

IMMEDIATE AND UNDERLYING CAUSES OF VESSEL FAILURES: IMPLICATIONS FOR INCLUDING MANAGEMENT AND ORGANISATIONAL FACTORS IN QUANTIFIED RISK ASSESSMENT

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This paper describes the causes of loss of containment for 230 reported incidents involving vessel failure. The aim is to better understand the role of organisational and management factors as a determinant of risk. For this reason the failures have been classified by both the direct causes, such as overpressure, and by failures of the underlying sociotechnical system. These underlying failures are both root causes (or origins) of failure such as poor design and failures of mechanisms which have the potential to prevent or recover unsafe situations. The importance of the results is discussed in terms of the use HSE makes of generic failure rates as part of RISKAT, the HSE Risk Assessment Tool.

INTRODUCTION

Failures of vessels at industrial and major hazard plant constitute one important class of failure which is considered when Quantified Risk Assessment (QRA) methods are used to calculate the levels of risk from such sites. The Health and Safety Executive (HSE) makes use of the results of QRA methods to give advice to local planning authorities concerning the use of land around major hazard sites (1). Recently, HSE has commissioned research to investigate the main factors which contribute to the failures of some important items of plant equipment such as pipework and vessels. The results obtained for the pipework study have already been described (2) while this paper describes the analysis for failures of vessels. The work reported here was carried out by the scientific and technical consultants 'Technica' Ltd (3).

In commissioning this research HSE aims to better understand the role of organisational and management factors in determining the levels of risk at major hazard sites. In the first instance two important items of equipment (i.e. pipework and vessels) have been chosen and their failures investigated in detail. A failure classification scheme has been developed and used to analyse available data. This classifies failures according to the direct (or immediate) cause e.g. corrosion, impact or operating error; the underlying cause (or origins of failure) e.g. a design fault, maintenance error or construction error; and by the failure of a preventive mechanism (recovery failure) which (in theory) could have been used to prevent the failure from occurring e.g. a HAZOP study which was not carried out or a failure to review operating procedures which were badly designed. Thus each failure is classified in a three dimensional manner e.g. a failure which results from corrosion caused by bad design which was not recovered by a HAZOP study.

This paper reports the results obtained from an analysis of the failures of 230 vessels classified according to this structure. The results are presented

firstly as the contribution from direct causes of failure and secondly by the underlying cause and preventive mechanism.

RESULTS

Direct Causes of Failure

The general classification scheme used in this study was the same as that used for the previous assessment of pipework failures (2). The structure of the scheme is shown in Figure 1. Vessel failure incidents were analysed from previous reports, for which direct causes were identified. Vessel failures of unknown direct cause were not included in the analysis. Further details of the sources of data are given in Appendix 1. A breakdown of the direct causes in rank order of prevalence is shown in Table 1. The percentage known direct causes are also given, where the contribution from defective equipment (equipment known but cause of defect unknown) was removed and percentages recalculated. These data are shown graphically in Figure 2. It can be seen that overpressure is the most common direct cause of the vessel failures with operating error also significant. These two categories alone account for almost 70% of the known direct causes of vessel failure.

A breakdown of direct causes to a secondary level of direct cause is given in Appendix 2. The tables in Appendix 2 provide a more detailed description of each of the direct causes of failure. The full report (3) includes a further description of each of the sub-causes given in Appendix 2.

Human Contribution to Vessel Failure

Operating errors accounted directly for 24.5% of known direct cause contributions, the majority of these being errors in control operation and operating errors due to failed communications. Operating errors involved leaving valves in the wrong status, filling the wrong vessels, but mostly overfilling and adopting inadequate or ad hoc procedures. Communication errors included inadequate information given to operators by the process control interface (procedures or verbally) assuming a vessel was safe when not, and poor permit to work systems. Other human contributions to failure involved vehicle impacts, overpressure due to the wrong material fed into a vessel and incorrect installation. The total direct human contribution to vessel failures (Table 2) is 32.8% of all known direct causes. Some of the entries in Table 2 are derived from the % of known direct causes and Appendix 2. For example, vehicle impact = $(5.6 \times 41.7\%) = 2.3\%$ from Table 1 and Table 6 Appendix 2. Other entries are similarly calculated using data from the full analysis (3). For example, "layering of reactive chemicals" is a sub-division of Appendix 2 not reported here.

Underlying Causes of Failure and Failures of Preventive Mechanisms

This section considers all the direct causes of failure and how the underlying causes of failure and failures of preventive mechanisms contribute to them.

