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A Review of Pressure Vessel Failure Experience — Some Failure Case Histories

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ABSTRACT

Notable failures of important pressure vessels are relatively rare and the accumulated service experience in the nuclear industry is insufficient to demonstrate directly the very low failure frequencies expected from its vessels. Data from relevant non-nuclear plant are required to enable a basic figure to be evaluated. Three pressure vessel failure data sources are reviewed and problems of terminology and definitions emphasised. Case histories of relevant pressure vessel failures have been compiled and are briefly summarised in this paper. How a population of vessels could be derived is hypothesised and a generic failure rate given.

INTRODUCTION

Non-nuclear pressure vessel experience can only be used to infer the reliability of nuclear vessels when data are gathered from plant which can be considered relevant. Failure circumstances should also be basically similar to those possible in nuclear vessels.

Analyses of major sets of data show that several philosophies are adopted when pressurised components have been reviewed either as surrogate items for vessel types having a small or empty data base or as an actual population for study. These are described below.

(i) The collection, reporting and analysis of failure events in terms of design equivalence, plant type, size, age, service condition, failure location cause and consequence. This allows a broad range of plant to be reviewed since vessel application is less significant than vessel design.

(ii) Another approach aims at establishing failure probability from theoretical propositions subjective engineering judgement and statistical arguments. Failure however tends to be multi-causal and random in nature, from a wide variety of component types, service conditions, materials and fabrication procedures, the theoretical model may thus be incomplete.

(iii) Also used is the like with like comparison. This is valid for mass produced or interchangeable components where large numbers of similarly operated items are concerned. For large mechanical parts, individually produced, subject to manufacturing tolerances, scatter in mechanical properties, variation in fabrication procedures and operated under widely differing working conditions, looking alike may not necessarily signify being alike. Applying this approach strictly can only result in small sample sizes which may not be statistically significant.

(iv) Yet another approach reviews the whole spectrum of component failure. Certain failures are then extracted and classified as risk relevant to the criteria against which the data are being assessed. Problems arise here in deciding the boundary conditions of risk relevancy and the population of components to which this relevance applies.

Each of the above methods will select a different sample size and quality from a given collection of vessel failures and consequently can give a different failure probability.

Every collection of failures will have its own characteristics depending on its make up and so the differences metioned above will be further accentuated when each method is associated with a particular collection. The degree of realism subsequently achieved in the application of such failure probability figures to actual items of nuclear plant will depend on the degree to which sample and plant quality agree. The different procedures also reveal a non-uniformity in failure definition and terminology.

DEFINITIONS

Failure can be defined in a number of ways. Catastrophic; disruptive; critical; non-critical; potentially dangerous; potentially disruptive; explosive and serious being the most commonly used. Some of these definitions relate to economic and others to safety consequences depending on how and where the data are needed.

If future surveys are to be undertaken there would be obvious advantages in harmonising definitions and the following categories are proposed:-

Potential failure - a defective condition which although not involving leakage requires repair before the component can be returned to service.

Perforation failure - implies a limited leak path through the component wall and consequent minor loss of contents.

Catastrophic failure - whereby a sudden massive loss of contents occurs and the component is destroyed, scrapped or requires major repair.

Disruptive failure - when the component breaks up and divides into separate pieces which could form missiles.

Reporting systems will need to be more precise in their presentation of service failure experience data. This could be accomplished by the use of a simple "tick box" type report form similar to that being used in the UK for a current data gathering undertaking.

POPULATION

For direct comparisons with nuclear RPVs non-nuclear vessels should be similar in design and manufacture. Thick vessels (100 mm) form a small proportion of the non-nuclear vessel stock. How small is not known although Ref 1 suggests less than 1% of high quality vessels. Japan Steel Works for example have produced over 300 thick walled vessels since 1967; in the UK the CEGB have about 60 steam drums with wall sections in excess of 125mm. Similar OECD data must exist on numbers of "thick vessels" but it is obvious that they will be numbered in hundreds rather than the many thousands of "thin" vessels.

