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# Casing Failure Analysis for API N-80 Grade in Sudanese Thermal Oil Recovery Production Wells: Case Study

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**ABSTRACT-** Implementation of the Cyclic Steam Stimulation (CSS) and Steam Flooding as thermally Enhanced Oil Recovery (EOR) methods increase the commercial value of the existence Field through increasing oil recovery and field extension. When the steam is generated, processed and injected with high peak temperature into shallow wells (total depth of 700m) for oil recovery, it may result in high thermally induced stresses, which might exceed its design limit of the material and lead directly to the plastic deformation in the casing and thread connection. The objective of this paper is to premineraly investigate and analyze the reasons behind the casing failure in some well candidates at Fula North East (FNE) thermal oilfield based on the analytical analysis targeting the related structural and operational aspects of these applications. There are several casing failures have been reported; but so far no enough evident to correlate these failures to the mentioned stresses. Therefore, Ensuring adequate structural integrity and seal ability of the connections over the full service life of a thermal recovery well is a significant challenge. In this work, the Root Cause Analysis (RCA) on premineraly manner has been used through correlation of the problem to casing's grade and materials, cement formulation, sand production and steam injection parameters and thermal insulation process, by using step by step methodology. The results show that some supporting measures are recommended in order to minimize the casing damage and extend the life time of the thermal wells in FNE oil field. The above mentioned methodology has been used as the first time in Sudan to analyze casing failure in thermal oilfield.

***Keywords: Cyclic Stimulation, Stresses, Cementing, Steam injection, Sand Production***

***المستخلص– يؤدي تطبيق التنشيط بالبخار الدوري (CSS) والفيضانات البخارية كاحدى الطرق لاستخلاص الزيت المعزز بالحرارة (EOR) إلى زيادة القيمة التجارية للحقل المنتج من خلال زيادة استرداد النفط وامتداد الحقل وذلك عندما يتم توليد البخار ومعالجته وحقنه بدرجة حرارة عالية في الآبار الضحلة (العمق الكلي 700 متر) لاستعادة الزيت ، فقد يؤدي ذلك إلى ضغوط عالية مستحثة حرارياً ، والتي قد تتجاوز الحد التصميمى للمادة المصنع منها مواسير التغليف مما يؤدي مباشرة إلى التشوه اللدن في مواسير التغليف والاطراف الموصله لها. الهدف من هذه الورقة هو دراسة وتحليل الأسباب الكامنة وراء فشل الغلاف في بعض الآبار في حقل النفط الحراري شمال شرق الفوله (FNE) بناءً على الاسلوب التحليلي و الذي يستهدف الجوانب الهيكلية والتشغيلية ذات الصلة لهذه التطبيقات.هناك العديد من حالات الفشل في مواسير التغليف ولكن حتى الآن لا يوجد ما يكفي لربط هذه الإخفاقات بالضغوط المذكورة. لذلك ، فإن ضمان السلامة الهيكلية الكافية وقدرة العزل للاطراف الموصله على مدى عمر الخدمة الكامل لبئر الاسترداد الحراري يمثل تحديًا كبيرًا. في هذا العمل ، تم استخدام تحليل السبب الجذري (RCA) بالمبادئ الاوليه من خلال ربط المشكلة بنوعيه مواد مواسير التغليف ، صياغة الأسمنت ، إنتاج الرمال ومعايير حقن البخار وعملية العزل الحراري ، باستخدام منهجية خطوة بخطوة.تظهر النتائج بان هنالك بعض الإجراءات الداعمة التى يوصى باتخاذها من أجل تقليل الأضرارفى مواسير التغليف وتمديد فترة حياة الآبار الحرارية في حقل FNE.مع العلم بان هذه المنهجية المذكورة أعلاه يتم استخدامها لأول مرة في السودان لتحليل فشل مواسير التغليف في حقل النفط الحراري.***

## INTRODUCTION

Investigation about CSS thermal casing damage has shown that there are several domestic failure modes, including plastic deformation, wellbore blockage and restriction, leakage and packer stuck. In FNE thermal oil field there were several wells suspecting the casing damage and encountering high water cut in the designated wells drilled from 2014 up to date (more than 34 wells); the above mentioned problem has been detected during the Workover and well intervention operations when the bevel edge and the lead stamp have been run and they could not pass and subsequently the sand cleaning and well intervention could not be performed in a complete manner which is affecting the total output production of heavy crude oil from FNE oil field; but so far no such study has been carried out.

