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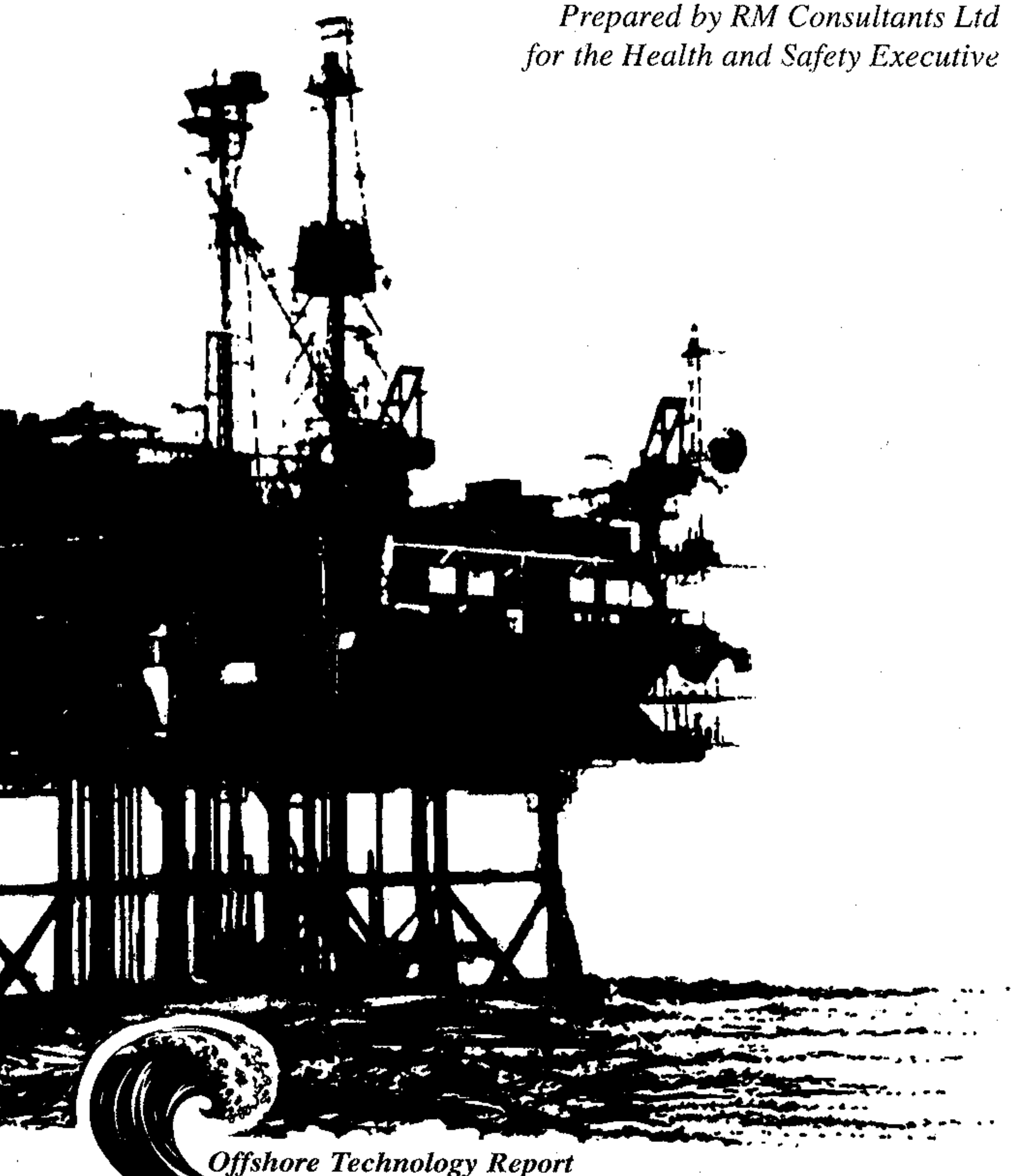
EXTENSION OF THE SUBSEA ISOLATION SYSTEMS RELIABILITY DATABASE

Prepared by RM Consultants Ltd
for the Health and Safety Executive



Offshore Technology Report

Health and Safety Executive

OTH 96 502

EXTENSION OF THE SUBSEA ISOLATION SYSTEMS RELIABILITY DATABASE

Author

M Humphreys

RM Consultants Ltd
Suite 7, Hitching Court
Abingdon Business Park
Abingdon
Oxon
OX14 1RA

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Background information and data arising from these research projects are published in the OTI series of reports.

SUMMARY

An earlier study by R M Consultants Ltd (RMC) collected failure data on Subsea Isolation Systems (SSIS) and analysed the reliability of a number of system configurations. That work was jointly funded (50%/50%) by UKOOA and the Offshore Safety Division of the Health and Safety Executive and was undertaken so that operators and HSE could address Lord Cullen's recommendation number 46 (consider ways of improving reliability and reducing costs of Subsea Isolation Valves (SSIV) so that it is more often reasonably practicable to install them). Data were collected on 50 SSIS.

That earlier study concentrated on SSIS which had been installed by 7 operators at that time. Subsequently some of these operators have installed more SSIS. HSE has now funded an extension of the database to cover the additional SSIS and those SSIS installed by other operators. Installation information and maintenance records were collected for an additional 63 SSIS during 1995. The new data have been combined with the existing data and analysed to obtain failure rates for major elements of SSIS. Most of the new SSIS have only limited operating experience at present and so it was still considered necessary to combine the collected data with generic data.

The effect of the additional experience on component failure rates and systems reliability is considered in this report.

CONTENTS

CONTENTS - Cont'd

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 BACKGROUND

RM Consultants Ltd (RMC) carried out a reliability study of Subsea Isolation Systems (SSIS) in 1993-94. The study was jointly funded by UKOOA and the Offshore Safety Division (OSD) of the Health and Safety Executive (HSE). The study was concerned with the reliability of subsea pipeline emergency isolation valves, their actuators and associated control systems (both subsea and topsides equipment). The results of that study were published in an OSD report [Ref 1]. The study was part of the joint response by UKOOA and HSE to Lord Cullen's recommendation number 46 [Ref 2], with respect to improving reliability and reducing costs of SSIS, so that it is more often reasonably practicable to install them. A configuration survey was carried out in 1993 in conjunction with the member companies of the UKOOA Subsea Valve Working Group. Subsequently operating and failure experience were collected for 50 SSIS and put into a reliability database. At the time of the survey it was known that other SSIS had been installed by companies not involved in the Subsea Valve Working Group. In addition a significant number have been installed since the survey. HSE has now funded (100%) the extension of the database to cover all SSIS installed on UKCS. Installation and maintenance records were collected for an additional 63 SSIS during 1995. This report presents the results of the database extension and considers the effect the extra operating experience has on the reliability of SSIS configurations.

1.2 OBJECTIVES

The main objectives of the study were to extend the SSIS database to cover all SSIS installed on the UKCS; to determine the effect of the additional experience on component failure rates and to re-analyse the reliability of SSIS configurations taking into account any revision of component failure rates. To achieve these objectives, several main tasks were identified as follows:

- establish contact with operators through UKOOA,
- obtain inventory and failure data on additional SSIS,
- analyse the data to determine component failure rates,
- review the effect of the additional data on the SSIS configuration reliability.

2. DATA COLLECTION SUMMARY

2.1 INSTALLED SSIS

At the time of the original study [Ref 1] there were known to be 83 SSIS installed on the UKCS. Operators provided design details for 53 UKCS systems and 2 non-UKCS systems (55 SSIS in total). That study examined maintenance histories for 48 of the UKCS systems and the 2 SSIS from non-UKCS operations (Norwegian and Danish sectors). Maintenance histories were not available for 5 systems. During the current study operators have provided design information on 63 SSIS, which have either been installed prior to 1995 or were installed during 1995. Thus entries have been made in the database for 116 SSIS installed on the UKCS (plus 2 non-UKCS). Some systems have 2 actuated valves in series. For this reason the database includes details of 123 SSIVs, contained in 118 SSIS. Note that an additional 2 years operating time has now been experienced by the SSIS included in the original study (1993 to 1995). However, collection of this additional experience was beyond the scope of the current study and so has not been requested from operators.

Some systems contain 2 actuated isolation valves in series, while others contain actuated bypass valves. Thus the total number of SSIV in the database is larger than the number of systems. Conversely, several SSIS are controlled by 1 topside control system and supplied from 1 HPU, so the number of these items is less than the number of SSIS.

2.2 OPERATING EXPERIENCE

A number of SSIS (6) were only installed during 1995 and so could not provide operating experience for this study. The total operating experience obtained for the remaining SSIS (57 systems with a total of 59 valves) was 207 years, equivalent to 3.3 years per system. This compares with the experience collected during the original study of 181 years for 50 SSIS giving 3.6 years per system. Thus the total operating experience represented in the database has increased from 181.1 years to 388.5 years, ie approximately double.

The data collected during the two studies relates to 4 basic valve/actuator types and the operating experience obtained for each type is as follows:

Subsea Valve Experience (Years)			
	Existing	New	Total
Check valves (NRV)	36.7	12.3	49
Spring return actuated, ball valve	79.6	110.4	190
Double acting actuator, ball valve	64.8	33.6	98.4
Spring return actuated, gate valve	0	51.1	51.1
TOTAL (all valves)	181.1	207.4	388.5

The proportionately larger increase in operating experience gathered for spring return actuated systems reflects the industry's move, in general, away from double acting actuators.

In conjunction with the subsea valve data, operators provided information on the associated control systems and HPUs. The change in operating experience for these systems is as follows:

Control System and HPU Operating Experience (Years)			
	Existing	New	Total
Multiplexed Control System	1.6	10.6	11.2
Solenoid Valve	115	55.8	170.8
Pilot Valve	115	55.8	170.8
Accumulator Bank	63.4	31.2	94.6
Umbilical	115	55.8	170.8
HPU	65.5	53.6	119.1

Inevitably, multiplexed control systems will control several valves, without providing topside SOV or pilot valves for each SSIV. The collection of data from a number of platforms with multiplexed systems, in the current study, has resulted in a relatively small increase (50%) in collected experience for SOVs etc, compared to the rise in experience for SSIV (100%).

2.3 OPERATOR MAINTENANCE RECORDS

2.3.1 Subsea Equipment Records

Due to the high cost of subsea maintenance operations most operators for subsea equipment have no planned maintenance activities. Where a problem has been identified, such as accumulator bladders perishing, then operators may initiate a replacement programme. Generally, only breakdown maintenance is carried out (i.e. if a problem occurs action is initiated to make the necessary repairs). This work is then reported in an annual subsea work report. However, these reports generally contain a brief account of the work done with insufficient detail to form an accurate failure report. The extra detail required by RMC for the study was obtained through discussions with the appropriate experienced personnel.

Most SSIS included in the current study have been installed within the last 4 years (average operating experience 3.3 years). In line with the earlier study very few failures have been recorded. The nature of SSIS (high cost and located subsea) ensures that any problems occurring will be known by an operator even if it is not fully documented. Therefore the data collected on subsea equipment is considered to be accurate.

2.3.2 Topside Equipment Records

Nearly all operators have the topside SSIS equipment, that is control systems and Hydraulic Power Units (HPU), covered under the platform Preventative Maintenance Routines (PMR). Work orders generated for this work are generally logged on computer. Also, all unscheduled maintenance is recorded as work orders are generated and completed. Operations personnel in some companies reviewed the records in the computer systems to provide RMC with details of all failures (critical or non-critical).

2.4 DISCUSSION OF SYSTEM FAILURES

The data collection exercise has provided only a small number of failures for subsea and for topside components. The following observations can be made from the data collected.