In assessing a population, minimum parameters of thickness, 19mm to ensure that fabrication would require several weld passes, and diameter 1.0m were set. Also in order to obtain a value for the generic failure rate from a population of vessel types it is necessary to compile as large a number of vessels as possible since it is this number rather than the number of failures which determines the order of magnitude frequency for a given confidence level. If the assumption is made that in industrial societies industrial experience is broadly the same then evidence from the USA indicates that the above dimensional parameters eliminates approximately 90% of non-nuclear pressure vessels since the vast majority of these are small units (0.8m^{2}registration surface area).

Over a 20 year period (1960-1980) about 8 x 10^7 vessel years service were accumulated from vessels registered with the National Board of Boiler and Pressure Vessel Inspectors (NBBPVI) in the USA. A judgement is made that about 5% of this experience is from vessels in excess of 19mm thick x 1.0m diameter. Therefore some 4 x 10^6 vessel years service have been accumulated by relevant vessels.

For a similar period (1959-1978) German data (Ref 2) suggests a figure of approximately 6 x 10^6 vessel years although many of the vessels comprising the population are smaller and thinner than the parameters given above. Only 5% of reported failures occurred in vessels thicker than 19mm but no data are given for vessel thickness distribution among the population.

It is probable that the number of pressure vessels correlates to some extent with economic indicators such as gross National Product. Ref 3 gives a figure for OECD countries as 2.7 times that of the USA. Using that figure as a yardstick gives a population of vessel years, based on American data, as approximately 1 x 10^7 in OECD countries.

With the current methods of data collection there is no reliable way of checking that figure, but since the mortality rate per annum of vessels is unknown it may be considered an upper limit.

CASE HISTORIES OF PRESSURE VESSEL FAILURES

It has not been the intention to investigate thoroughly or even claim to have knowledge of every pressure vessel failure that has taken place. Rather the case histories are a distillation of the experience of a number of organisations having extensive knowledge and experience of pressurised systems. The pool of accumulated experience amounts to several million vessel years from all types of vessel quality, design, construction, operating procedures, levels of inspection and testing and failure modes. This massive volume of historical data should embrace all causes of failure to which pressure vessels are subjected. Failures are restricted to those where severe disruption of the pressure vessel or a major discharge of contents has occurred. 76 failures of major pressure vessels have been studied and, where data exists, the circumstance surrounding the failures examined. Failure is in all cases multicausal with a principal cause accelerated by contributory causes whose effects are difficult to predict because of the uncertainty of their prior existence and the significance of their contribution to failure is unquantifiable.

Table 1 summarises principal and contributing causes of failure ascertained by examination of the case histories. Types of vessel from which failures were reported are also listed. Table 2 summarises a typical vessel failure case history. Tables 3, 4 and 5 list vessels from which failure information was sought.

Using the population figure given above a generic failure frequency for high quality vessels is calculated as

7.6×10^{6} per vessel year (1×10^{-5} per vessel year at 99% confidence level).

There are three other principal sources of generic data from which vessel failure frequencies may be derived. These are summarised below.

Ref 1 Smith and Warwick data were gathered from 20000 Class 1 quality components selected from AOTC portfolios. A total of 229 "failures" of all types were reported from unfired components which had accumulated 3.1×10^{5} vessel years service. There were 4 relevant catastrophic failures giving a failure rate of 1.3×10^{-5} per vesel year.

Ref 2 Oberender et al recorded 1482 failures from approximately 10000 steam drums accumulating 1.75×10^{5} vessel operating years and 330000 pressure vessels accumulating 5.9×10^{6} vessel operating years during the period 1959-1976. Explosions from 3 steam drums and 77 pressure vessels were considered relevant to LWR pressure vessels. These figures give 1.7×10^{-5} per vessel year and 1.30×10^{-5} per vessel year respectively.

