Giornata di studio su:

FAILURE ANALYSIS NELLA PRODUZIONE E TRASPORTO IDROCARBURI
S. Donato Milanese - 3 Dicembre 1966

NICKEL ALLOY STUD BOLTS FAILURE : A CASE HISTORY[1]

P.Fassina, M. Marangoni and G.Toffolo
AGIP SpA, Milan, Italy

ABSTRACT

High strength and corrosion resistance material as Inconel X-750 has been selected for the seal flange bolts in an off-shore field Libya, due to its properties at high temperature, needed for compliance with "Fire Safe" requirements. After 4 years from the production start-up, during a routinely maintenance of wellheads, some bolts have been found cracked. The paper deals with all the activities done in order to understand the cause of the failure. In particular failure analysis has been carried out through laboratory investigation, and shop tests have been conducted to confirm the field procedure and determine the tension on the bolts during the installation. The main conclusion was that the bolts failed due to the concurrence of stress (over-torque that means stress level higher than yield one) and corrosion (pit/crevice conditions). This environmentally assisted failure is known as Hydrogen Embrittlement (HE). Test carried out using the same X-mas tree mounted on the platform justifies the assumption that in the field, where the conditions are far from the ideal, it is possible that even when a uniform torque is set, the tensile stress applied to the bolts is not uniform, making the situation critical. From the corrosion side, the failed bolts showed some corrosion points near the cracks, as due to environment in the crevice/pitting conditions required to justify the hydrogen presence (the bolts are not chatodically protected). Fatigue has been demonstrated not responsible to the failure. Emphasis is devoted also to recommend solutions which can safely be adopted during the installation and the substitution of bolts on an existing wellhead, which is operative under pressure without shutting in the well, not impairing the safety operating envelope.

[1] Based on a presentation to the 15th International Conference on Offshore Mechanics and Arctic Engineering, Firenze, Italy, 1996, June 16-20

SUMMARY

This paper discusses a problem occurred in Bouri Field, Offshore Libya on February 1993. During a routinely maintenance of one wellhead, two bolts on the 13" 5/8, 5000 psi flange connecting the wellhead and the tubing spool (Fig. 1) were found failed. The flange has 16 Inconel X-750 bolts size 1 5/8". After a check on all the wellheads, three other bolts were found failed on another X-mas tree : one was in the same position of the previous failed bolts, while the others were between kill line and flow line connection, on the same side. The total number of failed bolts was 5. The failure incidence is 0.6%, and it occurred in only two wells (3.6 %). The wells where failures occurred were completed between 1989 and 1990.

Since this kind of bolt was installed on almost all X-Mas trees, there was a concern that the problem could involve many more wells. So it was mandatory to understand how many wells were interested in the problem and to find a solution as soon as possible.

With this paper we would like to describe all the actions taken to face the emergency, understand the problem and find a solution in order to avoid similar accidents in the future. We believe also that an understanding of the causes could be of general interest since it will point out how some actions or choices, even if taken according to recommended rules, could set together and lead to dangerous and costly situations.

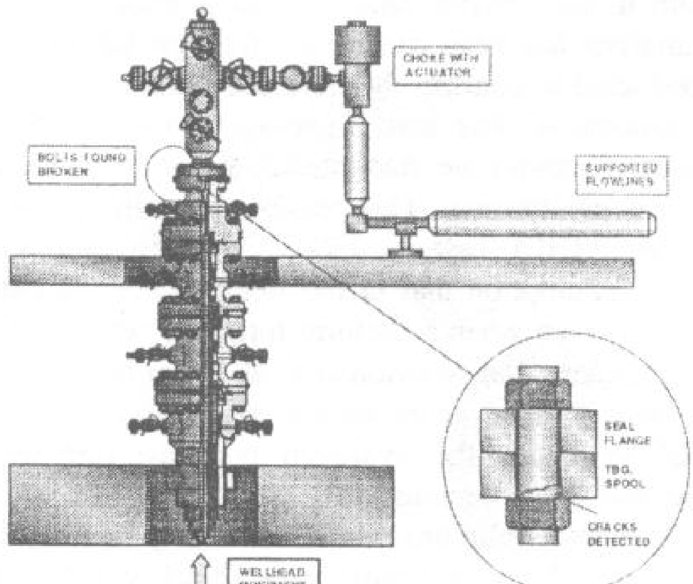


Fig. 1 - Wellhead and flowline scheme

INTRODUCTION

Bouri field is located in the Mediterranean sea, offshore Libya, and has two platforms with 55 wells. The first well was completed on 4/6/88 and the last one on 13/6/92.

