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Analysing Complex Oil Well Problems through Case-Based Reasoning

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Abstract

The history of oil well engineering applications has revealed that the frequent operational problems are still common in oil well practice. Well blowouts, stuck pipes, well leakages are examples of the repeated problems in the oil well engineering industry. The main reason why these unwanted problems are unavoidable can be the complexity and uncertainties of the oil well processes. Unforeseen problems happen again and again, because they are not fully predictable, which could be due to lack of sufficient data or improper modelling to simulate the real conditions in the process. Traditional mathematical models have not been able to totally eliminate unwanted oil well problems because of the many involved simplifications, uncertainties, and incomplete information. This research work proposes a new approach and breakthrough for overcoming these challenges. The main objective of this study is merging two scientific fields; artificial intelligence and petroleum engineering in order to implement a new methodology.

Case-Based Reasoning (CBR) and Model-Based Reasoning (MBR), two branches of the artificial intelligence science, are applied for solving complex oil well problems. There are many CBR and MBR modelling tools which are generally used for different applications for implementing and demonstrating CBR and MBR methodologies; however, in this study, the Creek system which combines CBR and MBR has been utilized as a framework. One specific challenging task related to oil well engineering has been selected to exemplify and examine the methodology. To select a correct candidate for this application was a challenging step by itself. After testing many different issues in the oil well engineering, a well integrity issue has been chosen for the context. Thus, 18 leaking wells, production and injection wells, from three different oil fields have been analysed in depth. Then, they have been encoded and stored as cases in an ontology model given the name Wellogy.

The challenges related to well integrity issues are a growing concern. Many oil wells have been reported with annulus gas leaks (called internal leaks) on the Norwegian Continental Shelf (NCS) area. Interventions to repair the leaking wells or closing and abandoning wells have led to: high operating cost, low overall oil recovery, and in some cases unsafe operation. The reasons why leakages occur can be different, and finding the causes is a very complex task. For gas lift and gas injection wells the integrity of the well is often compromised. As the pressure of the hydrocarbon reserves decreases, particularly in mature fields, the need for boosting increases. Gas is injected into the well either to lift the oil in the production well or to maintain pressure in the reservoir from the injection well. The challenge is that this gas can lead to breakdown of the well integrity and cause leakages. However, as there are many types of leakages that can occur and due to their complexity it can be hard to find the cause or causal relationships. For this purpose, a new methodology, the Creek tool, which combines CBR and MBR is applied to investigate the reasons for the leakages. Creek is basically a CBR system, but it also includes MBR methods.

In addition to the well integrity cases, two complex cases (knowledge-rich cases) within oil well engineering have also been studied and analysed through the research work which is part of the PhD. The goal here is to show how the knowledge stored in two cases can be extracted for the CBR application.

A model comprising general knowledge (well-known rules and theories) and specific knowledge (stored in cases) has been developed. The results of the Wellogy model show that the CBR methodology can automate reasoning in addition to human reasoning through solving complex and repeated oil well problems. Moreover, the methodology showed that the valuable knowledge gained through the solved cases can be sustained and whenever it is needed, it can be retrieved and reused. The model has been verified for unsolved cases by evaluating case-matching results. The model gives elaborated explanations of the unsolved cases through the building of causal relationships. The model also facilitates knowledge acquisition and learning curves through its growing case base.

The study showed that building a CBR model is a rather time-consuming process due to four reasons:

1. Finding appropriate cases for the CBR application is not straightforward
2. Challenges related to constructing cases when transforming reported information to symbolic entities
3. Lack of defined criteria for amount of information (number of findings) for cases
4. Incomplete data and information to fully describe problems of the cases at the knowledge level

In this study only 12 solved cases (knowledge-rich cases) have been built in the Wellogy model. More cases (typically hundreds for knowledge-lean cases and around 50 for knowledge-rich cases) would be required to have a robust and efficient CBR model. As the CBR methodology is a new approach for solving complex oil well problems (research and development phase), additional research work is necessary for both areas, i.e. developing CBR frameworks (user interfaces) and building CBR models (core of CBR). Feasibility studies should be performed for implemented CBR models in order to use them in real oil field operations. So far, the existing Wellogy model has showed some benefits in terms of; representing the knowledge of leaking well cases in the form of an ontology, retrieving solved cases, and reusing pervious cases.

Contents

1. Introduction

1.1 Background and motivation

In the domain of oil well engineering, there are many problems that are difficult to solve purely by traditional analytical or numerical approaches due to many uncertainties as well as numerous simplifications and assumptions. In spite of remarkable advances in computing technology, many businesses are still struggling with the problem of modelling and accessing data. Particularly, problems related to drilling and oil well technologies are not fully solved in spite of long-term activity and a fairly large amount of experience and data. Catastrophic blowouts of formation fluids (water, gas, oil) have not been eliminated in drilling practice. Less dramatic and more common events like stuck pipes, drillstring washouts or mud losses are still common drilling problems. For example, the industry usually plans for 5 -10 % of the total drilling time as contingency for problems related to the well instability (Fære et al., 2002). Well leakages during the life of the well are another example within the petroleum industry which is not fully understood in order to prevent in future wells (Abdollahi et al., 2006). Low oil production rates and poor well performance in the many mature oil fields are challenging tasks (Abdollahi et al., 2004). All of these examples from the oil industry have a nature of surprise and uncertainly, as they involve; formation rock, personnel, equipment, tools and other factors. There are many causal connections which can point to oil well problems, and the combined effects can be complex. This requires a huge amount of time to go through many documents.

Although there are vast databases in each oil company for systemizing, analysing and transforming the data can still be improved to extract more information and knowledge. Also some drilling and well data are measured indirectly and therefore can be inconsistent. Most of the data are used for statistic application without creating reasoning to extract and expand the body of knowledge. There are plentiful and valuable knowledge hidden behind the data. Human reasoning is needed to translate data to information and information to the knowledge. Moreover, the valuable experience gained through the cases is generally not stored or systemized in order to reuse in the future situations. Knowledge is also lost when experienced people leave the companies.
The goal here is to find a method to re-use experience from past cases to solve new complex problems in oil wells where the traditional mathematical and simulation techniques are not capable of solving those challenges alone. This method should extract stored and hidden knowledge from the cases and incorporate it with the existing knowledge for added value. This method should also be able to transfer and maintain valuable experience gained through the problems in the past. Therefore, in addition to the existing computing tools or databases, a knowledge-based approach is needed in order to be able to reuse the experience and lessons learned from real cases.

1.2 Methodology

Case-Based Reasoning (CBR) is a recent approach to knowledge-based problem solving. CBR is like case mining which enables reasoning based on similar solved problems in the past. So a new problem is solved by remembering one or more similar previously solved problems. The strength of CBR is adapting previous solutions for new problems in a domain which is not well understood. CBR methodology is not only considered as a problem-solver tool; CBR can also maintain the knowledge and enable sustained learning. The previous problems or past experience; both failures and successes, are encoded as cases, each containing features that are characteristic of the problem and its solution. Cases may contain specific knowledge, i.e. knowledge which is not common and well known or even has not been fully proven. Obviously it is more efficient to use specific knowledge than the use of general knowledge (well-known knowledge like the concepts behind equations and formulas). This is valid for drilling and well problems in the petroleum industry which needs both types of knowledge; general and specific. Therefore, in addition to pure CBR one requires another method to deal with general knowledge for representing the causal rules. In artificial intelligence, Model-Based Reasoning (MBR) refers to a method used in expert systems based on a model of the physical system. The MBR method is used for modelling the causal relationship based on general knowledge (rules).

The main reasons why combined CBR and MBR approaches have been selected as the methodology for this study are:

1. The vast scope of the petroleum industry (particularly, drilling and oil well engineering problems) is too complex to be described analytically
2. Huge amounts of data
3. The most of the drilling and oil well cases contain specific knowledge which are valuable to maintain and reuse in new situations
4. Traditionally people solve problems by human reasoning in oil well engineering, so by incorporating machine reasoning (CBR / MBR) in this context this gives added value to human reasoning
5. Recalling the best practice gained by previous cases either for problem-solving or learning purposes
6. CBR and MBR can maintain and reuse the knowledge that has been acquired
7. This methodology has only been used in the petroleum industry to a small extent (new area for the research)

1.3 Thesis objectives

This thesis presents research work which combines two different sciences; information technology (IT) and petroleum engineering. The idea is to apply and evaluate the new methodology or approach from IT for solving complex problems from petroleum engineering. Both these disciplines are fairly extensive, so the attention has been paid to specific methods and tasks.

The goal here is to evaluate a CBR tool for specific problem areas within the petroleum industry. The CBR tool that is used is called the Creek system which is of the type research software. The Creek system has been developed by the Department of Computer and Information Science at the Norwegian University of Science and

Technology (NTNU) in Trondheim. This program is in a research and development phase (R&D) and is not yet fully commercialized as a tool. Therefore, this thesis exemplifies and tests this new method for petroleum applications. This is a rather recent approach and only few related pieces of works have been published in the petroleum community (Skalle et al., 1998), (Skalle et al., 2000), (Skalle and Aamodt, 2004) and (Irrang et al., 1999).

One of the main challenges found during this study is the selection of appropriate cases for the CBR methodology. During the study it was found that the cases which are valuable for CBR need to be studied in depth by means of human-reasoning before implementation into the CBR system. The cases that we use in the Creek system are specific cases which need specific data. They are rich in knowledge with a complex structure; they are not simple cases such as mere data records. Three projects have been implemented as part of this PhD study:

- Well integrity study on three oil fields in the Norwegian Continental Shelf (NCS)
- Field development study in one of the Iranian oil fields
- One specific drilling problem study in another Iranian oil field

The first objective is to extract knowledge through the three research projects by human reasoning. The result will be a conceptual level model, in textual form this is referred to as a knowledge-level model. The second objective will be to implement and test CBR methodology for the transfer and reuse of specific complex drilling and well problems. The result will be a formalized model that is interpretable by the computer, referred to as a symbol-level model. This methodology explains how to create a general knowledge hierarchy (ontology) and transforming *cases* from text-level to symbolic-level to use in CBR system. The combination of cases and ontology will be demonstrated in the Creek system (as a framework) and results will be discussed.

The main steps to reach these objectives are:

- Performing *human reasoning* for complex cases through three research projects
- Modelling and formulating cases
    - Constructing a knowledge-level model through the case (ontology)
    - Transforming knowledge-level to symbolic level (formalizing cases)
- Demonstrating the model through the Creek knowledge editor
- Discussing the value of CBR

1.4 Thesis content

Initially, the subject of the PhD project was defined as “Optimization of Underbalanced Drilling (UBD) Methodology”. Later on, due to the lack of UBD data which was required as a starting point from the oil companies, the direction of the PhD work was shifted to CBR application in oil well engineering. This idea was initiated by my supervisor, Pål Skalle, and co-supervisor, Agnar Aamodt. Much of the time was spent to understand and test the CBR system used in this thesis (Creek system) with different simple examples in the oil well engineering such as, stuck pipe incidents, mud loss incidents, UBD cases, low rate of penetration (ROP) cases. Most of these examples were built and tested in Creek to understand the mechanisms involved in the CBR processes. These examinations have not been included in this PhD thesis. As the goal was to use complex oil well problems of real fields, in parallel to testing CBR, defined projects by the industry were studied. The objects of these projects were; 1) to describe and define the complexity of the cases 2) to transfer the project study from knowledge-level (written text) to symbolic-level (codes for input in the CBR system). For these purposes three research projects have been done during the study which are presented in this thesis. The main project which is given in both *knowledge-level* and *symbolic-level* descriptions, is "Well Integrity Study" which has been performed for Norsk Hydro. The second research study (SPE paper I, is presented in Appendix B) is related to the concept of field candidate selection for UBD application. This study is only included in this thesis at the *knowledge level*. The third research project (SPE paper II, is presented in Appendix C) and is about a specific drilling problem in which it is difficult to understand the causal relationships related to the failure (drillstring washout). This work is also included in this thesis at the *knowledge level*.

This thesis is divided into 6 chapters and 4 appendices:

Chapter 1 gives an overview to the motivation and thesis objectives, and it introduces the proposed methodology used in this study. Chapter 2 discuses the concepts of the CBR methodology in general terms, and the Creek system as an implementation tool used in this thesis. This chapter also addresses the CBR application in the oil well engineering domain. Chapter 3 describes well integrity issues as a selected topic to exemplify and test Creek as a CBR methodology. Chapter 4 demonstrates the modelling of the well integrity issues in the Wellogy model, and the results that are obtained are discussed. Chapter 5 presents the complex cases studied in terms of *knowledge-level* descriptions and explains how the case can be derived based on the different types of data sources, i.e., research work-based, paper-based, and data-based. Chapter 6 gives discussions about application of the CBR method in petroleum engineering and future improvements. The descriptions of modelled cases used in the Wellogy are given in Appendix A and the two SPE publications are included in Appendices B and C.

Appendix D is a poster prepared and presented at the SPE 2006 Forum Series I and II in Dubrovnik on "*Low Cost Reservoir Access and Intervention*" and "*From Casing Design to Well Life Prediction*?" The poster summarises topics covered in different research projects at SINTEF and NTNU and is related to maintained well integrity for different operations and situations during a lifecycle of a well (Nordskag et al., 2006). The project work was done for Petroleum Safety Authority Norway (PTIL) and Statoil.

2. Theory of CBR

2.1 Case-Based Reasoning

Case-Based Reasoning (CBR) is a process to solve problems by adapting the solutions that were used to solve old problems (Reisbeck and Schank, 1989). A driller who makes an oil well by remembering the previous solution to a stuck pipe problem and adopts that solution to the new stuck pipe is using CBR. In fact, in our daily lives we frequently use reasoning from past experiences to solve problems.

In the CBR process, the experiences gained through the previous cases are stored and merged with the general knowledge (some general rules and theories) for solving the new problem. CBR is also an approach for sustaining learning incrementally since a new experience is retained in the case-base or memory (Aamodt and Plaza, 1994).

The general structure of a CBR system is shown in ***Figure 2.1***. Here the general knowledge will be a basis for many solved cases and all together build a model for a CBR system. A new unsolved case is introduced into the model, and a new solution will be retrieved. A CBR system is able to read the unsolved case (as input data), and it retrieves the best similar solved case (as output data). The solution of the solved case will be suggested and approved for the unsolved case and a new solution will be derived. The new solution can be used directly in the new problem, or modified according to the differences between the input and output cases.

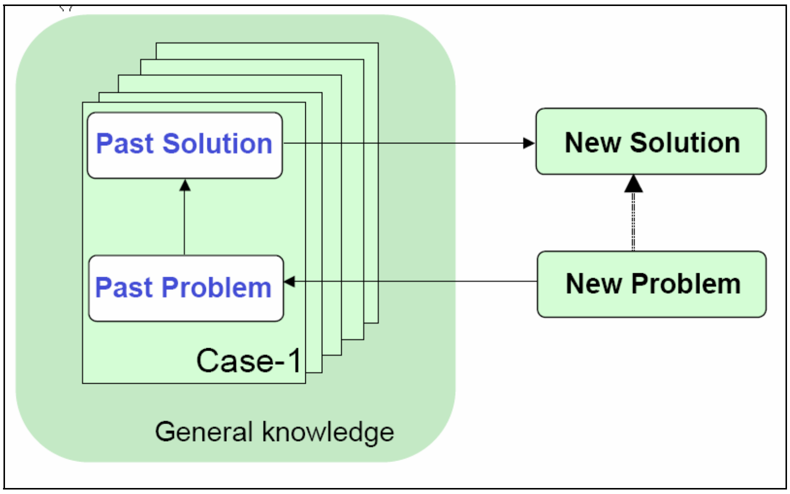


Figure 2.1 A simple schematic for a CBR system[1].

CBR should not be seen as a database, it is more like a knowledge base. Databases normally contain digital numbers, symbols, and characters. The data need to be transferred to pieces of information. The processed or learned information is called knowledge (Aamodt, 2004). For clarification, an example is given in ***Table 2.1***.

Footnote 1: This figure was taken from Aamodt's lecture notes, NTNU, 2004.

Table 2.1 **Typical examples showing how data are transferred to information and information to knowledge.**

Data	Information	Knowledge
1.1 s.g.	Low mud density	Low mud density leads to hole collapse
100 bar	Low pore pressure	Low pore pressure causes mud loss
61 $	High oil price	High oil price causes more drilling activity

In the CBR process, the knowledge is acquired and captured from the cases (specific knowledge) and merged with general knowledge. The combined knowledge is sustained and organized in a memory to reuse it for the new problems when needed. When the new case is solved it will be added to the case base. In this way the body of knowledge will be expanded.

CBR itself is a generic framework and it can be used for different applications where the domain has uncertainties and incomplete information. The core of CBR is a structural model which it deals with the problem domain.

2.1.1 History

The concept of CBR has a relatively young history from about 1977 (Pal and Shui, 2004). The original work related to CBR is widely referred to Schank and Abelson, (1977) at Yale. They proposed CBR as a tool for memory organization to store previous situations (cases) for both problem solving and learning purposes (Schank, 1982). From that time, the CBR activities have increased not only at the research level but also as applications in different areas. Aamodt and Palaz (Aamodt and Plaza, 1994) gave a philosophical basis for CBR methodology.

SYRUS was the first CBR system developed by Kolodner, (1993) which was used to store and retrieve events in the life of Cyrus Vance, who was then Secretary of State of the United States. Later on, many CBR systems have been developed for different applications. For example, HYPO was developed as a case-based interpretive program in the domain of law (Ashley, 1990) and (Ashley and Rissland, 1988). CASEY (Koton, 1989) and PROTOS (Bareiss, 1988) are other CBR systems which are used in medicine domain and auditory diseases respectively. Other early CBR systems can be found in Kolodner, 1993. Regardless of which systems are used, CBR can be used in different applications, mostly for open theory or weak domains. An open domain is one which cannot be realistically modelled, and a weak theory domain is one with uncertainty between the important concepts in the domain (Aamodt, 1994(a)). Different applications can be modelled by the CBR approach. These applications are; “CBR-planner”, “CBR-designer”, “CBR-diagnosis program”, “CBR-interpretive program”, “CBR-problem solver” (Kolodner, 1993).

CBR research is spread all over the world; several workshops regarding CBR have been held in Europe; for instance, (CBR-91, 1991), (EWCBR-93, 1993). Similar CBR activities in Asian countries have been running with the different approaches as for example in India (Venkatamaran et al., 1993) and Japan (Kitano, 1993). Currently the CBR activities are spreading out worldwide and there are trends towards increasing the applications of CBR.

2.1.2 Model-based reasoning

Model-based reasoning (MBR) is another concept in artificial intelligence and is part of reasoning methods. In MBR, knowledge is represented using "*causal rules*" based on some general rules or theories. MBR is designed for domains which are fully understood (strong theory domains); in contrast, CBR is designed for weak theory domains (Kolodner, 1993). MBR deals with the tasks which have large general knowledge, whereas CBR emphasizes the cases more.

Some CBR systems deal with the integration of CBR and MBR. The first CBR system which emphasized integrating general domain knowledge (MBR) and specific case knowledge (CBR) was PROTOS (Bareiss, 1989). Another is the Creek system (Aamodt, 1991). This integration of CBR and MBR has been defined as "knowledge-intensive" which assumes that cases are enriched with general knowledge (Aamodt, 2004).

2.1.3 CBR process

CBR can be considered as a machine which reads a new unsolved case, matches it with the many solved cases which have been stored previously in the machine memory and retrieves the most similar solved case. Therefore, the output of the machine is a proposed solution to the new unsolved case. A simple schematic for the CBR process is shown in ***Figure 2.2***.

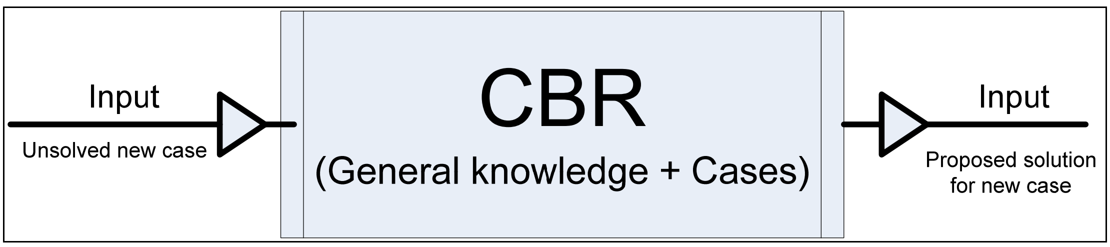


Figure 2.2 An illustration showing functionality of CBR.

The CBR machine can only contain cases without general knowledge (i.e. rules and theories). Such a case-base will be poor in the knowledge, and the assessment of similarity between unsolved and solved cases will be a simple process, just one by one attributes matching. On the other hand, the CBR model can be knowledge-rich and integrates general knowledge (theories and models) and cases. This type of CBR model is called the knowledge-intensive CBR model (Aamodt, 2004). Such a model will be implemented in this study.

Whether the CBR model is lean or rich in knowledge, the CBR process can be explained in different steps within what is called the CBR cycle. Aamodt and Plaza introduced four steps for the CBR cycle as illustrated in ***Figure 2.3*** (Aamodt and Plaza, 1994). These processes are:

1. Retrieving the most similar previously solved cases
2. Reusing the retrieved cases by copying or integrating the proposed solution
3. Revising or adapting the proposed solution
4. Retaining the new generated solution for future uses

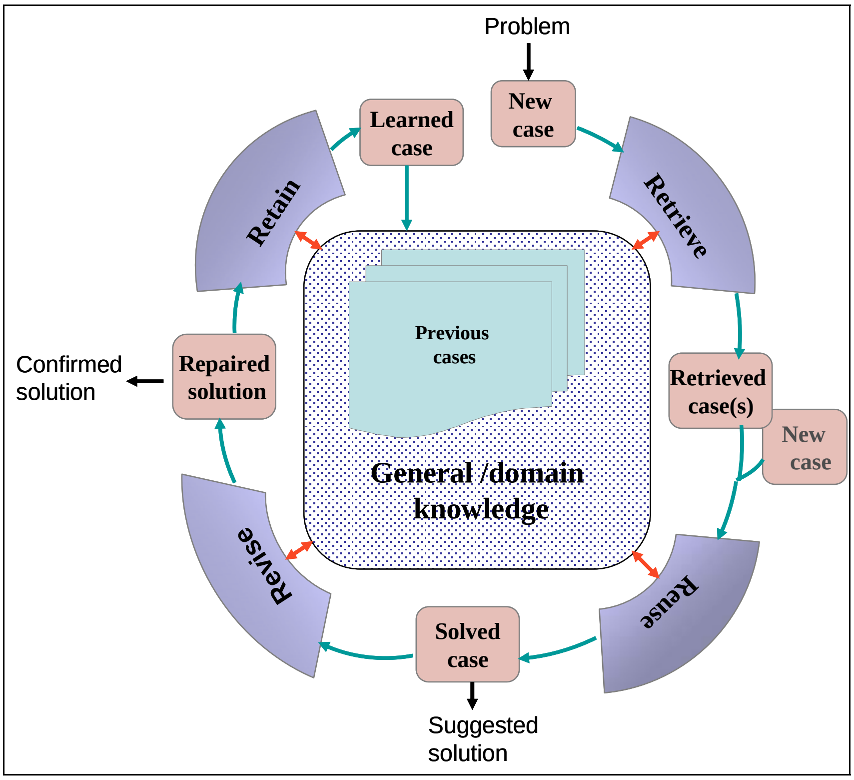


Figure 2.3 Cyclic process of CBR (from (Aamodt and Plaza, 1994)).

Figure 2.3 has been referred to and used in most of the CBR articles and papers. The detailed discussions and explanations for each step is given in this reference (Aamodt and Plaza, 1994).

However, the main challenge is how to build and implement an engineering domain by applying CBR-MBR approaches. Aamodt and Plaza, 1994, sorted these challenges into the five areas:

- Knowledge representation
- Retrieval methods
- Reuse methods
- Revise methods
- Retain methods

These challenges have been explained in detail in the book by Kolodner (Kolodner, 1993).

The first step in building a CBR model is the "*Representation of Cases*" as well as knowledge. This means how to define and describe the cases in the model in order to recall and reuse them for reasoning. The main challenges for case representation are:

- Searching and matching process for cases
- Integrating new cases in the existing memory (model)
- Type of data which should be stored in cases, qualitatively and quantitatively
- Organizing and indexing cases for effective retrieval and reuse
- Integrating cases with the general domain knowledge

In the retrieval step (first step), the closest similar solved cases are matched and retrieved. This step has been subdivided into three sub-steps; identify features, initially match, search and select executed in that order. Both solved and unsolved cases are defined the CBR model as a set of descriptors (features), CBR systems should identify features of cases either by *syntactical similarities* (superficial) or *semantical similarities*. For example, the CYRUS and ARC systems perform *syntactical similarities,* while PROTOS and Creek perform *semantical similarities* (Aamodt and Plaza, 1994). In Creek the CBR process has an *explanation engine* as a support for CBR processes to explain the reasoning (through the CBR processes) for the user or giving internal explanation that the CBR system may created during reaching the goal of the reasoning tasks. This engine has three subtasks: **activate-explain-focus** (Aamodt, 1994a). These subtasks are illustrated in ***Figure 2.4***. They have initial state description (input) and finial state description (output). **Activate**: making active the related features or concepts of the cases within the network knowledge structure (ontology). **Explain**: creating and explaining of derived information within the activated knowledge (from last step). **Focus**: focusing and selecting a conclusion which satisfies the goal.

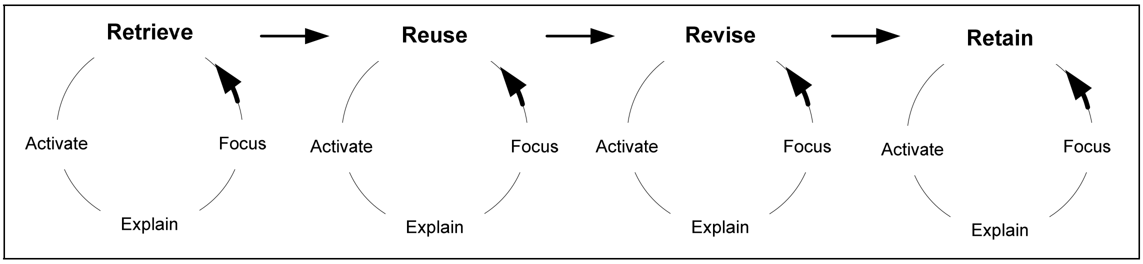


Figure 2.4 The CBR process and the explanation engine (Aamodt, 1994).

In the Reuse step, the focus is on the retrieved case solution for the new case in terms of similarities and differences of attributes of the two cases (input & output), and the system tries to select and transfer some part of the retrieved case to the new case. Therefore, the suggested solution will be derived. In the Revise step, the suggested solution will be evaluated and verified. The outcome of the Revise step can be either to use, the retrieved solution directly, or repair it by using the domain knowledge base. In the Retain step, the new cases will be evaluated to store in the existing model.

One of the important output parameters from the CBR process is similarity match percentage (fraction of 100) between the input case (new unsolved case) and the retrieved cases (previous solved cases). The retrieved cases will be ranked based on the similarity percentage. The total similarity percentage comprises two matches; direct match (*syntactical similarities*) and indirect match (*semantically similarities*). In the direct match part, the similarly is exact between the input findings of unsolved case and the output findings of solved, one-by-one similarity. However, in the indirect match part, the findings between the two cases are not necessarily full similarities like in the direct match, but they have different relations between each other (e.g. causal relations, associational relations, and structural relations).

In Creek, the match similarity is the function of a number of related findings, `predictive strength`[2] (degree of sufficiency), and `importance` (degree of necessity) which will be discussed in Section 2.2.5. The similarity function between input and output cases is given as (Lippe, 2001):

$$sim(C_{in}, C_{re}) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} sim(f_i, f_j) * relevance\ factor_{f_j}}{\sum_{j=1}^{m} relevance\ factore_{f_j}} \quad \text{(Eq.1)}$$

C_{in} and C_{re} are the input and retrieved cases respectively, n is the number of findings for the input case, and m is the number of findings for the retrieved case. The relevance factor is a number that represent the combines of `predictive strength` and `importance` of a finding of a case, and $sim(f_1, f_2)$ is given by:

$$sim(f_1, f_2) = \begin{cases} 1 & if \quad f_1 = f_2 \\ 0 & if \quad f_1 \neq f_2 \end{cases} \quad \text{(Eq.2)}$$

2.1.4 Case

In the CBR language, a *case* is usually denoted by a *problem situation* or an *episode*. Some situations recur with regularity and the solution of the problem in one situation is likely to be applicable in a similar situation. Cases are description of situations, episodes which contain valuable knowledge. A case can be considered as special *experience* which is worth to keep in a memory (case-base) for applying in the future. In CBR language this knowledge is called "specific knowledge" (Reategui et al., 1997) and (Aamodt, 1994b). Specific knowledge may be defined as part of the knowledge which cannot be easily modelled such as general knowledge (known as model-based).

Cases can have different shapes and sizes, for example, they may cover a situation that evolves over time (e.g. designing an oil well), or snapshot (e.g. mud losses incident during the drilling phase).

Footnote 2 - This font (`Courier New`) denotes phrases which are used in the Creek framework and the Oil Well CBR model (named Wellogy).

The common elements of any case are:

1. General description of the case
2. Task of the case (what to achieve / accomplish)
3. Problem description (set of findings)
4. Solution description to reflect the task
5. The final outcome of the solution (the degree of success of the implemented solution)

There is a strong integration between cases and general domain knowledge in the Creek system (Aamodt, 2004). ***Figure 2.5*** illustrates the generic Creek concept where the cases are linked to the general domain knowledge. As seen, general knowledge plays an important role in Creek system.

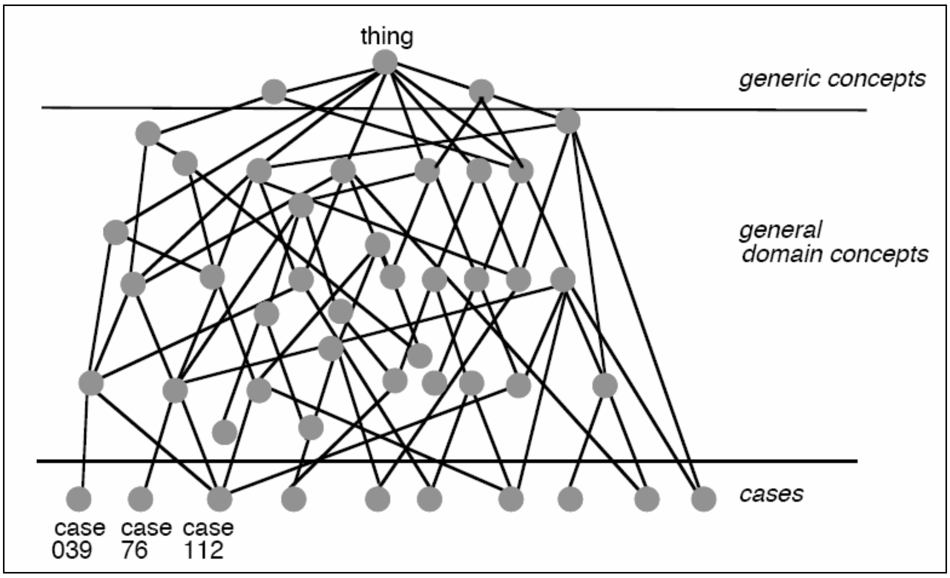


Figure 2.5 Integration between cases and general domain knowledge (Aamodt, 2004).

2.1.5 Ontology

In philosophy, ontology is the study of being or existence. It seeks to describe the basic categories and relationships of being and existence to define entities within a specific domain. Ontology is an organization and calcification of domain knowledge. In the recent years, ontological issues are being widely used for the purposes of knowledge sharing and reusing (Perez and Benjamins, 1999). Ontologies have been adopted in many business and scientific communities as a way to share, reuse, and process the domain knowledge. Ontologies are now central to many applications such as scientific knowledge portals, information management and integration systems, electronic commerce, and semantic web services. Noy and McGuinness (2000) stated that ontology is needed for:

- To share common understanding of the structure of information
- To reuse of domain knowledge

- To make domain assumptions explicit
- To analyse domain knowledge

In a simple definition applied in this study, the ontology is referred to as a hierarchical structure (entities & relations) representing the Wellogy model structure as a core of the CBR system. Therefore, the ontology represents the knowledge base in a format which can be used for the CBR purpose. In any ontology design, the goal is to translate the knowledge from information (e.g. text and graphs) into symbolic elements (similar to indexes in a book) and build it in a hierarchy structure. An illustration showing the contents of the ontology is depicted in ***Figure 2.6***. This figure shows that the ontology comprises three elements;

1) theory and general rules (denotes general knowledge)
2) cases or episodes (denotes specific knowledge)
3) human reasoning based on his / her mind and understanding

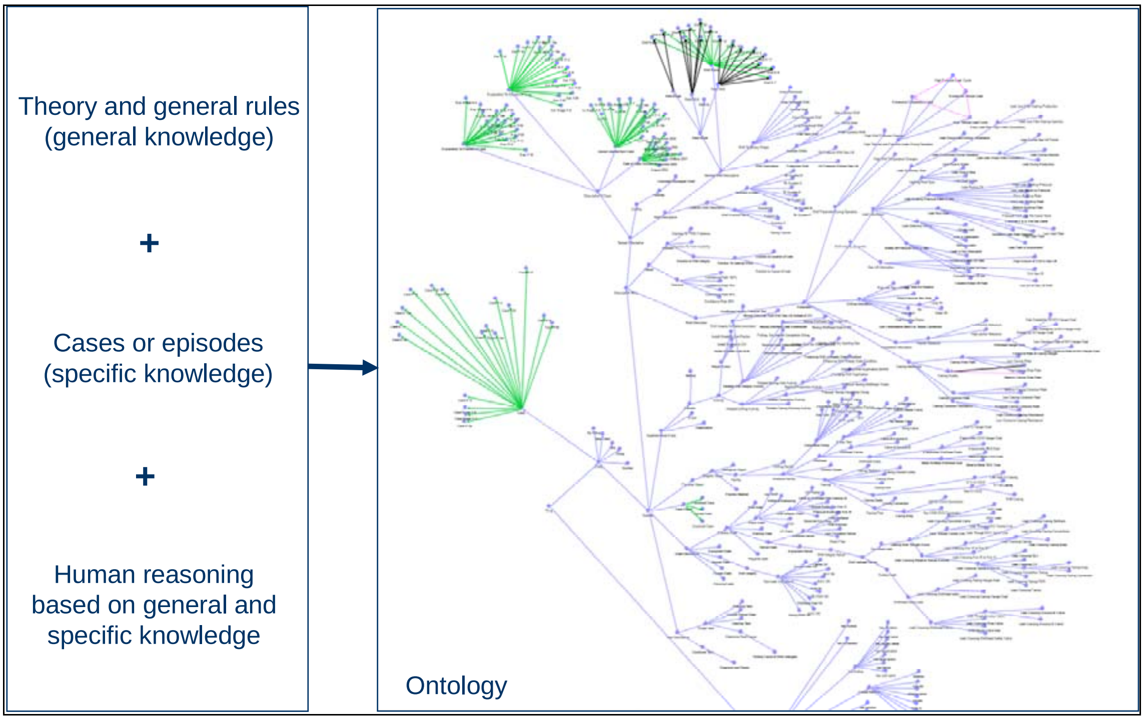


Figure 2.6 **Transformation of general knowledge, cases, and human reasoning behind a hierarchy structure (called ontology).**

According to Uschold and Gruninger (1996), there are three possible processes for developing an ontology:

1. Top-down development process
2. Bottom-up development process
3. Combined development process

These three options for developing an ontology are depicted in ***Figure 2.7***. In a top-down process, the ontology is developed only by general domain knowledge regardless of the cases, e.g. `Drilling` may be subdivided into two subclasses `Vertical Drilling` and `Directional Drilling`. We can further categorize `Directional Drilling` into `Horizontal Drilling` and `Slant Well Drilling` and so on. In a bottom-up process which is inverse of the top-down process, the ontology is only developed based on specific domain knowledge appearing in the cases. The most specific entities are extracted from the cases and extend the hierarchy with subsequent grouping of these entities into the more general concepts. In the combined process, both general knowledge and cases (specific knowledge) are used for building the ontology.

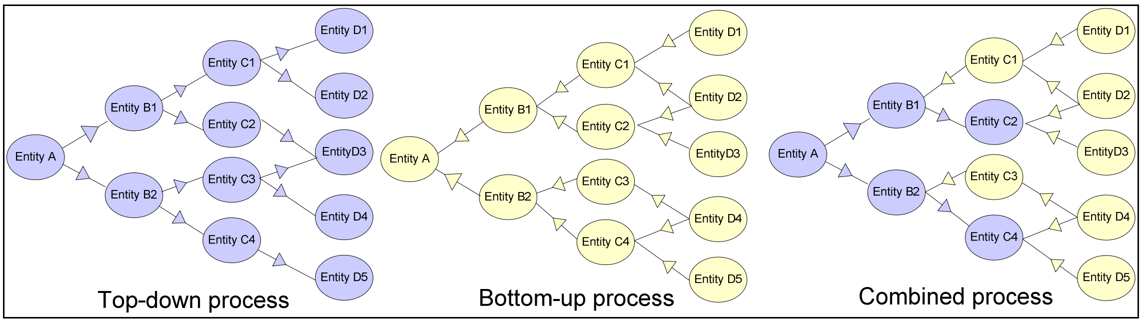


Figure 2.7 **Three different process options for building an ontology: top-down process is only based on general knowledge, bottom-up process is only based on case knowledge, combined process is based on both general knowledge and case knowledge (drawing is based on the concept of Uschold and Gruninger, 1996).**

2.1.6 History of CBR applied in the petroleum domain

There are limited published works of CBR / MBR methodology in the oil industry. Mendes et al. (2003) described cases (set of attributes) which are encoded by using fuzzy and generic algorithm (GA) for the adaptation process. Generally, this approach focuses on similarity function based on a mathematical approach and finding the best matches between cases without additional machine reasoning.

In the SPE e-library, using the searching function for CBR / MBR, finds only four papers. These are mostly related to the database and knowledge-base rather than CBR. Skalle and Aamodt (2004) published a paper concerning application of CBR / MBR in oil well drilling engineering. In a way this work can be considered as a basis for this thesis.

Perry et al. (2004) give a case-based knowledge repository for drilling optimization. They provided a software system to enable drilling problems to be queried in a database including lessons learned from previous practice. However, this system does not utilise the CBR methodology. Aminzadeh (2005) tried to demonstrate an application by using artificial intelligence and soft computing methods (neural networks and fuzzy logic) used for challenging problems in the oil industry, particularly related to geosciences. He examined a combination of human and machine intelligence and soft computing for solving problems. Irrgang et al. (1999) present a case-based system for capturing past drilled wells to optimize cost and time for planned wells.

As can be seen, there are few references for addressing applications of CBR in petroleum engineering literature.

2.2 The Creek framework

2.2.1 Creek overview

This section discusses the architecture of the Creek system for applying case-based reasoning. In this thesis the Creek system and architecture is used as a formal framework and knowledge editor. The oil well engineering model considered as a core of any CBR System is named Wellogy. The content of the model (mixture of cases and ontology) has been developed by the author.

As already mentioned, the Creek system is a CBR system which is being developed and implemented by the Department of Computer and Information Science at The Norwegian University of Science and Technology (NTNU) in Trondheim by Professor Aamodt and his group in NTNU and SINTEF. In the Creek system the cases are embedded within the general domain knowledge, so there is strong coupling between cases and the knowledge. The Creek system is software which implements the CBR method and is used in this study to demonstrate CBR applications in oil well engineering. Cases with general knowledge are interpreted and processed by Creek. Therefore, Creek is used not only as a CBR tool in this study but also as knowledge editor.

The Creek system contains an editor for integrating cases (set of problems / solutions) and general domain knowledge. Creek is trying to represent, formulate and store specific and general knowledge in a frame-based representation. In the Creek system the following operations can be done:

- Create and build an ontology such as a hierarchy
- Demonstrate the ontology
- Create relations and strength values between entities
- Build causal relationships
- Model cases
- Tune or adjust the attributes of the case through two parameters; "`importance`" and "`predictive strength`" i.e. giving the degree of necessary and sufficiency respectively for that specific attribute.
- Match processes between cases to find the best solved cases for an unsolved case
- Give explanation to justify the retrieved solution

The Creek program is encoded in Java and has been originally designed for solving and diagnosing problems. Here the focus is to realize the applicability of the Creek system for particular topics within the oil well engineering. How the Creek system has been developed or encoded is not the scope of this thesis. However, the details of the Creek system and its concepts can be found Sørmo (2004) and Aamodt (1991).

In a general description, a Creek model can be seen as a labelled, bi-directional graph (Skalle et al., 2005). It consists of `entities` and `relationships` *(nodes and links)*. The general definition for `entity` is: entity is an existing or real thing. The entities are shown as nodes; the `relationships` act as links which connect entities. ***Figure 2.8*** shows two entities with a relationship and the inverse relationship. To be more specific, the e*ntities* are names, phrases, glossaries, terms and concepts; for example, `Drilling`, `Well`, `Low Pressure`, `Low Mud Density`, `Drilling Bit` and so on. On the other hand, the `relations` are expressed as verbal forms such as; *causes*, *sometimes causes*, *leads to*, *implies* and so on. Each `relationship` has an `inverse relationship`, for example the inverse of "*causes*" will be "*caused by*" as shown in ***Figure 2.8***. Therefore, the ***Figure 2.8*** can for example represent:

`Low Mud Density` **`sometimes causes`** `Stuck Pipe`
`Stuck Pipe is` **`sometimes caused by`** `Low Mud Density` (inverse relationship)

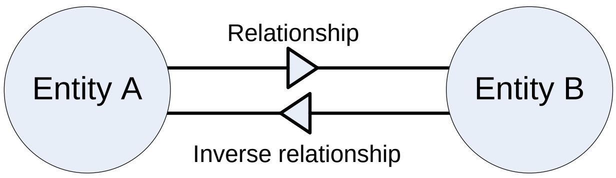


Figure 2.8 Entities and relationship used in the Wellogy model.

An example in the Wellogy model is given below for clarifying the concept how an ontology is built:

During drilling hole 8-1/2" on a platform in the North Sea in August 2002, the driller suddenly noticed a low rate of penetration (ROP). It is assumed that action needs to be taken due to this low ROP. In theory there are some parameters which cause low ROP as for example; low bit weight, low bit rotary speed, high rock strength and so on. According to Equation 3:

$$ROP = \frac{K}{S^2}\left[\frac{W}{d_b} - \left(\frac{W_o}{d_b}\right)\right]^2 N \qquad \text{(Eq. 3)}$$

where

K = constant of proportionality
S = compressive strength of the rock
W = bit weight
W_o = threshold bit weight
d_b = bit diameter
N = rotary speed

Therefore, some general causal relationships can be derived:

```
Low Rotary Speed **always causes** Low ROP
Low ROP **is led to by** High Compressive Rock Strength
```

and some of the entities can for example be defined in the ontology as below:

```
Bit Parameter has subclass Rotary Speed
Rotary Speed has subclass Low Rotary Speed
Bit Parameter has subclass ROP
ROP has subclass Low ROP
```

So the driller checked all related parameters and did not find any deviations from the normal conditions. He also checked rock strength with a geologist and the rock parameters were also the same. The driller remembered the same low ROP in a previous well. In that case low mud viscosity was the reason for low ROP. An increasing mud circulation rate increased the ROP. The drill cuttings will be accumulated around the bit due to low lifting capacity in low mud circulation rate. The cuttings will therefore be re-drilled by the bit and probably bit-balling might occur. This case gives additional information that can be added to the ontology as *specific knowledge* as below:

> `Low ROP` **`is sometimes caused by`** `Low Mud Circulation Rate. Low Mud circulation Rate` **`causes`** `Poor Mud Lifting Capacity. Poor Mud Lifting Capacity` **`leads to`** `Accumulation of Cuttings at Drill Bit which` **`causes`** `Bit Balling.`

Then, the acquired specific knowledge will be transformed as entities / relationships and finally integrated with the general knowledge into the model which is built into an ontology.

The ontology developed in the Wellogy model comprises many *entities* and *relationships* similar to the above mentioned example. The model represents a logic format for a specific domain. As shown the first letter of entities is written as upper-case, because Creek is a case-sensitive tool, and all relationships are written as lower-case. All entities in the Creek system should have relationship with other entities; otherwise, they would not contribute to the reasoning process.

2.2.2 Top level ontology in Creek system

A published reference related to petroleum ontology is given by Chen and Chan (2000). They presented a basic approach for building an ontology for specific application to the petroleum domain by defining 8 steps:

1. Obtain the domain knowledge through either document study or interviews with domain experts
2. Develop an initial ontology design
3. Choose an ontology editor to create ontologies

4. Use ontology tool as a user interface to generate knowledge acquisition
5. Build a knowledge base
6. Evaluate and validate the ontology model by experts or users
7. Adjust the model with references
8. Modify and adapt the model

The similar approach has also been considered in the Wellogy model.

The top level of the Wellogy model has been developed by researchers in Department of Computer and Information Science at NTNU. The top level of Creek is identical for any ontology. ***Figure 2.9*** shows the top level of ontology in the Wellogy model. The top level starts with an entity named "`Thing`". The definition of the "`Thing`" is "representing anything in the world worth naming or characterizing". This entity is the root of the model. All entities which come later will be a subclass of this entity. The uppermost entities at the top level of the Wellogy model are briefly explained below.

"`Thing`" has two subclasses: "`Entity`", "`Relation`". Each of these entities have their subclasses which are illustrated in ***Figure 2.9***. The definition of entities at the top level is given in the "Description box" in the Creek system. "`Entity`" is a real world objects, i.e. anything existing that we want to relate to other things existing.

Figure 2.9 illustrates the top level at the time of adopting Creek as the CBR tool (2002-2006). Today (2007) top level of Creek may be different.

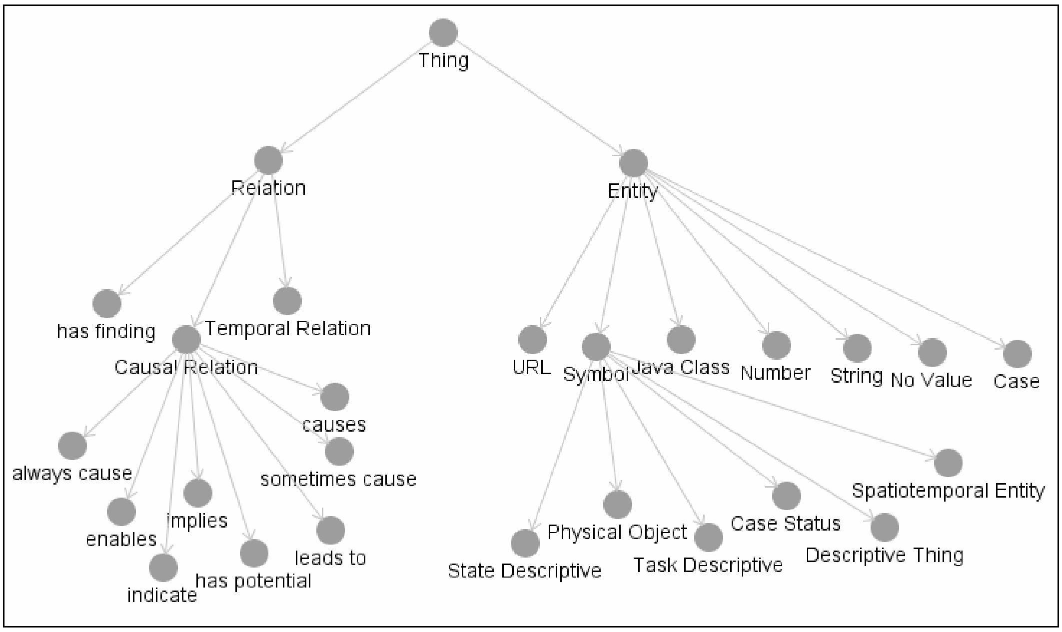


Figure 2.9 **Top level of ontology model developed in the Wellogy model (Creek framework, version 0.96 created at 20/01/2006).**

2.2.3 Relation

The entities are inter-linked through relationships in the Wellogy model. As discussed before, relationships represent verbal phrases. Four types of relationships have been considered in the Wellogy model:

1. Structural relation; abstract relation class. Captures relationships that structure knowledge into taxonomical and other types of hierarchies.
2. Implication relation; the origin will with some probability be the cause of the target.
3. Associative relation; general association class.
4. Temporal relation; Relates situations and states through time-dependent relationships.

2.2.4 Strengths

Instead of using relationships consisting purely of numerical values we have applied a list of verbs to help understanding the meaning behind retrieved reasoning results. Each relation has the strength valve 0 to 1. The allocated value for each relationship is default and defined by experts as shown ***Table 2.2***. Thus, the verbs are translated into numerical values in the CBR application.

Table 2.2 Strength values for relationships used in the Wellogy model.

Class descriptor	name	Default strength	Inverse name
Relation	Spatial Relation	0.5	Spatial Relation of
	Case Relation	0.5	Relation of
	Causal Relation	0.5	Causal Relation (inverse)
	has instance	0.9	instance of
	has solution	1.0	solution of
	Temporal Relation	0.5	Temporal Relation of
	Functional Relation	0.5	Functional Relation of
	has subclass	0.9	subclass of
	has default explanation strength	1.0	default explanation strength of
	transfers	1.0	inherits over
	has finding	0.5	finding of
	has comparator	1.0	comparator of
	Structural Relation	0.5	Structural Relation of
	Associational Relation	0.5	Associational Relation of
	has value type	1.0	value type of
Case Relation	has case task	0.5	case task of
	has outcome	0.5	outcome of
	has lessons learned	0.5	lessons learned of
	has case explanation summary	0.5	explanation case summary of
	has time occurrence	0.5	time occurrence of
	has case status	1.0	case status of
Causal Relation	indicates	0.4	indicated by
	sometimes causes	0.5	sometimes caused by
	leads to	0.5	led
	implies	0.4	implied by
	has potential	0.2	has potential of
	always causes	0.9	always caused by
	enables	0.5	enabled by
	causes	0.7	caused by
Functional Relation	performs	0.5	performed by
	can create	0.5	can be created
has finding	has failure	0.5	failure of
	has repair action	0.5	has repair action of
	has deviation	0.5	deviation of
	has observation	0.5	observation of
	has well name	0.5	has well name of
	has country name	0.5	has country name of
	has field name	0.5	ha field name of

2.2.5 Tuning the attributes of cases

In addition to the above strength value for relationships, for any finding of a case we need to set two relevance parameters. These are `importance` and `predictive strength`. The importance of a finding indicates the importance of an observation or a finding for predicting or pointing out the cause of the failure. The importance can be set to one of the following values: `Necessary`, `characteristic`, `informative` and `irrelevant`. Where `necessary` indicates the finding is of the highest importance for belonging to the given category, and `irrelevant` indicates the finding is not important. The predictive strength can be set to one of these values: `Sufficient`, `strongly-indicative`, `indicative` and `spurious`. Sufficient indicates the strongest predictive strength, and spurious the weakest. Both values for importance and predictive strength are numeric constants, i.e. the value `sufficient` for predictive strength sets the explanation strength to some predefined numerical value.

Note that predictive strength and importance only are set for cases that are solved. When you have an unsolved case you naturally do not have the solution, so it is not possible to set values for importance and predictive strength. The expert's view on what type of importance and predictive strength to select is based on theoretical knowledge, statistical knowledge or experience.

2.2.6 Computer program

As already mentioned, the Creek system is used in this study as a modelling tool and knowledge editor. This program has been built as in-house software at NTNU and it works on most platforms where Java is available. In this section, a brief overview representing the use of the software is briefly given in order to enhance understanding for readers. For demonstration, the previous example (low ROP) given in Section 2.2 is modelled here. However, the two detailed tutorials have been written (http://creek.idi.ntnu.no/), the first one is about general guidelines describing how modelling is done through the user interface (Brede et al., 2004), and the second one is a more specific tutorial for use in petroleum applications (Skalle et al., 2005).

Figure 2.10 illustrates a screenshot of the Creek software after loading, before starting to model (blank template). This figure shows the environment of the program used in this study. In the menu-bar, `Model` is used for entering input data for modelling in Wellogy. The `Model` button includes; `New Entity`, `New Relation`, `New Relation Type`, and `New Case`. On the right-hand side of the figure, different views for editing and searching inputs can be seen. The `Current Frame View` shows all information of a selected entity in the map view, such as description and relationship types for each entity. The `Entity List` button also shows the list of all entered entities in the model which can be looked at and searched when a new entity is inserted.

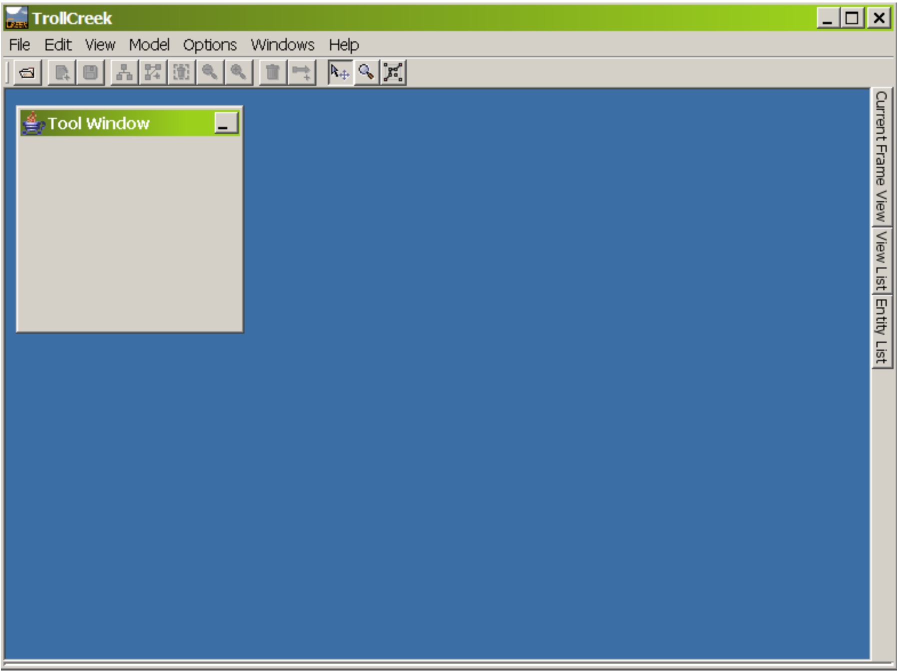


Figure 2.10 Screenshot of Creek software (knowledge editor).

Figure 2.1 depicts how to open a new knowledge model (e.g. low ROP model).

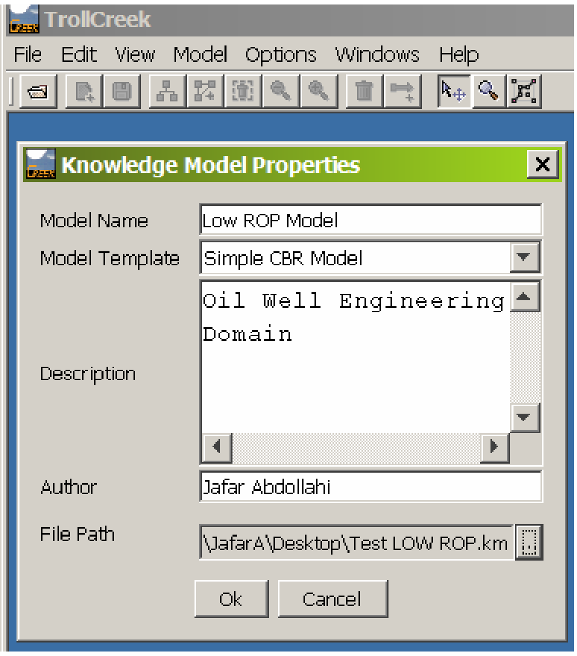


Figure 2.11 Creating a new knowledge model (e.g. low ROP failure).

From the ROP example, the extracted data and information from the case are given as semantic entities in two parts; general and specific knowledge as listed in ***Table 2.3***. General knowledge contains information which has previously been proven and well known as a theory of the concept. The specific knowledge gives information found and tied to the case.

Table 2.3 Extracted entities from the ROP example.

Case observations	Observations characterising the case
`Drilling Bit`	`Low Mud Circulation Rate`
`PDC Bit`	`Poor Mud Lifting Capacity`
`Bit Parameter`	`Accumulation of Cutting around the Bit`
`Rate of Penetration (ROP)`	`Increase Mud Circulation Rate`
`Low ROP`	`Norway`
`Rotary Speed`	`North Sea`
`Rotary per Minutes (RPM)`	`Well Number 1`
`Low Rotary Speed`	`Hole Size 12.25 inch`
`Normal Rotary Speed`	`Oil Base Mud`

These semantic entities are inserted together with the structural relationships in Creek as shown graphically in ***Figure** 2.12*. This figure represents the ontology (hierarchy form) for the ROP example. The entities are linked by structural relationships; e.g. `has subclass` (green lines in the figure) and `has synonym` (black line in the figure) with the same `Strength` values, 0.9.

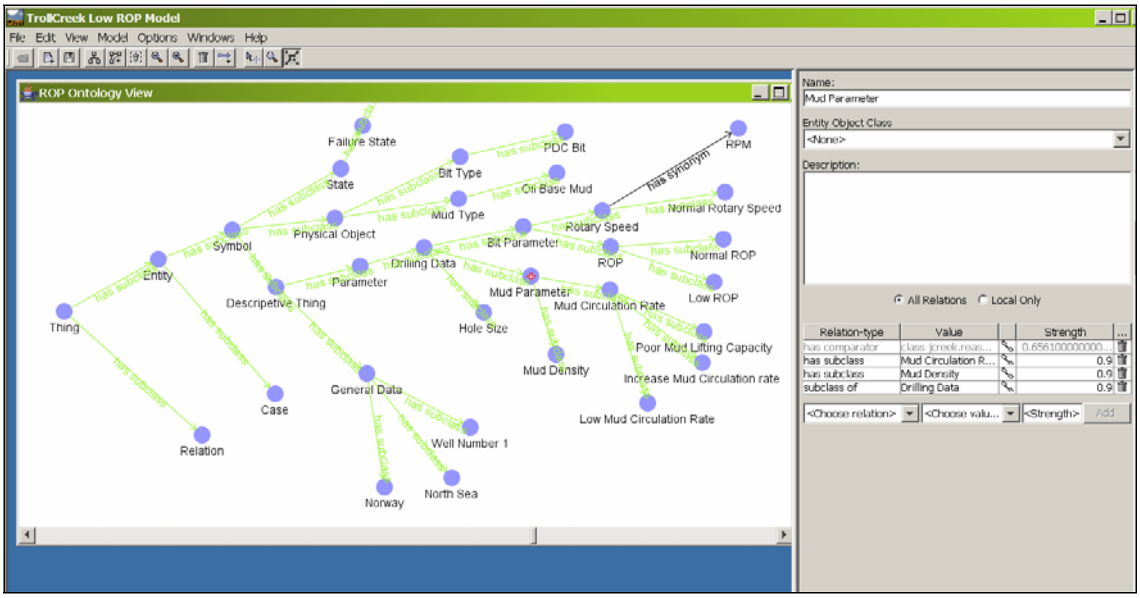


Figure 2.12 Representing knowledge as hierarchy form (ontology) for the ROP example in Creek (green links = `has subclass`, black link = `has synonym`).

Based on the theories and rules behind the concept of ROP, the causal relationships between parameters and findings of the case are developed as shown in ***Figure** 2.13*. The different relationships have different strength valves in the model. If a relationship is not already found in the model, the new domain relation can be defined and entered as shown in ***Figure** 2.13*. For example, the following cause model is given for the ROP case:

`Low Rotary Speed` **`always causes`** `Low ROP` (strength valve 0.9)

`Low ROP` **`sometimes caused by`** `Low Mud Circulation Rate` (strength valve 0.5) - (explanation: when the rate of mud circulation is low the drilled formation cuttings will be accumulated around the bit, and the bit will re-drill the cuttings and rate of penetration will be decreased).

