EDINBURGH OIL & GAS PLC

HATFIELD MOORS

ADDENDUM TO ANNEX B

MAY 1999

CONTENTS

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APPENDICES

1. Executive Summary

The original Annex B was issued in 1985 and under the development plan two wells, Hatfield Moors-1 and Hatfield Moors-3 have been used to produce gas via a dedicated pipeline to the Belton Brickworks factory now owned by Ibstock. Cumulative gas sales to Belton are approximately 1.4 bcf of which 1 bcf has been supplied from the Hatfield Moors field and 0.4 bcf from the Hatfield West reservoir.

In 1994 a new contract was entered into with ScottishPower to supply 2 bcf of gas over a 3 to 4 year period. The new contract required the construction of new facilities to process gas to meet the specifications of BG Transco and building a pipeline to tie into the local Transco transmission network. The location of the Transco above ground installation at Hatfield West also created the opportunity to complete for production the Hatfield West-1 well (previously suspended since 1984). An Addendum to Annex B was submitted and approved in 1994. There were no changes to the Development Area / PRT boundary under the Addendum. Cumulative gas sales under the ScottishPower contract are 2 bcf and the total field cumulative is 3 bcf.

In February/March 1998 the Hatfield Moors-3 well was abandoned and sidetracked. A new well was drilled and completed as Hatfield Moors-5. The well was drilled to improve the tail end productive potential of the field and to test whether the field, now significantly depleted, would be feasible for injection, storing and withdrawing third party gas to prolong its economic life. After studies the reservoir has been deemed suitable for a gas storage project.

Edinburgh Oil & Gas plc ("EOG") is now seeking an amendment to the present development plan to provide for the storage of third party gas. The new activity will also extend the economic life of the production of gas from the Hatfield Moors and Hatfield West fields resulting in an additional 1 bcf of recoverable gas. EOG will remain the Operator and 100 per cent owner of the Production Licences and retain full responsibility for the licence administration and reservoir management.

EOG has entered into a contract with ScottishPower to provide gas storage space for ScottishPower on an exclusive basis in the Hatfield Moors gas field. ScottishPower propose constructing a new compressor facility site approximately 1 mile from the wellsite and a large diameter pipeline connection between the wellsite, the compressor site and the Transco NTS connection point at East Butterwick. The Hatfield West gas field, which lies within the same PRT boundary, licence and development plan will continue to produce gas to the Belton Brickworks via the dedicated pipeline. The unproduced indigenous gas in the Hatfield Moors reservoir will remain in the ownership of the existing licensee. A new advanced sales contract for the supply of 0.5 bcf of gas has been agreed with ScottishPower. The gas will be produced at the end of the storage cycle (when third party gas has been emptied from the reservoir) during the first 5 years of the storage contract or at the termination of the storage contract.

Field management under the gas storage and production mode is expected to follow the following annual pattern:

June – September	-	Reservoir pressure 10 barg – injection of approximately 4 bcf gas from N.T.S., up to maximum reservoir pressure equal to or less than 45 barg.
October – February	-	Withdraw gas and export through N.T.S. system in response to ScottishPower gas portfolio requirements down to reservoir pressure of 20 barg.
March – April	-	Withdraw gas and export through Local Distribution Zone (LDZ) system down to reservoir pressure of 10 barg.

May	-	Produce indigenous gas through LDZ system down to reservoir pressure of 9 barg (maximum 0.5 bcf over 5 years).

2. Licensees and Operator

The Licensees of PL161b and PL162b at the time of the original Annex B were as follows:

Taylor Woodrow Energy Ltd (Operator)	14.25%
Candecca Resources plc	41.25%
RTZ Oil & Gas Ltd	25.00%
Elf UK plc	10.00%
Jas. Finlay plc	9.50%
	100.00%

Edinburgh Oil & Gas plc became the Operator on 1 October 1992 and at the time of the 1994 Addendum to Annex B the licencees were:

Edinburgh Oil & Gas plc (Operator)	30.625%
Kelt UK Limited	51.875%
Marinex Exploration Ltd	17.500%
	100.000%

EOG has subsequently acquired the interests of Kelt and Marinex and now holds 100 per cent of the licences.

3. Development Area

The development area to which this second Addendum applies is the same as that detailed in the original Annex B of 1985. The PRT area is similarly unchanged.

4. Geology and Geophysics

4.1 Geology

Hatfield Moors and Hatfield West

(i) Stratigraphy

The stratigraphic successions of both the Hatfield Moors and the Hatfield West areas are similar and are comprised of Westphalian (Carboniferous) deltaic sequences of shales, sandstones and coals truncated at the pre-Permian unconformity. The overlying strata consist of the Permian Magnesian Limestone succeeded by the Triassic Sherwood Sandstone which outcrops at surface.

(ii) Reservoir Rock

The reservoir rock at Hatfield Moors and Hatfield West is the Oaks Rock Sandstone of Westphalian B (Carboniferous) age.

The Oaks Rock has a thickness varying from 40 to 80 feet locally. It has a net pay thickness of about 45 feet at the Hatfield Moors-1, -3 and -4 wells. Average porosity is about 20% and permeability can be as high as 200 millidarcies. It therefore constitutes an excellent reservoir rock.

(iii) Cap Rocks

The cap rock at Hatfield Moors-5 consists of the shales, claystones and siltstones overlying the Oaks Rock Sandstone and extending up to the Magnesian Limestone.

Immediately overlying the Oaks Rock Sandstone is a tight, shaly siltstone from 1,419 to 1,433 feet TVDRKB. From 1,390 to 1,419 feet TVDRKB the section is shale within which are found three, thin seams of the Wheatworth Coal and a thin, tight siltstone bed. The uppermost thin coal is overlain by the Mansfield Marine Band consisting of dark shale (1,387 to 1,390 feet TVDRKB).

The shales throughout the whole of the above section (1,387 to 1,433 feet TVDRKB) were grey, sub-fissile, firm and non-swelling. They represent typical cap rocks for oil and gas accumulations as found throughout the East Midlands.

Overlying the Mansfield Marine Band is a 29 feet thick section of reddened claystones with some thin interbeds of siltstone and limestone. These claystones are soft and sticky, swelling in contact with water-based mud. The plasticity of these claystones is likely to have enhanced the sealing potential of the section. The integrity of the cap rock is discussed in the following section and in Appendix 1.

(iv) Hatfield Moors-5 : Geological and Well History Summary

Enclosure 1 : Composite well log of Hatfield Moors-5.
Table 1 : Stratigraphic summary of Hatfield Moors-5

In December 1997 a PONS application was made to abandon the production gas well Hatfield Moors-3, to plug it back above the perforated zone (Oaks Rock Sandstone) and then to drill a new well Hatfield Moors-5 sidetracked out of a window in the 9⅝" casing.

In February 1998 Hatfield Moors-3 was abandoned; a cement plug was set across the production perforations in the 9⅝" casing (perforation depth 1,446-1,456 feet MDRKB). The completion tubing was removed, a window was milled in the 9⅝" casing and a whipstock installed at 931 feet (MDRKB). The sidetrack well Hatfield Moors-5 kicked off from this window in Upper Magnesian Limestone formation.

Lithologies and depths from the Upper Magnesian Limestone to the base of the Lower Magnesian Limestone were identical to those of Hatfield Moors-3.

The 29 feet thick section from the Marl Slate to the Mansfield Marine Band consisted of light red-grey, soft, very sticky calcareous claystone that swelled in contact with water. This section required reaming to prevent partial sticking of the drill pipe when coming out of the hole.

From the top of the Mansfield Marine Band to the top of the Oaks Rock Sandstone the 46 feet thick section is also predominantly argillaceous but these sediments were not reddened and oxidised as in the overlying section. The shales are grey, dark-grey, sub-fissile and firm; they become siltier with some fine sand lenses near the top of the Oaks Rock. The shales were non-calcareous and non-swelling. Three thin coal seams of the Wheatworth Coal are interbedded with shales immediately below the Mansfield Marine Band.

It had been planned to set the 7" liner with the shoe in the top of the Oaks Rock Sandstone and to deal with problems of lost circulation if they occurred. This course of action was chosen to avoid possible problems that might have arisen if sticky claystones had been found overlying the Oaks Rock. Fortunately, the shales as described above, were well-indurated and stable so there were no shale-related problems.

By means of directional drilling and MWD logging the hole angle was built to near horizontal (87–89^o) close to the top of the Oaks Rock Sandstone reservoir. The top of the Oaks Rock was then penetrated but this resulted in severe lost circulation. Total depth at that stage was 1,732 feet MDRKB = $\pm$1,412 feet TVDSS (allowing for 89^o deviation and the MWD gamma sensor being 26 feet behind the bit). Losses were cured by setting two cement plugs, which extended from the Oaks Rock up to the Magnesian Limestone. The cemented section was then sidetracked and the hole redrilled. Drilling stopped at 1,640 feet MDRKB, 1,418 feet TVDRKB, 7" liner was set with shoe at 1,635 feet MDRKB with a 5 foot rat hole for cement.

The zone cased off by the 7" liner therefore includes all the shale section containing the thin coals, the overlying soft claystones and the Magnesian Limestone back to the 9⅝" casing. The zone below the 7" liner shoe to the top Oaks Rock Sandstone (1,420 – 1,433 feet TVDRKB) consists of black shaly siltstone.

In order to confirm the stability of the siltstone cap rock a two feet thick core section of the same rock from immediately overlying the Oaks Rock Sandstone (Core No.1, depths 1,443 to 1,445 feet) from Hatfield Moors-3 was subjected to triaxial strain analysis by Heriot Watt University Department of Petroleum Engineering (Appendix 1). The test results showed the cap rock to have impressive stability: even at zero reservoir pressure the rock would not become unstable. The integrity of the cap rock is therefore not in doubt.

Drilling continued with coiled tubing, underbalance, using nitrogen foam. The angle attained was 89-90° (horizontal).

The top of the Oaks Rock Sandstone was found at 1,433 feet TVDRKB, i.e. 1,407 feet TVDSS 1,710 feet MDRKB, based on cuttings and the MWD gamma ray log. Significant volumes of gas (150,000 ppm) were first recorded at depth 1,437 feet TVDRKB i.e. 1,411 feet TVDSS, 1,980 feet MDRKB. While drilling at near horizontal angles (88-91°) the well was gradually deepened to a maximum depth of 1,453 feet (TVDRKB). This increased the probability of encountering zones of high permeability that might otherwise have been missed. Excellent reservoir quality, coarse to very coarse sandstone was drilled in the zone 1,440 to 1,453 feet TVDRKB i.e. 1,414 to 1,427 feet TVDRKB. Gas was burned at the flare stack with flow rates estimated to be circa. 7 MMcfd.

Total depth was reached at 2,486 feet MDRKB. At that point a steel elbow joint in the flow line to the separator was eroded out by sand cuttings. As it was considered likely that elsewhere in the flow line or in the separator sand erosion could also have occurred, it was decided that to drill any further would be inadvisable.

Horizontal section was from 1,700 to 2,486 feet (MDRKB) = 786 feet. Horizontal section of excellent reservoir quality sandstone was from 1,950 to 2,486 feet = 536 feet.

(v) Volumetrics

The remaining gas reserves at Hatfield Moors field are calculated to be 2 bcf.

In 1998 an EOG re-interpretation found that the net sand thickness at Hatfield Moors-4 is 45 feet, not 20 feet as in a former operator's interpretation (Appendix 2). This means that a significant proportion of the GIIP would have been stored in the Hatfield Moors-4 area of the field. Total GIIP is not affected only its re-distribution. The importance of the re-interpretation is that in the area of the field extending from Hatfield Moors-1 and -5 to Hatfield Moors-4 the Oaks Rock Sandstone forms a continuous body of predominantly shale-free sandstone. This should benefit both extraction and injection of gas for storage purposes. It also diminishes the possibility of the Oaks Rock being divided into two units by a 20 feet thick shale bed forming a transmissibility barrier of unknown extent.

Concentration of the main GIIP in the above area is also supported by the reservoir simulation modeling carried out by EPS (1999).

One consequence of the redistribution of the GIIP is that the field area may be smaller than as currently mapped down to the GWC by seismic. Away from the areas of well control, seismic coverage is sparse and usually of indifferent quality and there may be areas of reservoir rock below the GWC having been downthrown by faults undetected by seismic. At the same time, the Oaks Rock is known to thin to zero towards the east and southeast, though how rapidly this thinning occurs cannot be readily predicted.

4.2 Geophysics

EOG has reprocessed (1995) and re-interpreted the available seismic covering the Hatfield Moors and Hatfield West fields.

The dataset used in the remapping comprised 85 kms of mixed vintage and source. The seismic data was acquired in 1981, 1982, 1984 and 1988 with dynamite, vibroseis and hydrapulse. Reprocessing achieved mixed results owing to poor seismic response and diversity of acquisition parameters; however, improvements to data quality were evident on some vintages, and the misties between surveys were more consistent than for the original processed data.

The main Hatfield Moors structure (Enclosure 2) is broadly similar to the previous mapping; namely an easterly dipping tilted fault block. The main sealing fault has a NE-SW strike and is downthrown to the NW. Elsewhere, the structure is dip closed to the north and east. Where the current interpretation differs is in the SW part of the structure. Here, because of poor seismic data quality, there is doubt about how far the main fault extends to the SW. Both interpretations recognise a structural high immediately to the west of Hatfield Moors-4. Ultimately, dip closure to the south is supported by Gate Farm well which encountered the Oaks Rock at 1,832 feet TVDSS.

Instead of being one simple fault block closure, the current mapping suggests the possible existence of a horst feature which marks the SW extent of the Hatfield Moors structure. This is coincident with the data being of very poor quality, and also at several line ends where the fold of cover is reduced. More seismic would be required to delineate this feature.

The Oaks Rock map only shows the main faults (which can be traced along their fault planes to corresponding discontinuities at higher and lower horizons). Smaller scale intra Westphalian and sub seismic faults are also present and may be important factors in determining the detailed reservoir structure. It is not possible to map the distribution of these lesser faults with any degree of certainty using the current 2D seismic dataset. The Hatfield Moors-5 well was incorporated into the Oaks Rock depth map by recontouring the area in proximity to the well track.

5. Development Drilling Workovers & Well Completion

(i) Development Drilling

Hatfield Moors-5 was drilled and tested in the first quarter of 1998.

The well was drilled as a sidetrack of the development well Hatfield Moors-3. Hatfield Moors-5 was drilled to increase recoverable reserves and to assess the suitability of the Hatfield Moors reservoir for the purpose of gas storage. Data gathered during the drilling phase and the interpretation of the well test data indicate that Hatfield Moors can be used for storing gas.

Hatfield Moors-5 was completed with a 7" monobore tubing string. A downhole safety valve nipple was installed at a depth of 262 feet to accommodate a wireline retrievable safety valve. The christmas tree is a 6⅜" McEvoy production tree complete with hydraulically controlled reverse actuating production valves. Figure 2 shows the completion diagram for Hatfield Moors-5. A wellhead control panel will be installed on site and will be capable of serving up to three wellheads.

(ii) Workover Activities

A number of workover options exist that would almost certainly improve the field deliverability and injectivity. A coiled tubing video survey was completed in April 1999 to investigate the open hole section in Hatfield Moors-5, which is partially blocked by various wireline tools. A fishing programme followed the camera survey but proved unsuccessful. The fish remains downhole and will certainly create a choking effect.

A few options are under consideration to recover this likely loss of well performance:

- Workover Hatfield Moors-1. The existing 2⅜" tubing can be removed and the top section of the 5" casing milled down to a depth of 200-250 feet. A 5½" completion will be installed complete with a downhole safety valve.

- Re-enter HM5 with a smaller coiled tubing BHA and attempt one of two programmes, i.e. drill around the fish and re-connect with the original wellbore or drill a new section of reservoir to obtain additional well performance.

- Drill a vertical well on the Hatfield Moors site and suspend Hatfield Moors-1.

- Drill a new development well on the Lindholme site. Planning permission has already been approved as part of the site development.

(iii) New Wells

Development drilling options have been addressed together with potential workover scenarios designed to restore field potential.

If a new well is not drilled at the Lindholme site to restore field production, it will remain as part of the longer-term strategy to expand the development. A well drilled from the Lindholme site would target the western side of the Hatfield Moors reservoir. A bottom hole location close to the Hatfield Moors-4 location should minimise the risk of drilling into an area with poor reservoir characteristics. Hatfield Moors-4 confirmed good reservoir properties as well as lateral continuity with the part of the field drained by Hatfield Moors-1 and Hatfield Moors-3.