Ref 4 NBBPVI data are not specifically a review of service experience but total numbers of vessels listed by registration surface area and numbers of failures. Since these figures are not cross-referenced it is not possible to correlate them. Assumptions have to be made when relating accidents and population and it is assumed that the "torn assunder" type failure would only be reported from vessels larger than minimum registration surface area of $0.8\ m^2$ (10 sq ft). This gives a population of 5.3×10^{5} vessels and 3.6×10^{6} vessel years service between 1973 and 1978 and a rate for "torn assunder" failures of 5.5×10^{-5} per vessel year.

The above figures illustrate that from generic data it is difficult to justify lower than the $10^{-4} - 10^{-5}$ decade. How appropriate this value is to a specific vessel will depend on the degree of conformity the vessel concerned shows with those comprising the bulk of the general population. With an RPV there are obvious major differences in quality; thickness; design precision; inspection requirements, material selection etc, so the generic figure may not be considered relevant and alternative procedures, such as probabilistic fracture assessment, employed to derive a failure frequency.

FUTURE WORK PROPOSALS

Regarding further surveys of operating experience and failure reporting there is a need for greater frankness on the part of operators and owners and more precise reporting of component failures. Study of a characterised population of vessels would provide a wealth of information on (a) the incidence and causes of cracking; (b) the effect of vessel quality on leak and burst type failures; (c) the effect of thickness; (d) the effect of cladding.

Benefits which could accrue from an information feedback to designers, operators, inspection organisations, legislative and regulatory bodies could provide for design simplification, improvements in operating procedures, give guidance on inspection techniques and intervals, monitor the effects of introducing new materials, standards and regulations, and it would enable new or rare causes of failure - the incredible event - to be identified.

CONCLUSIONS

1. Pressure vessels do fail.

2. Generic data suggest a failure frequency within the $10^{-4} - 10^{-5}$ decade.

3. Failure mechanisms repeat themselves through the years.

4. Individual vessels significantly different from those forming the generic population should be assessed on their merits.

5. There is a need for greater frankness of information and more open reporting of failure events.

6. It is neither feasible nor practical to claim that no vessel will ever fail at any time under any circumstances. This will continue so long as mistakes are made and we ignore or fail to learn from records of past experience.

REFERENCES

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3. Newspaper Enterprise Association Inc. The World Almanac and Book of Facts 1981 NEA Inc New York.

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TABLE 1

SUMMARY OF FAILURE CASE HISTORIES

Number and Type of Vessel

Boiler Drums	9	Heat Exchangers	17
Ammonia Plant Vessels	5	Pressure Vessels	5
Feedwater Heaters	5	Storage Vessels	14
Oil Refinery Vessels	5	Reactor Vessels	11
Reformer Vessels	5		

Principal Failure Causes

Overpressure Test at Ambient temperatures	22
Material below transition temperature	7
Creep failure	7
Failure due to corrosive media	8
Inadequate or no stress relief	5
Inadequate control of pressure relief	4
Not designed against fatigue	2
Explosive contents	1
No control of departure from design	1
Poor water control	2
Inspection difficulties eg austenitic welds	1
Failure causes not identified	16

Contributing Causes of Failure

Poor fabrication conditions; design errors in geometry and calculation; wrong electrodes used in fabrication or repair; maloperation of associated equipment; manufacturing defects which escape detection or are in locations where no inspection is required; brittle material introduced by weld repair; stress corrosion cracking; hydrogen embrittlement; HAZ material properties; alloying elements in construction materials which cause fabrication or PWHT induced cracking.

