Integrity Management of the Water Injection Networks in ADMA-OPCO "A Historical Review of Service Life Events and its Contribution to the Experienced Network Failure"

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ABSTRACT

Abu Dhabi Marine Operating Company (ADMA-OPCO) operates two production fields, namely: Zakum & Umm Shaif. Treated seawater (1.2 million barrels/day) is injected via a subsea pipeline network which extends for over 500 kilometers.

During the past 10 years many pipelines developed leaks which have resulted in replacement of 7 lines over the last 3 years. Very little pipeline integrity management measures have been implemented over the past 22 years to assure reliability/operability of the network. Recent Remnant Life Assessment study (RLA) suggests that the entire network will suffer catastrophic and uncontrollable failures by the year 2005.

A complete review of the network service events and operating regime was carried out together with condition data from internal and external inspection tools to quantify the size of the problem and to identify the mode of failures. It was evident that Micro-biological Induced Corrosion (MIC) is the main cause of the experienced failures. Accordingly, a comprehensive Integrity Management System was developed and implemented. As a result no single leak has been experienced since the year 2000. The corrosion rate has been significantly reduced and the water quality received at the injection wells now exceeds the original design specification requirements.

The subject paper reviews ADMA-OPCO Integrity Management System currently in place with a prime focus on the contribution of mechanical cleaning to the overall efficiency of the network.

ZK 145 to ZK 168, 14" water injection line failure was considered as a typical example to investigate the mode of failure and identify the root causes.

In conclusion, regular mechanical cleaning together with a structured chemical treatment program supported by comprehensive corrosion monitoring would have provided biological control and extended the service life of the network for many years to come.

1. HISTORICAL BACKGROUND

The 14" water injection pipeline, ZK 145 to ZK 168, was laid down in August 1979 and extended for 5405 meters (456 joints) at a water depth of 70 – 80 feet. The pipe material of construction is API 5L – X 60 grade with a nominal wall thickness of 0.625 inch (14.9 mm).

In October 1979 the line was hydrotested at a pressure of 4010 PSI (The design pressure is 3200 PSI) and subsequently commissioned in April 1980.

During the service life of the pipeline which extended for 19 years (from 1980 till 1999) the pipeline was cleaned twice; the first time was in August 1993 using foam & brush pigs and the second was in December 1997 using heavy mechanical cleaning tools.

In December 1999 after experiencing 6 leaks the line was declared unfit for service and finally decommissioned and replaced by another new line (like for like). The first leak took place in February 1997 which was clamped as well as the subsequent 4 leaks until the line was decommissioned.

2. INSPECTION HISTORY

The first ultrasonic wall thickness inspection survey to verify the internal wall thickness of the subject flowline was carried out in September 1993.

Joint No. 1 at ZK 145 end just after the subsea tubeturn was selected for U.T. inspection being easily accessible, free from concrete weight coat and has sufficient clearance at the 6 o'clock position to allow U.T. inspection preparatory work.

The inspected area extended for 1170 mm and measurements were carried out using a CYGNUS - 1 instrument. The thickness readings were found to be between 14.7 mm and 17.6 mm (nominal thickness is 14.9 mm). The same location was further scanned using marinised Wells KrautKramer USK – 7 and no anomaly was reported. As a result of the satisfactory findings obtained following the ultrasonic survey, the endorsement of the flowline till June 1997 was revalidated.

Following the pipeline decommissioning in 1999 the pipeline tubeturn toward ZK 145 & sections of the first 3 joints at ZK 145 end were retrieved for inspection together with four (4) other sections of the pipeline recovered with the associated leak clamps and all were considered in the failure investigation study.

