CHARACTERISTICS OF PIPE SYSTEM FAILURES IN LIGHT WATER REACTORS

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Topical Report

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LEGAL NOTICE

FOREWORD

This report is one of a series being produced by Science Applications, Incorporated (SAI) related to nuclear power plant availability and reliability. The work is part of an overall EPRI program to perform thorough analyses of existing industry performance and reliability data bases for the purpose of identifying the nature and impact of the various factors which influence plant reliability.

SAI has drawn from the large body of data submitted by nuclear power plants to the Nuclear Regulatory Commission in order to reach the conclusions presented in this report. The bulk of the data is in the form of Licensee Event Reports (LERs) supplemented as necessary by plant outage and maintenance data. Because the LERs are mostly concerned with events involving safety related plant systems, more detailed information is available on these events than on events involving other balance of plant equipment. This may tend to present a distorted picture of the extent to which specific plant systems are affected by piping problems. However, this report is not intended to quantify the reliability or safety of piping systems, but to give an overview of the nature of piping failures being experienced in nuclear plants and the effects of these failures on plant availability. In this context, the percentages and failure rates presented in this report should not be interpreted as being generic for piping systems in general because some fraction of piping failure events will not be reported to the data systems being used.

Studies of this type can point to the need for increased research and development in specific areas affecting plant reliability. Additionally, these studies should allow power plant designers and equipment manufacturers to observe trends in performance and take action where possible and appropriate.

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ABSTRACT

A statistical description of pipe system failures is presented in this report. The characteristics of these failures have been derived from reports submitted by the utilities to the Nuclear Regulatory Commission. In the present study, emphasis has been placed on identifying trends in the incidence of pipe failures and on the statistical characterization of the failure events to include impact on plant availability and capacity. Pipe system failures are compared from the standpoint of frequency of occurrence within plant types, i.e., PWR versus BWR, frequency of occurrence within plant subsystems, failure modes, pipe size categories, and time-to-failure from initial criticality. Hypotheses regarding differences between frequency distributions within PWR's versus BWR's are tested via standard nonparametric statistical methods.

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SECTION 1

1.0 INTRODUCTION AND SUMMARY

1.1 Background

Three major data systems are currently being supported by the electric power industry, namely EEI, NPRDS, and OUSR (Gray Books)*. Another data collection and retrieval system, namely the File of Evaluated and Event Data (FEED) is currently under development as part of EPRI project RP-705. This project includes preparation of topical reports relative to nuclear plant reliability. In contrast to EEI, OUSR, and NPRDS, the FEED system does not impose additional data reporting requirements on the utility industry. FEED is, in fact, a compilation of information extracted from the following sources:

(1) Utility reports such as letters, TWX's, special reports, AOR and LER submittals,

(2) Facility reports such as monthly, semiannual and annual operating reports, and

(3) NRC reports such as daily reports, current event report files, blue sheets, news releases, special studies and investigations, and library services including: technical specifications, PSAR's and FSAR's, vendor special studies, design criteria and analysis reports, papers on failure history, consultant reports for utilities and national laboratory studies.

Although a substantial volume of information has been collected, efforts to utilize the available information and provide useful feedback to the utilities have been minimal. The goals of the present project, an integral part of the FEED development program, are threefold:

(1) Demonstrate the feasibility of extracting useful information from the operational data currently available. Usefulness of information, in the present context, implies an ability to contribute to the decision-making process regarding operational policies, selection of equipment, proper maintenance and surveillance programs, safety, etc.,

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* EEI, NPRDS and OUSR refer to the Edison Electric Institute, Nuclear Plant Reliability Data System, and the Operating Units Status Reports, respectively.

(2) Provide EPRI and, in turn, the utilities with a positive return on their investment of time, money, and labor in the collection and reporting of the raw data, and

(3) Supply the FEED development team with ideas, constructive criticism, etc., regarding the content, format, and operation of the FEED system.

1.2 Objectives

The general goals of this project have been stated above. In the course of accomplishing these goals a series of topical reports have been prepared. The present report focuses on pipe system failures which have been reported by the nuclear power plants in commercial operation throughout the United States. The severity of these failures range from localized cracks, which may or may not have resulted in leaks, to complete rupture of the pipe wall.

The specific objectives of this report include:

(1) The characterization of pipe system failures which include: (a) ruptures, (b) leaks, and (c) defects which have been discovered and which require repair, and

(2) Estimation of the impact of pipe system failures on plant performance (availability and capacity).

Using the available data base summaries, an attempt has been made to verify or refute past claims (conclusions) regarding the factors which significantly influence pipe system integrity and to identify, if possible, new problems in need of corrective action or further investigation.

1.3 Scope and Limitations

The analyses contained herein are based entirely upon information presently contained in the NSIC data files, the FEED files, Gray Books, and past surveys of pipe system and pipe component problems. The latter were used for background information only.

The 55 nuclear plants commercially operating* in the United States comprise the population of interest in this study. The time frame covers the 16-year period beginning August 1960 (the date of initial criticality of Yankee Rowe) to August 1976.

The scope of this report is bounded by the following limitations:

(1) Inclusion of pipe failures only; heat exchanger tubes (e.g., steam generators, condensers) have been excluded from this study.

(2) Incompleteness of operational data caused, in part, by differences in event reporting procedures among plants, and

(3) Poor documentation of event times.

Completeness of the data sources, or lack thereof, refers to the fact that not all equipment failures are reported. Furthermore, events which are reported are often incomplete in the sense that much of the information pertinent to the assessment of reliability or availability is not available. This may be an unavoidable situation since key elements of information are frequently unknown at the time the event occurred or at the time the event was reported. For example, the mode of failure or probable cause, the physical environment, and/or the entire operational history of the failed item are frequently unknown. To illustrate this fact, 33.9% of all pipe failure reports issued by licensees listed the probable cause as "unknown" or simply did not report a probable cause. In the case of PWR pipe failures, 37.8% were listed as having "unknown" or "unspecified" causes. Little or no information is available on the total impact of a failure; e.g., maintenance and/or repair time, manpower requirements, and cost of materials. Also, the impact on plant availability and loss of capacity is difficult to estimate in the case of multiple failure events. The latter situation requires some rational scheme for distributing losses.

Pipe system failures are not usually classified as contributors to plant outage time for the following reasons:

(1) Roughly 50% of the time they are discovered during an outage, and

(2) The overall time devoted to pipe repair may be relatively small.

As mentioned above, poor documentation of event times represents another limitation. In many instances, the only information given relative to the

* Includes only PWR and BWR plants.

time (date) of an event is the date of the report submitted to NRC. In the case of a non-catastrophic failure, such as a small leak in a pipe or pipe component, one must realize that the time of discovery post-dates the time the event actually took place; this could be several months. In any event, data relative to the times at which events take place are not considered to be very accurate. This did not have a major impact on the present study since the event times were grouped into rather broad (10-month) intervals.

1.4 Summary of Conclusions

The following observations were derived on the basis of the operational experience reported to date. It should be noted that this experience only covers the initial stages of nuclear plant operation, i.e., 1-15 years:

(1) The impact of pipe failures* on plant availability is expressed in terms of the frequency of reactor shutdowns due to pipe failures, the distribution of outage times, and the frequency of pipe ruptures. The following observations have been made relative to these topics:

a) Approximately 47% of the pipe failures have been discovered during a plant shutdown. The remaining 53% of the pipe failures fall into the following categories:

(i) No shutdown required	(23%)
(ii) A normal plant shutdown is performed	(26%)
(iii) An automatic scram occurs	(2%)
(iv) A manual scram is performed	(2%).

b) The distribution of forced outage times due to pipe failures (for the period January 1974 to March 1976) are concentrated in the range of 0-50 hours. The seven (7) outages greater than 200 hours all occurred in BWR plants. The forced outages due to pipe failure represented 8% of the total forced outage time of all plants for the year 1975.

c) Approximately 9.0% of all the pipe failures involved a pipe rupture.

d) A forced reactor shutdown due to a pipe failure may be expected to occur, on the average, once every 3.6 plant-years.

(2) The principal causes of the reported pipe failures are not the result of inconsistencies or failure of current design

*The term pipe failure includes flaws which range in severity from local cracking which may or may not involve leaks to complete rupture of the pipe wall. Rupture or break will refer to cases where there is a rapid loss of fluid; that is, it will not be limited to the classical "double ended" pipe shear.

requirements (i.e., ASME Codes). They appear to be the result of phenomena which are not readily predicted; hence the methods of precluding pipe failures due to such phenomena have depended, for the most part, upon engineering judgement. These causes ranked by number of reported failures are:

a) Vibration (high cycle fatigue (25.1%)),

b) Fabrication errors (12.8%),

c) Stress corrosion cracking (11.3%),

d) Erosion (6.9%),

e) Thermal Fatigue (5.4%), and

f) Corrosion (2.9%).

The observation that high cycle fatigue caused by mechanical vibration or flow-induced vibration is a major contributor to pipe failures differs from the earlier pipe failure studies which concluded that low cycle fatigue was the principal failure mode. Vibration is the dominant mode in each plant type (19% of all BWR pipe failures and 34% of all PWR pipe failures). It was observed that stress corrosion cracking occurs roughly seven (7) times more frequently in BWR's than in PWR's. The difference between the distribution of failures by failure mode within the PWR's and the BWR's was found to be statistically significant.

(3) Statistically significant differences between the distribution of piping failures among plant subsystems; e.g., feedwater, gas, recirculation, charging systems, etc., exist when comparing the BWR's with the PWR's. Additional observations regarding the location of pipe failures are:

a) Approximately 27% of the PWR pipe failures have occurred in the primary plant charging system, 16% in the feedwater system, and 12% in the decay heat removal system.

b) BWR's exhibited pipe failures in the feedwater system (21.5%), recirculation system (19.0%), core spray piping, and condensate piping.

(4) The majority of the pipe failures reported involved small diameter piping. Specifically, 51.2% of all PWR pipe failures reported occurred in lines less than or equal to one inch in diameter; whereas, 29% of the BWR pipe failures reported were in this size category. In all, 70.7% of the PWR and 70.2% of the BWR pipe failures reported occurred in piping less than six inches in diameter.

(5) As far as specific location of piping failures is concerned, it was observed that:

a) 54% of the failures occurred in welds or in the weld heat-affected zones of piping,

b) 40% occurred in the pipe wall (base metal), and

c) 6% occurred in threaded pipe joints.

(6) Several interesting observations have been made relative to the distribution of the times-to-failure for PWR pipe systems

and BWR systems. The average time-to-failure for PWR piping is 35.8 months (roughly 3 years) from initial criticality. The average time-to-failure for BWR piping is 56.3 months. The time-to-failure distribution for PWR piping and the time-to-failure distributions for BWR piping are quite different. The PWR time distribution has a definite exponential shape whereas the BWR failure times exhibit a uni-modal distribution with the mode between 50 and 60 months from initial criticality.

(7) Of the pipe failures reported, 40% occurred in PWR plants; the remaining 60% occurred in BWR plants. Noting that approximately an equal number of plant-years of operation for PWR's and BWR's (~125) exists, there is a higher frequency of pipe failures occurring in BWR plants than in PWR's.

(8) The number of recorded pipe failures is largest for the recent operating history 1974-1976 since reporting requirements have become more stringent and data collection has also improved (see Section 3.1). Therefore, the types of failures are characteristic of the incidents occurring in the current generation of nuclear reactors.

1.5 Organization of This Report

A brief summary, or overview, of observations and conclusions found in the literature is presented in Section 2.0 which follows. Section 3.0 is devoted to the characterization of pipe system failures which have been reported. Emphasis is placed on the identification of the most significant problem areas, trends, and differences between pipe system failures found in PWR plants and those experienced in BWR plants. This is followed by a discussion of the impact of pipe system failures on plant operation in Section 4.0.

SECTION 2

2.0 PRIOR OBSERVATIONS

Extensive surveys[(1,2,3)*] covering a broad range of service experience have been conducted in order to identify combinations of factors and types of components which lead to failures in piping systems. In order to gain some insight into the nature of pipe failures and to pick up a few "bench-marks" prior to examining the information collected in the present study, it is appropriate to review the results of past investigations.

Generally, the documented failures indicate that the dominant mode of failure is fatigue resulting in a leak but not in a catastrophic boundary failure.

2.1 Results of the Gibbons-Hackney Survey (1964)

An industrial piping failure survey[(1)] covering 701 contacts in electric utilities, petroleum refineries, chemical processing, marine applications, etc., was conducted as part of the Reactor Primary Coolant Rupture Study. A total of 315 replies were received, when combined with published failure cases, these provided 399 failure case histories applicable to the study. The term "failure" was defined as any defect or condition encountered during start-up, testing, and/or service that required repair or replacement. On the basis of the 399 failure histories, Gibbons and Hackney came to the following qualitative conclusions:

(1) Piping systems which have been designed and constructed within established code criteria will exhibit high reliability, and a catastrophic failure (complete severance rupture) appears unlikely; however, less severe failures will obviously occur.

(2) The most probable failure will be cracking due to low-cycle fatigue.

*Numbers in parentheses denote references listed in Section 5.0.

(3) The most likely location for failure to occur is in the pipe or pipe weld heat-affected zone particularly in association with a structural discontinuity.

(4) The growth of cracking-type failures can generally be expected to result in leakage prior to gross or major failure.

(5) The detection of leakage associated with relatively small cracks should permit repair and prevention of further cracking and aid the study of design inadequacies.

Conclusions of a quantitative nature were (see Table 2.1 for details):

(1) Thirty-nine percent of the failures (155 out of 399) occurred in systems normally operating at 600°F to 1200°F.

(2) Only one failure was noted in the material selection category of probable cause for applications under 600°F; whereas 48.8 percent (119 out of 244) of the failures in the 600°F to 1200°F applications were attributed to material selection.

(3) The majority of cases reported were discovered upon evidence of leakage. In fact, the number of failures that occurred without evidence of leakage (25 out of 399) constituted only 6.2 percent of all failures.

(4) Of all the cases, 4.8 percent involved complete severance (19 out of 399).

(5) Column 10 in Table 2.1 indicates that the majority of failures (276 out of 399) occurred in the pipe itself. This statement must be qualified since the weld heat-affected zone was included in the "pipe" category for graphitization and Type 347 stainless steel failures. However, even if these and the "associated-with-welding" type are taken out of the total, leaving 175 (276-(59+38+4)) 44 percent may be classed as "pipe" failures. Welds constitute the next largest failure location (13.5%). If the heat-affected zone is defined as being part of the weld, the percentage changes from 13.5 percent to 38.8 percent.

(6) Although a much smaller percentage (7.0%) of failures occurred in castings, it is appropriate to note that a little over 46 percent of these (13 out of 28) were caused by base material defects, most frequently porosity resulting in a leakage-type failure without fracture.

Table 2.2 illustrates how pipe failures, reported in the Gibbons-Hackney survey, were distributed by failure mode.

2.2 Summary of Pipe Cracking Study Group Findings (1975)

On January 7, 1975, the Office of the Director of Licensing of the Atomic Energy Commission formed the Pipe Cracking Study Group (PCSG) within its Regulatory staff in order to coordinate a continuing investigation of the

Table 2.1. Results of Gibbons-Hackney Survey

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
						Location of Failure					
Primary Cause of Failure	Up to 600° F	600° F to 1200° F	Total-All Temperatures	Occurred Without Leakage	Complete Severance Cases	"Thermowell"	Nozzle	Fitting or Component(d)	Pipe	Casting	Weld
1. Design											
a. Mech. fatigue	8	10	18	2	6	7	2	3	6		
b. Expansion/flexibility	5	5	10		1				7		3
c. Section transition	1	1	2						1		1
d. Support		2	2						2		
e. Design-operation:											
1) Thermal-fatigue	4	28	32	3	1		1	1	28		2
f. Miscellaneous	5	4	9			1		1	3	1	3
Sub-total	23	50	73	5	8	8	3	5	47	1	9
2. Material Selection											
a. Misapplication		9	9		1			3	1		5
b. Metallurgical											
1) Type 347 stainless steel		59	59						59(b)		
2) Graphitization		41	41	11(a)	1			1	38(c)	1	1
3) "Stress-rupture"		5	5	1					3		2
4) "885" embrittlement		2	2		1		1		1		
c. Miscellaneous	1	3	4						4		
Sub-total	1	119	120	13+	3		1	4	105	1	8
3. Manufacturing											
a. Wrong material supplied		5	5					1	3		1
b. Base material defects	17	14	31	1	1			2	16	13	
c. Weld defects		1	1								1
d. Associated with welding	1	3	4						1	3	
e. Material not to specifications		1	1						1		
Sub-total	18	24	42	1	1			3	21	16	2
4. Fabrication-Erection											
a. Weld defects	19	8	27	1	1						27
b. Associated with welding	4	6	10				2	1	4	1	2
c. Wrong material used		4	4		2				2		1
d. Miscellaneous	2	7	9	1		1		1	7		1
Sub-total	25	25	50	2	3	1	2	2	13	1	31
5. Operation-Service											
a. Mis-operation	4	5	9	1	2			4	4		1
b. Thermal shock and shock	1	5	6	1	1			2	2	2	
c. Corrosion and/or erosion	82	12	94	2				5	80	7	2
Sub-total	87	22	109	4	3			11	86	9	3
6. Unknown	1	4	5		1		1		3		1
Total	155	244	399	25+	19	9	7	25	276	28	54

notes:
(a) Some of these occurred without leakage; precise data was not supplied
(b) Most of these occurred in the weld heat-affected zone, some were in component; specifics on distribution was not supplied
(c) Most of these were located in the weld heat-affected zone.
(d) Elbow, tee, wye, etc.

