THE PROBABILITY OF CATASTROPHIC FAILURE OF REACTOR PRIMARY SYSTEM COMPONENTS

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SUMMARY

Using recent information about failures in nuclear plants, the Author has derived the following estimates of the probability of failure events in prime piping systems of carbon and low-alloy steel:

Severance prior to service: 5.7×10^{-2} events per plant,

Severance during service: 5×10^{-3} events per plant-year.

The above numbers are higher, by one to two orders of magnitude, than the corresponding numbers used in calculations pertaining to nuclear safety.

In order to estimate the probability of severance of a reactor vessel (which here includes the large nozzles), the Author uses the logic of the Warner diagram. In the case of piping, it is noted that the ratio:

$$\frac{\text{Probability of severance prior to service}}{\text{Probability of severance during ten years of service}} = 1 \text{ (approx.)}.$$

Over the last ten years there have been at least 4 failures of heavy section steel vessels (UK & USA). Although there are good reasons to assert that vessels are much less prone to severance than piping, the Warner diagram speaks its logic.

Statistics gathered from hardware populations in existing plants will never be directly applicable to hardware populations in future plants because we are continuously introducing changes in the main parameters: Design, Materials, Manufacture, Operation.

Mr. S. A. Wilson, of GE, has developed methods for a priori calculations of the probability of failure events in piping systems, based on first principles, as he sees it.

Mr. Wilson considers that failures are due to fatigue, and bases his method on the Paris formula :$d(a)/d(n) = A.K^B$, with the stress parameter $K = \sigma.(a^{\frac{1}{2}})$.Constant.

In Mr. Wilson's scheme, each component slides down its path to failure, passing a specified series of stages where the parameters of his formulae are subject to random variations. The result is that a crack of initial size a_i (random) under the influence of stress σ (random) may grow to a depth exceeding the wall thickness, resulting in a leak. Or the crack may grow to critical size, and result in a severance triggered by a high stress (random).

Mr. Wilson's results compare favorably with the observed probabilities of leaks and severances during service, but is too low, by an order of magnitude, for the probability of severance prior to service.

Introduction

Licensing authorities and safety engineers responsible for the siting, design, and operation of nuclear power plants have, over the past couple of years, mounted an effort to establish numerical bases supporting their decisions in the area of nuclear safety, F.R.Farmer (1), R.O'Neil & G.M.Jordan(2) C.Starr & M.A.Greenfield(3), Th.Jaeger(4), O.Kellermann(5).

In the best selling traditions, slogans like "benefit versus risk" have been coined, thus making technocracy more palatable to the lay people.

The reasoning goes as follows: The risk potential, R.P., is equated with the amount of Iodine-131, expressed in curies, which might be released to the surroundings. The amount is estimated to one tenth of the inventory of I-131;

$$R.P. = 10^{-1} \times 10^{8} = 10^{7} \text{ curies} \qquad \text{eq. (1)}$$

The damage expectation, E(D), is then written as the product of the risk potential and event probability;

$$E(D) = R.P. \times P(e) \qquad \text{eq. (2)}$$

The total probability of a disaster event, P(e), is then rationalized to be 10^{-7} event/reactor-year. With this value, the damage expectation becomes:

$$E(D) = 10^{7} \text{ curies/event} \times 10^{-7} \text{ event/reactor-year}$$
$$= 1 \text{ curie/ reactor-year} \qquad \text{eq. (3)}$$

In its statutory provisions, the Price-Anderson Act has set the maximum D.P = 5×10^{8} dollar/event. The above reasoning leads to the following:

$$E(D) = 5 \times 10^{8} \times 10^{-7} = \$50 \text{ per reactor year} \qquad \text{eq. (4)}$$

Eq. (4) ought to set the insurance rates for public liability in the case of atomic power plants, if we could believe the safety engineers.

Let us consider that the disaster probability is derived from the individual probability products taken over the whole plant;

$$P(e) = \text{Summation}(\ p(1) \times p(2) \times p(3)\ ) \qquad \text{eq. (5)}$$

where: p(1) = probability of a particular component suffering a failure bearing on the safety of the plant.

p(2) = conditional probability that the primary failure shall trigger a domino reaction severing the primary loop.

p(3) = conditional probability that the containment structure shall fail to perform under the above circumstances.