The bolts in 13" 5/8, 5000 psi flange are 16 for each well: this means 880 bolts in the field. The 98 % of them are in Inconel X-750 material.

Original requirement for Inconel X-750 bolts was due to the need, at the time of Bouri design, to comply with "Fire Safe" requirements and with NACE MR 01-75 requirements. "Fire Safe" concept was a new concept still developing at the time; in particular Norwegian NPD regulations were just issued. Nevertheless since they were too restrictive in terms of configuration (huge forging blocks and enclosed protections) the particular compromise to use such alloy for the seal flange bolts was adopted together with the Fire Safe (API 6F RP improved) requirements for the valve blocks.

PRELIMINARY ACTIONS

Since in the same flange more then one bolt was found broken, that could mean that after the failure of the first one the increased stress on the others might lead to a quick failure on the whole flange, corrective actions have been started immediately, a troubleshooting team was organised and different studies were initiated.

The first action was to collect all available information about the general situation of the wells: completion reports and schemes, flow data, surface equipment and flowlines data, general inspection data and so on. A new inspection schedule was prepared in order to monitor constantly all the wellhead bolts and a procedure put in place to test the safety valves system more frequently to guarantee its function in case of an extended bolts failure. In this way it was possible to keep on producing with several studies in progress. It took few weeks to have a first idea about the problem, but completing the studies took almost 9 months .

The second action was to understand how many other wells were in a critical situation. To get this information two measurements were done on all bolts (880): an accurate length measurement and a UT check. The first gave a rough idea about the possibility that other bolts could have reached an elongation such to show a permanent deformation i.e. showing to be above the yield point. The second to check for possible cracks inside the bolts. 16 bolts (2% of the total) were suspected to be above the yield point on seven different wells, while UT check gave a blind or not clear response on 68 bolts (8%) on 26 different wells. This results gave a first picture of the situation. The most dangerous indication was the first one, so the first bolts to be changed were the stressed ones. Following a Lloyds request for continuous monitoring of in field installed bolts on a periodical basis (one month) to check for growing cracks, a contingency procedure was also issued. The procedure was intended as provisional waiting for final investigation results and was not meant to be exhaustive since it was confirming that several bolts, pertaining to different suppliers gave a blind response to UTS.

In parallel it was decided to proceed with:

- mechanical problems evaluation
- mechanical test
- failure analysis

MECHANICAL PROBLEMS EVALUATION

Several investigations were carried out to identify the possible cause. Several discussions have been held with the workover supervisors on board during the development completion and different installation procedures were discussed. The most important indications collected through this investigation and the problem evaluation results can be summarised as follows:

1. From a field report it was found that problems were experienced while nippling up the X-Mas trees since the crush metal seal rings were substituted with higher tolerances ones to achieve a good seal and higher torque was applied to the bolts.
   At this regard, the relevant rig report says:

   " Manufacturer suggested to tighten the bolts with 2,146 ftxlbs. make-up torque, but there were serious problems with the metal seals on neck tubing hanger and transfer carriers did not seal. So we had to increase the make up torque up to 2,400 ftxlbs. to have both the X-mas tree's flange and tubing spool mated and to energise more the metal seal. The maximum tension on the bolts remains within the limits according to the torque / tension table given by the manufacturer".

   It is clear that supervisor was sure that all operation were done within recommended limits.

2. A continuous movement between wellhead and platform was observed during production, mainly due to the waves. After the conclusion of the metallographic analysis that did not observe a typical fatigue failure on the broken bolts, fatigue was not taken into account. So the stress caused on the flange through the flowline was considered only as a static action to be added to other static forces. For the same reason, all actions caused by vibration did not have further investigations.

3. A relative movement between wellhead and platform was observed during the start up of the production, mainly due to the thermal elongation of the casing.
   Another report says:

" During oil production, the X-Mas tree goes up about 15 centimetres and the flowline does not remain on the support".

4. The choke connected to the wing valve is very heavy. The bending moment on the flange is small, but adds to the other static and dynamic forces on the bolts.
5. From the mechanical tests done at a later stage Breda Fucine it has been shown that even if applying the same torque the actual tension inside the bolts can be very different. This caused some bolts to reach the yield point sooner then the others. The problem will be explained better in the next paragraph.

