WELL ABANDONMENT TECHNIQUES

AMIR HUSAINY BIN ABDUL AZIZ

UNIVERSITI TEKNOLOGI MALAYSIA

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WELL ABANDONMENT TECHNIQUES

AMIR HUSAINY BIN ABDUL AZIZ

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Science (Petroleum Engineering)

Faculty of Petroleum and Renewable Energy Engineering
Universiti Teknologi Malaysia

JUNE 2014

I hereby declared that this thesis entitled, "***Well Abandonment Techniques***", is the result of my own work except the terms, tables, and figures that I have state the source.

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Name : **AMIR HUSAINY BIN ABDUL AZIZ**

Date : 25 June 2014

To my beloved mother Hamimah Binti Jaafar, father Abdul Aziz Bin Kidam, my 'super'soulmate Azimah Binti Abdul Kadir, my little princess Nur Zahra, my three sisters, supervisor and course mates, thank you for all your supports, encouragement, guidance and be my inspiration.

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ABSTRACT

Well abandonment (decommissioning) is a part of Field development Plan in oil and gas industry, but this activity has often being delayed because it is a non-oil generating activity. It is also most often ranked low when competing for the limited funds with other oil generating activities. When production from a well drops below an economic level, the well may be stimulated, worked over or be subject to secondary and tertiary recovery techniques. However, the well will eventually require abandoning when it is no longer economic. Operators traditionally accrue for this eventual abandonment. However the costs of abandonment have soared due to inflation, and the higher costs of meeting ever stricter environmental requirements. Current techniques involve plugging each of the casings in a large number of sequential steps, then removing the casing. It requires the mobilization of a rig and associated equipment to remove the casing from the well. A large cement plug is then placed to finally seal the well. Few case studies were observed and analyzed in detail especially plugging and abandonment (P&A) techniques in that particular fields. Basically P&A techniques are using the same conceptual methods which are by using cement and mechanical plugs. Abandonment practices are a little bit different among countries due to government legislation and regulation is neither uniform nor consistent. Isolation of all fresh water zones and production zones, prevent well leakage and maintain well integrity are the main objectives in any well abandonment programme.

ABSTRAK

Penutupan telaga (pelucutan tauliah) adalah sebahagian daripada Pelan Pembangunan Lapangan dalam industri minyak dan gas, tetapi aktiviti ini sering tertangguh kerana ia adalah aktiviti bukan penghasilan minyak. Ia juga paling kerap menduduki tempat rendah apabila bersaing untuk dana yang terhad dengan aktiviti yang menjana minyak yang lain. Apabila pengeluaran dari perigi jatuh di bawah tahap ekonomi, telaga itu boleh dirangsang, diulang kerja atau tertakluk kepada teknik-teknik pemulihan tahap kedua dan ketiga. Walau bagaimanapun, telaga yang akhirnya akan memerlukan aktiviti penutupan apabila ia tidak lagi ekonomi. Operator tradisional terakru untuk penutupan akhirnya ini. Walau bagaimanapun kos penutupan telah melonjak kerana inflasi, dan kos yang lebih tinggi untuk memenuhi akta alam sekitar yang sentiasa tegas. Teknik semasa melibatkan menyumbat setiap satu daripada sarung telaga dalam langkah-langkah yang berurutan, kemudian membuang sarung telaga. Ia memerlukan penggemblengan pelantar dan peralatan yang berkaitan untuk membuang sarung telaga ini. Satu palam simen besar akan ditempatkan untuk menutup telaga itu. Beberapa kajian kes telah diperhatikan dan dianalisis secara terperinci terutama teknik menyumbat dan penutupan (P & A) dalam medan yang terlibat. Pada asasnya teknik P&A bagi kawasan kajian adalah menggunakan kaedah yang sama iaitu konsep menggunakan simen dan palam mekanikal. Amalan penutupan adalah sedikit berbeza di kalangan negara-negara kerana undang-undang dan peraturan kerajaan tidak seragam dan tidak konsisten. Pengasingan semua zon air tawar dan zon pengeluaran, mencegah dan kebocoran dan mengekalkan integriti telaga adalah objektif utama dalam mana-mana program penutupan telaga.

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LIST OF ABBREVIATIONS

API - American Petroleum Institute
ASV - Annular Safety Valve
BHA - Bottom Hole Assembly
BOP - Blow Out Preventer
CO_2 - Carbon Dioxide
CT - Coil Tubing
DHSV - Downhole Safety Valve
DP - Drill Pipe
DTI - Department of Trade and Industry
FPSO - Floating Production Storage and Offloading
HUD - Hold Up Depth
IMO - International Maritime Organization
LSA - Low Specific Activiy
MDBRT - Measured Depth Below Rotary Table
MDT - Modular Dynamics Tester
P&A - Plugging and Abandonment
PJU - Pulling and Jacking Unit
POOH - Pull Out Of Hole
RIH - Run In Hole
ROV - Remotely Operated Vehicle
SBM - Synthetic Based Mud
SCSSV - Surface Controlled Sub-surface Safety Valve
SDWA - Safe Drinking Water Act
TD - Total Depth
TOC - Top of Cement
UKCS - United Kingdom Continental Shelf
UNCLOS - United Nation Convention of The Law of The Sea

LIST OF UNITS

bbl	-	Barrel
Bbls/day	-	Barrels per day
ft	-	Feet
gal	-	Gallon
lb	-	Pound
m	-	Meter
mD	-	mili Darcy
MMSTB	-	Million Stock Tank Barrel
ppg	-	Pound per gallon
psi	-	Per square inch
sk	-	Sack

CHAPTER 1

INTRODUCTION

1.1 Background

Wellbore abandonment is a part of the drilling operation. A well is abandoned when it reaches the end of its useful life. Well abandonment is a technique to terminate the ability of the well to produce oil and gas by isolating and plugging all penetrated zones using cement and mechanical plug in order to ensure the stability of the wellbore. Field decommissioning is completed in two phases which are well abandonment and platform abandonment.

Well preparation and well plugging are activities involved in well abandonment phase. Meanwhile platform abandonment phase activities are more toward pipelines, facilities and other structures decommissioning and removal.

An effective well abandonment plan must address all aspects of the abandonment process which are plug location and position, control of injection zone pressure, well conditions, removal of well materials, static well conditions and equipment availability.

Government regulations have been the principal considerations in deciding the abandonment programme. Although the regulations are neither uniform nor consistent between countries, operators need to view it as minimal guidelines for abandonment. Normally regulations imposed by the authority are complying with international environmental agreements.

Abandonment was perceived as a sunk cost. The plugging and abandonment (P&A) work takes capital to complete and provides no return on the investment for the contractors. Most well are plugged at the lowest cost possible following the minimum requirements set by the ruler's agencies.

Threats from improper abandonment wells are contaminated surface water entry by minerals or bacterias, surface leakage from shallow zones through well or leaking cement sheath, habitats ecosystem disruption, aquifers are being destroyed and detonation or falling down the well.

This thesis consists of technical guidance to assist readers in reviewing proposed well abandonment plans and execution tasks. Emphasizing that proper abandonment consists of more than cement plug placement, the thesis discusses all technicality aspects of well abandonment.

1.2 Objective

The following are the objectives of this study:

i. Compiling the standard operating procedure of well abandonment programme.

ii. Describe the well plugging requirements and practices.

iii. Suggest the materials, tools and equipments used in abandonment.

iv. Compare plugging and abandonment (P&A) practices between different countries.

1.3 Scope

Scopes of this study are:

i. Review plugging and abandonment (P&A) for oil and gas industry.

ii. Describe abandonment of offshore well.

iii. Analyze all technicality aspects of well abandonment.

iv. Differentiate well abandonment programme in two different countries using case studies.

v. Discuss on the plugging and abandonment (P&A) challenges

1.4 Thesis Organisation

This thesis contains five chapters and contains valuable data for well abandonment techniques. The first chapter of this thesis consists of introduction, objective and scope of the project.

The second chapter underlines the literature review on types and phases of well abandonment, wellbore considerations, plugging techniques, abandonment technologies and environmental regulations in details.

In chapter three, project's methodology is discussed. These include data collection, data classification, analysis and comparison, finding and thesis preparation. Two case studies that are used in this thesis are United Kingdom Continental Shelf field and Malaysian field.

The next chapter will be explained about the comparison result of both fields in terms of down hole abandonment and plugging and abandonment (P&A) techniques. This chapter also has discussion and comparison between the case study data with literature review on the similar topics

Lastly, in chapter five, the conclusions and recommendations for further study are summarized.

CHAPTER 2

LITERATURE REVIEW

2.1 Types of Well Abandonment

Well abandonment can be categorized into two which are temporary abandonment and permanent abandonment. Many oil and gas wells are shut-in or temporarily abandoned because they are not producing hydrocarbons in paying quantities or for other reasons and may be re-entered in the future. Meanwhile permanent abandonment is define as plug and abandoned at end of reservoir life (J.R. Nichol 2000).

Both types of well abandonment are intentionally to isolate and protect all fresh and near fresh water zones, protect all producing horizons for future development, prevent well leakage and maintain well integrity.

Requirements for isolation of formations, fluids and pressures for temporary and permanent abandonment are the same. However, choice of well barrier elements may be different to account for abandonment time, and ability to re-enter the well, or resume operations after temporary abandonment. Typical subsea production well is described in Figure 2.1:

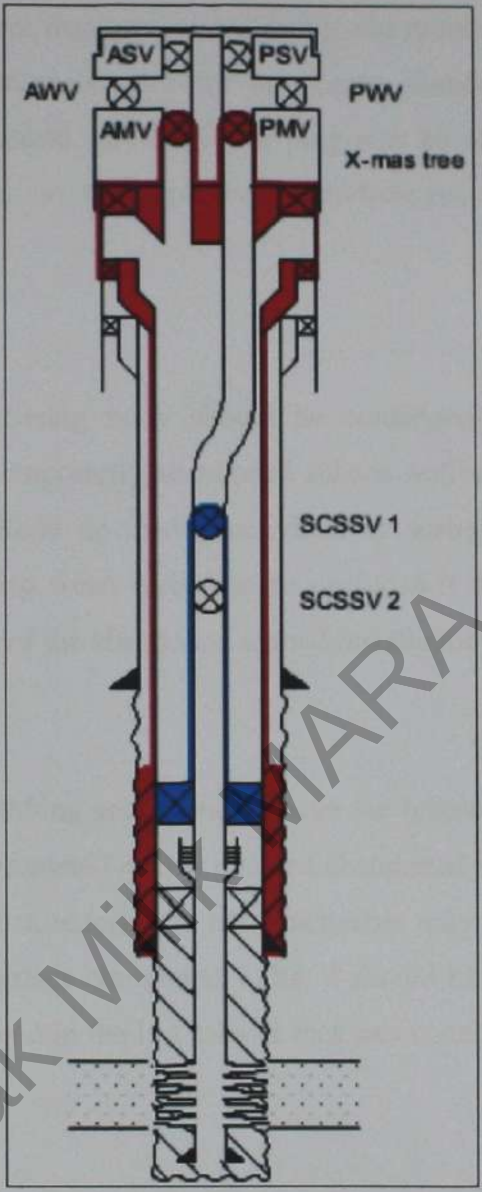


Figure 2.1: Typical subsea production well (Norsok 2004).

2.1.1 Temporary Abandonment

Temporary abandonment occurs during a long shut-down or waiting on a workover or waiting on field development or redevelopment. Well that temporarily abandoned is not presently being operated.

Few important activities are set plugs to prevent cross flow and production, isolate all flow and protect from pressures, testing and monitor the well and keep all records. Integrity of materials used for temporary abandonment should be top priority. Hence, a mechanical well barrier or plug may be acceptable for temporary abandonment depending on type, planned abandonment period and subsurface environment.

Degradation of casing body should be considered for longer temporary abandonment periods. Temporarily abandoned subsea wellheads and templates shall be protected from maritime or fishing activities or seabed activities. Temporary seabed protection for deep water wells can be excluded if there are no activities in the area and at the depth of the abandoned seabed installations.

The pressure in tubing and annulus above the reservoir well barrier shall be monitored if a subsea completed well is planned abandoned for more than a year. An acceptable alternative if monitoring is not practicable may be to install a deep set well barrier plug. For surface completed wells, it should be possible to monitor the pressure in the annulus and in the last tubular that was installed in production tubing or casing (Norsok 2004).

Example of temporary abandonment well is described as in figure 2.2:

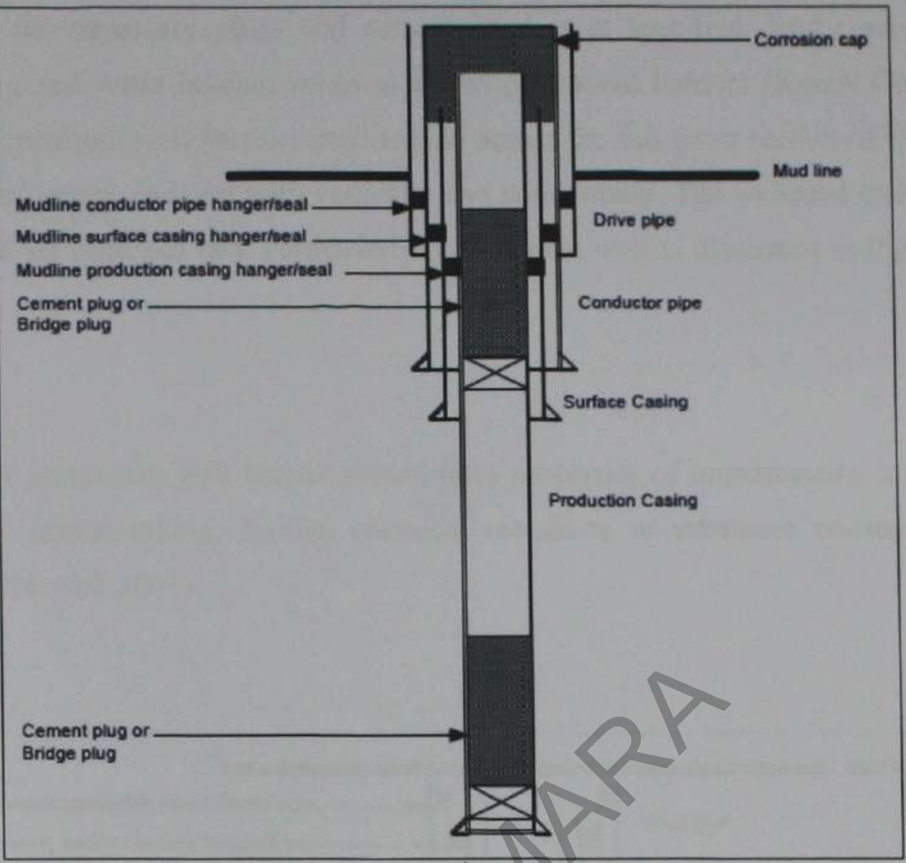


Figure 2.2: Temporary abandonment well (J.R. Nichol 2000).