Category p(1) probabilities are derived from statistics which, hopefully, reflect experience gathered from populations of similar components working under appropriate conditions of temperature and pressure. We will, in the following, limit our concern to one type of category p(1) failures i.e., severance of a piping component or pressure vessel. The conditional probabilities p(2) and p(3) are then predicated on the primary severance event, p(1).

In order to compare the disaster probabilities, P(e), associated with the types of plants of interest i.e.,

Type A – conventional coal- or oil-fired utility plant

Type B – commercial atomic power plant, land based

Type C – marine atomic power plant, all types

I have dressed Table 1 . In the table, I have ranked the probabilities as small, moderate or high within the same event category. From published statistics, we are able to assign numerical values to the primary events:

p(severance, piping and vessels, type A plants)

p(severance, steam piping, type B plants),

the other probabilities are given on a comparative basis, only.

Actual Failure Statistics

We have, in the literature, a certain amount of information about the frequencies of failures of pressure vessels and piping components. Table 2 gives a summary of pressure vessel failures, Table 3 gives a summary of piping failures. Table 4, taken from R.L.Scott(6), gives failure data encompassing 13 classes of components used in atomic power plants. By my reckoning, these data have been collected from 24 atomic reactors, and represent approximately 75 plant years of actual operation. Table 5 gives data from my personal notes about severances which have occurred in the primary steam piping of atomic power plants (USA) during pre-operational testing and actual operation.

In Table 6, I have made a comparison between the failure frequencies observed in type A plants and the corresponding frequencies observed in type B plants. One will note that the latter frequencies are higher by two orders of magnitude. Looking for some plausible explanation, I may point to the stricter reporting requirements excercised by the USAEC for atomic power plants. But a more sinister cause has been operative, and Table 7 tells this story.

The prevalence of human error as the basic cause for the high rate of failure experienced in atomic power plants ought to give reason for concern.

The Severance Probability Of Reactor Pressure Vessels

The severance of a RPV would spell total disaster were it ever to happen. Expressing the disaster probability in symbols we write;

$$p(e) = p(\text{severance RPV, type B plants}) \qquad \text{eq. (6)}$$

since p(2,B) = 1, and one has to postulate that p(3,B) = 1 for this event.

Nuclear plant designers, as well as manufacturers of hardware, have been busy proving that this event is associated with zero probability or, at most, with the mystical "infinitely small" concept inherited from calculus, Ref.(7)

Valid probabilities should, of course, be derived from event frequencies gathered from a large, homogeneous population of RPVs observed over many years. Since the history of RPVs started with a couple of vessels some 15 years ago, and we are dealing with very rare events, we are short of data. I am therefore forced to base my reasoning on experience derived from pressure vessels in general.

Table 8 is a compilation of catastrophic severances of pressure vessels, based on notes which I have kept over the last 32 years. Events like the boiler explosion at Sparrows Point, 1938, and others about which I completely ignore the details have been omitted from the list.

One will notice the high frequency of failures under proof testing. This fact has, strange to say, induced many engineers to advise against proof tests.

Students and PVRS may fail when tested, so the obvious remedy is to forgo the test.

If we from Table 8 eliminate the vessels which broke under proof testing, only two are left: the tank car and the Ensidesa vessel. Since the tank car failure is generally unknown, only the Ensidesa vessel remains. This vessel, however, was designed and built to a code different from the ASME Boiler and Pressure Vessel Code, and should probably not be accepted as a bona fide vessel to start with. Table 8 is now eliminated altogether, and this is the way failure statistics is presented, and failure frequencies calculated.

The conditions which will assure that a structure does not fail may be expressed in symbolic terms:

$$R - L \geqslant 0 \qquad \text{eq. (7)}$$

Eq. (7) merely states the obvious fact that if the load, L, exceeds the resistance capacity of the material, R, something will break.

Since the vessel manufacturer always will assure us that he knows the properties of the materials, including the welds, and the vessel designer seems equally convinced that he knows everything about the loads and stresses which the vessel will see, we ought to rest assured that equation (7) will remain satisfied over the lifetime of the vessel. Let me now look at the records.

