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Modeling the Deepwater Horizon blowout using STAMP

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MODELLERING AV DEEPWATER HORIZON-UTBLÅSNINGEN MED BRUK AV STAMP
(Modeling the Deepwater Horizon blowout using STAMP)

Eksisterende rammeverk for risikoanalyser ble utviklet for rundt 50 år siden og baserer seg i stor grad på den forståelsen man hadde den gang av ulykkesmodeller og hvordan ulykker skjer. Siden den tid er flere alternative forståelser av spesielt storulykker eller organisatoriske ulykker lansert. En av disse er ulykkesmodellen STAMP.

I denne oppgaven er målet å beskrive utblåsningen på Macondo-feltet med boreriggen Deepwater Horizon i 2010 ved hjelp av STAMP. Formålet er å danne seg en oppfatning av hvor egnet STAMP er for å modellere storulykker, hvor arbeidskrevende modelleringen er og også om bruk av en slik modell kan gi andre svar eller peke i andre retninger når det gjelder forklaringer av ulykker en de modellene som tradisjonelt brukes.

Oppgaven skal gjennomføres i følgende trinn:

1. Litteraturstudium – gjennomgang og oppsummering av relevant litteratur om STAMP samt sette seg inn i granskingsrapporter fra hendelsen.
2. Utvikle en modell som beskriver hendelsen, basert på STAMP.
3. Vurdere modellen som er utviklet og arbeidet som er utført med tanke på:
    a. Egnethet av STAMP for modellering av ulykker
    b. Arbeidsomfang
    c. Om en STAMP-modell peker i andre retninger når det gjelder forklaringer enn arbeid som alt er gjort.
4. Oppsummere og gi anbefalinger for videre arbeid.

Oppgaveløsningen skal basere seg på eventuelle standarder og praktiske retningslinjer som foreligger og anbefales. Dette skal skje i nært samarbeid med veiledere og fagansvarlig. For øvrig skal det være et aktivt samspill med veiledere.

Innen tre uker etter at oppgaveteksten er utlevert, skal det leveres en forstudierapport som skal inneholde følgende:

- En analyse av oppgavens problemstillinger.
- En beskrivelse av de arbeidsoppgaver som skal gjennomføres for løsning av oppgaven. Denne beskrivelsen skal munne ut i en klar definisjon av arbeidsoppgavenes innhold og omfang.
- En tidsplan for fremdriften av prosjektet. Planen skal utformes som et Gantt-skjema med angivelse av de enkelte arbeidsoppgavenes terminer, samt med angivelse av milepæler i arbeidet.

Forstudierapporten er en del av oppgavebesvarelsen og skal innarbeides i denne. Det samme skal senere fremdrifts- og avviksrapporter. Ved bedømmelsen av arbeidet legges det vekt på at gjennomføringen er godt dokumentert.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

Materiell som er utviklet i forbindelse med oppgaven, så som programvare eller fysisk utstyr er en del av besvarelsen. Dokumentasjon for korrekt bruk av dette skal så langt som mulig også vedlegges besvarelsen

Eventuelle reiseutgifter, kopierings- og telefonutgifter må bære av studenten selv med mindre andre avtaler foreligger.

Hvis kandidaten under arbeidet med oppgaven støter på vanskeligheter, som ikke var forutsett ved oppgavens utforming og som eventuelt vil kunne kreve endringer i eller utelatelse av enkelte spørsmål fra oppgaven, skal dette straks tas opp med instituttet.

Oppgaveteksten skal vedlegges besvarelsen og plasseres umiddelbart etter tittelsiden.

Innleveringsfrist: 11. juni 2012

Besvarelsen skal innleveres i 1 elektronisk eksemplar (pdf-format) og 2 eksemplar (innbundet).

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Preface

This report is my Master's thesis in RAMS at NTNU as part of the five year Mechanical Engineering program. The project was carried out in the spring of 2012 and written for the Department of Production and Quality Engineering at NTNU.
The thesis is vaguely connected to my Master's project carried out in the fall of 2011, which was an investigation of alternative frameworks for risk assessment.

Trondheim, 2012-06-11

Rolf-Arne Syvertsen

Acknowledgements

I would like to thank my supervisor Professor Stein Haugen at the Department of Production and Quality Engineering for help along the way. It has not been an easy Master's thesis to write and without him I would not have been able to complete this thesis.

Sammendrag

Denne masteroppgaven er i hovedsak et litteraturstudie basert på teori om «Systems-Theoretic Accident Model and Processes», STAMP, en systemisk ulykkesmodell tilnærming til ulykkesanalyse. Systemisk ulykkesmodellering har blitt utviklet etter de sekvensielle- og epidemiologisk ulykkesmodellene. Sikkerhet blir i systemisk ulykkesmodellering ansett som en frembrytende egenskap.

Ved å benytte STAMP skal oppgaven fokusere på ulykken som inntraff boreriggen Deepwater Horizon 20.april 2010. Granskningsrapporter om utblåsningen ved Macondo brønnen er lagt til grunn for å undersøke om STAMP og tilhørende rammeverk er egnet til å modellere ulykken.

STAMP er basert på tre grunnleggende begreper, sikkerhetskrav, hierarkiske sikkerhetskontroll strukturer, og prosessmodeller. Sikkerhets krav er det mest grunnleggende konseptet av STAMP, som dermed beveger seg bort fra dagens risikovurderingers fokus på hendelser. Dette understrekes av det faktum at hendelsene som fører til ulykker bare skjer fordi sikkerhets kravene ikke ble påtvunget korrekt. Fra systemteori blir et system sett på som en hierarkisk struktur, der hvert nivå pålegger krav på aktiviteter på underliggende nivå. Dette resulterer i at et høyere nivå sine krav tillater eller kontrollerer det lavere nivåets oppførsel. Prosessmodeller viser hvordan kontrolløren av en prosess håndhever sikkerhets kravene og tilbakemeldinger kontrolløren får fra systemet. Tilbakemeldinger er en svært viktig del av STAMP, ettersom STAMP ser på systemer som komponenter som er forbundet med hverandre og som holdes i en tilstand av dynamisk likevekt ved hjelp av tilbakemeldingssløyfer av informasjon og kontroll.

«Causal Analysis based on STAMP» (CAST) er en ulykkesanalyse metode utviklet for å analysere ulykker og hendelser. Dagens risikovurderings metoder er hovedsakelig hendelses basert, men STAMP ønsker å gå bort fra dette ved å vurdere risiko og sikkerhet ved hjelp av brudd på sikkerhetskrav som grunnlag for tapshendelser som resulterer i ulykker. CAST er en metode utviklet i tråd med den generelle rammen av STAMP, og har vært grunnlaget for ulykkesanalysen av Macondo utblåsningen i denne rapporten.

20. april 2010 startet boreriggen Deepwater Horizon prosessen for å forlate Macondo brønnen, men før brønnen kunne forlates måtte mannskapet på Deepwater Horizon sjekke integriteten til brønnen. Metodene for å teste integriteten til brønnen tok hele dagen og ble godkjent rundt kl. 8 på kvelden. Etter at brønnens integritet var godkjent var pumpe stigerøret knyttet til brønnhodet tomt for boreslam. Rundt kl. 8:50 ble Macondo brønnen underbalansert og brønnen opplevde et «kick» like etterpå. «Kicket» den 20. april skulle vise seg å bli en utblåsning og kl. 9:49 rammet den første eksplosjonen Deepwater Horizon. Ulykken forårsaket 11 dødsfall, tap av hele Deepwater Horizon og et massiv oljeutslippet i Mexicogolfen.

CAST analysen avdekket hvor viktig riktig håndheving av sikkerhets krav kan være, siden bruddet på sikkerhets kravene ved Macondo resulterte i en forferdelig ulykke. Modellene opprettet fra CAST analysen viste hvor utilstrekkelig systemet rundt Macondo var på å kontrollere sikkerheten til Macondo brønnen. Modellene viste at

reguleringen MMS opererte med ikke var i stand til å håndheve sikkerheten for dypvannsboring, og at BP ganske enkelt endret på prosedyrene sine etter at tillatelsen fra MMS var mottatt. Det verste med ulykken, i tillegg til de omkomne var at oljenæringen selv ble sjokkert etter at det som skjedde. Hvordan kunne de være, med tanke på hvordan de opererte?

Det gjør seg klart tydelig at en systemisk tilnærming til ulykkesmodellering er overlegne sammenlignet med den hendelsesbaserte tilnærmingen. Fra analysen utført i oppgaven er det tydelig at det ulykken var forårsaket av flere svikt gjennom hele den hierarkiske sikkerhetskontroll strukturen. De relasjonene som kommer til syne gjennom denne typen modellering ville ikke blitt belyst ved hjelp av andre tilnærminger. Dette beviser at en systemisk tilnærming er svært egnet for ulykkesmodellering og ett viktig verktøy for å utbedre fremtidige prosesser.

Summary

This thesis has been based on reviewing literature on Systems-Theoretic Accident Model and Processes theory of accident analysis and accident investigations of the Macondo well blowout.

Systems-Theoretic Accident Model and Processes is commonly known under its name STAMP and is a systemic accident modeling approach. Systemic accident modeling approaches have been developed after the sequential- and epidemiological accident models. In systemic accident models safety is seen as an emergent property.

STAMP is based on three basic constructs which are safety constraints, hierarchical safety control structures, and process models. A constraint is the most basic concept of STAMP, thereby moving away from the current risk assessments focus on events. This is underlined by the fact that events leading to losses only occur because safety constraints were not successfully enforced. From systems theory a system is viewed as a hierarchical structure, where each level imposes constraints on the activity on the level below, resulting in higher-level constraints allowing or controlling lower level behavior. Process models show how the controller of a process enforces the required safety constraints, and how the controller receives feedback from the process being controlled. Feedback is a very important aspect of STAMP, as STAMP views systems as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control.

Causal analysis based on STAMP (CAST) is a method developed for analyzing accidents and incidents. Risk assessment methods have predominantly been event based, but STAMP wishes to move forward in assessing risks and safety by using the violation of safety constraints as a basis for loss events resulting in accidents and incidents. CAST is a method developed in line with the overall framework of STAMP, and has been the basis for the accident analysis of the Macondo well blowout in this report.

On April 20th 2010 the Deepwater Horizon rig was set to perform a temporary abandonment, which refers to the procedures done after the completion of the drilling of a well in preparation for the drilling rig to abandon the well. During the temporary abandonment the crew on the Deepwater Horizon would check the wells integrity before they abandoned the well site. The wells integrity was tested during the day of April 20th 2010, and approved at around 8 p.m. The next stage of the temporary abandonment was to displace the drilling mud in the riser connected with the wellhead. At approximately 8:50 p.m. the Macondo well became underbalanced and the well soon experienced a kick. The kick on April 20th developed into a blowout and at 9:49 p.m. the first explosion hit the Deepwater Horizon rig. The accident caused 11 fatalities, the destruction of the Deepwater Horizon Rig and a massive oil spill in the Gulf of Mexico.

The CAST analysis performed uncovered how important the correct enforcement of safety constraints can be, as the result of violating the safety constraints at Macondo resulted in a horrific accident. Creating the models from the CAST analysis showed just how inadequate the system operations were at controlling the safety of the Macondo well. The models revealed that MMS did not have a regulatory structure capable of enforcing safety for deepwater drilling operations, and that BP quite carelessly changed

procedures after receiving permits from MMS. Not regarding the fatalities the worst part of the accident was that the industry itself was shocked after it happened. How could they be, considering how they operated?

The systemic accident approach is superior to the event based models. From the analysis it is evident that the accident was caused by a number of violations throughout the hierarchal safety control structure. Event based models may have concluded and blamed the lowest level for the accident and therefore ignored the problems throughout the hierarchical safety control structure. This proves the suitability for the systemic accident approach, especially as an important tool to improve future safety processes.

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Chapter 1

Introduction

1.1Background

As an ever expanding field, modern risk assessment developed as a scientific discipline shortly after WW2 (Rausand, 2011)for the purpose of aiding the military defense and defense industry, and soon after that in maintaining the safety in the nuclear power industry. The knowledge and experiences from these fields lead to methods and models which soon could be applied in other fields outside of these two industries.

The first accident modeling techniques were sequential accident models or event-based models, which searched for well-defined causes and cause-effect links for events (Hollnagel, 2004). The assumption was that by knowing the causes and links, one could eliminate or render causes and links ineffective by encapsulation (Hollnagel, 2004). Accident causation was explained as the result of a chain of discrete events that occurred in a sequential order, implying that an accident was the result of a single cause (Qureshi, 2008).

Following the sequential accident models was the development of epidemiological accident models, which searched for known carriers and latent conditions. Epidemiological accident models consider the events leading to an accident as analogous to the spreading of a disease (Rausand, 2011), and an accident was a result of a combination of manifested and latent factors that appear together in time and space (Rausand, 2011).

A major contributor in the epidemiological accident model development was James Reason, who introduced the "Swiss cheese model" in 1997 (Qureshi, 2008). The Swiss cheese model distinguished between immediate and latent causes of accidents, nearly all adverse events involve a combination of these two sets of factors (Qureshi, 2008). The distinction between latent and immediate causes is a very important aspect of the Swiss cheese model.

Immediate causes, also referred to as active failures, and can be defined as "the unsafe acts committed by people who are in direct contact with the patient or the system" (Qureshi, 2008). Latent causes or Latent conditions are the inevitable "resident pathogens" within the system (Qureshi, 2008).The latent conditions are implemented on a higher level in the organization by managers, designers, engineers etc.

The distinction between levels in an organization can be referred to as sharp end and blunt end, as seen in Figure 1.1. The sharp end is at operator level (where the accident occurs) and refers to the people working in the time and at the place where the accident occurs (Hollnagel, 2004). However, the people working at the sharp end are working under conditions and a nature of tasks determined at the corresponding blunt end. The blunt end is the influences of conditions and nature of tasks at the sharp end and has been defined as (Hollnagel, 2004):"the people who affected safety through their effect on the constraints and resources acting on the practitioners at the sharp end". In the light of blunt and sharp end logic, the latent conditions introduced in a system are a result of the actions performed at the blunt end (higher level) in the system.

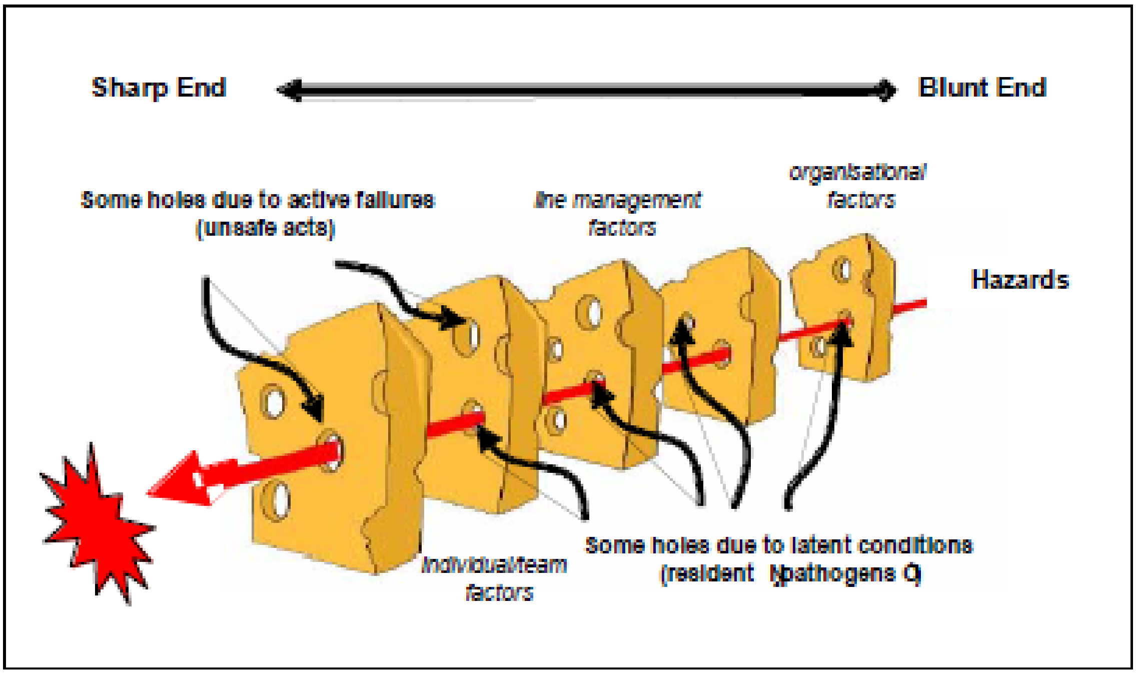

Figure 1. 1: Swiss Cheese Model of Defenses, Reason (1997) (Qureshi, 2008)

The result of the Swiss cheese model was that in addition to the previously developed event based models, this new model supported the understanding of accident causation beyond the proximate causes, proving helpful as an aid in accident investigation. This became an advantage in more complex systems with multi-failure situations. The previously developed sequential event chain models were designed with the objective of describing the propagation of faults in technical systems (Qureshi, 2008), the epidemiological models such as the Swiss Cheese Model were intended to also describe the organizational factors and their causal relationships to front end operators leading to an accident (Qureshi, 2008).

Today risk is still modeled and assessed based on the sequential- and epidemiological accident models. The focus on events enables us to identify failures and errors, resulting in means for accident prevention, reduction and mitigation caused by known risks. The problem is that systems are becoming more and more complex, and this makes it harder to control our risks.

April 20th 2010 in the Gulf of Mexico, the Deepwater Horizon (DWH) rig experienced a blowout of their newly drilled well, referred to as The Deepwater Horizon accident or the Macondo well blowout. The accident occurred as DWH was about to perform a procedure known as temporary abandonment. In the wake of this accident there have been conducted numerous reports to be able to assess and determine the causes which led to the accident.

1.2 Objective

The main objective of this thesis is to create a model of the processes involved in the Macondo well blowout on April 20th 2010. The assignment has been based on the following four steps:

1. Literature study – review and summary of relevant literature on STAMP, and also familiarization with written reports and analysis of the DWH blowout.
2. Development of a model describing the accident, based on STAMP.
3. Evaluate the model developed and the work performed focusing on:
    a. Suitability of STAMP for accident modeling
    b. Workload
    c. If a STAMP-model points in other directions regarding the explanations of work already performed.
4. Summarize and give recommendations for further work.

The thesis is set to provide an overview of STAMP as a systemic accident model used in risk assessment and develop a model describing the accident on April 20th 2010 according to the theory. STAMP has previously been used in many accident analysis reports, and by comparing STAMP models with accident investigations of the Macondo well blowout the aim is to assess the suitability for STAMP based accident models of major accidents, workload of the modeling and if the models provide better information or different perspectives on the accident then previously assumed.

The last step in the assignment will be to summarize and give future recommendations on work that should be performed.

1.3 Limitations

As the scope of this thesis is to analyze the Blowout at Macondo the explosion killing 11 people on the Deepwater Horizon, destruction of Deepwater Horizon, and the massive oil spill will not be discussed in detail. The main focus will be on the events leading up to the first explosion on DWH.

1.4 Approach

The approach of the thesis is a literature study of STAMP and CAST theory, together with the accident investigation reports created by the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. From this literature study models describing the accident will be created, based on the steps of CAST, and assessed. Finally there will be a conclusion and recommendations for future work to be done.

1.5 Structure of the Report

The remaining report is structured to provide an overview and understanding of the theory and accident. Chapter 2 gives an introduction to STAMP and CAST theory, while chapter 3 is an overview of the personnel involved at Macondo, the Macondo well and introduction to the accident. Chapter 4 is the development of the accident models for the accident and Chapter 5 focuses on the model and STAMP assessment. The conclusions and recommendations follow in Chapter 6.

Chapter 2

Theory and accident models

The Deepwater Horizon accident at the Macondo well will be analyzed by using a systemic accident model approach, meaning that the analysis will incorporate the whole system. Systemic accident models are regarded as the new generation accident models, following in the steps of the sequential- and epidemiological accident model approaches.

Based on systems theory, the systemic accident models view the system performance as a whole, including human-, technical-, and organizational factors. Accidents are perceived as an emergent phenomenon, meaning that there is no sudden change from a functioning system to a failure, but rather a drift towards critical safety levels. Accidents occur when several causal factors (e.g., human, technical, environmental) exist coincidentally in a specific time and space (Hollnagel, 2004).

The roots of the systemic accident models is systems theory which includes principles, models, and laws necessary to understand complex interrelationships and interdependencies between components (technical, human, organizational and management) of a complex system (Qureshi, 2008).

