of the cylinder. It is limited to several factors including variations in the thickness of the cylinder, eccentricities in the cylinder welds, weld strength, and bending stresses at the transition to the much-stiffer core with functional prestress. If the pipe has longitudinal forces applied through joint restraint, these forces compound the problem.

Failure of prestressing wires, and especially significant numbers of prestressing wires, should be recognized as fair warning that the pipeline is operating at a significantly reduced margin for safety and that its useful remaining life is finite.

Hydrostatic test pressures to which PCCP pipelines are tested are usually much lower margin above operating pressure than 150 percent. For example, the 1961 edition of AWWA Manual M9 *Concrete Pressure Pipe* states, “Test pressures are commonly specified as some value slightly greater than the operating pressure, such as 120 percent of operating pressure” (p. 103). It also states, “Requiring a test pressure considerably in excess of the operating pressure serves only to increase costs since the pipe strength and size of thrust blocks or harnessed joints must be significantly increased.”

The thrust restraint systems were likely also designed not for the hydrotest but only for the operating condition (e.g., class 475-10, etc.). The test pressures at 150 percent of design pressure would be about 130 percent in excess of that which would decompress the core and cylinder with all of the wires effective. The hydrostatic pressure at 150 percent of operating would also have exceeded the tensile stress limit for cracking the coating at the bottom and side of the pipe and for cracking at the top as well. The conclusion is that if a PCCP pipeline was

hydrostatically tested at 150 percent of design pressure then the pipeline coating has likely been cracked since that day.

DESIGN LIFE

Definition of Expected Service Life for PCCP

All pipeline materials have a finite useful life. The life expectancy varies by many factors. PCCP life expectancy varies from 50 years, to 100 years, to "indefinite" depending on the perception of the pipeline owner.

DATA PARTITIONS

As previously discussed in this study, PCCP has had a long and diverse history with many changes in standards and materials. To account for these changes and any impact they might have had on failure rates, the failure data was analyzed in groups of years that shared similar standards and materials. These groups are as follows:

- Pre-1955 (presumably as manufactured to AWWA 7B.2-T [1949])
- 1955–63 (presumably as manufactured to AWWA C301-55 or C301-58)
- 1964–67 (presumably as manufactured to AWWA C301-64)
- 1968–71 (presumably as manufactured to AWWA C301-64)
- 1972–78 (presumably as manufactured to AWWA C301-72)
- 1979–91 (presumably as manufactured to AWWA C301-79 or C301-84)
- 1992–2007 (presumably as manufactured to AWWA C301-92, although the Principal Investigators are aware of at least one project specified to AWWA C301-84 in 1994)

It is meaningful to understand that these partitions represent eras of similarly manufactured pipe. With standards and materials being equal within each group of years, it is assumed that there was no significant variation of failure rates within each data partition.

Classes of Failure

Three categories of PCCP failure have been defined:

1. Catastrophic ruptures and leaks (Category 1)
2. Significant deterioration or structural weakness discerned by inspection (Category 2) by
    - Visual, sounding, and accidental discovery
    - Electronic inspections
3. Loss of service (Category 3)
    - Time out of service
    - Full or partial replacement

FAILURE DATABASE

The failure database has a total of 592 independent entries representing a diverse collection of Category 1, 2, and 3 failures across all data partitions and across 35 states and the District of Columbia.

To be included in the database, every entry represented one pipeline that had recorded at least one failure and a corresponding location. No other lacking information precluded the entry from the database. The failure data cataloged three forms of failure (catastrophic ruptures, failure discerned by inspection, and failure through loss of service) in order to discern trends. It is appropriate to clarify how those classifications were established. For example, one utility reported that they had 18 ruptures and an additional 800 pipes failed (or are in need of repair due to risk) from an inspection program. In that instance, those were cataloged as 18 separate Category 1 failures and 800 Category 2 failures (broken wires discovered by nondestructive testing [NDT] inspections). Other PCCP users have had ruptures, adjacent pipe failed due to inspections, and had to condemn and abandon the use of thousands of feet of pipe in their systems.

These damaged or defective pipes discovered during inspection and pipes no longer deemed serviceable must be included in the calculations to get an accurate "failure rate" for the pipes. But because the condemned and abandoned pipes had not ruptured or leaked, they could not be cataloged as Category 1 failures. They had not been individually examined or inspected, so they could not be classified as Category 2 failures. Thus, the creation of a third category, Category 3, was warranted to account for these failures. However, it also became evident that Category 2 failures were often the proximate determination of Category 3 failures, so from a statistical analysis, they were lumped together, yielding an increased sample population size of the combined category.

Of the 592 independent entries, the database includes 435 Category 1 failures, or 61.1 percent of the entries. There were 35,662 Categories 2 and 3 failures, or 45.3 percent of the entries. Thirty-eight of the entries, or 6.5 percent, specified both a Category 1 and a Categories 2 and 3 failure. Of all the entries, 98.3 percent of the entries had a diameter specified, 97.8 percent had a pipe type (embedded, lined, etc.) specified or assumed based on the diameter, and 92.9 percent had a wire type (Class I, II, III, or IV) specified or assumed based on the installation year. In totality, 95.9 percent had the installation date specified and 92.0 percent had a fail date specified. With these, a total of 85.6 percent of the entries had both the installation date and the fail date, such that a pipe age could be calculated.

Looking at Category 1 failures by manufacturer, 41.8 percent of the entries were tabulated as Interpace Corporation pipe, 9.0 percent was attributed to other manufacturers by name, and the remaining 49.2 percent was unknown. Of the Categories 2 and 3 failures, 60.7 percent of the entries were Interpace pipe, 2.7 percent was attributed to other manufacturers, and the remaining 36.6 percent had no manufacturer recorded.

Breaking the database into the partitions in a meaningful manner required the pipeline age. This left the sample populations shown in Table 3.1 for further analysis:

Table 3.1 Sample populations		
Partition	Category 1 Failures	Categories 2 and 3 Failures
All samples	393	24,822
pre-1955	32	10
1955–63	40	2,381
1964–67	31	63
1968–71	60	46
1972–78 (all)	194	15,158
1972–78 (Interpace)	152	4,349
1972–78 (non-Interpace)	14	2,586
1979–91	35	5,864
1992–2007	1	1,299

It should be noted that the subset 1972-78 (Interpace) included all failures of pipe known to be manufactured by Interpace Corporation. However, the subset 1972-78 (unknown and non-Interpace) included both known non-Interpace manufactured pipe and unknown pipe; unknown pipe may be either Interpace or non-Interpace manufactured pipe.

HISTOGRAMS AND SIMPLE STATISTICAL ANALYSIS

Using the above-listed sample populations of entries with pipeline ages, lifespan histograms were produced. A histogram is a convenient graphical representation of a frequency distribution. In this case, the frequency distribution of failures was plotted as a function of the pipeline age for each of the corresponding data partitions.

PCCP Failures by Age

The first histogram, Lifespan Histogram-All Samples, Figure 3.1, illustrates the breakdown of failures into five-year incremented age categories. This histogram disregards which data partition to which each sample belongs, but is useful to observe the overall trend of all failures. On the left-hand axis, the solid blue bars represent Category 1 failures, or ruptures. The right-hand axis corresponds with the crossed magenta bars, or Categories 2 and 3 failures. The mode, or value that occurs most frequently, of Category 1 failures occurs in 6 to 10 years, while Categories 2 and 3 failures peak at the 26- to 30-year group. Both datasets are roughly normally distributed, or bell-shaped, with a moderate skew to the right for the Category 1 failures and a slight skew to the left for Categories 2 and 3 failures. The Categories 2 and 3 failure distribution generally lags the Category 1 failure distribution by 20 years. Although not perfectly normally distributed, the mean and standard deviation of both datasets were calculated. The means were 13.95 and 16.75 years for Category 1 and Categories 2 and 3 failures, respectively. The corresponding standard deviations were 8.95 and 10.24 years. By examining the total production of pipes, a failure rate for each dataset was calculated. With a total of 4,979,837 pipe (or individual pipe segments) produced between 1940 and 2006, the average failure rates for Category 1 and Categories 2 and 3 were -7.89 x 10^{-5} and 4.98 x 10^{-3} failures per pipe produced, respectively. This indicates that within 50 years of being installed, one rupture

and 66 Category 2 or Category 3 failures occurred for every 13,200 pipe segments (~50 miles of pipe).

The next histogram, Figure 3.2, examines those failed pipelines that were installed before 1955. For this era, the wire used was most probably Class I, 0.125-inch size, 45 percent design stress. Again, age is represented in five-year increments on the bottom abscissa. The approximate corresponding year is labeled below the age increments. The left-hand axis corresponds with the solid blue bars which are Category 1 failures. The right-hand axis corresponds with the crossed magenta bars, or Categories 2 and 3 failures. It is observed that the mode of both Category 1 and Categories 2 and 3 failures occurs in 21 to 25 years. Both datasets appear roughly normally distributed until after 31 to 35 years, with no failures occurring beyond this timeframe. The mean number of years for failures was 23.32 and 24.86, respectively, for Category 1 and Categories 2 and 3 failures. The corresponding standard deviations were 6.92 and 5.96 years. With 476,458 pipe produced in this timeframe, the failure rates were 6.72×10^{-05} and 2.10×10^{-05} Category 1 and Categories 2 and 3 failures per pipe segment produced, respectively. This indicates statistically that within 35 years of being installed, one rupture and 315 other failures occurred for every 15,000 pipe segments (~57 miles of pipe). After 35 years of age, there are no reported failures.

The histogram following pre-1955, Figure 3.3, is for pipelines installed between 1955 and 1963. For this timeframe, the wire used was most probably Class I, 6 gauge, stressed to 45 to 70 percent of the ultimate strength. The axes are the same as above. In this histogram, a bimodal distribution exists for both Category 1 and Categories 2 and 3 failures, occurring at 25 to 30 and 41 to 45 years. Although less meaningful in this type of distribution, the mean and standard deviation for Category 1 is 23.78 years and 10.21 years. For Categories 2 and 3, the mean is 29.79 and the standard deviation is 10.26. With 1,051,498 pipes produced between 1955 and 1963, the corresponding failure rates are 3.8×10^{-5} and 2.26×10^{-3} failures per pipe produced for Category 1 and Categories 2 and 3 failures, respectively. This means for every 35,800 pipe segment (~135 miles of pipe), there was one rupture and 81 Category 2 and Category 3 failures.

Figure 3.4, Lifespan Histogram–Installed 1964–67, looks at pipelines installed in this era. This timeframe represents the first time Class II wire is listed in the standard. Class II, 8 gauge, stressed to 75 percent ultimate tensile strength is the probable wire type used during this era. Age is again represented in five-year increments on the bottom abscissa. This is the first graph where present time is being approached, illustrated as being grayed out on the right-hand side. The approximate corresponding year is labeled below the age increments. The left-hand axis corresponds with the solid blue bars which are Category 1 failures. The right-hand axis corresponds with the crossed magenta bars which are Categories 2 and 3 failures. Category 1 failures are roughly normally distributed around the mode of 11 to 15 years, 10 years earlier than pipes produced during the previous era with Class I wire. Categories 2 and 3 failures are closer to being uniform than normally distributed, unless 0 to 5 and >30 years are neglected. The means were 15.13 and 16.90 years and the standard deviations were 6.71 and 10.06 years for Category 1 and Categories 2 and 3, respectively. With 594,367 pipes being produced in this timeframe, the failure rates were 5.22×10^{-05} and 1.06×10^{-04}, respectively, for Category 1 and Categories 2 and 3 failures. This equates to one rupture and two Category 2 or Category 3 failures for every 20,000 pipe segments (~75 miles of pipe).

Figure 3.5 illustrates failures of pipe installed in 1968–71. This timeframe also includes the first time a new wire class is listed in the standard, Class III. The most probable wire used in this era was Class III, 8 gauge, stressed to 75 percent ultimate strength. Age is still represented in five-year increments on the bottom x-axis. Present time is sill encroaching on the right-hand side of the graph; future time is illustrated as being grayed out. The approximate corresponding year is labeled below the age increments. Again, the left-hand axis corresponds with the solid blue bars which represent Category 1 failures. The right-hand axis corresponds with the crossed magenta bars which represent Categories 2 and 3 failures. Category 1 failures are more or less normally distributed around the mode of 6 to 10 years, 5 years earlier than pipes produced during the previous era with Class II wire. Again, Categories 2 and 3 failures are closer to being uniform than normally distributed. The mean number of years for failures was 11.07 and 13.47, respectively, for Category 1 and Categories 2 and 3 failures. The corresponding standard deviations were 6.01 and 8.14 years. With 551,345 pipes produced between 1968 and 1971, the failure rates were 1.09×10^{-04} and 8.34×10^{-05} Category 1 and Categories 2 and 3 failures per pipe produced, respectively. This indicates that within 40 years of being installed, one rupture and about one Category 2 or Category 3 failure occurred for every 9,200 pipes (~35 miles of pipe).

The next three graphs represent failures occurring in pipe installed in 1972–78. This timeframe represents an era when a loophole was used by Interpace Corporation and others to use higher strength wire, Class IV, while still adhering to the standard. Figure 3.6 looks at all pipe failures from this era, Figure 3.7 only looks at Interpace pipe, and Figure 3.8 looks at both Interpace pipe and pipe with unknown pipe manufacturer. It is noteworthy that over three times as many Category 1 failures occurred from this time period than from the last timeframe. Seventy-eight percent of the failures represented Interpace pipe and the remaining twenty-two percent represented non-Interpace pipe and pipe of unknown manufacturer. The most probable wire used in this era was Class III for non-Interpace pipe or Class IV for Interpace pipe, 8 gauge, 75 percent ultimate strength. For Category 1 failures, the all-samples (Figure 3.6), Interpace (Figure 3.7), and unknown/non-Interpace (Figure 3.8) graphs are all roughly normally distributed, with moderate skew to the right. The all-samples and Interpace graphs are modal around the 6- to 10-year point, markedly similarly to the last timeframe's Class III wire. The unknown/non-Interpace graph is roughly modal around the 16-20 point. For the all-samples graph, the Categories 2 and 3 failures are roughly normally distributed around the 26- to 30-year point with a slight skew to the left. A similar distribution is observed in the Interpace pipe graph, except being modal around 21 to 25 years. The unknown/non-Interpace graph has a modal distribution of Categories 2 and 3 failures at 26 to 30 years. The Category 1 means were 12.16, 10.38, and 17.90 years for all-samples, Interpace, and unknown/non-Interpace, respectively. The corresponding standard deviations were 7.70, 6.47, and 8.56 years. The Categories 2 and 3 means were 15.97, 12.44, and 22.62 years, again for all-samples, Interpace, and unknown/non-Interpace, respectively. The corresponding standard deviations were 9.75, 8.45, and 8.56 years.

The production of PCCP approached 856,323 pipes overall for this timeframe, with 468,296 coming from Interpace. This corresponds with Category 1 failure rates of 2.27×10^{-04}, 3.25×10^{-04}, and 4.90×10^{-05} failures per pipe produced for all-samples, Interpace, and non-Interpace, respectively. The difference between Interpace and unknown/non-Interpace failure rates is over an order of magnitude larger. The corresponding Categories 2 and 3 failures for the years 1972–78 were 1.77×10^{-02}, 9.29×10^{-03}, and 1.26×10^{-02} failures per pipe produced for all-samples, Interpace, and unknown/non-Interpace. Statistically, for 22,000 pipes (~83 miles) installed in this era, one rupture occurred if the pipe was unknown/non-Interpace, seven ruptures

occurred if the pipe was Interpace, and five ruptures occurred among all pipe manufactured in the era. For Categories 2 and 3 failures, for the same 22,000 pipes installed, 277 other failures occurred if the pipe was unknown or non-Interpace pipe, 204 failures occurred if the pipe was Interpace, and 389 failures occurred among all pipe manufactured in the era.

Figure 3.9, Lifespan Histogram–Installed 1979–91, represents the end of the Class IV loophole. Class III, 8 gauge, stressed to 75 percent ultimate tensile strength is the probable wire type used during this era. Age is again represented in five-year increments on the bottom abscissa. Almost half of the graph is future time, illustrated by being grayed out on the right-hand side. The approximate corresponding year is labeled below the age increments. The left-hand axis corresponds with the solid blue bars which signify Category 1 failures. The right-hand axis corresponds with the crossed magenta bars which signify Categories 2 and 3 failures. Category 1 failures are J-curved to the right, with the highest frequency of failures occurring in 0 to 5 years—five years earlier than the Class III/IV wire used in the previous timeframe. Categories 2 and 3 failures are approximately normally distributed around 21 to 25 years, similarly to the Categories 2 and 3 failures of Interpace pipe during the last era. The mean number of years for failures was 7.47 and 12.72, respectively, for Category 1 and Categories 2 and 3 failures. The corresponding standard deviations were 6.37 and 7.77 years. With 1,067,552 pipes produced in this timeframe, the failure rates were 3.28×10^{-05} and 5.49×10^{-03} Category 1 and Categories 2 and 3 failures per pipe produced, respectively. This indicates that within 30 years of being installed, one rupture and 176 Category 2 or Category 3 failures occurred for every 32,000 pipes (~120 miles of pipe).

The last lifespan histogram, Figure 3.10, representing the timeframe 1992–2007, is included for completeness. With one Category 1 failure and 1,299 Categories 2 and 3 failures from one database entry, the sample population is not statistically significant. Class III wire, 0.192 inch, stressed to 75 percent ultimate strength is the most probable wire installed in this timeframe. Seventy percent of the graph represents future time, illustrated as being grayed out on the right-hand side of the graph. With only a single entry (one pipeline that failed and was subsequently relined), the failure peak is depicted at the 11- to 15-year point for both Category 1 and Categories 2 and 3 failures. The "mean" is 12 years, with no standard deviation. With 382,295 pipes produced between 1992–2006, the corresponding failure rate was 2.62×10^{-06} and 3.40×10^{-03} Category 1 and Categories 2 and 3 failures per pipe produced, respectively.

PCCP Failures by Installation Date

The next four histograms, Figures 3.11 through 3.14, illustrate Category 1 and Categories 2 and 3 failures between 1942 and 2006 by installation date instead of by pipeline age. Because only the installation year and failure data are required to construct these histograms, several more data points are available. The sample population was represented by 403 Category 1 failures and 27,805 Categories 2 and 3 failures.

The first two histograms (Figures 3.11 and 3.12) represent Category 1 failures—the first without superimposed corresponding production, the second with. The next two histograms (Figures 3.13 and 3.14) represent Categories 2 and 3 failures—again, the third without superimposed production, the fourth with the production values. Installation year is incremented on the bottom abscissa throughout. On Figures 3.11 and 3.12, the left-hand axis corresponds with the solid blue bars which signify Category 1 failures. On Figures 3.13 and 3.14, the left-hand axis corresponds with the solid magenta bars which signify Categories 2 and 3 failures.

Additionally, on Figures 3.13 and 3.14, production data in individual pipe segments (sticks) has been superimposed, corresponding to the horizontally lined, coral-colored right-hand axis.

On Figures 3.11 and 3.12, the Category 1 failures are normally distributed around the year 1974; that is, the highest frequency of failures occurred from pipe installed in 1974. There is a slight skew to the left. On Figures 3.13 and 3.14, the frequency is roughly normally distributed around the installation year 1976. The mean number of failures between 1942 and 2006 were 6.20 and 428 Category 1 and Categories 2 and 3 failures, respectively. The corresponding standard deviations were 10.23 and 1,194 failures. Although the production values are superimposed on the second and fourth graph, they are not taken into account when calculating the failure frequency distribution. Since failures are inherently a function of how much pipe was produced, looking at the failures alone may lead to erroneous conclusions.

The next two graphs attempt to rectify this issue. Figures 3.15 and 3.16, named Normalized Failures by Installation Date Histogram, Category 1 and Categories 2 and 3, the failure frequency has been divided by the production in pipe for each corresponding installation year. The result is the normalized frequency of failures per pipe produced on the left-hand ordinate, plotted as a function of installation year, which runs across the bottom abscissa. The solid blue bars signify normalized Category 1 failures; the crossed magenta bars signify normalized Categories 2 and 3 failures. By taking into account production, the Category 1 failure distribution became bimodal: one peak occurred in 1975, the other in 1947. For Categories 2 and 3 normalized failures, the distribution is roughly normally distributed between 1975 and 1979. The fact that a mode still occurs in the mid-1970s for both Category 1 and Categories 2 and 3 confirmed the validity of the previous histograms by installation year that did not take into account production. The mean was 6.09×10^{-05} Category 1 failures per pipe produced with a corresponding standard deviation of 9.17×10^{-05} failures per pipe produced. For Categories 2 and 3, the mean was 4.01×10^{-03} failures per pipe produced with a corresponding standard deviation of 1.12×10^{-02} failures per pipe produced.

PCCP Failure Rates by Manufacturing Era

Figure 3.17 summarizes the PCCP failure rates as a function of timeframe, or era of pipe manufacturing. Figure 3.17 is plotted with standard axes. Like the preceding histograms, on Figure 3.17 the left-hand axis of the bar graph corresponds with the solid blue bars which represent Category 1 failures. The right-hand axis corresponds with the crossed magenta bars which represent Categories 2 and 3 failures. The pipe installation timeframe increases along the bottom x-axis. Observing the failure rate trends in Figure 3.17, it can be seen that the largest Category 1 failure rate occurred in the 1972–78 era with Interpace pipe. The largest Categories 2 and 3 failure rate occurred in the 1972–78 era with all samples. The most agreement between Category 1 and Categories 2 and 3 failures occurred in 1964–67 and 1968-71 timeframes.

PCCP Failures by Wire Class

Figure 3.18 illustrates PCCP failures as a function of wire class. Because pipeline age and installation year are not required for this analysis, several more database entries are available. The sample populations for this histogram are 397 and 25,809 Category 1 and Categories 2 and 3 failures, respectively. The left-hand axis corresponds with the solid blue bars which represent Category 1 failures. The right-hand axis corresponds with the crossed magenta bars which represent Categories 2 and 3 failures. Wire class increases across the x-axis. It is

observed that the highest frequency of Category 1 failures occurred with Class IV wire. The second highest frequency of failures occurred with Class II wire. For Categories 2 and 3 failures, the highest occurrence of failures also occurred with Class IV wire. The second highest frequency of failures occurred with Class III wire. The least number of Categories 2 and 3 failures were reported for Class II wire.

PCCP Failure Rates by Pipe Type by Installation Year

Figures 3.19 and 3.20, Failure Rates by Pipe Type by Installation Year for Category 1 failures and Categories 2 and 3 failures, examine failure rates between ECP and LCP as a function of the installation year. Because another parameter was added for this analysis, a decrease in the sample population resulted. The sample population was 387 and 24,400 for Category 1 and Categories 2 and 3, respectively.

Figure 3.19 observes Category 1 failures. The y-axis represents Category 1 failure rates, or the number of failures divided by the pipe produced per installation year. The x-axis represents the pipe installation year. The solid blue bars represent LCP failure rates. The horizontally-lined coral-colored bars represent ECP failure rates.

In Figure 3.20, the y-axis represents Categories 2 and 3 failures rates. For Category 1 failures, it is observed that LCP has a bimodal distribution—one peak in 1947, the other in 1975. The 1975 peak is roughly normally distributed; the 1947 peak is J-curved to the right. ECP is roughly normally distributed about the mean occurring in 1972.

The average failure rates between 1942 and 2006 were 0.0126 and 0.0188 failures per mile per year for LCP and ECP, respectively. Figure 3.20, representing Categories 2 and 3 failure rates, illustrates the trends for ECP and LCP. There were over five times as many reported ECP failures as LCP failures, although more than twice as much LCP was installed between 1942 and 2006. No orderly distribution was discernable for LCP. For ECP, the failure rates were more or less normally distributed around 1975. The average failure rates between 1942 and 2006 were 0.254 and 2.65 failures per mile per year for LCP and ECP, respectively.