`Low Mud Circulation Rate` **`causes`** `Poor Mud Lifting Capacity` (strength valve 0.7)

`Poor Mud Lifting Capacity` **`leads to`** `Accumulation of Cuttings around Drill Bit` (strength valve 0.5)

`Accumulation of Cuttings around Drill Bit` **`causes`** `Bit Balling` (strength valve 0.7)

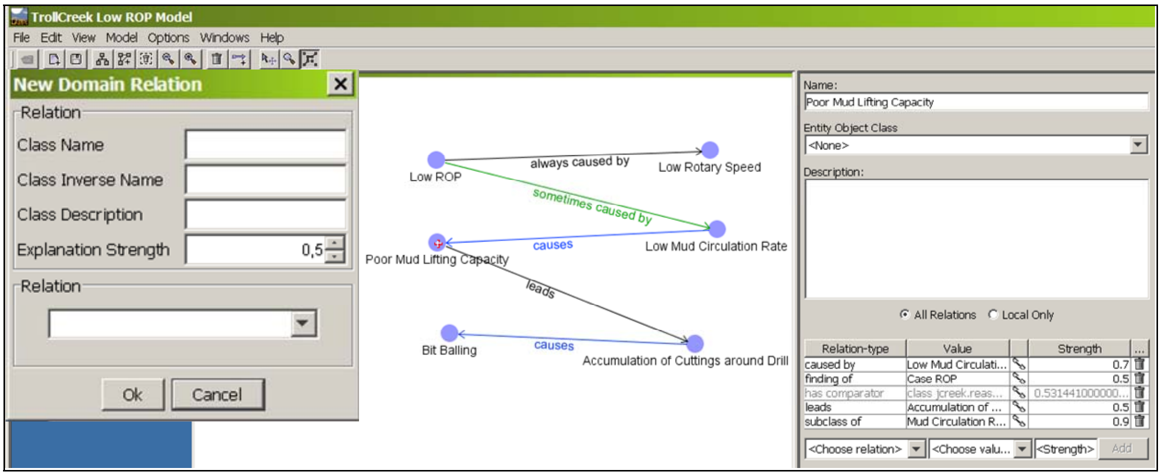


Figure 2.13 **Causal connections model (e.g. `Poor Mud Lifting Capacity` has two relationships with `Low Mud Circulation Rate` (`causes` has strength valve 0.7) and `Accumulation of Cuttings around Drill Bit` (`leads to` has strength value 0.5).**

The final step of modelling is constructing the ROP case in Creek. ***Figure 2.14*** shows snapshot of how creating a new case (e.g. `Case ROP`).

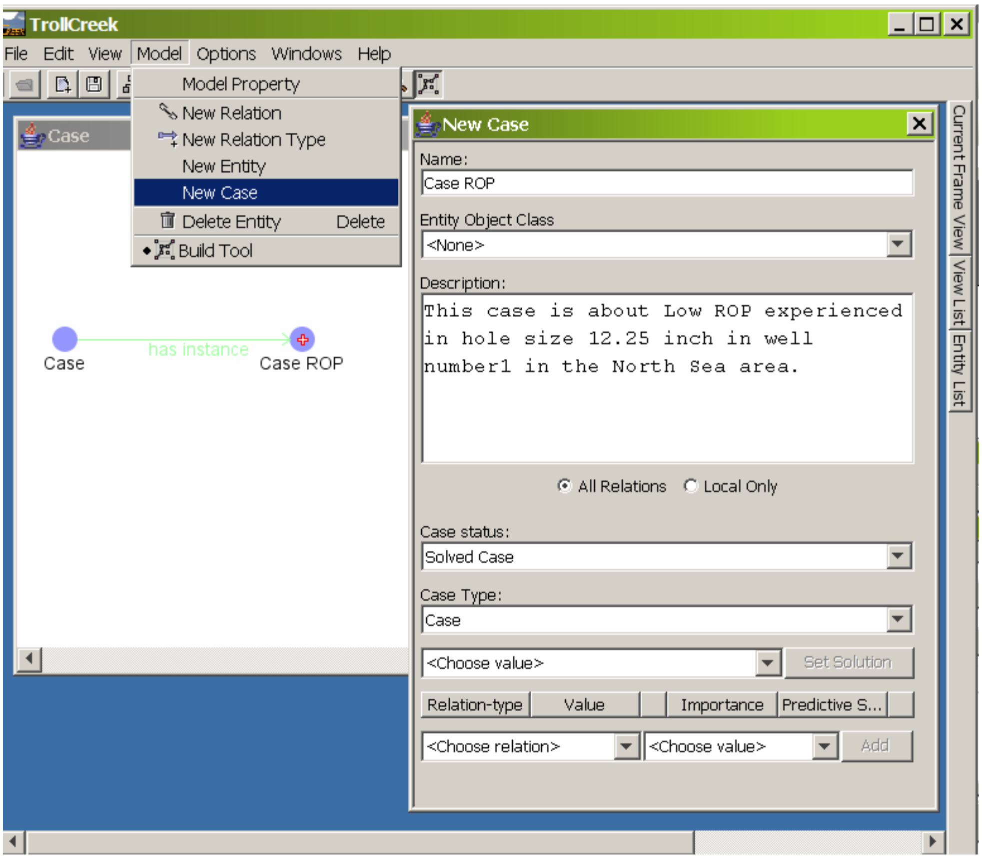


Figure 2.14 **Creating a new case in Creek (e.g. `Case ROP`).**

Figure 2.15 shows the case contents after filling the necessary information into the Case View. The name of the case is called "`Case ROP`" with a brief case description box. The solution to the failure (`Low ROP`) was found to be "`Increase Mud Circulation Rate`". The 10 findings have been allocated for this case with the different strength values. For example, the country is not such important information for the failure and solution of the case, so for this finding the strength value is low which given by combination of `Importance = Irrelevant` and `Predict Strength = Spurious`. This gives numerically 0.05 as an overall value (see the right-hand side of the figure).

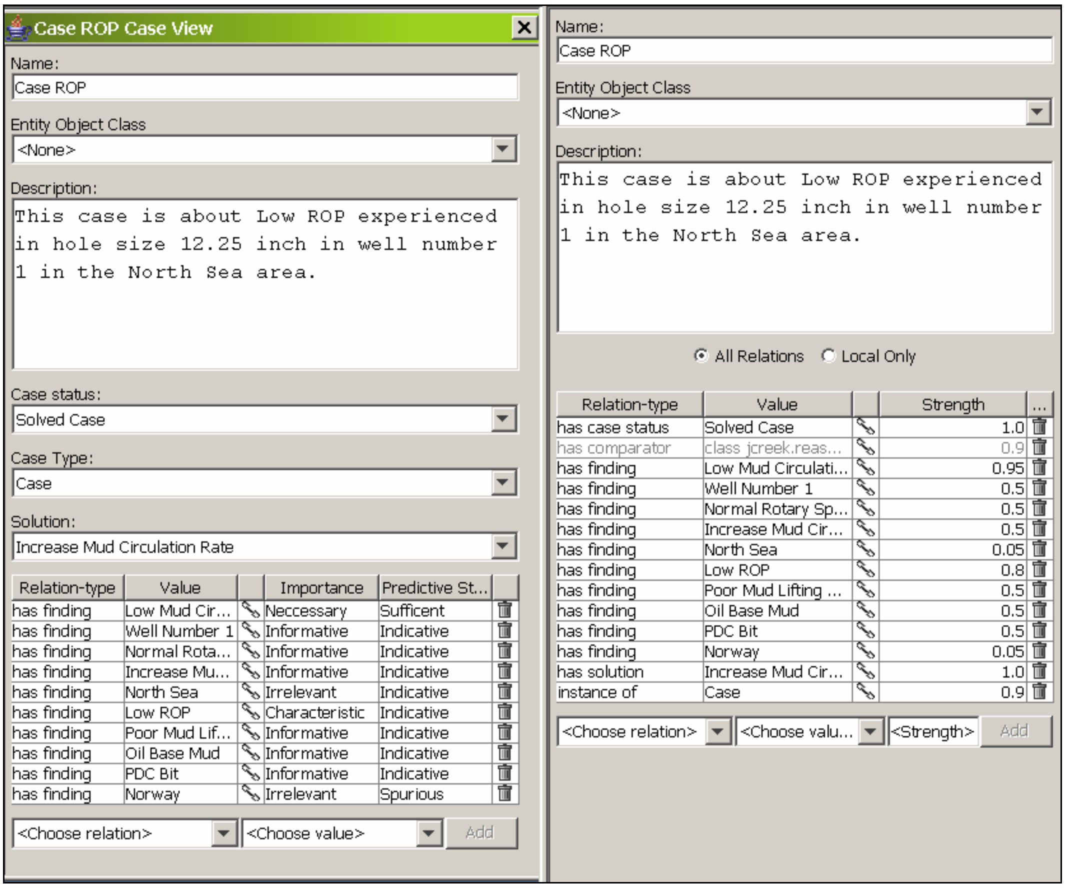


Figure 2.15 **View of Case ROP (failure = `Low ROP`, solution = `Increase Mud Circulation Rate`), 10 findings have been allocated for the case with different strength valves by adjusting `Importance` and `Predictive Strength`.**

2.3 Ontology and cases in the Wellogy model

Drilling and well cases can contain both general knowledge (rules and theory) and specific knowledge (experience), and the attention here is to transfer and reuse the combined knowledge in the future situations. So far, the experience is transferred manually with many limitations and constrains. For example, one challenge is that companies loose the knowledge and skills when a key employee leaves; the second challenge for example is the difficulty to remember at once all the relevant experience gained in the past cases and reuse it in the new occurring case. Thus, due to these and many other challenges, the attention is to use the computer to assist not only to store and remember past experience but also to perform artificial reasoning in addition to the human reasoning. For applying the machine reasoning (CBR) we need to encode cases and human knowledge stored in the brain of engineers to the CBR language.

The codes used in the Creek framework language are called "`entities`". In the Creek framework, both ontology and cases are represented by "`entities`" and "`relationships`" between the entities as shown in the previous section; therefore, the `entities` are playing an important role in Creek. How to create and name the "entities" is the first and main step in developing and constructing "ontology" and "case". There is no standard yet for this issue, particularly for the petroleum engineering applications. The related challenge is the lack of a unified language for oil well engineering. There is now a project running in several large oil companies for standardizing wellsite information which is called Wellsite Information Standard Markup Language (WITSML), (Companies, 2007). WITSML is a proposed standard and unified language for transmitting technical data between oil companies, service companies, drilling contractors, and application vendors. As this project is on-going we have not used the results of that work for naming the entities. This thesis can be considered the first attempt in this matter. The defined rules for naming entities are necessary for using the ontology model for upgrading and developing purposes. Nevertheless, there are limitations and challenges for defining the unique procedure for naming the entities.

2.3.1 Naming entities in the Wellogy model

During this study the naming of entities has been found to be a challenge and time consuming issue when building ontology and cases. A lot of discussions have been done on these topics throughout performing this research work. In fact, an entity in the Wellogy model is a concept which can be one word or combination of many words such as phrases. Each entity has a meaning in each particular domain. The writing format of an entity which contains more than one word, e.g. "Drilling Fluid", needs to be clarified. Here are some options:

1. Using space between words and capitalized each word: "`Drilling Fluid`"
2. Running the words together (without space) and capitalize each new word: "`DrillingFluid`"
3. Using underscore or dash or other delimiter in the name: "`Drilling-Fluid`"

In this study option 1 has been used. Whatever option is chosen, the aim is to name entity phrases as short and meaningful as possible. However, for some entity names which are not so clear at first glance, additional words are needed. Some entities which represent parameters, the values / attributes are added in addition to the main name of that entity, e.g. `High Mud Density`. However, it is possible to separate values / attributes from the main name of the entity by a dash line (-); for instance, `Drilling Fluid Density-High.`

An entity name represents a collection of objects. For instance, entity "`Drilling Fluid`" actually represents all drilling fluids. Therefore, it can be more natural for some designers to call the entity "`Drilling Fluids`" rather than "`Drilling Fluid`". However, whatever the choice, it should be consistent throughout the whole ontology. Most of the entities are written in the singular form in this study.

The entity names in the ontology can be written in a way which is totally depending on the developer without any justification. However, when new users want to continue or reuse the existing model which has been developed by a former person, they require guidelines or a manual for further evolution of the ontology in order to avoiding repetition the naming entities. If repetition in naming entities occurs, the quality of the CBR model may be decreased.

The searching function for an entity name in the Creek knowledge editor uses an alphabetically sorted list. Therefore, the first letter of the entity is important for the manual searching process. As mentioned before, entity names can be a phrase that contains words and sometimes numbers. These words have to be defined in the Wellogy model somehow to have meaning and also make it easy for later searching. The existing ontology has been constructed based on the natural oil well language. This approach has some advantages particularly for better understanding for entities that are more common in the drilling vocabulary, e.g. "`Stuck Pipe`". For other entities which are not used frequently in oil the well engineering domain, it has a disadvantage, e.g. "`Management Inadequate Maintenance Routine`". Moreover, it can also be a challenge for well known entity names when they are expanded with suffixes e.g. "`Stuck Pipe`". This entity can be renamed or even a new entity can be created by another user who later wants to evolve the model, e.g. "`Problem Is Stuck Pipe`". Another example is "`Mud Density High`" which can be named as "`High Mud Density`". To date, Wellogy is not able to recognize these two entities as one entity or even as synonym (because it is not yet built in). Therefore, the current searching function may not be useful for new users due to a lack of procedure or guide map.

Based on the discussed challenges, some guidelines for naming and indexing entities are required before implementing cases or constructing an ontology. The basic rules for naming entities used in this thesis are listed as below:

1. Meaningful; the first priority for naming entities is its meaning
2. Generalization instead of specification; it means that the phrase of entity should be created somehow to reuse them in new cases. Generalization has advantage when searching for entities
3. Predictability
4. Short and simple as possible

The entity names were formatted by considering the following rules:

1. Single and multi-words entities are allowed
2. Using space between the words
3. Capitalized first letters entity name (exception for relationships)
4. Avoiding digital numbers without having names as entity

When the entities consist of many words such as phrases or clauses, the ordering of the words will then become important. It is difficult to create ordering rules which could always be valid entirely during the process of creating ontology. However, after testing some cases and ontologies in Creek as trial attempts, we have found the following basic rules for ordering the words as entities in the Wellogy model. For clarifying these rules, we give some examples in ***Table 2.4*** and ***Table 2.5***.

1. Values or attributes come at the beginning of the entity names (e.g. High Well Pressure)
2. Generally the order of the words for an entity is as follow: value / attributes, verbal phrases, tangible object, and non-objects (concepts), (e.g. Very High Repeated Bit Balling).
3. Verbal phases are allowed. Three forms of verbal phrases may be used; imperative, participial form and gerund form. Imperative verbal form represents `task of the case` and appear at the first of the entity name (e.g. Increase Mud Density). Participial verbal form gives the value to the entity (e.g. `Increased Mud Density`) and gerund verbal form gives the meaning to entities as *activity* (e.g. Increasing Mud Density).
4. To facilitate of developing ontology, for example, recognizing which entity is belong to which main braches or super-class names, designers can level-up (subclass) naming entity to help in the searching process. At least two level-ups are practical. The level and main entity name is separated by a colon. For example, Anger is subclass of Human, and Human is subclass of State; it can be level-up as State:Human:Anger.
5. Using "is" as a connector between words where it is necessary. This helps in understanding the meaning of the entity.

Table 2.4 Examples of ordering the naming entities containing many words.

Entity	Value	Object	Non-object
Single word	High	Well	Pressure
Dual word	Very High	Bit Type	Capillary Pressure
Multi word	NA	Bit Type is PDC	Total Drilling Time

Table 2.5 Examples for different kind of entities.

Entity		Examples		
Numbers		Year 2002	Hole Size 12-1/4"	
Combination		Very High Mud Viscosity		
Temporal		Pipe stuck While Connection		
Special		Gas Leakage Through Wellhead		
Functional		Increased Mud Density Gradually		
Level-up rule		State	State: Human	State: Human: Anger
Verbal form	Imperative (task)	Change Bit	Reduce Mud Density	
	Gerund (activity)	Making Hole	Cementing	Running Casing
	Participial (state)	Increased Well Pressure		

2.3.2 Ontology development in the Wellogy model

The uppermost level of the Wellogy model that oil well ontology is started from is shown in ***Figure 2.16***.

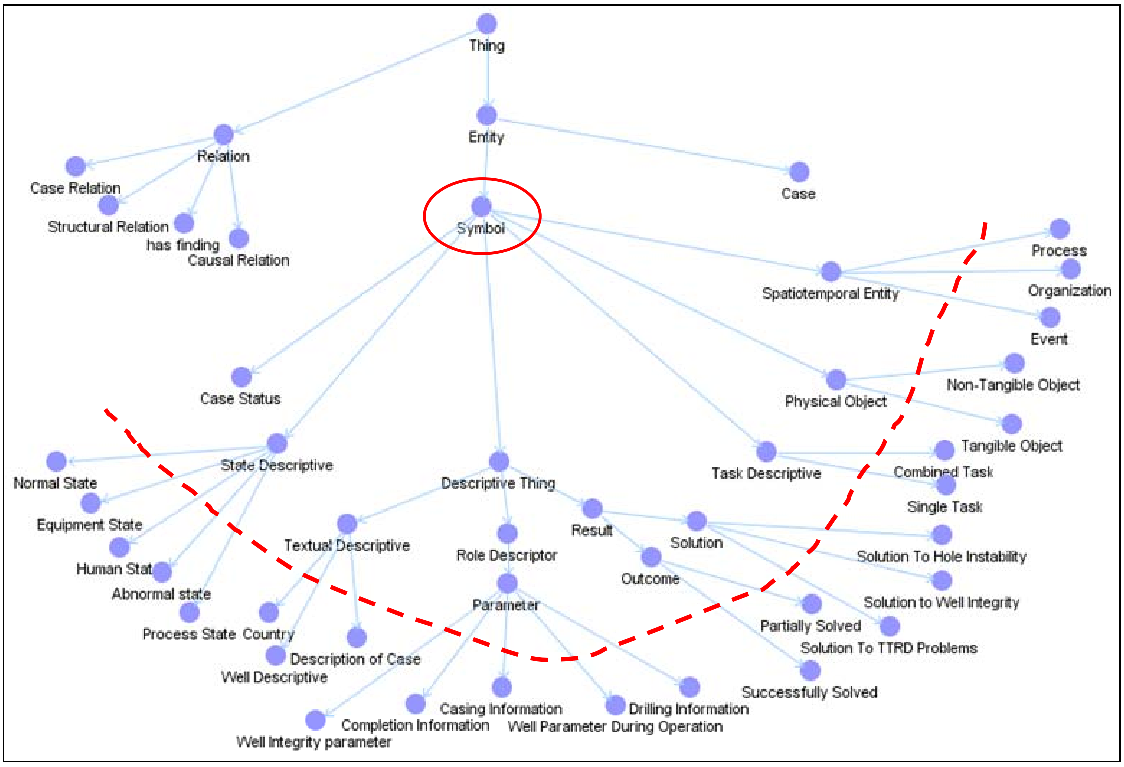


Figure 2.16 **Integration of uppermost level of the ontology of the Creek system (student version, version 0.96 created at 20/01/2006) and the Wellogy model (the red dotted line is the integration line).**

As the content of the cases is melted into the ontology structure, the ontology should reflect the case information. Most of the information and knowledge would belong to the `Symbol` node as shown in ***Figure 2.16***. The oil well ontology is extended under the following main entities which are subclasses of the `Symbol:`

- `Physical object, Tangible Object`
- `State`
- `Descriptive Thing, Role Descriptor, Parameter`
- `Spatiotemporal Entity, Process`
- `Task`
- `Case`

These main branches used for ontology development of the Wellogy model are explained below.

State means *[A collection of things at a snapshot of time (non-temporal entity). A state may be simple, such as a value of a parameter, or complex, such as a total (static) situation. (A collection of things in a temporal extension of time is called an event]* (TrollCreek, 2007). "*Snapshot of time*" means a short time period in a time interval, and "*non-temporal*" means describing processes or features which is not changed or endured over a period of the time.

As the Wellogy model is exclusively based on symbolic entities, all numerical values must be translated into the qualitative values, just like the relationships / strengths which already have been translated from verb to strength number (e.g. `causes` has strength value o.7). There are several ways of defining the magnitude or level of qualitative parameters. In the Wellogy model, each parameter may be defined in five levels as shown in ***Table 2.6***.

Table 2.6 Five levels for describing parameter used in the Wellogy model.

Level	Example 1	Example 2	Example 3	Example 4
1	very high	very large	very long	very shallow
2	high	large	long	shallow
3	medium	medium	medium	medium
4	low	small	short	deep
5	very low	very small	very short	very deep

2.3.3 Oil well cases

Cases can be defined in many shapes and sizes in the oil well domain. In respect of duration of a case built in the Wellogy model, two types of cases can be considered. The first case type may cover a short period situation (episode); for example, stuck pipe in a specific depth and time (assume 2 days). The second case type can cover a long period case; for example, the case for low production performance covers the entire field life. The second case type can be sometimes considered as a combination of many situations of shorter periods (first type).

From activities and process points of view, a case can be modelled in the Wellogy model with different shapes, particularly for oil well drilling. ***Table 2.7*** shows the many different time scale for building a case in the oil well drilling engineering domain.

Table 2.7 Different case shapes used in the Wellogy model.

Case type	Time interval	Example
Case based on field	The case covers a rather long period of the field history, years	Study of low production performance- diagnosis
Case based on well	Drill a complete well, months	Study of different down-time causes
Case based on drilled hole section	Drilling particular hole section, weeks	Mud losses encounter in a hole section
Case based on geology formation	Drill a particular information interval, days	Hole instability in a specific formation
Case based on bit run	From bit running into the hole to bit pulling out of the hole, days	Study of bit penetration rate problems - diagnosis
Case based on incident	From alarm state of the incident to repair and solved the incident, hours or days	One stuck pipe incident

The structure of cases in Wellogy consists of:

- General case description; contains entities which give a general introduction to the case which may or may not have minor contribution to the reasoning process (e.g. `Well Name`, `Field Name`, `Country Name`, and so on)
- Case administrative issues: (e.g. `has failure`, `has task`, `has solution`, `has outcome`, `has case status`) - this information is necessary for all of the cases
- Description of the problem; contains entities which give explanations to the problem (e.g. observations, deviations, repair actions, parameter changes, activities, alarm and failure states to answer these questions: how, when, where the problem happened?)
- The solution of the problem: the solution gives an answer to the task, e.g. the task can be to find the cause, and then the solution is the cause of the problem.
- Outcome of solution: gives the degree of success after the implementation of the solution
- Texts: texts are given to the case to assist in better understanding the case and can be used after case retrieval (e.g. lesson learned, operators explanation and recommendation, pointers to relevant databases of the oil company, URLs)

During our study we have found the following procedure for implementing a case in the Wellogy model:

1. Reading the document describing the episode carefully and evaluate for consideration as a case or not
2. Specify the purpose of the case; i.e. for what reason we want to store it in the Creek memory. This is an important checkpoint because this will affect structure and contents of the case later
3. The case will be abstracted so that it contains the most important parts of a case, such as; problem/situation description, solution, and outcome.
4. Translating text to symbols
5. Integration of different parts of the case and existing ontology in order to facilitate the retrieving process
6. Building the case and supplementing the Wellogy model (bottoms-up process) through the Creek framework.

3. Assessment of Well Integrity Cases

3.1 Motivation

Well Integrity has been defined by the Norwegian Standard of Petroleum (NORSOK) (NORSOK-STANDARD, 2004) as *"The application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of the well"*. This is an effective definition and has been adopted by many operators such as BP in Alaska (Anders et al., 2006). According to this definition, the well integrity is important to retain during the drilling and production phases. Here, the attention is given to well integrity during the production phase. The well integrity has impact on two important issues; safety and efficient oil recovery. When one pressure barrier has failed, the well will be closed due to safety reasons and as a consequence, if the problem is not repairable, the well will be abandoned and a new well must be drilled. Thus, the overall oil recovery will decrease in the long-term perspective.

The well integrity problems are a growing concern to several of the Norwegian offshore fields as well as other places in the world in terms of safety, well lifecycles; change the use of the wells, and overall oil recovery (Abdollahi et al., 2007). Due to growing number of mature fields, well integrity management has gained more emphasis in recent years. The well integrity goal is to prolong the well lifecycle and sustain oil production in an acceptable safe operation in areas where potential economic and HSE consequences are high. Annulus well leakage is identified as a typical challenge for well integrity for both production and injection wells. Diagnoses, localization and handling of different kinds of leaks need a special approach to understand a very complex picture. Huge amounts of data need to be addressed and changing operational histories and different well components must be included. The result of indirect measurements for monitor downhole well conditions for diagnoses and localization of the leaks may be inconclusive and uncertain. Different processes are involved in well integrity, for instance; human factors, technology, well conditions and so on. It becomes a challenge to find correct causal relationships.

A case-based approach for leaking wells is performed based on offshore oil field data to understand the complexity of causal relationships related to the well leakages. A knowledge-base is built for implementing Case-Based Reasoning (CBR) to improve overall well integrity based on leaking and non-leaking wells. For this purpose chronological documentation of the well activities, observations, actions and outcomes during well lifecycle has been studied.

This chapter discusses well integrity on the basis of experience from many oil and gas fields on the Norwegian Continental Shelf gained by SINTEF Petroleum Research through a long-term project study (Abdollahi et al., 2006). Initially, the statistic approach integrated with human reasoning has been used in this study to understand the complexity of causal relationships for the leaking wells. Afterwards, we decided to systemize and formulate this study by applying the CBR methodology as computer reasoning through the PhD programme by developing the Wellogy model in the Creek system. Therefore, this chapter will first explain and describe the well integrity issues textually in the different perspectives such as; leak components, related problems, causes, and solutions. Then, the cases will be given as a free text format (knowledge level). In Chapter 4, the cases together with the ontology will be defined and translated to codes (symbolic level) and implemented in Creek. Finally, the obtained results will be analysed and discussed in Chapters 5 and 6.

After each technical discussion, the important findings and human reasoning behind that concept are abstractly given as an example at the end of each paragraph (written in a different font). These information will be modified according to the Wellogy model in Chapter 4, and they will be used as input data to the model. For all leaking well cases which are intended to be modelled in Creek, a textual explanation is given for each case in Appendix A.

3.2 Well integrity in knowledge level (free text)

Totally eight oil fields in the North Sea area have been studied and audited for well integrity issues through a research project for Norsk Hydro. These fields are: Brage, Grane, Njord, Troll, Oseberg B, Oseberg C, Oseberg East, and Oseberg South. The definition of well integrity can be wide. However, in this study, well integrity is limited to the internal well leakage issues (i.e. annulus well leaks). Many wells have been reported and closed due to the annulus well leaks. Well integrity has been studied for the following industrial well applications:

- Production wells with and without using gas lift system (i.e. artificial lift for boosting oil)
- Water injection wells
- Gas injection wells
- Water Alternative Gas injection wells (WAG)

Symbolic-level

`Name of Operating Area (`e.g. `Norwegian Continental Shelf)`
`Name of the Field (`e.g. `Oseberg East)`
`Well Type (`e.g. `WAG Well)`

The well constructions and components for different well types are explained before discussing different well leaks and related causes.

3.3 Well integrity components

Well construction can be different according to the industrial application of the well as well as completion strategy. A typical well construction including major components and basic concepts in relation to the well integrity issue for an injection or natural production well (e.g. without gas lift system) is illustrated in ***Figure 3.1***. ***Figure 3.2*** shows a typical production well using gas lift. For a production well using gas lift, the well construction is different (more components involved) compared to for example a simple production well (not using gas lift). Therefore, the well barrier philosophy will also be different for those two well types. The well barrier issues will be discussed in the following section.

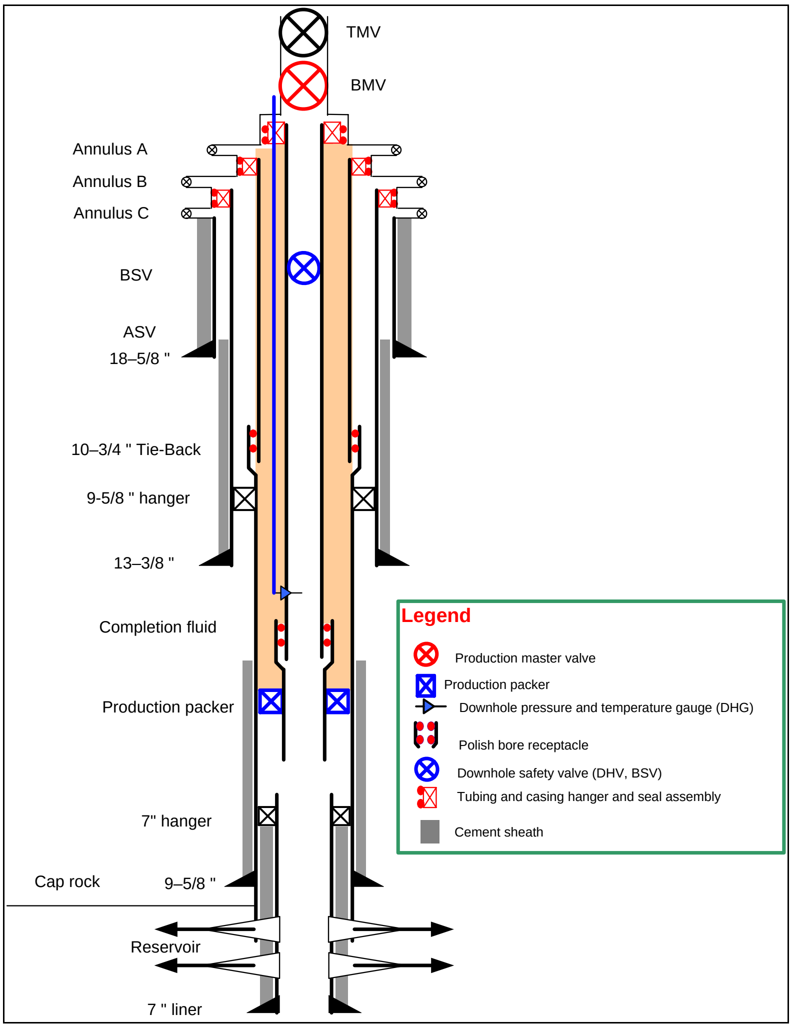


Figure 3.1 **A typical well construction with important well components related to the well integrity for an injection or production well (without gas lift system).**

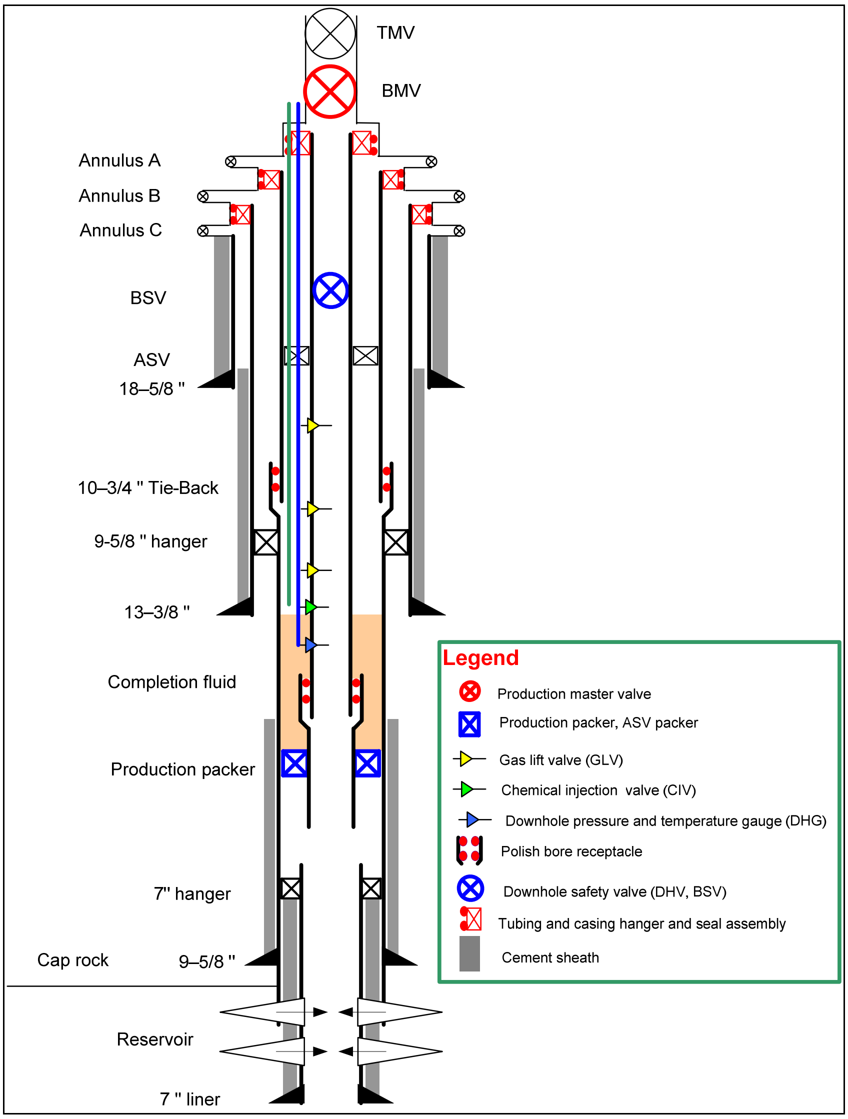


Figure 3.2 **A typical well construction with important well components related to well integrity for a production well using gas lift system.**

The annulus leak is defined as the escape of the reservoir and injection fluids through the completion and casings tubulars of the well. For simplification, a schematic presentation of a simulated well shows the relative volumes, pressure seals, and possible leak paths is depicted in ***Figure 3.3***. The relative well volumes which are important for leak studies are; completion tubing, annulus-A, and annulus-B. Annulus-A is the volume surrounded by the completion string (production tubing) and production casing while annulus-B is the volume surrounded by the production casing (liner + tie-back) and the intermediate casing, for example 13-3/8”. Depending on the application of the well, annulus-A can be either active (dynamic flow and pressure involved for example using gas lift) or non-active (static condition for example injection wells). In the gas lift wells for example, the gas is pumped through the annulus valve of the wellhead through annulus-A and into the completion tubing via the gas lift valve (GLV). Therefore, annulus-A is an active volume while annulus-B is an inactive volume. The following scenarios for leakage through the annuli may occur:

- Leak crossing completion tubing to annulus-A, either through the completion components (e.g. PBR, GLV, packer) or tubing bodies and connections)
- Leak crossing annulus-A to annulus-B, either through the tie-back system (junction between shallow casing and liner as shown in ***Figure 3.1*** and ***Figure 3.2***) or casing bodies and connections

The casing cements and production packers act as pressure seal elements (well barrier) at the deepest part of a well construction, while the "wellhead seal assemblies" and "wellhead valves" act as pressure seal elements at the surface of a well construction as shown in ***Figure 3.3***. These pressure seal elements must withstand any unwanted leaks through these elements during the well lifecycle. Tubing volume is directly exposed to the reservoir pressure and temperature when the reservoir fluids start to flow through this conduit (blue in ***Figure 3.3***). Therefore, one source of possible leaks can be the reservoir fluids which may escape from the tubing volume. Another leak source is injected gas lift fluids which flow through the annulus-A (yellow in ***Figure 3.3***). These fluids may escape from annulus-A and penetrate to annulus-B.

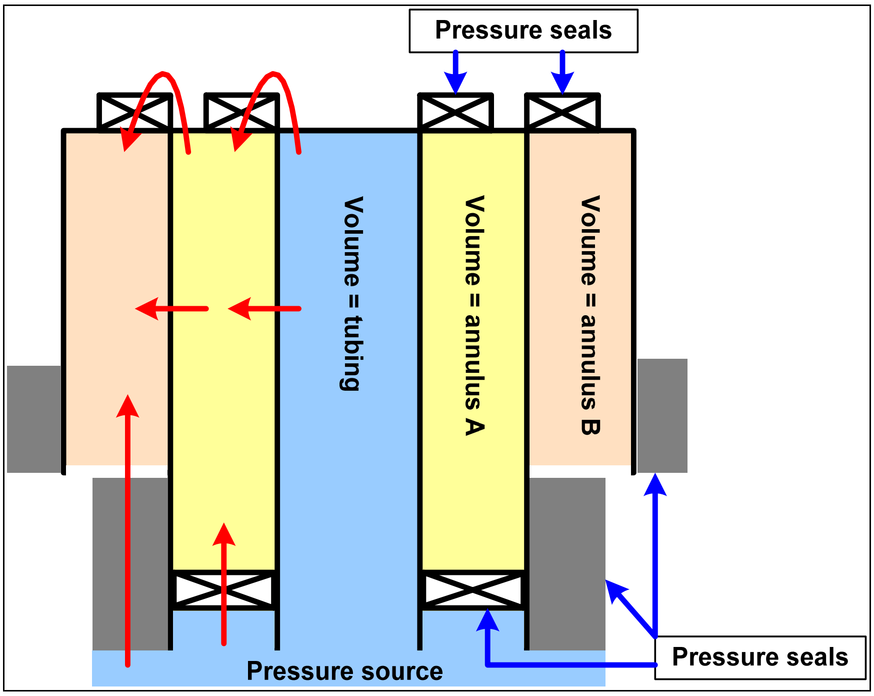


Figure 3.3 Leaks between relative well volumes; tubing and annuli (red arrows).

To meet the well barrier requirements, two surface controlled sub-surface safety valves (SCSSV) are needed for gas lift wells; one is placed along to the completion string which is called BSV and the other one is placed within annulus-A that is called ASV (see ***Figure 3.4***). The typical depths of these two valves are 200-500 m MD respectively (ASV is deeper than BSV). These two valves are controlled from the surface by using a small hydraulic pipe which is called the *control line*. The valves are regularly tested to ensure that they can withstand the design pressures during the operations (production / injection). This test is called the *in-flow test*. The possible leak paths crossing these valves are shown in ***Figure 3.4***. These types of leaks can be named "leak within one volume". As shown in ***Figure 3.4***, there are three kinds of leaks which might happen; 1) leaks crossing the annulus safety valve (ASV), 2) leak crossing the tubing safety valve (BSV), 3) leak crossing the X-mas tree (wellhead).

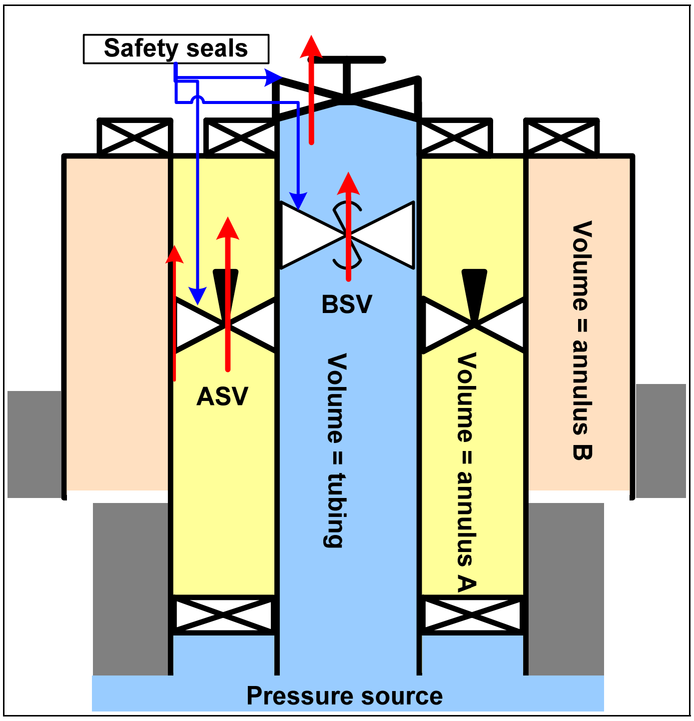


Figure 3.4 Leaks crossing within one volume (red arrows).

As a standard, two independent well barriers are required for any operations. Most of the internal well leakages lead to the destruction or reduce the functionality of well barriers. The NORSOK standard (NORSOK-D-010, 2004) has defined "well barrier" as *"envelope of one or several dependent barrier elements preventing liquids or gases flowing unintentionally from the formation into another formation or to surface"*. Based on this regulation each well must to be equipped with "two independent" barriers which are called *"primary barrier"* and *"secondary barrier"*. The *"primary barrier"* and *"secondary barrier"* are defined as the first and second objects that prevent unwanted flow from one source to other sources on to the surface (surrounding). ***Figure 3.5*** illustrates the well barriers elements and important well components for a typical production well using gas lift system. The blue line in the figure refers the *primary barrier* and the red line refers *secondary barrier*. In the right-hand side of the figure; the red box defines *secondary barrier* elements, the blue box defines *primary barrier* elements and the green box defines legends used in the figure.

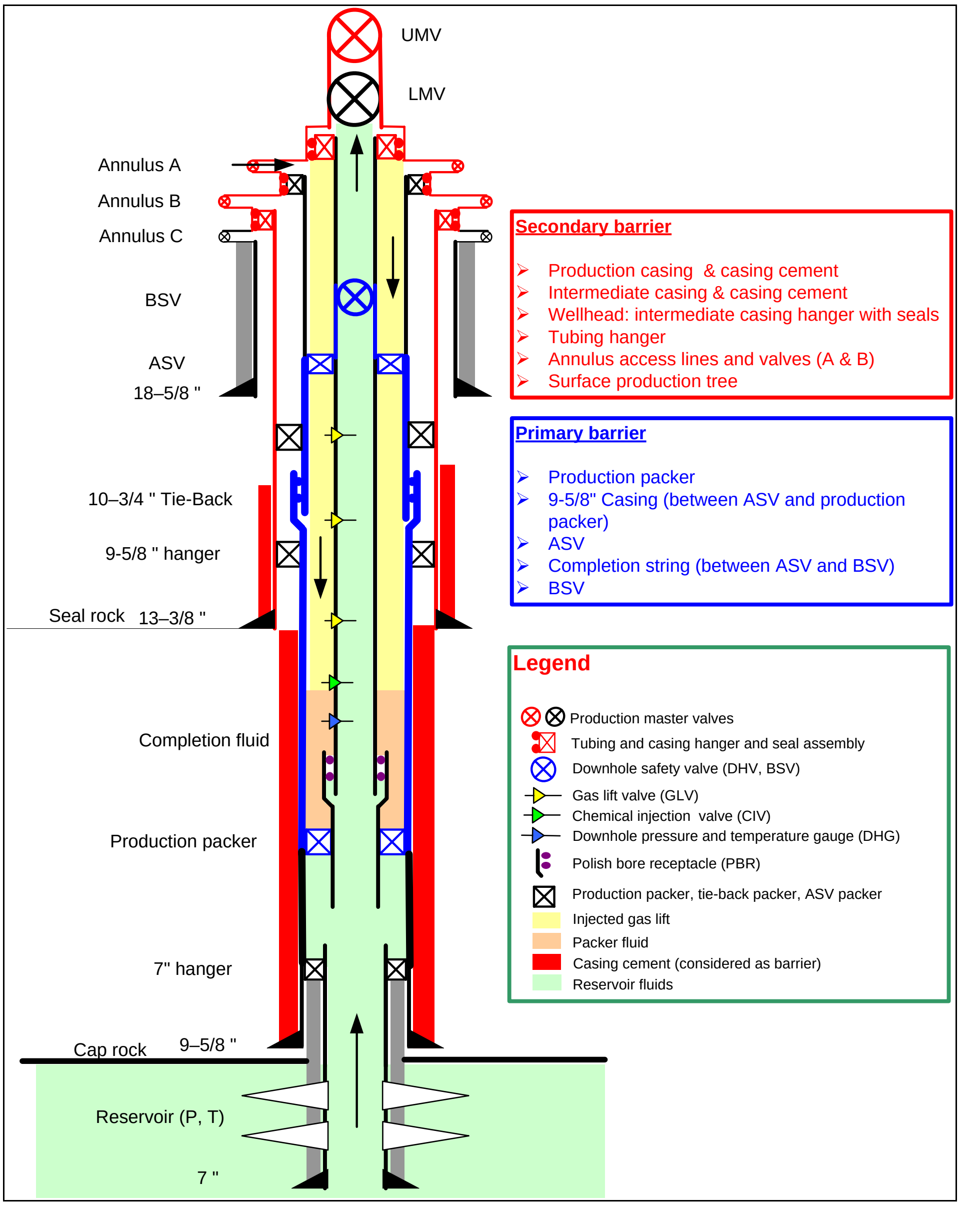


Figure 3.5 **Typical well schematic for production well with gas lift system showing well barriers and important well components related to well integrity.**

Because of the importance of the well barrier concepts, a new well barrier schematic has been drawn for better understanding in ***Figure 3.6***. This figure demonstrates a typical schematic well barrier diagram for a natural production well (without gas lift) or an injection well. The blue and red boxes denote the *primary* and *secondary* well barriers respectively which function as pressure and flow seal elements between the reservoir and surface. For simplicity, the well construction has been drown in three different volumes; tubing, annulus-A, and annulus-B. When oil production starts to flow, the reservoir fluids fill the tubing volume and the annular volume below the production packer. The primary barrier for the two flow paths (i.e. completion tubing and annulus-A) are the BSV and the production packer as shown in ***Figure 3.6***. However, cross-leakages can occur from the production tubing (below the BSV) to annulus-A, the interval between BSV depth and production packer depth. The main components which should withstand such leakages are: the tubing body and connections, PBR, GLV and other completion auxiliaries. These elements are also considered as the *primary barrier* for the production and injection wells. The secondary barriers which function as back-up seal elements are surface wellhead valves such as master valve or annulus valves (shown in the red boxes in ***Figure 3.6***). Another secondary barrier is the 9-5/8" casing which function as a seal when a leak crosses from the production tubing to annulus-A. In some well designs, tie-back casing may be run to the top liner instead of one piece casing. There are connector elements which link the tubing to annulus-A and denote the tubing hanger seal and the tubing itself shown in yellow in ***Figure 3.6***. For example, if the tubing hanger seal (located in the wellhead area) is leaking, then a fluid communication between the tubing volume and annulus-A will take place. This situation is not accepted according to the regulations.

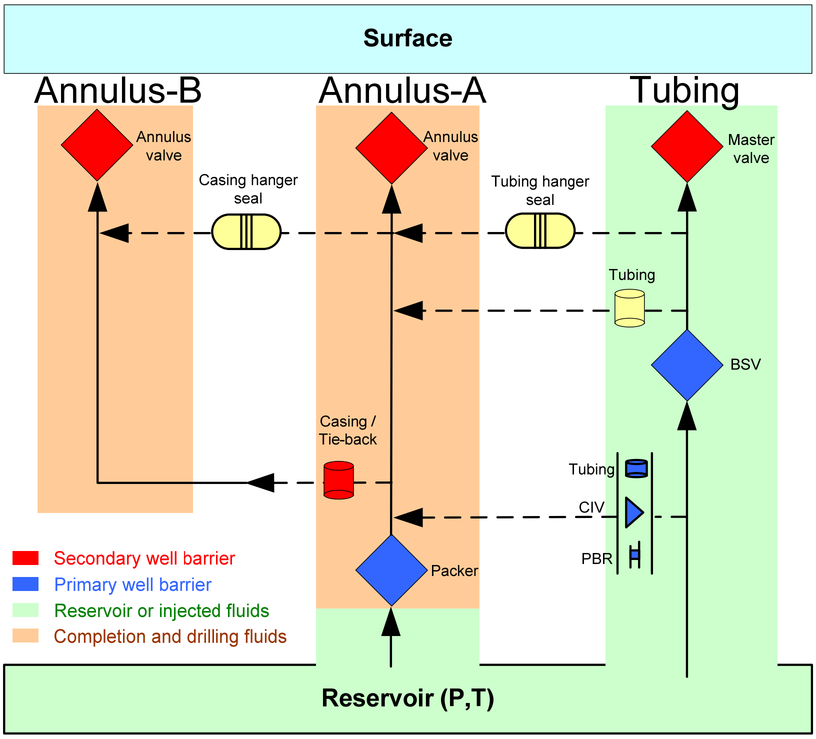


Figure 3.6 Well barrier diagram for a production or injection well.

Figure 3.7 shows the well barrier diagram for a gas lifted oil production well. In such wells, the annulus safety valve (ASV) is used for back-up safety in case of blowing out through the injected gas lift. So the ASV is used to increase the overall risk to the platform facilities with regard to fire or explosions (Grassick, 1992). Norwegian petroleum regulation (PSA) stipulate detailed requirements for the use of ASV in the gas lift completions in the Norwegian oil fields (Petroleumtilsynet, 2005). However, the application of annulus safety valves is not only limited to gas lift wells but can also can be used in other applications such as dual production wells in order to control the annulus flow.

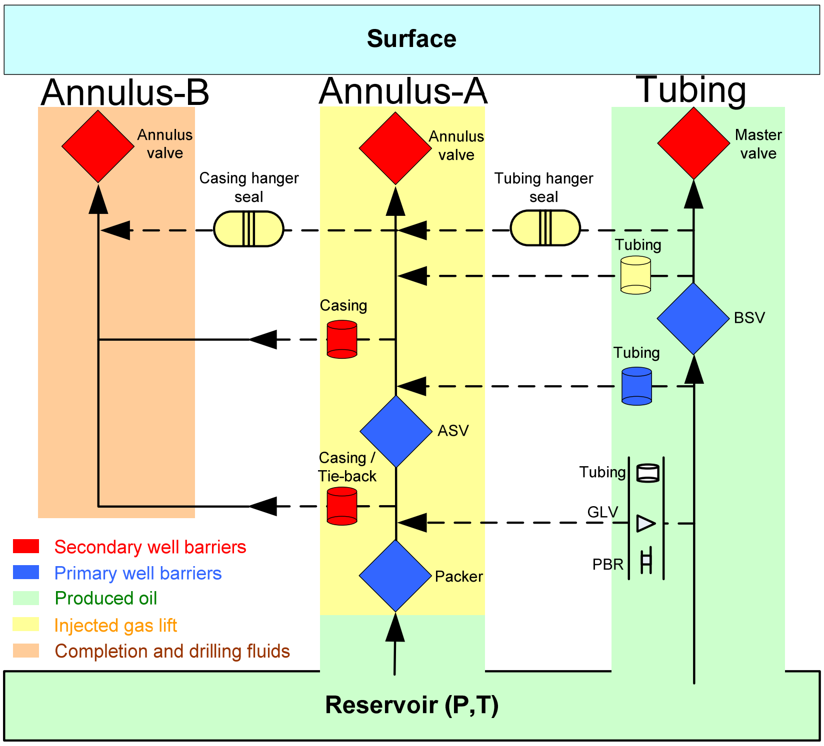


Figure 3.7 Well barrier diagram for gas lifted oil production well.

<u>Extracted symbolic-level (examples)</u>

- Completion Components (e.g. ASV, BSV, Casing); as physical object
- Well Annulus (e.g. Annulus-A; as Textual Descriptive
- Location of the Leak (e.g. Surface Leak / Downhole Leak
- Annulus Pressure Observations (e.g. Pressure Build-up in Annulus A); indicate the leak locations

3.4 Leak observations

Initially, the leaks are observed at the surface (wellhead area) by continuously monitoring the wellhead pressures during the production. Then, the investigations for identifying and localizing the leak(s) are established by running the leak detection log (sonic and temperature logs). The location of a leak is important to know before performing any treatments. However, in many cases there are limitations to detect downhole leaks either technically (leakages are too small) or economically (high intervention cost particularly in the subsea wells). There are generally two methods used to locate the depth of a leak:

- Pressure modelling study - the intersection point of two pressure gradient curves is considered as leak depth where the pressure reaches equilibrium (software method)
- Running sonic logs (leakage detector log)

When a leak is located, the in-depth investigations are performed to find the cause or causal relationships of the leak in order to repair the existing leak and avoid or mitigate such possible leaks in new wells (lessons learned). Leaks tend to show up during specific well phases (i.e. installation, production, injections, testing). The time references (time distance between installation and leak occurrence) and activity at the time of leaks are important to know for making preliminary reasoning to suggest the cause of the leaks. ***Figure 3.8*** illustrates these links between the annulus leaks and the well activities in different phases. This figure shows that there are three main phases that a leak can occur or be discovered during; 1) installation testing, 2) operations (production / injection), 3) routine test (in-flow test for BSV and ASV). For instance, assume a leak occurs during the installation phase or just after installation (completion of the well), the casing corrosion cannot be an issue for such leak, but other reasons such as; casing wear, equipment malfunctioning, and insufficient testing procedures, are likely. Another situation can be for example during "non-steady state operation", i.e. the operation changes from one state to another state (e.g., start-up gas injection (GI), water injection (WI, change rate of oil production, closing the well). These conditions obviously change the pressures and temperatures of wells which then lead to high thermal and pressure load cycles on the well constructions and cause leakages through completion components (packers, PBRs, etc.) and tubular threads.

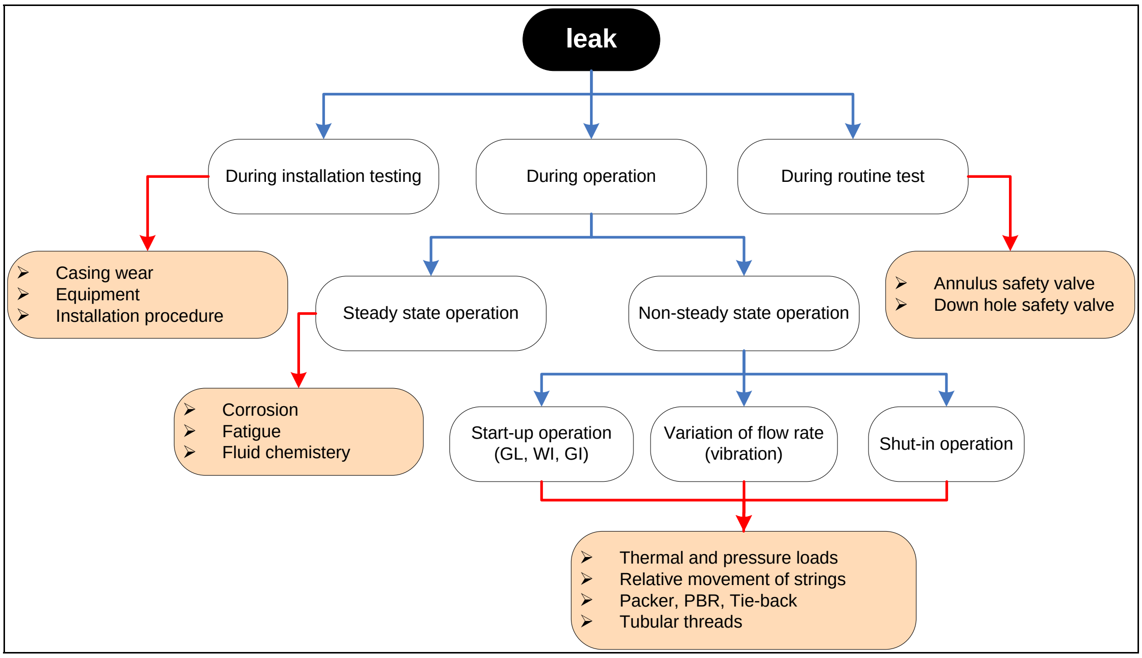


Figure 3.8 Likely cause(s) of the annulus leaks versus well activity (phases).

The effect of thermal and pressure loads on a WAG well has been calculated by this author (Abdollahi et al., 2006). ***Figure 3.9*** shows the result of these calculations. The smooth lines show the axial loads, without considering bending loads, on completion tubing from the surface to the production packer depth in a deviated well for different well conditions; landing, setting the packer, pressure testing, water injection, and gas injection. The two non-smooth lines are simulation results when considering bending effects (due to the actual dog-leg severity) for water injection scenario (blue curve) and gas injection scenario (yellowish curve). The calculations show that helical bucking is likely to occur at the bottom of the completion tubing (close to the packer) for the gas injection scenario. The helical bucking means that high compression loads are applied to the completion tubing leading to connection leaks. It should be noted that PBR (compensation tool for shortening and lengthening of the completion tubing) was not used for this typical well, because it was thought that PBR itself could lead to leakage.

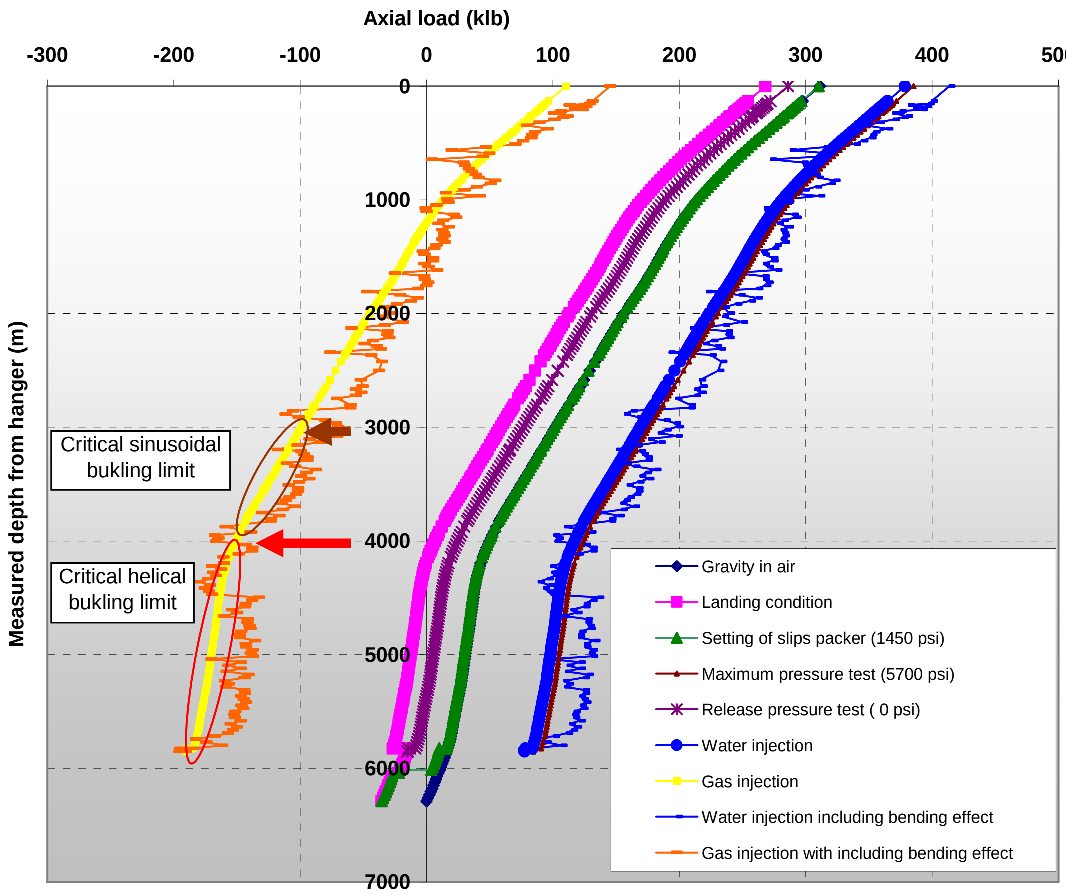


Figure 3.9 **Axial loads for different well conditions considering bending stress (Abdollahi et al., 2006).**

The design and installation of the well are important phases for well integrity issues. The low sealability of tubular connections (threads) and insufficient testing procedures can be more challenging for wells where the system is gas (e.g. gas injection or gas lifted wells) due to higher compressibility compared to oil and water. Sufficient testing time is important to compensate for temperature effects. Therefore, the tendency for leaks in the gas lift wells and gas injection wells is higher than for example in production wells without gas lift. Typical testing time for most of the wells is around 10 minutes and testing fluid is generally mud (contain particles) which therefore cannot represent real conditions when the system is gas. Casing wear creates casing ovality and sometimes cause micro leaks around the production packer which can be controlled or minimized during drilling (minimize drillstring rotation). The design envelope for the well must reflect real conditions for the pressure and temperature changes during the well lifecycle, because the relative movements of the tubular strings take place due to high temperature and pressure changes, leading to leaks crossing downhole components (packers & PBRs) and tubular connections (tool joints). This effect has been seen in the WAG wells (low water temperature and high gas temperature).