2.1.2 Permanent Abandonment

In most cases, permanent abandonment referred to well abandonment at the end of current economic operations. Sometimes, it also happened to well that had problem which cannot be economically repaired.

Typically, wells are abandoned by plugging the wells with two to three cement plugs whereby all tubular will be cut and retrieved at the minimum of 15 ft below the seabed to prevent hydrocarbon egress. The basics of a permanent well abandonment operation will vary little whether the well is on land or offshore. Permanent abandonment begin by removing the completion or production string, then set the necessary plugs and cement barriers at specified depths across the producing and water-bearing zones to act as permanent barriers (Kenny Campbell 2013). Permanent well barriers shall extend across the full cross section of the well, include all annuli and seal both vertically and horizontally. The wellhead and subsea hardware are removed last. Permanent abandonment well is illustrated in Figure 2.3 below.

A permanent well barrier should have properties of impermeable, long term integrity, non-shrinking, ductile, chemical resistance or substance resistance and wetting (Norsok 2004).

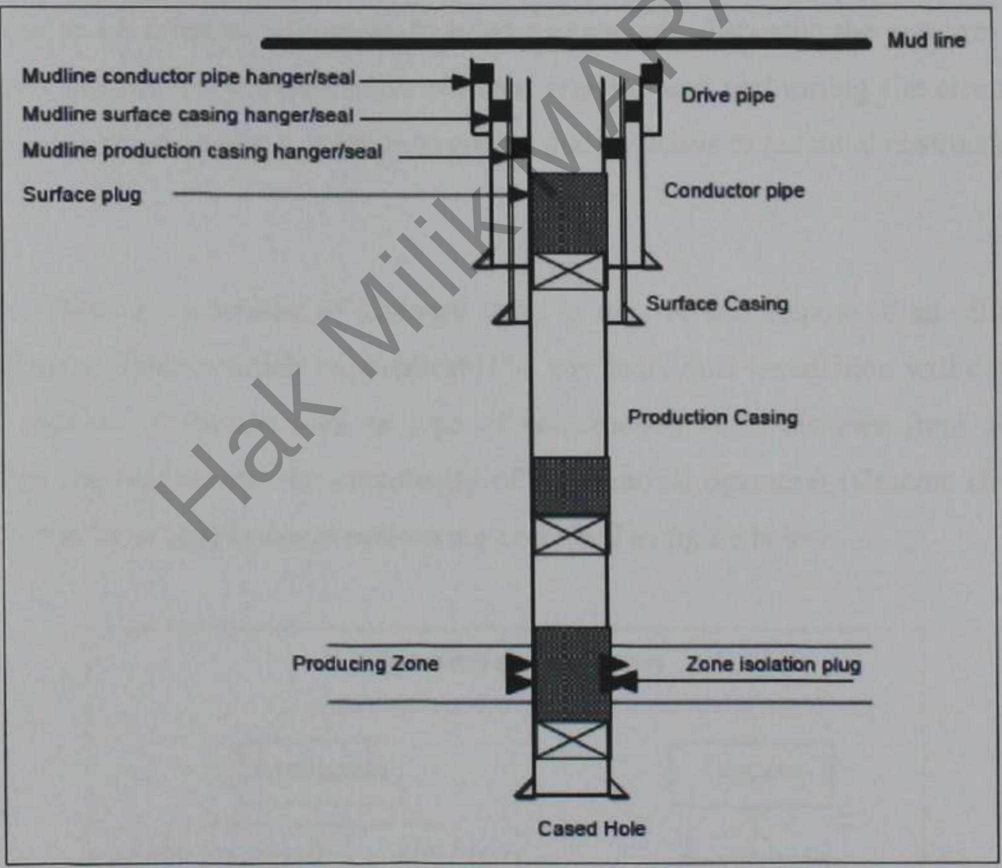


Figure 2.3: Permanent abandonment well (J.R. Nichol 2000).

2.2 Abandonment Phases

Field abandonment phases are divided into two which are well abandonment and platform abandonment. As we know, well abandonment is the most critical phase in well abandonment in order to maintain well integrity in the future. Normally this process is called Plug and Abandonment (P&A). Decommissioning of well generally focused on plugging well supported by the platform and severing the well casings 15 ft below the mud line, cleaning and removing all production and pipeline risers supported by the platform.

Meanwhile platform abandonment is refers to removing the platform from its foundation by severing all bottom-founded components, disposing the platform in a scrap or placing the platform at an artificial reef site and performing site clearance verification at the platform location to ensure that no debris or potential obstructions.

There are a number of different ways to remove and dispose of an offshore installation. Exactly which are applicable to any individual installation will depend on a number of factors such as type of construction, size, distance from shore, weather conditions, and the complexity of the removal operation (Graeme Gibson 2002). Platform abandonment options are described as figure below:

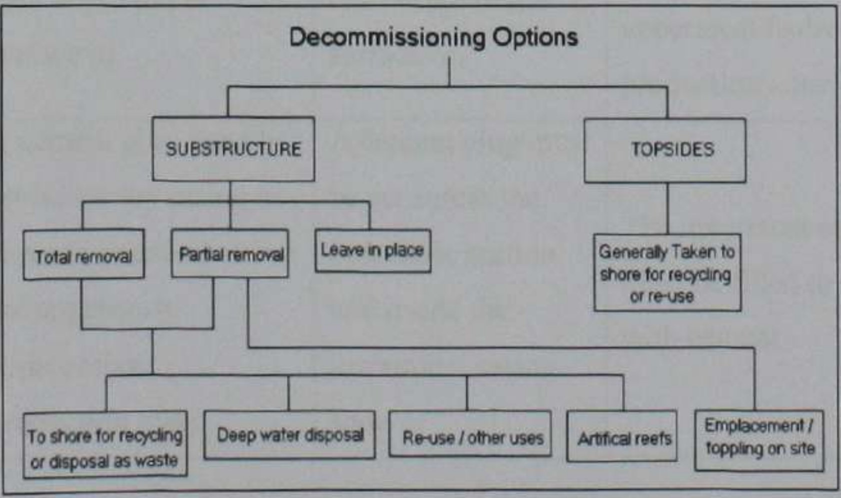


Figure 2.4: Decommissioning options (Graeme Gibson 2002).

2.2.1. Well Abandonment

The principles of well abandonment are isolate groundwater aquifers within the well from each other and hydrocarbon zones, isolate hydrocarbon zones within the well from each other, from groundwater aquifers or from zones of different pressure, isolate the surface casing and production casing from open hole, place a surface cement plug in the top of the casing and recover the wellhead.

Basically cement and few plugs are the primary sealing components in abandoning a well. Any well or drill hole that is to be abandoned shall be sealed and filled in such a manner to prevent leakage. Plugging and cementing minimum requirements as table below:

Table 2.1: Well plugging and cementing minimum requirements

Well / Activity	Production well	Exploration well	All well
1	The well is to be abandoned by cementing from the total depth to the surface or,	The well is to be abandoned by cementing from the total depth to the surface or,	There must be a minimum of 2 adjacent cement barriers across all formations above the uppermost hydrocarbon production zone and,
2	A cement plug must be set inside the casing as close as practical above the uppermost hydrocarbon production zone	A cement plug must be set across the open hole section and inside the lowermost casing shoe	The innermost casing string must be filled to surface with cement

Sometimes good industrial practices are use integrated open hole volume calculated from caliper on wireline logs to calculate cement volumes or 20-30% above theoretical volume should be used if no caliper data is available. Plugs should normally be a minimum of 45m in length (height). In general cement plugs should not exceed 150m in length. If the hole is badly washed out, it may be better to set two short plugs over the washed out section than to try to cover this interval with one plug (Code of Practice 2013)

Few matters in down hole abandonment that should be considered are construction characteristics of the well, geological formations encountered, hydrogeological conditions i.e. aquifers, environmental risk and regulatory requirements.

2.2.1.1 Well Equipment

Before Plugging and Abandonment can be done, all well completion equipments or production strings must be removed from the wellbore. All items are wellhead (blowout preventer or christmas tree), tubing hanger, production tubing, downhole safety valve (DHSV), surface controlled sub-surface safety valve (SCSSV), annular safety valve, side pocket mandrel, landing nipple, sliding sleeve, production packer, downhole gauge, perforated joint, formation isolation valve, centralizer and wireline entry guide. Well completion tubing string is described as in Figure 2.5:

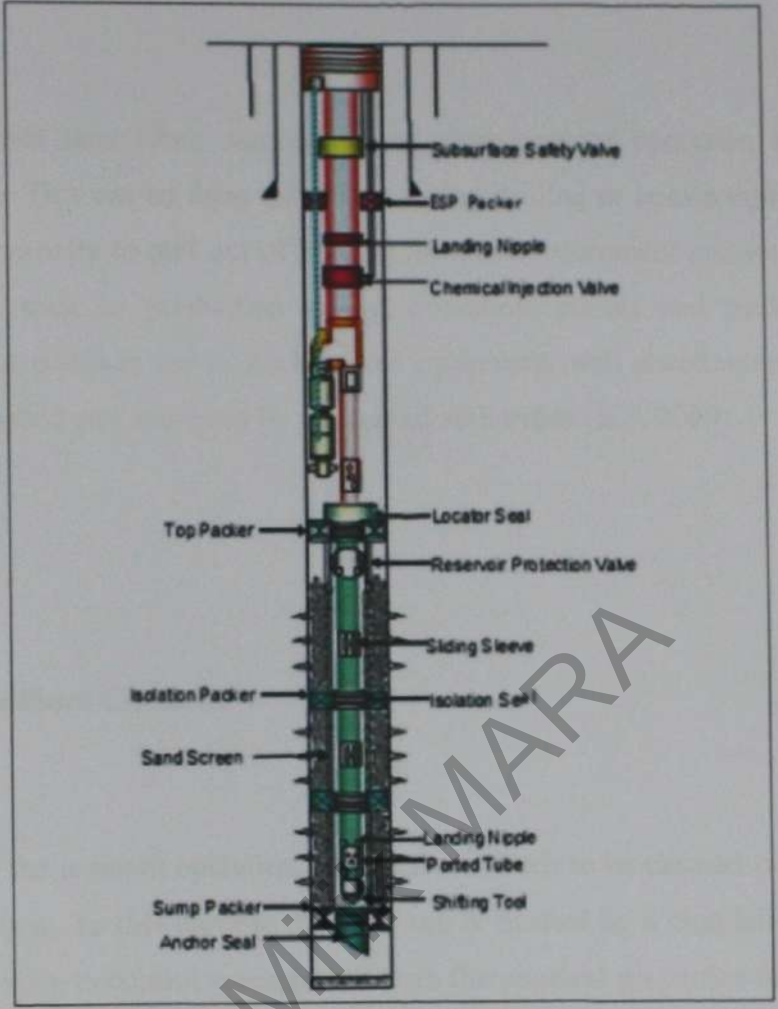


Figure 2.5: Well completion tubing string

2.2.1.2 Preliminaries Activities

Preliminaries activities in well abandonment are wellbore equipment removal and wellbore cleanout

2.2.1.2.1 Removing Downhole Equipment

The first step when starting a well abandonment operation is removing existing tools. This can be done using an existing drilling or conventional workover rig with the capacity to pull out of hole all downhole equipment previously used by the operator, such as production tubing, downhole pumps and packers. If tool removal is not possible due to stuck or lost equipment, well abandonment strategies have to be revised and approved by concerned authorities (IEA 2009)

2.2.1.2.2 Wellbore Cleanout

After the removal operation, the wellbore needs to be cleaned from fill, scale and other debris. To this purpose the wellbore is flushed by a circulation fluid with sufficient density to control pressure and with the physical properties that enable the removal of debris. Dependent on the specific conditions additional tools or additives may be required to successfully clean the hole (IEA 2009)

2.2.2. Platform Abandonment

To prepare a platform for decommissioning, tanks, processing equipment and piping must be flushed and cleaned and residual hydrocarbons have to be disposed of; platform equipment has to be removed, which includes cutting pipe and cables between deck modules, separating the modules, installing padeyes to lift the modules; and reinforcing the structure. Underwater, workers prepare the jacket facilities for removal, which includes removing marine growth.(Rigzone.com)

Figure 2.6: Topside facilities overview

2.2.2.1 Production Facilities

Production facilities are consist of wellhead, manifold or gathering, separator, metering, storage tank, utilities system, flaring system, helli deck and living quarters. All topside equipments and subsurface structures need to be removed during decommissioning.

Although there is a wide range of sizes and layouts, most production facilities have many of the same processing systems shown in this simplified Figure 2.7:

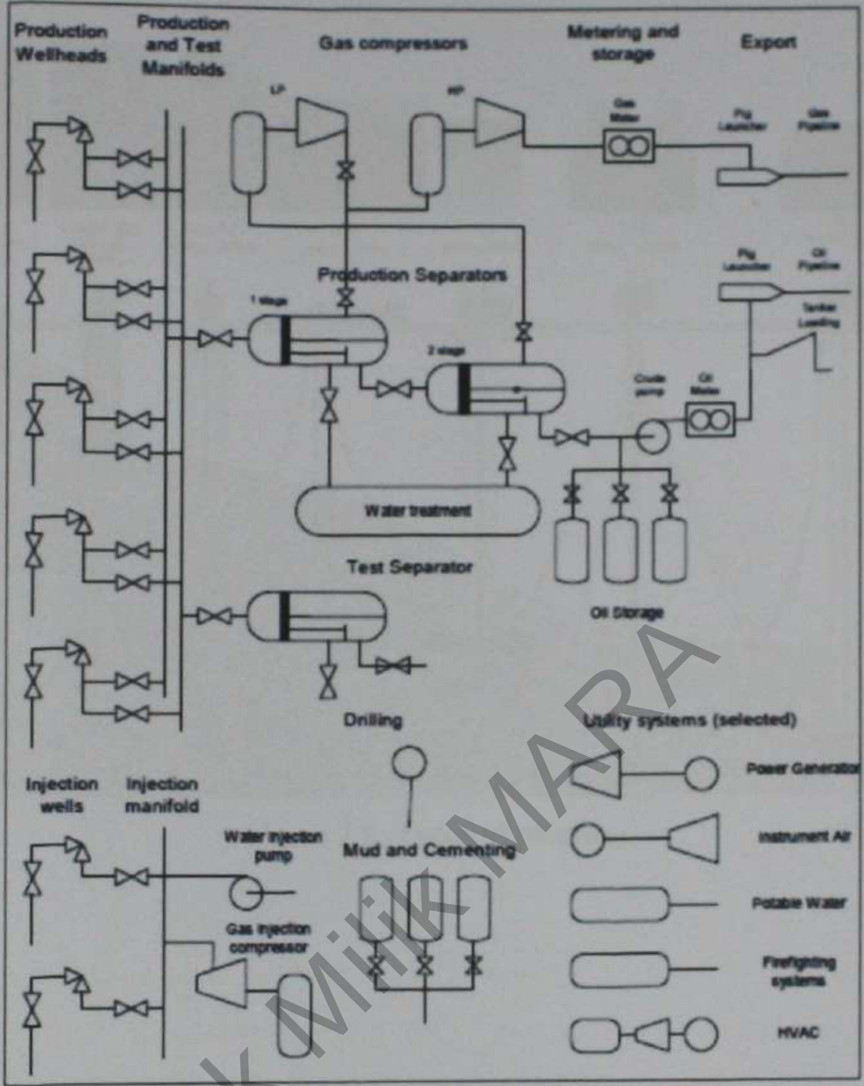


Figure 2.7: Oil and gas production overview (Havard Devold 2013).