3. FAILURE HISTORY

In February 1997 the 14" water injection flowline ZK 145 – ZK 168 developed its first leak in joint 155 located 1.8 Km from ZK 168. The leak (failure) history of the pipeline is detailed as follows:

3.1 First Failure

Date: 15th February 1997
Location: Joint number 155 from ZK 168

Visual & U.T Inspection

The leak was located at the 6 o'clock position and resulted from a longitudinal rupture which extended 120 mm long by 50 mm wide. The flowline appeared to have suffered permanent deformation before bursting as indicated by an observed bulge on one of the rupture edges (Figure 3, 4 & 5).

Manual U.T. inspection revealed a band of pitting corrosion 540 mm long and 80 mm wide. The minimum thickness within this band was reported to be 8 mm but as low as 5 mm adjacent to the rupture edges.

Sonomatic Scan

The Sonomatic U.T scan measurements carried out in April 1997 confirmed the readings reported by the manual U.T. measurement.

The cut-off joint recovered with the leak clamp was rescanned in October 2000 to validate earlier results and to measure the corrosion rate during the time period from the first scan and the line decommissioning. Figure 18 combines the two scans together for reference.

Repair Work

A leak clamp was installed.

3.2 Second Failure

Date: 25th April 1997
Location: Field joint number 451 from ZK 168 (5 from ZK 145)

Visual Inspection

The leak located at the 6 o'clock position 40 mm from the weld (toward ZK 145) resulted from a longitudinal rupture extended 370 mm long and 45 mm wide. Circumference measurement of the sound area was found to be 1120 mm compared to 1163 mm at the rupture area which indicated that the pipe has been bulged at the location of the burst (Figures 6 & 7).

Sonomatic inspection revealed some localized corrosion at the 6 o'clock position with clusters of pits measured to be up to 5 mm deep.

Repair Work

Repair clamp was installed on 2nd August 1992 and the line was satisfactorily hydrotested. However, the clamp was later retrieved and installed on other leaking locations on 14" ZK 168 to ZK 156. Reclamping of joint 451 was satisfactorily recompleted in April 1998.

3.3 Third Failure

Date: 11th October 1997
Location: Field joint No. 309 from ZK 168

Visual & Ultrasonic Inspection

The leak was located at the 6 o'clock position 740 mm from the weld (toward Zakum 145) of joint 309 from ZK 168 resulted from a longitudinal rupture 340 mm long and 50 mm wide. It was evident that the flowline had suffered permanent deformation in the vicinity of the crack (bulging) which indicated that the line had reached its maximum operating pressure limit before bursting (Figures 8 & 9).

The ruptured location was U.T. scanned using a flaw detector with 0 degree probe through 360 degrees for 1000 mm either side of the rupture and through the 3 to 6 to 9 o'clock on the external surface.

In addition to the rupture area a total of 13 spots were identified to be pitted with an average depth of 5 - 6 mm, all located at the 6 o'clock position. No Sonomatic survey was carried out at this location.

Repair Work

A standard leak clamp was installed in April 1998 and the pipeline was satisfactorily hydrotested at the maximum operating pressure.

Engineering Assessment

Engineering review of the pipe condition has confirmed that after calculating the minimum thickness requirement based on the maximum operating pressure that the minimum thickness reported during the U.T. inspection at the 13 spots is within the acceptable limit and can withstand the current operating pressure. Hence no remedial work was required. However, locations where the remaining thickness was 10 mm (original thickness = 15.9) are considered to be critical and require to be regularly monitored using adequate inspection technique to detect any further reduction in the wall thickness.

3.4 Fourth Failure

Date Occurred:	5th July 1998
Location:	Field joint No. 235 from ZK 168

Visual Inspection

The through wall defect was located at the 6 o'clock position starting at 240 mm from the weld (Toward Zakum 168) of joint No. 235 from ZK 168 resulted from a longitudinal rupture of 550 mm long and 80 mm wide. It was observed that the flowline has suffered permanent deformation in the vicinity of the crack (bulging).

The line was scanned through out its whole circumference on both sides of the leak using Zero degree ultrasonic probe and no significant internal corrosion was reported.

Apart from the rupture area, the minimum wall thickness was 14 mm.