Extracted symbolic-level for causal relationship (examples)

- Casing Wear **sometimes causes** Micro Leak around Packer
- Early Leak **indicates** Insufficient Testing Procedure
- High Temperature Changes **leads to** High Thermal Load Cycles which **causes** Tubular Connection Leak
- Helical Buckling **indicates** High Compression Load which **leads to** Tubular Connection Leak

3.5 Tie-back systems

The relationship between different tie-back systems and reported leaks has been reviewed as part of this study. The six tieback systems have been recognized for the studied fields as illustrated in ***Figure 3.10***. These tie-back systems are explained below:

A. This system is the most common design for most of the wells that have been drilled and completed from fixed platforms. In this scenario a packer is used at the bottom of the tie-back (above the PBR of the tie-back) as a back-up. The GLV depth is deeper than the tie-back.

B. This system is used in pre-drilled wells, i.e. the wells that have been drilled from floating rigs and later completed from the fixed platform.

C. This system is similar to system A, apart from the fact that the position of the gas lift valve is placed above the tie-back seal assembly.

D. This system is not a common design. It has been used only for well E-1 on Oseberg East. The tie-back packer was accidentally set before reaching the target depth due to running problems. As can be seen, the completion fluid is directly exposed to the external 13-3/8"casing.

E. This system has a one piece casing (no tie-back in the string)

F. This system is used for injector wells.

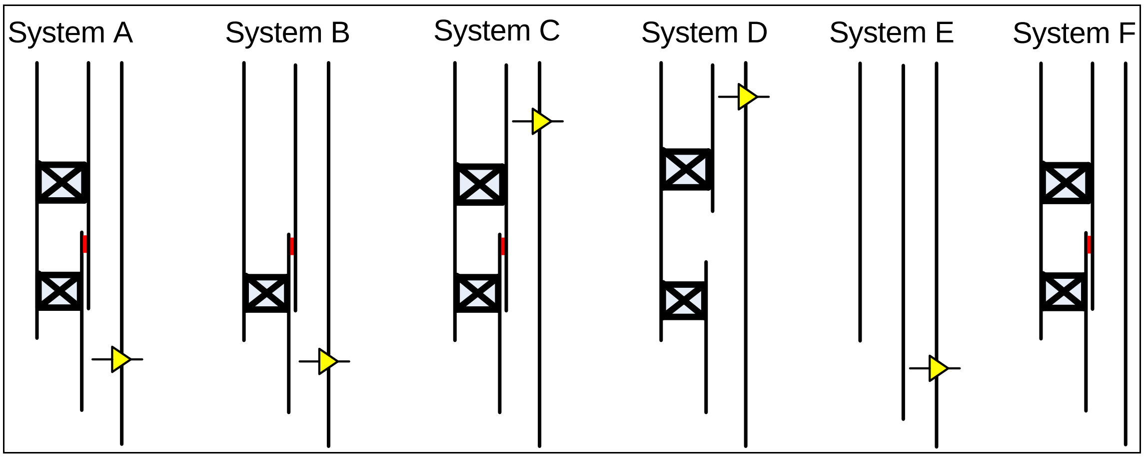


Figure 3.10 **Different tie-back configuration systems in fields used in Oseberg East, Oseberg South, and Grane fields**

Table 3.1, ***Table 3.2*** and ***Table 3.3*** show the relationship between leak components and tie-back systems for different well applications for the three fields, in order to find possible causal relationships or trends for the mentioned issues.

Table 3.1 **Leak components for different tie-back systems and wells for field Oseberg East (P = production well, WAG = water alternative gas injection, E = early leak) -texts in red show leak components, casing and tie-back (TB), which may relate to the tie-back system.**

Well	tie-back system					
	A	B	C	D	E	F
E-1 (P)				OK		
E-2 (P)-E					WH/CIV/CSG	
E-3 (P)	CSG above ASV					
E-4 (P)	TB /PBR (CIV leak)					
E-5 (P)					OK	
E-6 (WAG)						OK
E-7 (P)					PBR/packer/GLM	
E-8 (P)			OK			
E-9 (WAG)- E					PBR/packer	
E-11 (WAG)-E						GLM
E-12 (WAG)					OK	
E-14 (WAG)-E						ASV
E-15 (P)	CSG above ASV					

Table 3.2 **Leak components for different tie-back systems and wells for field Oseberg South (P = production well, WAG = water alternative gas injection, E = early leak).**

Well	tie-back system					
	A	B	C	D	E	F
F-5 (P)			OK			
F-12 (P)	OK					
F-14 (WAG)-E	PBR					
F-16 (WAG)-E			complex			
F-17 (P)			OK			
F-22 (P)	WH					
F-24 (P)			CSG below GLV (CIV leak)			
F-25 (P)			OK			
F-28 (P)			OK			
F-29 (P) -E			CSG probably below ASV			
F-30 (WAG)-E					packer	

Table 3.3 **Leak components for different tie-back systems and wells for field Grane (P = production well, GI = gas injection well, E = early leak).**

Well	tie-back system					
	A	B	C	D	E	F
C-5 (P)	OK					
C-6 (P)	OK					
C-8 (P)	OK					
C-9 (P)	OK					
C-10 (P)		OK				
C-11 (P)		OK				
C-17 (P)		OK				
C-18 (P)		OK				
C-19 (P)- E		**TB**				
C-20 (GI)		GI				
C-21 (P)		OK				
C-22 (P)		OK				
C-24 (GI)					OK	
G-25 (P)		OK				
G-26 (P) -E		WH				
G-27 (P)		OK				
G-28 (P)		OK				
G-40 (P)	OK					

Extracted symbolic-level for causal relationship (examples)

- `Tie-back System A for Production Wells` **`implies`** `Casing Leak for Field Oseberg East`
- `Tie-back System C for Production Wells` **`implies`** `Casing Leak for Field Oseberg South`

3.6 Leak classifications

In order to construct and model the knowledge for leaking well cases in the Wellogy system, leakages are classified into three different perspectives:

1. Leak classification based on the relative contained volume of the well as shown in ***Figure 3.3***:

   - Leak crossing from the completion tubing to annulus-A (T to A). Likely leak components are;
     - Completion components such as, PBR, GLV. CIV and etc
     - Completion tuning body and tool joints
     - Tubing hanger seal
   - Leak crossing from annulus-A to annulus-B (A to B)
     - Tie-back system
     - Casing body and tool joints
     - Casing hanger seal
   - Leak crossing annulus-B to annulus-C (B to C)
     - Casing body and tool joints
     - Casing hanger seal

2. Leak classification based on leak components:

   - Leak through production packer
   - Leak through completion telescope joint or Polish-Bore Receptacle (PBR)
   - Leak through casing tie-back system
   - Leak through tubings or casings body or connections
   - Leak through gas lift valve (GLV) or gas lift mandrel (GLM)
   - Leak through chemical injection valve (CIV)
   - Leak through control line to ASV and BSV
   - Leak through down hole safety valves; BSV and ASV
   - Leak crossing hanger seals (tubing and casing)

3. Leak classification based on the time of the leak occurrence

   - Early leak; including leaks that occurred in the early operation phase up to approximately one month from the starting time of the production / injection
   - Late leak; including leaks happened in the late operation phase, after one month from the starting time of the production / injection

3.7 Important field observations and trends related to leaks

In this section, human reasoning is made based on the important findings and trends gained from the three studied fields. All kinds of leaks for leaking wells were collected for three fields. ***Figure 3.11*** gives an overview for the three fields. As shown, 8 kinds of leaks have been recognized assuming that the severity of leak components increase upwards in of the bar chart.

The human reasoning is given below:

- Wells in Oseberg East have higher potential for leaks than in Oseberg South and Grane. This can be due to the life of the wells, or different operating conditions such as; pressure, temperature, corrosion environmental (different from the other field). Notice that three fields have artificial gas lifting systems.
- The Grane field is a rather new field; therefore, as expected there are no reported casing leaks (the cause of this kind of leak is believed to be corrosion)

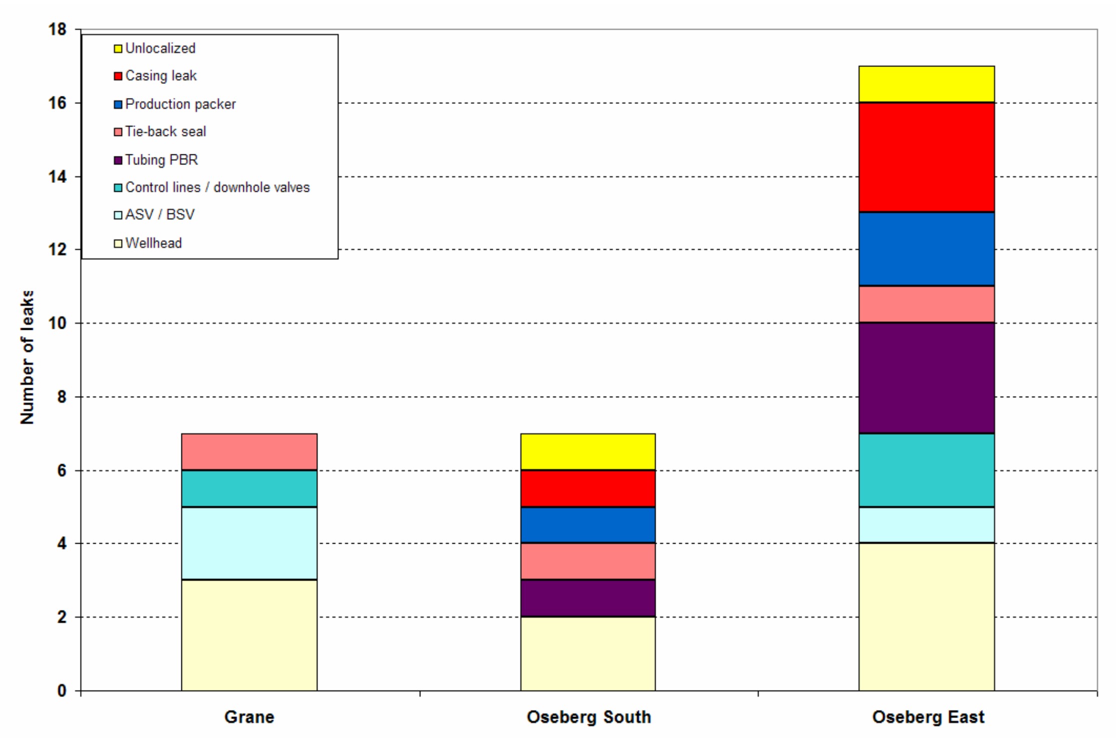


Figure 3.11 Different leak components for the three studied fields.

Figure 3.12 gives an overview of the overall well integrity with respect to time of leak and application of the wells for three example fields (Oseberg East, Oseberg South, and Grane). The *early leaks* are referred to as leaks which occur just after installation and *late leaks* are referred to as leaks which occur after a long period after installation. This chart indicates that the most of leaks for the gas lift wells are considered as *late leaks*, while for injection wells for example they are considered as *early leaks.* The reasoning can be as explained below:

In the gas lift wells, the system is more corrosive than the injection wells, and the gas lift is exposed generally to the 9-5/8” casings which are non-chrome casing and cause low corrosion resistance against the corrosive gas, while 7” completion tubing is more robust and equipped with 13 % chrome (high tubular quality). It seems that the gas wells suffer from the corrosion effect, while the injection wells suffer from thermal and pressure loads in the beginning of the operation phase.

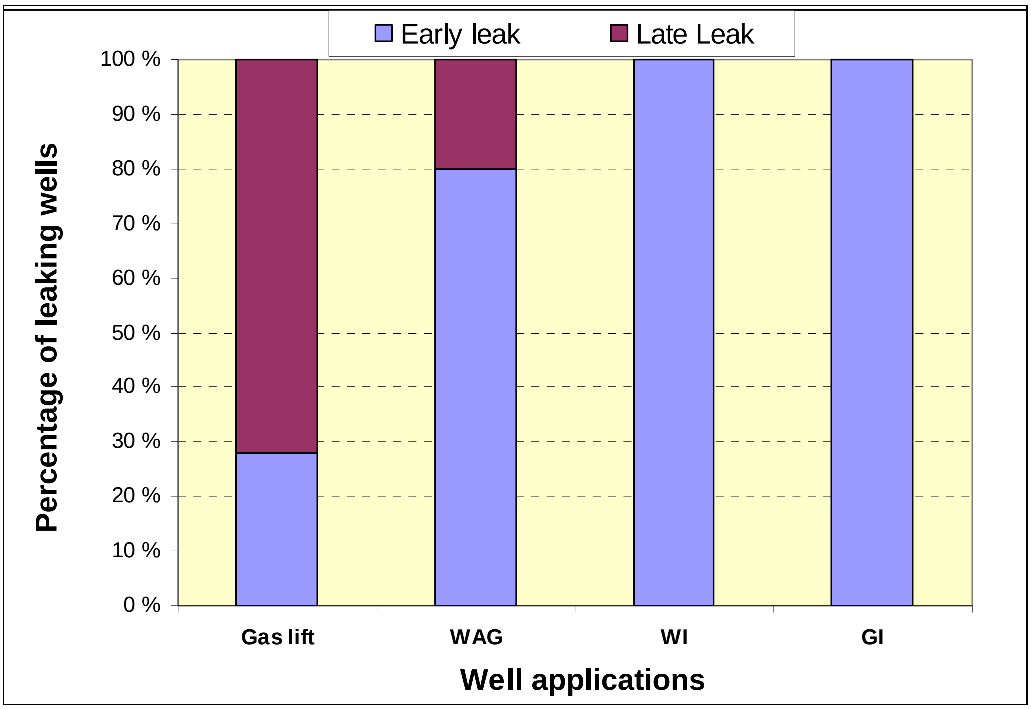


Figure 3.12 Early and late leaks for different well applications for three oil fields (Oseberg South, Oseberg East, Grane).

3.8 Important findings and related actions

Based on the lessons learned and observations from the leaking wells, the important findings and related actions are given for different phases of a well. The relations between the findings and actions can be used later for building a causal relationship model in the Wellogy system for modelling leaking wells. ***Table 3.4***, ***Table 3.5*** and ***Table 3.6*** summarize the important findings and actions for improving well integrity issues in the different well phases: design, drilling, completion, and production.

Table 3.4 Findings and actions for improving well integrity regarding leaking wells during the design phase.

Design phase		
Items	Finding	Action
Casing string	Connections exposed to excessive compressive forces due to thermal effect	Utilizing connection with 100 % compression strength- performing gas sealability connection test on compression condition
	High bending forces due to high dogleg severity cause excessive compression stress in one side and tensile stress in the other side of the connections	Simulate the real dog-leg conditions on the connection performance at laboratory scale. Simulator program should to be upgraded to reflect the dogleg factor on connection specifications
Gas lift well	Tie-backs (TB) are potential leak location for gas lifted wells where the GLV is below the TB depth (gas exposed to TB). This problem has mostly been observed in wells without TB's packer	If possible, the depth of deepest GLV should be above the TB to avoid gas exposure to TB
	Gas compositions such as CO_2, H_2S and water are not within the initial input specification for material selection in the design phase	PVT of gas of GL should be checked before final design. The use of 13 % CR CSG is recommended for CSG which are exposed to gas lift
	In most gas lifted wells, the hanger seals were elastomer seal type which are not qualified for gas system	Metal seal for both tubing and casing hanger seal are recommended for wells whenever the fluid is gas (gas lifted wells & gas injections)
WAG wells	WAG wells may be exposed to large load cycle effects because of changing temperature and pressure within a short period. This causes extra axial loads on completion and inner casings and tie-backs	The critical conditions should be considered in the design phase. Simulation at laboratory scale is needed for connection performance when temperature and pressure are cyclically changed

Table 3.5 Findings and actions for improving well integrity regarding leaking wells during drilling and completion phase.

Drilling and completion phase	
Finding	Action
Packer installation problems and in some wells micro-leaks around the packer were observed	Log the casing wear to map the important parameters- Minimize rotation time in casing and use hard-banding drill pipe.
Poor connection make up procedures	Mandatory training of best practice casing handling and running
	Specialized service for tubular handling
	Dope-free connections to eliminate contamination
Casing wear	Measure casing wear to establish data
	Consider hard banding
Procedure for pressure testing	Introduce new pressure test fluid for wellheads, N2
	Increase pressure testing time
	Perform FEA on tubulars with significant wear patterns in order to calculate remaining strength properties
	Perform sensitivity testing of packers inside casing (liner) which are exposed for wear
ASV leaking due to deposition of material on seal area	Improve washing procedure

Table 3.6 **Findings and actions for improving well integrity regarding leaking wells during production phase.**

Production phase		
Items	Finding	Action
Gas lift wells	Wet gas plus CO_2 lead to corrosive environment	Verify fluid compositions over time
		Dry gas by an extra heat exchanger

4. Modelling of Well Integrity Cases in Wellogy

The leaking well cases which have been generally discussed in Chapter 3 are evaluated and modelled in the Wellogy model in the Creek framework. So far cases have been presented and evaluated in a text format as explained in the previous chapter, and also in the form of references (documents and database). That part of the analysis is named *knowledge-level* (KL). In the Chapter 4 - upcoming process which is named *symbolic-level* (SL), the cases are encoded into the Wellogy model. The textual information and summarized information is given for each case in Appendix A.

4.1 Process of establishing the symbolic level

The following steps are done chronologically for creating a case and building / expanding the ontology used in the Wellogy model, and made possible in Creek system:

1. Design a database template for all leaking well cases (KL)
2. Perform human reasoning based on all cases to find relevant knowledge (KL)
3. Select knowledge-rich cases, i.e. cases containing enough information (KL)
4. Define basic features which are identical for all cases, e.g. “failure” and “task” entities (KL)
5. Produce a preliminary case structure in Excel before implementing in the Wellogy model (Kl - SL)
6. Create ontology based on the gained knowledge from the cases according to the combination process, i.e. top-down and bottom-up process (SL)
7. Build cases in the Wellogy system (SL)
8. Group solved cases based on similar solution (SL)
9. Establish causal relationships between entities (SL)
10. Perform qualify control of the model by evaluating the case match results (SL)

Totally 45 wells from 4 oil fields, leaking and non-leaking wells have been studied and analysed at the level of human reasoning to find causal relationships. 18 leak-wells have been selected for modelling for the Wellogy model. 12 leaking wells are solved cases and the rest are unsolved cases.

4.2 Selection of knowledge-rich cases

18 out of 28 reported well leaks are considered as `case` because sufficient data and information for these cases were available to build cases. The knowledge-rich cases mean that those cases which have sufficient explanation to the problem and solution parts and investigation activities for diagnosis of such leaks have been performed. Some cases had limited data; therefore, it was difficult to explain either the problem or solution parts. These types of cases were not selected for modelling. The following data sources and reports have been screened and studied for leaking wells before starting to build cases:

- General oil well documents

- Incident and unconformities reports
- Well-site observations in relation to leaks
- Annulus pressure observations (detected in production reports)
- Leak detection log reports
- Well observations after repairing the leaks
- Investigation and post-analysis reports (indirect observation)
- Final well reports; to look to the initial well constructions and possible deviations related to the installation phase
- Daily drilling reports
- Completion and hand-over reports

4.3 Identical features of the cases

All cases have the same `Failure` and `Task` in the Wellogy model. The `Failure` for all cases is a leakage problem, and the entity name of the failure is defined as "`Well Leakage Failure`". The `Task` plays an important role on the structure of ontology and cases, so this step of modelling is important. There are two possible options for considering `Task` for the leaking well cases:

1. Finding the cause of those leak incidents where the leak components and locations have previously been localized. The goal of this task is to treat existing leak(s) and to improve design specification for future wells. Although in some cases the leak was localized, it was difficult to conclude on the main reason behind the leak because of the involvement of combined effects.
2. Systemizing leaks for finding the location of the leaks for those cases where the leak point was still uncertain. For some of the leaking wells, the noise logs were run and results were inconclusive. It is crucial to find the location of leak before any actions.

Since the early days of developing CBR applications, diagnosis of problem cases was one of the relevant areas for application in weak domains (Kolodner, 1993) and (Magro and Torasso, 2000). Option 1 was found more suitable for the Wellogy model because the existing database better supported the chain of causal relationships of the failure rather than classification location of the leak. In addition, the oil company has stated the interest to knowing the direct cause or related causes of the leakage to take this knowledge into account in the design phase for the new wells. Option 2 is also possible to model in the Wellogy in order to assist unknown or hidden leaking well components. The reasons for having unknown leak well components can be either due to the size of leaks (small) which are impossible to detect by means of the existing technology, or due to cost reasons, particularly in subsea wells.

4.4 Preliminary case structure and production

After a study of a huge database for the well integrity issues, the important findings have been systemized and mapped on basis of possible factors which most likely caused the leakage(s). Because many cases were available, first, the statistical approach and human reasoning were applied to find an overall trend to answer this question: “why did many leaks occur in many wells in the specific fields?” In ***Figure 4.1*** we have summarized the most important factors, observations, and parameters. As shown in this figure, the upper part contains basic case information or case administration, the middle part gives general case attributes which has no or minor impact on the reasoning process, and the lower part contains specific information and knowledge which support problem and solution explanations.

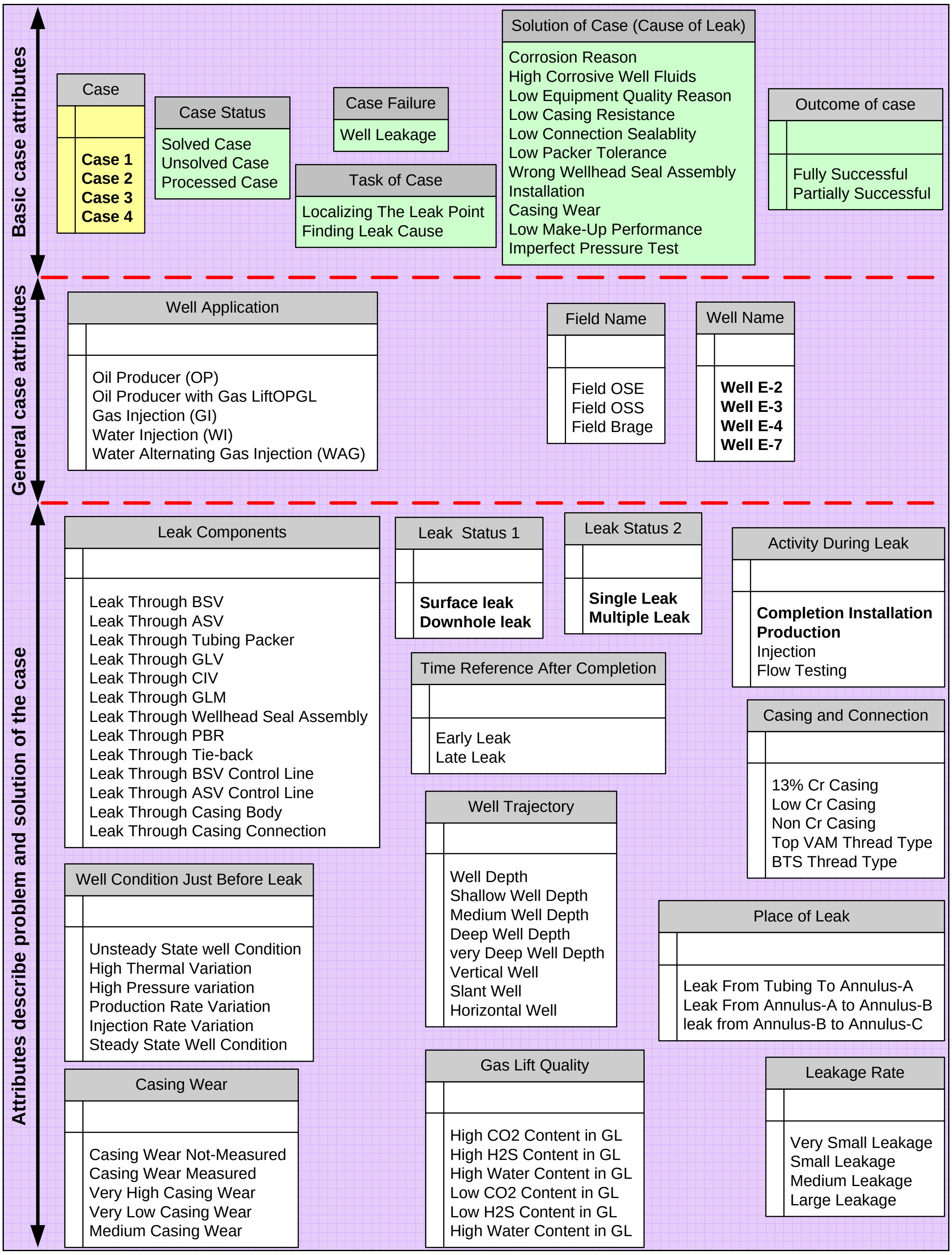


Figure 4.1 **The most important findings related to the leaking wells.**

A preliminary case production template has been developed in Excel before transferring and encoding in Wellogy. Clustering cases in one sheet helps to explain cases correctly when they are fairly given the similar number of features. The template can be found in Appendix A. In this template the basic case characteristics have the same amount of information to some extent.

4.5 Ontology of well integrity

To start building ontology for the leaking wells, the top level (root of the ontology) of the Creek system is required. ***Figure 4.2*** illustrates the top level which has been implemented by Department of Computer and Information Science, NTNU (version 0.96 created at 20/01/2006, newer version has subdivided this into three subclasses: `Entity`, `Relation` (between entities) and `Description Thing` (description of entities)). As shown in the figure `Thing` is the root of the model and has two basic subclasses; `Entity`, and `Relation`. To develop an ontology for any engineering applications, the Entity node is the starting point. All new entities for the cases should be linked to the `Entity` node and all defined relationships should belong to `Relation`. The `Entity` itself has the following subclasses as shown in ***Figure 2.9***:

`(URL, Symbol, Class, Number, String, No Value, and Case)`

The designers of the Creek framework (Sørmo, 2006) cited that all the findings of the CBR ontology model should be direct or indirect sub-classed / instanced of `Symbol` or `String` in order for the system to know how to treat and compare. The Wellogy model is developed on the `Symbol` node, because Creek will attempt to use causal relationships to compare findings for the reasoning and matching process. The uppermost entities used for the model of leaking well cases are:

- **Case Status** - gives the status of the case and has three options: solved / unsolved / processed
- **Physical Objects -** covers the equipment and materials used in the case
- **Descriptive Thing** - mainly has three uppermost subclasses; `Result`, `Textual Descriptive` and `Role Descriptor`.
    - **Solution:** the solution is a subclass of `Result`. In this branch the solutions to the reasoning task are given. These solutions are allocated to the solved cases
    - **Outcome:** the outcome is a subclass of `Result`. Here, the degree of successes of the solution to the solved case is given; e.g. `Successfully Solved / Partially Solved`
    - **Textual Description:** in this branch the entities which describe some of the findings of the cases are given. For instance, the description of well annulus name (annulus-A, annulus-B), time of case occurrence, well names, and field name are given in this line.
    - **Parameter**: the parameter is a subclass of `Role Descriptor` and consists of `Observable` and `Unobservable` / `Measurable` and `Immeasurable` / qualitative and quantitative parameters, related to the subject of the model (e.g. well integrity) are given in this branch.
- **State Descriptive** - describes the state of the entity and has three subclasses; normal, alarm and failure states. In this branch, the descriptions of the problem / failure are generally given.
- **Spatiotemporal Entity** - All activities of cases are sub-classified under `Process` which is subclass of `Spatiotemporal Entity`.

- **Task Descriptive** - process and activity related to the task of the model are subclasses of this branch.
- **Task**: in the task line, the identifications related to the purposes of the cases are given. There can be some options, for example, finding the diagnosis of failures, solving the problems, finding the root cause of the failures and classifying the failure.

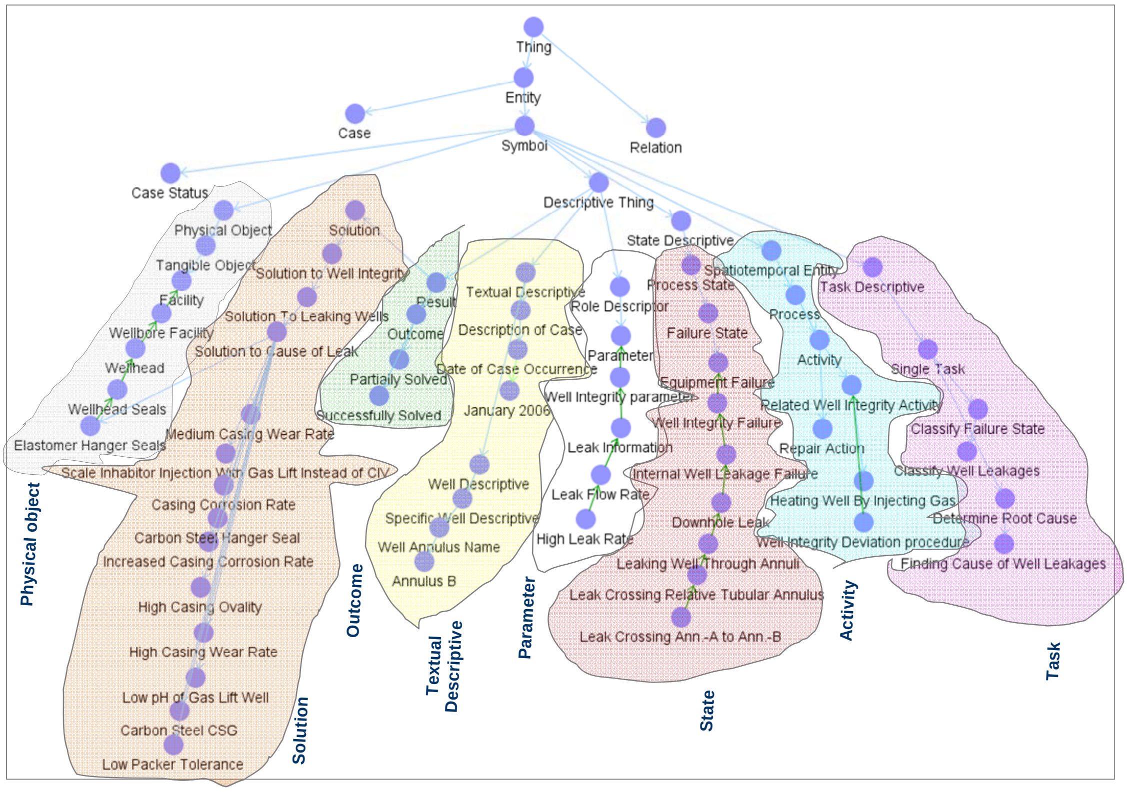


Figure 4.2 **The main parts of ontology constructed in the Wellogy model (the line relations = `has subclass`).**

Figure 4.3 illustrates some parts of the ontology which has been developed based on merging of general domain knowledge and cases for leaking wells in the Wellogy model. As shown, the process development is a combination of top-down and bottom-up processes which was discussed in Chapter 2.

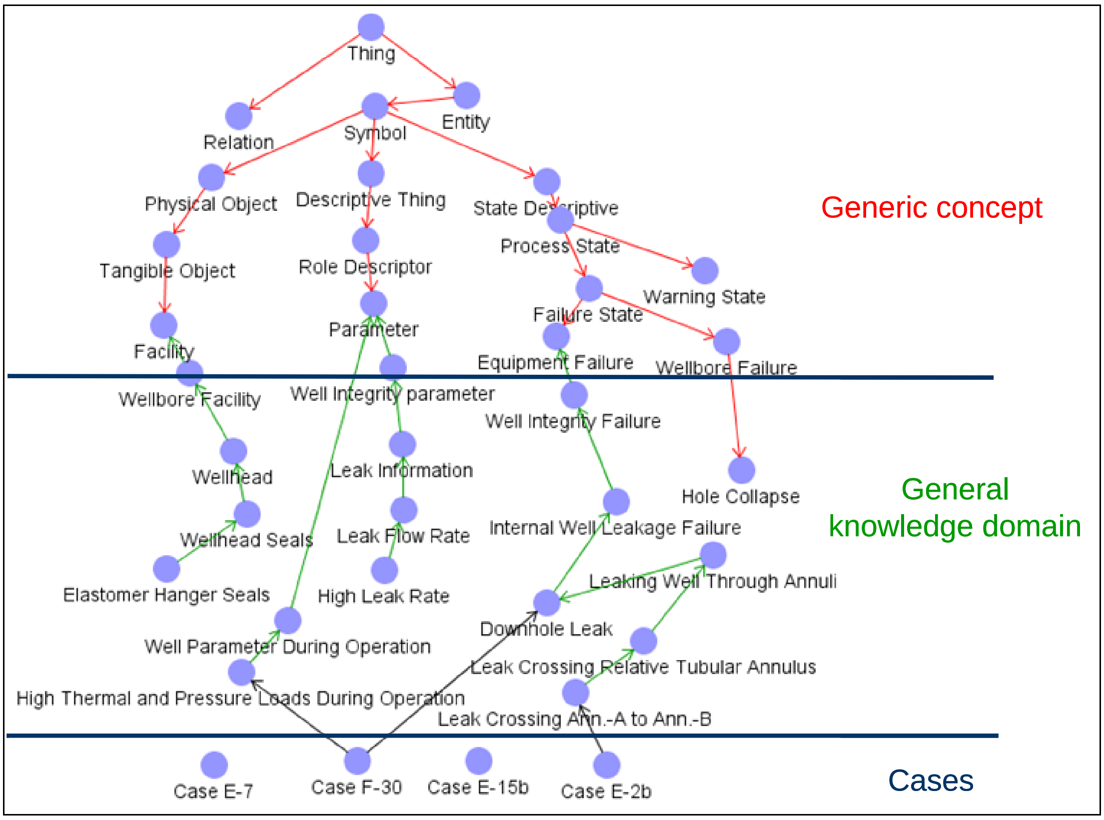


Figure 4.3 **Some part of integration between general domain knowledge and cases in the Wellogy model (the red lines show the development process is top-down, and the black & green lines show the bottom-up development process).**

4.6 Relations

All kinds of relations used in the Wellogy model are subclasses of `Relation` as shown in ***Figure 4.4***. The relations are divided into these groups:

- **Causal Relation** - gives the relation strength to entities which have contribution in the causal relationships. The strength value is between 0 and 1 (the weaker strength has lower value and stronger strength has higher value. This relations are (the numbers are strength value); always causes (0.9), causes (0.7), leads to (0.5), enables (0.5), sometimes causes (0.5), indicates (0.4), implies (0.4), has potential (0.2).
- **Structural Relation** - these type of relations are used in the hierarchy of ontology and normally the strength value is close to 1. There are only two structural relations; "`has subclass`" and "`has instance`".
- **Case Relation** - gives administrative relations to the case; has outcome, has case task, has case status, etc.
- **"has finding"** - gives the specific relations to finding of the case such as "`has repair action`", "`has case task`", "`has observation`" and "`has failure`".

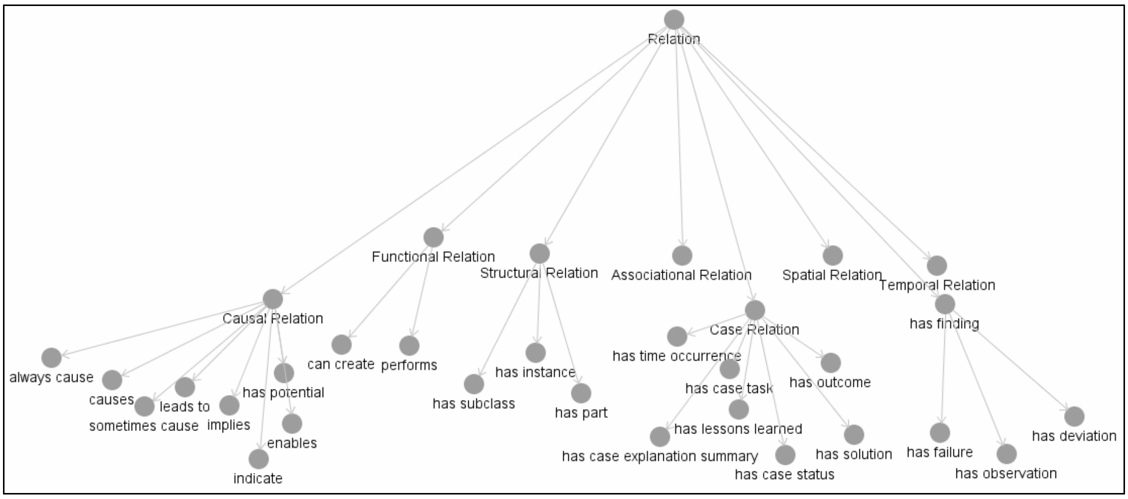


Figure 4.4 **Different kind of relations used in the Wellogy model (the relation line = `has subclass`).**

The strength value for all relations in oil well engineering domain was given in ***Table 2.2***.

4.7 Tangible objects for leaking wells cases

The screen shot of the `Tangible Object` for the leaking well model is shown in ***Figure 4.5***. The `Process Material` and `Equipment` involved in the leaking wells have been collected and classified in a hierarchically format, and belong to the `Physical Object`. The `Tangible Object` has two main subclasses; `Facility` and `Process Materials`. The `Facility` contains `Drilling and Downhole Equipment` and components, whereas `Process Material` contains generally `Drilling and Well Fluids`, and generated `Drilling Cuttings`.

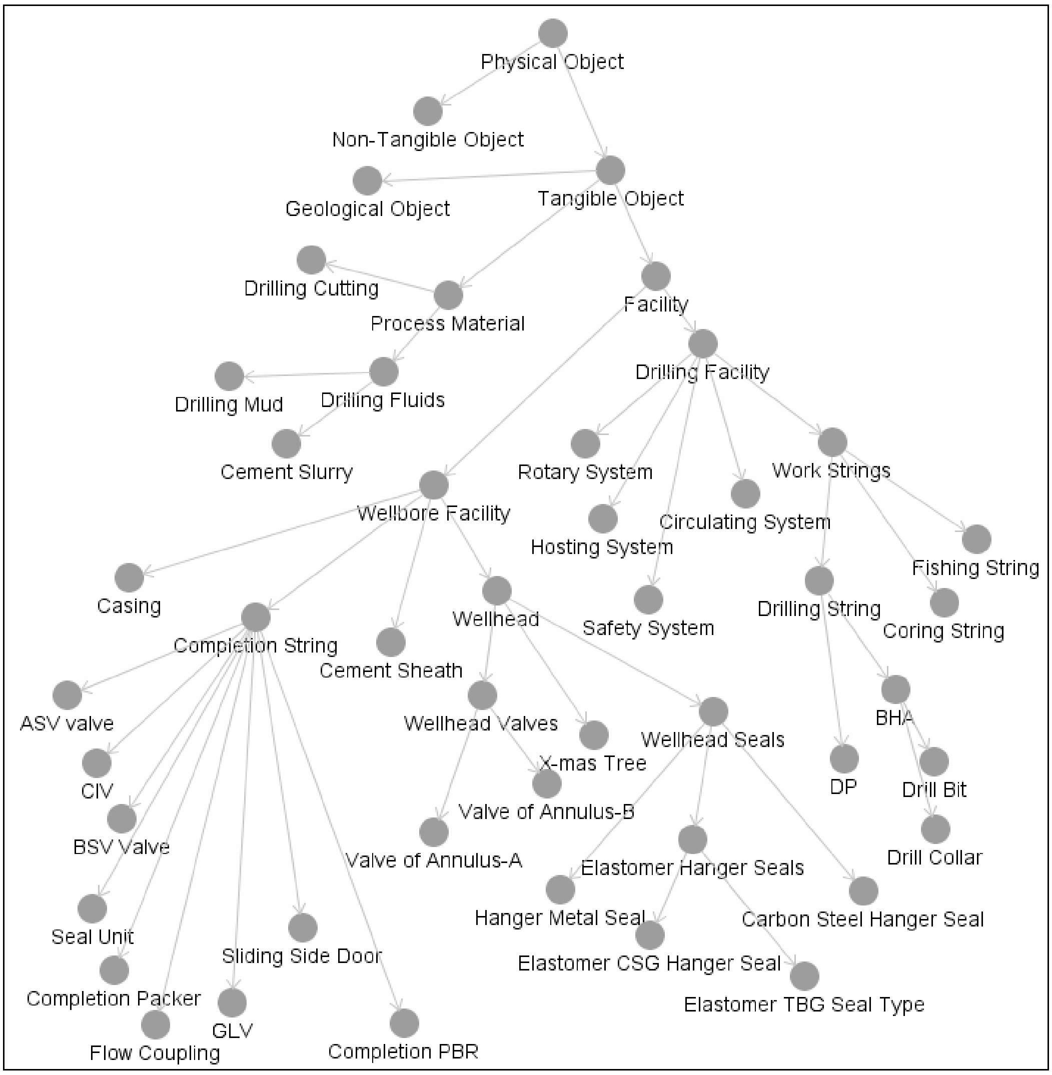


Figure 4.5 Physical object model for leaking well cases modelled in Wellogy.

4.8 Modelling of the parameter for leaking well cases

Figure 4.6 demonstrates modelling of the "`Parameter`" for the leaking well cases. The "`Parameter`" entity contains both qualitative and quantitative parameters. As the model is mostly built for the purpose of leaking wells, most of the findings (parameters) are related to the well integrity and particularly to leaking wells.

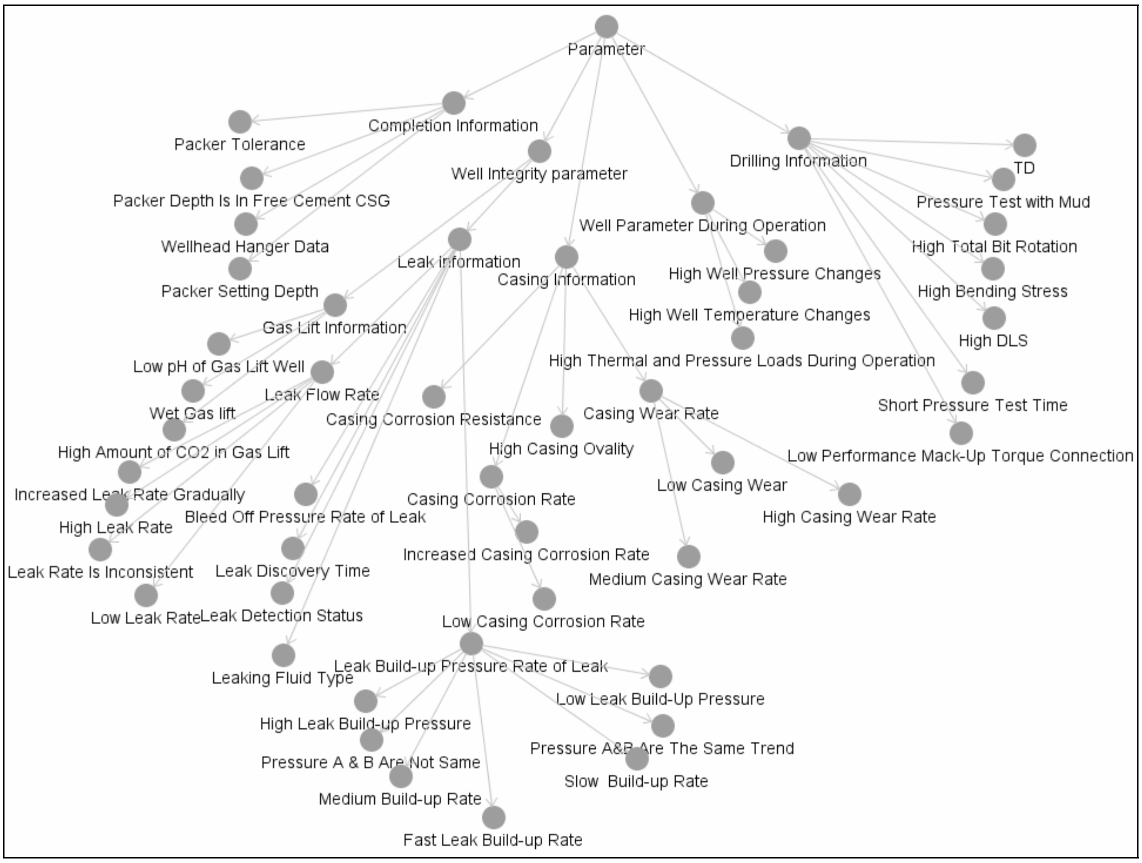


Figure 4.6 Modelling of "Parameter" for leaking wells in Wellogy.

4.8.1 State and task modelling

Figure 4.7 depicts the modelling for `State`. The description of the leak wells is given to this entity. The `State` entity has many subclasses. The main subclasses are; "`Normal State`, `Human State`, `Alarm State`, and `Failure State`. `Normal State` describes normal conditions (e.g. `Hole Condition Is Normal`). `Human State` also describes states of human or human factors connections with the problem of the case, and it covers both normal and abnormal states only related to the human. `Alarm State` is not a failure state, but it can be considered as indications of the failure state. For instance, `High ROP` can be considered as alarm state for `Well Kick`. In the `Alarm State` situations the processes and activities are not interrupted, in contrast of `Failure State` where all routine processes and activities turn to a new situation. `Failure State` covers abnormal set of situations, conditions, and episodes which occur during the time interval of the case. In this condition, all processes are turned to the failure mode, i.e. the time is spent on solving the failure. For instance, `Well Leakage Failure`, and `Stuck Pipe` are typical examples of `Failure State.`

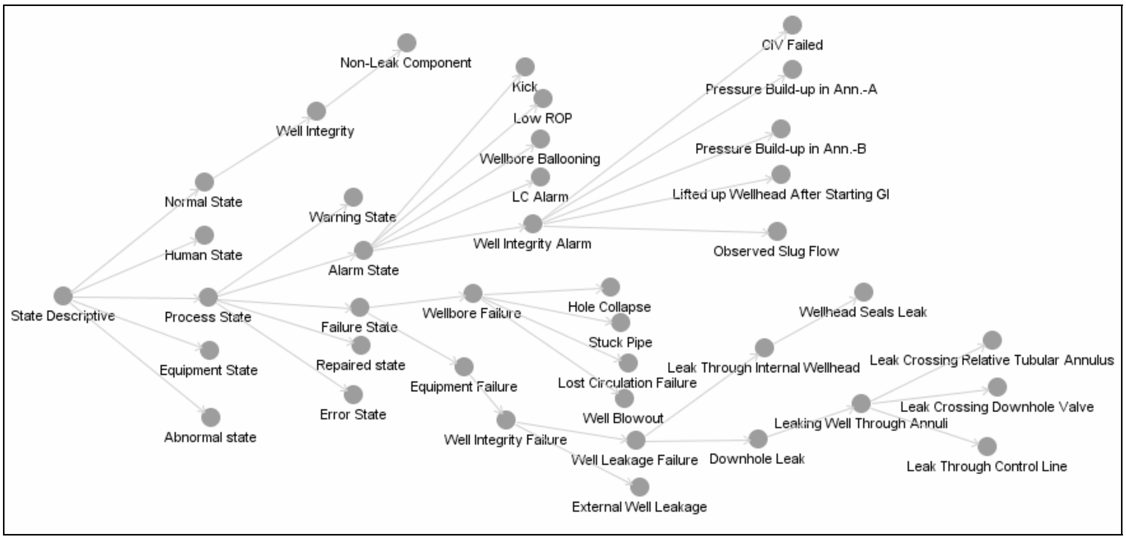


Figure 4.7 State for leaking well cases modelled in Wellogy.

As shown in ***Figure 4.8***, the `Task Descriptive` has two subclasses; `Single Task` and `Combined Task`. The `Single Task` refers to a specific and unique task which is expected to achieve, while in `Combined Task` more than one task are expected. As discussed previously, task is the objective of a CBR model which can be for example; solving, diagnosis, root cause, and classify of a failure.

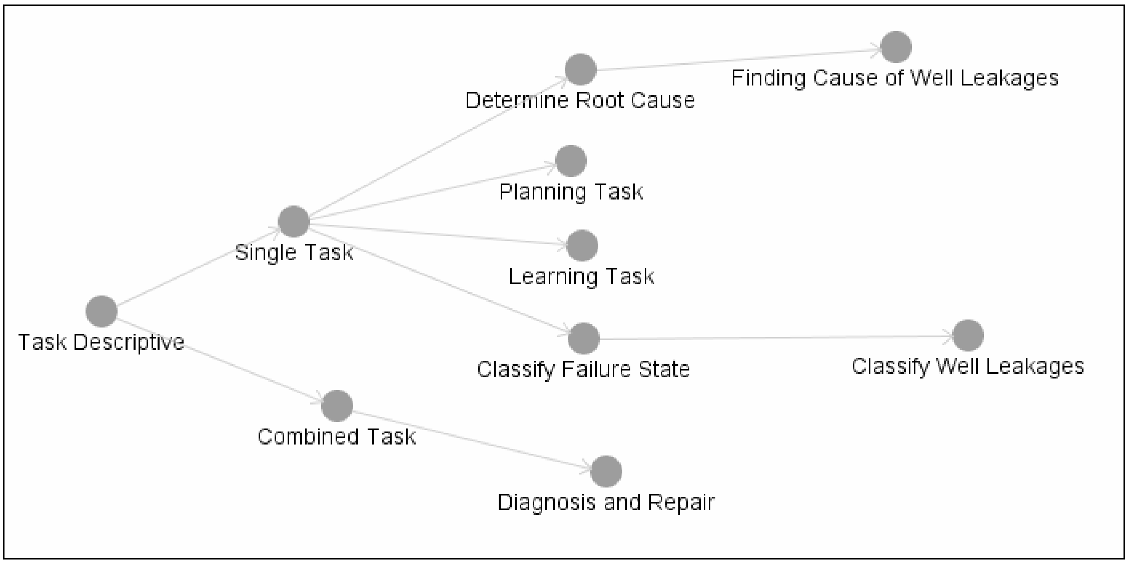


Figure 4.8 Task model for leaking well cases in Wellogy.

4.8.2 Textual description

Figure 4.9 shows the `Textual Description` model for leaking well cases. As illustrated in this diagram, those parts of the ontology which explain the case textually can be modelled below this branch. The textual entities which are giving more information about cases are inserted below the `Textual Description` entity. For instance, name of a country, a field and a well, type of a well, special well descriptions, and text boxes which explain the case characteristics are given in `Textual Description.`

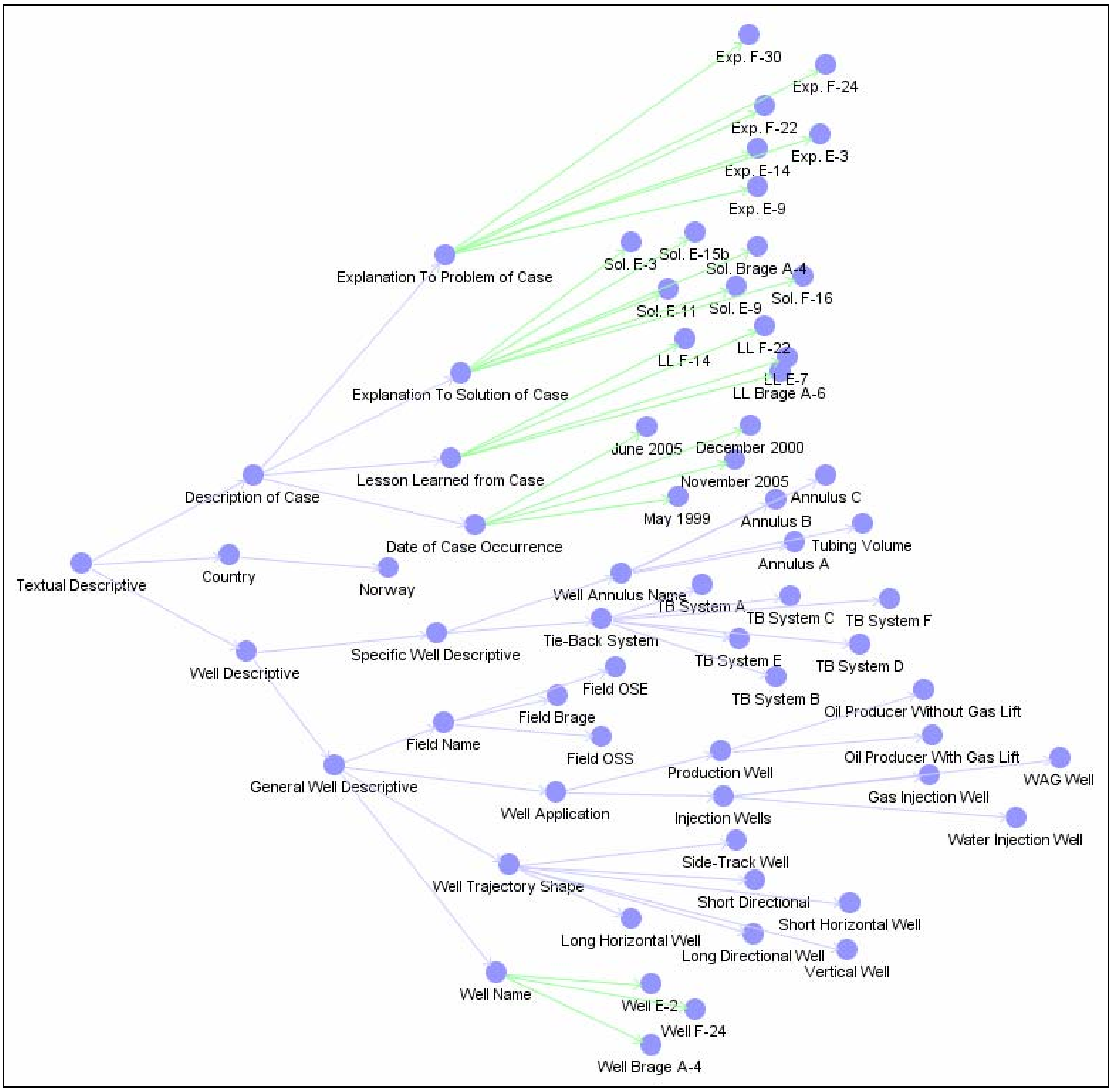


Figure 4.9 **Textual Description model for leaking well cases used in Wellogy (blue line = `has subclass`, green line = `has instance`).**

4.9 Case production for leaking wells

Based on the database for leaking wells, two types of cases are modelled. The first case type is solved cases (12 cases). In these cases, the leak components have been generally discovered and fully proven, and repair actions have been executed for most of them. The task is identical for all cases and defined as `Finding Cause of Well Leakages`. The unsolved cases, 6 cases, the leak components are unknown or have not yet been fully proven.

Table 4.1 shows a general template for constructing leaking well cases. The technical and process administration parts are fairly the same for solved, unsolved, and processed cases. 10 to 15 observations have been allocated for each case. The number of given observations are dependent on the available information for each case.

Table 4.1 Template for case structure of leaking wells.

Format	Type of case information (relation type)		Value
Symbolic code	Technical administration	Name of case	
		Well name	
		Field name	
		Wellhead Location	Platform / Subsea
		Time of leak	
		Country	
	Process administration	Failure of case	Well leakage through annuli
		Case statues	Solved / unsolved / processed
		Task of leak (option 1)	Finding cause of leak
		Task of leak (option 2)	Localizing leak location
		Outcome of case	The result of applied solution
	Observation	Observations type 1	5 to 8 observations for describing the failure
		Observations type 2	5 to 8 observations for describing the task
Text	Conclusion	Case description	Short written text about the case
		Explanation	
		Solution (to task)	
		Experience (lessons learned)	

The 12 solved cases have been categorized into 5 groups based on the found solutions (causes) as shown in ***Table 4.2***. These groups are:

1. Group A: the cause for this group is wrong material selection for TBG and CSG seal hanger. These group are divided into three subgroups; group A-1 contains three cases, wells A-4, A-6, E-7, where the cause for all three is `Carbon Steel CSG Hanger Seal`. Subgroup A-2 contains one case, well E-2a, and the cause is `Elastomer CSG Hanger Seal`. Subgroup A-3 also contains one case, well E-4, and the cause is `Elastomer TBG Hanger Seal`. All three subgroups have been reported as wellhead leak or surface leak. The location of the leak is illustrated in ***Figure 4.11***.

2. Group B: the cause for this group is `Non-Chrome Casing`. This group contains two wells; E-3 and E-15b. For the gas lift well, the production casings and tie-backs (9-5/8" - 10-3/4"), the high resistance casing for corrosion are needed, because the gas generally contains corrosive components such as CO2, H2S. The casings which meet this requirement should have high percentage of chrome e.g. 13 %. However, due to some reasons as for example changing well application during well lifecycle, the `Non-Chrome CSG` was used for some gas lift wells. The leak occurred downhole of the well and fluid crossing the casing caused fluid communication from annulus-A to annulus-B.

3. Group C: this group is similar to the group B in matter of leak component (casing). However, the reason or “cause” for this group is `Scale Inhibitor in GL`. This group contains two wells, E-4 and F-24. In both wells the line of chemical injection valve (CIV) failed and scale inhibitor was mixed with the gas lift and pumped through the annulus A. This caused a reduction in the pH of the gas lift and accordingly a speed-up in the corrosion rate of the casing and tie-back.

4. Group D: this group contains well E-9 and F-30. The cause for this group was found as `High Thermal and Pressure Loads during Operation`. For these two cases, the leak occurred just for a short time after start-up operation (production / injection) which found as a common practice for the WAG wells.

5. Group E: this group contains only one case, well F-14. The cause for this group is considered as `Insufficient Integrity Pressure Test`. This case has leaks in completion components such as GLV and PBR as shown in ***Figure 4.11***. The cause of this kind of failure was considered as insufficient or incomplete pressure test during installation. Generally, integrity pressure test is performed when completion string is installed. The test fluid is normally drilling fluids (mud) which contain particle which may seal small leak points and accordingly it could not see the leak during installation. Moreover, the pressure test period is about 10 minutes which is short to detect small leakages.

Table 4.2 **Categorizing the cases based on solutions (causes) and with respect to the location of the leaks.**

Group			Cases (leaking wells)	Problem	Location of leakage	Task	Solution
Solved cases	A	A1	A-4, A-6, E-7	Well integrity failure	Wellhead hanger seals (carbon steel CSG seal)	Finding cause of well leakage	Carbon steel CSG seal
		A2	E-2a		Wellhead hanger seals		Elastomer CSG hanger seal
		A3	E-14		Wellhead hanger seals		Elastomer TBG hanger seal
	B		E-3, E-15b		Casing / tie-back		Non-chrome casing
	C		E-4, F-24		Casing / tie-back		Scale inhibitor in GL
	D		E-9, F-30		Completion components (packer/PBR)		High thermal and pressure loads during operation
	E		F-14		Completion components (packer/PBR)		Insufficient integrity pressure test
Unsolved cases			E-2b, E-11, E-15a, F-16, F-22, F-29		Uncertain		Should be found

Figure 4.10 shows all solved and unsolved cases which have been modelled in the Wellogy model. As shown the 7 solutions have been obtained for the 12 solved cases.