2.4.1 Subsea Failures

No critical failures (fail to close/open, spurious operation etc) of subsea components were recorded in the earlier study and the same result has been found in the current study. However, several non-critical failures have occurred and are described below.

Check Valve

No failures of check valves have been reported in the current study. In the earlier study one check valve failure was recorded. This was an external leak of gas through a stem seal during preparations for pigging operations. The seal was re-made by injecting sealant into the seal area.

Ball Valve

Two failures were recorded with actuated ball valves in the earlier study. These were both external leaks from auxiliary ports on the valve body (drain plug and sealant injection port). The failures occurred over a total operating period of 144.4 years (covering 45 SSIS). These auxiliary ports in the valve body (which are appropriate for topsides use) are a source of minor problems only, but they still required subsea repairs at some time. In designing subsea valves for minimum maintenance (ideally maintenance free) then such auxiliary ports should be eliminated.

A failure also occurred with a manual ball valve. The valve failed to close fully and isolate the pipeline when required for maintenance of the SSIV. The failure was caused by the valve seat rings being fixed in position (after 5 years in-service without use).

Actuator

3 non-critical failures were recorded on actuators in the earlier study. The failures occurred on spring return actuators (attached to two 6" and one 30" valve). One external leak failure occurred at the actuator control panel, caused by galvanic corrosion of carbon steel connector caps. These were replaced by more compatible stainless steel caps. The other failures were attributed to a faulty status indication limit switch and to delayed operation of an actuator. The latter concerned the very slow opening of the SSIV after a test closure. This was caused by metal particle contamination of the hydraulic fluid resulting from a manufacturing process error on the metal plating of the actuator tie-rods.

Control Connections

In the current study 2 reports of valve limit (or proximity) switch failure were identified. Replacement was not considered necessary, with valve position being inferred from shutdown pressure readings. In the earlier study 2 identical failures were recorded where loss of valve position indication was caused by failure of the connection from the subsea control pod to the actuator limit switch. Hardwired connections from the control pod were replaced with connectors, which necessitated the replacement of the control pod with a modified version.

Subsea Umbilical Termination

Failures were recorded in which hydraulic fluid leaked from the hydraulic couplings at the umbilical termination panel. These were caused by corrosion of stainless steel couplings due to either the failure of cathodic protection or subsequently identified substandard materials. None of the failures would be considered critical to the SSIS operation as they did not cause or prevent valve closure. The earlier study identified a similar failure in that fluid leaked from a hydraulic coupling due to corrosion.

Accumulators

Failures have been recorded with subsea accumulator banks. In 1 report bladders in 2 accumulators had ruptured, while in an other incident a hydraulic hose leaked on 1 accumulator (of a bank of 3). Another operator identified a small puncture in a bladder when the accumulator bank was withdrawn for inspection (1 in a bank of 4), cause unknown but possibly due to human error when filling with nitrogen. All installations had several banks of accumulators so the reported failures would not have caused or prevented valve closure. The earlier study did not identify any failures of accumulators. In fact 1 operator had recovered an accumulator bank after ten years in service. Inspection of the unit showed it to be in good operable condition with only minor work hardening of the bladder material having occurred.

2.4.2 Topside Critical Failures

No critical failures of topside equipment were reported in the current study. However, in the earlier study a number of critical failures of the SSIS were attributed to topside control system and HPU components. The critical failures from the earlier study are described below.

Solenoid Valve

The control system solenoid valves contributed to 4 SSIV fail to close incidents. These were caused by sticking/seizing in position and thus failing to operate when required.

Pilot Valve

Control system pilot valves produced 2 critical failures, a spurious SSIV closure, and a failure to re-open the SSIV. Both were caused by blocked internal filters.

Pressure Regulator

Only 1 critical failure was recorded when the SSIV failed to open after a test closure due to a loss of hydraulic pressure caused by leakage of a pressure regulator.

Electrical Wiring

Only 1 critical failure - spurious operation of the SSIV - was attributed to an electrical wiring error.

HPU

No critical failures of HPUs were identified in this study. In the earlier study only 1 critical failure was attributed to the HPU. This occurred when the duty and standby pumps failed to cut-in as the hydraulic pressure dropped, due to a failure of the pump start pressure switch.

2.4.3 Topside Non-Critical Failures

In the current study a number of non-critical failures of topside equipment were reported by several operators. However, a number of operators were unable to provide details of such minor repair activities and so it is considered that there has been an under reporting of non-critical failures of topside control system and HPU failures. This does not detract from the main objective of the study which is concerned with the critical failures (fail to close and spurious closure). The non-critical failures reported were as follows:

- HPU pump stopped due to loss of air supply (Pipework failure)
- HPU pump replaced (providing inadequate pressure)
- HPU accumulator loss of nitrogen charge
- LP pilot valves replaced
- Pressure switch failure (leaking and diaphragm rupture)
- Solenoid valve spurious trip of air supply to pump
- Leakage from pump seals
- Control system hydraulic connection leaking
- Electrical power unit failures (tripping on earth leakage faults)
- Redundant computer locked up.

In the earlier study more non-critical failures were reported as follows:

-	Computer	Faulty Central Processor Unit (CPU) board causing loss of valve status indication
-	Relief valve	External leaks of hydraulic fluid requiring replacement on 3 occasions
-	Pressure regulator	External leak and adjustment errors necessitating replacement

Several non-critical failures were attributed to the HPU pumps, and this component appears to be a consistent source of problems with the HPU. Several minor failures of the back-up accumulator bank occurred, but only individual accumulators were affected and no complete loss of back-up occurred. The individual failures mainly occurred with associated valves and couplings but some bladder failures occurred. Of interest is the case where bladder material had perished from exposure to ozone (in plentiful supply at sea). The ozone caused stress corrosion cracking of the material leading to bladder failure. The bladder material was replaced with a different type that is more resistant to the effects of ozone.

3. BASE FAILURE DATA ANALYSIS

The SSIS data collection exercise did not, as expected, generate many component failures, particularly on subsea components, and did not identify critical failures in some components. Difficulties then arise in applying classical statistical methods to obtain meaningful failure rates for all significant failure modes. While it is possible to calculate sample mean and confidence bounds on the total failure rate for a component, the estimation of failure rates for critical failure modes based solely on collected data is not possible without using a considerable degree of pessimism.

The approach adopted in the study was to obtain existing data on similar components and use the data as a prior value. The collected data from existing SSIS was then combined with the prior data to produce a new estimated failure rate.

3.1 COLLECTED FAILURE DATA

The SSIS database now contains component inventory records for the 118 SSIS and all the failure records reported by operators. No failures have been reported for a number of systems. This is either because the systems are newly installed or there have been no (critical) failures. The database software allows components to be selected by the use of inventory and/or failure filters. A standard calculation was performed on the selected records to provide information on the numbers of failures, operating experience, failure rate and failure modes.

3.2 COMBINING PRIOR AND COLLECTED FAILURE DATA

A number of methods were available to combine prior and collected data. The basis for selecting a particular method depended on the form the prior data took, the number of failures recorded for the collected data and in some cases the similarity between components being combined. The general conditions for the use of one of the three methods were:

Bayesian:	Prior failure rate only and zero failures for collected data
Geometric Mean:	Prior failure rate only and collected data with failures
Aggregation:	Prior failure rate with number of failures and operating experience

The resulting combined failure data is summarised in Table 1.

3.3 COMBINED DATA LIMITATIONS

There is only limited subsea experience with check valves - 10 valves and 49 years experience. There is more experience with the actuated (ESD) ball valves - 68 spring return actuators with a total of 190 years experience and 28 double acting actuators with 98 years experience. Thus the total experience for ball valves (either actuator) is now 288 years. In the previous study no operating experience was obtained for gate valves. In this study a total of 51 years experience has been obtained.

The collected check valve data has been combined with prior data for onshore check valves (3270 years experience). While most prior data for actuated ball valve components are from offshore sources. It is possible that the onshore data could present a different view of check valve reliability. However, comparing the point estimate failure rates for external leaks for the onshore and subsea check valve sources (Table 1) there is very little difference. The collected subsea data gives a point estimate failure rate of 2.0×10^{-2} failures/year (f/yr) compared to 2.9×10^{-2} f/yr for the onshore data. This suggests that the onshore and offshore data sources are in reasonable agreement and gives confidence in applying the onshore "failure to close" frequency, given that there were no such failures in the relatively small offshore operating experience.

3.4 CHANGES IN FAILURE RATES

Table 2 identifies the changes in operating experience and resulting changes in calculated failure rates for all components of the SSIS.

As mentioned before, the additional experience obtained for check valves does not alter the calculated failure rates.

Similarly for gate valves the calculated failure rates have not changed. For a ball valve (excluding actuator) the doubling in operating experience, with no additional failures, results in a small reduction in calculated failure rate (from 4.9×10^{-3} to 2.9×10^{-3} f/yr for fail to close).

If the operating experience (288 years with no failure to close) is considered separately from the prior data, then it is possible to postulate, say, that 1 failure could have occurred. This would produce a failure rate of 3.5×10^{-3} f/yr. Taking a (statistical) confidence band of 90% the upper limit would equate to approximately 3 failures, giving a failure rate estimate of 1.0×10^{-2} f/yr, ie slightly below the figure provided by the prior (topsides) data. It can be concluded that the operating experience obtained is now sufficient to provide a robust estimate of the average failure rate of ball valves (excluding actuators). Existing data sources for topside valves show that there can be a variation in failure rate for different sizes of ball valve and for the same size of valve with different fluids (oil or gas). It is not possible to determine if this is also the case for subsea valves, from the current experience. Collection of additional operating experience would be required before robust estimates can be obtained for different valve sizes.

For subsea actuators (spring return and double acting combined) the new calculated failure rate for failure to close has reduced from 4.7×10^{-3} f/yr to 2.5×10^{-3} f/yr. Considering only the collected data (348 years), with an estimate of 1 failure (for none collected) the calculated failure rate would be 2.9×10^{-3} f/yr and the 90% upper bound proportionally higher (8.6×10^{-3} f/yr). The collected experience is now significantly higher than the experience provided by the prior data source (58 years).

It is now possible to separate the experience for each type of actuator and calculate failure rates. The combined (with prior data) failure rate for each is:

	fail to close (f/yr)
Spring return actuator	3.2×10^{-3}
Double acting actuator	6.4×10^{-3}

This result should be treated with caution, as the difference reflects the much larger experience for spring return actuators (250 years), with no failures, compared to 98 years for double acting actuators.

The additional operating experience has not significantly affected the calculated failure rates for multiplexed control systems, umbilicals, accumulator banks and solenoid valves. Small reductions in calculated failure rates for pilot valves and HPUs have resulted from the inclusion of the additional material.

4. FAILURE MODELLING AND RESULTS

To assess the reliability of the 9 configurations (Appendix A) identified for detailed evaluation in the earlier study, failure models were constructed for the following 3 undesired events.

- failure to close on demand
- spurious valve closure ie isolation of the pipeline
- subsea intervention required

The effect on pipeline availability was calculated using the data from the above models.

The fault tree models were constructed using LOGAN, a Fault Tree Analysis (FTA) software package developed by RM Consultants Ltd [Ref 3].

4.1 FAILURE MODELS

Failure to Close on Demand (Table 4)

Each fault tree modelled the sub-system or component failures which could prevent closure of the subsea valve. For the configurations employing a single valve, the fault tree simply combined the individual failures via OR gates. While, for configurations with redundancy (eg Configuration E), the fault tree took this redundancy into account. It also takes account of possible dependencies between the identical components, in terms of a Common Cause Failure (CCF) factor, which could result in both redundant sub-systems failing. Generally, only unrevealed failures preventing valve closure were included in the fault tree. Typical unrevealed failures are: the main valve sticking open; loss of accumulator pressure; solenoid valve sticking. These failures were combined with the appropriate test interval (3 or 12 months) to calculate the probability of failure on demand.