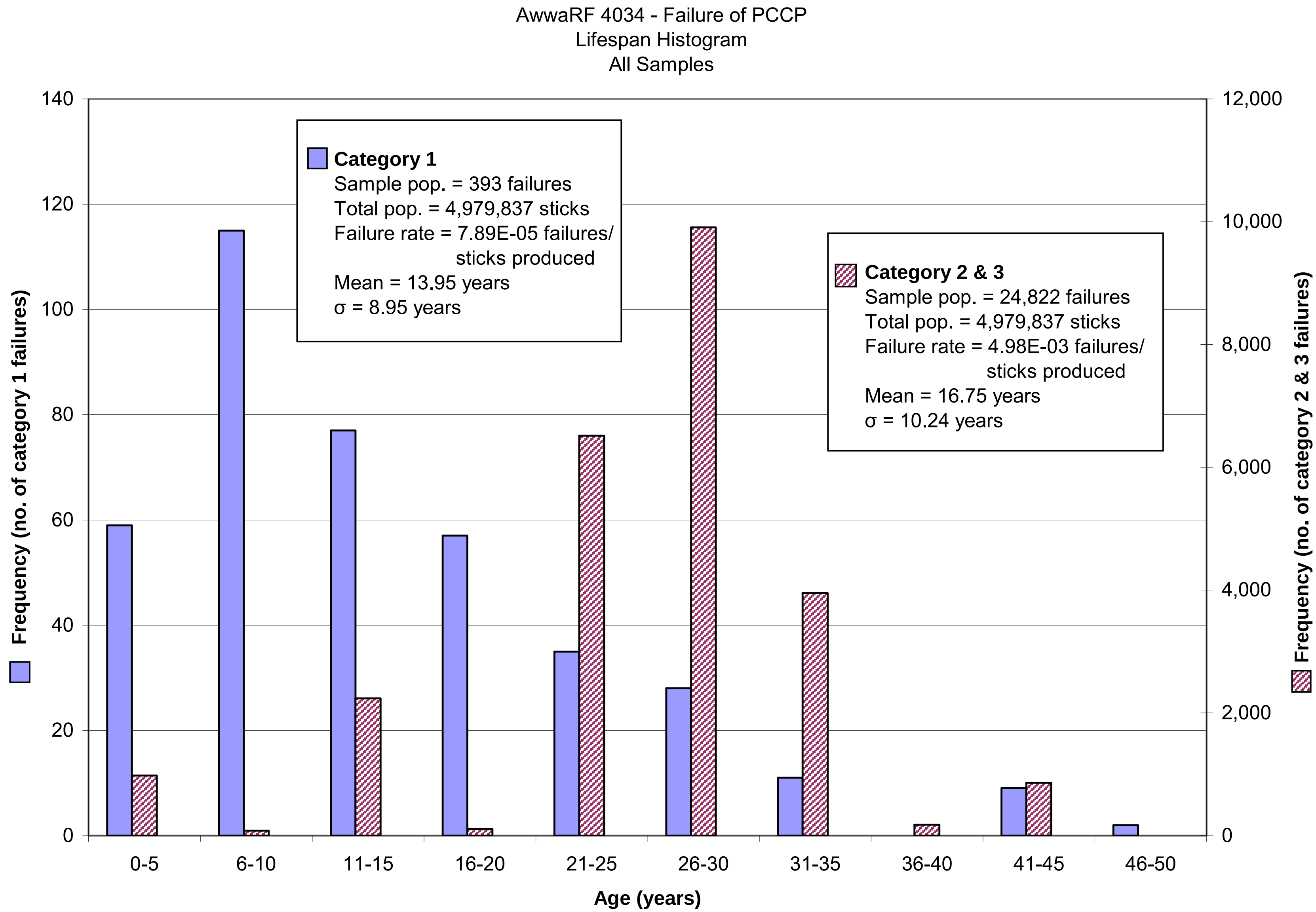

Figure 3.1 Lifespan histogram – all samples

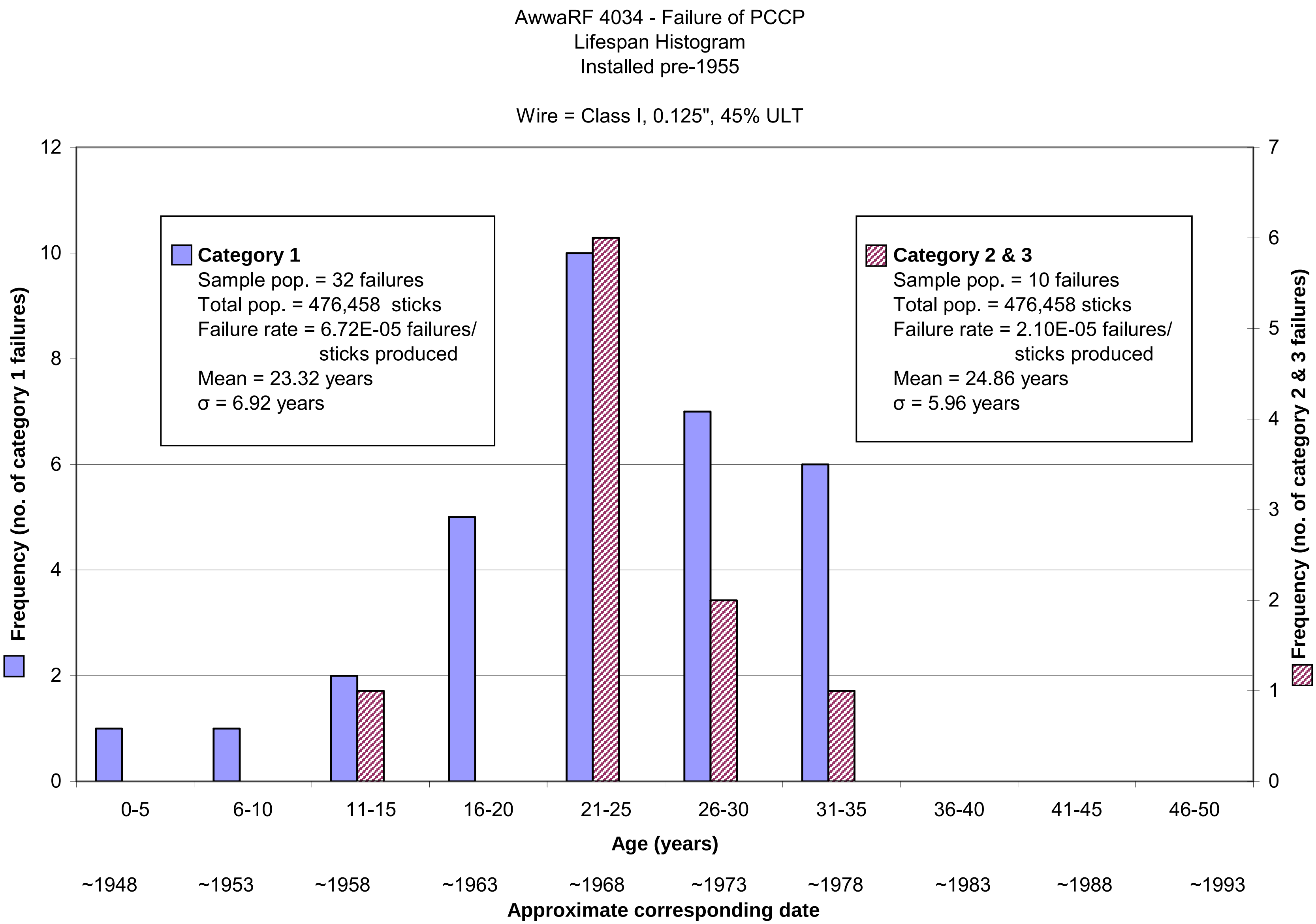

Figure 3.2 Lifespan histogram – installed pre-1955

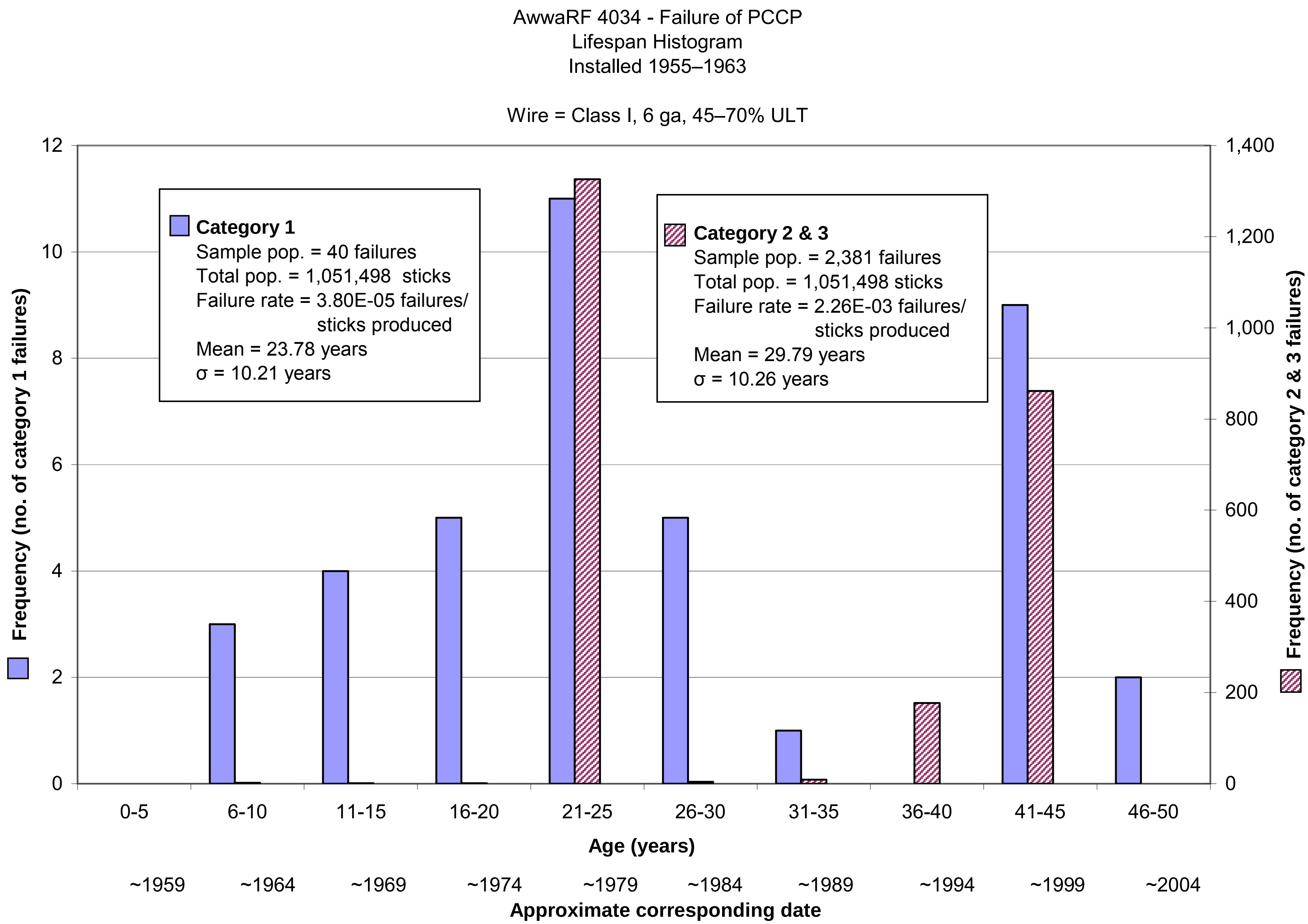

Figure 3.3 Lifespan histogram – installed 1955-1963

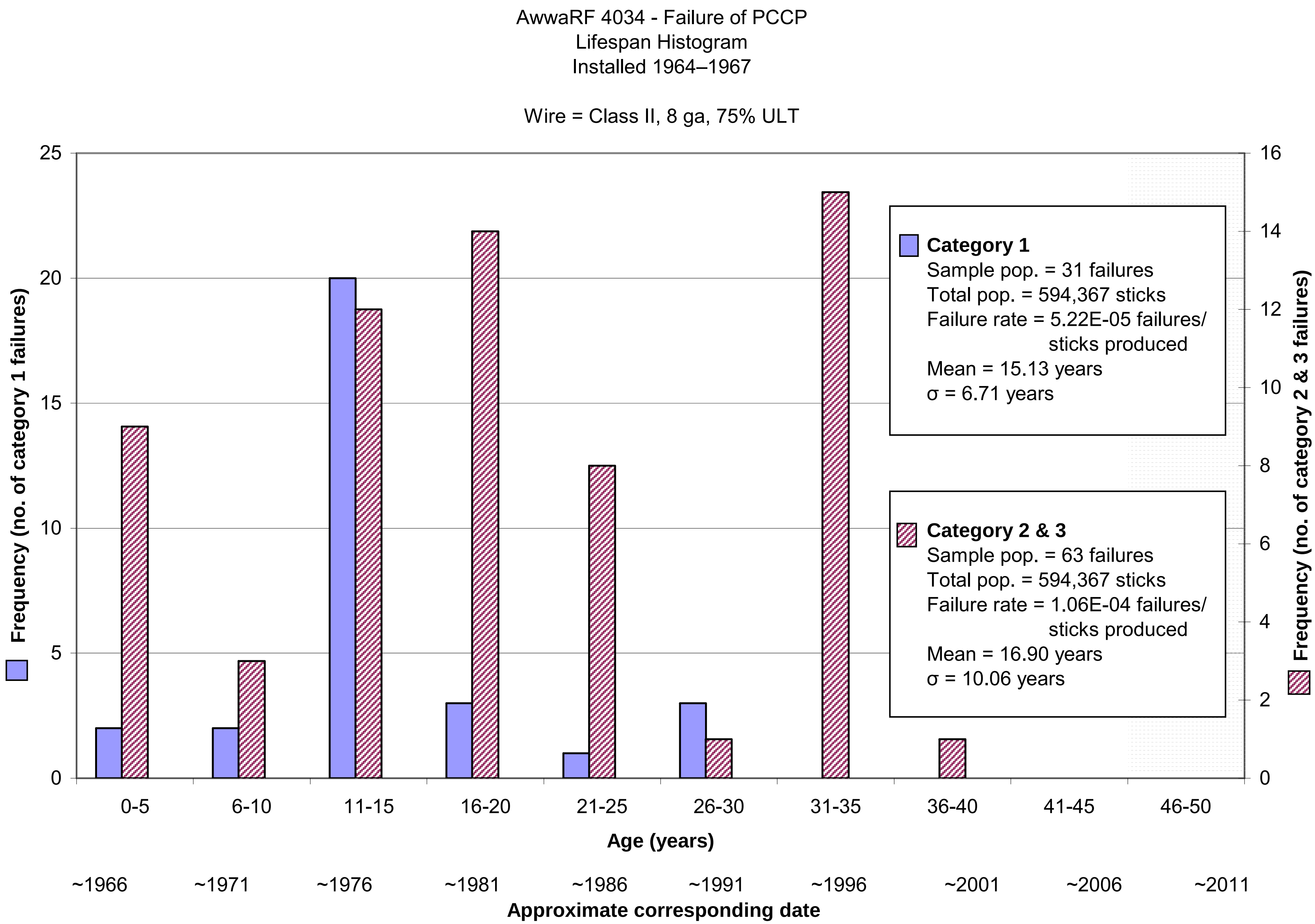

Figure 3.4 Lifespan histogram – installed 1964-1967

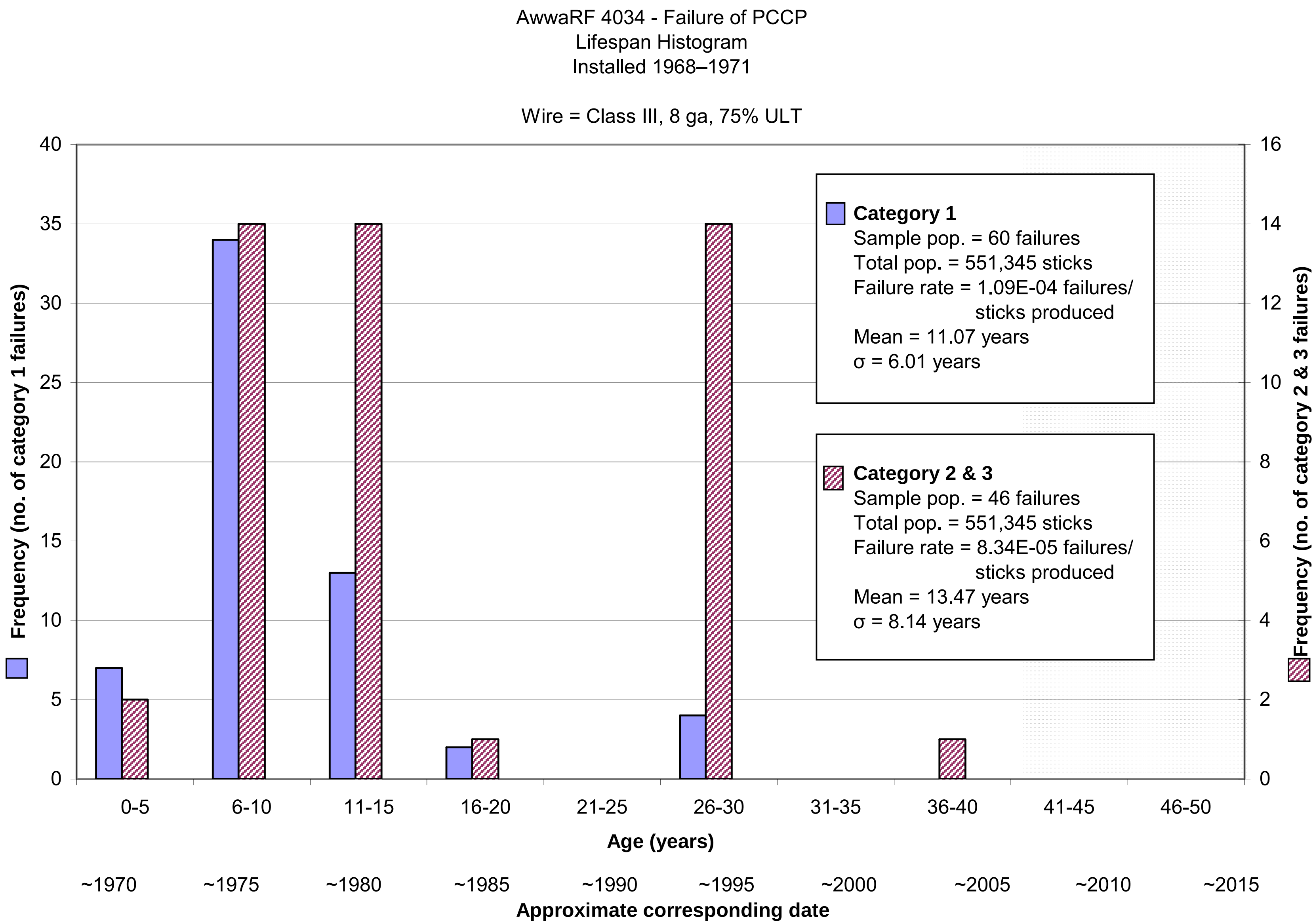

Figure 3.5 Lifespan histogram – installed 1968-1971

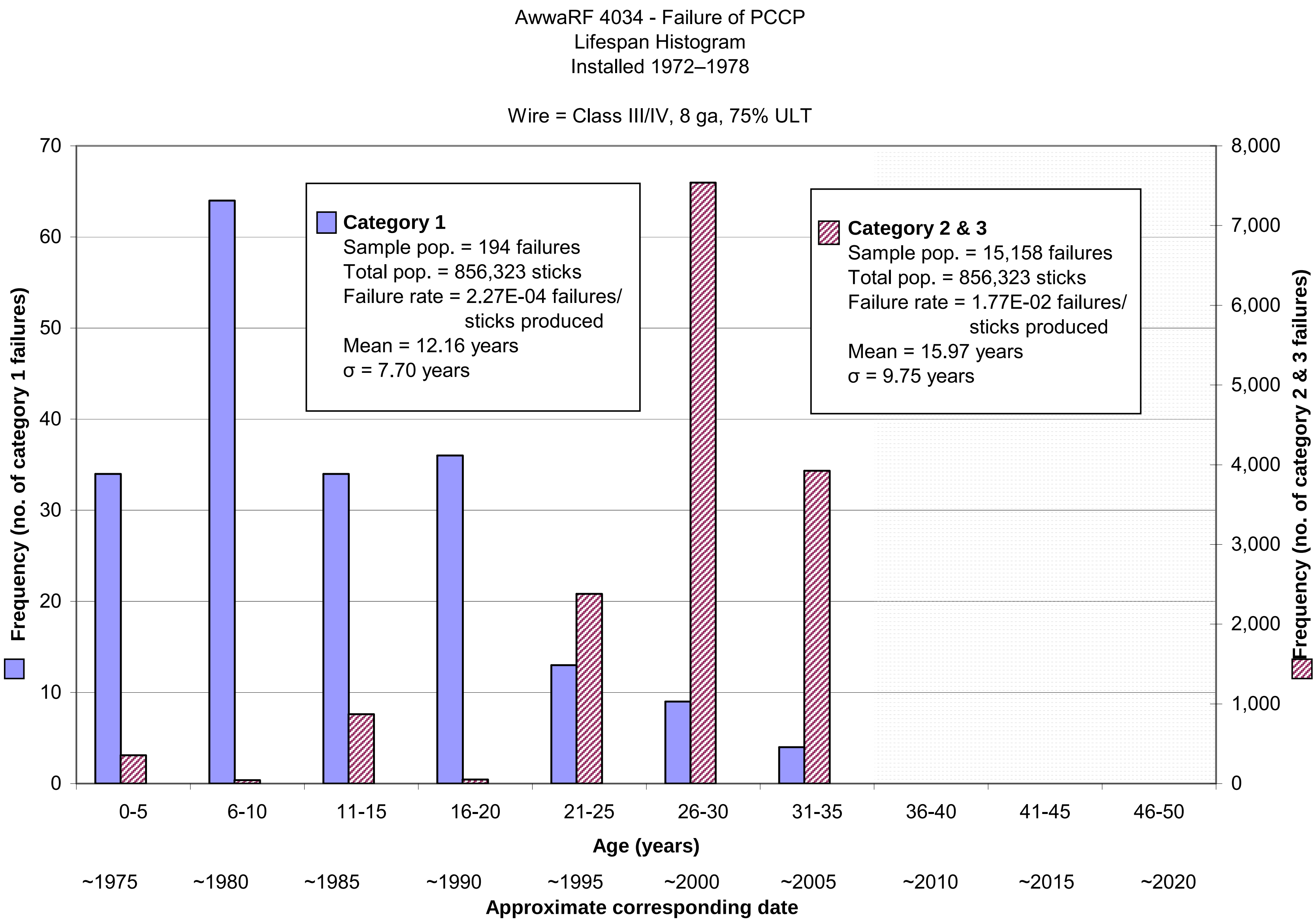

Figure 3.6 Lifespan histogram – installed 1972-1978

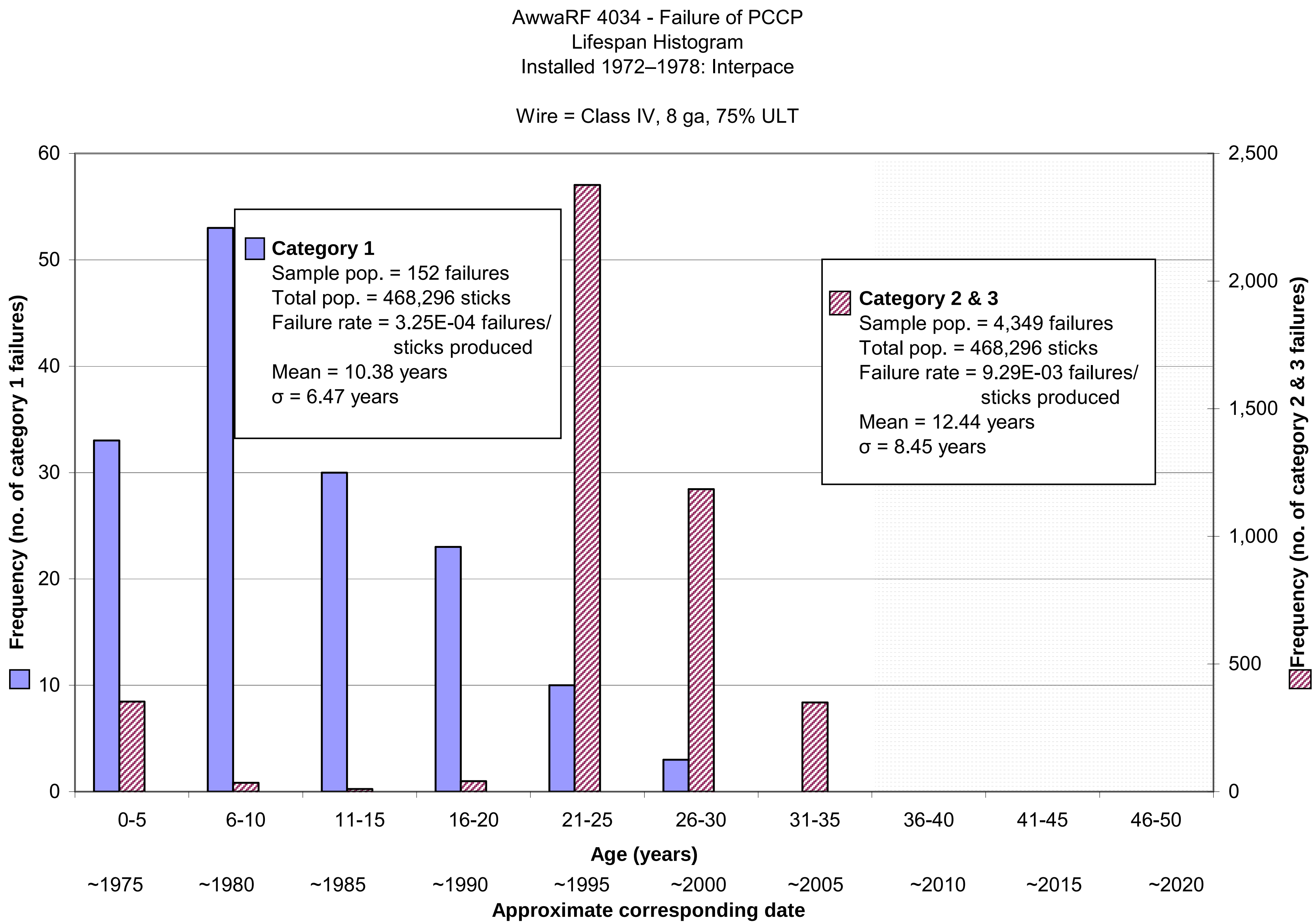

Figure 3.7 Lifespan histogram – installed 1972-1978: Interpace

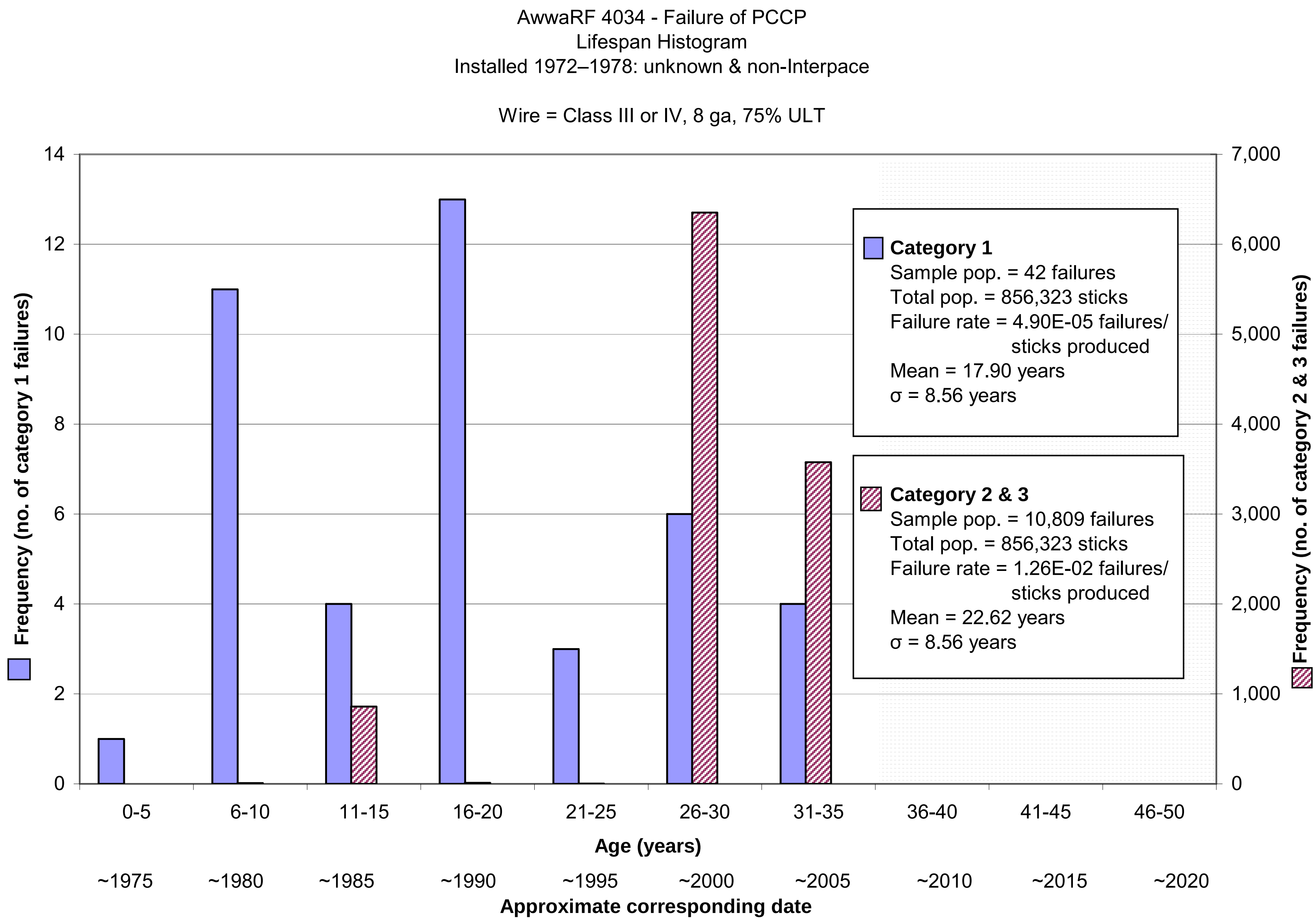

Figure 3.8 Lifespan histogram – installed 1972-1978: non-Interpace

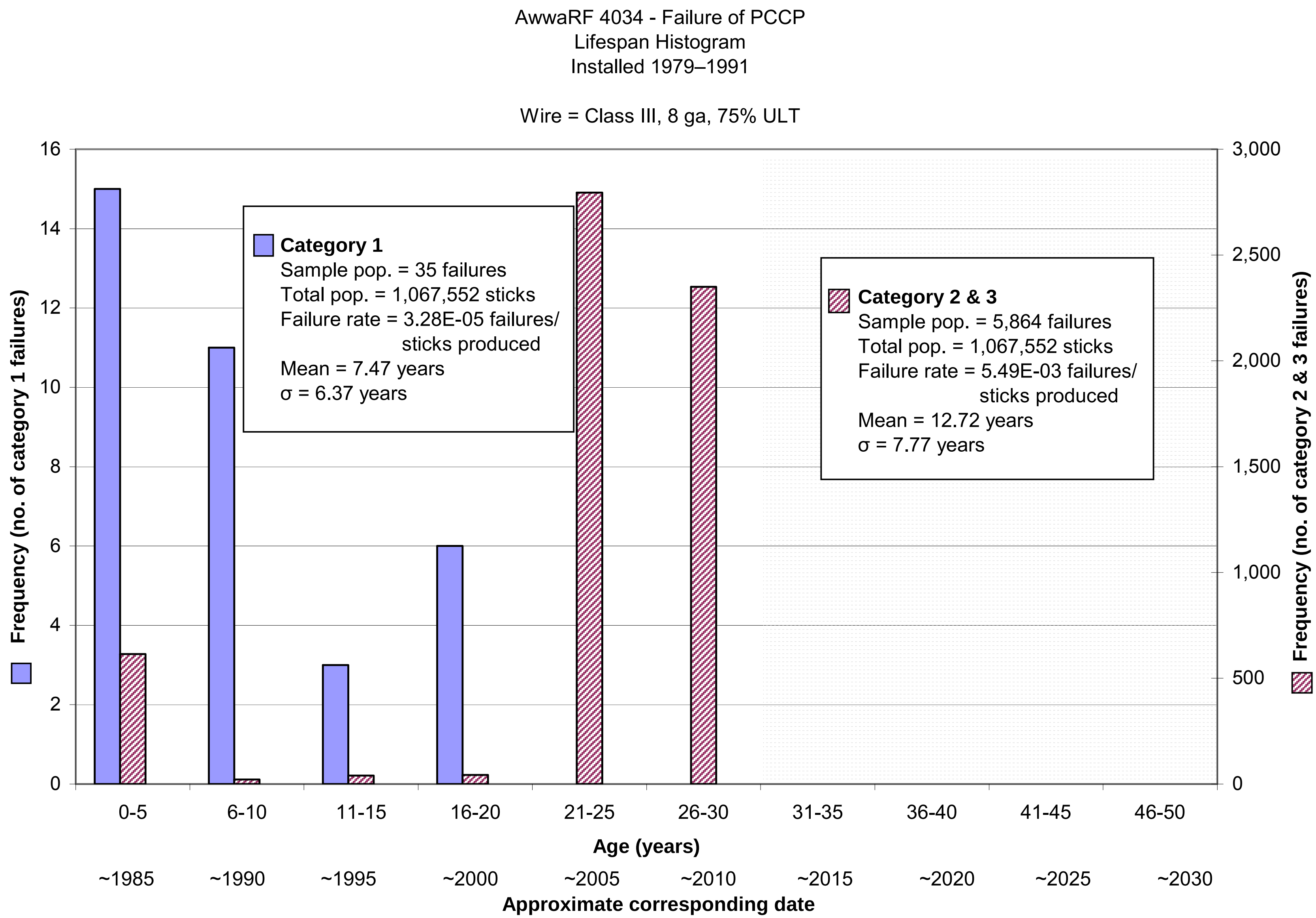

Figure 3.9 Lifespan histogram – installed 1979-1991

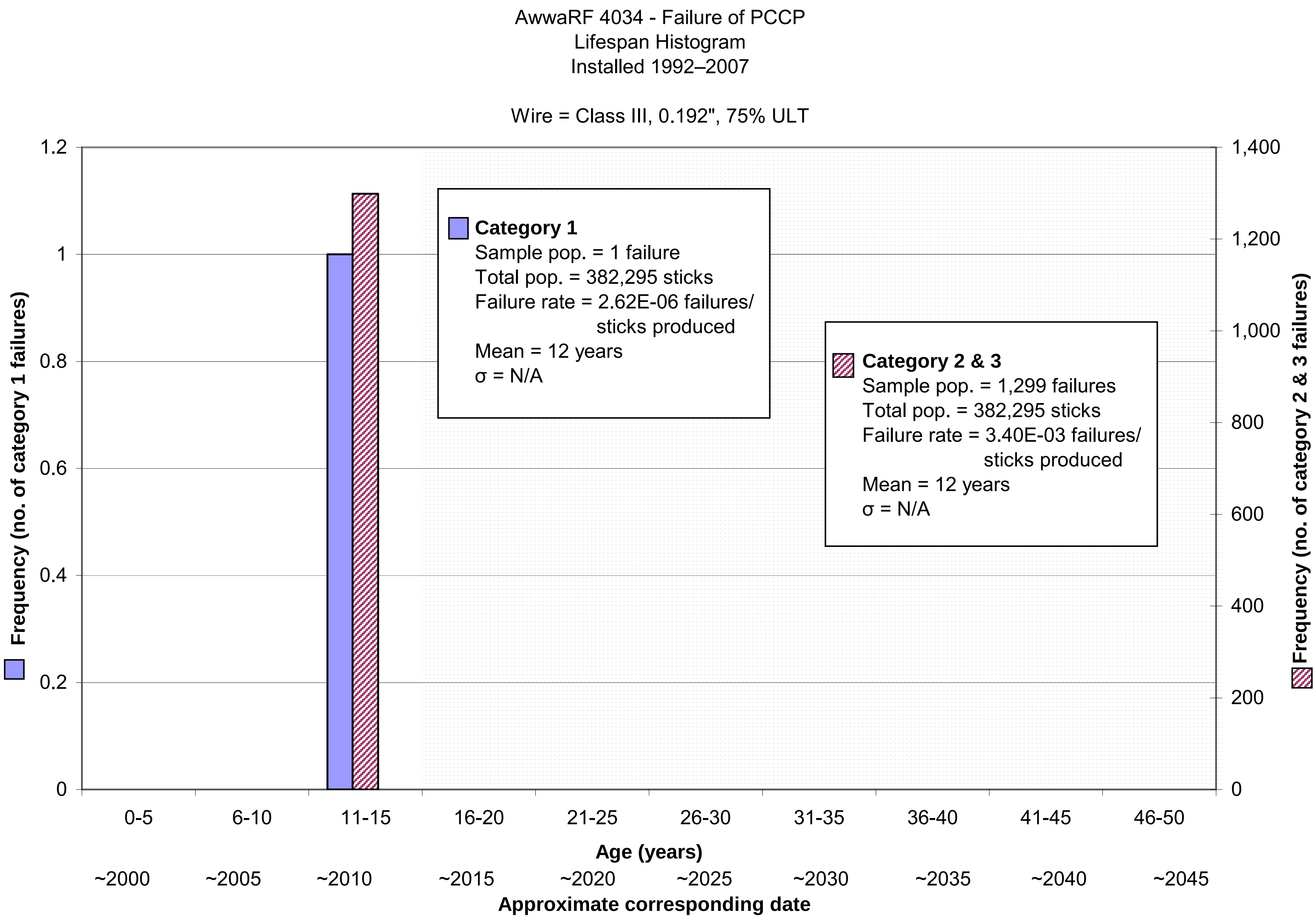

Figure 3.10 Lifespan histogram – installed 1992-2007

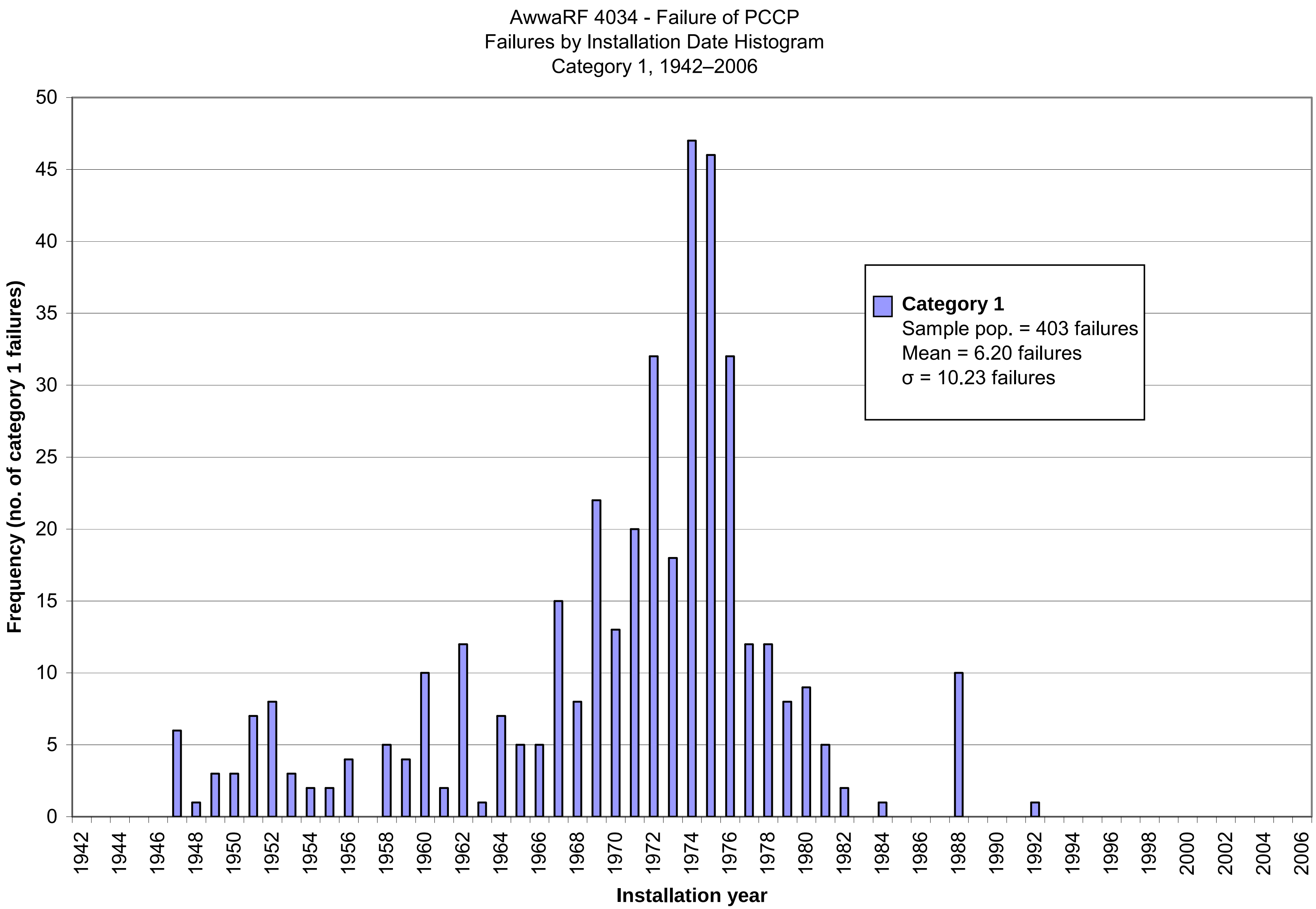

Figure 3.11 Failures by installation date histogram – Category 1, 1942-2006

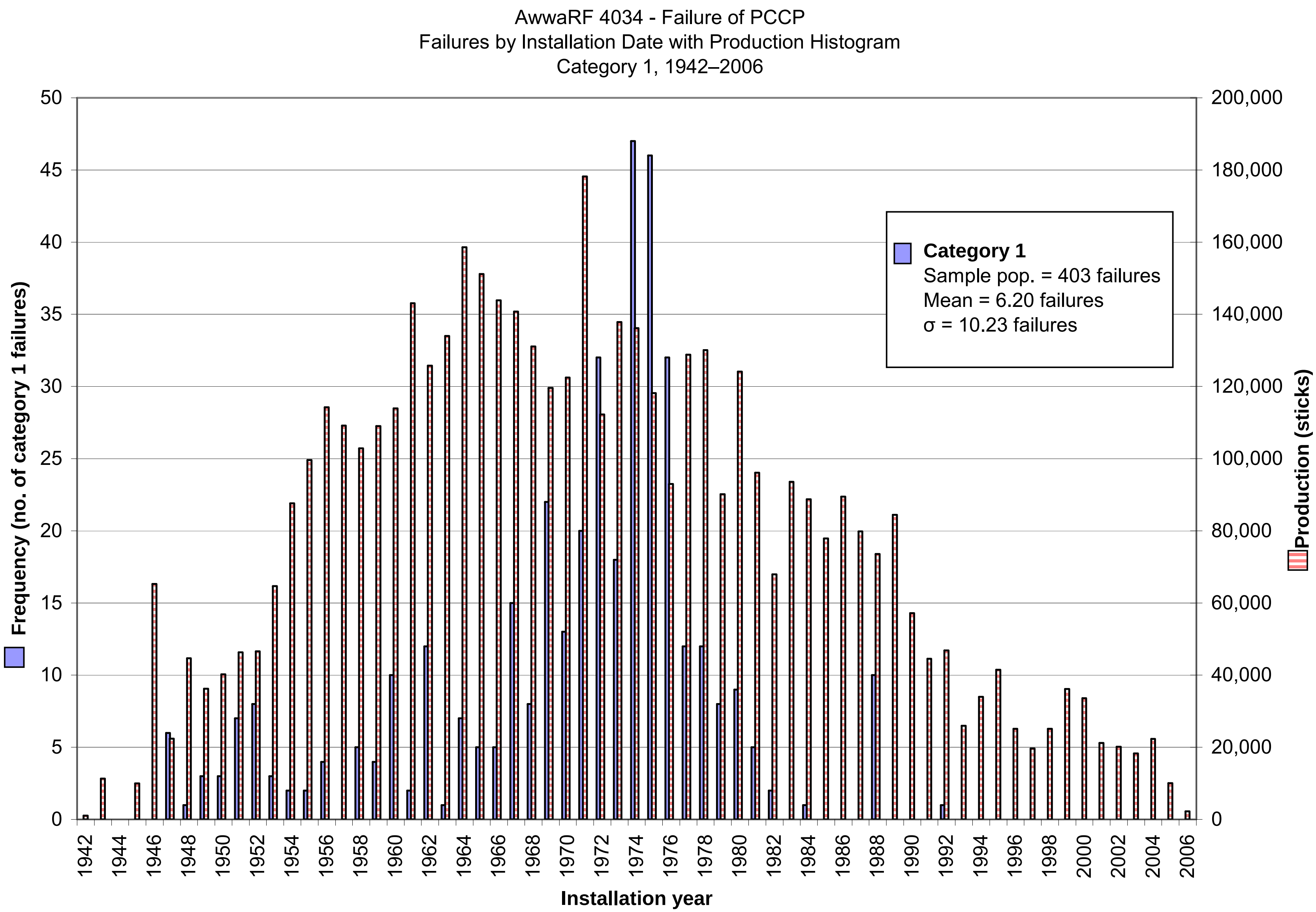

Figure 3.12 Failures by installation date with production histogram – Category 1, 1942-2006

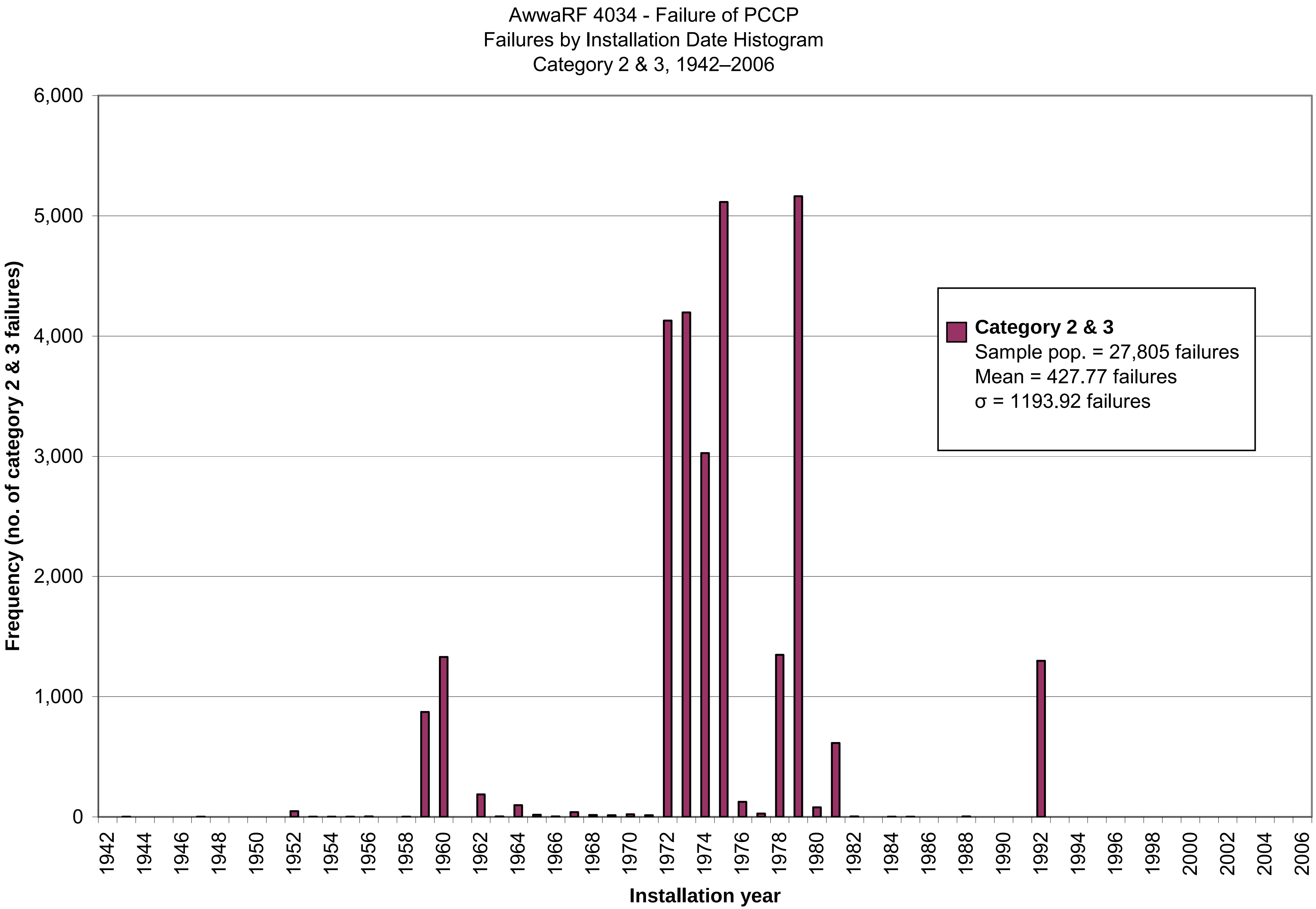

Figure 3.13 Failures by installation date histogram – Categories 2 and 3, 1942-2006

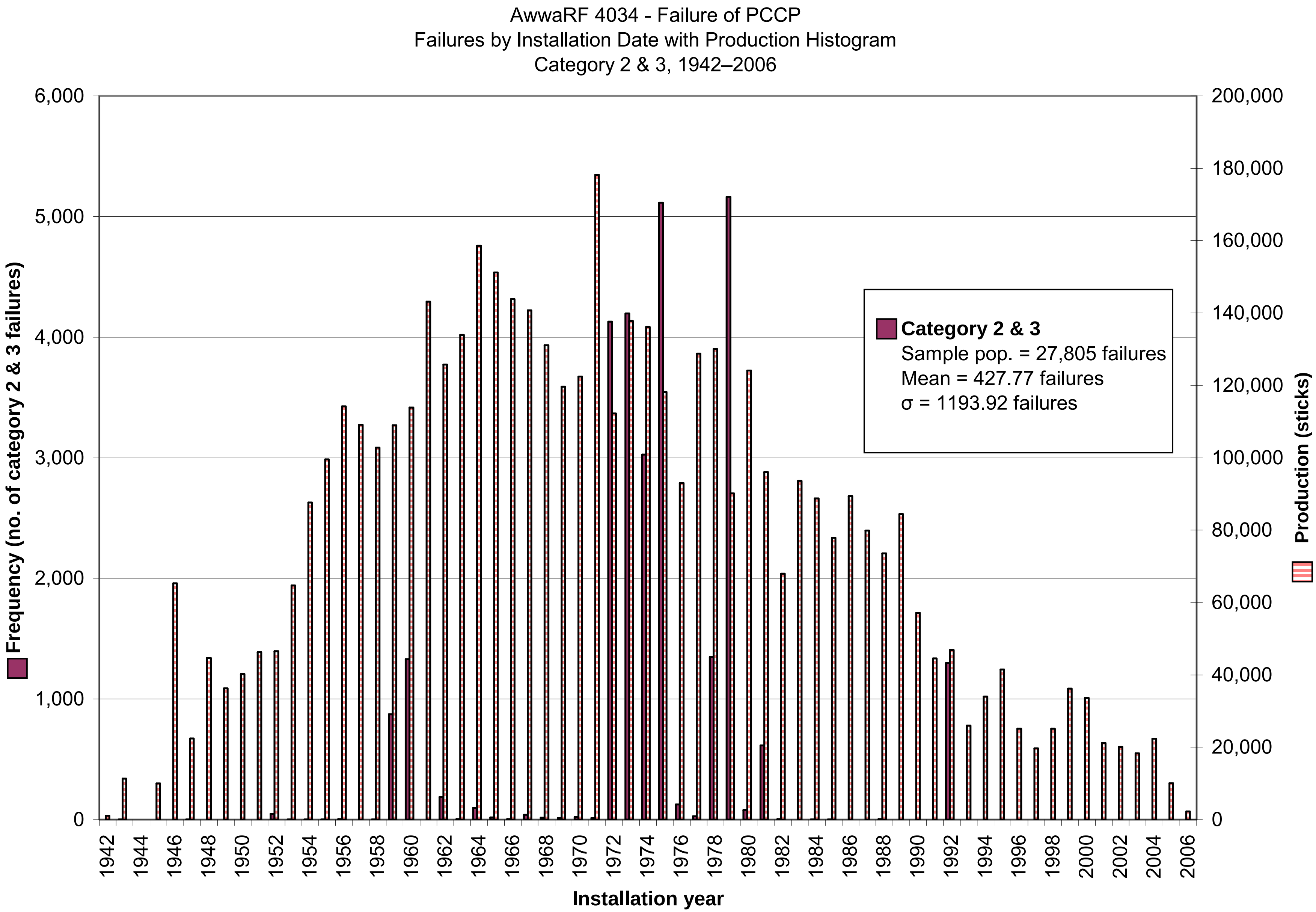

Figure 3.14 Failures by installation date with production histogram – Categories 2 and 3, 1942-2006