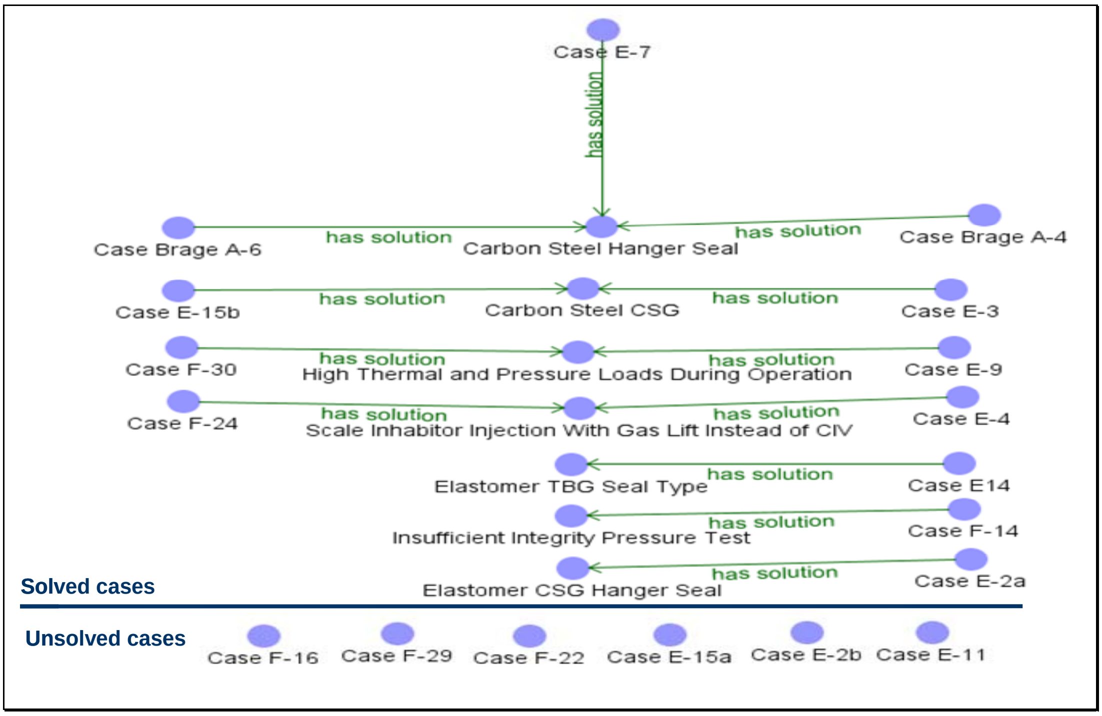


Figure 4.10 Solved cases with the solutions and unsolved cases modelled in Wellogy.

Figure 4.11 shows schematically different leak locations and different causes for group A-E.

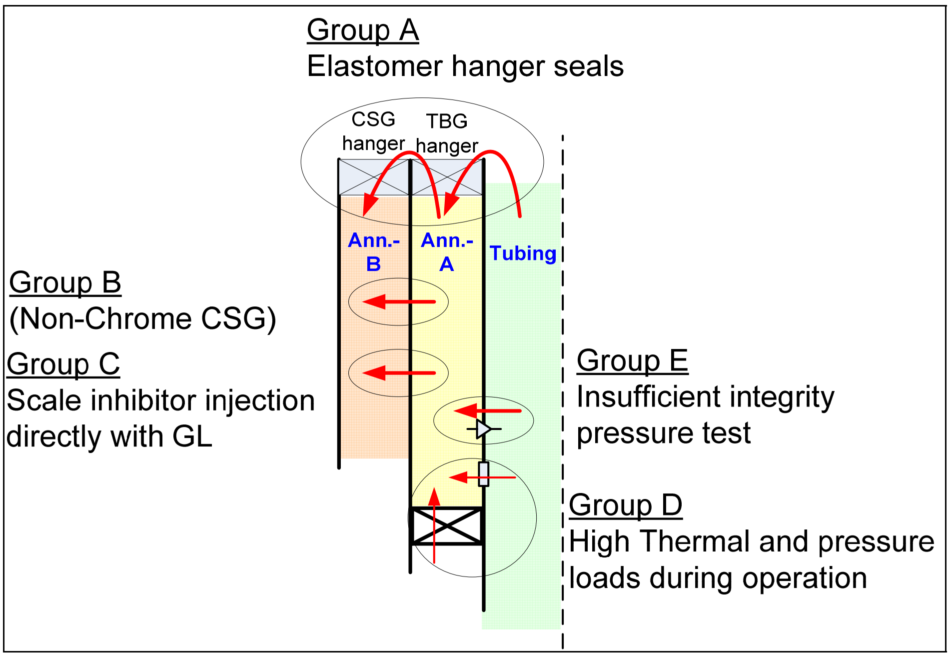


Figure 4.11 Grouping leak locations and causes.

Figure 4.12 shows the important part of the ontology structure and showing integration of general knowledge and cases. As discussed before, in the Creek system, CBR and MBR are combined together and build a single ontology model.

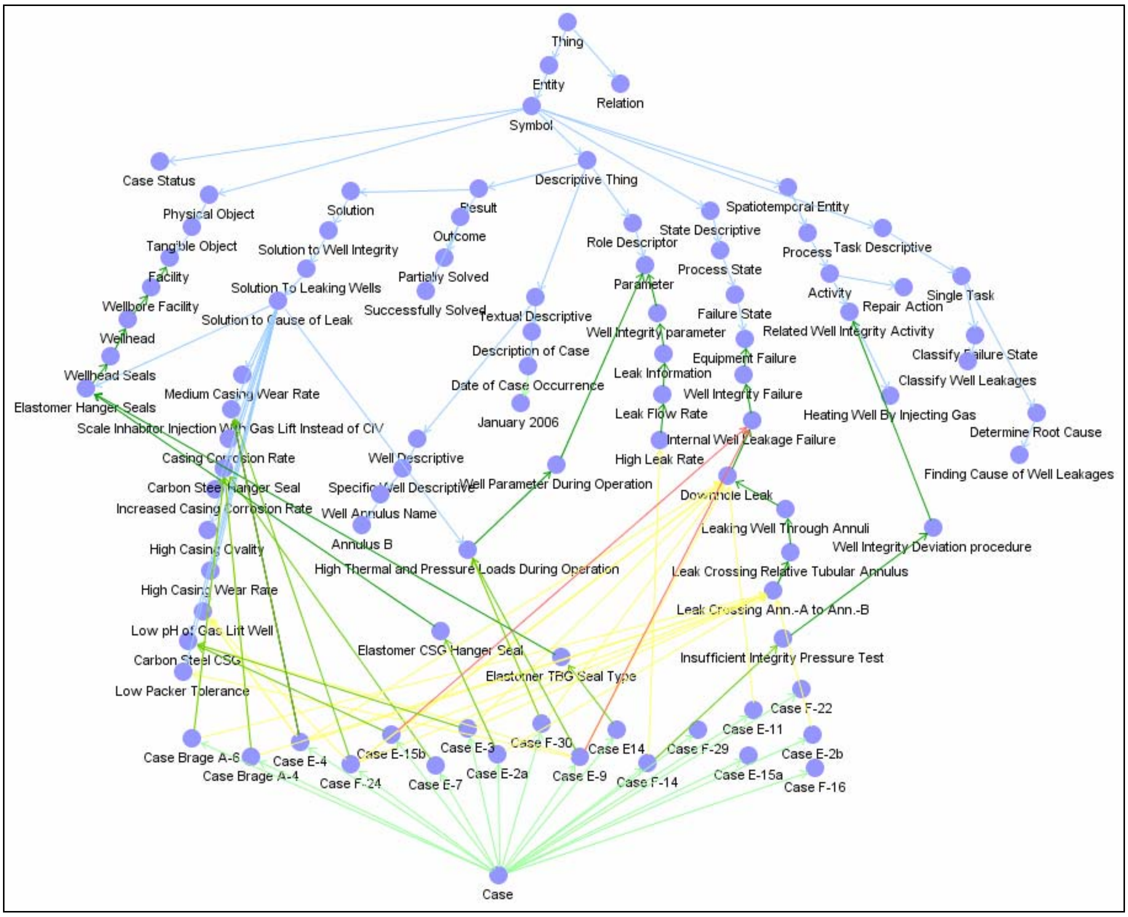


Figure 4.12 **Ontology structure showing integration between general knowledge (top) and cases (bottom) in the Wellogy model.**

Figure 4.13 shows a screen shot of 12 solved cases in the Wellogy model. The failure is identical for all cases, `Well Leakage Failure` as shown by the red lines. The seven (7) solutions (i.e. causes for the failure) are linked to the cases indicated by brownish lines. Each solution can have some causal relationships which are given in the "causal relationship model" as shown in ***Figure 4.14***. These relationships enhance the reasoning process to find closest solutions for the unsolved cases.

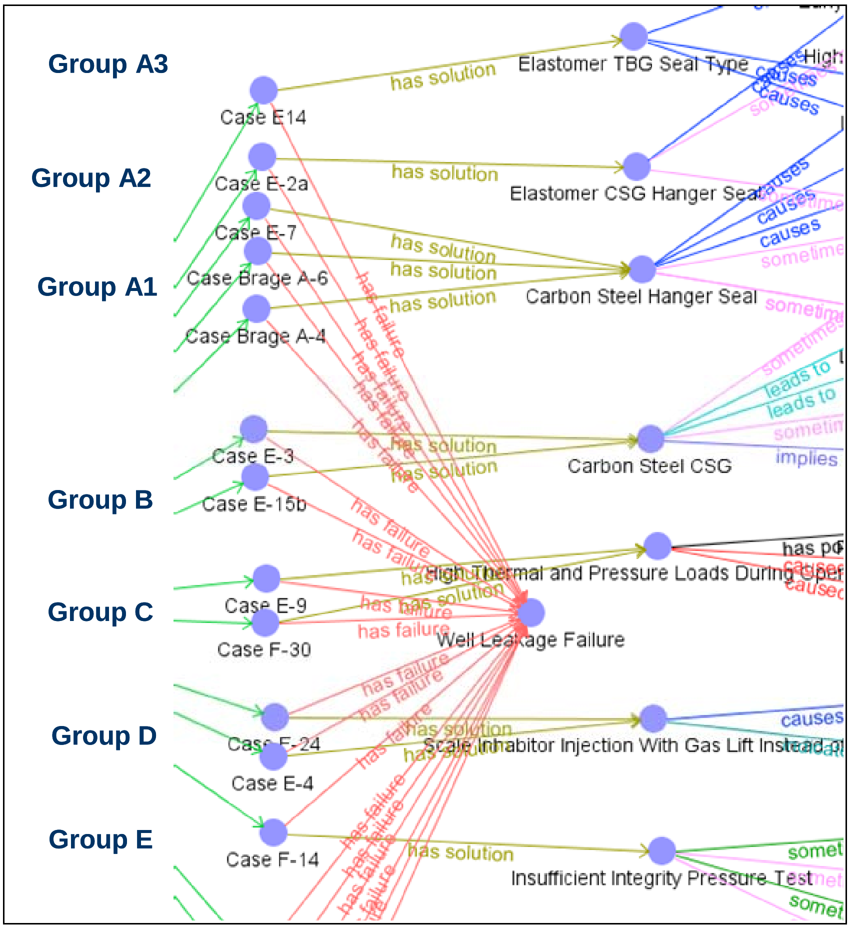


Figure 4.13 **Screen-shot of the Wellogy model for solved cases; groups, and solutions for one similar failure.**

4.10 Causal relationships

The centre of the model in Wellogy is `causal relationships`. These relationships are created based on the findings for the solved cases. The proven knowledge and information in relation to solved cased are encoded and the links (relations) with different strength valves are established. ***Figure 4.14*** shows a screen shot of causal relationships for leaking well cases modelled in Wellogy.

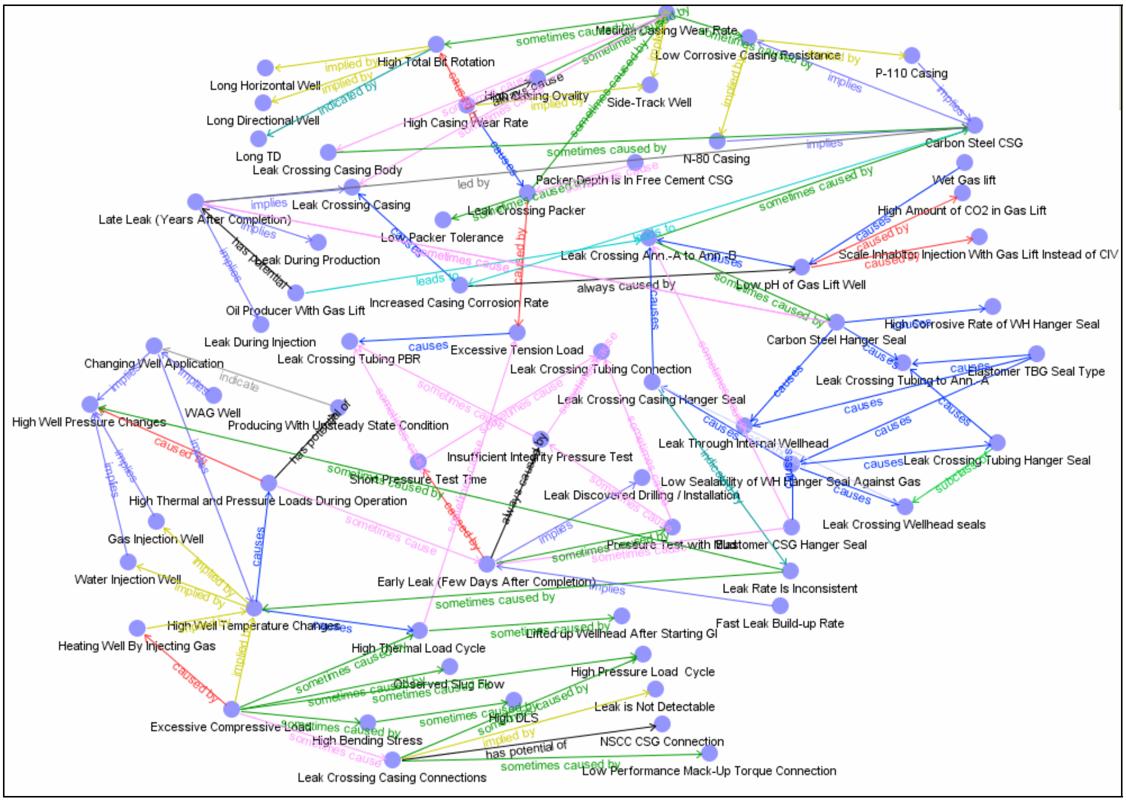


Figure 4.14 Causal relationship for leaking well case in the Wellogy model.

Totally 113 causal relationships between entities have been defined. By exporting the Wellogy model to an XML file, we can sort all causal relationships and demonstrating them in tables. The outputs of XML file for causal relationship are given in ***Table 4.3*** to ***Table 4.8*** for different types of causal relations. These tables give the list of causal relationships with different strength values established for the leaking well cases. As previously mentioned, the relation type for each strength-value can be defined as `direct-relation` and `inverse-relation`, e.g. `causes` and `caused by` has the strength value 0.7.

Table 4.3 Causal relationships when the relation is "`always caused by`" (strength value = 0.9) modelled in Wellogy.

From entity	Relation type	To entity
Early Leak (Few Days After Completion)	always caused	Insufficient Integrity Pressure Test
High Casing Ovality	always caused	High Casing Wear Rate
Increased Casing Corrosion Rate	always caused	Low pH of Gas Lift Well

Table 4.4 **Causal relationships when the relation is "causes" and inverse relation "caused by" - (strength value = 0.7) modelled in Wellogy.**

From entity	Relation type	To entity
Bit RPM Variation	caused by	Stick Slip
Drillstring Washout	caused by	Fatigue
Early Leak (Few Days After Completion)	caused by	Short Pressure Test Time
Excessive Compressive Load	caused by	Heating Well By Injecting Gas
High Casing Wear Rate	caused by	High Total Bit Rotation
High Pressure Load Cycle	caused by	High Well Pressure Changes
High Thermal and Pressure Loads During C	caused by	High Well Pressure Changes
High Thermal and Pressure Loads During C	caused by	High Well Temperature Changes
High Thermal Load Cycle	caused by	High Well Temperature Changes
Leak Crossing Ann.-A to Ann.-B	caused by	Low pH of Gas Lift Well
Leak Crossing Ann.-A to Ann.-B	caused by	Leak Crossing Casing Hanger Seal
Leak Crossing Casing Hanger Seal	caused by	Low Sealability of WH Hanger Seal Against Gas
Leak Crossing Tubing Hanger Seal	caused by	Low Sealability of WH Hanger Seal Against Gas
Leak Crossing Wellhead seals	caused by	Low Sealability of WH Hanger Seal Against Gas
Low pH of Gas Lift Well	caused by	Scale Inhibitor Injection With Gas Lift Instead of CIV
Low pH of Gas Lift Well	caused by	Wet Gas lift
Stick Slip	caused by	Sticky Formation
Carbon Steel Hanger Seal	causes	High Corrosive Rate of WH Hanger Seal
Carbon Steel Hanger Seal	causes	Leak Through Internal Wellhead
Carbon Steel Hanger Seal	causes	Leak Crossing Tubing to Ann.-A
Changing Well Application (GI-WI)	causes	Cooling Well By Water Injection
Cooling Well By Water Injection	causes	Excessive Tension Load
Corrosion	causes	Drillstring Washout
Drillstring Vibration	causes	Drillstring Washout
Elastomer CSG Hanger Seal	causes	Low Sealability of WH Hanger Seal Against Gas
Elastomer TBG Seal Type	causes	Leak Through Internal Wellhead
Elastomer TBG Seal Type	causes	Leak Crossing Tubing to Ann.-A
Elastomer TBG Seal Type	causes	Low Sealability of WH Hanger Seal Against Gas
Excessive Tension Load	causes	Leak Crossing Tubing PBR
Excessive Tension Load	causes	Leak Crossing Packer
High Amount of CO2 in Gas Lift	causes	Low pH of Gas Lift Well
High Casing Wear Rate	causes	Leak Crossing Packer
Increased Casing Corrosion Rate	causes	Leak Crossing Casing
Leak Crossing Tubing Hanger Seal	causes	Leak Crossing Tubing to Ann.-A

Table 4.5 **Causal relationships when the relation is "`sometimes causes`" and "`sometimes caused by`" - (strength value = 0.5) modelled in Wellogy.**

From entity	Relation type	To entity
Carbon Steel CSG	sometimes causes	Leak Crossing Casing Body
Carbon Steel CSG	sometimes causes	Leak Crossing Ann.-A to Ann.-B
Carbon Steel Hanger Seal	sometimes causes	Leak Crossing Ann.-A to Ann.-B
Carbon Steel Hanger Seal	sometimes causes	Late Leak (Years After Completion)
Elastomer CSG Hanger Seal	sometimes causes	Leak Crossing Ann.-A to Ann.-B
Elastomer Hanger Seals	sometimes causes	Wellhead Seals Leak
Excessive Compressive Load	sometimes causes	Leak Crossing Casing Connections
High Pressure Load Cycle	sometimes causes	Leak Crossing Casing Connections
High Total Bit Rotation	sometimes causes	Medium Casing Wear Rate
High Well Pressure Changes	sometimes causes	Leak Rate Is Inconsistent
High Well Temperature Changes	sometimes causes	Leak Rate Is Inconsistent
Insufficient Integrity Pressure Test	sometimes causes	Leak Crossing Tubing PBR
Insufficient Integrity Pressure Test	sometimes causes	Leak Crossing Tubing Connection
Low Corrosive Casing Resistance	sometimes causes	Medium Casing Wear Rate
Bit Balling	sometimes caused by	Sticky Formation
Clay Swelling	sometimes caused by	WBM
Decreasing Stick-Slip	sometimes caused by	Increasing Well Depth
Drillstring Twist Off	sometimes caused by	Poor Surface Recognition
Drillstring Twist Off	sometimes caused by	High Bit Torque
Drillstring Twist Off	sometimes caused by	Drillstring Washout
Early Leak (Few Days After Completion)	sometimes caused by	High Thermal and Pressure Loads During Operation
Early Leak (Few Days After Completion)	sometimes caused by	Pressure Test with Mud
Early Leak (Few Days After Completion)	sometimes caused by	Elastomer CSG Hanger Seal
Early Leak (Few Days After Completion)	sometimes caused by	Elastomer TBG Seal Type
Excessive Compressive Load	sometimes caused by	High Bending Stress
Excessive Compressive Load	sometimes caused by	High Pressure Load Cycle
Excessive Compressive Load	sometimes caused by	High Thermal Load Cycle
Excessive Compressive Load	sometimes caused by	Observed Slug Flow
Excessive Tension Load	sometimes caused by	High Pressure Load Cycle
Excessive Tension Load	sometimes caused by	High Thermal Load Cycle
High Bending Stress	sometimes caused by	High DLS
High Casing Ovality	sometimes caused by	Medium Casing Wear Rate
High Stick-slip	sometimes caused by	Shallower Well Depth
High Thermal Load Cycle	sometimes caused by	Lifted up Wellhead After Starting GI
Insufficient Integrity Pressure Test	sometimes caused by	Pressure Test with Mud
Insufficient Integrity Pressure Test	sometimes caused by	Short Pressure Test Time
Leak Crossing Casing	sometimes caused by	Medium Casing Wear Rate
Leak Crossing Casing Body	sometimes caused by	Medium Casing Wear Rate
Leak Crossing Casing Connections	sometimes caused by	Low Performance Mack-Up Torque Connection
Leak Crossing Packer	sometimes caused by	Low Packer Tolerance
Leak Crossing Packer	sometimes caused by	Medium Casing Wear Rate
Leak Crossing Packer	sometimes caused by	Packer Depth Is In Free Cement CSG
Leak Crossing Tubing Connection	sometimes caused by	Short Pressure Test Time
Leak Crossing Tubing Connection	sometimes caused by	Pressure Test with Mud
Leak Crossing Tubing PBR	sometimes caused by	Short Pressure Test Time
Leak is Not Detectable	sometimes caused by	Slow Build-up Rate

Table 4.6 **Causal relationships when the relation is "`leads to`" and inverse relation "`led to by`" - (strength value = 0.5) modelled in Wellogy.**

From entity	Relation type	To entity
Carbon Steel CSG	leads to	Late Leak (Years After Completion)
Carbon Steel CSG	leads to	Increased Casing Corrosion Rate
Early Leak (Few Days After Completion)	led to by	Short Pressure Test Time
Early Leak (Few Days After Completion)	led to by	Pressure Test with Mud
Leak Crossing Ann.-A to Ann.-B	led to by	Oil Producer With Gas Lift

Table 4.7 **Causal relationships when the relation is "`implies`" - (strength value = 0.4) modelled in Wellogy.**

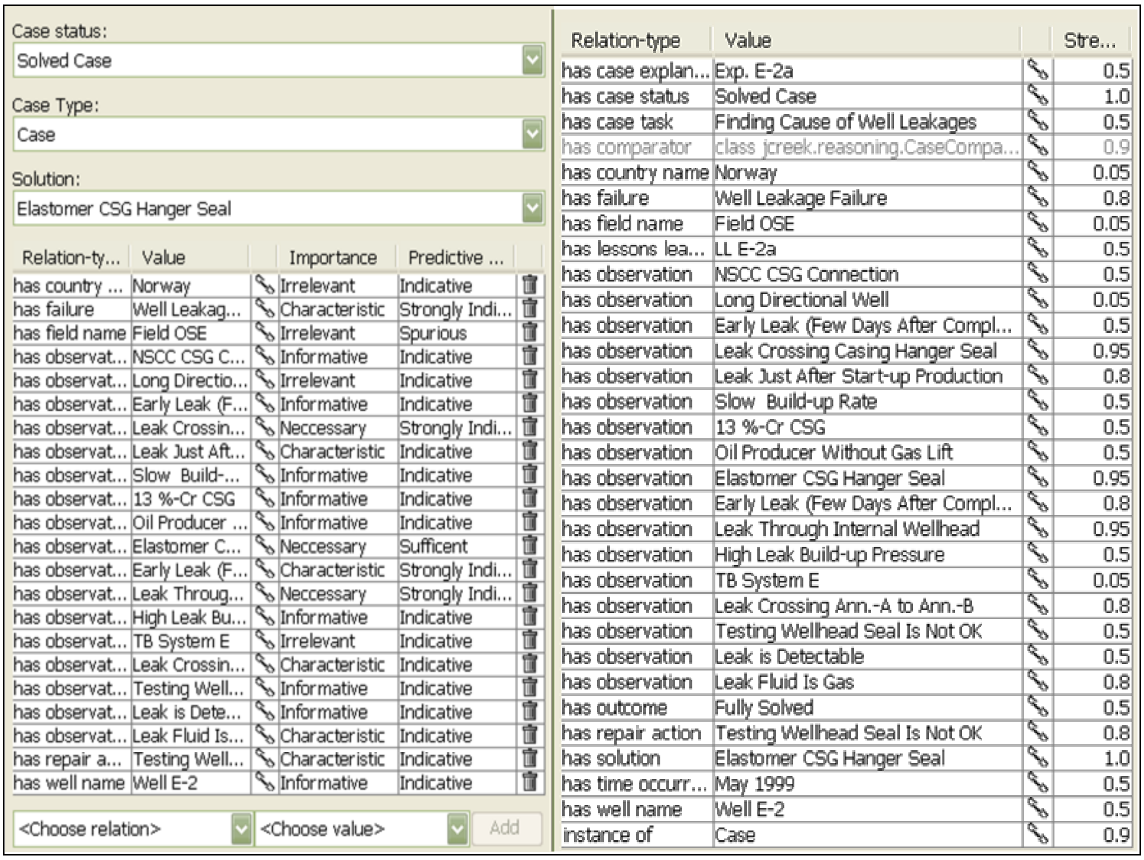
From entity	Relation type	To entity
13 %-Cr CSG	implies	High Corrosive Casing Resistance
Carbon Steel CSG	implies	Low Corrosive Casing Resistance
Changing Well Application	implies	High Well Pressure Changes
Changing Well Application	implies	High Well Temperature Changes
Early Leak (Few Days After Completion)	implies	Leak Discovered Drilling / Installation
Gas Injection Well	implies	High Well Temperature Changes
Gas Injection Well	implies	High Well Pressure Changes
High Leak Build-up Pressure	implies	Leak Crossing Casing
High Leak Build-up Pressure	implies	Leak Crossing Casing Tie-Back
Late Leak (Years After Completion)	implies	Leak Crossing Casing
Late Leak (Years After Completion)	implies	Leak During Injection
Late Leak (Years After Completion)	implies	Leak During Production
Leak is Not Detectable	implies	Low Leak Rate
Low Leak Build-Up Pressure	implies	Wellhead Seals Leak

Table 4.8 **Causal relationships when the relation is "`indicates`" and inverse relation "`indicated by`" - (strength value = 0.4) modelled in Wellogy.**

From entity	Relation type	To entity
Changing Well Application	indicated by	Producing With Unsteady State Condition
Downhole Leak	indicated by	Testing Wellhead Seal Is OK
Drillstring Washout	indicated by	Pump Pressure Drop
High Total Bit Rotation	indicated by	Long TD
Leak Crossing Ann.-A to Ann.-B	indicated by	Pressure Build-up in Ann.-B
Leak Crossing Casing	indicated by	Pressure A & B Are Not Same
Leak Crossing Casing	indicated by	Pressure A&B Are The Same Trend
Leak Crossing Casing Hanger Seal	indicated by	Leak Rate Is Inconsistent
Leak Crossing Tubing to Ann.-A	indicated by	Pressure Build-up in Ann.-A
Leak Crossing Wellhead seals	indicated by	Testing Wellhead Seal Is Not OK
CIV Failed	indicates	Scale Inhibitor Injection With Gas Lift Instead of CIV

4.11 Cases in the Wellogy model

The 18 cases have been encoded in the Wellogy model. ***Figure 4.15*** shows as an example for the solved case "well E-2a". As shown in this figure, there are two views; `Case View` and `Current Frame View`. These two views are fairly similar. The additional findings can be seen in the Current Frame View. These additional findings represent entities which are not belonged to `has finding;` e.g. `has case task`, `has lessons learned`, `has time occurrence`, and `has case explanation`. These kinds of findings which act as administrational findings for the case may not contribute in the reasoning process as well as and matching results.



Case status: Solved Case

Case Type: Case

Solution: Elastomer CSG Hanger Seal

Relation-ty...	Value	Importance	Predictive ...
has country ...	Norway	Irrelevant	Indicative
has failure	Well Leakag...	Characteristic	Strongly Indi...
has field name	Field OSE	Irrelevant	Spurious
has observat...	NSCC CSG C...	Informative	Indicative
has observat...	Long Directio...	Irrelevant	Indicative
has observat...	Early Leak (F...	Informative	Indicative
has observat...	Leak Crossin...	Neccessary	Strongly Indi...
has observat...	Leak Just Aft...	Characteristic	Indicative
has observat...	Slow Build-...	Informative	Indicative
has observat...	13 %-Cr CSG	Informative	Indicative
has observat...	Oil Producer ...	Informative	Indicative
has observat...	Elastomer C...	Neccessary	Sufficent
has observat...	Early Leak (F...	Characteristic	Strongly Indi...
has observat...	Leak Throug...	Neccessary	Strongly Indi...
has observat...	High Leak Bu...	Informative	Indicative
has observat...	TB System E	Irrelevant	Indicative
has observat...	Leak Crossin...	Characteristic	Indicative
has observat...	Testing Well...	Informative	Indicative
has observat...	Leak is Dete...	Informative	Indicative
has observat...	Leak Fluid Is...	Characteristic	Indicative
has repair a...	Testing Well...	Characteristic	Indicative
has well name	Well E-2	Informative	Indicative

<Choose relation> <Choose value> Add

Relation-type	Value	Stre...
has case explan...	Exp. E-2a	0.5
has case status	Solved Case	1.0
has case task	Finding Cause of Well Leakages	0.5
has comparator	class jcreek.reasoning.CaseCompa...	0.9
has country name	Norway	0.05
has failure	Well Leakage Failure	0.8
has field name	Field OSE	0.05
has lessons lea...	LL E-2a	0.5
has observation	NSCC CSG Connection	0.5
has observation	Long Directional Well	0.05
has observation	Early Leak (Few Days After Compl...	0.5
has observation	Leak Crossing Casing Hanger Seal	0.95
has observation	Leak Just After Start-up Production	0.8
has observation	Slow Build-up Rate	0.5
has observation	13 %-Cr CSG	0.5
has observation	Oil Producer Without Gas Lift	0.5
has observation	Elastomer CSG Hanger Seal	0.95
has observation	Early Leak (Few Days After Compl...	0.8
has observation	Leak Through Internal Wellhead	0.95
has observation	High Leak Build-up Pressure	0.5
has observation	TB System E	0.05
has observation	Leak Crossing Ann.-A to Ann.-B	0.8
has observation	Testing Wellhead Seal Is Not OK	0.5
has observation	Leak is Detectable	0.5
has observation	Leak Fluid Is Gas	0.8
has outcome	Fully Solved	0.5
has repair action	Testing Wellhead Seal Is Not OK	0.8
has solution	Elastomer CSG Hanger Seal	1.0
has time occurr...	May 1999	0.5
has well name	Well E-2	0.5
instance of	Case	0.9

Figure 4.15 **Case view in the Creek interface for case "well E-2a"- solved case (left view = `Case View`, right = `Current Frame View`). In the `Case View`, the degree of importance and predictive strength are given to the findings. In the `Current Frame View`, this degree is converted to numbers.**

In addition to the symbolic entities, the cases also contain text explanations for fulfilling the case story. This text information is given to enhance understanding the case and can be used after they are retrieved as best similar candidate case. The following texts are given for the cases:

- **Case Description -** the free text is given in a text-box which has been provided in the view of the software as a heading of the case which can be seen in "`Case View`" or "`Current Frame View`" describes or introduces the case.

- **Case Explanation** - this free text is given in a defined entity which is given only for this purpose (i.e. not for reasoning reason). For instance, Exp.E-2a is an entity used for explanation of well E-2a. This text explanation gives more detail about the failure of the case. This entity can be seen in ***Figure 4.15.***

- **Lesson Learned** - this free text is also given in a defined entity. For instance, LL E-2a denotes lessons learned from well E-2a. This text is supporting the solution and also giving recommendations and actions for the case. This entity can be seen in ***Figure 4.15.***

4.12 Test procedure for CBR results

In order to obtain better results, a high number of cases should be constructed in the Wellogy model. When all cases with ontology are built in the Wellogy model and causal contentions are made, the model can be tested. Cases are grouped with solved and unsolved cases. Solved cases which have the same failure can be regrouped based on solutions. Assume we have 14 cases, 12 solved and 2 unsolved cases as illustrated in ***Figure 4.16***.

Solved cases- group A	<u>**C1**</u> P1 S1	<u>**C2**</u> P1 S1	<u>**C3**</u> P1 S1	<u>**C4**</u> P1 S1
Solved cases- group B	<u>**C5**</u> P1 S2	<u>**C6**</u> P1 S2	<u>**C7**</u> P1 S2	<u>**C8**</u> P1 S2
Solved cases- group C	<u>**C9**</u> P1 S3	<u>**C10**</u> P1 S3	<u>**C11**</u> P1 S3	<u>**C12**</u> P1 S3
Unsolved cases	<u>**C13**</u> P1 - - -	<u>**C14**</u> P1 - - -		

Figure 4.16 **Case matrix for showing test procedure (C1 to C14 are cases numbers, P1 is defined problem for cases which is the same for all cases in three groups, S1-S2-S3 are solutions to group A, B, and C respectively).**

Figure 4.17 shows a flow chart and decision tree for test procedure when cases and ontology are modelled in a CBR model. This procedure has been applied for cases in the Wellogy model.

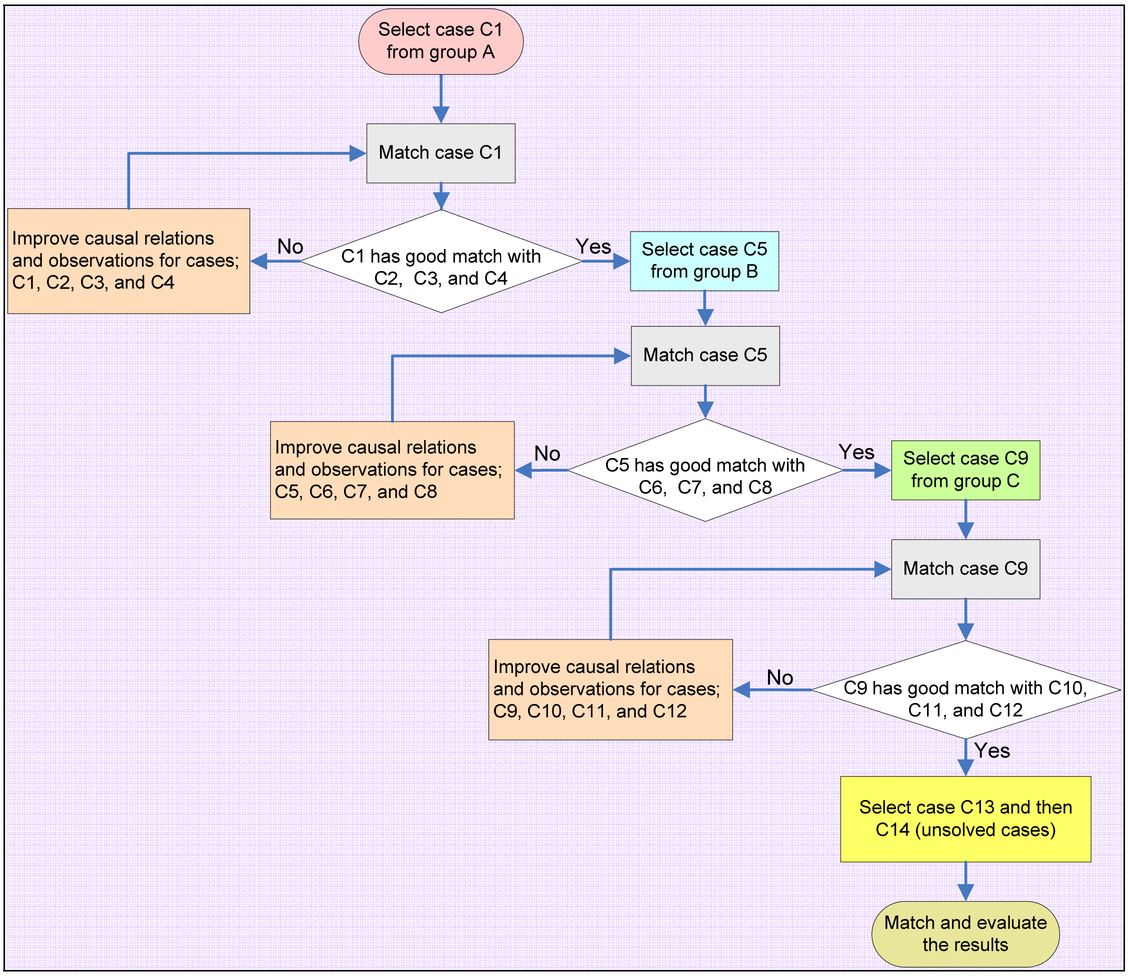


Figure 4.17 Flow chart for test procedure to increase the quality of cases in the Wellogy model.

4.13 Improving case quality

The cases have so far been modelled and inserted in the Wellogy model individually (i.e. without considering other similar cases). The mentioned test procedure should be performed when the preliminary Wellogy model (cases and ontology) is developed. In order to increase the reliability and quality of the model, the solved cases are needed to be checked and modified if needed for the numbers and role of attributes for each case. For this reason, the modelled solved cases are grouped manually based on similarity of the solutions. As already mentioned, in this model the solutions are the causes of failures). Since the findings are basically given according to the existing date (free-text-base), a querying and screening process is needed to go through for the contents of cases by experts. This process to some extent is similar to the Conversation Case-Based Reasoning (CCBR) (Gu, 2006) where designers of the case interview experts to achieve a sufficient level in respect of information to complete the case. Finally, the weight-values are given to the findings of the cases in respect of degree of importance and prediction strength of the findings. This value is yielded by combination of `importance` and `predictive strength` provided in Creek. The role of `importance` and `predictive strength` on findings of a case in the model was shown in ***Figure 4.15***.

Based on the above discussion three steps have been established for improving case quality:

Step 1: model the cases individually in Wellogy as a free-text-base
Step 2: screen and modify the cases by considering them as groups
Step 3: tune the attributes of cases based on the degree of `importance` and `predictive strength`

These processes have been performed for all cases, and the results for the example wells have been shown in ***Figure 4.18***. The solved case E-2a considered as an input case and matched with other solved cases. The best matched cases were: wells A-4, A-6, E-7 and E-14. These cases belong only to a single group: group A, (wellhead seal leak). However, wells A-4, A-6, E-7 belong to the subgroup A-1 in which the cause is `Carbon Steel CSG Seal`. Well E-14 belongs to the subgroup A-3 where the cause is `Elastomer TBG Hanger Seal`. From ***Figure 4.18*** we can see that similarity match percentage is increased when the quality of the cases are improved by going through step 1 to 3. For case Well E-7, however, the match percentage is decreased. This reveals that the quality process (step 1 to 3) causes similar cases to converge while the different cases diverge.

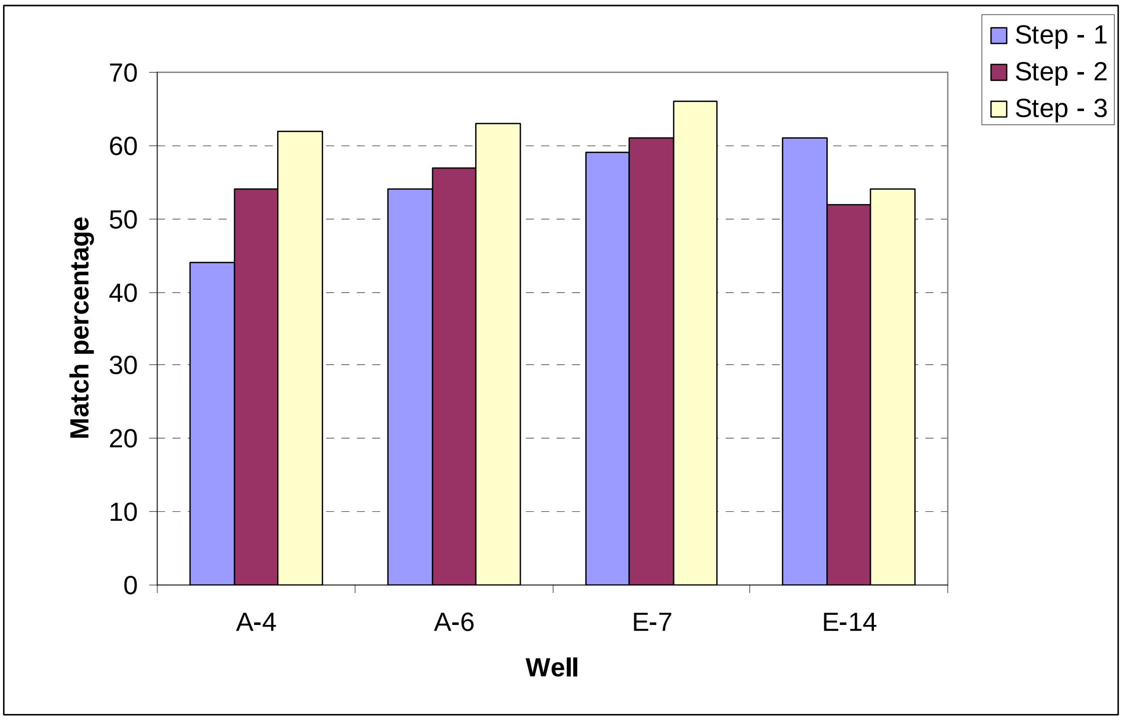


Figure 4.18 **Case-match result for one input case (well E-2a) and four output cases (wells A-4, A-6, E-7, E-14).**

Radar charts are used to display the matched results for the cases. The solved cases are renamed to their related group name for a better evaluation, e.g. cases A-4, A-6, and E-7. E-2a and E-14 are temporary renamed as group A. Then one solved case (e.g. well E-2a) is used as an input case, and then the case library is searched for the best matched cases. ***Figure 4.19*** shows the result for group A (input case is E-2a). This figure shows that the four best matched cases belonged to the same group. The other groups have lower similarity percentages. Similar results have been obtained for the groups C and D as shown in ***Figure 4.20*** and ***Figure 4.21***.

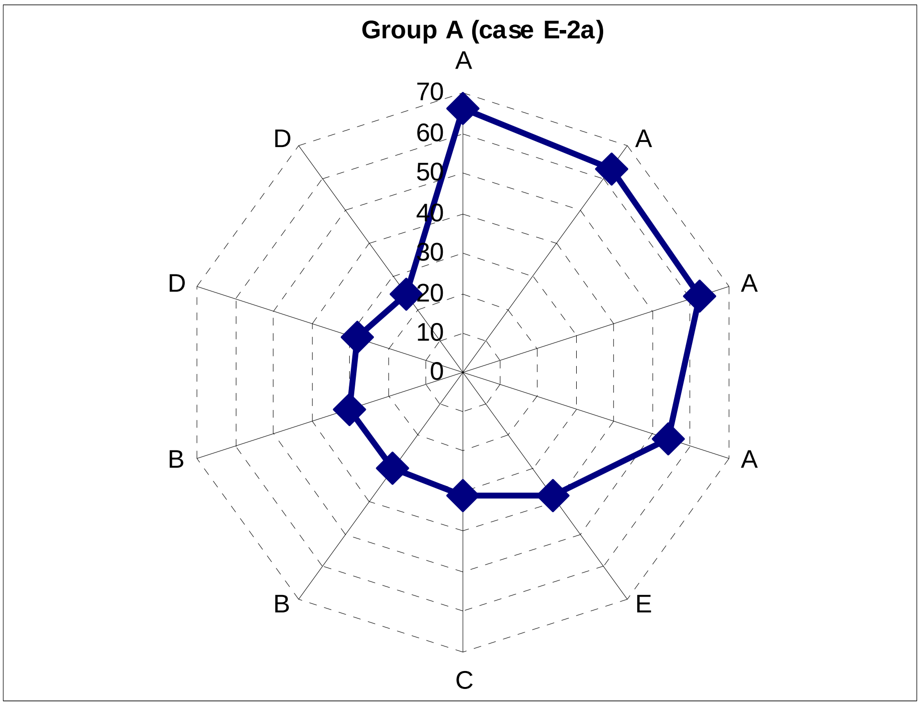


Figure 4.19 **Radar chart showing high similarity percentage for group A (input case belong to group A), and lower match for group E (1 match), group C (1 match), group B (2 match) and group D (the 2 lowest match).**

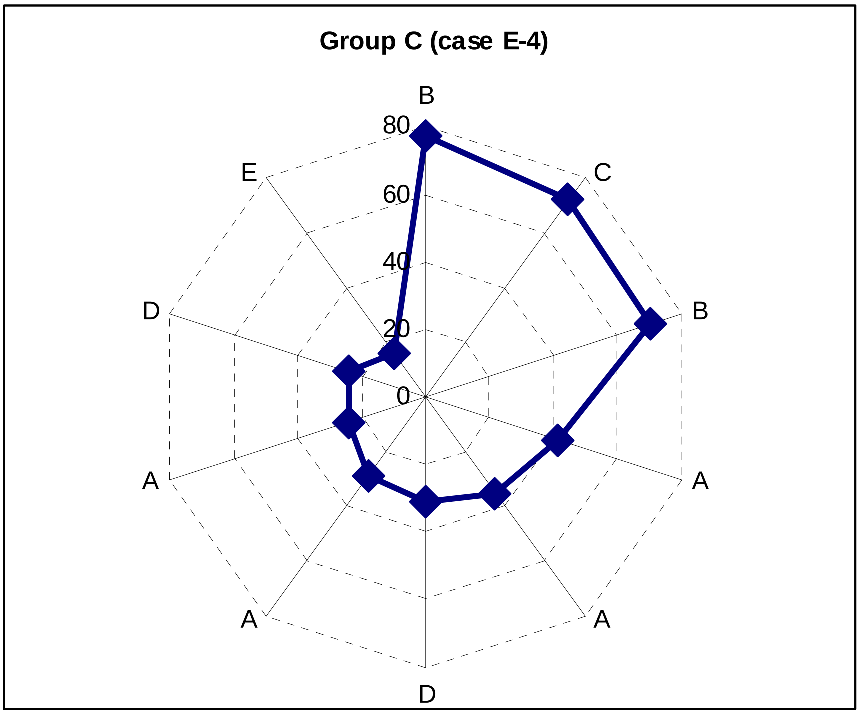


Figure 4.20 **Radar chart displays match results when the input case is from group C. The result shows that the closest cases are from the groups B & C. The results are reasonable because both Groups B & C are fairly similar from the perspective of the leakage path (i.e. casing / tie-back**

leak). Notice that there are only two cases in group C. The remaining cases have the lowest matches.

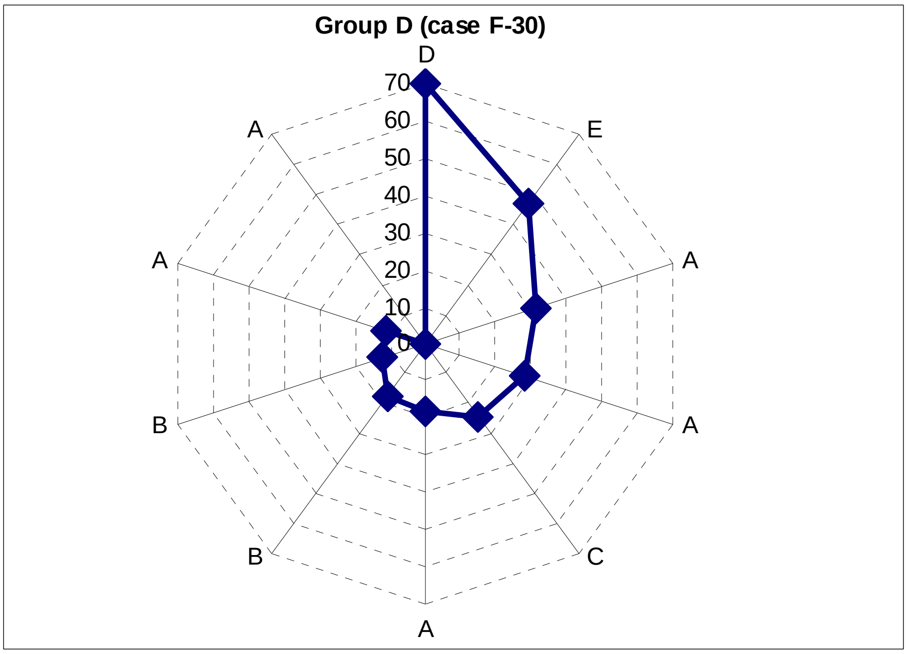


Figure 4.21 Radar chart displays match results when the input case is from group D. The result shows that the closest case belongs to the same group D. Notice that there are only two cases in group D. The remaining cases have the lowest matches.

4.14 Result of matching cases

In this section the obtained results from the Wellogy model for matching cases (6 unsolved and 12 solved cases) are discussed. We will consider the results of the best matched cases for the unsolved cases. First, the result view and related parts are presented through the one unsolved case, and then the results for the 5 unsolved cases are discussed. The obtained results for these cases are evaluated and examined by human reasoning as a crosscheck.

4.14.1 The view of match result

Figure 4.22 shows the complete screen shot of the result for the case match when the unsolved case is well E-11, and the retrieved case is well E-9. The blue shows `direct match`, while the red and grey show `indirect match`. For the direct match, the `input findings` and retrieved case findings are exactly the same for the input and output cases. On the other hand, for the `indirect match`, the findings of the cases do not have direct relations, but they have indirect relations produced from the causal relationship model which is built through the general domain model.

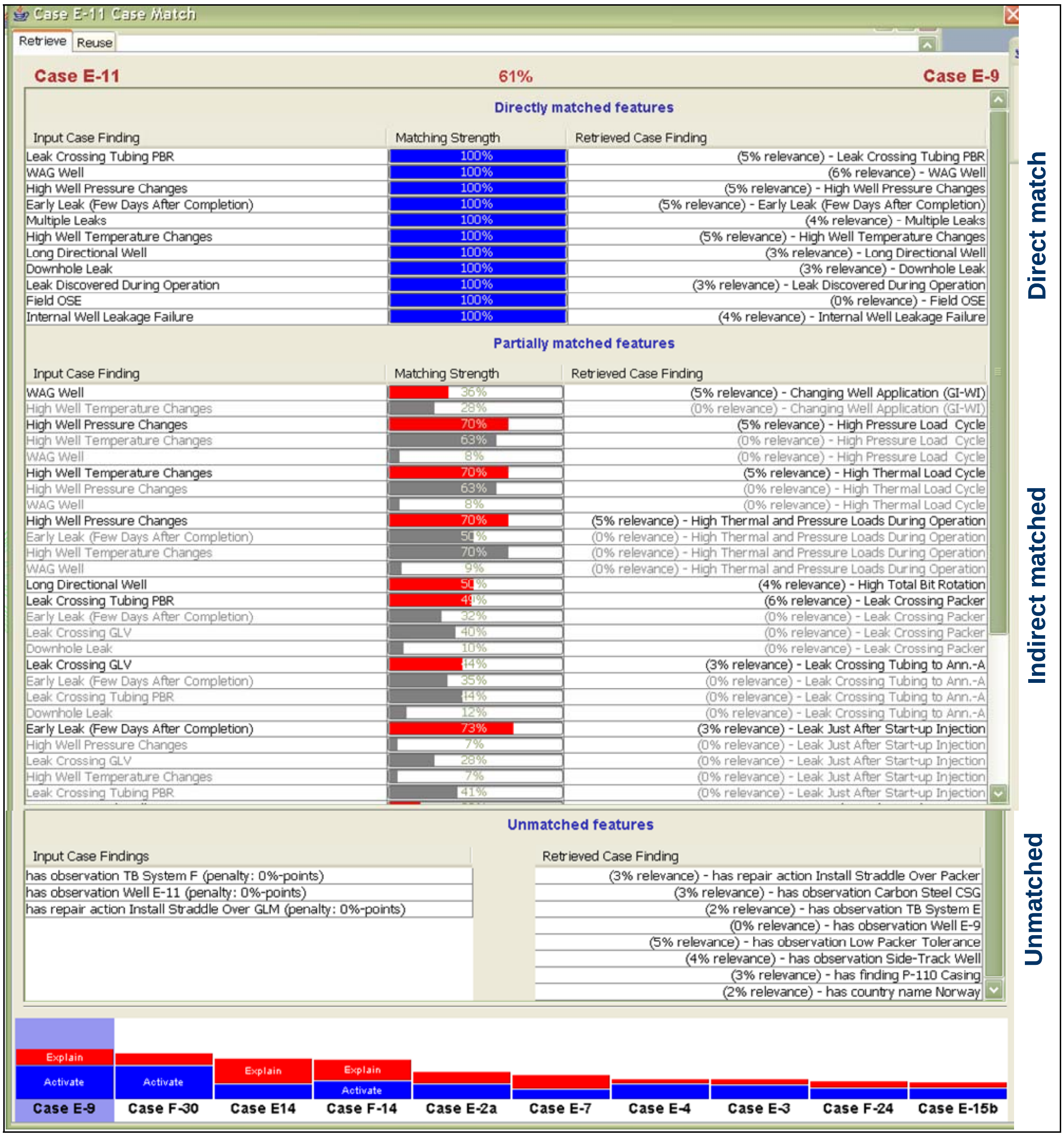
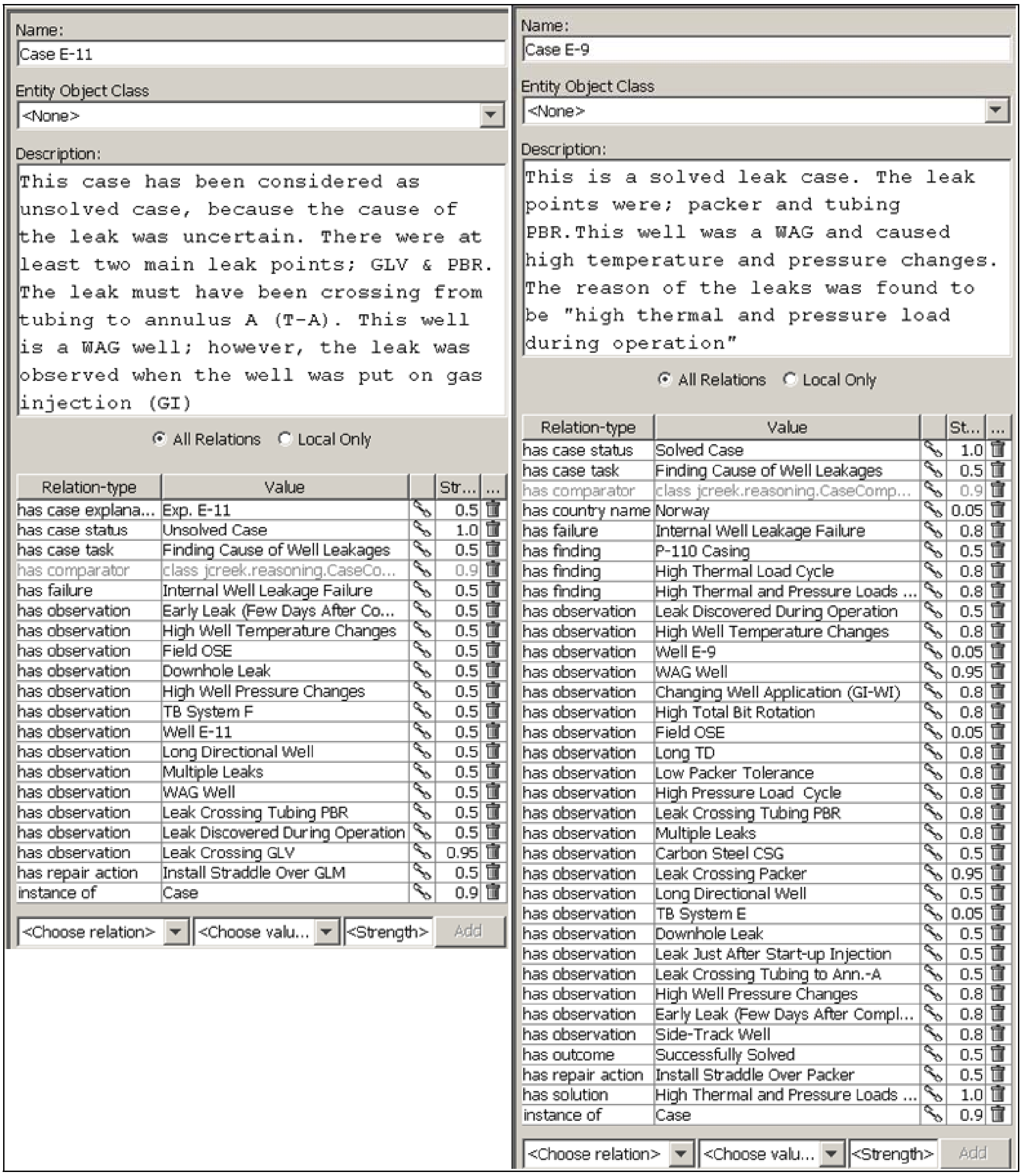


Figure 4.22 The result of case match showing; direct match (blue), indirect match (red), and unmatched findings when input case (unsolved case) is well E-11 and retrieved case is well E-9.

Figure 4.23 illustrates the case description for input and output cases in the Creek framework. The failure of the two cases is identical, `Internal Well Leakage Failure`. As shown in the figure, the weight-values of findings for solved cases are different, while the weight-values for the findings of the unsolved case are identical (0.5). This is due to the nature of solved and unsolved case. For a solved case, the case designers know which findings are important or not so important and they give the weight values to the findings, while for an unsolved case the importance of the findings are uncertain. As already explained, the digital numbers for weight values denote the combination of the degree of `Importance` and `Predictive Strength.`



Name:
Case E-11

Entity Object Class
<None>

Description:
This case has been considered as unsolved case, because the cause of the leak was uncertain. There were at least two main leak points; GLV & PBR. The leak must have been crossing from tubing to annulus A (T-A). This well is a WAG well; however, the leak was observed when the well was put on gas injection (GI)

All Relations / Local Only

Relation-type	Value	Str...
has case explana...	Exp. E-11	0.5
has case status	Unsolved Case	1.0
has case task	Finding Cause of Well Leakages	0.5
has comparator	class jcreek.reasoning.CaseCo...	0.9
has failure	Internal Well Leakage Failure	0.5
has observation	Early Leak (Few Days After Co...	0.5
has observation	High Well Temperature Changes	0.5
has observation	Field OSE	0.5
has observation	Downhole Leak	0.5
has observation	High Well Pressure Changes	0.5
has observation	TB System F	0.5
has observation	Well E-11	0.5
has observation	Long Directional Well	0.5
has observation	Multiple Leaks	0.5
has observation	WAG Well	0.5
has observation	Leak Crossing Tubing PBR	0.5
has observation	Leak Discovered During Operation	0.5
has observation	Leak Crossing GLV	0.95
has repair action	Install Straddle Over GLM	0.5
instance of	Case	0.9

<Choose relation> <Choose valu...> <Strength> Add

Name:
Case E-9

Entity Object Class
<None>

Description:
This is a solved leak case. The leak points were; packer and tubing PBR.This well was a WAG and caused high temperature and pressure changes. The reason of the leaks was found to be "high thermal and pressure load during operation"

All Relations / Local Only

Relation-type	Value	St...
has case status	Solved Case	1.0
has case task	Finding Cause of Well Leakages	0.5
has comparator	class jcreek.reasoning.CaseComp...	0.9
has country name	Norway	0.05
has failure	Internal Well Leakage Failure	0.8
has finding	P-110 Casing	0.5
has finding	High Thermal Load Cycle	0.8
has finding	High Thermal and Pressure Loads ...	0.8
has observation	Leak Discovered During Operation	0.5
has observation	High Well Temperature Changes	0.8
has observation	Well E-9	0.05
has observation	WAG Well	0.95
has observation	Changing Well Application (GI-WI)	0.8
has observation	High Total Bit Rotation	0.8
has observation	Field OSE	0.05
has observation	Long TD	0.8
has observation	Low Packer Tolerance	0.8
has observation	High Pressure Load Cycle	0.8
has observation	Leak Crossing Tubing PBR	0.8
has observation	Multiple Leaks	0.8
has observation	Carbon Steel CSG	0.5
has observation	Leak Crossing Packer	0.95
has observation	Long Directional Well	0.5
has observation	TB System E	0.05
has observation	Downhole Leak	0.5
has observation	Leak Just After Start-up Injection	0.5
has observation	Leak Crossing Tubing to Ann.-A	0.5
has observation	High Well Pressure Changes	0.8
has observation	Early Leak (Few Days After Compl...	0.8
has observation	Side-Track Well	0.8
has outcome	Successfully Solved	0.5
has repair action	Install Straddle Over Packer	0.5
has solution	High Thermal and Pressure Loads ...	1.0
instance of	Case	0.9

<Choose relation> <Choose valu...> <Strength> Add

Figure 4.23 Case description in the Wellogy model for unsolved case (left) and solved case (right).