TABLE 2

VESSEL TYPE: Waste Heat Boiler. DIMENSIONS: 57mm thick, length and dia N/A. DESIGN: Pressure 11.4 N/mm^2 (1670 psi) - Temperature 322°C. MATERIAL: BS 1501.222. GR32 B Tubeplate Ducol W30. 3½" thick. FAILURE CONDITIONS: Hydrotest at pressure 22 N/mm^2 (3200 psi) when scheduled for 23 N/mm^2 (3366 psi). The temperature was estimated at 20°C. Failure was in circumferential closure weld root defect. Geometric mismatch was forcibly corrected during fabrication. Welds had needed repair due to cracking and joint had been made over 6 periods of time between which preheat was withdrawn. Prior to PWHT the weld had been fully examined by ultrasonic and magnetic particle techniques. Examination of temperature records showed centre of vessel lagged furnace temperature by up to 100°C. No NDE after stress relief. Weld procedure and preparation were conducive to H_2 induced cold cracking. Ducol W30 was involved in tube plate/shell weld and precautions necessary when welding this material under high restraint due to mismatch were not taken. PWHT should have been for longer time to remove H_2 .

TABLE III

LIST OF VESSELS IN CASE HISTORY STUDY

VESSEL TYPE	MATERIAL	THICKNESS (mm)	PRESSURE MN/cm^2	TEMPERATURE °C	ENVIRONMENT	FAILURE	REMARKS
Ammonia Converter	Mn Cr Mo V Low Alloy Steel	150	35.1	120	New	Hydrotest	Brittle material
Boiler Drum	Mn Cr Mo V Low Alloy Steel	152	19.12	390	New	Hydrotest	Large Pre existing Defect
Feedwater Heater	C Mn Steel	229	N/A	N/A	Water	Hydrotest	No Stress Relief after welding
Oil Refinery Vessel	½ Mo Steel SS Clad	85.7	6.6	454		Brittle	Failed fr[illegible] repair weld
Heat Exchanger	Mn Cr Mo V Low Alloy Steel	57	2.1	N/A	New	Hydrotest	Brittle material
Boiler Drum	Mn Ni Mo V Low Alloy Steel	76	16.75	340	Water/Steam	Hydrotest	Large Pre existing Defect
Oil Refinery Vessel	C Mn Steel	38	1.2	N/A		Hydrotest	Poor design of attachment
Pressure Vessel	C Mn Steel	41.3	2.3	N/A		Hydrotest	Pre existing defect Brittle material
Heat Exchanger Shell	C Mn Steel	22.8	3.1	N/A	Water/Steam	Hydrotest	Poor design of attachments
Waste Heat Boiler	C Mn Steel Shell Mu Cr Mo V Tube Plate	57	11.4	322	Water/Steam	Hydrotest	Failed from weld repair - Brittle material
Thermal Cracker	½ Mo Low Alloy Steel SS Clad	23.8	1.0	454		Hydrotest	H_2 cracking
H P Heat Exchanger	ASTM A336 F22 SS Clad	203	207	N/A	Water/Steam	Hydrotest	Degraded material at SS/ferritic interface
Spherical Storage Tank	SM 50 VA	10.5m Dia x 18	Vacuum to 0.85			Hydrotest	Brittle material of attachment weld
Boiler	Mn Cr Mo V Low Alloy Steel	57 Shell 89 Tube Plate	15.5	N/A	Water/Steam	Hydrotest	Poor Design
Hydrodesulphurizer	1 Cr ½ Mo Steel	31	2.1	400		Hydrotest	Failed from attachment weld
Pressure Vessel	N/A	N/A	N/A	A		Hydrotest	Vessel was French Failure said to be similar to Item 1

TABLE III LIST OF VESSELS IN CASE HISTORY STUDY (continued)