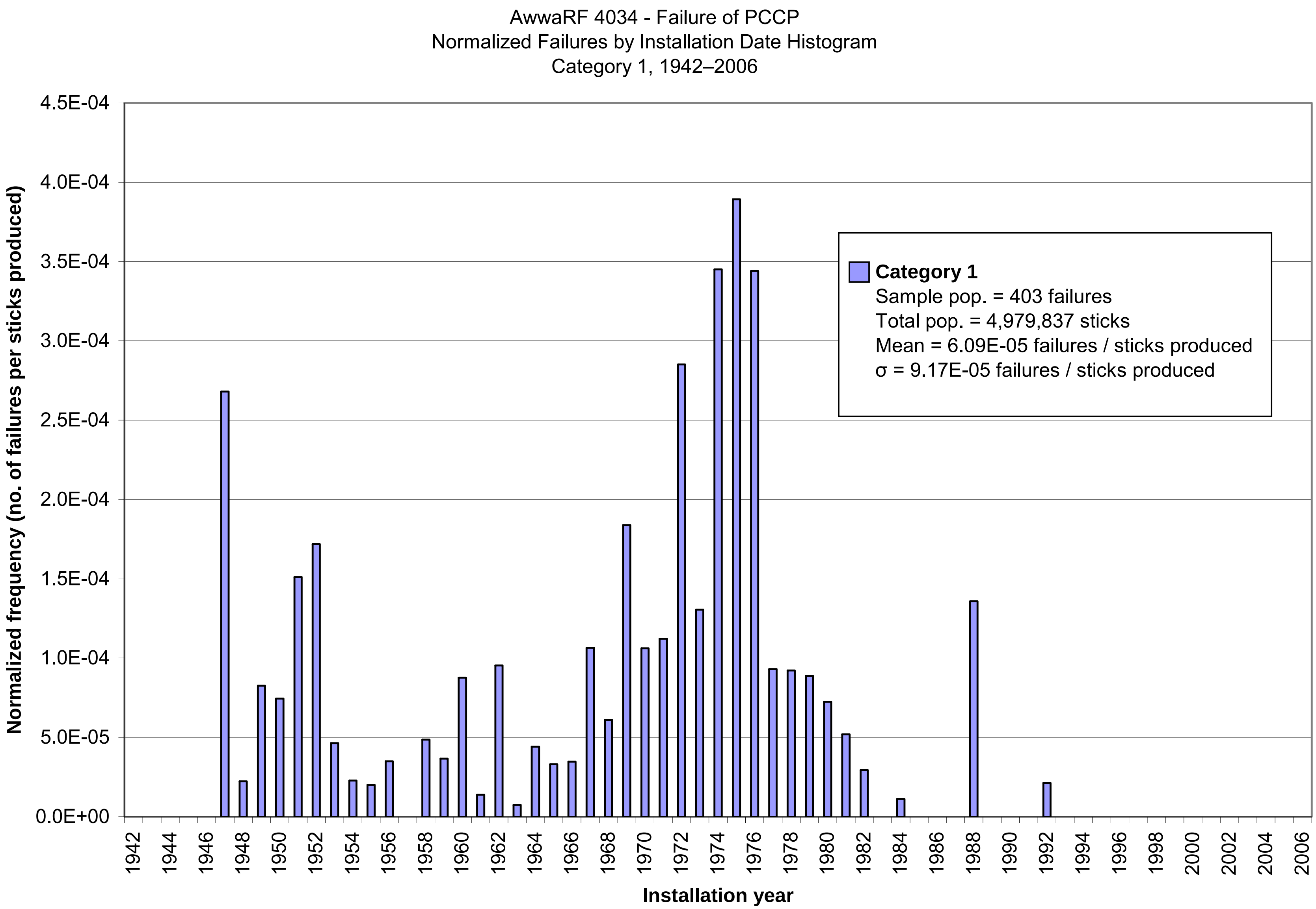

Figure 3.15 Normalized failures by installation date histogram – Category 1, 1942-2006

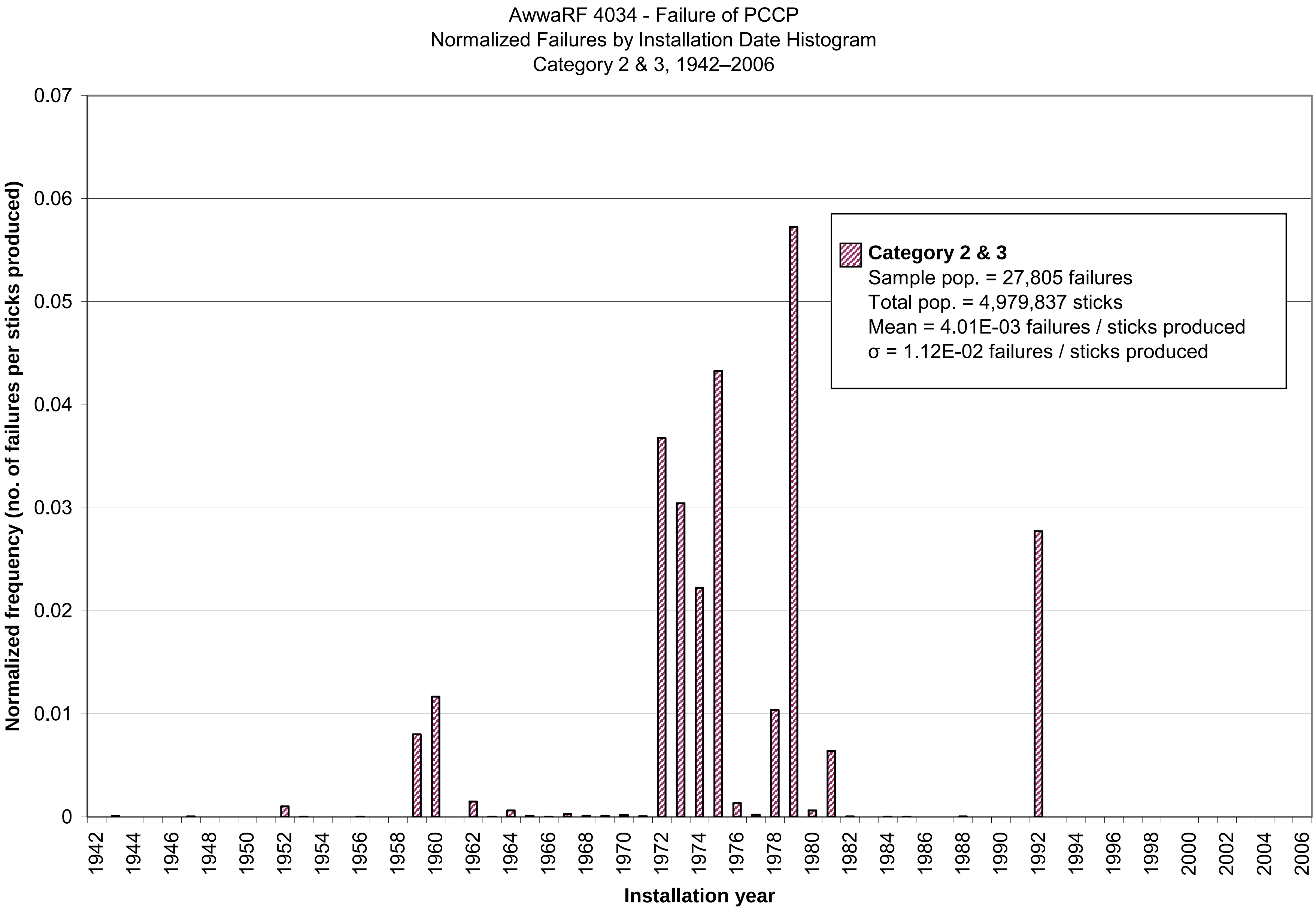

Figure 3.16 Normalized failures by installation date histogram – Categories 2 and 3, 1942-2006

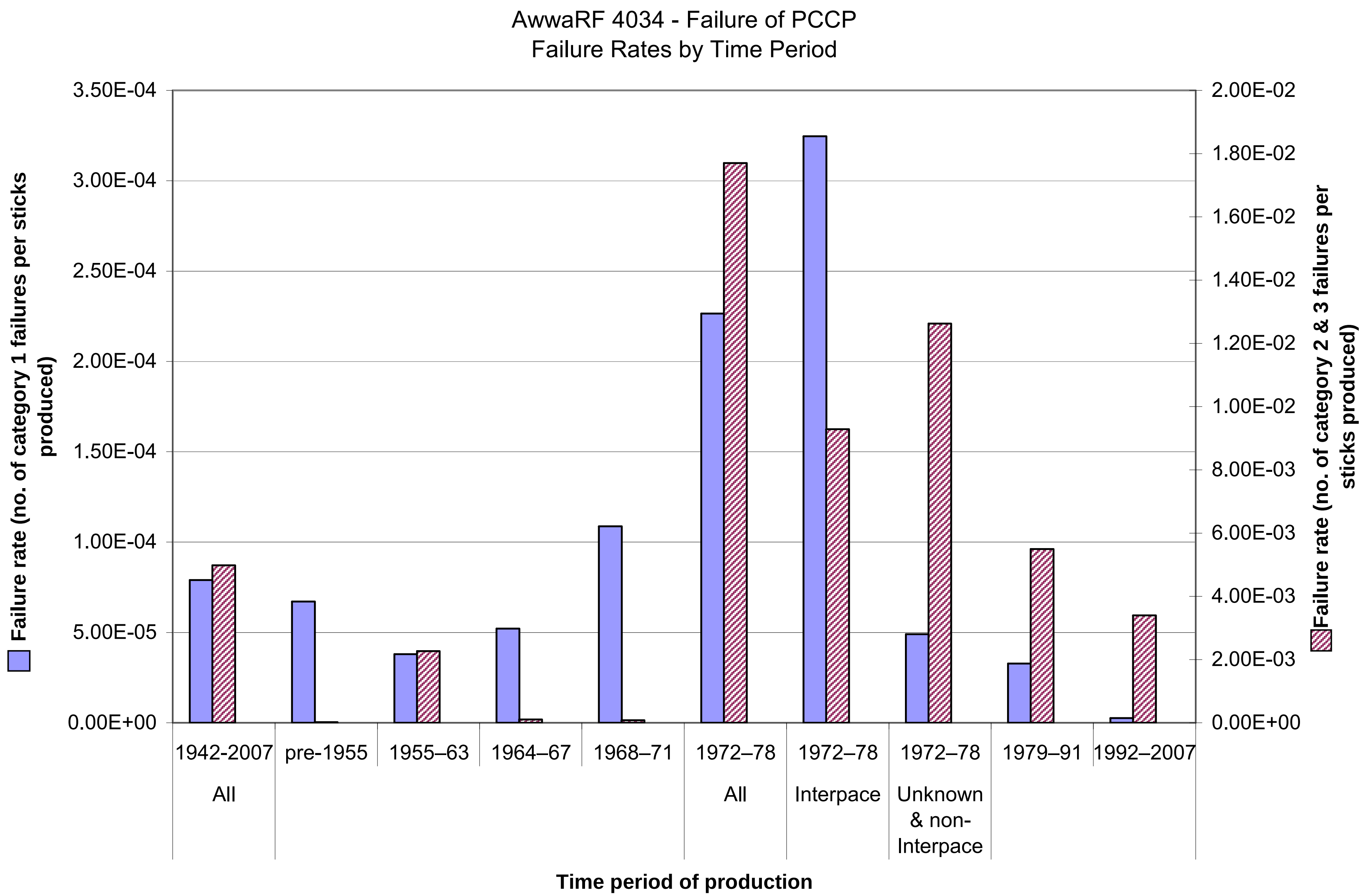

Figure 3.17 Failure rates by time period

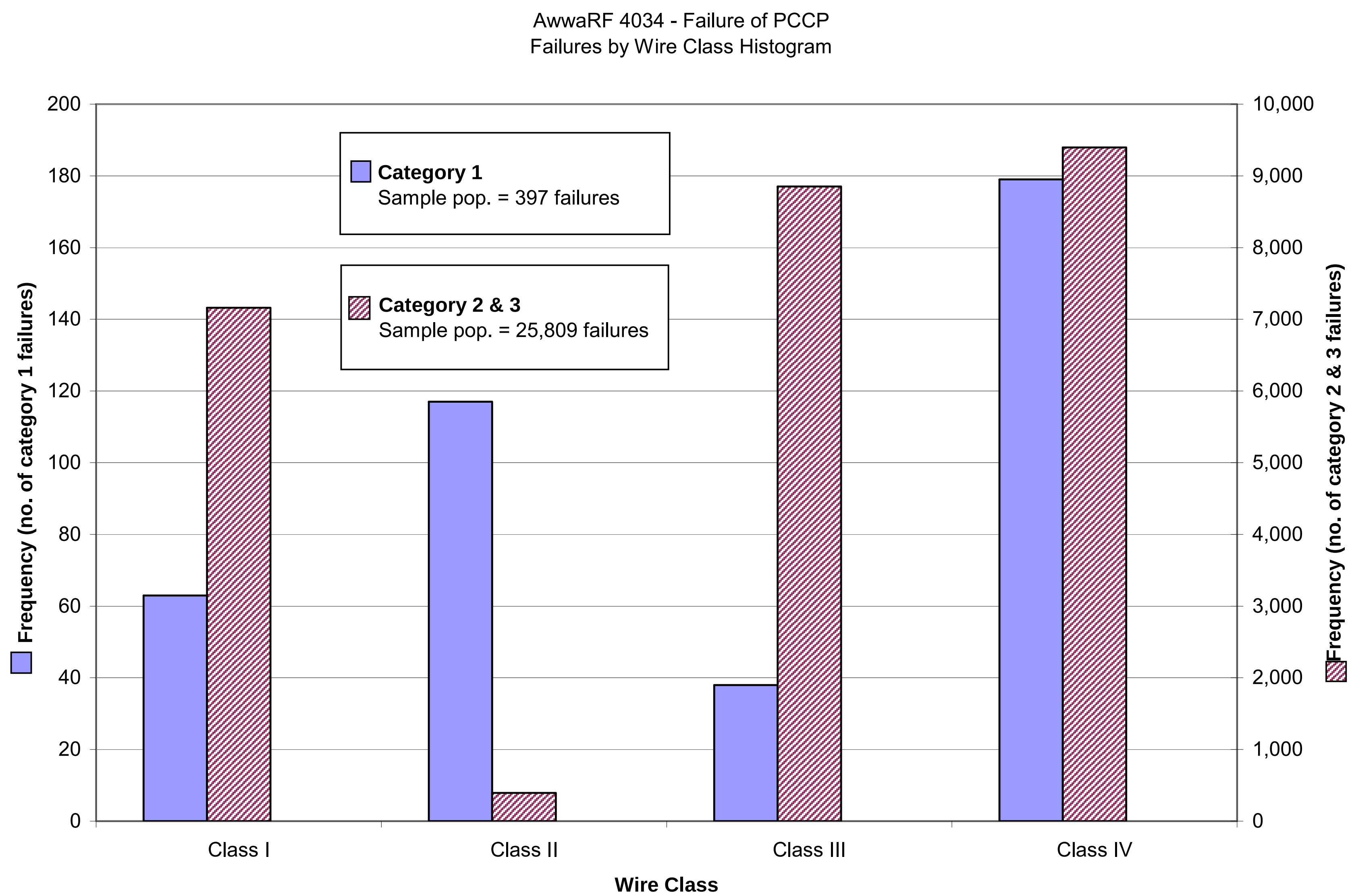

Figure 3.18 Failure by wire class histogram

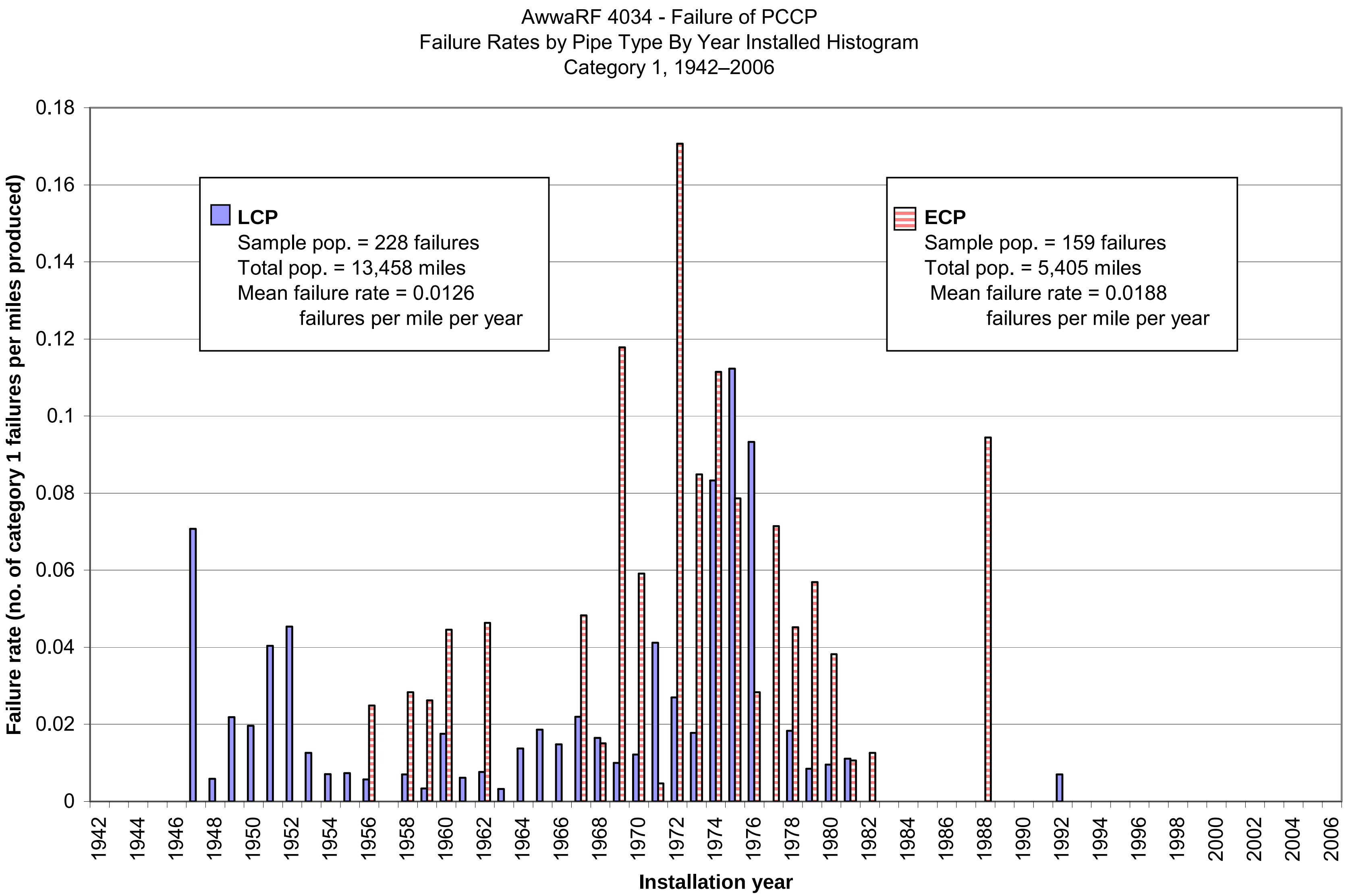

Figure 3.19 Failure rates by pipe type by year installed histogram – Category 1, 1942-2006

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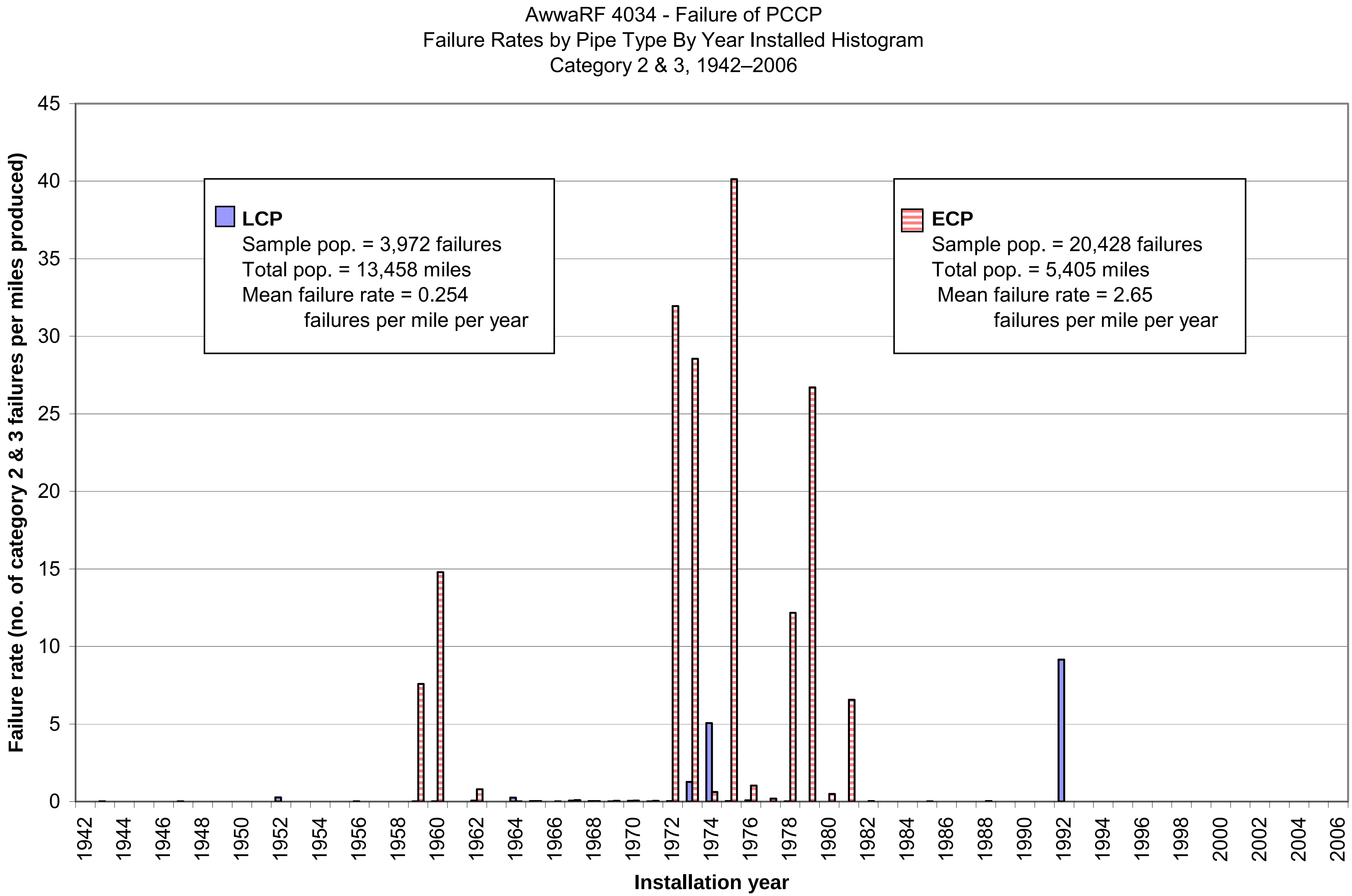

Figure 3.20 Failure rates by pipe type by year installed histogram – Categories 2 and 3, 1942-2006

CHAPTER 4
ASSESSMENT MODEL

ASSESSMENT METHODS – TYPES AND RESULTS

Risk is the combined measure of the chance of a particular asset failing (condition based) and the result of that failure. Calculation of risk for any event is based on a very simple formula:

$$\text{Risk} = \text{Likelihood (Probability of Occurrence)} \times \text{Consequence}$$

It is important to note that risk is related to not only condition of an asset but the impact of that event. The project at hand can only address the likelihood portion of the risk equation. The consequence of a failure is unique to a utility and pipeline.

Classically, risk can be quantitatively or qualitatively determined. Qualitative risk assessments require relative information and agreement on the likelihood (probability) and consequence of an event. Quantitative risk assessments require detailed information generally not available until risk management programs have been initiated using qualitative rankings. For the purposes of this study, only qualitative risk assessments of corrosion event have been considered. The creation of a risk assessment model is intended to increase operational integrity of the system and the credibility of the operator, especially when such techniques are offered for public viewing. In a concerted effort to demonstrate its dedication to public and environmental safety, while simultaneously seeking to reduce potential liabilities and regulatory requirements, the utility should investigate a number of risk management alternatives taking what measures seem appropriate for the complex and unique system it operates.

WORKSHOP WITH UTILITIES

The workshop was expected to accomplish the following:

- Introduce project participants to facilitate future discussions and participation in the project. (Relationships developed during the workshop will be extremely important, since participants will be asked to review outlines, draft products, act as general consultants to the work, and participate in testing of the concepts.)
- Refine and add to risk defining elements of PCCP design, manufacturing, installation, inspection, and operational parameters.
- Refine general risk weighting concepts for PCCP.
- Document the hurdles, and possibly the fatal flaws, that exist to development of each concept.
- Generate interest and enthusiasm for subsequent development of any tools. (Note that full development of a tool or technique may involve the investment of several million dollars, in which case an entrepreneur may ultimately need to step forward following conclusion of the AwwaRF project.)

The full-day workshop was held with participating utilities on January 31, 2007 at the Underground Technology Conference, Houston, Texas. Representatives of 15 utilities participated in the review of the project goals, definitions, and the draft utility assessment protocol. Those participating represent approximately 6 percent of the PCCP installed (by linear feet).

ASSESSMENT (EVALUATION) MATRICES

The goal of developing the PCCP assessment matrix is to allow a utility, utilizing its existing data, to define the initial priorities for allocation of scarce resources in further assessing the risk associated with its pipelines. The assessment matrix will become an initial screening tool, one that can be maintained for each PCCP pipeline or pipeline segment within the utility's system.

The basis of the matrix initially proposed during the utility workshop was related to the critical nature of five components of PCCP pipeline success and what is known about those risk components now:

- **Design** as thorough as possible within the context of the state-of-the-art at that time and either engineered by the owner or well reviewed by the owner
- **Manufacturing** by a manufacturer who is committed to making each length of pipe to the highest quality level attainable, consistent with the design
- **Inspection** by both manufacturer and owner, in the plant and during construction
- **Construction** by a contractor motivated to comply with the requirements of the construction documents
- **Maintenance and Operations** that do not place the pipeline at additional risk

The draft PCCP assessment matrix, in MS Excel™ format, is subdivided into five submatrices as described above. Included are some of the more important factors within the categories. The utility workshop resulted in significant refinement of these, as well as refinement of the weighting factors, as described below.

PCCP Data Weighting Factors

In order to keep weighting factors simple, the qualitative risk-ranking matrix proposed included only three rankings. They were intended to reflect the relative confidence in the data, without considering the severity of the consequence. In other words, the qualities that are being compared are compared on the equitable basis of knowledge. This allows the nuances of particular characteristics of PCCP to not be overshadowed by the big picture. Only after assembling the data and qualitatively assessing the sum of the confidence in the data can sound risk decisions be made. To that end, the following three ranks were proposed to allow the qualitative rating of any PCCP pipeline.

- High – Rank 1. The confidence in the data is high or the risk factor is not applicable to the PCCP pipeline being assessed.
- Medium – Rank 2. The risk factor could be present or applicable, but based on the data, it cannot be confirmed or denied.
- Low – Rank 3. The risk factor is confirmed or the utility has experience with the risk factor on the PCCP pipeline being assessed.

Please note that the intent was to score each item on the basis above, so that even a nonapplicable item still would rank 1. The intent was to establish through "truthing" of the matrix by the participating utilities, a range of total scores that could be condensed into three ranges of low, medium, and high confidence in the PCCP pipeline being assessed.

In the workshop, the participating utilities were asked what in their opinions the most important factors were related to PCCP failures experienced within their systems. Those were:

- Owner's risk factors (for material): wire class and size (No. 1), manufacturer (No. 2), slurry under wire (No. 3). Also cited were coating cast vs. sprayed, cylinder thickness, age or date of manufacture (birth), presence of electrical bonding, quality of external coating, plant vs. site manufactured pipe, and core quality.
- Inspection and installation factors: inspection and records (No. 1), contractor (No. 2), pressure class, quality of backfill, handling/transportation, joint mortaring/diapering, and electrical continuity. Also cited was the presence of physical preloading (or tension in the wire) actually present in the wire.
- Environmental/operations factors: surge (No. 1), soil (No. 2), cathodic protection/interference, fluctuating groundwater, surcharging (right-of-way) management, appurtenance maintenance, ground movement, internal corrosion of core, and underground to aboveground transition (aerials.)
- Maintenance factors: post-construction inspection and monitoring (No. 1), data analysis/study, life extension (rehab/repair), and design re-analysis.

The workshop participant's comments on the Initial Risk-Based Assessment Matrix can be summarized as follows:

- The assessment factors would be better understood written as questions.
- Each question should be written such that positive = less risk.
- Answers (and score) to be yes, no, don't know, such that lack of knowledge about a factor does not increase the risk. (After all, the assessment does not affect the risk either.)
- Possible scoring of answers: yes = 1, no = -1, don't know = 0.
- Length of pipeline needs to be factored in, assuming that as the size of the project increases, there is less effect on the learning curve of the manufacturer.

The participants stressed that in many instances, although it was clear that many factors influence the longevity of PCCP, there is limited information available for many pipelines. Poor record keeping is the norm, and reconstructing the information even when available is time-consuming. The participants requested that a two-tier approach be developed: one quickly determined assessment and another more extensive initial assessment based upon acquisition and review of available data. The intent is to be able to determine what if anything needs to be evaluated for any particular pipeline constructed of PCCP. The methodology is equally applicable to LC-PCCP and EC-PCCP.

Short-Form Assessment Matrix

The short-form assessment matrix addresses the top five factors that are both likely to be known about a PCCP pipeline and which have a significant effect on the pipeline. Scoring of answers should be: yes = 1, no = -1, don't know = 0. Thus, if a pipeline scores a negative total it may be prudent to evaluate it further.

Question 1. Was the pipeline constructed prior to 1964 or after 1992? This question relates to the higher statistical probability of PCCP constructed prior to 1964 (and the Principal Investigators have considered limiting this range to prior to 1955) and the failure of only one PCCP pipeline constructed since 1992.

Question 2. Is the pipe manufacturer still in business on the site at which the pipe was made? The intent of this pipeline may infer that pipe made by a certain company, assailed by the surviving manufacturers as the source of the troubles, may be condemned as a class. That is not so. Rather, the implication is that a manufacturer still in business on-site may have pursued a more conservative approach to manufacture and may have access to construction records necessary for any further assessment of the pipeline.

Question 3. Is the pipe constructed with 6-gauge (0.192-inch diameter) or larger wire? The highly stressed 8-gauge wire, although not solely the source of all wire breaks, but it is vulnerable. So score this -1 if the pipe was constructed with 8-gauge (0.162-inch diameter) wire.

Question 4. Was inspection done at the manufacturing site and at the time of installation by the owner or the owner's consulting engineer? There is no substitute for inspection. If there is no inspection, the likelihood of required tests being conducted or bedding placed as specified or the joints being properly mortared is speculative at best. Further, inspection records can be a great source of comfort should they be extant and confirm manufacturing and installation in conformance with the intent of the design.

Question 5. Is surge unlikely on the pipeline? Score -1 if pumped flow or other condition where surge is likely. The longevity of PCCP is significantly lessened when subject to variations in application of load. And surge pressures inadvertently applied in excess of the design curve tend to crack the coating, exposing the wires to moisture and subsequent corrosion.

Long-Form Assessment Matrix

The longer form assessment matrix addresses many of the factors that are both likely to be known (or can be discovered with examination of records) about a PCCP pipeline and which have a significant effect on the pipeline. Scoring of answers should be: yes = 1, no = -1, don't know = 0. The "zero" or "don't know" factor is intended to avoid skewing an assessment without justification. Thus, if a pipeline scores a negative total it may be prudent to evaluate it further. Factors that may indicate an appropriate **design** basis:

Question 1. Did the project specification include requirements in addition to AWWA Standard C301 or the USBR standard specification? Many designers specified factors in excess of those minimums stated in either the consensus standards or the manufacturer's suggested specifications. The assumption here is that an additional specification may have resulted in a slightly more conservative pipe design or manufacture. It should also be noted that the citation of the standards, particularly in more recent editions, requires the specification of multiple choices for items that can potentially affect the longevity of the product. A pipe order that was only "AWWA C301" was likely to be limited in those items to whatever the manufacturer chose to include.

Question 2. Did the project contract documents include minimum design requirements (wire size and spacing, etc.)? Score this -1 if the pipe manufacturer submitted the design. The assumption here is that a design by the manufacturer included no excess of conservatism.

Question 3. Was the design bedding angle less than or equal to 90 degrees? This is recognizing that the design practice using either Paris' or Olander's coefficients to assume a 90-degree bedding angle in design, but that if excess design moments and thrusts could be reduced by assuming 120 degrees then it was done. In actual practice, the shaping of bedding to achieve 90-degree bedding requires extra effort and is a requirement oftentimes ignored. A design based upon 120-degree bedding is at greater risk. Score this -1 if 120-degree bedding angle or greater was assumed.

Factors that may indicate an appropriate **manufacturing** quality:

Question 4. Is the pipe manufacturer still in business? The intent of this pipeline may infer that pipe made by a certain company, assailed by the surviving manufacturers as the source of the troubles, may be condemned as a class. That is not so. Rather, the implication is that a manufacturer still in business on-site may have pursued a more conservative approach to manufacture and may have access to construction records necessary for any further assessment of the pipeline.

Question 5. Was the pipeline constructed prior to 1964 or after 1992? This question relates to the higher statistical probability of PCCP constructed prior to 1964 (and the Principal Investigators have considered limiting this range to prior to 1955) and the failure of only one PCCP pipeline constructed since 1992.

Question 6. Was the pipe manufactured in a fixed plant? Score this -1 if the pipe was manufactured on-site. Pipe manufactured in a fixed plant is less subject to the effect of weather or a transient workforce on the quality of the product.

Question 7. Is the prestressing wire Class I or Class II? Score this -1 if Class III or Class IV. Class II and the so-called Class IV wire were stressed higher than the Class I and II wires by design.

Question 8. Is all the reinforcing wire greater than No. 6? Score this -1 if No. 8 wire was used. The highly stressed 8-gauge wire, although not solely the source of all wire breaks, is vulnerable. So score this -1 if the pipe was constructed with 8-gauge (0.162-inch diameter) wire.

Question 9. Is the steel cylinder 16 gauge or thicker? Score this -1 if 18-gauge cylinders are used. The thin cylinders were welded together with lap joints to avoid burning through by butt-welding. Those weldments create bending moments in the cylinder when the pipe is under pressure. The thin cylinders were also more difficult to weld on the spigot and bell rings without burn-through.

Question 10. Is the design wire stress ratio less than 70 percent? Score this -1 if 75 percent of ultimate strength. Wire stressed at lower ratio of the ultimate strength has more reserve capacity for vagaries in manufacturing and operational events (such as sudden valve closure surges.)

Question 11. Is the coating, cast or mortar, at least 7/8-inch thick? Thin coatings provide less resistance to chloride penetration than do thicker, denser coatings.

Question 12. Was mortar slurry placed under the prestressing wires? This was required after 1984, so if the date of manufacture is post 1984 and the pipe was specified to the 1984 or later standard, the score should be +1.

Question 13. Were bonding straps placed under wires to allow corrosion monitoring? Score this +1 if shorting cables were installed between pipe segments. Shorting straps allow the pipeline to be monitored for corrosion. It can be reasonably assumed that a pipeline owner that paid for shorting straps is motivated to monitor the pipeline.

Factors which may indicate appropriate **inspection** was done:

Question 14. Were pipe design submittals provided for review by owner? It can be reasonably assumed that a pipeline owner that did a careful review of the shop submittals got a better product manufactured.

Question 15. Was documentation of inspection and testing by manufacturer submitted to the owner for review? It can also be reasonably assumed that a pipeline owner that actually checked that required tests were done got a better product manufactured.

Question 16. Was any manufacturing inspection done by the owner or owner's engineer? There is no substitute for inspection. If there is no inspection, the likelihood of required shop tests being conducted is speculative at best. Further, inspection records can be a great source of comfort should they be extant and confirm manufacturing and installation in conformance with the intent of the design.

Question 17. Did the owner or owner's engineer do any on-site construction inspection? Again (and it needs to be repeatedly stressed), there is no substitute for inspection. If there is no inspection, the likelihood of required compaction tests being conducted or bedding placed as specified or the joints being properly mortared is speculative at best. Further, inspection records can be a great source of comfort should they be extant and confirm manufacturing and installation in conformance with the intent of the design.

Question 18. Were wire tests done in accordance with the then-current standards (i.e., mill certificates) and submitted to the owner for review? This also presumes that pipe was not supplied from manufacturer's stock.

Question 19. Did the pipe manufacturer provide on-site assistance to the installation contractor? Projects benefit from hands-on assistance from the manufacturer's instructions on-site to the installation contractor's field superintendent. So it can be assumed that projects that proceeded with installation without that assistance may have experienced difficulties resulting in damage during that installation.

Factors which may indicate that appropriate care was taken during **construction**:

Question 20. Was the pipe placed on shaped bedding? This is recognizing that the design practice using either Paris' or Olander's coefficients to assume a 90-degree bedding angle in design, but that if excess design moments and thrusts could be reduced by assuming 120 degrees then it was done. In actual practice, the shaping of bedding to achieve 90-degree bedding requires extra effort and is a requirement oftentimes ignored. A design based upon 120-degree bedding is at greater risk. Score this -1 if 120-degree bedding angle or greater was assumed.

Question 21. Was imported material utilized for bedding? Score this -1 if native soils were used for bedding. If native soils are clean sand then this can be scored +1.

Question 22. Was the hydrostatic test passed on the first attempt? A failure during hydrostatic testing may otherwise be indicative of rolled gaskets. Other failures during hydrostatic testing have resulted due to misplaced pipe. That may indicate that other pipe were misplaced and are operating at higher stress levels than intended.

Question 23. Was the hydrostatic test pressure no more than 20 percent over the design operating pressure? AWWA Manual M-9 indicates a maximum 120 percent increase over the design working pressure for the field hydrotest. In no case should the pipe at any point be hydrotested in excess of the upper bound of the combined stress design curve of Appendix A or B in AWWA C301. Unfortunately, the standard of practice in the waterworks industry is to test distribution pipelines at 150 percent of the working stress. That practice applied to PCCP pipelines results in permanently cracked coating.

Question 24. Were joint bonds installed and tested? Shorting straps installed in the pipe (see Question 12) are useless if the bond straps between pipes were not installed and tested.

Question 25. (If yes to the above question, otherwise score this 0) Is the pipeline electrically isolated from other pipelines? This is to check if inadvertent cathodic protection (stray current) is being applied to the pipe. If so, it should be scored –1 because of the potentially detrimental effect on the prestressing wires. Further investigation in the field may be warranted if the score is –1.

Question 26. Were joints welded for thrust restraint? Score this -1 if bolted joint restraints, which allow slight movement, were used. That movement would tend to open up circumferential cracks in the mortar coating and lining at the joints, leading to exposed steel to water.

Question 27. Were joints mortared inside and out? Inspection records may be necessary to make this determination, on a pipe-by-pipe basis.

Factors that may indicate appropriate **operation** and **maintenance**:

Question 28. Is surge unlikely on the pipeline? Score this -1 if pumped flow or other condition where surge is likely or control valves exist on the pipeline which could be accidentally closed, recognizing that the longevity of PCCP is significantly lessened when subject to variations in application of load. And surge pressures inadvertently applied in excess of the design curve tend to crack the coating, exposing the wires to moisture and subsequent corrosion.

Question 29. Is the earth fill over the pipeline substantially unchanged from when it was constructed? Additional fill placed over a PCCP pipeline when not addressed in design (such as a highway constructed on top of the alignment) may result in detrimental cracking of the mortar coating or concrete core. An alignment evaluation may be necessary to accurately score this item.