The bending moment generated by the actions described in 1, 2, 3 and 4 caused an extra tension on those bolts located on the opposite side with respect to the flowline. This justifies the fact that almost all broken bolts were found in that sector.

MECHANICAL TESTS

A mechanical test was performed at Breda Fucine on a X-Mas tree similar to the one on Bouri to verify the correct torque needed for a perfect matching of the flanges and the metal seals, using the same torque wrench used in the field. With a first test the minimum torque on the bolts to energise the metal seal and get the proper matching of the flanges has been determined.

A second test was performed in order to verify the transmission of the torque to the bolts, in respect to their different positions taking into account their lubrication.

A third test was performed to simulate the procedure established for the replacement of some bolts from a flange while monitoring the increased stress on the others.

The fourth and last test was performed to evaluate a tensioning system, a possible alternative solution for a more even distribution of the stresses between the different bolts of the same flange.

Determination of the torque required for a correct matching of the flange and the metal seal

Using the same wellhead and the same tools used on Bouri Field a flange has been closed applying 37 steps of torque; each steps corresponding to a decrement of 0.05 mm of the clearance between the two flanges. The test showed clearly that the metal seal was energized correctly before the flanges matched. The torque corresponding to the mating of the flanges was about 300 kgxm.

While applying the torque the length of the bolts was measured and it was noticed that the tensions induced on the 16 bolts during setting operation were different due to the different friction of each nut-flange mating and nut-bolt coupling. Since the difference was remarkable and the measurements were taken on four bolts only, a second test was carried out to investigate better the problem.

Determination of the Actual Tension on the Bolts

The hydraulic tong used to nipple up the bolts was the same used in the previous tests. The final torque of 400 kgxm was applied with two intermediate steps at 150 and 300 kgxm. Reason to perform a load test at 400 kgxm was to simulate overstressing of bolts due to (suspected) wrong calibration of the field used torque wrenches. To understand the influence of the lubrication, 8 over the 16 bolts were nippled up without grease. Tensions on the bolts have been evaluated measuring their microstrain while applying the torque.

Results have been presented by radar-type diagrams for a better understanding of the bolts behavior according to their position. (Fig. 2). For every bolt the diagram shows the measured elongation at the three different steps and the reference value obtained from API (API RP 6A correlation), supposing an ideal make-up between bolts and nuts. In Fig. 2 it is possible to see the comparison between the elongation corresponding to the theoretical tension (due to torque applied) and the actual one at steps 1, 2 and 3. It is easy to see that for all three steps the maximum tension was almost matching the API reference, while instead the average was always well below that value. It was 39 % below in the first and the second step and 16% smaller in the third step, indicating a large dispersion of tension values among bolts. The more uniform elongation value reached in the third step can be explained with the fact that friction between nuts and the flange surface affects less the individual bolt make-up, since the elevated specific load flattens localized imperfections (a smaller value of about 20% has been observed also during a second nippling up done the following day at 400 kgxm with all bolts correctly greased).