A whole range of different structures is used offshore, depending on size and water depth. Some of the common offshore structures are conventional fixed platform, compliant tower, tension leg platform, semi-submersible platform, Floating Production Storage and Offloading (FPSO), SPAR, subsea production system and etc. Types of offshore platform can be summarized in Figure 2.8:

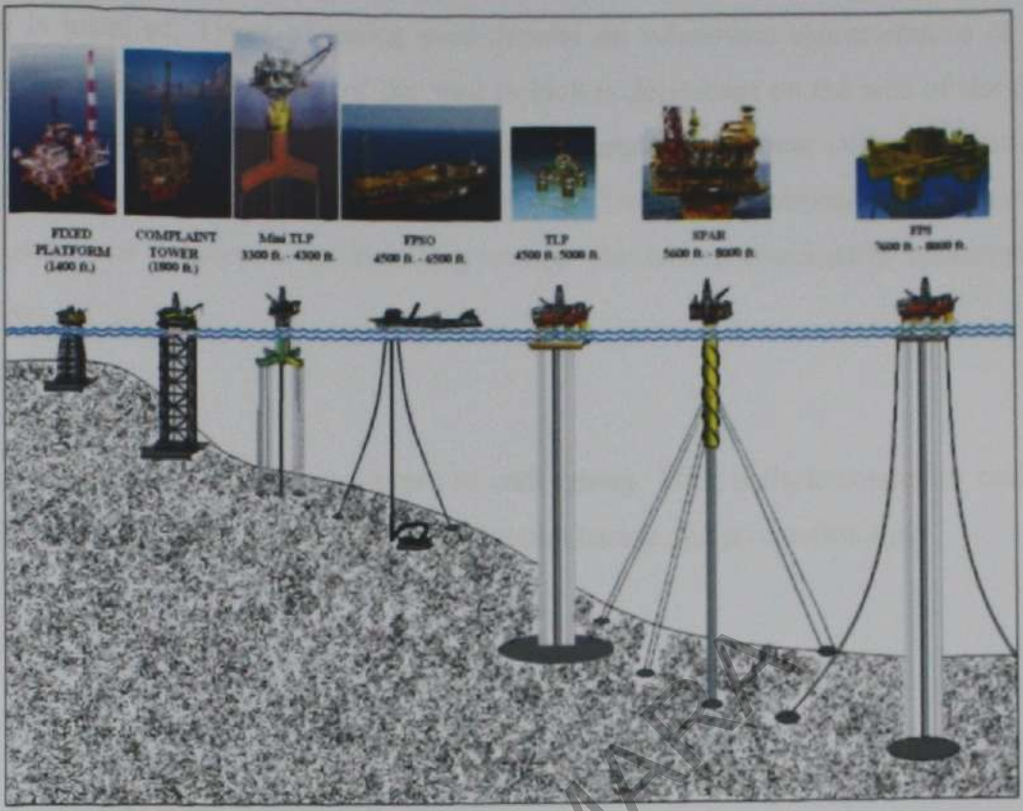


Figure 2.8: Types of platform

2.3 Types of Well Casing

Knowledge on well casing is important before prior to Plug and Abandonment (P&A) activities. Cementing process and plug installation are different between each casing type. As we know installing the well casing is an important part of the drilling and completion process. Well casing consists of a series of metal tubes installed in the freshly drilled hole. Casing serves to strengthen the sides of the well hole, ensure that no oil or natural gas seeps out as it is brought to the surface, and keep other fluids or gases from seeping into the formation through the well.

A good deal of planning is necessary to ensure that the right casing for each well is installed. Types of casing used depend on subsurface characteristics of the well, including the diameter of the well (which is dependent on the size of the drill bit used) and the pressures and temperatures experienced. In most wells, the diameter of the well hole decreases the deeper it is drilled, leading to a conical shape that must be taken into account when installing casing. The casing is normally cemented in place.

There are five different types of well casing. They include conductor casing, surface casing, intermediate casing, production casing and production liner.

2.3.1 Conductor Casing

Conductor casing, which is usually no more than 20 to 50 feet (7-17 m) long, is installed before main drilling to prevent the top of the well from caving in and to help in the process of circulating the drilling fluid up from the bottom of the well.

2.3.2 Surface Casing

Surface casing is the next type of casing to be installed. It can be anywhere from 100 to 400 meters long, and is smaller in diameter to fit inside the conductor casing. Its primary purpose is to protect fresh water deposits near the surface of the well from contamination by leaking hydrocarbons or salt water from deeper underground. It also serves as a conduit for drilling mud returning to the surface and helps protect the drill hole from damage during drilling (Havard Devold 2013).

2.3.3 Intermediate Casing

Intermediate casing is usually the longest section of casing found in a well. Its primary purpose is to minimize the hazards associated with subsurface formations that may affect the well. These include abnormal underground pressure zones, underground shales and formations that might otherwise contaminate the well, such as underground salt water deposits. Liner strings are sometimes used instead of intermediate casing. Liner strings are usually just attached to the previous casing with "hangers" instead of being cemented into place, and are thus less permanent.

2.3.4 Production Casing

Production casing, alternatively called the "oil string" or "'long string," is installed last and is the deepest section of casing in a well. This is the casing that provides a conduit from the surface of the well to the petroleum-producing formation.

The size of the production casing depends on a number of considerations, including the lifting equipment to be used, the number of completions required, and the possibility of deepening the well at a later date. For example, if it is expected that the well will be deepened later, then the production casing must be wide enough to allow the passage of a drill bit later on. It is also instrumental in preventing blow-outs, allowing the formation to be "sealed" from the top should dangerous pressure levels be reached (Havard Devold 2013).

2.4 Types of Well Completion

Well completion commonly refers to the process of finishing a well so that it is ready to produce oil or natural gas. In essence, completion consists of deciding on the characteristics of the intake portion of the well in the targeted hydrocarbon formation. There are a number of types of completions, including open hole, conventional perforated, sand exclusion, permanent, multiple zone and drain hole completion.

2.4.1 Open Hole Completion

Open hole completions are the most basic type and are only used in very competent formations that are unlikely to cave in. An open hole completion consists of simply running the casing directly down into the formation, leaving the end of the piping open without any other protective filter (Havard Devold 2013).

2.4.2 Conventional Perforated Completions

Conventional perforated completions consist of production casing run through the formation. The sides of this casing are perforated, with tiny holes along the sides facing the formation, which allows hydrocarbons to flow into the well hole while still providing a suitable amount of support and protection for the well hole. In the past, "bullet perforators" were used. These were essentially small guns lowered into the well that sent off small bullets to penetrate the casing and cement. Today, "jet perforating" is preferred. This consists of small, electrically-fired charges that are lowered into the well. When ignited, these charges poke tiny holes through to the formation, in the same manner as bullet perforating (Havard Devold 2013).

2.4.3 Sand Exclusion Completions

Sand exclusion completions are designed for production in an area that contains a large amount of loose sand. These completions are designed to allow for the flow of natural gas and oil into the well, while preventing sand from entering. The most common methods of keeping sand out of the well hole are screening or filtering systems. Both of these types of sand barriers can be used in open hole and perforated completions (Havard Devold 2013).

2.4.4 Permanent Completions

Permanent completions are those in which the completion and wellhead are assembled and installed only once. Installing the casing, cementing, perforating and other completion work is done with small-diameter tools to ensure the permanent nature of the completion. Completing a well in this manner can lead to significant cost savings compared to other types (Havard Devold 2013).

2.4.5 Multiple Zone Completions

Multiple zone completion is the practice of completing a well such that hydrocarbons from two or more formations may be produced simultaneously, without mixing with each other. For example, a well may be drilled that passes through a number of formations on its way deeper underground, or it may be more desirable in a horizontal well to add multiple completions to drain the formation most effectively. When it is necessary to separate different completions, hard rubber "packing" instruments are used to maintain separation.

2.4.6 Drain Hole Completions

Drainhole completions are a form of horizontal or slanted drilling. This type of completion consists of drilling out horizontally into the formation from a vertical well, essentially providing a drain for the hydrocarbons to run down into the well. These completions are more commonly associated with oil wells than with natural gas wells (Havard Devold 2013).

2.5 Well Abandonment Practices

Well abandonment involves activities listed in Table 2.2 below:

Table 2.2: Common well abandonment activities

No	Activity
1	well entry preparations
2	use of a slick line or coil tubing or wireline unit
3	filling the well with fluid
4	removal of downhole equipment
5	cleaning out the wellbore
6	plugging open-hole and perforated intervals at the bottom of the well
7	plugging casing stubs
8	plugging of annular space
9	placement of a surface plug
10	placement of fluid between plugs

2.5.1 Well Plugging Methods

The plugging methods employed on oil and gas wells have improved over time as regulators required better well plugging plans and as operators began to see the benefits of sealing the abandoned wells more securely. When cement was first being used to plug wells, the cement tended to not set up correctly and was often contaminated by the drilling mud and wellbore fluids. Through the implementation of cementing standards by the American Petroleum Institute (API) and more standardized plugging programs, the cement plugs became more uniform.

When wells were plugged in the late 1800s and early 1900s, cement was often emplaced in the well by pouring the cement from the surface. The wells were shallow and this method was somewhat effective. As the wells became deeper, cement was pumped down tubing to place the cement at the desired depth. To be able to pump cement down hole, oilfield cement companies developed specialized equipment that could transport the dry cement to a well site and then blend the cement mix while pumping it down the hole (J.D. Arthur 2011).

As operators started pumping cement downhole for cementing operations, they initially did not understand the need for hole cleaning prior to cementing. Therefore, many of the early plugs did not harden as desired. After the passage of the SDWA a new technique for placing cement in the well was researched and improved, now being known as the displacement method or the balance plug method. The displacement method minimizes the contamination of the cement by use of a cement that has good hole-cleaning characteristics and can displace leftover drilling mud. First, tubing is run into the well to the depth desired for the bottom of the cement plug where the cement is then placed into the well by pumping down the tubing. The cement goes out the bottom of the tubing and then flows back up the outside of the tubing.

Second, after the desired amount of cement is pumped, water is pumped behind the cement to displace the cement in the tubing to a predetermined depth. At that point the tubing is pulled out of the well and when done correctly, the cement in the tubing fills the space the tubing occupied in the well which leaves a good solid section of clean cement. When using the displacement method, operators can fairly accurately place the cement in the well at the desired depth and thereby prevent flow in the wellbore from the targeted depth intervals (J.D. Arthur 2011).

The types of materials used for plugging abandoned wells have not changed significantly over the last 30 years. While cement is the most common plugging material used to seal the abandoned wells, drilling mud, bentonite and mechanical plugs also are used frequently in conjunction with cement. In wells plugged prior to the more modern regulations and standards set in the 1950s and onward, many wells were abandoned with plugs consisting of brush, wood, paper sacks, linen or any other material that could be pushed into a well to form a basis for the dumping of one or two sacks of cement to "plug" the well. While that use of sundry materials was fairly common in the early days of the oil field, current procedures are significantly more disciplined and have higher success ratios of providing seals adequate to prevent future contamination issues.

2.5.1.1 Cement

A basic and widely used plugging material is formulated as a slurry of water and Portland cement that is compositionally managed in terms of gallons of water or pounds of additives per 94-lb sack of cement. Cement used in plugging of oil and gas wells has improved significantly over the past few decades. The cement composition in the early days of the oil industry is similar to what is used today, but today's cement uses a number of additives that enhance the sealing of the cement in the wellbore. With the advances in well drilling technology and the types of wells being drilled and completed, the cementing technology has improved to allow for cementing of horizontal wells, high-pressure wells, high temperature wells, low-temperature wells, CO_2 wells, and other specialty applications. Those same cement technologies can be used in the plugging of abandoned wells (J.D. Arthur 2011).

The American Petroleum Institute (API) first developed a classification system for oilfield cements in 1952. The API cements are all Portland cement-based with similar ingredients but are mixed in different proportions. The different classifications are ground to a different fineness and have different water requirements for mixing. API cement classification is describe in Table 2.3:

Table 2.3: API cement classification (J.D. Arthur 2011).

API Classification	Depths (Ft)	Water Requirement (gal / sk)	Slurry Density (lb / gal)	Description
Class A	0 to 6,000	5.2	15.6	Common or regular cement
Class B	0 to 6,000	5.2	15.6	Moderate to high sulfate resistance.
Class C	0 to 6,000	6.3	14.8	High-Early Cement. Fine grind, good availability
Class D	6,000 to 10,000	4.3	Varies	For Moderate Temperature and Pressure. Coarse grind plus retarder
Class E	10,000 to 14,000	4.3	Varies	High pressure, high temperature. All depths with retarders
Class F	10,000 to 16,000	4.3	Varies	Use for extremely high temperature and pressure
Class G & H	0 to 8,000	G -5.0 H – 4.3	G - 15.8 H – 16.4	Basic cement. Used at all depths with retarders.

When using the API cement for cementing a well or for plugging, various additives are blended into the cement for specific purposes. Each cementing company uses additives and blends cement based on the customer's specific cementing plan. Most companies have proprietary additives for specific applications along with the standard additives such as barite and bentonite.

