ExproSoft **ExproSoft AS** Enterprise no.: NO 881 559 692 **Main office - Trondheim** S. P. Andersens vei 15B N-7465 Trondheim, Norway Telephone: (+47) 73 59 11 48 Fax: (+47) 73 59 11 49 **Branch office – Stavanger/Sandnes:** Gravarsveien 32 N-4306 Sandnes, Norway Tlf./Phone: (+47) 51 67 63 70 Fax: (+47) 51 67 63 71	**MEMO** SUBJECT **Reliability of Acoustic BOP Controls,** ***Preliminary work***
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1. Acoustic Subsea BOP Control System Description

1.1 Introduction

An acoustic subsea BOP control system has up to now always been a back-up BOP control system. The intention of the system has been to control vital BOP functions in case of an emergency. Such an emergency would typical be a situation where the primary control system had failed completely and the BOP should be closed to prevent a hazardous situation. Today there are three major suppliers of acoustic back-up BOP control systems. They are:

- Nautronix (http://www.nautronix.com
- Sonardyne (http://www.sonardyne.com)
- Kongsberg Simrad (http://www.kongsberg-simrad.com)

They all deliver systems rated to 3000 - 4000 meters. The valve package is typical delivered by the BOP supplier.

1.2 Control Functions

Table 1 shows typical BOP acoustic system control functions.

Table 1 Typical BOP acoustic system control functions

Functions	Operations
Riser connector	Disconnect
Blind-shear ram	Close
Middle pipe ram	Close
Lower pipe ram	Close
Arm	Supply control fluid to slide valve manifold
Reset	Shut off control fluid to slide valve manifold

For ram preventers with a hydraulically operated lock function (for instance Cameron Wedgelocks) addition functions would be required. A typical acoustic control system that is delivered today can control up to 16 BOP functions.

The functions can either be activated via a permanently mounted control system on the platform, or via a portable unit from the platform, standby vessel or a life boat.

1.3 Main Subsystems

The main subsystems in a typical subsea acoustic control systems are:

Surface equipment
- Surface control units (one fixed and one portable with the same function)
- Transducers (hull mounted for the fixed control unit and portable)

Subsea equipment
- Subsea Control Unit (s), SCU (or Subsea Electronic Module, SEM)
- Transducers (one on each side of the BOP)

- Subsea valve package (solenoid valves and pilot valves)
- Accumulators
- Shuttle valves

In addition the systems are typically equipped with battery chargers and test units.

The subsea system either includes;
- two separate subsea control units (SCU), each connected one of the subsea transducers, or
- a single SCU with internal duplication, each part connected one of the subsea transducers

1.4 Command-/signal Sequence for Acoustic Control Systems

The operation of the BOP control system involves the following sequence of events, presupposed the system has been armed:

1. The operator selects and initiates the desired BOP control command in the surface control unit.
2. The command is transmitted into the water through the hull-mounted (or portable) transducer.
3. The subsea control unit receives the acoustic signal via one of the subsea transducers and decodes the acoustic message.
   - One supplier has a reed-back message stating that the command has interpreted correctly back to the surface control unit, before the surface unit transmits a signal commanding the required valve function to be executed
4. An electric signal is then sent to the appropriate solenoid in the subsea valve package.
5. The solenoid directs a pilot hydraulic flow to a pilot valve
6. The pilot valve shifts and allows hydraulic flow to the appropriate BOP function.
7. A feedback signal from the pilot valves that verifies that the operation is sent to the SCU.
8. The feedback information is then acoustically transmitted back to the surface.
9. The surface control unit via the hull-mounted transducer receives and interprets the reply and displays the appropriate command status.

Figure 1.1 shows the above sequence of events graphically. Each of the above steps is indicated.