Table 2.2. Classification of Pipe Failures by Failure Mode (Gibbons-Hackney Survey)

Mode	No. Cases	Percent
1. Cleavage	7	1.7
2. Fibrous	7	1.7
3. Creep Rupture		
a. General	15	3.8
b. Graphitization	41	10.2
c. Type 347 Stainless Steel	59	14.8
4. Fatigue		
a. High Cycle-elastic	20	5.1
b. Low Cycle-plastic	93	23.3
c. Not Clear a. or b.	3	0.7
5. Corrosion		
a. Austenitic-general	5	1.2
1) Transcrystalline	3	0.7
2) Intercrystalline	2	0.5
b. Ferritic-general	18	4.6
1) Transcrystalline	-	-
2) Intercrystalline	2	0.5
c. Erosion	82	20.4
6. No Fracture, Defect Leaked	24	6.2
7. Insufficient Data to Attempt Classification	18	4.6
	399	100.0

occurrences of cracking in 4-inch diameter bypass lines within BWR's. A thorough in-service inspection of the austenitic stainless steel piping within the reactor coolant pressure boundary of 23 domestic BWR plants was conducted. The following factors were investigated by the PCSG to determine the cause of pipe cracking:

(1) Metallurgy,
(2) Coolant water chemistry,
(3) History of plant operation, and
(4) Pipe configuration and mode of support.

Each of these factors is discussed in some detail in Reference 2. The PCSG states that plants which have experienced pipe cracking are those with:

(1) The earliest operating license and dates of initial criticality,

(2) The greatest gross thermal energy generated,

(3) The greatest equivalent thermal full power hours,*

(4) The greatest average thermal load factor,

(5) The greatest number of outages of at least 24 hours duration, and

(6) The greatest mean time between outages of at least 24 hours duration.

Specific statistics relating to the above factors are tabulated in Table 2.3 below.

Although the PCSG attempted to point out the most striking differences between BWR plants that have experienced pipe cracking and those which have not, no attempt was made to show that the differences were, in fact, statistically significant. In fact, no statistical procedures, e.g., hypothesis-testing, etc., were used. We shall return to this point in Section 3.0.

2.3 Surveys of Pipe and Pressure Vessel Failures in Great Britain

Failure statistics relevant to pressure vessels and piping in British boilers and pressure vessels have been compiled by Phillips and Warwick[3], and Smith and Warwick[4]. The Phillips-Warwick and the Smith-Warwick surveys involved 12,700 and 8,823 non-nuclear systems, amounting to 100,300 and 105,402 system-years, respectively. A total of 132 and 139 service failures were involved in each of these surveys. The Phillips-Warwick findings are tabulated in Table 2.4; those of Smith and Warwick are shown in Table 2.5 below.

Based on the data presented in Tables 2.4 and 2.5, Bush[5] calculated point and interval estimates of vessel and piping failure probabilities for 100,300 and 105,402 system-years of operation; these are presented in Table 2.6 below.

* Equivalent thermal full power hours represents a measure of plant age; specifically, equivalent full power hours = $\left(\frac{\text{gross thermal energy generated}}{\text{licensed thermal power level}}\right)$.

Table 2.3. Statistics Relevant to BWR Plants Which Have Experienced Cracking of Recirculation By-Pass and Core Spray Pipe*

Plant	Time To Failure (hours from initial criticality)	Gross Thermal Energy Produced (MWH)	Equivalent Full Power Hours (10^3 hours)	Average Thermal Load Factor (%)	Number of Outages of At Least 24 Hrs. Duration	Mean Time Between Outages (10^3 hours)
Dresden 2	30,635	50,912,000	20.14	47.25	29	1.41
Millstone 1	22,518	35,844,000	17.80	52.90	26	1.31
Monticello	23,626	41,681,000	20.18	56.77	24	1.37
Peach Bottom 3	425	1,076,000	1.21	34.30	2	0.64
Quad Cities 1	18,576	34,825,000	13.86	49.70	20	1.27
Quad Cities 2	18,255	35,997,000	14.34	62.43	29	0.72

*Data taken from Ref. 2.

Table 2.4. Results of the Phillips-Warwick Survey - Distribution of Failures Within 12,700 Systems (100,300 System-Years of Service).

Component and Probable Cause	Non-Catastrophic Leak	Non-Catastrophic No Leak	Catastrophic Failures
<u>Vessel</u>			
Fatigue	1	3	0
Corrosion	0	12	0
Pre-Existing Defect	1	3	0
Not Determined	1	9	0
Miscellaneous	0	0	0
Maloperation	0	3	4
	3	30	4
<u>Piping, etc.</u>			
Fatigue	17	24	2
Corrosion	0	14	0
Pre-Existing Defect	1	7	1
Not Determined	14	11	0
Miscellaneous	1	1	0
Maloperation	1	0	0
Creep	1	0	0
	35	57	3
Total	38	87	7

Table 2.5. Results of Smith-Warwick Survey - Distribution of Failures Within 8823 Systems (105,402 System - Years of Service)

Component and Probable Cause	Non-Catastrophic Leak	Non-Catastrophic No Leak	Catastrophic Failures
Vessel			
Fatigue	4	10	0
Corrosion	1	0	1
Pre-Existing Defect	3	36	1
Not Determined	3	7	0
Miscellaneous	6	1	0
Maloperation	4	3	3
	21	57	5
Piping, etc.			
Fatigue	4	2	0
Corrosion	1	0	1
Pre-Existing Defect	12	1	3
Not Determined	5	7	0
Miscellaneous	1	0	1
Maloperation	5	3	3
Creep	1	3	3
	29	16	11
Total	50	73	16

Table 2.6. Failure Rates and 99 Percent Confidence Upper Bound Failure Probabilities Derived from Statistics for (a) 100,200 and (b) 105,402 System-Years of Operation.

Condition	Failure Rate*		99% Confidence Upper Bound	
	"Potentially Dangerous"	Catastrophic	"Potentially Dangerous"	Catastrophic
For all data				
(a)	1.3×10^{-3}	7.0×10^{-5}	1.6×10^{-4}	1.6×10^{-4}
(b)	1.1×10^{-3}	1.5×10^{-4}		
Piping, etc.				
(a)	9.2×10^{-4}	3.0×10^{-5}	1.9×10^{-3}	1.1×10^{-4}
(b)	4.3×10^{-4}	1.1×10^{-4}		
Vessels alone				
(a)	3.3×10^{-4}	4.0×10^{-5}	1.1×10^{-3}	1.2×10^{-4}
(b)	7.4×10^{-4}	5.0×10^{-5}		

* per plant-year

2.4 Additional Observations

Table 2.7 compares pipe failure rate estimates found in various data sources. The following qualifications should be noted: (1) These estimates have been based on observations made over relatively short operational exposure times; therefore, they may differ significantly from the pipe failure probabilities pertinent to long periods of time: e.g., 40 years, and (2) it should be noted that pipe failure rates will, in general, vary with time. More will be said about time varying failure rates in Section 3.7 where pipe system reliability and hazard functions are discussed.

Table 2.7. Comparison of Pipe Failure Rate Estimates*

Source	Estimate Failure Rate
Phillips & Warwick (1962)	5×10^{-4} (potentially dangerous events) 2×10^{-5} (catastrophic events) per plant-year
Green & Bourne (1968)	3×10^{-6} - 2×10^{-3} per plant-year (for large scale rupture of primary system)
Salvatory (1970)	1×10^{-4} per plant-year (for catastrophic rupture of primary system)
Erdmann (1973)	1×10^{-4} - 1×10^{-2} per plant-year (pipe rupture)
Otway	1.7×10^{-7} per plant-year (for catastrophic failure of primary system)
General Electric Report GEAP 5474 (1964)	4×10^{-2} per plant-year (all failures) 2×10^{-3} per plant-year (severance of piping) 4×10^{-2} per plant-year (non-severance)
Wells-Knecht (1965)	1×10^{-7} per plant year (for rupture of primary coolant system piping)
Dept. of Transportation Natural Gas Piping Study	6×10^{-3} per plant-year

* Taken from WASH-1400[6].

SECTION 3

3.0 CHARACTERIZATION OF PIPE SYSTEM FAILURES

3.1 General

The characteristics of pipe system failures presented herein are based upon an analysis of 237 failure events reported to NRC*. It should be pointed out that a pipe system failure is defined in this study as a crack, leak, or complete rupture that has been detected subsequent to the date of initial criticality. An attempt has been made to present descriptive statistics which, to a certain extent, characterize piping failures. Emphasis is placed on the discovery of trends or the identification of new problem areas which have not been observed to date or at least have not been discussed in the literature. Secondary objectives include the independent verification of known facts concerning pipe failures and the identification of key elements of information which should be included in the FEED data base.

The various observations or descriptive statistics which characterize pipe system failure are presented in more or less ascending degree of detail starting with somewhat "global" features of piping failures and ending with descriptive statistics pertaining to more detailed topics.

As an aid in understanding the underlying causes or implications of the data, much of the failure data presented in the current study is separated according to plant type (BWR versus PWR). The purpose of displaying pipe failures separately for BWRs and PWRs is to highlight the possible effects of:

(1) Design differences,
(2) Operating characteristics, and
(3) Water chemistry/oxygen concentration.

However, since there may be different types and amounts of piping in BWRs and PWRs, the comparison of these two types of LWRs should not lead to any conclusions concerning the overall plant performance of either reactor type.

* The majority of the analysis is based upon 203 failure events listed in the NSIC; however, an additional 34 events, not included in the NSIC report, were found in the FEED file and in the Gray Books.

3.2 Trends in the Overall Occurrence of Pipe Failures

This section provides a profile of the data used in this study. Such a profile provides the basis for discussing the validity of the conclusions which are presented in subsequent sections. Figures 3.1 and 3.2 compare the number of recorded pipe failures with the number of LWRs in commercial operation per calendar year. An important observation in assessing the availability of data is that while utilities record and collect a large amount of data, and in some cases have computerized systems to store and retrieve failure-maintenance data, the data which is publicly available is a function of what the utility is required to report by the NRC or other agencies. Figure 3.1 shows that most of the data used in the current study was reported in the years 1974-1976. The increase in the availability of data during recent years is generally attributed to more comprehensive NRC reporting requirements such as the revised Regulatory Guide 1.16 and the more stringent plant technical specifications in the period 1974-1975.

In order to illustrate the trend toward increased reporting requirements to the government, we compared the number of pipe-related events with the total number of abnormal occurrence failure events recorded by NSIC on a per plant basis. Figure 3.3(a) indicates that the number of pipe failures and the total number of abnormal occurrences reported exhibit similar increasing trends. This is consistent with the hypothesis that increased NRC reporting requirements, especially in the period 1974-1975, have resulted in the utilities formally reporting additional data of all types.

The profile of recorded pipe failures can also be displayed versus plant age. Such a breakdown has led to the separate presentation of PWR and BWR plants to determine if any trends exist within plant types. The age-specific population of PWR plants is plotted in Figure 3.3(b). Also plotted in Figure 3.3(b) is the number of pipe system failures which have been reported by PWR licensees within successive six month intervals. The average number of pipe failures per PWR plant (shown in Figure 3.3(c)) exhibits a gradual decline over the first six years of operation. Similar plots for BWR plants are given in Figures 3.4(a) and 3.4(b). In the case of BWR plants, the average number of pipe system failures per plant increases gradually and reaches a peak between 4.5 and 5.0 years. Further details on the time variation of piping failures are given in Section 3.6.

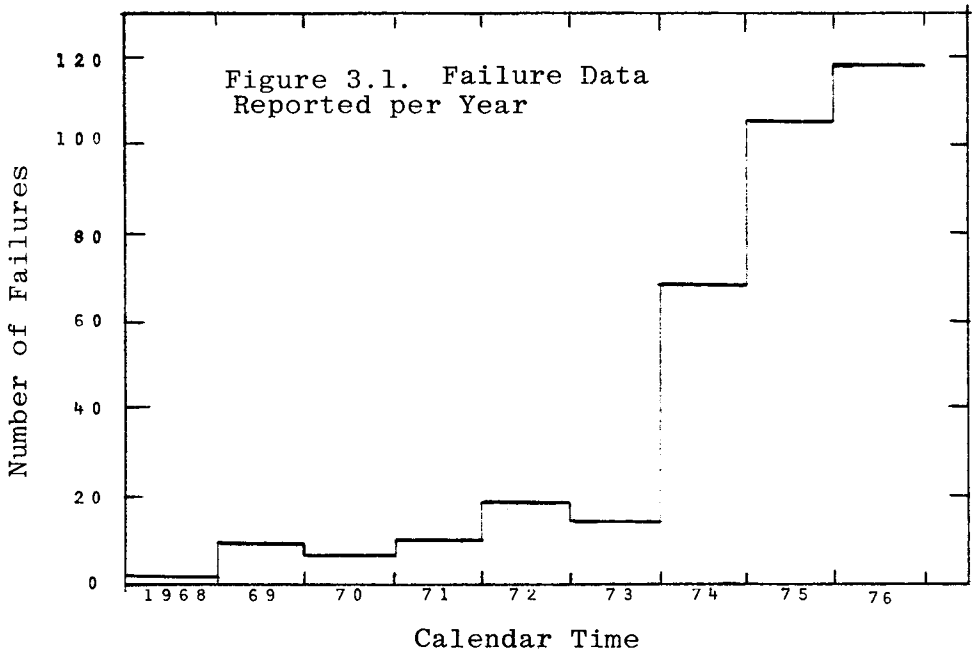


Figure 3.1. Failure Data Reported per Year
Number of Failures
120
100
80
60
40
20
0
1968
69
70
71
72
73
74
75
76
Calendar Time

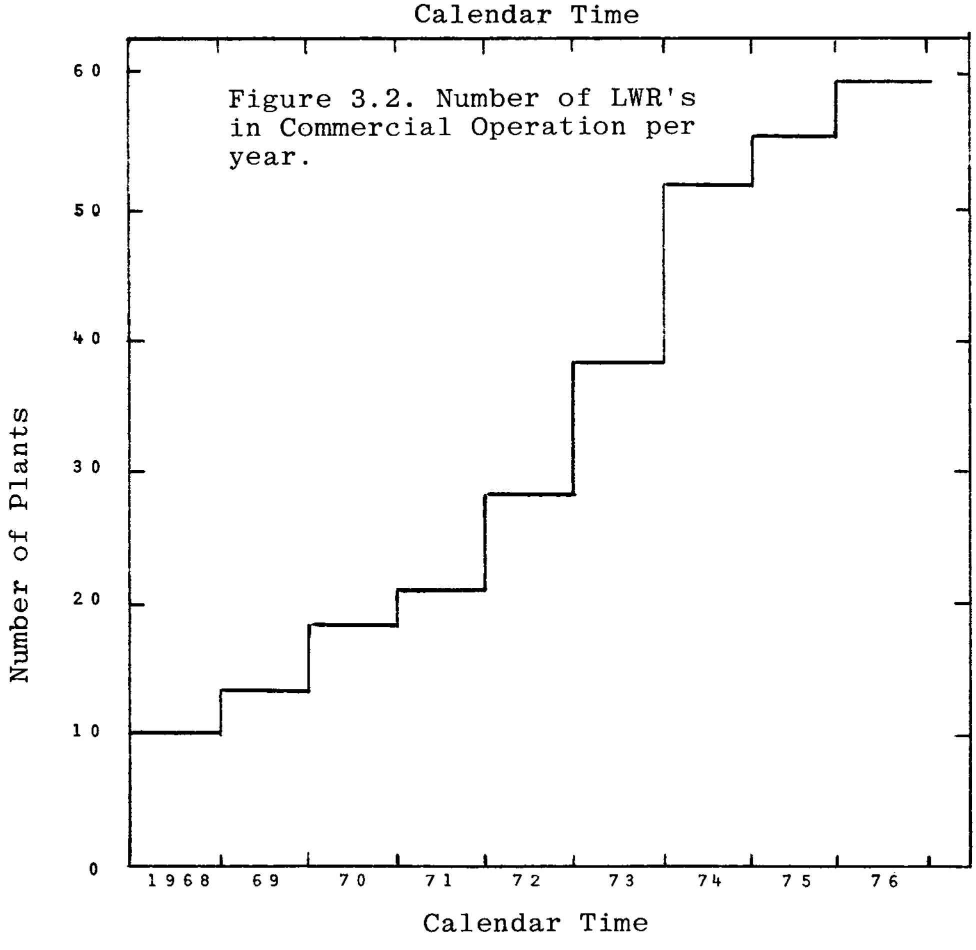


Figure 3.2. Number of LWR's in Commercial Operation per year.
Number of Plants
60
50
40
30
20
10
0
1968
69
70
71
72
73
74
75
76
Calendar Time