2.1 Systems – Theoretic Accident Model and Process – STAMP

Systems – Theoretic Accident Model and Process (STAMP) is one of the systemic accident model approaches. From the systems theory safety is an emergent property, which arises from interactions among system components (Leveson, 2011). Safety is an emergent property, which is controlled by imposing constraints on interactions among components and behavior among components. This way of managing safety means that safety is seen as a control problem, where the goal is to enforce safety constraints on the components and system. Conclusively accidents then will arise when there is an inadequate control or enforcement of safety-related constraints during development, design and operation of the system (Leveson, 2011)

The goal of controlling the components and systems is done by enforcing safety constraints. Controls must be established to accomplish this goal, which can be human or automated, but need not necessarily to be one of the above. Control of component interactions and component behavior, including failure, may also be achieved through physical design, through process (e.g. manufacturing processes and procedures) or through social control (Leveson, 2011). Social controls involve everything from organizational (management), governmental and regulatory structures, to cultural, policy and individual controls.

By using STAMP preventing future accidents requires a shift of focus from preventing failures, to the broader goal of designing and implementing controls that will enforce the necessary constraints (Leveson, 2011). In the STAMP framework it is important to understand why the control was ineffective to determine why an accident occurred. These principles form the basis of STAMP, which in turn underline three basic constructs: safety constraints, hierarchical safety control structures, and process models.

2.1.1 Safety Constraints

A constraint is the most basic concept of STAMP, thereby moving away from the current risk assessments focus on events. This is underlined by the fact that events leading to losses only occur because safety constraints were not successfully enforced (Leveson, 2011).

It has become increasingly difficult to identify safety constraints in design and operations of systems, due to the increase in complexity. Generally controls can be divided in two categories:

1. Passive controls
2. Active controls

Passive controls impose safety simply by their presence, e.g. the system design fails into a safe fail state or simple interlocks are used to limit interactions among system components to safe ones (Leveson, 2011). A simple example can be the guardrail on a car road, which is installed so vehicles are kept on the road in case of a crash, and not sliding of the road causing greater accidents.

Active controls require some action(s) to provide protection: (1) detection of a hazardous event or condition (monitoring), (2) measurement of some variable(s), (3) interpretation of the measurement (diagnosis), and (4) response (recovery or fails-safe procedures), all of which must be completed before a loss occurs (STAMP). The actions require some sort of control system most commonly implemented by a computer.

In order to describe the difference between a passive and an active control, an example will be used, where a safety constraint is enforced (Leveson, 2011).

"Consider the simple passive safety control where the circuit for a high-power outlet is run through a door that shields the power outlet. When the door is opened, the circuit is broken and the power disabled. When the door is closed and the power enabled, humans cannot touch the high power outlet. Such a design is simple and fool proof. An active safety control design for the same high power source requires some type of sensor to detect when the access door to the power outlet is opened and an active controller to issue a control command to cut the power. The failure modes for the active control system are greatly increased over the passive design, as is the complexity of the system component interactions are increased" - (Leveson, 2011)

Due to the growing complexity of systems today, in some cases exceeding intellectual capabilities of developers, designers and operators, systems have increased component interaction failures resulting in a general lack of safety constraint enforcement. As seen from the example a passive control system is less likely to fail than the active control system. The active control system is attractive because of the increased functionality, flexibility during design and ability to operate over a greater distance. The difficulties for the engineering process are the greater potentials for design error.

In order to provide the level of safety demanded by society today, we first need to identify the safety constraints to enforce and then design effective controls to enforce them. This is difficult and one may think that the answer is to solely create simple passive controls to eliminate the complexity, but this is not seen as an acceptable solution (Leveson, 2011).

2.1.2 Hierarchical safety control structure

From systems theory a system is viewed as a hierarchical structure, where each level imposes constraints on the activity on the level beneath, resulting in higher-level constraints allowing or controlling lower level behavior (Drilling, 2011). At each specific level of the hierarchy structure, inadequate control may result from missing constraints (unassigned responsibility for safety), inadequate safety control commands, commands that were not executed correctly at a lower level, or inadequate communicated or processed feedback about constraint enforcement (Leveson, 2011)

Feedback is a very important aspect of STAMP, as STAMP views systems as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control. (Leveson, 2004) Meaning that a system is not static but dynamic, and continuously adapting to achieve its goals and reacting to changes, both in the system and from its environment.

The processes leading up to accidents (loss event) can be described as an adaptive feedback function that fails to maintain safety as a performance changes over time to meet a complex set of goals and values (Leveson, 2004).

In general a hierarchical control structure is divided into two different control structures, one for the system development and one for system operations. There are connections between the two structures, since safety depends partly on the original design and development and partly on effective control and operations (Leveson, 2011).

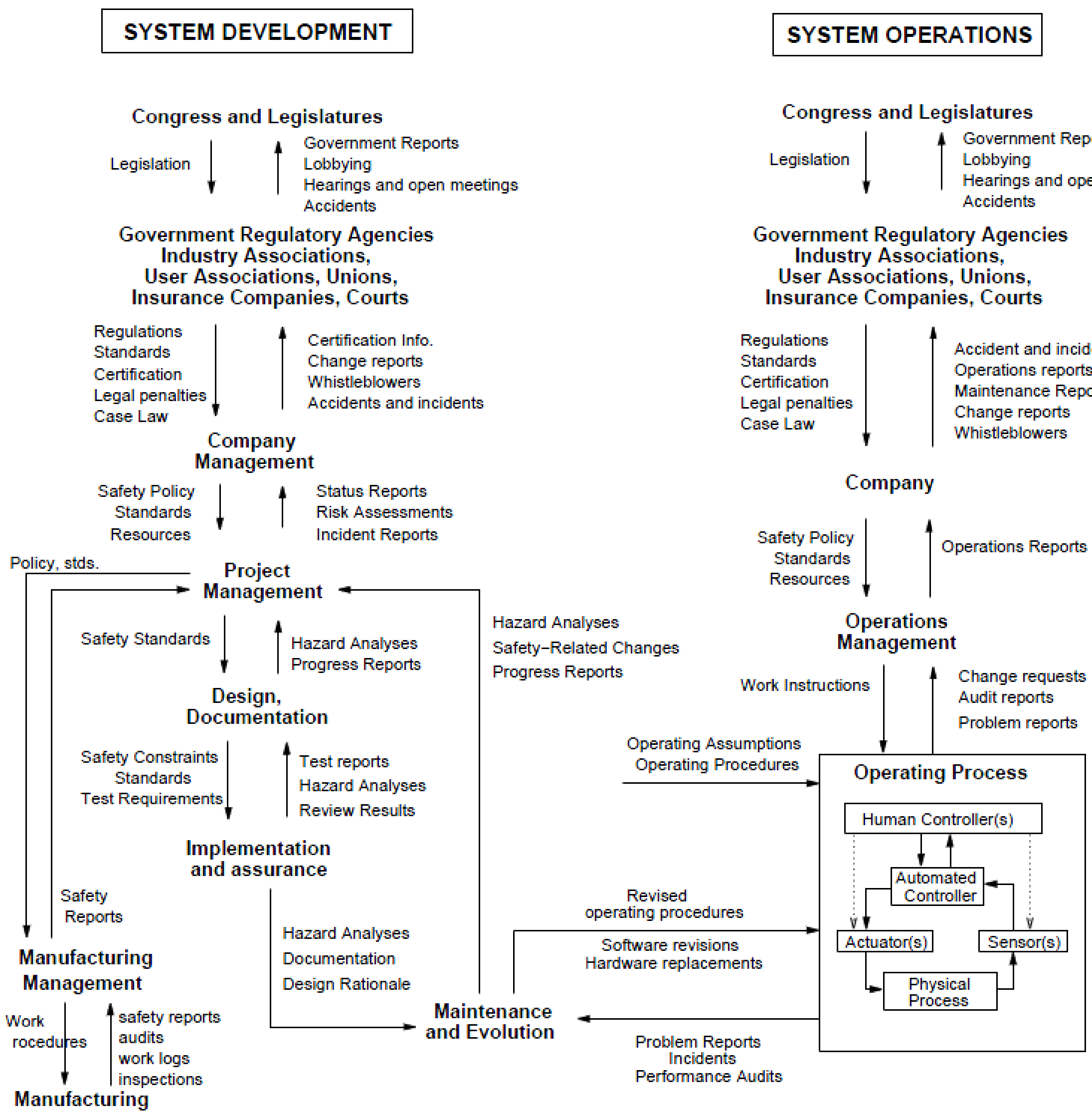

Figure 2. 1: General Form of a Model of Socio- Technical Control (Leveson, 2011)

Figure 2.1 above gives an insight into the complexity of the hierarchical control structure. Between the hierarchical levels there are different channels, which are important as they serve as the communication between the different levels in the hierarchy. Amid each level there is a two-way communication represented by arrows, called the reference channel and the measuring channel. The downward pointing reference channel provides information necessary to impose safety constraints on the level below. Providing feedback about how effectively the constraints are being satisfied is done by the upward pointing measuring channel as seen in Figure 2.2 below.

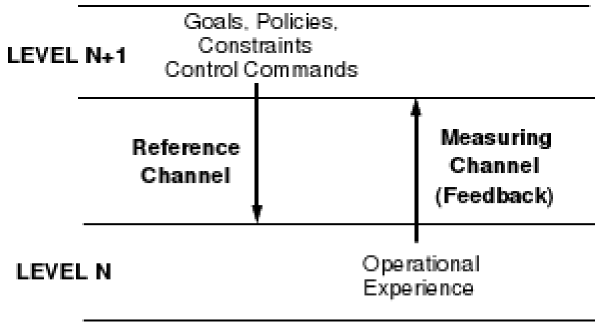

Figure 2. 2: Communication Channels between Control Levels (Leveson, 2011)

2.1.3 Process Models

STAMP describes systems and accidents as a control hierarchy of adaptive feedback mechanisms, as opposed to the event based models accident explanations in structural components and a series of events. Since STAMP is based on system theory some basic concepts are needed.

In systems theory, open systems are viewed as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control – (Leveson, 2004).

To affect control over a system four conditions are required (Leveson, 2011):

1. Goal condition - The controller must have a goal(s) (e.g. to maintain the set point)
2. Action condition **-** The controller must be able to affect the state of the system. In engineering, control actions are implemented by actuators.
3. Model condition - The controller must be (or contain) a model of the system.
4. Observability condition - The controller must be able to ascertain the state of the system. In engineering terminology, sensors provide observation of the state of the system.

A process model needs to fulfill these four conditions in order to be controllable. The first condition required for controlling a process is a goal, and in STAMP this goal is the safety constraints enforced by each controller in the hierarchical control structure. The second condition is the action condition, which are implemented through the downward pointing reference channels. Succeeding the action condition is the observability condition embodied by the upward pointing measuring channels. The final condition is the model condition: "Any controller – human or automated – needs a model of the process being controlled to control it effectively" (Leveson, 2011).

Either controlled by the control logic of an automated controller or in the mental model maintained by a human controller, the process model must contain the same kind of information. This information are the control laws, which is the required relationship among the system variables, the current values of the system, which is the current state, and the ways the process can change state (Leveson, 2011).

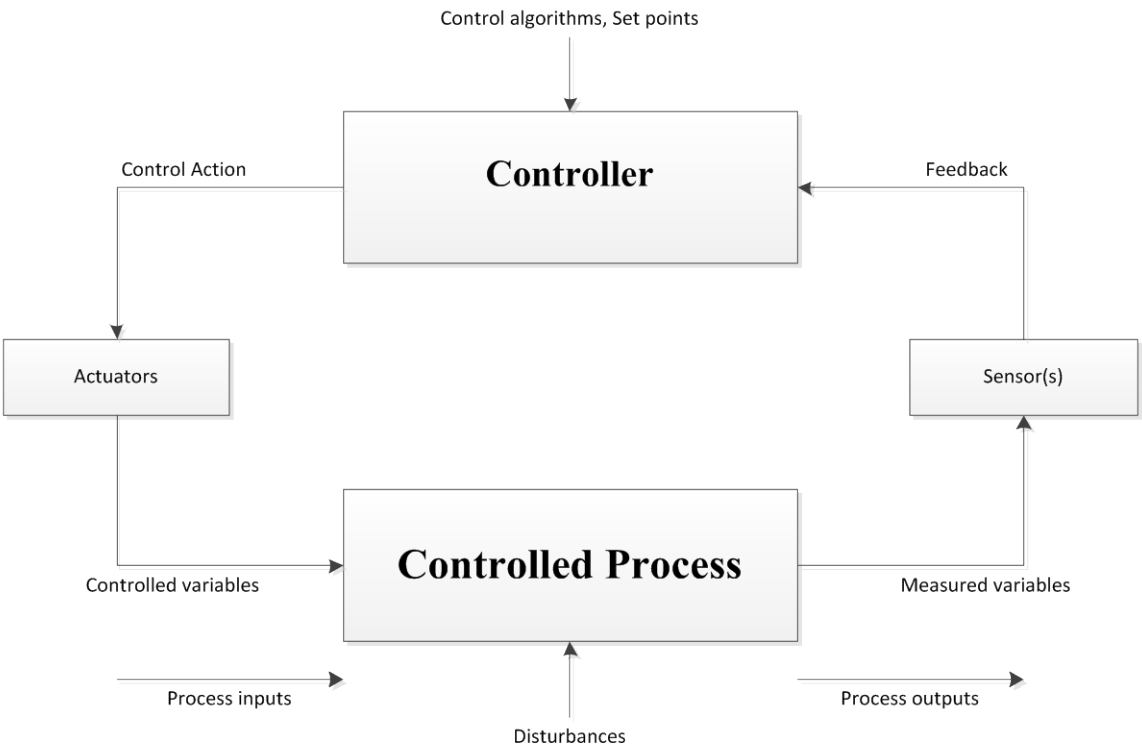

Figure 2. 3: Basic process loop (adapted from (Leveson, 2004) and (Leveson, 2011)

Figure 2.3 demonstrates the relationships between the controller and the process being controlled. The controller is reliant on feedback from the system to fulfill the observability condition and perform control actions as regards to the action condition. These control actions are manipulated variables, (controlled variables) initiated in order to maintain the system operations within predefined limits (constraints) or set points as regards to the goal condition. The disturbances inflicting the controlled process contribute to the measured variables changing and this change in measured variables requires a feedback system so that the controller can control the process. According to the model condition the controller must be (or contain) a model of the system, meaning that the required relationships among the system variables (the control laws), the current state (the current values of the system variables), and the way the process can change state, must be known by the controller.

The model is updated through feedback to be able to impose actions needed e.g. if the temperature measured in the room is below the set point, there is issued a control command to start the heating element. Sensors measuring the temperature provide feedback about the (expected) rise of the temperature.

Incorrect process models can usually be used as the explanation for component interactions accidents. In general, accidents often occur, particularly component interaction accidents and accidents involving complex digital technology or human error, when the process model used by the controller (human or automated) does not match the actual state of the process.

2.2 Causal Analysis based on STAMP - CAST

Causal analysis based on STAMP (CAST) is a method developed for analyzing accidents and incidents. Risk assessment methods have predominantly been event based, but STAMP wishes to move forward in assessing risks and safety by using the violation of safety constraints as a basis for loss events resulting in accidents and incidents. CAST is a method developed in line with the overall framework of STAMP, and will be the basis for the accident analysis of the Macondo well blowout in this report.

As an accident investigation is conducted the result is usually that the parties responsible for the investigation end their analysis after finding a root cause or multiple root causes. Contributory causes may also be presented, but are often explained incomplete as to why they occurred. The general accident analysis is completed as the investigators have found the party to blame for the accident, before the aftermath of the accident can be settled. This approach of analyzing accidents may not always be in the best interest to prevent future accidents as the cases are closed after a suitable party to blame is found (Leveson, 2011). This disinterest of searching for who to blame is one of the main goals of CAST, which instead wants to shift the focus to why the accident occurred and thereby succeeding in preventing future accidents (Leveson, 2011)

According to the theory, accident investigation is a large topic. When attempting to apply STAMP-based analysis to existing accident reports, it often becomes apparent that crucial information was not obtained, or at least not included in the report, that is needed to fully understand why the loss occurred and how to prevent future occurrences (Leveson, 2011). CAST is conducted by following a number of steps.

2.2.1 The 9 steps of CAST

Documentation of the accident process is done by showing the sociotechnical safety control structure for the system involved, and the safety constraints violated at the different levels of the specific control structure. It is important to stress that this documentation also should show why the safety constraints were violated. The result of this documentation is that it is possible to view accident(s) from different points of view, depending on the perspective used and what level in the control structure the loss is being viewed. It should be noted that although the process of analyzing accidents using CAST is described in steps, it is not implied that the analysis process is linear and that each step must be carried out one by one successfully (Leveson, 2011).

The 9 steps of CAST will be described based on (Leveson, 2011) and are as follows:

1. **Identify the system(s) and hazard(s) involved in the loss.**
2. **Identify the system safety constraints and system requirements associated with that hazard.**

Step 1 and 2 are closely related. Firstly the system(s) must be defined, and the system(s) hazard(s) identified. Following system definition and system hazard identification the system safety constraints and system requirements are identified. An example being a chemical plant with several controllers and processes that needs to be identified. So that hazards, such as release of a chemical, can be controlled by enforcing the proper safety constraints.

3. Document the safety control structure in place to control the hazard and enforce the safety constraints.

Step 3 is to document and create the safety control structure for the system(s) involved, creating an important overview of the system(s). This structure may be completed in parallel with later steps

The safety control structure can be created or based on the system safety requirements identified for the system. From these systems safety requirements the components in the structure and the responsibility for enforcing safety may then be identified. This structure includes the roles and responsibilities of each component in the structure as well as the controls provided or created to execute their responsibilities and the relevant feedback provided to them to help them do this.

In some accident analysis it will be possible to use general requirements and policies for the specific industry provided by some higher authority (government or professional associations), and together with the safety control structure of the system this can be used to compare the actual safety control structure with standards and best practices in the industry or country. In this way the accident analysis may help guide the analyst in considering what to define as inadequate controls.

Given that STAMP was used in the engineering design and development of the system a safety control structure may already be in place.

4. Determine the proximate events leading to the loss.

Step 4 is to determine the proximate events leading to the loss, and should not be misunderstood as event chains used today explaining the causality information, but rather so that the physical process involved in the loss can be understood

5. Analyze the loss at the physical system level.

Step 5 is to analyze the loss at the physical system level. In this step the goal is to determine why the physical controls in place were ineffective in preventing the hazard and identify the contribution of each of the following to the events: physical and operational controls, physical failures, dysfunctional interactions, communication and coordination flaws, and unhandled disturbances.

CAST examines the controls so that the controls not working adequately can be determined, together with why the controls did not perform. Already at this step it is reasonable to create several recommendations to avoid similar losses in the future. Current accident investigations often stop here with the physical process analysis or go one step higher in the system to determine what the operators (the direct controllers of the physical process) did wrong.

6. **Determine how and *why* each successive higher level allowed or contributed to the inadequate control at the current level.**

Step 6 is to analyze the higher levels of the safety control structure. While physical control inadequacies are relatively easy to identify in the analysis and are usually handled well in any accident analysis, understanding why those physical failures or design inadequacies existed requires examining the higher levels of safety control (Leveson, 2011). Implementing higher levels of safety in the accident analysis allows the focus to go beyond finding who or what to blame. A complete understanding of how and why the control allowed or contributed to the inadequate control at the level below, is required in order to fully understand the behavior at any level in the sociotechnical safety control structure

For each system safety constraint, either the responsibility for enforcing it was never assigned to a component in the safety control structure or a component or components did not exercise adequate control to ensure their assigned responsibilities (safety constraints) were enforced in the components below them. Any human decisions or flawed control actions need to be understood in terms of (at least): the information available to the decision maker as well as any required information that was *not* available, the behavior-shaping mechanisms (the context and the influences on the decision-making process), the value structures underlying the decision, and any flaws in the process models of those making the decisions and why those flaws existed.

A question that arises is where the limit of the components to be examined shall be drawn, since it is obvious that the analysis must consider the full picture while at the same time be practically to perform and keeping the analysis cost effective. Starting at the bottom level identifies the relevant components to consider, and at each level the flawed behavior or inadequate controls are examined to determine why the behavior occurred and why the controls were not effective at preventing that behavior. The stopping point in common accident analysis may be after identifying inadequate control action at lower levels, and the cause is attributed "operator error", which provides little to none information for prevention future accidents.

Going beyond the statement of a failure to be rooted in the general description "operator error" the analyst can start to analyze why people did the wrong thing or didn't do anything. Here again it is important to identify the context and behavior-shaping factors which then will make it possible to identify the reasons for the "operator error".

A set of general factors that may be used in investigation the statement "operator error" in an accident analysis may be some general factors made by (Stringfellow, 2010):

- History: Experiences, education, cultural norms, behavioral patterns, i.e., how the historical context of a controller or organization may impact their ability to exercise adequate control.