Spurious valve closure (Table 5)

Any failure, which causes valve closure, will inevitably be revealed almost immediately, by stopping flow through the pipeline. The fault trees calculated the total frequency of spurious valve closure due to components in the SSIS. They did not include spurious trip demands from the ESD systems.

Subsea Intervention (Table 6)

Subsea intervention was assumed to be required for all revealed subsea failures. In order to calculate a total frequency of subsea intervention, the failures causing spurious valve closure were included as were the subsea failures that were only detected at an annual test.

Availability (Table 8)

Spurious actuation of the SSIS (closure of the valve) will prevent product flow and so potentially cause loss of revenue. The availability of the SSIS (to allow continued product flow) was calculated by first calculating the unavailability. For most configurations the calculation was based on the spurious trip fault trees. For Configuration B (the single check valve) no spurious closure frequency could be calculated. It is unrealistic to assume this means there would be no loss of availability and so the data for other failure modes of check valves was utilised. In addition, Configurations F and H contain bypass valves, which did not affect the spurious closure frequency calculation, but will influence the system availability. These are taken into account in producing the results in Table 3.

4.2 ASSUMPTIONS AND LIMITATIONS

The reliability models have only been developed down to sub-system level. They do not include detailed component level failures (ie screws, joints, etc). They contain only the components or subsystems that are directly associated with the operation of the SSIS. The models are primarily intended to allow comparisons of the different configurations based on similar failure data and assumptions.

The following general limitations and assumptions have been made in this study.

i) Any component failures are considered to be randomly distributed in time. The equipment is still within its normal design life.

ii) All components are being used within their normal design limits (mechanical, environmental etc). The quality of materials and construction, particularly of the mechanical parts of the system, will affect the long term reliability. This is true for all the valve types and configurations considered in the study. For comparison purposes it is necessary to assume that each system has been, or would be, designed to meet the required duty.

iii) All components are assumed to be in "as good as new" condition after proof test or repair activity.

iv) All maintenance and proof testing of the system would have associated procedures (eg testing of platform ESD systems may involve inhibiting the SSIS trip). These procedures would ensure that once an item had been successfully tested the possibility of that item being left off-line (ie failure to re-instate the trip function) would be minimised. Such procedures are under the control of platform based personnel. Quantification of potential errors during these activities was not considered.

v) Only component and sub-system failures were considered in the study. Any possible human error or external force which may have an influence on the results have not been included.

vi) For Common Cause Failures of redundant sub-systems a beta factor of 0.1 was used.

4.3 PROOF TEST INTERVALS AND REPAIR TIMES

Proof tests are required to test the system and to detect otherwise unrevealed failures. For subsea components a proof test interval of 12 months has been assumed (representing an annual SSIS function test). For topside components a proof test interval of 3 months was assumed (a typical PMR interval). Some operators may use 4 or 6 month intervals for topsides equipment, in line with current legislation for topsides valves. However, to allow comparison of the system configurations it is essential to use the same intervals for each system. Increasing the topsides test interval would slightly worsen the probability of failure on demand for most systems. Reducing the proof test interval for subsea components would reduce the probability of failure on demand for each configuration. A reduction to 6 months would provide a factor of 2 improvement for most configurations, except for Configurations C and F (factor 1.5) and Configuration I (factor 4).

Repair times for revealed failures are required for availability calculations. For subsea components an average repair time of 5 days has been assumed. For topside components a repair time of 24 hours has been assumed. Although change out of a topside item could be effected in 2 to 4 hours, the total outage time would be longer. It would depend on the time of day when the failure occurred and the time taken to reinstate other systems following the resulting platform trip. Availability calculations are dominated by sub-sea repairs and so the chosen topsides repair time does not significantly affect the final results.

4.4 RESULTS

The results for the chosen SSIS configurations are presented in Table 3. 4 parameters have been calculated for each configuration:

- failure to close on demand (probability)
- spurious closure frequency (failures/year)
- subsea intervention frequency (failures/year)
- availability to allow product flow (percentage and days lost per year)

It should be noted that there is only limited subsea experience with check valves (49 years) and that this data has been combined with data for a range of check valves from onshore sources. While it is possible that the onshore experience is not totally applicable to subsea installations, Table 1 shows that the calculated external leak frequencies for the two environments are very similar and so the calculations for intervention frequency and availability are of the right magnitude. By inference the failure to close frequency (and therefore probability) is also considered to be applicable, but this inference must be treated with caution.

Overall Result

Due to the small reduction in component failure rates (discussed in Section 3.4), the system probabilities and frequencies have nearly all reduced slightly. However, there has been no change in the relative order of the results. If a simple ranking of frequencies or probabilities is done for each column in Table 3 and the results aggregated, then Configuration B, (the single check valve) produces the best result. The check valve has no calculated spurious closure frequency, marginally the lowest intervention rate and a failure to close on demand probability which is lower than all but the combination of check valve and actuated ball valve (Configuration I). However, the use of check valves has been limited to export risers as it provides protection in only one direction ie against reverse flow. In addition, check valves have only been installed subsea on gas export lines. Concern has been expressed regarding their use on oil lines, due to potential damage from surge-slugging. This "liquid hammer" effect is known to be a problem with check valves used on liquid lines, although this has not prevented their use in liquid lines onshore. There could be other operability factors, such as pigging requirements, which would influence the selection of check valves for gas export lines, or would require detailed consideration by designers and operators.

Fail to Close Probability

The lowest failure to close on demand probability is provided by Configuration I (check valve plus actuated ball valve). This does, of course, suffer the same usage limitation as the single check valve.

In situations where check valves cannot or would not be used, the lowest failure to close on demand probability is achieved by Configuration E (two spring return, ball valves in series). The probability is a factor of two better than the comparable configuration using double acting actuators (Configuration G) and the intervention rate is a factor of two lower, once in 14 years instead of once in 5.6 years. The failure probability for Configuration E is approximately a factor of 5 lower than for the single valve equivalent (Configuration C), while spurious operation is a factor of 2 higher.

In general, SSIS with a spring return actuated ball valve is a factor of two lower in failure probability and intervention rate than SSIS with double acting actuators or gate valves. This is not due primarily to any differences in the main valve (or actuator) failure rates, but to the ancillary subsea equipment associated with the other systems.

Availability

In terms of availability, the Configurations F and H with suitably sized actuated bypass valves give the highest availability (or lowest days lost per year). Reduced size bypass valves can be used at the export end of gas pipelines, as the platform export pressure can (in some cases) be increased temporarily to maintain flow at the same rate through the smaller orifice. In other situations, the bypass valve would need to be of a similar size to the main valve.

Of the single valve systems, Configuration B (check valve) marginally gives the best availability, but is still nearly a factor of 10 worse than the bypass configurations (in terms of days lost per year). Given the likely accuracy of the calculations, there is no significant difference between Configuration B, C (spring return) and D (double acting).

Intervention Rate

For SSIS containing a single actuated valve the subsea intervention rate ranges from once in 24 years, for the spring return actuated valve (Configuration C), to once in 9 years for the gate valve (Configuration A). These can be compared with the intervention rate for a single check valve (Configuration B) which is once in 29 years. Intervention rates for more complicated systems are higher than for single valve systems, as would be expected.

Comparing Configurations C and F, provision of a (normally closed) bypass valve around the main actuated valve only introduces a small increase in intervention rate from once in 24 years to once in 21 years. Provision of a second actuated valve in series with the main valve (Configuration E) increases the intervention to once in 14 years. A normally closed, actuated bypass valve could suffer the same failure modes as the main actuated valve. The failure rates for modes resulting in failure to close on demand or spurious closure may be lower than for the main valve. Also they would not be apparent until the bypass valve was required, which would not be until the main valve has failed and an intervention already required. If the bypass valve is tested annually and is found to be failed, it is quite possible that the operator would decide not to carry out a repair until intervention was required for other failures. For these reasons the failure to close on demand and spurious closure failure rates used for the main valves are not included in the bypass valve failure rate, which explains why the bypass valve does not contribute significantly to the intervention rate.

The contribution of manual valves to the intervention rate is very small, once in 140 years, compared to other components giving a total rate of once in 24 to once in 9 years for the single actuated valve SSIS. In addition, the manual valve will not contribute to the failure to close or spurious closure cases.

5. DISCUSSION

5.1 DATA COLLECTION AND ANALYSIS

Only a few failures were identified as affecting the main subsea valves, none were critical in terms of the failure to close on demand or spurious closure effects. Also there were only a small number of critical failures of pilot and solenoid valves. The possibility that there would be very few critical failures identified for SSIS had been considered at the start of the study and was the reason for proposing to combine the collected data with existing generic data. The operating experience obtained is now considered sufficient to provide a robust estimate of the average failure rate of ball valves (excluding actuators) but is not sufficient to determine if failure rate varies with size of valve or with type of fluid (oil or gas). While the total collected data for actuators exceeds that provided by the prior data, if separate estimates of failure rates are required for spring return and double acting actuators, it is still advisable to combine the collected and prior data. In addition, operating experience for other types of valves and other SSIS components is not yet sufficient to provide robust estimates without use of prior data. Thus further data collection is necessary in order to distinguish between different types of actuator, different sizes of valves, and for other SSIS components.

The SSIS reliability database has been expanded to include new installations. It could be updated at regular intervals to monitor the continued performance of SSIS and so provide additional assurance concerning the safety of personnel and the installations in the event of a major incident. The offshore industry has the opportunity to continue pooling maintenance data on these important systems and to update safety assessments in the future with real data.

At the start of the study some operators already had good maintenance reporting schemes for topsides and subsea. As a result of the study, some have become aware of the deficiencies in their recording and retrieval of data, particularly for subsea. These companies are proposing to improve their systems and it is possible that the remaining operators may also decide on improvements. Such improvements, combined with collecting an agreed minimum of parameters in an agreed format, would reduce the cost of any subsequent collection exercise.

5.2 SSIS CONFIGURATIONS

The study has been concerned with estimating the reliability and availability of SSIS so that operators may compare options for installing SSIS. Any conclusions reached in this report are based solely on considerations of these aspects. Operators will need to consider the cost implications of SSIS configurations and also practical design and operational requirements, some of which will be specific to individual operating companies.

The reliability modelling has concentrated on 9 configurations of SSIS. The configurations represent the main installed systems plus the most practical options considered likely to provide improved reliability, in terms of the failure to close on demand probability.

The results suggest that, for gas export lines, the single check valve (Configuration B) provides the lowest frequency of spurious operation and subsea intervention, while having a failure to close on demand probability which is lower than all but the combination of check valve in series with an actuated ball valve. This probability, however, can only be achieved if the valve is tested annually, eg by partially depressurising the riser and monitoring for leakage, (by detecting any pressure increase on the platform side of the SSIS) or by diver visual observation. The check valve arrangements have not been used on import lines (they normally provide protection against the reverse flow direction). Even on export lines there may be some situations when operators would prefer a positive closure with initiation controlled from the platform. In addition, check valves may not have been considered for oil export lines due to the perceived potential problems with surge slugging (water hammer effect). In all these cases one of the actuated arrangements would be considered more suitable or even essential.

The results show that SSIS Configuration E, two spring return valves in series, gives the lowest failure to close probability out of the actuated systems. However, it is likely that the single actuated valve configurations would provide an acceptable failure to close probability. The required probability will be influenced by the requirements of the platform safety case.

The probabilities calculated in this study for the single valve actuated systems are all around 1 to 2×10^{-2} failures/demand, which is the same order as calculated theoretically in the studies reviewed in detail by RMC.