6. Reservoir Fluid Parameters

Fluid samples were taken from Hatfield Moors-5 during the testing phase.

There is no change to the fluid composition from that submitted in the 1985 Annex B.

7. Reserves, Reservoir Engineering & Reservoir Management

(i) GIIP & Reserves

GIIP has been calculated as 5.1 bcf post-blowout plus an additional 1.4 bcf during the blowout giving a total 6.5 bcf in place pre-blowout. Commercial production started in 1987 and had reached 3.0 bcf by the end of 1998. Remaining GIP is 2.0 bcf. Remaining reserves in the Hatfield Moors reservoir have increased as a result of the Hatfield Moors-5 well. Improved deliverability should yield an additional 0.5 bcf. The remaining 2.0 bcf will be utilised as cushion gas during the storage operation but it is envisaged that 0.5 bcf will ultimately be used for. The storage project will also allow an additional 0.5 bcf to be produced from the Hatfield West reservoir that would not be economic to produce on a stand-alone basis.

Gas produced during the blowout had been estimated between 0.6-1.1 bcf. EOG used the 3D model to simulate the blow out and believe this estimate, 1.4 bcf, to be most the most reliable estimate. Additional simulation work will be required in order to improve the history match vis-a-vis the blowout.

(ii) Reservoir Engineering

Gas injection and gas production rates will vary according to the reservoir pressure. Production rates from a filled reservoir will be limited by the capacity of the export compressor. The compressor selected by ScottishPower has been sized for 60 MMSCFD.

A study, by Heriot-Watt University Department of Petroleum Engineering, had already confirmed that sand production should not occur at these operating conditions. Sand detection monitoring will be included in the surface design however to give an early warning of any long-term erosion. Erosion probes will be installed in the flowline downstream of the choke and will be connected to the ESD system.

Injection rates and injection pressure are expected to be higher than production rates. An additional study, by Heriot-Watt University, (see Appendix 3) on core plugs taken from both reservoir and cap rock samples, indicated that fracturing of the rock occurred at pressures of 2900-3000 psi. Maximum NTS pressure does not exceed 1200 psi and it is now planned to build up injection pressure to maximum NTS pressure. It is not planned to take the average reservoir pressure above the pre-blowout pressure of 650 psi in the first year. This strategy may change if greater confidence can be achieved that an increase in injected volume will not result in a loss of inventory.

(iii) Material Balance Studies

Hatfield Moors pressure depletion has indicated that aquifer activity is absent. The P/Z plot has produced a linear response with sixty percent of the post-blowout gas in place already produced, see figure 3.

A TDT study was completed in 1994 to address the potential for aquifer production and or coning prior to commencing the sale of 2.0 bcf to ScottishPower. The results of the log interpretation were that aquifer activity could not be detected.

It is concluded that aquifer activity is unlikely to present operational problems during the gas storage cycle so long as new wellbores are not inadvertently completed within close proximity of the gas water contact.

(iv) Reservoir Simulation Studies

A two-day well test was completed in March 1998 and confirmed that Hatfield Moors-5 had the necessary deliverability for use as a development well. A three rate well test produced the following results.

GAS RATE MMSCFD	DURATION HOURS	WATER RATE BBL/DAY
3.2	6	nil
9.9	6	nil
16.3	11	nil

Analysis of the data indicated that the reservoir is long and thin in shape. Radius of investigation studies indicated that a longer test period was required to assess more of the drainage area.

A thirty-day extended well test during July-August 1998 provided sufficient reservoir data to build a 3D model of the reservoir. The model was built in association with Edinburgh Petroleum Services, EPS. The interpretation was consistent with the short test confirming that Hatfield Moors-5 was located within a narrow but long section of reservoir. The impact of this geometry is the localised drop in pressure around the Hatfield Moors-5 wellbore area. The plateau rate of 60 MMSCFD is sustained for six days only before declining rapidly thereafter. This plateau can be maintained for nine days if a worked over Hatfield Moors-1 is included in the development plan.

(v) Reservoir Management

EOG will be responsible for all aspects of reservoir management during gas injection and gas production.

Gas storage will involve filling the reservoir from the NTS during periods when the demand for gas is low. The operating pressure of the NTS varies between 50-80 barg according to information supplied by BG Transco. This operating pressure is above the estimated initial pressure of the Oaks Rock, pre blow out. The Oaks Rock initial pressure has been estimated at 650 psig. It is proposed that the maximum allowable average reservoir pressure should not exceed 650 psig. This corresponds to a normal reservoir pressure gradient of 0.445 psi/ft at the gas water contact of 1,460 feet MSL.

Reservoir operating pressures will range from 650 psig when the reservoir has been filled, down to 150 psig, when the reservoir has been drained.

8. Facilities

The majority of the new facilities for the gas storage project will be located on a new site on Home Office land 1.5 km from the Hatfield Moors wellsite. These facilities will be constructed, owned and operated by ScottishPower.

The gas storage cycle will involve filling the reservoir with gas imported from the NTS at times of low gas demand and exporting gas from the reservoir at times of high demand. Gas from the NTS will flow to the Hatfield Moors wellsite via the new Lindholme site. Gas export to the NTS will also flow via the Lindholme site where it will be dried, compressed and metered prior to export. There will be some additional equipment installed at Hatfield Moors as part of the new development.

- A vertical gas liquid separator.
- A pig launcher and receiver.
- An emergency generation set.
- Phase 2 facilities will be converted from manual to automatic operation.
- An electro/hydraulic wellhead control panel.
- A chemical injection, glycol & methanol, package for hydrate control.

These facilities are designed to handle all situations associated with water production and also automate the site equipment making it compliant with the more rigorous safety demands of the new project. Figure 4 shows the wellsite layout with the additional equipment installed.

No significant volumes of gas condensate have been produced at the wellsite during the field life. Some small amounts may be produced at the new Lindholme Site through the interstage knockout pots of the compressor. Any condensate produced will belong to EOG and disposal will be the responsibility of EOG.

9. Resource Costs and Operating Expenditures

Substantially all the capital expenditure for the gas storage project is the responsibility of ScottishPower under the contract. The major elements of ScottishPower expenditure is on the new pipeline facilities and compressor station which are not on the Hatfield Moors wellsite and will be owned and controlled by ScottishPower. Capital expenditure for EOG is estimated at £150,000 and relates to Technical and Legal man-hours plus technical studies.

The operating expenditure forecast is detailed in the notes to Tables 2 and 3. The doubling of the operating costs under the gas storage mode compared to the production only status is due to significantly higher provisions for head office management and site supervision.

10. Economics

Payments to EOG under the storage contract relate to the provision of reservoir management services and the available storage capacity. The working capacity is determined by the amount of gas that can be injected into the reservoir in a 7 month period. At the minimum contract capacity of 2 bcf the capacity fee is 1p per therm equal to £200,000 and at the maximum contract capacity of 4.3 bcf the capacity fee is 2p per therm equal to £860,000. The capacity fee is indexed to oil and gas prices but cannot fall below the initial levels.

Tables 2 and 3 detail the forecast cash flows for the field with and without the storage project.

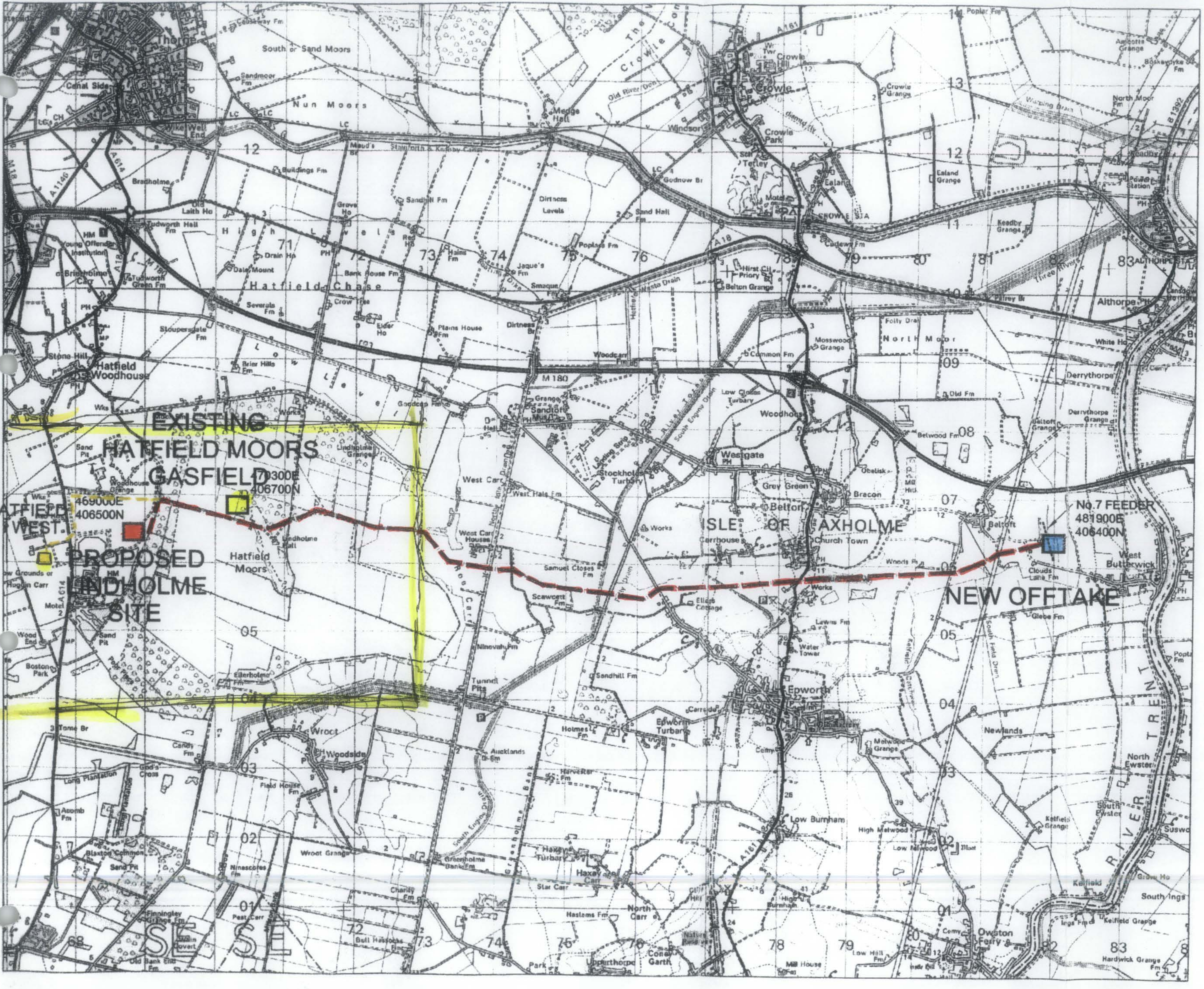


Figure 1

Proposed Total Development

Legend :

- Proposed Gas Pipeline Route (Assessed under separ Environmental Stateme
- Existing pipeline to Hatfield West
- Proposed Lindholme Site
- New Offtake
- Existing Hatfield Moors Gasfield
- Hatfield West

0 500 1000 1500 2000m

Edinburgh Oil & Gas plc

and

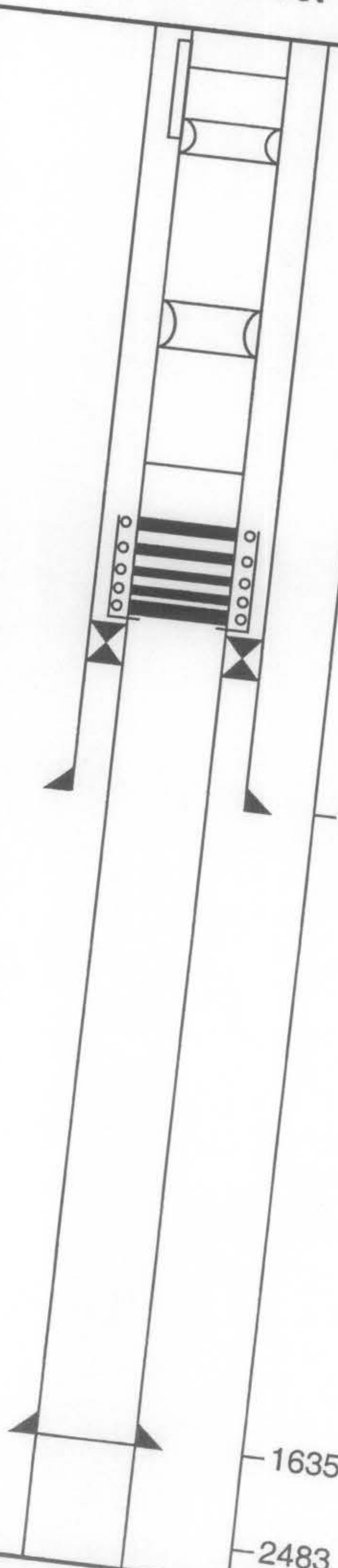
ScottishPower

EDINBURGH OIL & GAS plc

OPERATOR	**Edinburgh Oil & gas plc**
WELL	**Hatfield Moors-5**
FIELD	**Hatfield Moors**
COUNTRY	**United Kingdom**
DATE	**March 1998**
DST ☐	NEW COMPLETION ☒ WORKOVER ☐

CASING	LINER	LINER	TUBING 1	TUBING 2
SIZE	**7**		**7**	
WEIGHT (lb/ft)	**29**		**29**	
GRADE	**L80**		**L80**	
THREAD	**N. Vam**		**N.Vam**	
DEPTH	**1635**			

RKB - GL = 15 feet



Depth ft MDRKB	Tree Cap = 9.5" Otis
272	5.96" DHSV nipple c/w $^1/_4$" control line
622	5.96" landing nipple
722	Nodeco liner hanger c/w tie back packer
922	Top $9^5/_8$" casing window
1635	7" liner shoe
2483	T.D. T

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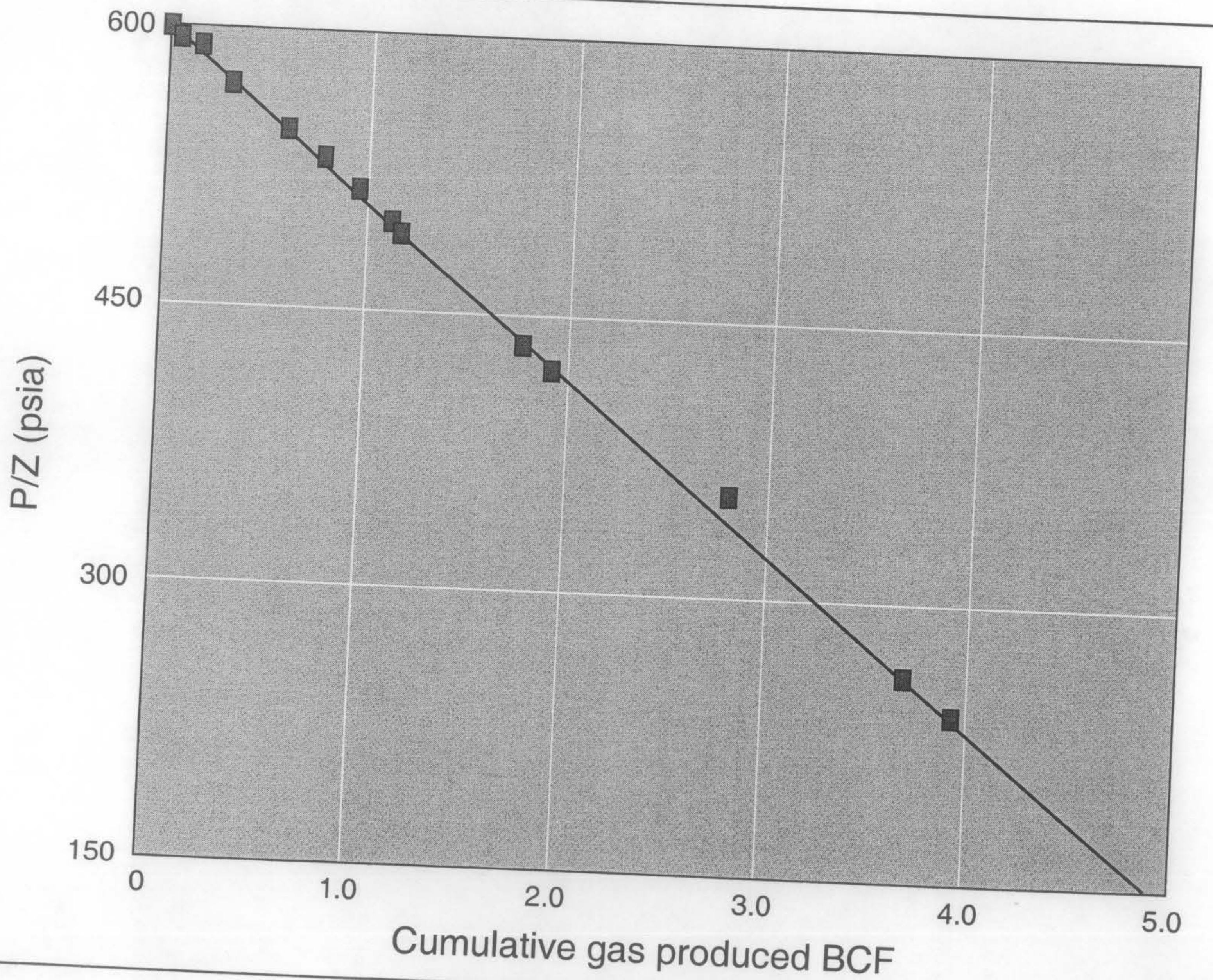
HATFIELD MOORS
RESERVOIR PERFORMANCE