- Resources: Staff, finances, time.
- Tools and interfaces: Quality, availability, design, and accuracy of tools. Tools may include such things as risk assessments, checklists, and instruments as well as the design of interfaces such as displays, control levers, and automated tools.
- Training: Quality, frequency, and availability of formal and informal training.
- Human cognition characteristics: Person-task compatibility, individual tolerance of risk, control role, innate human limitations.
- Pressures: Time, schedule, resource, production, incentive, compensation, political, Pressures can include any positive or negative force that can influence behavior.
- Safety culture: Values and expectations around such things as incident reporting, workarounds, and safety management procedures.
- Communication: How the communication techniques, form, styles, or content impacted behavior.
- Human physiology: Intoxication, sleep deprivation, and the like.

Together with these general factors the process models used in the decision making and the information they provided to the controller may be analyzed. Even if the analysis of the "operator error" reveals a complete lack of competence by the person(s) performing the operation(s) being analyzed, the accident analysis does not stop at this point. Then the question goes beyond the operator(s) seeking to reveal why the operator(s) had such an important job to begin with.

As in step 5 it is reasonable to create several recommendations at this step in the analysis.

7. Examine overall coordination and communication contributors to the loss.

Step 7 is the coordination and communication of the system. The previous steps have looked at each component separately, but it is also important to keep good coordination and communication between the components. As a basic example one can consider a component that has two or more controllers. The controllers may have different responsibilities, but at the same time have control actions that may conflict. Also the controllers may have control of the same aspects of the components, leading to confusion about who is responsible.

Investigations usually stop before finding out why the reporting channels were not used. Often an examination and a few questions reveal that the formal reporting channels are difficult or awkward and time-consuming to use. Redesign of a poorly designed system will be more effective in ensuring future use than simply telling people they have to use a poorly designed system.

8. Determine the dynamics and changes in the system and the safety control structure relating to the loss and any weakening of the safety control structure over time.

Step 8 is to determine the dynamics and changes in the system that have migrated the system to a higher risk state over time. If a system does not handle its safety issues over time it will tend to increase its own risk, and thereby reduce its safety over time. Operating at higher levels of risk over time will of course increase the chance for an accident, and it is

therefore important to understand the systems dynamics over time. Understanding the dynamics of the system allows for redesign of the system or safety control structure to make them more conductive to system safety.
A common problem is that if safety efforts are successful a feeling among the controllers may grow to the point where the controllers feels that an accident cannot occur, where at that point the safety efforts are reduced and an accident occurs. However it does not stop with this accident and the same cycle repeats itself over and over again.

Understanding why a migration occurs allows for redesign of the safety control structure so it may prevent or detect the migration as it occurs. “Thorough investigation of incidents using CAST and the insight it provides can be used to redesign the system or to establish operational controls to stop the migration toward increasing risk before an accident occurs”.

9. Generate recommendations.

Step 9 is to give recommendations. “The goal of an accident analysis should not be to address symptoms, to assign blame, or to determine which group or groups are more responsible than others”. In practice it will be hard not to assign blame, given pressures from various parties such as, insurance, politicians, public, and management. As every party involved have their own agenda and none of the parties wants to be the perpetrator.
After a comprehensive CAST analysis new safety management practices should be simple to establish based on STAMP.

Chapter 3

The Deepwater Horizon

On March 19th 2008 BP acquired the lease to Mississippi Canyon Block 252, which would eventually be known as the Macondo prospect, in the Central Gulf of Mexico (BP, 2010). The lease was for 10 years and stated that BP would be the lease operator of block 252, and has an ownership of 65 %, shared with Anadarko Petroleum (25 %) and MOEX Offshore (10%), of the site (BP, 2010).

After the initial explorations, Minerals Management Service (MMS) approved plans on April 16th 2009, BP stated its drilling plans and on May 22nd 2009 MMS approved BP's Application for Permit to Drill (APD) (BP, 2010).

The drilling started on October 6th 2009 and was to be done by a Transocean drilling rig, Marianas (BP, 2010), but the Marianas rig was damaged in Hurricane Ida November 8th the same year and had to be replaced by another Transocean rig called Deepwater Horizon (DWH). The DWH recommenced drilling at the Macondo prospect on February 6th 2010 and on April 9th 2010 the DWH reached its final depth of 18,360 feet. The drilling job was completed and the rig was set to move to a different location (BP, 2010). BP received its approval for the final procedures called temporary abandonment on April 16th 2010 from MMS and the DWH were in the midst of the temporary abandonment as the Macondo well blew out on April 20th 2010.

3.1 Parties involved

In order to develop the new accident model for the Macondo well blowout a description of relevant parties involved will follow. In Appendix B an organizational chart of the parties directly involved at the Macondo well can be found. The Organizational chart is taken from (Drilling, 2011). Figure 3.1 may be used to see where personnel were situated.

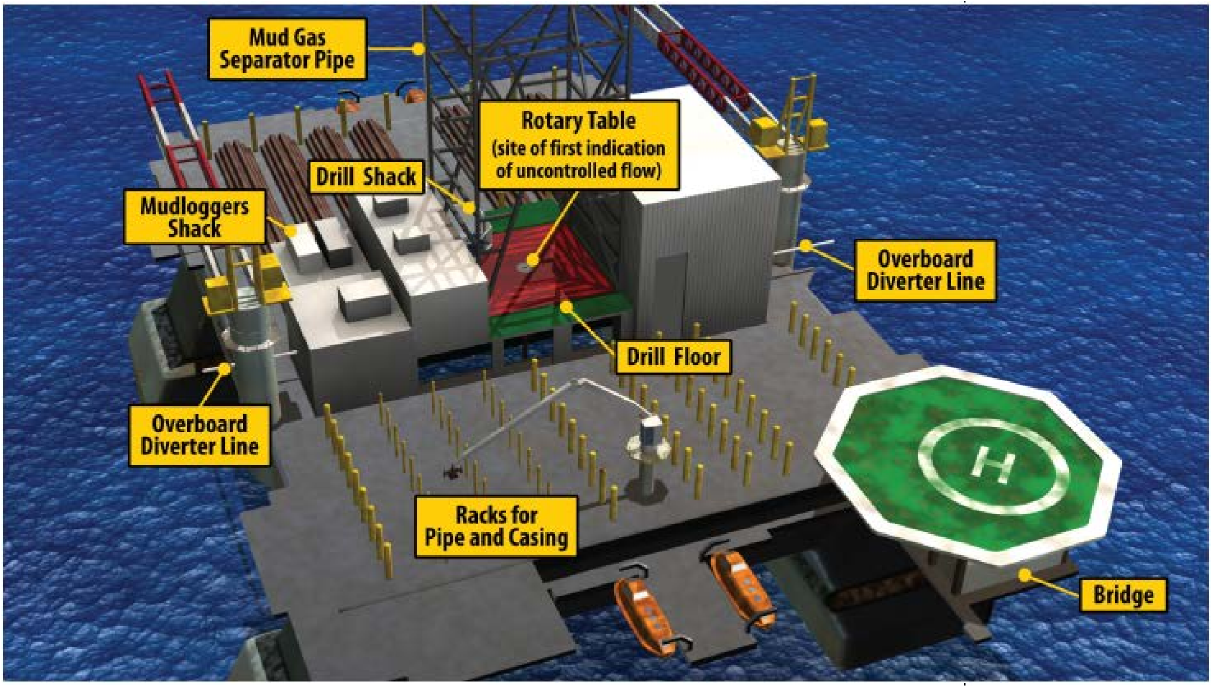

Figure 3. 1: Deepwater Horizon **(Drilling, 2011)**

3.1.1 Minerals Management Service – MMS

The Minerals Management Service (MMS) is an operating unit in the United States Department of Interior. The agency's main responsibilities are to receive and subsequently approve or disapprove applications for different operations regarding drilling and manage USA's minerals (oil and gas). By taking royalties from the production and ensuring that operations are done according to the legal safety and environmental requirements.

For the specific case of the Macondo well the MMS would receive BP's initial application for permit to drill (APD) and later on applications modifying this permit, application for permit to modify (APM).

3.1.2 BP

BP is a worldwide oil and gas company and was the legal operator of the Macondo well (Drilling, 2011)As most operators they hired a contractor to perform the drilling, but BP still had the legal responsibility of the well. BP's role in the drilling was to design the well and specifications on how the drilling was to be done. The people involved in the design and specifications were situated onshore, for the most in BP's regional headquarters in Houston. BP's partners Anadarko Petroleum and MOEX Offshore shared the costs of drilling with BP and would subsequently share the profits when the well started production. Neither of BP's partners' further involvement will be presented in this thesis.

On board the actual rig BP had two well site leaders instructing the rig crew of the plans they received from the onshore personnel and supervised the drilling operations on the rig. The well site leaders were BP's eyes and ears on the DWH rig and made decisions regarding drilling operations. Overseeing all drilling operations on the DWH rig the well site leader delegated minute-by-minute monitoring of the data, and monitored the well during critical processes.

At the time site leaders Don Vidrine and Bob Kaluza were onboard the DWH. Don Vidrine had only been at the rig a few months and Kaluza was filling in for Ronnie Sepulvuda who had left the rig a couple of days prior to April 20th to participate in a training program onshore (Drilling, 2011)There was also a well site leader trainee, Lee Lambert, on the rig.

For the purpose of this thesis the onshore personnel of BP will not be discussed. A note should be made that BP was in the midst of reorganizing their manager structure when the Macondo well blew out.

3.1.3 Transocean

Transocean is a contractor of offshore drilling rigs and had been hired by BP to drill the Macondo well. As the owner and operator of the rig Transocean employed the most of the personnel on DWH some of the key positions will be presented.

The DWH had two different leaders depending operating mode. While moving the DWH had a master, Captain Curt Kuchta, but as it was drilling at the time the highest ranking Transocean employee was the Offshore Installations Manager (OIM), Jimmy Harrell. He had no continuously involvement of the drilling operations, but would assist if needed. Next to the OIM was the senior toolpusher, Randy Ezell, who neither had a continuous involvement in drilling operations but assisted his subordinate the toolpusher when needed. Both the senior toolpusher and OIM had offices nearby the drill shack, and had their own monitoring displays such as the personnel in the drill shack.

In the drill shack, the driller, assistant drillers and toolpusher on duty were located. The DWH had two toolpushers, Jason Anderson and Wyman Wheeler, two drillers and four assistant drillers onboard. They worked in shifts counting one toolpusher, one driller and two assistant drillers on duty at the same time.

On duty the toolpusher disposed a small office inside the drill shack, and would generally be situated here during operations. The toolpusher supervised the driller and assistant driller(s) who sat in drilling chairs inside the drill shack. The driller would be in the A-chair when performing operations with all monitoring equipment situated in close proximity. The assistant driller would be in a similar B-chair next to the driller with the same monitoring abilities as the driller. The last assistant driller would be in an auxiliary chair (C-chair) in the drill shack, if not needed in other operations, monitoring as the other driller and assistant driller.

Arranged in order of rank, from low to high the different personnel were:

- **Drillers and assistant drillers:** Were in charge of operating the drilling machinery, and monitoring and controlling the well
- **Toolpusher:** Drilling managers onboard the DWH rig that directed and supervised day-to-day drilling operations. Responsible for confirming that all well control requirements are in place, performing all well control calculations, and assisting in killing a well in case of emergency. Usually located in the drill shack with the drillers

and assistant drillers, with a small office inside the drill shack and with access to all the drillers and assistant drillers monitors.

- **Senior toolpusher:** A senior operations supervisor with similar duties as the toolpusher, but one level higher in the internal hierarchy. Had no continuous role in operations and was not generally on the rig floor (had an office nearby), but was supposed to be consulted in case of anomalies or emergencies. Organized response actions and acted as a liaison to the well site leader in case of a well control event.
- **Offshore Installation Manager (OIM):** The OIM was in charge of the DWH rig during drilling and drilling related operations. Assisted in abnormal or emergency situations and had an office nearby the drill shack.

Transocean also employed floorhands and roustabouts who acted as the rigs workforce for drilling operations (Drilling, 2011).

3.1.4 Sperry Drilling

Sperry Drilling is a Halliburton subsidiary BP hired to provide oil field services, such as monitoring and training, on the DWH rig.

Sperry Drilling was hired to install a secondary monitoring system, Sperry Sun, to the internal Hitec system used by Transocean. From Sperry Drilling there were two mudloggers monitoring the well and training personnel in monitoring techniques. They were situated in the mudloggers shack and would assist the Transocean crew in the drill shack during operations.

3.2 The Macondo well

To be able to understand the accident a brief description of the Macondo well will be presented. Only the most essential parts and functions will be described, and seen in Figure 3.2.

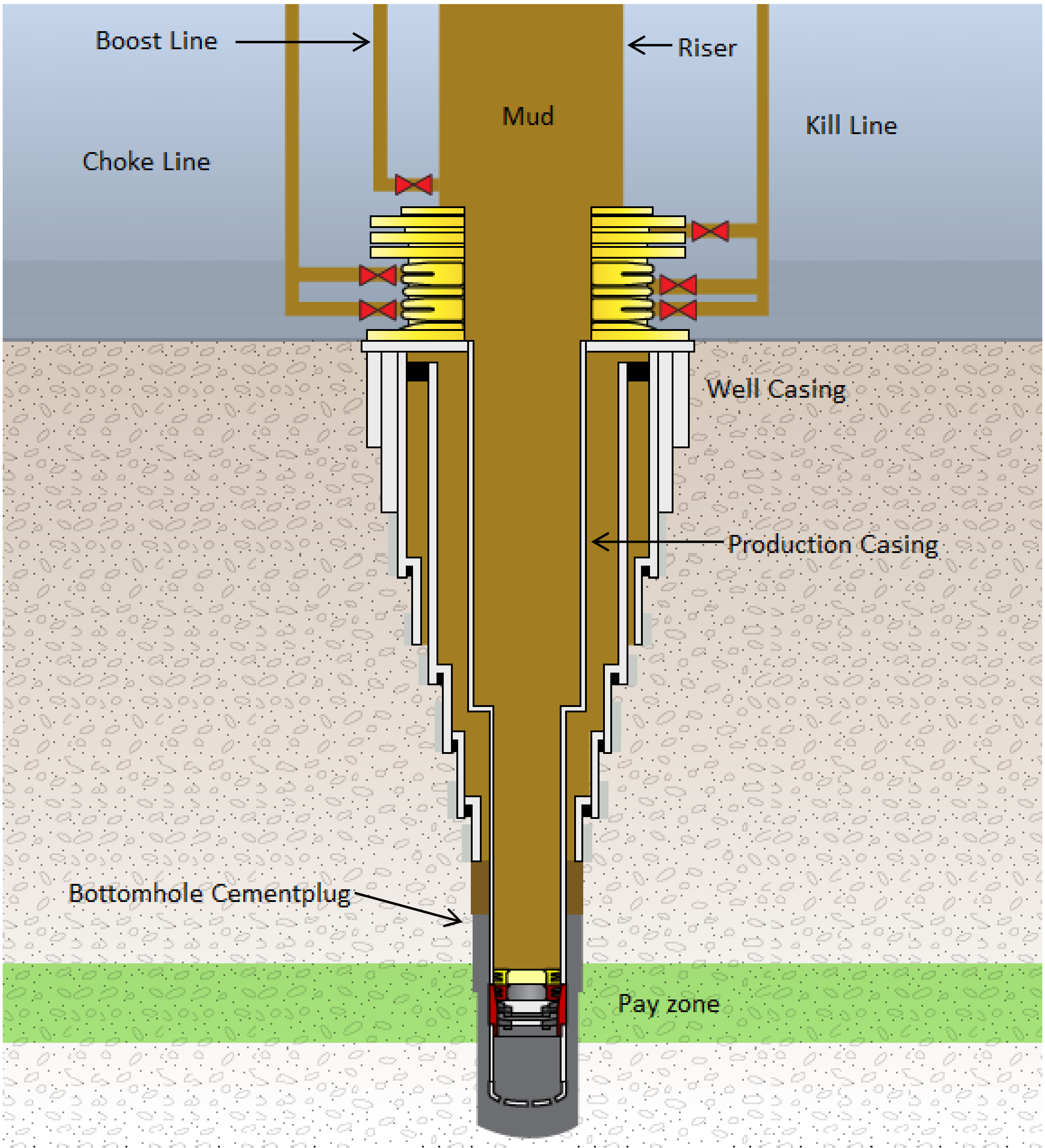

Figure 3. 2: The Macondo wellbore (adapted from (Drilling, 2011))

DWH was to drill a hole that in the future could be used for oil and gas production. The hole created during drilling is called the well bore (Drilling, 2011)The well bore at Macondo stretched from the seabed at 5067 feet below sea level to 18360 feet below sea level (Drilling, 2011), stretching over 13000 feet. Drilling is done in sections, as the diameter of the well bore becomes smaller as the depth increases. During drilling there will be used drilling mud in order to balance pressures inside the well with the pressure of the formation.

The rock formation surrounding the wellbore excerpt pressures, known as pore pressure or formation pressure, which the drilling mud must balance so the wellbore does not collapse (Drilling, 2011).

The weight of the mud will be adjusted as different depths of a well excerpts different pressures, and the pressure should be “equal to or greater than the formation pressure (pore pressure) (API, 2006).When the mud pressure is less than the pore pressure the well is underbalanced and fluids may start entering the wellbore. The well may also become overbalanced which is when the fluid pressure in the wellbore exceeds the pore pressure (API, 2006). An overbalanced well may be bad if the mud pressure reaches the fracture pressure of the formation. Fracture pressure denotes the pressure when the formation surrounding the wellbore fractures (Drilling, 2011)If this happens the drilling mud will flow into the formation which is known as lost returns or lost circulation (Drilling, 2011).

After drilling deeper a dilemma arises as the pore pressure at the drill head becomes higher than the fracture pressure of the formation higher in the well bore (Drilling, 2011)At this point drilling will stop and tubular steel section will be cemented into the wellbore. These steel sections are called casing strings and serves the purpose of protecting the more fragile formations higher in the wellbore from the mud pressures, and prevents high-pressure fluids from entering the well bore (Drilling, 2011). The casing strings in the Macondo well became smaller in diameter as the well became deeper and the final casing string had a diameter of 8 inches, while the first casing string had a diameter of 36 inches (Drilling, 2011).

There were several different casing strings inside each other in the wellbore, but only one of importance for this thesis. This casing string is the production casing and at Macondo BP had decided to use a long string production casing. A long string production casing, or long string, hangs from the wellhead and stretches all the way down to the bottom of the well (Drilling, 2011).

In the bottomhole of the well the casing contained different equipment used for the final cementing of the bottomhole; this is however beyond the scope of this report.
The bottomhole cement plug was cement that had been pumped into the well as the drilling was complete. The purpose of the cement was to isolate the hydrocarbons of the pay zone so they would not leak into the wellbore. This isolation is known as “zonal isolation” (Drilling, 2011).

The production casing which hangs inside the wellbore was connected to the wellhead on top of the wellbore, this area may also be referred to as the mudline. The wellhead is however not depicted on Figure 3.2. Instead Figure 3.2 depicts a simplification of the Blowout preventer (BOP). The BOP is depicted in Figure 3.2 as the yellow figure on top of the well. A closer explanation of the BOP can be found in Appendix C, but the purpose of the BOP is to seal the well confining the fluids inside the wellbore.

There were also three important pressure lines that went between the BOP and the DWH rig. These were the kill line, boost line, and choke line. These lines could be used to regulate the pressure inside the well and help circulate the fluids.

In case the annular preventer (see Appendix C) is closed the kill line and choke line can circulate the fluids. Generally the kill lines are used to pump fluids into the well and the choke lines are used to take fluids out of the well (Drilling, 2011), but they may also be operated the opposite way. The boost line was connected to the bottom of the riser and could be used to help circulate fluids, while annular preventer was open (Drilling, 2011).

3.3 The Deepwater Horizon Accident/Macondo well blowout

On April 20th 2010 the DWH was set to perform a temporary abandonment, which refers to the procedures done after the completion of the drilling of a well in preparation for the drilling rig to abandon the well. In turn another rig or vessel may take over the well, prepare it for production and finally produce from the well (Drilling, 2011). After the temporary abandonment procedures are done the riser and BOP may be disconnected from the wellhead on the seafloor, and the rig may move to its next destination.

At approximately 8:50 p.m. the Macondo well became underbalanced (Drilling, 2011) and the well soon experienced a kick. In the oil and gas industry a kick denotes the event when formation fluids start entering the well that has been drilled (well bore) (API, 2006). The kick on April 20th would later "mature" into what is now known as the Macondo well blowout or the DWH accident.

A blowout is an uncontrolled flow of well fluids and/or formation fluids from the well bore (API, 2006). As a wellbore is experiencing an intrusion of formation fluids, most likely hydrocarbons, it is said in the oil and gas industry that the well is "taking a kick" (Drilling, 2011). However if the fluids in the well bore start moving towards the surface and surpasses the wellhead and BOP, the well is said to have "blown out".