Repair Work

A subsea clamp was installed on 30th August 1998, but failed twice during hydrotesting. In 1st January 1999 a new clamp was satisfactorily installed. However, while hydrotesting, another leak was reported at joint No. 5 previously clamped in August 1997. The leaking clamp was subsequently replaced by another manufacturer clamp.

3.5 Fifth Failure

Date Occurred:	10th January 1999
Location:	Field joint number 451 from ZK 168 (5 from ZK 145)

Visual Inspection

This defect has occurred in the same joint (Field joint No. 451 from ZK 168) which was ruptured at the 6 o'clock position earlier on the 25th of April 1997 and was subsequently clamped in the 2nd of August 1997.

Visual inspection revealed that the leak was in the form of a very narrow split rather than open rupture which was the predominant mode of failure in the previous four failures.

Two through groove defects were reported located at both sides of the repair clamps and the findings are reported as follows:

Upstream Defect

The defect was located at 9 the o'clock position and starting at 970 mm from the toe of the field joint No. 5 weld (toward ZK 145) and resulted from a longitudinal split of 67 mm long and 15 mm wide. The pipewall thickness (Lip) adjacent to the longitudinal split was measured to be only 1 mm.

Downstream Defect

The defect was located at the 9 o'clock position and starting at 482 mm from the toe of the field joint No. 5 weld (toward ZK 168) and resulted from a longitudinal groove 53 mm long and 25 mm wide with a maximum depth of 9 mm.

Apart from these two defects, i.e. upstream and downstream the clamp, no other defects were observed.

Ultrasonic Survey

Wall thickness readings were taken in the vicinity of both defects using a CYGNUS – 1 U.T. instrument and were reported as:

Around the upstream defect between 15.4 mm and 15.7 mm.
Around the downstream defect between 16.4 mm and 17.0 mm.

Repair Work

The originally installed clamp was replaced by another manufacturer clamp to accommodate the affected location.

3.6 Sixth Failure

Date: 9th February 1999
Location: Field joint No. 162 from ZK 168

Visual & Ultrasonic Inspection

The leak was located at the 6 o'clock position of joint No. 162 from ZK 168 resulted from a longitudinal rupture extended 495 mm long by 83 mm wide started just at the weld center line toward ZK 168. Both lips of the defect were reported to be bulged outward.

Wall thickness readings recorded were reported to be between 8.8 and 17.1 mm.

A – Scan

The flowline was scanned between the 3 and 9 o'clock position on both sides of the defect and two main area of thinning in the wall thickness were reported.

Area "A"

Starting 510 mm downstream of field joint 162 and extended for 125 mm in length and 60 mm wide with a minimum wall thickness of 8.8 mm.

Area "B"

Starting 755 mm downstream of field joint 162 and extended for 25 mm in length and 20 mm wide with a minimum wall thickness of 10.5 mm.

Repair Work

It was recommended to install appropriate subsea clamp on the ruptured pipe section which extended from 120 mm upstream the toe weld of field joint No 162 up to 1080 mm downstream of the same joint.

However, as per General Management instructions, the requested clamp installation was suspended and a temporary clamp was installed.

4. POST DECOMMISSIONING INSPECTION

To further investigate the likely mode of failure of the replaced ZK 145 – ZK 168, the following parts of the decommissioned pipeline were recovered to assess the investigation:

A) Riser tubeturn and 60 cm segments of the first three riser joints including the field weld at ZK 168 end.

B) 4 pipe sections retrieved together with the recovered leak clamps.

The observation and findings are conveyed as follows:

4.1 Riser Tubeturn and the First Three Joints Segments

The tubeturn and the 3 segments (each 60 cm long) were visually and U.T inspected following grit blasting.

The four pieces showed numerous pits scattered throughout the entire internal surface of the pipe sections. The size of the pits ranged from 1 to 3 mm in depth and 2 to 8 mm in diameter. Figures 10 through 12 clearly show the pits size and distribution. Light scales of iron oxide/iron sulphide were evident and were found to be strongly adhered to the surface at a nominal thickness of 1 mm.