The Development of viscous oil in Sudan is considered as one of the important strategic goals of the country; as the heavy oil represents more than 50% of the country oil resources, therefore the suspected casing damage has a great effect in the total output production of heavy crude oil from FNE oil field which is directly affecting the economics of Sudan. Hence solving the above mentioned problem will positively enhance the oil production and economics indexes of the country.

In steam injection process, casing is heated by steam, the change of casing temperature produces thermal stresses in the casing, the casing deforms when stresses exceed the yield point of its material. Casing failure is becoming increasingly prominent in thermal recovery wells, which severely restricts the development effect of such reservoirs, improving casing life of thermal recovery well has become a urgent problem to be solved.

Steam injection has very specific conditions so the well undergoes high thermal stresses that if exceeded will increase the like hood of failure of the casing material during the cooling process. During this recovery method, the probability of casing damage is extremely high if the ideal conditions for the completion are not reached. This includes suitable materials, correct casing temperature and the right combination of cementing additives. Preventing casing damage is extremely crucial, not only because it would lead to decreased production and expensive repair jobs, but also because their failure can damage adjacent wells or lead blow outs [1].

The deformation of casing damage could be caused by many factors, and it is a comprehensive reflection of the of the whole process of production quality, including drilling, completion, gas injection and exploitation, and every aspect of the problem is likely to have a greater impact on the casing, therefore many on-site survey and analysis, reasons for casing damage have been done or are ongoing.

The geothermal energy development in East Africa presents the different Casing solutions and associated test protocol per down hole environment this approach of capitalizing from the oil and gas standards to satisfy the demanding requirements of geothermal industry illustrated by a case study [2].

Thermal expansion of casings in thermal wells and possible mitigation of resultant axial strain, discussed the possible solution to thermal expansion of casings in thermal wells and concluded that the casings are structurally constrained by cement and when the well reaches its working temperature, as a result of thermal expansion, stresses and strains reach beyond the yield strength in compression which in turn leads to plastic strain in the casings.

Possible solutions are limited to the axial direction of the well since bends are not an option. Casing segments are joined by threaded couplings and as the connections are designed for the oil industry, they must remain pressure tight. Currently connections are designed to have similar strength as the pipe body but have no means of reducing the axial strain that builds up with thermal expansion [3].

Excessive casing deformations leading to failure of steam stimulation wells have been documented in literature, the majority of these casing failures are noted to be the result of casing connection parting due to material failure in the stress concentration areas in casing connections. Some well failures occurred at the interface between the producing zone and the overlying shales and have been attributed to shear movement along what is assumed to be a very low friction boundary between the two formations. One theory to account for these failures is that the production-induced heat caused thermal expansion of the formations, resulting in a formation shear movement [4].

Some supporting measures have been proposed to improve the life time of the wells in in Shengli oilfield, China which has gotten better effect in recent years, the damage rate of thermal recovery well has decreased obviously and this can provide reference for the efficient development of similar reservoirs at home and abroad [5].

The deformation of casing damage could be caused by many factors, and it is a comprehensive reflection of the of the whole process of production quality, including drilling, completion, steam injection and exploitation, and every aspect of the problem is likely to have a greater impact on the casing [6], therefore many on-site survey and analysis, reasons for casing damage have been done or are ongoing.