As the well at Macondo became underbalanced monitoring of the well became extremely important, but between 9.40 p.m. – 9.43 p.m. mud began spewing from the rotary onto the rig floor and within minutes at approximately 9.49 p.m. on April 20th 2010 the first explosion on the DWH rig occurred (Drilling, 2011). Following the explosion was the death of 11 of the DWH personnel, destruction of the drilling rig, and the Macondo well uncontrollably releasing vast amounts of hydrocarbons into the open sea. BP operated the DWH using what is referred to as Ops notes. The DWH personnel used an Ops note as a general plan for different procedures, therefore BP's Ops note, for the temporary abandonment will be described briefly (Drilling, 2011).

3.2.1 Ops note April 20th 2010

As of April 20th 2010 the plan for how the crew onboard DWH would perform their temporary abandonment procedures had been changed multiple times. The final plan was only ready on the same day as the procedures were set to begin.

The first procedure the crew onboard DWH would do was to perform two well integrity tests of the well. These tests were: (see Appendix D for details)

1. The seal assembly test
2. Positive pressure test

The purpose of these tests was to check the integrity of the casing hanger seal assembly, and the wells casing and that the wellhead was properly installed and did not leak.

Following these two tests was another well integrity test, the negative pressure test (see Appendix D). The negative pressure test also investigated if the bottomhole cement could withstand the pressures from the formation in the “pay zone”.

From the Ops Note made by BP on April 20th 2010 this negative pressure test was supposed to be performed in a specific order:

1. Run the drill pipe into the well to 8,367 feet below sea level (3,300 feet below the mudline)
2. Displace 3,300 feet of mud in the well with seawater, lifting the mud above the BOP and into the riser.
3. Perform a negative pressure test to assess the integrity of the well (including the bottomhole cement) and ensure that outside fluids (such as hydrocarbons) are not leaking into the well
4. Displace the mud in the riser with seawater
5. Set the surface cement plug at 8,367 feet below sea level
6. Set lockdown sleeve in the wellhead to lock the production casing in place.

Chapter 4

Developing the new accident model

The following basic event explanation of the accident and causal analysis using CAST is based on the investigation reports made by the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling.

These reports will be referred to as “Report to the President” and “Chief Counsel’s Report”. The national commission was established by President Barack Obama on May 21, 2010 (House, 2010) and subsequently released its reports for the public on January 11th, and February 17th, 2011.

It is evident from the reports that the well was leaking and that hydrocarbons came inside the wellbore, why the wellbore lacked integrity is not the focus of this thesis, but rather the actions and decisions that failed to discover this failure and in the end lost control of the well.

The scope of this thesis is to describe the processes and models involved in the temporary abandonment of the Macondo well site, the explosion killing 11 people on the Deepwater Horizon, destruction of Deepwater Horizon, and the massive oil spill will not be discussed in detail. The main focus will be on the events leading up to the kick that started the blowout at Macondo, and up until the first explosion.

The steps from CAST will be used for the development of the accident models. To limit the analysis steps 8 and 9 are not included in the analysis as they are not relevant for the objective of developing a model that describes the accident, based on STAMP.

4.1 CAST accident model

4.1.1 Step 1 and Step 2

There were several parties involved in the system operating the Macondo well at the time of the accident. STAMP states that: Safety during operation depend partly on the original design and development and partly on effective control over operations (Leveson, 2011)In accordance with the limitations of the thesis the system operations side of the hierarchical safety control structure will be analyzed and modeled.

Defining the system(s) and hazards involved in the loss that occurred at Macondo.
The main processes involved in the Macondo Blowout are the drilling and well operation processes.

System Hazard	System Safety Constraint
Death or injury, loss of drilling vessel (equipment) and environmental catastrophe from loss of well control	System operation safety control structure must prevent loss of well control

Table 4. 1: System hazard and system safety constraint.

All the components in the system operations safety control structure at Macondo will contribute and have their own role in enforcing the system safety constraint, in Table 4.1. The individual components will in turn have their own safety constraints to maintain the system safety constraint.

4.1.2 Step 3

The hierarchical safety control structure in Figure 4.1 is based on Figure 2.1 in Chapter 2. Figure 4.2 depicts the formal definition of each safety control levels role in overall structure. Details on how each levels reference and measuring channels works will not be provided here as it is assumed that these communication channels are as in the general model in Figure 2.1.

There are however three additions to the general model. The control command from the operations management is added since this level of the hierarchy was capable of directly enforcing actions on the well. There was also a measuring channel that bypassed the formal reporting between operations management and human controllers of the operating process, and the operations management and company (BP). From this channel operations management were provided with all data directly from the sensors connected to the well in addition to the communication with the human controllers. The measuring channel going to BP onshore provided the onshore personnel with live data from the well, through the Sperry Sun system, in addition to the communication between BP's personnel onshore and the operations management personnel on DWH.

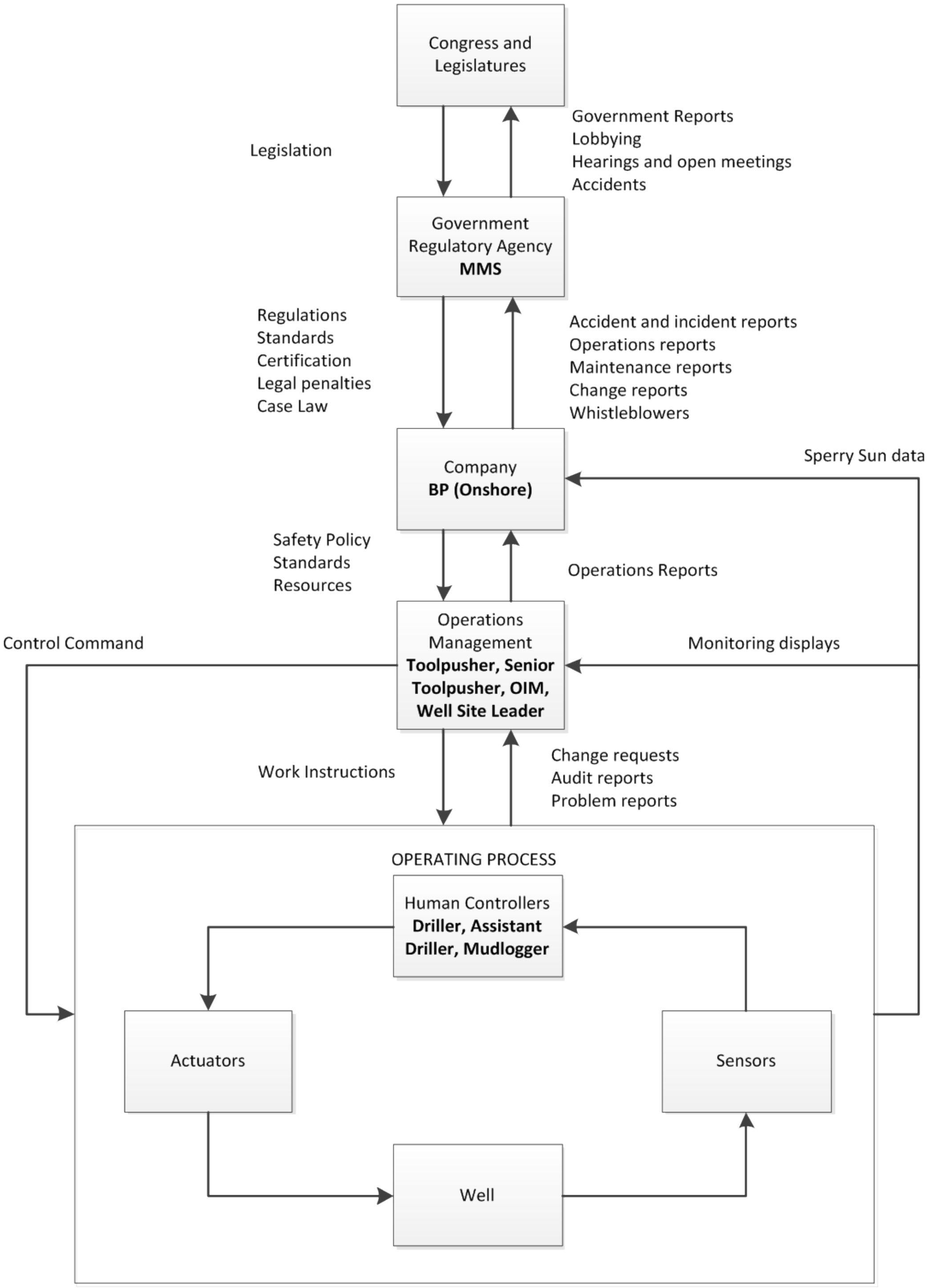

Figure 4. 1: Hierarchical safety control structure at Macondo, based on Figure 2.1 (Leveson, 2011)

From the steps that follow a more detailed structure of Figure 4.1, with detailed communication channels will be created.

4.1.3 Step 4 Sequence of events (The job went well)

As part of the CAST method there should preferably be created a proximal event chain in this step before the causal analysis in steps 5 and 6, to provide some sort of an overview of the prior events to an accident and the chain of events as the accident occurred (Leveson, 2011). The proximal event chain is found in Appendix E and is a short numerated list for the most important events of the Macondo well blowout. In this thesis a more thorough presentation will be presented, as the practice have been for similar projects such as the STAMP analysis of the LEX Comair 5191 accident (Nelson, 2008). This approach is more invasive, but suitable for an accident of this magnitude. All of the events took place on April 20^{th} 2010

The last cement job that was supposed to seal of the bottomhole of the well and maintain "zonal isolation" in the "pay zone" had been finished at around 5:45 a.m. At this time an e-mail was sent from a Halliburton cement engineer working onboard the DWH rig to a colleague onshore in Houston that read, *"We have completed the job and it went well"* (Drilling, 2011) marking that the drilling of the Macondo well now had been completed and that the DWH could start its final procedures before abandoning the well, known as temporary abandonment.

A series of tests were now to be conducted to verify the wells integrity before the drilling rig could move on to its next location. The first test was the seal assembly test and it had been conducted prior to this between 1:01 a.m. to 2:47 a.m. (Transocean, 2011), during at which time the crew had conducted two tests that both were reported as a success (Drilling, 2011).

At 7:30 a.m. during the daily operations conference call to BP in Houston, Texas, Brian Morel (a BP drilling engineer) whom had designed the well and was onboard the DWH during the final stages of the work at the well, discussed the good news with BP personnel onshore (Drilling, 2011). At this time a Schlumberger team, that had been flown in on April 18^{th} and 19^{th} to perform a cement evaluation of the new bottom cement seal, were onboard (Drilling, 2011).

BP had in advanced planned and documented, that if the cement job had gone smoothly without any lost returns (Drilling, 2011) they would not require Schlumbergers services in order to save time and money. The Schlumberger team then waited for their transport back to shore, accompanying them would be the aforementioned drilling engineer Morel. Right before they departed, at 10:43 a.m., he e-mailed his plans for the well integrity tests to be performed together with the general temporary abandonment procedures, the Ops Note previously described (Drilling, 2011). These plans were discussed at the daily pre-tour meeting 11:00 a.m. (Drilling, 2011) at the rig, as Morel and the Schlumberger team left the rig at 11:15 a.m. (Drilling, 2011).

As the Seal Assembly test was finished the rig crew was already conducting the positive pressure test while the pre-tour meeting was being held, starting with the test at 10:30 a.m. and finishing at approximately 12:00 p.m. (Drilling, 2011).The positive pressure test and seal assembly test were both successful (Drilling, 2011). Therefore it will be more important to describe the final negative pressure test, as this was the only test that could check the integrity of the bottomhole cement job.

After the positive pressure test was dealt with, the crew on DWH ran the drill pipe down into the wellbore. This was done directly after the positive pressure test had finished at noon (Drilling, 2011), and preparations were made for the negative pressure test to be conducted.

Prior to the negative pressure test the crew would have to lower the drill pipe down through the riser and into the well at a depth of 8367 feet. At 8367 feet the crew would start displacing all the mud used when drilling above the BOP. The BOP sitting on top of the wellhead was at approximately 5000 feet below sea level, and the crew would therefore have to displace roughly 3300 feet of mud with seawater (Drilling, 2011)In order to do so the crew would start by pumping a spacer fluid down into the well and inject seawater after the initial spacer. The reason for the use of spacer was to separate the seawater from the drilling mud, since drilling mud is expensive and reusable for other drilling operations (Drilling, 2011). After the displacement of the mud with seawater, the crew then would close an annular preventer around the drill pipe ensuring that the mud stayed above the BOP during the negative pressure test.

The reason for this displacement of mud with water was to simulate the conditions of the well when it would be abandoned (Drilling, 2011). This displacement of mud in the well sets the well in an underbalanced state, meaning that the pressure from the formation is higher than the pressure in the well, and in this underbalanced state the drill crew would be able to see if the well casing as well as bottomhole cement plug would keep the well intact.

It was now 4:55 p.m. as the crew started bleeding off the drill pipe that was in the well. Bleeding is a controlled release of fluids from a closed and pressured system in order to reduce the pressure (API, 2006). This first bleed off was done to equalize the pressure in the drill pipe and the kill line, to do so the crew opened the valve on the drill pipe to bleed the pressure down to 1250 psi, which was the current pressure in the kill line (Drilling, 2011). After bleeding the drill pipe to 1250 psi the crew opened the valve on the kill line so both the kill line and drill pipe were open.

After opening the kill line valve both pressure gauges should have been 1250 psi, but instead the pressure dropped to 645 psi in the kill line and increased to 1400 psi in the drill pipe (Drilling, 2011). The drill pipe and kill line should have behaved like two straws in the same glass of water (Drilling, 2011), since they both went to the same sealed off space. This was the first sign that something was amiss in the well, most likely the spacer above the BOP's annular preventer was leaking into the well (Drilling, 2011). The crew had prior to the bleeding experienced a pressure of 2325 psi in the drill pipe approximately 700 psi above what was expected (Drilling, 2011).

Moving on to 5:00 p.m. (Drilling, 2011) the crew now started the actual negative pressure test, by bleeding the drill pipe pressure down to 0 psi, but they were unable to get the pressure down below 260 psi. After shutting the valve the pressure jumped to 1262 psi. During the bleed the crew bled an uncertain amount of seawater from the well, the amount thought to have been bled from the well ranges from 23 to 25 barrels of seawater according to witnesses (Drilling, 2011).

At 5:10 p.m. (Drilling, 2011) after the first attempt to bleed off the well was unsuccessful the drill crew started to notice that the mud level in the riser had dropped. This could be visually confirmed as the crew would use a flashlight to check the level of mud inside the riser. At around this time the night crew started arriving for their shift, starting at 6 p.m., the crew on board DWH concluded that the system had not been closed properly. As a result the annular preventer was tightened and the riser was topped off with 20 to 25 barrels of mud (Drilling, 2011).

At 5:26 p.m. (Drilling, 2011) a second attempt to bleed off the well was started and the crew managed to lower the drill pipe pressure to 0 psi, but the amount of barrels needed to be bled was still very high (15 barrels were bled), and again the crew onboard DWH appeared to make no effort in calculating and predicting how many barrels would be needed. The Chief Counsel's Report suggests an amount of three to five barrels extracted from a well will be enough to reduce the pressure from 1262 psi to 0 psi (Drilling, 2011). As the drill pipe was shut at 0 psi, the pressure jumped back up to 773 psi, and the crew had to perform an immediately bleed off.

As the annular preventer had been securely closed this time there had to be another explanation to the pressure increase other than fluids leaking from the riser into the well and constituting in a failed negative pressure test. However at 5:53 p.m. (Drilling, 2011) the BP well site leader instead suggested a negative pressure test to be performed by using the kill line to bleed down the drill pipe pressure. Once again an uncertain amount of seawater was bled from the well, while the drill pipe pressure dropped to almost 0 psi, and as the crew was closing the valve on the kill line water was still spurting out on the top of the kill line.

Over the next 30 to 40 minutes the pressure built up to 1400 psi in the drill pipe, since the crew was changing shift more people than usual were present during discussions, both well site leaders were concerned about the pressure build up experienced during the tests that had been conducted. Discussion between the BP's representatives and the Transocean rig operators of what these tests concluded were held in the drill shack onboard DWH. The conclusion was that the bladder effect was the reason the pressure readings had not been what they were expecting. Bladder effect is the concept that the heavy drilling mud and spacer inside the riser exerts pressure on the annular preventer, and that this pressure results in a miscommunication between the well and rig as the pressure is manipulated to be higher than it is in reality (Drilling, 2011).

Following the discussions about the problems with the negative pressure tests, the well site leader taking over the night shift decided to move the test to the kill line, the drill crew started this procedure sometime after 6:40 p.m. (Drilling, 2011). Managing to bleed the pressure in the kill line down to 0 psi, the crew shut the kill line and monitored the pressure over the next 30 minutes. This time the pressure remained at 0 psi. Although the pressure on the drill pipe remained at 1400 psi, which the crew accepted as a result of the "bladder effect", this negative pressure test was approved and signed of as a success at around 8 p.m. (Drilling, 2011).

As the well's integrity had been approved and the bottomhole cement job had been signed off on, the crew continued with their temporary abandonment procedures by starting to displace the mud and spacer that now was in the riser. This would severely underbalance the well, and monitoring the well and detecting any signs of a kick was now crucial.

At 8:02 p.m. the annular preventer that had been closed during the negative pressure tests was opened and the crew started injecting seawater into the well, pushing the mud and spacer up the riser towards the rig.

8:00 p.m. to 9:00 p.m. was relatively uneventful on the DWH with its crew performing numerous actions simultaneously, from the investigations of the accident it has been stated that the well became underbalanced approximately at 8:50 p.m. (Drilling, 2011).

Around 9:00 p.m. the top of the spacer column in the riser reached the rig floor, and at 9:08 p.m. the pumps were shut off so the crew could perform a sheen test (Drilling, 2011). A sheen test is conducted to check what type of fluids that are coming out of the well. The sheen test would check if spacer fluids had reached the rig floor, and if so reroute the flow from the well overboard and dumping it into the ocean. The sheen test would ensure that DWH would not dump drilling mud overboard; since the mud was expensive and this would violate environmental regulations this was not desirable (Drilling, 2011). As the pumps were shut off the flow from the well would also stop if everything was in order. To see if the flow had stopped the crew would visually confirm this, and they confirmed that the flow stopped (Drilling, 2011).

The pumps were shut down from 9:08 p.m. to 9:14 p.m. as the sheen test was performed and started up after the test was approved, while this happened the flow out was also rerouted to the diverter. The diverter is a piping system which is used to dump fluids coming out of the well overboard and has two lines going to opposite sides of the rig, so the crew may choose which side to steer the flow overboard (Drilling, 2011). The crew on DWH also connected the flow from the well via their mud-gas separator and all this was done by 9:10 p.m. At 9:18 p.m. four minutes after the pumps were started the pressure release valve (PRV) on pump 2 blew. The main pumps were shut down, and crew members were sent to fix the valve (Drilling, 2011).

The DWH had four pumps: The valve blew on pump 2 which was used to pump down the kill lines, pumps 3 & 4 were the main pumps which were switched off after the blown valve, while pump 1 was kept on pumping water down the boost line (Drilling, 2011).

At 9:20 the primary pumps (3 & 4) were turned back on and everything was back to normal until 9:27 p.m. (Drilling, 2011) Finally at 9:27 p.m. the crew recognized anomalies in their pressure gauges as the kill line pressure rose to 800 psi. This caused a concern as the drill pipe pressure was at 2500 psi and this was a significant differential. Because of the differential pressure the pumps were shut down at 9:30 p.m. and an investigation was started.

Discussions about the differential pressure and close monitoring of the well followed after the pumps were stopped, and at 9:36 p.m. a crewmember was set to try and bleed off the

pressure in the drill pipe (Drilling, 2011).The pressure went down in the drill pipe, but in went slower than normal and as the pipe was closed the pressure shot back up again (Drilling, 2011).
Still trying to diagnose what was causing the differential pressure sometime between 9:40 p.m. and 9:43 p.m. mud began spewing from the well and onto the rig floor of DWH (Drilling, 2011).

At the same time the drill pipe pressure dropped by 1000 psi, indicating that hydrocarbons had surpassed the mud (Drilling, 2011). During the investigation of the differential pressure the crew had rerouted the flow back to the trip tanks (likely to see if there was any flow), which abruptly gained 12 barrels.

The toolpusher then activated the lower annular preventer at 9:41 p.m. As a result the drill pipe pressure increased as expected, but by now hydrocarbons were already in the riser. Realizing that the well was blowing out the alongside vessel Damon Bankston was told to move 500 meters away. The well was not completely shut in since the drill pipe pressure hadn't reached its expected shut-in pressure of 6000 psi, and was laying on around 1200 psi (Drilling, 2011). It is not clear now if the crew tightened the seal of the annular preventer or activated the variable bore ram, but by 9:47 p.m. the pressure increased dramatically, indicating that the well may have been shut in (Drilling, 2011).