Figure 4.24 show the match result and network connections (relationships) between the input case (E-11) and the output case (E-9). For each pair of entity (input finding / retrieved finding) for indirect match (red and grey in ***Figure 4.22***), a reasoning explanation for each pair of indirect findings is retrieved according to the causal model as shown in the right side of ***Figure 4.24***. At the bottom of ***Figure 4.24***, a set of best retrieved solved cases is shown and sorted from highest to lowest match percentages (left to right). In this version of Creek, there is no limitation for users to accept or reject the delivered results of the solved cases.

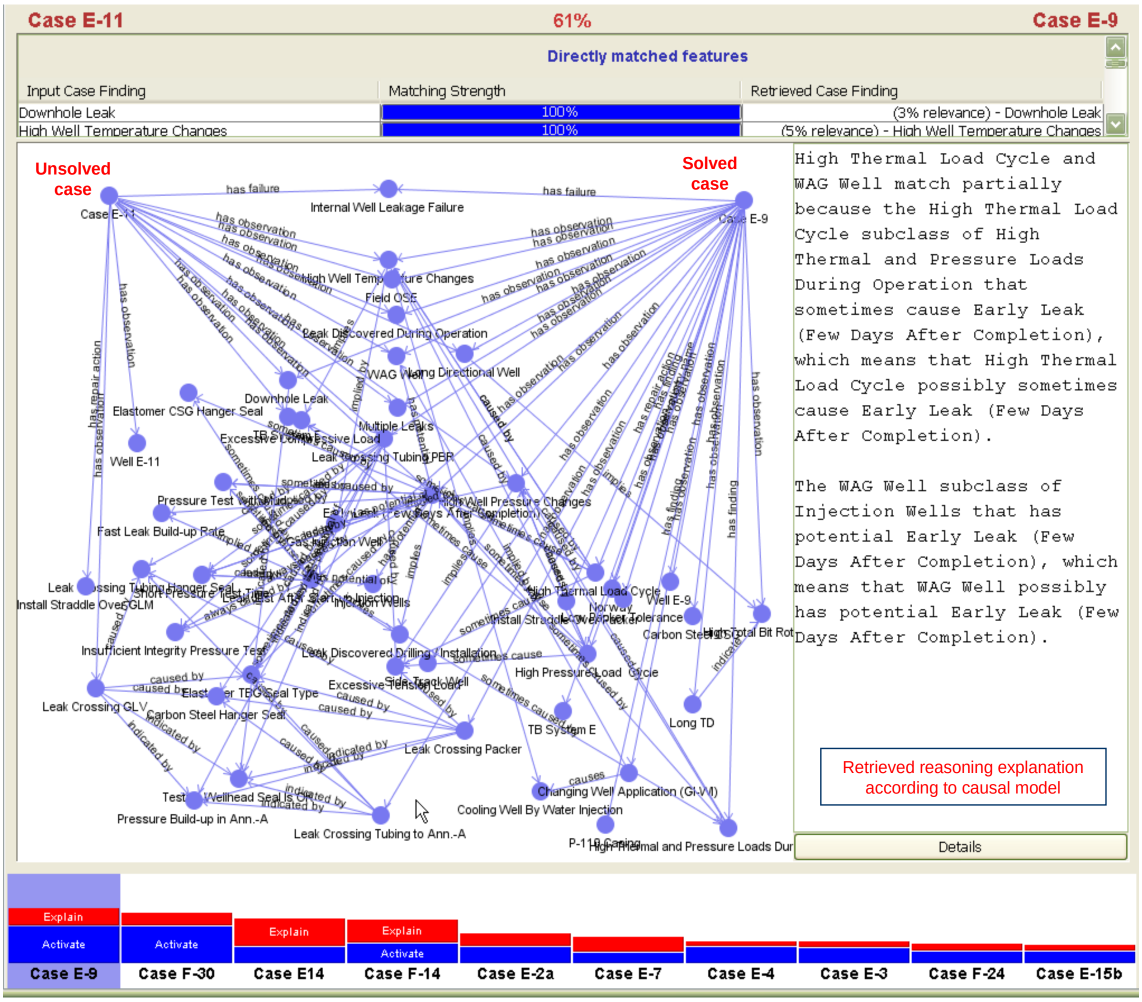


Figure 4.24 **Matched results and network relations between input case (E-11) and output case (E-9). A reasoning explanation for each pair of indirect match findings is retrieved on basis of causal model of Wellogy (e.g. `WAG Well` and `High Thermal Load Cycle`).**

4.14.2 Unsolved case E-2b

Figure 4.25 shows the view of case E-2b and retrieved solved cases. The result of the match is summarized below:

1. Similarity percentages of the three best matching cases: 57 %, 53 %, 51 %
2. Roughly 1/3 of the total match percentage is indirect match (red part in the figure)
3. The proposed solution: `Carbon Steel Hanger Seal`
4. The three best matching cases belong to one group: group A1

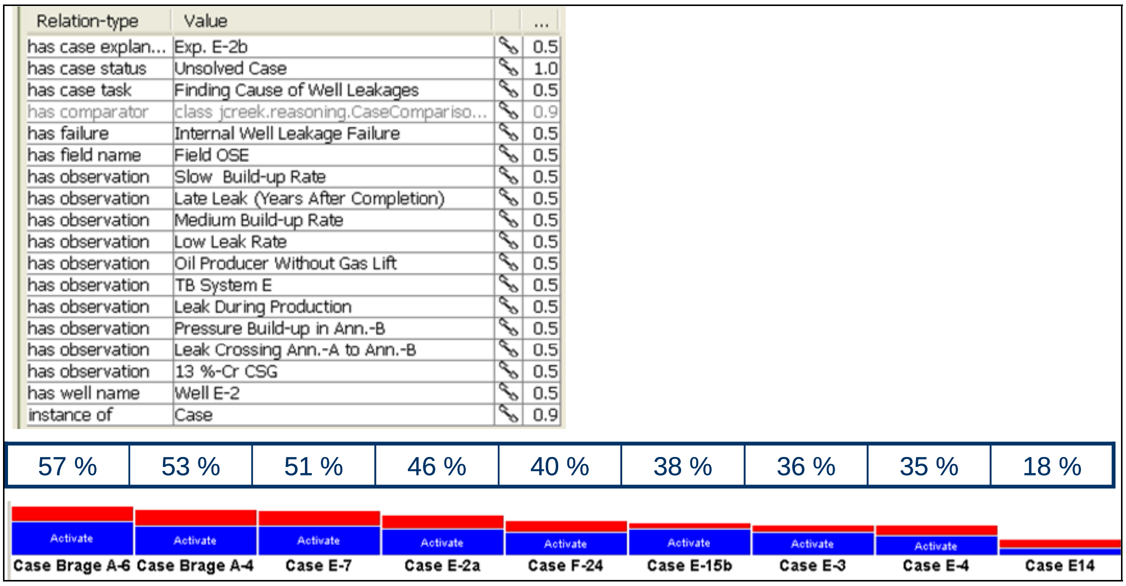


Figure 4.25 **Case view of E-2b (unsolved) and similarity percentages of the retrieved solved cases.**

Discussion on the obtained results:

Case E-2b is a late leak incident in which the leak crossed from annulus-A to annulus B. Therefore, the leak components can be either of type CSG or Hanger Seal. As the leak occurred in the late phase of production the `Elastomer Casing Hanger Seal` may not be the cause of the leak. On the other hand, the type of Casing is 13 % Cr, so the low quality of CSG may not be the main reason or cause for the leak. A possible reason for the leak can be `Carbon Hanger Seal`, because:

1. Leak occurred in late phase
2. Casing had good quality
3. Oil producer with Gas lift, i.e. the system was corrosive and casing hanger may not be high Cr percentage to resist against the corrosion

However, the case match percentage of such leaks is still low and it means that other reasons may exist; for example, tie-back system failure.

Conclusion

The three best matching cases are similar in terms of kind of problem and they all have one solution. This means that the results taken from the Wellogy model is reliable. The model also has remembered and retrieved particular knowledge which has not been directly given to the cases. The contribution of this indirect knowledge to the total similarly match percentage is 1/3.

4.14.3 Unsolved case E-11

Figure 4.26 shows the case view of input case (E-11) and retrieved solved cases. The result of the match is summarized as below:

1. Similarity percentages of the three best matching cases : 61 %, 57 %, 50 %
2. The proposed solution retrieved from best similar cases is: `High Thermal and Pressure Loads During Operation`
3. Roughly 1/3 of total match percentages of the best matching cases are indirect matches (red colour part in ***Figure 4.26***)
4. The two best matching cases belong to one group: group D

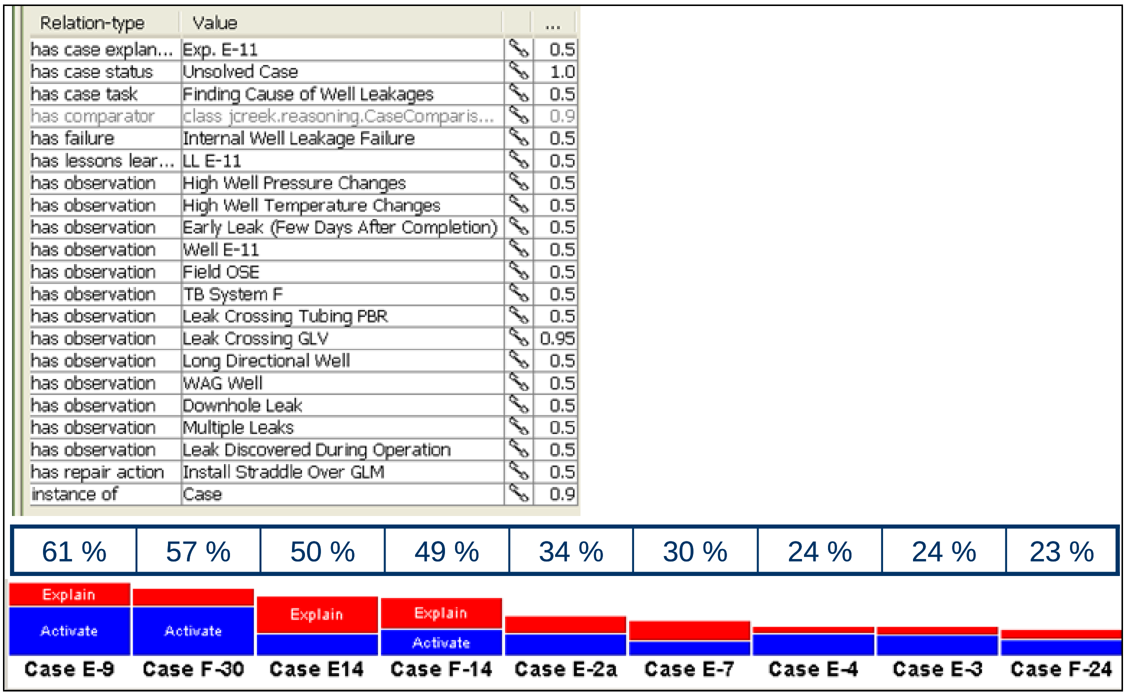


Figure 4.26 **Case view of E-11 (unsolved) and similarity percentages of the retrieved solved cases.**

Discussion on the obtained result:

Case E-11 is an early leak which is crossing from tubing to annulus-A.
Leak crossing PBR and GLV (completion components) were reported. The well application is WAG which leads to high thermal and pressure changes. Leaks were observed during operation, a short period after start-up. Thus, a strong suggestion of reason of the leak is `High Thermal and Pressure Loads`, which is fully in agreement with the two best matching retrieved solved cases (E-9 and F-30).

4.14.4 Unsolved case E-15a

Figure 4.27 shows the case view of the input case (E-15a) and retrieved solved cases. The matching result is summarized below:

1. Similarity percentages of the three best matching cases : 74 %, 69 %, 69 %
2. Most of the match percentages are direct matches (blue colour part in the figure)
3. The proposed solution from all three cases is: `Carbon Hanger Seal`

4. The three best match cases belong all to one group: group A1

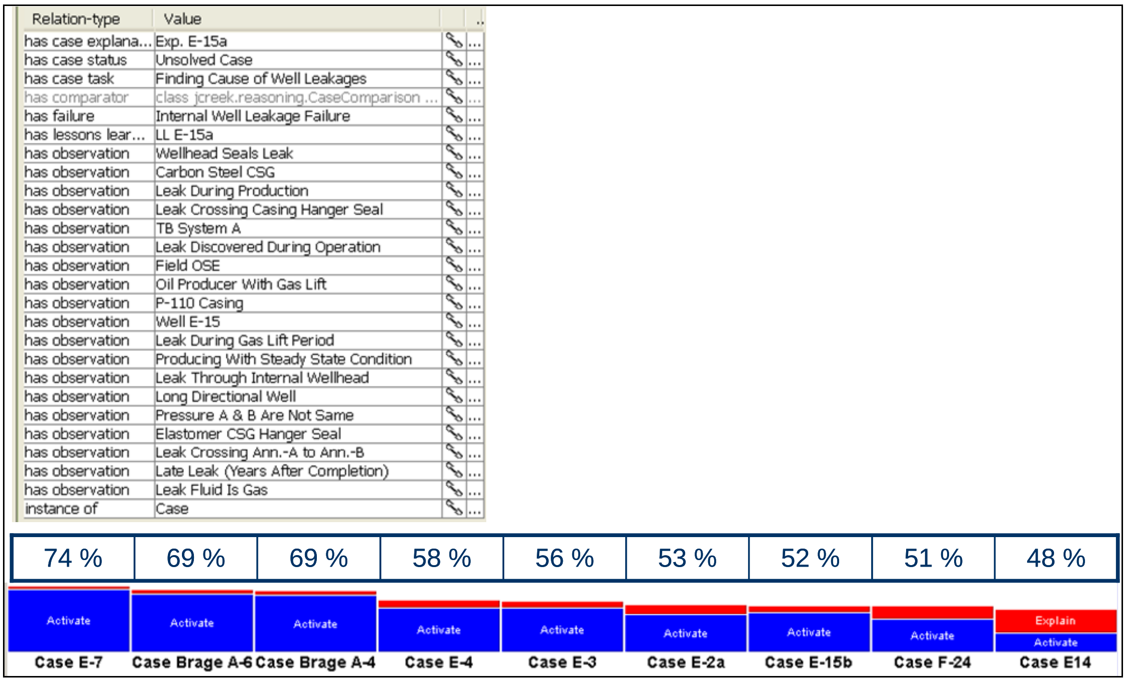


Figure 4.27 **Case view of E-15a (unsolved) and similarity percentages of the retrieved solved cases.**

4.14.5 Unsolved case F-16

Figure 4.28 shows case view of the input case (E-16) and retrieved solved cases. The result of matching is summarized below:

1. Similarity percentages of the best matching cases: 66 %, 55 %, 43 %
2. The first retrieved case has 1/3 indirect match while the next two retrieved cases have ½ indirect match
3. The proposed solution from the first solved case is: `Insufficient Integrity Pressure Test`
4. The first best matching case belongs to group E (group E only contains one case)

Discussion on the obtained results:

Case F-16 is an early leak and a pressure build-up was observed in annulus-A. The well is of type WAG application, and a leak was discovered just after injection start-up. A special observation was seen; "lifted-up wellhead after starting gas injection". If we refer to human reasoning for this case, we can conclude that the reasons behind the leak are:

1- Pressure test during installation does not fulfil the requirement for real operation condition. The pressure test is too short (10 minutes) and the test fluid is mud (contains solids). Small leaks may not be seen during the installation test. However, when gas injection starts the hidden leaks can be visible clearer, because of nature of gas to become leak in junctions and seal areas. The gas can penetrate through the leak points better that oil and water. This discussion agrees with the solution of the first retrieved case (case F-14)

2- High thermal and pressure changes can cause movement in the well construction (as rising of wellhead was seen after stating gas injection). This relative movement sometimes cause leak through completion components such as PBRs, GLVs and packers. This discussion agrees with the solution of the second best retrieved case (case E-14).

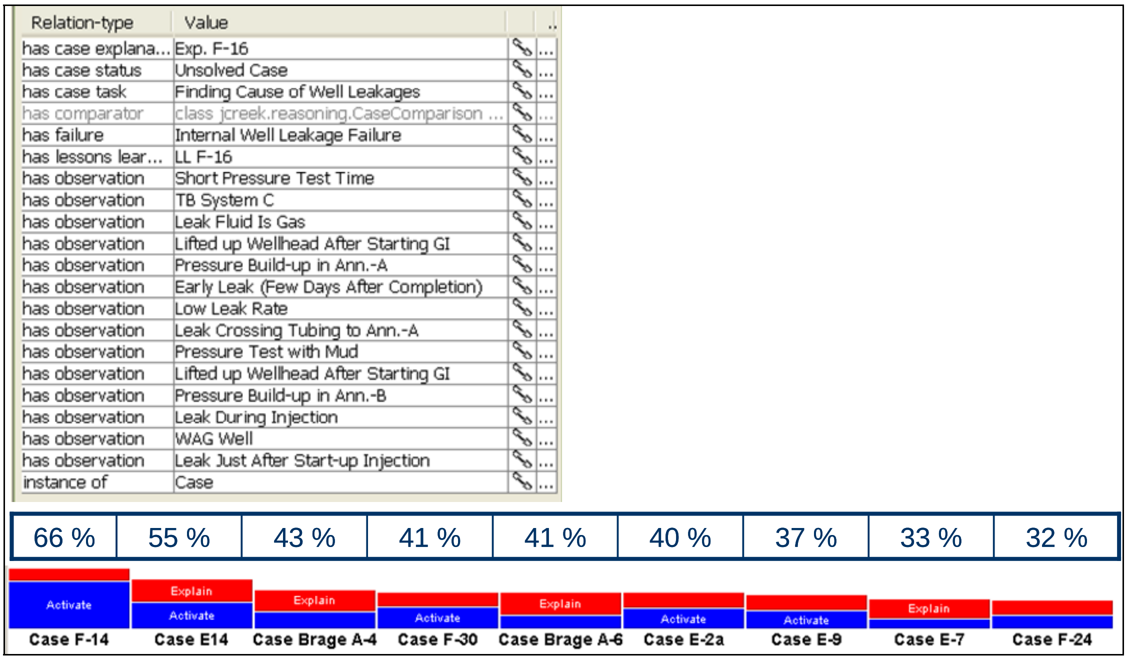


Figure 4.28 Case view of F-16 (unsolved) and retrieved solved cases.

Summary of matching of unsolved cases

The overall match results for the 5 unsolved cases and the three best matches for each case are shown in ***Table 4.9***. The results reveal that the model has potential to become reliable, because the three best retrieved cases belong to the same group for two of the unsolved cases E-26 and F-22.

Table 4.9 **The match results for five unsolved cases and match percentages for the best three retrieved cases for each unsolved case.**

Unsolved case	Closest cases	Match %	Group
E-2b	A-6	57	A1
	A-4	53	A1
	A-7	51	A1
E-11	E-9	61	D
	F-30	57	D
	E-14	52	A3
E-15a	E-7	74	A1
	A-6	69	A2
	A-4	69	A3
F-16	F-14	66	E
	E-14	56	A3
	A-4	43	A1
F-22	A-4	63	A1
	E-7	53	A1
	A-6	51	A1

The Wellogy model only contains 12 solved cases. The recommendation is to collect and construct more cases from the same area (e.g. well integrity and leakage cases) in order to improve the Wellogy model. Around 50 knowledge-rich solved cases could be enough to have a robust CBR model. Another area that can improve the Wellogy model is the quality of the cases in respect of data and information. Some cases were explained with limited descriptions by persons who observed and documented the case. The case builders need information to explain the case correctly (both problem and solution parts). Therefore, Wellogy can be improved by focusing on the following items:

- Increasing the number of solved cases (the knowledge body of the concept will be also expanded).
- Increasing the quality of cases (solved and unsolved) by giving a precise and complete explanation to the case. This can be prepared by case observers and/or reporters who directly involve the case.

5. Assessment of Research Project Cases

This chapter presents the study of three engineering problem areas in terms of *knowledge-level* (i.e. give the valuable knowledge in text before translating to the *symbolic-level*). The objective of this chapter is to show some complex tasks (called cases) within the petroleum engineering domain from a practical point of view. It shows how the important and valuable information can be extracted from practical work which can be stored in the Wellogy model for the later reuse. It explains how the cases can be derived based on the different type of data sources i.e., database, research work-based, and scientific paper-based. The first case is of database type and performed for a complete oil field. The task of this case is *"giving a new and correct technology advice for a production problem case"*. The recommended technology is Under-Balanced Drilling (UBD) and applies to optimizing production and minimizing drilling problems (Abdollahi et al., 2004). The second case format is concerning a specific drilling problem (drillstring washout) which is constructed based on operator company files (Abdollahi et al., 2003). The third case category is concerning wellbore stability problems and based on a published scientific paper.

5.1 UBD cases

Underbalanced drilling (UBD) is a rather new drilling procedure which has been recently applied in different oil and gas reservoirs. In the UBD condition, the well pressure is intentionally kept lower than the reservoir pore pressure. Therefore, it is expected that the reservoir fluids (oil, gas, and water) will flow to the well bore during drilling; therefore, the well control becomes important in such procedure. Controlling the formation damage induced by the drilling fluids, high drilling rate (ROP), and avoiding mud losses, are the main arguments for performing UBD techniques (McLennan, 1997).

UBD also offers other benefits more than avoiding formation damage and producing high ROP; for example, efficient well placement in fractured reservoirs and determining reservoir behavior while drilling for a better well completion (Abdollahi et al., 2004). An efficient completion strategy could be chosen later when the reservoir behaviour is well known while drilling. This is a great advantage of applying UBD. The UBD method is not yet common drilling practice for most oil operating areas. In the Middle East, where the reservoir formations are fractured carbonate, UBD has recently been applied (Murphy et al., 2006 and Hooshmandkoochi et al., 2007).

As a part of the PhD programme, a study on the UBD applications was conducted in a fractured carbonate oil field in Iran. This project was integrated with a project study performed in SINTEF Petroleum Research in Trondheim during 2002-2005. The result of this study was presented at the SPE/IADC Underbalanced Technology Conference and Exhibition held in Houston, Texas in 2004 (Abdollahi et al., 2004), (the full-text article is given in Appendix C). The goal here is to model this study for producing a case in the Wellogy model implemented in the Creek knowledge editor.

5.1.1 Knowledge level

The Dehluran (DH) field is a fractured carbonate field located in the south-western part of Iran close to the Iran-Iraq border. The field is around 45 km long and 8 km wide with an average reservoir thickness of 300 m (Taghavi, 2007). The field was discovered in 1970 and 22 wells have been drilled so far. Only 13 wells have reached the reservoir target. The rest of the wells have been abandoned due to serious drilling challenges like high salt pressure and also due to the Iraq-Iran war (1980-1988). The infill drilling programme for developing the DH field which has been done as plotted in ***Figure 5.1***. The overall field production performance so far has shown an unreasonable low oil production rate. The production history for each well in the field is shown in ***Figure 5.2***. This figure reveals that some wells produced for a short period and then became depleted or even dry; e.g. wells DH-11, DH-14, DH-18, DH-20 and DH-21. There are only a few wells with reasonable oil production rates and from which it has been produced oil for a rather long period (years), e.g. wells DH-2 and DH-5.

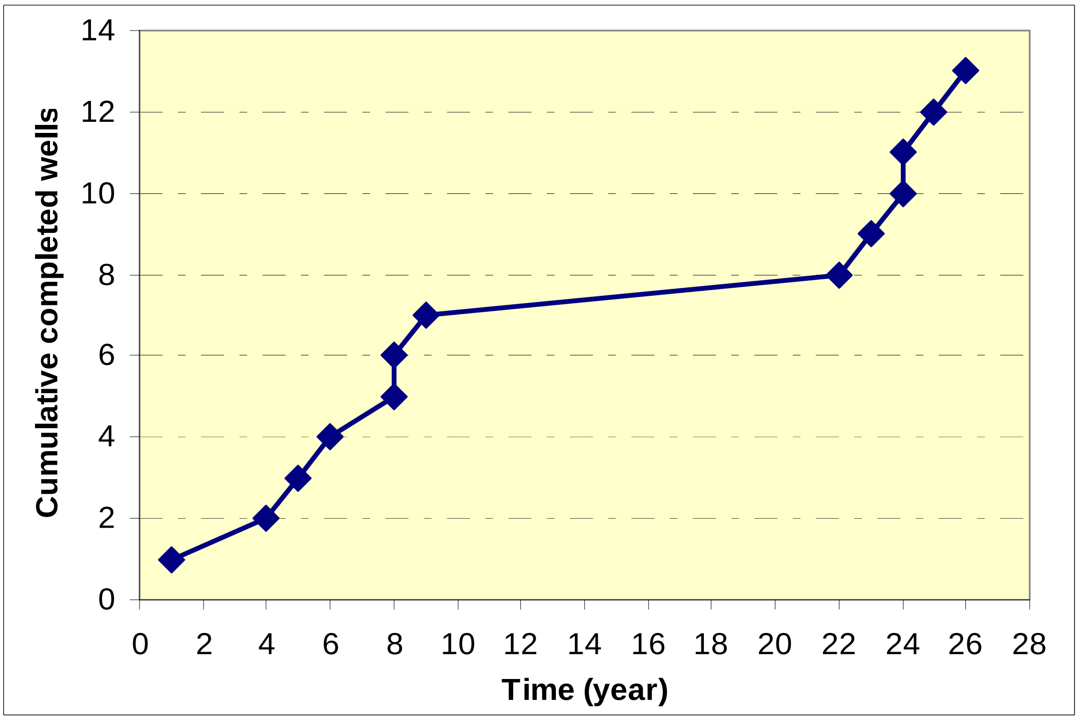


Figure 5.1 Infill drilling programme in the DH field versus time.

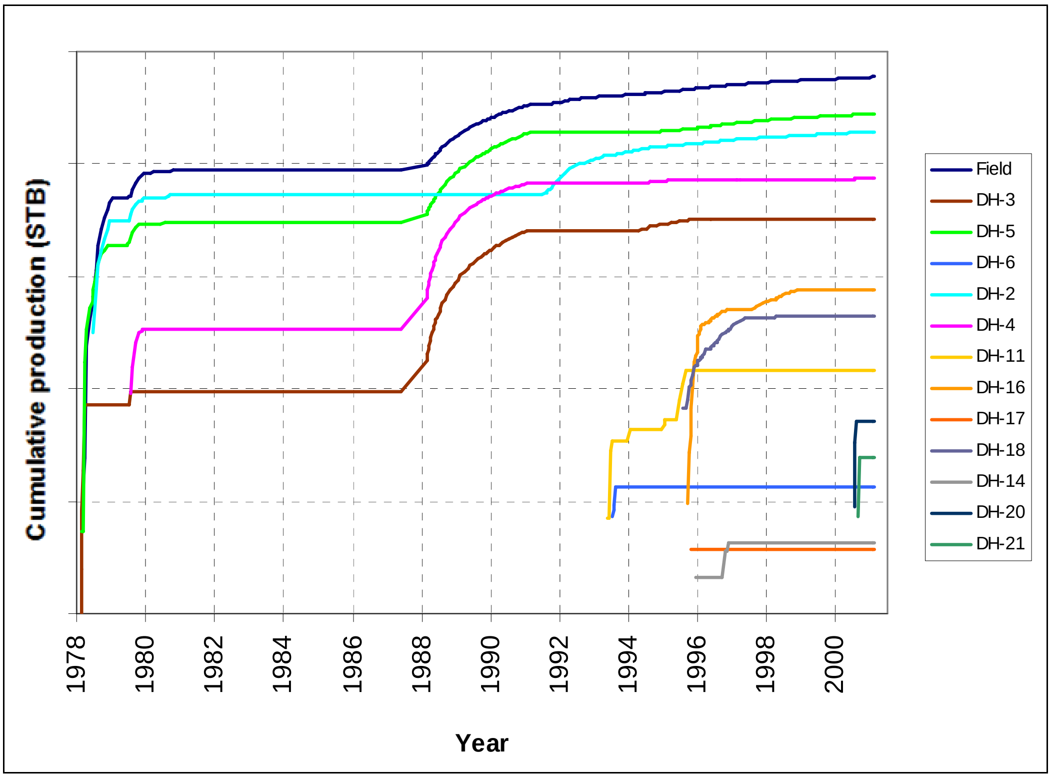


Figure 5.2 Cumulative oil production for each well in the DH field (SINTEF, 2004).

Figure 5.1 and ***Figure 5.2*** indicate that the increasing numbers of wells in the field (infill drilling solution) have not improved the total oil production rate, although the oil reserve volume is high. This was an important indication for the operating company (NIOC) to take action for further development. They stopped the development for a period and did not drill more wells until a comprehensive research study was performed to diagnose the problem. A comprehensive study was performed for the field by SINTEF Petroleum Research and provided a Master Development Plan (MDP) to upgrade the field.

Human reasoning is applied to see the similarities and dissimilarities of the wells in respect of production rates (high, medium, and low rates). The used drilling method and well construction were identical for all wells for the entire field. Mud parameters, casing points and completion strategies were similar for most of the wells. Based on geology and petrophysical logs all the wells were completed within the same oil bearing zone with the same rock properties. The drilling data have been studied and audited and mud losses encountered in the pay zone are plotted for each well as shown in ***Figure 5.3***. The small red dots with the numbers are the location and the name of the wells. The red circles around the some wells denote that mud losses occurred during the drilling in the oil-bearing zones (productions zone). While the blue circles refers to wells which produce oil with reasonable rates.

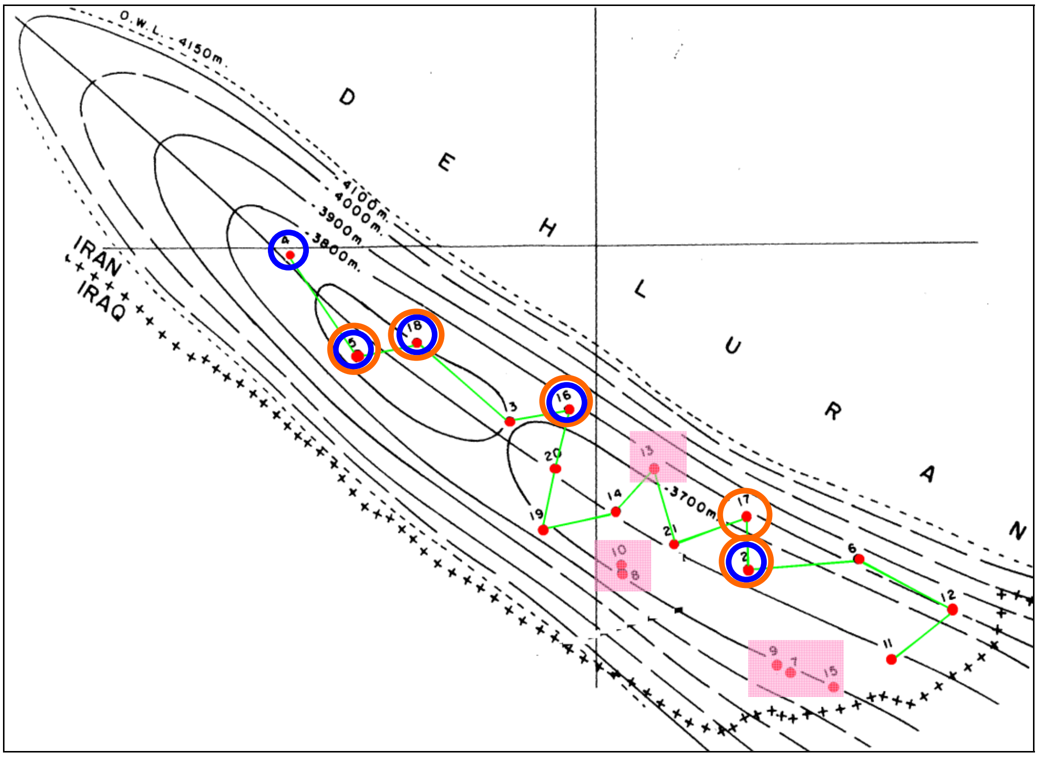


Figure 5.3 **Dehluran field map showing wells with reporting mud losses (red circle) and good production wells (blue circle).**

As the matrix permeability was so low, in a range of few milli-darcy, the natural fracture networks are obviously dominating the production rate. Fracture networks in the reservoir rocks have high flow conductivity to the mud losses which can be observed during drilling. This high conductivity can be also seen during production (Van Golf-Racht, 1982). Mud losses were encountered and reported for some wells where the well intersected the fractures. The severity of the mud losses into the formation depend on the opening and extension of the fractures as well as mud parameters (e.g. viscosity and solid content). As shown in ***Figure 5.3***, good producer wells are those wells which showed mud losses during drilling. This observation strongly proves the effect of fracture networks on capability of production of the wells. In addition to this observation, results from a production log tool (PLT) run in well DH-5 revealed the contribution of those layers where mud losses occurred as shown ***Figure 5.4***. The PLT log showed that 95 % of the total well flow was produced from one perforation (perforation number one in ***Figure 5.4***). The second perforation interval produced only 5 %, and the rest of the intervals did not contribute any at all.

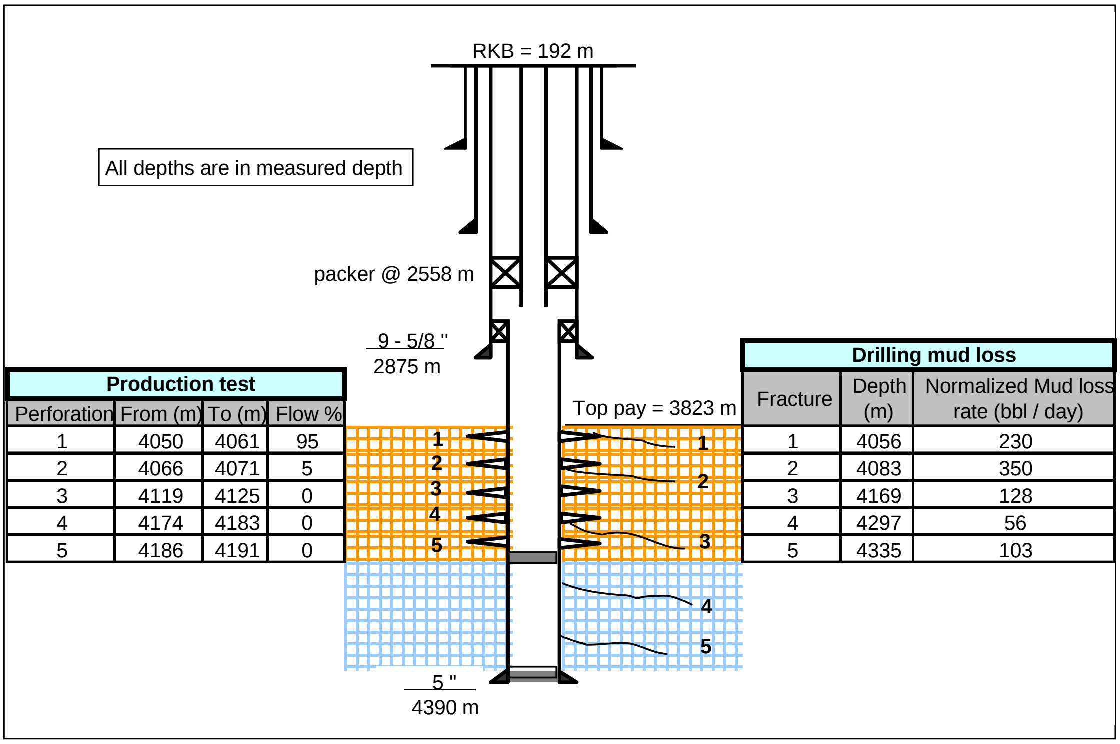


Figure 5.4 **Well sketch with perforation intervals and mud losses depths vs. contribution of fractures.**

Because the drilling mud losses were found important observations for the determination of the reservoir characteristics, the mud losses were plotted versus well depth as shown in ***Figure 5.5***. The net thickness of the pay zone was about 300 m and 2600 bbl mud was totally lost in this interval (about 250 bbl/day). ***Figure 5.5*** gives the total mud losses for entire drilled formation.

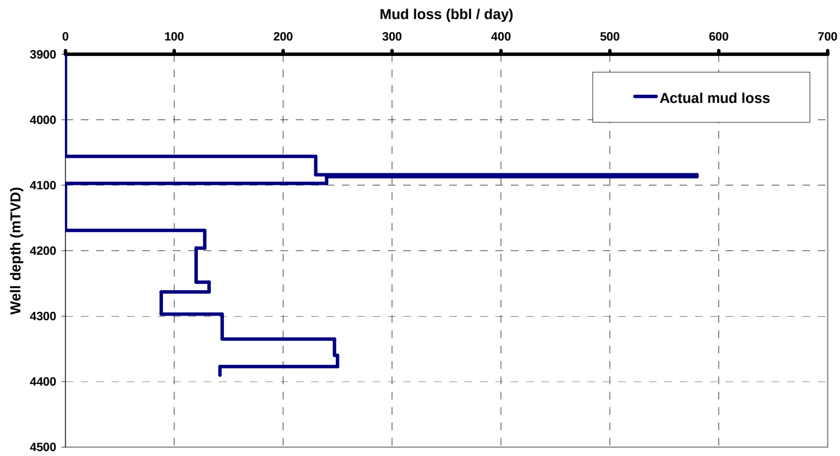


Figure 5.5 **Total mud losses encountered in the reservoir formation of well DH-5.**

Figure 5.5 shows the actual recorded daily mud losses versus well depth within the reservoir section. However, in order to localize the fracture depths as a function of the mud loss rates, the differences of the mud losses are needed to plot which is shown in ***Figure 5.6***. Peak mud losses represent fractures when the drill bit hits the fracture networks. It is assumed that the rate of mud loss into the previous fracture networks remains close to constant until the new fracture networks are intersected. Obviously, the total mud loss will be shared by the two sets of fractures. ***Figure 5.6*** describes the *differential mud loss* which is defined as the difference between the old and new observed losses given by:

$$\Delta Q_{differential} = Q_{new} - Q_{old} \qquad \text{(Eq. 4)}$$

The differential mud losses can be both positive and negative. If the well intersects new fractures the differential mud loss will be positive. On the other hand, if the losses are treated by lost circulation materials (LCM), the differential mud losses would be negative. ***Figure 5.6*** shows only positive differential mud losses which denote fracture networks.

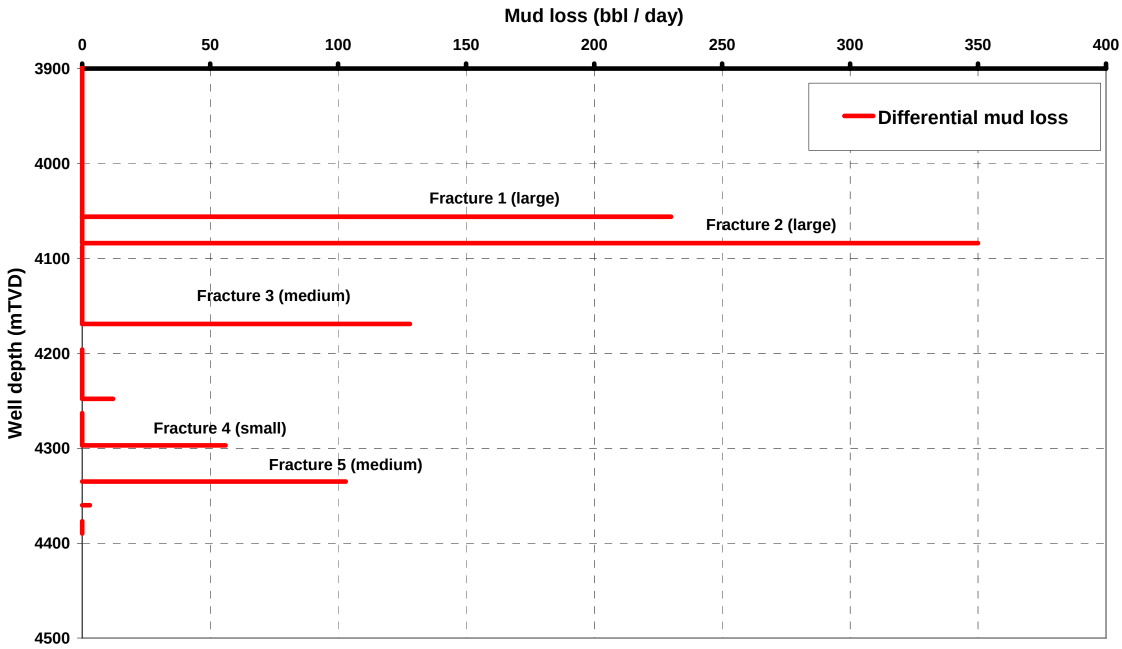


Figure 5.6 The differential mud losses during drilling versus fracture depths.

Although the mud losses are good indicators for localizing fractures and determining reservoir permeability, the mud losses lead to formation damage which impact long-term well production impairment. During overbalanced drilling most of the fractures are plugged by the mud filtrations and LCM. To make all the fractures producible, it is required to perforate all the fractured intervals and stimulate the different fracture systems individually. The successes of later stimulation activities in the micro-fractured reservoirs are extremely low.

The important conclusion for this field was a lack of reliable methods and tools for predicting fractures networks before drilling the well for better well placement in the reservoir formation. Optimized well direction and placement in the pay zone in respect to the fracture networks pattern is very important. Experience has shown that predicting and characterizing the fracture network prior to drilling is very difficult due to technology and modelling limitations and uncertainty.

Based on stated field observations, the UBD technique is therefore an interesting option for enhanced data acquisition, avoiding reservoir impairment and achieving completion contingency for optimized well production. UBD can be performed by different fluids (mud) and procedures as listed below (McLennan, 1997):

- UBD fluids
    - Dry air
    - Nitrogen
    - Natural gas
    - Mist
    - Stable foam
    - Stiff foam
    - Gasified liquids

- UBD Procedure
    - Flowdrilling
    - Mudcup drilling
    - Snub drilling
    - Closed systems

These different types of UBD techniques have been discussed by McLennan, 1997. For the DH field case, for some reasons Flowdrilling was recommended. Flowdrilling is a UBD technique where the well is left flowing while drilling. This technique is applicable for reservoirs with sufficient pore pressure to overcome the hydrostatic pressure in the well. The reservoir pressure gradient for DH field was measured to 0.464 psi / ft (~ 1.12 kg / l). Thus, the reservoir fluids can easily flow to the well bore when the mud is for example water. As the reservoir formation is fractured the influx of formation fluids to the well bore is noticeable. By monitoring the well bore pressures and flow rates versus drilling depth, fractures networks can be precisely localized and production capacity can be determined. Safety issues related to hole collapse and surface handling of the fluids need to be clearly defined. However, many producer wells have been completed in same area as open-hole completion (bare-foot) and producing oil for many years without indication of hole instability.

5.1.2 Human reasoning

According to the above discussion important observations and relationships can be abstractly made based on human reasoning as summarized below:

`Fractured reservoirs` **`imply`** `high fracture permeability.`
`Oil production in fractured reservoirs` **`is dominated by`** `fractures.`
`Carbonate reservoir` **`indicates`** `dense rock with low matrix permeability.`
`Vertical wells` **`cause`** `low chance of intersecting steep fractures.`

Increasing number of drilled wells **leads to** increase production rate, but this did not happen as expected.
Some drilled wells were dry (no production) due to lack of hitting the fracture networks.
The fractures can be plugged by drilling mud when drilling overbalanced.
Predicting the fracture networks before drilling **is difficult**.
Different production behaviours in one field **can indicate** the importance of the fracture networks.
In conventional drilling method (overbalance drilling) hitting the fracture networks are not easily seen when crossing them.
By applying UBD method, the fractures can be observed while drilling in the reservoir section, due to increase reservoir fluid influx into the wellbore
By recognizing the fracture networks while drilling, a better completion strategy can be achieved.

5.1.3 Case production

According to the mentioned procedure for case production, the UBD case can be modelled as shown in ***Table 5.1***.

Table 5.1 Initial design of the UBD case which can be implemented in the Wellogy model.

Relation type	Entity
general findings	Iran, Onshore field, SPE 85327
has failure	Low Oil Production Rate
has task	Finding Correct Technology Candidate
has solution	UBD Technology (characterizing fracture while drilling)
has observation	Low Oil Production Rate (low oil recovery rate)
	Carbonate Reservoir
	Reservoir with Natural Fracture Networks
	Hole Size 8-1/2"
	Conventional Vertical Wells do not Improve Oil Production
	Mud Losses Happen
	Dense Reservoir Rock
	Fast Well Pressure Decline
	Moderate Reservoir Pressure
	Formation damage
	Fracture Networks dominates Production
has repair action	Infill Drilling (increase drainage points)
	Stimulation (well cleaning)
	Acidizing
has case status	Processed case
has outcome	Pending (since solution has not yet been tested)
lesson learned	Many wells were similarly drilled in the same reservoir, but some wells showed a low production performance. Some wells only produced for few days. The reservoir characterizations were the same according to the petro-physical logs and sample cores. The specific observation is that the when pressure draw-down (difference between reservoir and well pressure) was high the oil rate decreased suddenly. This could be due the fractures are closed when pore pressure decreased suddenly. Another observation which could be playing an important role of the fracture networks were relation between mud losses and oil production. Good oil producer showed mud losses during drilling.
has action	Fracture networks are considered important for oil production, and forecasting facture networks before drilling is impossible. UBD method can be applied to find the fracture networks during drilling and implement better completion strategy for the well. Flowdrilling (i.e. let the well flow while drilling, one of the UBD techniques) can be planned in order to monitor reservoir characterizations

5.2 Drillstring washout

As in the last section the goal here is to produce a case in accordance with the Wellogy model from a published paper written by the author (Abdollahi and Skalle, 2003). The full paper is given in Appendix C. In this section, the only symbolic level is given for implementing the case in the Wellogy model.

5.2.1 General description of the case

A high number of drillstring washouts have been experienced in a specific geology formation in some onshore oil fields in the southern part of Iran. As a consequence, rig time as well as well cost is increased dramatically because of many trips to replace washout pipes, or in the worse case, fishing operations necessary to recover twisted drillstring. This problem happens in a specific formation at a rather shallow depth, before reaching reservoir formation. ***Figure 5.7*** shows a typical well schematic when drilling into the hazardous formation.

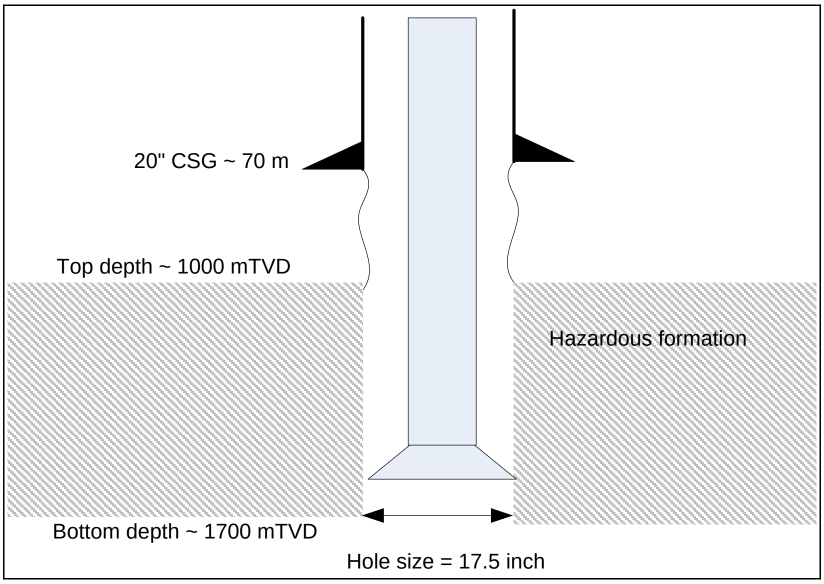


Figure 5.7 Schematic of the well when drilling into the hazardous formation.

5.2.2 Problem description

The title of the problem for this case is named "*Drillstring Failure*". This problem has been experienced not only in Iran but also in different fields in the Middle East area (Kriesels et al., 1999). This problem normally occurs in hard and sticky formations which lead to intensive vibrations. During drilling of the 17-1/2" hole size (the same as the bit size), in the hazardous formation (formation M1), a series of washouts occur. In some wells the frequency of failure is high, i.e. few metres drilling interval between reported washouts, from 10 to 70 failures per well. This problem is limited to the specific fields and specific formations. The other important observation is that this problem only occurs in one part of the field. The formation lithology contains sticky clay which is very sensitive to water (absorb water from the mud). Salty water, water based mud (WBM), is used with density and viscosity typically 1.2 kg/l and 7 cp respectively.

When drilling depth reaches the top formation M1, washouts start. Firstly, the washout is seen by monitoring the mud pump pressure. Obviously, when a washout occurs a pressure drop can be seen, and the amount of this pressure drop will be a function of the size of the washout. This is a primary and important signal to the driller's crew to stop drilling and perform further investigations. The driller turns the rotary-table off and pulls the drillstring a few metres off the bottom. The surface mud circulating system is checked for any possible surface leaks before pulling drillstring out of the hole (POOH). The drillstring is physically checked during POOH, and practically all washouts are discovered by eye. In some cases, bit balling in sticky clay is observed.

The shape of the washouts is similar to the cracks either vertically or perpendicularly to the axis for the drillpipe as shown in ***Figure 5.8***. Cracks perpendicular to the pipe axis has a length up to 1/4 pipe diameter and most of them are observed in the slips area (below the tool joint box). Most of the cracks parallel to the pipe axis occur in the middle of the pipe (pipe body). Approximately one third of the cracks were parallel and two-thirds perpendicular to the drillpipe axis.

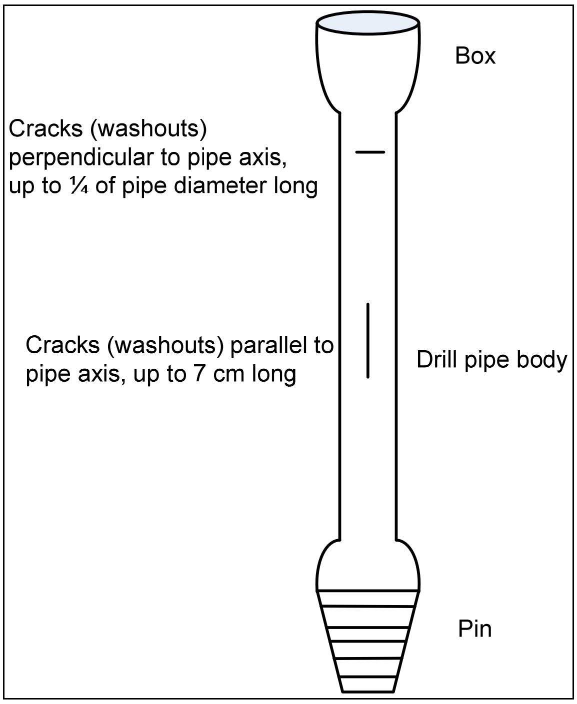


Figure 5.8 Crack direction and relative position.

5.2.3 Causal relationships

The possible factors (causes) affecting drillstring failures have been looked into in many resources, and especially a comprehensive database on drilling provided by API / IADC, (Seshadri and Allwin, 1992). The most important causes which lead to drillstring failures are listed in ***Table 5.2***.

Table 5.2 Factors causing drillstring wash-outs (Seshadri and Allwin, 1992).

Factors which affect drillstring failure (DSF)	Severity level	Comment
Chemistry issues	0 (no concern)	Non-corrosive environment
Tortuosity	1 (potential)	Variation of rock hardness
Fatigue (cyclic stress)	1 (potential)	Vertical well (but not straight)
Pipe quality (internal upset length)	1 (potential)	Failure in slip area related to stress concentration in internal upset
Rock hardness	2 (no critical)	Gray stick marl
Bit & BHA selection	3 (influence)	Mass-imbalance - bit cutter concentration
Axial vibration (bit bounce)	3 (influence)	Due to stick-slip (coupling effect)
Lateral vibration	3 (influence)	Due to drillstring whirl (coupling effect)
Accurate bit parameters	3 (influence)	Critical WOB & RPM to avoid stick-slip
Torsional vibration (stick-slip)	5 (critical)	Due to sticky clay and WBM
Mud type	5 (critical)	WBM induces swelling problems
Sticky rock	5 (critical)	Sticky clay induces stick-slip

Some of these factors have been discussed in detail in Appendix C.

5.2.4 Human reasoning

According to the above discussion the important observations and relationships can be abstractly made based on the human reasoning as summarized below:

```
Drillstring washouts were seen in particular area in the
field / geology.
Drillstring washouts were seen in a particular geology
stratigraphy.
After completing the drilling in hazardous formation the
drillstring washouts were not seen in the beneath
formations.
Similar BHA and drillpipe were used for the whole field.
```

Based on the above observations the following reasoning can be derived:

```
The quality of the drillpipe is not an issue.
The corrosion may not be an issue either because of non-
corrosive environment.
The washout problem is obviously related to the regional
geology / formation type.
```

The following important observations tied to the above reasoning were seen:

```
The formation was sticky.
Bit balling problems were seen.
```

High vertical and lateral vibrations were seen.
Mud was WBM and formation type was clay / Shale.
Swelling of clay was observed leading to additional drillstring torques.

5.2.5 Case model

This case has not been fully solved; however, some of the tested methods have been partly successful, especially the application of downhole motors, where we saw a failure rate decrease of approximately 25 - 30 %. Therefore, this case can be considered as unsolved case. As already discussed in the previous chapters, the case should contain:

- General case description
- Problem and relevant observation
- Special findings
- Repair actions and activities
- Solution of problem
- Outcome

Based on the above discussion the ***Table 5.3*** has been given for entities and their structural relationships (i.e. `subclass, instance, part` relations).

Table 5.3 Structural relationships for the finding entities of the case in the Wellogy model.

Entity 1	Relationship	Entity 2
Field A	is instance of	Field Name
Well A-18	is instance of	Well Name
Well A-18	is part of	Field A
Country Name	is instance	Iran
Drillstring Failure	is subclass of	Failure State
Finding Cause of Failure	is subclass of	Task
Processed Case	is case status of	Case
WBM	is subclass of	Mud Type
Shallow Well Depth	is subclass of	Well Parameter
Hole Size 17-1/2”	is subclass of	Well Parameter
Sticky Clay Formation	is subclass of	Geology parameter
High Drillstring Vibration	is subclass of	Well parameter
Drillstring Fatigue	is subclass of	Drillstring Failure
Drillstring Corrosion	is subclass of	Drillstring Failure
Drillstring Twist-off	is subclass of	Drillstring Failure

Table 5.4 shows some of the causal relationships for the case.

Table 5.4 Causal relationships for the drillstring failure case in the Wellogy model.

Entity 1	Strength relationship	Entity 2
Drillstring Washout	has synonym	Drillstring Crack
Drillstring Fatigue	causes	Drillstring Failure
Corrosion	causes	Drillstring Failure
Hard Rock Drilling	leads to	Drillstring Vibration
Drillstring Vibration	causes	Drillstring Fatigue
Sticky Formation	sometimes causes	Stick-Slip
Stick-Slip	causes	Drillstring Vibration
WBM	sometimes causes	Clay Swelling
Shallow Well Depth	sometimes causes	Higher Stick Slip
Sticky Formation	sometimes causes	Bit Balling
High Bit Torque	sometimes causes	Drillstring Twist Off
Poor Recognition of Drillstring Washout	sometimes causes	Drillstring Twist Off

Table 5.5 shows the case at the symbolic level

Table 5.5 Case representation at a symbolic level for Wellogy application.

Relation type	Entity
has failure	Drillstring Washout
has task	Finding Cause of The Failure
has solution	Stick-slip Vibration
has observation	Sticky Clay Formation
	Shallow Formation
	WBM
	Hole Size 17-1/2”
	High Number of Washout
	Washout in One Formation
	Washout in Slip Area
has after failure observation	Mud Pressure Dropping
has short-term repair action implement in well plan	Using OBM
	Using Stiffer BHA
	Using Mud Motor
	Using Corrosion Inhibitor (2 % by volume)
	Changing Bit Type
	Using Downhole Shock Absorber
	Avoiding Critical RPM
has further investigation action	Full statistic analysis in hazardous formation
	Reducing BHA weight
	Downhole vibration monitoring to measure the severity of vibrations in different modes
has case status	Processed case
has outcome	Partially Solved
lesson learned	Vibration (stick-slip) has been found to be one of the main factors leading to drillstring failure (crack or washout). Since the failure happened in only one specific formation, not observed in upper or lower formation with same drillstring and same parameter, we can say that poor pipe quality is not the reason for the failure. Drillstring vibration in the torsional mode is the most probable reason of the failure due to two reasons: 1) failures occur only in one specific formation 2) Formation rock is sticky which lead to stick-slip vibration. However, the problem is complex and combined effects are involved

5.3 Borehole instability cases

Additional cases are given to realize how to produce case for CBR application in a different perspective, because case production has been a challenging task for many users and researchers who are trying to implement CBR, especially in the petroleum engineering domain. Two cases concerning borehole instability are produced. The selected case is produced here based on a published paper (paper-based).

5.3.1 Hole instability case

This case is produced on basis of a published SPE paper concerning the hole instability problem (Russell et al., 2004). This case is built for the purpose of experience transfer like all other cases which are considered as knowledge-rich cases. The usefulness for the user of this case can be for example “solving a problem during execution of a sidetracking drilling plan” or “improving drilling efficiency” of sidetracked wells in the North Sea area. The case will show some operational observations or “red flags” which have been experienced during sidetracking in a depleted reservoir in the area. Most red flags were unforeseen in the initial well design due to many geology uncertainties. The purposes of the case can be summarized as:

1. To learn about a specific challenges when drilling a sidetrack through a faulted and partially depleted formation
2. To improve a sidetrack well plan to overcome such challenges
3. Introducing the specific failures mechanism (hole instability) for sidetracking applications
4. To exemplify case production in the Creek framework

5.3.1.1 Knowledge level

Summary

A sidetrack well was planned to be drilled from an existing well in North Sea (UK sector) by Shell UK in 2002. Sidetracking operation was exposed to a low reservoir pressure and complex geology area (faults) encountering many operational challenges such as stuck pipe, and mud lost circulation. The two sidetrack legs failed. The operator learned from the two incidents and applied the gained experience for a new attempt. They succeeded in completing the job in the third trial. A simple sketch of the well legs is shown in ***Figure 5.9***.

The solution for the third trial was:

- Change the well path in order to avoid crossing the faults and shortening the well path
- Improve mud performance in order to meet hole stability objectives
- Increase human awareness and improve well monitoring during execution of the plan

These suggestions were based on the experience gained from the two previous sidetracks.