In Table 8 are listed three vessels which do not belong among the rest, since they were made of special, high strength materials. They belong to a population of 1000 (approximately) MINUTEMAN First Stage casings.

The properties of the material of construction are such that, at proof pressure level, a long, sharp flaw of depth equal to, at least 1/8 inch can be tolerated.

Needless to tell that each casing had been subjected to the most careful inspection by every available means, and by the most competent NDT experts. In other words, the manufacturers were sure that they had delivered flawless materials. But out of 1000 proof tested vessels, 3 failed catastrophically due to previously undetected flaws in the welds of the cylindrical walls, J.E.Scrawley and J.B.Esgar (8), Victor Singer (9).

Inspection techniques therefore afforded no better than 0.997 probability of detecting flaws in excess of 1/8 inch depth (we are not concerned with the length of the flaw) in a 3/4 inch (approximately) thick wall.

What is the probability that a NDT-trained inspector will miss a flaw, or misjudge the size of a flaw indication in a reactor pressure vessel ?

I once attended a meeting where several NDT experts insisted very strongly that the indications they had seen on the screen,(UT), were due to flaws no larger than 1/4 inch. The structure in question was a nozzle of very large dimensions welded to a reactor vessel. An autopsy which was performed showed that the flaws were closer to 3/4 inch.

A refinement of eq. (7) leads to the Warner diagram, E.B.Haugen (10). R and L are considered as random variables having probability distributions f(R), and f(L). The difference of the two variates, Z = R – L , has a distributions which may be found by more or less involved mathematical manipulations, of statistical data gathered for this purpose.

A mathematical simplification is introduced by assuming that f(R) and f(L) are normally distributed around their mean values, with variances var(R) and var(L). Then, the difference density, f(Z) , becomes normally distributed about its mean, Z(mean) = R(mean) - L(mean) , and its variance, var(Z) = var(R) + var(L).

The failure probability is given by the negative area under the distribution curve, f(Z). The dividing point between negative and positive Z values is given by the "coupling formula" which may be written;

$$k = \frac{R(mean) - L(mean)}{(\,var(R) + var(L))^{\frac{1}{2}}} \qquad \text{eq. (8)}$$

Let us apply the method to the data of Table 9, extracted from Wylie (11). Any pressure vessel subjected to stress cycling will, in the end, either leak, or break catastrophically. The latter event happens when the load, L, exceeds the resistance, R, and the materialflies apart due to mechanical imbalance. In our mathematical model this happens at point k.

From Table 9, we extract the information that R(mean) = 1.45 x Y , and L(mean) = 0.75 x Y. We further simply guess that $var(R) = (0.4\ Y)^2$, and $var(L) = (0.4\ Y)^2$.

In writing the above equations, we have glibly identified R with UTS, and L with the applied stress. Both assumptions are open to criticisme.

Substituting the numerical values given above into eq. (8), we get;

$$k = \frac{1.45 - 0.75}{(0.16 + 0.16)^{\frac{1}{2}}} = \frac{0.7}{0.56} = 1.25 \qquad \text{eq. (9)}$$

The accumulated relative frequency of catastrophic failures is 2/18 = 0.11 Looking up the tabulation of the erf. , we find that the value of 0.11 corresponds to a k-value of 1.2 . The tabulated k value and the experimentally derived k value came out alarmingly close, for very obvious reasons.

In one test run it took 7,516 pressure cycles (to 90% of Y), and in another test run 11,707 (to 72 % of Y), to bring about catastrophic failures in small vessels of modest wall thicknesses. I would expect a markedly more pronounced tendency towards catastrophic breakes in a sample of heavy walled vessels of large diameter since, by analogy, tug boats never break while big ships sometimes do.

During the tests, the vessels deteriorated due to fatigueing, and maybe other influences. In our mathematical model, this means that the f(R) distribution became more dispersed. In other words, var(R) increased, and, perhaps R(mean) decreased. At the same time, the load, L , increased in a fracture mechanistic sense. Both processes work towards eliminating the safety gap between R and L. These effects are at work on every pressure vessel. In the case of the Cockenzie pressure vessel it took only five cycles at proof test pressure, Welding Research Abroad Vol XIII NO. 8.