A configuration involving 2 gate valves in series has not been assessed in this study. However, based on the improvement factors calculated for actuated ball valves, it is likely that a similar improvement would be achieved for gate valves. Thus the failure to close probability for an SSIS using two gate valves in series should be a factor of 4 or 5 lower than for the single gate valve. The spurious closure and subsea intervention frequencies would increase by similar factors.

For all configurations, reducing the interval between (subsea equipment) tests, from the nominal 12 month period, would improve the probability of failure on demand. However, many operators may not consider this to be a practical option due to the increased outage time and maintenance effort.

It should be noted that the provision of a manual isolation valve in series with the SSIS does not have any effect on the failure to close probability (or spurious closure rate). It will affect the subsea intervention rate, the inclusion of a manual valve increasing the intervention rate by a small amount. However, the manual valve would reduce the downtime of the pipeline during repair of the subsea parts of the SSIS, as it allows repair without flooding (and subsequent de-watering) of the pipeline. Thus provision of a manual valve may have a beneficial effect on the pipeline availability. The bypass valves included with some SSIS in this study are normally closed and so will not have any effect on failure to close probability or spurious closure rate. Bypass valves can have a significant effect on availability (to allow product flow) provided the bypass valve is sized to handle full flow capacity. For the gas import end of pipelines and for oil pipelines the bypass would need to be of the same size as the main valve, but for the gas export end it is possible to have a reduced size bypass and increase export pressure to maintain the line flow, during the time awaiting repair of the main valve.

Configurations F and H use a bypass valve and can achieve an availability figure (in terms of days lost per year) which is nearly an order of magnitude lower than for the single valve configuration. Configuration H (2 valves in series plus single bypass) combines a failure on demand probability, which is lower than for the single (actuated) valve configurations, with the highest availability. However, it also has the worst intervention rate and possibly higher capital cost, due to the increased complexity.

5.3 MAIN ACHIEVEMENTS

The main achievements of the reliability study can be summarised as follows:

i) Maintenance records have been obtained and analysed for 59 SSIS during this study and 50 in the earlier study. A total of 379 years operating experience (49 years for check valves, 330 years for actuated valves).

ii) The failure data has been coded and recorded in a database which is compatible with the OREDA software and is available to UKOOA members and HSE.

iii) The practical experience obtained for subsea equipment has been combined with wider (generic) experience to obtain subsystem failure rates which are more directly applicable to subsea installations than was previously possible.

iv) The reliability of SSIS has been quantified to allow comparison of various configurations and provide assistance to operators in selecting appropriate SSIS for future installations.

v) Availability (to allow product flow) has been calculated in terms of percentage and days lost per year. The availability calculations and details of the subsea interventions was supplied to the SSIS cost study consultants to be used in calculating whole life costs.

6. CONCLUSIONS

A number of conclusions can be drawn from the work carried out during the study.

i) While there have been some critical failures of SSIS control systems (solenoid and pilot valves etc), no critical failures of the subsea valves were identified in either of the data collection exercises.

ii) Reliability studies of SSIS have generally used generic failure data due to the absence of relevant subsea experience. This study combines generic experience with subsea experience collected during the study to provide failure rates which are more directly applicable to the offshore (subsea) environment and operation.

iii) Collected experience is now sufficient to provide robust average failure rate estimates for ball valves (excluding actuators) but not for specific valve sizes nor for other valve types or SSIS components.

iv) For SSIS containing single actuated valves, the system using a spring return ball valve provides the best results in terms of "failure to close" probability and subsea intervention rate. This is not due to any differences in the main valve (or actuator) failure rates, but to the ancillary subsea equipment associated with the other systems.

v) In cases where a check valve can be used, the SSIS containing single check valves have lower calculated values (for failure on demand, spurious trips and subsea interventions) than SSIS containing actuated valves, whether single or 2 in series. However, there are situations in which check valves would not be used.

vi) Putting two actuated isolation valves in series will improve the failure to close on demand probability, but will also increase the frequency of spurious closure and subsea intervention, subsequently reducing availability.

vii) SSIS incorporating suitably sized bypass valves can improve availability (of product flow) but this would involve higher capital cost and a higher frequency of subsea interventions.

viii) The data collected during the studies has been entered into a database in an anonymised form which is available to the members of UKOOA and HSE. The average operating experience is 3.3 years per SSIS and the original 50 SSIS now have a further 2 years experience which has not yet been collected. Thus the available experience will double in 2 years. The database has been extended to cover all other SSIS installed in the UKCS. Improving the database by collecting the additional experience from the original 50 SSIS would provide operators with the opportunity to review the longer term experience and would be useful in updating platform safety cases.

ix) For future data collection exercises, operators should agree on a minimum of key information to be recorded. This should ensure consistency in interpretation and help to reduce costs.

7. ACKNOWLEDGEMENTS

The SSIS information was collated through members of the UKOOA Pipeline subcommittee. The co-ordinator for HSE on the study was Dr T Al Hassan.

8. REFERENCES

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TABLE 1
Summary of Failure Data

(Only data under heading "Collected Data" is from installed SSIS and obtained during this study)
* indicates a subsea component

	Component	Failure Mode	Prior Data			Collected Data			Combined Failure rate (f/yr)	Data Comb Method
			No of failures	Experience (years)	Failure Rate (f/yr)	No of failures	Experience (years)	Failure Rate (f/yr)		
*	Check valve	Fail to Close	4	3272	1.2e-3	0	49.0	-	1.2e-3	A
		External Leak	95	3272	2.9e-2	1	49.0	2.04e-2	2.9e-2	A
*	Manual Gate Valve	External Leak	11	1448.4	7.6e-3	-	24.9	-	7.5e-3	-
*	Gate Valve	Fail to Close	N/A	N/A	1.3e-2	-	51.1	-	1.3e-2	-
		External Leak	N/A	N/A	2e-2	-	51.1	-	2e-2	-
*	Manual Ball Valve	External Leak	N/A	N/A	3.9e-3	2	288.4	6.93e-3	5.2e-3	C
*	Ball Valve	Fail to Close	1	58.4	2.1e-2	0	288.4	-	2.88e-3	A
		External Leak	N/A	N/A	3.9e-3	2	288.4	6.93e-3	5.3e-3	C
*	Actuator	Fail to Close	1	58.4	2.1e-2	0	348.3	-	2.46e-3	A
		External Leak	N/A	N/A	2.8e-2	1	348.3	2.87e-3	8.96e-3	C
*	Umbilical	Ruptured	N/A	N/A	5.9e-3	0	165.2	-	4.19e-3	B
		Blocked	N/A	N/A	4.5e-3	0	165.2	-	3.07e-3	B
	Accumulator Bank	No output	N/A	N/A	1.4e-2	0	94.6	-	9.7e-3	B
	Pilot Valve	Fail to Close	3	147.1	2e-2	1	170.8	5.85e-3	1.26e-2	A
		Spurious Operation	5	147.1	3.3e-2	1	170.8	5.85e-3	1.89e-2	A
		External Leak	7	147.1	4.6e-2	0	170.8	-	2.2e-2	A
		Internal Leak	1	147.1	6.7e-3	1	170.8	5.85e-3	6.3e-3	A
	Solenoid Valve	Fail to Close	N/A	N/A	6.7e-3	4	170.8	2.3e-2	1.27e-2	C
		Spurious Operation	N/A	N/A	4.7e-3	0	170.8	-	3.75e-3	B
		External Leak	N/A	N/A	1.3e-2	2	170.8	1.2e-2	1.25e-2	C
	Multiplexed Control System	Fail to close	N/A	N/A	9.3e-3	0	11.2	-	9.2e-3	-
		Spurious Operation	N/A	N/A	4.7e-2	0	11.2	-	4.6e-2	-
	HPU	No Output	2	73	2.8e-2	1	119.1	8.4e-3	1.56e-2	A

N/A - Base information on numbers of failures and operating experience was not provided by the data source. Only a mean failure rate was provided.

Failure Data Combination methods:

A - Aggregation
B - Bayesian
C - Geometric mean

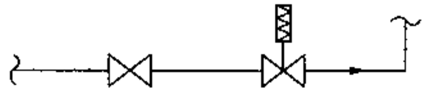
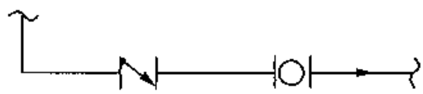
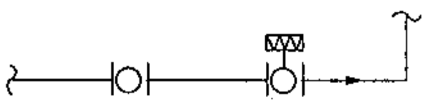
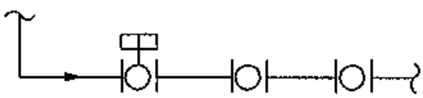
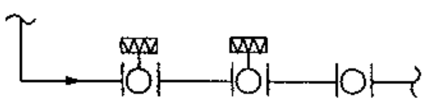
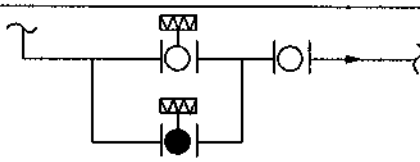
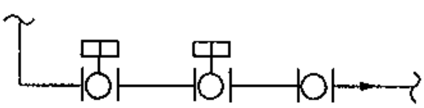
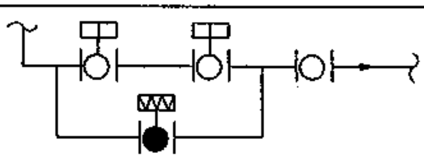
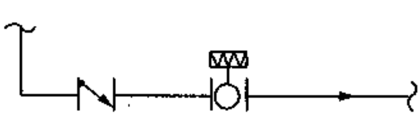
TABLE 2
Comparison of Previous Collected Failure Data with the Updated Collected Data

Component	Failure Mode	Previous Experience (years)	Updated Experience (years)	Previous Combined Failure Rate (f/year)	Updated Combined Failure Rate (f/year)
Check Valve	Fail to Close External Leak	36.7 36.7	49 49	1.20E-03 2.90E-02	1.20E-03 2.90E-02
Manual Gate Valve	External Leak	0	24.9	7.60E-03	7.50E-03
Gate Valve	Fail to Close External Leak	0 0	51.1 51.1	1.30E-02 2.00E-02	1.30E-02 2.00E-02
Manual Ball Valve	External Leak	144.4	288.4	7.40E-03	5.2E-03
Ball Valve	Fail to Close External Leak	144.4 144.4	288.4 288.4	4.90E-03 7.40E-03	2.88E-03 5.26E-03
Actuator	Fail to Close External Leak	153.2 153.2	348.3 348.3	4.70E-03 1.30E-02	2.46E-03 8.96E-03
Umbilical	Ruptured Blocked	115 115	165.2 165.2	4.40E-03 3.30E-03	4.19E-03 3.07E-03
Accumulator Bank	No Output	63.4	94.6	9.70E-03	9.70E-03
Pilot Valve	Fail to Close Spurious Operation External Leak Internal Leak	115 115 115 115	170.8 170.8 170.8 170.8	1.50E-02 2.30E-02 2.60E-02 7.60E-03	1.26E-02 1.89E-02 2.2E-02 6.3E-03
Solenoid	Fail to Close Spurious Operation External Leak	115 115 115	170.8 170.8 170.8	1.40E-02 3.40E-03 1.50E-02	1.27E-02 3.07E-03 1.25E-02
Multiplex Control System	Fail to Close Spurious Operation	1.6 1.6	11.2 11.2	9.30E-03 4.70E-02	9.20E-03 4.60E-02
HPU	No Output	65.5	119.1	2.20E-02	1.56E-02

