RELIABILITY STUDY INTO SUBSEA ISOLATION SYSTEMS

Prepared by RM Consultants Ltd for the Health and Safety Executive
RELIABILITY STUDY INTO SUBSEA ISOLATION SYSTEMS

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HSE BOOKS

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SUMMARY

This reliability study and the associated cost reduction study have been jointly funded (50%/50%) by UKOOA and the Offshore Safety Division of the Health and Safety Executive. The main objective of the study was to provide new reliability data and analyse Subsea Isolation System (SSIS) configurations so that operators and HSE can 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).

Prior to this study no failure data had been collected and analysed from installed SSIS. Reliability studies of SSIS have previously used theoretical synthesis, building system reliability from individual components and using generic data.

Participating operators (7 companies) were all members of the UKOOA Subsea Valve Working Group. They provided details of operating experience and maintenance activities, first by completing questionnaires developed by RMC and subsequently during visits to their offices or in response to further questions.

Maintenance records from 50 SSIS (out of 83 installed at the time of the study) have been analysed during the study and the resulting failure data placed in a database which was specifically developed for the study by RM Consultants. The database files were designed to be compatible with the OREDA software. The database can be readily extended to include all SSIS installed in pipelines on the UKCS and could be updated in future as additional operating experience is obtained.

The information in the database was analysed and combined with generic data to provide component failure rates which more accurately reflect the subsea environment than was previously possible.

The resulting failure data has been used to assess nine SSIS configurations, which represent the main installed systems plus two potential configurations which could result in improved reliability and/or availability.
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1. INTRODUCTION

This report describes the results of the reliability study of Subsea Isolation Systems (SSIS). The main study activities are presented, followed by a discussion of the achievements of the study and the results of the data analysis and systems evaluation.

1.1 BACKGROUND

RM Consultants Ltd (RMC) was awarded a contract by the UK Offshore Operators Association (UKOOA) to carry out a reliability study of SSIS. The study was jointly funded by UKOOA and the Offshore Safety Division (OSD) of the Health and Safety Executive (HSE). The study was carried out during 1993.

The study was part of the joint response by UKOOA and HSE to Lord Cullen's recommendation number 46 [Ref 1], with respect to improving reliability and reducing costs of SSIS, so that it is more often reasonably practicable to install them. In parallel with the reliability study undertaken by RMC, a cost reduction study has been carried out by Andrew Palmer & Associates Ltd (APAL) [Ref 2]. It is expected that the two studies will provide a basis for operators to make decisions regarding future installations and regarding operation and maintenance of existing installations.

The study was concerned with the reliability of subsea pipeline emergency isolation valves, their actuators and associated control systems (both subsea and topsides equipment).

A configuration survey was carried out in conjunction with the member companies of the UKOOA Subsea Valve Working Group (12 companies). Not all the companies had SSIS installed. Subsequently operating experience was collected for 50 SSIS.

The survey and collection of operating experience were carried out during 1993. It should be recognised that other SSIS had been installed at that time by companies not involved in the Subsea Valve Working Group and that a significant number of SSIS have been installed since the survey.

The study was divided into two phases. Phase 1 was effectively a pilot study, examining design and installation specific information on SSIS configurations from the 7 participating operators, with the intention of collecting reliability data from 3 operators. In Phase 2 maintenance records from participating operators were analysed, component failure rates were estimated and reliability characteristics of several SSIS configurations were calculated.

1.2 OBJECTIVES

The main objective of the study was to provide new reliability data and to analyse SSIS configurations in order that operators and HSE could address Lord Cullen's recommendation number 46 (para-phrased in Section 1.1). To achieve this, several main tasks were identified as follows:

- obtain failure data on existing SSIS,
- provide a database for the reliability data collected,
- analyse the reliability data and combine with existing data,
- use the resulting reliability data to analyse SSIS configurations,
- attempt to establish the most reliable SSIS designs.
2. SUMMARY OF STUDY ACTIVITIES

Reliability Studies

Several operators provided access to reliability studies of proposed SSIS. This provided a review of the generic failure data sources currently used in modelling the reliability of SSIS. Apart from data for control umbilicals, all other data sources were either for topside equipment or for onshore equipment.

Questionnaires

RMC developed questionnaires to obtain detailed information regarding the installed SSIS and so identify the main parameters associated with each installation; specific areas covered were:

- design data (eg type, size, pressures)
- location specific data (eg pipeline, flow rate)
- configuration data (eg single valve, bypass)
- maintenance and test data (eg testing schedule for topside equipment, subsca inspection)
- failure data (eg component failed, repair activities/times)

System Boundaries and Classification (Taxonomy)

Before any detailed analysis of maintenance records could be undertaken it was necessary to develop a definition of the system boundary and categorise the main types of system. In addition to including all subsea components, the SSIS boundary was defined to encompass topsides equipment which was specific to the control of the subsea equipment. The development of the system boundaries and taxonomy followed the approach proposed by OREDA [Ref 3]. The taxonomy is basically the breakdown of a particular "system" (or equipment categories) into identifiable types and taking account of function or type of service/usage of the equipment. For instance there are several types of valve (eg ball, gate, flapper) and function sub-divisions (eg oil export, gas wellhead). To allow detailed analysis of the collected data and ensure consistent results when looking at different levels in the system hierarchy, Subsea Isolation Systems were split into three equipment categories (or "systems"), namely:

- Valves
- Control Systems
- Hydraulic Power Units (HPU)

The boundaries of the "systems" are outlined in Figures 2, 3 and 4.

Database Development

A specification for a database, to store the collected operating and maintenance data, was prepared and subsequently a database was developed. The software allows users to calculate failure rates for components under a range of failure modes and to examine details of individual failure records. The file structure is compatible with the OREDA software and so companies which have access to that software can use it instead. The
SSIS database contains three separate "system" databases containing the data on each of the three major equipment categories identified above. The initial data collected included references to operators and manufacturers of the equipment. In order to make the database "non-attributable" these references have not been included in the database files distributed to the participating organisations.

Data Collection and Analysis

Operating experience and failure records were collected for 50 SSIS (48 on UKCS, 2 non-UKCS). The failures were categorised in accordance with OREDA Guidelines for Data Collection [Ref. 3] and entered into the appropriate "system" database along with the inventory information (equipment details). The data analysis confirmed the assumption made at the start of the project, that only a small number of critical failures would be identifiable for the valves and control systems. For this reason existing sources of failure data were examined [Refs 4 to 10 inclusive] to extract failure rates for components which exhibited similarities as close as possible to SSIS components. Data sources were justified by taking into account the following characteristics:

- similarity of design (e.g. size, type)
- operating environment (e.g. offshore, onshore)
- duty cycle (e.g. emergency shutdown, frequent use, infrequent use)

Examples of the existing data sources used are British Gas report on Failure Rate Analysis For Line Valves [Ref 4] and OREDA 92 [Ref 5].

The existing data formed the "Prior" data, a statistical term to indicate failure data from previous experience. This could then be compared to collected data to assess whether a Bayesian technique or other classical statistical methods should be used to combine the data. The intention was to add the data of the new experience obtained to existing data, thereby attempting to improve the quality, accuracy and relevance of the failure data for use in this study.

Reliability Analysis of Configurations

A set of SSIS configurations was proposed for detailed evaluation and is summarised in Figure 5. Most of the installed SSIS are covered in this set along with practical alternative configurations which could potentially provide improved reliability.

Fault Tree Analysis (FTA) was carried out on the proposed configurations. FTA is a standard reliability technique for determining the logical combination of component failure events which would lead to a specific system failure or Top Event. Fault trees were generated for three undesired events:

- failure to close on demand
- spurious isolation of pipeline
- subsea intervention required

The combined failure rate data was incorporated into the fault trees and used in the calculation of production availability (or conversely days lost per year). The results were used to compare the various SSIS configurations.
3. SSIS CATEGORISATION

9 configuration options were proposed for detailed evaluation (Figure 2). Contained within these 9 options are the majority of installed SSIS and some realistic alternatives for improving reliability. They are considered to cover the practical range of SSIS configurations (for reliability assessment purposes) that operators will actually select, to achieve their safety and availability targets and cost limitations.