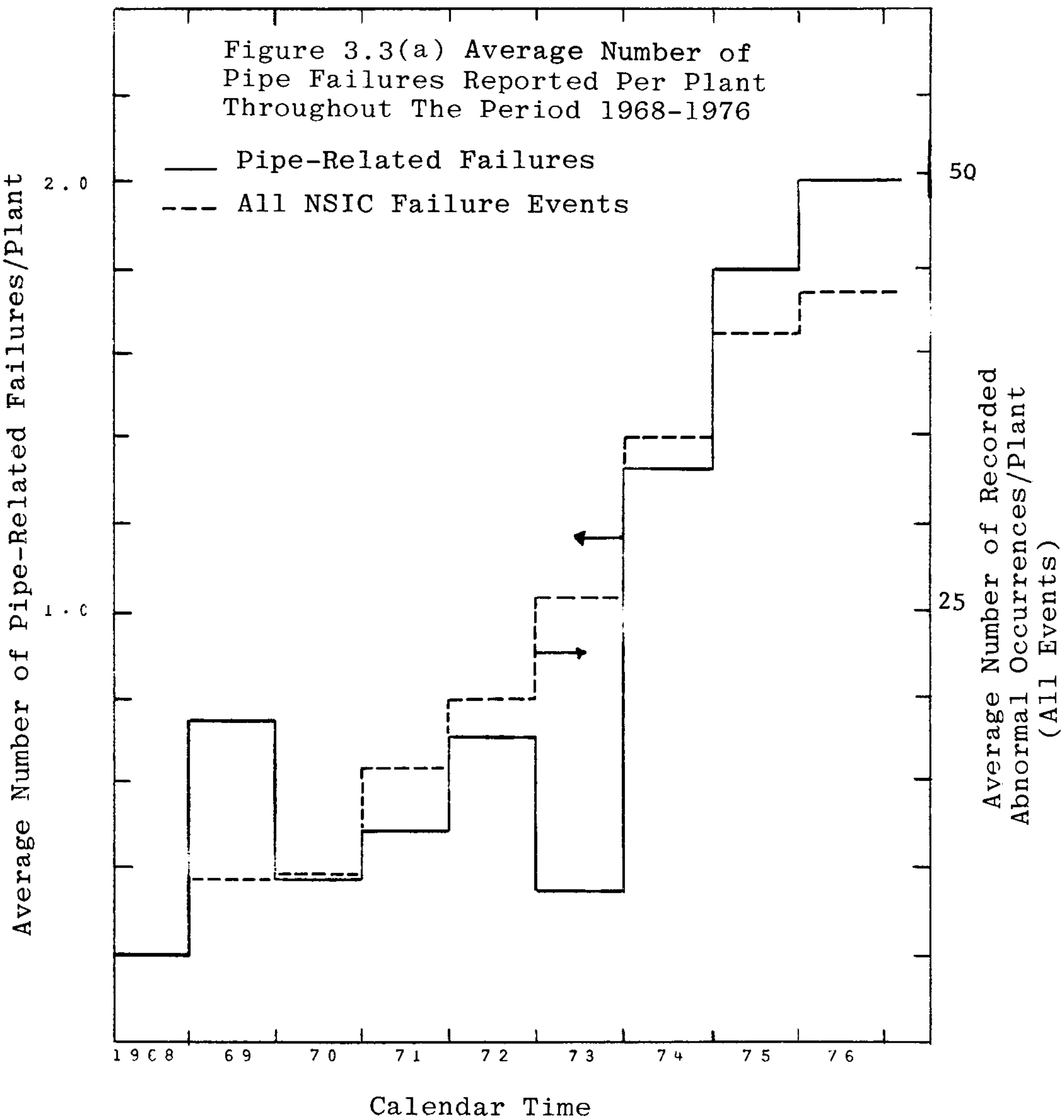


Figure 3.3(a) Average Number of Pipe Failures Reported Per Plant Throughout The Period 1968-1976

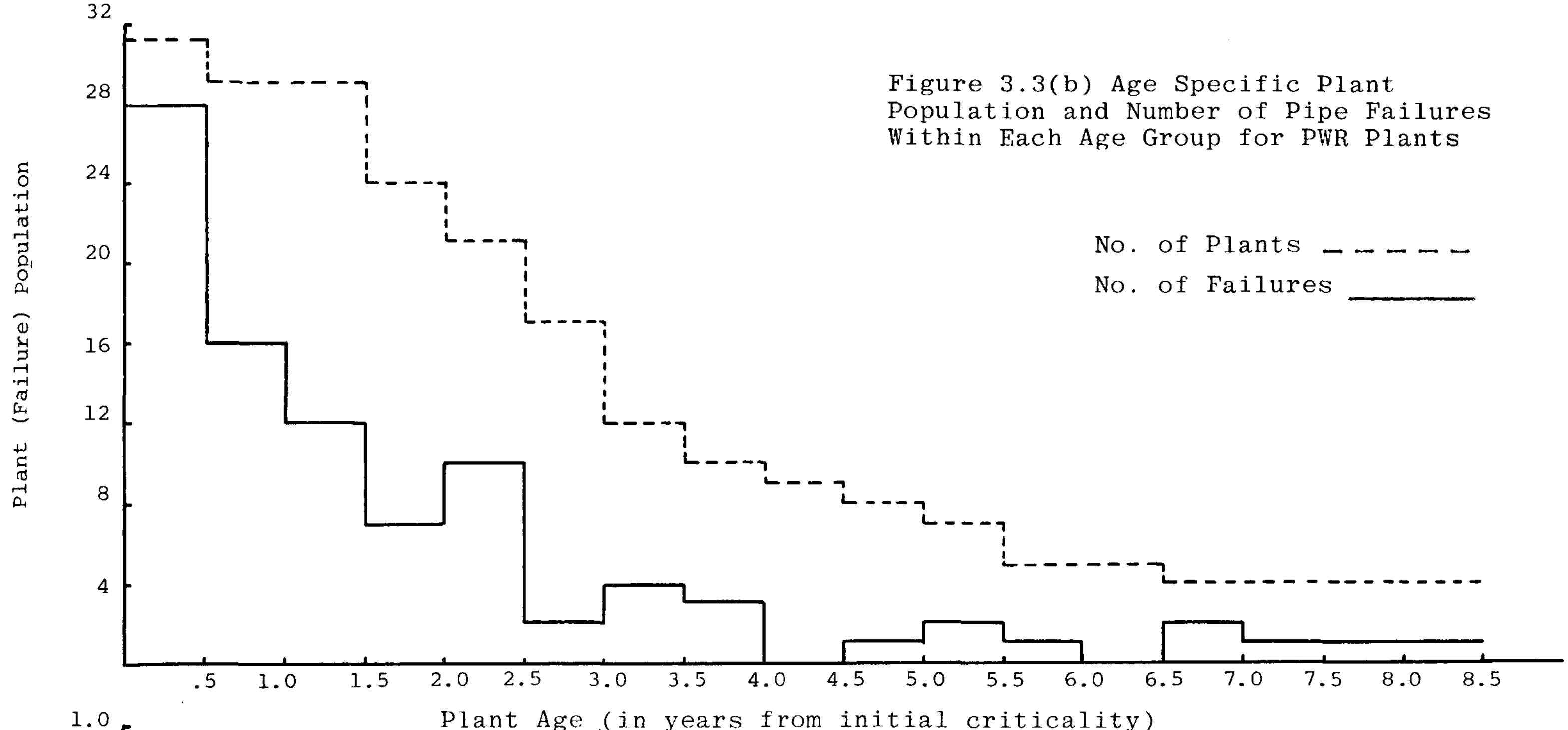


Figure 3.3(b) Age Specific Plant Population and Number of Pipe Failures Within Each Age Group for PWR Plants

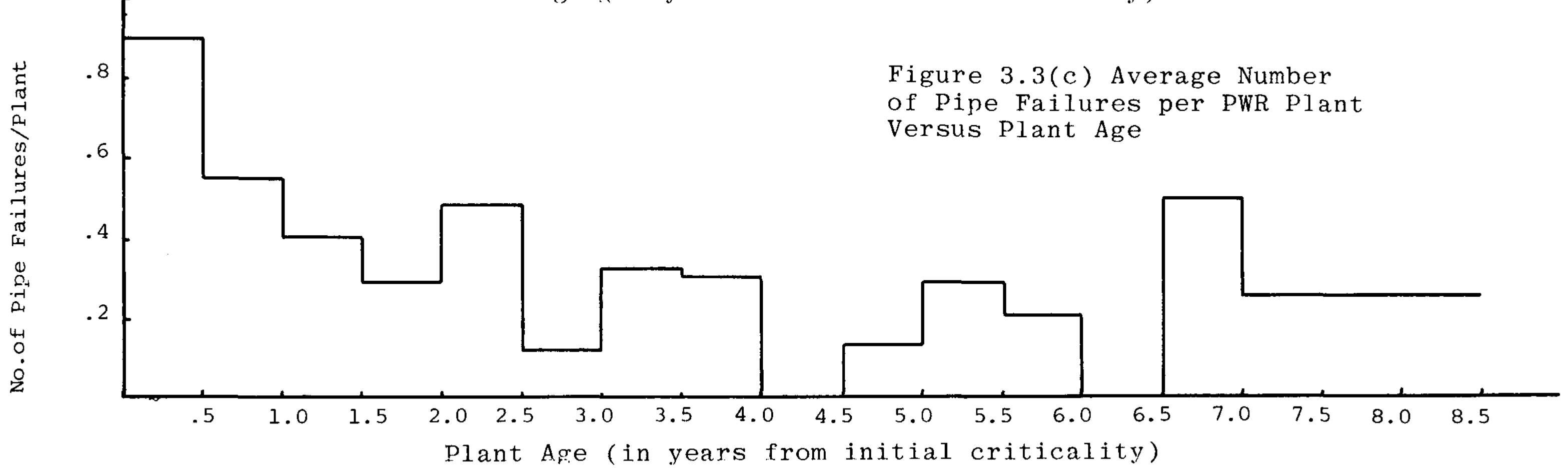


Figure 3.3(c) Average Number of Pipe Failures per PWR Plant Versus Plant Age

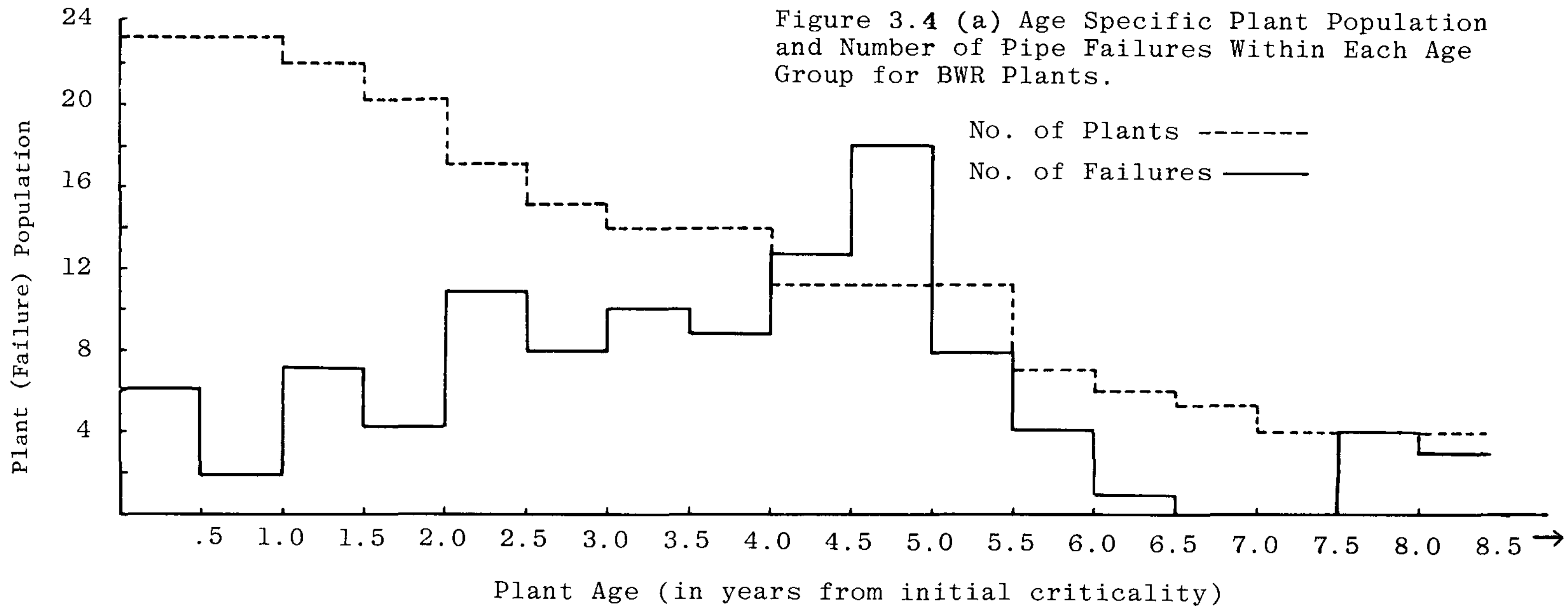


Figure 3.4 (a) Age Specific Plant Population and Number of Pipe Failures Within Each Age Group for BWR Plants.