VESSEL TYPE	MATERIAL	THICKNESS (mm)	PRESSURE MN/cm^2	TEMPERATURE °C	ENVIRONMENT	FAILURE	REMARKS
Boiler Drum	ASTM A515 Gr70	178	N/A	N/A	Water/Steam	Hydrotest	Failure due to faulty machinery
Spherical Catalytic Reformer Vessel	C. Steel	41	3.7	275		Brittle	In Service embrittlement
Gas Cooler Vessel	Mn Cr Ni Mo Low Alloy Steel	175	46.5	130	Water	Brittle	H_2 embrittlement
Heat Exchanger	Mn Ni Mo V Low Alloy Steel	150	31.4	60	Gaseous Effluent Water Cooled	Brittle	In Service
Ammonia Storage Vessel	C Mn Steel	25	1.7	Ambient	Ammonia	Brittle	While Filling
Ammonia Plant Pressure Vessel	Mn Ni Mo V	67 strokes to 308 head	37.8	26	Ammonia and gases	Brittle	In Service H_2 cracking
LPG Storage Vessel	C Mn Steel	18	1.5	Ambient	LPG	Burst	No stress relief stress corrosion
Superheater Outlet Header	1 Cr ½ Mo Steel	N/A	11.4	525	Steam	Creep	Nozzle ejected
Primary Superheater Header	½ Mo Steel	25.4	6.54	505	Steam	Creep	In Service Burst and discharge of contents
Reheat Loop	Cr Mo V Low Alloy Steel	19mm Pipe 81 Steamchest	3.6	56.6	Steam	Burst	At welded joint
Superheater/ Attemporator	1 Cr ½ Mo Steel	N/A	19	N/A	Steam	Creep	In Service failure
Continuous Digester	C Steel	32	1.0	115/135	Caustic	Stress Corrosion	Top Section Blown off
Feed Heater	Mn Ni V Low Alloy Steel	22	1.95	178	Water	H_2Cracking	In Service Failure
H.P Pre Heater	11 Ni Mo V 53 Low Alloy Steel	22	4.75	300/350	Water	Stress Relief Cracking	In Service Failure Manufacturing Defect
Feed Water Tank	Mu Ni V Low Alloy Steel	28	1.6	200	Water	H_2 and stress corrosion cracking	In Service Failure Vessel scrapped
Reformer Reactor Vessel	1¼ Cr ½ Mo Steel	35.5	4	500		H_2cracking	
Boiler Drum	Low Alloy Steel	N/A	N/A	N/A	Water/Steam	Stress Corrosion Cracking	Poor NDE
Feed Heater Vessel	C Mn Steel	191	27.6	N/A	Water	Brittle	Overpressure
Triform Pipe Tee	C Steel	35	9.3	196	Water	Brittle	Fatigue
Steam Accumulator	Low Alloy Steel	28	4.3	255	Steam	Brittle	Corrosion/Fatigue
Electrolyter	N/A	N/A	2.9	N/A	Mixed ls	Brittle	Internal Explosion
Steam Flash Vessel	C Mn Steel	57	0.7	150	Steam	Failure of Head to flange Weld	Poor Design and Manufacture
Steam Generator	C Mn Mo Steel	75 to 100	16	325	Water/Steam	Thermal Fatigue	Poor Water Control
Injection Cooler	N/A	22	2	150	Water	Corrosion	Poor Water Control
LPG Storage Tank	9% Ni Alloy Steel	49	6	+75 to -130	LPG	Ductile	In Service Fatigue