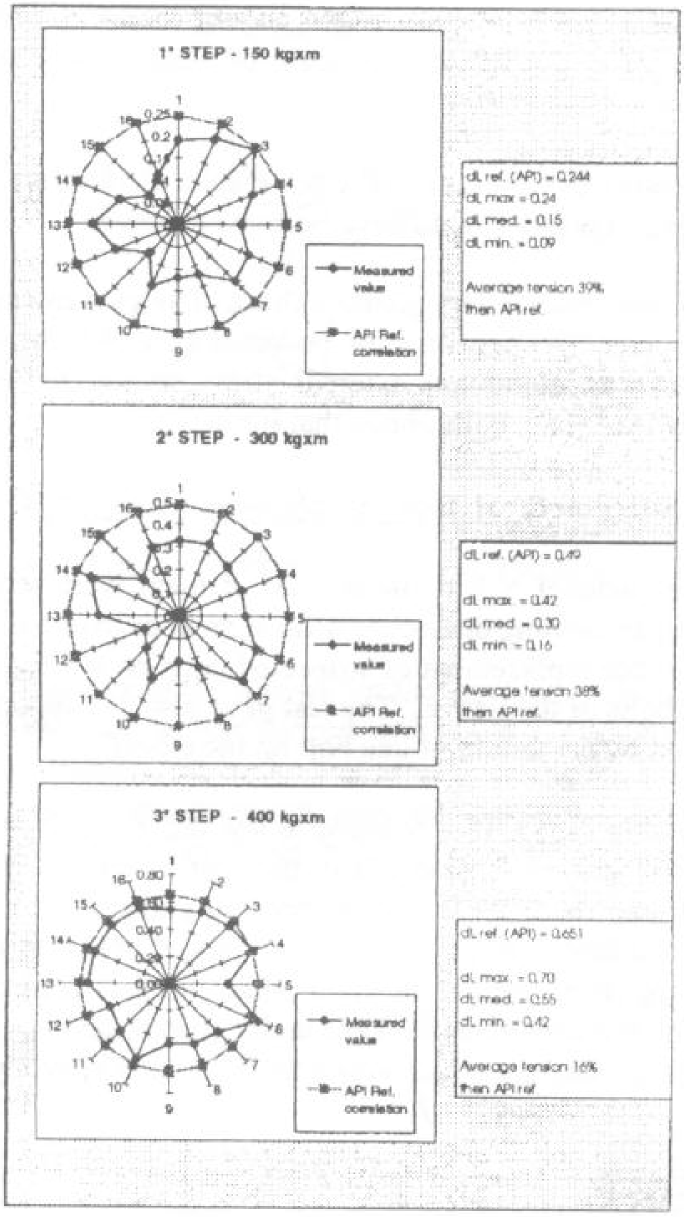


Fig. 2 - Determination of the actual tension on the bolts

The influence of the lubrication is important. The average tension on the bolts made up with the grease was about 10 % higher than the others.

It is important to highlight that 300 kgxm (2146 ftxlbs) is the API recommended torque to energize the flange and all the metal seals involved.

From a field report instead the following is reported:

"A production wellhead has been nippled up applying an initial uniform torque of 2100 ftxlbs, subsequently raised at 2400 ftxlbs (because of metal seal leakage), and sometime raised up to 2700 ftxlbs."

It is evident from above extra-torque and from results of third step of simulation done (Fig. 2) that in some cases few bolts could have been overstressed.

For what concerns the distribution of the values, it is evident in all steps a tension difference over the 16 bolts. The phenomenon becomes critical if the tensions are near the yield value. In that case an additional external stress caused for example by flowline movement, could easily lead some bolts above that limit.

Replacement Test (Replacement of four X-750 bolts with four B7 Steel bolts)

After tightening 16 Inconel X-750 bolts, four of them were replaced separately and loaded by means of four tensioning devices to a value smaller than before. This was done in order to simulate a possible replacement of suspected bolts on a wellhead and calculate the influence on the other bolts of the flange. The test gave also the opportunity to evaluate the increase of stress caused by the failure of one bolt on the others.

Results are reported in Fig. 3. It is possible to see that the tension over the other bolts has increased due to the smaller tension left in the four new ones. This must be properly evaluated before removing the bolts for a replacement, particularly if the unchanged bolts are already near the yield limit. Only if the tension induced in the new one is similar to the others or all of them are clearly below the yield point, this fact is negligible, otherwise the tension over the unchanged ones must be kept under control and, if necessary, in some of them the tension must be decreased according to the others (paying attention not to de-energize the flange).

Test of Tensioning System

The fourth test was carried out to evaluate the performance of the hydraulic tensioning device and the possible applications in the field, particularly for Bouri wellheads (Fig. 4). The elongation has been measured by means of a micrometer comparator. Pressure steps of 100 bars have been applied up to 1000 bar final pressure (yield limit was reached at about 900 bar) and for each step the length of the bolt was measured before and after releasing the pressure.

The system works with extended bolts, and consists of a hydraulic jack which grabs and lifts the extended bolts above its nuts reacting with the flange surface. Exerting the correct hydraulic pressure which corresponds to 50% of yield (according to API), and then mating the nut to the flange surface manually, allows for an even energization of the flange itself.