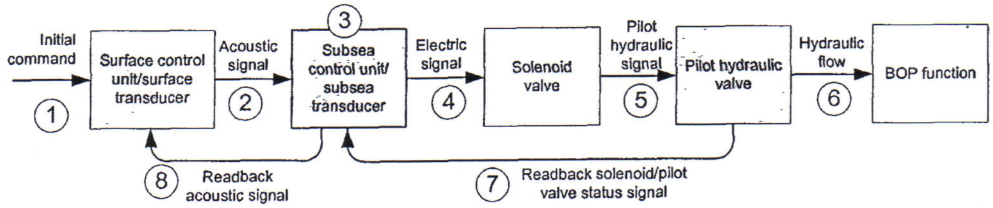

Figure 1.1 Command-/signal sequence for acoustic control systems

1.5 Electro-hydraulic Signal Conversion and Interfaces with the Main Control System

Figure 1.2 shows a typical electro-hydraulic signal conversion and interfaces with the main control system and subsea control unit for and acoustic BOP control system.

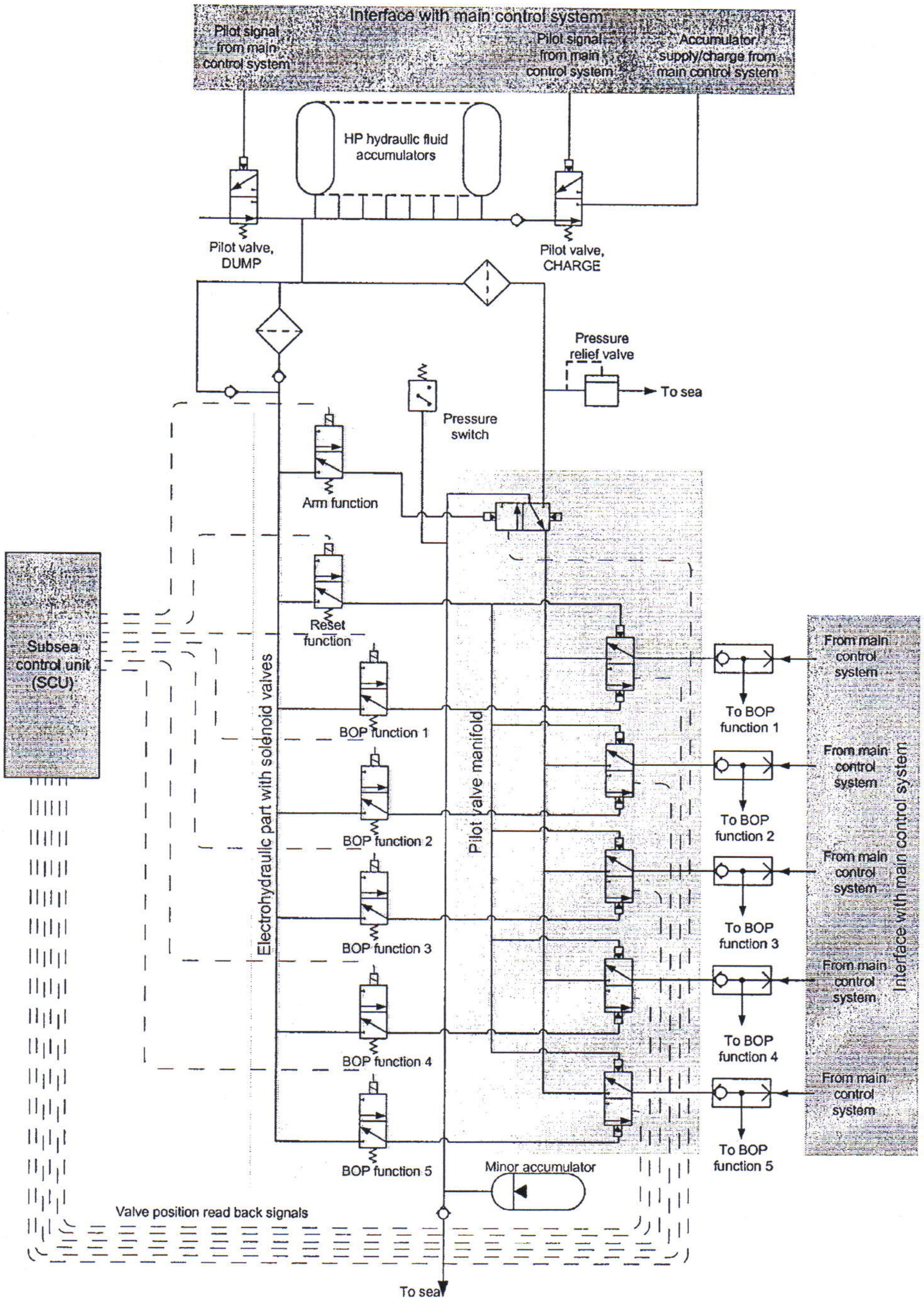

Figure 1.2 Electro-hydraulic signal conversion and interfaces with the main control system and subsea control unit