The objectives of this paper are to analyze and review the suspected reason(s) caused the casing failure in FNE wells and in Sudan as well, considered using step by step methodology on an analytical approach including casing and cement design, completion design, steam injection aspects, and finally Proposed the supporting measures to minimize the casing failure and improve the life time of the wells which are implementing in both CCS and steam flooding.

## 1. Thermal Well Design

A CSS thermal well follows the same global design rules as Oil and Gas wells. All CSS Steam wells are vertical wells designed depending on the stress-based design as completed with thermal completion which are thermal well head and casing head of 3000 psi and 370°C working pressure and temperature respectively.

Surface casing is run and cemented firstly, then the production casing is run same just before the Vacuum insulated tubing (in which the fluid will be produced, which is one significant challenge in this application). In the bottom part of the well a thermal-metal sensitive packer is installed. These tubulars will be submitted to a range of loading cases, corrosion, and temperature cycles and much more during its life.

The key point is to do the right choices at each step (i.e size, material, connections, which will undoubtedly have an impact on well integrity) while keeping in mind the optimization of the total cost of the thermal well. Figure 1 is showing a typical CSS well schematic in FNE where we identify common sizes as 10 3/4'' for surface casing and 7'' for production casing (which is perforated to produce oil form Bentiu reservoir zone) then 4 1/2" Vacuum insulated tubing of (2.44'' Inner diameter, BTC) guided with the bell mouth and followed by the thermal-metal sensitive packer and attached with telescopic pipe are run as completion string.

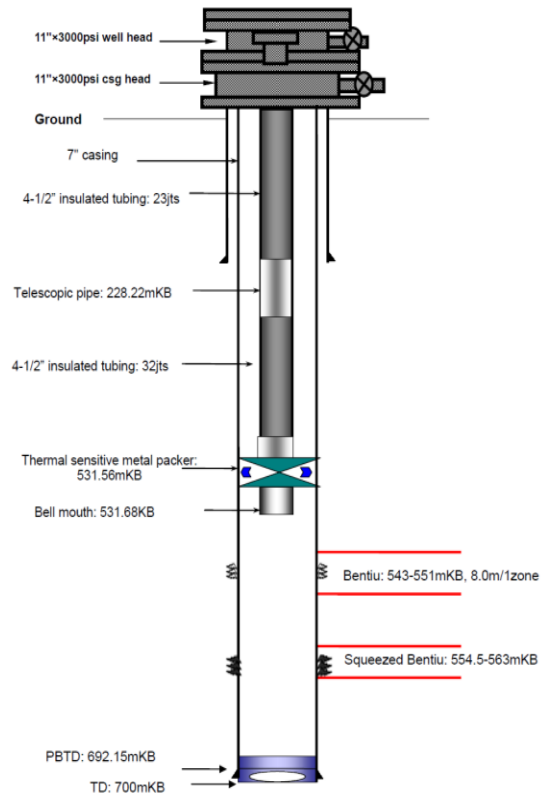


**Figure 1: Typical CSS well schematic in FNE**

### 1.1 Thermal Well Casing Design

Traditional methods for casing structural design use the stress-based design concept which limits the casing stress to the elastic state. However, in many design cases for thermal well casings, the magnitudes of casing strains resulting from thermal loading, casing buckling and formation movement exceed the elastic strain limit, making the conventional stress-based design method inappropriate for these applications [4].

#### 1.1.1 Stress-Based Design Considerations

It's shortcomings of method based on stress which are not considering the cumulative plastic strain caused by multi alternating stress as well as the problem of the higher thermal stress produced by the higher casing grade.