For 16% of incidents, the origin of failure (underlying cause) and recovery failures were unknown. Table 3 shows the percentages of known origin of failure and recovery failure for the remaining data. Table 3 was produced by considering all the direct causes together and represents Figure 1 "collapsed" into a single table. These data are shown graphically in Figure 3.

TABLE 1 - Breakdown of direct causes of Incidents

DIRECT CAUSE	CONTRIBUTION *	% CONTRIBUTION	% KNOWN CONTRIBUTION +
Overpressure	97.0	42.2	45.2
Operating error	52.66	22.9	24.5
Temperature	24.0	10.4	11.2
Defective equipment	15.33	6.7	N/A
Corrosion	13.5	5.9	6.3
Impact	12.0	5.2	5.6
External	5.5	2.4	2.6
Other	5.5	2.4	2.6
Wrong equipment/ location	4.0	1.7	1.9
Erosion	0.5	0.2	0.2
Vibration	0	0	0
TOTAL	230	100	100

* For some incidents it was necessary to make a judgement when more than one direct cause was involved, eg 2/3 of direct cause due to operating error and 1/3 due to defective equipment.

+ Based on those accidents classified other than "defective equipment", ie $230 - 15.33 = 214.67$.

TABLE 2 - Human contribution to the direct causes of Vessel Failure

	% OF KNOWN DIRECT CAUSES
Operating Error	24.5
External caustic attack due to repeated overfilling	0.2
Vehicle Impact	2.3
Vessel hits protruding object/s dropped while being moved	1.4
Layering of reactive chemicals due to agitator not used	0.5
Wrong material fed into vessel	0.5
Overfilling	1.5
Incorrect installation at correct site	1.9
TOTAL	32.8%

It can be seen that operations (32.0%), design (29.5%) and maintenance (22.2%) are all large origins of failure, with domino also significant (12.7%). Hazard analysis (37.0%) and human factors review (30.2%) are the major potential recovery mechanisms. 13.5% of failures were not recoverable, and were events of domino, natural or sabotage origin. The checking of the state of the plant was sub-divided into checking that activities such as replacement of equipment had been carried out (task checking) and activities which were part of the vigilance system, eg inspection (routine checking).

Matrix Analysis

The results can also be examined by looking at individual boxes of the underlying cause/failure of preventive mechanism matrix for each direct cause.

Table 4 gives the values of the eight most significant matrix boxes, as a percentage of known origins of failure/recovery mechanism. The columns in Table 4 do not add up to the entries in Table 3 because only the most significant contributions are listed.

TABLE 3 - % Contribution of Failures according to underlying cause of Failure and Failure of preventive mechanism (unknown origin, unknown recovery removed)

	NOT RECOVERABLE	HAZARD STUDY	HUMAN FACTORS	TASK CHECKING	ROUTINE CHECKING	TOTAL
Natural Causes	0.5					0.5
Design		29.0			0.5	29.5
Manufacture						
Construction		0.3		1.8		2.1
Operations		5.4	24.53	2.1		32.0
Maintenance		2.1	5.7	3.6	10.8	22.2
Sabotage	1.0					1.0
Domino	11.9	0.3			0.5	12.7
TOTAL	13.5	37.0	30.2	7.5	11.8	100.0

The table highlights the best strategies for reducing failures:

- hazard reviews of designs to identify potential overpressure problems (21.0%)
- human factors review of normal operations to identify potential operating errors (18.3%)
- human factors review of normal operations which could result in overpressure (4.6%)
- human factors review of maintenance activities to identify potential operating errors (4.4%)
- routine maintenance for corrosion problems (3.9%)
- hazard review of operations to prevent overpressure failures (3.6%)

These six categories alone would theoretically reduce 55.8% of failures. This figure would actually be 64.5% of recoverable failures, since overall 13.5% of incidents were not considered recoverable. Alternatively, referring back to Table 3 it can be seen that hazard review and human factors review would recover 67.2% of failures, equivalent to 77.7% of recoverable failures.