The acoustic system has interfaces to the main control system. The acoustic accumulators are charged by the main control system, the acoustic system dump valve are controlled by the main control system, and the acoustic BOP functions are separated from the main control system functions by a shuttle valve. The typically pre-charged hydraulic pressure is 3000 psi.

To actually activate an acoustic BOP function at first the *arm* signal has to be transmitted. This signal will shift the arm solenoid that again will shift the arm pilot and allow high pressure fluid to the BOP function pilot valves. When activating a BOP function solenoid valve this will shift the associated BOP function pilot valve and allow high pressure fluid to the associated BOP function. The pilot valves have read-back signals so it can be verified that they have actually shifted position.

Typically the acoustic systems are function tested without arming the system. The read-back signals from the pilot valves verify that they have actually shifted position. The arm function is typically tested by activating the shear ram when they are out of hole, frequently in association with a casing test.

From time to time other BOP functions are actually tested with the acoustic control system as well.

2. Acoustic System Failures

The reliability experience used as input data for the proposed study is based on various studies carried out by Per Holand when he was employed by SINTEF. The various studies carried out are listed at http://www.sintef.no/units/indman/sipaa/prosjekt/bop.htm.

2.1 Reliability data experience and data sources

Table 2 shows the available statistical material regarding acoustic BOP control systems reliability.

Table 2 Acoustic reliability data experience

Year Completed	Study	Drilling period and area	No. of wells	Total no. of BOP days	BOP days w/acoustic system	No. of failures recorded	Downtime caused by acoustic system (hrs)
1985	Reliability of Subsea BOP Systems - *Phase II*	1977-1983, Norway	150	8115	6161	35	458.5
1987	Reliability of Subsea BOP Systems - *Phase IV*	1984-1986, Norway	58	3809	3809	13	455
1989	Subsea BOP Systems, Reliability and Testing. *Phase V*	1987-1989, Norway	47	2636	2636	8	134
1997	Reliability of Subsea BOP Systems for Deepwater Application, *Phase I DW*	1992 – 1996, Brazil, Nor-way, Italy, Albania	138	4846	3718	13	258.5
1999	Reliability of Subsea BOP Systems for Deepwater Application, *Phase II DW*	1997 – 1998, US GoM OCS	83	4009	0	-	-
Total			476	23415	16324	69	1306

BOP-days is defined as the number of days from the BOP has landed on the wellhead the first time until it is pulled from the wellhead the last time. If the BOP is pulled during the operation due to a BOP failure this is regarded as included in the BOP time. If the well is temporarily abandoned and the rig is carrying out other operations before returning to the well, this is not included in the BOP-days.

About the studies

The Phase II study was based on wells drilled in Norwegian water in the period 1977 – 1983. The water depth was between 70 to 370 meters (230 – 1200 ft) of water. The use of acoustic back-up BOP control systems was not mandatory in Norway before 1981, so therefore for some of the wells an acoustic back-up system was not included.

The Phase IV study was based on wells drilled in Norwegian water in the period 1984 – 1986. The water depth was between 91 to 405 meters (300 – 1330 ft) of water. Acoustic backup systems were used for all the BOPs.

The Phase V study was based on wells drilled in Norwegian water in the period 1987 – 1989. The water depth was between 85 to 491 meters (280 – 1610 ft) of water. Acoustic backup systems were used for all the BOPs.

The Phase I DW study was based on deepwater wells mainly drilled in Brazilian waters and "shallow" water wells drilled in Norwegian waters. In addition eight deepwater wells were drilled in Italian and Albanian waters. Acoustic back-up systems were used for all the wells drilled in Norway and many of the wells drilled in Brazil. The wells were drilled in the period 1992 – 1996. The water depth was between 55 to 1855 meters (180 – 6090 ft).