3.1 EXISTING (INSTALLED) CONFIGURATIONS

Pre-Piper Alpha

Historically 8 of the UKCS and 5 of the non-UKCS systems were installed (all in gas export lines) before the Piper Alpha disaster of July 1988. Most, if not all, of these systems were primarily concerned with security of pipeline inventory and most were substantial distances from the platforms (1 km or more), outside of the generally accepted 500 m "safety" zone.

Several of these were installed in 1982 in branches of the Northern Leg Gas Pipeline (NLGP). Nearly all use double acting actuated ball valves (as Configuration D but without manual isolation valve). The Brent A to St Fergus pipeline has a non-return valve (check valve) installed. The Norwegian sector pipeline (from Statfjord B), which incorporates provision for a subsea pig receiver, also has a check valve in the pipeline. This provides for inventory containment of non-Statfjord gas in case of leakage at the pig receiver.

Apart from the NLGP systems (ball valves), all other pre-Piper Alpha SSIS use check valves typically with a manually operated ball valve to isolate pipeline inventory when check valve maintenance is required (Configuration B).

Post-Piper Alpha

Of the post-Piper Alpha retrofit installations all but one use actuated ball valves as the primary isolation valve (mainly Configurations C and D, with or without manual valves), the exception being a single gate valve (gas export from Highlander to Tartan A). Actuators are primarily spring return on sizes up to and including 16" (Configuration C), and double acting (Configuration D) for sizes 24" and above. However, spring return actuators have been used for 24", 30", and double acting actuators have been used by one operator for all sizes of ball valves, including 10", 16" and 20", as well as 30".

The use of isolation valves and/or bypass valves does not appear to correlate with duty, direction of flow, or line diameter, although all systems with bypass valves also have a single manual isolation valve. Most of the SSIS without manual isolation valves were installed in the immediate aftermath of Piper Alpha, however, there is probably no particular significance attached to this.

All of the retrofit SSIS have been installed within the 500 m "safety" zone, and all make use of direct or pilot operated hydraulic control (via control umbilicals), which provide acceptable response times over this distance for valve opening and closing.
Of the SSIS installed (post-Piper Alpha) as part of new build pipelines, most are ball valves (although some satellite production well SSIS use gate valves). Many have manual isolation valves to facilitate maintenance. None have bypass valves fitted. Spring return and double acting hydraulic actuators are used and nearly all are either direct or pilot hydraulic operated, except for 3 installations, which have multiplexed electrohydraulic control (see Appendix C). One installation uses a check valve which was installed as part of the new build pipeline.

### 3.2 CONFIGURATIONS PROPOSED FOR DETAILED EVALUATION

This section describes the 9 configurations proposed for detailed evaluation in the study (see Figure 5). Schematic representations of the systems are presented in Appendix B. The objective was to analyse typical configurations and also propose systems which could provide improved reliability. The set of configurations were established in consultation with, and advice from, a specialist Subsea Engineer. An indication is given of the expected typical application, to illustrate the basis for configuration selection. Most of the installations to date fit into one or other of the following configurations.


- Typical use for sizes up to 10" for import of high pressure produced fluid - oil and/or gas - from satellite development. Small hydrocarbon inventory. Upstream shutdown under control of same platform operator. Small economic consequence of spurious failure - limited deferment of revenue until repaired.

B Single check valve with manual isolation ball valve on pipeline side.

- Typical use for sizes up to 36" for gas export/trunk lines and for export of oil to a Floating Storage Facility. Moderate to large hydrocarbon inventory.


- Typical use for sizes up to 24" at import end of lines, particularly to a manned platform, but have been used on 30" lines.

D Single ball valve with double acting hydraulic actuator, piloted hydraulic control system, double block and bleed manual isolation ball valves on line side. The double acting systems have accumulators effectively providing a "gas spring" for closure instead of a mechanical spring.

- Typical use in large diameter import or export gas lines where line depressurisation for maintenance must be avoided or in shared pipeline systems where shutdown is unacceptable to third party operators.

E Two ball valves in series with spring return hydraulic actuators, direct hydraulic control system. Manual isolation ball valve providing double block and bleed facility, on line side.

- Typical use in large diameter import or export oil or gas lines where actuator or control system reliability is seen as a problem.
F Two ball valves in parallel (one normally closed), with spring return hydraulic actuators, direct hydraulic control system. One (or more) isolation ball valves on line side.

- Typical use in gas export line with heavy penalties for gas non-availability on demand.)

G Two actuated plus one manual ball valve in series (as Configuration E). Double acting hydraulic with actuators piloted hydraulic control system.

- Typical use in very large diameter export gas lines where spring return actuators are not readily available.

H Three ball valves in series, two actuated (as Configuration G) with a small diameter bypass for pressurisation/depressurisation. Bypass contains one or two normally closed ball valves with spring return actuators.

- Typical use in major international gas trunk lines.

I A single check valve with an actuated ball valve in series on line side, spring return hydraulic actuator, direct hydraulic control system.

- Conceived for situations where very high reliability is required, for example high H₂S gas export.

3.3 FUTURE DEVELOPMENTS

Some new developments have been identified which could potentially reduce capital and operational costs. These are briefly described below.

a) Electric Subsea Actuators:

These have been considered for gate valves and would provide a number of advantages over present hydraulic actuators; advantages include:

- reduced reaction time in emergency
- reduced umbilical diameter and cost
- fewer connectors required

d) Acoustic Control (Frequency) - Hydraulic Actuators:

Subsea located hydraulic power for the actuator is controlled by acoustic signals through either water or pipeline fluid. The umbilical would only be required to carry a supply line to accumulators. No loss of control if umbilical severed.

c) Valve Developments:

A major ongoing development is the improvement to valve design which will allow subsea repair, where valve body internals are being made as an insert capable of being retrieved as a whole. A special sleeve is also incorporated which can be rotated to isolate the flow while the valve body insert is removed and replaced. This has the potential to reduce repair times so improving availability, but does not
improve the other reliability parameters. To date, experience shows that valves are performing as specified i.e. no maintenance over lifetime required.

None of the above have been sufficiently developed or have gained enough experience to be included in the reliability modelling. However, they do indicate the continuing effort to reduce costs for subsea equipment.
4. DATA COLLECTION SUMMARY

4.1 SSIS INSTALLED IN THE UKCS

The total number of SSIS installed in the UKCS at the time of the study (1993) was 83. The 7 operators co-operating in the study provided maintenance histories for 48 SSIS.

6 additional SSIS were identified in the Norwegian and Danish sectors of the North Sea. These are all check valve configurations (Configuration B) which were nearly all installed pre-Piper Alpha. RMC obtained maintenance information on 2 of these systems.

4.2 OPERATING EXPERIENCE

Total operating experience for the 50 SSIS was 181.2 years, equivalent to 3.6 years per system.

The data collected during this study relates to 3 basic valve/actuator types and the experience obtained for each type is as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Experience</th>
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<tr>
<td>Check valve</td>
<td>36.7 years</td>
</tr>
<tr>
<td>Spring return actuated ball valve</td>
<td>79.6 years</td>
</tr>
<tr>
<td>Double acting actuator, ball valve</td>
<td>64.8 years</td>
</tr>
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</table>

The data has been collected for 48 SSIS associated with 22 platforms on the UKCS, plus two non-UKCS systems.

4.3 OPERATOR MAINTENANCE RECORDS

4.3.1 Subsea Equipment Records

Operators made readily available their maintenance records where such records existed. The approach to keeping records varied between and within operators. An agreement between operators to record at least a specific minimum of relevant data for each event would prove very useful for future data collection exercises. An example of a form identifying the likely minimum data requirement is presented in Appendix H.

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 study have been installed within the last 4 years (average operating experience 3.6 years). Experience is thus limited and 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 and complete. Several subsea incidents caused by external events have been noted (described in Appendix E) but were not categorised as system failures affecting reliability of equipment. Examples of these events are:

- Isolation valves on accumulator banks left closed after installation

- Excessive delay in valve actuation (opening) due to the presence of metal particles in hydraulic fluid (manufacturing error)

- Umbilical damage during installation

These external events which have affected the operation of SSIS have not been included in the database or the reliability assessment because such events are not inherent failure mechanisms of the equipment. In addition it was considered that the study should address generic configurations of SSIS and not include such practical aspects which could be specific to a particular installation. Such specific aspects of SSIS could possibly mask the comparison of configurations for design purposes.