#### 1.1.2 Casing Material Selection

Thermal well designs typically utilize materials with favorable post-yield characteristics for intermediate and production casing strings. API grades such as K55 and N80 are the most commonly used grades in FNE thermal operations due to their ability to withstand increasing strain beyond the material yield point (i.e. they have a relatively high ratio of ultimate strength to yield strength).Higher-strength casing grades, such as P110, are sometimes considered with the intention of increasing the elastic load capacity of the casing material; however, the post-yield strain capacity is lower in these materials, which may decrease the material's ability to accommodate large plastic deformations associated with strain localizations. Higher-strength grades also tend to increase susceptibility to environmental effects such as hydrogen embrittlement or stress corrosion cracking. Given the elevated operating temperatures of thermal wells, the impact of temperature on the stress-strain response of the casing material must also be considered. Generally, a higher operating temperature results in reduced yield strength, reduced ultimate strength and an increased magnitude of stress relaxation[8].

#### 1.1.3 Connection Selection

Buttress Threaded and Coupled connection (BTC) type of connections is commonly used for FNE thermal well operation based on Thermal Well Casing Connection Evaluation Protocol (TWCCEP)/ ISO PAS 12835.

#### 1.1.4 Thermal Cement

The conventional class G oil well cement with silica sands cannot effectively meet the quality of oil well cementing and requirements of exploration and production as its poor resistance to high temperature. The procedure of cement is as follows:

Formula of slurry = thermal recovery cement +0.1~0.3% G603 (De-foamer), 1.85g/cm3 slurry returned to the surface and the shoe track integrity test is performed. Table VI and VII are showing the thermal cement formulation and property and the Cement stone Compressive Strength under high temperature respectively.

#### 1.1.5 Well-insulated Tubular

Research and theoretical studies have proved that the heat insulation pipe insulation directly affect the thermal stress of well casing.

The main factors that affect the insulating effect of the insulation tube are insulation performance of insulated pipe, the link sealing performance, and other process conditions. The first introduction of the Liaohe Oilfield is common insulated tubular, insulation performance is not very good. After development of vacuum insulated tubing, the insulation performance has been greatly improved [7]. Now similar insulated tubular has been used in FNE thermal oil field.

## 2. Methodology and Material Methodology

Step by step methodology has been used in this paper to premineraly analyzing the raised concerns in 700 m depth well candidates which is to review, analyze the wells reports then to review from the literature how the casing failure in the thermal wells being correlated to casing's grade and materials, cement bond failure, sand production and steam injection parameters and thermal insulation process as well as the influence of other operation through analytical approach then recommend some future supporting measures to minimize the casing damage and extend the life time per step basis [9].

## 3. Results and Discussion:

Several thermal wells had been stopped suspecting casing problem which are Casing deformation and blocked at 524.95m at the well FNE-X1, Tag restriction at depth of 450.88m at the well FNE-X2 and Packer stuck and cannot pull out of hole at the well FNE-X3. Accordingly the sand cleaning and well intervention could not be performed in a complete manner which is affecting the total output production of heavy crude oil from FNE oil field.

Hence solving the above mentioned problem will positively enhance the oil production and economics indexes of the country. Starting by analyzing the reason behind the occurred failure on step by step basis including but not limited to the followings; material integrity, thermal cement formulation and operation, steam injection parameters, sand flow in the wellbore and The influence of other operation:

### A. Material and structural integrity:

Considering Fula North East CSS well completion design with 287 ℃ as the average temperature of steam and sometimes even more than 300 ℃, the temperature cycles impose cyclic compressive casing stress during heating and tensile stress during cooling. When "ultra-high temperature" is used (for example, peak temperatures over 300°C, depending on casing grade), the casing can potentially yield under tensile stress during cool-down, leading to possible failure modes of low cycle material fatigue, connection leakage and connection parting.

Therefore the minimum Pressure limit for API N80 casing is 552Mpa is under 220℃, while under 300 ℃ the maximized stress of N80 casing will get to 700Mpa, when the temperature goes beyond the maximum limit, is highly suspecting N80 casing to deform. Figure 3 shows the design limits of pressure and temperature (Minimum vs. Maximum).