Reactor Primary Coolant System Rupture Study, GE-AEC Contract AT(04-3)-189

Task "A" of this program started out under the heading "Reliability

Engineering", but was later changed to "Probability Study". Part of the work under Task "A" is condensed in a topical report, GEAP-10452 "Estimating Pipe Reliability By The Distribution Of Time To Damage Method" by S.R.Wilson (12).

In this study, S.R.Wilson uses very involved statistical methods such as Monte Carlo using importance sampling. Since the purpose, as it appears in GE AP-10452, is to estimate the probability of pipe leakage in a 40 years period due to low cycle fatigue, I am tempted to say "quel bruit pour une omelette".

S.A.Wilson's second major undertaking involved estimating the probability of severance (and incidentally, of leak), using the basic approach expressed by means of eq. 7 , and the reasoning I have outlined earlier. Piping severances may be due to a host of causes. In order to tackle the problem with a reasonable chance of succes, S.R.Wilson is concentrating on severance due to low cycle fatigue. His starting point is the P. Paris formula:

$$d(a)/d(n) = A.K^B \qquad \text{eq. (10)}$$

where K is the stress intensity factor, a fracture mechanics concept. The crack, of initial size a_i, will grow at little bit with each cycle depending on the stress level. The race towards failure will terminate in one of the three possible events:

(i) The material will be retired from service before the crack has grown to a dimension which spells failure.

(ii) The crack grows through the material and becomes a leaker before the load L , overpowers the resistance, R , in a fracture mechanistic sense.

(iii) The crack grows to a size where the associated stress intensity factor K exceeds the resistance capacity of the material, resulting in disaster.

In this method, the probability of severance is estimated considering the multitudinous fault causes and fault conditions which conceivably could cause the presence of large flaws and high stresses in piping systems. Table 10 list the fault causes which, according to S.R. Wilson, affect the stress level. Table 11 list the fault causes which affect initial crack size. In addition, S.R.Wilson has listed six secondary fault conditions: transition temperature, sensitization by welding, surface cold work, exposure to the elements, unfavorable environment chemistry in service, frequency of cyclic loading.

S.R.Wilson considers three separate groups of piping components: Spools, Ells & Bends, Tees. He subdivides them in two sizes: Larger than 16 inch, 16 inch and below. He considers two categories of materials: Stainless steel, Carbon steel. He subdivides the time in three periods: Prior to service, First five years which includes the hot testing, Last thirtyfive years.

S.R.Wilson's standard plant is composed of a mixed population of 300 pieces which seems rather modest since GE has, in an earlier report, has given the following break down: 430 Spools, 180 Elbows, 80 Bends, 80 Valves, 14 Equipmnt.

Table 12 gives the combined failure rates of all separate estimate categories of the 300 piece pipin system, calculated by S.R.Wilson. He makes however the following caveat: The results in this table are from a method under development. Do not use without appropriately taking into account the input used". Despite this, I shall permit myself to make a brief comparison with observed failure rates in atomic power plants.

Number of leaks during the first 5 years of plant service:

Wilson predicts 1.326 leak events per piping system without UT.

From Scotts statistics we obtain the adjusted rate of $\frac{17}{24} \times \frac{120}{75} = 1.13$ event

The two rates compare well.

Number of severances during the first 5 years of plant service:

Wilson predicts 0.021 severances per piping system without UT. Since his prediction includes the period of hot testing, his rate must be compared with the rate calculated from 3 catastrophic severances adjusted to a time unit of five years i.e., 3 x 5/200 = 0.075 event. Wilson's prediction, which does not include human error, is on the low side.

Conclusions, (for nomenclature see Table 1):

Tables 2 & 3 show that the primary severance events for piping, and PVs occur with low frequencies in type A plants. By comparison, the severance frequency for piping in type B plants is one to two order of magnitude higher. We ignore the failure frequency for RPVs since no such event has occurred. We can not dismiss the thought that the zero event might be due to the limited number of RPV-years in the statistics.