Figure

N
1142-CS-1"-1C3-A
(ON EXIST. SLEEPERS)
25-V-622-CA1-2T
1149-NI-1"-1G2-N
(ON EXIST. SLEEPERS)
1150-NI-1"-1G2-N
(ON EXIST. SLEEPERS)
NITR. CILINDERS
1168-PV-6"-1C1-N
1016-FG-1"-1C1-N
Y1201
X1201
X1200
S1201
HM5
HM1
V0012
V0004
T 1
T 11
W.P. EL : 3.766
LOWEST POINT
2°/..
10%
10%
E:400.000
N:500.000
FOR DETAIL SEE DWG 82592-732-TU-3035
DIESEL GENERATOR
HOLDS :
Y-1201 INPLANTING PRELIMINARY
B ? DED JDS VBP PRE/COM ?
A 19/05/99 GIG JDS VBP PRE/COM FIRST ISSUE
REV. DATE INI. SIGN. INI. SIGN. INI. SIGN. STATUS SUBJECT OF REVISION DOCF
REVISION DRAWN CHECKED APPROVED
SCOTTISH POWER
HATFIELD MOORS GAS STORAGE PROJECT
EDINBURGH OIL & GAS plc
HATFIELD MOORS
GENERAL PIPING LAY-OUT
FIGURE 4a
REFERENCES
SCALE : 1/200
SIZE: A1 SHEET:
1st ISSUE: 19/05/99
REFERENCES TRACTEBEL INDUSTRY ENGINEERING
Tractebel Engineering International
Avenue Ariane , 7 - B-1200 Brussels
8 2 5 9 2 7 3 2 T U 3 0 3 4 B
PROJECT Nr SERVICE CODE NUMBER REV.

REV.	DATE	DRAWN INI.	DRAWN SIGN.	CHECKED INI.	CHECKED SIGN.	APPROVED INI.	APPROVED SIGN.	STATUS	SUBJECT OF REVISION	DDCF
B	?	DED		JDS		VBP		PRE/COM	?	
A	19/05/99	GIG		JDS		VBP		PRE/COM	FIRST ISSUE	

SCOTTISH POWER

HATFIELD MOORS GAS STORAGE PROJECT

EDINBURGH OIL & GAS plc

HATFIELD MOORS SITE
PIPING LAY-OUT DETAILS

REFERENCES

FIGURE 4b

SCALE : 1/50 | SIZE: A0 | SHEET: | 1st ISSUE: 19/05/99

Tractebel Engineering International
Avenue Ariane , 7 - B-1200 Brussels

REFERENCES TRACTEBEL INDUSTRY ENGINEERING

PROJECT Nr	SERVICE	CODE	NUMBER	REV.
82592	732	TU	3035	B

DECC 002b.

Enclosure 1
DECC 002C

EDINBURGH OIL & GAS plc

COMPOSITE LOG: HATFIELD MOORS - 5

LICENCE	PL162b DTI Well No. L46/11-A	
WELL LOCATION	HATFIELD MOORS GAS FIELD SOUTH YORKSHIRE ENGLAND	
CO-ORDINATES	Lat 53°33'06"N Long 00°56'15"W	
OS GRID REFERENCE	SE 40383 406669	
ELEVATIONS	Ground level AMSL	12 feet
	RKB above GL	14 feet
	RKB AMSL	26 feet
RIG	BDF Rig 28	
SPUD DATE	4 February 1998	
T.D. REACHED	3 March 1998	
T.D.	1453 feet TVDRKB (2486 feet MDRKB)	
GEOLOGIST	J Ward (EOG)	

CASING

20" set at 44 feet
$13^3/_8$" set at 872 feet
$9^5/_8$" plugged back with bridge plug set at 1250 feet AHBDF

CONTRACTORS

Drilling Contractor	Boldon
Mud logging	Datalog
MWD Gamma Ray	Integrated Drilling Services Ltd (IDS) and Scientific Drilling (horizontal hole)

WELL STATUS/CLASSIFICATION

Hatfield Moors - 5 was a deviated well drilled from the abandoned (plugged back) gas producer Hatfield Moors - 3. The well was drilled through a window milled in the $9^5/_8$" casing at 931 feet in Hatfield Moors - 3. The well is a horizontal open - hole completion in the Oaks Rock Sandstone and is a gas production/gas storage well.

NOTE 1:

Gamma ray measurements from 931 - 1420 feet TVDRKB on scale 0 - 200 API (MWD on drill pipe).

Gamma ray measurements from 1420 - 1453 feet TVDRKB on scale 0 - 150 API (MWD on coiled tubing).

NOTE 2:

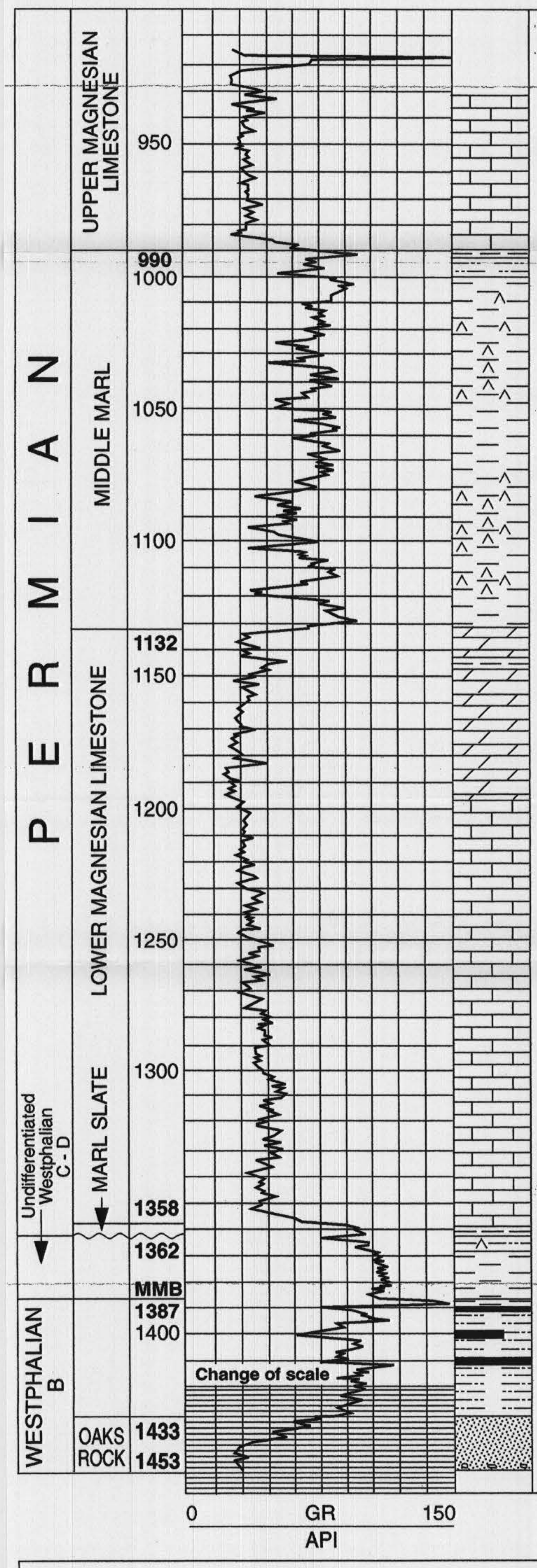
The Oaks Rock: 1433 - 1453 feet TVDRKB was drilled at near - horizontal angles;
MD 1710 - 2486 feet.

Surveys through the horizontal section recorded in report by Scientific Drilling.

LITHOLOGY KEY

CLAY	GYPSUM	DOLOMITE	OOLITHS, PISOLITHS
CLAYSTONE/SHALE	ANHYDRITE	CALCAREOUS/DOLOMITE	MICA
SILTSTONE	HALITE	VOLCANICS, TUFF etc.	FELDSPAR
SANDSTONE	POLYHALITE/SYLVITE	BASIC INTRUSIVE	PYRITE
CONGLOMERATE	MARL	ACID INTRUSIVE	GLAUCONITE
BRECCIA	CHALK	METAMORPHIC	FOSSILFEROUS
FIRECLAY/SEAT EARTH	LIMESTONE	CHERT	NO SAMPLES
COAL/LIGNITE	DOLOMITIC LIMESTONE	FERRUGINOUS CARBONATE RIBS, CONCRETIONS	
SANDY	SILTY	ARGILLACEOUS	
CARBONACEOUS	CALCAREOUS	DOLOMITIC	

STRATIGRAPHY (SYSTEM / FORMATION / DEPTH)	GAMMA RAY (0 GR 200 API)	LITH. Depth (ft) TVDRKB	SURVEYS	REMARKS



SURVEYS

Survey: 914.00, Depth 914.00 Inc 0.4, Azi 139.1
Survey: 955.90, Depth 958.00 Inc 7.7, Azi 242.3
Survey: 988.30, Depth 989.00 Inc 12.6, Azi 238.7
Survey: 1017.40, Depth 1019.00 Inc 16.6, Azi 229.0
Survey: 1046.70, Depth 1050.00 Inc 20.7, Azi 234.9
Survey: 1076.30, Depth 1082.00 Inc 24.6, Azi 234.5
Survey: 1096.10, Depth 1104.00 Inc 27.0, Azi 232.2
Survey: 1127.50, Depth 1140.00 Inc 31.6, Azi 232.2
Survey: 1153.30, Depth 1171.00 Inc 35.3, Azi 231.6
Survey: 1176.10, Depth 1202.00 Inc 38.7, Azi 232.0
Survey: 1202.60, Depth 1234.00 Inc 41.4, Azi 234.0
Survey: 1226.40, Depth 1266.00 Inc 42.4, Azi 234.5
Survey: 1246.90, Depth 1297.00 Inc 44.6, Azi 234.9
Survey: 1271.70, Depth 1330.00 Inc 47.6, Azi 233.6
Survey: 1291.40, Depth 1360.00 Inc 50.6, Azi 234.1
Survey: 1309.80, Depth 1390.00 Inc 53.6, Azi 234.5
Survey: 1329.80, Depth 1422.00 Inc 55.2, Azi 234.9
Survey: 1346.90, Depth 1453.00 Inc 57.6, Azi 232.7
Survey: 1363.40, Depth 1485.00 Inc 60.5, Azi 231.5
Survey: 1377.90, Depth 1516.00 Inc 63.6, Azi 231.4
Survey: 1390.90, Depth 1547.00 Inc 66.8, Azi 231.0
Survey: 1402.30, Depth 1578.00 Inc 70.1, Azi 230.6
Survey: 1410.30, Depth 1603.00 Inc 72.6, Azi 230.7

REMARKS

931 feet TVDRKB Kick - off point from window in $9^5/_8$" casing

LIMESTONE Off white, light grey-brown, moderately hard, microcrystalline, oolitic, slightly dolomitic especially near top.

CLAYSTONE Reddish-brown, locally grey-green, purplish, firm, locally silty, trace sandy, trace micaceous, non-to trace calcareous, with interbeds.

ANHYDRITE White, translucent, moderately hard, microcrystalline also white, soft, amorphous, trace fibrous gypsum.

DOLOMITE White, off white, light tan, with occasional grey spots/streaks, moderately hard, microcrystalline to very fine crystalline, locally peletal, locally anhydritic, poor intercrystalline to locally good intraparticle pellet, mouldic and micro-vuggy porosity, with occasional thin interbeds.

LIMESTONE Off white, light, light brown, moderately hard, microcrystalline, blocky, trace dolomite, poor intercrystalline porosity.

From Marl slate (1358 - 1362 ft) to Top Mansfield Marine Band 1387 ft:
CLAYSTONE Light grey, light red, soft, sticky, calcareous, swelling on contact with water.

Mansfield Marine Band (MMB) to base Wheatworth Coal 1387 - 1411 ft:
SHALE Grey, dark - grey, sub-fissile, firm, silty.
Coal seams at depth 1390 - 1391 ft; 1400 - 1402 ft; 1410 - 1411 ft

1411 - 1419 ft Shale
SILTSTONE Grey, firm, trace of very fine sand (poor returns)

7" Liner at 1419 feet TVDRKB

1433 - 1453 ft Oaks Rock Sandstone only loose sand grains in returns.
SAND Clear, white, fine to coarse grained, becoming coarse to very coarse below depth 1440 ft, sub-angular to rounded

T.D. 1453 feet

Enclosure 2

DECC 002d.

TABLE 1

HATFIELD MOORS-5: STRATIGRAPHY

Hatfield Moors-5 was kicked off at 931 feet TVDRKB from a window milled in the 9⅝" casing in the abandoned production well Hatfield Moors-3. Lithologies above depth 931 feet are therefore the same as for Hatfield Moors-3.

KB = 26 feet AMSL

	Depth (Feet) TVDRKB
PERMIAN	**931 – 1362**
Upper Magnesian Limestone	931 – 990
Middle Marl	990 – 1132
Lower Magnesian Limestone	1132 – 1358
Marl Slate	1358 – 1362
CARBONIFEROUS	**1362 – 1453**
Westphalian	1362 – 1453
Undifferentiated Claystones and Shales	1362 - 1387
Westphalian B	1387 – 1453 (TD)
Mansfield Marine Band	1387 – 1390
Wheatworth Coal (3 seams)	1390 – 1391 1400 – 1402 1410 – 1411
Shale/Siltstone	1411 – 1419
Siltstone grading to fine sandstone with depth	1419 – 1433
Oaks Rock Sandstone	1433 – 1453 (TD – no base reached)

TABLE 2

Hatfield Moors

(i) Current Development – Economics Assessment

	(£'000)					
	1999	2000	2001	2002	2003	2004
Belton Sales (MMSCFD)	0.25	0.25	0.25			
Sales Price (£/MSCF)	2.2	2.2	1.50			
Revenue (£'000)	200	200	136			
Opex (i)	140	140	140			
Operating Cash Flow	60	60	(4)			
Capex (Abandonment)	---	---	(100)			
Cum Cash Flow	60	120	16			

NB – Figures in 1999 money

(i) Current Opex £140k p.a. (Prod.Ops. £50k, Rent/Rates £50k, HQ £20k, Misc £20k).

TABLE 3

(ii) **Proposed Development – Economic Assessment**

	(£'000)					
	1999	**2000**	**2001**	**2002**	**2003**	**2004**
Belton Sales (MMSCFD) (Cum Vol = 0.6 bcf)	0.25	0.25	0.25	0.25	0.25	0.25
SP Sales (MMSCFD) (Cum Vol = 0.5 bcf)	0.25	0.25	0.25	0.25	0.25	0.25
Sales Price/Belton (£'MSCF)	2.20	2.20	1.50	1.50	1.50	1.50
Sales Price/SP (£'MSCF)	0.80	0.80	0.80	0.80	0.80	
Belton Sales Revenue (£'000)	200	200	136	136	136	136
SP Sales Revenue (£'000)	73	73	73	73	73	
Total Sales Revenue	273	273	209	209	209	136
Gas Storage Revenue(i)	200-860	200-860	200-860	200-860	200-860	200-860
Total Revenues	473-1133	473-1133	409-1069	409-1069	409-1069	336-996
Opex(ii)	300	300	300	300	300	300
Operating Cash Flow	173-833	173-833	109-769	109-769	109-769	36-696
Capex(iii)	150	---	---	---	---	---
Cash Flow	23-683	173-833	109-769	109-769	109-769	36-696
Cum. Cash Flow Min	23	196	305	414	523	559
Cum. Cash Flow Max	683	1516	2285	3054	3823	4522

NB – Figures in 1999 money

Notes

(i) Varies with Reservoir Injectivity performance. Low case 2 bcf at 1p per therm and High case 4.3 bcf at 2p per therm.