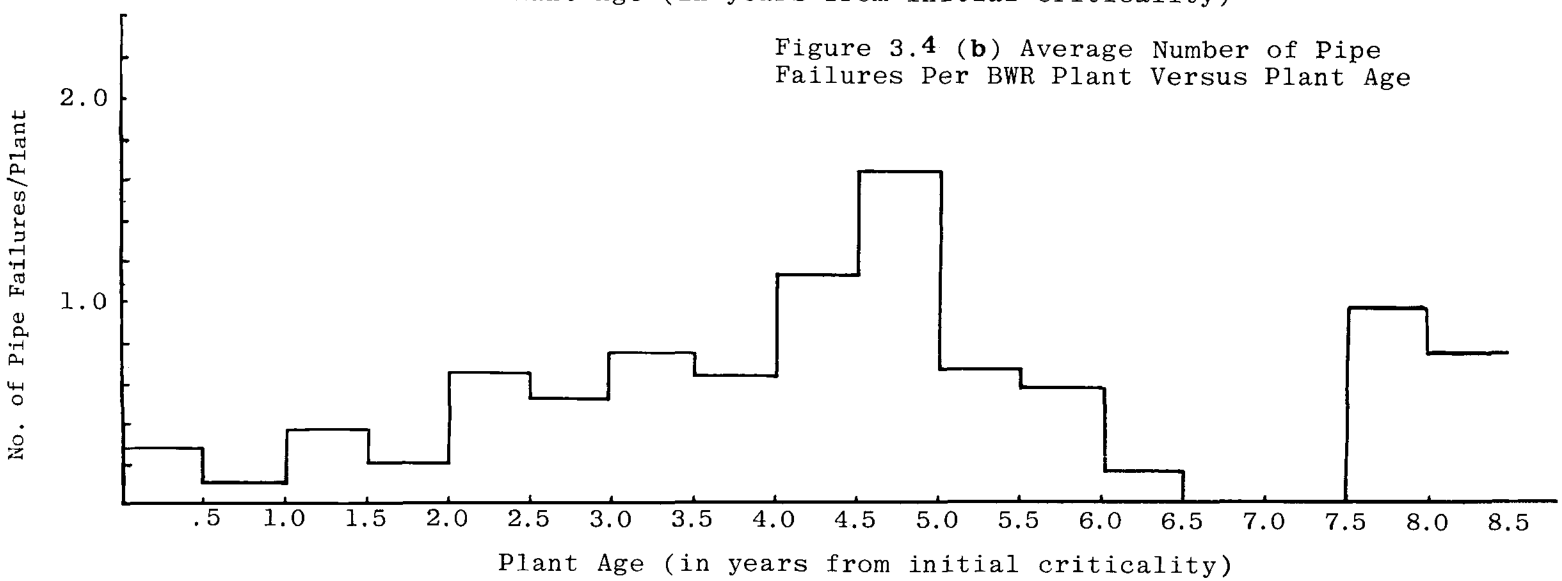


Figure 3.4 (**b**) Average Number of Pipe Failures Per BWR Plant Versus Plant Age

3.2.1 Piping Failures in PWRs Versus BWRs

Of the 203 pipe system failures, 82 (40.4%) occurred in PWR plants. The remaining 121 failures (59.6%) occurred in BWRs. It appears that the 23 BWR plants have experienced a larger proportion of pipe failures compared to the 32 PWRs. Note that the 32 PWRs account for 58.2% of the commercially operating light water reactors; however, they gave rise to only 40.4% of the 203 pipe system failures reported. In contrast to this, we note that the 23 BWRs account for 41.8% of the LWR population; however, they gave rise to 59.6% of the 203 pipe system failures reported. If the 20 failure events which have been attributed to stress-corrosion cracking, e.g., core spray and bypass lines in BWRs and the three events attributed to stress corrosion cracking in PWRs are momentarily ignored, we find that the 23 BWRs (41.8% of the LWR population) account for 56.1% of the remaining 180 non-stress-corrosion cracking failures. In the same light, the 32 PWRs (58.2% of the LWR population) gave rise to only 43.9% of the 180 non-stress-corrosion cracking failures. In other words, the elimination of the cases involving stress-corrosion cracking does not totally account for the larger number of piping failures in BWRs over those in PWRs. It might be argued that the number of BWRs versus the number of PWRs is not a good basis for comparison and that the number of PWR plant-years versus the number of BWR plant-years is more appropriate. With this in mind we note that the number of PWR plant-years and the number of BWR plant-years are nearly equal (over the time frame of this study). This leads to the conclusion that based upon data available at the time this study was performed, BWR plants have a higher pipe failure rate compared with PWR plants.

The distribution of pipe failures among the individual PWR and the individual BWR plants is given in Tables 3.1 and 3.2, respectively. Having ranked the individual plants in accordance with the total number of piping failures reported, one may observe that the top seven PWR plants account for over half (52.4%) of all PWR pipe system failures. The top five BWRs account for over half (56.2%) of the BWR pipe failures. Based upon the number of failures which have occurred in each plant and the time-to-failure (in months from the date of initial criticality), a rate of occurrence has been calculated for each plant (number of failures divided by the time from initial criticality through March 1976). An attempt was made to determine whether plant size (expressed in terms of design capacity) has an influence on the occurrence

Table 3.1. PWR Plants Ranked According to Total Number of Pipe System Failures

PLANT	DESIGN POWER (MWe)	AGE* (MONTHS)	NUMBER OF FAILURES	OCCURRENCE RATE $(\text{Plant-mo.})^{-1}$	PERCENT OF TOTAL PWR FAILURES	CUMULATIVE PERCENTAGE
Robinson 2	707	65	9	.14	10.97	10.97
Arkansas 1	850	18	8	.44	9.76	20.73
Indian Pt. 1	265	162	6	.04	7.31	28.04
Yankee Rowe	175	187	6	.03	7.31	35.35
Zion 2	1050	14	5	.36	6.10	41.45
Three Mile Is. 1	819	20	5	.25	6.10	47.55
Kewannee	560	23	4	.17	4.87	52.42
Oconee 3	886	17	4	.24	4.87	57.29
Palisades	821	57	4	.07	4.87	62.16
Calvert Cliffs	845	16	3	.19	3.66	65.82
Conn. Yankee	575	103	3	.03	3.66	69.48
Cook 1	1090	14	3	.21	3.66	73.14
Ginna	490	75	3	.04	3.66	76.80
Prairie Is. 1	530	27	3	.11	3.66	80.46
Prairie Is. 2	530	14	3	.21	3.66	84.12
Surry 1	823	52	3	.06	3.66	87.78
Indian Pt. 2	873	35	2	.06	2.44	90.22
Ft. Calhoun	457	29	1	.03	1.22	91.44
Maine Yankee	790	40	1	.03	1.22	92.66
Millstone Pt. 2	795	5	1	.20	1.22	93.88
Oconee 2	886	27	1	.04	1.22	95.10
Point Beach 1	497	63	1	.02	1.22	96.32
Turkey Point 3	745	40	1	.03	1.22	97.54
Turkey Point 4	745	32	1	.03	1.22	93.76
Zion 1	1050	32	1	.03	1.22	99.98

*Through February 1976

Table 3.2. BWR Plants Ranked According to Total Number of Pipe System Failures

PLANT	DESIGN POWER (MWe)	AGE* (MONTHS)	NUMBER OF FAILURES	OCCURRENCE RATE $(Plant\text{-}mo.)^{-1}$	PERCENT OF TOTAL BWR FAILURES	CUMULATIVE PRECENTAGE
Dresden 2	809	74	21	.28	17.36	17.36
Dresden 1	200	196	15	.08	12.40	29.76
Dresden 3	809	62	11	.07	9.10	38.86
Quad Cities 1	809	52	11	.07	9.10	47.96
Millstone Pt. 1	690	64	10	.16	8.26	56.22
Quad Cities 2	809	46	8	.17	6.61	62.83
Monticello	545	63	6	.10	4.96	67.79
Oyster Creek	650	69	5	.07	4.13	71.92
Peach Bottom 2	1065	29	5	.17	4.13	76.05
Big Rock Pt. 1	72	159	4	.03	3.31	79.36
Humboldt Bay	65	156	4	.03	3.31	82.67
Lacrosse	50	103	4	.04	3.31	85.98
Brown's Ferry 1	1065	30	3	.10	2.48	88.46
Hatch 1	786	17	3	.18	2.48	90.94
Nine Mile Pt. 1	610	77	3	.04	2.48	93.42
Cooper Station	778	24	2	.08	1.65	95.07
Peach Bottom 3	1065	19	2	.11	1.65	96.72
Vermont Yankee	514	47	2	.04	1.65	98.37
Brown's Ferry 2	1065	19	1	.05	0.82	99.19
Fitzpatrick	821	15	1	.07	0.82	100.00

*Through February 1976

of pipe failures. In general, there appears to be some correlation of a positive nature; however, the variability (scatter) in occurrence rates for the larger plants (>400 MWe) is extremely high. It is suggested that further effort be devoted to the analysis of differences in the occurrence rates of pipe failures in plants of the same type; i.e., PWRs and BWRs. Important factors to consider are: (1) the number of outages of at least 24 hours duration, as suggested in Reference 2, (2) installation practices, and (3) operational procedures in effect during the power ascension or start-up phase.

3.3 Distribution of Pipe Failures by Subsystem and Plant Types

The distribution of piping failures relative to the major subsystems within a plant have been considered. The specific differences between the distribution within PWR and the distribution within BWR plants may be observed in Table 3.3.

A chi-squared test was performed in order to test the hypothesis that there is a difference between the distribution of BWR failures and the distribution of PWR failures among the ten subsystem categories. On the basis of this test we conclude that there is a statistically significant difference between the distribution or failures within PWRs versus the distribution within BWRs. (See Appendix A for details concerning this test).

It is perhaps useful to comment on the pipe failures within PWR and BWR subsystems:

a. PWRs experience a significant number of piping failures (~27%) in the primary plant charging system. Many of these failures (50-60%) are due to vibration caused by the positive displacement charging pumps. The pipe in the charging system is small diameter (less than 6 in.) and contains fluid at high pressure and relatively high velocity.

Table 3.3. Distribution of Failures Among Subsystems

SUBSYSTEM	NUMBER OF FAILURES		
	BWR	PWR	TOTAL
1. Feed Water System	26	13	39
2. Gas Systems	16	8	24
3. Recirculation System (BWR)	23	0	23
4. Charging System (PWR)	0	22	22
5. Steam Piping	9	9	18
6. Instrumentation	10	8	18
7. Decay Heat Removal	6	10	16
8. Service Water/Radwaste	8	8	16
9. Core Spray/ Coolant Injection	13	2	15
10. Demineralizer	10	2	12
TOTAL	121	82	203

b. BWRs have exhibited pipe failures in the recirculation system, core spray piping, the condensate piping, and the demineralizer system, and

c. The BWR and PWR subsystems which have comparable failure frequencies are:

- Steam piping,
- Instrumentation,
- Decay heat removal, and
- Service water/radwaste.

The failure frequencies, by subsystem, are compared graphically in Figure 3.5.

3.4 Distribution of Failures According to Pipe Size and Plant Type.

The distribution of pipe failures according to pipe size (expressed in terms of diameter) and plant type is illustrated in Table 3.4. It is clear that the majority of failures that have been reported occurred in small diameter piping (less than 6 inches). Specifically, 70.7% of the PWR pipe failures

Table 3.4. Distribution of Pipe Failures by Plant Type and Pipe Size

		Pipe Size Category (Diameter in inches)				
		(≤1)	(>1,≤6)	(>6,≤10)	(>10)	Not Specified
PWR Plants (32)	Number of Pipe Failures Reported	42	16	6	3	15
	Percent of Total PWR Pipe Failures	51.2	19.5	7.3	3.6	18.3
BWR Plants (23)	Number of Pipe Failures Reported	35	50	8	6	22
	Percent of Total BWR Pipe Failures	28.9	41.3	6.6	4.9	18.2

have occurred in piping less than six inches in diameter; 70.2% of the BWR pipe failures occurred in piping less than six inches in diameter. At the risk of overemphasizing this point, note that 51.2% of all PWR pipe failures occurred in lines less than or equal to one inch in diameter.

The amount of piping in a nuclear power plant has previously been estimated in the Reactor Safety Study (WASH-1400) to be approximately 35,000 feet (the same for PWR and BWR plants). Of this piping it is judged that 53% of the total piping is "large" pipe (>4" diameter). Based upon Table 3.4, it appears then that small diameter piping is subject to a higher failure rate than larger diameter piping. This may be due to more attention to detail in larger piping along with better quality control.

A statistical test was performed in order to determine whether the size distribution of PWR pipe failures illustrated in Table 3.4, was significantly different, in a statistical sense, from the size distribution of BWR pipe failures. On the basis of this test, we conclude that the distribution of BWR failures by pipe size differs from the distribution of PWR pipe failures (see Appendix A for details).

3.5 Failure Modes of Pipe Systems

Identification of the dominant modes of failure is required if we are to select appropriate corrective measures, maintenance and surveillance policies and, on a broader scale, make recommendations for future research and development programs.

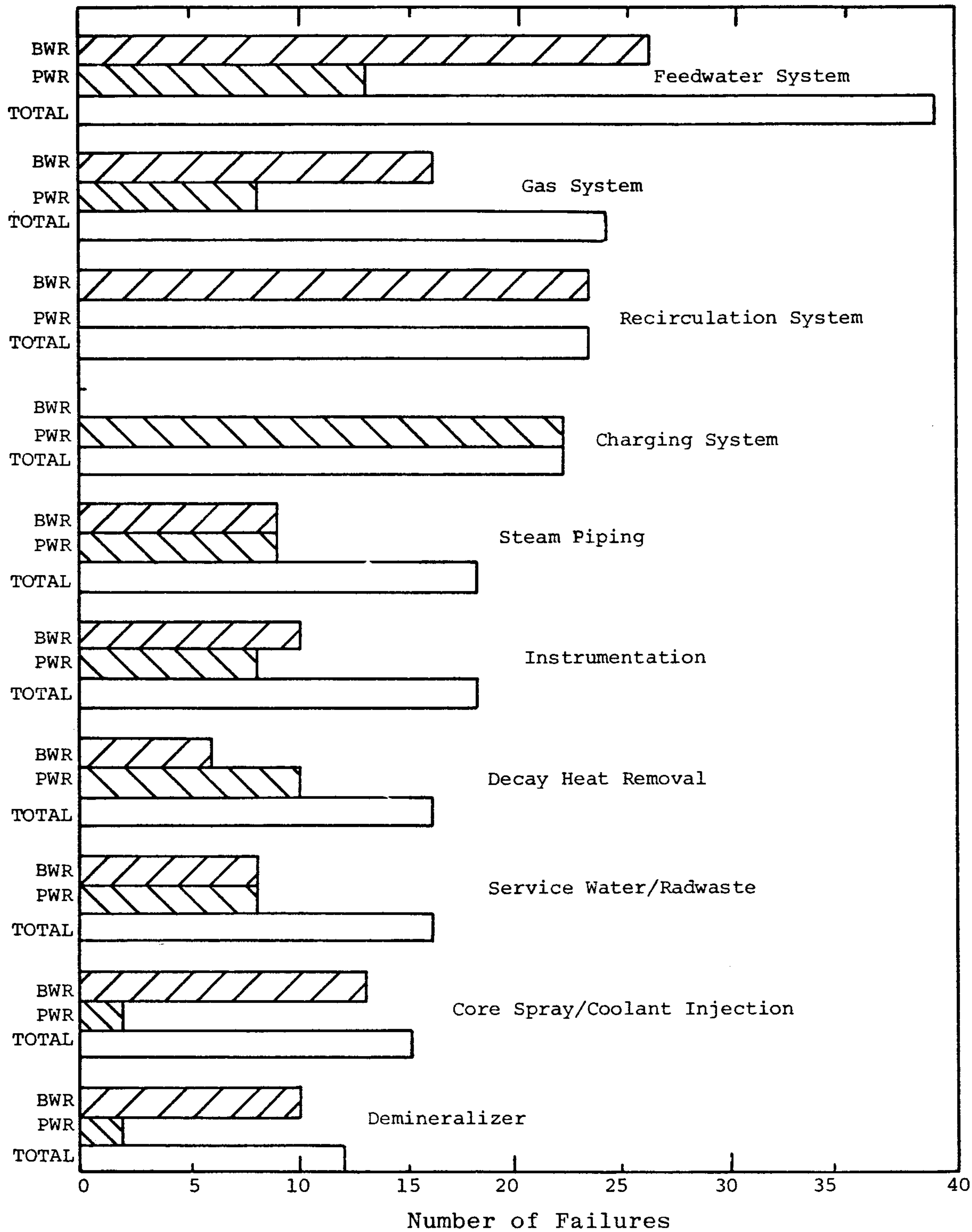


Figure 3.5. Frequency of Pipe Failures Within Subsystems

The various modes of failure or, more accurately, the probable causes of failures that have been reported to date are:

(1) Vibration (both forced vibration by an external source such as a pump and flow-induced vibration),

(2) Thermal and cyclic fatigue,

(3) Fabrication problems (welding flaws, etc., created in the shop or during installation),

(4) General corrosion (chemical or galvanic attack),

(5) Erosion of pipe wall by high velocity impingement,

(6) Stress corrosion cracking by intergranualr corrosion attack of sensitized austenitic stainless steel, and

(7) Unknown.

In this section, we shall examine the frequencies at which these modes of failure have been observed in both PWR and BWR plants. This will be followed, in Section 3.6, by an analysis of the time-to-failure for each failure mode. Table 3.5 illustrates how the failure modes are distributed, on the basis of frequency of occurrence, of the BWR and PWR plants (see also Figure 3.6 for a graphical representation).

On the basis of the data presented in Table 3.5, it is clear that vibration (mechanical fatigue) is the major cause of reported failures in all plants, (25% of all failures in BWRs and PWRs combined). Vibration is also the primary mode of pipe failure in the individual plant types (19% of all BWR pipe failures and 34% of all PWR pipe failures). This conclusion is different from that reached by Gibbons-Hackney(Section 2.1) and Phillips-Warwick (Table 2.4) where low cycle fatigue was given as the chief cause of failure. Fabrication problems are next in line as far as the percentage of all pipe failures are concerned; these are followed by stress corrosion cracking. Although there is a significant number of pipe failures for which the cause of failure is not given (approximately 35%), it is judged that the distribution of pipe failures by cause is similar to that given in Figure 3.6.