4.3.2 Topside Equipment Records

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. Print-outs from such computer systems provided much of the data collected, the rest coming from filed reports and work orders.

The computerised systems vary in the information contained and the methods used for transfer of data from the platform to the onshore maintenance database. One operator records all maintenance activities by electronically scanning the work order report sheets offshore, as they are completed by the offshore maintenance personnel. The scanned images are then transmitted to the onshore maintenance base for direct storage in the maintenance database, where they are available future inspection. This process eliminates the potential loss of useful data that would occur if data was transferred manually from the report sheets to a maintenance database.

The quality of information contained in these systems varied from a full description of the work, through partial description, to no information at all. The latter case involved the regular reporting of preventive maintenance work but with no details of the work done and of any defects, if any, repaired. This did cast some doubt in assuming that no failures had occurred on the system over the period covered. In these cases, discussions took place with the relevant experienced maintenance personnel to confirm if data in the records was as complete as possible within the limitations of such systems.

The major limitation with the data collected stems from the accuracy of the maintenance history records and their completeness. It was considered that, in general, the records can be relied on to be an accurate history of events, particularly when the recording systems used are work order based systems, which is the majority.
4.4 DISCUSSION OF SYSTEM FAILURES

The data collection exercise has provided only a small number of failures for subsea components, but significantly more failures for topside components. There is therefore less scope for considering typical problems with subsea components than there is for topside components. However, the following observations can be made from the data collected.

4.4.1 Subsea Failures

No critical failures (fail to close/open, spurious operation etc) have been recorded of subsea components, but several non-critical failures have occurred and are described below.

Check Valve

Only one check valve failure has been recorded over a total operational time of 36.7 years. 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. One other maintenance action (damage during pigging) was identified but not included for analysis due to the same reasons as given in Section 4.3.1. The item is described in Appendix E2.3.

Ball Valve

Two non-critical failures occurred with actuated ball valves. 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 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 or at least permanently plugged.

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. 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

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

1 failure was recorded when hydraulic fluid leaked from the hydraulic couplings at the umbilical termination panel. This was caused by corrosion of stainless steel couplings due to connection of dissimilar stainless steel types.

Accumulators

No failures have been recorded with subsea accumulator banks, but some operators replace these units for servicing approximately every five years. This is due to concern with the condition of the bladder. One operator has recently 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.

4.4.2 Topside Failures

All critical failures of the SSIS were attributed to topside control system and HPU components. These 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. Two non-critical failures - external leaks - were also recorded. The failures occurred over a total operating period of 115 years (covering 30 control systems).

Pilot Valve

2 critical failures were caused by the control system pilot valve. One caused a spurious SSIV closure, the other failed to open the SSIV. Both were caused by blocked internal filters.

Pressure Regulator

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

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

No other topside control system components caused critical failures of the SSIV. Several non-critical failures occurred with other components:

- 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

HPU

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.

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 have been affected and no complete loss of back-up has occurred. The individual failures have mainly occurred with associated valves and couplings but some bladder failures have 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.
5. 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.

5.1 DERIVATION OF PRIOR FAILURE DATA

The first requirement was to identify sources of appropriate data and, if several sources were available, to take the geometric mean of these values to obtain the prior estimate. In some cases RMC has basic data on numbers of failures, failure modes and operating experience. None of the sources provide details of times to failure, so it was not possible to determine the type of distribution. In other cases only failure rates are quoted i.e. no details of numbers of failures and operating experience. The form, and to some extent the applicability, of the prior data generally determined the method adopted to combine it with the collected data.

5.2 DERIVATION OF COLLECTED FAILURE DATA

The SSIS database contains component inventory and failure records for the 50 SSIS. 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.

5.3 COMBINING PRIOR AND COLLECTED FAILURE DATA

1 of 3 methods was used 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. Appendix F presents a detailed description of the methods used for combining the data.
5.4 COMBINED DATA LIMITATIONS

There is only limited subsea experience with check valves - 5 valves and 37 years experience. There is more experience with the actuated ball valves - 28 spring return actuators with a total of 80 years experience and 17 double acting actuators with 65 years experience. However, this does mean the average experience per valve is longer for check valves (7 years) than for the actuated ball valves (3 to 4 years).

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 $2.7 \times 10^{-2}$ failures/year (f/yr) compared to $2.9 \times 10^{-2}$ 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.
6. FAILURE MODELLING AND RESULTS

To assess the reliability of the 9 configurations identified for detailed evaluation in Section 3.2, failure models were constructed for the following 3 undesired events:

- failure to close on demand
- spurious valve closure i.e. 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 11]. Examples of the fault trees are presented in Appendix D.

6.1 FAILURE MODELS

Failure to Close on Demand

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 (e.g. 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

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

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

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 2.

6.2 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.

6.3 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 subsea repairs and so the chosen topsides repair time does not significantly affect the final results.

6.4 RESULTS

The results for the chosen SSIS configurations are presented in Table 2. 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 (37 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, Section 5.4 shows that the calculated external leak frequencies for the two environments is 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

If a simple ranking of frequencies or probabilities is done for each column in Table 2 and the results aggregated, then Configuration B, (the single check valve) produces the best result in Table 2. 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 i.e. 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-slogging. This "water 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 11 years instead of once in 5 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 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 19 years, for the spring return actuated valve (Configuration C), to once in 10 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 27 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 19 years to once in 16 years. Provision of a second actuated valve in series with the main valve (Configuration E) increases the intervention to once in 10.7 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 20 to once in 10 years for the single actuated valve SSIS. In addition, the manual valve will not contribute to the failure to close or spurious closure cases.
7. DISCUSSION

7.1 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 development of a database was only a small part of the total project. The primary purpose of the database was simply to provide storage plus rapid analysis and retrieval of the collected data for use by RMC during the study. A subsequent consideration was to make any computerised database compatible with the OREDA software and to provide the data files to all participants. Not all companies have the OREDA software and so a user interface was developed to allow these companies access to the data. Now that an SSIS reliability database is available to UKOOA and HSE it could be expanded to include new installations and 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 a subsequent collection exercise. The existence of the database, already containing inventory data on most SSIS, should mean any future collection exercise will be cheaper than the original study.

7.2 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. RMC supplied the results of the reliability study to Andrew Palmer and Associates Ltd for combination with cost information so they could determine the whole life cycle costs. The results of that analysis were subsequently reported by APAL to UKOOA and HSE.

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 divert 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 all 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 $1 \times 10^{-2}$ 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 II (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.

7.3 MAIN ACHIEVEMENTS

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

i) Maintenance records have been obtained and analysed for 50 SSIS, giving a total of 181 years operating experience (37 years for check valves, 144 years for actuated ball 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.
8. 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 the data collection exercise.

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) 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.

iv) In cases where a check valve can be used, then SSIS containing a single check valve 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.

v) 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.

vi) 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.

vii) Some theoretical studies of SSIS reliability have been examined during this study. The probabilities calculated for failure on demand (1 to 2 x 10⁻²) are in reasonable agreement for single actuated valve systems.

viii) The data collected during the study 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 3.6 years per SSIS, so the available experience will double in 3 to 4 years, if only the same installations are considered. If the database was extended to cover all other SSIS installed in the UKCS, then the operating experience would be doubled much sooner. Improving the database by collecting the additional experience would provide operators with the opportunity to review the longer term experience and would be useful in updating platform safety cases.

ix) Future data collection, on the systems already included in the database, should be considerably cheaper than the original collection exercise. An annual update with use of appropriate standard forms would require only limited input from operators.

x) 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.
9. ACKNOWLEDGEMENTS

The SSIS information was collated through members of the UKOOA Subsea Valve Working Group, which was chaired by Mr R R Macheder of British Gas. The working group appointed a Study Co-ordinator (Mr E Smith of BP Research and Engineering), whose advice and assistance during the study was much appreciated. The co-ordinator for HSE on the study was Dr T Al Hassan, with additional advice provided by Mr B Ralph. A detailed review of the technology used in SSIS was provided by Mr K Bond of Foster Wheeler.
10. REFERENCES

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2. OTO 95 024, SSIS Cost Reduction Study, Andrew Palmer and Associates Limited, HMSO.