TABLE IV LIST OF VESSEL FAILURES FOR WHICH THERE ARE LITTLE OR NO DATA

Vessel Type	Material	Size	Pressure	Temperature	Environment	Fracture
Reaction Vessel	Carbon Steel	4.0" thick	5000 psig	-5°C to -15°C	Ammonia	Brittle
Heat Exchanger	C Si Mn V Ni Mo steel	85mm to 150mm	235 ats	35°C	N_2H_2; NH_3; A	Brittle
Heat Exchanger	2¼ Cr ½ Mo	2" - 4" thick	422 kg/cm^2	543°C	Hydrocarbons	Creep
Heat Exchanger	1 Cr ½ Mo	1 5/8" thick	550 psi	1010°F	Hydrocarbons	Creep
Reaction Vessel	Carbon Steel	2" - 4" thick	275 psi	175°C	N_2 H_2 CO CO_2	Overload
Reaction Vessel	1 Cr ½ Mo	2" - 4" thick	150 psi	460°C	Town Gas	Creep hydrotest
Vessel	30T Carbon Steel	4.0" thick	1000 psi	ambient	Air	Fatigue
Heat Exchanger	A 321	2" - 4" thick	900 psi	150°C	Mixed hydrocarbons	Stress corrosion
Reaction Vessel	Incoloy 800	2.0" thick	150 psi	815°C	Benzene	Creep
Reaction Vessel	30T Carbon Steel	2.0" thick	150 psi	200°C	Mixed hydrocarbons	Overpressure
Reaction Vessel	30T Carbon Steel	2.0" thick	145 psi	130°C	Steam	Overpressure
Reaction Vessel	BS1501 - 821/A321	2.0" thick	200 psi	170°C - ambient cycles	Hydrocarbons/water/steam	Stress corrosion and fatigue
Reaction Vessel	A304	2" - 4" thick	120 psi	185°C/30°C cyclic	Biological nutrient	Stress corrosion
Heat Exchanger	Mild Steel	2" - 4" thick	1830 psi	268°C	Water	Corrosion fatigue
Reaction Vessel	Mild Steel clad with SS	2.0" thick	157 psi	155°C	Cyclohexane	Stress corrosion
Heat Exchanger	Ducol W30	2" - 4" thick	566 psi	270°C	New	Hydrotest
Reformer Reactor	N/A	83mm thick	39 bar	500°C	Oil	Hydrogen cracks/corrosion
Reaction Vessel	2¼Cr 1Mo Clad 347	N/A	N/A	N/A	Oil	Nozzle failure
Cracker	Alonized Ferritic Steel	N/A	N/A	N/A	Leaded Gasoline	Corrosion
Reaction Vessel	HT Austenite	2.0" thick	N/A	N/A	Chloride	Stress corrosion
Boiler	C Si Mn Cu Ni Mo	2 3/16 thick	2050 psi	N/A	Steam/Water	Thermal shock
Water Cooler	C Si Mn V Ni Mo	4.0" thick	304 bar	N/A	N/A	Brittle fracture
Road Tanker Barrel	TI Steel	N/A	250 psi	-33°C to +50°C	Liquid Ammonia	Brittle fracture from scc
Boiler	Ducol W30	2 7/16 thick	N/A	N/A	N/A	Hydrogen cracking
Platform Reactor	1¼Cr ½Mo	42mm	25 bar	416°C	N/A	N/A

TABLE V

From a survey of the hydro carbon and chemical industries (Ref 5) 10 events have been selected because the initiation cause was unknown or was a consequence of equipment mal-functions. In all cases major missiles were generated.

1. A hydro-former reactor vessel fragmented throwing missiles, some weighing 60 tons, as far as 365 meters.

2. A filling gauge mal-function caused failure of 2 large spheres which ruptured. Other tanks 180 meters away were struck by missiles and also exploded.

3. A chlorination process vessel failure blew its cover through the roof of a 3 storey building and drove the vessel down through the floor causing major damage over a 300 meter radius.

4. Improper sampling resulted in the failure of a 14.5 meter diameter sphere. Pieces of steel weighing 100 tons travelled 400 meters.

5. A 180 mm thick hydro cracking reactor operated by computer at 17.25 MN/m^2 failed explosively causing severe damage.

6. Failure of a temperature transmitter caused failure of a reactor vessel. The explosion threw the reactor head 425 meters.

7. A 260 000 barrel tank failed disruptively. Failure originated at a weld which had been repaired 12 months earlier.

8. An unidentified failure of a large sphere led to a massive release of light hydrocarbons causing a tremendous fireball. Massive pieces of the tank travelled in all directions, the top section being flung 250 meters demonlishing firefighting facilities.

9. A massive failure of a 4 meter diameter pressure vessel flung the 15 ton vessel head 575 meters.

10. Rupture of a 1 meter diameter gas line caused a violent explosion. The force of gas escaping at 6.8 MN/m^2 destroyed a compressor building 76 meters away, the control building and meter house 180 meters away and auxiliary workshops.