(ii) Cum.Storage Opex £300k (Prod.Ops. £100k, HQ/PE £100k, Maintenance/Consumable £50k, Rent/Rates £50k).

(iii) Capex £150k (Feasibility Studies, Pet.Engineering, Legal).

Edinburgh Oil & Gas plc

Report on Testing of

Siltstone Cap Rock Sample

By

Heriot-Watt University

Rock Mechanics Research Group

Appendix 1

The enclosed correspondence and report by Heriot-Watt University Rock Mechanics Research Group followed a request by Edinburgh Oil & Gas plc for triaxial strain testing of a sample of siltstone cap rock from Hatfield Moors-3. The top two feet of Core No.1 (1,445-1,447 feet) in that well consisted of hard, black, shaly siltstone forming the bottom part of the cap rock for the underlying gas bearing sandstone which comprised the rest of the core.

The tests carried out on the siltstone confirmed that the rock was very stable. It was concluded that the siltstone would not break down even if pressure in the wellbore were to be reduced to zero.

J Ward

Edinburgh Oil & Gas plc

Heriot-Watt University
Edinburgh

Department of Petroleum Engineering

FAX TRANSMISSION LEADER SHEET

FROM FAX NUMBER: 0131 451 3127

DATE: 10/3/99

This transmission consists of 3 page(s) (including this leader)

If there are any problems with the receipt of this fax, please call the sender on the number below for assistance.

To:

Name: Jim Ward

Company: Edinburgh Oil and Gas plc

Fax No: 0131 220 2253

From:

Name: Jim Somerville

Company:

Telephone No: 0131 451 3162

Message:

Dear Jim,

here is a copy of the siltstone cap rock results and a calculation of the yield zone - as you see it could stand up with nothing in the hole! We'll prepare a report and send it shortly

Regards

Jim

Head of Department
Professor Brian G D Smart
BSc, PhD, CEng, FIMinE

Heriot-Watt University
Edinburgh EH14 4AS

Tel: 0131-449 5111 (Switchboard)
Fax: 0131-451 3127
www: http://www.hw.ac.uk/

Heriot-Watt University
Edinburgh

Department of Petroleum Engineering

Direct Tel: 0131 451 3162
Fax: 0131 451 3127
Email: jim_somerville@pet.hw.ac.uk

12 March 1999

Mr Jim Ward
Edinburgh Oil & Gas plc
10 Coates Crescent
EDINBURGH
EH3 7AL

Dear Jim

Please find enclosed a copy of the report on the Hatfield Moor Cap Rock.

Yours sincerely

pp Dr JM Somerville

Encl.

Head of Department
Professor Brian G D Smart
BSc, PhD, CEng, FIMinE

Heriot-Watt University
Edinburgh EH14 4AS

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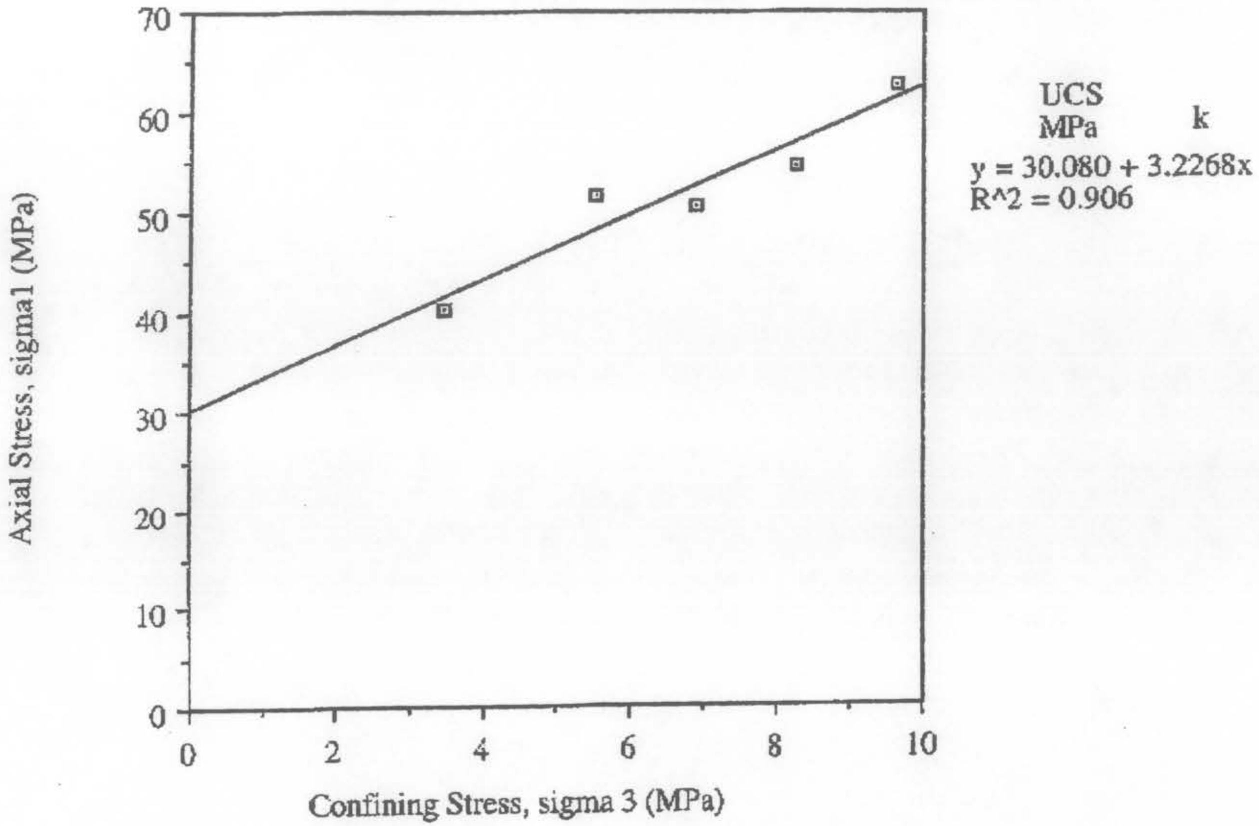
Fax: 0131-451 3127
www: http://www.hw.ac.uk/

Well No. PL 162a: Cap Rock



Yield Zone Equation

$$P_w > \left[\frac{2q - \sigma_0 + p'(k+1)}{k+1} \right] - p'$$

q = hydrostatic earth stress, equivalent to 1 psi/ft at depth = 1444 ft = 9.95 ...

σ_0 = Unconfined compressive strength, = 30 MPa (from Triaxial test)

p' = augmentation to strength caused by friction on broken rock surfaces, normally about 0.1 MPa

k = Triaxial stress factor = 3.23 (from Triaxial tests)
P_w = wellbore pressure

To prevent yield, $P_w > \dfrac{2 \times 9.95 - 30 + 0.1(3.23+1)}{(3.23+1)} - 0.1$

$$> \frac{19.9 - 30 + 0.423}{4.23} - 0.1$$

$$> -2.38 \text{ MPa}$$

i.e. Theoretically the wellbore pressure could be negative, therefore it can be taken that at zero wellbore pressure, the rock would not yield.

HERIOT-WATT UNIVERSITY

DEPARTMENT OF PETROLEUM ENGINEERING

Rock Mechanics Research Group

REPORT ON TESTING OF SILTSTONE CAPROCK SAMPLE FROM Well No. PL162a FOR EDINBURGH OIL AND GAS

March 1999

1 Objective

The objective of this report was to determine the stability of the siltstone cap rock from the top of Core 1, Hatfield Moor - 3.

2 Preparation

The sample was cut from the whole core using a diamond tipped core barrel with air flush to ensure no contamination of the plug. The plug was then trimmed to the required length for triaxial testing. The optimal sample length to ensure no influence on failure by the ends requires a length to diameter ratio of [illegible] to 4.

3 Equipment

The testing equipment consisted of a servo-controlled stiff testing machine, Hoek cell with pressure intensifier and datalogger.

3.1 Servo-Controlled Stiff Testing Machine and Pressure Intensifier

The stiff testing machine was an RDP Howden servo-controlled hydraulic machine rated to 1000kN axial load. It consisted of a straining frame which held an hydraulic ram, several platens and a load cell. The ram operated vertically with the load cell located in the crosshead of the straining frame. The position of the ram was monitored electronically by an LVDT connected to it, and this signal together with the signal from the load cell allowed the flow of hydraulic oil to the ram to be controlled. Thus the load and rate of loading were controlled.

Associated with the stiff testing machine was a pressure intensifier. This used the same principles (and hydraulic circuit) to control the confining pressure in the Hoek cell.

3.2 Hoek Cell

The cell provided a means of applying confining pressure to the samples. It consisted of a steel cell rated to 68.9MPa (10000psi) within which was located a polyurethane sleeve. Hydraulic oil filled the annulus between the body of the cell and the sleeve. The rock samples were located within the sleeve and the hydraulic oil was pressurised by a connection to the intensifier. The pressure and volume of the oil introduced or removed from the cell during the tests was monitored electronically by the testing machine to ensure a constant pressure.

4 Tests Conducted

4.1 Triaxial Tests

A series of multi-failure tests were performed to determine the failure criteria describing the development of rock strength with increasing confining pressure. The tests were driven using axial load and axial deformation outputs recorded in real time on the flat-bed plotter. At the agreed confining pressures the axial load was permitted to increase until imminent failure was detected as indicated by a rapid reduction in the rate at which the load increased. The confining pressure was increased to the next level and the axial load allowed to increase as before. The tests were terminated at the maximum confining pressure of the loading cycle by allowing the samples to fail.

A Mohr-Coulomb failure criterion was determined from the data. This is a simple linear function which can be expressed in terms of principal stress as follows:

$$\sigma_1 = \sigma_0 + \sigma_3 k$$

where σ_1 is the maximum principal stress (the axial stress in the test configuration), σ_3 is the confining pressure ($\sigma_3 = \sigma_2$), σ_0 is the unconfined (uniaxial) compressive strength and k is the triaxial stress factor (the slope of the line), where:

$$k = \frac{1+\sin\theta}{1-\sin\theta}$$

and:

θ = angle of internal friction, degrees.

The Mohr-Coulomb parameters, cohesive strength, C_o, and angle of internal friction, q, which describe the rock failure envelope (shear stress versus normal stress relationship):

$$\tau = C_o + \sigma\tan\theta$$

(where τ is the shear stress), is obtained from the $\sigma_1 = \sigma_0+\sigma_3 k$ relationship as follows:

$$C_o = \frac{\sigma_0}{2\sqrt{k}}$$

and:

$$\tan\theta = \frac{k-1}{2\sqrt{k}}$$

If the plot of axial stress versus confining pressure deviates from the straight line (elastic) relationship defined by $\sigma_1 = \sigma_0+\sigma_3 k$ as a result of plastic behaviour (strain increasing without increasing load), the Mohr-Coulomb failure parameters are calculated from the data in the elastic region.

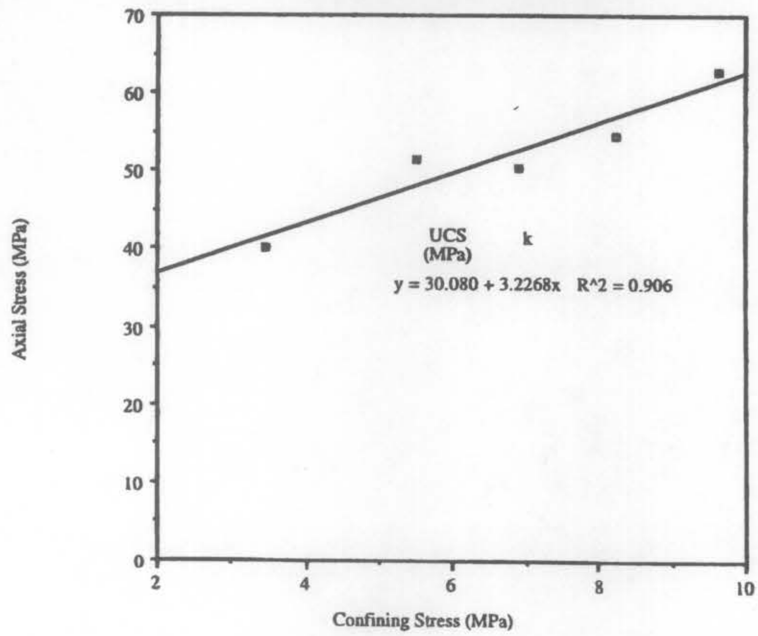
5 Test Results

A summary of the test results is given in Table 5.1 and the relationship between maximum and minimum principal stress at failure shown in Figure 5.1. The output from the flatbed plotter is given in the Appendix. A linear fit to these data produce the triaxial stress factor, k and the unconfined compressive strength, σ_0.

Diameter (mm)	Confining Stress (MPa)	Axial Load (kN)	Axial Stress (MPa)	Triaxial Stress Factor, k	Unconfined Compressive Strength (MPa)	Apparent Cohesion (MPa)	Angle of Internal Friction (°)
24.87	3.45	19.50	40.14	3.23	30.08	8.37	31.82
	5.51	25.00	51.46				
	6.89	24.50	50.43				
	8.27	26.50	54.55				
	9.65	30.50	62.79				

Table 5.1 Summary of Triaxial Test Results

Figure 5.1 Principal Stress Plot of Well No. PL162a Cap Rock



6 Determination of Stability Using Yield Zone Deformation

The determination of the stability of a borehole depends on the magnitude and direction of the principal stresses in the earth, the azimuth and inclination of the borehole and the deformation mechanism of the rock.

This involves the concept of a yield zone developing around an over-stressed hole. It is summarised in the reference by Smart and Somerville[1] and has found considerable use in UK coal mining. Briefly, the redistributed stresses around the borehole are in excess of the strength of the rock which fails. However, the broken rock still has a limited strength based on the friction between the individual sections of broken rock and the confinement around the borehole. This leads to a shedding of the redistributed stresses from the side of the borehole farther into the formation where the confinement is sufficient to fully support them. This produces a yield zone around the hole. The width of this is defined as

$$\frac{r}{r_o} = \left[\frac{2q - \sigma_o + p'(k+1)}{(p+p')(k+1)}\right]^{\frac{1}{k-1}}$$

where r is the radius of the yield zone, r_o is the radius of the borehole, q is the overburden, σ_o is the unconfined compressive strength, p' is the augmentation to strength caused by the friction on the surfaces of the broken rock (it is typically 0.1MPa for broken coal measures rocks of sandstone, siltstone and shale), k is the triaxial stress factor and p is the borehole pressure. For the condition of no yield zone i.e. stability, the equation can be rearranged to determine the borehole pressure:

$$p_w = \left[\frac{2q - \sigma_o + p'(k+1)}{(k+1)}\right] - 0.1$$

The data for the Yield Zone calculations was taken from the triaxial test results as follows:

q = hydrostatic earth stress, equivalent to 1psi/ft at depth 1444ft = 9.95Pa

σ_0 = unconfined compressive strength (from triaxial test) = 30.08MPa

p' = augmentation to strength caused by friction on the broken surfaces = 0.1MPa

k = triaxial stress factor (from triaxial test) = 3.23

Using the above data, to prevent yield the wellbore pressure p_w must be greater than -2.38MPa, i.e. at zero wellbore pressure the rock would not yield.

7 References

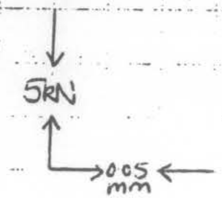
1 The Prediction of Yield Zone Development Around a Borehole and Its Effects On Drilling and Production, BGD Smart, JM Somerville, KJ MacGregor, Rock Mechanics As A Multidisciplinary Science. Proceedings of the 32nd Symposium 1991.