After the mud had begun to spray over the rig floor and out of top of the derrick, the crew activated the diverter system (Drilling, 2011). The mud spray stopped abruptly and eyewitnesses thought the crew had the well under control. The diverter system has two pipes that either sent the fluids over the starboard or port side of the rig, the reason for this is to send the fluids out on the side of the rig that the wind is blowing so there won't be any accumulation of a gas cloud near the rig. At the time of the accident the seas were calm and there was little to no wind (Drilling, 2011), a very unfavorable situation in case of emergency dumping of well fluids.

The crew on the rig did not fully understand the magnitude of the blowout and had routed the gas influx to the diverter, which was still coupled with the mud-gas separator. This coupling was not necessary, but for environmental concerns and economical concerns it is not desirable to dump drilling mud overboard. Given the magnitude of the influx coming to the rig the mud-gas separator did not have the capacity to handle the blowout.

As the mud gas separator was failing a gas cloud accumulated on the rig and at 9:49 p.m. the first explosion occurred (Drilling, 2011). Following more explosions and chaos on DWH the crew decided to engage its Emergency Detachment System (EDS) at 9:56 p.m. (Drilling, 2011). The EDS was supposed to seal the well (by engaging the blind shear rams) and sever the rigs riser from the wellhead (Drilling, 2011), so the rig would be cut loose from the blowout. The EDS however failed to perform on demand, although the signal lamps on the rig indicated separation from the wellhead. Regardless of failed EDS the DWH had a back-up system Automated Mode Function (AMF). AMF is a "dead man" system that is enabled if the power, communication and hydraulic connections with the rig are cut, performing the same function as EDS (Drilling, 2011).

The events that followed this first explosion are beyond the scope of this thesis, but as we know the explosion killed 11 men, the DWH rig sank, and possibly the worst environmental disaster was a fact.

4.1.4 Step 5

There will be some repetition of events in both step 5 and 6 as they are the causal analysis of CAST. At the end of each level analyzed there will be a figure with the components and findings from each level.
CAST framework is a bottom up approach, starting at the lowest level. In step 5 a causal analysis of the loss at the physical system level will be executed. The lowest level of control will be dealt with in this part of the analysis, which is the level of the sharp end operators of the actual process. The sharp end operators refer to the personnel with the closest proximity to the actual process controlled (Hollnagel, 2004), in this case the drill crew onboard the DWH rig.

The floorhands and roustabouts will not be a part of the analysis as their implication of safety control on the processes onboard the DWH is seen only as superficial. In the Chief Counsel's Report the roustabouts and floorhands are sometimes referred to as the drill crew, but here the term drill crew represents the drillers, assistant drillers and mudloggers.

Using the terminology from STAMP, the important parties at the drill crew level titled the controllers were the drillers, assistant drillers and mudloggers. The drillers and assistant drillers were directly in control of operating the drilling machinery, and monitoring and controlling the well (Drilling, 2011). In addition mudloggers from Sperry Drilling were monitoring data from the well in parallel, and interpreting this data continuously (Drilling, 2011). The mudloggers themselves had no control over operations on the DWH rig, but would notify the drillers and assistant drillers if there were any discrepancies (Drilling, 2011).

The day of the accident the drill crew was performing tasks needed for the temporary abandonment, which will be the starting point for the further analysis. The focus of the analysis will be from when the drill crew started the negative pressure test and up until the well blew out.

As the most basic concept of STAMP is a constraint, and not an event, the analysis will start by explaining the constraints enforced by the DWH drill crew. A constraint may also be seen as a requirement on the system enforced by the controller (Leveson, 2011). In the case for the drill crew the correct enforcement of constraints and requirements is achieved if they are maintaining well integrity, detecting and identifying kicks and respond appropriately to a well control situation.

The first constraint at the Macondo well to be analyzed is the drill crew's responsibility of ensuring well integrity. The most important test for ensuring well integrity is the negative pressure test. This test must eventually be approved by the well site manager from BP, but in the discussions in the drill shack, where the drillers and assistant drillers on the DWH were situated, all parties had been involved in the decision making process.

The first negative pressure test was started 5 p.m. resulting in not being able to bleed the pressure down to 0 psi (only 260 psi) in the drill pipe before closing the valve, indicating that something was wrong. Prior to the negative pressure test the drill crew was experiencing pressure anomalies that from the Chief Counsel's Report and Report to the President conducted seem to have been overlooked by the drill crew. These anomalies were the unusually high pressure in the drill pipe (2325 psi) before the equalization of pressure in the kill line and drill pipe, and after the equalization was done the drill pipe pressure jumped from 1250 to 1400 psi as the kill line dropped from 1250 psi to 645 psi when both lines were opened. From the Chief Counsel's Report it is stated that when opening both the drill pipe and kill line they should have acted like two straws in the same glass of water. The fact that the pressure dropped in the kill line and jumped in the drill pipe may have indicated that the spacer pumped down into the well during the mud displacement was not completely above the BOP, which was needed to perform the negative pressure test (Drilling, 2011).

After the first negative pressure test the explanation made on the rig was that the annular preventer should be tightened as it was leaking (Drilling, 2011). This would imply that spacer fluids were leaking into the well, which would confound the negative pressure test requiring further displacement of the fluids beneath the annular preventer. Nevertheless the crew did not proceed in opening the annular preventer and displacing the spacer that had leaked into the well.

The first bleed off attempt from the well also resulted in far more barrels bled off than usual. Approximately 23 – 25 barrels (Drilling, 2011) were bled off, some witnesses state almost 50 (BP, 2010), which was unusually high. Monitoring the bleed off seems to have been inadequately performed by the drill crew (Drilling, 2011).The second attempt succeeded in bleeding the pressure to 0 psi for the drill pipe, but jumped back up again to 773 psi as the crew closed the valve. The crew actually needed to bleed the drill pipe immediately after they closed the valve because of the pressure jump (Drilling, 2011).

After these two unsuccessful attempts to bleed and monitor the drill pipe pressure experts interviewed for the accident investigations have stated that this would constitute a failed negative pressure tests (Drilling, 2011). Meaning that the well lacked integrity, and the well would therefore not be able to hold the hydrocarbons outside the well bore when the time to abandon the well came.

The DWH was at the time of the accident 6 weeks behind schedule and 58 million dollars over budget (Drilling, 2011), and it seems as the crew was rushing to finish operations. Indications that the well lacked integrity and needed additional work were repeatedly overseen during the integrity testing. The crew seemed to have been more eager to prove that the well would hold, no matter how many times the tests showed that something was wrong with the well. This circumstance is believed to have affected all the levels of the safety control structure, not including the authorities.

Discussions went on about what to do at the Macondo well after the two unsuccessful attempts to bleed of the well. The well site leader in charge decided for a bleed off using the kill line. This bleed off was successful with lowering the pressure to 0 psi, but the drill pipe pressure rose to 1400 psi after closing the valve. Yet another sign of something not being right in the well, but discussions onboard the rig pointed in another direction.

Around 6 p.m. the crew experienced a shift change as the night crew was relieving the day crew. The night crew had started arriving around 5 p.m. (Drilling, 2011), and an assumption can be made that they were updated with the situation with the negative pressure tests not going according to plan. However this is just an observation as it is very difficult to know for sure how well informed and up to date the crew was as the night crew replaced the day crew.

In the discussion, prior to the shift change, regarding the three failed bleed off attempts the Transocean toolpusher present in the drill shack hinted that the readings experienced was caused by the bladder effect, but this not an officially recognized well situation (Drilling, 2011). It is however not the purpose of this thesis to prove or disprove the theory of the bladder effect. It is worth noting that the drill crew believed that there was such an effect, just by being told by their toolpusher, which indicates a lack of training and understanding of deepwater drilling in general.

The well site manager, taking over operations as part of the night crew, decided that a new negative pressure test was to be taken using the kill line. This was also in accordance with the permit the crew had received from the MMS of BP's temporary abandonment plans for the Macondo well (Drilling, 2011). The earlier violation of the MMS permit, performing negative pressure test using the drill pipe, is an indication together with the acceptance of the bladder effect as the reason for the failed bleed off attempts, that the drill crew lacked standard procedures, plans and training of deepwater drilling in general.

The second attempt to perform the negative pressure test on the kill line was started at 6:40 p.m. This time the drill crew managed to bleed the kill line pressure down to 0 psi, monitored the pressure for 30 minutes, and approved it as a successful test as the kill line pressure remained at 0 psi. Still at this point the drill pipe pressure was 1400 psi, but it was accepted as the result of the bladder effect. From this point on the DWH started to displace the rest of the spacer and mud in the riser, as the next procedure in the temporary abandonment. From now on all the future procedures at the Macondo well were done in the belief that the well was secure, and that the bottomhole cement job would hold.

During the displacement of the spacer and mud in the riser the drill crew opened the annular preventer and started to inject seawater into the well. This would severely underbalance the well, and the drill crew's most important task was now to monitor and detect for signs of a kick. Transocean drillers were responsible for detecting kicks and responding properly to a kick (Drilling, 2011). Aiding in this task were the assistant drillers and the independent mudlogger on duty. From the approval of the negative pressure test around 8 p.m. and onwards the drill crew's safety constraint was to detect kicks and respond if a well control situation occurred. See Appendix F for techniques used at Macondo.

The injected seawater forced the spacer and mud up the riser and to the rig. Flow-out was monitored by active pits (Appendix F), but seawater was taken directly from the ocean, creating a non-closed loop system. The drill crew could therefore not read off any flow-in data. With the seawater injected directly from the ocean the monitoring job was complicated and even more complicated by several operations on the rig the same time (Drilling, 2011). However simple calculations for the expected flow-in can be done, as they are standard during a displacement where there are no flow-in readings (Drilling, 2011).

It will not be discussed in detail in this thesis all the procedures that went on at the DWH rig, which complicated the monitoring of pit gain and flow-in versus flow-out. Some aspects however will be drawn out to comment on the communication between the drill shack and mudlogger shack.

Between 8:28 p.m. and 8:34 p.m. the crew on DWH emptied one of two trip tanks, sending the fluid through the flow line and into the pits with the rest of the return from the well (Drilling, 2011). The primary use of a trip tank is to measure the amount of drilling fluid required to fill the drill pipe hole while pulling pipe to determine if drilling fluid volume matches pipe displacement (API, 2006). The fluid in the trip tank may be sent into the well as pipe is being pulled out, to compensate for the volume, of pipe, removed (Drilling, 2011). As fluid was sent into the active pits from the trip tank this complicates the monitoring of flow-out because of the added fluid from the trip tank. It is unknown if the crew did any calculations to compensate for this excess fluid as it was sent to the pits (Drilling, 2011).

After 8:34 p.m. the crew on DWH did several simultaneous operations, with the result being that the active pit system was eliminated as a well monitoring tool (Drilling, 2011) and the returns were routed to two separate places so the flow-out meter readings were artificially low (Drilling, 2011). This required calculations to be done in order to be able to sufficiently monitor the well, but it is unknown if any of these calculations were done (Drilling, 2011).

As the drill crew in the drill shack was complicating their monitoring tasks with simultaneous operations the mudlogger at one point called, as he had noticed a pit gain in the active pits, apparently unaware of the simultaneous operations being ordered from the drill shack (Drilling, 2011).

Approximately 8:50 p.m. the Chief Counsel's Report, based on the investigations done by BP and Transocean, has concluded that the well became underbalanced. Up until this point there had been no signs of a kick (Drilling, 2011), but simultaneous operations, poor communication and the lack of calculations had severely complicated the well monitoring process onboard the DWH.

Shortly after the well became underbalanced the mudlogger on duty notified the drill shack and took a short break. During this short break the rig crew decreased the pump rates on the rig simultaneously and started emptying the trip tanks. When a pumps rate is decreased it is natural that the flow-out rate decreases as well, but the flow-out readings actually increased (Drilling, 2011). The reasons for the flow-out readings to increase were that the trip tanks were being emptied. If a kick was underway at this point it would have been disguised by the emptying of the trip tanks (Drilling, 2011).

Around the same time at 9:01 p.m. the drill pipe pressure changed direction and began rising. Up until this point the displacement operations done had resulted in lowering the drill pipe pressure, as it should, since the lighter seawater was taking the place of the heavier mud and spacer fluids (Drilling, 2011). The pressure increase in the drill pipe had increased with approximately 100 psi by 9:08 p.m. (Drilling, 2011).

Returning from the short break the mudlogger went through the logs of the around 10 minutes away on break, but did not notice anything wrong. Stating in interviews after the accident that “nothing seemed to be worth investigating” (Drilling, 2011). The reason may be that the pressure changes on the Sperry Sun displays were subtle and the fact that the wells integrity had been approved by the negative pressure tests, the well was thought to be safe.

The Chief Counsel’s Report has stated the drill pipe pressure increase of 100 psi may have been subtle on the Sperry Sun displays, indicating that the tools and interfaces may have been inadequate in their design as the mudlogger going through the data log of his break, and the driller and assistant drillers did not see the pressure change. The underlying notion on the rig that the well had passed its integrity tests may also have played an important role in the monitoring of the well during the final operations of the temporary abandonment as the drill crew may have been more relaxed and less vigilant since the well was safe and that they did not expect anything to go wrong at this point. Pointed out in Chapter 2 if a safety effort has been performed (being the negative pressure test) the operator may lower its vigilance as operations continue thereby lowering safety of the operations to be performed. This is a sign of bad habits, but is quite common in any operations practice.

Meanwhile at 9:08 p.m. the top of the spacer column in the riser was reaching the rig and the crew shut the pumps off in order to perform a sheen test before dumping the spacer overboard. During this procedure the mudlogger on duty would visually confirm that there was no flow from a camera filming the flow line (Drilling, 2011).

As pumps are shut off on a drilling rig there will be some flow for a short period of time. This flow is known as residual flow and each rig has its own residual flow-out signature (Drilling, 2011)]. According to (Drilling, 2011) the residual flow should be systematically measured and recorded to ensure response. Data from the Sperry Sun has shown that the residual flow continued beyond the signature of the DWH rig, indicating a kick (Drilling, 2011). As most of the other signals from the well the mudlogger, driller or assistant drillers did not discover this. No personnel were either sent physically to inspect the flow a normal practice if there had been any anomalies, but there had not been any concerns raised by the drill crew (Drilling, 2011).

In interviews after the accident the mudlogger admitted to only have monitored the residual flow for 30 – 45 seconds, while residual flow on the DWH rig lasted typically for 3 to 5 minutes (Drilling, 2011). An assistant driller noted that a credible visual confirmation of no flow from the well required 5 to 7 minutes after the pumps were stopped (Drilling, 2011), another indication of lack of training, standard procedures, vigilance and bad habits on DWH.

As the sheen test was conducted the rig crew prepared for the next step, which was to reroute the flow with the diverters in preparation for dumping the spacer overboard.

Rerouting only took 2 minutes, not nearly enough time to visually confirm no flow (Drilling, 2011). In addition this rerouting would bypass the active pits system and the Sperry Sun flow-out meter. The bypass effectively made the Sperry Sun flow-meter incapable of monitoring the flow out of the well and now only the Hitec flow-out meter was monitoring the flow out (Drilling, 2011). This has made the accident investigations unable to find out what the flow-out readings were at this point (Drilling, 2011). Since the drill crew had not paid attention to the irregular residual flow, signs of a kick were overseen. The Hitec datalog, which would potentially have shown flow-out readings after the rerouting, was lost in the accident and uncertainty about whether the flow-out meter for the Hitec systems malfunctioned or if the crew simply overlooked the kick signals, is difficult to answer.

In addition to the rerouting of the flow the crew started to empty the active pits, most likely for cleaning (Drilling, 2011), and during this none of the DWH's crew took the time for a simple comparison of fluid pumped into the well and with the volume of the fluid returned from the well. This lack of vigilance suggests once again that the drill crew were not adequately monitoring fluids coming out of the well.

During the time the pumps were shut down from 9:08 p.m. – 9:14 p.m. for the rerouting and sheen test the drill pipe pressure increased by 250 psi indicating movement in the well; this was also overlooked by the drillers, assistant drillers and mudlogger. Movement in a well at this time is an anomaly, as a secure well will not have any movement when the pumps are shut down (API, 2006).

After the pumps were turned on at 9:14 p.m. one of the four pumps blew its PRV at 9:18 p.m. This was pump 2 and it had been turned on to pump down the kill lines and blew out because of a closed valve on the line, an uncommon but not unheard of or significant failure (Drilling, 2011).

As crew members accompanied by an assistant driller went to fix the PRV on pump 2 and open the kill line valve the main pumps 3 and 4 were turned off and only pump 1 pumping water down the boost line was in function. Pumps 3 and 4 were turned back on at 9:20 p.m. From the pumps initially had been turned on at 9:14 p.m. to 9:27 p.m. there was no clear sign of anomalies, other than the PRV blowing out, and partly because in investigation of the accident the only data available is from the Sperry Sun system, which in turn had many of its sensors disengaged because of the rerouting of the flow (Drilling, 2011).

At 9:27 p.m. the crew finally recognized anomalies in their pressure gauges as the kill line pressure rose to 800 psi. This caused a concern as the drill pipe pressure was at 2500 psi and this was a significant differential (Drilling, 2011), the pressure pumps were shut down at 9:30 p.m. and an investigation was started.

Within five minutes after the pumps being shut down, the drill pipe pressure increased by 550 psi (Drilling, 2011), again indicating movement. At 9:36 p.m. a floorhand was ordered to attempt to bleed of the differential pressure. Interviews of the floorhand indicate that this was taking longer than usual, and the bleed was stopped at 9:38 p.m., resulting in the increase of the drill pipe pressure after closing. Still trying to figure out the differential pressure the drill crew made no attempt to perform a flow check, hinting that the drill crew did not believe they were dealing with a kick (Drilling, 2011).

In these crucial moments before the blowout the drill crew in the drill shack did not notify any of the leaders (senior toolpusher, OIM, well site leaders) or communicated with the mudlogger. From 9:40 p.m. – 9:43 p.m. mud overflowed the rig floor and the drill pipe pressure dropped by 1000 psi. This pressure drop most likely indicated that the lighter hydrocarbons had surpassed the mud in the well and were now on their way to the riser (Drilling, 2011). The crew had, during the investigation, rerouted the flow back to the trip tanks (likely to see if there was any flow) which gained 12 barrels as the mud flowed up to the rig.

The toolpusher on duty supervising the driller and assistant driller in the drill shack then activated the lower annular preventer at 9:41 p.m. and as a result the drill pipe pressure increased as expected, but by now hydrocarbons were already in the riser (Drilling, 2011). The well was not completely sealed however since the drill pipe pressure hadn't reached its expected shut-in pressure of 6000 psi, and was laying on around 1200 psi (Drilling, 2011). It is not clear now if the crew tightened the seal of the annular preventer or activated the variable bore ram, but by 9:47 p.m. the pressure increased dramatically, indicating that the well may have been shut in (Drilling, 2011).

After the mud reached the rig floor and out the top of the derrick the crew activated the diverter system (Drilling, 2011). The mud spray stopped abruptly and eyewitnesses thought the crew had the well under control (Drilling, 2011). At the time of the accident the seas were calm and there was little to no wind, a very unfavorable situation in case of emergency dumping of well fluids.

The crew on the rig didn't fully understand the magnitude of the blowout and had routed the gas influx to the diverter and coupled this with the mud-gas separator. This coupling was not necessary, but for environmental concerns and economical concerns it is not desirable to dump drilling mud overboard (Drilling, 2011). Given the magnitude of the influx coming to the rig the mud-gas separator did not have the capacity to handle the blowout. In accordance with (API, 2006) the diverter was correctly engaged and the valves were open, but since the crew was feeding the flow through the mud-gas separator it got overrun by the blowout.

As the mud gas separator was failing a gas cloud started gathering on the rig. The first explosion was at 9:49 p.m. and the drill crew now tried to close in the well. There is no evidence that the rig crew activated the shear ram in the BOP prior to the first explosion (Drilling, 2011). Figure 4.2 depicts the result of the causal analysis of the drill crew.

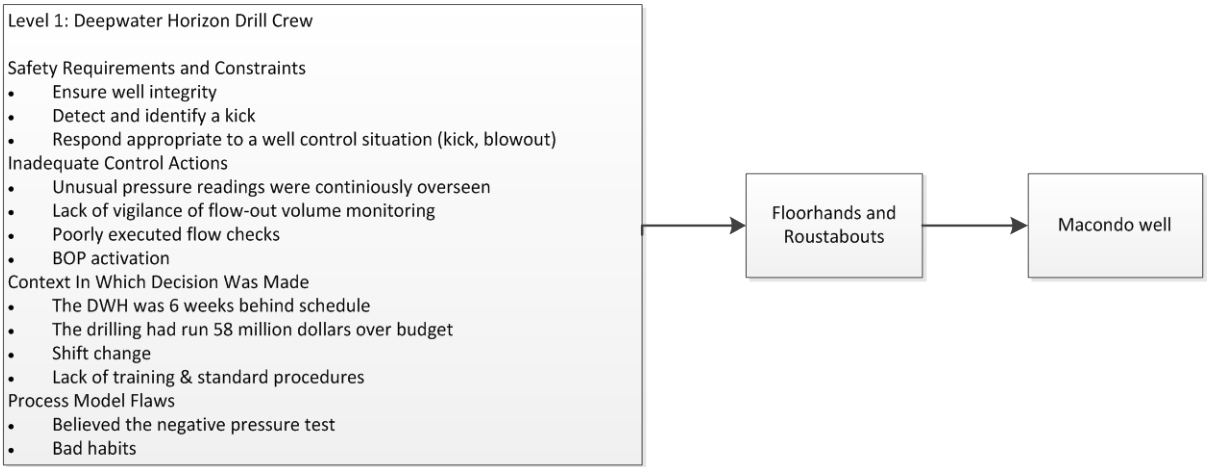

Figure 4. 2: DWH drill crew level analysis.