At the 6 o'clock position pits were slightly deeper, down to 4 mm with many pits interconnecting to form a longer channel type groove which extend up to 10 cm wide at places.

It is clear from the morphology and the distribution of the pits that they resulted from oxygen ingress into the system (Oxygen Induced Corrosion). The calculated average corrosion rate based on 20 years service is 0.15 mm/year.

The predominant corrosion mechanism is considered to be oxygen ingress, however, SRB may have contributed to the corrosion process at the 6 o'clock position. Based upon this corrosion rate the total expected service life of the line could come up to 60 years.

4.2 Pipe Sections Retrieved with Clamps

Four (4) sections of the pipeline associated with the recovered leak clamps were visually and U.T. inspected on the 27th of September 2000 to confirm previous in service findings and assumptions.

The following sections of the pipeline were considered:

Joint No. 155 for ZK 168	Failed on 15th February 1997
Joint No. 235 for ZK 168	Failed on 05th July 1998
Joint No. 309 for ZK 168	Failed on 11th October 1997
Joint No. 451 for ZK 168	Failed on 25th April 1997 & reoccurred on 10th January 1999.

4.2.1 Joint No. 155 from ZK 168 This joint had experienced the first leak of the subject pipeline which took place on the 15th of February 1997 and is considered the most informative section out of the four retrieved parts where the area of burst was not trimmed off during clamp installation.

Based on Sonomatic scan and UT measurements made available in April 1997 the average corrosion rate was calculated to be 0.77 mm/year while assuming a uniform and linear corrosion growth rate.

This calculation is based on the fact that the wall thickness at the lips of burst part, which was measured to be 2 mm, is the pipewall thickness when bursted.

Further Sonomatic scan was carried out in October 2000 on the cut-off piece of the recovered joint which indicated a wall thickness loss measured since the previous scan in the range of 0.1 to 0.5 mm. The time period where the line was actually in service between the two scans is 32 months (April 1997 till December 1999) which implies an overall average corrosion rate of 0.1 mm/year.

This average corrosion rate although high on its absolute magnitude is, however, very much less than the overall average calculated at the burst location. The reduced corrosion rate was most likely attributed to the fact that the line was mechanically cleaned just after the first leak (1997). The mechanical cleaning would have removed or reduced the established biofilm allowing the biocide treatment regime to be effective, thereby reducing the corrosion rates by a factor of 5. This in conclusion confirmed the effectiveness of the mechanical cleaning/biocide treatment in mitigating microbial corrosion.

The defect geometry of the corrosion profile indicated by the Sonomatic survey provided excellent correlation with visual appearance of the retrieved section.

Figures 13, 14 & 15 clearly showed the pitting pattern and distribution as physically seen in the retrieved joint.

Comparisons between the two Sonomatic scans (1997 & 2000) revealed that pits had expanded in length and become interconnected within the same position (6 o'clock position).

Further thinning of the pipewall in general is evident as indicated by the increase of the density and distribution of the red spots in Figure 18.

Figure 18 combines in one page the two Sonomatic scans (Landscape colour palette), i.e. April 1997 and October 2000 for easy comparison.

The absence of any other significant corrosion damage (apart from the 6 o'clock position) suggested that oxygen induced corrosion has little contribution to the corrosion process and evidently confirmed that Microbial Induced Corrosion is the prime cause of failure.

4.2.2 Joints No. 235, No. 309 & No. 451 from ZK 168 Generally the other 3 joints were similar to joint No. 155 from ZK 168. Photographic presentation of these joints is documented in Figures 16 & 17.

It is obvious from the photos that the area of rupture was trimmed off to allow leak clamp installation.