Appendix

Edinburgh Oil & Gas

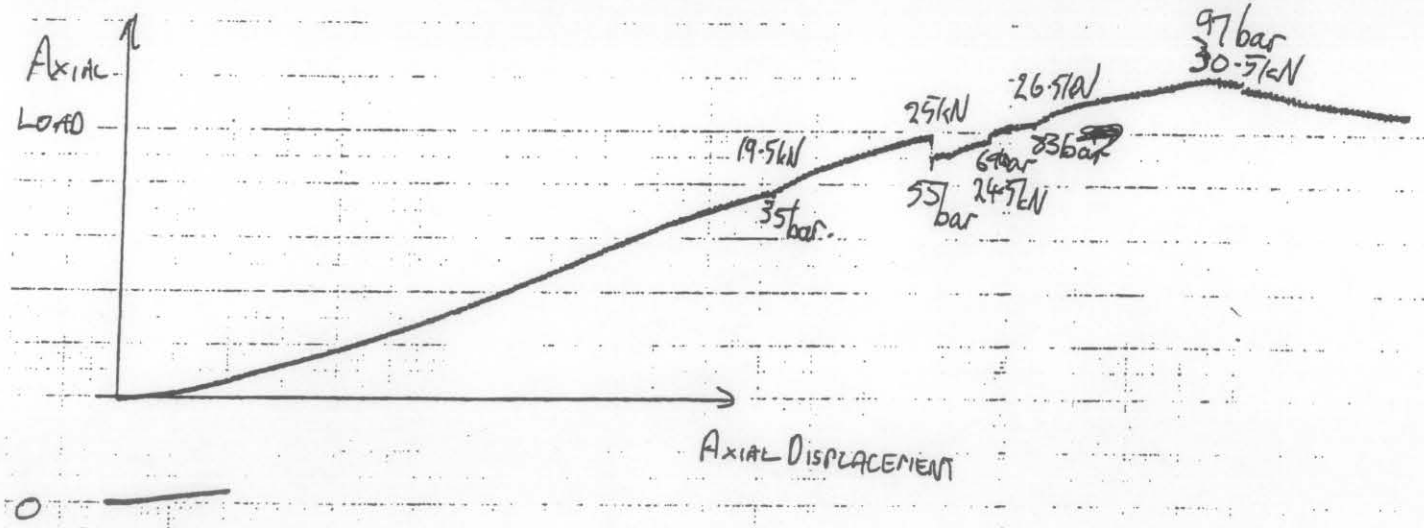
MFS Testing

Caprock from Top of Core 1.



5kN/

0.05 mm/



Edinburgh Oil & Gas plc

Re-Interpretation of the Lithology

of the Oaks Rock at

Hatfield Moors-4

Appendix 2

Re-interpretation of the Lithology of the Oaks Rock at Hatfield Moors-4

In the Hatfield Moors-4 Completion Log, Taylor Woodrow (1986) interpreted the interval 1,451-1,473 feet (TVD) within the Oaks Rock to be shale (figure 1a). The Taylor Woodrow interpretation appears to have been based on the gamma ray log recorded over the Oaks Rock in Hatfield Moors-4. This gives a shaly response over a twenty feet thick interval in the middle of the formation. No comparably thick interval of shale has been encountered in the Oaks Rock in any of the eight other wells or boreholes in the area. The gamma ray in Hatfield Moors-4 was recorded through production tubing in a high angle micro-drilled hole. Open hole logging tools had been unable to reach the bottom of the hole. This shale response has an unusual appearance and may be an artifact of the non-conventional tool. On the other hand a neutron log also run in the tubing over the same interval provided a signature that very closely resembles that of the density log obtained over the corresponding interval in Hatfield Moors-2 which was cored and consists predominantly of sandstone with only minor coaly lenses. The similarities of these two log characters are shown in figures 1b and 1c. The mud log and wellsite geology logs of Hatfield Moors-4, based on cuttings, also describe the Oaks Rock as being sandstone with shale only present (4 feet) at the base of Core no.3. Nor is there any mention of a 22 feet thick shale section in the Hatfield Moors-4 Completion Report.

To resolve lithological uncertainty the Hatfield Moors-4 cuttings have been re-examined (J Ward, 1998). No shale cuttings were present in the Oaks Rock other than cavings of evaporitic red bed facies from the section underlying the Magnesian Limestone higher up the hole. Such cuttings contamination could be expected on resumption of drilling following the cutting of Core No.3. The remaining cuttings were of abundant medium loose sand grains derived from a clean sandstone. The Oaks Rock lithology based on the re-examination is shown in figure 1b. Comparison of the core description for the corresponding section in Hatfield Moors-2 shows the two sections to be reasonably similar. It is concluded that in Hatfield Moors-4 the Oaks Rock is predominantly sandstone with a 4 feet thick shaly bed at 1,445-1,449 feet (TVD).

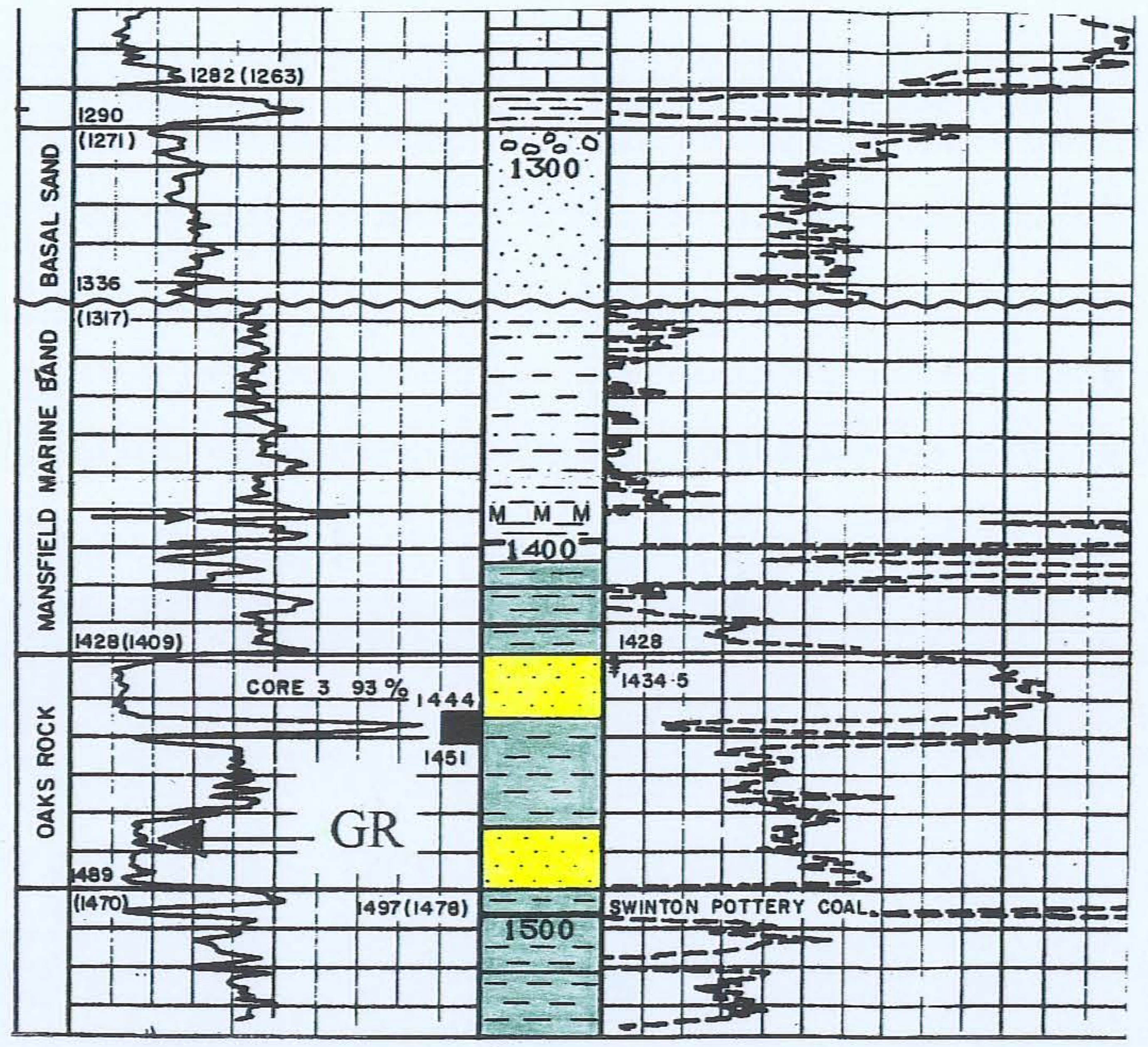
The net sandstone in the Oaks Rock at Hatfield Moors-4 is therefore 45 feet, not 20 as in previous interpretations. It is now more likely that there is a continuous body of thick reservoir sandstone extending from Hatfield Moors-4 to Hatfield Moors-1 and Hatfield Moors-5 and the possibility that the Oaks Rock middle section might become predominantly shaly in the southwest part of the field now appears less likely. It follows that with a thicker net sand section the volumes of gas present in the rock in that area will be greater than in previous calculations. The overall field gas reserves are not increased, only re-distributed, but gas recovery may be more efficient.

DECC 002e

Figure 1a

Taylor Woodrow Interpretation

Hatfield Moors-4



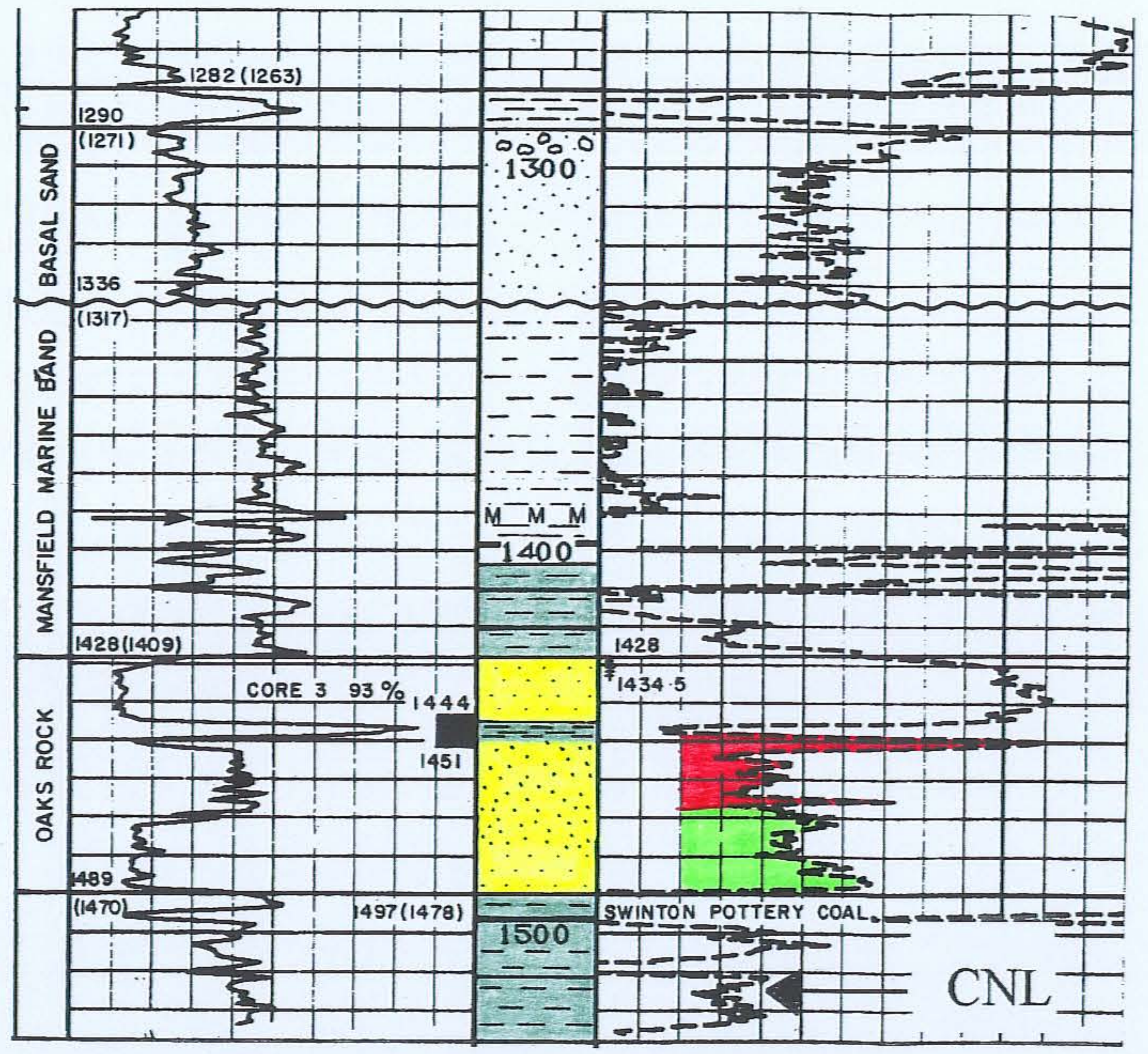
Taylor Woodrow Interpretation

In the Taylor Woodrow interpretation the Oaks Rock includes a 27 feet thick shale bed (1,445-1,472 feet).

Figure 1b

Re-interpretation of the Oaks Rock lithology by Edinburgh Oil & Gas plc

Hatfield Moors-4



Re-interpretation of the Oaks Rock lithology by Edinburgh Oil & Gas plc

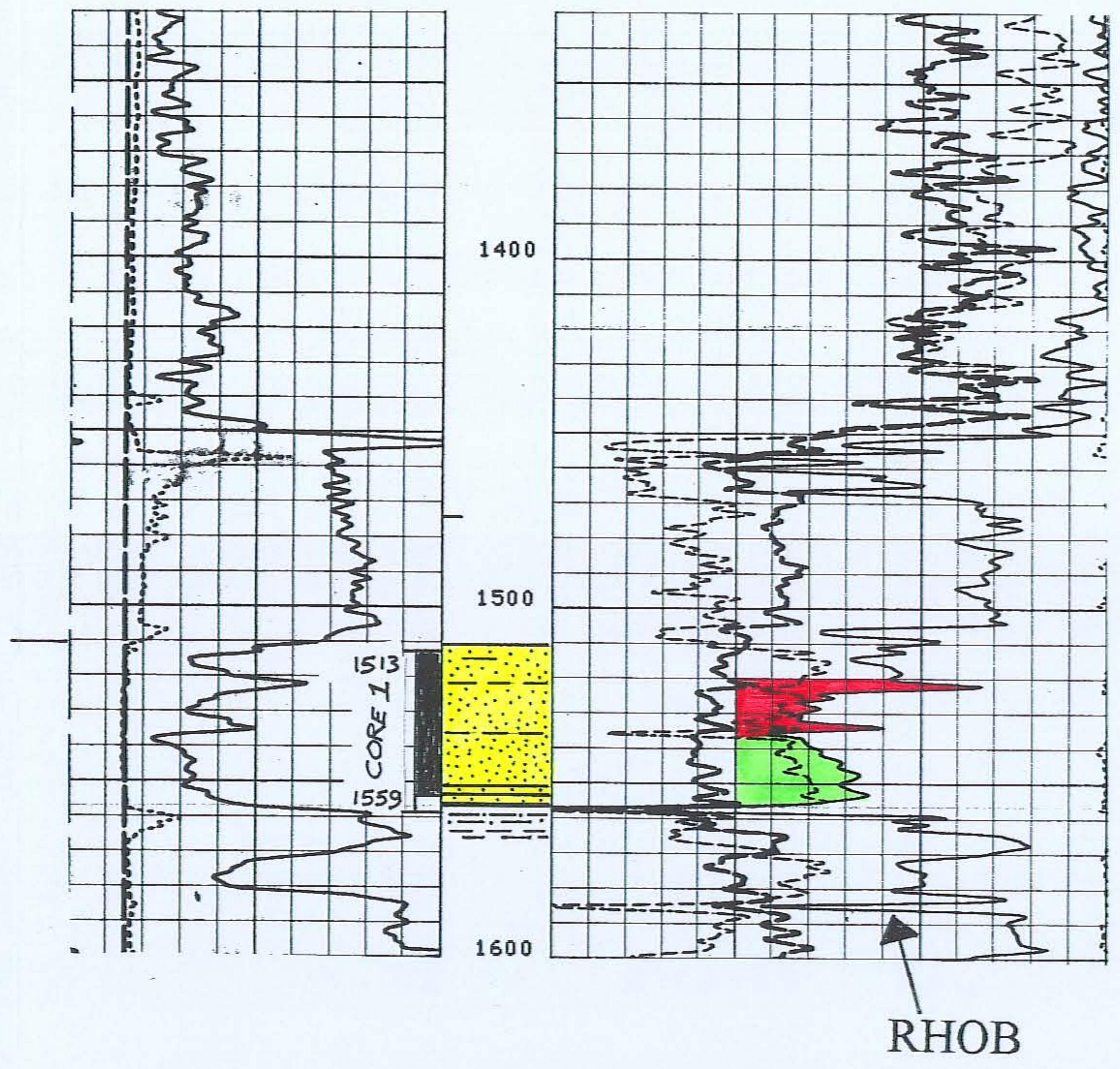
Re-examination of cuttings from the Oaks Rock section of Hatfield Moors-4 shows the lithology to be predominantly sandstone.