Table 3
Summary of Fault Tree Analysis

Configuration	Failure Parameter			Production Availability	
	Fail on Demand Probability	Spurious Operation Frequency f/yr	Total Subsea Intervention Frequency f/yr	%	(days lost per year)
A	2.16 E-2	8.25 E-2	1.1 E-1	99.87	(0.5)
B	6.0 E-4	-	3.4 E-2	99.977	(0.08)
C	9.0 E-3	5.55 E-2	4.2 E-2	99.957	(0.16)
D	1.9 E-2	5.35 E-2	8.1 E-2	99.94	(0.22)
E	1.76 E-3	9.5 E-2	7.0 E-2	99.92	(0.3)
F	9.0 E-3	5.55 E-2	4.7 E-2	99.996	(0.013)
G	4.9 E-3	8.68 E-2	1.77 E-1	99.89	(0.39)
H	4.9 E-3	8.68 E-2	1.8 E-1	99.997	(0.009)
I	5.4 E-6	5.55 E-2	6.5 E-2	99.957	(0.16)

Table 4
Probability of Failure on Demand

A		2.16×10^{-2}
B		6.0×10^{-4}
C		9.0×10^{-3}
D		1.9×10^{-2}
E		1.76×10^{-3}
F		9.0×10^{-3}
G		4.9×10^{-3}
H		4.9×10^{-3}
I		5.4×10^{-6}

FL8/TBL003/J1757

Table 5
Frequency of Spurious Closure (f/yr)

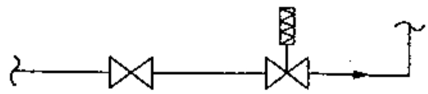
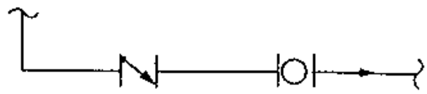
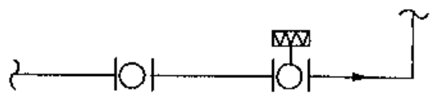
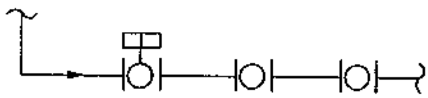
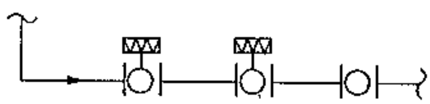
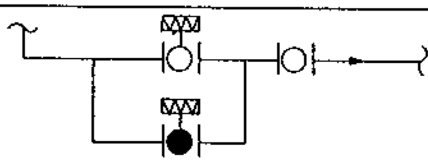
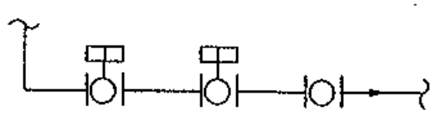
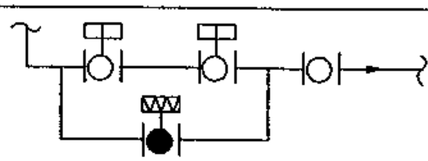
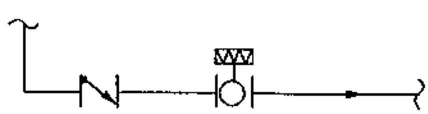
A		$8.25x10^{-2}$
B		-
C		$5.55x10^{-2}$
D		$5.35x10^{-2}$
E		$9.50x10^{-2}$
F		$5.55x10^{-2}$
G		$8.68x10^{-2}$
H		$8.68x10^{-2}$
I		$5.55x10^{-2}$

Table 6
Frequency of Subsea Intervention (f/yr)

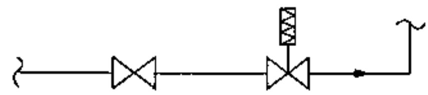
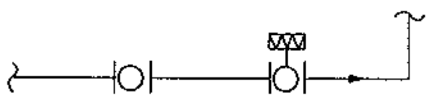
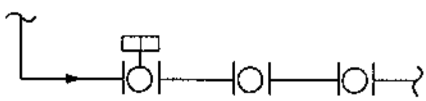
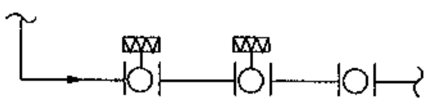
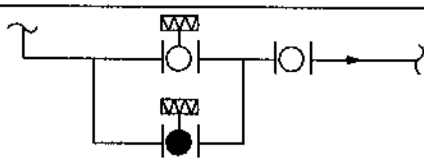
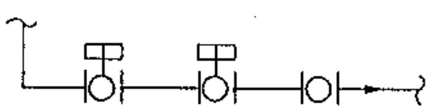
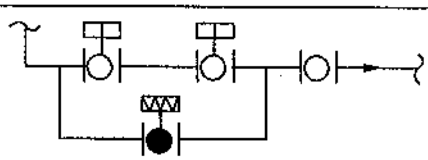
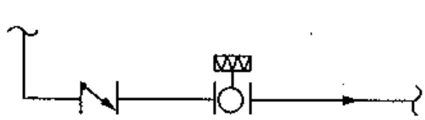
A		1.1×10^{-1}
B		3.4×10^{-2}
C		4.2×10^{-2}
D		8.1×10^{-2}
E		7.0×10^{-2}
F		4.7×10^{-2}
G		1.77×10^{-1}
H		1.8×10^{-1}
I		6.5×10^{-2}

Table 7
Meantime Between Subsea Interventions

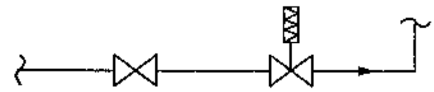
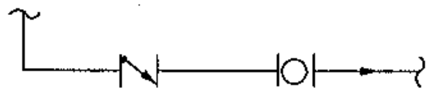
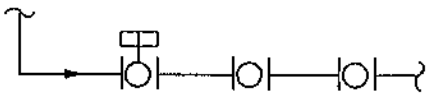
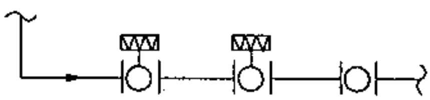
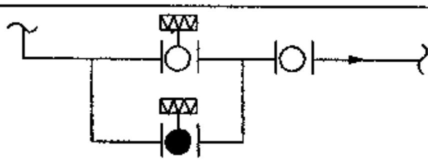
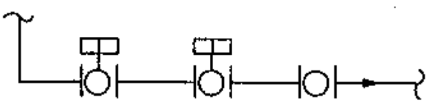
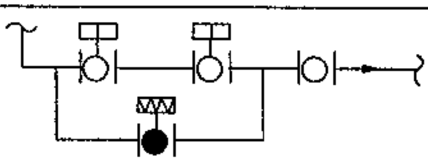
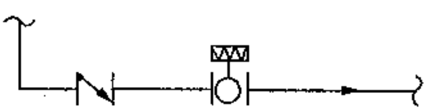
	YEARS
A 	9
B 	29
C 	24
D 	12
E 	14
F 	21
G 	5.6
H 	5.6
I 	15

Table 8
Production Availability %

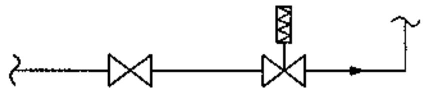
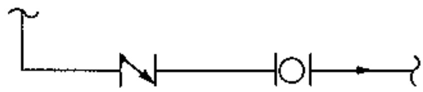
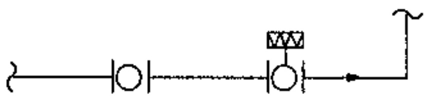
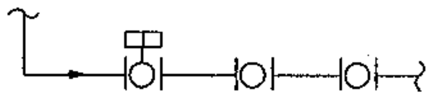
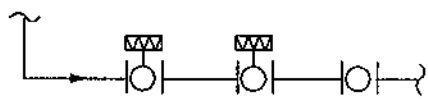
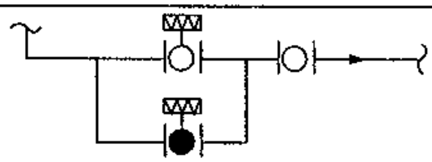
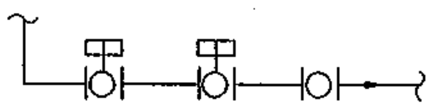
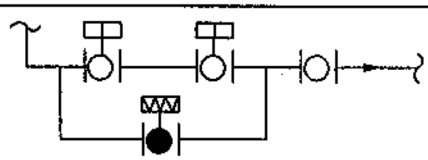
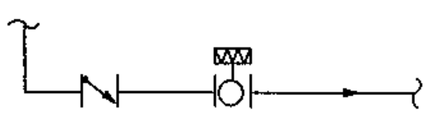
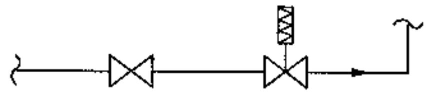
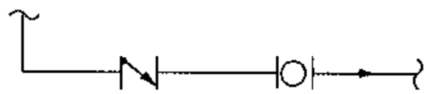
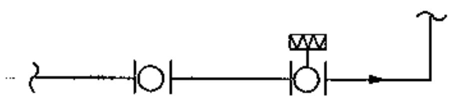
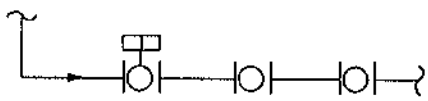
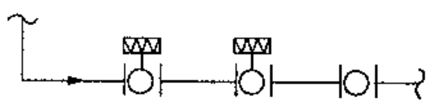
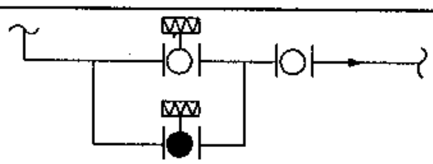
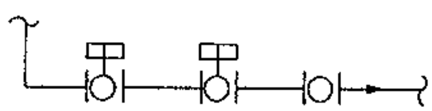
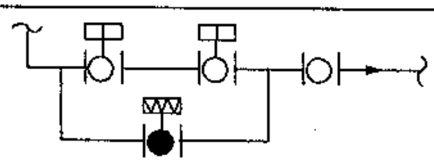
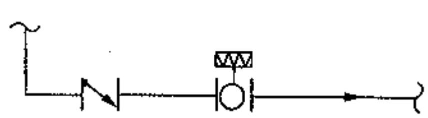
A 	99.87
B 	99.977
C 	99.957
D 	99.94
E 	99.92
F 	99.996
G 	99.89
H 	99.997
I 	99.957

Table 9
Production Unavailability - Days Lost

		PER YEAR	IN 20 YEARS
A		0.5	10
B		0.08	1.6
C		0.16	3.2
D		0.22	4.4
E		0.3	6
F		0.013	0.26
G		0.39	7.8
H		0.009	0.18
I		0.16	3.2

VALVES		
Valve	Actuator	Pipeline
- Valve body w/internals - Valve seat - Seals	- Actuator - Position indicator	- Pipe spool - End connection