TABLE 4

Percentage breakdown of the most significant underlying cause/failure of preventive mechanism type for each direct cause

	DESIGN/ HAZARD STUDY	OPERATIONS/ HUMAN FACTORS	DOMINO/ NOT RECOVERABLE	MAINTENANCE/ ROUTINE INSP.	MAINTENANCE/ HUMAN FACTORS	OPERATIONS/ HAZARD STUDY	MAINTENANCE/ CHECKING .
CORROSION	2.8			3.9			
IMPACT		1.6	2.6			0.8	
OVERPRESSURE	21.0	4.6	0.5	2.5	1.0	3.6	0.5
TEMPERATURE	2.1		8.8	0.5			
WRONG EQUIPMENT							0.8
OPERATING ERROR		18.3		0.3	4.4	1.0	2.1
DEFECTIVE EQUIPMENT	0.3			2.3	0.3		0.3

Comparison of Vessel Failures with Pipework Failures

A summary of the pipework and vessel failures data is given below in Table 5.

It can be seen that the two major direct causes were the same for both pipework and vessels. However, operating error was the dominant direct cause for pipework, followed by overpressure but for vessels overpressure was the major direct cause, followed by operating error.

The major origin of failure (underlying case) for pipework failures was maintenance, compared to operations as the major origin for vessels. The origin of failure is obviously related to the direct cause.

The major recovery failure (preventive mechanism) is obviously related to the direct cause and origin of failure. For pipework, where operating errors of maintenance origin were significant, a human factors review was the most significant recovery failure. For vessels, where overpressure incidents were the greatest direct cause, some form of hazard review (e.g. HAZOP or hazard review of procedures) was the major recovery failure.

Looking at the matrix analysis (individual origin of failure/recovery failure categories) the picture is similar. A hazard review of designs (Des/Haz) is the major cell in the matrix for both pipework and vessels. However, a human factors review of maintenance (Maint/HF) for pipework, and operations (OP/HF) for vessels, are the second largest matrix cells, reflecting the different major origins. *Non-recoverable domino effects are more significant for vessels.*

Despite some differences between causes of vessel and pipework failures, the general picture presented is very similar. Overpressure and operating error predominate. These two direct causes are often linked. In terms of underlying causes, design and hazard review failures are a clear theme. Maintenance and normal operations failures, both with human factors review failures, also predominate for pipework and vessels respectively.

TABLE 5 - Comparison of Pipework and Vessel Failure data showing main causal contributions as a percentage of known contributions

	PIPEWORK	VESSELS
Human contribution to direct cause of failure	41%	32.8%
Known direct causes	Operating error (30.9%) Overpressure (20.5%) Corrosion (15.6%)	Overpressure (45.2%) Operating error (24.5%) Temperature (11.2%)
Major underlying cause of failure	Maintenance (38.7%) Design (26.7%) Operating (13.7%)	Operating (32.0%) Design (29.5%) Maintenance (22.2%)
Major recovery failure (preventive mechanism)	Human factors (29.5%) Hazop (25.4%) Checking (24.4%)	Hazop (37.0%) Human factors (30.2%) NR (13.5%)
Matrix analysis	Design/Haz Rev (24.5%) Maint/HF (14.5%) Maint/Checking (12.7%)	Design/Haz Rev (29.0%) OP/HF (24.5%) Dom/NR (11.9%)

DISCUSSION

Land Planning and RISKAT

As explained in the introduction, HSE is committed to using Quantified Risk Assessment (QRA), in particular the risk assessment tool RISKAT (1) to provide advice to planning authorities about land use around major hazard sites. An important question is how does RISKAT take account of managerial and organisational issues.

The approach used at present is to assume that the installation is managed at least to average standards with monitoring by the regulatory authorities to check this. QRA is then carried out on a "hardware only" basis using generic failure rates from all causes including design errors, operating errors and so forth. Thus human and organisational factors are implicitly included in the generic failure rate data which are then applied in a site-specific way according to details of vessel sizes, pipe sizes and process conditions.

In this approach (1) a representative set of failure cases are listed (for example failure of vessels, leaks from vessels, failures of pipework, leaks from pipework); the failure rates for each case are based on generic failure data and the consequences are calculated using appropriate models for dispersion of toxic gases, radiation from a fireball etc. This enables the risk associated with the installation to be found.

This approach can be contrasted with a very detailed approach in which component failure rates specific to a plant are used with fault-tree analysis to arrive at the probability for each release type. These two approaches are very similar at a conceptual level but it needs to be stressed that the resource requirements for the two methods are quite different.

The first approach using generic failure rates is generally appropriate for HSE in the land planning area in which consistent advice can be offered to local authorities within the available resources.