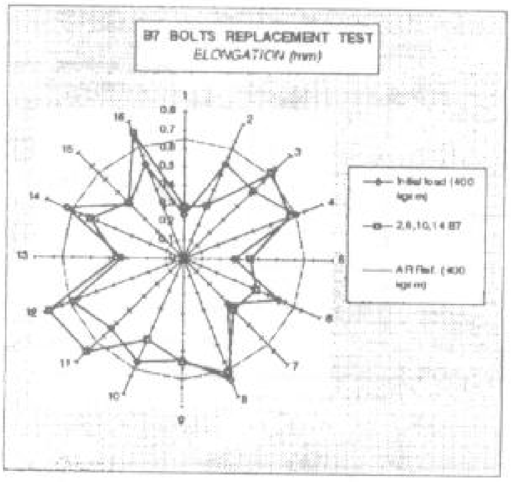


Fig. 3 - Bolts replacement test results

To evaluate the importance of the manual torque applied to tighten the nut, two series of test have been carried out, one closing the nut with about 1,5 kgxm and one with about 10 kgxm. As expected, the tension left in the bolt after releasing the pressure was about 30% less than the maximum value reached during pressure application; this is due to the fact that, being the bolt longer, an extra tension needs to be supplied to obtain the same net elongation of a conventional bolt.

Fig.4 - Hydraulic tensioning device

Results are reported on Fig. 5. This ratio suggested by the tensioner supplier was confirmed by the test. This is an average of several values obtained during the test, taking into account the last part of the graph, after ring joint plastic deformation (400 bar). Finally it can be said that the different manual torque applied lead to a negligible difference in the final result.

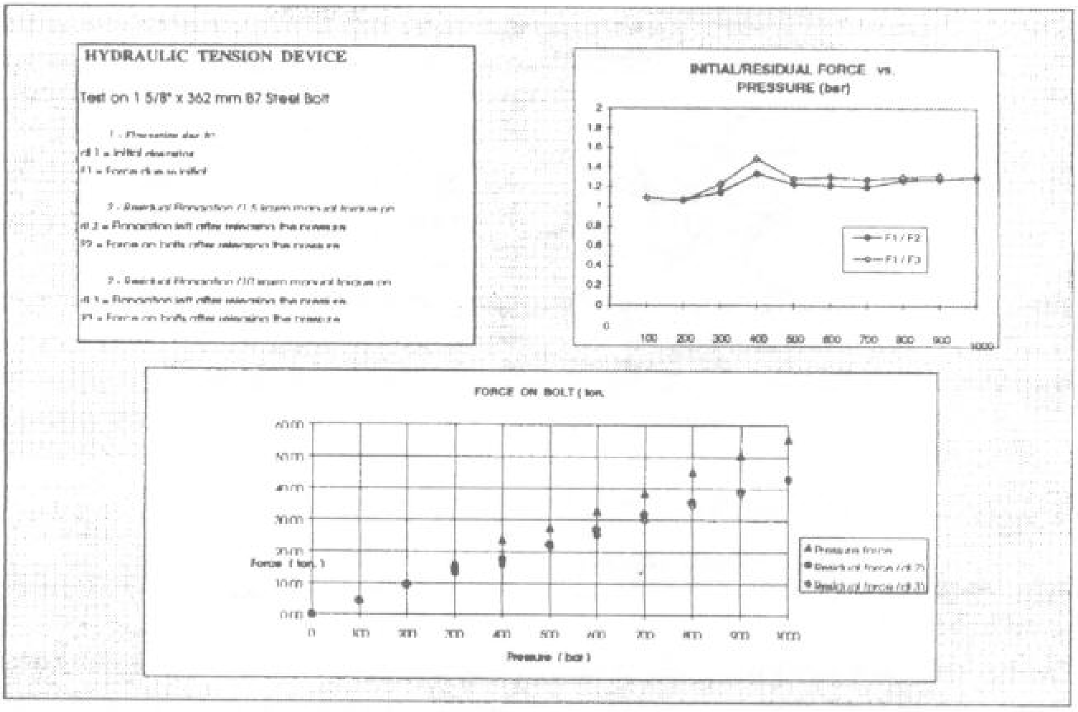


Fig. 5 - Test results on tensioning system

FAILURE ANALYSIS

An experimental work has been carried out on the failed bolts in order to :

1. Verify the material correspondence to the specification requirements (chemical analysis, mechanical tests, hardness, microstructure)
2. Inquire the failure cause (fracture surface examination by optical and electronic microscope, assisted by ESCA, dimensional control)
3. Support the failure mechanism (fatigue, corrosion assisted by constant load and SSRT).

The main conclusions are here below summarized.