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**Table 1:** Summary of Failure Data

- Indicates a suspect component
- Only data under heading "Collected Data" is from initial 3 days and obtained during this study.
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Prepare Questionnaire
   i) Types of SSIS installed
   ii) Maintenance/failure data

Anlysis results of installation questionnaire

Categorise
   - system types
   - sub-system boundaries

Prepare taxonomy
Propose data classification

Develop database

Collect and analysis failure/maintenance records

Prepare SSIS reliability models

Combine limited data with topsides data

Assess results

FIGURE 1
Outline of Study Activities
### VALVES

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<td>- Seals</td>
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Valves, Sub-division in maintainable items

**Control & Monitoring**

![Diagram of control and monitoring system with actuator and valve](image)
FIGURE 3
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 4
Boundary Definition for Hydraulic Power Units
APPENDIX A

SSIS DESIGN - TECHNOLOGY OVERVIEW
A1. INTRODUCTION

A2. FUNCTIONAL REQUIREMENTS OF SSIS INSTALLATIONS
A1 INTRODUCTION

The purpose of this Appendix is to review some of the principal technological features of Subsea Isolation Systems, as an aid to understanding requirements which influence their reliability. It is not intended either as an exhaustive historical database or a comprehensive design guide. It serves rather to identify a series of factors which influence the design of SSIS installations. Of particular importance are the options for valve and control system configuration, which have a major bearing on system reliability, and just as importantly, system availability. Where appropriate, reference is made to a significant body of public domain information concerning specific installations and general principles.

The emphasis throughout is on the UKCS, and the major change in attitude, if not regulatory requirement, following the Piper Alpha disaster of July 1988. However, brief reference is made to the Danish sector of the North Sea, where an SSIV was first installed to provide safety for platform personnel, and to the Norwegian sector which has historically given more emphasis than in the UK sector to quantified reliability analysis and to the capability for condition monitoring of pipelines by "intelligent" pigging.
A2. FUNCTIONAL REQUIREMENTS OF SSIS INSTALLATIONS

A2.1 General

The basic purpose of a Subsea Isolation System (SSIS) is to contain the inventory of a subsea pipeline in case of an actual emergency (uncontrolled outflow) at the end of the pipeline. For the purposes of this report the end of the pipeline is at surface platform (not subsea tie-in or shore terminal), which may or may not be manned. The SSIS provides protection in case the mandatory platform riser ESV is disabled, or in case the pipeline and riser between the SSIV and ESV is ruptured. The primary hazards to be avoided are fire and explosion, posing risk to the facility and any personnel on board. Further hazards to the facility that are to be considered include gas cloud suffocation and H₂S poisoning.

Additional hazards to be evaluated include those to the pipeline system itself, including loss of (valuable) inventory, potential pollution damage and clean up costs, and the time related costs of pipeline dewatering and recommissioning, lost production, and possibly supply contract penalties (see Reference 12). In respect of these hazards the SSIS need not provide bubble tight shut off. Its purpose is to avoid a major incident endangering the integrity of the surface facility. Consequently mild leakage, the effects of which can be countered by platform emergency systems, are considered acceptable. For each of these hazards it is clear that the severity increases with increasing length, diameter and operating pressure of the pipeline; also with the vapour pressure of the contents, so that gas is more hazardous than stabilised oil. The hazard consequences are also different for manned and unmanned platforms. Each situation must thus be evaluated individually, as part of the Formal Safety Assessment required to gain Development Consent (for new installations) or Operating Consent (for existing facilities). Just as the need for an SSIS requires individual evaluation and is outside the scope of this study, so is the question of optimum location of the SSIS. Discussion on this can be found in Reference 14.

In addition to its function of isolating the pipeline inventory automatically on demand, within a specified time interval and with acceptable reliability, SSIS must meet other functional requirements by virtue of its own existence as part of the pipeline system. These may include:

a) Maintainability (including repair and hydrotest)

b) Piggability (including intelligent pigs)

c) Testability (including Test Monitoring)

d) Installability

e) Availability

f) Manual Operability (Locally or Remotely)

Each of these functional requirements is briefly discussed in turn, with regard to its impact on SSIS reliability and configuration.
A2.2 MAINTAINABILITY

Pipeline systems are expected to have service lives typically of 10-25 years. Major gas trunk lines may be designed for lives of up to 50 years. Eventually as experience builds up and reliability data is acquired and analysed through projects such as this, confidence will grow in the reasonable maintenance-free life expectancy of such systems. However, at the moment, the presumption must be that maintenance will be required, either routinely on a scheduled basis or in response to failures detected through routine scheduled testing.

Such maintenance of seabed installations generally implies removal and replacement rather than in-situ refurbishment, and is very expensive, both in terms of the cost of carrying out the work and the cost of lost production from the resulting system downtime. Consequently there is a considerable economic incentive to plan for maintenance and include facilities to reduce maintenance durations. However it is clearly important not to do anything that would introduce unreliability, resulting in increased maintenance frequency.

A particular aspect of the maintenance of seabed pipelines, particularly those carrying gas, is the time taken to remove any water which enters the line. This can take a period of several months, if a line is accidentally flooded. Consequently it is very common to install an isolation valve on the pipeline side of an SSIV. These valves are described as manually operated, in the sense that they cannot fail closed. Actual operation may be by diver turning a handwheel, but may equally be by diver deployed hydraulic actuator, diver or ROV hydraulic ‘hot stab’ connection or surface deployed diverless actuator tool.

In some circumstances it may be desirable to have the capability to maintain (or replace) the SSIV without depressurising the pipeline system, for example gas lines with a downstream connection into a high pressure system with no compression capability. In these cases two manual isolation valves can be justified, providing a double block and bleed isolation capability between the high pressure pipeline inventory and the SSIV, allowing safe access for divers.

Other isolation devices are available or under development instead of installed manual isolation valves, such as plugs, stoppers, high friction pigs, tethered pigs, acoustically inflatable spheres, etc. Such devices have been widely used during SSIS retrofit installation, when manual valve isolation was not of course available. None of these is considered likely to completely replace the pre-installed manual valve for isolation for SSIV maintenance.

The manual isolation valve is also a convenient device against which to hydrotest after SSIV maintenance. If adequately specified it can be used to test the reinstated pressure containment envelope, as well as a test on the pipeline side of the closed valve, to verify tight shut off.

A2.3 Piggability

A whole variety of different types of pig are now available which may be considered for running in a pipeline, for a whole variety of reasons, including spheres, maintenance pigs, gel pigs and intelligent pigs. For the purposes of SSIS design and reliability evaluation it is necessary to consider only spheres and intelligent pigs.
Spheres are typically used on a regular basis in gas lines to control liquid accumulation (hydrocarbon condensate and/or water). Many of the existing Southern Sector gas platforms have facilities to handle spheres, but not the longer, heavier, body pigs or intelligent pigs. Spheres have the advantage that they can pass through short radius bends, but they can get stuck, with fluid flow bypassing them, in the cavities of tees, wyes and swing check valves. This effectively precluded the use of swing check valves as retrofit SSISs in the majority of existing gas pipelines. Of course duo-check valves, butterfly valves etc do not have a full bore conduit and are not therefore used in pipelines.

Maintenance pigs and intelligent pigs typically can successfully negotiate wyes and swing check valves, but require longer radius pipe bends, which can influence SSIS layout, particularly for retrofit installations. However they are more sensitive than spheres to sharp steps in the pipe wall. This means that gate valves must be of the ported gate type (rather than wedge gate) and that high precision is required for actuator end stops on both gate and ball valves, in the full open position, to allow pig passage. Loss of precision resulting in pig damage, or even a stuck pig, results in expensive maintenance and downtime. This also has implications for actuator interchangeability between valves.

A2.4 Testability

There are no mandatory requirements for testing of SSIS. Nevertheless the expected reliability depends on frequency of testing, and many operators are testing SSIVs on a similar basis to the topsides ESV.