A useful additional approach is starting to evolve in which a "hardware only" QRA of the type carried out using RISKAT is used to calculate risk for a site using generic failure rates. The risk figure is then modified on the basis of a site specific audit of safety management systems. This class of approach is thus called the modification of risk approach. The approach can only be fully validated when the following questions can be answered:

- what are the key indicators, or factors, which relate to, or measure, the quality of the safety management at a plant
- how are those factors recorded and scored
- what effect does changing these factors have on the risk from a plant i.e. what weights can be attributed to them in a risk analysis.

A contribution to these questions is provided by the analysis reported in this paper. Thus the generic failure rates used for vessels in RISKAT can be considered to be made up of components from different direct causes e.g. Table 1, 24.5% of the failures are due to operating errors. Perhaps more importantly the generic failure rates can also be considered to be the sum of contributions from the origins of failure and preventive mechanism failures which are at the root of the hardware failures.

Generic failure rates must reflect the direct causes which have given rise to the actual incident.[2] However, the direct causes are symptoms of sociotechnical system failures. These sociotechnical failures are reflected in the underlying causes of origin and recovery failures as defined by the structure of the classification (Fig 1). Therefore, although the human contribution was 41% and 32% of known direct causes of failure for pipework and vessels respectively (with operating error being 31% and 24.5% respectively) this is not a useful way to categorise the various contributions to generic failure rates for the purpose of comparing different plants. The underlying sociotechnical causes are more valid in this respect. Thus we see from Table 3 that 29% of the generic failure rate for vessels is made up from design errors which are not recovered by HAZOP type studies.

Other aspects of the research which HSE has commissioned are aimed at providing answers to the first two questions posed above. The aim is to provide an audit system which can measure the quality of safety management at a plant, and to link the results of the audit into QRA procedures via modification of generic values for such items as failure rates.

CONCLUSIONS

This paper has described the causes of loss of containment for 230 reported incidents involving vessel failure. The aim was to better understand the role of organisational and management factors as a determinant of risk. For this reason the failures have been classified by both the direct causes, such as overpressure, and by failures of the underlying sociotechnical system. These underlying failures are both root causes (or origins) of failure such as poor design and failures of mechanisms which have the potential to prevent or recover unsafe situations. The importance of the results is discussed in terms of the use HSE makes of generic failure rates as part of RISKAT, the HSE Risk Assessment Tool.

REFERENCES

- (1) Hurst N W, Nussey C and Pape R P Development and application of a Risk Assessment Tool (RISKAT) in the Health and Safety Executive. Chem. Eng. Res. Des. 67, 1989.
- (2) Hurst N W, Bellamy L J, Geyer T A W and Astley J A A classification scheme for pipework failures to include human and sociotechnical errors and their contribution to pipework failure frequencies. J. Haz. Mat., 1990.
- (3) HSE contract research by Technica 1991. Organisational, Management and Human Factors in Quantified Risk Assessment, Interim Report by L J Bellamy and T A W Geyer, Ed J C Williams.

APPENDIX 1 - Sources of data

A variety of data sources were examined including general literature (journals etc) and also databases available in the HSE. These are listed below.

A definition is also given of 'Vessel Failure'.

General Literature/Journals

Hydrocarbon Processing
Petroleum Review
Oil and Gas Journal
Loss Prevention Bulletin
Plant/Operations Progress
M and M Protection Consultants, Chicago, "100 Large Losses" 11th Edition
Lloyd's List

Databases

MHIDAS (SRD/HSE Major Hazards Incident Data Service) searched for the incident origin "PSVESSEL" (pressurised storage vessel)

MARCODE 1 and 2, the HSE databases of selected investigated accidents and dangerous occurrences searched for wordstem "VESS" in the text description field.

Definition of Vessel Failure

Incidents included in the analysis had to fulfil all the following:

- involve the failure of a vessel or associated equipment (eg vessel valve, sight glass, etc). Failures of hoses/couplings were not included.
- occur on land based installations using, manufacturing or storing chemicals (including associated loading/unloading facilities).
- occur on site.
- have led to a release of materials from a vessel with the potential to cause death or injury.