Note: The CNL log of Hatfield Moors-4 (1,451-1,490 feet) resembles the character of the RHOB (density) log of Hatfield Moors-2 (1,520-1,556 feet).

That section in Hatfield Moors-2 was cored and contains only very thin (less than 1 foot) lenses of shale. (Figure 1c)

Figure 1c

Hatfield Moors-2



Edinburgh Oil & Gas plc

Hatfield Moors Gas Field

Re-interpretation of the lithology of the Oaks Rock at Hatfield Moors-4 and comparison with Hatfield Moors-2

J Ward	March 1999

Edinburgh Oil & Gas plc

Report on Borehole Stability

Analysis of Well PL162a

By

Heriot-Watt University

Rock Mechanics Research Group

Appendix 3

Heriot-Watt University
Edinburgh

Department of Petroleum Engineering

Direct Tel: 0131 451 3162
Fax: 0131 451 3127
Email: jim_somerville@pet.hw.ac.uk

AAB	A
TO	BR / JW
INFO	
12 MAY 1999	
ACT	
FILE	

11 May 1999

Brian Ramsay
Edinburgh Oil and Gas
10 Coates Crescent
Edinburgh
EH3 7AL

Dear Brian

Please find enclosed a copy of the report on the stability of well PL162a - Hatfield Moor.

Yours sincerely

Dr JM Somerville

Encl.

Head of Department
Professor Brian G D Smart
BSc, PhD, CEng, FIMinE

Heriot-Watt University
Edinburgh EH14 4AS
Tel: 0131-449 5111 (Switchboard)
Fax: 0131-451 3127
www: http://www.hw.ac.uk/

HERIOT-WATT UNIVERSITY

DEPARTMENT OF PETROLEUM ENGINEERING

Rock Mechanics Research Group

REPORT ON BOREHOLE STABILITY ANALYSIS OF WELL PL162a FOR EDINBURGH OIL AND GAS

May 1999

DETERMINATION OF THE FAILURE LIMITS OF A WELLBORE

1 Introduction

This report details the determination of the stability of a wellbore in sandstone with a silty mudstone caprock. Analytical solutions to the stress distribution around the hole were used; they represent conditions of elastic and inelastic failure in porous and nonporous rock for vertical and horizontal holes.

The majority of the strength data were generated in previous studies; the tensile strength data are reported in this work.

2 Objectives

The first objective was to determine the tensile strength of a series of samples from a sandstone reservoir and the caprock of silty mudstone.

The second objective was to determine the stability limits of a wellbore subjected to various stresses generated around it.

3 Preparation

Table 1 shows the availability of the core for tensile testing after previous work had been conducted. From the available core, discs of rock were cut using a diamond tipped saw with air flush. The dimensions are shown in Table 2.

4 Equipment

The testing equipment consisted of a servo-controlled stiff testing machine within which the discs were loaded.

5 Brazilian disc test

Stress analysis shows that the tensile stress developed at the centre of a disc loaded in compression across its diameter is as follows:

$$\sigma_t = \frac{2 * Load}{\pi * d * t}$$

where σ_t is the tensile stress, d is the diameter of the disc and t is the thickness of the disc.

6 Tensile Test Results

The results of the tensile tests are shown in Table 2. Where more than one disc was tested, the average value has been reported. The overall average for the sandstone was 1.45MPa and 4.31MPa for the caprock. The raw data are shown in Appendix 1

7 Analysis of stability

The stability analysis used the analytical solutions presented in Appendix 2 with the rock test results. Previous work[1,2] measured the compressive strength parameters from some of the reservoir sections (Table 1), however, not all of the core was available for a full suite of tests on all of the reservoir section and where there was a shortfall, assumptions as to the strength values have been made.

The analysis was conducted in 4 sections:
i) elastic shear and tensile failure - no pore fluid
ii) poro-elastic shear and tensile failure - pore fluid
iii) yield zone development - no pore fluid
iv) thick wall cylinder analysis.

Most of the failure criteria are developed in Fjaer et al[3]; some additional geometries were developed for this analysis and are shown in Appendix 2.

7.1 Elastic analysis

The elastic analysis consists of

i) vertical well- hydrostatic stress
ii) vertical well - different horizontal stresses
iii) horizontal well - equal horizontal stresses (which are 75% of the vertical stress)
  - a: limit to wellbore pressure where the tangential stress is greater than the radial stress (wellbore pressure)
  - b: limit to wellbore pressure where the axial stress (i.e. along the length of the well) is greater than the radial stress (wellbore pressure)

For each of these, the failure criterion can be either shear caused by too low wellbore pressure; shear caused by too high wellbore pressure and finally tensile failure caused by too high wellbore pressure which overcomes the tensile strength of the rock.

7.2 Poroelastic analysis

The poroelastic analysis is identical to the elastic analysis but includes the effect of pore pressure. There are 2 conditions:

i) vertical well, equal horizontal stresses, impermeable borehole wall
ii) vertical well, equal horizontal stresses, permeable borehole wall and steady state fluid flow.

The failure criteria are the same as for the elastic analysis above.

7.3 Yield zone analysis[4]

This was restricted to the case of hydrostatic stresses with no pore fluid. The failure criterion predicts the minimum wellbore pressure to resist the formation of a yield zone.

The results are close to the pure elastic analysis since the assumption has been made that no failure would be allowed.

7.4 Thick wall cylinder analysis

This relates the strength of the cylinder to elastic failure depending on the nature of the applied stresses: hydrostatic or different horizontal and vertical stress.

The results are used to predict the bottomhole pressure that a wellbore could sustain before failure. There is an upper and lower bound based on the assumption of equal earth stresses (upper) or different vertical and horizontal stresses (lower). The high TWC results mean that numerically, the bottomhole pressure could be less than zero, therefore it has been taken that for both conditions, the bottomhole pressure could be zero. This is considerably lower than the elastic, poroelastic and yield zone analysis and probably reflects the difficulty of applying realistic stresses to the sample, i.e. the stress insitu will probably not be hydrostatic and will lead to the development of a complex series of shear and normal stresses around the borehole and in the borehole wall.

7.5 Results

Appendix 3 shows the results of the stability analysis. For sample 2, the summary sheet is followed by the individual analytical solutions for various stresses etc. For samples 3 to 10 and the caprock, only the summary sheets are shown. The input data are as shown: where there was no test result, a typical value was assumed based on the results for the surrounding samples. The most important result is for the combination of poroelasticity, no flow at the wellbore for a vertical well: Table 3 summarises the upper limits of pressure applicable to cause failure. All of the reservoir samples show an average tensile limit of 2637psi and an average shear limit of 2629psi. The limits for the caprock are and 2922psi for the tensile and 2904psi for the shear failure modes. Assuming the overburden gradient is 1psi/foot, values of 2900psi pore pressure would exceed the overburden pressure and the reservoir would not remain intact. These values may be sustainable around the wellbore (if there was no leakage into the reservoir) where the redistributed overburden stresses are greater than the far field overburden stresses, however, realistically, pore pressures during injection would need to be below overburden to prevent failure of the reservoir rock.

8 References

1 Report on Sand Production Study of Well No. PL162a for Edinburgh Oil and Gas, February 1998

2 Report on Testing of Siltstone Caprock Sample from Well No. PL162a for Edinburgh Oil and Gas, March 1999

3 Petroleum Related Rock Mechanics, E Fjaer, RM Holt, P Horsrud, AM Raaen, R Risnes, Elsevier, 1992

4 The Prediction Of Yield Zone Development Around A Borehole And Its Effect On Drilling And Production, BGD Smart, JM Somerville, KJ MacGregor, Rock Mechanics As A Multidisciplinary Science. Proceedings of the 32nd US Symposium 1991

Core samples tested as part of sand production determination		Core samples available for tensile strength determination	
Sample Number	Depth (ft)	Sample Number	Depth (ft)
2	1148	2	1148
3	1454		
4	1458	4	1458
5	1466		
6	1481	6	1481
		7	1488
		8	1495
		9	1498
10	1540	10	1540
caprock	<1148	caprock	<1148

Table 1 Sample Availability

Sample Number	Diameter (mm)	Length (mm)	Load at failure (kN)	Tensile strength (MPa)	Average tensile strength (MPa)
2	24.40	24.29	1.10	1.18	1.18
4a	37.98	20.38	0.90	0.74	0.85
4b	37.92	20.14	1.15	0.96	
6a	24.61	12.25	0.40	0.84	1.20
6b	24.53	13.27	0.80	1.56	
7a	38.10	22.10	2.15	1.63	1.48
7b	38.12	21.77	1.75	1.34	
8a	38.17	20.76	3.00	2.41	2.17
8b	38.17	20.34	2.35	1.93	
9a	38.13	20.38	2.25	1.84	1.81
9b	38.16	21.01	2.25	1.79	
caprock 1	75.00	34.81	14.80	3.61	4.31
caprock 2	25.27	26.19	5.20	5.00	

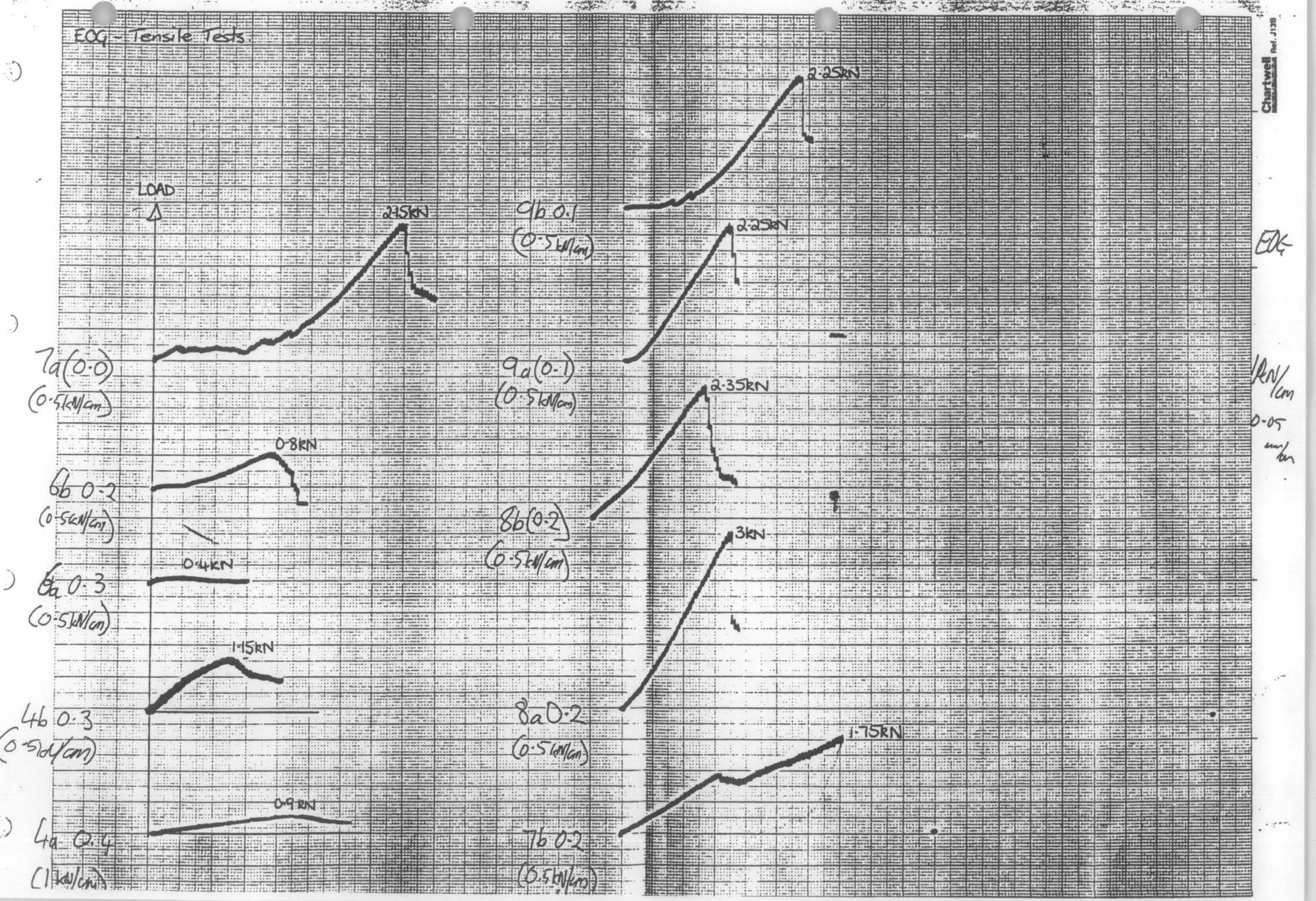
Table 2 Tensile Test Results

Sample Number	Shear failure if wellbore pressure is above		Tensile failure if wellbore pressure is above	
	(MPa)	(psi)	(MPa)	(psi)
2	16.22	2350	17.70	2565
3	18.42	2670	17.66	2560
4	17.49	2535	17.27	2503
5	18.02	2611	16.63	2410
6	19.18	2780	18.16	2632
7	17.36	2516	18.54	2687
8	19.11	2769	19.33	2801
9	18.26	2647	19.01	2755
10	19.20	2782	19.48	2823
caprock	20.04	2904	20.16	2922

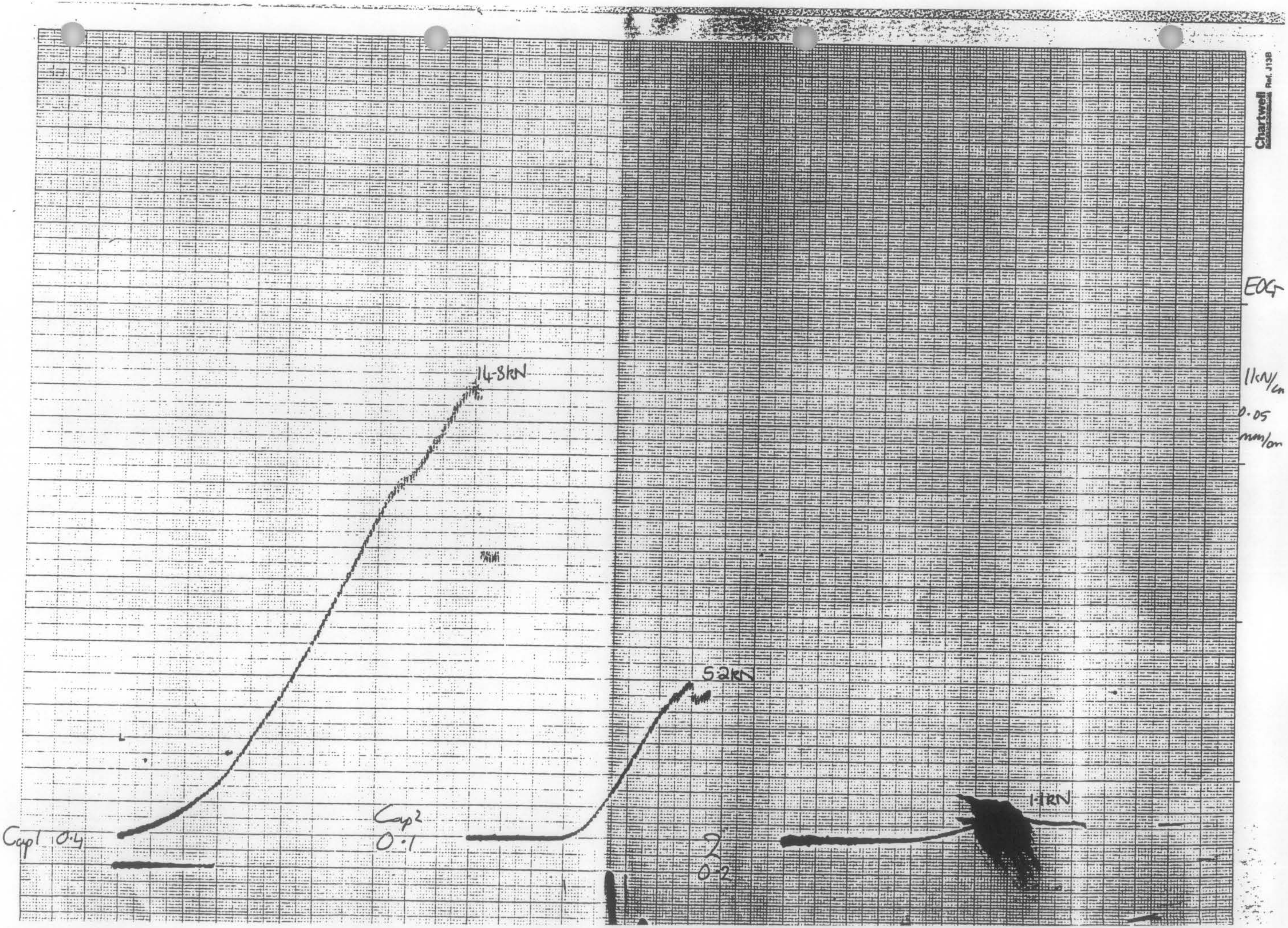
Table 3 Upper Limits to Wellbore Pressure