Here again an actuated ball valve SSIV is preferred to a check valve as the test (partial closure) can be initiated and confirmed without interruption to pipeline flow. SSIV movement, detectable by actuator position indicators and/or hydraulic fluid pressure or flow sensing, subsea, is considered an acceptable test as the valve does not need to close bubble tight to achieve its function, and is most unlikely to fail part closed once ball rotation has begun.

A check valve test would normally involve interruption of export flow, (partial) depressurisation of the riser, and monitoring of riser pressure. If additional equipment was fitted then a partial closure test could be performed as for actuated valves. However, such extra equipment would affect the calculated reliability values adversely.

A2.5 Installability

There are very many aspects to be considered in the design of SSIS for installability. Many of these depend as much on operator philosophy as an application specific criteria, including:

- Diverless or diver assisted maintenance
- Welded or flanged connections
- Overtrawiability, dropped object protection
- Installation before or after pipelay
- Installation by semi-submersible, diving support vessel or towed sled technique

However, after due consideration, it is considered that these are unlikely to be of major significance to reliability evaluation.
A2.6 Availability

The availability of a system is a parameter as important as its reliability. It can be defined as that fraction of a time span for which the system can operate as intended if called upon to do so. It is the parameter most closely associated with the revenue earning capability of the facility, particularly in the case of export oil and gas pipelines. Downtime, or non-availability equates to lost or deferred production. The lost production due to say a failed SSIV in a gas export line may not just be the gas production at that platform, but also the oil production, and any gas production tied in to that platform from other fields upstream.

Improved SSIS reliability to close on real demand will generally be associated with improved reliability to close on test, but not necessarily with improved reliability to avoid spurious closure.

A2.7 Manual Operability

It may sometimes be desirable to manually operate an SSIV, for example to close it to isolate the platform riser from the pipeline, or to hold it open regardless of an ESD signal. The latter may be considered for passage of an instrumented pig, and may not be hazardous if the pig is run at low line pressure or in an extended slug of water, but could be very dangerous at other times.

In the case of ball valve type SSIVs, it is relatively straightforward to provide these manual override functions from the surface or subsea as required. There appears to be no significant implications for reliability in allowing manual closure. However a manual facility to hold open a valve, would introduce the possibility of human error (failing to re-instate the trip function) with the fail to close case. In the case of swing check valves, some sort of actuator may be required, and this would reduce valve reliability.

SSIS configurations have been proposed to overcome this, such as a check valve with a piggable bypass valve (manual, normally closed) but none has been used to date so far as the authors are aware.
APPENDIX B

SYSTEM CONFIGURATIONS

FOR DETAILED EVALUATION
B1. 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 H

SSIS Configuration I
APPENDIX C

GENERAL DESCRIPTION OF THE
MAIN SSIS COMPONENTS
CONTENTS

C1. VALVES
C2. ACTUATORS
C3. CONTROL SYSTEMS
C4. HYDRAULIC POWER SOURCE
C5. HYDRAULIC CONTROL VALVES
C6. UMBILICAL
C1. VALVES

C1.1 BALL VALVES

Ball valves in use as SSIVs or as manual isolation valves are ¼ turn valves and range in size from 3" to 36". They may be all welded, top-entry or split body. All welded constructions are generally contained in a pipeline spool piece which is flange connected to the main pipeline. Top-entry valves, considerably heavier than the all-welded type, can provide access to valve internals without springing or cutting the pipe. Subsea in-situ maintenance is possible but is generally not carried out.

Ball valves have good sealing properties. Soft seals can provide total sealing, but can be damaged by debris between the ball and the seal and wear out with frequent operation. However, this is perhaps not a problem as SSIVs are not designed for frequent operation. Metal-to-metal seated valves may not seal as well as soft seals but have an advantage in longevity of the seals.

C1.2 CHECK VALVES

Check valves close automatically if pipe flow stops or reverses. Any tendency for reverse flow to occur will cause pressure build up against the clapper causing the clapper to seal more tightly. Hence fluid flow is permitted in only one direction. Swing check valves are used since they offer little flow resistance.

Check valves are simple in design and do not need actuators to operate them, but the clapper is in constant agitated motion which may cause mechanical parts to fail in a relatively short timescale due to wear (but not so far). Check valves have the facility to raise the clapper manually into an open position to permit pigging.

As the check valves are self-acting the major disadvantage is that positive control is not possible nor is it easy to monitor the position of the clapper.

For pigging operations, the flapper can be latched open to allow free passage of the pig. This has normally been carried out by diver, but in some cases actuators have now been fitted to allow ROV operation of the mechanism.

Subsea maintenance is possible with a top-entry check valve. A modified top-entry check valve with an internal longitudinal sleeve to allow maintenance of a clapper without flooding the pipeline has been developed.

C1.3 GATE VALVES

Gate valves are not generally used for SSIV duty although there are a few installed (Piper B & Scott) on pipelines from satellite wells where high pressures are encountered. Most subsea applications are within Xmas trees and associated manifolding.

The main disadvantage of a gate valve is its larger size for large diameter pipelines. The chamber is required to house the gate when the valve is in the open position which
makes the bonnet area at least one pipe diameter in size. When actuators are added the space envelope becomes very large.

Gate valves could be considered for application in smaller diameter, high pressure, pipelines.

C2  ACTUATORS

C2.1 Hydraulic Spring Return

External hydraulic power is applied to drive the valve in one direction only, at the same time compressing a return spring which drives the valve in the opposite direction on removal of the hydraulic power. Spring return actuators are inherently fail-safe when oriented to operate the valve in the shut safe direction (ie closed). For a given valve size, the spring return actuator is considerable larger in physical size compared with the double acting actuator. This has in the past made it unsuitable for use with larger valve sizes but developments have taken place enabling these actuators to be used on larger valves.

C2.2 Hydraulic Double Acting

External hydraulic fluid is applied to drive the valve in both directions. This type of actuator is only fail-safe when designed to be so by the provision of hydraulic fluid accumulator banks mounted close to the actuator. A hydraulic pilot valve is also required to direct the fluid to the required side. Double acting actuators are generally more compact than spring return actuators for a given valve size over 12". The added complexity of the subsea control system potentially reduces the reliability and could impair the fail-safe characteristic desired.

C3  CONTROL SYSTEMS

Two principle control circuit techniques are used for SSIS; direct acting control and piloted control.

C3.1 Direct Acting

This consists of a simple circuit which directly operates the actuator from the hydraulic power source (platform). This type of circuit has the main advantage that it provides a greater measure of fail-safe protection as certain failures of the valve and actuator are the only ones that would not allow a fail-safe position. This type of system is generally used with spring return actuators.

C3.2 Piloted

This consists of a control circuit that utilises locally stored power i.e. accumulators on the SSIV skid, and a control pod containing a pilot valve to switch the hydraulic power. Control is from the platform by either hydraulic pilot line or electrical pilot line. This
type is generally used with double acting actuators. It contains more components than the direct acting type which increases the probability of a failure. This could be seen in the event of a sticking pilot valve, where it would be impossible to close the SSIV without subsea intervention. Despite this disadvantage, the piloted control system is in common use for SSIS as a direct result of the selection of double acting actuators.

The control system can be open circuit or closed circuit.

C3.3 Open Circuit (Spring Return Only)

This system generally employs a "dump-to-sea" philosophy whereby the actuation of the spring return of the actuator initiates the opening of a non-return valve that allows all the hydraulic fluid stored within the actuator to dump to sea. It has the inherent advantages of speed of response and reduced umbilical core requirements, but suffers the disadvantage of possible environmental pollution and the lack of control of the actuator for valve testing operations.

C3.4 Closed Circuit

This system is totally sealed from the environment in that it has a hydraulic supply from the platform with a hydraulic return to the same source.

Hydraulic fluid is not lost from the system at any point. It suffers the disadvantage of the requirement for a fluid return hose within the main umbilical and the response time of the actuator is dependent on the fluid return rate, which is governed by the distance of the SSIV from the platform. This system does permit greater control of the actuator for valve testing operations.