APPENDIX 2

BREAKDOWN OF DIRECT CAUSES TO A SECONDARY LEVEL

1. OVERPRESSURE

	CONTRIBUTION	% OF OVERPRESSURE
Uncontrolled/unexpected chemical reaction	15.25	15.7
Explosion/fire	39.0	40.2
Inadequate vent/pressure relief system	10.83	11.2
Hydrostatic pressure	2.0	2.1
Source pressure exceeds vessel pressure	1.83	1.9
Overfilling	3.33	3.4
Surge pressure/water hammer	3.0	3.1
Changed equipment/process allows overpressurising	2.0	2.1
No/inadequate cooling of vessel	0.5	0.5
Release of material from safety relief valve/bursting disc/vent/sight glass	11.25	11.6
Freezing contents cause overpressure	1.0	1.0
Unknown	7.0	7.2
TOTAL	97.0	100

2. OPERATING ERROR

	CONTRIBUTION	% OF OPERATOR ERROR
Error in (control) operation	37.41	71.0
Operating errors due to failed/no communication	13.25	25.2
Insufficient isolation	1.5	2.8
Inadequate cleaning of vessel leaves reactive residue	0.5	0.9
Unknown	0	0
TOTAL	52.66	100

3. TEMPERATURE

	CONTRIBUTION	% OF TEMPERATURE
External fire	20.0	83.3
High temperature effects	2.5	10.4
Cold external environment	0.5	2.1
Unknown	1.0	4.2
TOTAL	24.0	100

4. DEFECTIVE EQUIPMENT (Cause Unknown)

	CONTRIBUTION	% DEFECTIVE EQUIPMENT
Valve	6.33	41.3
Level measuring equipment/gauge	3.0	19.6
Regulator on cylinder	1.0	6.5
Seal	0.5	3.3
Safety interlocks	0.5	3.3
Glass viewing port	1.0	6.5
Extraction system	1.5	9.8
Condenser nipple	1.0	6.5
Unknown	0.5	3.3
TOTAL	15.33	100

5. CORROSION

	CONTRIBUTION	% DEFECTIVE EQUIPMENT
External caustic attack due to repeated overfilling	0.5	3.7
Stress corrosion	6.0	44.4
Valve corrosion allows release of vessel contents	1.0	7.4
External corrosion	1.0	7.4
Chemical stress	1.0	7.4
Brittle fracture	2.0	14.8
Unknown	2.0	14.8
TOTAL	13.5	100

6. IMPACT

	CONTRIBUTION	% OF IMPACT
Vehicle impact	5.0	41.7
Impact of other plant equipment	1.0	8.3
Vessel hits protruding object/ is dropped while being moved	3.0	25.0
Missile attack	1.0	8.3
Unknown	2.0	16.7
TOTAL	12.0	100

7. EXTERNAL LOADING

	CONTRIBUTION	% OF EXTERNAL LOADING
Failure of vessel supports	2.0	36.4
Earthquake	1.0	18.2
Bending/dynamic stresses imposed when in use	1.5	27.3
Dynamite attack	1.0	18.2
Unknown	0	0
TOTAL	5.5	100

8. OTHER

	CONTRIBUTION	% OF OTHER
Software failure	2.0	36.4
Formation of product/dirt in valve prevents closure	2.5	45.4
Uncontrolled chemical reaction	1.0	18.2
Unknown	0	0
TOTAL	5.5	100

9. WRONG EQUIPMENT/LOCATION

	CONTRIBUTION	% OF WRONG EQUIPMENT/LOCATION
Incorrect installation at correct site	4.0	100
Unknown	0	0
TOTAL	4.0	100

10. EROSION

	CONTRIBUTION	% OF EROSION
Section of broken equipment erodes vessel interior	0.5	100
Unknown	0	0
TOTAL	0.5	100