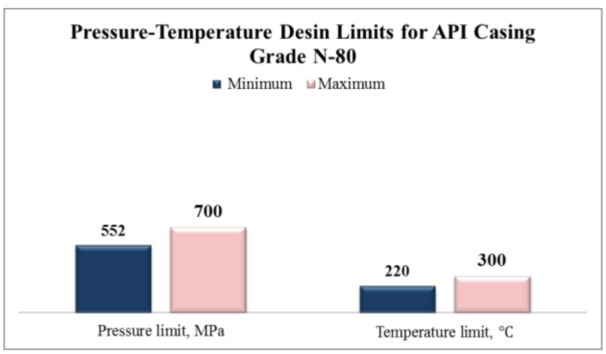


**Figure 2: Pressure-Temperature Limits (Min vs. Max)**

### B. Thermal cement formula and its operation:

The main suspected reasons behind the casing failure related to thermal cement and its operation in FNE field are including but not limited to using less optimized thermal cement materials and additives, Un applying the pre-Stress Cementing Technology, Un satisfied Cement stone expansion rate (Even the cement formula has been improved) cement stone expansion rate is far less than casing (API Grade N-80 casing Thermal expansion rate 25.45×10-6/℃), Existence of sand production, Anticipating of water channeling and Suspecting the malfunction of the thermal heat stress cement compensator and down ground anchor.

The current technology specification and standard for thermal well (released by China Petroleum Cooperation-CNPC, Articles; 26, 27 and 142 in May, 2009) as follows:

**TABLE I: THERMAL CEMENT SPECIFICATIONS REQUIRED VS. ACTUAL**

| No | Item | CNPC | Petro-Energy |
|---|---|---|---|
| 1 | Cement Slurry API Fluid Loss, ≤ ml | 50 | 42 |
| 2 | Minimum Cement Stone 24h-48h Compression Strength, ≥ MPa | 14 | 19 |
| 3 | Minimum Proportion of Silica and Class G Cement, % | 40 | 54 |
| 4 | Cement Stone Compression Strength, ≥ MPa | 14 | 18 |

From Table I and Figure 3 the thermal cement specifications have been analyzed and found that all specifications designed by Petro Energy are matching with that required by CNPC standard and even more.

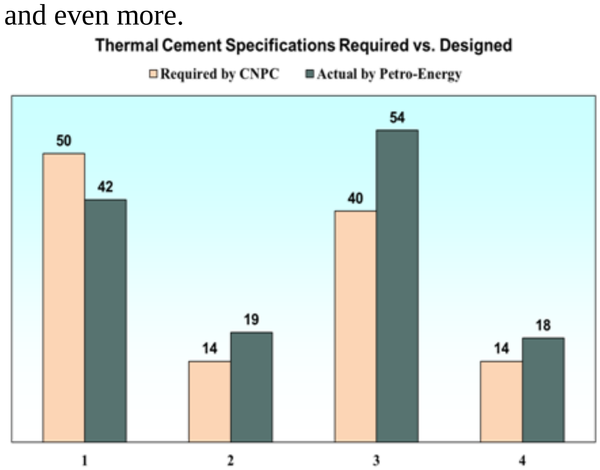


**Figure 3: Thermal Cement Specification**

Figure 4 is showing Thermal Expansion Rate Casing vs. Cement. On the left is the value concerning casing shown in 10×6/℃, on the right is for cement. As shown the expansion rate achieved by cement is much less than that designed for casing, Thermal expansion of casings is one of the major structural concerns for high temperature thermal wells.

Unlike casings in the well, pipes on the surface are designed with bends that are included for mitigating thermal expansion. Casings in thermal wells on the other hand are straight steel pipes that reach 700m length in typical high temperature wells and wellbore temperature changes of 200-350°C are common.

The casings are structurally constrained by cement and when the well reaches its working temperature, as a result of thermal expansion, stresses and strains reach beyond the yield strength in compression which in turn leads to plastic strain in the casings. In order to utilize superheated and even supercritical steam injected in the well, need to continue looking for satisfied cement stone expansion rate.