Appendix 1

Tensile Strength Data



EOG - Tensile Tests
LOAD
2.75kN
7a (0.0)
(0.5kN/cm)
0.8kN
6b 0.2
(0.5kN/cm)
0.4kN
6a 0.3
(0.5kN/cm)
1.15kN
4b 0.3
(0.5kN/cm)
0.9kN
4a 0.4
(1kN/cm)
2.25kN
9b 0.1
(0.5kN/cm)
2.25kN
9a (0.1)
(0.5kN/cm)
2.35kN
8b (0.2)
(0.5kN/cm)
3kN
8a 0.2
(0.5kN/cm)
1.75kN
7b 0.2
(0.5kN/cm)
EOG
1kN/cm
0.05 mm/cm
Chartwell



Chartwell Ref. J13B
EOG
1kN/cm
0.05
mm/cm
14.8kN
5.2kN
1.1kN
Cap1 0.4
Cap2
0.1
2
0.2

Appendix 2

Development of Borehole Stability Equations

Borehole Stability

Non-permeable, non-poroelastic.

1. Vertical hole, isotropic σ_h

principal stresses at wall

$$\sigma_r = P_w$$
$$\sigma_\theta = 2\sigma_h - P_w$$
$$\sigma_z = \sigma_v$$

| out of book + OK

Shear failure

a) for $\sigma_\theta > \sigma_z > \sigma_r$

Mohr Colomb is $\sigma_\theta = C_0 + \sigma_r \tan^2\beta$ $\quad (\sigma_1 = k\sigma_3 + \text{UCS})$

i.e. $P_w = \dfrac{2\sigma_h - C_0}{\tan^2\beta + 1}$ | book

b) $\sigma_r > \sigma_z > \sigma_\theta$

$$\sigma_r = C_0 + \sigma_\theta \tan^2\beta$$

$P_w = \dfrac{2\sigma_h \tan^2\beta + C_0}{\tan^2\beta + 1}$ | book

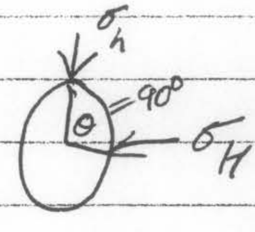
Tensile failure

$P_w = 2\sigma_h + T_0$ | book

2. Deviated hole, anisotropic σ_h

at b/hole wall

a) vertical well, $\sigma_H > \sigma_h$, Shear



$$P_w = \frac{3\sigma_H - \sigma_h - C_0}{\tan^2 \beta_H}$$ | book

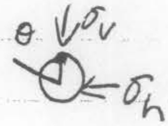
Tensile

$$P_w = 3\sigma_h + \sigma_H + T_0$$ | book

b) Horizontal Well, $\sigma_H = \sigma_h$, b/h wall, no shear stress. (σ_H actually $= \sigma_z$)

$$\sigma_r = P_w$$
$$\sigma_\theta = \sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - P_w$$
$$\sigma_z = \sigma_h - 2\nu\cos 2\theta(\sigma_v - \sigma_h)$$ | book

i. $\sigma_\theta > \sigma_z > \sigma_r$



$$\sigma_\theta = C_0 + \sigma_r \tan^2\beta$$

$$\sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - P_w = C_0 + P_w \tan^2\beta$$

$$\sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - C_0 = P_w + P_w \tan^2\beta$$
$$= P_w(1 + \tan^2\beta)$$

$$P_w = \frac{\sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - C_0}{(1 + \tan^2\beta)}$$

check ✓

2. $\sigma_z > \sigma_\theta > \sigma_r$

$$\sigma_r = P_w$$

$$\sigma_\theta = \sigma_h + \sigma_v - 2\cos 2\theta(\sigma_v - \sigma_h) - P_w$$

$$\sigma_z = \sigma_h - 2\nu\cos 2\theta(\sigma_v - \sigma_h)$$

Mohr : $\sigma_z = C_0 + \sigma_r \tan^2\beta$

$$\sigma_h - 2\nu\cos 2\theta(\sigma_v - \sigma_h) = C_0 + P_w \tan^2\beta$$

$$\sigma_h - 2\nu\cos 2\theta(\sigma_v - \sigma_h) - C_0 = P_w \tan^2\beta$$

$$P_w = \frac{\sigma_h - 2\nu\cos 2\theta(\sigma_v - \sigma_h) - C_0}{\tan^2\beta}$$

Check ✓

Poro-elastic

1. Impermeable

Failure criterion $\sigma_1 - \alpha P_f = C_0 + (\sigma_3 - \alpha P_f)\tan^2\beta$ | book OK

Vertical well.

for $\sigma_\theta > \sigma_z > \sigma_r$, shear failure, horiz. iso stress.

$$P_w \le \frac{1}{\tan^2\beta + 1}\left[2\sigma_h + \alpha P_f\left(\tan^2\beta - 1\right) - C_0\right]$$ | book OK

$\sigma_r > \sigma_z > \sigma_\theta$

$$P_w \ge \frac{1}{\tan^2\beta + 1}\left[2\sigma_h \tan^2\beta - \alpha P_f\left(\tan^2\beta - 1\right) + C_0\right]$$ | book OK

Vertical well, isohoriz, Tensile failure

$$P_w = 2\sigma_h - \alpha P_f + T_0$$ | book OK

2. Permeable stress with flow.

Book OK → Given

$$\sigma_r = \sigma_h - (\sigma_h - P_w)\left(\frac{R_i}{r}\right)^2 + (P_{fo} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha\left[\left(\frac{R_i}{r}\right)^2 - \frac{\ln(R_o/r)}{\ln(R_o/R_i)}\right]$$

$$\sigma_\theta = \sigma_h + (\sigma_h - P_w)\left(\frac{R_i}{r}\right)^2 - (P_{fo} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha\left[\left(\frac{R_i}{r}\right)^2 + \frac{\ln(R_o/r)}{\ln(R_o/R_i)}\right]$$

$$\sigma_z = \sigma_v - (P_{fo} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha\,\frac{2\ln(R_o/r) - \nu}{\ln(R_o/R_i)}$$

R_i = borehole radius, R_o = outer radius.

for stresses at b/hole, $r = R_i$

$$\therefore \sigma_r = \sigma_h - (\sigma_h - P_w)\times 1^2 + (P_{f_0} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha\left[1^2 - 1\right]$$

$$= \sigma_h - (\sigma_h - P_w)$$

$$= P_w$$

$$\sigma_\theta = \sigma_h + (\sigma_h - P_w)\times 1^2 - (P_{f_0} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha\left[1^2+1\right]$$

$$= \sigma_h + (\sigma_h - P_w) - (P_{f_0} - P_w)\frac{1-2\nu}{2(1-\nu)}\alpha . 2$$

$$= \sigma_h + (\sigma_h - P_w) - (P_{f_0} - P_w)\frac{1-2\nu}{(1-\nu)}\alpha$$

$$= 2\sigma_h - P_w - (P_{f_0} - P_w)\frac{1-2\nu}{1-\nu}\alpha$$

Check

Failure criterion:

$$\sigma_1 - \alpha P_f = C_0 + (\sigma_3 - \alpha P_f)\tan^2\beta$$

book OK

Since borehole now permeable and pore pressure changes, P_f is now P_{f_0} at the initial condition and P_w at the well.

1. $\sigma_\theta \geq \sigma_z \geq \sigma_r$ $= \sigma_\theta = \sigma_1$; $\sigma_r = \sigma_3$

$$\sigma_\theta - \alpha P_w = C_0 + (\sigma_r - \alpha P_w)\tan^2\beta$$

$$2\sigma_h - P_w - (P_{f0} - P_w)\frac{(1-2\nu)}{(1-\nu)}\alpha - \alpha P_w = C_0 + (P_w - \alpha P_w)\tan^2\beta$$

$$2\sigma_h - P_w - P_{f0}\alpha\frac{(1-2\nu)}{(1-\nu)} + P_w\alpha\frac{(1-2\nu)}{(1-\nu)} - \alpha P_w = C_0 + P_w\tan^2\beta - \alpha P_w\tan^2\beta$$

$$2\sigma_h - P_{f0}\alpha\frac{(1-2\nu)}{(1-\nu)} - C_0 = P_w - P_w\alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha P_w + P_w\tan^2\beta - \alpha P_w\tan^2\beta$$

$$= P_w\left(1 - \alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha + \tan^2\beta - \alpha\tan^2\beta\right)$$

$$= P_w\left(1 - \alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha + \tan^2\beta(1-\alpha)\right)$$

Check

$$P_w = \frac{2\sigma_h - C_0 - P_{f0}\alpha\frac{(1-2\nu)}{(1-\nu)}}{1 - \alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha + (1-\alpha)\tan^2\beta}.$$ ✓

2. $\sigma_r \geq \sigma_z \geq \sigma_\theta$: $\sigma_r = \sigma_1$; $\sigma_\theta = \sigma_3$

$$\sigma_r - \alpha P_w = C_0 + (\sigma_\theta - \alpha P_w)\tan^2\beta$$

Check

$\sigma_r = P_w$

$\sigma_\theta = 2\sigma_h - P_w - (P_{f0} - P_w)\frac{(1-2\nu)}{(1-\nu)}\alpha$ ✓

$$P_w - \alpha P_w = C_0 + \left(2\sigma_h - P_w - (P_{f0} - P_w)\frac{(1-2\nu)}{(1-\nu)}\alpha - \alpha P_w\right)\tan^2\beta$$ ✓

$$P_w - \alpha P_w = C_o + \left(2\sigma_h - P_w - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}\alpha + P_w\frac{(1-2\nu)}{(1-\nu)}\alpha - \alpha P_w\right)\tan^2\beta$$

$$P_w - \alpha P_w = C_o + 2\sigma_h\tan^2\beta - P_w\tan^2\beta - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}\alpha\tan^2\beta + P_w\frac{(1-2\nu)}{(1-\nu)}\alpha\tan^2\beta$$

$$- \alpha P_w\tan^2\beta$$

$$P_w - \alpha P_w + P_w\tan^2\beta - P_w\tan^2\beta\,\alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha P_w\tan^2\beta = C_o + 2\sigma_h\tan^2\beta - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}$$

$$P_w\left(1 - \alpha + \tan^2\beta - \tan^2\beta\,\alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha\tan^2\beta\right) = C_o + 2\sigma_h\tan^2\beta - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}\alpha$$

Check

$$P_w\left(1 - \alpha + \tan^2\beta\left(1 - \alpha\frac{(1-2\nu)}{(1-\nu)} + \alpha\right)\right) = C_o + 2\sigma_h\tan^2\beta - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}\alpha$$

$$P_w = \frac{C_o + 2\sigma_h\tan^2\beta - P_{f_o}\frac{(1-2\nu)}{(1-\nu)}\alpha}{\left(1 - \alpha + \tan^2\beta\left(1 + \alpha - \alpha\frac{(1-2\nu)}{(1-\nu)}\right)\right)}$$

✓

V Good

Appendix 3

Results of Borehole Stability Analysis

Borehole Stability Analysis
sample 2
1. General Data

Average Triaxial Stress Factor, k	3.25	
Angle of internal friction	31.97	deg
Augmentation to rock strength,p'	0.10	MPa
Augmentation to rock strength,p'	15	psi
Normal to Failure Plane Angle, β	60.98	degrees
Tan^2β	3.25	
Uniaxial Compressive Strength, Co	11.73	MPa
Uniaxial Compressive Strength, Co	1702	psi
Tensile Strength, To	1.18	MPa
Tensile Strength, To	171	psi
Thick wall cylinder strength, TWC	54.44	MPa
Thick wall cylinder strength, TWC	7901	psi
Depth	1449	feet
Initial Pore Pressure, Pf or Pfo	630	psi
Drawdown Pore Pressure	260	psi
Initial Poisson's ratio	0.19	
Under Max Drawdown Poisson's ratio	0.16	
Biot's Constant	0.80	

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	281	2617	3069
vertical well, σH>σh	367	#N/A	4881
horizontal well σH=σh, σθ>σr	367	#N/A	#N/A
horizontal well σH=σh, σz>σr	-147	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	548	2350	2565
vertical well σH=σh permeable	437	2715	#N/A
Yield zone			
No yield zone	Pw>		
	281		
TWC			
BHP>	0		

2. Elastic Analysis

2.1 No Pore Fluid/ Vertical Hole

Two horizontal stresses in the plane of the well; vertical stress axially down well

2.1.1 Shear Failure

$1. \sigma_\theta > \sigma_z > \sigma_r$

tangential stress greatest, radial stress smallest
failure occurs if the wellbore pressure is less than

$$Pw < \frac{2\sigma_h - C_o}{\tan^2 \beta + 1}$$

$\sigma_h (psi)$	1449
Pw (psi)	281

$2. \sigma_r > \sigma_z > \sigma_\theta$

radial stress greatest, tangential stress smallest
failure occurs if the wellbore pressure is greater than

$$Pw > \frac{2\sigma_h \tan^2 \beta + C_o}{\tan^2 \beta + 1}$$

$\sigma_h (psi)$	1449
Pw (psi)	2617

2.1.2 Tensile Failure

radial stress greatest; overcomes tangential stress and fails by tensile failure

failure occurs if the wellbore pressure is greater than

$$Pw > 2\sigma_h + T_o$$

$\sigma_h (psi)$	1449
Pw (psi)	3069

2.2 No Pore Fluid/ Deviated Hole

2.2.1 Shear Failure/Vertical Well

maximum horizontal stress greater than minimum horizontal stress

$$\sigma_H > \sigma_h$$

$$\sigma_\theta > \sigma_z > \sigma_r$$

tangential stress greatest, radial stress smallest

failure occurs if the wellbore pressure is less than

$$Pw < \frac{3\sigma_H - \sigma_h - C_o}{\tan^2\beta + 1}$$

$\sigma_H(psi)$	1449
$\sigma_h(psi)$	1087 (75% of max stress)
Pw (psi)	367

2.2.2 Tensile Failure/Vertical Well

$$\sigma_H > \sigma_h$$

radial stress greatest; overcomes tangential stress and fails by tensile failure

failure occurs if the wellbore pressure is greater than

$$Pw > 3\sigma_h + \sigma_H + T_o$$

$\sigma_H(psi)$	1449
$\sigma_h(psi)$	1087 (75% of max stress)
Pw (psi)	4881

2.2.3 Shear Failure/Horizontal Well

maximum horizontal stress equal to minimum horizontal stress $\sigma_H = \sigma_h$

$1. \sigma_\theta > \sigma_z > \sigma_r$

tangential stress greatest, radial stress smallest

failure occurs if the wellbore pressure is less than

$$Pw < \frac{\sigma_h + \sigma_v - 2Cos2\theta(\sigma_v - \sigma_h) - C_o}{\tan^2 \beta + 1}$$

$\sigma_v (psi)$	1449	
$\sigma_h (psi)$	1087	
θ	90	(angle between max and min stress i.e. vertical and horizontal stress: worst case is 90degree)
Pw	367	