An item which is conspicuous by its absence from the above list is failure due to exceeding a primary stress limit. Although it is possible that such a failure mode is included in the "unknown" or "not specified" category or has not been recorded, it appears that pipe systems are being conservatively

Table 3.5. Distribution of Failure Modes in BWR's versus PWR's

PLANT TYPE		VIBRATION	THERMAL & CYCLIC FATIGUE	FABRICATION PROBLEMS	CORROSION	EROSION	STRESS-CORROSION CRACKING	UNKNOWN OR NOT SPECIFIED
BWR	Frequency	23	9	13	6	9	20	41
	Percentage of BWR Failures	19.0	7.4	10.7	5.0	7.4	16.5	33.9
PWR	Frequency	28	2	13	0	5	3	31
	Percentage of PWR Failures	34.1	2.4	15.9	0	6.1	3.7	37.8
Column Totals	Frequency	51	11	26	6	14	23	72
	Percentage of all Failures	25.1	5.4	12.8	2.9	6.9	11.3	35.5

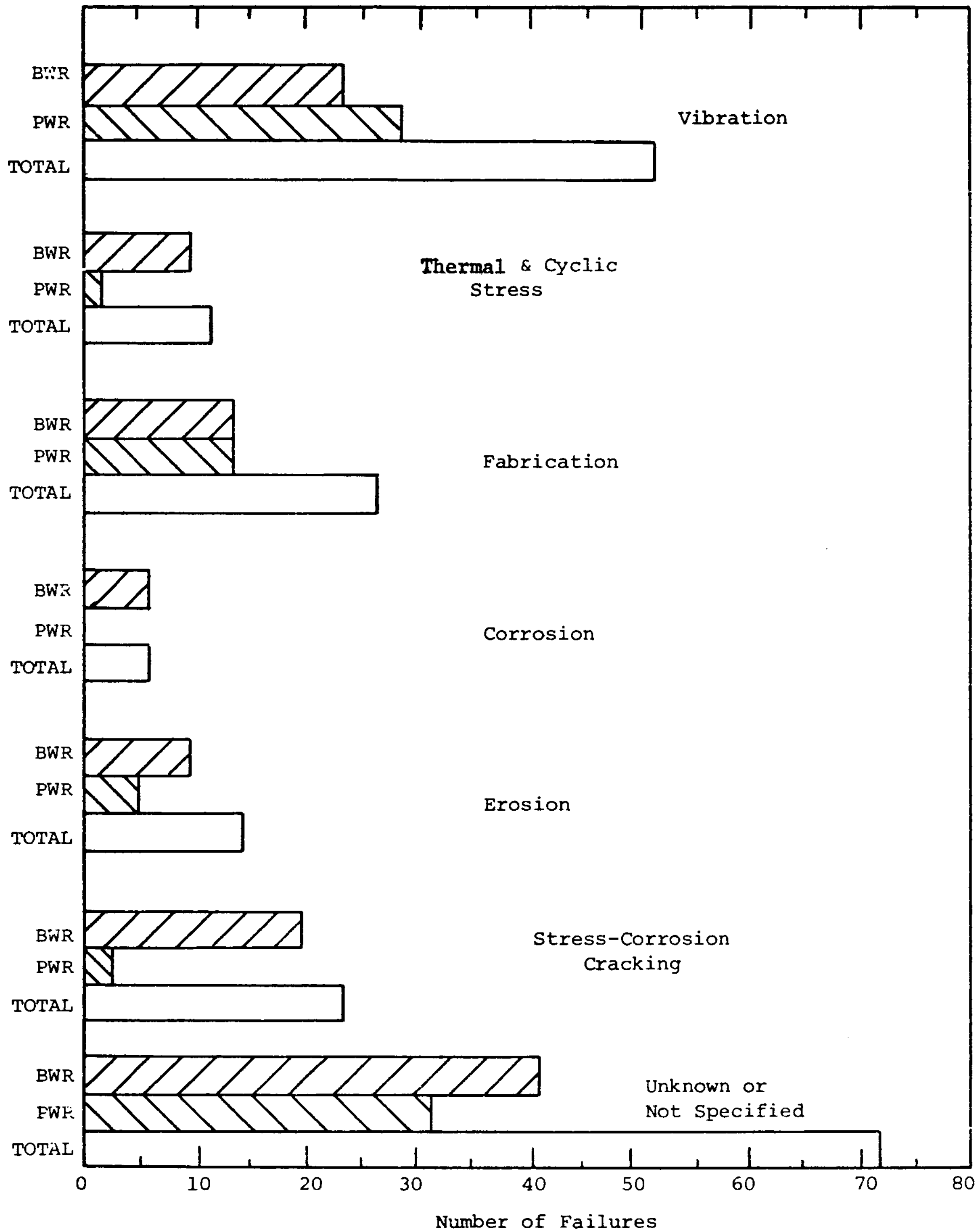


Figure 3.6. Comparison of Failure Modes Within BWR's Versus PWR's.

designed to meet steady state stress limits. The reported failure mechanisms, as cited above, are those which do not have specific design rules, or "textbook" solutions and are avoided more by engineering judgement than by strict ASME code rules.

Since the primary cause of the pipe failures which have been reported (vibration) is also the most difficult to analyze, predict, and design against, we have summarized the techniques commonly cited as corrective actions to preclude further vibration-induced failures:

(1) <u>For Mechanical Vibration</u>

   a. Increased rigidity in pipe supports,

   b. Isolation of vibrating equipment from piping by flexible connections, and

   c. Separation of the natural frequency of piping from the frequencies it is exposed to, and

(2) <u>For Flow-Induced Vibration</u>

   a. Reduced fluid velocities,

   b. Incorporation of smooth flow transitions,

   c. Mechanical designs which account for high fluid velocities, and

   d. Avoidance of flow vortices.

Another failure mode which strongly influences pipe failure is stress corrosion cracking (SCC). Utilities and designers are aware of the nature of the problem, and a conscious effort is being made to reduce the incidence of SCC failures. As noted in Table 3.5, SCC occurs approximately seven times more frequently in BWRs than in PWRs.

As in the above cases involving the distribution of observed frequencies, we have applied a statistical test to the frequency data contained in Table 3.5. In this case, our objective is to determine whether or not the frequency of various pipe system failure modes observed within PWR plants is the same (statistically) as the frequencies that have been observed in BWR plants. Once again, a chi-squared test was employed, the details of which may be found in Appendix A. On the basis of this test, we found that the differences between the distribution of BWR failure modes and the distribution of PWR failure modes are statistically significant at the .01 level.

For each of the failure modes discussed above, the location of the failures and the mechanisms by which they are initiated and propagated through the pipe are items of information essential to the selection of corrective measures and/or new designs. The failures which have been reported to date are distributed over the following local sites:

(1) Welds and heat affected zones (HAZ) (54%),
(2) Pipe wall (base metal) (40%), and
(3) Threaded joints (6%).

The entries listed in Table 3.6 indicate that the failures which have been reported most frequently do not seem to be biased relative to the location of the failure (weld or HAZ or pipe wall (base metal)). This is an important observation and is consistent with the conclusions of Gibbons-Hackney (refer to Section 2.1 above). This suggests that the utility industry should not concentrate all of its effort on the improvement of welding technology at the expense of the other areas, (e.g., adequate pipe restraints or pipe quality control). However, the failure rate per unit surface area is much higher for welds or weld heat-affected zones than for base metal pipe.

Table 3.6. Mode and Location of Failures

MODE OF FAILURE	LOCATION OF FAILURE	
	WELD OR HAZ	PIPE
Vibration (fatigue)	29%	12%
Stress-Corrosion Cracking	15%	8%
Erosion	0%	10%
Corrosion	0%	4%
Installation/Fabrication Error	0%	12%
Poor Weld	10%	0%

3.5.1 Pipe Size - Failure Mode Distribution

The statistical tests performed so far have shown that the PWR and the BWR pipe failures differ statistically as far as the frequencies within pipe size categories are concerned (Section 3.4) and the frequencies within failure modes (Section 3.5). We now consider the distribution of pipe size versus failure mode. In other words, we shall address the question of whether certain pipe sizes are more susceptible to certain failure modes than others. Since the frequency distributions over both size and failure mode differ in accordance with plant type (i.e., PWRs versus BWRs), we shall examine the distribution of pipe size versus failure mode within PWRs and within BWRs separately. The distributions in question are listed in Tables 3.7 and 3.8 below. It has already been pointed out that vibration is the dominant mode of failure in all plants, PWRs and BWRs combined. The entries in Tables 3.7 and 3.8 show that vibration is the primary contributor to the failure of piping less than one inch in diameter regardless of plant type.

Fabrication errors are next in line in terms of frequency of failures in one-inch lines. In the case of PWR plants, vibration accounts for the majority of failures in piping greater than one inch but less than or equal to six inches in diameter. In BWR plants, stress corrosion cracking accounts for the majority of failures in the one-to-six-inch size category. Stress corrosion cracking also accounts for the majority of failures in the six-to-ten-inch pipe size category for both PWRs and BWRs. Due to the small number of failures reported on pipes with a diameter greater than 10", it is perhaps meaningless to consider a dominating failure mechanism for this size category. For PWRs the three failures which occurred in high pressure steam lines (>10" diameter) were attributed to vibration or pressure surges not accounted for in the design.

3.6 Time Distribution Associated with Piping Failures

Several interesting observations have been made relative to the temporal behavior of pipe failures. As mentioned above (Section 3.1), the point of origin or reference time for the failure associated with a given plant is taken to be the date of initial criticality. Hence, a time to failure of 65 months implies that the particular component in question failed 65 months after the date of initial criticality.

An attempt has been made to detect differences between BWR and PWR pipe system failure times. Two of the factors considered in conjunction with failure times were pipe size and mode of failure. The obvious differences between PWR and BWR time distributions are illustrated in Figure 3.7. It is clear that pipe systems in the PWRs exhibit failure times that are exponentially distributed. The expected (average) time-to-failure of a PWR pipe or pipe component is 35.78 months (roughly 3 years) with a standard deviation of 49.57 (roughly 4 years). In contrast to the PWRs the BWR pipe failure times appear to have a unimodal distribution with the mode between 50 and 60 months (4 to 5 years) from initial criticality. Other than that, the BWR distribution possesses a relatively long right-hand tail as does the PWR distribution. The expected (average) time-to-failure for a BWR or pipe component is 56.27 months (4.7 years) with a standard deviation of 42.63 months (3.6 years).

Since the failure times of PWR and BWR piping appear to have been drawn from different* distributions, an attempt was made to determine a rational explanation for this observation. The failure times were separated into distinct groups, in accordance with the reported failure modes, and frequency histograms of the failure times associated with each failure mode were constructed (Figures 3.8 and 3.9). One of the most conspicuous differences between the two sets of histograms is that corrosion was not observed, or at least not reported to the same extent in PWRs as it was in the case of BWR plants. In the case of BWR piping failures, it appears that several failure modes contribute to the unimodal character of the BWR distribution. Another general observation, relative to the differences between the PWR and BWR time distributions, is that the PWR failures, regardless of failure mode, tend to occur early in the life of a plant, whereas the onset of BWR pipe failures occurs later (c.f. average failure times listed on the individual histograms in Figures 3.8 and 3.9 and Table 3.9).

* The Kolmogorov-Smirnov two-sample test (see Appendix A) indicates that the PWR and the BWR time-to-failure distributions are statistically different at the 0.001 level.

Table 3.7. Pipe Size versus Failure Mode Distribution for Pipe Failures Within PWR Plants*

Failure Mode	Pipe Size Category by Diameter				Row Sum
	(≤ 1")	(>1",≤6")	(>6",≤10")	(>10")	
Vibration	21(60.0)**	4(57.1)	2(33.3)	3(75.0)	30
Thermal & Cyclic Fatigue	1(2.9)	0	0	1(25.0)	2
Fabrication	11(31.4)	1(14.3)	0	0	12
Corrosion	0	0	0	0	0
Erosion	2(5.7)	2(28.6)	1(16.7)	0	5
Stress Corrosion Cracking	0	0	3(50.0)	0	3
Column Sums	35	7	6	4	52

* Note: The entries in this table only include the 52 failures out of 82 for which the failure mode and pipe size were both specified.

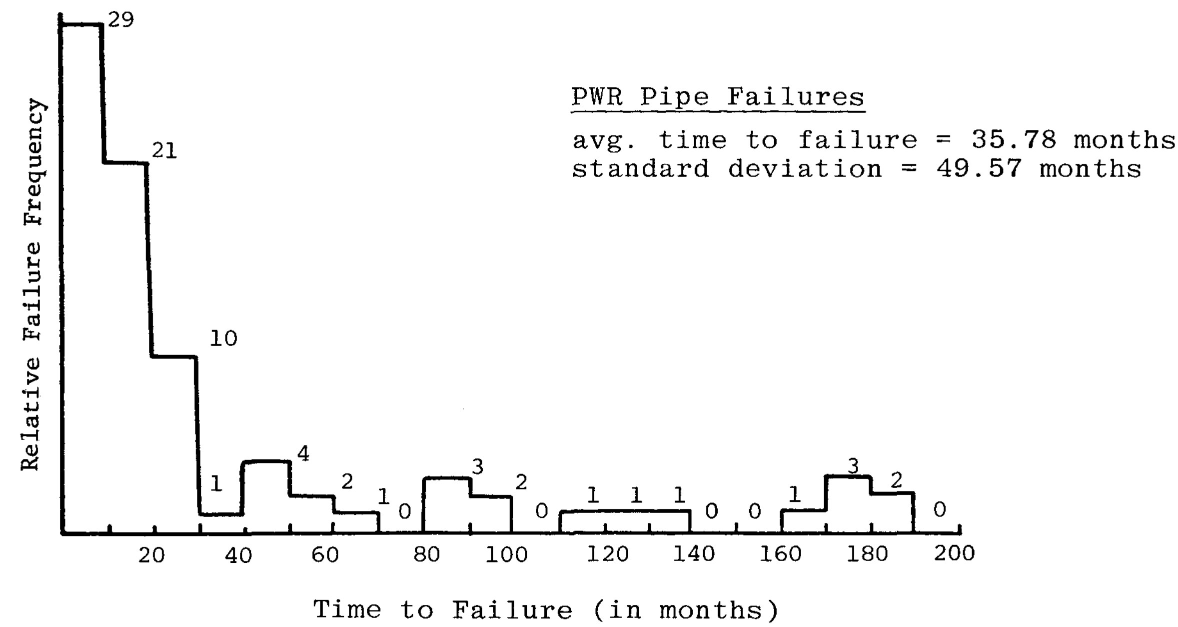
** Entries in parenthesis represent percentage of column sum.

Table 3.8. Pipe Size Versus Failure Mode Distribution for Pipe Failures Within BWR Plants*.

Failure Mode	Pipe Size Category by Diameter				Row Sum
	(≤1")	(>1",≤6")	(>6",≤10")	(>10")	
Vibration	15(53.6)	7(17.9)	1(16.7)	0	23
Thermal & Cyclic Fatigue	4(14.3)	3(7.7)	0	1(50.0)	8
Fabrication	6(21.4)	4(10.3)	1(16.7)	0	11
Corrosion	1(3.6)	3(7.7)	0	1(50.0)	5
Erosion	1(3.6)	7(17.9)	1(16.7)	0	9
Stress Corrosion Cracking	1(3.6)	15(38.5)	3(50.0)	0	19
Column Sums	28	39	6	2	75

*Note: The entries in this table only include the 75 failures out of 121 for which the failure mode and pipe size were both specified.

**Entries in parenthesis represent percentage of column sum.



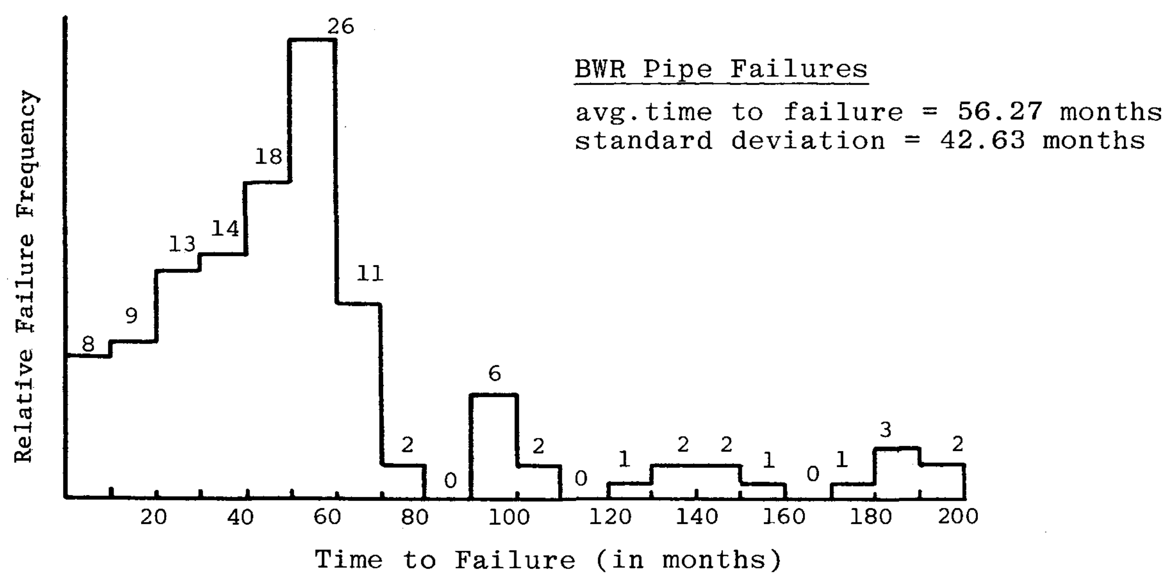


Figure 3.7. Time to Failure Histograms for BWR and PWR Pipes and Pipe Components.