Statistics regarding primary severance events for type C plants is generally available except in the case of N.S."Savannah" where we have seen some dumb failures. Since its hull structure encompasses the engine room, a ship is very vulnerable to the domino event triggered by the primary failure event. Two nuclear submarines have been lost at sea. I surmise that the nuclear sub "Thresher" was lost due to a chain of events, the probability of which I have written as: p(e) = p(1,C)p(2,C)p(3,C) with both p(3,C) and p(2,C) equal to One.

If this is the case, the severance frequency for piping systems in type C plants becomes of the order predicted by S.R.Wilson for the first 5 years. The event might have been a statistical outlier since I can not conceive that US Navy could accept such high failure frequencies. US Navy has ample means to take remedial action, and in all probability has done just that.

Unlike a nuclear ship, the commercial atomic power plant feels pretty safe behind its Maginot line, the containment structure. In the parlance of probability, it means that the last term of the product: p(1,B)p(2,B)p(3,B) is supposed to be small.

I have tried to estimate p(3,B) by calculating the fraction of the total operating time that any of the containments would have failed to perform on demand, and averaged for all commercial reactors. One event which weighs heavily in this calculation has been described by T.J.Thompson (13). My conclusion is that $p(3,B) = 10^{-1}$. O'Neil & Jordan (2) have given the values of 10^{-1} to 10^{-2}.

Eq. 5 gives the probability of the disaster event as the sum products where each product is generated by a primary severance event. The leading term will always be the severance probability associated with the RPV which includes its nozzles. Ref.(10) tells us what might happen when cracks start at nozzles.

References

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(3) C.Starr & M.A.Greenfield & D.F.Hausknecht - "Public Health Risks of Thermal Power Plants" - A report Prepared for The Resources Agency of California, Sacramento. UCLA-Eng-7242, May 1972. See also ENR 8/17/72 "Nuclear Plants 10 times safer than oil-fired units".

(4) Thomas A.Jaeger - "Das Resikoproblem in der Technik" Vortrag gehalten an der Generalversammlung des SVMT vom 29.Mai in Winterthur.

(5) Otto Kellermann - "Unfallanalyse in der Kerntechnik" TU Bd.13(1972) Nr. 11, S.330/335 .

(6) R.L.Scott, Jr. - "A Review Of Safety Related Occurrences In Nuclear Power Reactors From 1967 - 1970" ORNL-TM-3435

(7) APED-5496 "Availability Analysis- A Useful Tool For Improving Systems Design". Under the heading "Time To Restore Incoming Power": "Data from TVA indicates that they have had four station power blackouts in 112 station years. The blackout lasted for 61, 40, 5, and 1 minutes. On distribution networks the repair time distributions are, to a reasonable approximation, exponential in nature. Assuming that an exponential distribution applies also to transmission systems, the best curve fitting the meager data is described approximately by the equation $P_1 = e^{-3T}$, where P_1 is the probability that the repair time exceeds T hours, and T is the repair time in hours." Or, during a blackout on the East Coast, one nuclear power station lost all external power for 18 hours. The calculated probability is $P_1 = e^{-54}$ = approx. 10^{-23} for that event. We forget that technology is constantly becoming more and more daring, this making predictions based on past experience invalid.

(8) J.E.Scrawley & J.B.Esgar - "Investigation of Hydrotest Failure of 260 - inch Motor Case," TM-1194, National Aeronautics and Space Administration, Washington, D.C., January 1966.

(9) Victor Singer, Thiokol Chem. Corp. Private communication to the Author.

(10) E.B.Haugen - "Probabilistic Approaches to Design", John Wiley & Sons,Inc.

(11) R.D.Wylie - "Summary Of Pressure Vessel Test Programs At SouthWest Research Institute", SwRI Project No. 07-1348, April 21, 1965

(12) S.A.Wilson - His work on the probability of severance is reported in Progress Reports 21 to 23, 25 and 27 of the GE-AEC R&D Project.