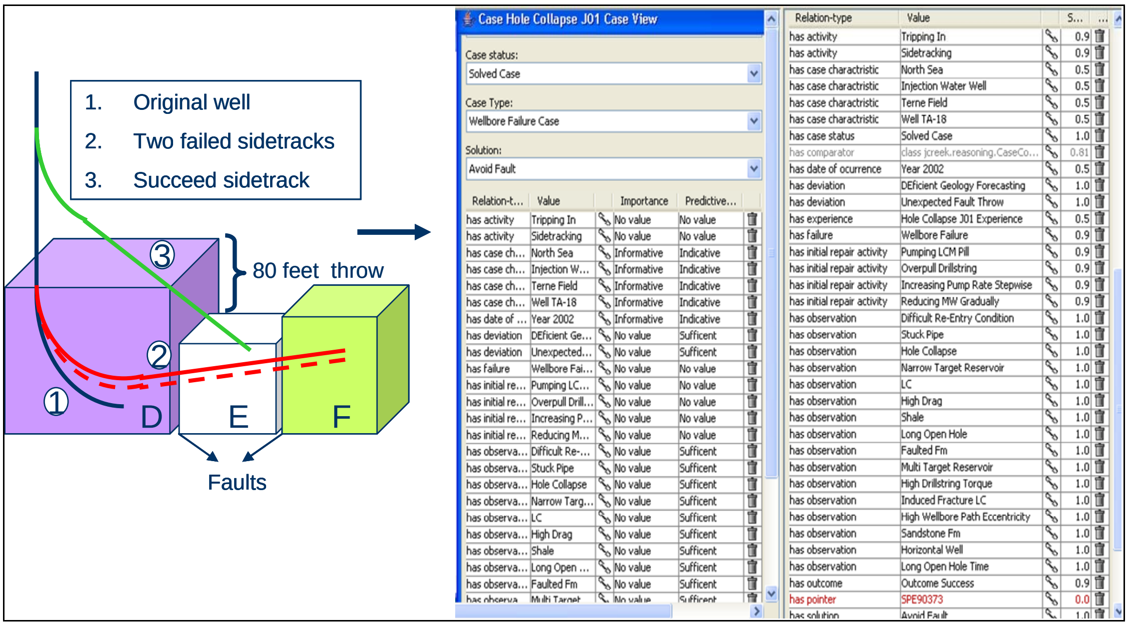


Figure 5.9 Illustration of the three well paths and transforming of episode to symbolic codes.

Summary of the problem

Several mud losses were observed in the Lower Ness formation in Block D during the first sidetrack. Two reasons for mud losses were considered; a) low reservoir pressure and b) faults. Attempts to reduce the losses were made by pumping pills and reducing the mud weight. A long section was drilled at an inclination angle greater than 90 deg. A significant, unexpected throw across the main D/E fault of approximately 80 ft was then encountered. This resulted in strong steering corrections to get the well path back to the Upper Ness reservoir sands. Increases in torque-and-drag were observed in the Upper Ness in Block E were dealt with by circulating the hole clean. The bottom hole assembly (BHA) became stuck unexpectedly while moving the drillstring prior to a make-up pipe connection. The mechanism that caused the stuck-pipe incident was not clear. Possibilities considered were differential sticking (because of depleted reservoir pressures), geometrical sticking (caused by steering corrections), poor hole cleaning (indicated by increased torque-and drag), and borehole collapse. The attempts to free the stuck pipe failed, thus the well was abandoned.

Repair action based on first failed sidetrack

The second sidetrack was followed with the similar plan as the first sidetrack. The mud losses were experienced again and drilling time was increased once more due to equipment failures. High slip-stick and increasing torque-and-drag were then observed. Total depth (TD) was called early because of deteriorating hole conditions. The trip out of the open hole took around 4 days and was characterized by the excessive mud losses, overpulls, and packing off the annulus. When the drillstring was out of the hole, an additional delay of five days was incurred because of breakdown of the draw-works. On attempting to re-enter the hole, it became apparent that the second sidetrack was lost.

Gained experience from the two failed sidetracks

- The Mid-Ness shale indicated low compressive shear
- High wellbore offset was in the form of eccentricity from the main well path. ***Figure 5.10*** shows offset measured in the study case. These measures were taken a short time after the well was drilled. High wellbore offset can be the cause of high wellbore side forces and stuck pipe. The reason of the wellbore offset is believed due to slightly relative movement of two faults.
- The sudden mud losses were observed in fractures and faults
- Due to the low reservoir pressure, the jump of pore pressure from the depleted reservoir to the normally pressured shales has caused a reduction the fracture gradient in the intersecting interval. As a result, the shale fractured and mud losses were experienced at mud weights lower than those used to drill the early development wells before reservoir pressure depletion had taken place.

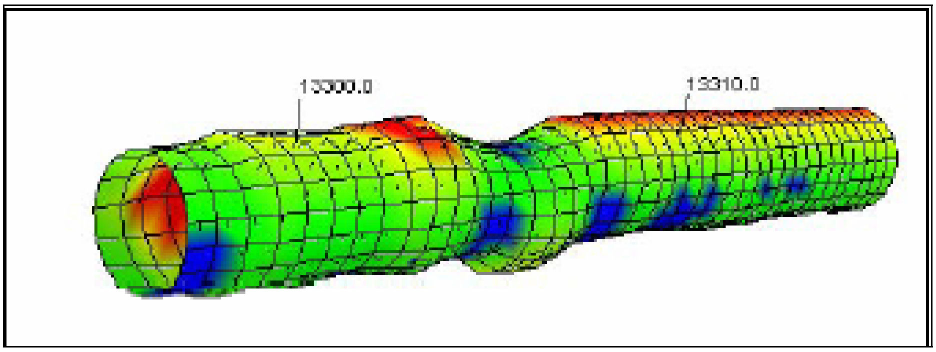


Figure 5.10 Illustration showing wellbore offset, i.e. eccentricity due to a geology fault (Russell et al., 2004).

Reasons for failure

The cause of the failure was unexpected movement on the fault. Fault throw was also recognized as a reason for wellbore offset (degree of eccentric) and heavy mud losses. Russell et al. (2004) suggest that *"the exact mechanism for the creation of the offset is difficult to determine, but could have been caused by minor movement made possible by hydraulic lubrication of the faulted material in the interval*". However, it is unclear what they mean by hydraulic lubrication. It is possible that the mud loss changed the in-situ pore pressure and effective stress. The change in the reservoir pressure promoted wellbore instability.

Solution for the third sidetrack

They altered the well path to avoid the hazardous fault area. The new well path was drilled through only one reservoir block at a much lower inclination. An integrated technical team was established to perform a careful operation plan and monitor this challenging well.

Outcome of the solution

The third sidetrack was drilled with success.

Reference

The reference can be addressed as an entity; for instance, for this case the reference is `SPE 90373` (Russell et al., 2004).

5.3.1.2 Symbolic level

Complete case in word format

The findings of the case "`Hole Collapse 01`" are shown in ***Table 5.6***.

Table 5.6 **Findings of the case `Hole Collapse 01`.**

Relation type	Entity
has pointer	SPE 90373
has case characteristic	UK
has date of occurrence	Year 2002
has case characteristic	Shell UK
has case characteristic	Tern Field
has case characteristic	Well TA-18
has new well objective	Injection well
has activity	Sidetracking
has activity	Tripping in
has failure	Wellbore failure
Has task	Improve Well plan
has observation	Horizontal Well
has observation	Shale Fm
has observation	Sandstone Fm
has observation	Narrow Reservoir Target
has observation	Multi Reservoir Target
has observation	Reservoir P Low
has observation	Long Open Hole Time
has observation	High Drillstring Torque
has observation	High Drag
has observation	Natural Fracture LC
has observation	Difficult Re-entry Condition
has observation	Stuck Pipe
has observation	Hole Collapse
has observation	LC
has observation	High Well bore Eccentric
has observation	Difficult Re-entry Condition
has deviation	Deficient Geology Forecasting
has deviation	Horizontal well
has deviation	Unexpected Fault Throw
has initial repair activity	Increasing Pump Rate Stepwise
has initial repair activity	Reducing MW gradually
has initial repair activity	Overpulling
has initial repair activity	Pumping LCM Pill
has initial repair activity	New Sidetrack
has solution	Change Well Path
has solution	Avoid Faults
has outcome	Successful Outcome

Has experience and pointer

has summary Hole Collapse 01 Summary

a) History of the incidents

b) Reasons for occurring of the incidents
c) Repair actions and solutions

`has experience` `Hole Collapse 01 lessons learned (LL)`
a) Lessons learned from the incidents
b) Recommendations

`has pointer` (similar as reference) `SPE 90373`

Figure 5.11 shows snapshots of description of the `Hole Collapse 01 Summary` and `Hole Collapse 01 Lessons Learned (LL)` for case "`Hole Collapse 01`" in the Wellogy model.

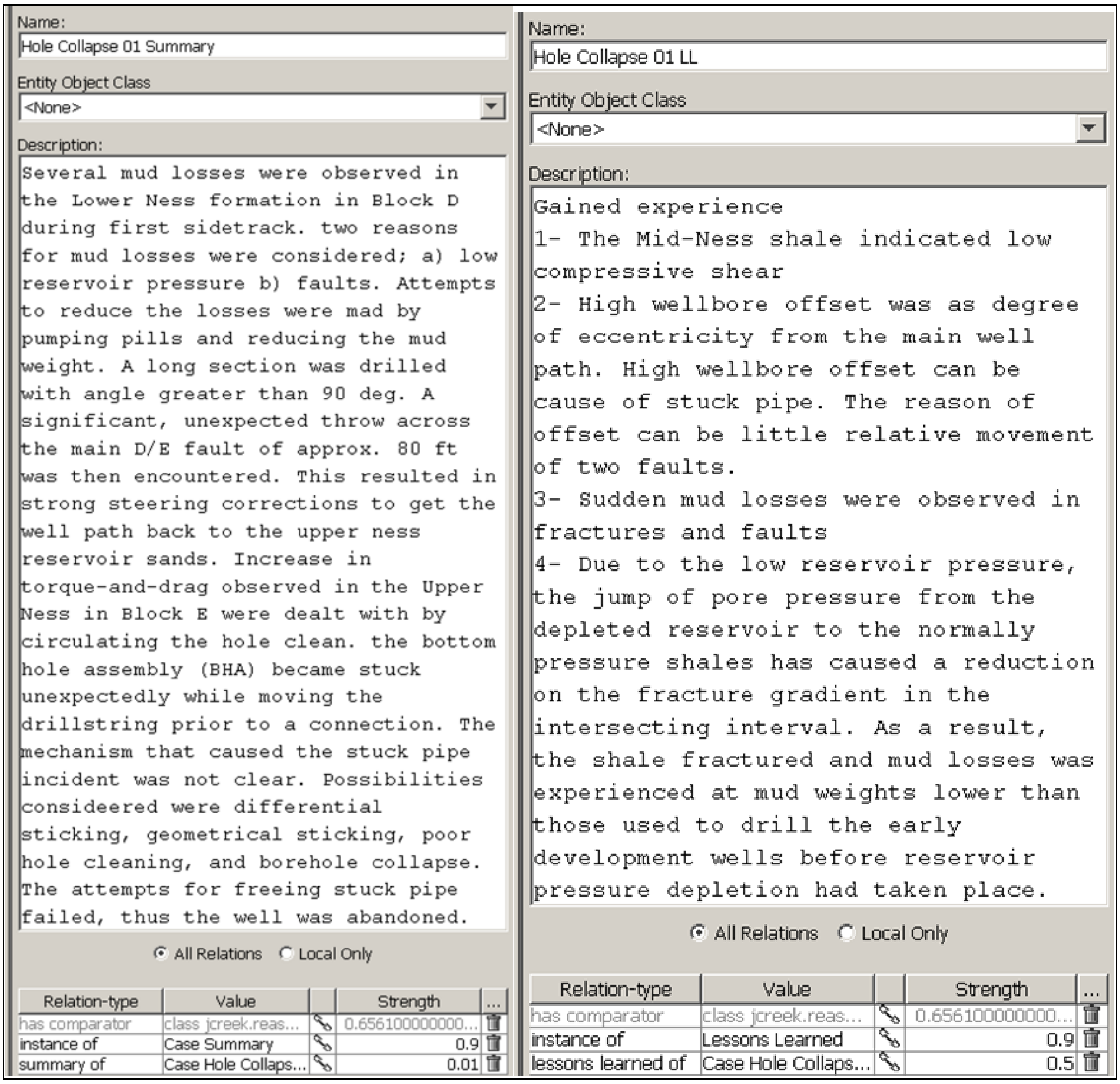
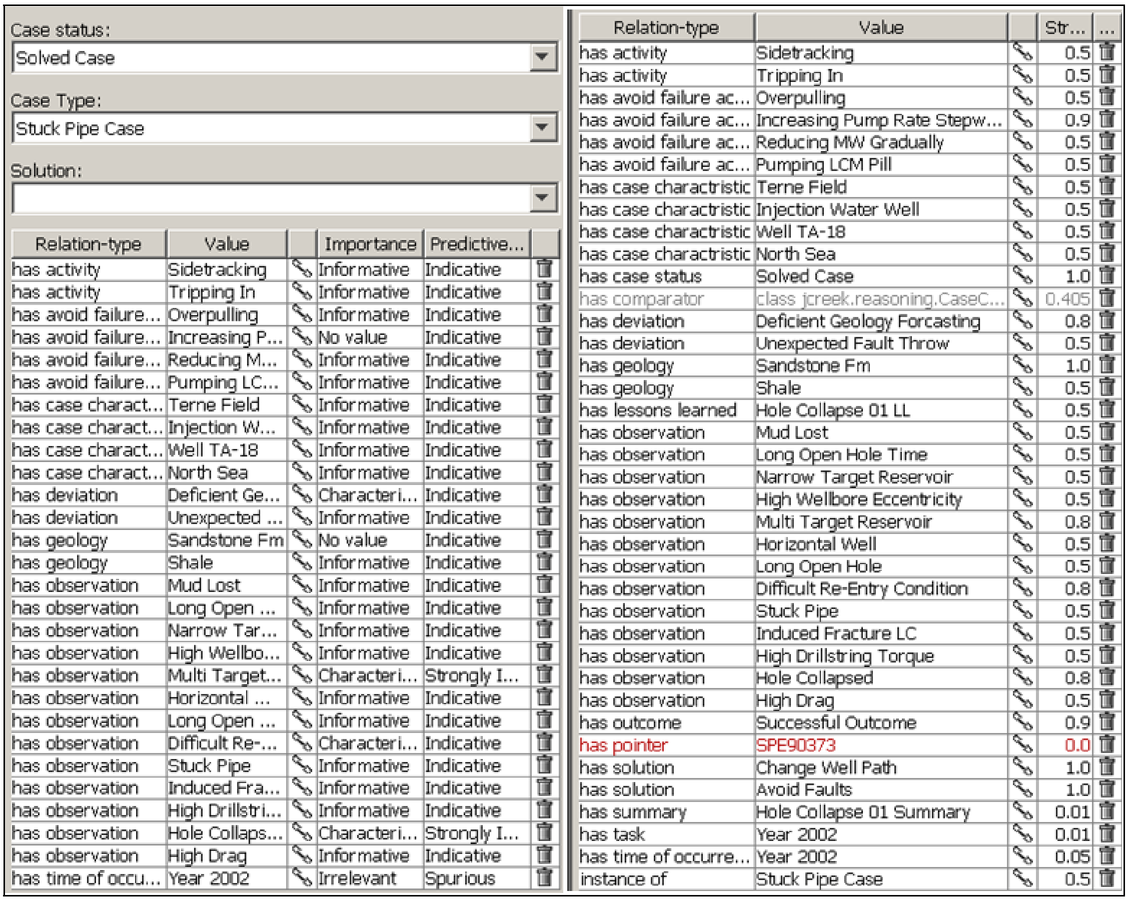


Figure 5.11 **Textual descriptions for "`Hole Collapse 01 Summary`" (left) and "`Hole Collapse 01 LL`" (right).**

5.3.1.3 Representing the complete case in the Wellogy model

Figure 5.12 shows the contents for case "`Hole Collapse 01`" in the *case view* (left) and *frame view* (right). As already explained, in the *case view*, the degree of `Importance` and `Strength Value` is given to each finding of the case by a couple of textual phrases (e.g. `Informative, Indicative`) , while in the *frame view*, these two phrases will be converted to a digital number varied 0 to 1.



Case status: Solved Case

Case Type: Stuck Pipe Case

Solution:

Relation-type	Value	Importance	Predictive...
has activity	Sidetracking	Informative	Indicative
has activity	Tripping In	Informative	Indicative
has avoid failure...	Overpulling	Informative	Indicative
has avoid failure...	Increasing P...	No value	Indicative
has avoid failure...	Reducing M...	Informative	Indicative
has avoid failure...	Pumping LC...	Informative	Indicative
has case charact...	Terne Field	Informative	Indicative
has case charact...	Injection W...	Informative	Indicative
has case charact...	Well TA-18	Informative	Indicative
has case charact...	North Sea	Informative	Indicative
has deviation	Deficient Ge...	Characteri...	Indicative
has deviation	Unexpected ...	Informative	Indicative
has geology	Sandstone Fm	No value	Indicative
has geology	Shale	Informative	Indicative
has observation	Mud Lost	Informative	Indicative
has observation	Long Open ...	Informative	Indicative
has observation	Narrow Tar...	Informative	Indicative
has observation	High Wellbo...	Informative	Indicative
has observation	Multi Target...	Characteri...	Strongly I...
has observation	Horizontal ...	Informative	Indicative
has observation	Long Open ...	Informative	Indicative
has observation	Difficult Re-...	Characteri...	Indicative
has observation	Stuck Pipe	Informative	Indicative
has observation	Induced Fra...	Informative	Indicative
has observation	High Drillstri...	Informative	Indicative
has observation	Hole Collaps...	Characteri...	Strongly I...
has observation	High Drag	Informative	Indicative
has time of occu...	Year 2002	Irrelevant	Spurious

Relation-type	Value	Str...
has activity	Sidetracking	0.5
has activity	Tripping In	0.5
has avoid failure ac...	Overpulling	0.5
has avoid failure ac...	Increasing Pump Rate Stepw...	0.9
has avoid failure ac...	Reducing MW Gradually	0.5
has avoid failure ac...	Pumping LCM Pill	0.5
has case charactristic	Terne Field	0.5
has case charactristic	Injection Water Well	0.5
has case charactristic	Well TA-18	0.5
has case charactristic	North Sea	0.5
has case status	Solved Case	1.0
has comparator	class jcreek.reasoning.CaseC...	0.405
has deviation	Deficient Geology Forcasting	0.8
has deviation	Unexpected Fault Throw	0.5
has geology	Sandstone Fm	1.0
has geology	Shale	0.5
has lessons learned	Hole Collapse 01 LL	0.5
has observation	Mud Lost	0.5
has observation	Long Open Hole Time	0.5
has observation	Narrow Target Reservoir	0.5
has observation	High Wellbore Eccentricity	0.5
has observation	Multi Target Reservoir	0.8
has observation	Horizontal Well	0.5
has observation	Long Open Hole	0.5
has observation	Difficult Re-Entry Condition	0.8
has observation	Stuck Pipe	0.5
has observation	Induced Fracture LC	0.5
has observation	High Drillstring Torque	0.5
has observation	Hole Collapsed	0.8
has observation	High Drag	0.5
has outcome	Successful Outcome	0.9
has pointer	SPE90373	0.0
has solution	Change Well Path	1.0
has solution	Avoid Faults	1.0
has summary	Hole Collapse 01 Summary	0.01
has task	Year 2002	0.01
has time of occurre...	Year 2002	0.05
instance of	Stuck Pipe Case	0.5

Figure 5.12 Contents of the case "Hole Collapse 01" in both views; case view (left) and *frame view* (right).

The extracted new entities

The existing Wellogy model has been searched to enter the new entities by using "searching tool". This step should be performed precisely to avoid repetition for inserting entities. The new entities are listed ***Table 5.7***.

Table 5.7 **The new entities (left column) which represent the `Hole Collapse 01` and their relations to the existing entities which have already been found in the Wellogy model (right column).**

from Entity	Relationship	to Entity
Drilling Operational Data	has subclass	Drilling Time
Drilling Time	has subclass	Long Open Hole Time
Case Description	has subclass	Reference
Reference	has subclass	SPE Paper
SPE Paper	has instance	SPE 90373
Well Characteristic	has subclass	Date of Occurrence
Date of Occurrence	has instance	Year 2002
Drilling Description	has instance	Drilling Operation Description
Drilling Operation Description	has subclass	Re-entry Condition
Re-entry Condition	has subclass	Difficult Re-entry Condition
Fault Description	has subclass	Active Fault
Fault Description	has subclass	Unexpected Fault Throw
Well inclination	has subclass	Horizontal Well
Terne Field	has part	Well TA-18
Operators Name	has instance	Shell UK
Improve Well Plan	has subclass	Change Well Path
Improve Well Plan	has subclass	Avoid Faults
Axial movement after stuck	has subclass	Drillstring Over-pull
Operation Complexity Underrated	has subclass	Deficient Geological Forecasting

Definition of the new entities:

Each new entity can be explained in the Wellogy model. This explanation is given in order to define the entities (i.e. findings of the case). Each entity has a textual description box provided in the Creek knowledge editor. The following findings for `Hole Collapse 01` are defined and given as examples:

`Drill Time`

"`Drilling Time`" is defined as cumulative time for drilling activities which cover both productive drilling time and non-productive drilling time.

`Pointer`

"`Pointer`" is additional information stored outside of the Wellogy model. It can be; URLs, SPE paper, research reports, books, etc.

.

`Time of Occurrence`

"`Time of Occurrence`" is the time at which failure occurred. This entity is obviously not referring to the date of the published the paper or the constructed case.

Active Fault

This entity defines a geological event. A large or small formation moves quickly along its fault plane. If this fault is crossed by a drilling well, the wellbore change its geometry and it can be observed while drilling.

Unexpected Fault Throw

This entity refers to a situation when faults are thrown more than indicated by expectation or forecasting. This is normally an issue when drilling through complex geology (faulted rocks and formations). Corrective measures may be needed.

Shell UK

Shell is a company name and has an instance of “company name”. If a company has several branches in a different region, an extension name of the region is added to the company name, e.g. “Shell UK”.

The new causal relationships for the case

The new causal relationships found for case "`Hole Collapse 01`" is given in ***Table 5.8***.

Table 5.8 The causal relationships for the case "Hole Collapse 01"

Entity	Relationship	Entity
Hole Collapse	causes	Poor Hole Cleaning
Difficult Re-entry Condition	caused by	Thick Mud Cake
Thick Mud Cake	caused by	LC
Difficult Re-entry Condition	caused by	High Wellbore Path Eccentricity
Difficult Re-entry Condition	indicated by	High Drag
Difficult Re-entry Condition	sometimes caused by	Active Fault
Difficult Re-entry Condition	always caused by	Hole Collapse
Hole Collapse	occasionally caused by	Long Open Hole Time
High Wellbore Path Eccentricity	occasionally caused by	Unexpected Fault Throw
Active Fault	causes	High Wellbore Path Eccentricity
Faulted Fm	causes	High Wellbore Path Eccentricity
High Open Hole Time	sometimes caused by	Waiting on Equipment / Material
High Open Hole Time	sometimes caused by	Waiting During LC Repair
Hole Collapse	occurs in	Shale
Pipe Stuck Alarm	sometimes caused by	Unstable Shale Fm
High Drag	sometimes caused by	High Dog Leg Severity
High Drag	sometimes caused by	Dog Leg

Figure 5.13 shows the network of the causal relationships for the case "`Hole Collapse 01`". The different relationships are shown by the different colours.

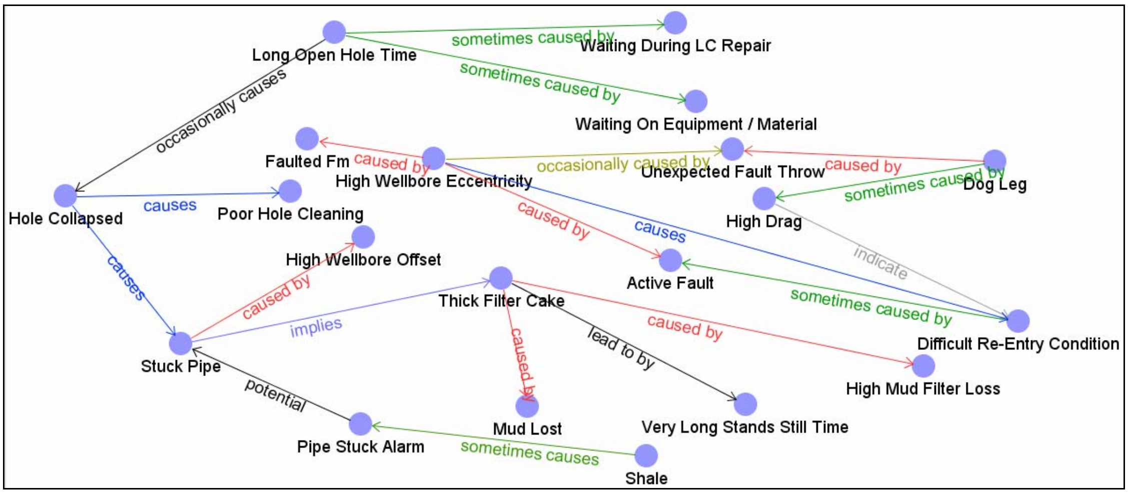


Figure 5.13 Some part of the new causal relationships for the case "`Hole Collapse 01`" in the Wellogy model.

6. Discussions

This chapter discusses issues that have been found important during the implementation of the Wellogy model for the oil well engineering domain.

6.1 Task of cases in the oil well domain

In the oil well knowledge domain different problems can be modelled which are difficult to explain by mathematical approaches due to the complexity and uncertainties of the process. The role of an engineer in solving a problem by reasoning is important. People continuously gain experience through solving oil and gas well problems on a daily basis. However, people are moving around and knowledge may be lost or at least not stored in a systematic way. Oil well cases which contain knowledge can be found either in the mind of the workers or written down as texts and documents. They are not stored systematically in order to reuse them in future application.

A recurring question when we talk about CBR modelling is what types of cases within oil well engineering should be stored for the CBR model? Before answering this question, we need to list the repeated problems observed in the domain. When this list is provided, the causes behind each problem should be derived. The history of oil and gas wells has show that most of the repeated problems in this domain are due to incomplete information (data) or uncertain conditions of the media. It is difficult to measure most of the downhole data needed for different applications for the oil well engineering domain. Imagine, the behaviour of the formation rock (i.e. physics and chemistry of the rock) is complex and uncertain. It is worth pointing out that the formation rock is an important component of the oil well domain. Abnormal pore pressures, stuck pipes, lost circulations, fluid blowouts, low oil production recoveries; all have connections to the rock behaviour.

Another problem is the downhole well condition and monitoring. Small hole diameter (typically 6 inch), long distance to the surface (typically 6000 m), and high temperatures and pressure, lead to some challenges in terms of measuring the correct information in order to diagnose oil and gas well problems. Typical examples in this context are well leakages. It is difficult to install permanent and reliable tools along the well construction to continuously record the data and diagnose the well diseases.

With this background, it can be mentioned that the task of the cases modelled in Wellogy is important to be defined prior to creating the model. The diagnosis of problems in the oil well domain is more important than its solutions. A CBR model which deals with the diagnosis of problems can be called *CBR-diagnosis*. In the Wellogy model implemented for the leaking well cases, the task was defined as "*finding the cause*". Obviously, when the causes of the problems are found, the solutions can be fairly straightforward for the engineer.

6.2 Matching results

The matching process between two selected cases is non-symmetric process. It means that the matching percentages between two cases, input and output cases, are different. For instance, the Case A has 60 % similarity to the Case B, but in opposite direction, it will not be the same percentage.

When the matching function is activated in the Creek knowledge editor, the retrieved cases are ranked according to the match percentages. This result is the first indication for the users to choose and examine the output case (solved case). However, as the number of findings of the cases are given in an open set and unconstrained way (i.e. some cases have a higher number of information and some have lower number), a high match percentage with a solved case may not necessary mean it is the case which most resembles the unsolved case. The users need to go through the solutions of the solved cases to verify the result. The retrieved solutions can be either used directly or adjusted (repaired) by aquatically using the causal relationships defined in the Wellogy model. Generally this part of the process is called "*revising*" in the CBR cycle. We have already shown that the retrieved case solutions with the highest match percentage were to some extent the most reasonable solutions when comparing with the human reasoning, after minor adjustment and repair to satisfy human reasoning.

Another point is about the quality of the unsolved cases. The attributes of the unsolved case have a default strength valve of 0.5 and unchangeable in the Creek framework. However, in the real world, when describing a problem for an unsolved case by a set of entities, some entities are more important than others.

6.3 Human dependency on the CBR model

At least three times during the implementation of the CBR model human judgments are needed:

1. When giving the strength values to the different causal relationships in the model
2. When giving the degree of `Importance` and `Predictive Strength` for findings of the solved cases
3. The number of findings given to the cases

These parameters are given to the model according to human expertise. Cases can have unlimited / undefined number of findings (features). Hence, the number of findings would be accounted for in the match percentage (Eq.1), so the result of the model would be affected by these parameters. Although more findings given to the cases are advantageous, because they improve the explanation of the case, they should be provided for the similar cases with the rather same amount (same number of findings). As explained before, the findings of cases can be divided into the three categories;

1) Basic case findings

2) General case findings
3) Findings which directly or indirectly explain the problem and solution of the case

The first two categories can have almost the same number of findings; however, the third category can have different number of findings depending on both the availability of case information and of the case builder.

The strength values which are given for causal relationships between two entities also depend on the case builder expertise. The values as discussed before vary between 0 and 1. Generally, the causal relationships modelled in the CBR tools play the same role as mathematical operators. Let us go back to Eq. 3 for drilling rate of penetration:

$$ROP = \frac{K}{S^2}\left[\frac{W}{d_b} - (\frac{W_o}{d_b})\right]^2 N \qquad \text{(Eq. 3)}$$

Causal relationships can be derived (the relationship strengths are given as verbs - bold font):

For the *N* parameter (bit rotation speed) the following causal relationships can be given:

`High N` **`always causes / causes / leads to / sometimes causes`** `High ROP`

For the *W* parameter (rock strength) the following causal relationships can also be given:

`High W` **`always causes / causes / leads to / sometimes causes`** `High ROP`

As seen, it is possible to define different strength values between the two parameters. This is entirely up to the case builders. However, as the equation shows, the effect of *W* on *ROP* is higher than *N*. Therefore, it is logical to give a higher strength value to the *W*. Similar evaluation has already been considered in the Wellogy model.

Note that the causal relationships are not only physical / mathematical equations, but they can also be facts and broader understanding relationships between two concepts which engineers find when solving the case. For instance, for the ROP example given in Chapter 2, the driller found low mud circulation rate was the reason for low ROP, he could therefore establish such causal relationships in the CBR model;

`Low GPM` **`causes`** `Poor Lifting Capacity`
`Poor Lifting Capacity` **`causes`** `Cutting Accumulation around the Bit`
`Cutting Accumulation around the Bit` **`causes`** `Low ROP`

These types of relationships are created based on the observations taken from the real cases which may be difficult to model in a mathematical format. This is part of the knowledge which is called specific knowledge elicited through the cases.

The degree of importance of the findings for solved cases are expressed by combination of two phrases in Creek; degree of `Importance` and `Predictive Strength`. There are no general rules for giving these characteristics to the findings of the solved cases; however, the `Importance` generally refers the degree of importance of a finding tied to the solutions of the case, and the finding has been reported many times in many similar cases. For instance, `Pressure Build-up in Annulus-B` is an important finding for the leaking well cases representing a leak crossing from annulus-A to annulus-B. Because this finding has been reported for all similar cases, this finding will get a high degree of `Importance.` However, the `Predictive Strength` indicates how significant a finding is when predicting a problem solution. For instance, `Non-Chrome Casing` has high `Predictive Strength`, but since it has not been reported for all similar cases, it will get low `Importance` degree. This type of giving weights on the findings of cases is recommended to perform when the cases are clustered according to the similarities between them. In the Wellogy model these issues have been regarded by clustering cases in the five groups based on the solutions.

6.4 Conversational CBR

As the case designer is not the same as the people who directly solve the case, the case components will entirely depend on the builders' expertise. Therefore, it is highly recommended to develop a format or defined template for each application which the case information and its findings should be filled in. This was done to a certain extent for the Wellogy model by developing a table as shown in ***Table 4.2***. After building this preliminary case structure, separate tables can be provided for the cases individually as shown in Appendix A.

In this context, conversational CBR (C-CBR) may have an advantage. In recent years the development of C-CBR has extended the applicability of CBR to facilitate case construction (Aha et al., 2001). By applying C-CBR, users may construct the case incrementally through a question-answering scheme (Gu, 2006). Generally cases are described and documented by people who directly involve to the case. They may not give the full description to the case. When a case is constructed by the case builders (who may not directly involve to the case) additional information may needed which could be not covered in the text document provided by other people. For this reason, C-CBR may be helpful, because the C-CBR method can provide a dialogue for describing cases in a defined template. For instance, for a `Stuck Pipe` case the following typical pair of questions / answers can be provided as shown in ***Table 6.1***.

Table 6.1 **Example showing C-CBR for a typical stuck pipe case.**

Questions		Answers
Information before failure	Kind of stuck pipe	Collapsed formation
	Type of formation	Shale
	Mud type	Water based mud
	The time of stuck	During pipe connection
	Hole clearance	Low
	Mud circulation rate	Low
	Rate of penetration before stuck	High
	Mud viscosity	Low
	Returned cutting on shaker	Low
Information after failure	Circulation after stuck	Restricted circulation
	Drillstring rotation after stuck	No rotation
	Drillstring movement (up / down)after stuck	No movement
	Pump pressure	Increased
From these questions and answers, the cause for the problem can be concluded. For instance, the hole collapse due to inappropriate hole cleaning can be the solution (cause) of the case.		

6.5 Future improvements

6.5.1 Found constrains for constructing the Wellogy model

Since we are not able to apply conditional relation links like "IF" and "THEN", some entities are extended in terms of creating long phrase when naming entities to fulfil the meaning of the entity. For instance, some entities are extended just in order to complete the meaning for answering to; "where", "how" and "when". Here are some examples:

- "High Drilling Time in Open Hole" - means that time consumption was high during drilling in an open hole section before running the casing - answer to the "where".
- "Stuck Pipe While Tripping" - means that the pipe got stuck while tripping out or into the hole - answer to the "when".
- "Annular Well Pressure Increased Gradually" - means that the pressure trend in the well annulus is slowly rising- answer to the "how"

During developing the Wellogy model, some different subjects within the oil well engineering domain have been embedded into the Wellogy model; for instance, UBD, well integrity, through tubing drilling (TTD), lost circulation, and stuck pipes. It seems when the model is expanded with different tasks (i.e. problem-solving, finding the cause of a problem) the functionality of the system with respect to the naming entities and developing causal relationships needs to be implemented precisely. Generalization of naming the entities, entities which could deal with the different subjects in one domain, could improve the efficiency of the model.

Within the case time period, several activities or actions may be happening at the same time, and it is worth retaining this information in the case content. They are usually defined in the case to describe how / when / where the problem happened, and how / when / where the solution was achieved. When several activities are given in a case, there is no chronological system to show the ordering of activities; for instance, first `Drilling`, second `Getting Stuck Pipe`, third `Apply Over-pull of String`, and fourth `Circulating LCM Pill`. Such action-outcome chain processes may be significant to follow to enhance the reasoning and understanding process.

During the development of the Wellogy model, it was sometimes necessary to search for entity names or concepts. Searching function used in Creek only looks for the first letter of the first word of the entities. However, as most of the entities contain more than one word, the searching for a concept is not so simple. For instance, we want to search for “`Mud`”, and this entity in Wellogy is for example named as “`Drilling Mud`”, the searching function may not find this entity. For this purpose, we had to transfer the Wellogy model to an XML file in several steps during the development of the model. The XML file is then downloaded in an Excel or Word file to use the search functions to find the target entity.

Cycling or looping of entities must also be avoided. There would be a cycle in the hierarchy when for example entity “A” has subclass “B” and at the same time “B” has subclass “A”.

6.5.2 Combined relationships

For the causal relationship model, multi-entities which yield one outcome (e.g. IF A & B & C exist THEN D occurs with a high probably) in the Creek framework (university version) was not implemented. Up to now, the existing model only links one entity to another one for expressing the causal relationship; for instance, “`High Mud Density`” ***sometimes causes*** “`Mud Loss`” (weak relationship). However, another option can be; IF “`High Mud Density`” and “`Formation is Naturally Fractured`” exist at the same time, both conditions ***cause*** “`Mud Loss`” (stronger relationship). These types of relations are needed for the oil well engineering domain. ***Table 6.2*** shows an example for combined relationships for a causal relationship.

Table 6.2 Examples of combined causal relationships.

<table>
<tr><th>Income entity</th><th>Relation name</th><th>Relation strength (assumed)</th><th>Outcome</th><th>Remarks</th></tr>
<tr><td>A</td><td>sometimes causes</td><td>0.4</td><td rowspan="5">D</td><td rowspan="3">can be modelled in the Creek framework</td></tr>
<tr><td>B</td><td>sometimes causes</td><td>0.4</td></tr>
<tr><td>C</td><td>sometimes causes</td><td>0.4</td></tr>
<tr><td>A + B</td><td>causes</td><td>0.7</td><td rowspan="2">recommended in the future</td></tr>
<tr><td>A + B + C</td><td>always causes</td><td>0.99</td></tr>
</table>

6.5.3 Sustaining success and failure attributes for the cases

Most of the attributes or findings which are allocated for the cases are attributes which describing failures such as indicative observations and alarms, for example, "`Low Chrome Casing`" causes "`Casing Corrosion`" which causes "`Casing Leak`". Here, the "`Low Chrome Casing`" is a *negative finding*. On the other hand, we have sometimes a *positive finding;* for example, "`High Chrome Casing`" which causes increase in "`Casing Resistance against Corrosion`", which finally leads to reduction of the chance of "`Casing Leak`". By giving such finding to a leak well case, those cases with the solution of "`Casing Leak`" due to "`Non-Chrome Casing`" will be retrieved with low similarity percentages. Therefore, the result of the model will become more reliable by retrieving the closest similar retrieved cases. These kinds of relationships have not been implemented in the Wellogy model yet. In the daily human life, normally *success* characters or *positive observations* are useful for deductive and inductive reasoning. This issue was discussed and realized too late to implement it in this study. So the recommendation is to use success characters in addition to failure characters for better reasoning results.

6.6 CBR system background information for engineers

When implementing a new case in an existing ontology, a defined procedure or guideline is needed for naming new entities which are found in a new case. It is also difficult to remember previous similar entities (similar with respect to semantic) which already exist in the model and should be allocated for a new case. Therefore, repetition of similar entities with respect to the meaning can occur. If similar entities (duplications) are renamed and entered into the model, it could cause a reduction of the quality of the model in term of causal relationships. As Creek understands the name of entities (i.e. the form of writing of the phrases), it will treat two entities with the same meaning differently. The solution to this problem is to use one of the entities as a synonym to the other one.

Another point is locating the correct place (branch) in the hierarchy (ontology) for inserting of a new entity found in a new case. This can mostly happen in a rather large ontologies (i.e. model with the thousands entities). Therefore, integrating of the cases and existing hierarchy model is needed to create a sophisticated CBR model. However, the two-dimensional graph in the Creek software is sometimes helpful.

For petroleum engineers to be working on CBR applications, the users need to fully understand the functions of the CBR systems and tools (e.g. the Creek framework). The users should know how the CBR system deals with the components of the model (e.g. Wellogy). The requirements of the model and case structures should be defined by both parties. For this reason, the new users and students in petroleum engineering who choose this topic for research should have CBR courses. The focus should be put on CBR functions such as; retrieving, reusing, revising and retaining from a practical point of view.

6.7 Further applications of CBR in petroleum engineering

Different cases in the petroleum engineering domain have been examined and modelled in the Wellogy model. These cases cover rather complex oil well problems. They are complex, because they are difficult to predict, understood, model, and solve. The typical examples in the oil well engineering domain are well integrity in terms of leakage during the life of the well, mud loss circulations, and stuck pipe during drilling phase. The benefits of using the CBR approach for such problems are:

- Remembering and recalling similar cases; if the number of cases in case memory are high (around hundred cases), the trend can be obtained by use of CBR model
- Storing and connecting different parts of the knowledge for a specific problem; in this way CBR model can provide additional information to the unsolved case
- Compensating missed and forgotten information and data of the case

As discussed before, if the human factor is taken away, the causes of most of the oil well problems are related to the lack of understanding rock behaviour or unpredictable behaviour. Therefore, the CBR approach is advantageous to use for problems which are induced by rock and geology formations. Generally, a well trajectory intersects different geological layers or formations. Each layer has different behaviour and reactions observed while drilling. One option is to follow one typical problem which is repeated in many wells (e.g. stuck pipe) in a specific geological layer. Then, many cases can be constructed for one particular problem in a CBR model. The cause (solution) of these cases is not necessarily identical. The solved cases contain for instance the successful solutions to many stuck pipe problems in a typical layer. The cases may have different and similar sets of information which the CBR model would be able to store similar cases for an unsolved case (input case). Based on this discussion the structure of a case can be defined with a different time scale. ***Table 6.3*** shows the possible options for different case structures in order to model cases within the oil well engineering domain.

Table 6.3 Five options for case structure with in the oil well engineering domain.

Case types based on time interval	Example
Bit run	Low ROP cases
Geology layer	Lost circulation / stuck pipe cases
Hole section	Drill string washout case
Well	Well leakages / well productivity
Field	Technology candidate for the fields

7. Conclusions and Future Works

The main objective of this study was to demonstrate and analyse some complex problem-cases within the oil well engineering domain through the CBR methodology. For this purpose, a CBR model called Wellogy was implemented which contains ontology and many selected knowledge-rich cases from different areas all within the oil well engineering domain. Based on the model and results, the following important conclusions and recommendations for future works can be made:

1. Selection of appropriate case candidates applied with the CBR tool was the first main step in the process of building the Wellogy model.
2. To obtain a reliable and an efficient CBR model, many cases are needed. We suppose that at least 100 solved cases for knowledge-lean cases and around 50 for knowledge-rich cases are required. In the Wellogy model, we only succeeded to build only 12 solved cases due to the lack of data.
3. For completing the Wellogy model the following steps were followed for the case production:

    a. Selection of suitable case candidate
    b. Definition of the task for the case before starting to built it
    c. Describing and analysing the case and specifying the human reasoning behind (this part of study was called *knowledge level)*
    d. Putting attention in describing the case problem correctly and completely as much as possible. The solution part can be defined abstractly and needs to establish some relationships between solution and problem findings
    e. Expanding the knowledge level for the case by integrating case information and general knowledge for the case (i.e. rules and theories) in the hierarchy format (ontology) and establishing causal relationships
    f. Indexing the case by creating vocabularies (i.e. terminologies) and abstracted phrases. This representation of the *knowledge level* was called the *symbolic level*
    g. Building cases in a preliminary template and then clustering them with the other similar cases
    h. Encoding and inserting cases in the CBR knowledge editor and linking it with the existing ontology
    i. Improving the quality of the cases by tuning and modifying the strength values of the findings of cases

4. Different types of cases in the oil well domain were considered in the Wellogy model. Single episode cases are defined as cases that occur and are solved within a continuous time interval, and normally this period is short (less than one week). Stuck pipes, lost circulations, drillstring washouts, and well leakages are case-examples which can occur in a single episode. Some cases consist of multi-episodes and last for a rather long time (months or even years); for instance,

when building a case for low production diagnoses for an oil field, or when studying of hole instability in a specific geology layer and specific drilling hole size in an area.

5. Obtained results from the Wellogy model were carefully audited by human reasoning. The retrieved solutions of the 5 unsolved cases for leaking well cases agreed with common sense.
6. The overall efficiency of the model can be measured by both selected CBR tool and CBR model.
7. For applying CBR methodology the case candidate should have the following characterizations:
    a. It should be a repeatable problem in many similar cases
    b. As many factors are involved in the case problem it is difficult to build a comprehensive and explicit mathematical model
    c. The case can be defined despite incomplete information and lack of data, but this may be sufficient to find causal relationships
8. More research activities regarding implementation are needed before utilizing the model in real operations (i.e. user driven).
9. Close cooperation is needed when merging two different sciences (i.e. information technology and petroleum engineering). The future for this type of interdisciplinary merging looks very promising.
10. It is recommended to define and develop different templates for case production. The templates should reflect the tasks and contents of the cases. Such tasks of cases can be: failure diagnosis, solving problems, planning tools, and interpretive tools.
11. Transforming the knowledge-level to the symbolic-level for the production case is a time-consuming issue. The defined templates may help in this matter. In addition, some guidelines for naming entities can be beneficial to some extent.
12. In order to extract experience from documents and texts and build cases within the oil well engineering domain, case builders require some level of expertise and field experience.

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Appendices

Appendix A: Appendix A gives case explanation to 18 leaking well cases. The case explanation presents case history briefly in text for leaking well cases. Then, a table for each case is provided which is considered as a preliminary template for the case production before modelling in the Wellogy.

Appendix B: SPE/IADC paper 85327, which was prepared for presentation at the SPE/IADC Middle East Drilling Technology Conference and Exhibition held in Abu Dhabi, UAE, 20-22 October 2003. The title of the paper is "*Case Study: Abnormal Drillstring Washout and Fatigue Experienced when Drilling Hazardous Formation in Iranian Oil Field*".

Appendix C: SPE/IADC paper 91579, which was prepared for presentation at the 2004 SPE/IADC Underbalanced Technology Conference and Exhibition held in Houston, Texas, U.S.A., 11-12 October 2004. The title of the paper is "*Underbalanced Drilling as a Tool for Optimized Drilling and Completion Contingency in Fractured Carbonate Reservoirs*".

Appendix D: A poster prepared and presented at the SPE 2006 Forum Series I and II in Dubrovnik on "*Low Cost Reservoir Access and Intervention*" and "*From Casing Design to Well Life Prediction*?" (Abdollahi et al., 2006). The poster summarises topics covered in different research projects at SINTEF and NTNU and is related to maintained well integrity for different operations and situations during a lifecycle of a well. The project work was done for Petroleum Safety Authority Norway (PTIL) and Statoil.

Appendix A Explanation of leaking well cases

Representation of leaking well cases

Totally 18 cases (12 solved and 6 unsolved) from three fields; Oseberg South, Oseberg East and Brage, are modelled:

- Oseberg East
  - 7 solved cases (wells: E-2a, E-3, E-4, E-7, E-9, E-14, and E15b)
  - 3 unsolved cases (wells: E-2b, E-11, E-15a)

- Oseberg South;
  - 3 solved cases (wells: F-14, F-24, and F-30)
  - 3 unsolved cases (wells: F-16, F-22, and F-29)

- Brage
  - 2 solved cases (wells: A-4 and A-6)

The operational data was limited to explain the full story of the leaks. The Synergy system used by the operating company is a system for reporting incidents, deviations and unconformities. We have used this system for preliminary leak investigation. These types of reports do not fully cover the leak history. Therefore, complementary reports have been studied in addition to the synergy reports. Here, we will give the description of the cases in text format. Before modelling case in Wellogy, they have to be presented in sheets as a preliminary case-format. Then they are modelled in Wellogy model as discussed in Chapter 3.

Well E-2a

Well E-2 was completed as an oil producer with gas lift in May 1999. A fluid communication was observed between annuli-A to annulus-B in May 1999 during the well completion. As a consequence, the gas lift system was not used. A one piece 9-5/8" x 10-3/4" production casing was used (without tie-back). In May 2003, two leaks were reported from tubing to annulus-A which was related to the SRL seal (wellhead seal assembly) at the surface and downhole related to the CIV. The CIV leak was repaired by installation of a dummy. The reference for this case in Synergy System is "Synergy 518430 dated 14.04 2005". Case E-2a is presented in symbolic form in ***Table A.1***.

Table A. 1 Summarized case information given in the case template for well E-2 (solved).

Format	Relation-type		Value	Comments
Symbolic code	Technical administration	Name of case	Case E-2a	
		Well name	Well E-2	
		Field name	OS E	potential of leak
		Wellhead Location	Platform Wellhead	easy to detect
		Time of leak	Time of Leak: May 1999	
		has pointer	Synergy 518430	
		Country	Norway	
	Process administration	Failure of case	Well Leakage Failure	
		Case statues	Solved	
		Task of leak (option 1)	Finding Cause of Well Leakages	
		Task of leak (option 2)	Verify Location of Leak	
		Outcome of case	No further Problem	
	Observations	Observations 1	Early Leak (Few Days After Completion)	has relation
		Observations 2	Leaking from Annulus-A to Annulus-B	
		Observations 3	Slow Build-up Pressure Rate	
		Observations 4	Well Purpose: OPGL	
		Observations 5	Pressure Testing After Completion Installation	there is relation between activity and leak
		Observations 6	Discovered Leak By Testing Wellhead Seal	
		Observations 7	Leak Through Casing Hanger Seal Assembly	
		Observations 8	Elastomer Casing Hanger Seal Type	
		Observations 9	Small Leakage Rate	
		Observations 10	Single Leak	easy to detect
		Observations 11 (rep. act)	Activity: Testing Hanger Seal Assembly- Not Ok	
		Observations 12	Medium Well Depth	4364 mMD
		Observations 13	Slant Well	
		Observations 14	Surface Leak	This has relation with repair action
		Observations 15	Leak Fluid Is Gas	
		Observations 16	Leak is Detectable	
	Solution to tasks)	Solution to task 1	Elastomer Casing Hanger Seal Type	potential for leak when system is gas
		Solution to task 2	Use Metal to Metal Casing Hanger Seal	
		Action	Use Metal to Metal Casing Hanger Seal	
Text	Conclusion	Case description	Well E-2 was completed as an oil producer with gas lift in May 1999. A fluid communication was observed between annuli A to B in the same time during the well completion	
		Explanation	This leak was discovered at the surface during wellhead test after installation of completion string. This type of leaks are easy to detect especially for platform wells, because they are touchable. This leak occurred in the early phase before put in production. As finding of the leak is rather easy, so the case does not need more observations.	
		Solution (to task)	Not Fit for Purpose Wellhead Seal Assembly. The solution can be for example changing wellhead seal type or cancelling gas lift operation (changing well purpose)	
		Experience	The important lesson learned for this case is to use metal-to-metal wellhead seal assembly instead of elastomer seal, when the well is put to use for gal lift application	

Well E-2b

In March 2005, a pressure build-up with a rate of 1.5 bar / 10 day was noticed in annulus-B and stabilized at 80 bar. Pressure in annulus-C was measured to 9 - 10 bar and may be due to fluid expansion. This leak was considered as medium to small leak rate. Cameron did a wellhead pressure test without observing any leaks which could be related to the wellhead. It seems that the leak could be related to a casing leak. The well is now producing with a close monitoring of annulus-C. An internal evaluation is planned. Case E-2b is presented in symbolic form in ***Table A.2***.

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Table A. 2 Summarized case information given in the case template for well E-2 (unsolved).

Format	Relation-type		Value	Comments
Symbolic code	Technical administration	Name of case	Case E-2b	
		Well name	Well E-2	
		Field name	OS E	
		Wellhead Location	Platform	
		Time of leak	Time of Leak: March 2005	
		Country	Norway	
	Process administration	Failure of case	Well Leakage Failure	
		Case statues	Unsolved	
		Task of leak (option 1)	Finding Cause of Well Leakages	
		Task of leak (option 2)	Verify Location of leak	
		Outcome of case	Pending	
	Observations	Observations 1	Late Leak (Years After Completion)	
		Observations 2	High Pressure Leak	80 bar
		Observations 3	Very Small Pressure Build -up Rate	1.5 bar / 10 day
		Observations 4	Pressure Build-up in Annulus-B	
		Observations 5	Oil Producer	
		Observations 6	Low Fluid Leak Rate	2.46 l / day (calculated.)
		Observations 7	13% Cr 9-5/8" Casing	
		Observations 8	Tie-Back System E	no tie-back
		Observations 9	Very Low Pressure Difference A-B	4 bar
		Observations 10	Casing Connection- Non VAM	
		Observations 11	Medium Well Depth	4364 mMD
		Observations 12	Slant Well	
		Observations 13	OPGL	
		Observations 14	Leak Crossing Ann.-A to Ann.-B	
		Observations 15	Leak During Production	
		Observations 16 (act)	Activity Just before Failure- Steady State OP	
Text	Conclusion	Case description	This well was completed in May 1999 and leak was observed in March 2005. This case is an unsolved case, because the leak has not been confirmed yet. The pressure build-up was seen in annulus B. There is not gas lift operation, so the annulus-A was filled by NaCl water (brine). The casing is 13% Cr and there is no tie-back for this well (System-E)	
		Explanation	Pressure build-up on annulus-B is 15 bar /25 days (2.46 l / day) assuming annulus-B is filled with water/brine, and this is in agreement with seen fluid during bled-off. Due to different pressure in tubing (18 bar) and annulus-A (60 bar), it was concluded that there is no communication between these two annuli. The fluid in annulus-A was NaCl brine (1.2 s.g) and 1.55 sg OBM in annulus B. It is believed that the leak could be below ASV through 9-5/82 casing due to wellhead pressure manipulating	
		Possible solution (to task)	1- Fluid expansion, 2- Casing leak (either through connection or casing body)	
		Experience	As the leak rate is very small, the pressure build-up could be due to fluid expansion. There is an ongoing investigation to find the leak location	

Well E-3

Well E-3 was completed as an oil producer with gas lift in 2002. A 10-3/4" tie-back was run. A pressure build-up was observed in annulus-B during December 2005 with a leak rate of 1.5 to 2.5 bar / 6 hour. The pressure in annulus-B was stabilized at 82 bar while the pressure in A was 127 bar. Leak inspection was performed and the leak is believed to be below the ASV through the casing body or connections. The intersection depth of two pressure profiles of annuli-A & B is at 528 m and has been recognized as a possible leaking point by Hydro. The future plan is to run detection log (TecWel, see http://www.tecwel.com/) to verify the suspected leaking point. The well is currently closed. The reference for this case in Synergy System is "Synergy 592762 dated 5.1.2006". Case E-3 is presented in symbolic form in ***Table A.3***.

Table A. 3 Summarized case information given in the case template for well E-3 (solved).

Format	Relation-type		Value	Comments
Symbolic code	Technical administration	Name of case	Case E-3	
		Well name	Well E-3	
		Field name	OS E	
		Wellhead Location	Platform	
		Time of leak	Dec. 2005	
		has pointer	synergy 592762	
		Country	Norway	
	Process administration	Failure of case	Well Leakage Failure	
		Case statues	Solved	
		Task of leak (option 1)	Finding Cause of Well Leakages	
		Task of leak (option 2)		
		Outcome of case	Pending	
	Observations	Observations 1	Pressure Build-up in Annulus-B	
		Observations 2	Medium Pressure Build-up Rate	1.5 ~2.5 bar / hr
		Observations 3	Medium Pressure Leak	82 bar
		Observations 4	Pressure A & B Are Not Same	(127-82) bar
		Observations 5 (rep. act)	Testing wellhead Seal Assembly - Ok	downhole leak
		Observations 6	OPGL	
		Observations 7	Carbon Steel Casing	P-110
		Observations 8	NSCC CSG Connection	NSCC
		Observations 9	Deep Well Depth	6792 mMD
		Observations 10	Slant Well	
		Observations 11	Tie-Back System A	TB and deep GLV
		Observations 12	Late Leak (Years After Completion)	no connection to installation
		Observations 13	Downhole Leak	
		Observations 14	Pressure A&B Are The Same Trend	
		Observations 15	Leak During Gas Lift Period	
		Observations 16	Producing With Steady State Condition	
		Observations 17	Long Directional Well	
		Observations 18	Wet Gas lift	
		Observations 19	Leak During Production	
			Wellhead Seal Ok	
			Leak Crossing Casing	
			High Amount of CO2 in Gas Lift	
			Leak Crossing Ann.-A to Ann.-B	
		Observations 20 (act)	Activity Just before Failure- Unsteady State OPGL	
Text	Conclusion	Case description	Well E-3 was an OPGL and completed in 2002. A pressure build-up was observed in annulus-B during Dec. 2005.	
		Explanation	The well started production in June 2002. The three SPMs operated on Sep. 2002, feb. 2003 and Nov. 2004 from top depth to bottom depth. Gas lift rates in annulus-A showed that before leak occurred, the injection rate was zero and seemed there was no gas injection. However, in the mid Dec. 2005 gas injection was resumed. The pressure chart shows that the pressures in annulus-A and annulus-B followed each others. But the two pressure were not the same. The leakage point was not verified, but the plan was to run noise log for this issue.	
		Solution (to task)	Carbon steel leak, the possible leak could be through the 9 5/8" casing (below ASV) due to corrosion	
		Experience		

Well E-4

Well E-4 was completed as an oil producer with gas lift. The production started in September 1999 without the use of gas lift. A possible deformation of the tubing was detected in May 2001. In October 2002 the gas lift system was put into use through the GLV number 1. In December 2003 the GLV number 2 was also put into use. A hydrocarbon leak through the BSV control line was observed in December 2003 (Synergy 20265 dated 13.12.2003 (11:24)).

TecWel's WLD was run in June 2005 and following leak were observed:
Leak: T-A = PBR @ 2901 m MD (2898 m MD?)
Leak: A-B = 1780 m MD (tie-back casing)

A pressure build up in annulus-B was observed in July 2005. No available documentation has been found on which actions were made. Another leak was noted in the BSV control line in December 2005. A leak between the tubing to annulus-A and annulus-A to annulus-B with a rate of 0.27 lit / min. was also reported.

Cameron performed a pressure test and communication between annulus-A to annulus-B was reported at the topside. A leaking cavity was found around the 10-3/4" seal assembly. The well was converted to water injection with a WHP = 100 bar, but with no further report on the leak status. The mentioned reason for the barrier failures is BSV through control line, probably collapsed PBR and leakage through the casing below the ASV. The well is permanently closed from November 2005 and the future plan is re-complete the well. This case has been considered as unsolved case. The chemical inhibitor was directly injected through annulus-A instead of CIV, because it was failed. The reference for this case in Synergy System is "Synergy 589098: 20.12.2005". Case E-4 is presented in symbolic form in ***Table A.4***.

Table A. 4 Summarized case information given in the case template for well E-4 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-4
		Well name	Well E-4
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	June 2005
		has pointer	Synergy 589098
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	Fully Successfull
	Observations	Observations 1	Downhole Leak
		Observations 2	Leak Crossing Ann.-A to Ann.-B
		Observations 3	Late Leak (Years After Completion)
		Observations 4	Leak Through Casing Body
		Observations 5 (rep. act)	Running Leak Detection Log
		Observations 6	Carbon Steel CSG
		Observations 7	NSCC CSG Connection
		Observations 8	Medium Well Depth
		Observations 9	Slant Well
		Observations 10	Corrosive Gas Lift
		Observations 11	Tie-Back System A
		Observations 12	OPGL Well Application
		Observations 13	Gradually Increased Leak rate Over the Time
		Observations 14	CIV Failed
		Observations 15	Wet Gas lift
		Observations 16	Increased Leak Rate Gradually
		Observations 17	Slow Build-up Rate
		Observations 18	Leak During Gas Lift Period
		Observations 19	High Amount of CO2 in Gas Lift
		Observations 20	Low pH of Gas Lift Well
		has diviation	Scale Inhabitor Injection With Gas Lift Instead of CIV
		Observations 21 (act)	Activity Just before Failure- Unsteady State OPGL
Text	Conclusion	Case description	The leak is sever leak, i.e. fluid communication between annulus-A and annulus-B through 10 3/4" tie-back CSG at depth 1780 mMD. This leak is late leak, after some years of production, and this means corrosion reason could be possible reason for the cause of leak. The well is closed for intervention.
		Explanation	Specific observation: chemical inhibitor for scaling was directly mixed and pump with gas lift through the annulus-A, instead of injecting through CIV line. This cause to increase rate of corrosion. The history of production and gas lift is: start production without gas lift on Sep. 1999, SPM1 on Oct. 2002 and SPM2 on Dec. 2003.
		Solution (to task)	Scale inhibitor injection in GL (Corrosion)
		Experience	As leak was detected by log at depth of 1780 mMD of 10 - 3/4" tie-back, and leak occurred after some years of production, the possible reason for the leak could be corrosion. This reason is also supported by the above explanation about using chemical inhibitor in annulus-A which increases the rate of corrosion.