Question 30. Is the pipeline subject to regular corrosion monitoring? It is assumed that a pipeline that is monitored is likely to be in better condition than one that is not.

Question 31. If cathodic protection is applied, is the voltage applied < 850 mv? Score this -1 if > 1,000 mv and score it 0 if between these values or no cathodic protection has been applied to the pipeline. Tests done in a laboratory setting have demonstrated that cathodic protection applied below these limits if not exceeded are unlikely to cause hydrogen embrittlement of the prestressing wire.

Other Factors which may indicate **condition**:

Question 32. The pipeline has experienced neither a leak nor a break. Score this -1 if it has leaked, etc., thus assessing the known failures appropriately as failures.

Question 33. If an internal inspection has been done (of any type) there is little or no indication of damage/cracks/spalls/broken wires. Score this -1 if damage/cracks/spalls/broken wires are indicated. No attempt here is made to assess the quality of the other assessment data or conclusions, merely that if any indication of damage or defect are indicated. The evaluation of those data are beyond the limits of this assessment.

Question 34. If soil corrosivity tests were performed, were all laboratory saturated soil resistivities greater than 1,000 ohm-cm or field resistivities greater than 1,500 ohm-cm found at pipe depth? If no soil corrosivity tests were performed, score this zero. It is generally understood that PCCP in soil environments less resistive than these limits are at greater risk of corrosion.

Question 35. If soil chemistry tests were performed, were all chloride levels less than 350 ppm (mg/kg)? If no soil chemistry tests were performed, score this zero. It is generally understood that PCCP in soil environments more "salty" than this limit are at greater risk of corrosion.

Question 36. If soil chemistry tests were performed, were pH values greater than 5.5? Again, if no soil chemistry tests were performed, score this zero. Acidic soils with pH less than 5.5 will attack the mortar or concrete coating used to protect the prestressing wire.

Question 37. If close interval pipe-to-soil potentials have been measured, are any areas greater than 50 feet in length more negative than -300 millivolts to copper-copper sulfate? If no soil corrosivity tests were performed, score this zero. This test can discern limited lengths of pipe at risk to corrosion due to changes in the electropotential differences in the soils environment.

Question 38. Groundwater levels are stable. Score this -1 if any portion of the pipeline is in an area of fluctuating groundwater levels. The fluctuating groundwater leads to wetting-drying cycles that can lead to corrosion of the wires.

Repeating the instructions to the initial assessment process, scoring of answers should be: yes = 1(positive one), no = -1 (negative one), don't know = 0 (zero, or no score). Thus, if a pipeline scores a negative total, it may be prudent to evaluate it further.

VALIDATION OF ASSESSMENT MATRICES

The final assessment forms were utilized by participating utilities to evaluate 22 pipelines. Of those 22, nine short forms were also completed, allowing comparison. Short forms total scores ranged from -5 to 0 for pipelines that had experienced a failure. Long forms total scores ranged from -9 to +24 for pipelines that had experienced a failure. It is clear then that for use of the short form, any net score less than +1 should be a candidate for further evaluation.

Examining the scores of the long-form assessments it became clear that those that scored below zero had multiple problems. What was most curious about those that had high scores and still experienced failures was that the common thread was excessive surge pressures. Examination of the contract documents of those also revealed little evidence of design consideration for the surge or the hydrostatic test as design conditions. Those two items are red flags waving. Clearly, a PCCP pipeline can have one or two negatives against it and fail, for the weight of the positives may not override the weaknesses in the system.

The checklists are thus not intended to be a definitive failure predictor, rather part of a multiphased approach. The intent is to provide a tool to the PCCP-owning utility to do a preliminary self-assessment of its pipelines (using the short form) followed, if indicated, by a more refined self-assessment. It was not uncommon for utilities to include with their assessments comments similar to “One thing this showed us is that we don't have nearly as much info as we should.” Carefully completed, it is intended that the assessment checklists, both long and short form, will be useful as pipe inspection and maintenance prioritization tools and possible input to risk assessment of PCCP pipelines.

CHAPTER 5
PREDICTING SERVICE LIFE

OGIVES AND FAILURE FORECASTING

The previous histograms and simple statistical analyses examined PCCP failures that had already occurred. The next progression is to utilize these failure data in order to forecast likely future occurrences.

One way to do this is by cumulative frequency distributions, usually expressed graphically in a line graph called an ogive (pronounced ō'jīv'). Histograms visualize the existing data. Ogive uses historical data to make predictions based only on what failed (no credit given for the population that is still in service). The ogive plots cumulative frequency versus the upper boundary of a class. The main use of an ogive is to calculate percentiles, or estimates, of the proportion of data that falls above and below a certain value. Here, the ogive is used to plot the cumulative frequency of PCCP failures as a function of age. This allows the determination of the 25^{th}, 50^{th}, and 75^{th} percentiles (also called the 1^{st}, 2^{nd}, and 3^{rd} quartiles or even the lower quartile, median, and upper quartile). These values represent the number of years it took for 25, 50, and 75 percent of the pipe failures to occur. The value is obtained by linear interpolation between upper class boundaries.

On the first ogive (Figure 5.1), the left y-axis, or ordinate, is the cumulative frequency of all Category 1 failures and is represented by blue lines with blue diamonds. The right ordinate is the cumulative frequency of all Categories 2 and 3 failures, illustrated by pink lines and boxes. Age is incremented in five-year intervals along the x-axis, or abscissa. The distribution of both datasets is S-shaped, indicative of normally distributed data. It can be seen that the slope of both curves drastically decreases after 35 years. This equates with a reduction of failure frequency after this time period. Now turning attention to forecasting, after 6.7 years of pipe age, 25 percent of the Category 1 failures had occurred. After 11.5 years, half of the Category 1 failures had occurred. After 18.8 years, 75 percent of the Category 1 failures had occurred. Categories 2 and 3 failures, with a 10– to 15-year delayed response from the Category 1 failures, took 22.1 years, 26.3 years, and 29.4 years for 25 percent, 50 percent, and 75 percent of the Categories 2 and 3 failures to occur, respectively. Red leader lines depict where each of these values lie in relation to the cumulative frequency for their respective dataset.

The next ogive, Figure 5.2, illustrates the cumulative frequency of Category 1 and Categories 2 and 3 failures occurring in pipes installed before 1955. The left ordinate is the cumulative frequency of Category 1 failures and is represented by blue lines with blue diamonds. The right ordinate is the cumulative frequency of Categories 2 and 3 failures, illustrated by pink lines and boxes. Age is again incremented in five-year intervals along the abscissa. The distribution of both datasets is S-shaped, indicative of normally distributed data. It can again be seen that the slope of both curves drastically decreases after 35 years, or approximately the year 1983. This equates with a reduction of failure frequency after this time period. Looking at forecasting, it was found that it took 19.0 years, 23.5 years, and 28.6 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. As for Categories 2 and 3 failures, it took 21.3 years, 23.3 years, and 26.3 years for 25 percent, 50 percent, and

75 percent of the Categories 2 and 3 failures to occur, respectively. This represents less than a two-year gap between Category 1 and Categories 2 and 3 failures. At the 25-year mark, Categories 2 and 3 failures even lead the Category 1 failures. This is indicative that the Categories 2 and 3 failures in this timeframe were more independent failures then reactions to Category 1 failures.

The next ogive, as found in Figure 5.3, depicts the cumulative frequency of Category 1 and Categories 2 and 3 failures for pipelines installed between 1955 and 1963. The axes are as described above. Both curves have changes in slope occurring at 40 years, indicative of deviations from normal distribution. The constant zero-value of Categories 2 and 3 failures for the first 20 years, followed by a large change in slope further indicates a non-normal distribution. It was found that it took 18.0 years, 23.6 years, and 40.6 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. The 25th and 50th percentiles for this era were nearly identical that of previous timeframe, however, the 75th percentile for this era occurred 12 years later than the last eras. This indicates that failures were occurring over a longer stretch of time in this timeframe. As for Categories 2 and 3 failures, it took 22.2 years, 24.5 years, and 41.5 years for 25 percent, 50 percent, and 75 percent of the Categories 2 and 3 failures to occur, respectively. Again for the Categories 2 and 3 failures, the 25th and 50th percentiles for this era were similar to the last eras. Here again also, the 75th percentile occurs after a longer time lapse, in this case over 15 years than the previous timeframe.

Figure 5.4, the next ogive, illustrates the cumulative frequency of failures occurring in pipe installed in 1964–67. Present time is being approached in this graph; the grayed out area between 45 and 50 years represents future time. A change in slope in the Category 1 failure curve at 10 years and in the Categories 2 and 3 failure curve at 30 years are indicative of deviation from normal distribution. It was found that it took 10.9 years, 12.9 years, and 14.8 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. This represents a decrease of 7.1 years, 10.7 years, and 25.8 years for the corresponding percentiles of the last timeframe. For Categories 2 and 3 failures, it was found that it took 11.6 years, 17.7 years, and 30.1 years for 25 percent, 50 percent, and 75 percent of the failures to occur, respectively. These correspond with a decrease of 10.6 years and 6.8 years for the 25th and 50th percentile of the last eras, and an increase of 15.2 years for the 75th percentile. This indicates that more failures occurred in a shorter amount of time in the beginning, but later failures occurred over a longer stretch of time when compared to those pipes installed in the previous era.

Figure 5.5, the lifespan ogive for pipe installed between 1968 and 1971, represents the cumulative frequency of failures for this era. Present time is again being approached in this graph; the grayed out area between 40 and 50 years represents future time. The Category 1 failure curve is relatively S-shaped, indicative of normally distributed data. The Categories 2 and 3 failure curve has a change in slope at 25 years and a constant slope between 5 and 15 years, both indicators of a non-normal distribution. Turning to the forecast, it took 6.2 years, 8.4 years, and 11.5 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. This represents a decrease of 3–5 years for the corresponding percentiles of the last timeframe. For Categories 2 and 3 failures, it was found that it took 8.4 years, 12.5 years, and 26.3 years for 25 percent, 50 percent, and 75 percent of the failures to occur, respectively. These also correspond with a decrease of 3–5 years for the 25th, 50th, and 75th percentiles of the last era.

The next ogive, depicted as Figure 5.6, show the cumulative frequency of all failures for pipelines installed in 1972–78. Both the Category 1 and Categories 2 and 3 failure curves are relatively S-shaped, indicative of normally distributed data. The Categories 2 and 3 failure curve is more elongated in the 25–35 timeframe. Turning to the forecast, it took 6.1 years, 9.9 years, and 16.9 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. This represents an increase of 0–5 years for the corresponding percentiles of the last timeframe, reversing the trend of the last three eras. For Categories 2 and 3 failures, it was found that 25.1 years, 27.6 years, and 30.2 years passed for 25 percent, 50 percent, and 75 percent of the failures to occur, respectively. These values correspond with an increase of 16.7 years, 15.1 years, and 3.9 years respectively for the 25^{th}, 50^{th}, and 75^{th} percentile of the last era, again a reversal of the trend observed over the last three eras.

The next two figures, Figure 5.7 and 5.8, illustrate the breakdown of cumulative failures in the 1972–78 era between Interpace Corporation pipe, and unknown/non-Interpace Corporation pipe. As far as sample populations, there was nearly a fourfold increase of Interpace-related failures versus unknown/non-Interpace failures in this timeframe. Both the Interpace and unknown/non-Interpace Category 1 failures followed an S-curve shape, indicating normally distributed data.

The Categories 2 and 3 failures described in Figures 5.7 and 5.8 for both Interpace and unknown/non-Interpace had changes in slope that point toward behavior of non-normally distributed data. Examining the forecast, it was found that it took 5.5 years, 9.1 years, and 14.7 years for Interpace pipe and 9.3 years, 16.9 years, and 24.2 years for unknown/non-Interpace pipe for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. This represents a 4- to 10-year difference between the Interpace and unknown/other manufactured pipe. For Categories 2 and 3 failures, it was found that it took 21.4 years, 23.7 years, and 26.9 years for Interpace pipe and 26.4 years, 28.6 years, and 31.2 years for unknown/non-Interpace pipe for 25 percent, 50 percent, and 75 percent of the failures to occur, respectively. These represent a five-year difference between the Interpace and other manufactured pipe. In every percentile, Interpace pipe failed sooner than its unknown/non-Interpace counterpart. A distinct increase in both Interpace and unknown/non-Interpace Categories 2 and 3 pipe failures occurred in the 20- to 25-year range.

The following ogive, Figure 5.9, represents the cumulative Category 1 and Categories 2 and 3 failures for the 1979–91 data partition. The distributions of both datasets are irregular, indicative of non-normally distributed data. For Category 1 failures, the large constant curve indicates a J-shaped distribution. For the Categories 2 and 3 failure curve, the change in slope at 20 years followed by large constant line indicates a skewed J-shaped curve. As far as forecasting, it took 2.9 years, 6.1 years, and 10.4 years for 25 percent, 50 percent, and 75 percent of the Category 1 failures to occur, respectively. This is decrease of 3–6 years from the all-samples population of the last era. For Categories 2 and 3 failures, it took 21.3 years, 24.0 years, and 26.9 years for 25 percent, 50 percent, and 75 percent of the Categories 2 and 3 failures to occur, respectively. This represents a 3–4 year decrease from the corresponding percentiles from the last era and a 16–18 year difference between Category 1 and Categories 2 and 3 failures during this era.

Figure 5.10 illustrates the cumulative frequency of failures for pipe installed between 1992 and 2007. Similar to the lifespan histogram for this era, this ogive is provided for completeness—statistically, not enough failures have occurred to accurately forecast failures.

Both Category 1 and Categories 2 and 3 failure curves are irregularly shaped. As far as the forecast, it took 11.3 years, 12.5 years, and 13.8 years for 25 percent, 50 percent, and 75 percent for both the Category 1 and Categories 2 and 3 failures to occur. It should be stressed that these values were obtained by interpolating over a single failure entry a pipeline that experienced a Category 1 failure and was subsequently relined, and any inference of the results may be quite erroneous.

Table 5.1 summarizes in tabular form all the data presented here.

WEIBULL ANALYSIS AND FAILURE PREDICTION

Initially, histograms and simple statistical analyses were used to examine failures that had already occurred. Next, ogives were prepared that utilized these statistical data in order to forecast likely future occurrences of failures based on trends and percentiles. The last step is to incorporate unfailed pipe in order to predict future failure rates.

One way to do this is by Weibull (commonly pronounced 'wI'bul) probability distribution, usually expressed graphically as unreliability, or probability of failure, versus time on a log-log graph—a graph with logarithmic scales on both axes. Weibull gives credit for population still in service and allows prediction of failure probability as a function of age. In order to adequately model the failure data, the three-parameter Weibull probability density function was employed:

$$f(\mathrm{T}) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

where:

$f(\mathrm{T})$ = Weibull probability density function at time T
β (Beta) = shape parameter or slope (dimensionless)
η (Eta) = scale parameter (units of T)
γ (Gamma) = location parameter (units of T)

In order to determine how well each function fit the data, a correlation coefficient (ρ, rho) was used. For the three-parameter Weibull density function, a nonlinear regression analysis was employed to fit the data to a curve rather than a line. The nonlinear model was then approximated by linear terms and standard regression (least-squares method) used in order to obtain the correlation coefficient. The closer the coefficient is to ±1, the better the function fits the data. A coefficient of zero indicates random data with no correlation to the function.

Table 5.1
Summary statistics

	Failures by Age										Failures by Install Date	
	All 1942-2007	pre-1955	1955–63	1964–67	1968–71	All 1972–78	Interpace 1972–78	Unknown & non-Interpace 1972–78	1979–91	1992–2007	Failures	Normalized failures
Category 1												
Sample pop. (ruptures)	393	32	40	31	60	194	152	42	35	1	403	403
Total pop. (sticks)	4,979,837	476,458	1,051,498	594,367	551,345	856,323	468,296	856,323	1,067,552	382,295		
Failure rate (failures/sticks made)	7.89E-05	6.72E-05	3.80E-05	5.22E-05	1.09E-04	2.27E-04	3.25E-04	4.90E-05	3.28E-05	2.62E-06		
Mean (years)	13.95	23.32	23.78	15.13	11.07	12.16	10.38	17.90	7.47	12.00	6.20	6.09E-05
Standard Dev (years)	8.95	6.92	10.21	6.71	6.01	7.70	6.47	8.56	6.37	N/A	10.23	9.17E-05
25th percentile (years)	6.7	19.0	18.0	10.9	6.2	6.1	5.5	9.3	2.9	11.3		
50th percentile (years)	11.5	23.5	23.6	12.9	8.4	9.9	9.1	16.9	6.1	12.5		
75th percentile (years)	18.8	28.6	40.6	14.8	11.5	16.9	14.7	24.2	10.4	13.8		
Category 2/3												
Sample pop. (sticks)	24,822	10	2,381	63	46	15,158	4,349	10,809	5,864	1,299	27,805	27,805
Sample pop. (database entries)	217	7	19	30	30	98	64	34	32	1	256	256
Total pop. (sticks)	4,979,837	476,458	1,051,498	594,367	551,345	856,323	468,296	856,323	1,067,552	382,295		
Failure rate (failures/sticks made)	4.98E-03	2.10E-05	2.26E-03	1.06E-04	8.34E-05	1.77E-02	9.29E-03	1.26E-02	5.49E-03	3.40E-03		
Mean (years)	16.75	24.86	29.79	16.90	13.47	15.97	12.44	22.62	12.72	12.00	428	4.01E-03
Standard Dev (years)	10.24	5.96	10.26	10.06	8.14	9.75	8.45	8.56	7.77	N/A	1194	1.12E-02
25th percentile (years)	22.1	21.3	22.2	11.6	8.4	25.1	21.4	26.4	21.3	11.3		
50th percentile (years)	26.3	23.3	24.5	17.7	12.5	27.6	23.7	28.6	24.0	12.5		
75th percentile (years)	29.4	26.3	41.5	30.1	26.3	30.2	26.9	31.2	26.9	13.8		

Database Percentages	Pop.	% Interpace	% Other	% Unknown
Category 1 failures	435	41.84%	8.97%	49.20%
Category 2/3 failures	35,662	60.73%	2.69%	36.58%
Production (sticks)	4,979,837	52.25%	47.75%	-

Failures by Wire Class	Total pop.	Class I	Class II	Class III	Class IV
Category 1 failures	397	63	117	38	179
Category 2/3 failures	25,809	7,162	395	8,853	9,398

Failures by Pipe Type	Sample pop.	Production	Mean failure rate
LCP Category 1 failures	228	13,458	0.0126
ECP Category 1 failures	159	5,405	0.0188
LCP Category 2/3 failures	3,972	13,458	0.254
ECP Category 2/3 failures	20,428	5,405	2.65

By using the Weibull distribution with suspensions (right censored data, or unfailed samples), a more accurate model of life data analysis for PCCP was achieved. These unfailed pipe were calculated by subtracting the known failures from the total production of pipe on a year-by-year basis.

Weibull analysis was performed on each of the data partitions to obtain failure rates for every era of PCCP pipe manufacturing. In this study, ReliaSoft®'s Weibull++® 7 software was used to compile the forthcoming charts. Other commercial software packages are available.

The first Weibull plot, Figure 5.11, utilizes all the available failure sample population and suspensions (unfailed individual sticks of pipe). The y-axis, logarithmically scaled, is the probability of Category 1 failures in percent failed per pipe produced. The x-axis, also logarithmically scaled, represents the age of the pipeline in years. Using the Weibull parameters β and η, the probability function was plotted in black diamond unadjusted points and black unadjusted line.

An arbitrary location factor, γ, was selected and subsequently iterated to best fit the data as a straight line. This can be seen on the plot as the blue round adjusted points and blue adjusted line. A ρ value of 0.9801 demonstrates a relatively good fit of the curve to the data points. It should be noted that the last failures occur in the 45-year age range, points along the line to the right of these failures represent the prediction of failures at a future time. Because this plot is

representative of the failure probability of all pipe manufactured between 1942 and 2006, points before 45 years may also be used predicatively. The failure rate probability at 10 years and 100 years was 2.82 x 10^{-03} and 0.03 percent, respectively.

The next Weibull plot, Figure 5.12, examines the failure rate prediction for Categories 1 and 2 failures for all samples. Adding the Category 2 failures effectively doubled the failure sample population, to a total of 758 failures. The number of suspensions, or unfailed pipe, remained the same at 4,951,634 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9832 demonstrates relatively good fit of the curve to the data points and is also a slightly better fit than the last Weibull plot of just the Category 1 failures. Again, because this sample population represents all pipe manufactured between 1942 and 2006, any point on the function may be used predicatively. The Categories 1 and 2 probability of failure at 10 and 100 years was 4.62 x 10-03 and 0.07 percent, respectively.

Next, Figure 5.13 looks at the failure rate for Categories 1, 2, and 3 failures for all samples. Adding Category 3 failures increased the failure sample population 33-fold, for a total of 25,217 failures. The number of suspensions, or unfailed pipe, still remained the same at 4,951,634 pipes. The logarithmically scaled y-axis is the probability of Category 1 and Categories 2 and 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9535 demonstrates a decent fit of the curve to the data points but is lower than those obtained for the Category 1 and Categories 1 and 2 plots. Graphically, this can be seen as more data points deviating from the path of the curve. Once again, because this sample population represents all pipe manufactured between 1942 and 2006, any point on the function may be used predicatively. The Category 1 and Categories 2 and 3 probability of failure at 10 years and 100 years was 0.03 and 3.38 percent, respectively.

Figure 5.14, the next Weibull plot, looks at just the Category 3 failures from 1942 to 2006. The failure sample population was 24,459. The number of suspensions, or unfailed pipe, still remained the same at 4,951,634 pipes. The logarithmically scaled y-axis is the probability of Category 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9659 demonstrates a decent fit of the curve to the data points but is lower than those obtained for the Category 1 and Categories 1 and 2 plots. The Category 3 probability of failure at 10 and 100 years was 0.03 and 23.75 percent, respectively.

Simply put, given all PCCP already produced and those already failed, it is predicted that any particular remaining stick of PCCP has a 0.03 percent probability of rupturing within 100 years of its installation and a 3.38 percent probability of experiencing some other failure or replacement within the same 100 years. That said, PCCP pipe produced in some eras is more or

less susceptible to failure than others, as previously discussed in this report. More accurate predictions can be made by narrowing down the timeframe that the PCCP was installed. These more refined predictions follow.

Figure 5.15, the next Weibull plot, looks at Category 1 failures from PCCP installed prior to 1955. The failure sample population was 32. The number of suspensions, or unfailed pipe, is 476,376 pipes. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9931 demonstrates an excellent fit of the curve to the data points, as can be seen graphically by how the data points are grouped closely around the curve. The Category 1 probability of failure at 10 and 100 years was 4.03 x 10-04 and 0.34 percent, respectively.

Next, Figure 5.16 looks at the failure rate for Categories 1 and 2 failures from PCCP installed prior to 1955. The number of suspensions, or unfailed pipe, still remained the same at 476,376 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9865 demonstrates a good fit of the curve to the data points. The Category 1 and Categories 2 and 3 probability of failure at 10 years and 100 years was 2.00 x 10-02 and 0.37 percent, respectively.

The next Weibull plot, Figure 5.17, examines the failure rate prediction for Category 1 failures for PCCP installed in 1955–63. The sample population was 40 failures. The number of suspensions, or unfailed pipe, was 1,049,061 pipes. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9829 demonstrates relatively good fit of the curve to the data points and is also a slightly better fit than the Weibull plot of all Category 1 failures. The Category 1 probability of failure at 10 and 100 years was 2.32 x 10-04 and 0.02 percent, respectively.

Figure 5.18, the next Weibull plot, looks at the Categories 1 and 2 failures from 1955 to 1963. The failure sample population was 73. The number of suspensions, or unfailed pipe, remained the same at 1,049,061 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9896 demonstrates a good fit of the curve to the data points and is higher than that obtained for the Category 1 failures for the same era. The Categories 1 and 2 probability of failure at 10 and 100 years was 2.83 x 10-04 and 0.03 percent, respectively.

Next, Figure 5.19 looks at the failure rate for Categories 1, 2, and 3 failures from PCCP installed in 1955 to 1963. The number of failed pipe and suspensions was 2,422 failures and 1,049,061 pipes, respectively. The logarithmically scaled y-axis is the probability of Category 1

and Categories 2 and 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.8605 demonstrates a much worse fit of the curve to the data points as compared to the Category 1 or Categories 1 and 2 plots in the same era. The Category 1 and Categories 2 and 3 probability of failure at 10 and 100 years was 2.07 x 10-04 and 12.21 percent, respectively.

To verify that by including Category 3 failures in the previous plot worsened the prediction, Category 3 failures for 1955–63 were plotted alone in the next Weibull plot, Figure 5.20. The failure sample population was 2,349, the bulk of the failures presented in the previous plot. The number of suspensions remained the same at 1,049,061 pipes. The logarithmically scaled y-axis is the probability of Category 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.8272 verified the poor fit of the curve to the data points. The Category 3 probability of failure at 10 and 100 years was 0.09 and 0.72 percent, respectively.

Figure 5.21, the next Weibull plot, looks at Category 1 failures from PCCP installed in 1964–67. The failure sample population was 31. The number of suspensions, or unfailed pipe, was 594,178 pipes. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9707 demonstrates a good fit of the curve to the data points. The Category 1 probability of failure at 10 and 100 years was 1.61 x 10-03 and 0.02 percent, respectively.

The next Weibull plot, Figure 5.22, examines the failure rate prediction for Categories 1 and 2 failures for PCCP installed between 1964 and 1967. Adding the Category 2 failures more than doubled the failure sample population, to a total of 81 failures. The number of suspensions remained at 594,178 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9643 demonstrates a decent fit of the curve to the data points but worse than that obtained for Category 1 failures alone for the same era. The Categories 1 and 2 probability of failure at 10 and 100 years was 3.57 x 10-03 and 0.04 percent, respectively.

Next, Figure 5.23 looks at the failure rate for Category 1 failures from PCCP installed in 1968–71. The number of failures and suspensions was 60 failures and 551,218 pipes, respectively. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. The function was adjusted on the plot as illustrated by the blue round points and the blue line by using the γ location factor. A ρ of 0.9429 demonstrates a decent fit of the curve to the data points. The Category 1 probability of failure at 10 years and 100 years was 4.47 x 10-03 and 0.13 percent, respectively.

Figure 5.24, the next Weibull plot, looks at the Categories 1 and 2 failures from 1968 to 1971. The failure sample population was 82. The number of suspensions, or unfailed pipe, remained at 551,218 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9540 demonstrates a decent fit of the curve to the data points; better than that obtained for the Category 1 plot in the same era alone. The Categories 1 and 2 probability of failure at 10 and 100 years was 5.99 x 10-03 and 0.12 percent, respectively.

The next Weibull plot, Figure 5.25, examines the failure rate prediction for Category 1 failures for PCCP installed in 1972–78. The sample population was 194 failures. The number of suspensions was 838,154 pipes. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9704 demonstrates relatively good fit of the curve to the data points and is also a slightly better fit than any of the Weibull plots of the last two eras. The Category 1 probability of failure at 10 and 100 years was 9.34 x 10-03 and 0.10 percent, respectively.

Next, Figure 5.26 looks at the failure rate for Categories 1 and 2 failures from PCCP installed in 1972–78. The number of failures and suspensions was 350 failures and 838,154 pipes, respectively. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. The function was adjusted on the plot as illustrated by the blue round points and the blue line by using the γ location factor. A ρ of 0.9790 demonstrates a good fit of the curve to the data points and slightly better than the Category 1 failures in this era alone. The Categories 1 and 2 probability of failure at 10 years and 100 years was 0.01 and 0.21 percent, respectively.

Figure 5.27 looks at the failure rate for Categories 1, 2, and 3 failures for the 1972–78 era. Adding Category 3 failures increased the failure sample population 44-fold, for a total of 15,354 failures. The number of suspensions, or unfailed pipe, still remained the same at 838,154 pipes. The logarithmically scaled y-axis is the probability of Category 1 and Categories 2 and 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9303 demonstrates a decent fit of the curve to the data points but is the lowest of all the plots in this era. Graphically, this can be seen as more data points deviating from the path of the curve. The Category 1 and Categories 2 and 3 probability of failure at 10 years and 100 years was 0.08 and 4.01 percent, respectively.

Figure 5.28, the next Weibull plot, looks at just the Category 3 failures from 1972 to 1978. The failure sample population was 15,004. The number of suspensions, or unfailed pipe, still remained the same at 838,154 pipes. The logarithmically scaled y-axis is the probability of Category 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9661 demonstrates a decent fit of the curve to the data points. The Category 3 probability of failure at 10 and 100 years was 0.05 and 100 percent, respectively. This alarming probability of failure is a function of the nature of Category 3 failures. More of this is discussed in the results section of this report.

The next Weibull plot, Figure 5.29, examines the failure rate prediction for Category 1 failures for PCCP installed in 1979–91. The sample population was 35 failures. The number of suspensions, or unfailed pipe, was 1,061,650 pipes. The logarithmically scaled y-axis is the probability of Category 1 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years, and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9398 demonstrates a decent fit of the curve to the data points. The Category 1 probability of failure at 10 and 100 years was 2.18 x 10-03 and 7.81 x 10-03 percent, respectively.

Figure 5.30, the next Weibull plot, looks at the Categories 1 and 2 failures from 1979 to 1991. The failure sample population was 116. The number of suspensions remained at 1,061,650 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9335 demonstrates a decent fit of the curve to the data points. The Categories 1 and 2 probability of failure at 10 and 100 years was 3.84 x 10-03 and 0.10 percent, respectively.

Next, Figure 5.31 looks at the failure rate for Categories 1, 2, and 3 failures from PCCP installed in 1979 to 1991. The number of failed pipe and suspensions was 5,899 failures and 1,061,650 pipes, respectively. This represents a 50-fold increase of the failure sample population. The logarithmically scaled y-axis is the probability of Category 1 and Categories 2 and 3 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is also logarithmically scaled. The unadjusted probability function was plotted in black diamond points and the black unadjusted line. Using the γ location factor, the function was adjusted on the plot as illustrated by the blue round points and the blue line. A ρ of 0.9357 demonstrates a similar fit of the curve to the data points as compared to the Categories 1 and 2 plot for the same era. The Category 1 and Categories 2 and 3 probability of failure at 10 and 100 years was 0.05 and 1.36 percent, respectively.

Similar to the histogram and ogive for the 1992–2006 era, the Weibull plot for this time period, Figure 5.32, is included only for completeness. A failure sample population of 1 is not significant enough to make serious predictions. The number of suspensions for this era was 380,997 pipes. The logarithmically scaled y-axis is the probability of Categories 1 and 2 failures in percent failed per pipe produced. The x-axis represents the age of the pipeline in years and is

also logarithmically scaled. A single sample population necessitated the use of a simpler two-parameter Weibull probability density function. The Category 1 probability of failure at 10 and 100 years was 6.70 x 10-05 and 99.82 percent, respectively.

Likewise for Category 3 failures for the 1992–2006 era, Weibull plot Figure 5.33 is included for entirety. A single failure event consisting of 1,299 pipes cannot accurately predict PCCP failure rates for this era. The suspensions remained at 380,997 pipes. The single failure event here also necessitated the use of a simpler two-parameter Weibull probability density function. The Category 3 probability of failure at 10 and 100 years was 0.09 and 100 percent, respectively. Although based on very limited statistics, this alarming probability of failure is discussed in the results section of this report.

PROBABILITY OF PCCP FAILURE BY ERA

The next two graphs, Figures 5.34 and 5.35, summarize the predicted probabilities of PCCP failures as a function of timeframe, or era of pipe manufacturing. The first bar graph summarizes the probability of failure after 10 years; the second summarizes the probability of failure after 100 years. The left-hand axis corresponds with the solid blue bars which represent the probability of a Category 1 failure. The right-hand axis corresponds with the crossed magenta bars which represent the probability of Category 1 or 2 failure. The pipe installation timeframe increases along the bottom x-axis. Observing the probabilities trends in the first graph, it can be seen that the largest Category 1 failure probability occurred in the 1972–78 era. This seems to agree with the simple statistics derived earlier in this study. The highest Categories 1 and 2 failure probability was bimodal, peaking both in the 1972–78 era and the pre-1955 era.

On the 100-year probability chart, Figure 5.35, it can be seen that the Category 1 failure probability trend was multimodal, with peaks in the 1972–78 era, pre-1955 era, and 1992–2006 era. If the 1992–2006 peak is ignored due to the aforementioned lack of sample size, the trend becomes bimodal. The Categories 1 and 2 failure probability trend appeared bimodal around the 1972–78 era and the pre-1955 era, very similarly to the 10-year probability plot. Unlike the 10-year probability plot and seemingly unintuitive when compared to the simple statistics derived earlier in this study, the Category 1 failure probability does not peak in the 1972–78 era.

Table 5.2 summarized in tabular form all the Weibull data presented herein.

Table 5.2
Weibull summary statistics

	1942-2007 All	pre-1955	1955–63	1964–67	1968–71	all 1972–78	1979–91	1992–2006
Category 1								
Failed pop. (F)	393	32	40	31	60	194	35	1
Suspensions (S)	4,951,634	476,376	1,049,061	594,178	551,218	838,154	1,061,650	380,997
Beta (β)	1.0585	4.2785	1.4728	0.9444	1.3053	1.0019	0.5358	6.9731
Eta (η)	1.83E+05	429.8055	3.50E+04	6.53E+05	1.61E+04	9.56E+04	4.60E+09	76.8097
Gamma (γ)	0.775	-13.5775	4.77	4.4975	2.515	0.915	0.8425	-
Rho (ρ)	0.9801	0.9931	0.9829	0.9707	0.9429	0.9704	0.9398	-
f(t = 10 years) (%)	2.82E-03	4.03E-04	2.32E-04	1.61E-03	4.47E-03	9.34E-03	2.18E-03	6.70E-05
f(t = 100 years) (%)	0.03	0.34	0.02	0.02	0.13	0.1	7.81E-03	99.82
Category 1+2								
Failed pop. (F)	758	396	73	81	82	350	116	-
Suspensions (S)	4,951,634	476,376	1,049,061	594,178	551,218	838,154	1,061,650	-
Beta (β)	1.1602	1.2624	1.5723	0.8886	1.1414	1.1349	1.5554	-
Eta (η)	5.07E+04	8407.738	1.68E+04	6.17E+05	3.63E+04	2.23E+04	8595.679	-
Gamma (γ)	0.6975	0.5975	5.0325	3.9	2.755	0.85	-2.46	-
Rho (ρ)	0.9832	0.9865	0.9896	0.9643	0.954	0.979	0.9335	-
f(t = 10 years) (%)	4.62E-03	2.00E-02	2.83E-04	3.57E-03	5.99E-03	0.01	3.84E-03	-
f(t = 100 years) (%)	0.07	0.37	0.03	0.04	0.12	0.21	0.1	-
Category 1+2/3								
Failed pop. (F)	25,217	-	2,422	-	-	15,354	5,899	-
Suspensions (S)	4,951,634	-	1,049,061	-	-	838,154	1,061,650	-
Beta (β)	2.005	-	4.1361	-	-	1.6758	1.3825	-
Eta (η)	535.2077	-	158.2652	-	-	667.3259	2214.765	-
Gamma (γ)	0.325	-	3.3175	-	-	0.845	0.7525	-
Rho (ρ)	0.9535	-	0.8605	-	-	0.9303	0.9357	-
f(t = 10 years) (%)	0.03	-	2.07E-04	-	-	0.08	0.05	-
f(t = 100 years) (%)	3.38	-	12.21	-	-	4.01	1.36	-
Category 3								
Failed pop. (F)	24,459	-	2,349	-	-	15,004	-	1,299
Suspensions (S)	4,951,634	-	1,049,061	-	-	838,154	-	380,997
Beta (β)	4.8065	-	51.8054	-	-	118.532	-	6.9861
Eta (η)	154.8987	-	2528.539	-	-	810.5559	-	27.4499
Gamma (γ)	-18.065	-	-2198.8	-	-	-749.84	-	-
Rho (ρ)	0.9659	-	0.8272	-	-	0.9661	-	-
f(t = 10 years) (%)	0.03	-	0.09	-	-	0.05	-	0.09
f(t = 100 years) (%)	23.75	-	0.72	-	-	100	-	100

Category 3 Failure Prediction Interference

It was noted that Category 3 failures (loss of service, i.e., full or partial replacement) dramatically impacted the failure probabilities when included in Weibull prediction analysis. Figure 5.18 vs. 5.19 is a keen example of the marked degradation of how the function fit the data (i.e., curve fit) when adding Category 3 failures, as was Figure 5.26 vs. 5.27 and Figure 5.12 vs. 5.13.

This phenomenon is believed to be caused by the inherent severity of Category 3 failures. When a PCCP pipeline alignment is partially or completely replaced, many pipes of as-yet unfailed pipe are removed from service. This removal of many similarly manufactured pipes at one particular time is not easily described by the Weibull probability function. An analogy would be trying to calculate the failure probability of a product after a large nationwide recall—many unfailed products would unavoidably be counted as "failed."

In an attempt to describe the rapid increase of failures, the Weibull function curve increases dramatically. The result is large and unreliable predictions of failure probabilities. Figures 5.14 and 5.19 saw double-digit probabilities of failure at the 100-year mark. Figures 5.27 and 5.33 observed alarming 100 percent failure probabilities at the 100-year mark.

To compensate for this occurrence, the Weibull analysis was performed for Categories 1 and 2 failures for all the manufacturing eras (except 1992-2006, which had no Category 2 failures). Category 2 failures, or failures by inspection, still accounted for nonruptured pipe failures without counting the as-yet unfailed pipe. The results were a more plausible, credible failure model.