Material assessment

The material of the bolts satisfy the specification requirements (ASTM B637, material NO7750, type I) from chemical and mechanical points of view; also the additional hardness requirement of NACE MR 01-75 specification (35 HRC) is achieved (Table 1).

The microstructure shows a typical austenitic alloy in final condition (solution treated + stabilized + precipitation hardened), as stated in aforementioned specification.

	σ_y (MPa)	σ_R (MPa)	Elong. (%)	Area R (Z %)	HB_{min}	HRC_{max}
bolt	683	1081	11	9	298	35 *
ASTM B637	620	965	> 8	--	262	31-35

*NACE MR0175

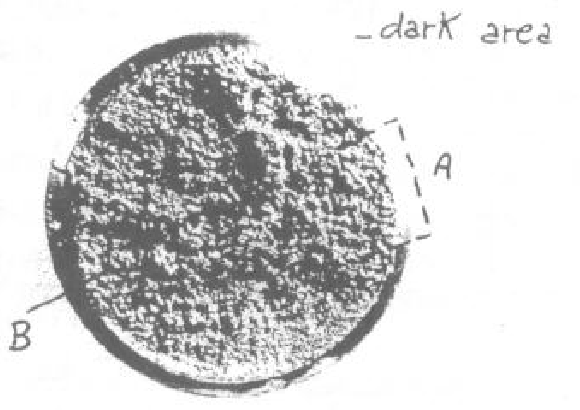
Tab. 1 - Mechanical characteristics

Failure analysis

The fracture is intergranular with no area reduction (brittle fracture). In a bolt there is a secondary crack in the thread, intergranular too, in correspondence of some corrosion points (Fig. 6). No secondary branches are present in the other examined failures.

There is some contamination (S, Cl, Zn) in the zone of crack initiation and (S, Pb, Fe, and Al) in the localized corrosion points. This is mainly due to the sea water and grease in contact with threads.

Sound bolts, removed from the same wells where the failures occurred, have been loaded to an higher value than the yield stress: this is evident from the dimensional control of the length (+0.4%), the pitch (0.22% more in the central zone than where there is the nut) and from the slip lines in the structure.



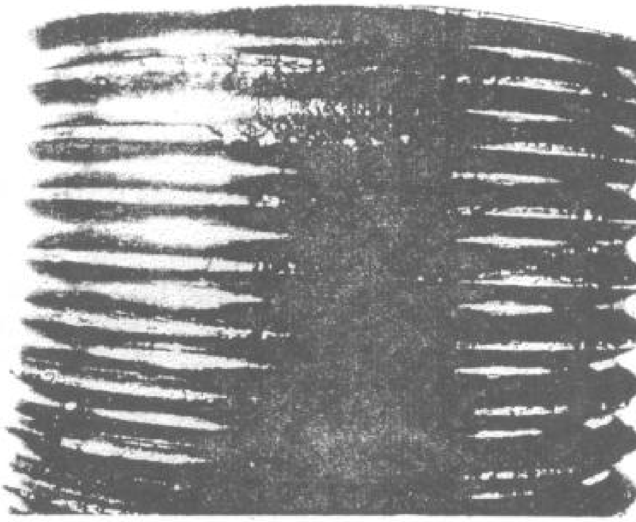


Fig. 6 - Failed bolts

Failure mechanism

The failure analysis brings to the conclusion that the main cause of the failure was the hydrogen embrittlement (HE), where the corrosion is due to the environment in pit / crevice situation and the stress comes from the loading of the bolt at higher stress than the yield one. This conclusion has been verified by some additional tests: fatigue and corrosion test assisted by stress (Tabs. 2 - 3). To produce the hydrogen needed to the hydrogen embrittlement, some tests have been carried out under cathodic protection (CP).

ENVIRONMENT	APPLIED STRESS	CYCLE	FREQ.
air	$60 \pm 20\% \sigma_y$	244000	29
	$50 \pm 15\% \sigma_y$	468000	30
sea water	$50 \pm 15\% \sigma_y$	353000	2
sea water + CP	$50 \pm 15\% \sigma_y$	1400000	2

all samples from in service bolts

Tab. 2 - Fatigue test

Fatigue was not the main cause of the failure: as a matter of fact, the fracture morphology in the fatigue samples for each environments tested (air, sea water and sea water with CP) is transgranular, instead of intergranular, as found in the failed bolts.