Some of the additives commonly used are listed in Table 2.4:

Table 2.4: Cementation additives (J.D. Arthur 2011)

No	Additive	Remark
1	Retarder	added to slow down the setting time to allow for longer pump times and/or the removal of the tubing used to place the cement.
2	Accelerator	used to shorten the setting time. These are used in wells to allow the cement to set up faster to prevent gas or fluid channeling, to prevent backflow in the tubing and when plugging the additive can shorten the wait time between plugs.
3	Pozmix	which includes pozzaline (a mixture of lime and volcanic ash), is added to Portland cement to achieve a more durable calcium silicate cement mixture. The use of pozzaline also reduces the amount of Portland cement in the mixture which reduces the overall cost of the cement.
4	Lost Circulation Material	Selected materials are added to cement to reduce the loss of cement to the formation prior to hardening. Materials such as walnut shells, cottonseed hulls, fibers, flaked cellophane and diesel oil
5	Weighting Additives	Materials are added to the cement to increase its weight to combat higher formation pressures. Materials such as barite and sand.
6	Light-Weight Additives	These materials are added to cement to reduce the cement density and thereby lessen the chances of losing cement to high-permeability or lowfracture-gradient formations. Materials such as Pozmix™, gel and foam are used to "lighten" cement mixtures.
7	Water-Loss Additives	Water-loss additives are combined with the cement mixture to reduce the rate of water loss from the cement mixture. By reducing water loss prior to setting, the cement can harden properly and avoid premature drying which can reduce the strength of the cement.

Specialty Cements. While most wells can be cemented with standard cements, there are situations that can require a special cement blend to create the best seal in the well. Some of the well types that require a specialized blend of cement include moderate to high-pressure gas wells, horizontal wells, wells completed through salt zones, high temperature wells, and wells that are very deep (below 15,000 ft.). Plugging such wells with conventional systems can be done in many instances but there is a risk of channeling or mud contamination from gas or fluids that can create a pathway for fluids to migrate out of the zones being plugged. The following Table 2.5 discuss the types of wells and situations that require specially cement blends.

Table 2.5: Special cement application (J.D. Arthur 2011).

No	Situation	Remark
1	Moderate to high pressure gas wells	Cementing of natural gas wells to prevent the flow of gas outside the casing has plagued the oil and gas industry for years. As the demand for gas increases, this issue becomes larger as more wells are drilled and the gas migration causes casing pressure problems and gas leaking into other formations and the fresh water. The cements used for these wells require that the cement be designed to reduce the gas migration while the cement is curing. Many cementing companies have developed additives that can reduce the gas cutting through the cement.
2	Horizontal wells	The horizontal orientations introduce different gravitational effects compared with vertical wells. In a typical vertical well, where there is a large column of cement, some migration of the solids downward or the water upward does not cause a significant change in the cement properties. In a horizontal well, the solids migrating to the bottom of the section and the water migrating to the top can provide areas of the well that

		do not have a complete seal. If the water in the cement separates from the mixture before the cement is set, it can migrate to the top of the wellbore and form a channel along the top of the wellbore which can allow migration of formation fluids. If the solids in the cement mixture settle to the bottom of the cement before the cement can harden, the solids can cause the cement to not set up correctly and the weakened area along the bottom of the wellbore can fail under pressure during stimulation activities (Salehi and Paiaman, 2009).
3	Salt zones	Salt mixed into cement functions as an accelerator of solidification. If a well is drilled through a natural salt zone and the cement mixture is not adjusted for the salt, the cement can set up prematurely. When cementing wells that have been drilled through a salt layer, special precautions must be taken to prevent contamination of the cement by the salt. Special additives must be used to prevent the premature setting of the cement caused by salt entering the cement mixture as the mixture it is pumped past the natural salt layer.
4	Deep wells	Cementing of deep wells requires long pump times to get cement pumped to the bottom of the well and displaced upward. With long pump times there is a chance that the cement could harden prematurely and cause pumping problems. Special cement retarders are used to allow for adequate pumping time to place the cement where desired. In addition, with the long stands of pipe to pump through, friction becomes an issue and friction reducers may be required to make pumping the cement easier.

Table 2.6: Plugging methods (IEA 2009)

Abandonment Method	**Description**	**Benefits / Limitations**
Balanced Plug[2]	The more common method of abandonment, whereby the tubing is placed at the target plug depth, and the cement slurry is then injected onto a bridge plug device which forms the plug base. Cement is then pumped into the annulus until it is equal to the level inside the casing.	One of the simplest techniques, incurring lower costs than some, the main limitation is caused by the potential for cement contamination. This can be minimised by use of best practice and best suited plug base materials, as described later in this overview.
Cement Squeeze	Squeeze cementing involves pressurised forcing of cement at a pre-determined depth coinciding with perforations in the casing. The pressure forces the liquid of the slurry into the formation, leaving the cement to form a seal.	Often used as a remedial measure for flawed or damaged primary cement, the exact quantity of cement required cannot always be calculated, leading to possible excess cement which can enter the casing above the packer. This would effectively stick the tubing into the hole, preventing future removal.
Dump Bailer[3]	A known quantity of cement is lowered into the wellbore on a wireline, and the bailer is activated when it reaches the correct position, just over the bridge plug and raising the bailer releases the cement.	The stationary nature of the slurry during the descent can lead to premature setting, so this is more suited to setting plugs at shallower depths
Two-plug	A complex process whereby a top and bottom plug are set at calculated depths, the lower plug cleans the well as it is lowered, and the cement can then be placed with minimal contamination from other fluids.	Allows maximum accuracy of placement with minimum cement contamination. The isolation of the cement slurry from other fluids ensures predictable cement performance.

2.5.1.2 Bentonite and Drilling Mud

In many of the wells currently being plugged, drilling mud and bentonite are still being used to fill those portions of the well that are not cemented. Bentonite, which is a natural material rich in swelling clays, is used commonly to form the base of most drilling muds. Bentonite powder is mixed with water to form a fluid that has the ability to lift cuttings from a well and suspend them at times when the mud pumps are shut down. Drilling mud has historically been used to plug most wells in the United States. A review of historical well records will show that most wells were filled with heavy mud, or drilling mud at the time of plugging. In California, records from wells in Los Angeles County that were drilled and plugged in the 1930s through the 1950s in many cases had a small cement plug at the top of the production zone and then were filled with mud that ranged from 9.1 pounds per gallon (ppg) to over 12 ppg depending on the depth (J.D. Arthur 2011).

The use of drilling mud for well plugging relies on the characteristics of mud weight and gel strength to prevent upward flow of reservoir fluids. For upward flow of fluids to occur, the formation fluids must overcome the downward pressure exerted by the weight and gel strength of the mud column in the wellbore. The gel strength of mud is the resistance to shear that develops when the mud is not moving. When mud is being pumped (moving) it has gel strength of less than one pound per one-hundred square feet (1 lb/100 sq. ft) but once the mud stops moving the gel strength increases by up to 100%. A study of the pressure effects of the static mud column in abandoned wells, found that over time the gel effect is reduced slightly due to the mud drying out, but that the gel strength should still be calculated at around 25 lb/100 sq. ft. Gel strength increases the pressure required to start fluid moving uphole in a mud-filled well (J.D. Arthur 2011).

Bentonite plugging of wells is still used in some areas. In the Bakersfield and Coalinga Districts of California bentonite is approved as an alternative to cement to plug wells. The bentonite must be in a compressed form and can only be used in wells that are larger in diameter than 2-7/8 inches. The bentonite must be hydrated for 24 hours and, if the plug is to go across the fresh water zone, the surface casing must be cemented through the fresh water interval. The rules state that bentonite may not be used when there is a 500 pounds per square inch (psi) pressure differential between zones of a wellbore.

Bentonite, when placed as a compressed solid and then hydrated, will form a dense and lowpermeability solid mass in the wellbore based on its character as a clay material that swells when water is added. Bentonite clay is often used in surface applications where low-permeability clay is needed to prevent migration of liquids such as the liner for a landfill or pond (J.D. Arthur 2011).

2.5.1.3 Mechanical Plugs

Mechanical plugs are used in some wells to reduce the amount of cement required to plug a well or to provide additional protection from formation pressure in the well. Two types of mechanical plugs utilized to plug and abandon wells are a bridge plug or a cement retainer. The choice of which plug type to use is based on whether cement needs to be pumped below the plug to seal the perforations (squeeze cementing). If cementing below the plug is not required, or if a balanced cement plug was installed below the mechanical plug setting depth, a bridge plug can be used. Mechanical plugs can be set in the well using workstring tubing, coiled tubing, or with a wireline. When working in wells with pressure, the use of tubing and or coiled tubing is typically required.

The mechanical plugs consist of four major parts which are the body of the plug which can be made of steel, cast iron and composite material, the slips which are metal parts that grab the casing to hold the plug in place, the packing material which is a rubber or nylon ring that is squeezed outward when the plug is set in the well and the on/off tool that allows the plug to be set and then released to pull the tubing or wireline out of the well after setting.

Setting the tool downhole is accomplished in a number of ways depending on the specific manufacturer's design. Typically the tool is lowered to the desired location and then rotated to release the slips that will grab the casing to hold the plug. Then the plug is raised or lowered (depending on the specific application) to expand the sealing element against the casing. Once the desired tension on the tool is applied, either the tool is set and can be released, or, if required, it is rotated to release a secondary set of slips that will keep the tool expanded and set prior to release. In the case of a wireline set tool, some versions use explosives or hydraulic systems to set the slips and packing element prior to release (J.D. Arthur 2011).

Bridge plugs are a mechanical plug that is used to provide a solid seal within a wellbore for plugging. Some bridge plugs are designed to be easily drillable in case the well is desired to be re-entered at a later date. Bridge plugs are typically made of cast iron with duel slips with a sealing element between the slips. The plug is designed to be set in a wellbore and then have cement set on top to provide a complete seal of the reservoir below. In cases where there is a potential for moderate or high pressure gas to be flowing from the area below the setting depth, a bridge plug can be set to seal the wellbore prior to cementing to reduce the chances of the pressurized water or gas to contaminate the cement. Figure 2.9 shows a typical cast iron bridge plug used to plug and abandon wells.

Figure 2.9: Cast iron bridge plug (J.D. Arthur 2011).

A cement retainer is a mechanical plug that can be set above a zone to be cemented. This type of plug is especially useful when plugging higher pressured zones that need to be squeeze-cemented prior to plugging. Cement retainers are usually built from drillable material so will yield to later re-entry of the reservoir as needed. The cement retainer is set in the well in a method similar to that used for a bridge plug.

Once the tool is set in the well, cement can be pumped through the plug to squeeze cement through the perforations or open-hole area below the retainer. Pressure can be applied to the area below the retainer without a concern for cement traveling uphole past the cement retainer. The application of pressure to squeeze the cement through the perforations provides a good method of sealing the well at plugging (J.D. Arthur 2011).

Once the desired amount of cement is squeezed below the retainer, the tubing is pulled upward out of the retainer and a mechanical flap closes the hole to effectively seal the cement below the cement retainer. Cement is then typically placed on top of the cement retainer to provide a more complete seal of the reservoir. Figure 2.10 shows a typical cement retainer.

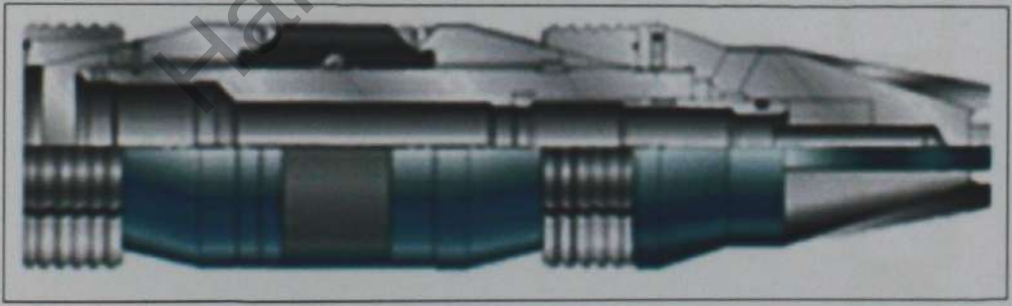


Figure 2.10: Cement retainer (J.D. Arthur 2011).

2.5.2 Minimum Abandonment Standards

There are few common plugging and abandonment activities as listed below:

i. Cement plug across and 100 ft above producing zones
ii. Cement plug across and 100 ft above and below production and surface casing laps
iii. Sufficient cement outside of casing strings to isolate hydrocarbon bearing Strata from surface
iv. Water shut off at base of usable fresh water for land and tidal zone Wells
v. 25 ft (or more in offshore wells) cement surface plug
vi. Inert mud of sufficient density to control well pressure between all cement Plugs
vii. Remove wellhead and casing to a depth not to exceed 5' below mudline or grade

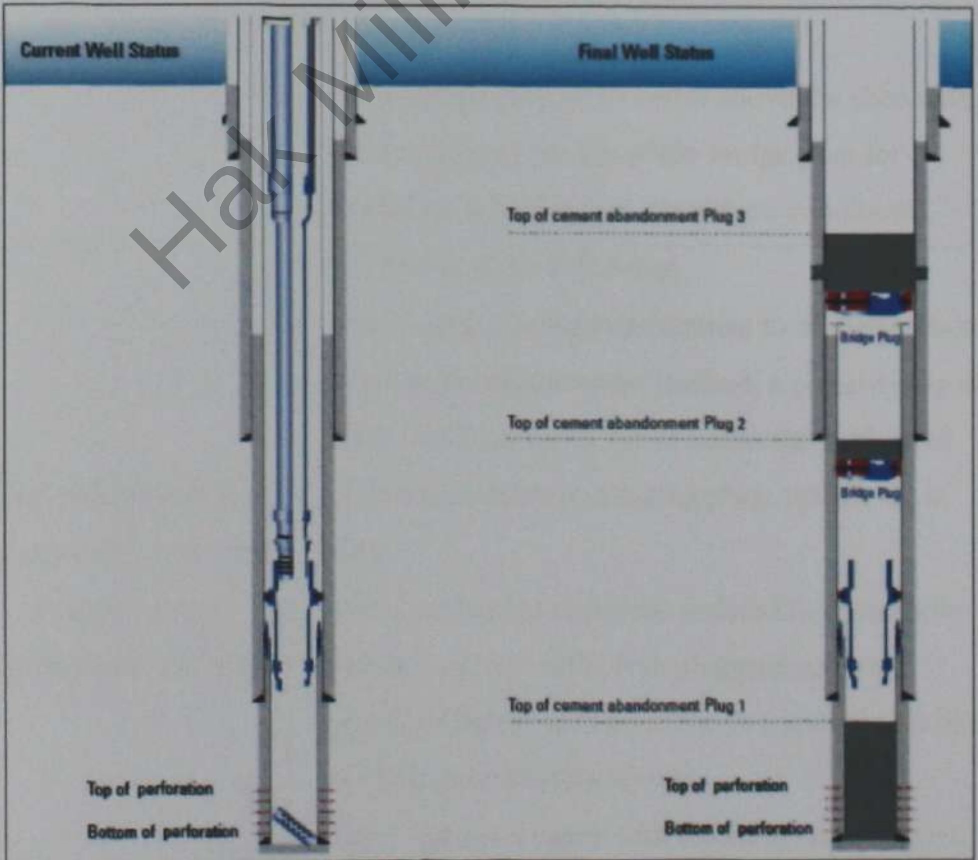


Figure 2.11: Plugging and abandonment technique (Kenny Campbell 2013)

Plugging and abandonment regulations are depending on types of completion of that particular well. Regulations guide is described as in Table 2.7:

Table 2.7: US P&A Regulations Guide (Abshire et al. 2012).