Table 3 Water depth for Phase I DW wells where an acoustic back-up BOP control system were used

	Water depth (m)				
	< 400	*400-800*	*800-1200*	*>1200*	*Total*
Number of wells drilled	42	19	29	13	103

The Phase II DW study was based on US GoM OCS deepwater wells. None of these BOPs were equipped with an acoustic back-up control system.

Data source
The main data source for all the BOP studies has been the daily drilling reports from the wells included in the studies. In the earlier studies hard copies of the daily drilling reports have been used as data source. In the later studies the electronic versions of the daily drilling reports have been used.

2.2 Acoustic control system failures

2.2.1 Observation of Failures

Failures on the acoustic systems are normally observed during testing of the systems. From 1992 there has been a requirement to function test the acoustic system weekly when the BOP is located at the seafloor. Before 1992 the typical test of the acoustic system was to close the blind shear ram to test casing before drilling out of casing

Table 4 shows an overview of the BOP location when acoustic system failures were observed.

Table 4 Overview of the BOP location when observing acoustic system failures

Study	Location of BOP			Total
	On the rig prior to running	On the wellhead	During running BOP	
Phase II	22	13		35
Phase IV	3	9	1	13
Phase V		7	1	8
Phase I DW	5	8		13
Total	29	38	2	69

Table 4 shows that of the failures observed more than 50% of the failures were observed when testing the BOP when it was on the wellhead. From a safety point of view the failures observed when the BOP is on the rig during running and during the BOP installation test have no effect.

2.2.2 Failure Modes

Table 5 shows the failure modes for the failures that were observed during the BOP installation test and during regular BOP tests or operation.

Table 5 Failure modes for failures observed during the BOP installation test and during regular BOP tests or operation

Failure mode	BOP is on the wellhead		
	Installation test	Regular test or operation	Total
Failed to operate BOP	11	11	22
Failed to function on hull mounted transducer		3	3
Spurious operation one BOP function	2		2
Failed to operate one BOP function by the acoustic system	3	3	6
Loss of redundancy (one of two electronic channels dead)	1		1
Wrong valve position indication		1	1
No readback signal	1		1
Unknown		1	1
Total	18	19	37

Failures that occur when the BOP is on the rig, during running of the BOP and during the installation testing are not regarded as critical failures in terms of well control. During these phases of the operation the BOP is not acting as a well barrier. After the installation testing is completed and accepted, the drilling starts and the BOP is acting as a well barrier. Failures that occur after the installation test are regarded as safety critical failures. The failures that are observed during regular BOP tests or operations are the failures interesting from a safety point of view.

When looking at the failure modes it is observed that the majority of failures affect the complete system, and the result of the failure is that the system can not be operated. Only few failures are affecting one function only.

Table 6 shows the failure modes vs. the type of failure that have occurred.

Table 6 Type of failure vs. failure mode

Failure mode	Type of failure for failures observed during regular test or operation				
	Electric/-electronic	Mechanical	Signal transmission	Unknown	Total
Failed to operate BOP	2	4	4	1	11
Failed to function on hull mounted transducer	3				3
Failed to operate one BOP function by the acoustic system		2		1	3
Wrong valve position indication	1				1
Unknown		1			1
Grand Total	6	7	4	2	19

Table 6 shows that the electric/electronic, mechanical and signal transmission is equally responsible for the critical failure modes *Failed to operate BOP* and *Failed to function on hull mounted transducer*.

One of the electric/electronic failures was related to both one subsea transducer and the subsea control unit for the other transducer. For one failure the failed equipment is unknown. Three of the failures were caused by failures in the hull mounted transducer.

The mechanical failures were all related to hydraulic subsea leaks in the supply area between the accumulators and the arm valve.

2.2.3 Failure Frequencies

The signal transmission failure are related to problems with the acoustic communication in the sea water, and not any specific equipment/part failure.

Table 7 shows the Mean Time To Failure (MTTF) for the various BOP studies carried out.