4.1.5 Step 6

As CAST is a bottom up approach the higher levels, as seen in the hierarchical structure in Figure 4.1, will be analyzed in step 6. Operations Management level follows the drill crew level. The parties involved here are presented in chapter 3.1, together with their responsibilities during drilling operations on the DWH.

The level comprised of a mix of Transocean personnel and BP's offshore personnel. BP represented by the well site leaders and Transocean represented by toolpushers, senior toolpusher and the Offshore Installation Manager (OIM).
The senior toolpusher and OIM were not continuously involved in the operations during the temporary abandonment procedures. On the day of the accident both the senior toolpusher and OIM were expecting executive visitors from BP and Transocean, and gave the executives a tour of the rig (Drilling, 2011).

As the first failed bleed off attempt, for the negative pressure test was discussed by the drill crew in the drill shack, the OIM and senior toolpusher, accompanied by their guests entered the drill shack (Drilling, 2011). Around 5 p.m. the OIM decided to tighten the annular preventer, as it was believed that something was leaking inside the well and also the riser level was dropping (Drilling, 2011). The daytime toolpusher on duty, Wyman Wheeler, then ordered the refilling of the riser, since it had been decreasing, and topped the riser off with 20 to 25 barrels of mud (Drilling, 2011).

The executives on the rig tour left the drill shack after this, but the OIM and senior toolpusher stayed and assisted the drill crew and toolpusher (Drilling, 2011). At around 6 p.m. (Drilling, 2011) the senior toolpusher left the drill shack and did not participate in any significance for the rest of the temporary abandonment procedures. The OIM had also left the drill shack after tightening the annular preventer and refilling the riser, and had no knowledge of what was happening when the first explosion occurred at 9:49 p.m.

The daytime well site leader, Bob Kaluza, had received the Ops Note at 10:43 a.m. on April 20th 2010. As presented in Chapter 3.2.1 the Ops Note contained a thought set of procedures for the temporary abandonment that was to take place at the Macondo well. At the 11:00 a.m. pre-tour meeting on DWH the daytime well site leader Kaluza presented the procedures.

In the Chief Counsel's report it has been pointed out that Kaluza was temporarily filling in as well site leader and that his inexperience may have been a contributing factor to why the negative pressure test was poorly managed. In the aftermath of the accident the OIM on DWH has claimed he had to remind well site leader Kaluza of the negative pressure test, as Kaluza forgot to mention it during the pre-tour meeting (Drilling, 2011). However this was found highly unlikely by the Chief Counsel's Report since Kaluza had discussed the negative pressure test with onshore personnel earlier that day and had just received the Ops Note where the negative pressure test was part of the temporary abandonment procedures (Drilling, 2011).

Both well site leaders, Kaluza and Vidrine were relatively inexperienced on the DWH rig. The fact that Kaluza had to ask how the negative pressure test was to be conducted, on the day it was supposed to be conducted, is proof of serious lack of understanding of BP's temporary abandonment procedures. Vidrine had only been onboard a few months prior to the accident, and since the most experienced well site leader, Sepulvuda, was onshore it is fair to assume that BP's current well site leaders lacked in both experience and competence for the upcoming temporary abandonment procedures.

During the initial attempts to perform the first negative pressure test the well site leader on duty, Kaluza, had not been in the drill shack overseeing any of the operations. Kaluza had neither performed any sort of calculations of pressures that the rig crew might experience during the displacement, equalization bleed off, or first bleed off attempt of the drill pipe (Drilling, 2011).

The well site leader's responsibility was to instruct the crew with BP's plans and supervise the plans in action. Kaluza was not present during initiation of the negative pressure test and therefore he had not seen the unusually high pressure in the drill pipe before the equalization bleed off, when the pressure jumped in the drill pipe and dropped in the kill line as the valves were opened, or the first bleed off and when the riser was refilled. Kaluza had not been around since he had participated in a safety briefing before the displacement had commenced at 3 p.m. and returned to the drill shack at around the same time as the riser was refilled (Drilling, 2011).

During the second bleed off attempt Kaluza was present and saw the pressure reach 0 psi, before it went up to 773 psi as the valve was closed and the crew started an immediate bleed off. Kaluza then ordered the bleed of using the kill line trying to lower the drill pipe pressure this way. Again the pressure dropped to 0 psi, but rose to 1400 psi. Perhaps since Kaluza not had seen what had happened during the opening of kill line and drill pipe valves he did so, since this might have raised some suspicion, either way no one argued with the decision to bleed off the kill line (Drilling, 2011).

By this time the shift change had started and Kaluza would be replaced by well site leader Vidrine. Before the shift change a discussion on why the bleed off attempts were failing was held on the drill floor, which both well site leaders, night time toolpusher (Anderson), well site leader trainee (Lambert) and a driller (Drilling, 2011). At this crucial meeting the theory of the bladder effect was presented by toolpusher Anderson.

Well site leader Vidrine ordered at this time a new bleed off attempt only using the kill line. The pressure dropped to 0 psi, was monitored for 30 to 40 minutes and approved at around 8 p.m. Vidrine has later claimed he was unsure of the bladder effect explanation as he ordered the negative pressure test to be done using the kill line, but had been convinced by toolpusher Anderson and the driller in the drill shack after the negative pressure test using the kill line (Drilling, 2011).

Looking back on all negative pressure test attempts it has been found that none of the well site leaders calculated pressures and volumes prior to the negative pressure tests. According to experts this is a regular practice and shows unfamiliarity with the test (Drilling, 2011). Neither Vidrine nor Kaluza performed calculations for incidents such as expected pressure readings during negative pressure tests.

Suggested in the Chief Counsel's Report even the calculations done during the displacement of 3,300 feet of mud and spacer in preparation for the negative pressure tests had been inadequate. BP's internal investigation of the accident calculated a margin of only 12 feet above the BOP, and Transocean report is even worse calculating that the tail end of the spacer fluids had not been above the BOP at all before the annular preventer was closed (Drilling, 2011).

It was stated in the analysis of the drill crew's operations that a lack of vigilance by the drill crew on DWH affected the monitoring abilities of the drill crew during the temporary abandonment. The uncertain amounts of fluids bled during the first negative pressure, ranging from between 23 to 25 barrels. The second bleed also bled excessive amounts of fluids, 15 barrels. Calculations after the accident show an expected bleed of only 3 to 5 barrels for the second bleed off (Drilling, 2011). The third bleed attempt, with the kill line was not calculated either and the bleed has said to be ranging from 3 to 15 barrels according to witnesses (Drilling, 2011).

After the accident Transocean has blamed BP for the lack of supervision and control during the temporary abandonment. BP however expected and trusted the Transocean crew to have the competency and skills needed to perform a negative pressure test. According to Transocean drillers and toolpushers they were not responsible for interpreting data from the negative pressure test (Drilling, 2011), but they assisted in the process. This assistance eventually convinced well site leader Vidrine that the cause of the excessive drill pipe pressure of 1400 psi was from the bladder effect. As it was not mandatory and not part of BPs temporary abandonment procedures neither well site leader Vidrine or Kaluza called onshore for assistance during the negative pressure tests (Drilling, 2011).

BP onshore did not provide guidance in how to perform negative pressure test, and relied heavily on the Transocean's crews expertise (Drilling, 2011), indicating the lack of standard procedures. The practice of performing negative pressure tests without proper specification had highly likely been done numerous times during temporary abandonment procedures, if not an underspecified negative pressure test probably some other operations. This is just an assumption, but given the fact that Kaluza started a procedure he was very unsure of and lacked the specifications of, may indicate that this statement is true.

As normal practice after an accident, blame was handed out by both BP and Transocean to each other with the intention of being perceived as the professional and responsible party. This is the problem with hindsight bias as it will not help in preventing such incidents and accidents in the future, and it is not the purpose of this analysis to find who to blame.

Vidrine was present in the drill shack as the negative pressure test was approved and the start of the displacement of the riser fluids. He later left and would not interfere with the temporary abandonment again until the pumps were stopped for the sheen test between 9:08 - 9:14 p.m. Vidrine awaited the results of the sheen test and as they came back directed the crew to start dumping the spacer from the well overboard, he then retired to his office and was not involved with the temporary abandonment after this point (Drilling, 2011). About the same time, 9:20 p.m., the last conversation between the drill shack and senior toolpusher prior to the blowout was held. Senior toolpusher, Ezell, questioned the negative pressure test, which he had not been involved in since leaving the drill shack at 6 p.m. and if the final displacement procedures were on route. Toolpusher Anderson replied that everything was ok and they were expecting to be finished soon (Drilling, 2011).

Toolpusher Anderson whom followed the driller and assistant drillers the closest during the temporary abandonment was the one who decided to stop the pumps and investigate the differential pressure at 9:30 p.m. He did however never notify any of his superiors of this investigation. As he had the chance to close the well at this point the investigators have deemed his actions severely lacking (Drilling, 2011). The events that followed, after the investigation was started, were covered in the causal analysis of the drillers.

The senior toolpusher was called at 9:45 p.m., as mud was overflowing the rig, by an assistant driller from the drill shack, claiming that toolpusher Anderson was sealing in the well, but they needed the senior toolpushers help (Drilling, 2011). According to toolpusher Anderson's statement after the accident he had activated the lower annular preventer at 9:41 p.m., but Transocean later admitted that it was the upper annular preventer that had been activated at this time. As described in the casual analysis of the lower level there where confusions as to whether or not the annular preventers were tightened or the variable bore ram was activated. The datalog however shows that at 9:47 p.m. the pressure increased dramatically to 5700 psi, which may have indicated that the well was shut in (Drilling, 2011). Despite these efforts the first explosion at 9:49 p.m. was a fact. The OIM was at the time of the first explosion in the shower unaware of the problems prior to the explosion (Drilling, 2011). After the first explosion he found his way to the bridge and ordered EDS at 9:56 p.m. (Drilling, 2011). The EDS however failed, and what followed is beyond the scope of this thesis. Figure 4.3 depicts the results from the Operations Management level.

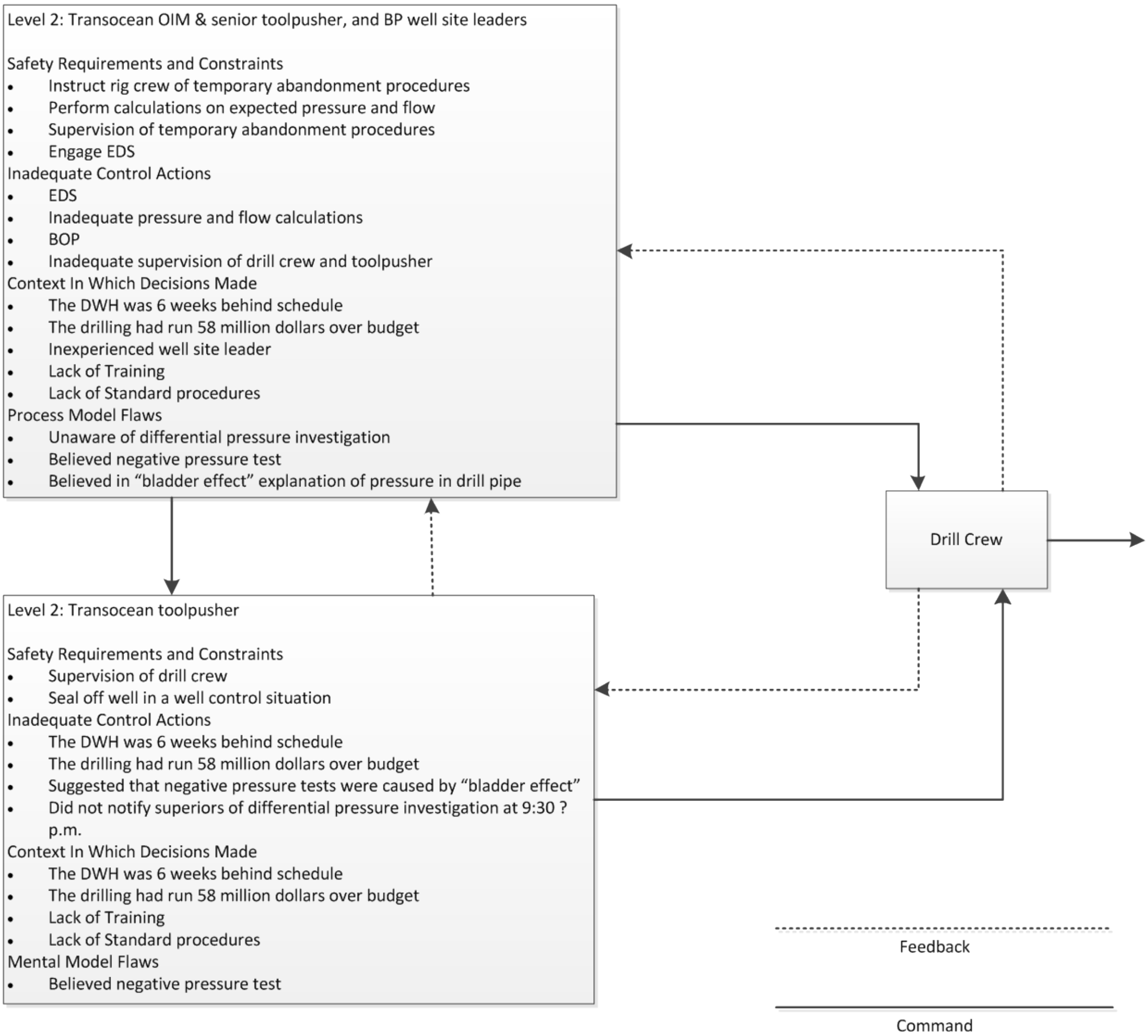

Figure 4. 3: Operations Management level analysis.

The level succeeding the operations management in the safety control structure is the company management of the operating process (see Figure 4.2). In reality the company management level included BP, Transocean, Sperry Drilling, and others, but responsible for all operations and legal operator of Mississippi Canyon Block 252 was BP.

BP made all plans and procedures for well design, drilling specifications and created the temporary abandonment procedures. Therefore BP will be the only company discussed at this level in the CAST analysis. As mentioned the objective of this thesis is to identify the control levels on the system operations side of the system at Macondo, and therefore system development and design will not be discussed.

At the time of the accident BP was undergoing a reorganizing process, dividing its report structure onshore between engineering and operations. In addition to changes in reporting processes, some of the managers onshore were new to their positions and had only been in their positions for a couple of months prior to the Macondo blowout.

The temporary abandonment plan had been altered several times before the temporary abandonment was started as shown in Figure 4.4. The focus of the analysis will be on the changes in the well integrity tests in the different temporary abandonment plans made for the Macondo well

Figure 4. 4: BP´s revisions to the temporary abandonment procedure (Drilling, 2011).

The initial temporary abandonment procedures draft of April 12th 2010, for the Macondo well did not contain a negative pressure test. The draft was sent to well site leader Sepulvuda on DWH, whom well site leader Kaluza was temporarily replacing on April 20th. Sepulvuda responded that a negative pressure test needed to be included (Drilling, 2011). In hindsight a question can be raised as to what a well site leader such as Kaluza would have done after seeing a temporary abandonment draft without a negative pressure test.

The new draft of April 14th was e-mailed to well site leader Sepulvuda, this time including a negative pressure test to be performed after a 300 foot cement plug, known as a surface plug (Drilling, 2011), was set in the well. This meant that the test checked the integrity of the surface plug and not the bottomhole cement plug sealing the pay zone of the well. The surface plug was a safety barrier that was meant to seal the well if the well itself lacked integrity when it was abandoned. The negative pressure test would also be conducted with base oil in kill/choke line to the well head (Drilling, 2011).

Base oil in negative pressure tests is normal in the industry (Drilling, 2011), but setting the surface plug 3,300 feet below the mudline is not (Drilling, 2011). Using base oil in the negative pressure test is done by filling the choke or kill lines with base oil, which simulates well conditions as they would have been if the mud had been displaced (Drilling, 2011).

The plan was changed again on April 15, before it was submitted to MMS. Now the procedures would start with a negative pressure test to sea water gradient, displacement of approximately 3,300 feet of mud between the wellhead and surface plug at 8367 feet, and a new negative pressure test before setting the surface plug. Together with this plan an alternative to the surface plug being set at 5,800 feet instead of at 8367 feet was created, since setting a surface plug 3,300 feet below the mudline was 2000 feet lower then MMS regulations allowed (Drilling, 2011).

On April 16th the application was sent to MMS, and approved in less than 90 minutes (Drilling, 2011). In hindsight of the permit approval BP realized that by displacing all mud down to 8367 feet, this would severely underbalance the well before setting the surface plug, and performing a negative pressure test with base oil would not be able to simulate these conditions. The oil was therefore traded with seawater. The application had only specified that the negative pressure test would be conducted with a seawater gradient equivalent which could mean seawater or base oil (Drilling, 2011).

The Ops Note of April 20th was another change to the temporary abandonment procedure as the initial negative pressure test was skipped and the crew should start directly with displacement for the negative pressure test. The changes made were not communicated to MMS and the rig crew started the temporary abandonment based on the Ops Note.

These changes in the temporary abandonment procedure during April of 2010 have not been presented to analyze which procedure would have been the most appropriate one, but to indicate BP's vague relationship to the process of a temporary abandonment. Especially the negative pressure test was not standardized in any way, and given the instructions provided for the DWH relied heavily on the rig crew on DWH knowing how to do a negative pressure test.

BP had monitors showing the Sperry Sun data onshore in Houston, but did not interfere with the rig crew's work during temporary abandonment. Communication before the temporary abandonment between BP onshore and well site leader Kaluza was the only guidance BP gave to the crew on DWH the day of the accident. Kaluza had also asked about the alterations of the temporary abandonment compared to the permit received from MMS. BP onshore answered that they had decided to do the temporary abandonment differently, which may indicate that BP violated its permits regularly.

Well site leader Vidrine talked with BP onshore at 9 p.m. which is the only record of communication between onshore and offshore personnel regarding the negative pressure test after it had been started (and finished) (Drilling, 2011). Vidrine called for information on the upcoming surface plug to be set in the well, not much of the conversations contents is known, but it is believed that Vidrine most likely did not mention any difficulties or signs of distress, since nothing was changed after this point (Drilling, 2011).

Finally an important part of BP's safety requirements at this level was to ensure that its personnel were competent enough to work with the complex tasks of deepwater drilling. Relying on well site leader Kaluza and Vidrine was clearly not good judgment of BP, during a crucial stage of the drilling operations at Macondo. Figure 4.5 represents the results from the causal analysis of the company level.

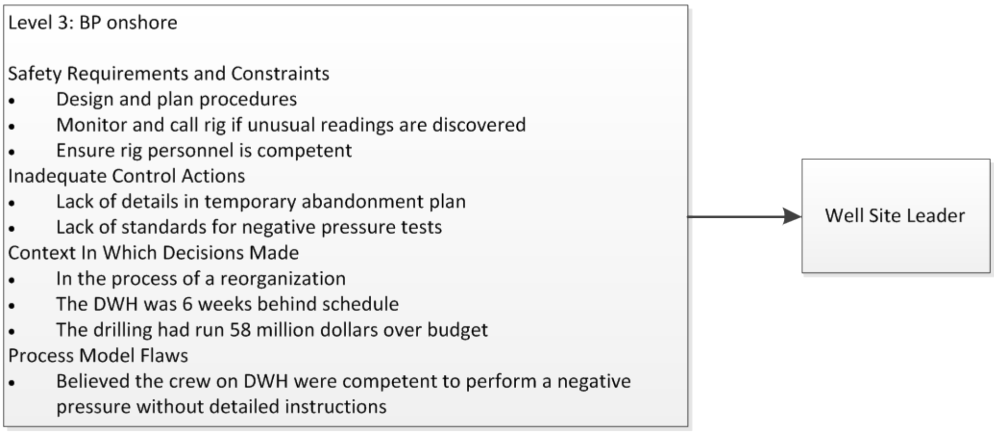

Figure 4. 5: Company level analysis.

Succeeding BP in the hierarchy of the safety control structure was the MMS an agency under the United States Department of Interior's operating units. Their main responsibilities were to receive, approve or disapprove applications for different operations regarding drilling, and manage USA's minerals (oil and gas) by taking royalties from the production and ensuring that operations were done according to the legal safety and environmental requirements (Drilling, 2011).