Situation	**Procedure**
Zones in open hole	Set cement plug(s) from at least 100 ft [30 m] below the bottom to 100 ft above the top of oil, gas and freshwater zones to isolate fluids in the strata.
Open hole below casing	Perform one of the following: • Set, by the displacement method, a cement plug at least 100 ft above and below the deepest casing shoe. • Set a cement retainer with effective backpressure control 50 ft [15 m] to 100 ft above the casing shoe, and a cement plug that extends at least 100 ft below the casing shoe and at least 50 ft above the retainer. • Set a bridge plug 50 to 100 ft above the shoe with 50 ft of cement on top of the bridge plug for expected or known lost circulation conditions.
Perforated zone that is currently open and not previously squeezed or isolated	Perform one of the following: • Use a method to squeeze cement to all perforations. • Set, by the displacement method, a cement plug at least 100 ft above to 100 ft below the perforated interval, or down to a casing plug, whichever is less. • If the perforated zones are isolated from the hole below, use any of the five plugging methods specified below instead of the two specified in this section, immediately above. • Set a cement retainer with effective backpressure control 50 to 100 ft above the top of the perforated

	interval and a cement plug that extends at least 100 ft below the bottom of the perforated interval with at least 50 ft of cement above the retainer. • Set a bridge plug 50 to 100 ft above the top of the perforated interval with at least 50 ft of cement on top of the bridge plug. • Set, by the displacement method, a cement plug at least 200 ft [60 m] in length, with the bottom of the plug no more than 100 ft above the perforated interval. • Set a through-tubing basket plug no more than 100 ft above the perforated interval with at least 50 ft of cement on top of the basket plug. • Set a tubing plug no more than 100 ft above the perforated interval topped with a sufficient volume of cement so that it extends at least 100 ft above the uppermost packer in the wellbore with at least 300 ft [90 m] of cement in the casing annulus immediately above the packer.
Casing stub with the stub end within the casing	Perform one of the following: • Set a cement plug at least 100 ft above and below the stub end. • Set a cement retainer or bridge plug at least 50 to 100 ft above the stub end with at least 50 ft of cement on top of the retainer or bridge plug. • Set a cement plug at least 200 ft long with the bottom of the plug no more than 100 ft above the stub end.
Casing stub with the stub end below the casing	Set a plug as specified in the openhole sections, above, as applicable
Annular space that communicates with	Set a cement plug at least 200 ft long in the annular space; for a well completed above the ocean surface,

open hole and extends to the mudline	pressure test each casing annulus to verify isolation.
Subsea well with unsealed annulus	Use a cutter to sever the casing; set a stub plug as specified in casing stub sections, above.
Well with casing	Set a cement surface plug at least 150 ft [45 m] long in the smallest casing that extends to the mudline with the top of the plug no more than 150 ft below the mudline.
Fluid left in the hole	Maintain fluid in the intervals between the plugs that is dense enough to exert a hydrostatic pressure that is greater than the formation pressures in the intervals.
Permafrost areas	Leave, in the hole, fluid that has a freezing point below the temperature of the permafrost and a treatment to inhibit corrosion and use cement plugs designed to set before freezing and that have a low heat of hydration

2.5.3 Tubing Cement Displacement and Site Clearance

Tubing cement displacement is a process that isolates two zones in the wellbore. Normally, reservoir isolation cement plugs were set using coil tubing or wireline unit. The objectives were to place a column of cement across perforated intervals, bringing it up to the vicinity of the production packer in order to provide the best chance of isolating the reservoir and then a substantial balanced cement plug was set above the production packer, where it would provide a second barrier both inside the tubing and within the annulus (John Reid 2010)

Next activities are cutting and recover tubing and casing. The objective was to place surface cement plugs within the wellbore, and hence secure it to the extent that the remaining abandonment work would not require the installation of BOP equipment.

In general this involved recovering the topmost 1500 ft of tubulars (excepting conductor and surface casing) and was done with the rig. However, where there was concern over the quality of the original production casing cement job, some remedial work was also programmed.

The use of mechanical casing cutters, abrasive hydraulic cutters, and explosives, are all being considered for parting of the conductors. It may thereafter be required to cut the cement bonded casings into manageable lengths using band saw, hydraulic 'snipping' tool, diamond wire, abrasive hydraulic cutter (refer to Figure 2.12), and thermic lance.

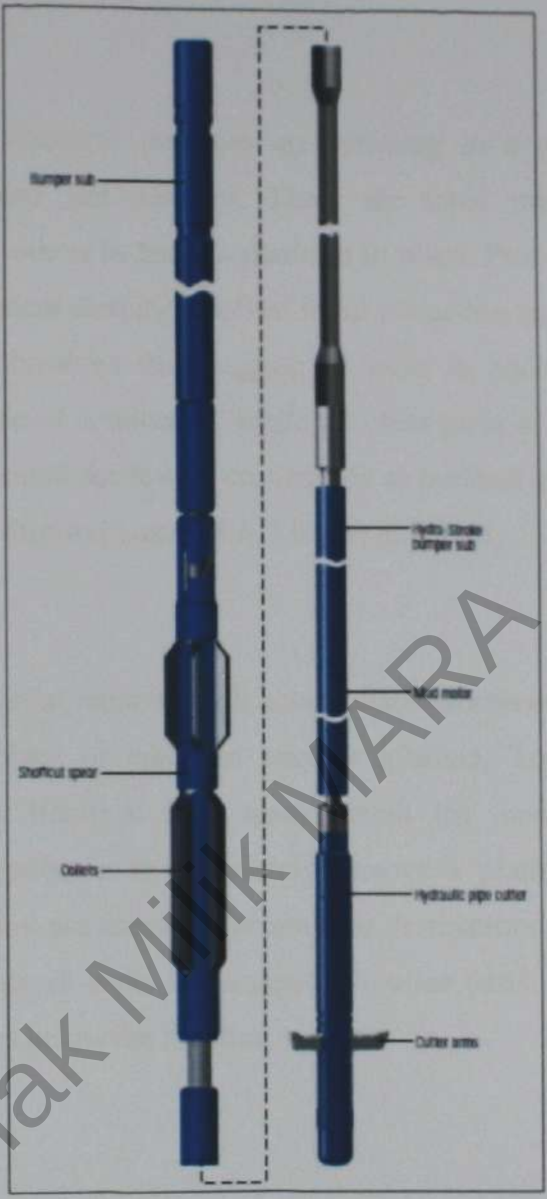


Figure 2.12: Example of hydraulic cutter (Abshire et al. 2012).

Tubing site clearance is refers to surface cleanup and removal of the casing strings. The final step in permanently abandoning a well is the removal of the wellhead and the recovery of the casing strings to a depth that will help ensure a safe environment for future activities. On land, casing strings are normally recovered from at least 3 to 5 ft below the flowline. Offshore, casings are normally recovered from at least 15 ft below the mudline to prevent current movements from exposing the casing stub. The recovery depth is fairly arbitrary and normally specified in the regulations governing a specific geographic area.

2.6 Platform Abandonment Practices

Platform abandonment practices are referring to a part of abandonment programme in oil and gas industry. There are three main decommissioning alternatives. The first one is to leave a platform in place. Proper shutting down and stripping of all equipment directly involved in oil extraction are the key components of this option. This involves the plugging of wells in addition to the complete removal and severance of conductors, while all other parts of the platform remain. This scenario would entail the lowest costing due to minimal planning, engineering, and mobilization and disposal costs (M.S. Liew et al. 2014)

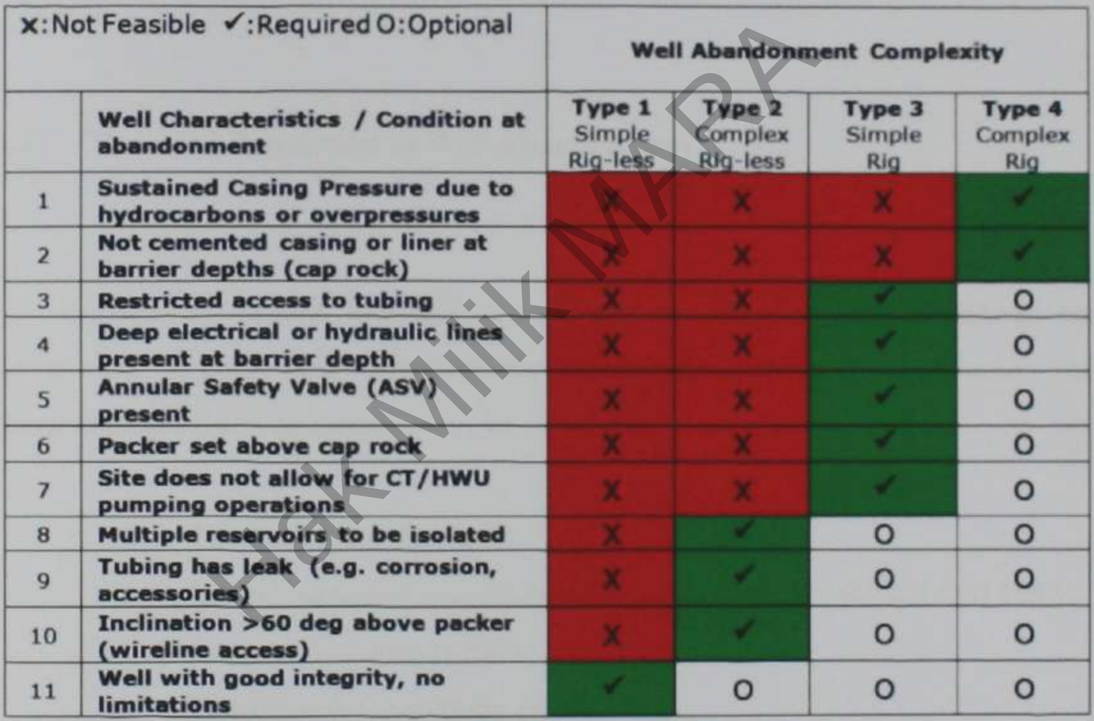
Secondly, a partial removal with either offshore/onshore disposal of material that is toppled in place or taken to another location. Topsides must first be completely removed. Removal here would entail the most expensive removal costing. The third option is to completely remove a platform from the ocean. Materials from platform are removed for multiple destinations for reuse or recycling purposes after ensuring all wells are plugged. No other parts of the platform would remain above 5 meters below the mudline.

2.7 Abandonment Equipment and Tool

In general, a large number of well abandonment operations could be carried out in a rigless manner. Rigless abandonments include the use of highly mobile equipment spreads, such as pumping skids and jacking units. However, the complexity of the initial well design, coupled with possible well issues such as multiple annular pressure issues and lack of wellbore access, may dictate that a rigbased approach is required.

Depending on water depth, offshore well abandonment can be staged from a fixed platform such as jackup rig, from a large floating platform such as a semisubmersible drilling rig or from a support vessel with dynamic positioning. In UK waters, abandonment from a fixed platform is the least expensive about US$ 1 to 2 million per well. By contrast, abandonment operations using a semisubmersible or dynamically positioned floating drilling unit typically cost operators US$ 5 to 6 million per well. Types of rig used in abandonment are depending on the condition of the reservoir as stated in Table 2.8:

Table 2.8: Types of rig (J. Shoenmakers 2013)



✗: Not Feasible ✓: Required O: Optional		**Well Abandonment Complexity**			
	Well Characteristics / Condition at abandonment	**Type 1** Simple Rig-less	**Type 2** Complex Rig-less	**Type 3** Simple Rig	**Type 4** Complex Rig
1	**Sustained Casing Pressure due to hydrocarbons or overpressures**	✗	✗	✗	✓
2	**Not cemented casing or liner at barrier depths (cap rock)**	✗	✗	✗	✓
3	**Restricted access to tubing**	✗	✗	✓	O
4	**Deep electrical or hydraulic lines present at barrier depth**	✗	✗	✓	O
5	**Annular Safety Valve (ASV) present**	✗	✗	✓	O
6	**Packer set above cap rock**	✗	✗	✓	O
7	**Site does not allow for CT/HWU pumping operations**	✗	✗	✓	O
8	**Multiple reservoirs to be isolated**	✗	✓	O	O
9	**Tubing has leak (e.g. corrosion, accessories)**	✗	✓	O	O
10	**Inclination >60 deg above packer (wireline access)**	✗	✓	O	O
11	**Well with good integrity, no limitations**	✓	O	O	O

Most of Abandonment programmes use wireline or slickline or coil tubing service as conveyance and measurement tool. Lift Mast and Rigless systems were among the topside equipments. Meanwhile for mechanical services, equipment and tool are described as Table 2.9:

Table 2.9: Mechanical service equipments (IPM Schlumberger 2014)

Activity	Equipment
Perforation	Wireline or Slickline or Coil Tubing
Tubular	Fishing Service, Section Milling, Abrasive Perforation, Casing Cutting, Impact Tools and Conductor Removal
Barriers	Cementing Services, Bridge Plugs, Inflatable Packers and Wireline Plugs

2.8 Rule and Regulation in Well Abandonment

There are several key legislative documents that must be considered and taken into account when planning for abandonment all over worldwide. This documents are listed as follow:

i. The Petroleum Act 1987
ii. United Nations Convention of the Law of the Sea (UNCLOS) 1982
iii. London Convention 1972
iv. The Geneva Convention 1958
v. The Coastal Protection Act 1949
vi. International Maritime Organisation 1987
vii. 1992 Convention on Biological Diversity

The Petroleum Act 1987 does not define the actual removal standards as the UK government has held in abeyance such standards until such times that there is an international agreement. However, the UK government has stated in 1989 and 1990 that removal standards will include and take into account on fishing interests, environmental considerations and the guideline published by the International Maritime Organisation (IMO) (T.W. Bartlett 1994).

The Coastal Protection Act 1949 governs exploration and exploitation in the UKCS, but it is not specific with regard to platform abandonment, removal and disposal. Following this, the Coastal Protection Act required permission from the Department of Trade and Industry (DTI) to install offshore structures, provided that there was no obstruction or danger to navigation. The provisions under this Act were extended in 1964 under the Continental Shelf Act, under which permission to remove any object from the seabed must first be obtained from the DTI (T.W. Bartlett 1994).

The Geneva Convention 1958 under Article 5.5 it states that an installations either disused or abandoned must be removed to seabed level, these regulations were later adopted at the first United Nations Conference on the Law of the Sea (UNCLOS) (T.W. Bartlett 1994).