5. UNDERSTANDING THE FAILURE MECHANISM

Typical water analysis at selective injector wellheads has revealed a bacterial enumeration at 10^4 - 10^5, which is extremely high. Both Planktonic & Sessile bacteria were identified and isolated.

Bacteria is chemically attached to the pipelines inner steel surface. Attachment at some stage becomes irreversible as a result of a production of Extracellular Polysacchardies Substances (EPS) which act as strong adhesives and bacterial growth commences. This initial layer is generally termed Micro-fouling or Bio-film and is developed within hours and may be further thickened by trapping in organic particles (silt) from the water adding to its resistance and complexity [4].

Micro-fouling and corrosion are inextricably linked. They act together to change the pH and chemical composition of the water at the interface. Biofilm acts both as a barrier to oxygen diffusion and as an active oxygen consumer due to bacterial respiration. Differential aeration cells result in pitting corrosion at the end. Bacteria can alter pH in a number of ways. Some can produce acids as formic, succinct, acitic and sulphuric acid. pH values of 1 or 2 under discreet bio-deposits were reported.

Other bacteria are involved in metabolizing sulphur compounds by oxidizing sulphur and sulphides to sulphate and ultinely sulphuric acid [5].

Others, notably anaerobic SRB reverse the process and reduce sulphates to sulphides often producing corrosive hydrogen sulphide (H_2S). The exact Microbial mechanism which took place in ADMA-OPCO Subsea lines was not particularly identified but the end results were very evident which lead to 17 leaks in the network and an expensive replacement of over 20 kilometers of subsea pipelines (5 lines).

Bio-film structure is very complex and cannot readily be attacked by most Bactericides even at very high concentration. It is well established that the Bacterial population in particular sessile group is not sensitive to how good or bad is the Biocide treatment due to the shielding effect exerted by the presence of a dense and complex bio-film [7].

Routine mechanical cleaning/pigging will force disturbing the bio-film and exposing the bacterial adhered to the surface so allowing biocides to attack the membranes structure and eventually kill the bacteria.

The effect of bacteria growth in the water injection network will not only result in catastrophic failure of the pipeline and surface equipment but may also result in formation plugging and expensive downhole well bore stimulation to restore the wells injectivity.

Additionally experience in water floods with other operators including the North Sea and Oman Oil Company [6, 8] suggests that maturing reservoir souring in many cases is attributed to Microbial Induced Corrosion generated by Sulfate Reducing Bacteria (SRB) introduced to the reservoir via contaminated water injection system.

6. MECHANICAL CLEANING

One of the major short falls in the design of the water injection network in ADMA-OPCO is the absence of launchers and receivers.

During the 19 years service life of the 14” water injection flowline ZK 145 – ZK 168, the line was cleaned twice while using temporary pig launcher and receiver. The first cleaning was carried out in 1993 using foam & brush pigs while the second was carried out in 1997 where hard mechanical cleaning pigs were considered. Apart from the 1993 & 1997 cleaning campaigns the subject pipeline was never cleaned. Illustrative drawings of the mechanical cleaning pigs are attached as Figure 19.

It is worth mentioning that the collected samples during the pigging operation were found to contain up to 17.2% weight organic matters which were mainly bacteria (living or dead) together with bacteria organic bi-products/bio-film which revealed active microbiological contamination of the system.

It was noted that during the two cleaning campaigns no biocides sterilization program was employed immediately following the pigging process to ensure efficient killing of the sessile bacteria colonies (SRB) which were found to be directly responsible for the observed pitting corrosion of the carbon steel pipes and subsequent perforation.

ADMA-OPCO through continuos efforts was able to maintain the water quality at modules at its absolute value by scheduled overhaul of modules and appropriate selection of treatment chemicals.

However, while the injection water was travelling through the network the water quality dramatically deteriorated. The average particle count at modules most of the time was better than the design specification. However, upon arrival at the injection wells its average may reach over 2000 particles with excursions at some towers even higher at 8000 - 9000 particles. Also iron count significantly increases as the water travels to exceed 0.6 mg/litre (specification call for < 0.2 mg/litre). The high particle count is mainly associated with increased bacterial count and bio-film growth while iron count associates with dissolution of the pipelines metallic carbon steel body.