C3.5 Multiplexed Electrohydraulic Systems

A multiplexed electrohydraulic control system is one where several actuated valves can be controlled from a single control system. Such systems use an electrical signal line, from a topside control system, to a subsea control module containing the multiplex unit. Signal transmissions for all valves pass along the single line and are decoded in the subsea unit. Solenoid valves for each SSIV are then energised/de-energised as required to control the hydraulic pressure to the SSIV actuator through individual jumper lines.

The system can be used for both direct acting (spring return actuated) and piloted (double acting actuated) systems. It is typically used for SSIS on import lines from satellite wells where the control of the SSIS and wellhead valves are from the same control system. It has also been used to control eight SSIS around a single platform. However, control of multiple SSIS does not always necessitate a multiplex control system. A number of valves can be controlled by individual control systems on the platform.

C4 HYDRAULIC POWER SOURCE

Where a subsea hydraulic power source is required, it generally takes the form of one or more hydraulic fluid accumulator banks which are kept in the fully charged state by
trickle charging from the surfaced HPU. Typically, the accumulators are mounted in the vertical position to facilitate retrieval of bottles for maintenance and to give greater protection against system hydraulic fluid aeration in the event of a bladder failure. The accumulators are pre-charged with Nitrogen gas.

The surface HPU is typically a standard platform hydraulic power source, consisting of: a hydraulic fluid reservoir, duty and standby hydraulic pumps plus an emergency back-up, accumulator banks, pressure regulator etc.

C5 HYDRAULIC CONTROL VALVES

Hydraulic pilot control valves are used for control of the direction of hydraulic fluid flow.

Subsea Control valves are installed within the control module and in close proximity to the main SSIV actuator. Its purpose is to direct the hydraulic supply from the accumulators to the SSIV. In the case of double acting actuators to direct the fluid either to the open or close side of the actuator.

In the case of spring return actuators that do not use subsea accumulators, the valve is normally mounted in the platform based SSIV control panel. There is one disadvantage in this in that larger umbilical hoses may be required to attain the required SSIV closure times.

C6 UMBILICAL

A typical SSIV control umbilical would contain the following services:

1 off Main Hydraulic supply hose
1 off Hydraulic return hose (double acting system)
2 off Spare hose
3 off Twisted and screened electrical pairs for monitoring accumulator pressure and for SSIV open and closed positions
3 off Spare twisted and screened electrical pairs

The umbilical is normally double steel wire armoured over its complete length for seabed stability and protection.
APPENDIX D

FAULT TREE ANALYSIS
This Appendix contains the representative examples of Fault Trees generated by the reliability modelling exercise. The Fault Trees have been produced using the RMC LOGAN software package (Ref 11). The following describes the data contained in each column:

**Event Ref:** This is an event descriptor code used in the logic equations that produce the required combination of events. The reference is attached to a unique event within a fault tree.

**Data Ref:** Normally used to provide a means of tracing/cross referencing the data used with its source. Not used in this study as the data is of a combined nature from existing sources and newly collected data.

**Event Description:** Describes the type of failure event.

**Failure Rate:** The Failure rate in f/yr for the event described. Cross reference to Table 1 (column 9).

**T_{repair}/T_{test}**: Repair time or Proof Test interval. Where the failure is unrevealed (U) the entry is a proof test interval and where the failure is revealed (R) the entry is repair time. (Time in years.)

**Prob:** The probability of the event occurring.

**R/U:** Denotes an Unrevealed or Revealed failure.
**FIGURE 1. FAILURE LOGIC DIAGRAM FOR SUSPENSE VALVE CONFIGURATION C FAULT TO CLOSE ON DEMAND**

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10E-2</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
<tr>
<td>1.10E-2</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
<td>BALL VALVE SLEEVES OPEN</td>
</tr>
<tr>
<td>1.75E-3</td>
<td>SPOOL VALVE FAILS</td>
<td>BALL VALVE SLEEVES OPEN</td>
</tr>
<tr>
<td>2.50E-3</td>
<td>SOLENOID VALVE FAILS</td>
<td>BALL VALVE SLEEVES OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>SOLENOID VALVE FAILS</td>
<td>BALL VALVE SLEEVES OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
<tr>
<td>1.00E-3</td>
<td>PILOT VALVE FAILS</td>
<td>SOLENOID VALVE FAILS TO OPEN</td>
</tr>
</tbody>
</table>

**REFERENCES**

**FIGURE 2. FAILURE LOGIC DIAGRAM FOR SUBSEA VALVE CONFIGURATION D FAILS TO CLOSE ON DEMAND**
<table>
<thead>
<tr>
<th>EVENT REF</th>
<th>DATA REF</th>
<th>EVENT DESCRIPTION</th>
<th>FAILURE RATE</th>
<th>Repair/ Test</th>
<th>PROB</th>
<th>R/U</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIRLK</td>
<td></td>
<td>Major fluid leak from semi rotary actuator</td>
<td>1.30E-2</td>
<td>1.90E-2</td>
<td>2.47E-4</td>
<td>R</td>
</tr>
<tr>
<td>SOLVSP</td>
<td></td>
<td>Solenoid valve leaks across spool or fails closed</td>
<td>3.40E-3</td>
<td>2.70E-3</td>
<td>9.18E-6</td>
<td>R</td>
</tr>
<tr>
<td>PILOT</td>
<td></td>
<td>Pilot valve fails open or leaks int. or ext.</td>
<td>2.30E-2</td>
<td>2.70E-3</td>
<td>6.21E-5</td>
<td>R</td>
</tr>
<tr>
<td>UMSSRUP</td>
<td></td>
<td>Umbilical rupture or major fluid leak</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>MOSEZLK</td>
<td></td>
<td>Local jumper hose to actuator ruptures or leaks</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>NOPRESS</td>
<td></td>
<td>Loss of hydraulic pressure from topsides MPU</td>
<td>2.20E-2</td>
<td>2.70E-3</td>
<td>5.94E-5</td>
<td>R</td>
</tr>
</tbody>
</table>

Generated by LOGAN v3.09 RNC Southern Office copy on (m-d-y) 08-12-1993
Fault tree file: CONCS
Proof test intervals simultaneous
Sub-trees used. Cutset order = 6

FIGURE 4. FAILURE LOGIC DIAGRAM FOR SUBSEA VALVE CONFIGURATION C SPURIOUSLY ISOLATES PIPELINE
<table>
<thead>
<tr>
<th>EVENT REF</th>
<th>DATA REF</th>
<th>EVENT DESCRIPTION</th>
<th>FAILURE RATE</th>
<th>Repair/Test</th>
<th>PROB</th>
<th>R/U</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTA</td>
<td></td>
<td>Major fluid leak from semi rotary actuator</td>
<td>1.30E-2</td>
<td>1.90E-2</td>
<td>2.47E-4</td>
<td>R</td>
</tr>
<tr>
<td>SOLVVA</td>
<td></td>
<td>Solenoid valve fails to open (topsides)</td>
<td>1.40E-2</td>
<td>2.70E-3</td>
<td>3.78E-5</td>
<td>R</td>
</tr>
<tr>
<td>PILOTA</td>
<td></td>
<td>Pilot valve fails open or leaks int. or ext.</td>
<td>2.30E-2</td>
<td>2.70E-3</td>
<td>6.21E-5</td>
<td>R</td>
</tr>
<tr>
<td>UNSARUP</td>
<td></td>
<td>Umbilical fluid supply line ruptured</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>HOSE</td>
<td></td>
<td>Local jumper hose to actuator ruptures or leaks</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>ACTB</td>
<td></td>
<td>Major fluid leak from semi rotary actuator</td>
<td>1.30E-2</td>
<td>1.90E-2</td>
<td>2.47E-4</td>
<td>R</td>
</tr>
<tr>
<td>SOLVGB</td>
<td></td>
<td>Solenoid valve fails to open (topsides)</td>
<td>1.40E-2</td>
<td>2.70E-3</td>
<td>3.78E-5</td>
<td>R</td>
</tr>
<tr>
<td>PILOTB</td>
<td></td>
<td>Pilot valve fails open or leaks int. or ext.</td>
<td>2.30E-2</td>
<td>2.70E-3</td>
<td>6.21E-5</td>
<td>R</td>
</tr>
<tr>
<td>UNSARUP</td>
<td></td>
<td>Umbilical fluid supply line ruptured</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>HOSEZLKB</td>
<td></td>
<td>Local jumper hose to actuator ruptures or leaks</td>
<td>4.40E-3</td>
<td>1.90E-2</td>
<td>8.36E-5</td>
<td>R</td>
</tr>
<tr>
<td>TOPPRESS</td>
<td></td>
<td>No pressure from topsides MPU</td>
<td>2.20E-2</td>
<td>2.70E-3</td>
<td>5.94E-5</td>
<td>R</td>
</tr>
</tbody>
</table>