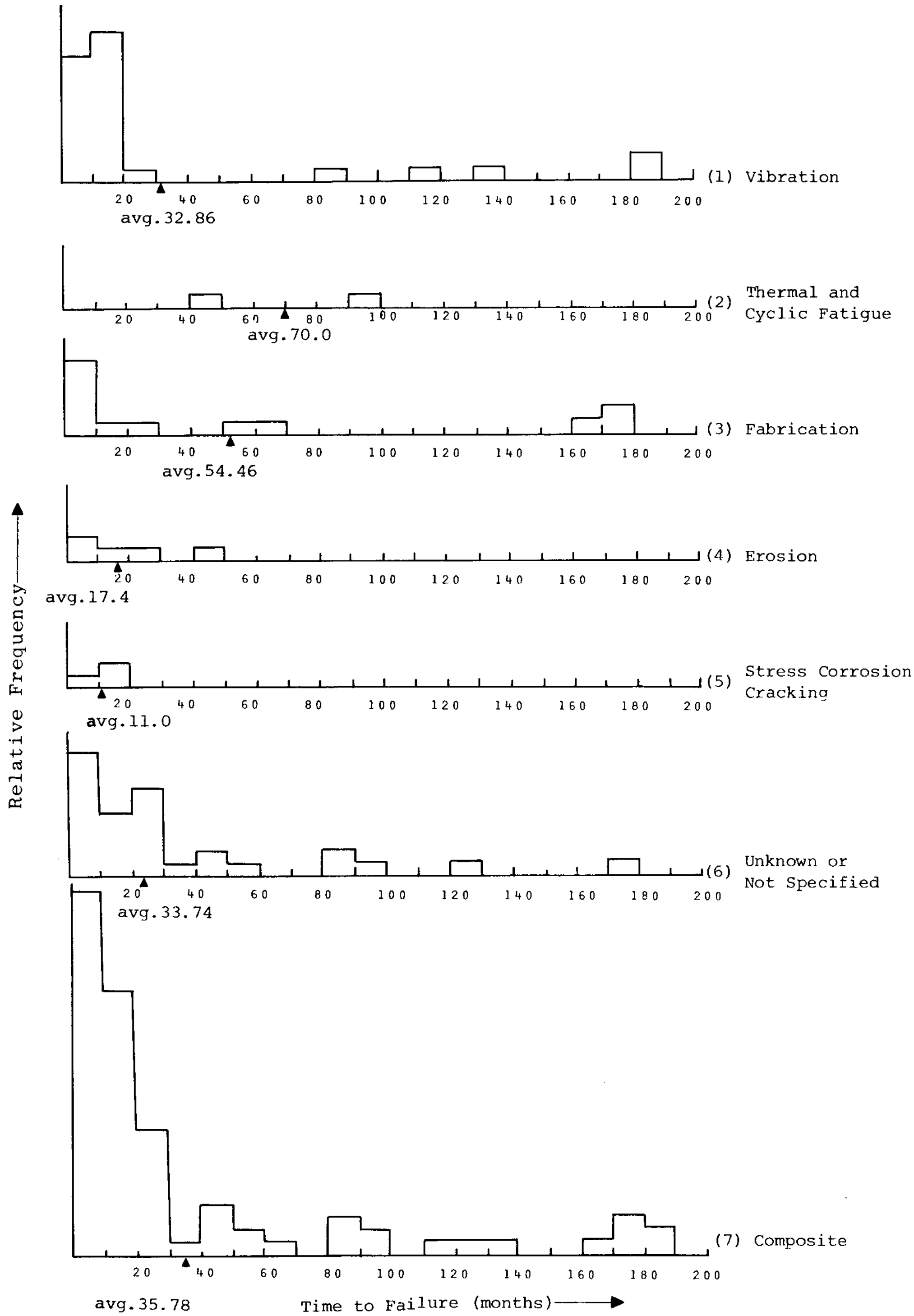


Figure 3.8. Distributions of PWR Pipe System Failure Times Associated with Specific Failure Modes.

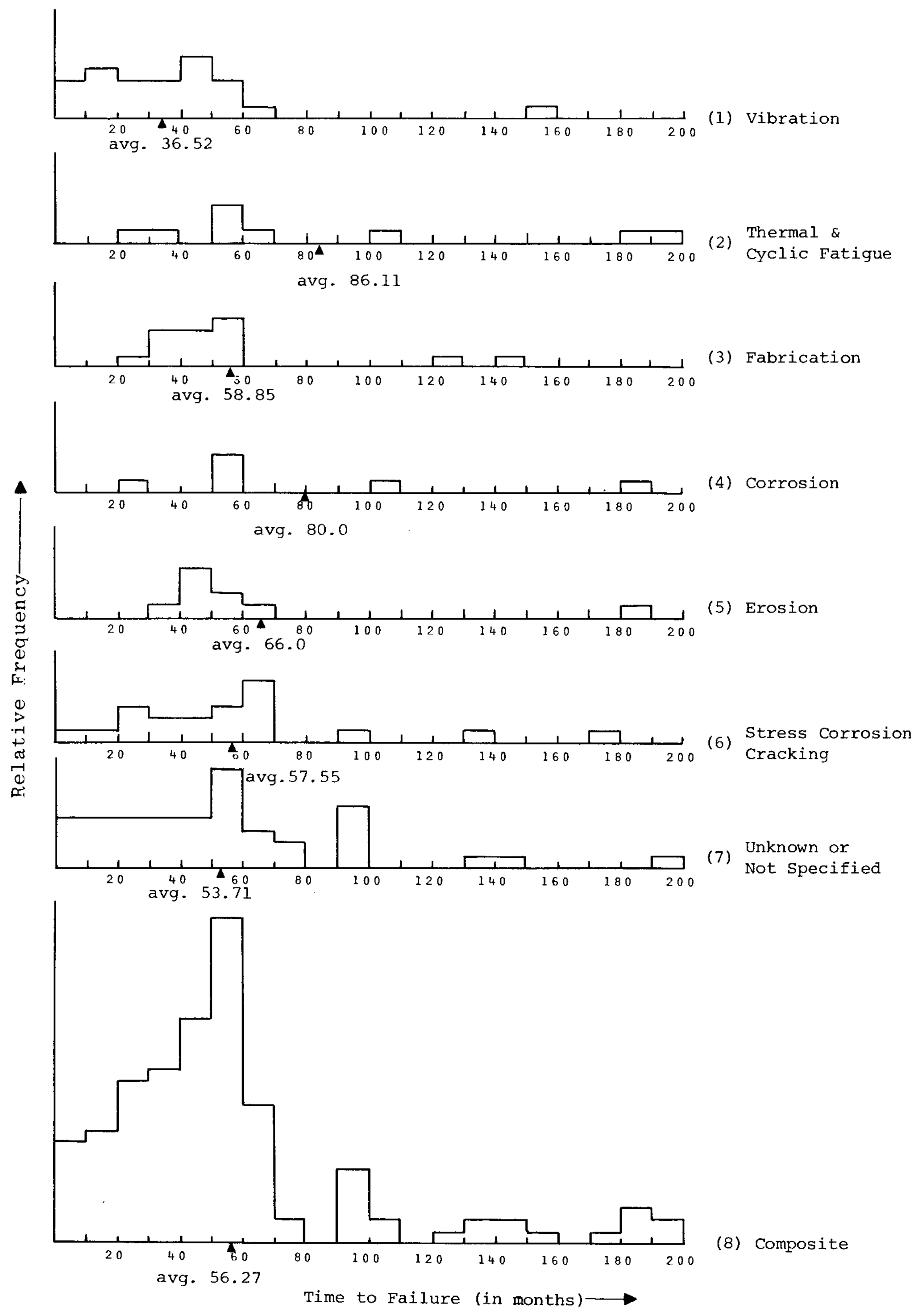


Figure 3.9. Distributions of BWR Pipe System Failure Times Associated with Specific Failure Modes.

Table 3.9. Comparison of Average Time to Failure for the Various Failure Modes and the Two Plant Types

Plant Type	Probable Cause of Failure						
	Vibration	Thermal & Cyclic Fatigue	Fabrication Problems	Corrosion	Erosion	SCC	Unknown or not Specified
BWR	avg.36.52* std.dev.31.91** no.23	86.11 61.85 9	58.85 36.11 13	80.0 58.55 6	66.0 46.34 9	57.55 40.40 20	53.71 40.11 41
PWR	avg.32.86 std.dev.53.61 no.28	70.0 39.59 2	54.46 70.26 13	- 0	17.4 17.77 5	11.0 4.58 3	33.74 40.24 31

* average time to failure in months from the date of initial criticality.

** standard deviation of the observed times to failure, expressed in months from the date of initial criticality.

3.7 Pipe System Reliability and Failure Rate Functions (Statistical Analysis)

When rare events are distributed in time, the assumption is usually made that the number of events in a fixed interval of time has a Poisson distribution. It follows from this assumption that the time intervals between events are exponentially distributed. There are two situations which give rise to an exponential distribution of interarrival times[7,8]:

(1) If the systems in question are "run in", i.e., subjected to pre-service examination or burn-in tests which eliminate manufacturing defects and degraded components are replaced, and

(2) The systems in question are complex systems wherein individual components are replaced or otherwise restored to origianl condition as soon as a failure occurs.

Clearly, these conditions do not hold for pipe systems in general; hence, we consider a more general model in the next section.

3.7.1 Competing-Risk Model

A complex system may fail due to the action of one or more failure mechanisms or what we have referred to above as failure modes. The ultimate concern is whether or not the system in question is able to perform its intended function over a specified interval of time. The probabilistic treatment of such questions involves, in general, three closely related mathematical functions. The first is the distribution of system or component lifetime, which we shall denote by $f(t)$. Next is the cumulative distribution function $F(t)$ associated with $f(t)$. The cumulative distribution function $F(t)$ expresses the probability that the item in question will fail prior to time t. The third function of interest is the failure rate or hazard function, $h(t)$. The hazard function $h(t)$ expresses the conditional probability that a item will fail in the interval $(t,t+dt)$ given that it has operated properly up to time t. We shall now show how these functions are related and proceed to estimate them via the operational data at our disposal.

Suppose that pipe systems are susceptible to k modes of failure (risks), say m_1, m_2, ..., m_k and that a random lifetime of piping occurs as follows. When the pipe system begins operation, each failure mode m_j, generates a random lifetime that is independent of the other modes. Thus, k lifetimes, denoted T_1, T_2, ..., T_k, begin simultaneously, T_j corresponds to the jth mode of failure. Failure of the piping occurs as soon as any one of the lifetimes, say T_j, is realized. Therefore, the lifetime of the piping, denoted by T, is given by

$$T = \min (T_1, T_2, \ldots, T_k).$$

If $F_{T_j}(t)$ is the cumulative distribution function of T_j, the cumulative distribution function which expresses pipe system lifetime, T, is given by

$$F_T(t) = 1 - \prod_{j=1}^{k} 1-F_{T_j}(t) \qquad (1)$$

This, so called, competing risk model allows for inclusion of any family of individual failure mode distributions such as those illustrated in Figure 3.7 (Section 3.6). The underlying assumption is, of course, that the k failure modes act independently. The above expression can be rewritten in a form which illustrates the effect of the individual failure modes more explicitly. As mentioned above, the functions h(t), f(t) and F(t) are closely related; specifically,

$$h(t) = \frac{f(t)}{1-F(t)}$$

The funtion 1-F(t) is the reliability at time t; i.e., 1-F(t) expresses the probability that the system will function properly at least to time t. Since $F(t) = \int_0^t f(x)dx$, we have:

$$\frac{dF(t)}{dt} = f(t)$$

Therefore,

$$h(t)dt = \frac{dF(t)}{1-F(t)}$$

Equivalently, we may write

$$\int_o^t h(x)dx = - \ln [1-F(x)] \Big|_o^t$$

or

$$1-F(t) = \exp \left\{ -\int_o^t h(x)dx \right\} .$$

Now, with this in mind, we may re-write (1) in the following way

$$F_T(t) = 1 - \exp \left\{ - \int_o^t \sum_{j=1}^{k} h_j(x)dx \right\}$$

This expression describes the probability that a pipe failure will occur within the time interval [o,t] .

In the event that individual hazard functions are constant, we have

$$\sum_j h_j (x) = \lambda$$

This assumption, in turn, gives rise to the exponential failure distribution

$$F(t) = 1 - \exp \{ -\lambda t \} .$$

Underlying the publication of constant failure rate estimates such as those listed in Table 2.7 (Section 2.4, above) is the assumption that the time-to-failure is exponentially distributed. We have already observed that in the case of BWR pipe systems, such an assumption is not valid. Hence the competing risk model with time-varying failure rates appears to be a more appropriate model.

An attempt has been made to derive empirical hazard functions for PWR and BWR pipe systems on the basis of the available operational data. These are shown in Figures 3.10 and 3.11. The objective here is not to achieve great accuracy, since this is difficult, if not impossible, to do with the information presently available. It should be noted that the hazard function , h(t), represents a frequency; hence, it is subject to large random variations especially for increasing values of t where 1 - F(t) becomes extremely small. The objective in presenting the empirical hazard functions is simply to form the basis for some qualitative comparisons between the BWR pipe systems and the PWR pipe systems.

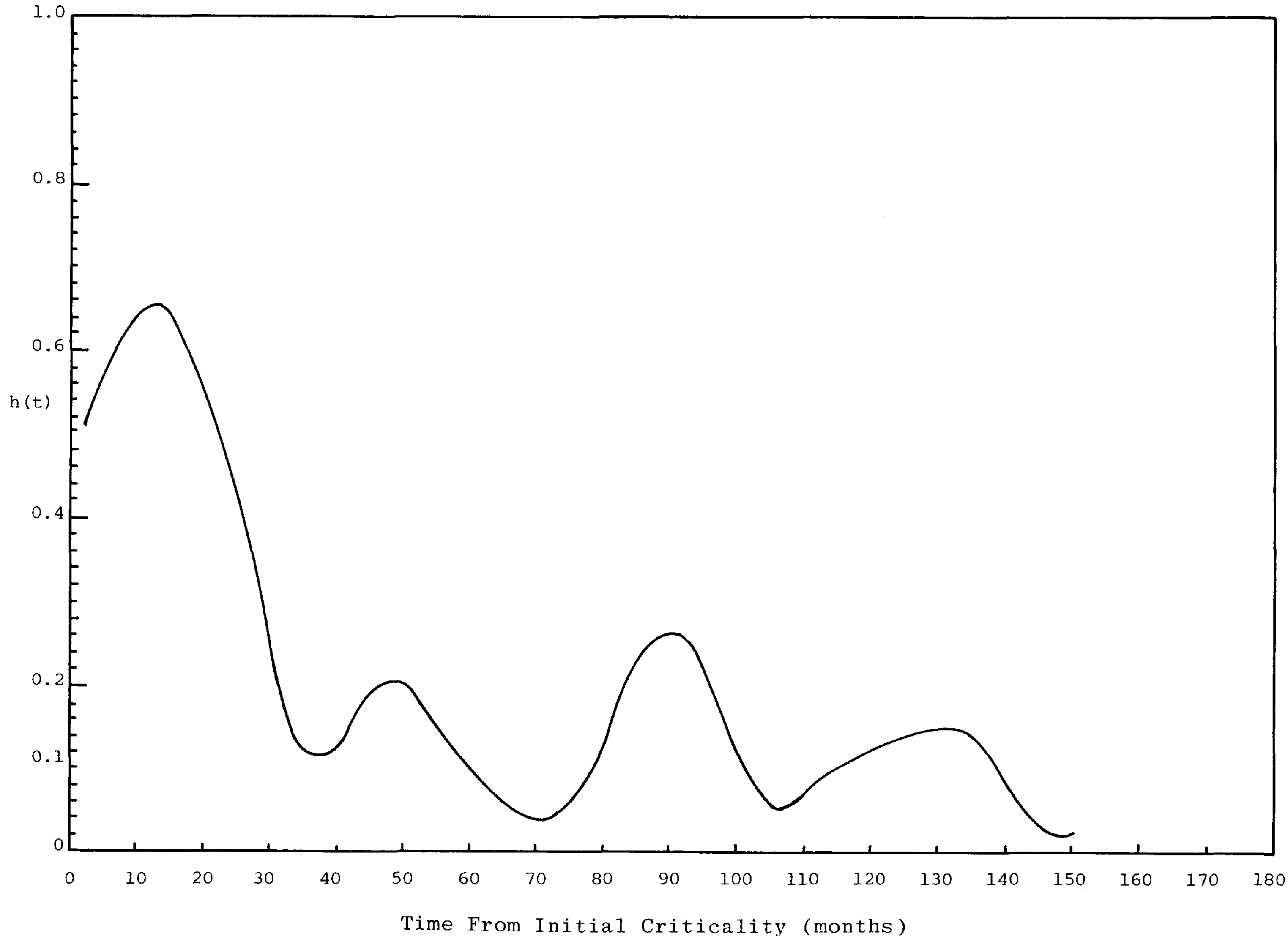


Figure 3.10. Empirical Hazard Function Associated With Pipe Failures in PWR Plants.