Due to the rapid advances in technology it became evident that the existing National and International law including the 1958 convention would require significant changes. In United Nations Convention of the Law of the Sea (UNCLOS) 1982 a major review was undertaken and the bases of the conference were:

i. Notice should be given of all proposals for the construction of offshore platforms.
ii. There must be permanent means of warning of their presence.
iii. Abandoned and disused structure shall be removed to give safety to all navigation with respect to existing navigation standards.
iv. The position, depth and dimension of all partially removed structures shall be made public knowledge.

London Convention 1972 introduced regulations primarily to govern and protect the marine environment from pollution. The London Convention prohibits global dumping of oil and requires a special permit to be granted for the dumping of scrap metal and bulky material, this would include such things as platform topsides and structures.

Malaysia's national oil company, Petronas, has adopted Decommissioning Guidelines which require that offshore installations be fully decommissioned, except where non-removal or partial removal is consistent with the standards and requirements imposed by those guidelines. Decommissioning of structures and installations must be evaluated on a case-by-case basis. There are also signs that the Department of Environment is working on new legislation and guidelines for the country (Youna Lyons 2014).

The laws and regulations adopted in the above noted Malaysia show their awareness of the general obligation of removal but also highlight the uncertainty surrounding the possibilities to not remove abandoned offshore installations. Interestingly, the most recent rules and guidelines adhere closely to the principles set in UNCLOS and in the 1989 IMO Guidelines.

CHAPTER 3

METHODOLOGY

3.1 Project Flowchart

This study can be categorized as qualitative approach. Most of the inputs are come from unstructured interviews, documents, journals, magazines, conference papers and books. This project consists of few stages which are data collection, data classification, analysis, comparison and finding as described in Figure 3.1:

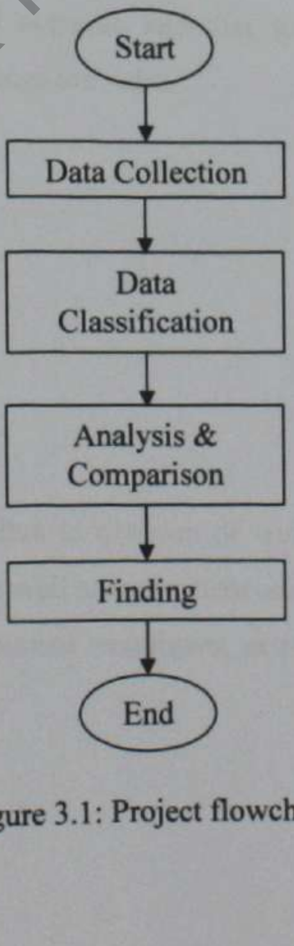


Figure 3.1: Project flowchart

3.2 Introduction

This chapter introduces the research methodology used for this study and how it has guided data collection, data classification, analysis and comparison and finding. This is likely to be the methodology of theoretical analysis where selection and discussion of theoretical material and descriptive material, in context, and detailed comparison of theories in terms of their applicability.

3.3 Data Collection

Most of data gathered in this study are secondary data. Secondary data collection were conducted by collecting information from a diverse source of documents, journals, articles, books, magazines, catalogues and electronically stored information. A formal data collection process is necessary as it ensures that data gathered are both defined and accurate and that subsequent decisions based on arguments embodied in the findings are valid.

3.4 Data Classification

Data classification is refers to division of well abandonment data gathered into 2 main categories which are well abandonment and platform abandonment. Each category are consists of abandonment techniques, activities, procedures, equipments and regulations.

3.5 Analysis and Comparison

For this entirely literature-based study, comparison well abandonment techniques in two or more fields are conducted. Both data are not really similar but still comparable. Each field in case study is located in different continent. This will provide a lot of information and competitive result for this study.

3.6 Finding

Data will summarize based on comparison result between few fields. The findings are including abandonment plan, Plug and Abandonment (P&A) techniques and platform decommissiong programme. It is the most important part of this study to ensure information is fully analyze to achieve an objective of this project

CHAPTER 4

RESULT & DISCUSSION

4.1 Introduction

All results concerning well abandonment programme, plugging and abandonment (P&A) techniques, platform abandonment activities were reported. In addition detailed analysis via two case studies also discusses in this chapter.

4.2 Plugging and Abandonment Operation

The basics steps of the plugging and abandonment (P&A) operation are as followed:

i. Log cement bonding and tubing condition on wireline unit
ii. Cut tubing on wireline unit
iii. Displace well to seawater
iv. Set cement plug in tubing by coil tubing
v. Pull tubing by pulling and jacking unit (PJU)
vi. Log 9 5/8” casing by wireline through PJU

vii. Cut casing by wireline through PJU
viii. Pull casing by PJU
ix. Log 13 3/8" casing by wireline through PJU
x. Cut casing by wireline through PJU
xi. Pull casing by PJU
xii. Set surface cement plug and pull conductors by CT

As we can see plugging and abandonment operation is consists of wireline and coil tubing in order to perform intervention task.

Wireline is the most common technology used when performing simple intervention tasks that do not require too much force. Since wireline is versatile and easy to set up, it is being used in many different operations for examples scale removing, bailing sand, remove wax, setting and retrieving plug or valve, fishing and perforating. A wireline system has two separate cable systems, slickline and braided line. Braided line and slickline has almost the same surface equipment. The main thing separating them is that slickline operates with stuffing box while the braided line has a grease injection head on topside (E. Mikalsen 2012).

Meanwhile coiled tubing was initially developed to perform remedial work on live wells. But as the years have gone by there has become many other advantages by using coiled tubing for intervention operations. Speed and economy is now the key advantages for applying coiled tubing. Time spent on rig-up and trip time is far lower for CT than if the same operation should be performed by the rig itself. Coiled tubing also takes up less deck space and requires fewer personnel than a rig operation. Not only will the cost go down, but multiple operations can be performed simultaneously when the rig is free to perform its own operations.

Where wireline is even faster to rig up than coiled tubing, coiled tubing offers a more powerful solution when the well operation requires much force. One of the main features of coiled tubing is that it offers the possibility to circulate the well during operations. If it is possible to plug the well with cement using coiled tubing, tremendous cost may be saved. This is one of the possibilities this thesis takes a closer look upon. In table 4.1 below it shows a summary of the similarities and differences between wireline and coiled tubing. Also an overview of the advantages and challenges of the two methods versus drilling rig is summarized.

Table 4.1: Wireline and coil tubing summary (E. Mikalsen 2012).

Similarities	i. No need for rig assistance ii. Operational area: Perforation, set/pull plug, logging & fishing iii. Logging while operating iv. Require little deck space
Differences	i. CT is able to circulate while operating (produce & place cement) ii. WL BOP an CT BOP iii. WL uses tractor in high inclination wells iv. Operational area: CT is able to place cement, CT is used for well stimulation and WL is more used for well cleaning v. Medium/heavy operation = CT, Light operation = WL
Advantages vs rig	i. Small rig-up time ii. Cheap and simple iii. Rig can perform simultaneously tasks on other wells iv. RIH/POOH time is reduced drastically v. Require fewer personnel
Challenges vs rig	i. Push/Pull forces ii. Getting stuck iii. Pressure control equipment iv. Heavy force operations v. Cementing, small diameter of CT makes it difficult to place large amount of cement in hole. Needs to be careful not to get stuck.

When installing a barrier, the barrier must fulfill four criteria to successfully pass as a installed permanent barrier which are length, cross-section, positioning and verification.

The length of a cement plug must be either 50m or 100m, depending on foundation of the plug. If there is a mechanical plug as a base, the cement plug must be at least 50m. If there is no plug as base the cement plug must be 100m long. If the annulus casing cement functions as primary and secondary barriers the length must be 200m, 100m as a primary barrier and 100m as a secondary barrier.

For cross section, the barrier must extend to the full cross section of the well and include all annuli and seal both vertical and horizontal.

For positioning, the well barrier must be placed at a depth with sufficient formation integrity. It is normal to place the barrier as close to the source of inflow as possible, although there is one exception. For an open hole with surface barrier where the exposed zone are documented as impermeable the base of the barrier does not has to be at a depth with sufficient formation strength (E. Mikalsen 2012).

For verification, a pressure test with 70 bar over the fracture gradient verifies the integrity of the barriers installed. When performing a pressure test it is important that the pressure exceeds the formation strength in the direction of flow. This ensures that it is the barrier that is holding the pressure and not the formation. If the pressure test is performed on a surface plug it is sufficient with 35 bar over fracture pressure. If it cannot be done by pressure test, a load test with 10 tons will be performed.

4.3 Case Study 1 (Malaysian Field)

Field A was completed in a single selective string and producing from K-28 and K-30 (2898.0-2914 m MD and 2928 – 2941 m MD). Initially it was on commingled production with oil rate of 750 stb/d, GOR of 6200 scf/stb and water cut of 0%. K-28 was isolated in July 2001 to produce from K-30 reservoir only. Water cut was observed to remain low but it suddenly increased to 80% in Dec 2001 and jump to 100% in Feb 2002. The Water cut has increased from 10 to 100% just within 8 months of production history.

A pressure build-up was ran in April 2002, the permeability of K-30 sand are less than 1 mD. It look like the low permeability was the main factor of the low productivity. The well was switched zone in Sep 2002 to produce from K-28 only where gas is expected to be dominant. However, 100% water was observed. Now the well is shut-in with cumulative production is only 0.09 MMstb from both zones. Based on the performances of this well, the well has little left of the reserve.

4.3.1 Pre-job Checks of Down hole Abandonment

Pre-job checks are listed below:

i. Make sure all equipment is onboard for the open hole abandonment.
ii. Inspect cement stinger, ensure free of debris.
iii. Drift all string components to 2.625".
iv. Pits to be organized to accommodate SBM displaced from the hole by the cement plugs & Hi-Vis pills.
v. Ensure wiper balls available.
vi. The final slurry recipes have been received from town.

4.3.2 Plug and Abandonment Technique

After completion of Modular Dynamics Tester (MDT) logging operations, abandonment operations will commence. Operations are as listed below:

i. Pull the wear bushing.

ii. Run in hole (RIH) with slotted mule shoe on +/- 350m of tubing. RIH on 5" and 5 1/2" DP as required to TD. Break circ when running in and circulate 2 times bottoms up at TD with max flow.

iii. RIH with continuous gyro survey tool, slick, to TD at 2298m and complete survey.

iv. Circulate bottoms up at max rate.

v. Pump and spot 2 balanced 300m cement plugs from TD at 2298m to approx 1700m (10%xs).

vi. Pull above top plug 1 stand and circulate bottoms up until mud weight constant at 10.3ppg. Flush choke and kills and function all rams (no shear) flush c&k

vii. Pump and spot 1 balanced 300m cement plugs from 800m to 500m (10%xs). (TOC to be 150m MD above H-Group, which was observed at 1848m MDBRT, Shallowed Hydrocarbon is I-35U sands 2110m MD BRT).

viii. Pull to 100m above Top Of Cement (TOC) and pump 10bbl to ensure tubing clear of cement. Drop wiper ball and circulate bottoms up until mud weight constant at 10.3ppg. Pulling Out Of Hole (POOH) with cement stinger.

ix. Spot a viscous pill from 900m to 800m.

x. Spot balanced abandonment plug from 800m to 500m.

xi. POOH to 2 stands above top of cement, drop wiper ball and circulate bottoms up at maximum rate. Flush choke and kills and function all rams (no shear) flush c&k.

xii. POOH L/O stinger and inspect for cement. (If sufficiently clean this should be kept aside for future cement job).

xiii. RIH with jet sub, jet all rams and H4 connectors, function rams and flush c&k, re jet rams and H4 connectors.

xiv. Laydown Drill Pipe (DP) to allow for cement to harden (see thickening time on recipe) in preparation for rig move to NOC.

xv. RIH and tag plug set across the 13 3/8" casing shoe with 15klbs and pressure test to 1200psi for 10mins.

xvi. Spot HiVis Pill from 300m to 200m

xvii. POOH with DP and lay down in preparation for the move.

Abandonment schematic for Field A is described as Figure 4.1 below:

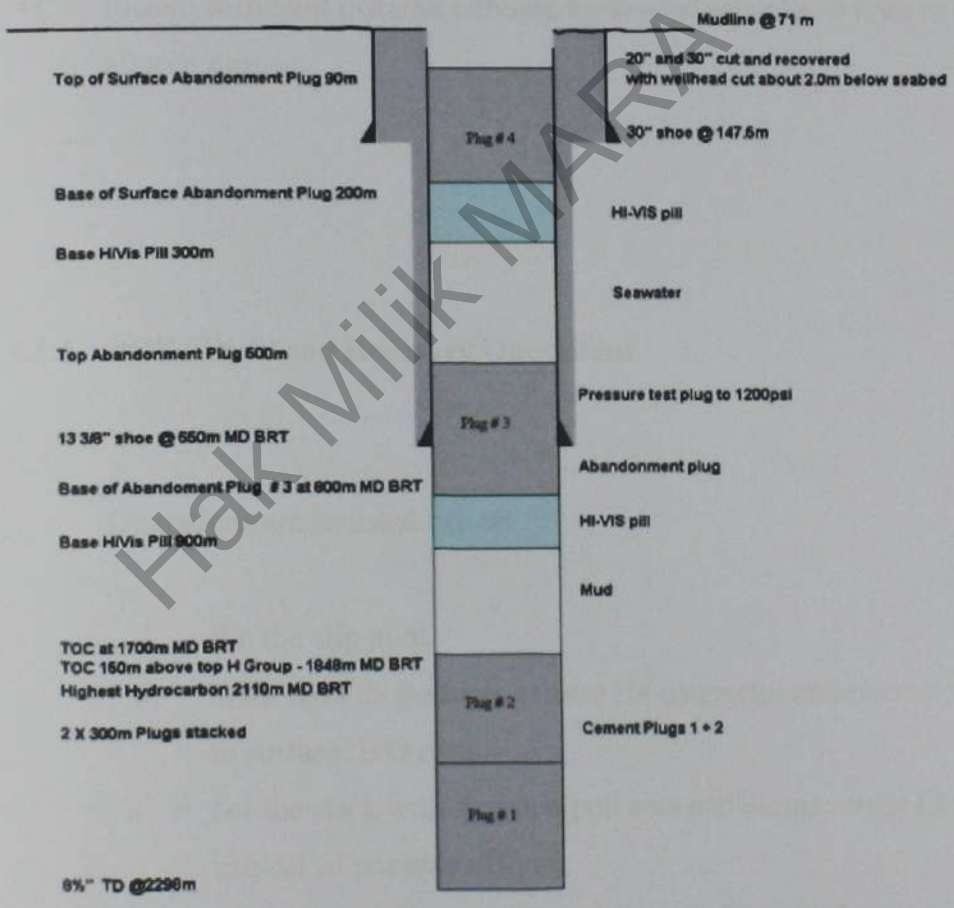


Figure 4.1: Abandonment schematic of Field A

4.3.3 Pre-job Checks of Blowout Preventor (BOP) / Wellhead Recovery

Pre-job checks are listed below:

1. Launch ROV to monitor BOP recovery
2. Ensure full 20" and 30" Smith abandonment package and JRC explosives equipment onboard.
3. Prepare deck space to lay out marine riser
4. Ensure Mathey slick-line unit in an operational condition (max pull 2050lbs)
5. Anchor handling boats to be ready to commence anchor recovery
6. Ensure sufficient material onboard for several sets of soft lines to centralize all tool runs

4.3.4 BOP / Wellhead Recovery Operations

Operations are as listed below:

i. Pin the slip joint.
ii. With ROV in position, release H4 connector and recover BOP stack to surface, L/O riser
iii. Set the stack back in moon pull area and secure. Split LMRP and inspect (if possible offline).
iv. M/U cement stinger (with soft lines to the guideframe) and RIH to 200m. Pump and spot a balanced cement plug to 90m.
v. POOH to 90m and circulate out cement. Circulate at max rate to clean out stinger.
vi. POOH and L/O cement stinger.
vii. M/U 20"/30" cutting BHA.

viii. RIH with Guideframe and land spear grapple in 17 5/8" upset (with compensator open). Take test overpull of 50Klbs and slack off to working of 15/20Klbs.

ix. Cut casing as per Appendix 4 and with Smith engineers instructions 2.5m below seabed,

x. After casing cut, take overpull to free from the seabed.

xi. Recover casing stumps, wellhead and PGB, maintain tension on guidelines while spooling in as POOH.

xii. Break out components at surface with guide base landed on spider beams.

xiii. Prepare for rig move operations.