Valves, Sub-division in maintainable items

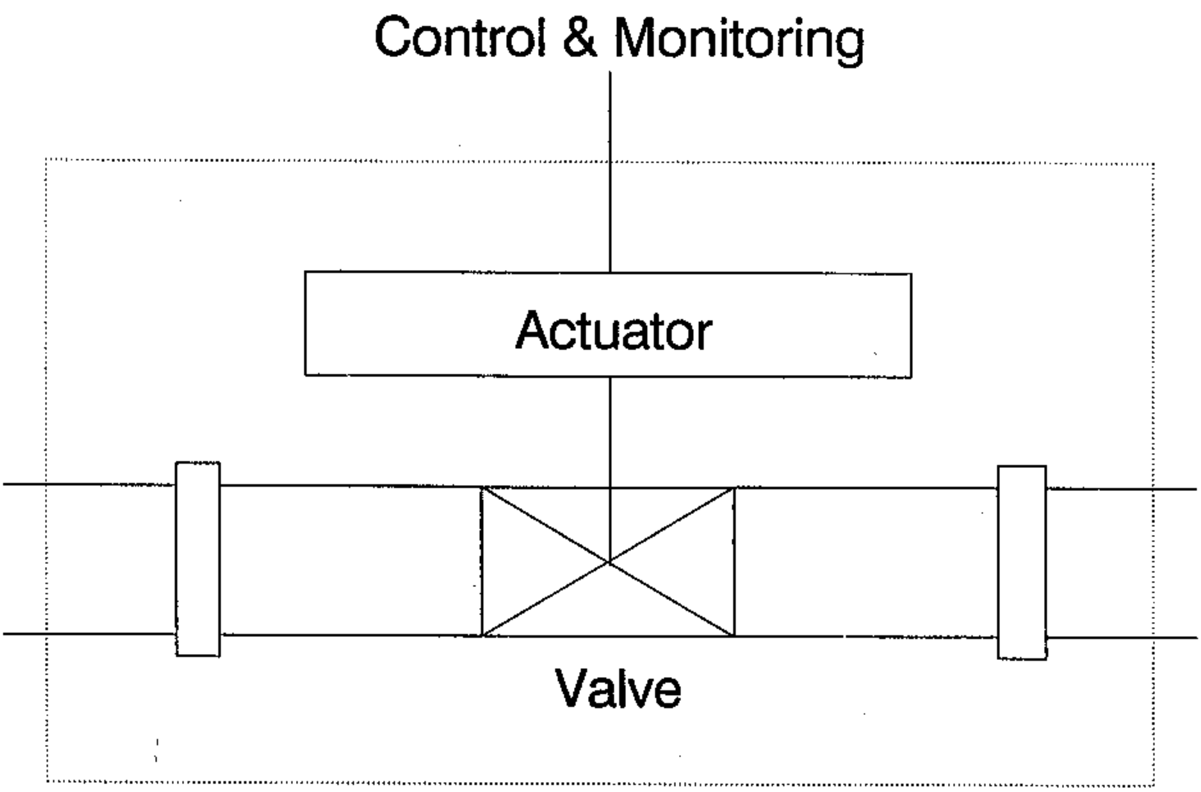


FIGURE 1
Boundary Definition for Valves

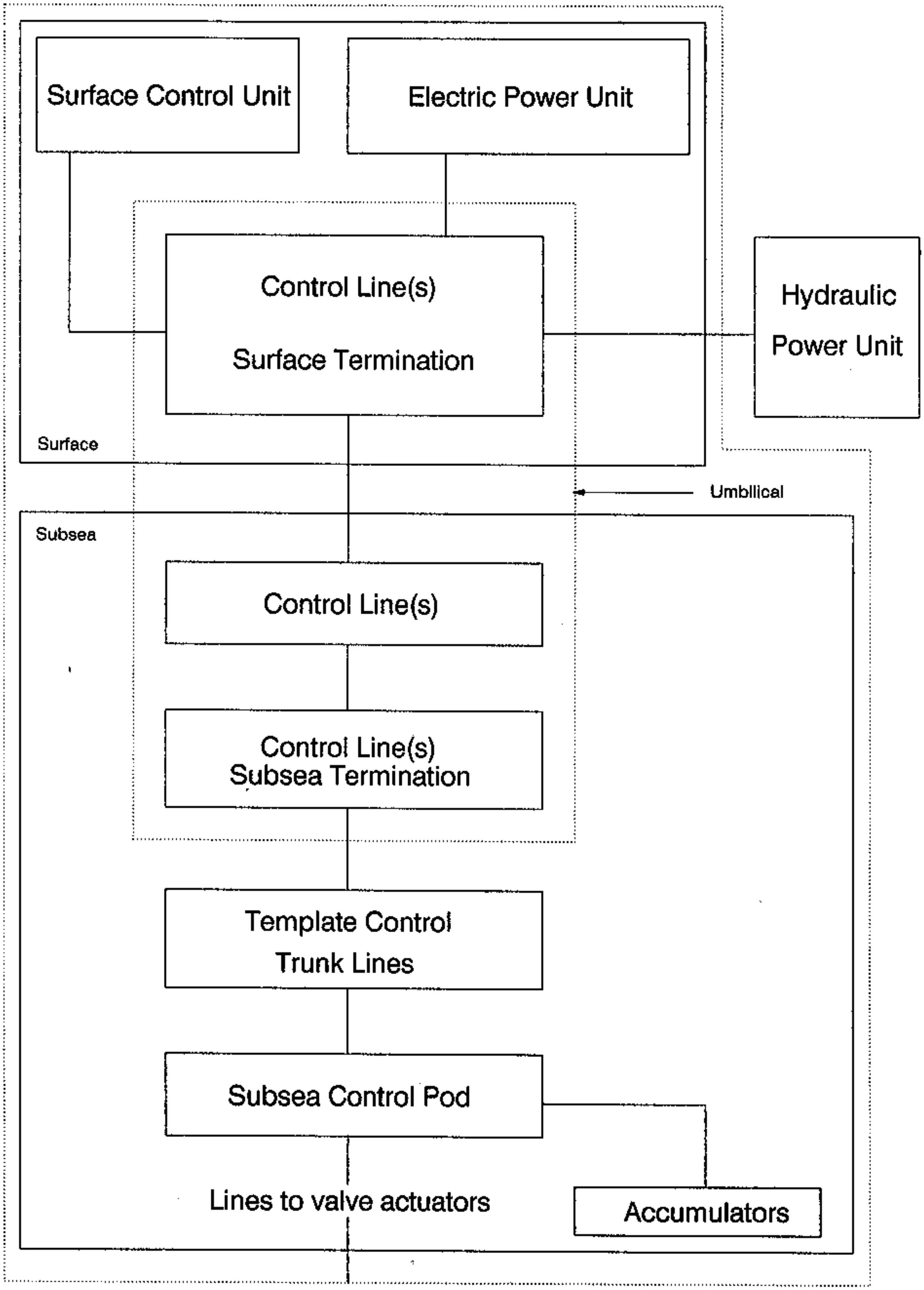


FIGURE 2
Boundary Definition for Control Systems

Main Items

Motors/Pumps
Accumulator Bank
Supply Reservoir
Local Control Panel
Pressure Sensors
Others (e.g. control valves, level switches)

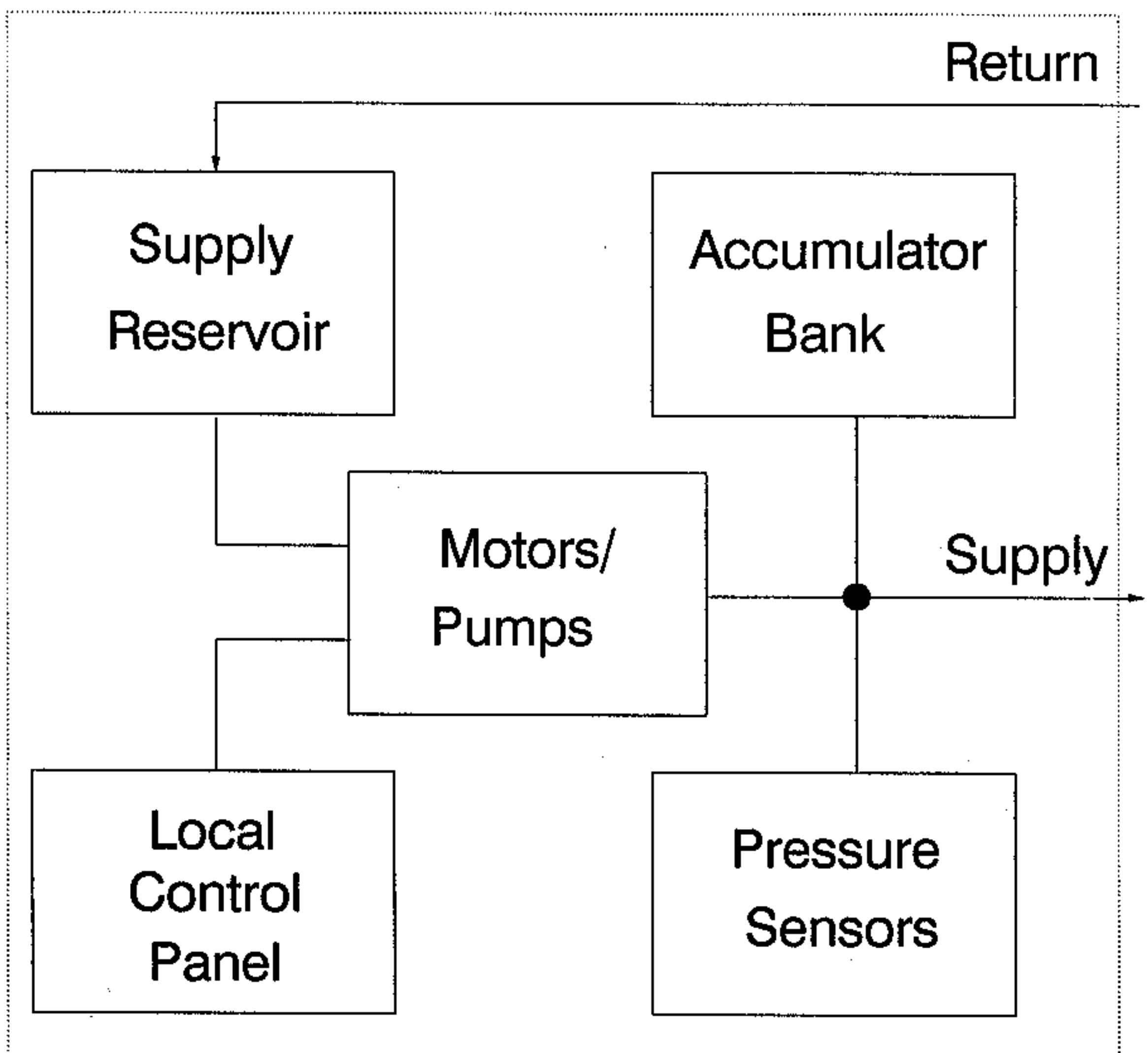


FIGURE 3
Boundary Definition for Hydraulic Power Units

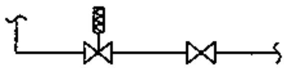
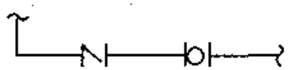
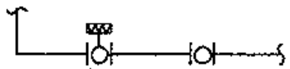
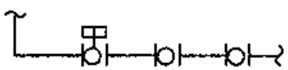
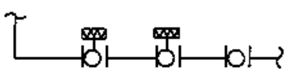
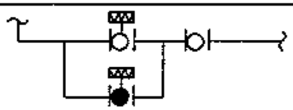
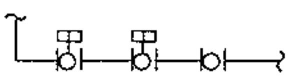
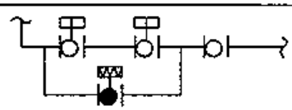
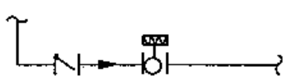
Configuration		SSIV type	Manual isolation	Bypass valve	Actuator type	Number known to be installed at time of study (1995)			Notes
						Oil	Gas	Condensate	
A		Gate	✓	-	Spring Return	6	5	1	
B		Check	✓	-	-	-	9	2	
C		Ball	✓	-	Spring Return	20	21	6	Also 18 with no MVs
D		Ball	✓	-	Double Acting	-	15	-	Also 9 with no MVs
E		Ball (2)	✓	-	Spring Return	1	-	-	
F		Ball	✓	✓	Spring Return	4	2	-	
G		Ball (2)	✓		Double Acting	-	2	-	
H		Ball (2)	✓	✓	Double Acting	-	-	-	
I		Check & Ball	-	-	Spring Return	-	-	-	