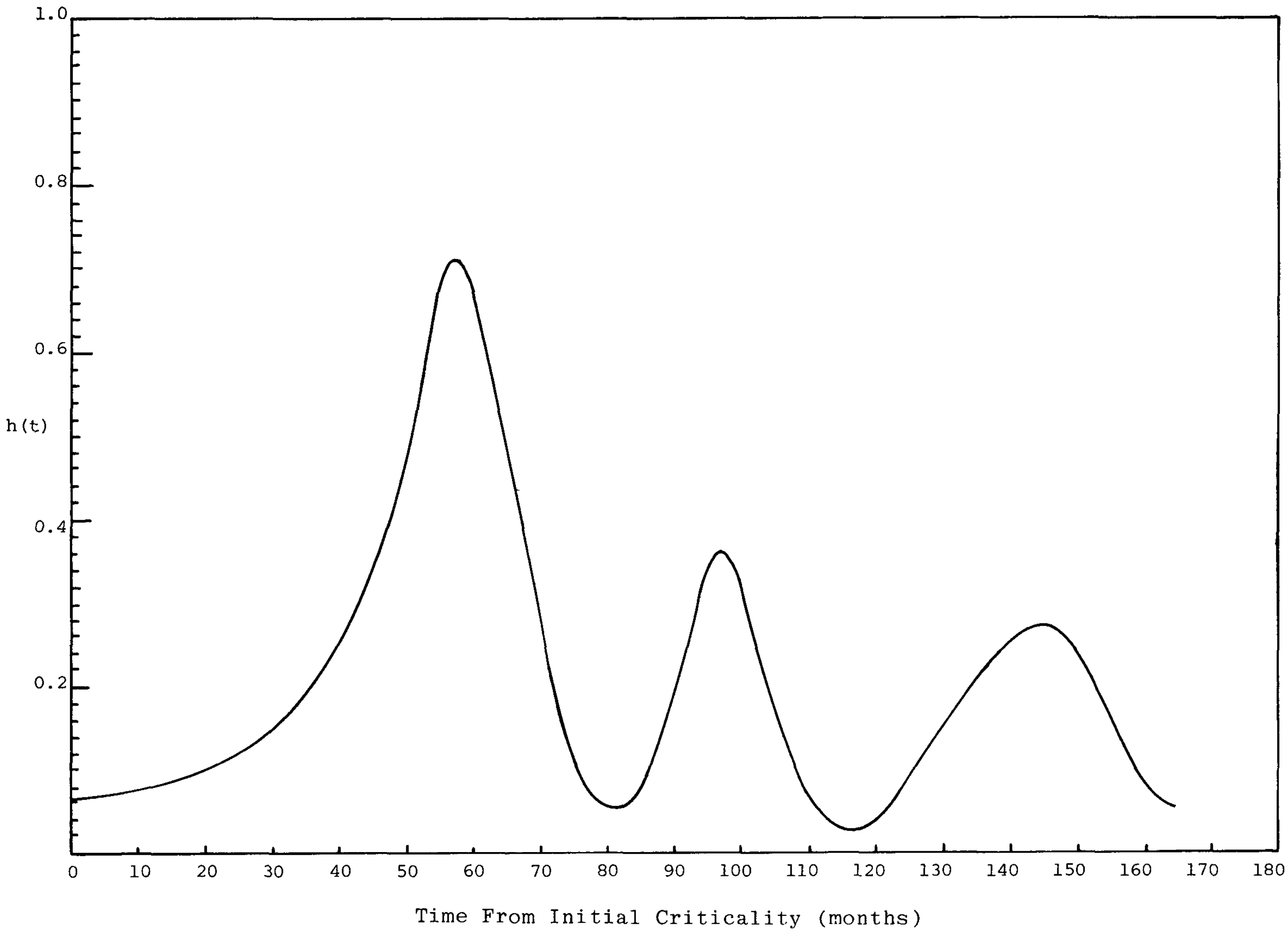


Figure 3.11. **Empirical Hazard Function Associated With Pipe Failures in BWR Plants.**

It is clear that the BWR and PWR pipe systems exhibit failure rates which are anything but constant. Furthermore, the two failure rate functions are markedly different. Both, however, appear to be a superposition of several independent hazard functions. As in Figures 3.5 and 3.6, above, the PWRs experience a relatively large number of early failures (within the first 2.5 years of service), whereas the BWR failures are most prevalent in the 50 to 60 month range with three secondary modes appearing thereafter.

SECTION 4

4.0 IMPACT OF PIPE FAILURES ON PLANT AVAILABILITY

Several criteria may be used in assessing the effect of pipe failures on plant availability . In this section we consider:

(1) Frequency of reactor shutdowns due to pipe failures,
(2) Distribution of forced outage times due to pipe failures, and
(3) Frequency of pipe ruptures.

4.1 Reactor Shutdown Caused by Pipe Failures

One measure of the effect of pipe failures on plant availability is the frequency of reactor shutdowns caused by pipe failures. Figure 4.1 shows that approximately one-half of the reported pipe failures were discovered during shutdown. This estimate is probably low since the pipe failures discovered during maintenance are not always reported and are therefore not included in this anlysis. The effect of pipe failures on plant status is summarized in Table 4.1 along with the frequency of occurrence.

4.2 Forced Outages

The effects of the forced shutdowns cited in Section 4.1 can be assessed by considering the resulting plant outages.

Figure 4.2 compares the distribution of forced outages due to pipe failures (BWR versus PWR) which have been reported throughout the period January 1974 to March 1976. The forced outages are predominantly distributed over the 0-50 hour range. Seventeen (17) reported outages exceeded 100 hours (these represent 26% of the reported incidents and approximately 80% of the total outage time).

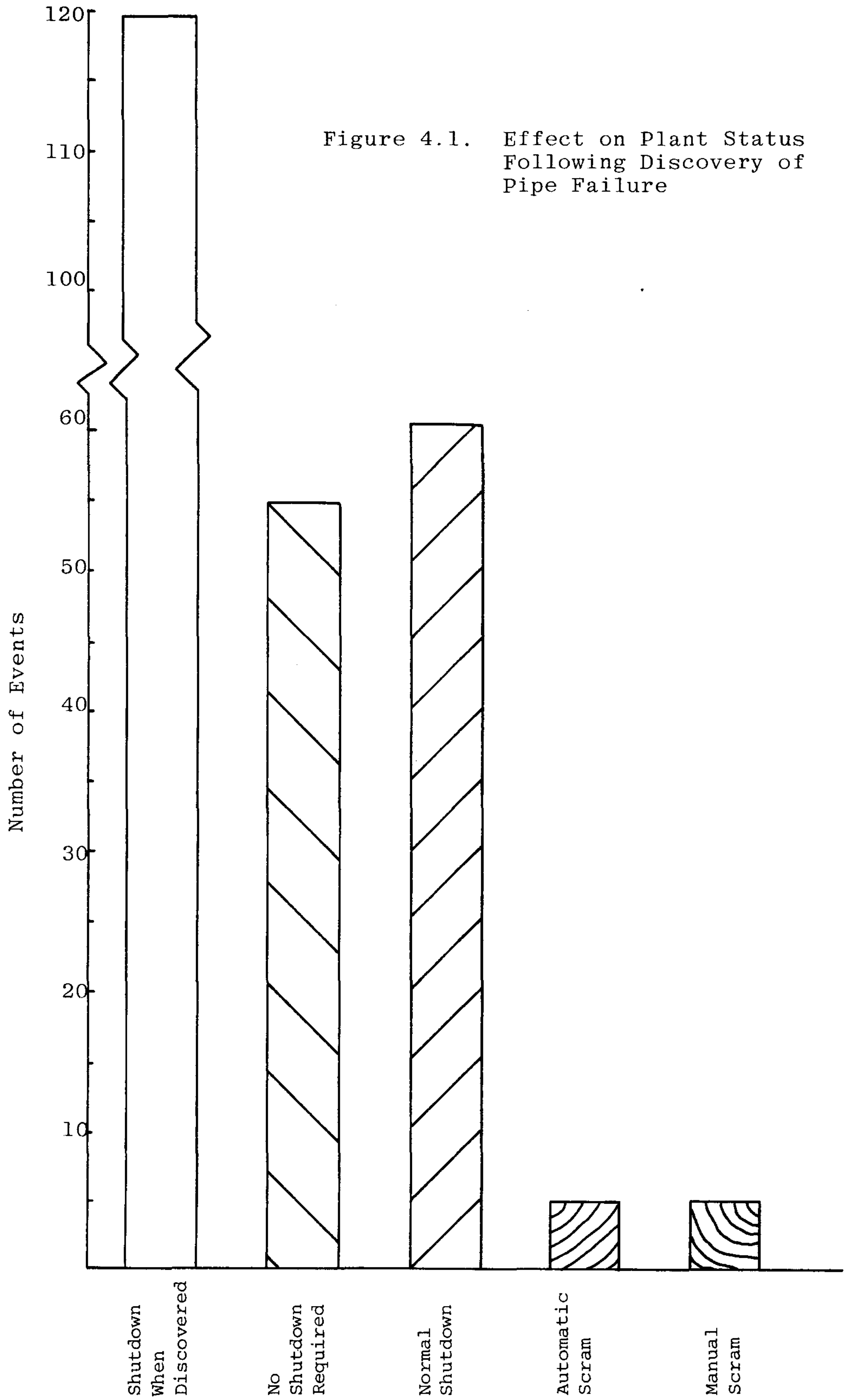


Figure 4.1. Effect on Plant Status Following Discovery of Pipe Failure

Table 4.1.* The Effect on Plant Status Following Discovery of Pipe Failure

Effect of Failure	(Percent)	Frequency $(\text{Plant-Year})^{-1}$
No Shutdown Required	23%	.22
Normal Plant Shutdown	26%	.24
Automatic Scarm	2%	.02
Manual Scram	2%	.02
Failures Discovered During Shutdown	47%	-

*Table 4.1 breakdown implies that: (1) A scram due to pipe failure has occurred, on the average, once every 25 plant-years, (2) Approximately 30% of the pipe failures have resulted in plant shutdown, and (3) A forced shutdown has occurred once every 3.6 plant-years due to pipe failure.

The data indicates that long duration forced outages as a result of pipe failures are relatively rare events however they may have a significant impact on plant availability.

In order to put these forced outages in perspective, the outage times associated with pipe failures should be compared to the outage times associated with other equipment. The reported pipe failures in 1975 resulted in 8% of the total forced outage time caused by equipment failures. Of this 8% it is important to note that approximately one-half of the pipe-related outage time is attributed to two BWR incidents:

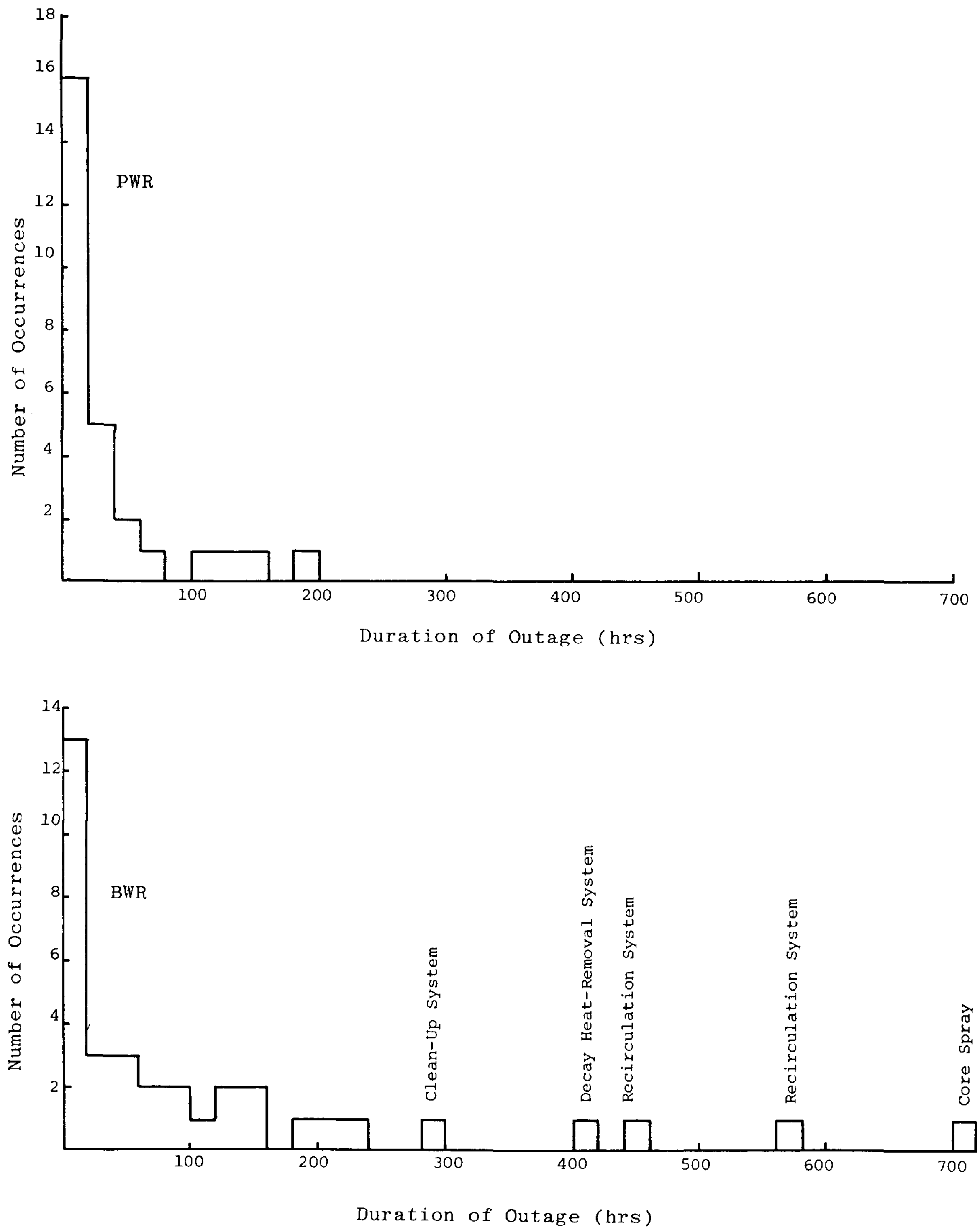


Figure 4.2. Comparison of Forced Outage Times Resulting From Pipe Failures (PWR vs BWR) (Data for the years Jan. 1974 - Mar. 1976)

Table 4.2. Comparison of Forced Outage Times for 1975

	1975												
	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
Length of Outages (Hrs.) Pipe Failures	459	8	720	0	13	0	360	215	320	179	283	63	2,620
Length of Outages (Hrs.) All Equipment	2874	1786	2215	1738	1484	4236	3060	2283	4462	3508	2536	3414	33,576
Ratio of Hours of Outage $\left(\frac{\text{Pipe Related}}{\text{All Equipment}}\right)$	.16	~0	.33	0	.01	0	.12	.09	.07	.05	.11	.02	.08

(1) Core spray repair at Dresden 2, and

(2) Recirculation piping repair at Quad-Cities 1.