4.4 Case Study 2 (Block 211 of the United Kingdom Continental Shelf)

The Brent field was discovered by Shell-Esso in 1971 and is one of the largest oilfields in the UK North Sea. A discovery well was drilled around 1km down-dip to the west of the tip of the buried high. It is located 150km north-east of Shetland and lies in a water depth of 142m.

First oil from the Brent field was produced in November 1976. The field underwent a £1.3bn upgrade in the mid-1990s. It was the largest and most comprehensive field redevelopment ever undertaken in the North Sea. The project depressured the reservoir and modified three of the four Brent platforms to support low-pressure operations. The modification unlocked substantial quantities of natural gas from the reservoir and extended the field life up to 2010 and beyond.

Although the field will produce over a period of 30 years, production has declined from providing 10% of the UK's gas consumption to around 1-2%. The flow of oil and gas from Brent will reach a saturation point when it will not be viable to operate the field

4.4.1 Pre-job Checks of Downhole Abandonment

Preparatory work prior to rig or coil activities as listed below (R.S Matkowski 1994):

i. Dismantle the gas lift line to minimize unknown variables.
ii. Rig up chicsan lines from the wellhead 'A' annulus and christmas tree to direct flow to either the rig floor choke/kill manifold or to the production facilities. Test lines and the christmas tree valves. Ensure serviceability of all gauges monitoring tubing and annulus pressures.
iii. Monitor annulus & tubing pressures

4.4.2 Plug and Abandonment Technique

Production Abandonment Using Coiled Tubing (CT) as listed below (R.S Matkowski 1994):

i. Skid rig. Responsibility for all well control aspects transferred to the Abandonment Supervisor. Isolate the well from the platform shutdown systems .
ii. Rig up and test CT.

iii. Run in hole (RIH) with coil: BHA to include phased puncher gun & circulating ball-fired head, tubing end locator, hydraulic disconnect, and double check valve.

iv. Whilst RIH use the cement unit to circulate seawater at about 1/4 barrels per minute (bpm) to prevent the flow ports from becoming blocked.

v. Make use of the tubing exit to check on the depth accuracy of the coil measuring device. Pull back and position the tubing punch in the tailpipe about 50 ft below the production packer.

vi. Pump the ball over the gooseneck and allow to land out at the firing head. Slowly increase the CT pressure to activate the firing head and reestablish circulation.

vii. RIH and position the bottom of the BHA above the fill.

viii. Circulate bottoms up, recording operating parameters to obtain a "percentage of full returns" baseline. Further check on cement job anticipated losses by manipulating the choke to effect an injectivity test. This should simulate the increased hydrostatic which will result from the 'in-place' cement column at conclusion of the job.

ix. Prepare the cement unit to pump 20 bbls of a strong water wetting surfactantholvent pre-flush (to enhance cement/pipe bonding).

x. Batch mix and perform QA tests on sufficient 16 pounds per gallon (ppg) 'squeeze' cement to fill the liner from hold up depth (HUD) to the punched tailpipe joint 50 ft below the production packer. Dependent upon the result of the injectivity test it may be determined to include additional excess slurry volume to compensate for expected losses.

xi. Position the BHA 30 ft above HUD (to allow for coil stretch during the cement job), and pump the pre-flush followed by the cement. Maintain constant pump rate throughout cementing procedures.

xii. Displace planned cement volume down to the flow ports, followed by 5 bbls of contaminant, 10 bbls of viscous spacer, then seawater. Keep track of pumped and return volumes on a pumping schedule prepared in advance.

xiii. Allow cement top to rise 50 ft, thereafter maintaining the cementing nozzles this distance below the rising cement top, as calculated by monitoring the CT annulus returns at the trip tank. In order to encourage the cement to fill the void behind the tailpipe, do not allow the cementing nozzles to be brought inside the tubing until the last 3 bbls are being pumped. [NB: for deep wells it may not be possible to POH with the coil until all the cement has been placed, since the required pull could exceed the limit on coil yield.]

xiv. Ensure that the flow ports are positioned at the production packer depth by commencement of spotting the contaminant pill, and then pull back 50-100 ft so that the remainder of the contaminant is swept uphole, followed by the viscous spacer. Circulate bottoms up.

xv. At approximately 50 ft above the production packer mark the coil to help correlate the perforation depth on the next run.

xvi. POH with CT and WOC. Note: depending upon the level of confidence surrounding the tubing integrity and pressure tightness of the Christmas tree flowline valves it may be determined at this point to make up an expandable packer on the coil and RIH to above the top of cement (TOC) in order to better obtain a successful pressure test against the cement plug.

Typical program for abandonment using drilling rig as listed below (R.S Matkowski 1994):

i. Remove the production tree. Nipple up and test the riser & 13-5/8" BOPS. Take control of the sub surface safety valve (SSSV).

ii. Run the landing string into the tubing hanger. Back out the tie down bolts.

iii. Rig up a wireline pack-off onto the landing string. Run a jet cutter and cut the tubing at +/- 1500 ff with the string in tension.

iv. Pull and lay down the tubing. Monitor for low specific activity (LSA) scale.

v. Run and set a 9-5/8" bridge plug on drill pipe at +/- 1500 ft.

vi. Jet wash the well head with seawater and recover the 9-518npack-off.

vii. Make up the 9-5/8" casing cutting BHA and RIH to cut depth at +/- 1300 ft. Monitor returns for an increase as the casing is cut. If increased returns are seen, shut in the well, open the 'B annulus wellhead valve and circulate out the annulus fluid into the pits via the choke manifold. Continue to circulate until clean returns. Close the 'B' annulus and complete the cutting of the casing.

viii. Pull and lay down the 9-5/8" casing using a spear and heavy duty tongs.

ix. Make up a 13-3/8" scraper assembly and run to +/- 1300 ft.

x. Run and set a 13-3/8" bridge plug on drill pipe at +1- 1250 ft.

xi. Make up the 13-3/8" casing cutting BHA and RIH to cut depth at +/- 950 ft. Monitor returns for an increase as the casing is cut. If increased returns are seen, shut in the well, open the 'C' annulus wellhead valve and circulate out the annular fluid into the pits via the choke manifold. Continue to circulate until clean returns. Close the 'C' annulus and complete the cutting of the casing.

xii. Nipple down the BOPS and 'B section of the wellhead. Recover the 13-3/8" pack-off.

xiii. Pull and lay down the 13-3/8" casing using a spear and heavy duty tongs.

xiv. Run in with cementing U-tube control tool and set a balanced cement plug from the 13-3/8" bridge plug back to 750 ft. Pull back to 730 ft and pump 200 barrels sea water prior to POH.

xv. Protect the well slot by placing a fabricated 'bin lid' over the casing head and skid off.

xvi. Run the landing string into the tubing hanger. Back out the tie down bolts.

Abandonment schematic for Block 211 UKCS is described as Figure 4.2 (R.S Matkowski 1994):

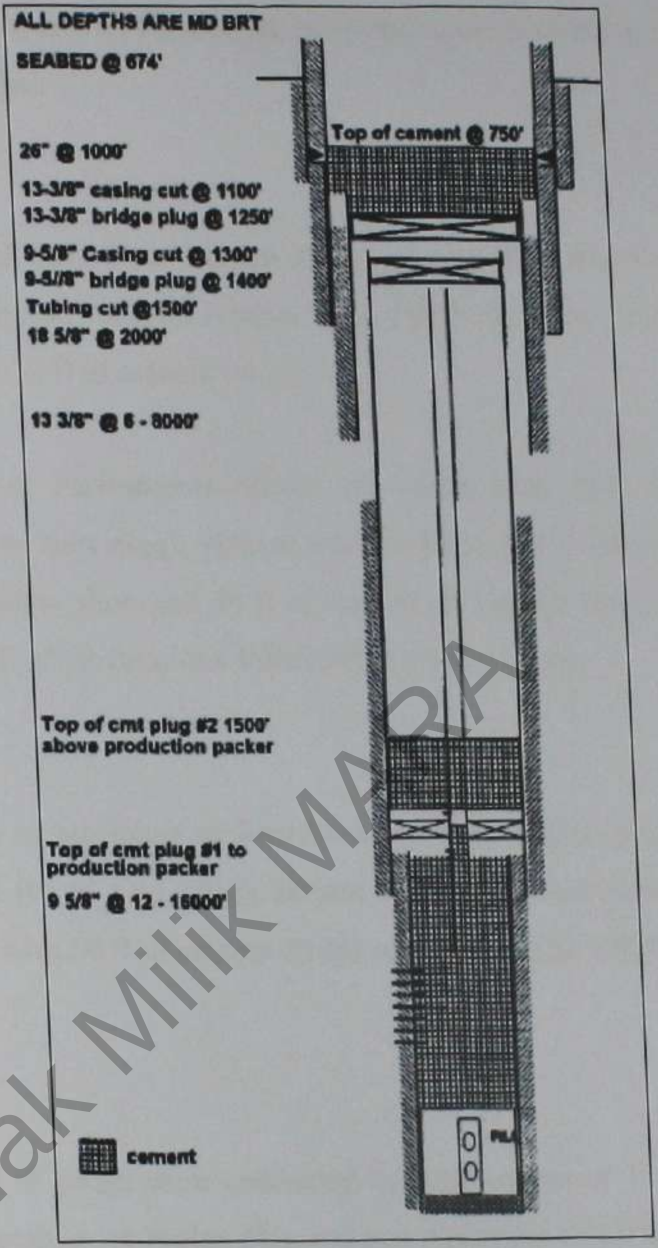


Figure 4.2: Abandonment schematic for Block 211 UKCS

4.5 Discussion

Both fields have most activities of well abandonment in common. Well preparation, wellbore cleanout and well testing must be conducted prior to Plug and Abandonment (P&A). Well preparation activities involved tubing, packer and production strings removal. Meanwhile wellbore cleanout refers to flushing, fishing and milling activities.

Isolation of Open Hole consists of cement plug 100ft above and below lower-most shoe in open hole, cement retainer 50 to 100 ft above the shoe and cement 100 ft below shoe and 50 ft of cement on top.

Isolation of Perforations consist of cement plug 100ft above and below perforations (or to next plug), cement retainer 50 to 100 ft above the perforations, cement 100 ft below shoe and 50 ft of cement on top and lastly permanent bridge plug within 150 ft of perforations with 50 ft of cement on top.

Isolation of lap joints or liner tops consist of cement plug 100ft above and below liner top (or to next plug), cement retainer or permanent bridge plug 50 ft above the liner with 50 ft of cement on top and cement plug 200 ft long within 100 ft of liner.

Testing of plugs were conducted by pipe weight of 15,000 lbs on cement plug, cement retainer, or bridge plug and pump pressure of 1,000 psi with maximum 10% drop in 15 minutes.

Fluid Left in the Hole or fluid fill between plugs must exert a fluid density at least higher than the greatest formation pressure in the intervals between the plugs at the time of abandonment.

Well Plugging consideration are including plug location, injection zone pressure, well condition, removal of well materials, positioning of the plug, static well condition and equipment availability.

All general informations gathered from both case studies are summarized in Table 4.2 below:

Table 4.2: Brief information for both case studies

No	Description	Field A (Malaysian Field)	Block 211 UKCS
1	Location	Malay Basin	East Shetland Basin, North Sea
2	Water Depth	71m	140m
3	Total Depth (Well)	2298m	4877m
4	Types of Abandonment	Permanent	Permanent
5	Well Completion	Open Hole	Perforated
6	Conveyance & Measurement	Coil Tubing	Coil Tubing
7	Plug Used	4 Balanced Plug	2 Bridge Plugs, 2 Balanced Plug, Squeeze Cement
8	Mud	Synthesis Based Mud	Water Based Mud
9	Mud Weight	10.3 ppg	-
10	Environmental Services Used	Hi-Viscous Pill	-
11	Wellhead Recovery	Remote Operated Vehicle (ROV)	-
12	Wellhead Cut	2.5m below mudline	-

Comparison between both case studies in their respective well abandonment techniques are represented in Table 4.3 below:

Table 4.3: Comparison between both case studies

No	Description	Field A (Malaysian Field)	Block 211 UKCS
1	Pull DHSV, bullhead and drift well	Yes	Yes
2	Run caliper logging tool	Yes (using Modular Dynamic Tester)	Not mention
3	Log cement bonding and tubing condition on wireline unit	Yes (Using Gyro Survey Tool)	Yes
4	Cut tubing on wireline unit	Yes	Yes
5	Displace well to seawater	Yes	Yes
6	Set cement plug in tubing by coil tubing	Yes	Yes
7	Pull tubing by pulling and jacking unit (PJU)	Yes	Yes
8	Log 9 5/8" casing by wireline through PJU	No	Yes
9	Cut casing by wireline through PJU	No	Yes
10	Pull casing by PJU	No	Yes
11	Log 13 3/8" casing by wireline through PJU	Yes	Yes
12	Cut casing by wireline through PJU	No	Yes
13	Pull casing by PJU	No	Yes
14	Set surface cement plug and pull conductors by CT	Yes	Yes

Lastly, Platform decommissioning plan is not available in both cased studies.