TEST	ENVIRONMENT	APPL. STRESS	FAILURE TIME
16 h CP+SSR	sea water + C.P.	106 σ_y	10 h (■)
		116 σ_y	7 h (■)
		76 σ_y	5.5 h ( )
Constant load	c.s. ring + sea water + $FeCl_3$	132 σ_y	no failure (732 h) (■)
	sea water (3d)+CP	116 σ_y	4 h (■)
	sea water + N_2 + c.s. ring coated	100 σ_y	no failure (732 h) ( )
	sea water + CP	100 σ_y	8.5 h (■)
		80 σ_y	no failure (761 h) (■)

(■) samples from new bolts ( ) samples from in service bolts

Tab. 3 - Slow Strai Rate (SSR) and Constant Load Tests

The HE susceptibility of Inconel X-750 has been demonstrated by SSRT. The fracture was always mainly intergranular, with some traces of ductility in the middle: no area reduction was found. It is important to note that the removed bolts were more susceptible to the phenomenon (they failed at a lower stress), due to the in service plastic deformation: 80% σ_y is the threshold stress of HE for the Inconel X-750 material in the tested conditions. This value has been obtained by corrosion test at constant load in presence of an high source of hydrogen (-1500 mV CP). The sample did not failed after 762 hours; on the notch some pits and micro cracks have been found.

Final conclusion

The Inconel X-750 bolts have failed in Bouri field during normal operation due to the Hydrogen Embrittlement. Threshold stress is 80% σ_y in very severe condition (CP with high hydrogen level). Permanently yielded bolts removed by wells and resulted sound after accurate checking, demonstrate that the field conditions are not so severe in term of H_2 level, as simulated in our test. In the case under investigation the condition to promote hydrogen embrittlement (potential lower than -0.4 SHE and pH lower than 4), due to the absence of chatodic protection, are possible only in pit / crevice environment.

CONCLUSIONS

The causes responsible for the failures are several, but mainly due to the concurrence of a mechanical stress that led the bolts above the yield point and a pit crevice condition in the environment surrounding the wells that justifies the brittle failure of the bolts at a stress smaller then the expected (Hydrogen Embrittlement).

The mechanical stress was due mainly to an overtorque applied while nippling up the X-Mas tree and the action of external forces applied to the flange, caused by the weight of flowline and choke and by the motion between wellhead and platform.

From the corrosion side, the hydrogen, needed to the HE phenomenon, is supposed to be present in pit / crevice conditions, where the local environment can be of appreciably lower pH than that of the bulk environment. It can be said that all these factors played an important rule even if it is not possible to say which one caused the failure.

Probably the overtorque gave the "biggest hit" to the yield limit, this would be justified by the fact that several bolts were found within the same strain in the same flange, but the action of the external forces through the flowline was very important since the position of almost all the broken bolts was opposite to the flowline connection. And the fact that rupture occurred without a reduction of the cross section is the proof that the material failed before reaching its tensile stress. So all these factors must be considered carefully in similar situations.

Final conclusions and recommendations can be summarised as follows:

- It has been shown that Inconel X-750 is sensitive to HE and this can lead to the premature failure for stresses smaller than its tensile stress. With very high hydrogen concentration failure can be obtained for stresses lower than yield stress.

- Operators in charge of nippling up with hydraulic wrenches should know very well the physical limits of the bolts and should be aware of the damage caused by an overtorque. They should also check frequently the torque wrenches calibration. They must also refer every problem caused during this operation.

- The mechanical actions on the wellhead must be considered carefully. Very often happens that completion and flowlines design are done by different departments. Engineers that design flowlines system do not consider the wellhead as a fragile structure with possible weak points, while completion engineer design up to the choke and interacting forces are neglected.

After connecting the flowline, routine checks must be done to make sure that the movements between all the parts are minimised and the flowline is supported correctly in production and during shut-in period (especially for very hot wells).

Even if failures were not due to fatigue, the action of the continuous forces applied through the flowline is alternate and all the system must be verified for fatigue safety factors.

- As a result of the incorrectly applied field procedures, the uneven tension in the bolts induced by standard torque tools and as a further result of the test performed with hydraulic tensioners, the overall Company procedures for flange nippling up have been modified.

Since the available tensioners on the market did not satisfy the API flange bolting arrangements, a special design has been performed in house and at the moment the hydraulic tensioning system (Fig. 4) is being spread over all domestic operations, on a standard basis.