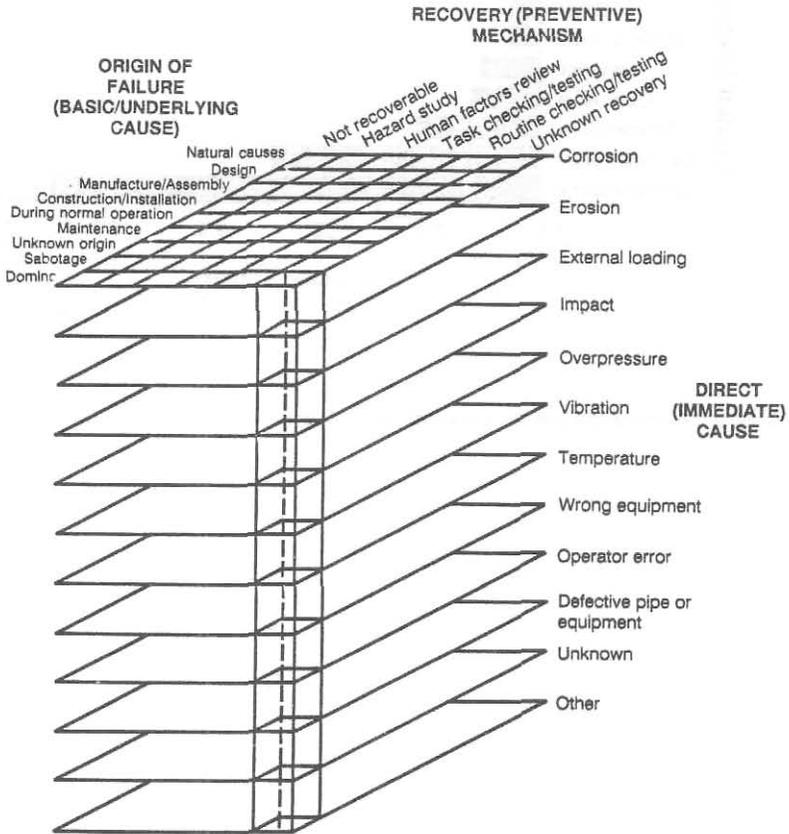


Figure 1 Structure of classification scheme showing direct cause. Origin of failure and recovery failure

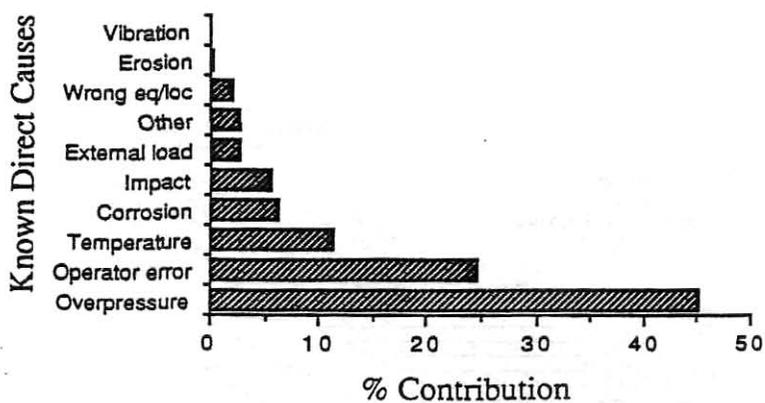


Figure 2 % contribution of known direct causes

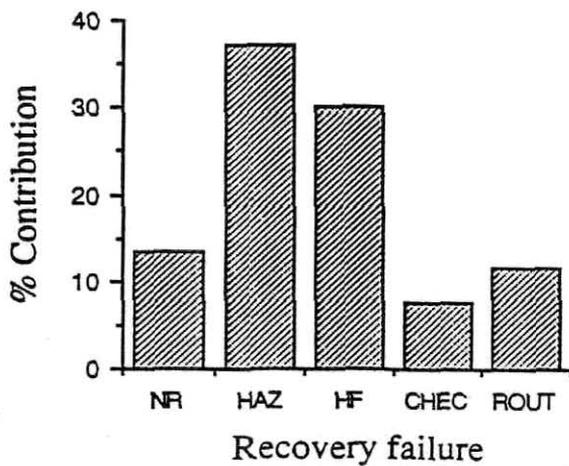
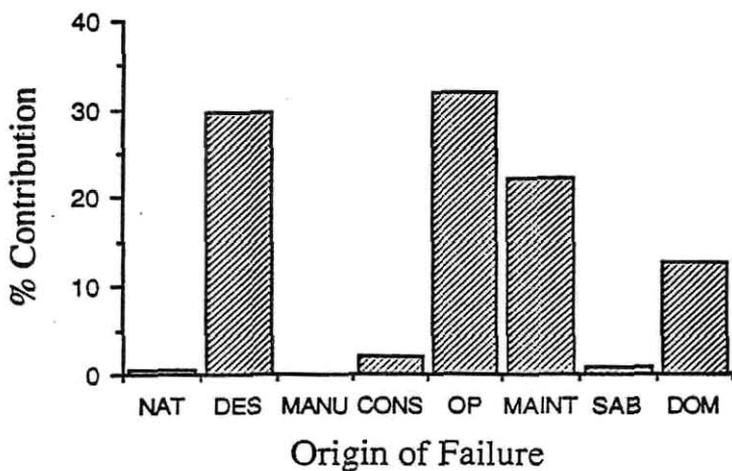


Figure 3 % contribution of origin of failure and recovery failure for vessels