FIGURE 4
SSIS Configurations Proposed for Detailed Evaluation

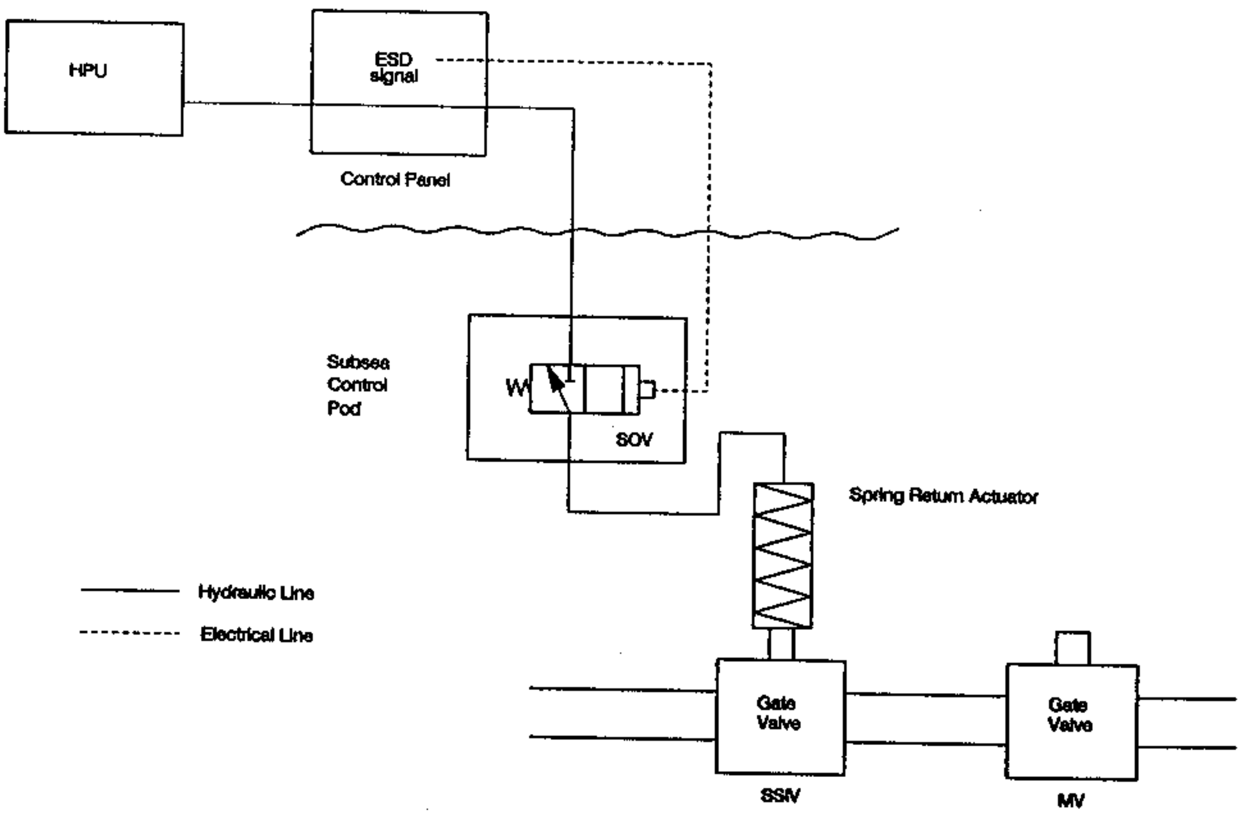
APPENDIX A

SSIS CONFIGURATIONS

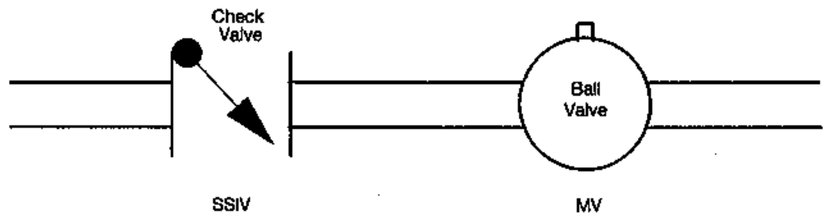
FOR DETAILED EVALUATION

A1. SSIS CONFIGURATIONS FOR DETAILED EVALUATION

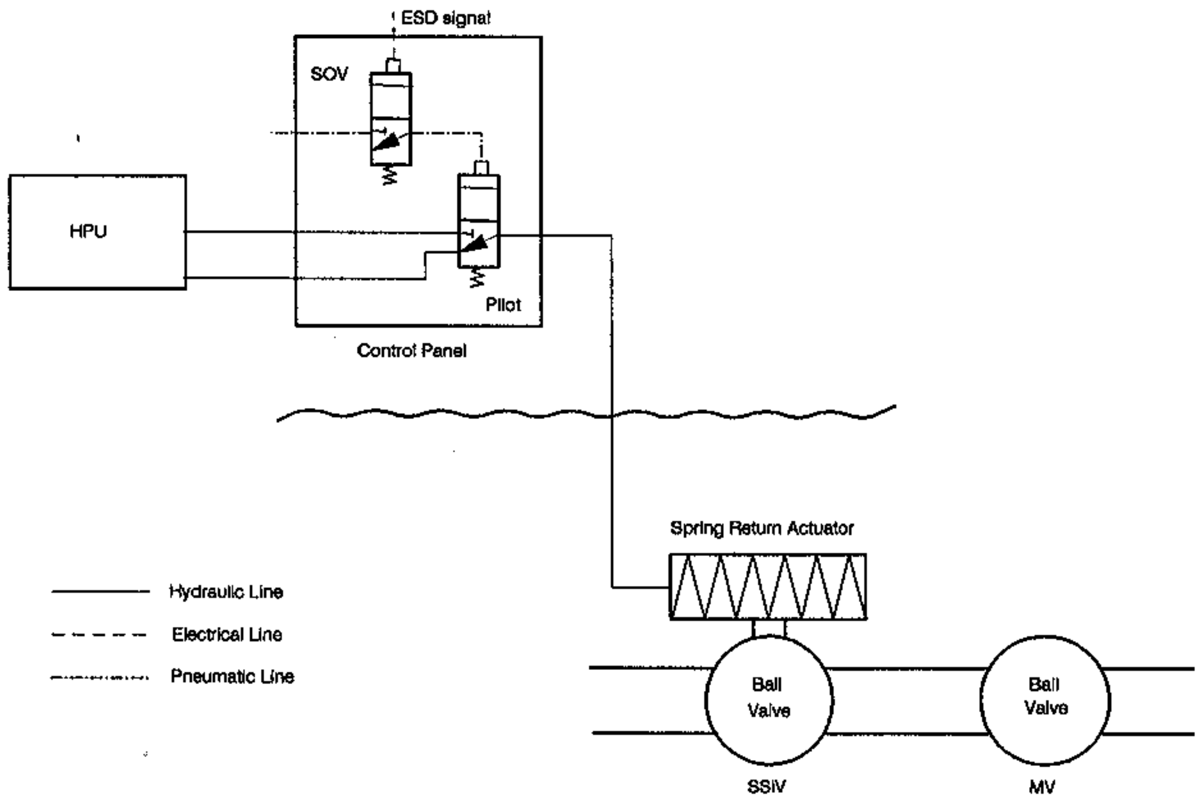
Contained in this Appendix are schematic drawings of the 9 configurations identified for detailed evaluation. They show the components that have been included in each model for which a fault tree has been constructed to determine overall reliability. The models are simplified using only the important and common elements of SSIS. This then enables a comparison to be made based on similar failure data for each configuration.