(13) T.J.Thompson & J.G.Beckerley - "The Technology Of Nuclear Reactor Safety"

Table 1

Comparison of risks associated with three types of power plants, USA

Category of Events	Type A Conventional Utilities	Type B Commercial Atomic Power, land-based	Type C Marine Atomic Power, all types
1 Primary events	p(1,A) = small	p(1,B) = moderate	p(1,C) = small
2 Domino events	p(2,A) = minimal	p(2,B) = small	p(2,C) = moderate
3 Confines broken	not applicable	p(3,B) = moderate	p(3,C) = high
Disaster events p(e)	not applicable	p(1,B)p(2,B)p(2,C)	p(1,C)p(2,C)
Damage Potential	limited	unlimited	limited to plant and complement
Recent experiences	1 boiler-drum fractured during pre-operational testing. One 24 inch steam pipe severed catastr. during service	No serious mishap during approximat. 200 reactor years of operation. One 4 inch steam-line severed during operation	Two total losses during approximat. 200 years of operation. Causes not disclosed,if adequately known.

Table 2

Summary of two surveys of pressure vessel failures, UK & Germany

Source	Size of population Number of events	Failure Rate per vessel year
Survey by UKAEA British built pressure vessels Phillips & Warwick AHSB (S) R 162	12,700 vessels totalling 100,300 vessels years of oper. 60 potentially dangerous failures (req. remedial action)	6×10^{-4}
	2 catastrophic failures	2×10^{-5}
Survey by TUV German built pressure vessels Kellermann, Mieze Slopianka, Tietze IAEA -SM-127/24	241 boiler drums 2500 vessel years of operation assumed here 33 failures	1.32×10^{-3}

Table 3

Summary of three surveys of failures in piping systems, UK and USA

Source	Size of population Number of events	Failure rate per plant-year
National Bureau of Casualty Underwriters, 4½ years of records to 06/1961, GEAP-4574 (May 1964)	Not reported	1.67×10^{-3}
Survey by UKAEA, British and USA power and research reactors, to 06/1967, Phillips & Warwick in "A Survey Of Defects In Pressure Vessels Built To High Standards Of Construction Ands Its Relevance To Nuclear Primary Circuit Envelopes "	UK = 260 reactor years US = 1092 reactor years 17 failures of which 12 cracks (70.5%)	12.6×10^{-3}
Survey in GE Pipe Rupture Study. From 701 contacts asked, 315 answ.	Approx. 9000 plant-years of operation. 399 failures of which 4 excessively severe service failures	44.3×10^{-3} 4.4×10^{-4}

Table 4

Components most frequently identified in nuclear facility incidents, R.L.Scott(6)

Component	Total
Control rod system	75
(Stuck rods)	(23)
Valves	73
(Leaks)	(34)
Instrumentation	46
Heat exchangers	34
(Tube leaks)	(24)
Pipe	30
(Leaks)	(17)
Pumps	24
Welds	17
Fuel	17
Power supplies	15
Diesel generators	11
Sensitized material	6
Nozzle safe ends	6
Turbine	5

Table 5

Failure frequencies observed with atomic power plants (Commercial) USA

Number of power reactors in the statistics	35
Total number of reactor years in service, approximately	200
Number of severances (piping) during tests bef. service	2
Number of severances (piping) during service	1
Failure rate: prior to service = 2/35 = 0.057 per plant	
Failure rate: in service = 1/200 = 0.005 per plant year	

Table 6

Failure frequencies in prime piping during service, events/plant-year

Type of Failure	Type A Conv. Utility	Type B Atomic Power	
	Source:GEAP-4574	Source: Scott	Source: Holt
Leaker	4.4×10^{-2}	23×10^{-2}	
Catastrophic severance	4.4×10^{-4}	------	5×10^{-3}

Table 7

Causes most frequently identified in facility incidents, R.L.Scott(6)

Cause	Frequency	
* Design Error	38	38
* Operator Error	31	31
Debris in core or system	31	
* Maintenance Error	28	28
Corrosion	26	
* Administrative Error	13	13
Crud (film deposits)	12	
Vibration	10	
Act of God	4	
Grand total	193	110
Percentage Human Error = 57%		