Well E-7

Well E-7 was completed as an oil producer with gas lift. The casing configuration departs from a regular casing program as a simplified casing configuration has been used. The production without the use of gas lift was started in March 2001. The gas lift system was started in October 2002 through the GLV number 1 and the GLV number 2 was added in August 2005.

A WLD was run in June 2005 and following leak observations were made:
SABL packer @ 2875 m MD - production packer

PBR @ 2867 m MD
GL mandrel 3
GL mandrel 2

A pressure build up in annulus-B was observed in August 2005. Cameron did a wellhead pressure test and a leak was observed in the 10-3/4” seal assembly (topside leak). A wrong seal type had been used and was the cause for communication between annuli-A & B.

The well is permanently closed with a plug below the production packer. The future plan is to re-complete or to perform a sidetrack. Although there are obviously several leak happened though completion components (tubing to annulus), but the leak crossing annulus-A to annulus-B through the wellhead seal assembly is consider as a case in the Wellogy model. The reference for this case in Synergy System is “Synergies 589536 and 592509, August 2005”. Case E-7 is presented in symbolic form in ***Table A.5***.

Table A. 5 Summarized case information given in the case template for well E-7 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-7
		Well name	Well E-7
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	August 2005
		has pointer	Synergies 589536, 592509
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	Verify Location of leak
		Outcome of case	Pending
	Observations	Observations 1	Surface Leak
		Observations 2	Multiple Leak
		Observations 3	Late Leak (Years After Completion)
		Observations 4	Leak Wellhead Seal Assembly
		Observations 5 (rep. act)	Testing wellhead Seal Assembly - Not Ok
		Observations 6	Leak Crossing Ann.-A to Ann.-B
		Observations 7	Oil Producer With Gas Lift
		Observations 8	Tie-Back System E
		Observations 9	Medium Well Depth
		Observations 10	Slant Well
		Observations 11	Leak During Production
		Observations 12	Elastomer Hanger Seals
		Observations 13	OPGL Well Application
		Observations 14	Increased Leak Rate Gradually
		Observations 15	13 %-Cr CSG
		Observations 16	Leak Through Internal Wellhead
		Observations 17	Carbon Steel Hanger Seal
		Observations 18	Elastomer CSG Hanger Seal
		Observations 19	Leak Crossing Casing Hanger Seal
		Observations 20	Leak Fluid Is Gas
		Observations 21 (act.)	Activity Just before Failure- steady State OPGL
		Observations 22 (act.)	Running Leak Detection Log
Text	Conclusion	Case description	This case is about leakage through seal assembly in wellhead area, similar as case E-2a. Although this type of leak would be occured close to time of starting production, this leak-casue occured in the late phase, i.e, after some years of production. After further invistication, it was revealed that wellhead seal assembly type was not 13% CR. So, corrosion of wellheas seal could be happened after some year of production.The WLD (well leak detector) log was run and a possible leak also found below ASV through CSG (leak between annulus-A and annulus-B); however, this leak is uncertain yet. Due to many leaks crossing completion tubing, PBR, Packer, GLMs, the well is closed for further intervention.
		Explanation	This well is an OPGL and started production in March 2001. Gas lift started to use through SPM1 and SPM 2 on Oct. 2002 and Nov. 2003. A pressure build-up was observed in annulus-B on August 2005.
		Solution (to task)	Not Fit for Purpose Wellhead Seal Assembly. The solution can be for example changing wellhead seal type or cancelling gas lift operation (well application deviation)
		Experience (LL E-7)	

Well E-9

Well E-9 is completed as a WAG well. The casing configuration departs from a regular casing program as a simplified casing configuration has been used. A leak through the tubing was observed in August 2004 as water contaminated with gas. The leak was reported across the production packer (SABL-3) and a straddle packer was set in November 2004. Another leak was observed across the PBR in December 2004. There is an exception from PTIL to continue water injection with low pressure (76 bar at wellhead). The well is currently injecting water and the future plan is to set another straddle over the PBR. The reference for this case in Synergy System is “Synergy 594660, August 2004”. Case E-9 is presented in symbolic form in ***Table A.6***.

Table A. 6 Summarized case information given in the case template for well E-9 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-9
		Well name	Well E-9
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	August 2004
		has pointer	Synergy 594660
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	Verify Location of leak
		Outcome of case	Pending / no further problem
	Observations	Observations 1	WAG Application
		Observations 2	Leak Crossing Tubing PBR
		Observations 3	Leak Crossing Tubing to Ann.-A
		Observations 4	High Pressure Load Cycle
		Observations 5 (rep. act)	Running Leak Detection Log
		Observations 6	Slant Well
		Observations 7	High Thermal Variation
		Observations 8	Changing Well Operation: GI to WI
		Observations 9	Sidetrack well
		Observations 10	Multiple Leaks
		Observations 11	Downhole Leak
		Observations 12	Long TD
		Observations 13	Carbon Steel CSG
		Observations 14	High Thermal and Pressure Loads During Operation
		Observations 15	High Well Pressure Changes
		Observations 16	TB System E
		Observations 17	High Total Bit Rotation
		Observations 18	Long Directional Well
		Observations 19	Early Leak (Few Days After Completion)
		Observations 20	Leak Crossing Packer
		Observations 21	High Well Temperature Changes
		Observations 22	Leak Just After Start-up Injection
		Observations 23	Low Packer Tolerance
		Observations 24	Leak Discovered During Operation
		Observations 25 (act)	Install Straddle Over Packer
Text	Conclusion	Case description	Well E-9 is completed as a WAG well. The casing configuration departs from a regular casing program as a simplified casing configuration has been used. A leak through the tubing was observed in August 2004 as water contaminated with gas. The leak was reported across the production packer (SABL-3) and a straddle packer was set in November 2004. Another leak was observed across the PBR in December 2004. There is an exception from PTIL to continue water injection with low pressure (76 bar at wellhead). The well is currently injecting water and the future plan is to set another straddle over the PBR.
		Explanation	This well is WAG well. First the well was put on gas injection and then on water. Therefore, there should be high temperature changes, and it seems that the leak occurred just after injection fluids changes. Therefore, the possible reason for leakage through PBR can be thermal load on completion string
		Solution (to task)	High thermal and pressure loads during operation (leak through PBR)
		Experience	It is important to consider the effect operation conditions on load calculations on completion tubing components (PBR) for WAG wells, where the pressure and temperature variation are high. The design condition of completion components MUST meet the requirement for real well condition during different operations.

Well E-11

Well E-11 is completed as a WAG well. The casing configuration departs from a regular casing program as a simplified casing configuration has been used. A leak through the tubing was observed through on of the GLM in November 2004 when used for gas injection (GI). A straddle was set over GLV in June 2005. The well is currently closed. The future plan is to use the well for gas injection if no leak is found. The reference for this case in Synergy System is "Synergies 515084, 592200, November 2004". Case E-11 is presented in symbolic form in ***Table A.7***.

Table A. 7 Summarized case information given in the case template for well E-11 (unsolved).

<table>
<tr><th>Format</th><th colspan="2">Relation-type</th><th>Value</th></tr>
<tr><td rowspan="30">Symbolic code</td><td rowspan="7">Technical administration</td><td>Name of case</td><td>Case E-11</td></tr>
<tr><td>Well name</td><td>Well E-11</td></tr>
<tr><td>Field name</td><td>OS E</td></tr>
<tr><td>Wellhead Location</td><td>Platform</td></tr>
<tr><td>Time of leak</td><td>November 2004</td></tr>
<tr><td>has pointer</td><td>Synergy 515084, 592200</td></tr>
<tr><td>Country</td><td>Norway</td></tr>
<tr><td rowspan="5">Process administration</td><td>Failure of case</td><td>Well Leakage Failure</td></tr>
<tr><td>Case statues</td><td>Unsolved Case</td></tr>
<tr><td>Task of leak (option 1)</td><td>Finding Cause of Well Leakages</td></tr>
<tr><td>Task of leak (option 2)</td><td></td></tr>
<tr><td>Outcome of case</td><td>Pending</td></tr>
<tr><td rowspan="18">Observations</td><td>Observations 1</td><td>Fluid Communication from Tubing to Annulus-A</td></tr>
<tr><td>Observations 2</td><td>Leak Crossing GLV</td></tr>
<tr><td>Observations 3</td><td>WAG well</td></tr>
<tr><td>Observations 4</td><td>Early Leak (Few Days After Completion)</td></tr>
<tr><td>Observations 5 (rep. act)</td><td>Install Straddle Over GLM</td></tr>
<tr><td>Observations 6</td><td>High Well Pressure Changes</td></tr>
<tr><td>Observations 7</td><td>Leak Discovered During Operation</td></tr>
<tr><td>Observations 8</td><td>High Well Temperature Changes</td></tr>
<tr><td>Observations 9</td><td>Leak Crossing Tubing PBR</td></tr>
<tr><td>Observations 10</td><td>Multiple Leaks</td></tr>
<tr><td>Observations 11</td><td>Downhole Leak</td></tr>
<tr><td>Observations 12</td><td>TB System F</td></tr>
<tr><td>Observations 13</td><td>Long Directional Well</td></tr>
<tr><td>Observations 14</td><td>Leak Crossing GLV</td></tr>
<tr><td>Observations 15</td><td>Leak Crossing Tubing PBR</td></tr>
<tr><td>Observations 16</td><td>Leak Discovered During Operation</td></tr>
<tr><td>Observations 17</td><td>Long Directional Well</td></tr>
<tr><td>Observations 18(act)</td><td>Install Straddle Over GLM</td></tr>
<tr><td rowspan="4">Text</td><td rowspan="4">Conclusion</td><td>Case description</td><td>Well E-11 is completed as a WAG well. The casing configuration departs from a regular casing program as a simplified casing configuration has been used. A leak through the tubing was observed through on of the GLM in November 2004 when used for GI. A straddle was set over GLV in June 2005. The well is currently closed. The future plan is to use the well for gas injection if no leak is found.</td></tr>
<tr><td>Explanation</td><td>This a WAG well. The fluid communication between tubing and annulus-A was observed on November 2004 (completion date March 2001). The leak was only observed during gas injection. During water injection, no leakage was observed. This case could be considered as Case E-9.</td></tr>
<tr><td>Solution (to task)</td><td>GLV Leak</td></tr>
<tr><td>Experience (LL E-11)</td><td></td></tr>
</table>

Well E-14

The well application of well E-14 is WAG which originally completed as a tubing and annulus-A injection. A leak was observed from tubing to annulus-A (both with gas and water injection). ASV and X-over sleeve (topside in wellhead) were reported as leak cases. There is an exception from PTIL to continue water injecting. The well is currently injecting water. The reference for this case in Synergy System is "Synergies 541904, 592204, November 2004". Case E-14 is presented in symbolic form in ***Table A.8***.

Table A. 8 Summarized case information given in the case template for well E-14 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-14
		Well name	Well E-14
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	January 2001
		has pointer	Synergy 541904, 592204
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	
	Observations	Observations 1	Long Directional Well
		Observations 2	Leak Crossing Tubing Hanger Seal
		Observations 3	Leak Through Internal Wellhead
		Observations 4	Elastomer TBG Seal Type
		Observations 5	Leak Discovered Drilling / Installation
		Observations 6	Testing Wellhead Seal Is Not OK
		Observations 7	TB System F
		Observations 8	Leak Just After Start-up Injection
		Observations 9	Gas Injection Well
		Observations 10	Elastomer TBG Seal Type
		Observations 11	Leak Crossing Tubing to Ann.-A
		Observations 12	13 %-Cr CSG
		Observations 13	Early Leak (Few Days After Completion)
		Observations 14	Well E-14
		Observations 15	Leak Fluid Is Gas
		Observations 16	Single Leak
		Observations 17	
		Observations 18(act)	
Text	Conclusion	Case description	The well application of well E-14 is WAG which originally completed as a tubing and annulus A injector. A leak was observed from tubing to annulus A (both with gas and water injection). ASV and X-over sleeve (topside in wellhead) were reported as leak cases. The well is currently injecting water.
		Explanation	
		Solution (to task)	
		Experience (LL E-11)	

Well E-15

The original well application of well E-15 is oil producer with gas lift. A 10-3/4" tie-back was run. Production without gas lift was started in August 2000 and in December 2001 gas lift system was commenced through the GLV number 1. In February 2003, GLV number 2 was started to operate.

A pressure build-up in annulus-B was observed in March 2005. A leakage was observed in 10-3/4" seal assembly (cavity) in Jan 06. Additional leaks are believed above and under ASV according to ASV test. As a result, gas lift system was stopped and investigation program is ongoing. Well is currently producing without using gas lift.

Note: pressure date when leaking: WH = 25.6 barg, annulus-A = 131 barg, annulus-B = 100 barg. The reference for this case in Synergy System is “Synergies 589537, 612355, March 2005 and January 2006”. Case E-15 is presented in symbolic form in ***Table A.9*** and ***Table A.10***.

Table A. 9 Summarized case information given in the case template for well E-15 (unsolved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-15a
		Well name	Well E-15
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	March 2005
		has pointer	Synergy 589537
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Unsolved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	
	Observations	Observations 1	Pressure Build Up in Annulus-B
		Observations 2	Leak Crossing Casing Hanger Seal
		Observations 3	High Pressure Difference A-B
		Observations 4	Tie-Back System A
		Observations 5 (rep. act)	Testing wellhead Seal Assembly -Not Ok
		Observations 6	Constatnt Leak Pressure in Annulus-B
		Observations 7	Late Leak (Years After Completion)
		Observations 8	Steady State Well Condition
		Observations 9	Carbon Steel CSG
		Observations 10	NSCC CSG Connection
		Observations 11	Deep Well Depth
		Observations 12	Oil Producer With Gas Lift
		Observations 13	Producing With Steady State Condition
		Observations 14	Pressure A & B Are Not Same
		Observations 15	Leak Crossing Ann.-A to Ann.-B
		Observations 16	Leak Through Internal Wellhead
		Observations 17	Leak During Production
		Observations 18	Elastomer CSG Hanger Seal
		Observations 19	Leak Discovered During Operation
		Observations 20	Leak Fluid Is Gas
		Observations 21	Leak During Gas Lift Period
		Observations 22	Long Directional Well
		Observations 23	Wellhead Seals Leak
		Observations 24 (act)	
Text	Conclusion	Case description	The original well application of well E-15 is oil producer with gas lift. A 10-3/4" tie-back was run. Production without gas lift was started in August 2000 and in December 2001 gas lift system was commenced through the GLV number 1. In February 2003 GLV number 2 was started to operate.
		Explanation	The well E-15 is an OPGI well and production started on August 2000. Gas lift started in Dec 2001 and Feb. 2003 from SPM1 and SPM 2 respectively. One surface leak was observed and treat on well head seal assembly.
		Solution (to task)	Leak Through Wellhead seal assembly, not-fit-for purpose
		Experience	

Table A. 10 Summarized case information given in the case template for well E-15 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case E-15b
		Well name	Well E-15
		Field name	OS E
		Wellhead Location	Platform
		Time of leak	January 2006
		has pointer	Synergy 612355
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	Verify Location of leak
		Outcome of case	Pending
	Observations	Observations 1	Pressure Build Up in Annulus-B
		Observations 2	Leak Through Casing Body
		Observations 3	High Pressure Difference A-B
		Observations 4	Tie-Back System A
		Observations 5 (rep. act)	Flow Testing of ASV
		Observations 6	Constant Leak Pressure in Annulus-B
		Observations 7	Late Leak (Years After Completion)
		Observations 8	Producing With Steady State Condition
		Observations 9	Carbon Steel CSG
		Observations 10	NSCC CSG Connection
		Observations 11	Deep Well Depth
		Observations 12	Oil Producer With Gas Lift
		Observations 13	Pressure A & B Are Not Same
		Observations 14	Leak Discovered During Operation
		Observations 15	Leak Crossing Ann.-A to Ann.-B
		Observations 16	Downhole Leak
		Observations 17	Wet Gas lift
		Observations 18	Leak Crossing Casing
		Observations 19	Leak During Production
		Observations 20 (act)	Testing Wellhead Seal Is OK
Text	Conclusion	Case description	This is a late leak, and well is OPGL. The leak crossing from annulus-A to annulus-B through the casing base on some indication: pressure chart of annuli and ASV flow test.
		Explanation	The well E-15 is an OPGI well and production started on August 2000. Gas lift started in Dec 2001 and Feb. 2003 from SPM1 and SPM 2 respectively. Additional leak was observed. This leak could be at depth of 341 mMd crossing CSG (TB) by using pressure chart in annulus-A and annulus-B. Flow test of ASV showed also that the position of leak should be above the ASV. The important observation for this case is: the difference of pressure in annulus-A and annulus-B after equilibrium
		Solution (to task)	Carbon steel CSG (Corrosion as possible root cause)
		Experience	

Well F-14

Well F-14 is a WAG well and was completed in May 1999. The well was pre-drilled well and gas injection started in October 2000. A pressure build was noted in annulus-A in November 2000 with a rate of 100 bar / day. The annulus pressure was bled-off and the return fluid was gas. The leak was localized below the BSA. The well was converted to water injector in May 2001 and operations continued until October 2004 with an acceptable leak rate. The well was re-completed excluding the PBR and has been used for GI since December 2004 and is currently injecting gas.

The completion report is not available to check how the completion string was run and tested. The initial completion string was with a 7-5/8" tubing 13 % chrome and NSCC connections. The reference for this case in Synergy System is "Synergy 206272, November 2000". Case F-14 is presented in symbolic form in ***Table A.11***.

Table A. 11 Summarized case information given in the case template for well F-14 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case F-14
		Well name	Well F-14
		Field name	OSS
		Wellhead Location	Platform
		Time of leak	November 2000
		has pointer	Synergy 206272
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	Verify Location of leak
		Outcome of case	Pending
	Observations	Observations 1	Pressure Test with Mud
		Observations 2	Pressure Build-up Annulus A
		Observations 3	Leak Crossing Tubing to Ann.-A
		Observations 4	High Leak rate
		Observations 5 (rep. act)	Running New Completion String Without PBR
		Observations 6	Early Leak (Few Days After Completion)
		Observations 7	Leak Crossing Tubing PBR
		Observations 8	TB System A
		Observations 9	Insufficient Integrity Pressure Test
		Observations 10	Gas Injection Well
		Observations 11	Leak Fluid Is Gas
		Observations 12	Leak During Injection
		Observations 13	Short Pressure Test Time
		Observations 14 (act)	Injecting Gas Through Tubing
Text	Conclusion	Case description	F-14A was pre-drilled well from a floating rig, and completed from the platform for WAG application. The well started with gas injection and suddenly pressure build-up observed in annulus-A.
		Explanation	Well history: 07- Oct- 2000: Gas injection started Feb 2001: Tubing to annulus leakage detected May 2001: Converted to water injection Nov. 2004: Workover (recompletion) 03-Dec-2004: Converted to gas injection.- The annulus pressure was bled-off and the return fluid was gas. The leak was localized below the BSA. The well was converted to water injector in May 2001 and operations continued until October 2004 with an acceptable leak rate. The well was re-completed excluding the PBR and has been used for GI since December 2004 and is currently injecting gas.
		Solution (to task)	Leak Through PBR
		Experience	

Well F-16

Well F-16 is a pre-drilled WAG well completed in December 2000 with a 9 5/8" x 10 3/4" tie back. The gas injection started just after the completion date. Drilling fluid came out of annulus-C & D and the X-mas three was observed to rise when the well was put on operation. The well was converted to water injector in July 2002. A leak was observed in annulus-B in April 2003 (0.03 l/ min) and the well was re-completed at the same time. The well was used for water injection until September 2004. In November 2004 gas injection was started and again backflow of drilling fluid from annulus-C to the surface was noticed and X-mas three raised 20 cm. In March 2005 well was converted to water injection. The well is currently closed due to high reservoir pressure.

Initial completion and later re-completion report is not available. This is rather long well and two packers were used in the initial completion string (SABL-3 & HP1). The inner casing is 13-3/8" with steel quality P-110 and NSCC connections.

The leak has been reported when using gas. Annulus-C was filled with two fluids; sea water above the seabed to the wellhead and OBM below the seabed. It is reported that there is no pressure communication between the tubing and annulus-A to annulus-C. It is believed that the leak can be through the seal assembly in the subsea wellhead. In addition, the lock ring was not installed for 13-3/8” seal assembly.

It is believed that there is an oil-based fluid communication between the disposal well F-2 and this well. The horizontal distance between the two wells at the injection point of F-2 at1273 mTVD is 650 m. Well F-16A is not cemented at this depth. The reference for this case in Synergy System is “Synergies 457666, 495584, 498709, November 2000”. Case F-16 is presented in symbolic form in ***Table A.12***.

Table A. 12 Summarized case information given in the case template for well F-16 (unsolved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case F-16
		Well name	Well F-16
		Field name	OS S
		Wellhead Location	Platform
		Time of leak	December 2004
		has pointer	Synergies 457666, 495584, 498709
		Country	Norway
	Process administration	Failure of case	Well Leakage
		Case statues	Unsolved Case
		Task of leak (option 1)	Find Cause of Leak
		Task of leak (option 2)	Verify Location of leak
		Outcome of case	Pending
	Observations	Observations 1	WAG Well
		Observations 2	Pressure Build-up Annulus A
		Observations 3	Leak Crossing Tubing to Ann.-A
		Observations 4	Low Leak rate
		Observations 5 (rep. act)	Performing BSV Flow Test - Leak Below BSV
		Observations 6	Early Leak (Few Days After Completion)
		Observations 7	Very Deep Well
		Observations 8	Slant Well
		Observations 9	Downhole Leak
		Observations 10	Complex Leak
		Observations 11	TB System C
		Observations 12	Pressure Test with Mud
		Observations 13	Leak Fluid Is Gas
		Observations 14	Pressure Build-up in Ann.-B
		Observations 15	Leak Just After Start-up Injection
		Observations 16	Short Pressure Test Time
		Observations 17	Leak During Injection
		Special observation	Lifted up Wellhead After Starting GI
		Observations 18 (act)	Injecting Gas Through Tubing
Text	Conclusion	Case description	Well F-16 is a pre-drilled WAG well completed in December 2000 with a 9 5/8" x 10 3/4" tie back. The gas injection started just after the completion date. Drilling fluid came out of annulus C / D and the X-mas three was observed to rise when the well was put on operation. The well was converted to water injector in July 2002. A leak was observed in annulus B in April 2003 (0.03 l/ min) and the well was re-completed at the same time. The well was used for water injection until September 2004. In November 2004 gas injection was started and again backflow of drilling fluid from annulus C to the surface was noticed and X-mas three raised 20 cm. In March 2005 well was converted to water injection. The well is currently closed due to high reservoir pressure. This is rather long well and two packers were used in the initial completion string (SABL-3 & HP1).
		Explanation	Well history: 06-Feb-2001: Start-up gas injection (reported, but not documented (P = 310 bar, T = 125 C) observation; drilling fluid seeped out of annulus C/D on surface, and xmas tree was raised) 18-Jul-2002: Converted to water injection Sep. 2002: Tubing to annulus leakage detected April 2003: Workover (re-completion) 17-Sep-2004: Water injection stopped 14- Nov-2004: Converted to gas injection 25-Nov-2004: Backflow of drilling mud from annulus C to surface started. At about the same time, a tubing to annulus leakage was detected. 23-Feb-2005: Gas injection stopped because xmas had risen (~ 20 cm ?) 5-Mar-2005: Converted to water injection
		Solution (to task)	
		Experience	This case is complex case and need deep investigation. It is believed that the leak can be through the seal assembly in the subsea wellhead. In addition, the lock ring was not installed for 13-3/8" seal assembly

Well F-22

Well F-22 was originally completed as an oil producer with gas lift and the operations started in April 2003. Some special observations were made: sand production, fairly stable well flow and the sudden increased slugging during production. A pressure build up in annulus-B was noted in January 2006 after the pressure had been stable for a long time without bleed-off annulus-B. Leakage paths were found in the X-mas tree and in the topside piping. The well is currently in normal operation. The reference for this case in Synergy System is “Synergy 595070 dated January 2006”. Case F-22 is presented on symbolic form in ***Table A.13***.

Table A. 13 Summarized case information given in the case template for well F-22 (unsolved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case F-22
		Well name	Well F-22
		Field name	OS S
		Wellhead Location	Platform
		Time of leak	January 2006
		has pointer	Synergy 595070
		Country	Norway
	Process administration	Failure of case	Well Leakage
		Case statues	Unsolved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	No Further Problem
	Observations	Observations 1	Surface leak
		Observations 2	Late Leak (Years After Completion)
		Observations 3	Oil Producer With Gas Lift
		Observations 4	Leak Through Wellhead
		Observations 5 (rep. act)	
		Observations 6	Wellhead Seals Leak
		Observations 7	Pressure Build-up in Ann.-B
		Observations 8	Leak Through Internal Wellhead
		Observations 9	Leak Crossing Casing Hanger Seal
		Observations 13	Observed Slug Flow
		Observations 14 (act)	
Text	Conclusion	Case description	Well F-22 was originally completed as an oil producer with gas lift and the operations started in April 2003.A pressure build up in annulus B was noted in January 2006 after the pressure had been stable for a long time without bleed-off B. Leakage paths were found in the X-mas tree and in the topside piping. The well is currently in normal operation. F-22 is an oil producer with a long horizontal section.
		Explanation	Well history: 30-Apr- 2003: Start-up of oil production 30-March 2004 Gas Lift started Since July 2003: sand production, possibly sanding in of the horizontal section in May 2004. From July 2004 to September 2005: severely slugging well flow Sep- to mid. Dec. 2005: fairly stable well flow Mid. December 2005: sudden increase in slugging 13- Jan-2006: Pressure build-up on B-annulus observed Leakage stopped during investigation of possible leakage paths in xmas-tree and in topside piping. Well is currently in normal operation.
		Solution (to task)	Wellhead Seal Assembly
		Experience	

Well F-24

Well F-24 was originally completed as an oil producer with gas lift and the operations started in July 2002. Scale inhibitor was used in the gas lift system and pumped through annulus-A. Sand production started in April 2003. A pressure build up was noted in annulus-B in November 2005. The well was shut-in during this time for logging. The detection log (TecWel) was run but results were inconclusive. Believed reason for the leak is corrosion due to the use of sour scale inhibitor. In January 2006 a leak detector revealed a micro-annulus around the production packer. The well is currently under workover for re-completion.

The downhole chemical injection line failed during running the completion string. It was then decided to mix the scale inhibitor with the gas at surface and inject through annulus-A instead of using the CIV. The inner string consists of 9-5/8” liner and 10-3/4” tie-back L-80 material and NSCC connections. The reference for this case in

Synergy System is “Synergies 578233, 594205, 596872 dated October 2005, January 2006, ”. Case F-24 is presented in symbolic form in ***Table A.14***.

Table A. 14 Summarized case information given in the case template for well F-24 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case F-24
		Well name	Well F-24
		Field name	OS S
		Wellhead Location	Platform
		Time of leak	October 2005
		has pointer	Synergies 578233, 594205, 596872
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	Late Leak (Years After Completion)
	Observations	Observations 1	OPGL
		Observations 2	Pressure Build-up in Annulus-B
		Observations 3	TB System C
		Observations 4	Leak Though CSG
		Observations 5 (rep. act)	
		Observations 6	Downhole Leak
		Observations 7	Steady State Well Condition
		Observations 8	Low Cr Casing
		Observations 9	NSCC CSG Connection
		Observations 10	Leak Crossing Ann.-A to Ann.-B
		Observations 11	Medium Well Depth
		Observations 12	Slant Well
		Observations 13	Leak During Production
		Observations 14	CIV Failed
		Observations 15	Oil Producer With Gas Lift
		Observations 16	Leak Crossing Casing Body
		Observations 17	Leak Crossing Casing
		Observations 18	Low pH of Gas Lift Well
		Observations 19	Leak Fluid Is Gas
		Observations 20	Producing With Steady State Condition
		has deviation	Scale Inhabitor Injection With Gas Lift Instead of CIV
		Observations 21 (act)	Producing Oil with Gas Lift
Text	Conclusion	Case description	Well F-24 is an oil producer (start production 20 July 2002. Later, a pressure build-up on B-annulus was detected early in November 2005. Testing indicated annulus A to B leakage both above and below the ASV. As a result of this, F-24 was shut-in on Nov. 10. The well was recently logged for leakage detection, but the logging was inconclusive. A workover is planned within the next month.
		Explanation	Well F-24 was originally completed as an oil producer with gas lift and the operations started in July 2002. Gas lift started 20.06.2004). Scale inhibitor was used in the gas lift system and pumped through annulus A, instead of CIV line, because CIV line was damage when completion the well. A pressure build up was noted in annulus B in November 2005. The well was shut-in during this time for logging. The detection log (TecWel) was run but results were inconclusive. Believed reason for the leak is corrosion due to the use of sour scale inhibitor. In January 2006 a leak detector revealed a micro-annulus around the production packer. The well is currently under workover for re-completion.
		Solution (to task)	Scale Inhabitor Injection With Gas Lift Instead of CIV (leak through casing. The main reason is corrosion)
		Experience	The downhole chemical injection line failed during running the completion string. It was then decided to mix the scale inhibitor with the gas at surface and inject through annulus A instead of using the CIV.

Well F-29

Well F-29 was originally completed as an oil producer with gas lift and the operations started in December 2005. A pressure build-up in annulus-B was noted with a rate of 15 bar / 2 hours. A leak detection log (TecWel) was run but the results were inconclusive. It is believed that the leak depth is below ASV. The GLV was retrieved and a dummy was set and the tubing qualified as a barrier. The inner string is 10-3/4" tie-back with L-80 material and VAM-TOP connections. The reference for this case in Synergy System is "Synergy 597342 dated December 2005". Case F-29 is presented in symbolic form in ***Table A.15***.

Table A. 15 Summarized case information given in the case template for well F-29 (unsolved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case F-29
		Well name	Well F-29
		Field name	OS S
		Wellhead Location	Platform
		Time of leak	25-Dec-2005
		has pointer	Synergy 597342
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Unsolved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	Early Leak (Few Days After Completion)
	Observations	Observations 1	OPGL Application
		Observations 2	Pressure A & B Are Not Same
		Observations 3	Low Leak Rate
		Observations 4	Oil Producer With Gas Lift
		Observations 5 (rep. act)	
		Observations 6	Carbon Steel CSG
		Observations 7	NSCC CSG Connection
		Observations 8	Leak Fluid Is Gas
		Observations 9	Multilater Well
		Observations 10	Deep Well
		Observations 11	Slant Well
		Observations 12	Long Horizontal Well
		Observations 13	Long TD
		Observations 14	Leak is Not Detectable
		Observations 15	Leak Crossing Ann.-A to Ann.-B
		Observations 16	Leak During Production
		Observations 17	TB System C
		Observations 18 (act)	
Text	Conclusion	Case description	Well history: 25-Dec-2005: start-up oil production. 27-Dec-2005: pressure build-up on annulus-B was observed. 15-Jan-2006: leakage detection logging (inconclusive). Gas lift valves were retrieved and replaced by dummy valves. Tubing qualified as barrier. This means that gas-lift operation is cancelled.
		Explanation	Well F-29 was originally completed as an oil producer with gas lift and the operations started in December 2005. A pressure build-up in annulus B was noted with a rate of 15 bar / 2 hours. A leak detection log (TecWel) was run but the results were inconclusive. It is believed that the leak depth is below ASV.
		Solution (to task)	Casing / (tie-back ?)
		Experience	Because the leak occurred in early time of production, the reason for leakage can be related to equipment and installation testing. Because the flow test of ASV show the leak can be either above and under ASV, the leak can be through the CSG-connection.

Well F-30

Well F-30 was originally completed as an oil producer. However, the reservoir testing during completion showed a tight reservoir rock. Bullheading with the gas was tried in summer 2005 but it was unsuccessful. The well was then fractured using LTO (similar to diesel) in order to improve the injectivity. The well was used as water injector in September 2005 with maximum wellhead pressure of 100 bar. A pressure build-up was observed in annulus-A (00 bar). Water injection was continued until January 2006. TecWel was run to detect the leak and the result showed a micro leak around the packer. The reference for this case in Synergy System is “Synergy 570798 dated October 2005”. Case F-30 is presented in symbolic form in ***Table A.16***.

Table A. 16 Summarized case information given in the case template for well F-30 (solved).

<table>
<tr><th>Format</th><th colspan="2">Relation-type</th><th>Value</th></tr>
<tr><td rowspan="33">Symbolic code</td><td rowspan="7">Technical administration</td><td>Name of case</td><td>Case F-30</td></tr>
<tr><td>Well name</td><td>Well F-30</td></tr>
<tr><td>Field name</td><td>OS S</td></tr>
<tr><td>Wellhead Location</td><td>Platform</td></tr>
<tr><td>Time of leak</td><td>December 2005</td></tr>
<tr><td>has pointer</td><td>Synergy 570798</td></tr>
<tr><td>Country</td><td>Norway</td></tr>
<tr><td rowspan="5">Process administration</td><td>Failure of case</td><td>Well Leakage Failure</td></tr>
<tr><td>Case statues</td><td>Solved Case</td></tr>
<tr><td>Task of leak (option 1)</td><td>Finding Cause of Well Leakages</td></tr>
<tr><td>Task of leak (option 2)</td><td>Verify Location of leak</td></tr>
<tr><td>Outcome of case</td><td>Early Leak (Few Days After Completion)</td></tr>
<tr><td rowspan="21">Observations</td><td>Observations 1</td><td>WAG Well</td></tr>
<tr><td>Observations 2</td><td>Leak Around Packer</td></tr>
<tr><td>Observations 3</td><td>Changing Well Application (GI-WI)</td></tr>
<tr><td>Observations 4</td><td>Carbon Steel CSG</td></tr>
<tr><td>Observations 5 (rep. act)</td><td>Running Leak Detection Log</td></tr>
<tr><td>Observations 6</td><td>High pressure Fracturing</td></tr>
<tr><td>Observations 7</td><td>High Well Temperature Changes</td></tr>
<tr><td>Observations 8</td><td>High Pressure Variation</td></tr>
<tr><td>Observations 9</td><td>Long TD (6559 Mmd)</td></tr>
<tr><td>Observations 10</td><td>Non Cr Casing (p-110)</td></tr>
<tr><td>Observations 11</td><td>VAM-Top Thread</td></tr>
<tr><td>Observations 12</td><td>Slant Well</td></tr>
<tr><td>Observations 13</td><td>High Well Pressure Changes</td></tr>
<tr><td>Observations 14</td><td>NSCC CSG Connection</td></tr>
<tr><td>Observations 15</td><td>Leak Crossing Packer</td></tr>
<tr><td>Observations 16</td><td>Long Directional Well</td></tr>
<tr><td>Observations 17</td><td>Leak Crossing Tubing to Ann.-A</td></tr>
<tr><td>Observations 18</td><td>High Thermal and Pressure Loads During Operation</td></tr>
<tr><td>Observations 19</td><td>Leak Crossing Packer</td></tr>
<tr><td>Observations 20</td><td>Downhole Leak</td></tr>
<tr><td>Observations 21 (activity close to failure)</td><td>Fracturing Operation</td></tr>
<tr><td rowspan="4">Text</td><td rowspan="4">Conclusion</td><td>Case description</td><td>Well history:
Because F-30A was drilled into the oil zone, the well was initially hooked up as an oil producer. However, the well did not flow, and several attempts during the summer of 2005 to bullhead the well using gas were unsuccessful.
While waiting for topside hook-up to water injection, in July 2005 the well was fractured using LTO in order to prove infectivity.
In late September 2005 F-30A was converted to a water injector.</td></tr>
<tr><td>Explanation</td><td>A pressure build-up on the A annulus was detected in October 2005.
Investigation of pressure history indicated that leakage had occurred already during the initial fracturing with LTO.
Water injection continued until January 2006, when logging for leakage detection was performed. A leakage through the production packer was detected.
After the intervention, the well has been operated on a provisional internal "Avvik", but is currently being prepared for workover.</td></tr>
<tr><td>Solution (to task)</td><td>Leak Around Packer. The reason can be pressure and thermal load during fracturing operation</td></tr>
<tr><td>Experience</td><td>Casing wear (casing ovality) and low packer tolerance could be also reasons for this case</td></tr>
</table>

Well A-4

This well was completed on 1993 as producing well. On Dec. 2006, a pressure build up in annulus-B was observed around 42-73 bar in 24 hrs. Wellhead type used in Brage is FMC. FMC did a test investigation in the wellhead based on test program by Hydro (Koldal, 2007). The conclusion was that the leak between annulus-A and annulus-B occurred through the SBMS-2 in tubing head and 10-3/4" pack-off. The leak was high as that the pressure did not go up (build-up pressure did not reach). FMC claimed that there is possible to reduce leak rate by pumping seal material (packing off material) in 10 3/4" and 13 3/8" pack-offs; however, there is not possible to perform the same for SBMS-2. The reference for this case in Synergy System is "Synergy 693291 dated January 2007". Case Brage A-4 is presented in symbolic form in ***Table A.17***.

Table A. 17 Summarized case information given in the case template for well A-4 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case Brage A-4
		Well name	Well Brage A-4
		Field name	Brage
		Wellhead Location	Platform
		Time of leak	January 2007
		has pointer	Synergy 693291
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	Pending
	Observations	Observations 1	Carbon Steel Hanger Seal
		Observations 2	Oil Producer With Gas Lift
		Observations 3	13 %-Cr CSG
		Observations 4	Low Leak Rate
		Observations 5 (rep. act)	Testing Wellhead Seal Is Not OK
		Observations 6	Leak Through Internal Wellhead
		Observations 7	Leak Crossing Ann.-A to Ann.-B
		Observations 8	Late Leak (Years After Completion)
		Observations 9	Leak Fluid Is Gas
		Observations 10	Leak During Production
		Observations 11	Leak Rate Is Inconsistent
		Observations 12	Leak Crossing Casing Hanger Seal
		Observations 13	Elastomer CSG Hanger Seal
		Observations 20	
		Observations 21 (activity close to failure)	
Text	Conclusion	Case description	This well was completed on 1993 as producing well 6. On Dec. 2006a pressure build up in annulus-B was observed around 42-73 bar in 24 hrs. Wellhead type used in Brage is FMC. FMC did a test investigation in the wellhead. The conclusion was that the leak between annulus-A and annulus-B occurred through the SBMS-2 in tubing head and 10-3/4" packoff. The leak was high as that the pressure did not go up (build-up pressure did not reach). FMC claimed that there is possible to reduce leak rate by pumping seal material (packing off material) in 10 3/4" and 13 3/8" Packoffs; however, there is not possible to perform the same for SBMS-2.
		Solution (to task)	Carbon Steel Hanger Seal
		Experience	This is late leak (leak occurred after some years of production). The wellhead seal assembly was elastomer seal type and carbon steel hanger. So the corrosion or fatigue can be the cause of the leak crossing hanger seal.

Well A-6

The leak between annulus-A and annulus-B was observed. The location of leak was uncertain; however, the leak rate was low. FMC has not yet performed the integrity of wellhead for possible leaks. Generally, experience has showed that many leaks have been observed at the wellhead seal assemblies (test port / pack-off). The reference for this case in Synergy System is "Synergy 693291 dated January 2007". Case Brage A-6 is presented in symbolic form in ***Table A.18***.

Later, FMC perform wellhead integrity test according to Hydro procedure (Koldal, 2007). The similar leakage as well A-04 was found, i.e. leakage crossing SBMS-2 and pack-off in the wellhead area. However, the rate of leak was much lower that the leak rate in well A-04.

Table A. 18 Summarized case information given in the case template for well A-6 (solved).

Format	Relation-type		Value
Symbolic code	Technical administration	Name of case	Case Brage A-6
		Well name	Well Brage A-6
		Field name	Brage
		Wellhead Location	Platform
		Time of leak	January 2007
		has pointer	Synergy 693291
		Country	Norway
	Process administration	Failure of case	Well Leakage Failure
		Case statues	Solved Case
		Task of leak (option 1)	Finding Cause of Well Leakages
		Task of leak (option 2)	
		Outcome of case	
	Observations	Observations 1	13 %-Cr CSG
		Observations 2	Leak Crossing Casing Hanger Seal
		Observations 3	Carbon Steel Hanger Seal
		Observations 4	Low Leak Rate
		Observations 5	Elastomer CSG Hanger Seal
		Observations 6	Leak Crossing Ann.-A to Ann.-B
		Observations 7	Leak During Production
		Observations 8	Leak Fluid Is Gas
		Observations 9	Leak Through Internal Wellhead
		Observations 10	Late Leak (Years After Completion)
		Observations 11	Oil Producer With Gas Lift
		Observations 12	Testing Wellhead Seal Is Not OK
		Observations 13	Leak During Production
		Observations 14	
		Observations 15 (activity close to failure)	
Text	Conclusion	Case description	This well was completed on 1993 as producing well 6. On Dec. 2006 a pressure build up in annulus-B was observed around 42-73 bar in 24 hrs. Wellhead type used in Brage is FMC. FMC did a test investigation in the wellhead. The conclusion was that the leak b
		Solution (to task)	Carbon Steel Hanger Seal
		Experience	This is a late leak (leak occurred after some years of production). The wellhead seal assembly was elastomer seal type and carbon steel hanger. So the corrosion or fatigue can be the cause of the leak crossing hanger seal.

Case production template

A template for facilitating case production has been built for all cases. The template is filled by findings of cases after all cases are transformed from *knowledge-level* to *symbolic-level*. The template is shown in ***Table A. 19*** to ***Table A. 21***.

Table A. 19 Case information filling in case production template.

Case features	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Case Name	Case E-2a	Case E-2b	Case E-3	Case E-4	Case E-7	Case E-9
Field	OSE	OSE	OSE	OSE	OSE	OSE
Well name	E-2	E-2	E-3	E-4	E-7	E-9
Country	Norway	Norway	Norway	Norway	Norway	Norway
Wellhead location	Platform	Platform	Platform	Platform	Platform	Platform
Time occurrence of failure	May 1999	March 2005	Dec. 2005	June 2005	August 2005	August 2004
Case Description	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box
Explanation to Case	Exp. E-2a	Exp. E-2b	Exp. E-3	Exp. E-4	Exp. E-7	Exp. E-9
Lessons learned	LL E-2a	LL E-2b	LL E-3	LL E-4	LL E-7	LL E-9
Case Status	Solved	Unsolved	Unsolved	Solved	Solved	Solved
Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure
Task	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages
Solution	Elastometer Casing Hanger Seal			Mixing Scale Inhibitor with Gas lift	Non Cr Hanger Seal	High Thermal & Pressure Loads
Outcome	Fully understood				Partially understood	Partially understood
Plan	Use Metal to metal Hanger Seal			Do not Inject Chemical Fluid in GL	Use 13% Cr Hanger Seal	
well type	OPGL	OP	OPGL	OPGL	OPGL	WAG
Time of leak	Early leak	Late Leak	Late Leak	Late Leak	Late Leak	Early leak
Time of leak	Leak Just After Start-up Production	Leak During Production	Leak During Production	Leak During Production	Leak During Production	
Leak crossing volume	A-B			A-B	A-B	T-A
Leak component	Leak Crossing Caning Hanger Seal			Leak Crossing CSG	Leak Crossing Caning Hanger Seal	Leak Crossing PBR
Type of casing hanger	Elastometer Seal				Elastometer Seal	
Leak fluid system	Gas				Gas	
Test fluid	Water					
Activity To Reveal Leak	Wellhead Test-Not Ok	Wellhead Test-Ok				
Casing Type	13% Cr CSG	13% Cr CSG	Non Cr CSG	13% Cr CSG		
Leak Rate		Small				
Tie-back System	TB System E	TB System E	TB System A	TB System A	TB System A	
CSG Connection	NSCC	NSCC	NSCC	NSCC		
Observation		pressure build-up in B	pressure build-up in B			Leak Crossing Packer
Observation			Not-same Pressure A-B			Multiple Leak
Observation			Same Pressure trend A-B			
Observation	Surface Leak		Downhole Leak	Downhole Leak	Surface Leak	Downhole Leak
Observation				Increasing Corrosivity of GL		Sidetrack Well
Observation						Unsteady State Well Condition (GI-WI)
Observation						High Pressure Variation
Observation				CIV Failed		High Thermal Variation
Deviation				Mixing Chemical Fluid With GL instead of CIV	Non Cr Hanger Seal	
Deviation				Increased Gradually Leak Rate	Increased Gradually Leak Rate	
Deviation	Wrong Material Selection			Corrosion	Corrosion	
Deviation	Wrong Hanger Seal			Wrong procedure	Wrong Hanger Seal	

Table A. 20 Case information filling in case production template.

Case features	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
Case Name	Case E-11	Case E-14	Case E-15a	Case E-15b	Case F-14	Case F-16
Field	OSE	OSE	OSE	OSE	OSS	OSS
Well name	E-11	E-14	E-15	E-15	F-14	F-16
Country	Norway	Norway	Norway	Norway	Norway	Norway
Wellhead location	Platform	Platform	Platform	Platform	Platform	Platform
Time occurrence of failure	November 2004	January 2001	March 2005	March 2005	November 2000	Dec. 2000
Case Description	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box
Explanation to Case	Exp. E-11	Exp. E-14	Exp. E-15a	Exp. E-15b	Exp. F-14	Exp. F-16
Lessons learned	LL E-11	LL E-14	LL E-15a	LL E-15b	LL F-14	LL F-16
Case Status	Unsolved	Solved	Solved	Solved	Solved	Unsolved
Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure
Task	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages
Solution		Elastometer TBG Hanger Seal	Elastometer Casing Hanger Seal	Non Cr CSG	High Thermal & Pressure Loads	
Outcome		50 %		Partially understood	Fully understood	
Plan		Use Metal to metal Hanger Seal		Use 13 % Cr	Re-completion Without PBR	
well type	WAG	GI	OPGL	OPGL	WAG	WAG
Time of leak	Late Leak	Early Leak	Late Leak	Late Leak	Early leak	Early leak
Time of leak		Leak Just After Start-up Injection	Leak During Production	Leak During Production	Leak During Gas Injection	Leak During Gas Injection
Leak crossing volume	T-A	T-A	A-B	A-B	T-A	T-A
Leak component	Leak Crossing GLM	Leak Crossing TBG Hanger Seal	Leak Crossing Casing Hanger Seal	Leak Crossing CSG	Leak Crossing PBR	
Type of casing hanger			Elastometer Seal			
Leak fluid system	Leak Gas	Gas			Gas	
Test fluid						
Activity To Reveal Leak		Testing Wellhead seal is Not OK	Wellhead Test-Not Ok	Wellhead Test-Ok		
Casing Type		Wellhead seal Leak	A-B	Non Cr CSG		
Leak Rate					High leak rate	Low Leak Rate
Tie-back System		TB System F	TB System A	TB System A	TB System A	TB System C
CSG Connection			NSCC	NSCC		
Observation			pressure build-up in B		pressure build-up in B	pressure build-up in B
Observation			Not-same Pressure A-B	Not-same Pressure A-B		pressure build-up in C
Observation						
Observation			Surface Leak			Raising Wellhead
Observation						
Observation		Surface Leak	Steady State Well Condition	Steady State Well Condition		
Observation	High Pressure Variation					High Pressure Variation
Observation	High Thermal Variation					High Thermal Variation
Deviation						lock ring was not installed for 13-3 / 8" seal assembly
Deviation						
Deviation	PBR Not Used					
Deviation						

Table A. 21 Case information filling in case production template.

Case features	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18
Case Name	Case F-22	Case F-24	Case F-29	Case F-30	Case Brage 4	Case Brage 6
Field	OSS	OSS	OSS			
Well name	F-22	F-24	F-29	F-30	Brage A-4	Brage A-6
Country	Norway	Norway	Norway	Norway	Norway	Norway
Wellhead location	Platform	Platform	Platform	Platform	Platform	Platform
Time occurrence of failure	January 2006	November 2005	Dec. 2005	Oct. 2005	2007	2007
Case Description	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box	Given in case text box
Explanation to Case	Exp. F-22	Exp. F-24	Exp. F-29	Exp. F-30	Explain Brage A-4	Explain Brage A-6
Lessons learned	LL F-22	LL F-24	LL F-29	LL F-30	LL Brage A-4	LL Brage A-6
Case Status	Solved	Solved	Unsolved	Solved	Solved	Solved
Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure	Well Leakage Failure
Task	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages	Finding Cause of Well Leakages
Solution		Mixing Scale Inhibitor with Gas lift		High Thermal & Pressure Loads	Elastometer Casing Hanger Seal	Elastometer Casing Hanger Seal
Outcome				Partially understood	Fully understood	Fully understood
Plan					Use Metal to metal Hanger Seal	Use Metal to metal Hanger Seal
well type	OPGL	OPGL	OPGL		OPGL	OPGL
Time of leak	Late Leak	Late Leak	Early leak	Early leak	Late Leak	Late Leak
Time of leak		Leak During Production	Leak During Production		Leak During Production	Leak During Production
Leak crossing volume		A-B	A-B	T-A	A-B	A-B
Leak component	Leak Crossing Casing Hanger Seal	Leak Crossing CSG		Leak Crossing Packer	Leak Crossing Casing Hanger Seal	Leak Crossing Casing Hanger Seal
Type of casing hanger					Elastometer Seal	Elastometer Seal
Leak fluid system			Gas		Gas	Gas
Test fluid						
Activity To Reveal Leak					Wellhead Test-Not Ok	Wellhead Test-Not Ok
Casing Type		Non Cr CSG		Non Cr CSG	13% Cr CSG	13% Cr CSG
Leak Rate					Very Low Leak Rate	Very Low Leak Rate
Tie-back System		TB System C	TB System C	TB System E		
CSG Connection		NSCC	NSCC	NSCC		
Observation	pressure build-up in B	pressure build-up in B				
Observation					Inconsistent Leak Behaviour	
Observation					Leak Was Sensitive to Pressure	
Observation	Surface leak	Downhole Leak		Downhole Leak	Leak Was Sensitive to Temperature	
Observation					Repeated Bleed-off Caused Increasing in Leak Rate	
Observation		Steady State Well Condition		Deep Well		
Observation	Slug Flow			High Pressure Variation		
Observation		CIV Failed		High Thermal Variation		
Deviation		Mixing Chemical Fluid With GL instead of CIV		Well Application Was Changed (OP-WAG)		
Deviation						
Deviation						
Deviation						

Appendix B

Paper I

SPE 85327

Case Study: Abnormal Drillstring Wash-out and Fatigue Experienced when Drilling Hazardous Formation in Iranian oil Field

J. Abdollahi and P. Skalle, Norwegian University of Science and Technology (NTNU)

This paper was prepared for presentation at the SPE/IADC Middle East Drilling Technology Conference & Exhibition held in Abu Dhabi, UAE, 20 - 22 October 2003.

SPE 85327

Case Study: Abnormal Drillstring Wash-out and Fatigue Experienced when Drilling Hazardous Formation in Iranian oil Field

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Abstract

High frequency of wash-outs and cracks in drillstring has been experienced in a specific formation in oil fields located in the Southern part of Iran. The rig time consumed on this challenge was high due to time spent on replacing damaged pipes. In a few cases fishing operations were necessary to recover twisted off drillstrings. The majority of drillstring failures happened during top hole drilling (17-1/2" hole section). So far several solutions have been tried out to overcome the drillstring failure, which to some extent has decreased the washout frequency.

In this work we tried to define the challenge as precisely as possible; where, how and why the problem occurred. The state-of-the-art with respect to cause/solution to pipe washouts is included in the paper. Possible reasons and practical solutions to this challenge are evaluated.

Analysis of relevant factors that affect drillstring failure revealed that drillstring vibration in torsional mode is the most probable factor to induce drillstring failure in the hazard formation. This factor is therefore discussed in detail. Inasmuch as the failure occurred just in one particular formation, the lithology that induced vibration is another factor that was investigated and analyzed in this study. The complete understanding of the cause of the problem has however still not been reached.

Introduction

Drillstring failures (DSF) increase drilling cost dramatically especially in high drilling cost environment. The types of failure experienced and reported in this study were drillstring wash-outs, cracks and twist offs. As often is the case in drilling, the consequence of one drilling problem induced another. The consequence of DSF can be; loss of bottom hole assembly (BHA), fishing, bit balling and hole instability. One of the main consequence of DSF was hole instability in term of hole wash-out due to time consuming operations leading to interaction between mud and formation.

There are two main processes that can lead to DSF; fatigue and corrosion. The drillstring is subjected to different types of forces. One of the harmful forces is vibration. Improper BHA design and wrongly selected drilling parameters in hard rock or sticky formation can lead to intensive vibrations. In Iran, as also in several parts of the Middle East, the rate of DSF is reported to be high mainly due to hard rock and sticky formation[1]. In this paper we will report a case study of extraordinarily many DSF while drilling through a specific formation which we will refer to as either the hazardous formation or simply M1. In the M1 formation the rate of failure in some distinctive parts of two fields, called field A and B, out of about 30 neighboring fields, were extremely high; from 10 to 70 DSF per well. In others field the rate of DSF was relatively low, typically 1 or 2 DSF per well. This relatively low failure rate was also observed in field A and B outside three distinctive areas within field A and B. These distinctive areas cover only approximately 20 % of the total area of field A and B. The M1 formation exists in most fields in Southern Iran placed below the surface formation and normally penetrated with the 17-1/2" BHA. The relevant potential causes of DSF are discussed and we will suggest some solutions which are easy to implement. In the mean time, several methods have been tested out in order to decrease washout frequency. These methods were;

- Use of downhole mud motor
- Changed BHA (increased stiffness)
- Use of corrosion inhibitors
- Increased bit lubricity (up to 2 % oil)
- Changed bit type
- Changed to brand new drill pipe

- Decreased axial tension by reduction weight of BHA

Some of the tested methods have been partly successful, especially the applying of down hole motors, while we saw a failure rate decrease of approximately 25 – 30 % was observed. However, the problem can be characterized as unsolved.

Formation

The formation age is Pliocene-Miocene which consists mainly of gray marl (more than 70 %) with minor silty and limestone interbeds. The marl is quite sticky when mixed with filtration / filter cake from the mud. Bit balling is frequently experienced in this formation. The top formation was found at a depth varying from 700 to 1500 mTVD with an average thickness of 650 m. A typical well sketch is shown in Figure1.

Characteristic of Failure

Tables 1 to 3 and Figure 2 demonstrate failure rate in 3 wells in fields A and B. The frequency of DSF is high and at some time reached 13 failures per every 100 m drilled. Most failures happened in formation M1. After passing formation M1 the failure rate decreased to zero. A typical BHA used for drilling the17-1/2” hole is presented in Table 4. The same drill pipe (grade E and G) was used for the whole well. Since no failure happened below M1, we can say that poor pipe quality is not the reason for the failures.

The majority of the failures are shaped like a straight, single crack, 1 to 7 cm long and most of them are visible with the eye. Approximately one third of the cracks were parallel and two thirds perpendicular to the drill pipe axis (see Figure 3). The most of the DSF were located within the first three stand pipes above the BHA; however, some cracks were observed in BHA even in stabilizer. Tables 1 to 3 show the location and type of failure versus well depth. In some cases the crack developed into a complete twist off. This occurred when surface recognition of initial progress of wash-out was poor or torque value reached to tortional limit suddenly. The only surface indication was a sudden pressure drop in the circulating system. No down hole recording was installed.

Potential Causes

There are a lot of factors which affect DSF. In this case study, we have listed relevant factors based on severity level as shown below.

Severity level	Remarks
0	No concern
1	Potential
2	Non critical
3	Influence
4	Critical
5	Severe

Factors which affect DSF	Severity level	Comment
Chemically	0	Non-corrosive environment
Tortuosity (crooked hole)	1	Variation of rock hardness
Fatigue (cyclic stress)	1	Vertical well (but not straight)
Pipe quality (internal upset length)	1	Failure in slip area related to stress concentration in internal upset
Rock hardness	2	Gray sticky marl
Bit & BHA selection	3	Mass-imbalance - Bit cutter concentration
Axial vibration (bit bounce)	3	Due to stick-slip (coupling effect)
Lateral vibration	3	Due to stick-slip (coupling effect)
Accurate bit parameters	3	Critical WOB & RPM to avoid stick-slip
Tortional vibration (stick-slip)	5	Due to sticky clay and WBM
Mud type	5	WBM induces swelling problems
Sticky rock	5	Sticky clay induces stick-slip

We have picked four of the most important factors for further discussion in this paper.

Fatigue (cyclic stress)

Fatigue is the progressive structural change that occurs at a highly stressed location in the material when subjected to fluctuating stress and may result in cracks or fractures after a finite number of stress cycles. Fatigue cracking may occur at stress levels that are well below the drill pipe yield stress. Stress concentrations in a drill pipe are usually caused by slip cuts, short tapers at the internal upset, corrosion pits etc. In practice most of the failures occur in slips area where the concentration of stress is high. The Wohler’s diagram for steel[2] (see Figure 4) shows how alternating stresses reduce the resistance to fatigue. Under normal conditions we see that this can not be cause, because the normal cyclic stress level is far below $\sigma_{fatigue}$. In fact, if cyclic stress is the reason of the problem, this problem should have continued after passing the M1 formation.

Pipe Quality

A comprehensive database on drillstring failures has been complied by IADC/API[3]. The objective of the task group was to establish relationships between the internal upset length and drill pipe failure and explore the cause that lead to such failures. The result of this study showed that the length and radius of internal upset is important for stress concentration in slips area. The database showed that the failure frequency is high happens in slips area approximate 20 inch below from top pipe box. This failure concentration is confirmed through our findings.

Bit and BHA Selection

Three boundary conditions are considered during BHA design; 1) maximum weight on bit (WOB) as recommended by the manufacture is seldom or never surpassed, 2) the neutral point (tension / compression) is designed to be placed inside the drilled collar (75-80% of the BHA weight is used for WOB), 3) Clearance size between hole size and outside DC which stiffness of BHA is considered[4]. Since all three boundary conditions of BHA design have been met and supervised, this cannot be the reason for high failure frequency, although improper BHA design can enhance lateral vibration in term of "mass imbalance"[5].

Vibration

It is commonly known that severe vibration frequently occurs at the bottom of the drillstring during drilling. In drilling operations there are four types of vibration which may be generated either by the bit-formation interaction or by string-formation interactions further up in the drillstring[6]. These four vibrations are; torsional (stick-slip), axial (bit bounce), lateral (bending) and eccentric (BHA whirl). In the present case torsional vibration is the main mode of vibration and the most probable cause of DSF while drilling in M1. This is discussed in detail in the next subchapter.

Stick-slip

Stick-slip is defined as an alternate slowing and acceleration of the BHA rotation. Stick-slip occurring while drilling with a tri-cone bit is usually due to drillstring or wellbore contact. A typical stick-slip vibration phenomenon is presented in Figure 5[7]. Drillstring vibration in tortional mode is the most probable reason of failure in Iranian oil fields due to two reasons. Firstly, failures occur only in a specific formation while in other formations not, even if the BHA is identically designed, secondly, rock characterization of the M1 formation is sticky and hard compared to formations above and below the M1. Whereas drillers want to have constant rotary speed (RPM) in a specific interval they will in practice seldom obtain the constant RPM due to bit stick-slip motion of the drillstring. The surface RPM is quite different from bit RPM. The rotary speed can be zero or even negative for a fraction of time. The main reason of stick-slip motion is the high friction force excreted on the bit and the rest of the BHA. High friction depends on many factors, but in our case the sticky gray marl is important. The estimation of stick time fraction for typical drilling parameters in M1 formation is presented in appendix.