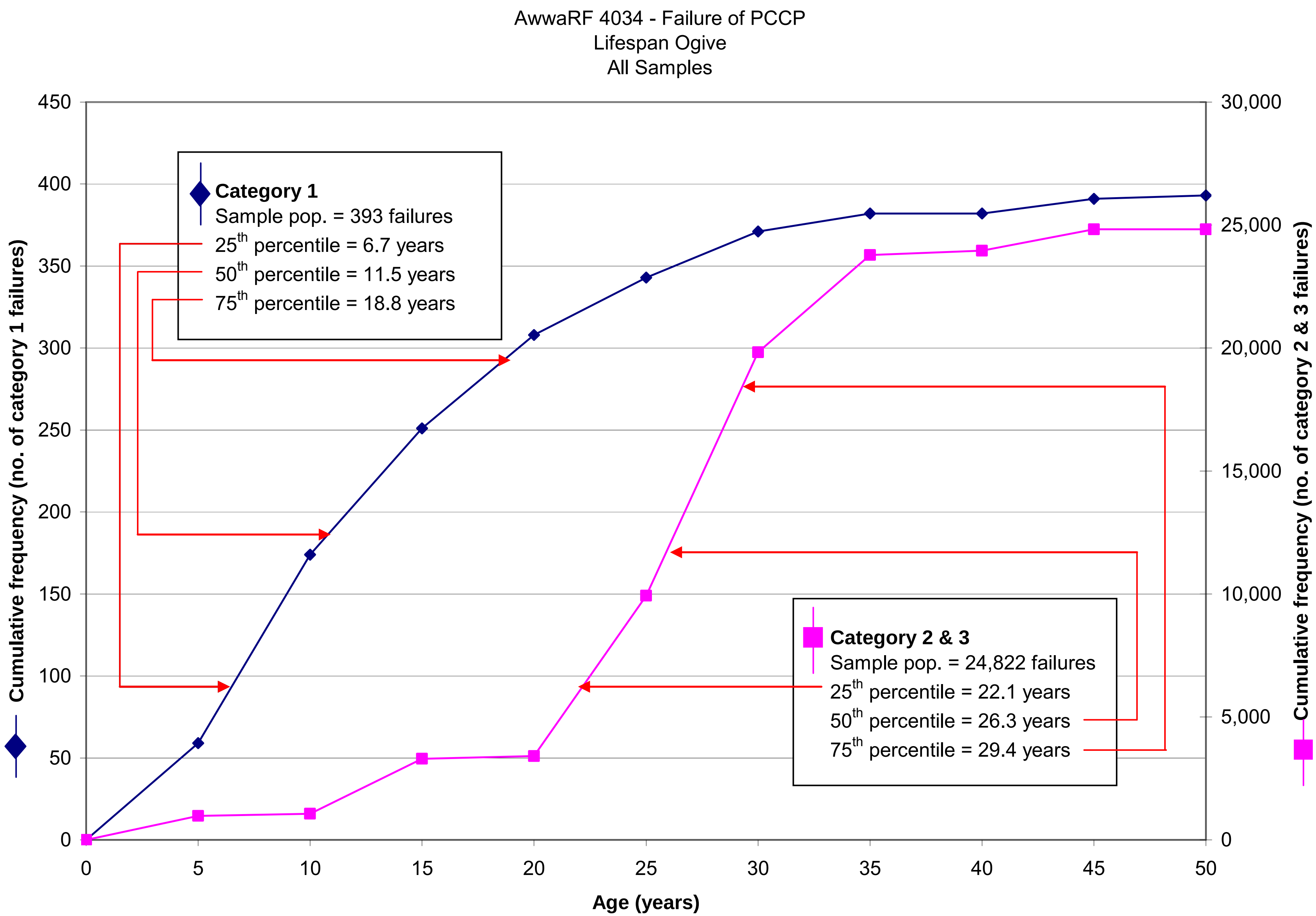

Figure 5.1 Lifespan ogive all samples

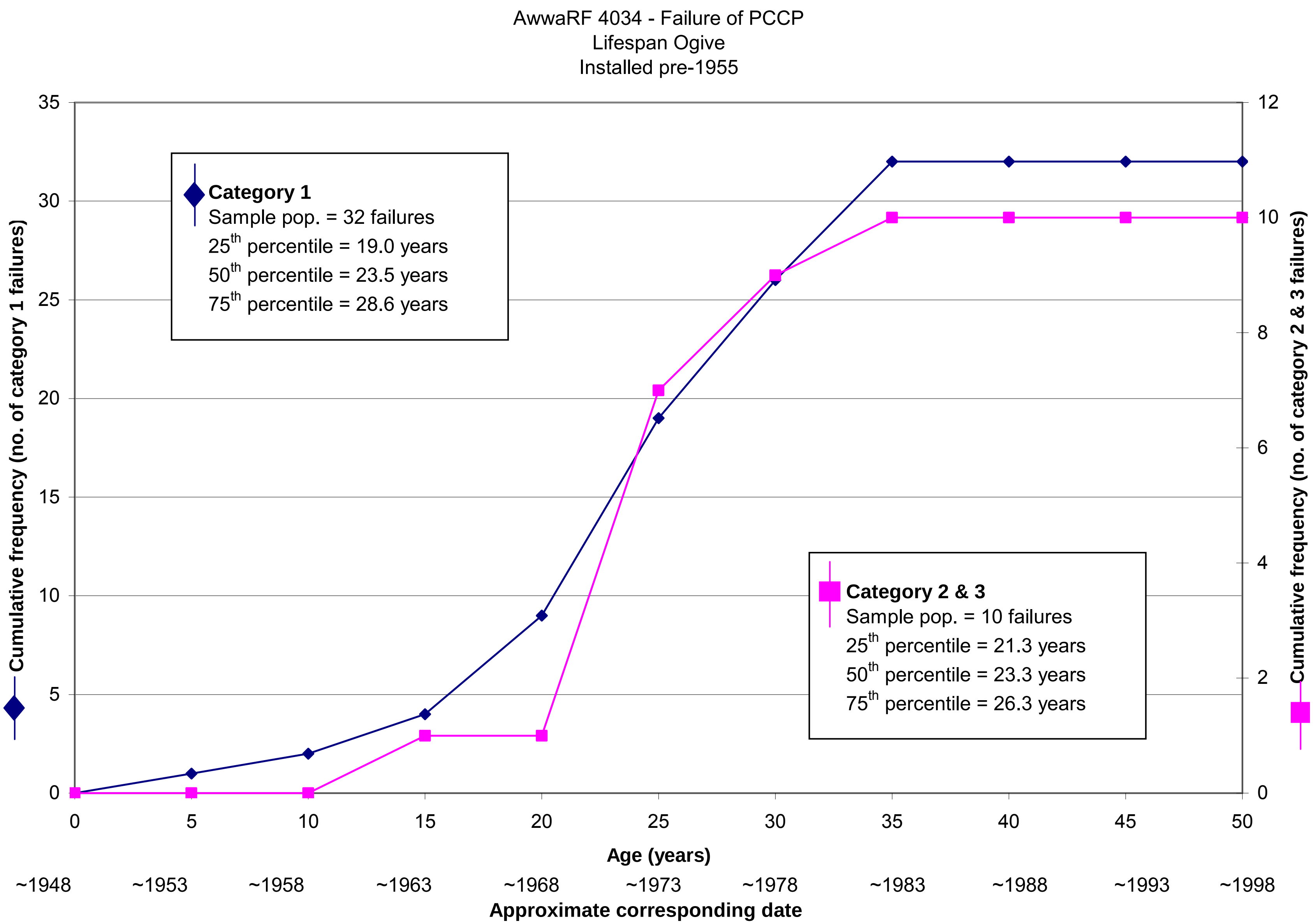

Figure 5.2 Lifespan ogive installed pre-1955

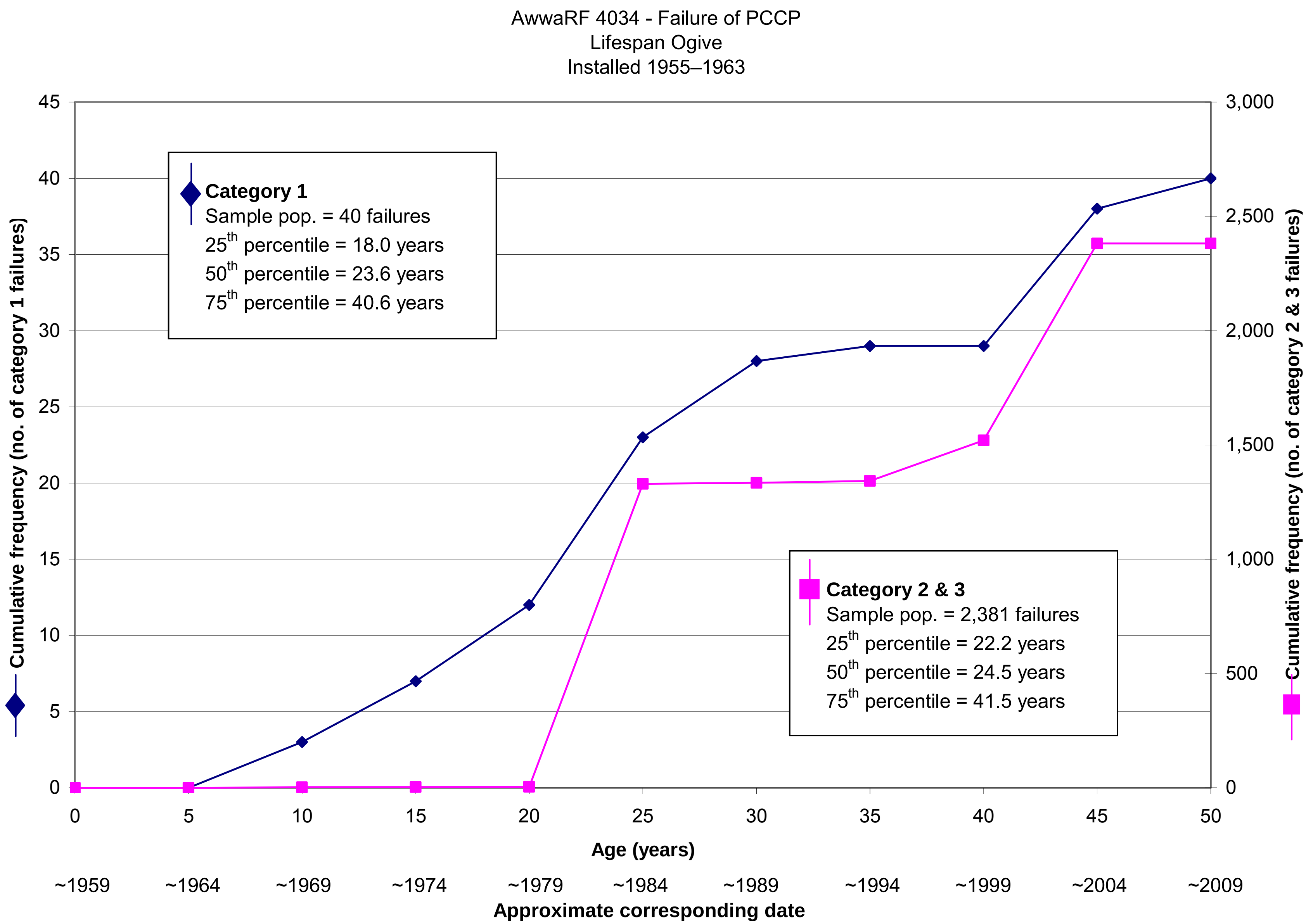

Figure 5.3 Lifespan ogive installed 1955-1963

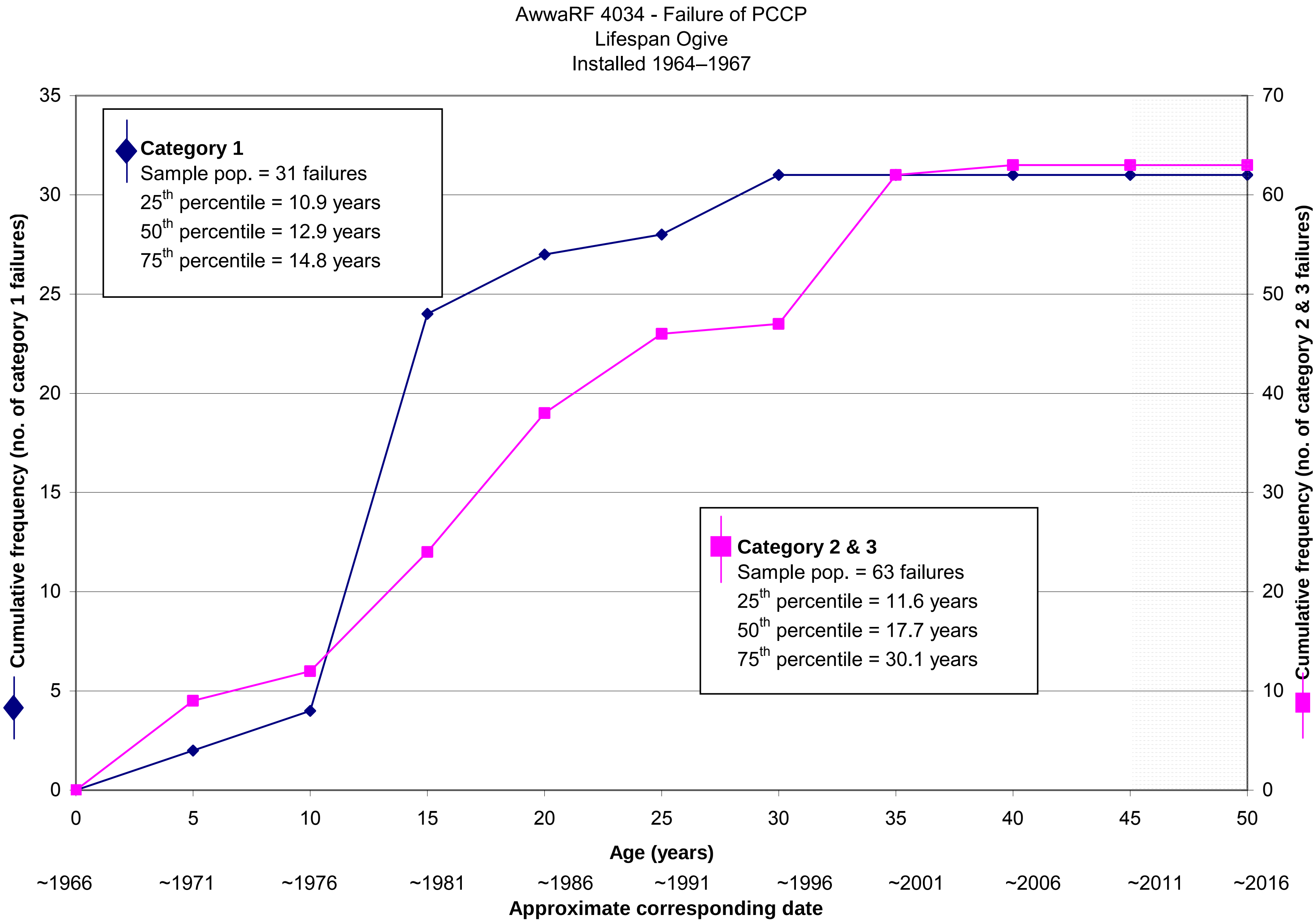

Figure 5.4 Lifespan ogive installed 1964-1967

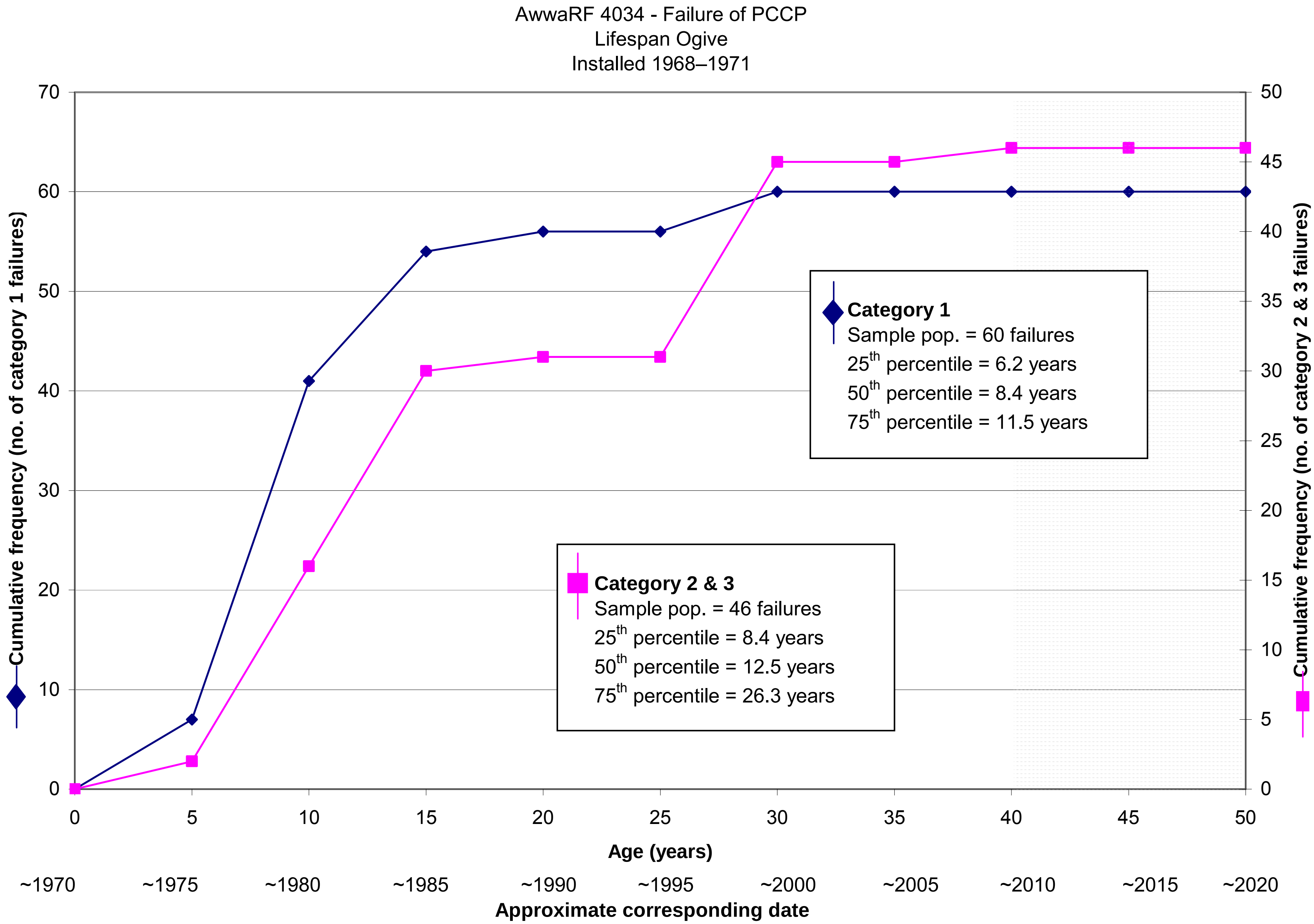

Figure 5.5 Lifespan ogive installed 1968-1971

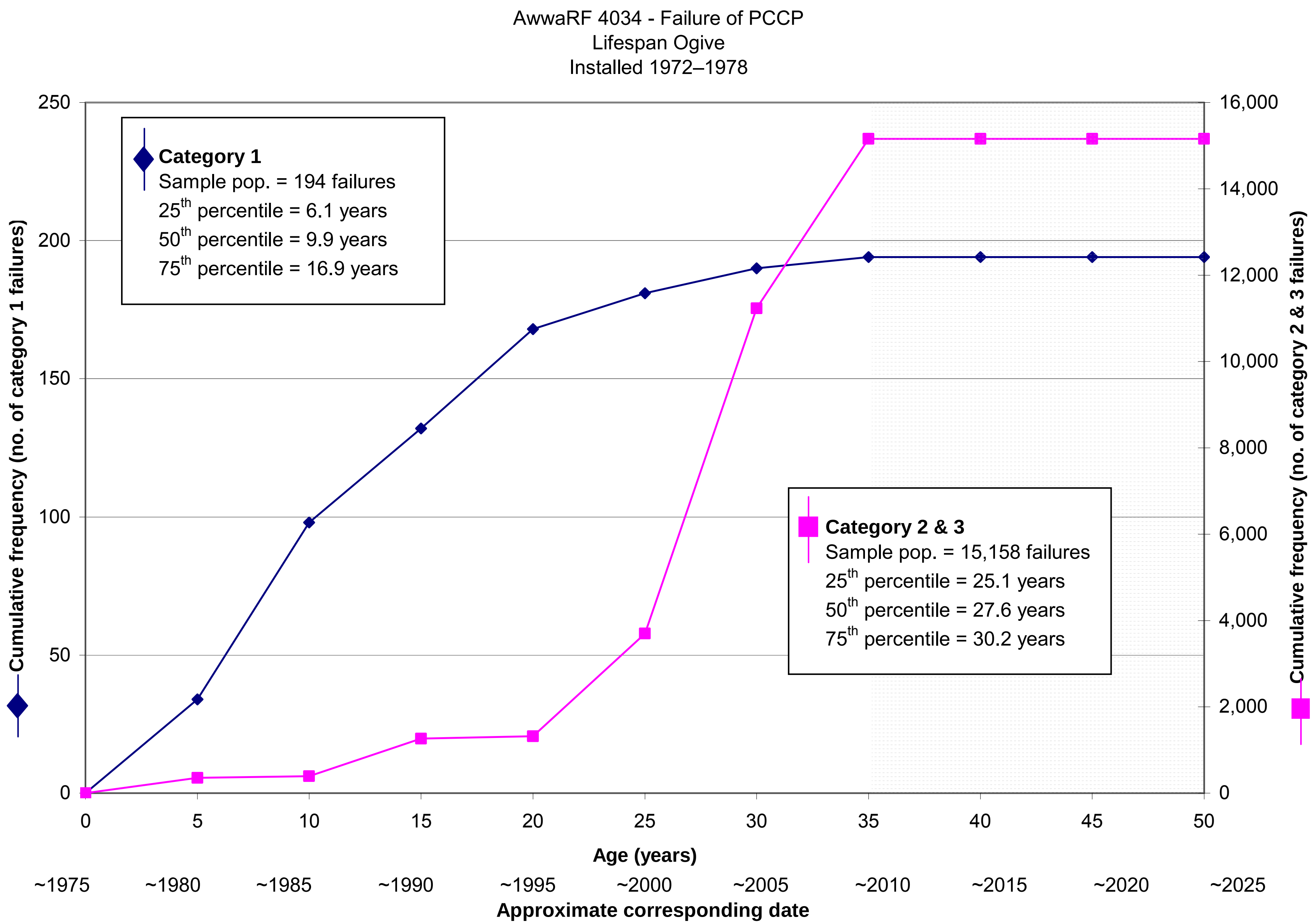

Figure 5.6 Lifespan ogive installed 1972-1978

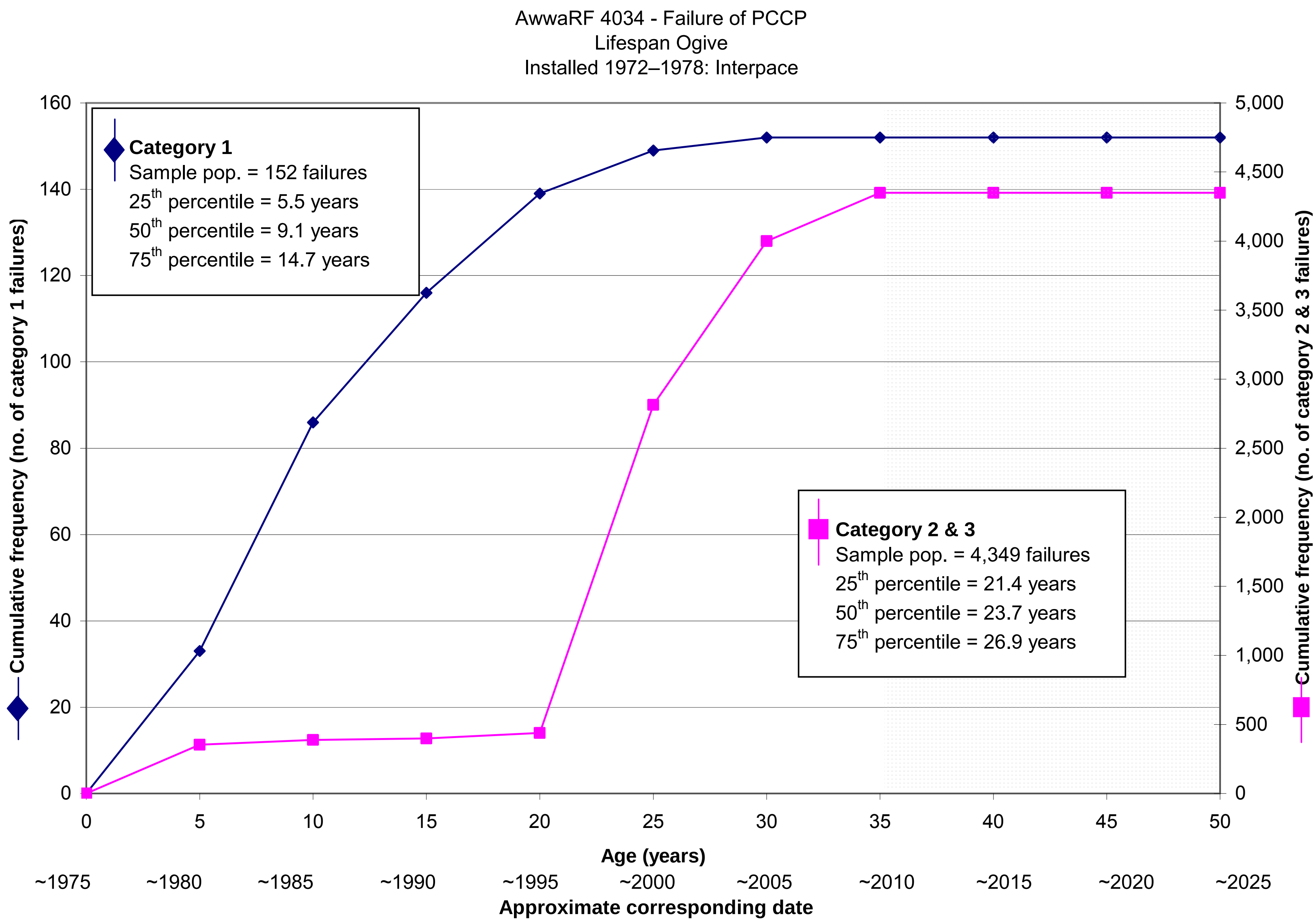

Figure 5.7 Lifespan ogive installed 1972-1978: Interpace

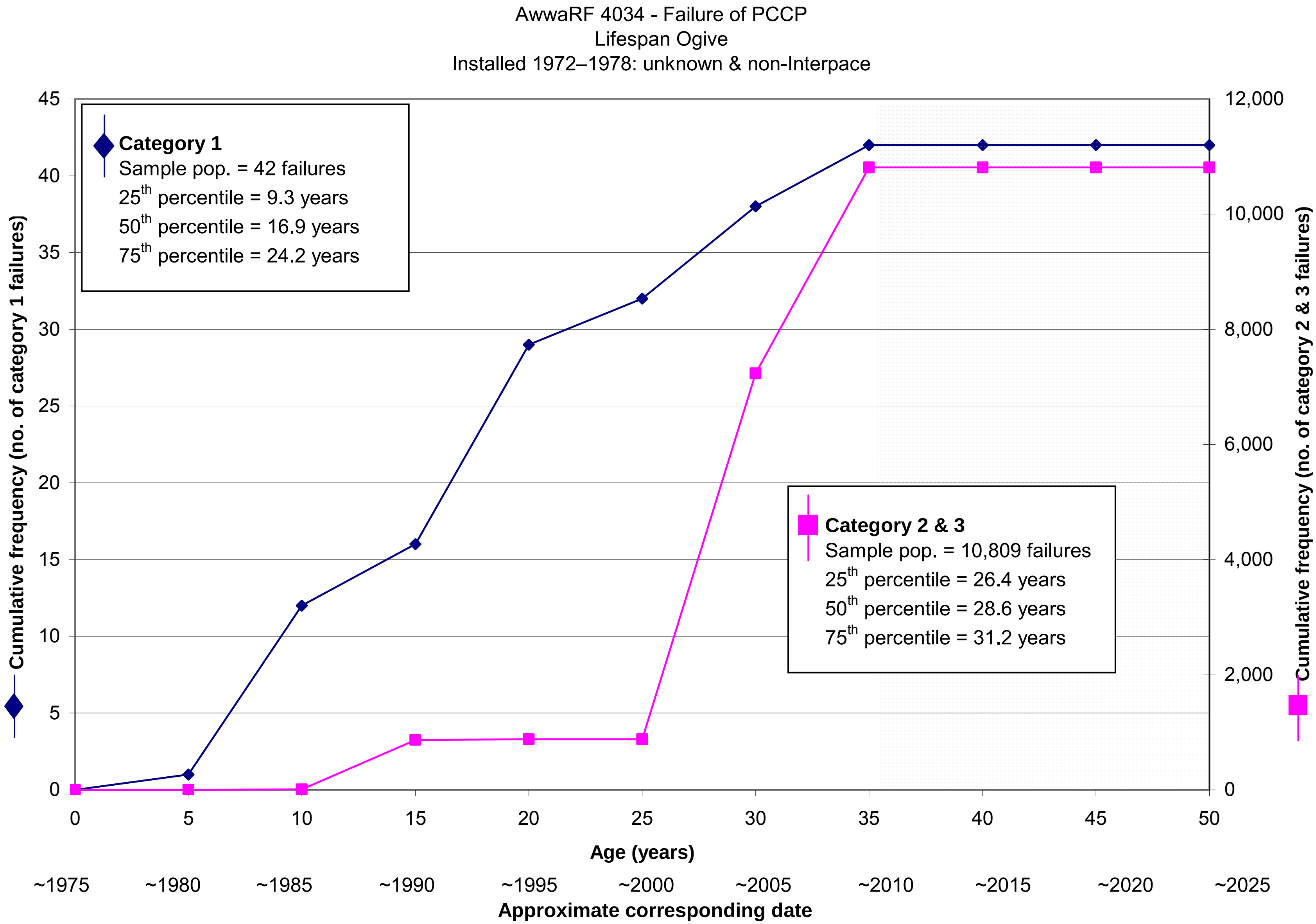

Figure 5.8 Lifespan ogive installed 1972-1978: unknown and non-Interpace

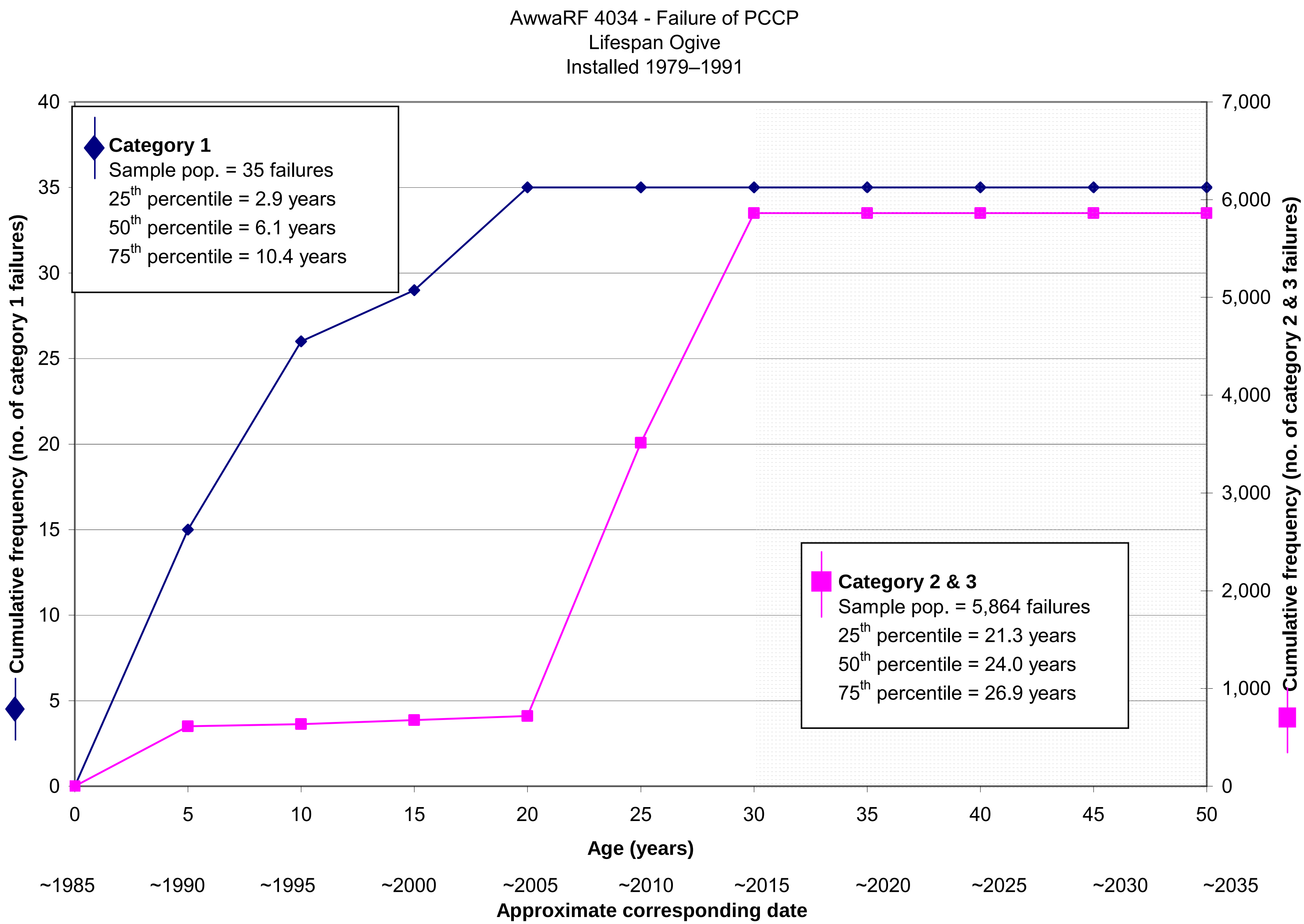

Figure 5.9 Lifespan ogive installed 1979-1991

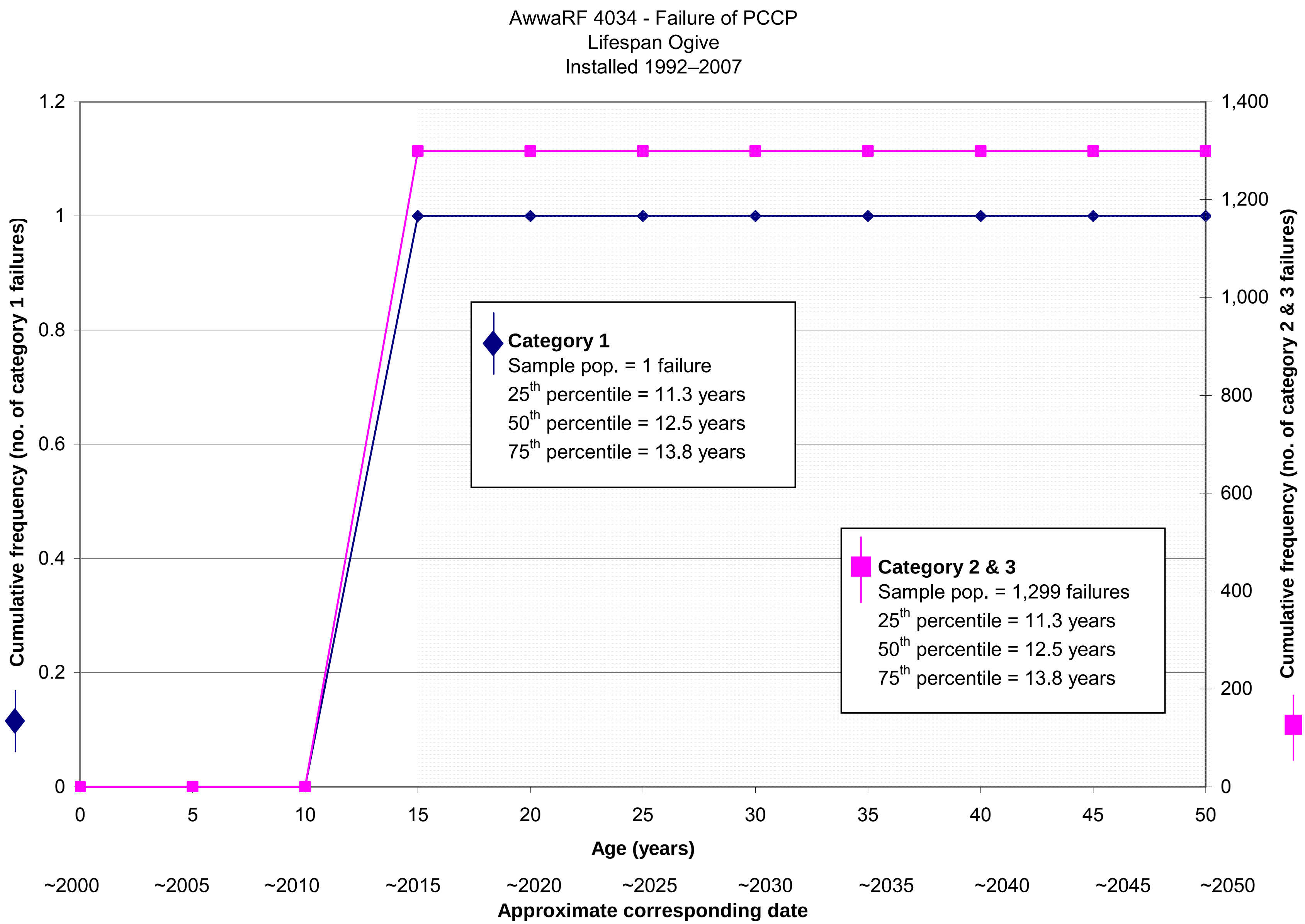

Figure 5.10 Lifespan ogive installed 1992-2007

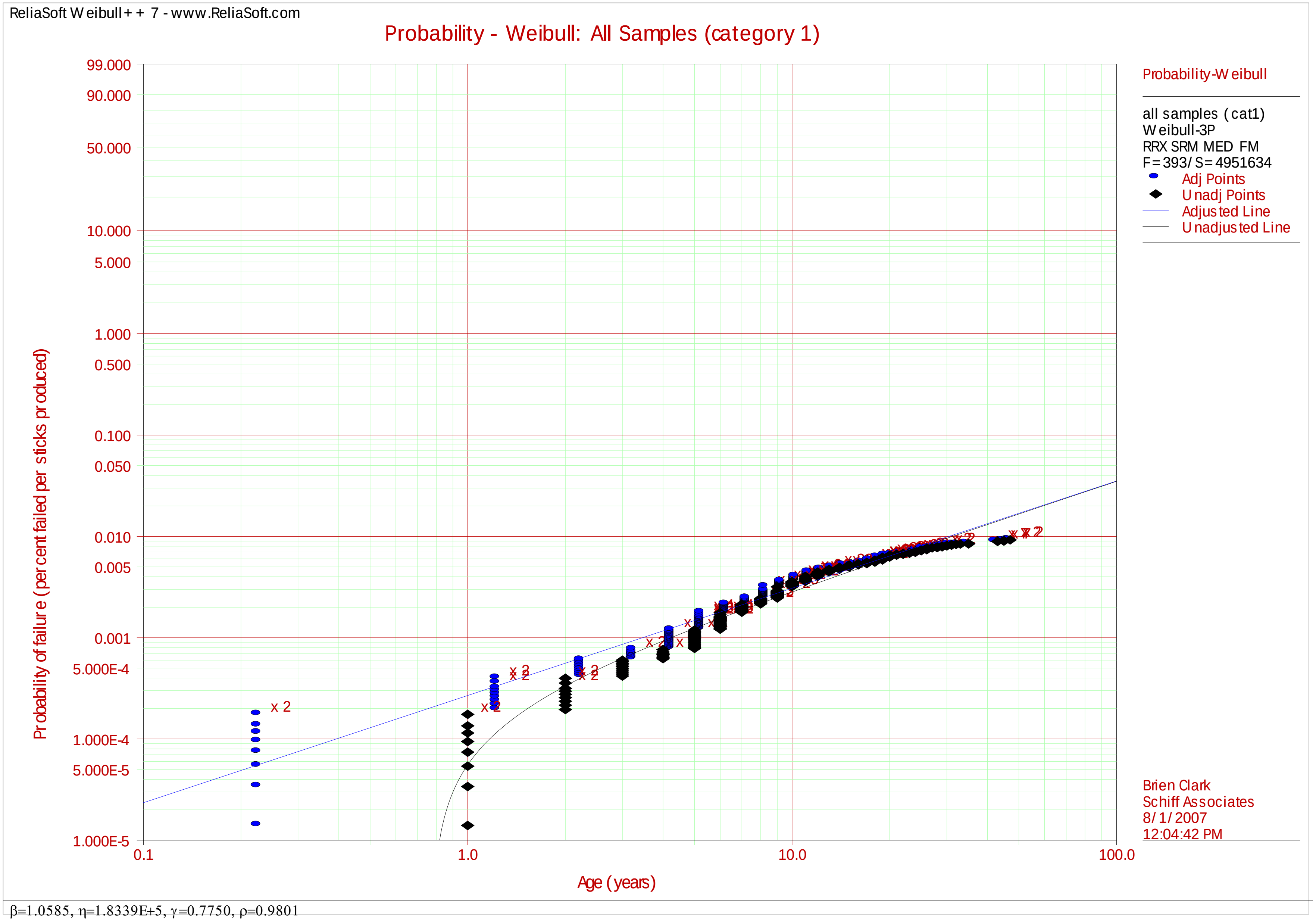

Figure 5.11 Probability – Weibull: all samples (Category 1)