For the Macondo well the MMS would receive BP's initial application for permit to drill (APD) and later on applications modifying this permit, application for permit to modify (APM). This was MMS way of ensuring that operators in the Gulf of Mexico would follow legislations and regulations. The final permit sent from BP to MMS contained the temporary abandonment plans for the Macondo well. As mentioned previously approval of this permit resulted in approving a surface plug over 2000 feet further down the wellbore than MMS regulations allowed. However MMS approved the permit in less than 90 minutes.

To find out why this happened the circumstances and context MMS operated in may be looked at. A constant dilemma MMS had to operate with was that they promoted offshore drilling, which interfered with its mandate to ensure safe drilling and environmental protection (Drilling, 2011). Oil and gas drilling has had a rapid technology development needed for deepwater drilling, while MMS's regulations were outdated and unable to correctly address the risks of deepwater drilling with their current regulatory structure (Drilling, 2011). The clearest example of this is that MMS had no requirement of a negative pressure test to be performed during temporary abandonment.

In addition of approving permits for drilling operations MMS inspected well sites and certified equipment used on offshore installations. Most of MMS's installation inspections were announced, less than 3 % of the inspections were unannounced in 2009 (Drilling, 2011). The trend of not having unannounced inspections had started around the millennium (Drilling, 2011). Overall the trend had been that as the oil and gas industry had started operating more complex vessels and operating in tougher and more extreme areas the MMS's ability to keep oversight was reduced and the staff operating the vessels that was to be monitored had become more inexperienced (Drilling, 2011). The inexperienced staff on drilling vessel was a product of a new area in the gulf of Mexico where new rigs and vessels were being built and launched and needed personnel for operating new equipment and technology for operating wells that had not been drilled previously.

Given these circumstances it was very important that MMS performed inspections and certifications which ensured that the equipment used in the drilling operations was safe. An oversight in an inspection on the DWH rig on April 1st 2010 had led MMS not to discover any noncompliance or problems that would have forced a stop in the operations on DWH (Drilling, 2011). This oversight was that neither the BOP or diverter system had been recertified since 2000 (Drilling, 2011). MMS's policies required re-certification every 3 to 5 years (Drilling, 2011). This oversight may have been critical since the BOP failed to seal the well when the well blew out. Figure 4.6 represents the government regulatory agency level, which is the highest level analyzed.

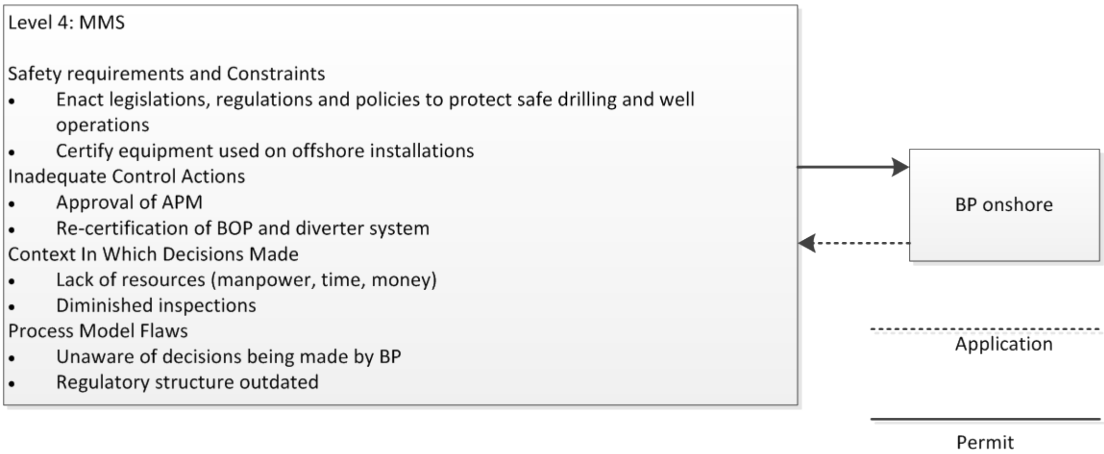

Figure 4. 6: Government regulatory agency level analysis.

Level 5 in the causal analysis was the Congress and Legislatures. For the purpose of this report the safety constraints enforced by this component in the safety structure has not been analyzed.

4.1.6 Step 7

Step 7 is the last step of CAST used in this thesis. Here the coordination and communication between the components in the safety control structure have been assembled, based on the results from steps 5 and 6, together in Figure 4.7.

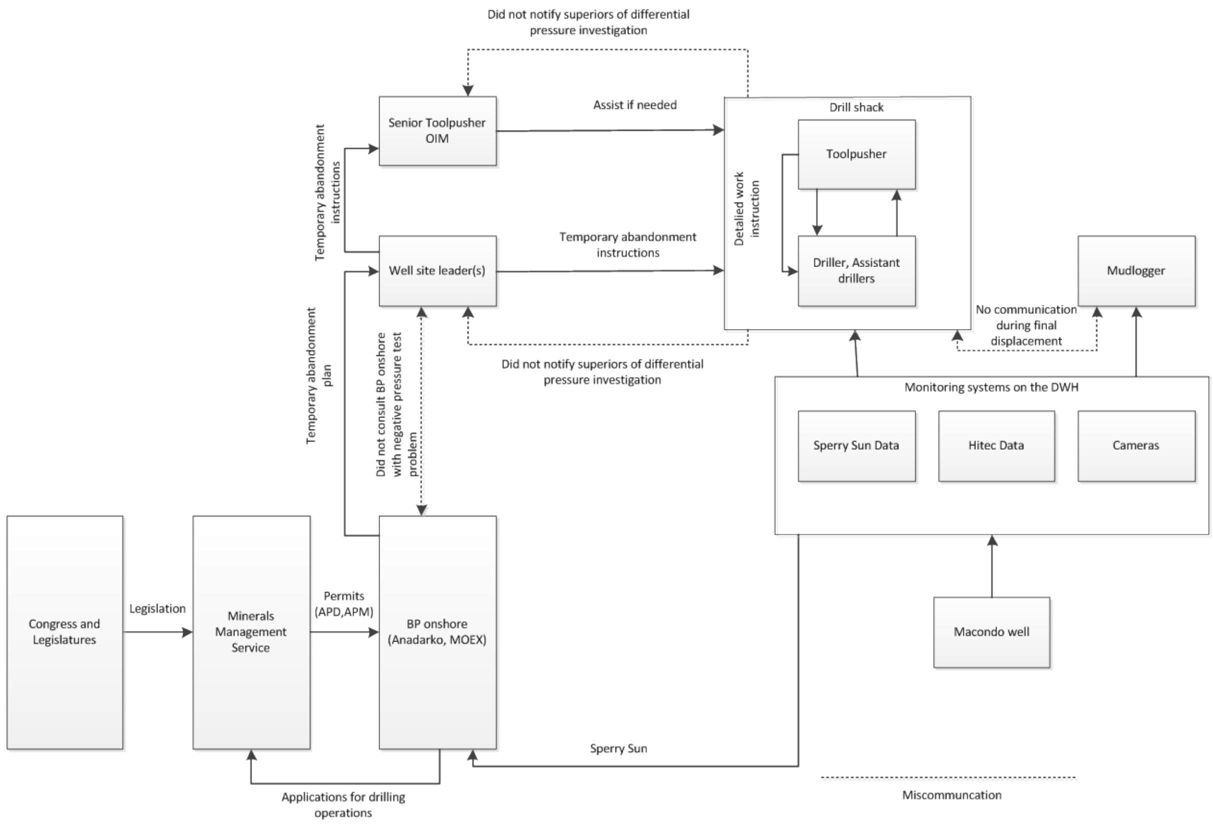

Figure 4. 7: Communication within the safety control structure at Macondo.

Arrows going from the top or bottom of the boxes represent communication, feedback. Arrows going into the left side of a box represents controls. Figure 4.7 focuses on the miscommunication between the parties during the temporary abandonment process, and therefore the communication arrows are limited to that.

Chapter 5

Assessment of the accident model

5.1 Suitability of STAMP for accident modeling

Systemic accident models have been developed as it has become evident that the sequential and epidemiological models are becoming outdated and obsolete. The sequential and epidemiological models have contributed to the understanding of accidents; however, they are not suitable to capture the complexities and dynamics of modern sociotechnical systems (Qureshi, 2008).

Common accident modeling is generally based on sequential- and epidemiological accident model approaches. These models are event based and inadequate at addressing non-linear relationships such as feedback and are currently being stretched to their limits (Leveson, 2004).
Most accident analyses do a good job of identifying the physical contributors to the event (Leveson, 2011). Based on the three basic concepts, safety constraints, hierarchical safety control structures and process models STAMP provides an overview that event based models are unable to generate.

While the physical control inadequacies are relatively easy to identify in the analysis and are usually handled well in any accident analysis, understanding why those physical failures or design inadequacies existed requires examining the higher levels of safety control (Leveson, 2011). Analyzing the Macondo blowout, using STAMP, reveals the non-linear interactions between components and addresses the systemic factors of the accident. In order to understand and prevent similar accidents the systemic approach uncovers several flaws that could lead to failure then only focusing on the one event.

Given that there were many inadequate actions by individuals on DWH, a simple accident analysis may easily point the blame to the physical system level operators of the Macondo well. Exploiting the accident using STAMP methodology reveals all of the correlating processes throughout the entire control structure contributing to the accident. As a great number of accident analysis place blame to quickly STAMP has been dedicated to more clearly specify the term “operator error”. The term does not provide any explanation as to why there was an operator error. Discovering why will in the end help in how we learn and eliminate “operator errors” in the future.

The models created in this thesis did not address the dynamics and migration of risk over time. Most major accidents result from a migration of the system toward reduced safety margins over time (Leveson, 2011). With this in mind it is easy to understand that the technology developments for deepwater drilling and deepwater drilling in general had reduced the safety margins considerably as MMS had not been able to follow this development with adequate regulations.

Accident models created in line with STAMP framework of the safety control structure in general and for the individual components can not only be used to identify why accidents occurred, but also contribute in the work of preventing future events. The models created in this thesis, using CAST, are meant to give the reader an overview of the operations and communications between the parties involved in the Macondo accident. For large scale accidents as the tragic Macondo well blowout a common event based analysis would be insufficient over time. Placing the blame and not fully understanding the reason for the accident will not eliminate future accidents.

5.2 Workload

It will be hard to assess the workload of an accident analysis and modeling based on the work done for this thesis alone. However being that STAMP is a systemic accident model for safety and accident analysis some assumptions can be made regarding the workload.

A systemic accident model is more complex and powerful than sequential- and epidemiological accident models (Hollnagel, 2004). This complexity and power requires vast amounts of information about the system surrounding the physical failure, hence modeling an accident with this approach requires more research and information than a sequential- and epidemiological model.

Analyzing a "whole" system also demands the analyst to have good oversight of the system in general and insight of specific processes. Making the analyst's task of processing the relevant information complicated. Information needed to perform an accident analysis or modeling based on STAMP is not always available, as common accident investigations do not gather the information required for an accident analysis based on STAMP. This because most accident investigations limit themselves to the physical system level of the accident and an accident analysis based on STAMP requires information of the higher system levels.

5.3 Results (Other directions)

This thesis has been based heavily on the Chief Counsel's Report and Report to the President of the Macondo well blowout. Being an accident of this magnitude causing such devastation a national commission was appointed by President Barack Obama to investigate the accident. The Final Report to the President was the commission's first report which stated that: The blowout was not the product of a series of aberrational decisions made by rogue industry or government officials that could not have been anticipated or expected to occur again (Drilling, 2011). The report stated that the root causes were systemic (Drilling, 2011). After the Final Report to the President the commission released its Chief Counsel's Report which was aimed at investigating the technical, managerial and regulatory causes more in detail than the first report (Drilling, 2011).

The national commission's reports were because of the magnitude of the accident very detailed and far beyond the physical system level of the accident. Taking into account all components in the system, as an analysis based on STAMP would have done. The amount of details in both reports show that the national commission went a long way to uncover the context and circumstances in which decisions were made of the parties involved at the Macondo well. As an independent entity the commission was not hindered by hindsight bias in its investigation stating that the reason for the accident was: systemic failures by industry management and also by failures of government to provide effective regulatory oversight of offshore drilling (Drilling, 2011).

The CAST analysis has not provided results that differ from the national commission's reports, but has merely been an attempt at utilizing the information provided by these reports to create models of the components involved in the accident.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

An inadequate cement job done in the bottomhole of the well and a BOP failing to seal a well may be the answer to what physically failed at the Macondo well, but it does not express what the parties involved at Macondo either physically present or onshore were doing to avoid an incident like this to happen. These parties either individuals, companies, regulatory agencies or the US congress & legislatures were all responsible for some of the operations at Macondo. The reason for stating this is not to assign blame, but to give a bigger picture of the accident as such. Drawing to the extreme one might say that everyone is in some way responsible as the global energy demand is increasing and a large part of this is supported by fossil fuels.

This statement can be viewed as futile, but to paint the picture as to what STAMP and CAST can provide to accident modeling we need to think differently. An accident occurs in a process, but the process is part of a bigger system. To be able to use systemic accident modeling approaches this way of thinking is essential.

Performing a CAST analysis uncovered how important the correct enforcement of safety constraints can be, as the result of violating the safety constraints was possibly the worst "man made" environmental disaster since the Chernobyl accident. While creating the models of the Macondo blowout it was frightening to discover just how inadequate the system operations were at controlling the safety of the well. The fact that MMS did not have a regulatory structure capable of enforcing safety for deepwater drilling operations reveals a lacking understanding of the severity of the process carried out. The fact that BP quite carelessly changed procedures after receiving permits may indicate that this had been going on for some time. Other than the fatalities, the tragedy is that the industry itself was shocked when the accident occurred. How could they be, considering how they operated? In more common accident analysis the lack of regulation and understanding would not be revealed.

6.2 Recommendations

Stated in the scope of the CAST analysis the purpose was to create models a system operations side of a sociotechnical system. In this case that system was the parties involved at the Macondo well.

The analysis was made with some limitations regarding what the extent of the analysis would and could cover. The models created did not cover operations prior to the temporary abandonment or after the first explosion on the DWH rig. Other limitations were to not go into detail of the onshore personnel and their actions, and to not discuss the congress and legislatures involvement in system operations in detail.

Work to be done in the future therefore will be to create bigger models and include additional components of the hierarchical safety control structure, which may include details on the already developed system operations side of the sociotechnical system or adding the system development side of the sociotechnical system.

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Appendix A

Abbreviations

AMF - Automated Mode Function
APD – Application for Permit to Drill
APM – Application for Permit to Modify
BOP – Blowout Preventer
BSR – Blind Shear Rams
CAST - Causal Analysis based on STAMP
CSR – Casing Shear Rams
DWH – Deepwater Horizon
EDS - Emergency Detachment System
LMRP - Lower Marine Riser Package
MMS - Minerals Management Service
OIM - Offshore Installations Manager
STAMP - Systems – Theoretic Accident Model and Process
VBR – Variable Bore Rams

Appendix B

Organizational chart of parties directly involved at Macondo

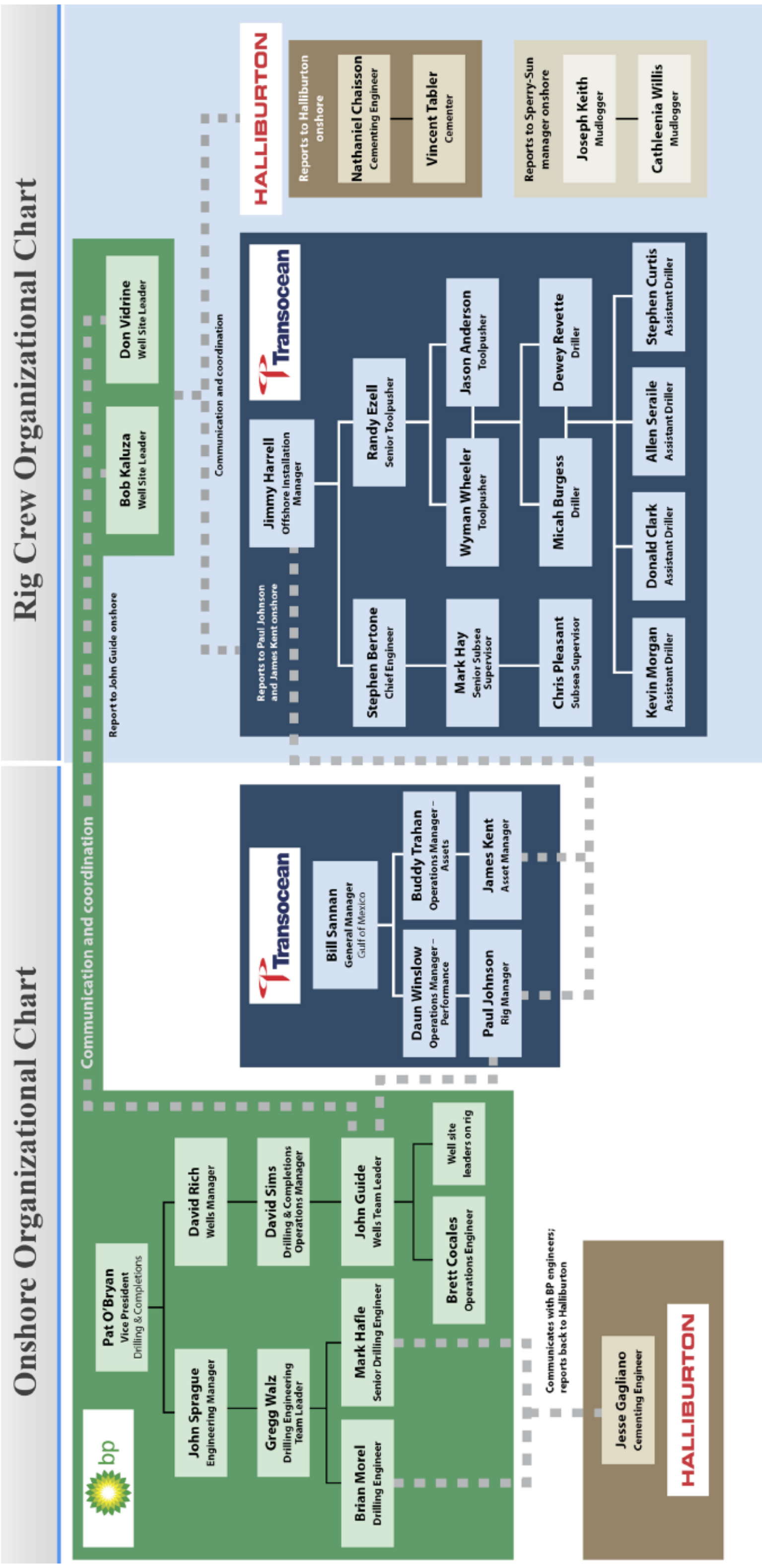

Figure B. 1: Parties directly involved at Macondo (Drilling, 2011).

Appendix C

Blowout Preventer - BOP

A blowout preventer (BOP) is defined in (API, 2006)as: A device attached to the casing head that allows the well to be sealed to confine the well fluids to the well bore.

The term BOP usually refers to a BOP stack, which in turn is defined as: The assembly of well control equipment including preventers, spools, valves and nipples connected to the top of the wellhead (API, 2006). The term BOP itself does not say anything about how to seal off a well, but in order to seal off a well the BOP stack has several different types of preventers that can seal of the well.

The drill crew used the BOP at Macondo during operations and for sealing off the well. The BOP sits on top of the wellhead, underneath the riser, and drilling equipment goes through it on the way into the well. The BOP used at Macondo consisted of two major parts and was controlled by electronic signals sent down from the DWH rig. The signals sent down went to the control pods on the BOP (upper). There were two pods on the BOP stack, where only one was used at a time, making the second control pod redundant.

The control pods controlled the annular preventers and rams installed in the BOP stack. These annular preventer and rams were either used to seal of the well or contain pressures inside the well. An annular preventer is a large rubber donut shaped element that expands inwards to seal of the well when activated. If a drill pipe is in the well when activated the annular preventer packs itself around the drill pipe.

As deployed on the sea floor, the Deepwater Horizon BOP stack consisted of an upper section known as the lower marine riser package (LMRP) and a lower section known as the BOP ram stack (lower BOP stack). Combined, the two sections formed the BOP stack.
The BOP system comprises individual BOPs (ram and annular) and the valves and piping (kill and choke lines) that are used to maintain control of pressure in a wellbore. The BOPs and valves are hydraulically operated. A typical BOP system for deepwater use has five to six ram-type preventers and one to two annular-type preventers: (BP, 2010)

- Variable bore rams (VBRs) are designed to close and seal around drill pipe.
- Blind shear rams (BSRs) are designed to close and seal the wellbore, shearing the drill pipe if it is present.
- Casing shear rams (CSRs) are designed to shear casing without sealing the wellbore.
- Annular preventers are positioned above ram preventers since they are not typically rated to working pressures as high as those of the ram preventers. Annular preventers are designed to close around a wide range of tubular sizes and can seal the wellbore if no pipe is present.