In our work this was not been studied any further due to limited data and time issue.

Discussion

We have shown above that stick-slip is the major cause of the problem. The washout problem is purely a mechanical problem; different type of corrosion can be ruled out for two reasons; 1) the pipes are regularly inspected and replaced wherever a pit is detected, 2) the H_2S level while drilling the M1 formation is zero. The dynamic forces in terms of vibration require therefore a full program for analyzing and monitoring it before we can quantify the vibrations in different modes.

The formation lithology contains sticky clay, and clay is very sensitive to water (absorb water from WBM). The WBM was a mixed salt water mud with density and viscosity typically 1.2 kg/l and 7 cp respectively. Sticky formation has the potential to create stick-slip motion (torsional vibration type) due to high friction between BHA and the formation. When mud motor was applied, the friction on the BHA above the motor was eliminated, causing a reduction in slip-stick motion. The length of the drillstring is importance for stick-slip induction. Short strings (shallow well depth) are more critical than longer strings for similar condition (e.g.; force, torque, hole size and etc.). Stick-slip is much more critical in the fields A and B than in the other fields, since the top M1 formation depth is shallower here than in the other fields.

Since slip-stick and associated bit bounce is quickly destroying the drillstring, there are two obvious ways to reduce the problem of drillstring wash-outs:

1. Monitoring vibration (downhole and surface). It is vital to use equipment to identify down hole vibration in real time. By having those data, it is possible to adjust accurately surface drilling parameters; RPM and WOB. These parameters are essential in controlling drillstring vibration.
2. Reduction vibration by a) using a downhole mud motor and / or b) using oil based mud instead of WBM.

These two countermeasures will a) completely change the spring characteristics of the drillstring and b) reduce the friction and thereby the "stick" part of the stick-slip motion. If no stick there will be no slip, and accordingly no bit bounce.

Conclusion

This study concludes that vibrations in the drillstring are the main factor leading to DSF for the two fields being investigated in Southern part of Iran. To reduce DSF the following recommendations are given:

- Use OBM in the hazardous formation. Selection of OBM is purely based on technical reasons; oil will now be the wetting phase of both the borehole wall and the cuttings, the interaction between clay and water and the friction between bit and rock will be largely reduced.
- Require full statistical analysis in hazardous formation concerning DSF phenomena.
- Light weight BHA is preferable to avoid tensile stress (use low WOB in the M1 formation).
- Use mud motors whenever possible.
- Use stiffer BHA to avoid hole deviation (approach a straight hole), and consequently, reduce lateral and torsional vibration.
- Use downhole thrusters / shock absorber.
- Find critical rotational speeds if possible, and change bit parameters (RPM and WOB). For this purpose there are now available several devices on the market.

Downhole vibration monitoring will be beneficial for further investigation and optimization. Some of the systems available are;

- String Dynamics Control (SDC), AGIP / Mud Logging Services[8].
- Soft Torque Rotary System (STRS), Shell[9].
- Co-pilot, Baker Hughes[10].

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Appendix: Stick Time Fraction Calculation

A mathematical model presented by Kyllingstad *et* al.[11] were applied in the estimations.

Input Data

Length of drill pipe section	1385 m
Length of drill collars section	115 m
Drill pipe momentum (5" OD, 4.125"ID)	11.8E-06 m^4
Drill collar momentum (10" equivalent OD, 3"ID)	405E-6 m^4
Shear modulus of steel	81.4E+9 pa
Density of steel	7890 kg/m^3
Extra starting torque	4 kNm
Rotary speed (120 RPM)	12.6 s^{-1}

Output Data

Static torsional stiffness	620 Nm/rad
Pendulum frequency	0.149 Hz
Slip-stick period	6.77 s
Sticking time fraction	0.152

Variable rotary speed (constant torque = 4 kNm).

Rotary speed (RPM)	150	120	90	60
Sticking time fraction	0.122	0.152	0.2	0.29

Variable torque (constant RPM = 120).

Torque (kNm)	4	5	6	7
Sticking time fraction	0.152	0.188	0.223	0.257

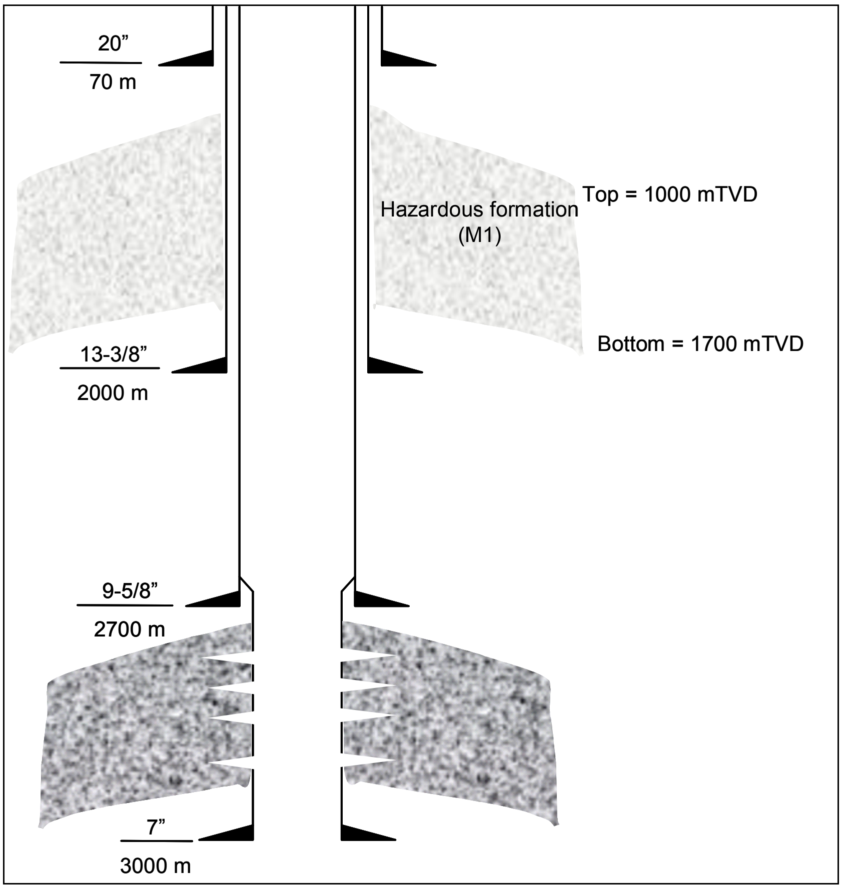


Fig. 1 - Typical well sketch in fields A and B.

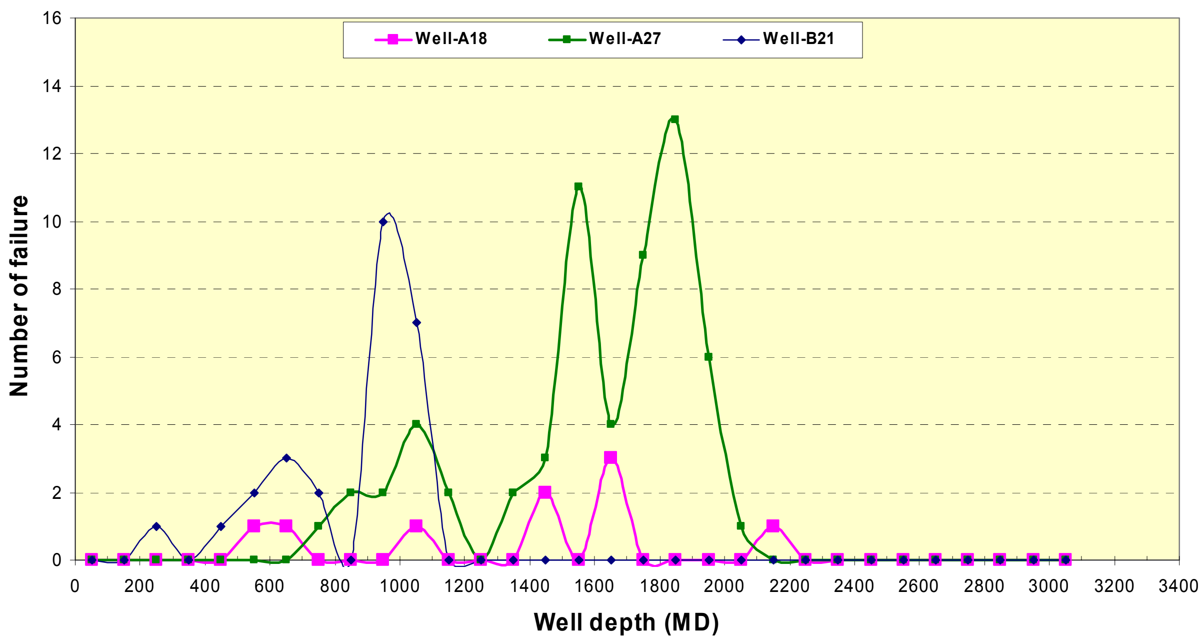


Fig. 2 - Failure frequency in tree wells. Depth intervals of M1 formation are; well A18: 1437 – 2200 m, well A27: 1360 – 2100 m and well B21: 630 – 1140 m.

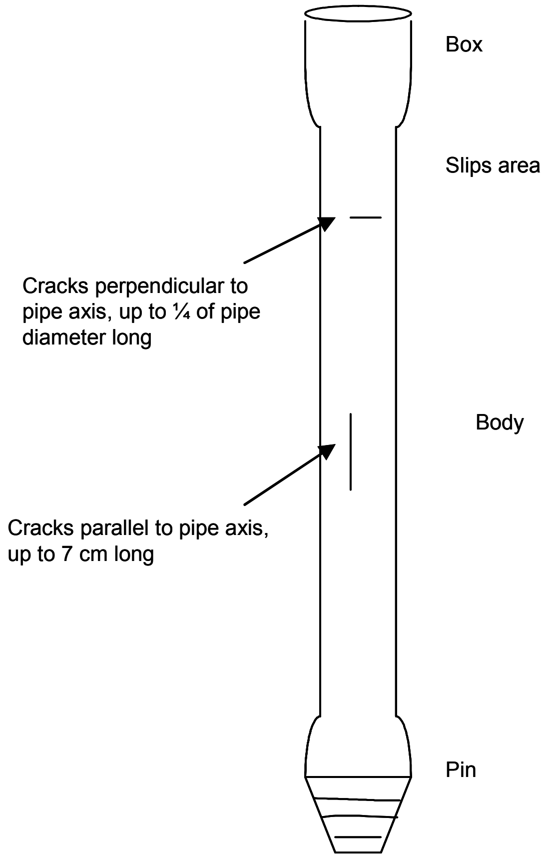


Fig. 3 - Crack direction and relative positions.

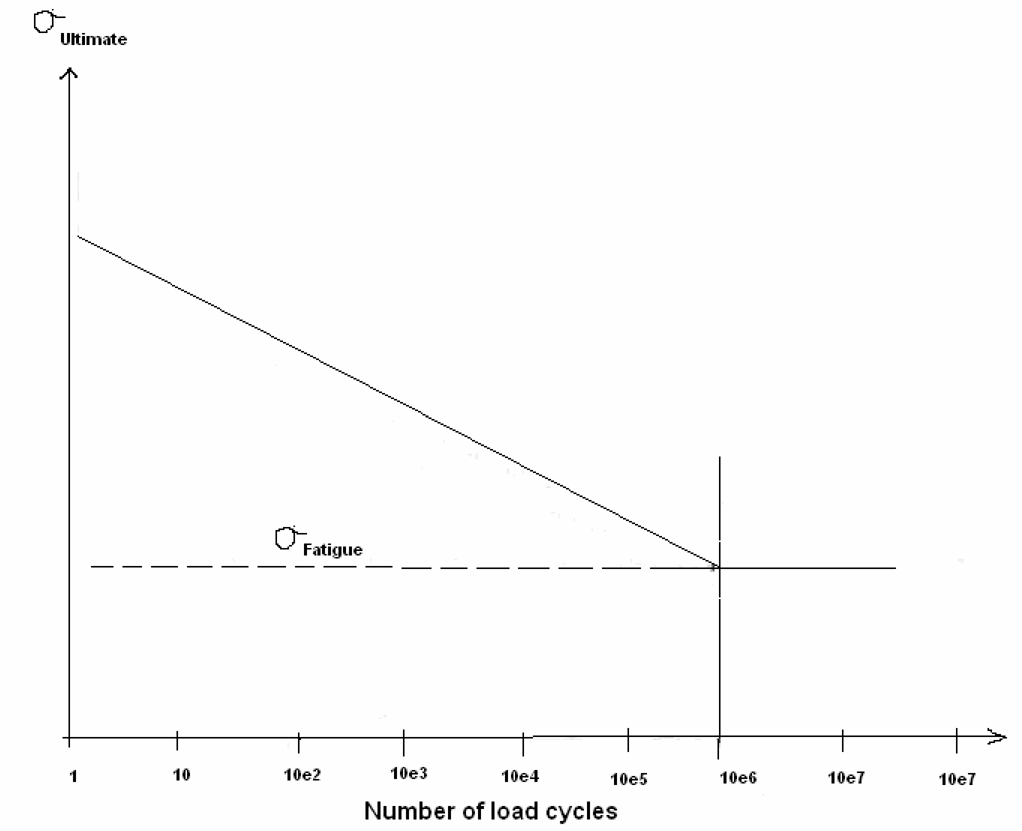


Fig. 4 - A Wohler's diagram. A pipe break due to fatigue if cycled 10e6 times at a stress level of f_{atigue}.

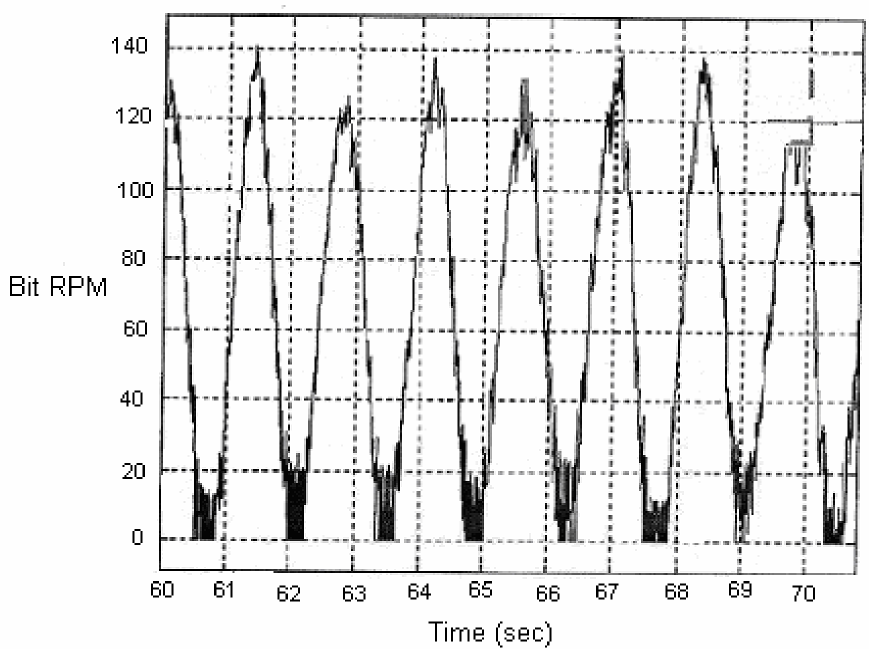


Fig. 5 - Bit RPM vs. time showing stick-slip vibration (RPM=60).

Table 1 - Details of drillstring wash-outs (one complete twist off) recorded in well A27 (67 failures totally).

Well- A27		
Well depth (mTVD)	Fatigue type and its relative location of drillstring failure	Formation
0 - 782	No drillstring failure	Non-hazard formation
782	Drill pipe (body)	
813	Drill pipe (body)	
888	Drill collar (body)	
929	Drill pipe (body)	
994, 1053, 1062, 1067	Drill pipe (slips area)	
1086, 1095, 1151, 1181	Drill pipe (slips area)	
1365, 1393, 1400, 1430	Drill pipe (slips area)	Hazardous formation (M1)
1489	Drill pipe (slips area) + drill collar	
1501	Drill pipe (slips area)- 2 points	
1528	Drill pipe (body)- 2 points	
1535	Drill pipe (body)	
1541	Drill pipe (body)- 2 points	
1543	Drill pipe (slips area)	
1554	Drill pipe (body)- 2 points	
1556	Drill pipe (body)- 2 points + drill collar	
1566	DP-slips area	
1569, 1576, 1580, 1631	Drill pipe (body)	
1637	Twist off from DP	
1684, 1697	Drill pipe (slips area)	
1713, 1717	Cross over sub	
1721	Drill pipe (slips area) - 2 points	
1738, 1748, 1759	Drill pipe (slips area)	
1770	Drill collar	
1781, 1795, 1833, 1850	Drill pipe (slips area)	
1851, 1853, 1864, 1865, 1868	Drill pipe (slips area)	
1870.5	Drill collar	
1873, 1878, 1884, 1889, 1892	Drill pipe (slips area)	
1925	Drill collar	
1929	Drill pipe (slips area)	
1931	Drill pipe (slips area) - 2 points	
1962	Drill pipe (slips area) + drill collar	
1966, 1970	Drill pipe (slips area)	
2031	Drill pipe (slips area) - 3 points	
2036	Drill pipe (slips area) - 2 points	
2100	No drillstring failure	
2100 - 3500	No drillstring failure	Non-hazard formations

Table 2 - Details of drillstring wash-outs recorded in well A18 (9 failures totally).

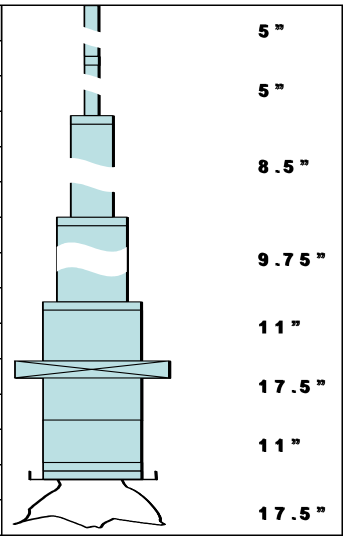
Well - A18		
Well depth (wash-out points), meter	Type and location of drillstring failure	Formation
0 - 698	No drillstring failure	Non-hazard formation
698	Drill pipe (body)	
816	Drill pipe (body)	
1046	Toll joint (drill pipe)	
1436	Cross over sub	Hazardous formation (M1)
1453	Drill pipe (body)	
1606	Stabilizer	
1625	Drill pipe (body)	
1645	Stabilizer	
2150	Drill collar	
2150 - 3500	No drillstring failure	Non-hazard formation

Table 3 - Details of drillstring wash-outs (and two complete twist off) recorded in the well B21 (25 failures totally).

Well - B21		
Well depth (wash-out points), meter	Type and location of drillstring failure	Formation
0- 476	No drillstring failure	Non-hazard formation
476	Drill pipe (body)	
523	Cross sub	
588	Twist off - drill collar	
629	Twist off - drill pipe	
634	Drill pipe (body)	Hazardous formation (M1)
684, 741	Cross sub	
750, 907	Drill pipe (body)	
925	Cross sub	
931	Drill collar	
934	Drill pipe (body)	
938	Cross sub	
961, 972, 974, 980	Drill pipe (body)	
984	Cross sub	
1109	Drill pipe (body)	
1112	Cross sub	
1123, 1127, 1130, 1139, 1139.5	Drill pipe (body)	
1140 - 3200	No drillstring failure	Non-hazard formation

Table 4 - Typical bottom hole assembly in the 17-1/2 “hole section in M1 formation.

Items	Size (outside)	
	inch	meter
Drill pipe (grade e)	5	Drill pipe (grade E and G)
Heavy weigh drill pipe	5	130
Cross over sub	8 - 1/2 * 5	1
Drill collar	8 - 1/2	28
Cross over sub	9 - 3/4 * 8 - 1/2	1
Drill collar	9 - 3/4	54
Cross over sub	11 * 9 - 3/4	1
Drill collar	11	11
Stabilizer	17-1/2	2
Drill collar	11	20
Bit sub	11	1
Shock sub	11	1
Bit (tricone - tooth)	17 - 1/2	0.4



Appendix C

Paper II

SPE/IADC 91579

Underbalanced Drilling as a Tool for Optimized Drilling and Completion Contingency in Fractured Carbonate Reservoirs

J. Abdollahi, I.M. Carlsen, S. Mjaaland, SPE, SINTEF Petroleum Research, P. Skalle, SPE, Norwegian U. of Science & Technology, A. Rafiei, S. Zarei, Iranian Central Oil Fields Company

This paper was prepared for presentation at the 2004 SPE/IADC Underbalanced Technology Conference and Exhibition held in Houston, Texas, U.S.A., 11–12 October 2004.

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SPE/IADC 91579

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Abstract

Maintained pressure management and fracture network mapping are key issues for successful well construction in fractured carbonate reservoirs. Prediction and characterization of the fracture network prior to drilling is very difficult and challenge optimized well direction and placement in respect to the fractures. Avoiding productivity impairment by loss of drilling fluids is another major challenge.

Later stimulation of a micro-fractured reservoir invaded by drilling mud is extremely difficult or even impossible. Open hole completion is generally preferred in these type of reservoirs. Underbalanced drilling (UBD) is therefore an interesting option for enhanced data acquisition, avoiding reservoir impairment and achieving completion contingency for optimized well production and added value.

Locating and characterizing the natural fractures while drilling is a vital issue for appropriate well placement and selection of completion options during the field development strategy. Depending on the opening and extension of the fractures, the mud loss rates and volumes can differ from low to heavy. The associated fracture network is the main parameter contributing to well production.

Underbalanced drilling is one of the main recommended technologies for further development of fractured carbonate reservoirs in South-West Iran. Flow drilling, allowing the hydrocarbons to flow to surface while drilling, will be advantageous. With sufficient reservoir pressure, this method enables better fracture characterization and a dynamic decision process can be applied for drilling horizontal wells with optimized well trajectory intersecting more fractures. Formation damage can be avoided and dramatically reduce unsuccessfully drilled wells.

Introduction

UBD is a drilling practice where the dynamic wellbore pressure intentionally is less than the formation pore pressure. Underbalanced drilling may improve drilling efficiency and enhance well productivity. However, for operational safety overbalanced drilling is generally preferred and the value of UBD is not yet fully acknowledged. At the same time UBD is increasingly used in many parts of the world. The technology involved is matured and the experience is increasing. UBD may be the only solution to unlock further drilling in depleted reservoirs with abnormal pressure ramps. UBD is applied for a variety of reservoir types at different complexity levels[1].

For field development projects in Iran, underbalanced drilling has a great potential and the National Iranian Oil Company (NIOC) has initiated a UBD technology program. UBD projects are related to some partially depleted fields in the south of Iran. The motivation is to increase the drilling efficiency and to enhance production. Normal drilling procedures, even with minimum conventional mud density (0.8 s.g) is not possible in many of the fields due to heavy to complete mud loss. In practice, drilling horizontal wells with heavy mud loss creates two severe drilling challenges:

- Stuck pipe due to cutting accumulation
- Loss of data transmission

In fractured carbonate reservoirs commonly found in Iran, non-producing wells are a major challenge either due to formation damage by loss of drilling fluids or not appropriate well placement and direction to intersect the fractures. The key aspects for promoting UBD in Iran are;

- Improved drilling performance
  - Avoiding drilling fluid loss
  - Improved ROP
  - Less bit wear and tripping time
- Improved reservoir fracture productivity
  - Early and improved fracture detection
  - Avoiding reservoir impairment
  - Allowing open hole completion
  - Reduced need for well stimulation

This paper discusses the above mentioned challenges to Iran and in relation to underbalanced drilling as a tool for optimized drilling and completion contingency in fractured carbonate reservoirs. Data and experience from West-Zagross fields located in South-Western part of Iran have been used as a basis for the study.

Underbalanced Drilling Technology

The UBD methodology involves two major technologies:

- Types of UBD fluid; gas, foam, gasified- and one phase liquids
- Circulating system; open system, closed loop system and snubbing unit

There are two ways to create underbalanced conditions which are also dependant on the formation pore pressure:

- Artificially underbalanced
- Naturally underbalanced

Artificially underbalanced operations apply to depleted reservoirs where the pore pressure gradient is less than the water pressure gradient. Gas is then required and mixed with the drilling fluids. Natural underbalanced operations mean that the reservoir pressure is able to flow the well by itself. However, starting the underbalanced condition, the mud column of the well has to be unloaded by a lighter fluid. The method is referred to as "flow-drilling" [1].

UBD systems are modular and self-contained and can in principle be installed independently of the drilling rigs. Some extension of the surface pad is needed for the equipment involved. Top-drives are advantageous, avoiding the square drilling kelly running through the rotating control head (RCH) creating extra wear on the seals. A standard UBD package is designed as a closed loop system. Flexibility is a key issue allowing production while drilling and reservoir testing. Drilling with volatile fluids (high GOR) and managing H_2S environments are important safety issues.

Well Construction Challenges in Fractured Carbonates

Maintaining underbalance in both drilling and completion is a complex and challenging operation. Due to this complexity, some underbalanced drilled wells may be completed in overbalance and the initial production capabilities of the well may be lost. Underbalanced conditions are important for all phases of the well construction comprising:

- Drilling
- Tripping (in and out)
- Logging and formation testing
- Running casing and pumping cement
- Perforation and completion

Hard rock drilling and low rate of penetration (ROP) is a common challenge in the Middle East. In tight carbonated reservoirs in Iran an ROP of one meter per hour has been experienced. This low ROP impacts the drilling costs and is also very relevant to the formation damage issue due to increased time of exposure of mud to the reservoir. The bit life is generally low and several bit runs are required. UBD can dramatically reduce drilling time and up to 10 times improvement has been reported[2, 3].

Abnormal pressurized salt water formations and depleted and fractured reservoirs need to be carefully addressed. Logistic is a very important issue and impacts the drilling efficiency and the ability to handle critical well operations. With UBD it is possible to manage unforeseen pressure regimes and mitigate the logistics challenge related to heavy mud loss.

Mud losses occur when fractures are encountered ahead of the bit. Depending on the fracture characteristics the mud loss rates can vary. Dyke[4] described three types for fracture apertures. With micro-fractures (less that 250 μm) mud will block the fracture near the wellbore without any detectable mud loss. Fracture openings between 250 and 500 μm can be detected by monitoring the mud loss, but will be blocked by the mud after some time. When the fracture opening is larger than 500 μm, mud can not seal the fracture by itself and lost circulation material (LCM) may be required to stop losses. However, using LCM can destroy the conductivity of the fractures damaging the production potential of the well. This risk need to be balanced with the potential drilling hazards such as stuck pipe and gas blow out. In some cases the data acquisitions programme has to be cancelled due to mud loss. During well completion, back flushing is generally carried out to clean the well. A successful clean up or stimulation of the fracture network is hard to achieve. This is demonstrated with field data in the further discussion.

Optimized well direction and placement in respect to the fracture network pattern is very important. Experience has shown that predicting and characterizing the fracture network prior to drilling is very difficult. UBD can assist for early detection and assessment of the fractures.

Field Study

90 % of the discovered fields in Iran are in carbonate reservoirs putting Iran as one of the largest carbonate producers in the world[5]. The normal production mechanism of carbonate reservoirs is through natural fracture networks with high conductivity. The dense matrix usually feeds the fracture network. If the well trajectory does not intersect any fractures, production will be low or even absent. In such cases, field experiences have shown that stimulation efforts like acidizing often are unsuccessful.

New master development plans (MDP) have been developed for upgrading of seven Iranian oil fields in south west of Iran. A location area map is shown in **Figure 1**. Although the production history has been poor, the potential of the fields have been found to be high, but dependent on efficient exploitation methods like horizontal wells, underbalanced drilling and smart data acquisition programs.

The Dehluran (DH) field is a relevant field for UBD operations because of the nature of the field and the long and problematic production history. DH is located in the south-western part of Iran close to the Iran-Iraq border. The field is 20 km long and 9 km wide with an average reservoir thickness of 300 m. The DH field map is presented in **Figure 2**. The field was discovered in 1970 and 22 wells have been drilled so far. Only 13 wells have reached the reservoir target. The rest of the wells have been abandoned due to serious drilling challenges like high salt pressure and also due to the Iraq-Iran war (1980-1988). The estimated recoverable oil is 15 % by natural depletion. So far only 10 % of recoverable oil is produced. To date, horizontal wells have not been drilled.

The integrated study showed:

- The majority of wells has poor production history
- General lack of fracture knowledge

- Uncertainties apply with respect to reservoir compartments and fluid contacts

Only a few wells have shown a reasonable production potential. It is assumed that the exposure to the fracture network govern the well productivity. It was not possible to explain the production capabilities from the available petropysical log data.

Fractures can be identified and characterized by different methods. With formation image logs the fractures can be visualized directly. Accurate mud loss detectors combined with annulus pressure sensors near the drill bit can give a continuous log of minor to severe losses. Small fractures may however be difficult to detect by this method. The micro-fractures will be filled and blocked by mud within few seconds when the mud is non-Newtonian[4].

Mud loss logs or image logs were not available for the Dehluran field. Mud loss data, extracted from the daily drilling reports was thus studied as an approach to characterize fractures. The wells were ranked with respect to mud loss rate as follows:

- No mud loss (zero)
- Partial mud loss (1 to 9 bbl / hour)
- Moderate mud loss (10 to 49 bbl / hour)
- Severe mud loss (50 bbl / hour to complete mud loss)

The results are shown in **Table 1** together with the cumulative production. The mud loss distribution is summarised in **Figure 3** and shows that 65 % of the wells had no mud loss to partial mud loss while 35 % of the drilled wells had severe to moderate mud loss. The rapid and unexpected mud loss observation is the main indication for existence of fractures. The complete mud loss probably happened when large fractures were hit.

The productive wells and the mud loss history are indicated on the field map in **Figure 2**. A correlation is found between the mud-loss and production history. It seems as the northern part of the field has higher probabilities of fractures. No systematic regional fracture pattern can however be deduced.

Fracture Interpretation in Well DH-5. Out of the 13 wells reaching the reservoir in the DH field the well DH-5 has been selected for an in-depth study. A simple well sketch is shown in **Figure 4**. This well was chosen due to the following:

- A successfully drilled well with a reasonable production rate
- Available production tests with draw-down and build-up tests and production logging (PLT)
- Available cores
- Complete drilling history with daily mud loss data
- Production rate history

The entire mud loss history of the pay zone was interpreted. The net thickness of the pay zone was about 350 m. 2600 bbl mud was lost in this interval by 250 bbl/day average loss rate and with 15 % solid by volume. The mud properties are summarized in **Table 2**. The mud rheology is non-Newtonian and can be considered as Bingham. 600 sacks of LCM (mica) were pumped to reduce the mud losses. The differential or normalized daily mud loss, new mud loss rate minus old ones, was used for fracture analysis. The data is shown in **Figure 5**. There are five mud loss peaks at different depths which are assumed to represent fractures. They are named fracture 1 to 5 in the figure. There is a possibility that only one fracture (fracture 1) is present, being opened in succeeding time periods. Therefore, the fracture interpretation was done for two cases; one case which considered only one fracture and a second case with five independent fractures. The well was perforated in five intervals. Perforation intervals were probably selected mainly from petrophysical logs with porosity indications. However, only one perforation interval was placed exactly against fracture indications (fracture 1) taken from the mud loss analysis. The PLT log showed that 95% of total flow was produced from this perforation. The second perforation interval produced 5% and the rest of the intervals did not contribute to any production. The length of both producing perforation intervals is 21 m.

A temperature survey also indicated an anomaly from 4040 to 4070 mMD which corresponds to fracture 1. Therefore, the first fracture was verified from four sources:

- PLT log
- Mud loss
- Temperature survey
- Well test

A production test, including draw-down and build-up tests in three periods, was carried out in well DH-5 after well completion. The calculated result showed negative skin (-3 to -5) which indicates fracture conductivity. The corresponding fracture permeability is 70 to 120 mD. As the mud losses continued for a long period we assume the fracture networks can be treated as infinite acting conductivity.

The fracture permeability, fracture porosity and fracture extension are essential parameters for the reservoir evaluation and the field development. In addition, these parameters are vital for the driller to select LCM and to design the well trajectory.

Muskat[7] and Jones[8] have shown that the fracture permeability (k_f) and porosity (ϕ_f) for parallel fractures spreading horizontally are given by:

$$k_{fp} = w^3 / (24\ \delta_p) \qquad (1)$$

$$\phi_f = w / \delta \qquad (2)$$

whereas the permeability for conjugated fracture pattern[9] is given by:

$$k_{fc} = w^3\ /\ (12\ \delta_c) \qquad (3)$$

The average fracture spacing can be obtained by dividing the net pay zone thickness with the number of fractures. Since five fractures were indicated during drilling 350 m of pay zone, the average fracture spacing in DH-5 is 70 m. The reservoir geology is layered with interbedded shale. The main producing interval is 100 m thick and the first fracture was indicated in this layer. The well test was also carried out here. Therefore, in the well DH-5 case the fracture spacing can be 100 m. It has been shown that there is a relation between fissure pseudoskin and fractures spacing in the absence of mud loss and LCM. This skin is only related to the nature of the fracture network and is always negative[10]:

$$S_f = \pi / 2(1 - 2r_w / \delta) + \ln(2r_w / \delta) \qquad (4)$$

When the fracture spacing is known, fissure pseudoskin can be obtained. The obtained value for skin will be between -4 to -5 by using fracture spacing 70 to 100 m which is in good match with the well test result.

During overbalanced drilling most of the fractures will be immobilized by mud or LCM. To make all the fractures produce it is required to perforate all fractured intervals and to stimulate the different fracture systems individually. It is assumed that lack of perforation as well as insufficient stimulation is a major contribution to poor productivity in many of the DH wells.

Dehluran Logistics. The drilling logistic issue is very important when operating in remote and desert areas like the Dehluran field. Rough terrain with long access roads and also military regulations due to the closeness to the Iraqi border is a challenge. The logistics are related to both human support and securing of needed equipment and materials. A downtime analysis from daily drilling reports shows that while hole condition problems was the major issue for early wells, the logistics are the major area of concern for the later wells. The major factors involved for the logistics are transportation and the availability and quality of materials and spare parts. **Figure 6** shows downtime analysis of nine DH wells. The downtime is caused by severe mud losses and securing water supply is the most predominant issue and impacts the ability to handle critical drilling operations.

Validating Underbalanced Well Construction

Different field and formation characteristics need to be screened with respect to the potential benefits of underbalanced well construction:

- Fields or formations where UBD can obviously offer advantages; depleted formations, hard rock formations and formations subject to damage.
- Fields or formations which need in-depth evaluation; low permeable formations, very permeable formations, macro-fractured formations and abnormal pressurized formations.
- Fields or formations where UBD is not recommended; highly unconsolidated formations and swelling formations.

Before commencing drilling operations the following considerations need to be carefully addressed:

- Wellbore collapse or enlargement
- Drilling operation safety
- Net present value (NPV)

UBD operations should be evaluated for different contributions to validate the enhancements:

- Short-term enhancement related to drilling ability and ROP achievements
- Long-term production enhancement related to improved well productivity.

In the seven fields study UBD solutions for production enhancement have been addressed. The fields have been screened and drilling and production histories were evaluated for UBD applications. Fracture characteristics and pressure gradients have been analysed and **Table 3** summarizes the findings. Three out of the seven fields have more than 5 wells drilled while the rest still are in an exploration phase. Recommendations with respect to UBD application in the seven fields are summarized in **Table 4.**

Flow Drilling. In fractured reservoirs, the reservoir fluid can flow easily when exposed to an underbalanced condition due to the high flow conductivity of the fractures. The observed reservoir pressures in DH are between 414 – 428 bar at the datum depth of 3900 mss. Normally 10% overpressure in the reservoir is required to achieve underbalanced conditions.

For safety issues criteria for hole collapse and procedures for surface handling of the fluids need to be clearly defined. The open hole production history in the field shows that the rock is generally stable and the use of crude oil fluid should be acceptable and recommended both with respect to reservoir evaluation and rock compatibility. Surface handling of fluids need to be carefully assessed by the service contractor.

Fracture Characterisation by UBD. The Dehluran study showed the importance of precise positioning and characterization of the intersected fractures. This is of special importance if the reservoir section is completed with a casing and the production intervals are perforated.

When the flow-drilling method is applied, influx to the well will increase rapidly after the bit intersects fractures. By monitoring the rate of flow at the surface fracture interpretations can be made. This evaluation may be integrated with data from the Logging While Drilling tool (LWD) in real time and comprehensive fracture knowledge can be achieved. Micro-fractures which are difficult to detect by overbalanced mud loss may be observed by flow-drilling.

Completion and Stimulation. Later stimulation of a micro-fractured reservoir invaded by drilling mud is extremely difficult. Open hole completion is generally preferred in these competent formations and type of reservoirs due to larger reservoir exposure. Drilling overbalanced contaminates the fractured reservoir and open hole stimulation is difficult. An effective treatment requires selective stimulation of each fracture. To perform this in open hole time consuming straddle pack operations are required. A liner is normally set and perforated. In natural fractured reservoir one needs to perforate in the exact position of the fractures which is very difficult to achieve. Underbalanced well construction will help to avoid reservoir impairment maintaining the option of an open hole completion. Moreover, production diagnoses are simpler in complex fields by applying UBD and flow-drilling. With UBD, fracture monitoring can be done while drilling and it is possible for completion and reservoir engineers to make dynamic decision how to complete the wells.

Logistics with UBD. Downtime due to logistics problems represents a challenge as shown in the Dehluran field. UBD can help to reduce this downtime if an appropriate technique is selected. For example, using foam as the UBD drilling fluid does not need conventional water amounts. A closed UBD system will minimize waste of drilling fluids and improve environmental issues.

The specific field locations need attention as an UBD equipment package needs some extra space. However, assembling an UBD system onshore is simpler than offshore due to less space limitations.

UBD operations require a more careful planning than a conventional drilled well. It is therefore possible to reduce the downtime significantly and to improve the drilling efficiency and safety. As discussed before the root causes of mud losses or blowouts are unknown or not well-known fractures and associated pore pressure. UBD is an operation which plays with the well hydraulics, and thus adjusts the well pressure to the pore pressure.

UBD Time and Cost. Introducing UBD will add service cost to the drilling campaign. However, simple time and cost estimates can also illustrate potential cost savings in addition to improved well performance. **Table 5** compares estimated rig days with conventional drilling and with UBD for a DH well and **Table 6** compares the total drilling costs for the same well. It is assumed that rate of penetration with UBD will be twice compared to conventional drilling. Furthermore, it is assumed that additional daily rates of UBD is comparable to a rig rate of 25000 $. Saved time on drilling and tripping in the reservoir interval without stimulation needs sums up to 12 rig days saved and a total cost almost equal to a conventional drilled well.

As most of the advantages of UBD come in the production phase a reasonable net present value calculation of UBD should be as a lifetime calculation of the well.

Conclusions

In the evaluation of productivity improvements of fractured carbonate reservoirs in Iran UBD technology has been identified as a promising tool. The value has been found to be mainly related to:

- Improved fracture network identification and characterization
- Improved well productivity avoiding fracture contamination
- Avoiding time consuming and risky stimulation operations
- While drilling decision support for optimized well placement and completion contingency
- Less need for drilling water supply and mitigating logistics related to mud materials
- Faster drilling with less rig days

A pilot program for a suite of wells may be needed to justify the associated mobilization costs.

Acknowledgment

The authors would like to thank Iranian Central Oil Field Company and SINTEF Petroleum Research for their support for the work and approval of publication.

Nomenclature

w = fracture opening, m
δ = fracture spacing, m
r_w = wellbore radius, m
S_f = fissure pseudoskin, dimensionless
k_f = fracture permeability, mD
Φ_f = fracture porosity, percent

Subscript

p = parallel
c = conjugated

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Table 1 Dehluran cumulative production and mud loss

Dehluran				
Well	Cumulative production (MMSTB)	Average daily rate (BOPD)	Mud loss	Mud type
2	19.4	3796	Severe	WBM
3	9.7	1898	0	OBM
4	21	4110	0	WBM
5	40	7828	Severe	OBM
6	0.01	2	0	NA
11	0.14	27	0	OBM
12	0	0	0	OBM
14	0.004	1	0	NA
16	0.75	147	Severe	WBM
17	0.004	1	Moderate	WBM
18	0.46	90	Moderate	WBM
19	0	0	0	OBM
20	0.05	10	Partial	OBM
21	0.02	4	Partial	OBM
	91.538	1280		

Table 2 Mud properties in well DH-5.

Mud density	Plastic viscosity	Yield point	Solid	Oil / water
s.g	cp	lb / 100 sq.ft.	%	volume ratio
1.2	19	8	15	70 / 30

Table 3 –Summary of seven fields screening for UBD application.

Field	No. Of wells	Production activity	Development status	Size of fracture	Frequency of fractures	Pressure gradient (Kpa / m)
1	22	Yes	Partially develop	Small to medium	low	11,8
2	6	Yes	Limited develop	Small to medium	very low	11,8
3	5	Yes	Limited develop	Small to medium	low	11,8
4	3	Limited	Exploration	Large	very low	8,8
5	2	Limited	Exploration	Large	NA	8,8
6	1	Limited	Exploration	NA (sandstone)	NA	11,8
7	1	No	Exploration	Large	NA	9,8
	40					

Table 4 – Resulting and recommendations after fields study.

Field	UBD fluid	UBD method	UBD application
1	one phase	Flow drilling	Formation damage
2	one phase	Flow drilling	Formation damage
3	one phase	Flow drilling	Formation damage
4	two phase	Foam	Mud loss and safety
5	two phase	Foam	Mud loss and safety
6	NA	NA	NA
7	two phase	Aerated	Mud loss and safety

Table 5- Historical conventional drilling operation time compared to plan UBD in DH field.

Items	Nomenclature	Unit	OBD case	UBD case
UBD interval length	L	m	1000	1000
Rate of penetration in reservoir interval	R_r	m / hour	3	6
Total drilling time	T	hour	333	167
Tripping time in reservoir interval	T_{tr}	hour	24	0
UBD installation time	T_{iubd}	hour	NA	24
Stimulation time	T_s	hour	120	0
Completion time	T_c	hour	120	120
Total reservoir drilling time	T_r	hour	**597**	**311**
Saved rig - days	**Delta T**	**day**	**12**	

Table 6- Historical conventional drilling operation cost compared to plan UBD in DH field.

Items	Nomenclature	Unit	OBD case	UBD case
UBD service cost	C_{ubd}	$ /day	NA	25 000
Rig cost	C_{rig}	$ /day	25 000	25 000
Location cost	C_{loc}	$ / well	150 000	200 000
Stimulation cost	C_s	$ / well	50 000	NA
UBD service cost	C_{ubd}	$	NA	323 611
Rig cost	C_{rig}	$	622 222	323 611
Total reservoir drilling cost	C_{res}	$	**822 222**	**847 222**
Additional cost	**Delta C**	**$**	**25 000**	

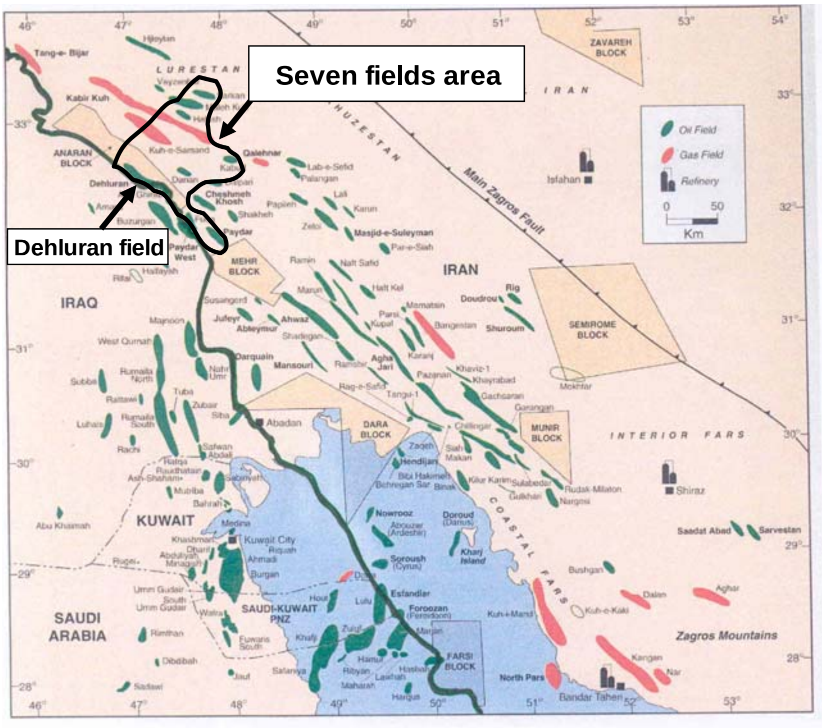


Figure 1- Location of the seven fields area. The Dehloran field was selected for evaluation.

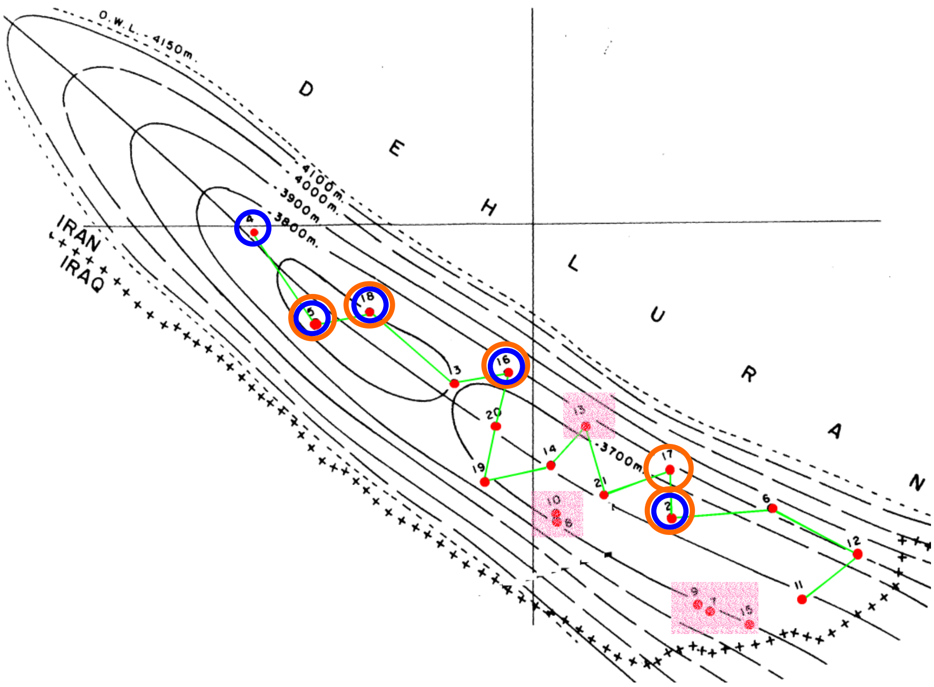


Figure 2- Dehluran field map showing wells with mud loss (red circle) and production wells (blue circle). Wells not reaching the reservoir are indicated with pink squares

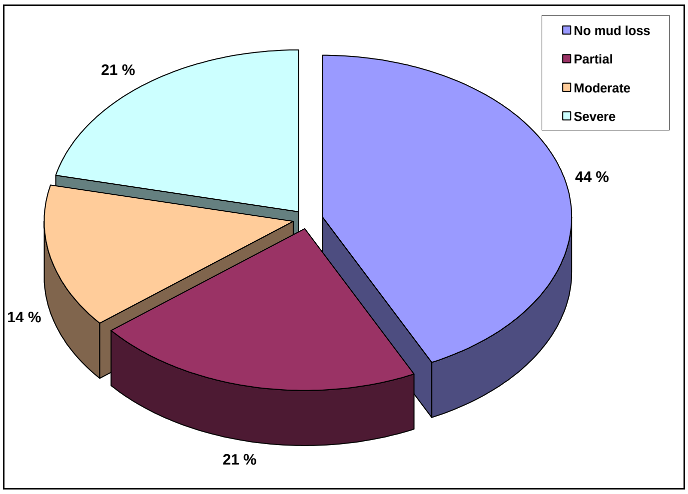
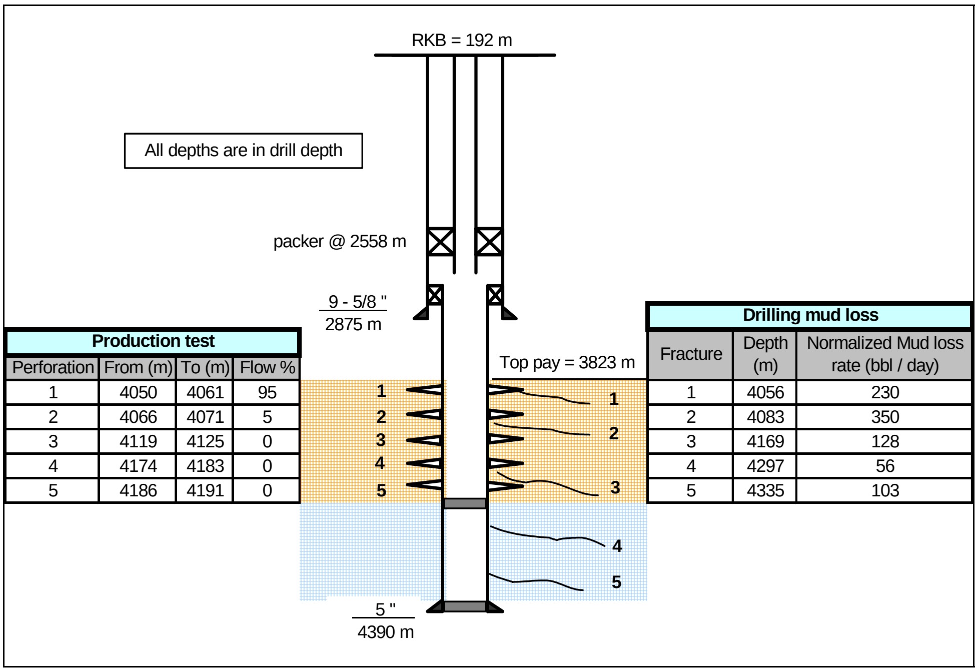


Figure 3- Mud loss type distribution in the DH field wells (reservoir section).



Production test

Perforation	From (m)	To (m)	Flow %
1	4050	4061	95
2	4066	4071	5
3	4119	4125	0
4	4174	4183	0
5	4186	4191	0

Drilling mud loss

Fracture	Depth (m)	Normalized Mud loss rate (bbl / day)
1	4056	230
2	4083	350
3	4169	128
4	4297	56
5	4335	103

Figure 4- Well sketch with perforation intervals and fracture depths.

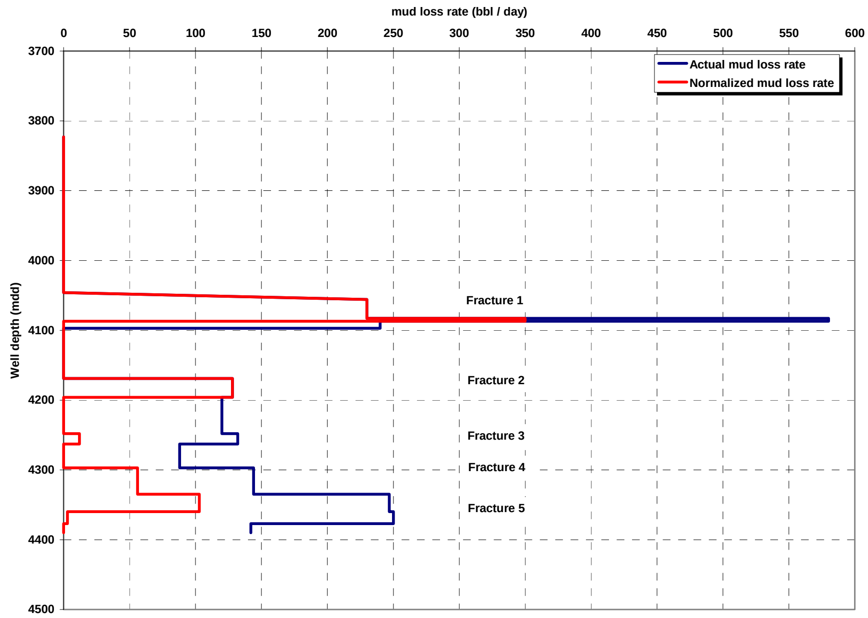


Figure 5- Drilling mud loss in the pay zone of well DH-5 (normalized and actual).

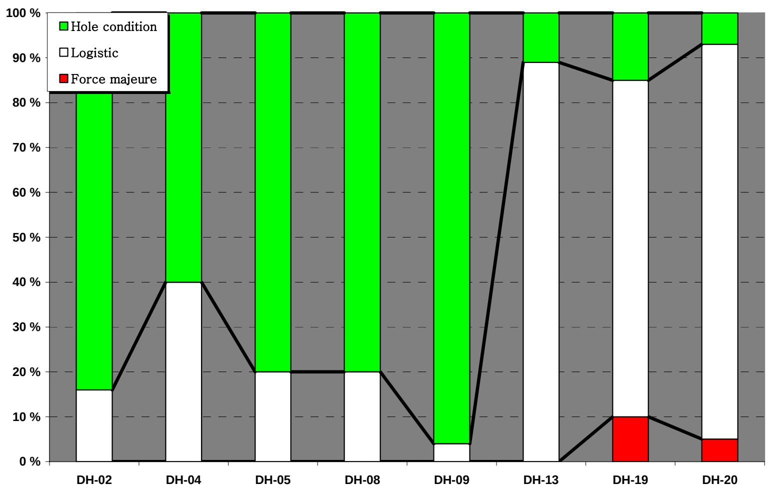


Figure 6- Analysis of root causes for drilling downtime.

Appendix D

SPE Poster

Maintained Well Integrity, Meeting the Urge for Extended Well Life Cycle and Changing Well Applications

J. Abdollahi, P. Randhol, and I.M. Carlsen, SPE, SINTEF Petroleum Research

Appendix D is a poster prepared and presented at the SPE 2006 Forum Series I and II in Dubrovnik on "*Low Cost Reservoir Access and Intervention*" and "*From Casing Design to Well Life Prediction*?" The poster summarises topics covered in different research projects at SINTEF and NTNU and is related to maintained well integrity for different operations and situations during a lifecycle of a well. The project work was done for Petroleum Safety Authority Norway (PTIL) and Statoil.

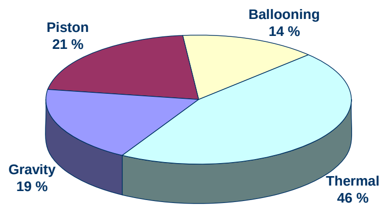
Maintained Well Integrity

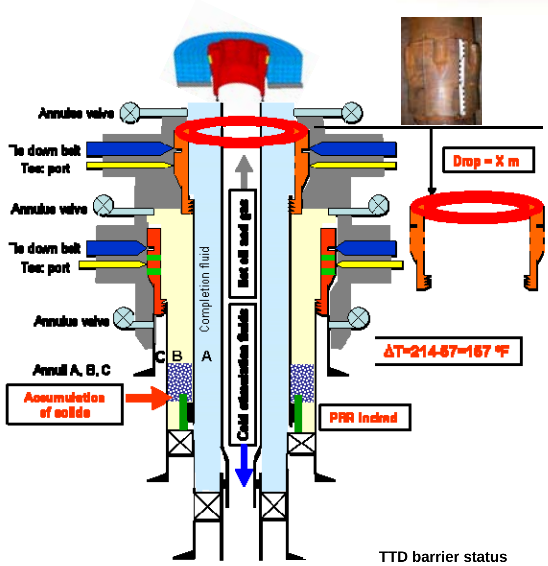
Meeting the Urge for Extended Well Life Cycle and Changing Well Applications

Jafar Abdollahi, Preben Randhol and Inge Manfred Carlsen,
SINTEF Petroleum Research, NO-7465 Trondheim, Norway

Well Stimulation Effects

❖Complex well tubular loads during well stimulation
- Completion design envelope
- Thermal effects of well fluids
- Hydraulic loads
- Well life cycle and effects on well completion components



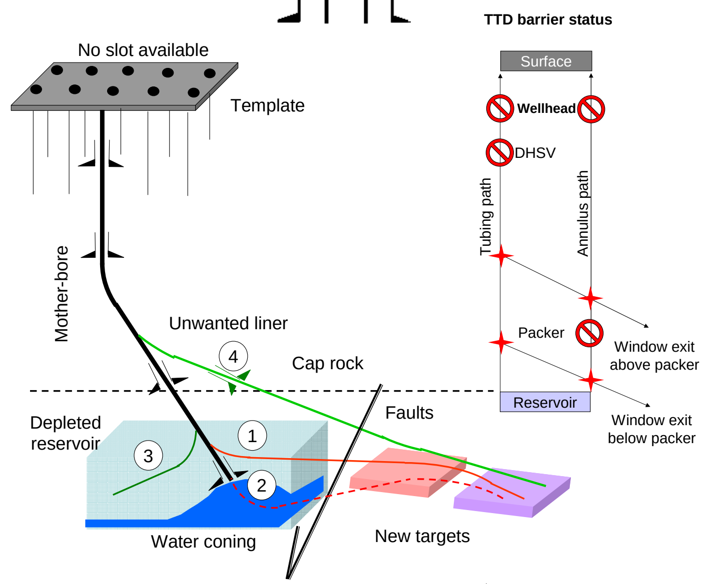


TTRD Challenges

❖Re-use of the well infrastructure
- Window exit scenarios
- Tubular and equipment wear
- Well barrier maintenance

❖Small size well construction
- Less contingency
- Avoiding completion telescope effects
- Pressure integrity in multiple reservoir targets

❖Subsea intervention
- Dynamic loads
- Bit and drill string performance
- ECD and surge and swab



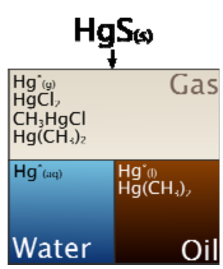
Impact of Well Chemistry

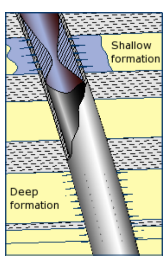
❖Scale
- Scale blocking safety valve ($BaSO_4$, $CaCO_3$)
- FeS_x corrosion-scale

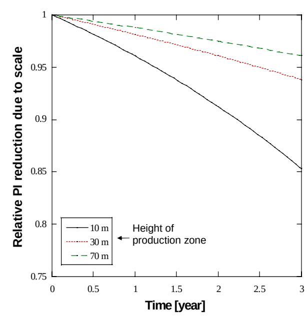
❖Scale treatments
- Acid stimulation
- Milling

❖Corrosion
- CO_2 in gas lift and CO_2/WAG injection
- Sulphide/SRB

❖Mercury
- Reacting with iron oxide corrosion products
- Amalgamates with metal surfaces

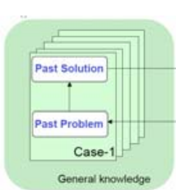


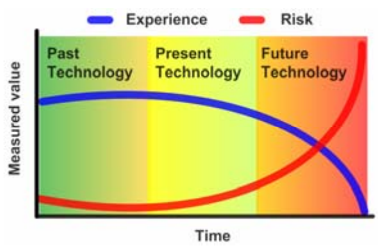




Case Based Reasoning (CBR)

❖Bridging the limited TTRD experience
- Using artificial intelligence for experience transfer
- Re-using of previous experience and knowledge base





Well integrity

The application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of the well.

(NORSOK standard)

$$\text{risk of unforeseen problems} \propto e^{-\text{experience}}$$

SINTEF

SPE FORUM SERIES: Forum I: Low Cost Reservoir Access and Interventions, Forum II: From Casing Design to Well Life Prediction?, Dubrovnik, 3 – 15 September 2006

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