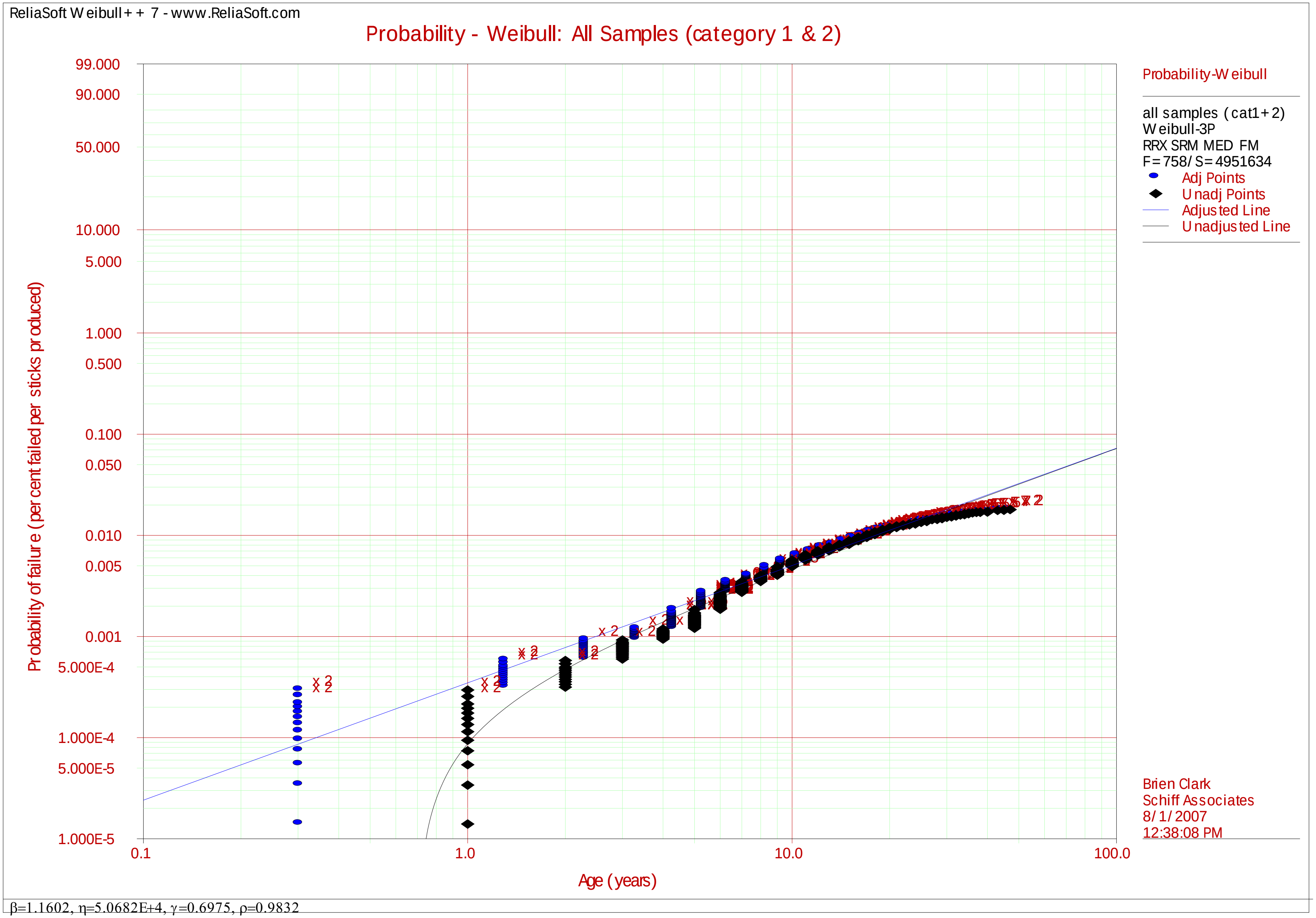

Figure 5.12 Probability – Weibull: all samples (Categories 1 and 2)

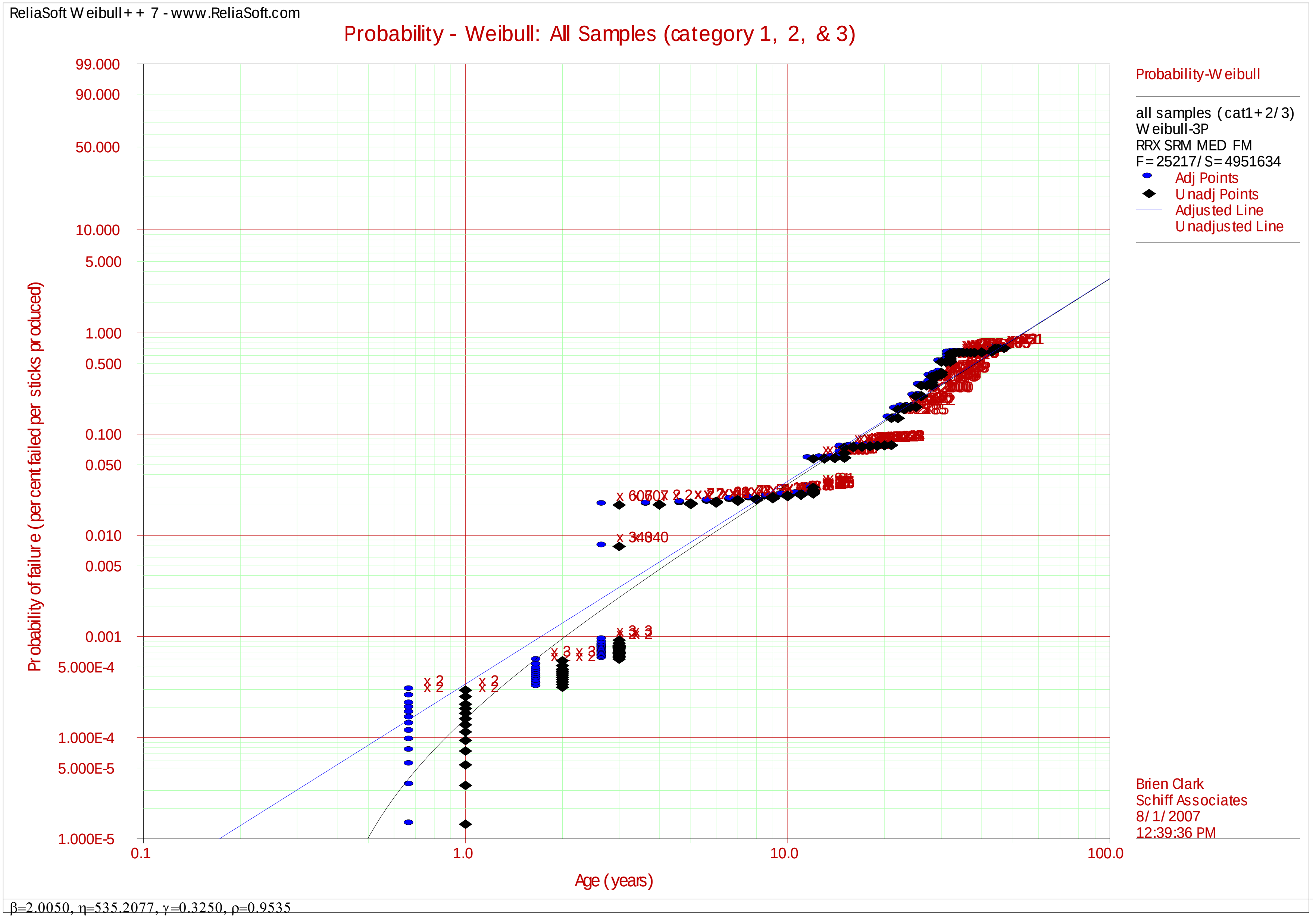

Figure 5.13 Probability – Weibull: all samples (Categories 1, 2, and 3)

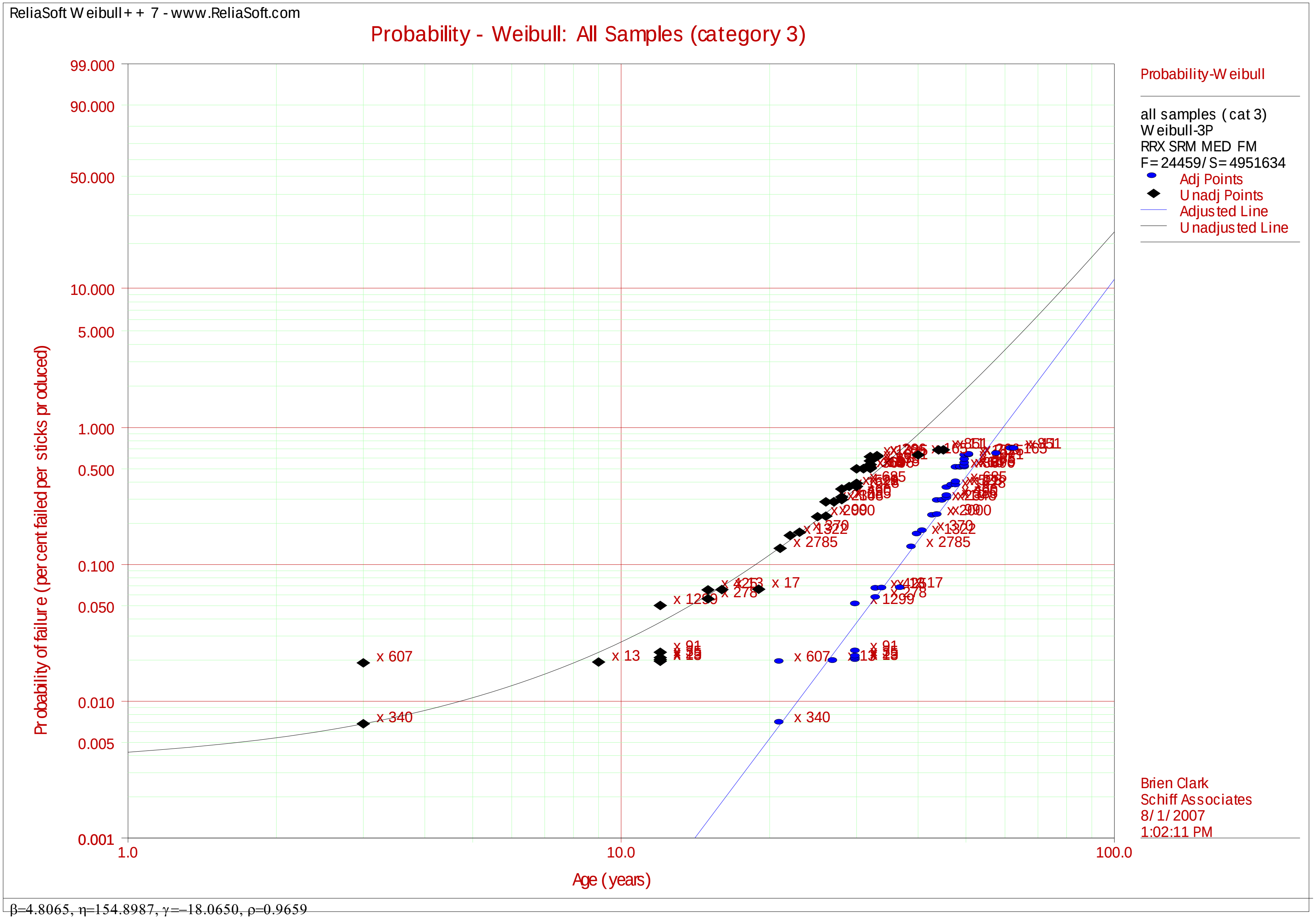

Figure 5.14 Probability – Weibull: all samples (Category 3)

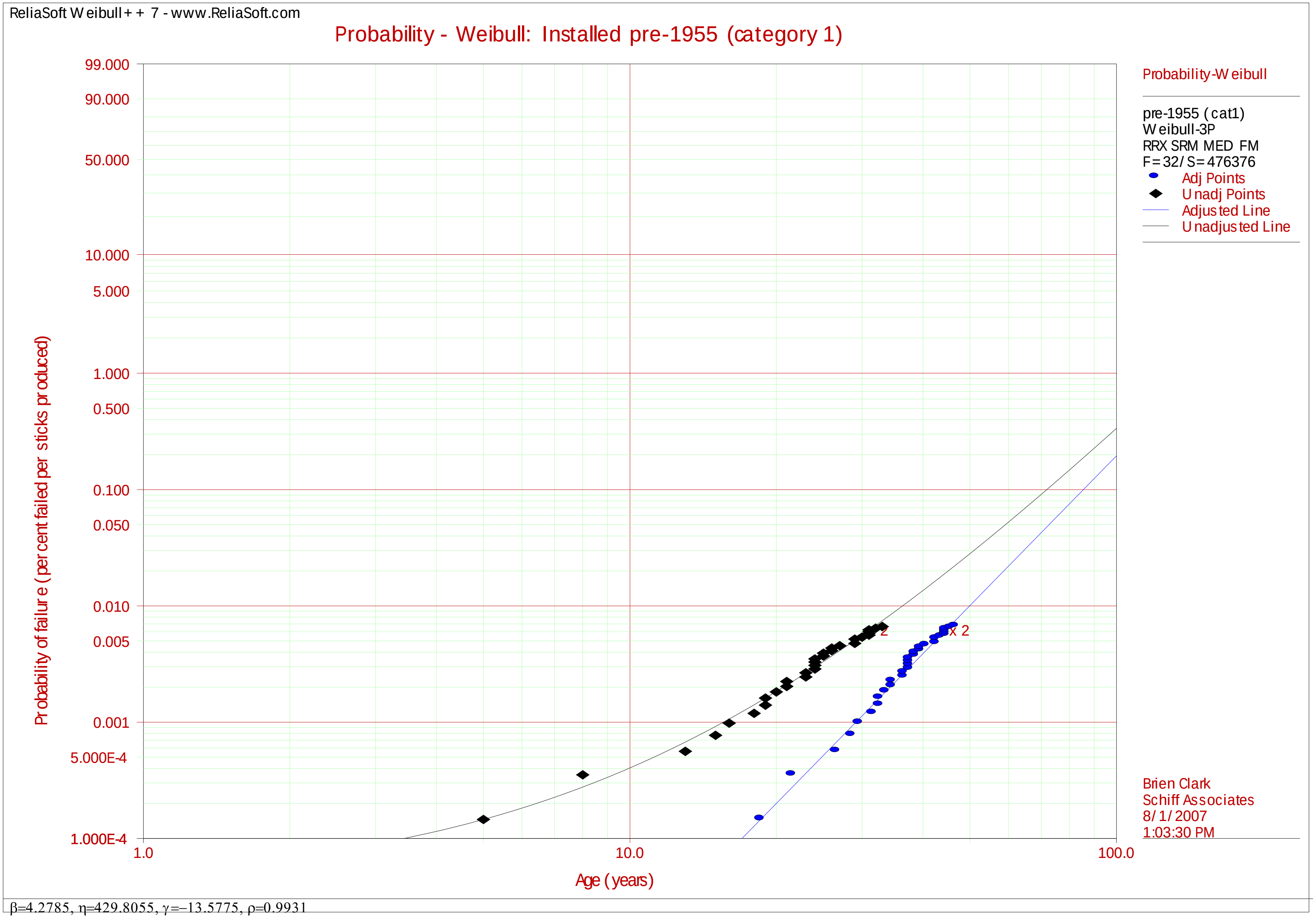

Figure 5.15 Probability – Weibull: installed pre-1955 (Category 1)

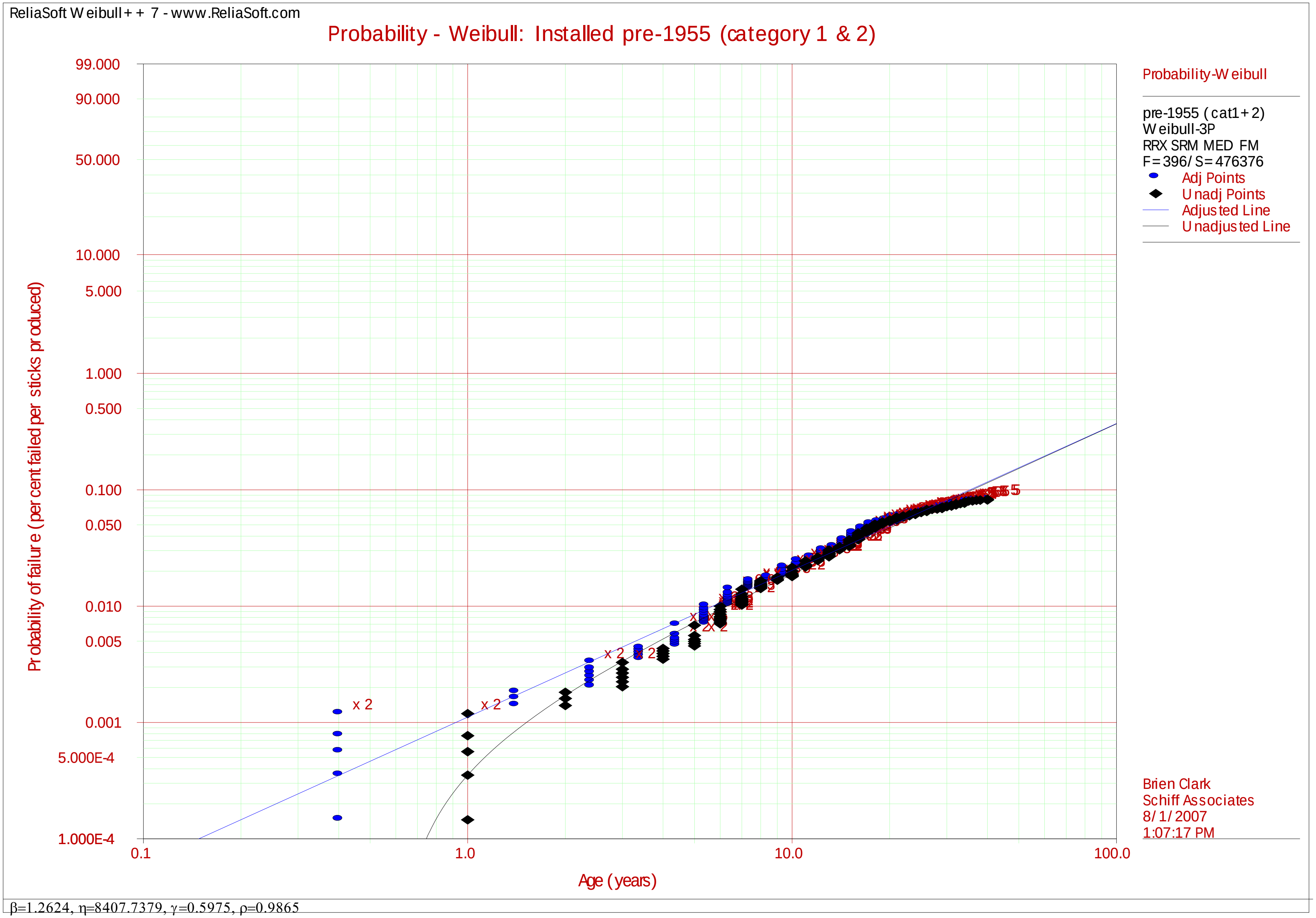

Figure 5.16 Probability – Weibull: installed pre-1955 (Categories 1 and 2)

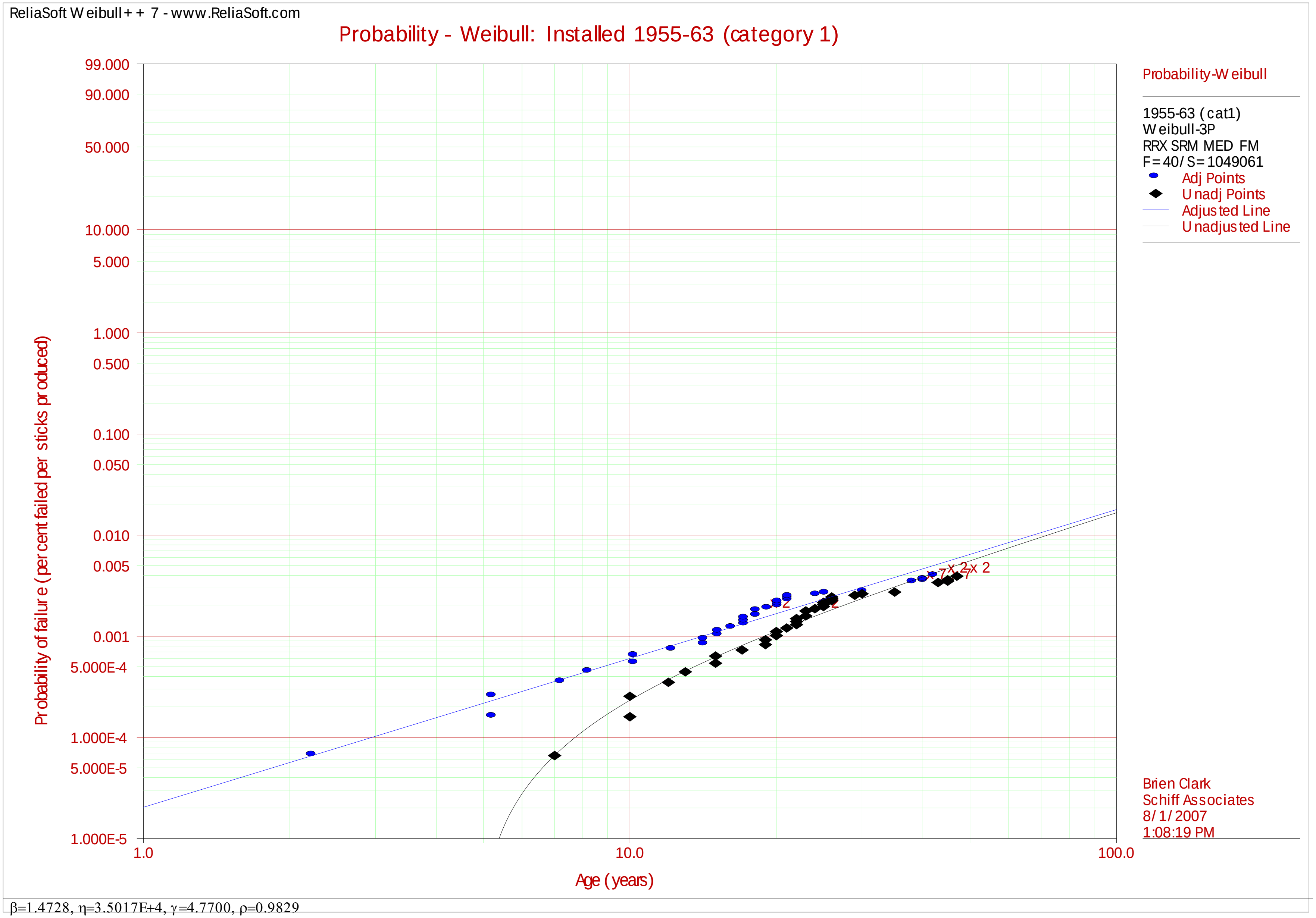

Figure 5.17 Probability – Weibull: installed 1955-63 (Category 1)

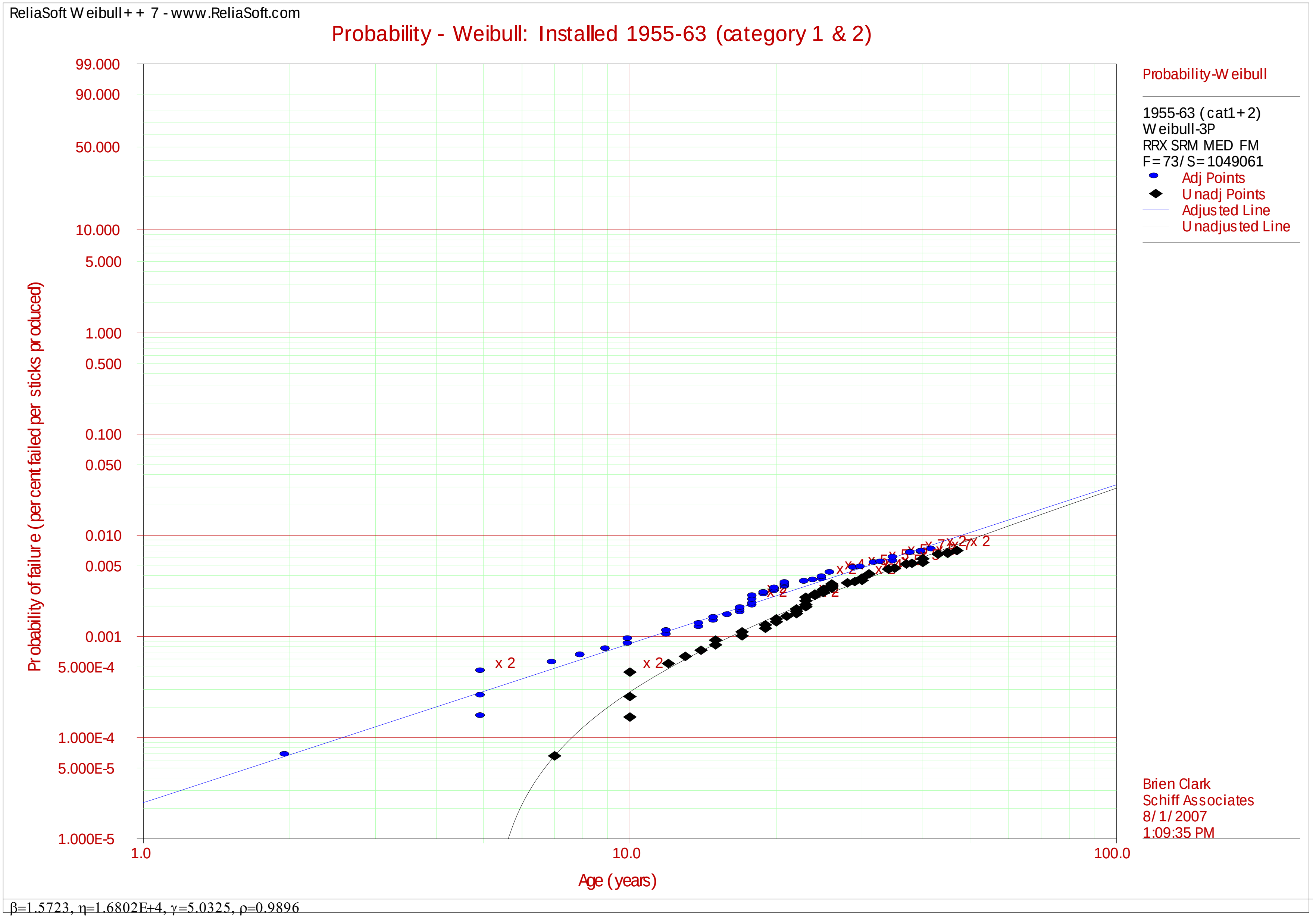

Figure 5.18 Probability – Weibull: installed 1955-1963 (Categories 1 and 2)

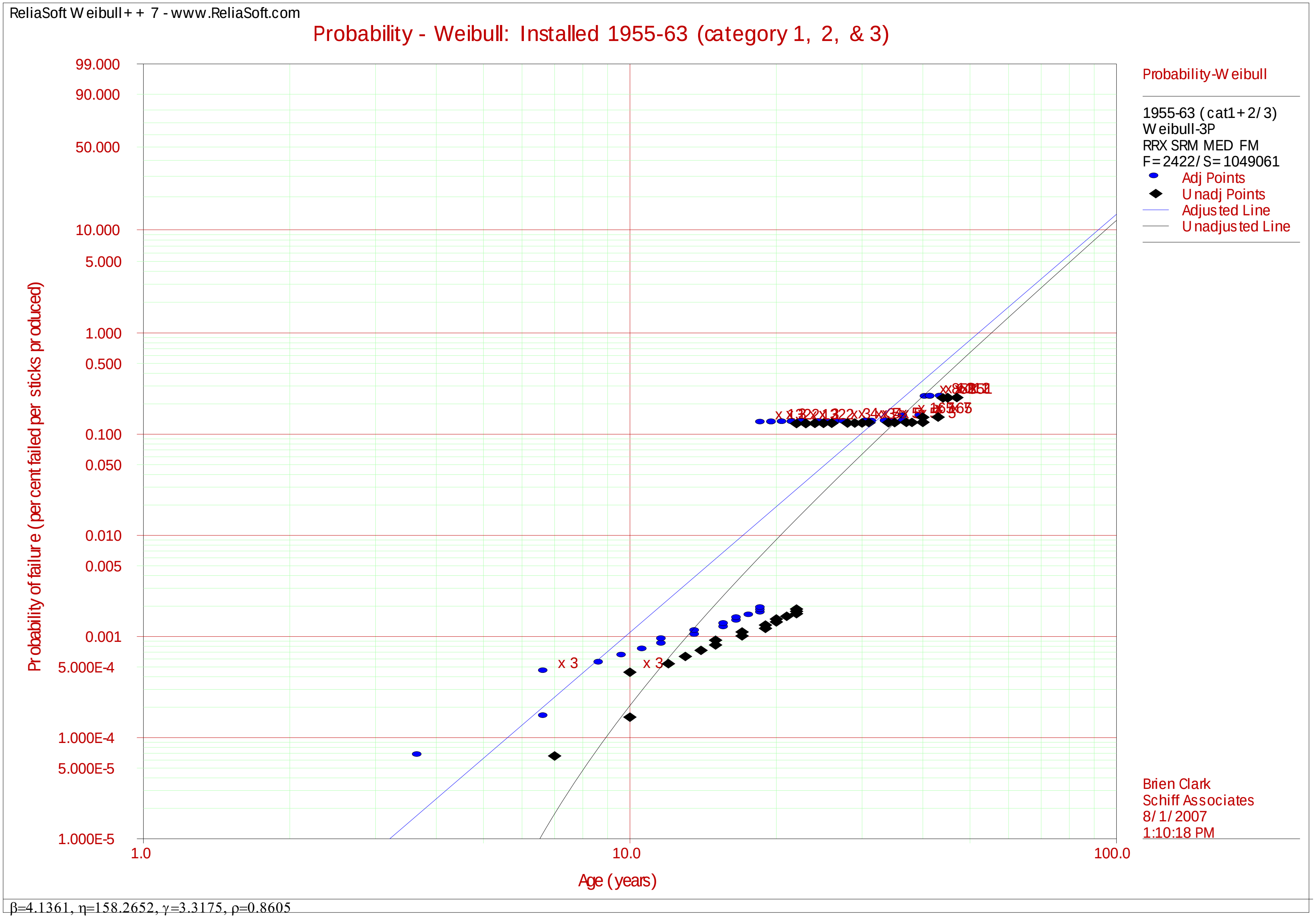

Figure 5.19 Probability – Weibull: installed 1955-63 (Categories 1, 2, and 3)

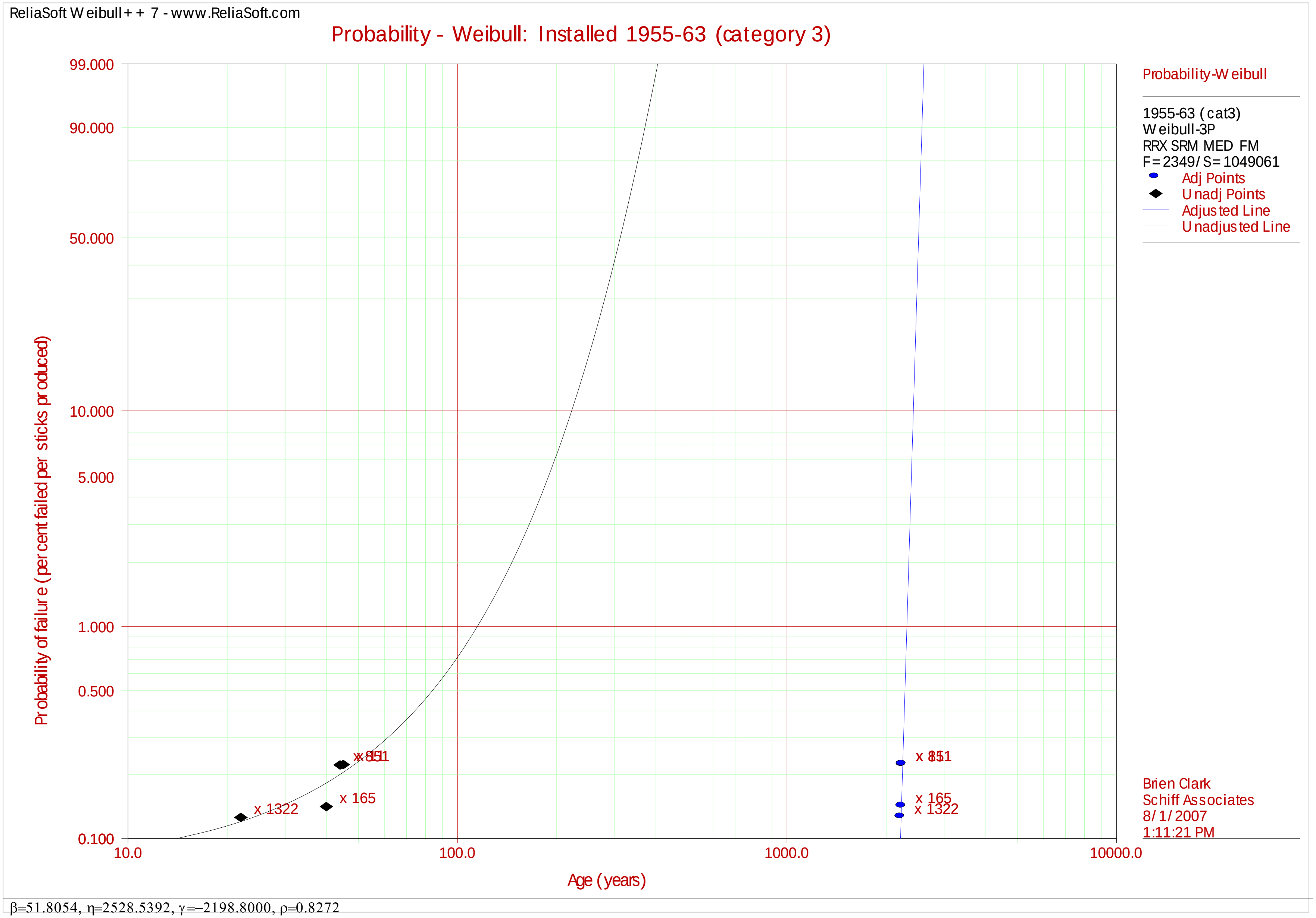

Figure 5.20 Probability – Weibull: installed 1955-63 (Category 3)

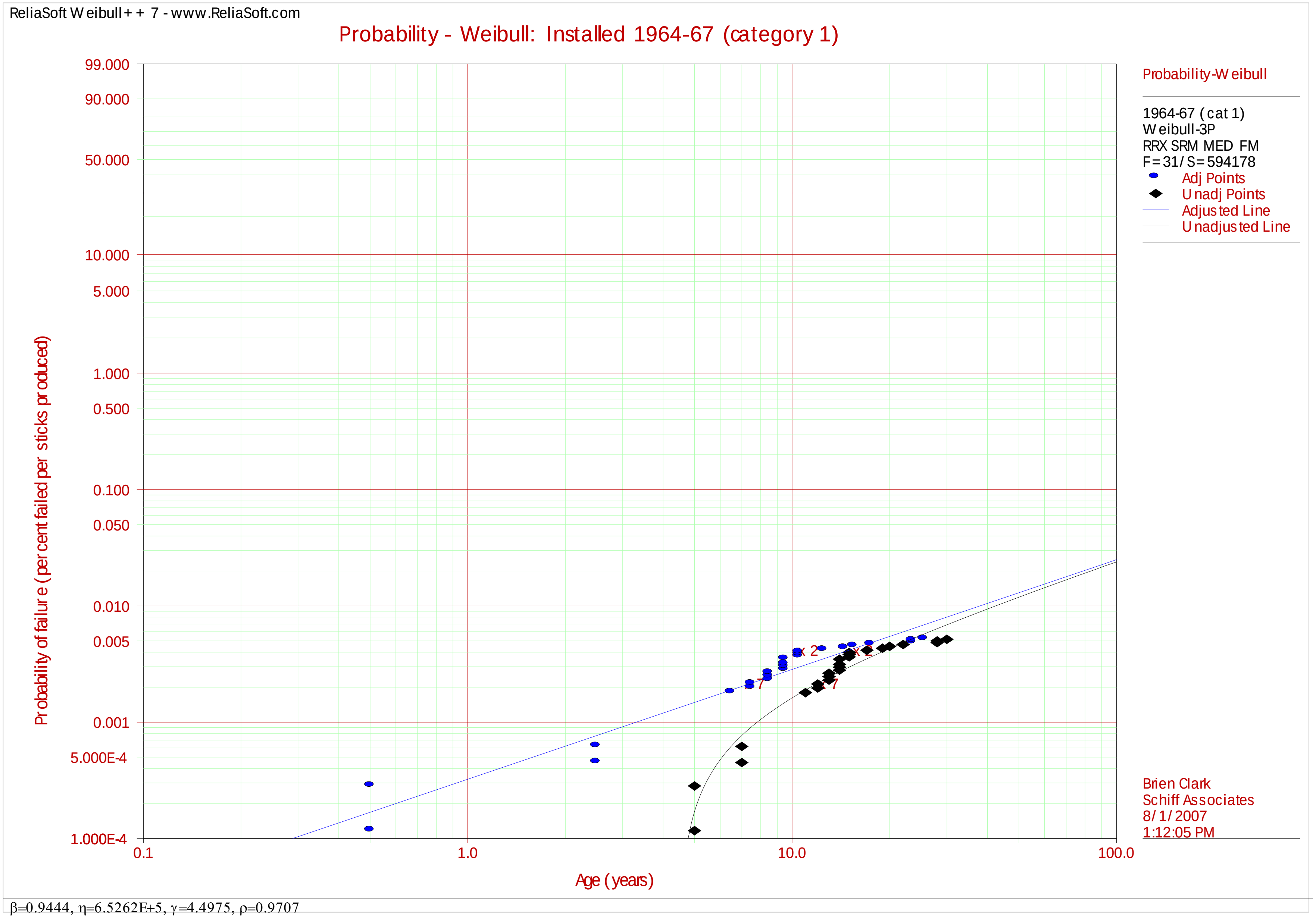

Figure 5.21 Probability – Weibull: installed 1964-67 (Category 1)