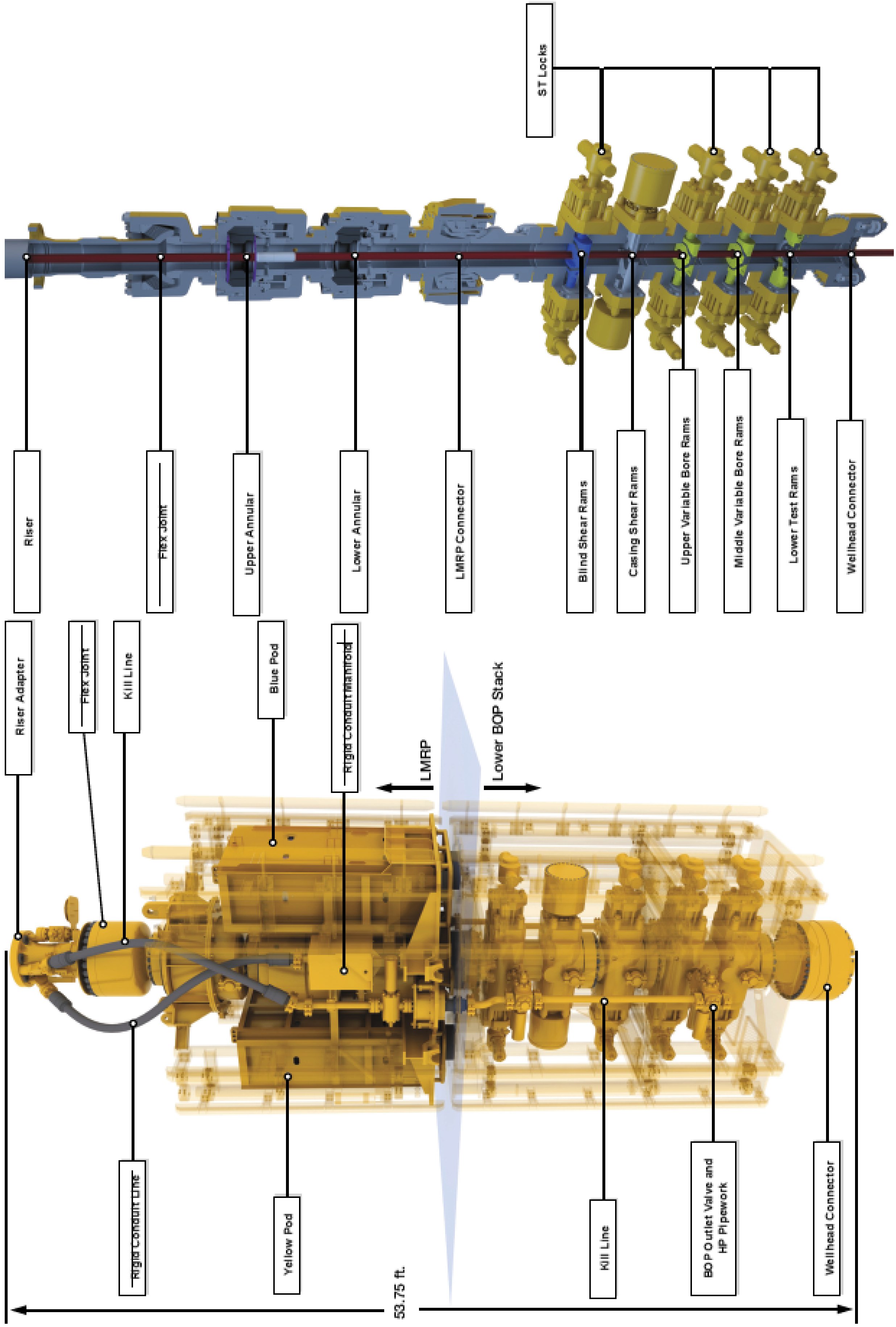

Figure C. 1: Blowout Preventer – BOP (Transocean, 2011).

APPENDIX D

Well Integrity Tests

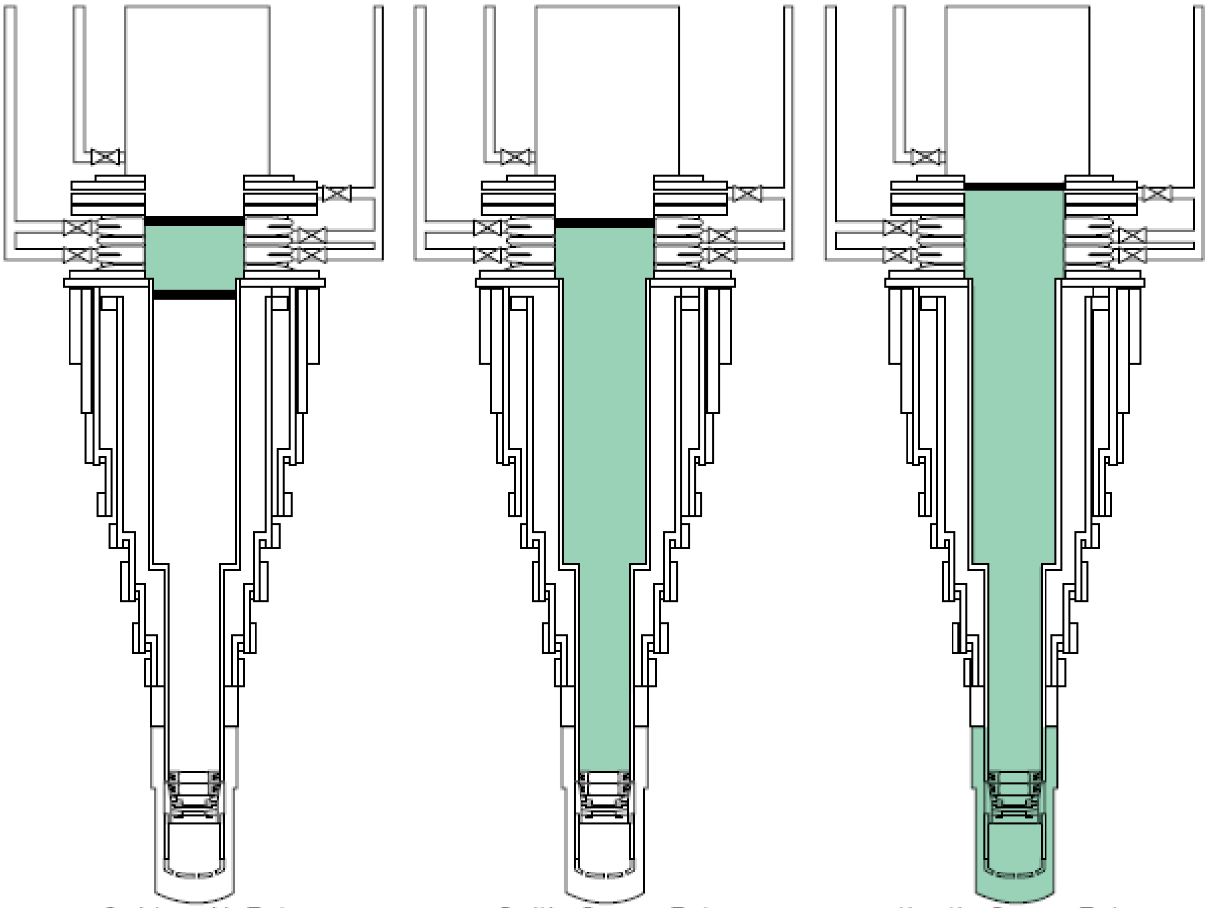

Figure D. 1: Well Integrity Tests (Drilling, 2011)

The colored area in Figure D.1 depicts the area sealed off and pressure tested during the three well integrity test.

Seal Assembly Test

Shortly explained the seal assembly test is performed to ensure that the casing hanger seal does not leak. The casing hanger hangs inside the wellhead and supports the production casing hanging from the wellhead and seals off the annular space outside the top of the casing. To test the seal between the wellhead and the casing hanger for leaks a plug (called a packer) is mounted on the bottom of the drill pipe and the plug is placed below the casing hanger. Above the casing hanger a variable bore ram in the BOP is closed and the area between the bore ram and plug is sealed off from the well. Symbolized by the green area in seal assembly test figure in Figure D.1, this area is then pumped with additional fluid to increase the pressure. The pressure is then monitored for a period of time, and if the pressure remains constant, the casing hanger seal is capable of handling high internal pressure (Drilling, 2011), meaning that it does not leak.

Positive Pressure Test

The objective of his test is similar to the seal assembly test, but for a larger area of the well. A positive pressure test is performed by removing the drill pipe in the wellbore, and then closing the blind shear rams (in the BOP). The blind shear rams separates the well from the riser, and allows the rig crew to conduct a positive pressure test on the entire well. Similar to the seal assembly test the crew pumps fluids into the sealed off well and monitors the pressure for a period of time. If the pressure remains constant it indicates that the casing inside the well is not leaking when the well is overbalanced, meaning that the pressure inside the well is higher than the pressure exerted on the well from the surrounding formations.

Negative Pressure Test

Briefly explained the negative pressure test checks for the integrity of the wells casing (as the Positive Pressure Test), and also to ensure that the bottomhole cement plug is intact and able to seal off the hydrocarbons in the "pay zone" located at the bottom of the well.

Appendix E

Proximal Event Chain

As a helpful guide in analyzing the accident an event chain of the actions and incidents prior to the accident has been made. STAMP states that this proximal event chain is created to give a superficial impression of what happened in in close proximity to the accident (Leveson, 2011).

The proximal event chain will start from when the operators of the Macondo well started preparing the temporary abandonment of the well. This would be their last operation on the Macondo well.

1. 1:01 a.m. – 2:47a.m. Two seal assembly pressure tests performed and both were successful
2. 5.45 a.m. , April 20 2010 Halliburton Company cementing engineer "We have completed the job and it went well"
3. 7.30 a.m. Operations conference call to BP in Houston, discussing the good news of the final cement job in the well.
4. 10:43 a.m. Drilling engineer Morel e-mail the temporary abandonment plans to the crew, also known as the Ops Note.
5. 11.00 a.m. Daily pre-tour meeting of the rig discussing the procedures from the Ops note. Schlumberger team and Morel left the rig by helicopter at 11:15 a.m.
6. 10.30 a.m. - Noon: Positive pressure test conducted to check well integrity. Blind shear ram locked, pressure pumped to 250 psi for 5 minutes, followed by pressure of 2500 psi for 30 min. Positive test confirmed no leak from fluids inside the well to the outside formation.
7. Noon – 5:00 p.m.: Drill pipe run into the well as part of preparation for negative pressure tests later in the evening. Displaced 3,300 feet of drilling mud in preparation for the negative pressure test and closed annular preventer.
8. 5.00 p.m. – 6:00 p.m.: Negative pressure test (Round 1);
    a. Pressure in kill line and drill pipe equalized to 1250 psi. After opening both valves kill line pressure went down to 645 psi, while drill pipe pressure went up to 1400 psi.
    b. First bleed off unable to bleed drill pipe pressure to 0 psi. Pressure bled to 260 psi and jumped back up to 1262 psi after closing the drill pipe valve.
    c. Fluid in riser decreasing. Riser refilled and annular preventer tightened.
    d. Second bleed of able to bleed drill pipe pressure down to 0 psi. Pressure jumped back up to 773 psi after closing the valve, and immediate bleed off was performed.
    e. Third attempt to bleed off the drill pipe pressure, but this time by using the kill line. Pressure in drill pipe almost bled to 0 psi, monitored for 30 to 40 minutes, as drill pipe pressure climbed up to 1400 psi.

9. 6.00 p.m. Discussing the Negative pressure test, while the crew changed shifts. 1400 psi in drill pipe explained by the "bladder effect"
10. 6:40 p.m. – 8:00 p.m.: Negative pressure test (Round 2);
    a. Moved test to kill line. Bled kill line to 0 psi, monitored for 30 minutes, no pressure build up. Pressure in drill pipe still 1400 psi, thought to be caused by the "bladder effect".
11. 8:00 p.m.: Negative pressure test a success.
12. 8:02 p.m.: Annular preventer opened (Well open) and displacing of mud and spacer in the riser. Preparation for the surface cement plug is initiated.
13. 9.00 p.m. : Relatively uneventful – Drill pipe pressure steadily decreasing
14. 9.01 p.m. : Pressure in Drill Pipe increasing (Pump rate remained constant) in a 7 minute span pressure went from 1250 psi to 1350 psi.
15. 9.08 p.m. : Pumps shut down to conduct "sheen test". A valve on the flow line carrying fluids to the pit system is closed. Sheen test on the returning spacer was conducted, while a visual flow check concluded there was no flow from well while pumps were off.
16. 9.08 – 9.14 p.m. : Downtime of pumps while Sheen test was conducted. Sheen test approved. While pumps were down the drill pipe pressure increased by 250 psi indicating a large anomaly (perhaps overlooked by the crew) and the restart of the pumps at 9.14 p.m. obscured the signal. Drill pipe pressure still rising.
17. Approx. 9.18 p.m.: A pressure release valve on one of the pumps blew. Crewmembers were sent to fix the problem.
18. 9.30 p.m. : the odd pressure difference between the kill line and drill pipe noticed. Pumps shut off to investigate (reports that the surface cement plug would be delayed).
    a. Drill pipe pressure decreased after pumps were shut off, but increased by 550 psi in 5.5 minutes. Pressure on kill line remained significantly lower.
19. 9.36 p.m. : Bleed off the drill pipe to eliminate difference between kill line and drill pipe. Pressure dropped, but began climbing again (No visual flow check performed or shut down of well)
20. 9.39 p.m. : Drill pipe pressure decreasing (bad sign)
21. 9.40 p.m. – 9.43 p.m. : Mud begins spewing from the rotary onto the rig floor. Firs evidence of the crew realizing the kick. Actions:
    b. Routing of the flow from the riser to the diverter system, and to the mud-gas separator (not directly into the sea)
    c. Closed one of the annular preventers on the BOP to seal in the well.
22. 9.45 p.m. : Reports of the well blowing out. Actions to shut down the well are too late. Hydrocarbons have passed the BOP and are expanding up the riser, and overwhelming the mud-gas separator.
23. 9.46 p.m. : Activated variable bore ram
24. 9.49 p.m. : First explosion on the drilling floor

25. As the blowout becomes evident the crew tries to engage the Emergency Detachment System (EDS). Some confusion of its deployment as lights indicated that separation is complete, but it becomes evident that the EDS has failed. “Deadman” system of the BOP fails.

Appendix F

Monitoring techniques and equipment

Principles of well control
Formation flow during drilling and well servicing operations is generally referred to as a "kick". Formation fluid that flows into the well bore is referred to as "well influx". If not controlled, a kick may result in a blowout. Well control procedures are intended to safely prevent or handle kicks and re-establish primary well control. – (API, 2006)

- **Primary well control:** Prevention of formation fluid flow by maintaining a hydrostatic pressure equal to or greater than formation pressure – (API, 2006)

In this Appendix some general used techniques used for well control on an offshore oil and gas well will be presented, along with the techniques and equipment used at the Macondo well. The source for this has been taken from Chief Counsel's Report.

Equipment at the Macondo well
The DWH had two separate monitoring systems on the rig. The internal Hitec system which would only be available for the personnel on the rig, and the Sperry Sun system installed by Sperry Drilling on behalf of BP, which would be displayed for the onshore personnel as well as the personnel on the rig. Sharing some of the sensors the Hitec and Sperry Sun systems would have similar numerical values, or could easily be calculated to match each other. After the accident the only data available for the investigator have been the Sperry Sun data, since the Hitec logs were lost together with the rig.

The Hitec system had been deemed satisfactory in a rig condition assessment recorded on April 12, 2010 and there is no evidence that the Sperry Sun system had malfunctioned either at the time of the accident (Drilling, 2011).

There were also cameras in key areas on the DWH giving the crew a visual display of important parts on the rig. The most important ones were the cameras monitoring the flow line, which would be used for flow checks when the pumps were shut down. The flow line camera was placed overlooking the pits on the drilling rig, so if the flow was directed overboard (using the diverters) the crew would have to physically perform the flow check (Drilling, 2011).

Monitoring techniques and the Deepwater Horizon

The main safety tasks at Macondo during the temporary abandonment procedure were to detect and monitor pre-kick signals, identify kicks and respond to a well control situation where the well was experiencing well influx. In order to do so the parties involved at Macondo had several techniques and monitoring equipment.

Some of the important parameters monitored at Macondo well were pit gain or loss, flow-in versus flow-out and drill pipe pressure.

Pit gain or loss

Monitoring the volumetric gain or loss of a pit is important in ensuring that well is stable. The volume of the fluid pumped into the well should be equal to the volume the pit receives in return. The easiest way making volumetric comparisons of flow- in and flow-out of a well is by using a single pit (Drilling, 2011), known as single-pit monitoring. This is not always possible since many operations use several different fluids in their well operations and these will most desirably be kept separate when on the rig. If this is the case an active pit system may be used where all the different pits are monitored by aggregating their volumes into one pit by using computers (Drilling, 2011). The same rules apply for the single pit system and active pit system, which is that volume in should equal volume out.

Pit gains are kick indications when monitoring the pits, while a pit loss may indicate a formation fracture (API, 2006).

For monitoring the pits the easiest way of doing it is by using the fluids from the pits monitored as volume in and the volume of the fluids out as returned to the active pits, keeping the system in a closed loop (Drilling, 2011).

However pits are often bypassed by not taking fluids from the pits on the rig or not returned to the pits on the rig, creating non-closed-loop systems. E.g. if the crew uses seawater as the fluids sent into the well directly from the sea, now the crew must perform calculations (pump strokes x volume per pump stroke) in order to estimate the volume of the flow-in, since in this case the pits will gain in volume continuously even if the well is stable (Drilling, 2011). It becomes even tougher if the fluids flowing out of the well are directed straight overboard, using the diverters (Drilling, 2011). Using the diverter makes it often impossible to monitor the volume of the flow out (Drilling, 2011).

A rig like the DWH used several different fluids (seawater, mud, spacer) during the temporary abandonment, where the fluids are kept in separate pits on the rig, an active pit system is the most appropriate monitoring technique in this case. The DWH therefore did use an active pit system during their temporary abandonment.

Flow-in versus flow-out

Another way of monitoring flow-in vs. the flow-out of a well is to monitor the rate of the flow instead of the volume. The flow rate of flow-in (pump rate x volume per pump stroke) is easy to calculate and has only a small margin of error (Drilling, 2011).
Flow-out is generally monitored by sensors in the flow line coming from the well. It is a less reliable measure since it relies heavily on the quality of the sensors registering the flow-out rate (Drilling, 2011).

The rule for rate comparison of flow-in vs. flow-out is the same as for the pit monitoring: If the well is stable, flow-in and flow-out should be equal (Drilling, 2011). The easiest time to perform a rate comparison is when a rig has shut of its pumps, not pumping fluids into the well (Drilling, 2011). In other words the flow-out rate at this point should be zero. To check

the flow-out is zero the DWH rig could use its sensors in the flow line, but it could also perform visual flow checks of the flow line, either by cameras or by physically checking the flow line.
A flow at this point may indicate several things, but one of the things it may indicate is a kick and regardless of what the cause is an investigation is warranted (Drilling, 2011).

It should be noted that there will be some flow after the pumps have shut off even if the well is stable. This is called the “residual flow” and it will continue for a short time after the pumps have stopped. Depending on the rig each rig has its own “signature” flow-out pattern after the pumps have stopped that shall be documented and compared to the residual flow when the pumps stop (API, 2006). A residual flow may last for several minutes and it is only after the signature flow-out has stopped (or should have stopped) that it can be verified if there is no flow (Drilling, 2011).

Drill pipe pressure
Drill pipe pressure is a measurement of the pressure exerted by the fluids inside the drill pipe (Drilling, 2011) If the pumps on the rig are shut off there should be no movement in the well and the pressure will therefore be constant. As for the temporary abandonment at Macondo the DWH's drill pipe pressure would be positive at first since the fluids on the outside (mud) was heavier than that on the inside of the drill pipe (spacer, seawater). As lighter fluids are pumped down to displace heavier fluids in the well the drill pipe pressure will decrease.

If the pressure increases in the drill pipe it may indicate a kick, but also be result of a clog in the drill pipe or wrong fluids pumped into the well. The clearest indicator of a kick by monitoring the drill pipe pressure is if the pressure suddenly falls, as this may indicate that lighter fluids such as oil and gas have flowed in and around the drill pipe (Drilling, 2011). It is hard to detect a kick by the drill pipe, but sudden changes in pressure should warrant an investigation (Drilling, 2011)