Table 8

Some catastrophic pressure vessel failures known to the Author

Identification of Pressure Vessel	Approximate Wall thickn.	Circumstances of Failure
Tank car	3/4 in approx.	during service
Mountain Top	7 in approx.	pre service proof testing
Seizewell vessel	2¼ in	pre service proof testing
J. Thompson vessel	5-7/8 in	pre service proof testing
BKW Mannheim vessel	3 in approx.	proof testiing follow.repair
Ensidesa vessel	1-1/8 in	during service
Madrid vessel	1-½ in	pre service proof testing
Recent boiler drum, US	?	pre service proof testing
Thre rocket casings	3/4 in approx.	pre service proof testing

Table 9

Data pertaining to some model vessels w. nozzles tested in fatigue, Wylie(10)

Test Run	Matrl.	UTS	Yield Y	Peak**** stress	Stress % of Y	Cycles theor.	Cycles failure	Type of failure
1	A 2o1B	68.8	46.2	41,600	90 %	20,000	5,174	leaker
2	A 201B	68.8	46.2	41,600	90 %	20,000	6,845	leaker
3	A 201B	68.8	46.2	41,600	90 %	20,000	7,223	leaker
4	A 201B	68.8	46.2	41,600	90 %	20,000	7,516	catastrophic*
5	A 201B	68.0	46.0	25,500	55 %	100,000	123,618	leaker
6	A 302B	87.0	65.8	42,000	64 %	20,000	8,990	leaker
7	A 302B	87.0	65.8	32,450	50 %	100,000	40,041	leaker
8	A 302B	87.0	65.8	32,450	50 %	100,000	48,437	leaker
9	A 302B	87.0	65.8	32,450	50 %	100,000	67,636	leaker
10	A 201B	68.0	46.0	25,180	64 %	100,000	23,908	major repair
11	A 201B	68.0	46.0	25,180	64 %	100,000	63,000	major repair
12	A 212B	85,7	59,4	25,180	50 %	100,000	227,685	leaker
13		84,0	57,0	56,650***	100 %	20,000	82,614	cracking
14		68.0	44.0	55,200***	125 %	20,000	19,666	leaking
15		70.0	46.0	33,250	72 %	20,000	11,707	catastrophic**
16		70.0	46.0	55,500***	120 %		95,000,	leaker
17	A 212B		(60.0)	40,300	67 %		95,172	leaker
18	A 212B		(60.0)	40,300	67 %		48,146	leaker

mean stress =75 % of yield

*Crack initiated at Nozzle 6 and prop. in base metal remote from long. w.seam

**UT prior to fatigue test revealed no unacct. defects. Insp. at 5,000 cycles and at 10,000 cycles showed no growth of ext. incl. or formation of defects.

*** Nozzles tested in bending

**** Stresse by cycling pressure, pD/2t stress

Table 10

Fault causes which affect the stress level		Probability
3	Being oval (straight sections)	0.03
4	Being oval (elbows)	0.03
5	Having uneven wall thickness	0.03
8	Incorrect installation (rerouting)	0.03
9	Unplanned installation and hanger location	0.03
11	Late design changes w. unreconciled discrp.	0.03
12	Mislocated restraints on pipe whip	0.01
13	Equipment or structures impair flexibility	0.003
15	In-service modification	0.03
16	Frequent local thermal stressing	0.01
17	High load non operating conditions (water slugs etc)	0.003
18	Use in non-flow legs	0.2

Table 11

Fault causes which affect the initial crack size		Probability
1	Purchased from a marginal raw-matrl. manufacturer	0.2
2	Purchased from a marginal piping manufacturer	0.2
6	Purchased from a marginal assembly manufacturer	0.2
10	Difficult installation (faulty welding)	0.01
15	in-service modification	0.03

Table 12

Probability of leaks and severances by the method of GEAP-1o2o7

Type of Failure and Years of service		Probability: total for system Level of original Quality Control with UT	 without UT
Leaks:	Prior to service	0.06600	0.12700
	First 5 years	0.62800	1.32600
	Last 35 years	0.83700	2.07800
	Total over 40 years	1.53100	3.53100
Severances:	Prior to service	0.00002	0.00205
	First 5 years	0.00764	0.01995
	Last 35 years	0.01147	0.03130
	Total over 40 years	0.01913	0.05330