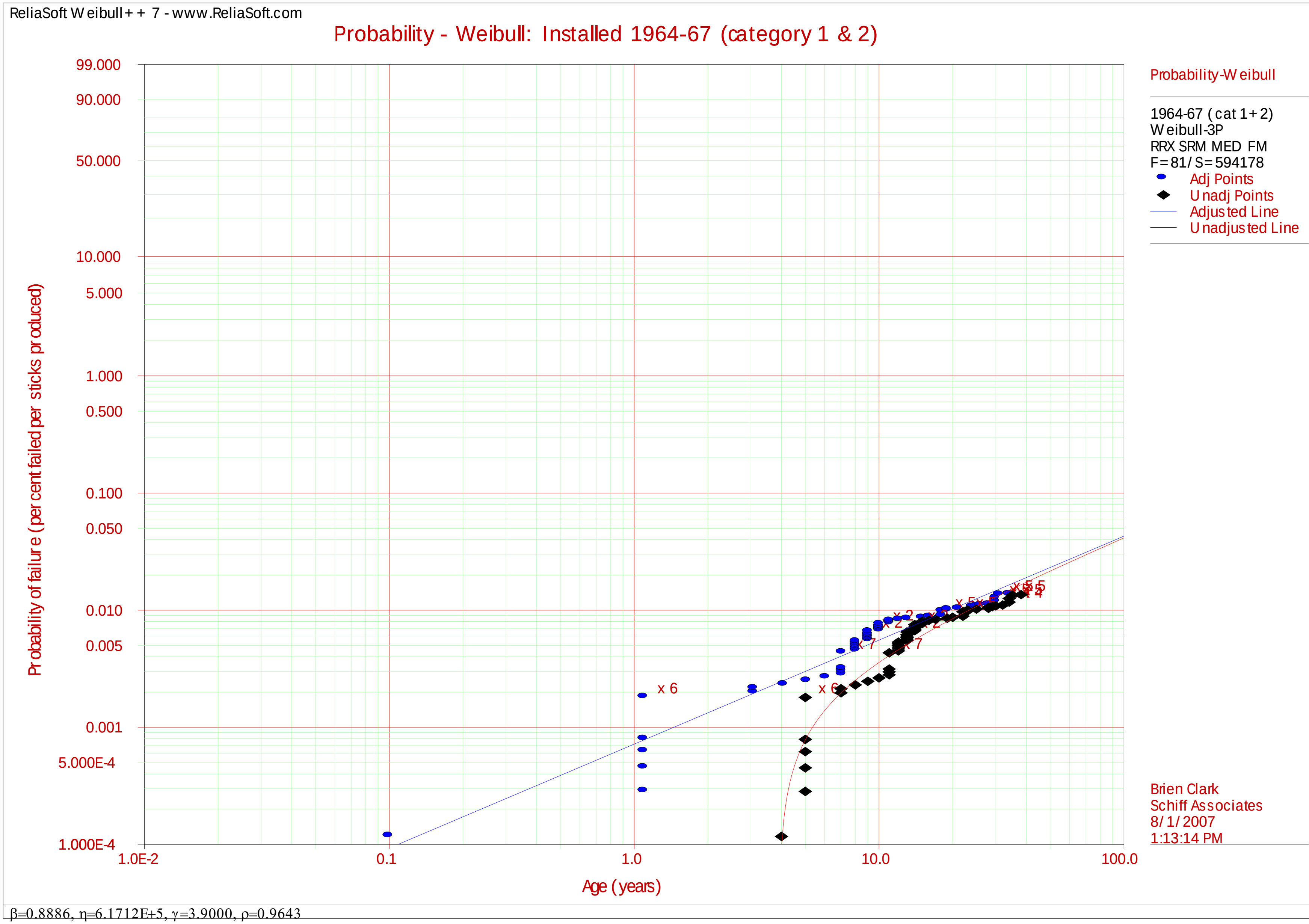

Figure 5.22 Probability – Weibull: installed 1964-67 (Categories 1 and 2)

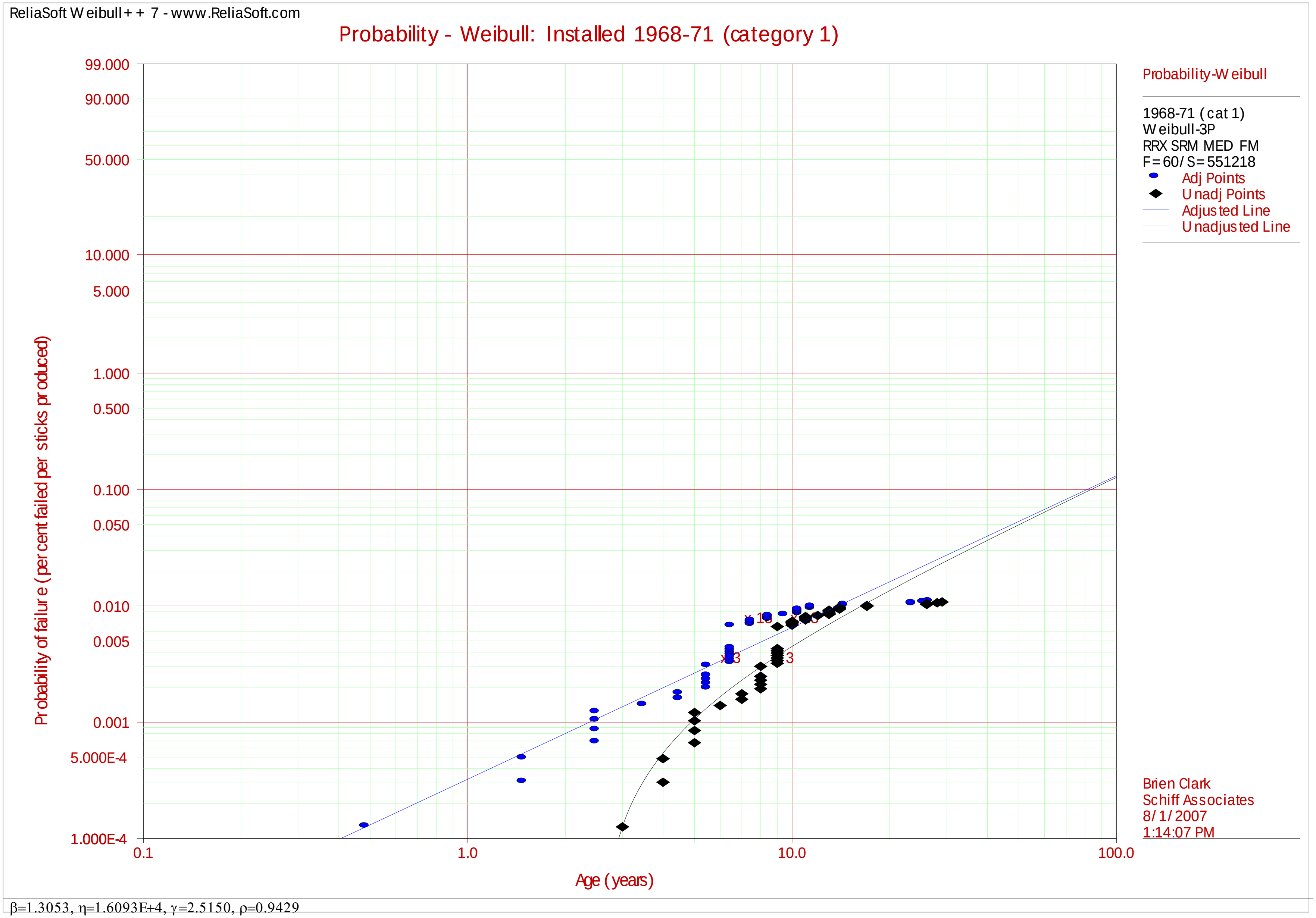

Figure 5.23 Probability – Weibull: installed 1968-71 (Category 1)

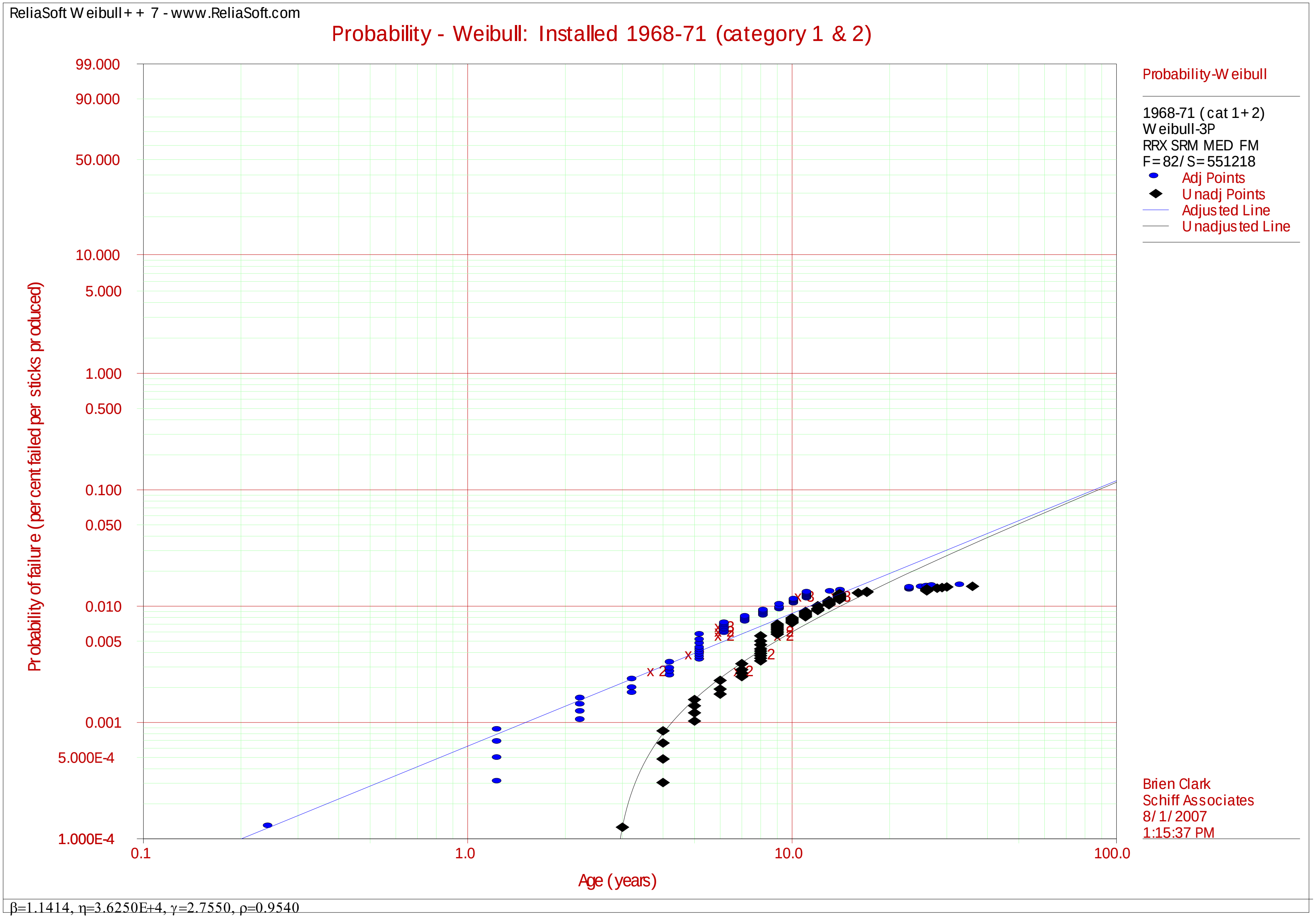

Figure 5.24 Probability – Weibull: installed 1968-71 (Categories 1 and 2)

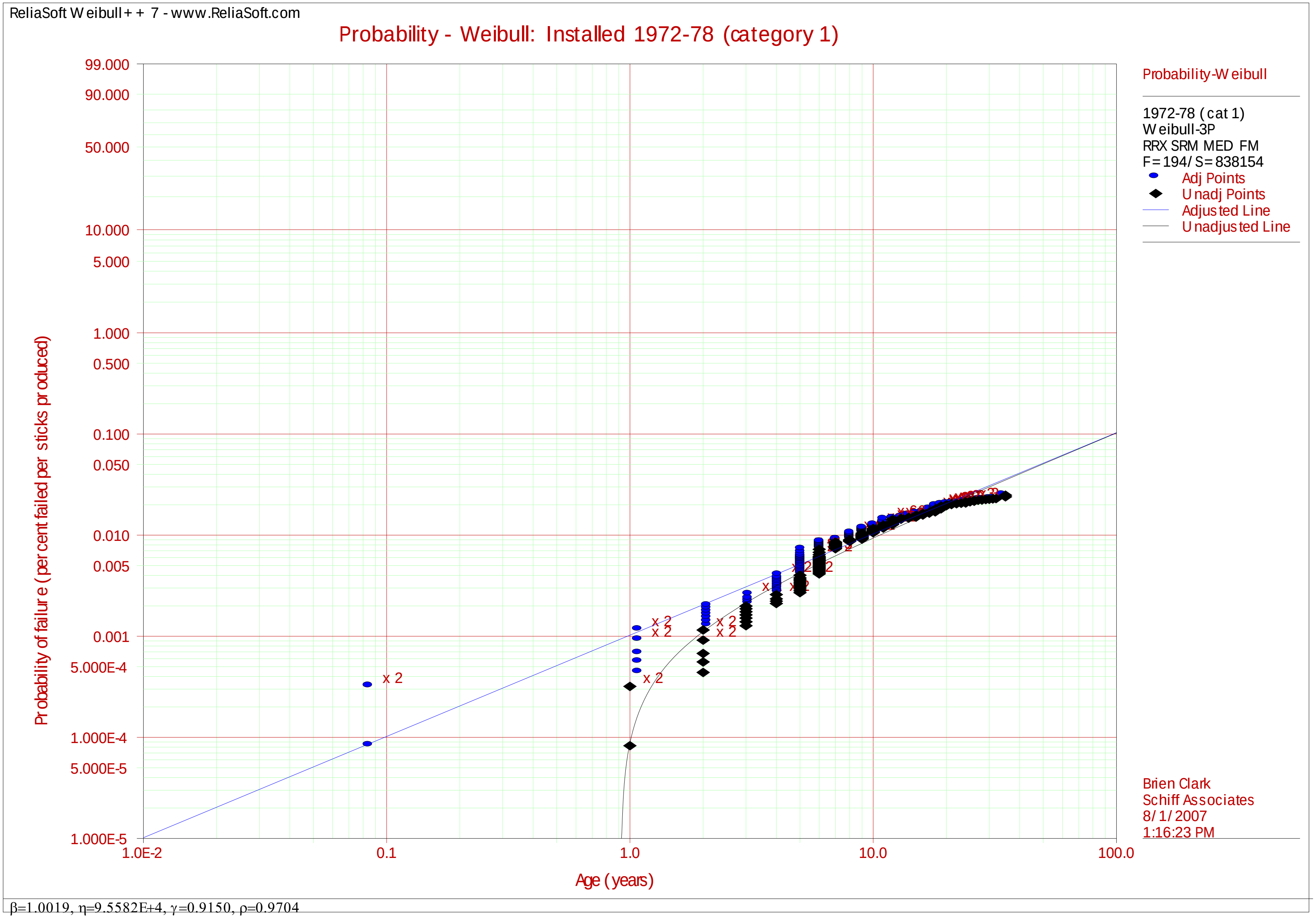

Figure 5.25 Probability – Weibull: installed 1972-78 (Category 1)

Figure 5.26 Probability – Weibull: installed 1972-78 (Categories 1 and 2)

Figure 5.27 Probability – Weibull: installed 1972-78 (Categories 1, 2, and 3)

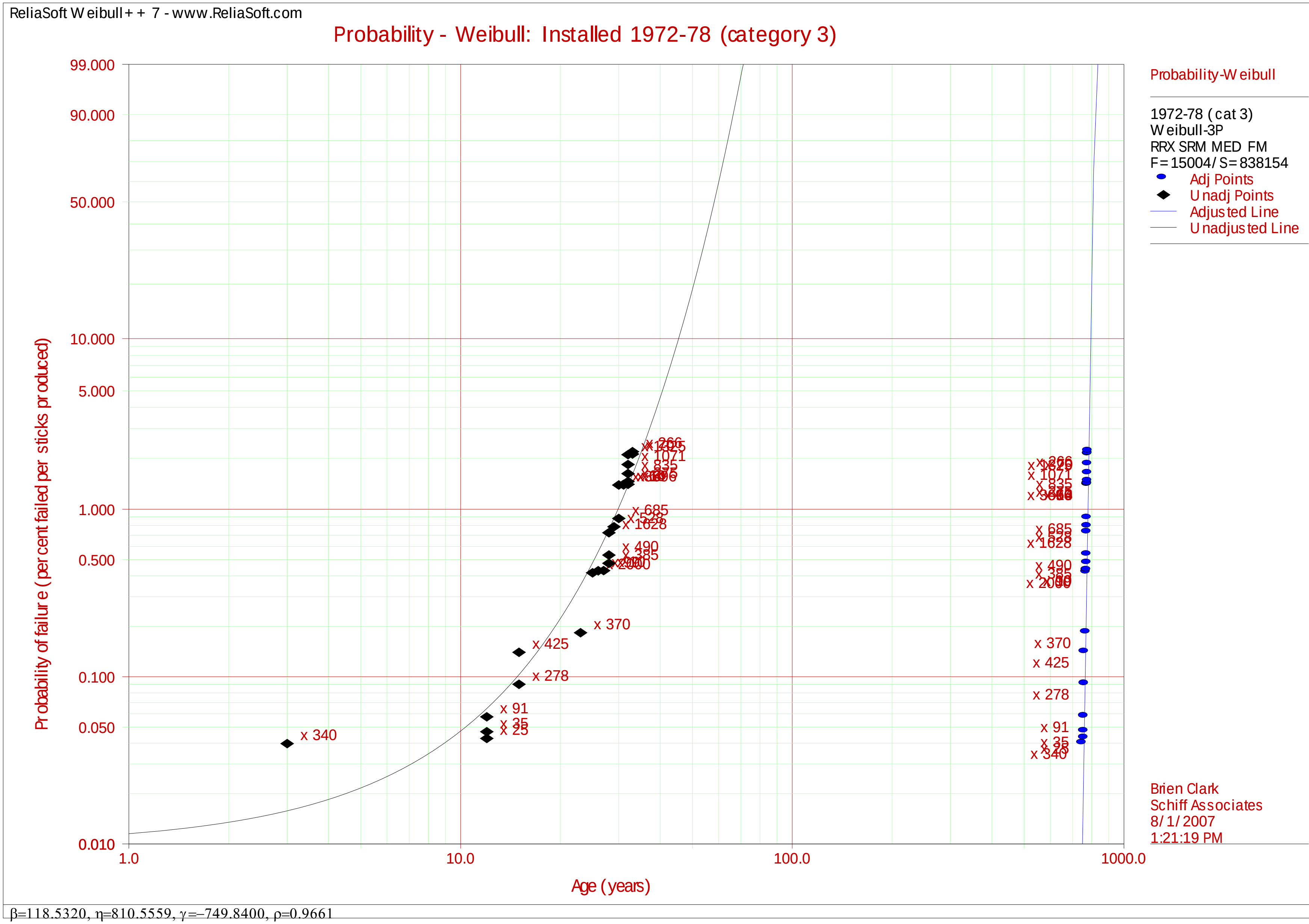

Figure 5.28 Probability – Weibull: installed 1972-78 (Category 3)

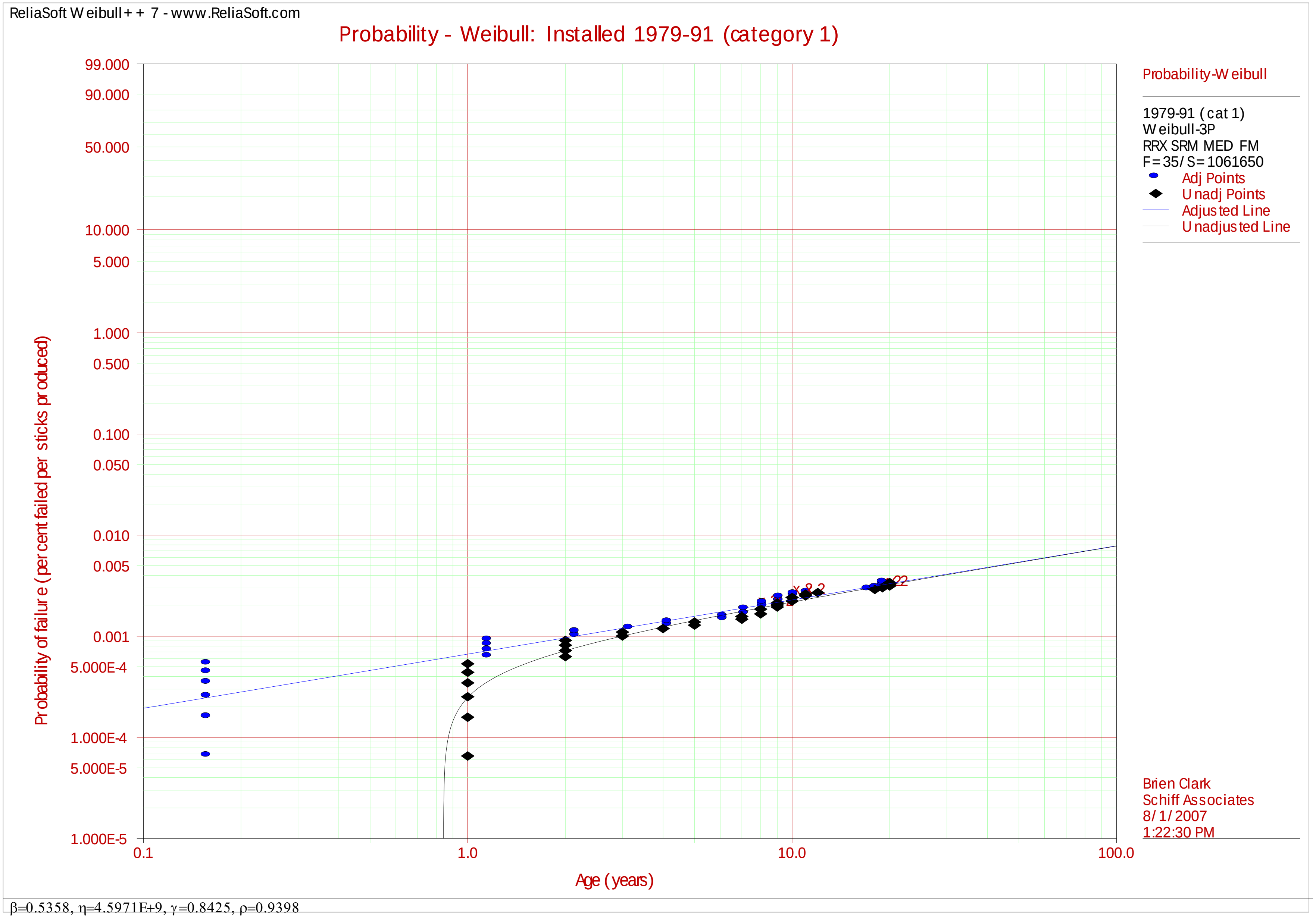

Figure 5.29 Probability – Weibull: installed 1979-91 (Category 1)

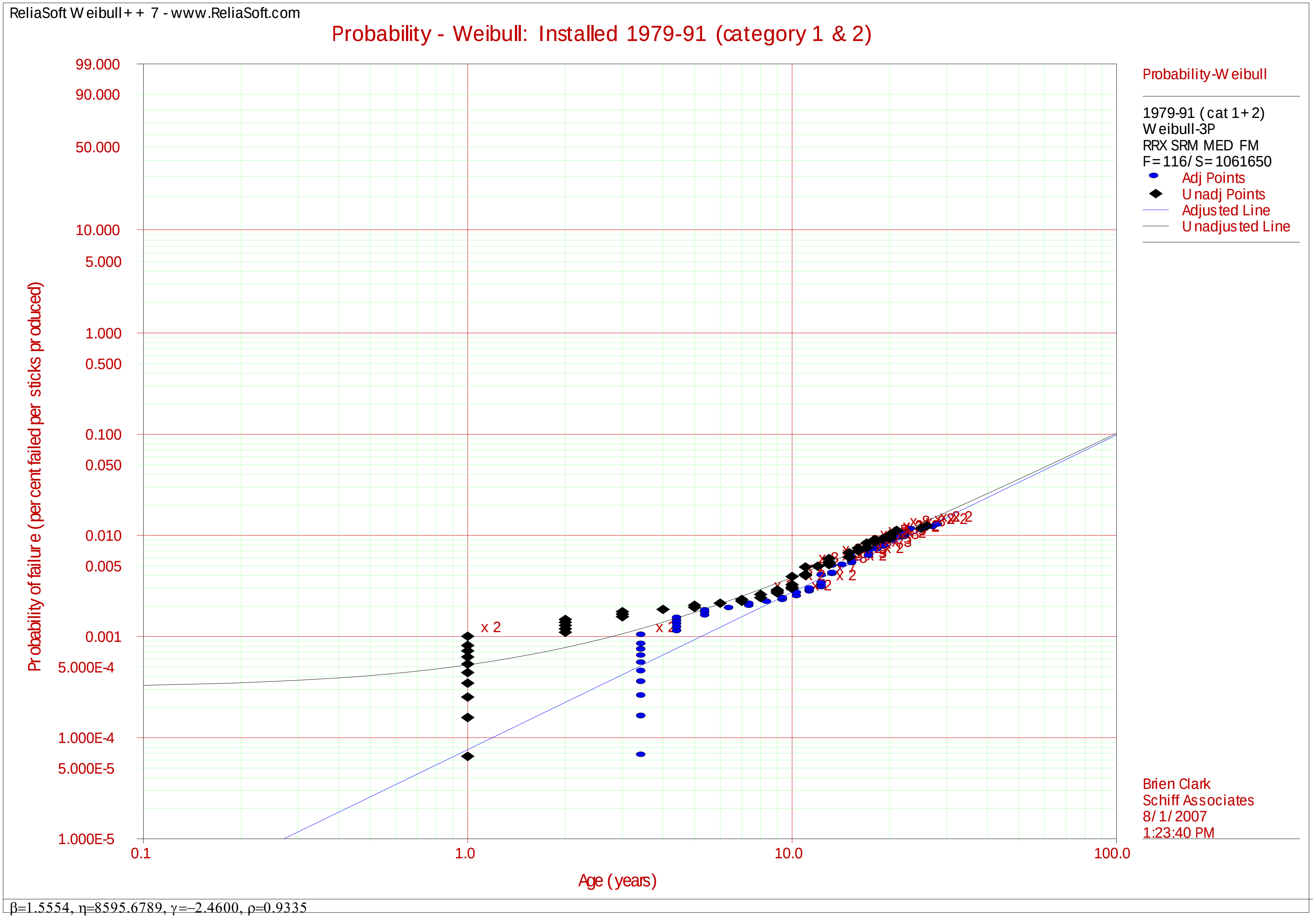

Figure 5.30 Probability – Weibull: installed 1979-91 (Categories 1 and 2)

Figure 5.31 Probability – Weibull: installed 1979-91 (Categories 1, 2, and 3)

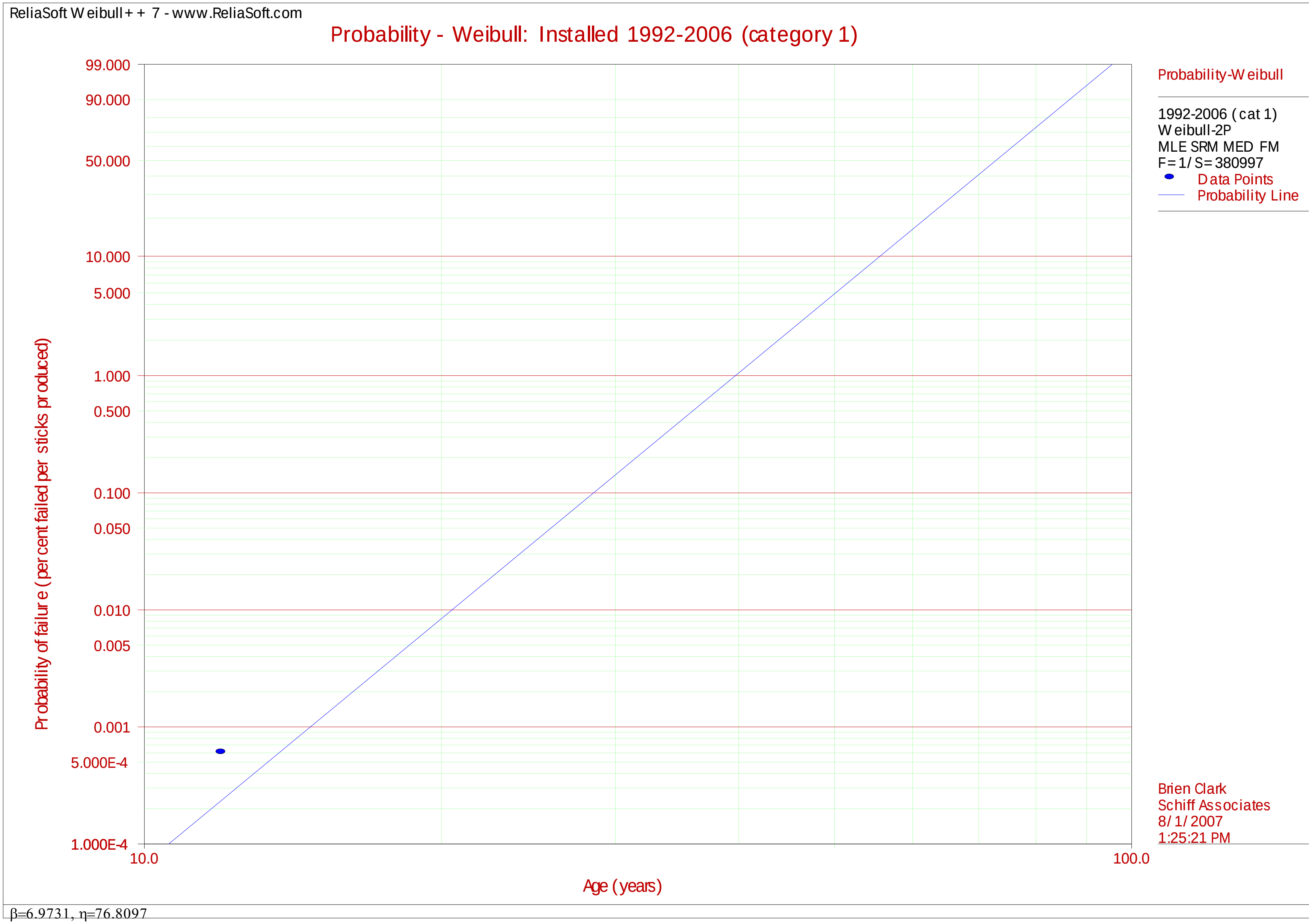

Figure 5.32 Probability – Weibull: installed 1992-2006 (Category 1)

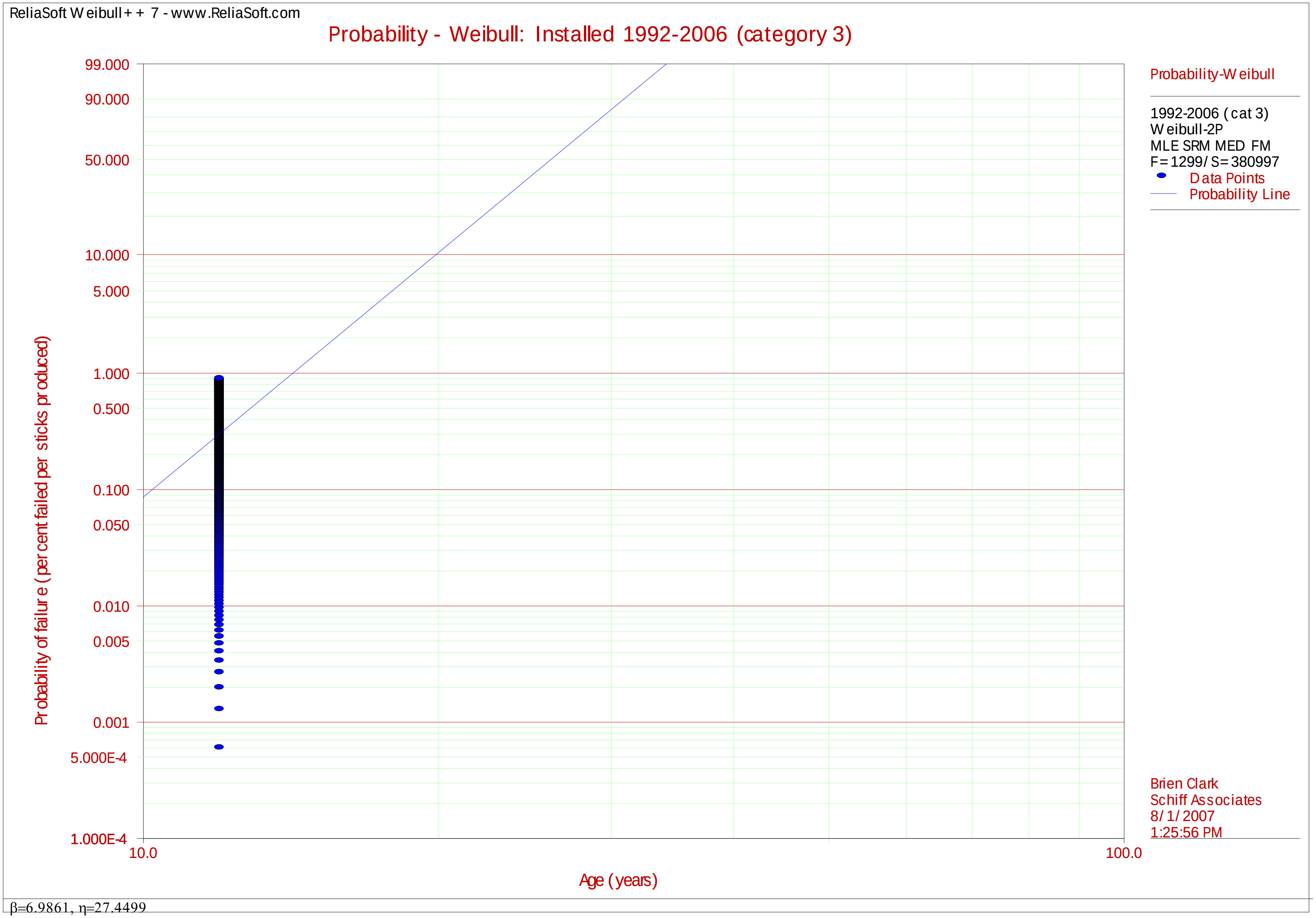

Figure 5.33 Probability – Weibull: installed 1992-2006 (Category 3)

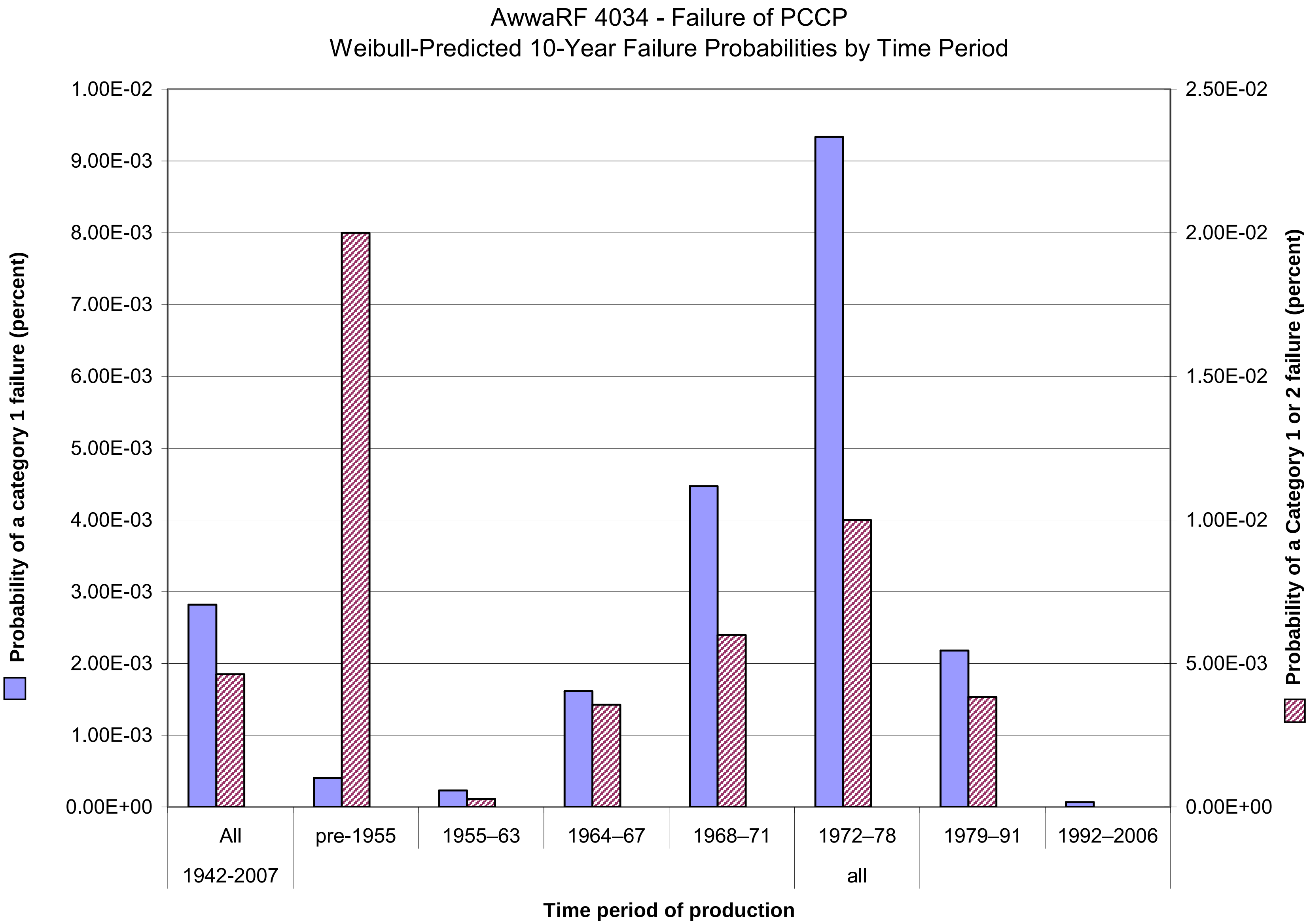

Figure 5.34 Weibull-predicted 10-year failure probabilities by time period

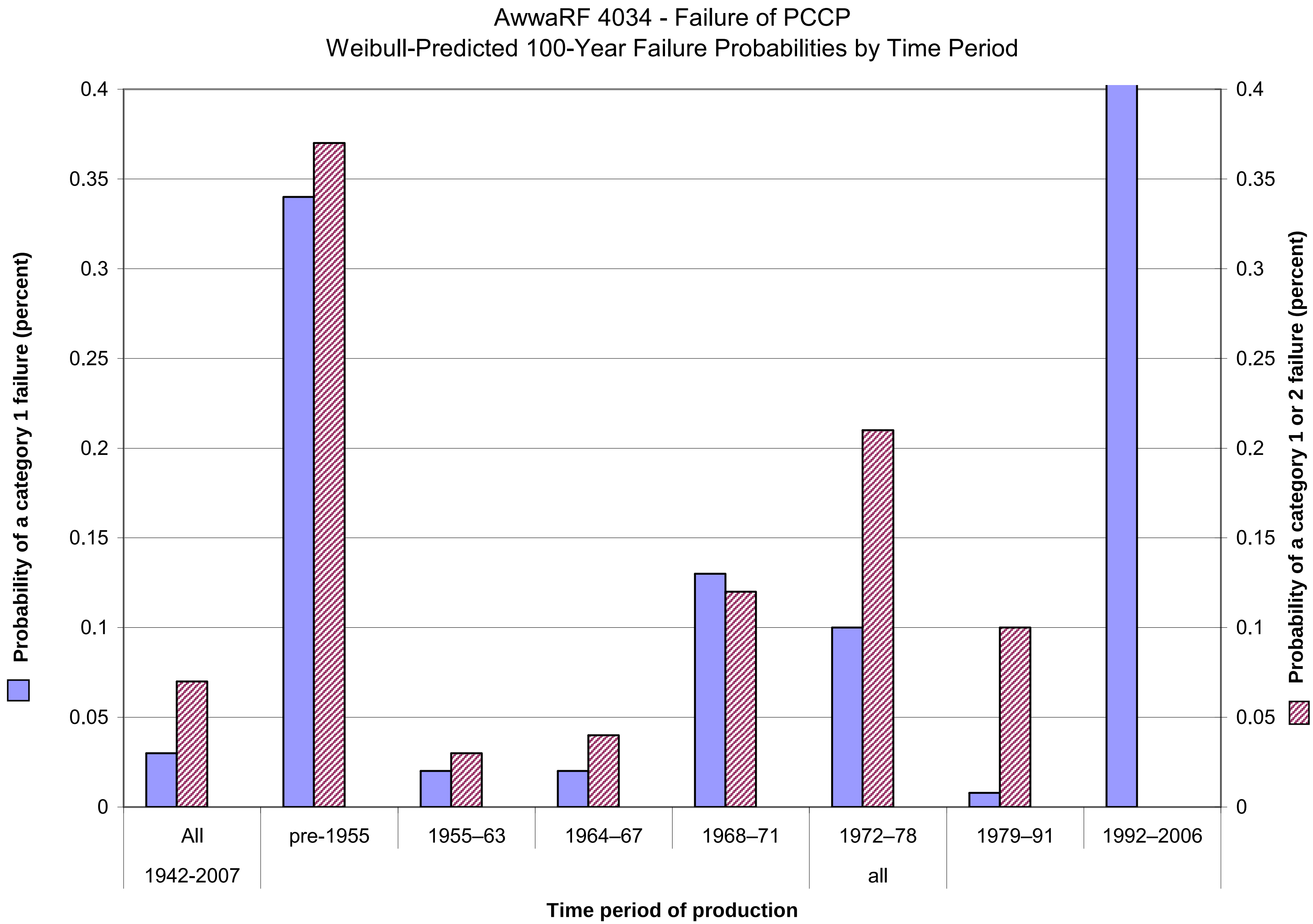

Figure 5.35 Weibull-predicted 100-year failure probabilities by time period

CHAPTER 6
CONCLUSIONS

The research objectives of this AwwaRF project were twofold: 1) development of a general PCCP evaluation matrix, and 2) statistical analysis of PCCP failure data.