$2. \sigma_z > \sigma_\theta > \sigma_r$

stress along borehole greatest, radial stress smallest

failure occurs if the wellbore pressure is less than

$$Pw < \frac{\sigma_h - 2\nu Cos2\theta(\sigma_v - \sigma_h) - C_o}{\tan^2 \beta}$$

$\sigma_v (psi)$	1449	
$\sigma_h (psi)$	1087	
θ	90	(angle between max and min stress i.e. vertical and horizontal stress: worst case is 90degree)
Pw	-147	

2.3 Poro Elastic Formation

2.3.1 Impermeable wellbore, vertical well, equal minimum and maximum horizontal stresses

Shear failure

$1.\sigma_\theta > \sigma_z > \sigma_r$

tangential stress greatest, radial stress smallest

failure occurs if the wellbore pressure is less than

$$Pw < \frac{1}{\tan^2\beta + 1}\left[2\sigma_h + \alpha P_f(\tan^2\beta - 1) - C_o\right]$$

$\sigma_h(psi)$	1449
alpha	0.8
Pw	548

$2.\sigma_r > \sigma_z > \sigma_\theta$

radial stress greatest, tangential stress smallest

failure occurs if the wellbore pressure is greater than

$$Pw > \frac{1}{\tan^2\beta + 1}\left[2\sigma_h \tan^2\beta - \alpha P_f(\tan^2\beta - 1) + C_o\right]$$

$\sigma_h(psi)$	1449
alpha	0.8
Pw	2350

2.3.2 Tensile failure

radial stress greatest; overcomes tangential stress and fails by tensile failure

failure occurs if the wellbore pressure is greater than $Pw > 2\sigma_h - \alpha P_f + T_o$

$\sigma_h(psi)$	1449
alpha	0.80
Pw	2565

2.3.3 Permeable wellbore, vertical well, equal minimum and maximum horizontal stresses
Shear failure

$1.\ \sigma_\theta > \sigma_z > \sigma_r$

tangential stress greatest, radial stress smallest

failure occurs if the wellbore pressure is less than

$$Pw < \frac{2\sigma_h - C_o - P_{fo}\alpha \frac{1-2\nu}{1-\nu}}{1-\alpha\frac{1-2\nu}{1-\nu} + \alpha + (1-\alpha)\tan^2\beta}$$

$\sigma_h (psi)$	1449
alpha	0.80
1-2v/1-v	0.809524
Pw	437

$2.\ \sigma_r > \sigma_z > \sigma_\theta$

radial stress greatest, tangential stress smallest
failure occurs if the wellbore pressure is greater than

$$Pw > \frac{2\sigma_h \tan^2\beta + C_o - P_{fo}\alpha \frac{1-2\nu}{1-\nu}}{1-\alpha + \tan^2\beta\left(1+\alpha-\alpha\frac{1-2\nu}{1-\nu}\right)}$$

$\sigma_h (psi)$	1449
alpha	0.80
1-2v/1-v	0.809524
Pw	2715

3. Yield Zone Analysis

Condition of no yield

$$\sigma_h = \sigma_H = \sigma_v$$

all stresses equal
no yield zone occurs if wellbore pressure greater than

$$Pw > \frac{2q - \sigma_o + p'(k+1)}{k+1} - p'$$

$\sigma_h (psi)$	1449
Pw	281

4. Thick Wall Cylinder Strength

failure occurs if $\sigma_{ff} - BHP > TWC$

σ_{ff} is the far field stress. There are two bounds: all stresses equal vertical stress

upper bound $\sigma_{ff} = \sigma_v$

vertical and horizontal stresses not equal

lower bound $\sigma_{ff} = \frac{1}{2}(\sigma_v + \sigma_h)$

$\sigma_v\,(psi)$	1449
$\sigma_h\,(psi)$	1087

upper bound, BHP> -6452 i.e. no failure down to Pw=0

lower bound, BHP> -6633 i.e. no failure down to Pw=0

Borehole Stability Analysis
sample 3
1. General Data

Average Triaxial Stress Factor, k	3.86	
Angle of internal friction	36.05 deg	
Augmentation to rock strength,p'	0.10 MPa	
Augmentation to rock strength,p'	15 psi	
Normal to Failure Plane Angle, β	63.02 degrees	
Tan^2β	3.86	
Uniaxial Compressive Strength, Co	18.30 MPa	
Uniaxial Compressive Strength, Co	2656 psi	
Tensile Strength, To	1.83 MPa	assumed
Tensile Strength, To	266 psi	
Thick wall cylinder strength, TWC	54.63 MPa	
Thick wall cylinder strength, TWC	7929 psi	
Depth	1454 feet	
Initial Pore Pressure, Pf or Pfo	630 psi	
Drawdown Pore Pressure	260 psi	
Initial Poisson's ratio	0.16	
Under Max Drawdown Poisson's ratio	0.18	
Biot's Constant	0.80	assumed

Summary			
Elastic	Shear	Shear	Tensile
	Failure if	Failure if	Failure if
	Pw(psi) <	Pw(psi) >	Pw(psi) >
vertical well, no fluid	52	2856	3174
vertical well, σH>σh	127	#N/A	4991
horizontal well σH=σh, σθ>σr	127	#N/A	#N/A
horizontal well σH=σh, σz>σr	-375	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	348	2560	2670
vertical well σH=σh permeable	-73	2847	#N/A
Yield zone			
No yield zone	Pw>		
	52		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 4
1. General Data

Average Triaxial Stress Factor, k	3.45	
Angle of internal friction	33.41 deg	
Augmentation to rock strength,p'	0.10 MPa	
Augmentation to rock strength,p'	15 psi	
Normal to Failure Plane Angle, β	61.70 degrees	
Tan^2β	3.45	
Uniaxial Compressive Strength, Co	15.93 MPa	
Uniaxial Compressive Strength, Co	2312 psi	
Tensile Strength, To	0.85 MPa	
Tensile Strength, To	123 psi	
Thick wall cylinder strength, TWC	53.72 MPa	
Thick wall cylinder strength, TWC	7797 psi	
Depth	1458 feet	
Initial Pore Pressure, Pf or Pfo	630 psi	
Drawdown Pore Pressure	260 psi	
Initial Poisson's ratio	0.18	
Under Max Drawdown Poisson's ratio	0.15	
Biot's Constant	0.80	assumed

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	136	2780	3039
vertical well, σH>σh	218	#N/A	4862
horizontal well σH=σh, σθ>σr	218	#N/A	#N/A
horizontal well σH=σh, σz>σr	-315	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	413	2503	2535
vertical well σH=σh permeable	103	2890	#N/A
Yield zone			
No yield zone	Pw>		
	136		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 5
1. General Data

Average Triaxial Stress Factor, k	3.50		
Angle of internal friction	33.75	deg	
Augmentation to rock strength,p'	0.10	MPa	
Augmentation to rock strength,p'	15	psi	
Normal to Failure Plane Angle, β	61.87	degrees	
Tan^2β	3.50		
Uniaxial Compressive Strength, Co	12.69	MPa	
Uniaxial Compressive Strength, Co	1842	psi	
Tensile Strength, To	1.26	MPa	assumed
Tensile Strength, To	183	psi	
Thick wall cylinder strength, TWC	56.71	MPa	
Thick wall cylinder strength, TWC	8231	psi	
Depth	1466	feet	
Initial Pore Pressure, Pf or Pfo	630	psi	
Drawdown Pore Pressure	260	psi	
Initial Poisson's ratio	0.25		
Under Max Drawdown Poisson's ratio	0.16		
Biot's Constant	0.80		assumed

Summary			
Elastic	Shear	Shear	Tensile
	Failure if	Failure if	Failure if
	Pw(psi) <	Pw(psi) >	Pw(psi) >
vertical well, no fluid	242	2690	3115
vertical well, σH>σh	324	#N/A	4947
horizontal well σH=σh, σθ>σr	324	#N/A	#N/A
horizontal well σH=σh, σz>σr	-160	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	522	2410	2611
vertical well σH=σh permeable	368	2763	#N/A
Yield zone			
No yield zone	Pw>		
	242		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 6
1. General Data

Average Triaxial Stress Factor, k	3.12	
Angle of internal friction	30.97	deg
Augmentation to rock strength,p'	0.10	MPa
Augmentation to rock strength,p'	15	psi
Normal to Failure Plane Angle, β	60.48	degrees
Tan^2β	3.12	
Uniaxial Compressive Strength, Co	22.60	MPa
Uniaxial Compressive Strength, Co	3280	psi
Tensile Strength, To	1.20	MPa
Tensile Strength, To	174	psi
Thick wall cylinder strength, TWC	70.54	MPa
Thick wall cylinder strength, TWC	10238	psi
Depth	1481	feet
Initial Pore Pressure, Pf or Pfo	630	psi
Drawdown Pore Pressure	260	psi
Initial Poisson's ratio	0.05	
Under Max Drawdown Poisson's ratio	0.13	
Biot's Constant	0.80	assumed

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	-77	3039	3136
vertical well, σH>σh	13	#N/A	4987
horizontal well σH=σh, σθ>σr	13	#N/A	#N/A
horizontal well σH=σh, σz>σr	-683	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	182	2780	2632
vertical well σH=σh permeable	-428	3275	#N/A
Yield zone			
No yield zone	Pw>		
	-77		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 7
1. General Data

Average Triaxial Stress Factor, k	3.12		assumed
Angle of internal friction	30.97	deg	
Augmentation to rock strength,p'	0.10	MPa	
Augmentation to rock strength,p'	15	psi	
Normal to Failure Plane Angle, β	60.48	degrees	
Tan^2β	3.12		
Uniaxial Compressive Strength, Co	14.80	MPa	assumed
Uniaxial Compressive Strength, Co	2148	psi	
Tensile Strength, To	1.48	MPa	
Tensile Strength, To	215	psi	
Thick wall cylinder strength, TWC	70.54	MPa	assumed
Thick wall cylinder strength, TWC	10238	psi	
Depth	1488	feet	
Initial Pore Pressure, Pf or Pfo	630	psi	
Drawdown Pore Pressure	260	psi	
Initial Poisson's ratio	0.15		assumed
Under Max Drawdown Poisson's ratio	0.17		assumed
Biot's Constant	0.80		assumed

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	201	2775	3191
vertical well, σH>σh	291	#N/A	5051
horizontal well σH=σh, σθ>σr	291	#N/A	#N/A
horizontal well σH=σh, σz>σr	-295	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	460	2516	2687
vertical well σH=σh permeable	239	2880	#N/A
Yield zone			
No yield zone	Pw>		
	201		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 8
1. General Data

Average Triaxial Stress Factor, k	3.12		assumed
Angle of internal friction	30.97	deg	
Augmentation to rock strength,p'	0.10	MPa	
Augmentation to rock strength,p'	15	psi	
Normal to Failure Plane Angle, β	60.48	degrees	
Tan^2β	3.12		
Uniaxial Compressive Strength, Co	21.70	MPa	assumed
Uniaxial Compressive Strength, Co	3149	psi	
Tensile Strength, To	2.17	MPa	
Tensile Strength, To	315	psi	
Thick wall cylinder strength, TWC	70.54	MPa	assumed
Thick wall cylinder strength, TWC	10238	psi	
Depth	1495	feet	
Initial Pore Pressure, Pf or Pfo	630	psi	
Drawdown Pore Pressure	260	psi	
Initial Poisson's ratio	0.15		assumed
Under Max Drawdown Poisson's ratio	0.17		assumed
Biot's Constant	0.80		assumed

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	-39	3029	3305
vertical well, σH>σh	52	#N/A	5174
horizontal well σH=σh, σθ>σr	52	#N/A	#N/A
horizontal well σH=σh, σz>σr	-614	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	221	2769	2801
vertical well σH=σh permeable	-313	3152	#N/A
Yield zone			
No yield zone	Pw>		
	-39		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 9
1. General Data

Average Triaxial Stress Factor, k	3.12	assumed
Angle of internal friction	30.97 deg	
Augmentation to rock strength,p'	0.10 MPa	
Augmentation to rock strength,p'	15 psi	
Normal to Failure Plane Angle, β	60.48 degrees	
Tan^2β	3.12	
Uniaxial Compressive Strength, Co	18.10 MPa	assumed
Uniaxial Compressive Strength, Co	2627 psi	
Tensile Strength, To	1.81 MPa	
Tensile Strength, To	263 psi	
Thick wall cylinder strength, TWC	70.54 MPa	assumed
Thick wall cylinder strength, TWC	10238 psi	
Depth	1498 feet	
Initial Pore Pressure, Pf or Pfo	630 psi	
Drawdown Pore Pressure	260 psi	
Initial Poisson's ratio	0.15	assumed
Under Max Drawdown Poisson's ratio	0.17	assumed
Biot's Constant	0.80	assumed

Summary			
Elastic	Shear	Shear	Tensile
	Failure if	Failure if	Failure if
	Pw(psi) <	Pw(psi) >	Pw(psi) >
vertical well, no fluid	90	2906	3259
vertical well, σH>σh	180	#N/A	5131
horizontal well σH=σh, σθ>σr	180	#N/A	#N/A
horizontal well σH=σh, σz>σr	-446	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	349	2647	2755
vertical well σH=σh permeable	-18	3021	#N/A
Yield zone			
No yield zone	Pw>		
	90		
TWC			
BHP>	0		

Borehole Stability Analysis
sample 10
1. General Data

Average Triaxial Stress Factor, k	3.38		
Angle of internal friction	32.91	deg	
Augmentation to rock strength,p'	0.10	MPa	
Augmentation to rock strength,p'	15	psi	
Normal to Failure Plane Angle, β	61.46	degrees	
Tan^2β	3.38		
Uniaxial Compressive Strength, Co	22.16	MPa	
Uniaxial Compressive Strength, Co	3216	psi	
Tensile Strength, To	2.20	MPa	assumed
Tensile Strength, To	319	psi	
Thick wall cylinder strength, TWC	69.79	MPa	
Thick wall cylinder strength, TWC	10129	psi	
Depth	1504	feet	
Initial Pore Pressure, Pf or Pfo	630	psi	
Drawdown Pore Pressure	260	psi	
Initial Poisson's ratio	0.14		
Under Max Drawdown Poisson's ratio	0.14		
Biot's Constant	0.80		assumed

Summary			
Elastic	Shear	Shear	Tensile
	Failure if	Failure if	Failure if
	Pw(psi) <	Pw(psi) >	Pw(psi) >
vertical well, no fluid	-48	3056	3327
vertical well, σH>σh	38	#N/A	5207
horizontal well σH=σh, σθ>σr	38	#N/A	#N/A
horizontal well σH=σh, σz>σr	-587	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	226	2782	2823
vertical well σH=σh permeable	-349	3224	#N/A
Yield zone			
No yield zone	Pw>		
	-48		
TWC			
BHP>	0		

Borehole Stability Analysis

sample cap rock

1. General Data

Average Triaxial Stress Factor, k	3.23		
Angle of internal friction	31.82	deg	
Augmentation to rock strength,p'	0.10	MPa	
Augmentation to rock strength,p'	15	psi	
Normal to Failure Plane Angle, β	60.91	degrees	
Tan^2β	3.23		
Uniaxial Compressive Strength, Co	30.08	MPa	
Uniaxial Compressive Strength, Co	4366	psi	
Tensile Strength, To	4.31	MPa	
Tensile Strength, To	626	psi	
Thick wall cylinder strength, TWC	#N/A	MPa	
Thick wall cylinder strength, TWC	#N/A	psi	
Depth	1400	feet	
Initial Pore Pressure, Pf or Pfo	630	psi	
Drawdown Pore Pressure	260	psi	
Initial Poisson's ratio	0.14		assumed
Under Max Drawdown Poisson's ratio	0.14		assumed
Biot's Constant	0.80		assumed

Summary			
Elastic	Shear Failure if Pw(psi) <	Shear Failure if Pw(psi) >	Tensile Failure if Pw(psi) >
vertical well, no fluid	-370	3170	3426
vertical well, σH>σh	-287	#N/A	5176
horizontal well σH=σh, σθ>σr	-287	#N/A	#N/A
horizontal well σH=σh, σz>σr	-996	#N/A	#N/A
Poro Elastic			
vertical well σH=σh impermeable	-104	2904	2922
vertical well σH=σh permeable	-1119	3373	#N/A
Yield zone			
No yield zone	Pw>		
	-370		
TWC			
BHP>	0		