FIGURE 6. FAILURE LOGIC DIAGRAM FOR SUBSEA VALVE CONFIGURATION E SPURIOUSLY ISOLATES PIPELINE
APPENDIX E

SUMMARY OF SUBSEA FAILURE INCIDENTS
E  SUMMARY OF SUBSEA FAILURE INCIDENTS

This Appendix describes two categories of subsea failure incidents.

i) Incidents causing failures which have been included in the SSIS database and have contributed to the failure data used in the reliability assessment. These were failures which could be associated with the system component failure mechanisms.

ii) Incidents which have not been included in the SSIS database and reliability assessment as they are not considered to be failures, due to external events or installation/commissions problems etc.

E1 SUBSEA FAILURES INCLUDED IN THE SSIS DATABASE

i) Check valve stem seal leak.

During preparations for pigging operations the check valve clapper was manually latched open. During this activity the stem seal failed and a leak occurred. Sealant injection was used to re-make the seal.

ii) Actuator position indication switch connectors.

Loss of actuator position indication was caused by faults with the connection from the subsea control module. The original connection was hard wired from the control module with connectors at the actuator position switch. This connection was replaced with normal jumper connections (connectors at both ends) and involved the replacement of the control module with a modified unit.

iii) Ball valve body sealant injection ports leaking.

A gas leak was identified during preparations for subsea intervention on the SSIV skid. The leak was located to a sealant injection port on the SSIV body. The manual maintenance valve was closed and the riser depressurised to enable the removal of the plug fitted in the port. Gas passing the NPT threads on the plug were identified as the cause of the leak. PTFE tape was applied to the threads and the plug re-instated. The gas leak was stopped. The same problem re-occurred eighteen months later and rectified in a similar manner.

iv) Ball valve body drain plug leak.

A product leak was identified through a valve body drain plug. The item was re-tightened to stop the leak.
E2 SUBSEA FAILURE INCIDENTS NOT INCLUDED IN THE SSIS DATABASE

The incidents in this category have been separated into four sub-categories:

- Operational incidents
- Installation/Commissioning incidents
- Design problems
- Other aspects arising from the data collection

E2.1 Operational Incidents

i) Subsea umbilical snagged and severed.

A subsea umbilical was snagged (cause unknown) and, as a result of the loading placed on it, the explosive severance device automatically operated to protect the SSIV skid. The SSIV closed fail-safe and was subsequently manually locked open to allow production to continue. Repair of the umbilical was effected approximately five months after the incident. The SSIV was located 2km from the platform and outside of the platform 500m safety zone. This incident highlights the ever present risk of interference from shipping/fishing activities but should not be regarded as relevant to future SSIS installations, which are invariably located within the platform safety zone.


During repair activities on an SSIV the manual isolation valve was operated to isolate the pipeline. The valve did not fully close as the seat-rings had settled in a fixed position and did not allow sealing of pressure. The rings were reactivated by flushing them with diesel oil and turning them by opening and closing the valve several times.

E2.2 Installation/Commissioning Incidents

i) Isolation valves on the subsea accumulator module not opened.

During the installation of an SSIS the isolation valves on the subsea accumulator module were not opened. This error was not picked up during the commissioning tests and did not come to light until the next function test was performed.

ii) Hydraulic jumper connections made-up incorrectly.

During the installation of an SSIS the hydraulic jumper connections from the subsea accumulator module were incorrectly made. The error was not picked up during the commissioning tests and did not come to light until the next function test was performed.
iii) Umbilical extensively damaged.

During installation of an umbilical, extensive damage occurred to the electrical cores. The umbilical was useable but lost all redundant capacity for the electrical signal lines.

iv) Umbilical extensively damaged.

During installation of an umbilical, extensive damage occurred causing loss of all redundant capacity within the umbilical.

v) Subsea accumulator balancing.

During commissioning of an SSIS, minor problems were experienced in balancing the accumulators in the subsea accumulator module.

E2.3 Design Problems

i) Check valve damaged by pigging operation.

During first pigging of the pipeline the check valve was damaged. It was discovered that the blocking and retarding mechanism on the valve was no longer connected to the clapper shaft itself. The retarding mechanism installed by the supplier was working in the clapper opening direction as well as the closing direction and only designed for the latter (not dimensioned for the opening direction). The damage probably occurred when the retarding mechanism was working against the force being used to open the clapper (the pig trying to lift the clapper).

ii) SSIV cover panels dislodged and damaged actuator.

Damage occurred when cover panels, on top of the SSIV skid, were dislodged and fell onto the valve actuator. The position sensors were damaged and the actuator was changed-out. The problem appeared to be caused by the strong tidal conditions encountered in the southern sector of the North Sea. The incident delayed the installation of two further, identical, systems while the problem was rectified.

iii) Corrosion of subsea connectors.

A problem with the connectors at a subsea umbilical termination unit was initially identified topside by a loss of hydraulic fluid. R.O.V. inspection revealed corrosion product on the stainless steel (316L) couplings and the bulkhead. Investigation indicated pitting corrosion due to design of fittings (lots of threaded sections) and joining of 316 to 316L s/s (design specification error). All hydraulic couplings (umbilical and jumper connections) changed to Inconel 625 and the s/s bulkhead replaced by a nylon version. Unable to change umbilical electrical connections so new 316 s/s connectors fitted on electrical jumpers and all connected to a local anode.

iv) Actuator failure due to metal plating error.

A failure of a spring return actuator was identified when, during a function test, the valve took 55 minutes to open. Investigation revealed that hydraulic fluid, collected from the dump valves during the closing stroke, contained bright metal particles,
consistent with metal plating loss within the hydraulic cylinders of the actuators. The problem was traced back to a fault in the metal plating process on the hydraulic cylinder internal tie-bars. These were replaced with ones of the latest design with the desired surface hardness and wear resistance. The sealing arrangement was also modified by the addition of an extra trunnion seal to ensure the cylinder piston ran true on the tie-bars.

E2.4 Other Aspects Arising from the Data Collection

i) Reliability of subsea accumulators.

Concern was expressed by one operator about the reliability of subsea accumulators. The following aspects were of particular interest:

- Migration of nitrogen pre-charge gas into the hydraulic fluid by either permeation through the bladder material or from a bladder rupture.
- Frequency of bladder ruptures.
- "Flaking" of bladder material into the hydraulic fluid.

The same operator has recently recovered a subsea accumulator bank that has been in service for 10 years without any maintenance carried out on it. The condition of the accumulators was unknown when recovered but subsequent inspection has shown all units to be in good working order with a slight work-hardening of the bladder material.
APPENDIX F

METHODS FOR COMBINING EXISTING AND COLLECTED FAILURE DATA
F. METHODS FOR COMBINING PRIOR AND COLLECTED FAILURE DATA

This appendix describes the 3 methods that were used to combine the existing 'prior' failure data and the collected failure data to produce a new estimated failure rate that reflects the new experience gained from the data collection exercise.

F1. AGGREGATION

This method of combining failure data was used where the prior and collected data contained details on the number of failures and operating experience.

Ideally if the prior data is regarded as homogeneous data than the collected data can simply be regarded a further batch of data contributing, like other batches, to an overall estimate.

In practice there is evidence of heterogeneity in the some of prior data i.e. there is variability between batches. For example, the check valve prior data includes valves of varying sizes. Visual inspection of the data did not reveal any obvious trend in this regard. As a result, the variability between batches is difficult to explain. It is questionable whether the differences in this existing data truly reflects any size differences. The assumption is made that this is part of the inherent variability of the data.