4.3 Pipe Ruptures or Breaks+

For the purposes of determining impact on plant performance or safety, one may only be interested in pipe ruptures, since cracks or leaks in piping would provide some warning before producing a potentially catastrophic failure. Twenty-two of the 237 reported pipe failures (i.e., approximately 9.3%) involved pipe ruptures, breaks or failures of such a nature so one would conservatively classify them as ruptures or breaks. Thirteen of these incidents which occurred in pressurized water or steam systems are summarized in Table 4.3. Since there have been relatively few events in the nuclear industry which can even conservatively be included as a pipe break or rupture, we have included Table 4.3 to better characterize the failures which have occurred. One interesting point which surfaces from this data is that the failures are induced by mechanisms which are difficult to predict because of their complex nature. Vibration and pressure surges appear to be principal modes of these failures. Table 4.3 indicates that based upon operating nuclear experience for pressurized water and steam systems the following failure rates can be inferred:

No. of Incidents	% of All Reported Failures	Location and Key Characteristic	Failure Rate $(\text{Plant-year})^{-1}$
13	5.5%	pressurized systems	.07
7	3.0%	pressurized pipes >4" diameter	.03
6	2.5%	pressurized pipe and required a scram following failure	.02
2	.8%	>1" diam. pipe and required scram following failure	.01

In addition to the thirteen* ruptures cited in Table 4.3, there were nine (9) additional reported rupture events; these occurred in:

(1) Control air piping (6), and

(2) Radwaste piping (3).

+Ruptures or breaks as used in this report imply a failure which causes a rapid loss of fluid from the pipe. It is not a double ended shear of the pipe.

*Note that some ruptures are included in more than one category.

Table 4.3. Reported Pipe Breaks

Date of Occurrence	Approx. No. of Operating Years	Reactor	Type	Failure Location	Pipe Size	Probable Cause	Reactor Status	Characterization Of the Event by Utility
Feedwater System								
7/71	4	Connecticut Yankee	PWR	Expansion Joint	-	Poor welding	-	"Rupture"
6/74	7	Connecticut Yankee	PWR	Pipe	3/4"	-	-	"Broken"
11/73	1	Indian Pt.2	PWR	Pipe-HAZ	10"	Pressure Surge	Auto Scram	"180" Circuferential Break"
8/75	3½	Quad Cities 2	BWR	4"x6" Reducer	4"	Vibration	Manual Scram	"Break"
10/75	3½	Quad Cities 2	BWR	Pipe	3/4"	Vibration	Auto Scram	"Break"
Condensate System								
1/64	5	Dresden 1	BWR	Pipe	-	Pump Seizure Split Pipe	-	"Split Pipe"
9/74	5	Dresden 2	BWR	Pipe Nipple	1"	-	Manual Scram	"Rupture"
10/70	8	Humboldt Bay	BWR	Expansion Joint	-	-	Auto Scram	"Rupture"
Steam Piping								
10/73	½	Ft.Calhoun	PWR	Expansion Joint	10"	Vibration	No Shutdown Req'd.	"Rupture"
1/73	10½	Indian Pt.1	PWR	Pipe	4"	-	Manual Scram	"Failed"
6/71	1	Robinson 2	PWR	Pipe Nozzle	6"	-	During Shutdown	"Complete Failure"
6/72	½	Turkey Pt.3	PWR	Pipe	10"	Surge	During Shutdown	"A Failure"
8/72	½	Surry	PWR	Pipe Nozzle	4"	Surge	During Shutdown	"Nozzle Separated From Pipe"

Table 4.4. Estimated Occurrence Rates for Pipe Ruptures*

Pipe Ruptures (total)	$8x10^{-2}$ ruptures/plant-year (approx. 1 pipe rupture per plant in 12 years).
Pipe Ruptures Causing a Scram	$2x10^{-2}$ ruptures/plant-year (approx. 1 pipe rupture induced scram every 50 years).
Large Diameter (> 10")Pressurized Pipe Rupture	$1.2x10^{-2}$ruptures/plant-year (approx. 1 large diameter pipe rupture every 83 plant-years)

* Note that the above estimates imply equal weighting of all plants regardless of size, age, etc.

Control air piping is usually small diameter piping and is pressurized. Radwaste piping is generally large diameter piping operated at low pressure.

Assuming a total of 249 plant-years of operation, the failure rates are estimated in Table 4.4 .

SECTION 5

5.0 REFERENCES

(1) Gibbons, W.S., Hackney B.D.; Survey of Piping Failures For the Reactor Coolant Pipe Rupture Study, General Electric Report GEAP-4574, May 1964.

(2) Pipe Cracking Study Group, NRC; Investigation and Evaluation of Cracking in Austenitic Stainless Steel Piping of Boiling Water Reactor Plants, Nuclear Regulatory Commission Report 75/067, October 1975.

(3) Phillips, C.A.G., Warwick, R.G. ; A Survey of Defects in Pressure Vessels Built to High Standards of Construction and Its Relevance to Nuclear Primary Circuit Envelopes, AHSB(S) R162, UKAEA, 1969.

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(5) Bush, S.H., Pressure Vessel Reliability, Trans, AMSE J. Press. Vessel Technology, February 1975.

(6) WASH-1400, Reactor Safety Study, Appendix III Failure Data, August 1974.

(7) Barlow, R.E., Proschan F.; Mathematical Theory of Reliability, John Wiley and Sons, 1965.

(8) Barlow, R.E., Proschan, F.; Statistical Theory of Reliability and Life Testing, Holt, Rinehart and Winston, 1975.

APPENDIX A

STATISTICAL TESTS AND SUPPORTING CALCULATIONS

A.1 The χ^2 Test for Two Independent Samples

When data consist of frequencies in discrete categories, the χ^2 test may be used to determine the significance of differences between two independent groups.

The null hypothesis, H_o, under test is that the two groups do not differ with respect to some characteristic and therefore with respect to the relative frequency with which group members fall in several categories. To test this hypothesis, we count the number of cases from each group which fall in the various categories, and compare the proportion of cases from one group in the various categories with the proportion of cases from the other group.

The null hypothesis is tested by considering the following statistic:

$$\chi^2 = \sum_{i=1}^{r} \sum_{j=1}^{k} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} ,$$

where O_{ij} = observed number of cases categorized in i-th row and j-th column.

E_{ij} = number of cases expected under H_o to be categorized in i-th row and j-th column. Note that the double sum is over all rk cells in the contingency table.

The values of χ^2 are distributed approximately as a chi-squared random variable with (r - 1)(k - 1) degrees of freedom, where r represents the number of rows and k represents the number of columns in the contingency table.

To find the expected frequency for each cell, E_{ij}, multiply the two marginal totals common to a particular cell, and then divide this product by the total number of cases. We shall illustrate the procedure via the calculations required to test whether or not the distribution of pipe failures by subsystem is the same for the BWR's and the PWR's (see Table A-1 below).

Table A-1. Example Calculations For χ^2 Test - Failures by Subsystem

Subsystem*	BWR	PWR	Row sums
1	26 (23.25)**	13 (15.75)	39
2	16 (14.31)	8 (9.69)	24
3^{+} & 4^{+}	23 (26.82)	22 (18.18)	45
5	9 (10.73)	9 (7.27)	18
6	10 (10.73)	8 (7.27)	18
7	6 (9.54)	10 (6.46)	16
8	8 (9.54)	8 (6.46)	16
9	13 (8.94)	2 (6.06)	15
10	10 (7.15)	12 (4.84)	12
Column Sums	121	82	203

* See Table 3.3 for listing of subsystems.

** Numbers in parentheses are expected values under the null hypothesis.

\+ Subsystems 3 (BWR recirculation) and 4 (PWR charging) have been combined for the purposes of this test since both are unique primary system piping systems peculiar to each plant type.

The expected frequencies, under the null hypothesis, are easily calculated by taking the product of the two marginal totals (row and column sums) associated with a given cell and dividing by the total number of observations in the table. As an example, consider E_{12}. The marginals associated with E_{12} are 39 and 82; therefore, $E_{12} = \frac{(39)(82)}{203}$.

The chi-squared statistic is then calculated as follows:

$$\chi^2 = \frac{(26-23.25)^2}{23.25} + \frac{(13-15.75)^2}{15.75} + \frac{(16-14.31)^2}{14.31} + \frac{(8-9.69)^2}{9.69} +$$

$$\frac{(23-26.82)^2}{26.82} + \frac{(22-18.18)^2}{18.18} + \frac{(9-10.73)^2}{10.73} + \frac{(9-7.27)^2}{7.27} +$$

$$\frac{(10-10.73)^2}{10.73} + \frac{(8-7.27)^2}{7.27} + \frac{(6-9.54)^2}{9.54} + \frac{(10-6.46)^2}{6.46} +$$

$$\frac{(8-9.54)^2}{9.54} + \frac{(8-6.46)^2}{6.46} + \frac{(13-8.94)^2}{8.94} + \frac{(2-6.06)^2}{6.06} +$$

$$\frac{(10-7.15)^2}{7.15} + \frac{(12-4.84)^2}{4.84}$$

$$\chi^2 = \underline{23.62}$$

The number of degrees of freedom (df) is (r-1) (k-1). In this case df = 8.

The critical value of χ^2 at the $\alpha = 0.01$ level of significance is 20.09 (from tabulated values of the χ^2 distribution). Since the calculated value of χ^2 (23.62) exceeds the critical value (20.09) we <u>reject</u> the null hypothesis at the 0.01 level. In other words, we claim that there is, in fact, an inherent difference between the distribution of PWR pipe failures and the distribution of BWR pipe failures as far as location by subsystem is concerned. The meaning behind the $\alpha = 0.01$ level of significance is easily explained as follows: If the null hypothesis were, in fact, true (i.e., no differences exist), then the value of the χ^2 statistic would only have a 0.01 probability of exceeding the critical value 20.09 Another way of saying the same thing is that the probability of rejecting the null hypothesis when it is, in fact, true is only 0.01.

The basic calculations performed in support of other chi-squared tests in Section 3 follow.

Table A-2. χ^2 Test for Differences Between BWR and PWR Failures According to Pipe Size.

Pipe Size Category	BWR	PWR	Row Sum
≤ 1	35 (45.92)	42 (31.1)	77
$>1, \leq 6$	50 (39.36)	16 (26.64)	66
$>6, \leq 10$	8 (8.35)	8 (5.65)	14
≥ 10	6 (5.37)	3 (3.63)	9
Column Sums	99	67	166

df = 3

$$\chi^2 = \frac{(35-45.92)^2}{45.92} + \frac{(42-31.10)^2}{31.10} + \frac{(50-39.36)^2}{39.36} + \frac{(16-26.64)^2}{26.64} +$$

$$\frac{(8-8.35)^2}{8.35} + \frac{(8-5.65)^2}{5.65} + \frac{(6-5.37)^2}{5.37} + \frac{(3-3.63)^2}{3.63}$$

$$= \underline{\underline{14.72}}$$

Since the critical value of χ_3^2 is 11.34 at $\alpha = 0.01$ we conclude that the distribution of PWR piping failures versus pipe size differs from the distribution of BWR failures versus pipe size.

Table A-3. Test for Differences Between Failure Mode Frequencies of BWRs and PWRs.

Probable Cause	BWR	PWR	Row Sum
Vibration	23 (31.15)	28 (19.85)	51
Thermal/Cyclic Fatigue	9 (6.72)	2 (4.28)	11
Fabrication	13 (15.88)	13 (10.12)	26
Corrosion	6 (3.66)	0 (2.34)	6
Erosion	9 (8.55)	5 (5.45)	14
SCC	20 (14.05)	3 (8.95)	23
Column Sums	80	51	131

One of the requirements for use of the χ^2 test is that the expected frequency within the cells must not be smaller than 5 for no more than 20% of the cells (in the above case, 2 cells). We, therefore, combine the corrosion and erosion failure modes into one, called "erosion-corrosion" in order to increase the expected frequency, thus permitting the use of the χ^2 test (see next page).

Table A-3.1. χ^2 Test for Difference Between the Distribution of Failure Modes within BWRs and PWRs.

Probable Cause	BWR	PWR	Row Sum
Vibration	23 (31.15)	28 (19.85)	51
Thermal/Cyclic Fatigue	9 (6.72)	2 (4.28)	11
Fabrication	13 (15.88)	13 (10.12)	26
Erosion/Corrosion	15 (12.21)	5 (7.79)	20
SCC	20 (14.05)	3 (8.95)	23
Column Sums	80	51	131

$$\chi^2 = \frac{(23-31.15)^2}{31.15} + \frac{(28-19.85)^2}{19.85} + \frac{(9-6.72)^2}{6.72} + \frac{(2-4.28)^2}{4.28} +$$

$$\frac{(13-15.88)^2}{15.88} + \frac{(13-10.12)^2}{10.12} + \frac{(15-12.21)^2}{12.21} + \frac{(5-7.79)^2}{7.79} +$$

$$\frac{(20-14.05)^2}{14.05} + \frac{(3-8.95)^2}{8.95} = \underline{\underline{16.91}}$$

Since the critical value of χ^2_4 at $\alpha = 0.01$ is 13.28, we conclude that the distribution of PWR failure frequencies within failure mode categories differs from the distribution of BWR failure mode frequencies

A.2 The Kolmogorov - Smirnov Two Sample Test

The Kolmogorov-Smirnov two-sample test may be applied to determine whether or not two independent samples have been drawn from the same population (or from populations with the same distribution). The two-tailed test is sensitive to any kind of difference in the distributions from which the two samples are drawn - differences in location (central tendency), in dispersion, in skewness, etc. The one-tailed test is used to decide whether or not the values of the population from which one of the samples was drawn are stochastically larger than the values of the population from which the other sample was drawn; e.g., to test the prediction that the scores of an experimental group will be "better" than those of the control group.

If the two samples have in fact been drawn from the same population then the cumulative distributions of both samples may be expected to be fairly close to each other, inasmuch as they both should show only random deviations from the population distribution. If the two sample cumulative distributions are "too far apart" at any point, this suggests that the samples come from different populations. Thus a large enough deviation between the two-sample cumulative distributions provides evidence for rejecting the null hypothesis that the two samples have been drawn from the same population.

To apply the Kolmogorov-Smirnov two-sample test, we construct the cumulative frequency distribution of each sample of observations, using the same intervals for both distributions. Within each interval we subtract the value of one function from the value of the other. The test focuses on the <u>largest</u> of these observed deviations.

Let $S_{n_1}(X)$ represent the observed cumulative step function of one of the samples, that is, $S_{n_1}(X) = K/n_1$, where K represents the number of observations equal to or less than X. And let $S_{n_1}(X)$ denote the observed cumulative step function of the other sample, that is $S_{n_2}(X) = K/n_2$. Since the sampling distribution of the statistic

$$D = \text{maximum } |S_{n_1}(X) = S_{n_2}(X)|$$

is known, the probabilities associated with the occurrence of values as large as an observed D under the null hypothesis (that the two samples have come from the same distribution) are also known and have been tabulated. When n_1 and n_2 are larger than 40, the critical values shown in Table A-4 may be used when applying the K-S test. On the basis of the observed data, we calculate D as indicated above. If the observed value of D is equal to or larger than the critical value (see Table A-4 of critical values), then the null hypothesis may be rejected at the level of significance selected. In the case of the time to failure distributions, we have selected 0.001 as the level of significance (this is an arbitrary choice). The critical value of D is therefore

$$D_{crit.} = 1.95\sqrt{\frac{n_1+n_2}{n_1 n_2}}$$

$$= 1.95\sqrt{\frac{203}{(82)(121)}}$$

$$= 0.2789$$

Since the observed value ($D_{obs.}$ = 0.4838 shown in Table A-5) is greater than the critical value (0.2789), we conclude that the pipe system failure times for PWR's have been drawn from a different population than the BWR time to failure observations.

Table A-4. Critical Values of D in the Kolmogorov-Smirnov Two-Sample Test (Large samples: two-tailed test)*

Level of significance	Value of D so large as to call for rejection of H_0 at the indicated level of significance, where D = maximum $\lvert S_{n_1}(X) - S_{n_2}(X)\rvert$
.10	$1.22\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
.05	$1.36\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
.025	$1.48\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
.01	$1.63\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
.005	$1.73\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
.001	$1.95\sqrt{\frac{n_1+n_2}{n_1 n_2}}$

* Adapted from Smirnov, N. 1948. Tables for estimating the goodness of fit of empirical distributions. *Ann. Math. Statist.*, **19**, 280–281