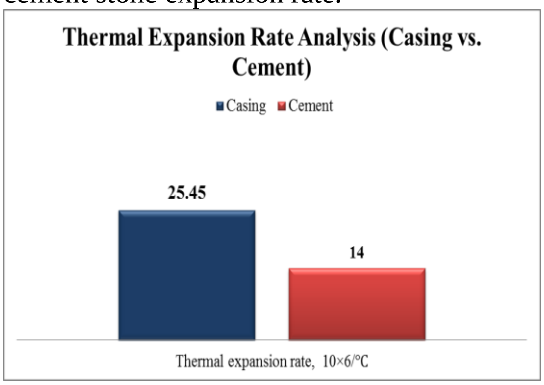


**Figure 4: Thermal Expansion Rate Analysis**

Figure 5 is describing Compressive Strength vs. Temperature in different conditions; 280, 320 and 350 ℃ at same pressure of 21 MPa and duration of 28 days, the above graph is showing how the compressive strength of API Casing Grade N-80 is decreasing (i.e. 25, 22.4 and 18.1 MPa) under the increase of the correspondence working temperature respectively.

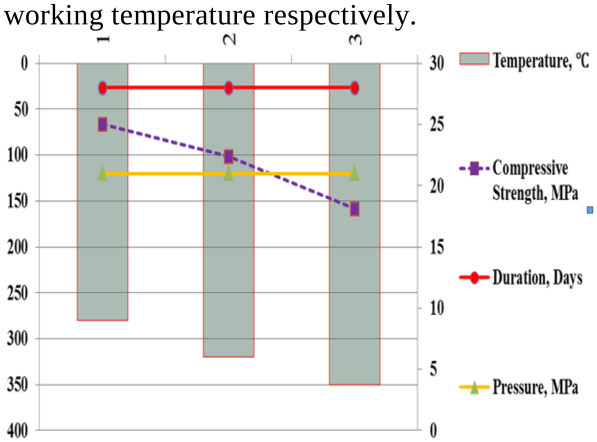


**Figure 5: Compressive Strength vs. Temperature**

**C. Parameters of steam injection and its relation:**

In FNE steam injection process, casing is heated by steam; the change of casing temperature produces thermal stresses in the casing, which it might cause a plastic deformation when stresses exceed the yield point of its material. Casing failure is becoming increasingly prominent in thermal recovery wells, which severely restricts the development effect of such reservoirs, improving casing life of thermal recovery well has become a urgent problem to be solved.

The average steam injection temperature of 278 degree C, the steam injection pressure of 5~7MPa, steam injection quality of 0.6, steam injection rate of 1.6m3/d/ha/m, and 1.2 as the recovery ratio.

During steam injection periods, the temperature increases along the wellbore from as low as initial reservoir values of 10 to 25°C to peak temperatures of 330 to 350°C for CSS wells. Assuming that the cement and formation provide sufficient axial constraint to axial movement, the temperature-induced thermal expansion of casing material will introduce significant axial compressive loading to the casing string. In the late part of a thermal cycle or during well servicing, when temperature decreases from the production peak value, the axial compressive force in casings may reverse to tensile force if the temperature drops sufficiently.

Steam injection has very specific conditions so the well undergoes high thermal stresses that if exceeded will increase the like hood of failure of the casing material during the cooling process. During this recovery method, the probability of casing damage is extremely high if the ideal conditions for the completion are not reached. This includes suitable materials, correct casing temperature and the right combination of cementing additives.

**D. Sand Production:**

General Investigation indicates that Sand production in oil layer lead to casing damage i.e. The hydrocarbon reservoir of FNE Oilfield is concentrated in Bentiu and Aradeiba formation, strata formation is composed of weakly consolidated loose Sandstone and shale, its strata has easily lost and vulnerable to collapse.