Every effort has been made to select existing data for similar components to those used in the SSIS models.

Two examples of the method of aggregation are shown below:

F1.1 Check Valve (External Leak Mode)

Prior Data: 4 failures in 3272 years
Collected: 0 failures in 36.7 years
Aggregated Data: 4 failures in 3308.7 years

Combined Failure Rate = 1.2 e-3 f/yr

F1.2 Pilot Valve (Fail to Close)

Prior Data: 3 failures in 147.1 years
Collected Data: 1 failure in 115 years
Aggregated Data: 4 failures in 262.1 years

Combined Failure Rate = 1.5 e-2 f/yr
F2 GEOMETRIC MEAN

The method of taking a geometric mean of the prior failure data and collected data was applied when a failure rate only was available from the prior data and the collected data contained a number of failures enabling a failure rate to be calculated. The geometric mean of the two failure rates was simply calculated as shown below:

eg Manual ball valve (external leak)

Prior failure data:- 3.9 e-3 f/yr
Collected failure data:- 2 failures in 144.4 years
          = 1.4 e-2 f/yr

Geometric Mean = \( \sqrt{3.9 \times 10^{-3} \times 1.4 \times 10^{-2}} = 7.4 \times 10^{-3} \) f/yr

F3 BAYESIAN TECHNIQUE

The Bayesian technique to combine failure data was used where only a prior failure rate was available (ie source did not record number of failures and operating experience) and when zero failures had been recorded from the data collection exercise. Use of the aggregation or geometric mean methods in this situation is only possible if it is assumed that a failure would have occurred immediately after the end of the data collection period. This then enables a failure rate to be calculated. However, where the data is accurate, as for subsea critical failure modes, this assumption can double the failure rate. Therefore it was decided to implement the Bayesian technique.

F4 GENERAL PRINCIPLES

Bayesian methods provide a basis for combining a prior estimate of a parameter (in this case a failure rate), which may be subjecting or objecting determined, with subsequent newly observed values to form a new estimate.

In addition to the prior failure rate, an estimate is also required of the uncertainty (or variance) of this parameter.

The continuous version of Bayesian Theorem was applied.

\[
f(\theta | X) = \frac{f(X | \theta) P(\theta)}{\int_0^\infty f(X | \theta) P(\theta) \, d\theta}
\]
where:

\[ X = \text{The number of failures recorded} \]
\[ \theta = \text{The prior failure rate} \]
\[ f(\theta/X) = \text{The probability density function (pdf) of } \theta \text{ given that } X \text{ failures occur} \]
\[ P(\theta) = \text{The prior pdf of } \theta \text{ allowing for a level of uncertainty} \]
\[ f(X|\theta) = \text{The probability of } X \text{ failures occurring when the failure frequency is } \theta. \]

The following equations were used:

i) For \( P(\theta) \) the normal pdf was used.

\[
P(\theta) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(\theta - M)^2}{2\sigma^2} \right)
\]

where \( \sigma = \text{standard deviation of } \theta \text{ (variance)} \)
\( M = \text{mean value of } \theta \)

ii) For \( f(X|\theta) \) the Poisson distribution was used

\[
f(X|\theta) = \frac{\theta^X}{X!} \exp(-\theta)
\]
APPENDIX G

PHASE 1 SSIS CONFIGURATION QUESTIONNAIRE
Background: The purpose of this questionnaire is to establish the types of subsea isolation systems installed or planned so that typical configurations can be selected to be examined and reliability data collected. When complete, the form should be returned to:

M Humphreys
R M Consultants Ltd
Suite 7
Hitching Court
Abingdon Business Park
Abingdon
Oxfordshire
OX14 1RA

Tel: (01235) 555755

A. General Information

Operator Name
Field Name
Is the SSIS
   Existing
   or Committed for installation
   or Planned

Was the SSIS installed with pipeline or retrofit?
Which platform is SSIS installed/planned near?
What is the installation date/planned installation date?
What is the SSIS Company TAG number (or equivalent)?
B Pipeline Data

Which installation is the pipeline from __________________________ to __________________________.

What product is carried by the pipeline? __________________________.

Is any flow rate indication provided, if so what type? __________________________.

What is the pipeline identification number? __________________________.

- Diameter? __________________________ inches
- Total line length? __________________________ km
- Flow rate? __________________________ m³/h
- Operating pressure? __________________________ barg
- Maximum pressure? __________________________ barg

C SSIV Data

Valve vendor __________________________

Valve type (e.g. Ball, gate, check) __________________________

Valve pressure rating __________________________ barg

Valve construction (e.g. fully welded side entry, top entry, etc.) __________________________

Valve end type (e.g. flanged, welded) __________________________

Is any position indication provided, if so what type? __________________________
D Configuration of SSIS

What is the configuration of the SSIS system (eg SSIV alone, SSIV with one isolation valve, etc.)

What is the distance along the pipeline from the riser base to the SSIV?

Is a bypass arrangement included?

Is a protective structure present?

Please sketch the SSIS configuration (or include relevant drawings)
### E Controls

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>How is SSIV closure initiated?</td>
<td></td>
</tr>
<tr>
<td>Control system vendor</td>
<td></td>
</tr>
<tr>
<td>Is the actuator directly controlled or by pilot?</td>
<td></td>
</tr>
<tr>
<td>If a pilot system is used, is it electrical or hydraulic?</td>
<td></td>
</tr>
<tr>
<td>What type of power unit is present?</td>
<td></td>
</tr>
<tr>
<td>Any redundancy of power unit?</td>
<td></td>
</tr>
<tr>
<td>Are accumulators used?</td>
<td></td>
</tr>
<tr>
<td>Any redundancy of accumulators?</td>
<td></td>
</tr>
<tr>
<td>How long an umbilical is used?</td>
<td></td>
</tr>
<tr>
<td>Does the umbilical have protection, if so what?</td>
<td></td>
</tr>
<tr>
<td>What type of umbilical is used? (ie electrical, electrohydraulic etc.)</td>
<td></td>
</tr>
<tr>
<td>Is a control valve used?</td>
<td></td>
</tr>
<tr>
<td>Is the control/power system topsides or subsea?</td>
<td></td>
</tr>
</tbody>
</table>

### F Actuator

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Vendor</td>
<td></td>
</tr>
<tr>
<td>Is the actuator fluid oil or water based?</td>
<td></td>
</tr>
<tr>
<td>What is the pressure of the hydraulic supply?</td>
<td></td>
</tr>
<tr>
<td>Any redundancy of actuation system?</td>
<td></td>
</tr>
<tr>
<td>barg</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX H

SSIS FAILURE RECORD DATA REQUIREMENTS
SSIS FAILURE RECORD DATA REQUIREMENTS

The following list is the minimum data required to form a failure record for entry to the SSIS database.

1. Operator
2. Installation name
3. SSIS tag number
4. Subsystem failed*
5. Component failed
6. Date of failure
7. Description of the failure
8. How was the failure detected
9. Repair action required
10. Repair action resources
11. Repair manhours
12. SSIS downtime

The following sheets show how the failure record data could be compiled on a standard proforma.

N.B. For SSIS not included in the study it would be necessary for operators to complete a configuration questionnaire; to provide inventory data before any failure data could be collected and entered on the database.

*List of Subsystems
- Valve
- Actuator
- HPU
- Umbilical
- Surface Control Unit
- Subsea Control Pod
- Subsea Accumulator Bank
- Control Lines
POSSIBLE SSIS FAILURE RECORD QUESTIONNAIRE

1. Operator
2. Installation name
3. SSIS tag number
4. Subsystem failed (see list)
5. Components failed
6. Date of failure
7. Description of failure

8. How was the failure detected

9. Repair action required
10. Repair resources

11. Repair manhours

12. SSIS downtime

N.B. The information required above will only apply to SSIS already contained in the database. Any new systems will require an Inventory questionnaire to be filled in prior to any recording of failures.

List of Subsystems (see O.4)

- Valve
- Actuator
- HPU
- Umbilical
- Surface Control Unit
- Subsea Control Pod
- Subsea Accumulator Bank
- Control Lines