CHAPTER 5

CONCLUSION & RECOMENDATION

5.1 Conclusion

Some of the findings for this study are:

i. Most wells are still plugged with cement and well abandonment of oil and gas wells has not changed significantly over the past 30 years. There has been improvement in the quality of the materials and changes to the methods used to plug wells, but there has not been a specific change that has elevated the technology of plugging wells.

ii. Wireline and coil tubing are services that important in any well abandonment programme.

iii. The casing must be clean to ensure that each cement plug will bond to the pipe wall.

iv. Mechanical plugs should be used during abandonment to minimize the risk of gas contamination and to ensure that the cement plug remains in place while the cement sets.

v. Standard operating procedure of well abandonment programme are consist of removing down hole equipment, wellbore cleanout, plugging, tubing site clearance and wellhead removal activities.

vi. Well abandonment techniques are slightly different among countries due to neither uniform nor consistent of regulations imposed by their respective rulers.

5.2 Recommendation

Some of the recommendations for future work:

i. Comparison of well abandonment cost using rig and rigless system.

ii. Introduce platform decommissioning activities in analysis of case studies.

iii. Analyze decommissioning and well abandonment regulations in Malaysia.

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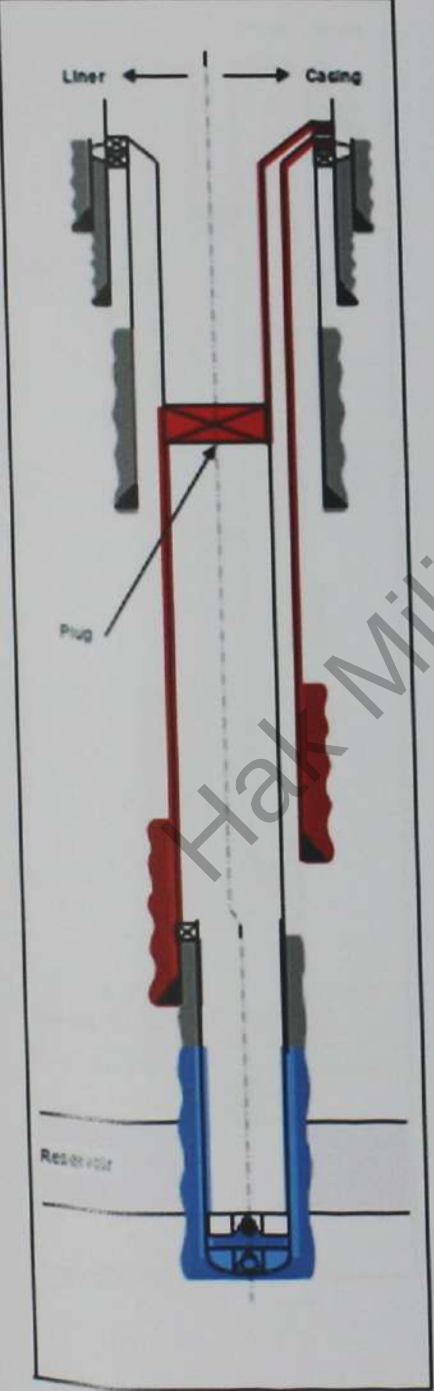
APPENDIX A

9.8 Attachments – Well barrier schematics (WBS)

9.8.1 Temporary abandonment – Non-perforated well

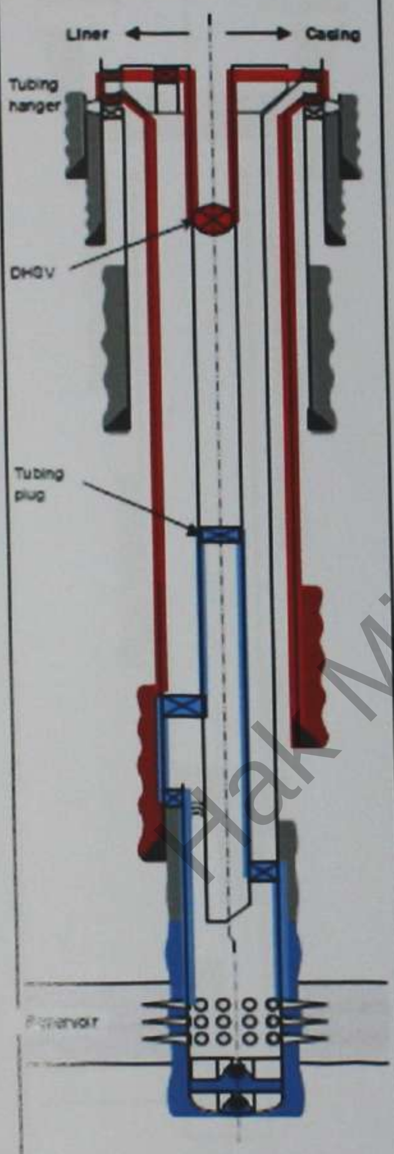


Well barrier elements	See Table	Comments
Primary well barrier, last open hole		
1. Cement plug	24	Shoe track.
2. Casing (liner) cement	22	
3. Casing (reservoir liner)	2	Un-perforated w/2 each float valves.
or		
1. Cement plug	24	Shoe track.
2. Casing cement	22	
3. Reservoir casing	2	Un-perforated w/2 each float valves.
Secondary well barrier, temporary abandonment		
1. Casing	2	
2. Casing cement	22	
3. Cement plug or mechanical plug	24 28	Shallow plug.
or		
1. Casing cement	22	
2. Casing	2	Intermediate
3. Wellhead	5	
4. Casing	2	Production casing.
5. Cement plug or mechanical plug	24 28	Shallow plug.

Note
None

APPENDIX B

9.8.2 Temporary abandonment – Perforated well with BOP or production tree removed

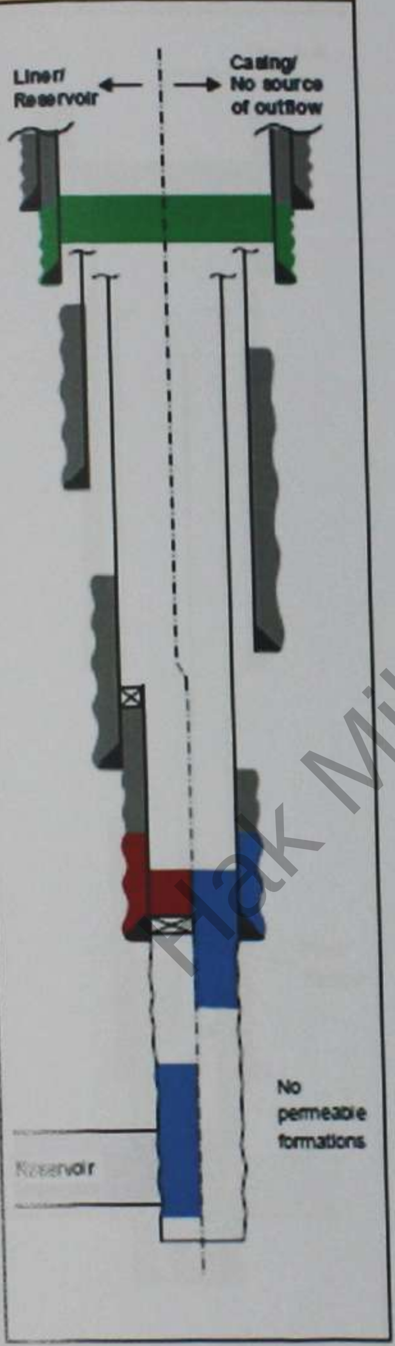


Well barrier elements	See Table	Comments
Primary well barrier		
1. Casing (liner) cement	22	
2. Casing (liner)	2	Liner above perforations.
3. Liner top packer	43	
4. Casing	2	Below production packer.
5. Production packer	7	50 m below TOC in casing annulus.
6. Completion string	25	
7. Deep set tubing plug	6	
or,		
1. Casing cement	22	
2. Casing	2	Above perforations.
3. Production packer	7	
4. Completion string	25	
5. Deep set tubing plug	6	
Secondary well barrier, reservoir		
1. Casing cement	22	Above production packer.
2. Casing	2	Common WBE, between liner top packer and production packer.
3. Wellhead	5	
4. Tubing hanger	10	
5. Tubing hanger plug	11	For SSWs.
6. Completion string	25	Down to SCSSV.
7. SCSSV	8	
or,		
1. Casing cement	22	Intermediate casing.
2. Casing	2	Intermediate casing.
3. Wellhead	5	
4. Tubing hanger	10	
5. Tubing hanger plug	11	For SSWs.
6. Completion string	25	Down to SCSSV.
7. SCSSV	8	

Note
None

APPENDIX C

9.8.3 Permanent abandonment - Open hole



Well barrier elements	See Table	Comments
Primary well barrier		
1. Cement plug	24	Open hole.
or, ("primary well barrier, last open hole"):		
1. Casing cement	22	
2. Cement plug	24	Transition plug across casing shoe.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Cased hole cement plug installed on top of a mechanical plug.
Open hole to surface well barrier		
1. Cement plug	24	Cased hole cement plug.
2. Casing cement	22	Surface casing.

Notes

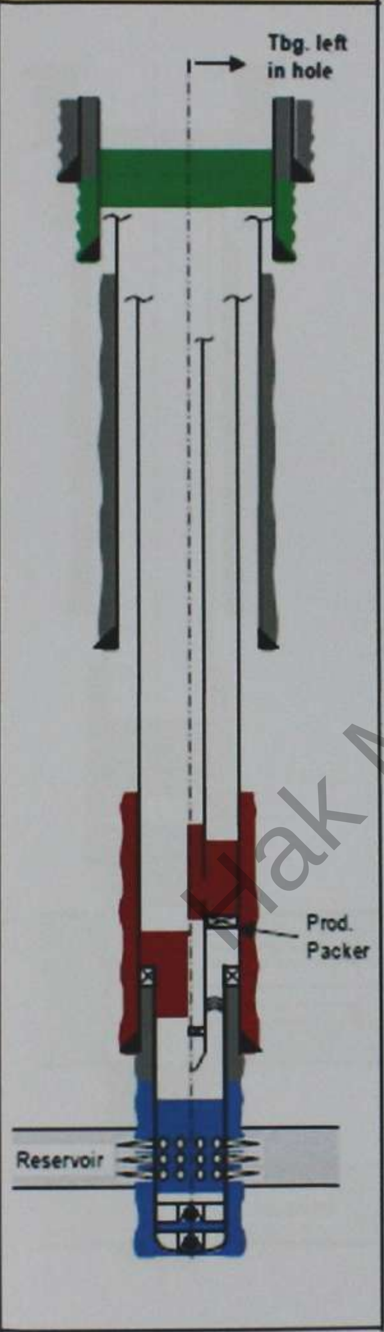
a. Verification of primary well barrier in the "liner case" to be carried out as detailed in Table 22.

b. The well barrier in deepest casing shoe can for both cases be designed either way, if casing/liner cement is verified and O.K.

c. The secondary well barrier shall as a minimum be positioned at a depth where the estimated formation fracture pressure exceeds the contained pressure below the well barrier.

APPENDIX D

9.8.4 Permanent abandonment - Perforated well



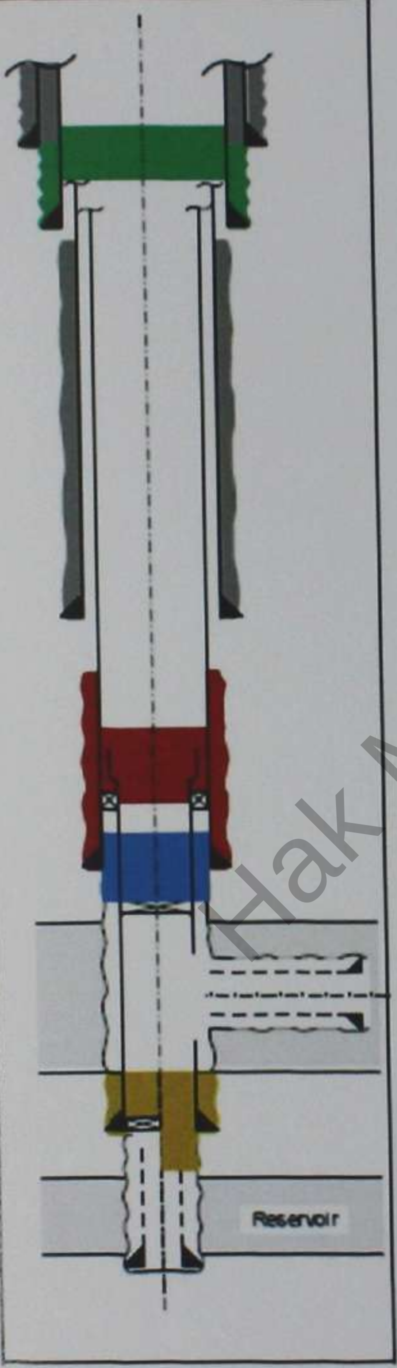
Well barrier elements	See Table	Comments
Primary well barrier		
1. Liner cement	22	
2. Cement plug	24	Across and above perforations.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Across liner top.
or, for tubing left in hole case:		
1. Casing cement	22	
2. Cement plug	24	Inside and outside of tubing.
Open holes to surface well barrier		
1. Cement plug	24	
2. Casing cement	22	Surface casing.

Notes

1. Cement plugs inside casing shall be set in areas with verified cement in casing annulus.
2. The secondary well barrier shall as a minimum be positioned at a depth where the estimated formation fracture pressure exceeds the contained pressure below the well barrier.

APPENDIX E

9.8.5 Permanent abandonment - Multibore with slotted liners or sand screens



Well barrier elements	See Table	Comments
Barrier between reservoirs		
1. Casing cement	22	
2. Cement plug	24	Cased hole.
or,		
2. Cement plug	24	Transition plug across casing shoe.
Primary well barrier		
1. Cement plug	24	Across wellbore and casing shoe.
Secondary well barrier, reservoir		
1. Casing cement	22	
2. Cement plug	24	Casing plug across liner top.
Open Holes to surface wellbarrier		
1. Cement plug	24	Cased hole cement plug.
2. Casing cement	22	Surface casing.

Notes

1. The "well barrier between reservoirs" may act as the primary well barrier for the "deep" reservoir, and "primary well barrier" may be the secondary well barrier for "deep" reservoir, if the latter is designed to take the differential pressures for both formations.
2. Secondary well barrier shall not be set higher than the formation integrity at this depth, considering that the design criteria may be initial reservoir pressure, as applicable in each case.