Table 7 Comparison of acoustic system reliability in the various studies

Study	Failure mode	BOP is on the wellhead		
		Regular test or operation	BOP days in service	MTTF (days)
Phase II	Failed to operate BOP	5		
	Failed to function on hull mounted transducer	2		
	Wrong valve position indication	1		
	Unknown	1		
Phase II Total		9	6161	685
Phase IV	Failed to operate BOP	3		
	Failed to function on hull mounted transducer	1		
Phase IV Total		4	3809	952
Phase V	Failed to operate BOP	1		
Phase V Total		1	2636	2636
Phase I DW	Failed to operate BOP	2		
	Failed to operate one BOP function by the acoustic system	3		
Phase I DW Total		5	3718	744
Total		19	16324	859

Table 7 shows that the while Phase II, Phase IV and Phase I DW all have approximately same MTTF, while Phase V show better results. The reason why there is a difference has not been investigated, but it is likely that random statistical variations is the major cause.

Table 8 shows the average failure mode specific MTTFs.

Table 8 Failure mode specific MTTFs

Failure mode	Regular test or operation	BOP days in service	MTTF (days)
Failed to operate BOP (mechanical, electric/electronic failure)	7	16324	2332
Failed to operate BOP (signal transmission problems)	4	16324	Not relevant, on demand probability*
Failed to function on hull mounted transducer	3	16324	5441
Failed to operate one BOP function by the acoustic system	3	16324	5441
Wrong valve position indication	1	16324	16324
Unknown	1	16324	16324
Total	19		

* Signal transmission problems comes and goes the probability of occurrence is more likely to correlate to number of tests than number of days in service

It was selected not to give a MTTF figure to the failure mode *Failed to operate BOP (signal transmission problems)* since this is a random failure that comes and goes. If this failure occurs typically the acoustic system is tested some hours later and everything is OK. When carrying out the above studies drilling personnel claimed that these problems occurred fairly frequently, but they were normally not reported in the daily drilling reports. To see if this still is a problem with acoustic BOP control a maintenance superintendent that have experience from several rig, of them a fairly new floating production platform. He said that this still was a problem. From time to time they have to call up the acoustics several times to get contact, and sometimes they loose the contact with the BOP during the acoustic testing. This failure type will be followed up by talking to subsea engineers working offshore Norway for both new rigs and deepwater rigs to check if this problem has been improved.

2.3 Probability of Acoustic System Function Failure when Demanded

For simplicity only the failure modes affecting the complete acoustic system have been used for the quantified analyses of the unavailability. The failure mode affecting one BOP function only will have an insignificant effect on the system unavailability, and has therefore been disregarded. The failure modes included in the quantified analyses are:

- Failed to operate BOP (signal transmission problems)
- Failed to operate BOP (mechanical, electric/electronic failure)
- Failed to function on hull mounted transducer [1]

2.3.1 On Demand Probability

The on demand probability is used for the failure mode *Failed to operate BOP (signal transmission problems).* If assuming that the an acoustic test have been carried out before drilling out of casing, disregarding the 30" conductor and surface casing, a total of 473 tests of the acoustic system were carried out in Phase II, IV and V. For Phase I DW, 129 tests including an acoustic test were listed. This gives a total of 602 acoustic tests in the data material.

The on demand probability for a failure can be estimated by:

No. of failures/No. of demands

Based on the 4 signal transmission failures and the 602 tests the on demand probability will be:

4/602 = *0.66%.*

2.3.2 Mean Fractional Dead Time (MFDT)

The mean fractional dead time is used for the failure modes *Failed to operate BOP (mechanical, electric/electronic failure) and Failed to function on hull mounted transducer*. The MFDT of a component is the mean proportion of the time where the component is in a failed state. Consider a component with failure rate λ. Failures are only assumed to be discovered at tests, which are performed after fixed intervals of length τ. Failed components are repaired or replaced immediately after discovery.

The mean fractional dead time of such a component is

$$MFDT = (\lambda * \tau)/2$$

[1] The effect of running the portable unit into the sea has not been considered. This will take some time. For the Shell SSODD concept there will be no time for running the portable unit if an emergency shear and disconnect operation.