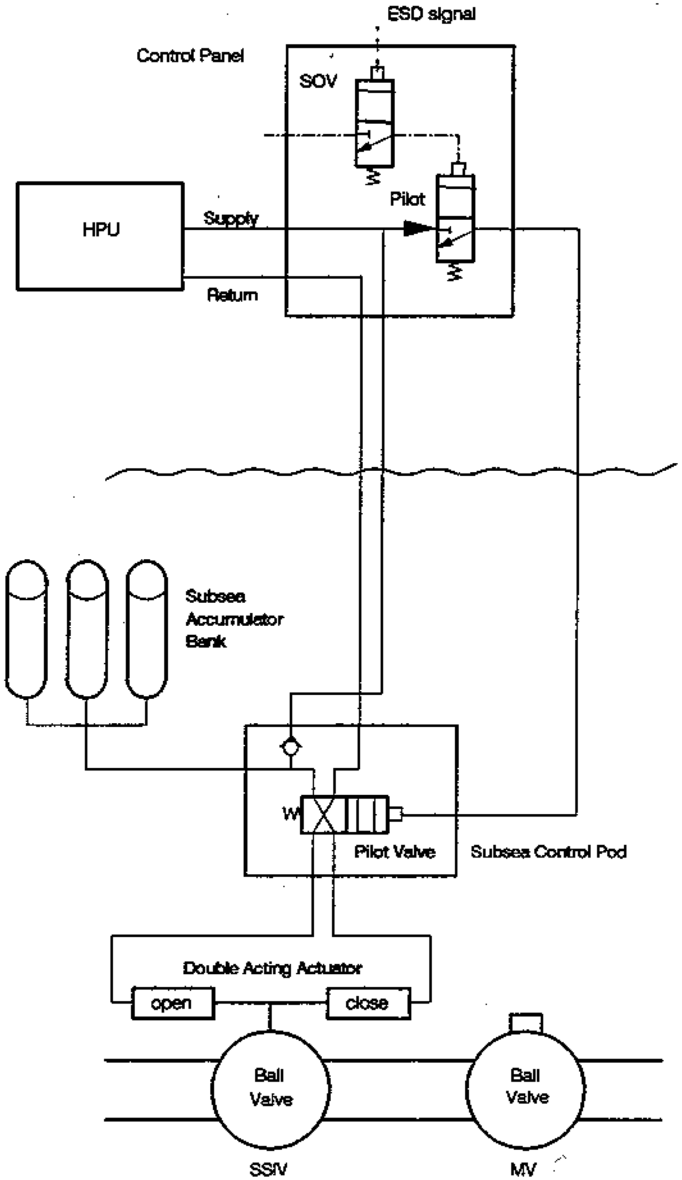
SSIS Configuration A



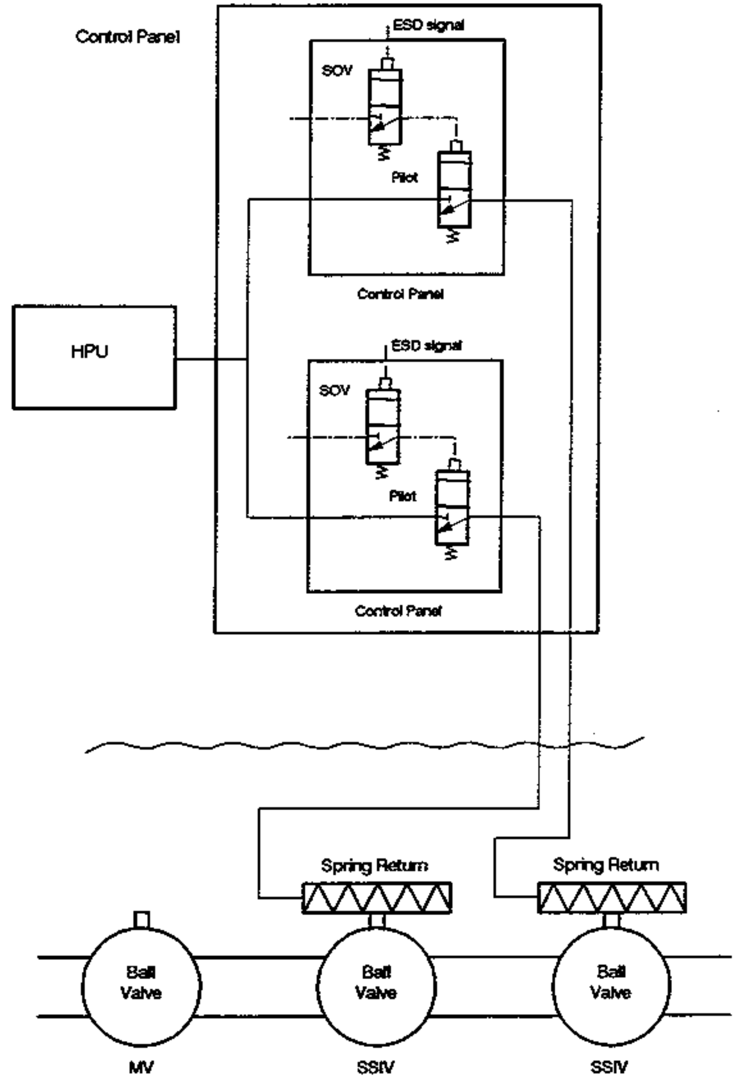
SSIS Configuration B



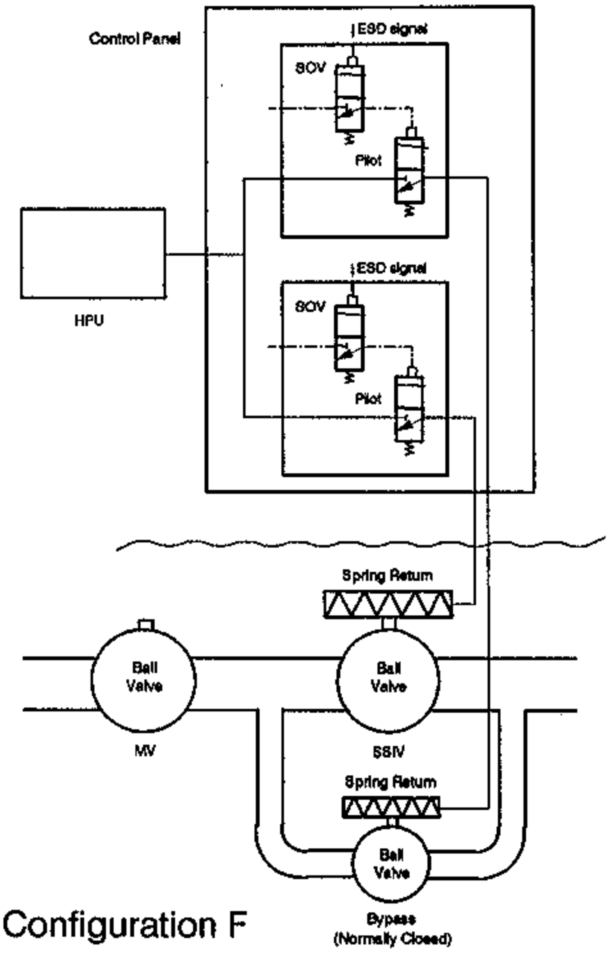
SSIS Configuration C



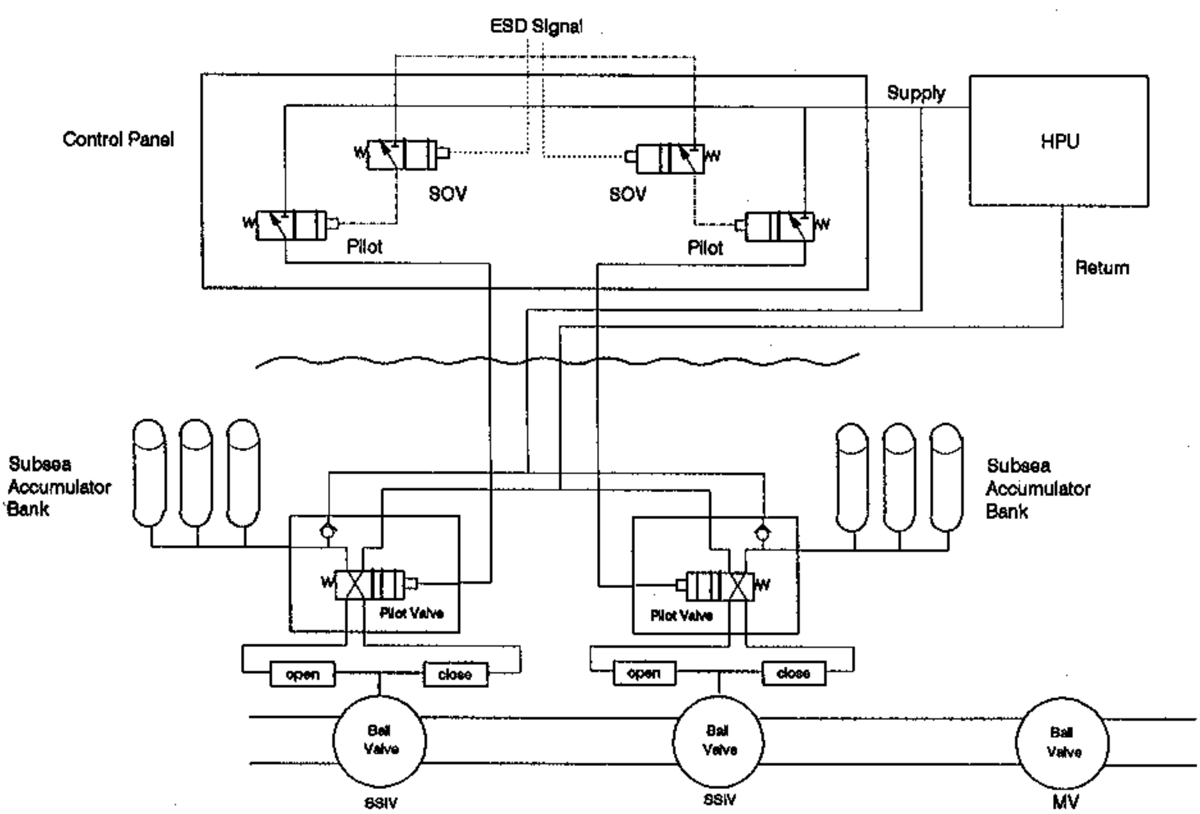
SSIS Configuration D



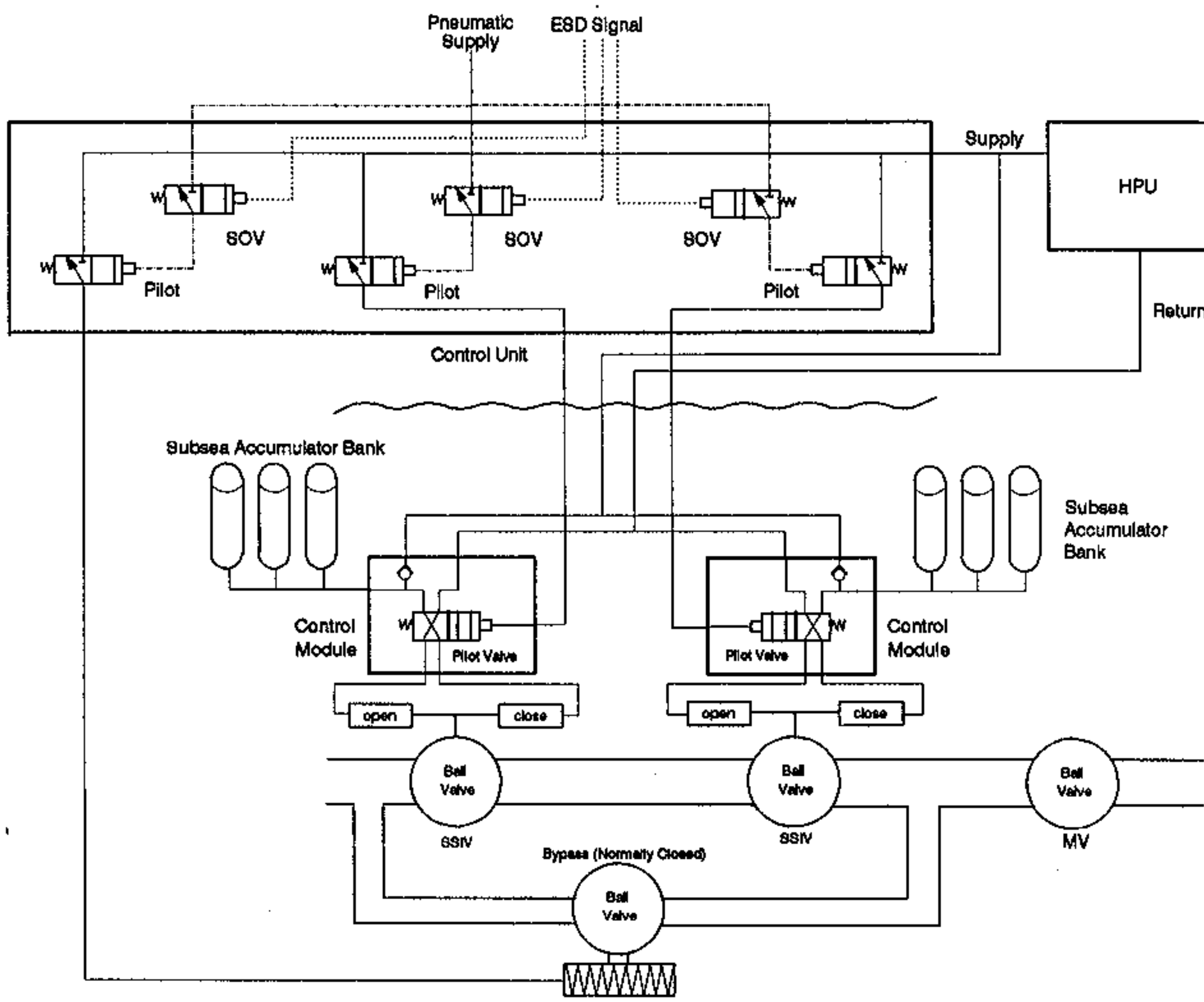
SSIS Configuration E



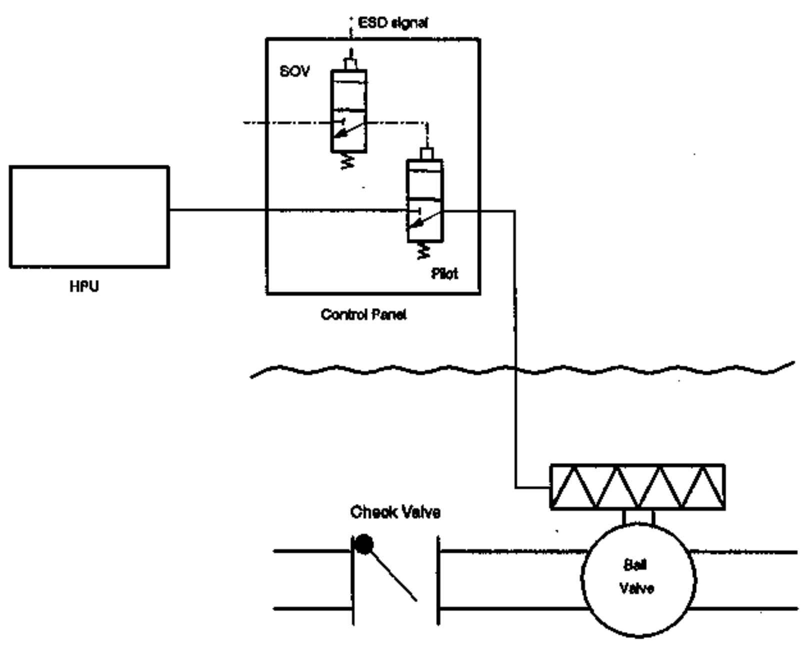
SSIS Configuration F



SSIS Configuration G



SSIS Configuration H



SSIS Configuration I

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