A general evaluation matrix to assist water utilities identify PCCP at risk of failure in their systems began with research prepared for the proposal for this project. The matrices developed for both LC-type PCCP and EC-type PCCP provide a tested tool to PCCP-owning utilities. The tool is intended to be utilized as a screening method to allow allocation of resources toward the PCCP at greatest risk of failure within their systems. The resultant matrix is included as Appendix A for this purpose.

The statistical analyses of PCCP failure data took an actuarial or insurance view of the population of PCCP. Based on data made available to the investigators, there was a population of about 100 million feet of PCCP pipe produced between WWII and 2006 in the United States.

The failure data were characterized based on three forms of failure: catastrophic ruptures, failure discerned by inspection, and loss of service which were classified as Category 1, Category 2, and Category 3 failures, respectively. Then the data were grouped based upon the AWWA standard in effect in the year of manufacture. Histograms were prepared that allow both determination of failure frequency by year of manufacture as well as comparison of the relative differences in failure frequency. Statistical analyses of the populations using ogive and Weibull methods allowed preliminary estimates of remaining service life of the PCCP pipelines. The complete failure database (Table 1.1) is provided for independent review and for any future analysis the reader might wish to undertake. Histograms, ogives, bar graphs, and Weibull probability failures are included to assist the PCCP utility owner and are included as Figures 3.1 through 3.20 and Figures 5.1 through 5.35.

From the first issue of PCCP standard 7B.2-T (1949), the AWWA PCCP standards were revised in 1952, 1955, 1958, 1964, 1972, 1979, 1984, 1992, 1999, and 2007. Each of the standards revisions were studied, and 57 items within those which were revised at least once were tabulated and compared, including:

- Size and pressure ranges for EC and LCP
- Quality of concrete and mortar
- Materials and dimensions of steel cylinders
- Materials and dimensions and allowable stresses of wire reinforcement
- Core tolerances
- Joint tolerances
- Coating thickness and quality

Some notable trends were discerned from the material changes in the standards including:

- Initial conservatism in Standard 7.2-T (1949) was increased for some parameters in AWWA C301-52.
- Subsequent revisions to the standard prior to 1984 generally resulted in reduced dimensional minimums and higher effective component stresses until the 1984 revision. The net effect was the highest rate of failure for pipe manufactured between 1967 and 1979. Fully 50 percent of the catastrophic ruptures and leaks recorded were

of pipe manufactured between 1971 and 1979. See Figure 6.1. Most of the pipe inspected and found to be defective (61 percent) were made within the same time frame. See Figure 6.2.

- Significantly increased product requirements were included in AWWA C301-92, and significantly increased design basis complexity was added in AWWA C304-92. The PCCP made to that standard have performed statistically significantly better than their predecessors.

The reasons for PCCP failures are many. They included:

- Rupture or break – broken wires found after the failure – many causes
- Leaking at joints – many causes including out-of-roundness of joint and construction damage
- Cracks in core – many causes including alkali-silica reactivity of the aggregate
- Low quality of core – poor concrete strength
- H_2S (force mains) – unlined
- Dented cylinder – fabrication and construction
- Cracks in cylinder welds – poor cylinder fit-up
- Low quality of wires – not just Type IV
- Overwrapping of wire – inadequate total prestress
- Wire spliced and re-stressed – inadequate total prestress
- Low quality of mortar – low density, low thickness, and low cement content
- High chlorides in soil – corrosive/aggressive soil inappropriate for mortar-coated pipe
- Inadequate joint restraint – pipe moved exposing joint to environment
- Construction damage – coatings damaged and not repaired
- Coating delamination – many causes
- Hydrogen embrittlement of wire – excessive cathodic protection applied to susceptible wire
- Inadequate prestress –wires broken and spliced without re-tensioning – resulting in low core compression
- Cantilever (bending or broken back) – many causes including poor bedding
- Settlement – general and at structures
- Poor bedding – not corresponding to design assumption
- Surge – unanticipated and above design value
- Looped gasket – joint fit-up
- Wrong pipe class – pipe laid out of order
- Cracks in joint welds – poor/no field inspection
- Hydro test pressure in excess of design pressure
- Excess external load – greater than design assumption
- Missing joint coating

This variety of causes is related to the complexity of the product. It requires a good deal of attention during the design, manufacture, installation, and operation in order to be successful. Failure to pay appropriate attention to any part of the design, manufacturing, inspection, construction, and operation of PCCP can lead to failure of the pipeline.

EXPECTED SERVICE LIFE FOR PCCP

As anything gets older, it gets closer to the end of its useful life. The same is true for pipe, it's just that the life expectancy varies by many factors. Life expectancy varies from 50 years, to 100 years, to "indefinite" depending on the perception of the pipeline owner.

Some of the utility's options to assess the service life beyond the statistical methods presented in this report include:

1. Develop a risk-based assessment protocol to determine from that basis which of the utility's PCCP is of the greatest risk for failure. Development of a risk-based assessment is addressed in previous studies (Romer and Bell 2004; Kleiner, Sadiq, and Rajani 2004 and 2005).
2. Reduce operating pressures below cracking stress of the core restrained by the steel cylinder only. If that is not feasible, reduce operating pressures below yield strength of the steel cylinders. Both of these require structural analysis because they are not part of the original design basis. These are short-term actions that may result in a longer time available to investigate and evaluate alternative courses of action.
3. Review the utility's PCCP pipeline operating practices to make sure that rapid variations in pressure, such as due to variable flow rate and valve closure do not occur.
4. Conduct nondestructive evaluations. Those evaluations can include: (a) internal inspection looking for cracks and delamination; (b) internal inspection of the pipe by indirect assessment methods; and (c) acoustic monitoring to determine if wires are actively breaking.
5. Conduct an external inspection of the pipe, by excavation and visual inspection of pipe. At that time, consider removal of coating for petrographic testing of the mortar for soundness and chemical constituents and removal of the coating in the identified area(s) and inspect the wire. The pipeline should be depressurized prior to excavation. Consideration should also be given to having a rehabilitation or replacement plan in-place prior to excavation.
6. Should the investigations and risk assessment, coupled with the corrosion and other assessments result in the need to remediate the pipeline, consideration can be given to (a) structural rehabilitation of selected segments of the pipeline; (b) removal and replacement of selected segments of the pipeline; or (c) replacement of the pipeline.

Each of these options should be evaluated in detail prior to execution. The determination of which option or options may have priority should be aided by a risk-based evaluation (Item 1 above), which is all beyond the scope of this study.

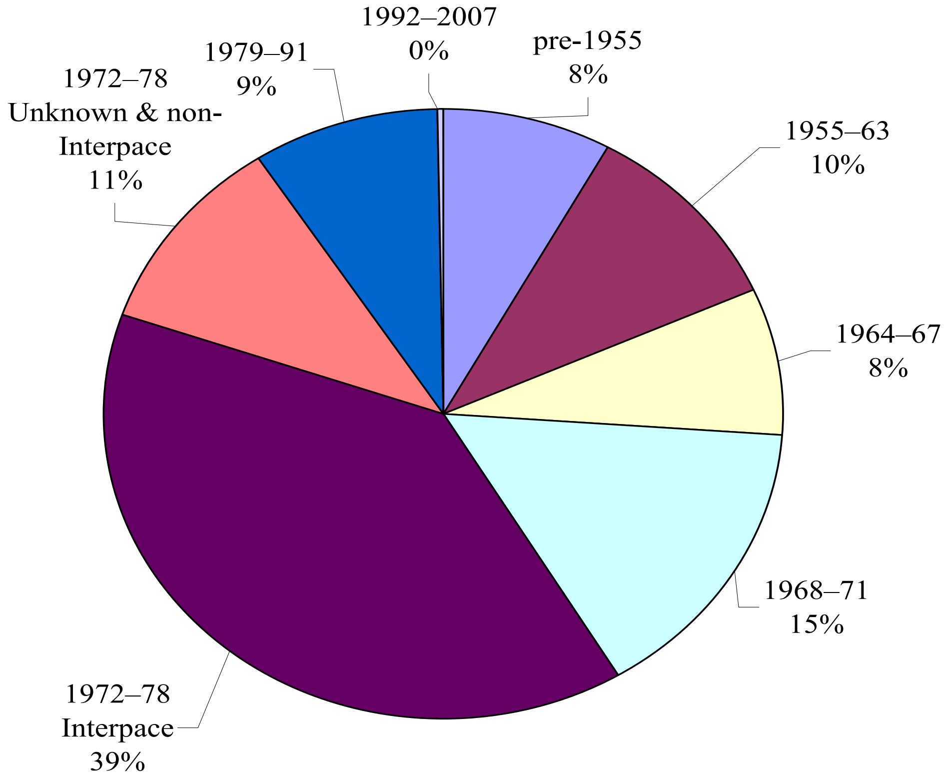

Figure 6.1 Category 1 PCCP failures by manufacturing era

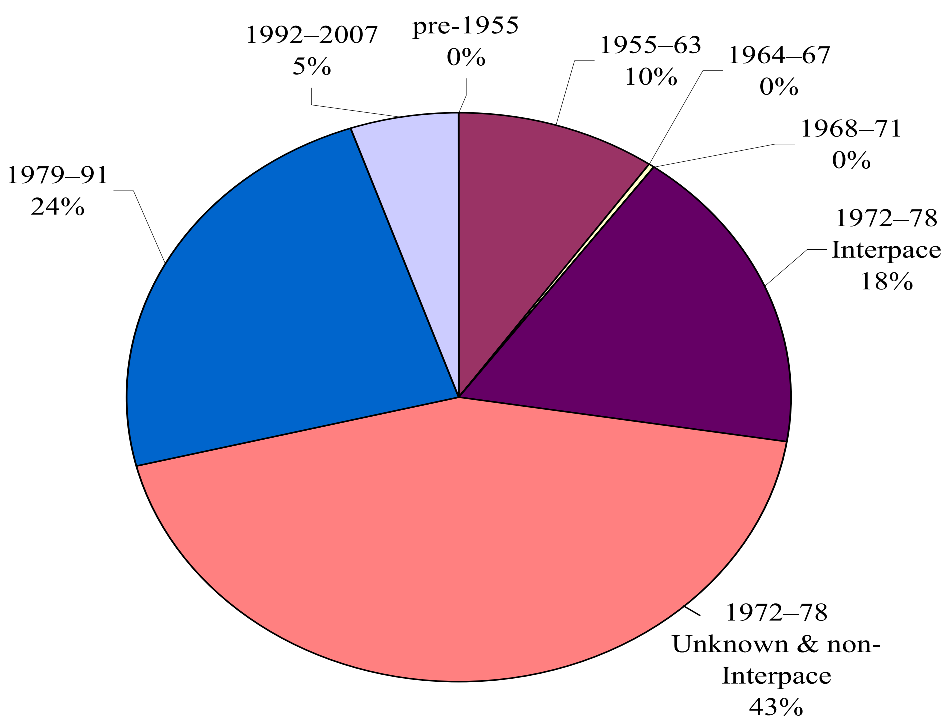

Figure 6.2 PCCP failures by manufacturing era

CHAPTER 7
FUTURE STUDY RECOMMENDATIONS

Future study recommendations:

- Determine effectiveness of NDT examinations of PCCP in reducing the rate and frequency of PCCP failures. The investigators could only determine that the most probable cause of the failure rate reduction in pipe manufactured and installed since 1992 is the increase in conservatism in design and manufacturing since the 1992 standard was adopted.
- Complete the production database by obtaining production data from manufacturers unwilling to cooperate with this study, then revise the statistical analyses.
- Expand the failure database. Utilities not included as participants in this study invariably know of previous failures not listed here. The larger the sample database, the better the statistical analysis and predictive modeling will be. A survey or information request kit may be distributed to collect additional database entries.
- Maintain the failure database. This will require annual funding and the cooperation of the AwwaRF subscribers to contribute data that may otherwise be kept private pending possible litigation. It will be particularly interesting to gain a better insight on performance of LC-PCCP.
- Study the effects of uncontrolled surge on the performance of PCCP. Case studies appear to be the most appropriate approach.
- Study the limits of soil chemistry and resistivity that have been recommended for PCCP longevity and determine their effectiveness. That would include a program of field soil tests and physical examination of successful PCCP pipelines.
- Integrate the statistics developed in this study with a risk management program. A case study or two may be appropriate. The mathematics developed for managing the risk inherent with PCCP pipes must not be daunting to management.
- Determine the cost effectiveness of repair techniques in extending the service life of PCCP.

APPENDIX A:
QUALITATIVE ASSESSMENT MATRIX

Appendix A1: Short Form

Assessment of Prestressed Concrete Cylinder Pipe

	Pipeline:			
	Diameter (in) :			
	Pressure Range (psi):			
		Score		
No.	**Factor**	**NO** (score -1)	**DON'T KNOW** (score 0)	**YES** (score +1)
1	Was the pipeline constructed prior to 1964 or after 1992?			
2	Is the pipe manufacturer still in business on the site at which the pipe was made?			
3	Is the pipe constructed with 6 gauge (0.192" diameter) or larger wire? (Score this -1 if the pipe constructed with 8 gauge (0.162" diameter) wire.)			
4	Was inspection done at the manufacturing site and at the time of installation by the owner or the owner's consulting engineer?			
5	Is surge unlikely on the pipeline? (Score -1 if pumped flow or other condition where surge is likely)			
	Subtotals	0	0	0
	Total Assessment Score		0	

Brief description of pipeline:

Appendix A2: Long Form Failure Assessment of Prestressed Concrete Cylinder Pipe				
	Pipeline:			
	Diameter (in) :			
	Pressure Range (psi):			
		Score		
No.	**Question**	**NO** (score -1)	**DON'T KNOW** (score 0)	**YES** (score +1)
	Factors which may indicate an appropriate DESIGN basis:			
1	Did the project specification include requirements in addition to AWWA Standard C301 or the USBR std. spec?			
2	Did the Project Contract Documents include minimum design requirements (wire size and spacing, etc.?) (Score this -1 if the pipe manufacturer submitted the design.)			
3	Was the design bedding angle less than or equal to 90 degrees? (score this -1 if 120 degree bedding angle or greater was assumed.)			
	Factors which may indicate an appropriate MANUFACTURING quality:			
4	Is the pipe manufacturer still in business?			
5	Was the pipeline constructed prior to 1964 or after 1992?			
6	Was the pipe manufactured in a fixed plant? (Score this -1 if the pipe was manufactured on-site)			
7	Is the prestressing wire Class I or Class II? (Score this -1 if Class III or Class IV.)			
8	Is all the reinforcing wire $\geq$ No. 6? (Score this -1 if No. 8 wire was used.)			
9	Is the steel cylinder 16 ga. or thicker? (Score this -1 if 18 ga. cylinder is used.)			
10	Is the design wire stress ratio $\leq$ 70%? (Score this -1 if 75% of ultimate strength.)			
11	Is the coating, cast or mortar, at least 7/8 inch thick?			
12	Was mortar slurry placed under the prestressing wires? (This was required after 1984.)			
13	Were bonding straps placed under wires to allow corrosion monitoring? (Score this +1 if shorting cables were installed between pipe segments.)			
	Factors which may indicate appropriate INSPECTION was done:			

Appendix A2: Long Form
Failure Assessment of Prestressed Concrete Cylinder Pipe

	Pipeline:			
	Diameter (in) :			
	Pressure Range (psi):			
		Score		
No.	**Question**	**NO** (score -1)	**DON'T KNOW** (score 0)	**YES** (score +1)
14	Were pipe design submittals provided for review by owner?			
15	Was documentation of inspection & testing by manufacturer submitted to the owner for review?			
16	Was any manufacturing inspection done by the owner or owner's engineer?			
17	Was any on-site construction inspection done by the owner or owner's engineer?			
18	Were wire tests done in accordance with the then-current standards (i.e. mill certificates) and submitted to the owner for review?			
19	Did the pipe manufacturer provide on-site assistance to the installation contractor?			
	Factors which may indicate that appropriate care was taken during CONSTRUCTION:			
20	Was the pipe placed on shaped bedding? (90 deg. shaped bedding is the typical design assumption.)			
21	Was imported material utilized for bedding? (Score this -1 if native soils were used for bedding.)			
22	Was the hydrostatic test passed on the first attempt? (May otherwise be indicative of rolled gaskets.)			
23	Was the hydrostatic test pressure no more than 20% over the design operating pressure?			
24	Were joint bonds installed and tested?			
25	(If yes to the above question) Is the pipeline electrically isolated from other pipelines?			
26	Were joints welded for thrust restraint? (Score this -1 if bolted joint restraints, which allow slight movement, were used.)			
27	Were joints mortared inside and out?			
	Factors which may indicate appropriate OPERATION and MAINTENANCE:			
28	Is surge unlikely on the pipeline? (Score -1 if pumped flow or other condition where surge is likely)			

	Appendix A2: Long Form Failure Assessment of Prestressed Concrete Cylinder Pipe			
	Pipeline:			
	Diameter (in) :			
	Pressure Range (psi):			
		Score		
No.	Question	NO (score -1)	DON'T KNOW (score 0)	YES (score +1)
29	Is the earth fill over the pipeline substantially unchanged from when it was constructed?			
30	Is the pipeline subject to regular corrosion monitoring?			
31	If cathodic protection is applied, is the voltage applied < 850 mv? (Score this -1 if > 1000 mv and score it 0 if between these values or no C-P.)			
	Other Factors which may indicate CONDITION:			
32	The pipeline has experienced neither a leak nor a break. (Score this -1 if it has leaked, etc.)			
33	If an internal inspection has been done (of any type) there is little or no indication of damage/cracks/spalls/broken wires. (Score this -1 if damage/cracks/spalls/broken wires are indicated.)			
34	If soil corrosivity tests were performed were all laboratory saturated soil esistivities greater than 1000 ohm-cm or field resistivities greater than 1500 ohm-cm found at pipe depth?			
35	If soil chemistry tests were performed were all chloride levels less than 350 ppm (mg/kg)?			
36	If soil chemistry tests were performed were pH values greater than 5.5 ?			
37	If close interval pipe to soil potentials have been measured, are any areas greater than 50 feet in length more negative than -300 millivolts to copper-copper sulfate?			
38	Groundwater levels are stable. (Score this -1 if any portion of the pipeline is in an area of fluctuating groundwater levels.)			
	Subtotals	0	0	0
	Total Assessment Score		0	

Brief description of pipeline:

GLOSSARY

Accelerator:	A chemical substance that increases the rate at which a chemical reaction (e.g., curing) would otherwise occur.
Active:	(1) The negative direction of electrode potential. (2) A state of a metal that is corroding without significant influence of reaction product.
Alkyd:	Type of resin formed by the reaction of polyhydric alcohols and polybasic acids, part of which is derived from saturated or unsaturated oils or fats.
Anerobic:	Free of air or uncombined oxygen.
Anion:	A negatively charged ion that migrates through the electrolyte toward the anode under the influence of a potential gradient.
Austenitic Steel:	A steel whose microstructure at room temperature consists predominantly of austenite.
Anode:	(1) Corrosion: The electrode of a corrosion cell that has the greater tendency to corrode or oxidize. (2) Cathodic Protection: The expendable materials, which is buried and through which direct current flows into the soil. Common materials used for this purpose are graphite, high silicon iron, magnesium, zinc, and scrap iron.
Anode Field:	The area in which the soil potential is raised because of current flow away from a ground electrode (anode). The extent of this influence is a function of soil resistivity and the magnitude of current flow.
Anodic Interference:	Current discharge from a structure caused by current pickup in an anodic area. The current pickup results from a raised soil potential due to the concentration of current flowing in the soil away from an anode. Not always a problem, can be soil attenuation effect only.
Backfill:	The material (such as sand) which is placed around a buried pipeline. Also, the material which is placed around anodes to ensure uniform current discharge and to extend the useful life of the anode. Coal coke or petroleum coke is used in conjunction with carbon or duriron anodes, while a mixture of gypsum, bentonite and salt is used with zinc, magnesium, and scrap iron anodes.

Bituminous Coating:	An asphalt or coal-tar compound used to provide a protective coating for a surface.
Cathode:	The electrode of a corrosion cell where a net reduction reaction occurs. In corrosion processes, the cathode is usually that area which does not corrode.
Cathode Field:	The area in which the structure to soil potential is lowered because of current flow. The extent of this influence is a function of soil resistivity and current density in the soil.
Cathodic Disbondment:	The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction, typically hydrogen.
Cathodic Interference:	Current discharge from one structure caused by an adjacent soil potential which results from a concentration of protection current flowing to an adjacent bare or poorly coated structure.
Cathodic Polarization:	That portion of the polarization of a cell which occurs at the cathode.
Cathodic Protection:	Reduction or prevention of corrosion of a metal surface by making it cathodic, for example, by the use of sacrificial anodes or impressed current rectifier protection systems. In cathodic protection, the structure is made a part of an external electrical circuit in which sufficient direct current flows through the surrounding electrolyte, from an external anode, into the surrounding electrolyte, from an external anode, into the structure. This current opposes the corrosion cell currents discharged at the anodic (-) areas and the entire surface of the structure is changed to a cathodic (+) or protected state; hence the name “cathodic protection.”
Cation:	A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient.
Cell:	A circuit consisting of an anode and a cathode in electrical contact in a solid or liquid electrolyte. Corrosion generally occurs only at anodic areas. Examples – Concentration Cell: A corrosion cell due to the potential difference between the anode and cathode caused by differences in composition of electrolyte. Local Cell: A galvanic cell caused by small differences in composition in the metal or the electrolyte. Oxygen Concentration Cell: A galvanic cell caused by a difference in oxygen concentration at two points on a metal surface.

Coating: A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Coating Resistance: The electrical resistance of a coating to the flow of current. Unit of measurement is ohms per square foot. Values range from 1,000 to more than 1,000,000 ohms per square foot for conventional organic coatings.

Concentration Cell: An electrochemical cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. (This difference leads to the formation of discrete cathodic and anodic regions.)

Contact: A term used to describe an undesired metal-to-metal junction between two different structures underground or defective and bypassed meter or flange insulation.

Copper- Copper Sulfate Electrode: A standard or reference electrode used for determining potentials of metals in soils or other electrolytes. It is the reference half-cell used most in the field of corrosion. The half-cell, as it is known, is called a saturated cooper-copper sulfate reference electrode. This is written as such, $CuCuSO_4$. The first Cu stands for the copper core which is centered in the phenolic holder. The $CuSO_4$ represents the copper sulfate solution that is used to provide contact between the porous end plug and the copper core. The term half-cell is used because the electrode is only half of what is required to have a readable circuit.

With proper instrumentation, this half-cell can be used for many measurements. The most common being the structure to soil potential. This difference is created by the current flow through the electrolyte (soil, water, etc.) around the structure and the resistance between the point of reference and the structure.

If the structure is well coated, the half-cell is normally placed directly over the structure because most of the resistance between the structure and earth consists of the resistance of the coating itself. With a bare or poorly coated structure, the resistance between structure and earth consists of the contact resistance of the earth mass surrounding the structure. This means that to read the maximum potential between the structure and the reference it becomes necessary to place the half-cell far enough away to compensate for the major part of this resistance.

When the half-cell is remote and the degree of cathodic protection is being measured, both the on (current being drained) and off potentials should be obtained. This will then indicate the degree of polarization or holding potential for the subject structure.

Other uses will not be recapped; however, their use with the Vibroground and other meters for stray current surveys may be required at a later date.

Corrosion:	The deterioration of a material or its properties, usually a metal, resulting from a reaction with its environment.
Corrosion Inhibitor:	A chemical substance or combination of substances that, when present in the environment, prevents or reduces corrosion.
Corrosion Rate:	The rate at which corrosion damage proceeds.
Corrosion Potential (Ecorr):	The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as rest potential, open-circuit potential, freely corroding potential, or free-corrosion potential).
Corrosion Resistance:	Property of a material, usually a metal, to withstand corrosion in a given environment.
Corrosivity:	The tendency of an environment to cause corrosion.
Crevice Corrosion:	Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity of the metal to the surface of another material.
Critical Pitting Potential (Ep, Epp):	The lowest value of oxidizing potential (voltage) at which pits nucleate and grow. The value depends on the test method used.
Curing:	Chemical process of developing the intended properties of a coating or other material (e.g., resin) over a period of time.
Current Density:	The current per unit area of metallic surface, usually expressed in terms of milliamperes per square foot.
Deep Grounded:	One or more anodes installed vertically at a nominal depth of 15 meters (50 feet) or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection.
Depolarization:	The removal of factor resisting the current in an electrochemical cell.
Dielectric Coating:	A coating that does not conduct electricity.

Disbondment: The loss of adhesion between a coating and the substrate.

Drain-Drainage: Conduction of current from an underground metallic structure by means of a metallic conductor to another underground structure, usually by deliberate design, and/or conduction of current from an underground metallic structure to a cathodic protection station.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electro-Negative: A term used to designate the metal most likely to corrode in a bimetallic corrosion cell. Magnesium and zinc, for instance, are electro-negative with respect to copper or steel. In the same relationship, copper and steel are electro-positive.

Electrochemical Cell: A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

Electrolysis: The production of a chemical change in an electrolyte resulting from the passage of electricity and often traditionally used to describe any and all forms of corrosion.

Electrolyte: An ionized chemical substance or mixture that will conduct electric current, such as water, soil, and many chemical solutions.

Electrode: Either the corroding or noncorroding portion of a corrosion cell; see anode or cathode, whichever is appropriate. Also, used loosely to describe half cells such as the copper-copper sulfate, silver-silver chloride, and the calomel reference electrodes.

Embrittlement: Loss of ductility of a material resulting from a chemical or physical change.

Enamel: (1) A paint that dries to a hard, glossy surface.

(2) A coating that is characterized by an ability to form a smooth, durable film.

Epoxy: Type of resin formed by the reaction of aliphatic or aromatic polyols (like bisphenol) with epichlorohydrin and characterized by the presence of reactive oxirane end groups.

Ferrite: The body-centered cubic crystalline phase of iron-based alloys.

Film: A thin, not necessarily visible layer of material.

Galvanic Cell:	A cell in which chemical change activates the source of electric current. It usually consists of two dissimilar metals in contact with one another, in a uniform or varying electrolyte, or two similar metals in a dissimilar electrolyte.
Galvanic Series:	A list of metals and alloys arranged according to their relative potentials in a given environment.
Graphitic Corrosion:	Deterioration of cast iron alloys in which the metallic constituents are selectively leached or converted to corrosion products, leaving the graphite intact.
Graphitization:	The formation of graphite in iron or steel, usually from decomposition of iron carbide at elevated temperatures.
Grit:	Small particles of hard material (e.g., iron, steel, or mineral) with irregular shapes that are commonly used as an abrasive in abrasive blast cleaning.
Grit Blasting:	Abrasive blast cleaning using grit as the abrasive.
Groundbed:	One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.
Half-Cell:	A pure metal in contact with a solution of known concentration of its own ion, at a specific temperature, develops a potential that is characteristic and reproducible; when coupled with another half-cell, an overall potential that is the sum of both half-cells develops.
Holidays:	A break or imperfection in a coating exposing the substrate or base metal.
Hydrogen Embrittlement:	A loss of ductility of a metal resulting from absorption of hydrogen.
Hydrogen Stress Cracking:	Cracking that results from the presence of hydrogen in a metal in combination with tensile stress. It occurs most frequently with high-strength alloys.
Impressed Current:	Cathodic protection current provided by rectifier-type protective systems.
Inclusion:	A nonmetallic phase such as an oxide, sulfide, or silicate particle in a metal.
Inorganic Zinc-Rich Coating:	Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an inorganic vehicle.

Insulation: Fittings (e.g., unions, coupling, flanges) which permit metallic separation of one section of structure from another without disturbing the mechanical continuity and/or material used to provide physical separation between external surfaces of structures.

Ion: An ion is an atom or molecule normally electrically neutral that gains or loses one or more electrons or protons.

Long Line Current: Current flowing through the earth from an anodic to a cathodic area and then returning through an underground metallic structure. Usually found in areas where structures are continuous for a considerable distance and where the current results from galvanic cell or foreign action.

Mill Scale: The oxide layer formed during hot fabrication or heat treatment of metals.

Noble: The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.

Noble Metal: (1) A metal that occurs commonly in nature in the free state.

(2) A metal or alloy whose corrosion products are formed with a small negative or a positive free-energy change.

Noble Potential: A metal is said to exhibit a noble potential when it is cathodic to other metals. Copper is noble compared to magnesium. This term is analogous to electro-positive.

Ogive: An X-Y plot line graph of a cumulative frequency or cumulative relative frequency distribution often presented in percentages. An ogive has the following components:

A title, which identifies the population or sample.

A vertical scale, which identifies either the cumulative frequencies or the cumulative relative frequencies.

A horizontal scale, which identifies the upper class boundaries. The horizontal scale for an ogive is always based on the upper class boundaries.

The main use of an ogive is to estimate percentiles. The twentieth percentile is the value below which 20 percent of the data falls. Important percentiles are the median (50 percent), lower quartile (25 percent), and upper quartile (75 percent).

Open Circuit Potential:	The measured potential of a cell from which no current flows in the external circuit. Can also be defined as the potential differential between two separate poles.
Organic Zinc-Rich Coating:	Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an organic resin.
Oxidation:	(1) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures.
Oxidation-Reduction Potential:	The potential of a reversible oxidation-reduction electrode measured with respect to a reference electrode, corrected to the hydrogen electrode, in a given electrolyte.
Paint:	A pigmented liquid or resin applied to a substrate as a thin layer that is converted to an opaque solid film after application. It is commonly used as a decorative or protective coating.
Passivation:	The process or processes by which a metal becomes inert to a given environment or environments.
Passive:	(1) The positive direction of electrode potential.
	(2) A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product.
pH:	A measure of the acidity or alkalinity of a solution. A value of seven is neutral; low numbers are acid, large numbers are alkaline. Strictly speaking, pH is the negative logarithm of the hydrogen ion concentration.
Pitting:	Cavities formed in a material caused by localized corrosion.
Polarization:	The change of electrode potential resulting from the effects of current flow, measured with respect to steady-state potentials.
Pozzolan:	A pozzolan is a finely divided material that reacts with calcium hydroxide and alkalies to form compounds possessing cementitious properties.
Primer:	A coating material intended to be applied as the first coat on an uncoated surface. The coating is specifically formulated to adhere to and protect the surface as well as to produce a suitable surface for subsequent coats.

Protective Potential:	A term sometimes used in cathodic protection to define the minimum potential required to suppress corrosion.
P/S:	A measurement of the difference in potential between a structure and a copper-copper sulfate half-cell electrode in contact with an electrolyte, soil or water.
Reduction:	Gain of electrons by a constituent of a chemical reaction, occurs at cathode.
Resistivity:	The relative degree to which soil or water resists the flow of electric current. The most common terms in use are the ohmmeter and the ohm-centimeter.
Rust:	Corrosion product consisting primarily of iron oxide. A term properly applied only to iron and other ferrous metals.
Sacrificial Protection:	Reduction or prevention of corrosion of a metal in an environment by coupling it to another metal which is electrochemically more active in that particular environment.
Short:	An inadvertent, undesirable contact between two buried metals, or the electrical failure of installed insulation which destroys the desired metallic isolation or a system.
Soil Potential Gradient:	The voltage drop in the soil caused by direct current flowing away from or to a ground electrode, anode or cathode. The voltage gradient is measured between two copper-copper sulfate half-cell electrodes "D" distance apart on a radius line from the ground electrode.
Stray Current Corrosion:	Corrosion caused by direct current flowing through paths other than the intended circuit; for example, corrosion caused by current originating from direct current transportation or direct current transmission systems.
Stress Corrosion Cracking:	Cracking of a material produced by the combined action of corrosion and tensile stress (residual or applied).

Throw:	The polarization that occurs as the result of a rectifier station is generally greatest at the anode bed and decreases along the protected structure. In the case of an impressed current rectifier station that produces a direct current output, the protection "attenuates" along the electrically continuous segments of the structures. In the case of pulse rectifier stations that produce short pulses of high voltage direct current, the protection will not theoretically be limited by electrical discontinuities along the pipeline and the distance protection is achieved is referred to as "throw."
Throwing Power:	The relationship between the current density at a point on a surface and its distance from the counterelectrode. The greater the ratio of the surface resistivity shown by the electrode reaction to the volume resistivity of the eletrolyte, the better is the throwing power of the process.
Void:	(1) A holiday, hole, or skip in a coating.
	(2) A hole in a casting or weld deposit usually resulting from shrinkage during cooling.
White Metal Blast Cleaned Surface:	A white metal blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter.
Wire Drawing:	The art or process of wire drawing is to pull or draw a wire of a bigger diameter through a hole with smaller diameter thereby reducing the diameter through plastic deformation while the volume remains the same.

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ABBREVIATIONS

a-c	Alternating current
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
AwwaRF	Awwa Research Foundation
CCMP	Corrosion control master plan
CCP	Concrete cylinder pipe
CSE	Copper-copper sulfate reference electrode
d-c	Direct current
DWR	Department of Water Resources
EC-PCCP	Embedded-cylinder type prestressed concrete cylinder pipe
ECS	Electromagnetic conductivity surveys
EIS	Electrochemical impedance spectroscopy
EMF	Electromotive force
ENR	Engineering-News Record
GASB	Governmental Accounting Standards Board
GDP	Gross domestic product
GIS	Geographic information systems
GNP	Gross National Product
GPS	Global Positioning System
HE	Hydrogen embrittlement
ICCP	Impressed current cathodic protection
IEEE	Institute of Electrical Engineers
IRC	Institute for Research in Construction

JLF	Joint leak frequency
LC-PCCP	Lined-cylinder type prestressed concrete cylinder pipe
LF	Lineal feet
LPR	Linear polarization resistance
LWC	Louisville Water Company
ma	Milliampere
MBF	Main break frequency
ml	Milliliters
MRRP	Main replacement and rehabilitation program
mV	Millivolts
MWDSC	Metropolitan Water District of Southern California
NACE	National Association of Corrosion Engineers
NBS	National Bureau of Standards
NDT	Nondestructive testing
NEC	National Electrical Code
NIST	National Institute of Science and Technology
OD	Outside diameter
PAC	Project Advisory Committee
PCCP	Prestressed concrete cylinder pipe
PPIC	Pressure Pipe Inspection Company
ppm	Parts per million
PRCP	Pulsed rectifier cathodic protection
P/S	Pipe to soil
psi	Pounds per square inch
QA/QC	Quality assurance/quality control

RCPP	Reinforced concrete pressure pipe
RFEC	Remote field-eddy current
RF/TC	Remote field/transformer coupling
SCADA	Supervisory control and data acquisition
SCVWD	Santa Clara Valley Water District
SDCWA	San Diego County Water Authority
SSPC	Steel Structures Painting Council
TC	Transformer coupling
UL	Underwriters Laboratory
USBR	U.S. Bureau of Reclamation

Figure 2.1 PCCP Timeline

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