If assuming that the acoustic system is function tested every week; $\tau = 7$ days

MTTF = 16324 BOP days/ (7 + 3) failures = 1632 BOP days

λ = 1/MTTF = 0.0006126 failures/BOP day

MFDT = 0.0006126* 7/2 = *0.21%*

2.3.3 Acoustic System Unavailability

The sum of the above *on demand probability (0.66%)* and the *MFDT (0.21%)* will be an approximation for the unavailability, i.e. probability that the acoustic system will fail if it is needed. The unavailability will then be:

0.66% + 0.21% = ***0.87%***

2.3.4 Discussion

It is likely that the majority of failures related to the serious mechanical and electric/electronic failures are included in the basis for the above MFDT, but the *on demand probability* calculated based on the acoustic transmission problems is assumed to be all too optimistic. This because temporary lack of acoustic contact between the rig and the BOP is underreported in the data source used (see section 2.2.3). Even with the relatively few acoustic communication problems reported this problem dominates the acoustic system unavailability. If the occurrence rate of this failure type has been underestimated, this failure type will totally dominate the probability of a unsuccessful operation. Further investigation related to the probability of this type of failure will be carried out.

3. Shell concept vs. Conventional BOP Acoustic Systems

A conventional BOP acoustic system has a limited amount of functions related to closing some selected preventers and disconnecting the LMRP. The Shell shut off and disconnect device (SSODD) will need far more functions both related to opening the preventers and connectors and controlling the acoustic system itself.

If the proposed SSODD shall be built similar as an acoustic BOP control system it will need the following functions:

1. Arm function
2. Disarm function
3. Riser connector lock
4. Riser connector un-lock
5. Riser connector secondary un-lock
6. Ram 1 close
7. Ram 1 open
8. Ram 2 close
9. Ram 2 open
10. Wellhead connector lock
11. Wellhead connector un-lock
12. Dump valve open
13. Charge valve open
14. Transducer arms expand
15. Transducer arm collapse

The system will need a hydraulic supply line to charge the accumulators.

As shown in Section 2.3 the main problem from a safety point of view will be failures that affects all functions, and the increased number of functions is thereby not expected to significantly reduce the system availability. From an operational point of view the increased number of functions will however cause a regularity problem. Failures in pilots and solenoid valves needs to be repaired, this will cause rig downtime. New BOP acoustic systems have pods that can be pulled for repair. Similar type of pods should be investigated wrt the SSODD.

Relying on an acoustic system with a ROV back-up seems questionable. For normal operations as connecting riser to the wellhead, disconnecting in bad weather situations, and closing opening rams for routine purposes it seems acceptable. But for transmitting an emergency signal that starts a shear and disconnect sequence it seems dubious. If the acoustic system fails there will be no time for using an ROV. The probability of an acoustic system failure seems fairly high and a back-up emergency system that can be activated fast enough should be evaluated.

Such a systems could be a strain gauge system that is activated in case the stress on the riser exceeds a certain level. Alternatively the primary control of the SSODD device could be a simple single pod multiplex system with the acoustic system as a back-up system.

Other SSODD Considerations
When evaluating the success probability of a close and disconnect sequence for the SSODD it will also be important to evaluate that the connector may be stuck due to mechanical problems and that the shear ram may actually fail to shear the pipe. This part of the problems will, however, be similar to a conventional deepwater BOP operation.

In a study carried out for Norske Shell some years ago Norwegian wells drilled in the period 1984 – 1996 were reviewed. The blind shear rams were activated to cut pipe during operation six times. Of the six activations five was successful and one was not. For the activation that failed they attempted to shear a tooljoint. Tracking tooljoints and blind shear ram shear capacities vs. pipe used will be utmost important.

Based on the BOP studies carried, a connector will fail to disconnect in approximately one out of 100 attempts.

To be able to test the subsea shear ram wrt. internal leaks, a choke line below the ram is normally required.

When testing the BOP system including both surface BOP and the SSODD, the test plug should be set in the subsea wellhead to verify that there are no external leaks in the SSODD and the riser.