With long-term intensive production, sand hollow is formed in the oil layer after mass sand produced, overlying strata lost support and vertical deformations, causes collapse of overlying rocks. When collapsed to a certain extent, the gravity born by the reservoir before transferred to the fluid in the hollow partially and the other part transferred to the casing. When the transferred pressure exceeds the ultimate strength of the casing, caused casing failure, deformation, and in serious cases, caused the casing breaks.

FNE have serious sand production due to viscous oil reservoir, weak formation cementation and steam injection for hot extraction, thus sand production is more serious. The sand production affects the normal production of oil and accelerates the casing damage as follows:

- The compressive stress distribution at casing cross section is not uniform, and the compressive stress on the outside of casing wall is the maximum. Usually, at the place of local compression force concentrated, the casing will be destroyed when the compressive force exceed yield strength.
- The hollow will be formed outside of the cement circle. When oil temperature exceed 300 °C, the compress on the inner of the casing exceed the Thermo-elastic yield strength, the compress will be transferred on the outside of the cement circle, and one the compress on the cement circle caused by the casing deformation exceeds the limit of cement circle, the cement circle will be damaged. Local damaged cement circle loses the bundle on the casing, and the casing deformation will occur under thermal stress, the deformation form depending on the degree of loss of cement bound. The hollow part formed by sand production is the main site of stress fatigue and deformation damage of the casing.

### E. The influence of other operation:

The deformation of casing damage could be caused by many factors, and it is a comprehensive reflection of the of the whole process of production quality, including drilling, completion and gas injection, every aspect of the problem is likely to have a greater impact on the casing.

In later development stage, if operations occurred, such as milling and grinding, fishing, drilling and grinding of cement plug and so on, a long time frequent oscillation and cutting sleeve of inner wall in certain section.

The above mentioned operations will lead to the strength of the casing decreased and poor concentrate quality of cement circle then the local stress of casing will be out of balance which causes casing deformation.

From the well intervention observation or while completion phase it has been noticed that a negative impact will be induced due the nature of the designated activities and its relation to life time of thermal well as well as the structural design and used materials.

## 4. CONCLUSIONS

Based on the above analysis, the deformation of casing damage could be caused by many factors, and it is a comprehensive reflection of the of the whole process of production quality, including drilling, completion, steam injection and exploitation, and every aspect of the problem is likely to have a greater impact on the casing, Accordingly the following remarks need to be considered:

- In FNE Oil field, the average temperature of steam is about 287 °C, sometimes even more than 300 °C, so it is obvious that the current stress-based casing design with N-80 grade used in thermal wells is easy to be damaged, therefore is highly recommended to develop a sound basis for a plastic strain-based design of thermal well casings with considering the required structural integrity as well as casing connection seal ability.
  - Future research on cementation procedures and cement formulation under high temperature and pressure is required to adopt cement systems with tailored thermal and mechanical properties up to a temperature of at least 300- 350° C beyond the maximum steam injection temperature of the field. This new cement system will reduce the risk of cement sheath failure and unnecessary steam migration and provides a long-term well integrity solution.
  - To ensure conducting cement job operation under tension meanwhile to confirm the integrity of the thermal stress compensator and down hole ground anchor.
  - Optimizing parameters of steam injection, Adopting High-Performance Insulation Tubing (Different insulation measures have great effect upon casing stress, and high-performance

insulation pipe can significantly decreases equivalent stress on casing wall), Using of double packer and proper adjustment of its setting depth and Ensuring injecting high quality steam.

- To study the casing damage due to geochemical attack and its associated problems (i.e. casing-cement-formation interaction) meanwhile to take measures to control the sand production as well as to optimize the casing-cement-formations interface in order to minimize geochemical attack and its associated problems.
- To continue practicing work-permit based on the pre-job safety analysis (PSA) and pre-job hazard analysis (PHA) as well as pre-job risk analysis (PRA) prior conducting other related operations to reduce its influence of casing deformation in FNE thermal wells.

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