Following mechanical cleaning the iron count dropped from 0.5 - 0.6 down to 0.2 mg/litres and the particle count from an average of 2000 particle / 0.05 ml down to less than 130 partial which exceeds the specification requirements (<200 partial / 0.05 ml). Current compliance of the water injection major traffic light indicators i.e. particle, iron count and bacteria are presented in Figure 21.

To verify the cleanliness of the mechanical cleaning pipelines, 8 pipelines were internally video inspected immediately after being cleaned and the cleaned surface was described as being 90% back to metallic surface with all the corrosion bi-products removed from the pits.

7. CHEMICAL TREATMENT

Many chemical treatment regimes of different production chemicals suppliers have been used by ADMA-OPCO through out the lifetime of the network.

The success of these treatments has been variable and dependent on conditions at the time.

Toward the end of the service life of the subject flowline two types of biocides were injected downstream of the injection pumps at water injection platforms.

The biocide treatment program is described as follows:

- Biocide A (Gluteraldelyde base) dosed at 1000 ppm for 1.5 hours every 10 days.
- Biocide B (Formaldelyde base) dosed at 500 ppm for one (1) hour every 10 days at the mid period between two successive injections of biocide A.

Until now ADMA-OPCO has not been able to keep the bacterial growth in the network fully under control. This is very much dependent on the fact how clean is the pipeline to allow the biocide to come into contact with the colonized bacteria rather than how effective is the biocide. Experience has proven that the key point of any biocide treatment regime is the pipeline cleanliness.

While recognizing the significant importance of the quality of the chemical package on the performance of the water injection modules and the integrity of distribution network, ADMA-OPCO has developed a chemical treatment testing strategy to ensure that the best treatment regimes are used to protect the company assets.

Further more a stringinant QA/QC procedures were put in place to ensure that the delivered chemicals fully compile with the specified products.

To this regard a routine laboratory test on chemicals delivery is currently implemented which are carried out by independent laboratory where the following tests are performed.

- FTIR
- Type & concentration of active ingredient
- Type & percentage of the solvent package

8. CORROSION MONITORING AND TESTING

Unavailability of appropriate corrosion monitoring elements at most locations due to absence, wrong placement, inaccessibility and/or failure of monitoring fittings was a major concern.

Accordingly, an ambitious plan to install an appropriate corrosion-monitoring element at every tower was launched and its implementation is in progress. Additionally bio-probes were installed directly to the pipelines or as side steams at all radials [1].

To complement the corrosion monitoring program, residual biocide measurement is routinely carried out every 3 months at the end towers to verify the efficiency of the chemical treatment.

Particle counts, iron counts and SRB counts are carried out at all towers every 10 days, however, at modules oxygen & chlorine level, SRB, particle & iron counts are measured at least once a day.

Once the recommended corrosion monitoring and testing recommendations are fully implemented the accumulated data should enable understanding the facilities in a better way, allowing decision making and immediate intervention whenever any changes may take place in the system.

9. FUTURE REPLACEMENT NETWORK

ADMA-OPCO has taken steps towards the replacement of the entire network during the next 20 years. The main characteristics of the future network are that the network will be made of 9 Clusters based on towers locations, system pressure and water supply demand (existing & future field maps are represented as Figures 1 & 2). Each cluster is composed of a number of lines of the same size, the feature of the new clusters is as follows:

1. Each cluster can be cleaned using appropriate pigs launched at one end and received at the other extreme end (up to 7 lines in one pig launch). This enhancement in the network design should decrease the interruption to the water supply and minimize pigging operation cost and enable shorter pigging frequency.

2. Each Wellhead Tower will be provided with 4 monitoring / Testing fittings:

   - One weight loss coupon
   - LPR coupon
   - Bio-Probe
   - Spare fitting to allow Corrosion monitoring/chemical injection in the future

3. No subsea tie-in.

4. Maintain a minimum velocity of 1 metre/second in all the pipelines, whenever possible.

5. Side steam at the end of each cluster to enable additional monitoring facilities and residual chemical testing.

6. Provision for cable operated/Fiber optics intelligent pigging inspection tools to allow inspection for all the lines.

10. REMNANT LIFE ASSESSMENT STUDY (RLA)

ADMA-OPCO was very much concerned regarding the integrity of the water injection pipelines. These concerns are related to:

- Age
- Limited pigging facilities
- Low fluid velocities or stagnant flow
- Ineffective distribution of the water treatment chemicals

- No corrosion allowance in the original design
- Poor corrosion monitoring system
- Limited Inspection data

To date, 17 leaks have been experienced in the water injection pipelines of ZAKUM Field (5 lines out of 48). All leaks developed as a result of under-deposit corrosion in the bottom segment due to active SRB. The leak frequency statistics is graphically presented in (Figure 20).

To overcome these concerns ADMA-OPCO has initiated a Remnant Life Assessment study (RLA) which includes all the water injection pipelines. A fundamental deliverable is to provide a damage mechanism model to describe the current condition of the pipelines and predict their future performance [2, 3].

Limited inspection data obtained from the intelligent pigging of 9 pipelines together with data collected from the received failed joints and spot Sonomatic inspection were made available to the RLA consultant to develop its Probabilistic Remnant Life Assessment Model (end of life criteria).

The outcome of the study can be summarized as:

- A total of 42 lines out of 47 lines should fail within a further five years of operation due to Micro-biological activity acting on the internal surface of the pipelines (Table 1).

<u>Note:</u>

The study was completed in 2000.

The study has assumed a steady corrosion rate and the rate is calculated based on failure data and earlier operating regime prior to the Mechanical Cleaning Campaign.

Today, towards the end of the year 2003, no single leak has developed in the entire network and earlier experienced water quality deterioration is no longer reported. The credit of such improvement is primarily attributed to the mechanical cleaning program. Other parameters such as better chemical distribution and pro-active shutdown sterilization program, and advanced chemical treatment regime have contributed to this improvement to a lessor extent.

11. CONCLUSIONS

1. Oxygen induced corrosion has little contribution to the corrosion process. Its rate is 0. 15 mm/year maximum.

2. Microbiological influenced corrosion (MIC) most probably SRB is the cause of all experienced failures and high thinning throughout the entire subsea network.

3. The subsea pipeline network Mechanical cleaning campaign commenced in 1998 had resulted in slowing down the corrosion process rate from 0.77 mm/year down to 0.1 mm/year which provided additional service life to the network.

4. The quality of injection water significantly improved following the mechanical cleaning where the particle count reduced from an average of 2000 particle down to less than 70 particle/0.05 ml

which by far exceeds the specification requirements. Iron counts also reduced from more than 0.40 mg/l to 0.20 mg/l.

5. Running the water injection plants to their design output is the operators concern, conducting non-destructive testing is the inspection authorities concern, ensuring that the corrosion measures are applied and the results are assessed is the corrosion engineers concern, securing and maintaining the water injection wells injectivity is the petroleum engineers concern, but the <u>Integrity Management of the entire water system is everyone's concern.</u>

6. Maintaining the integrity of the water injection network will not only protect the company investment and ensure the water injection supply to maintain the reservoir pressure but it also will minimize the deterioration of quality of the injection water and reduce formation plugging due to debris accumulation and minimize subsequent expensive formation stimulation treatment. It will also minimize the risk of introducing bacteria in the reservoirs and the possibility of souring the reservoir due to its growth and metabolism.

12. RECOMMENDATIONS

1. Emphasis should be on the implementation of routine in-house pipelines cleaning using hard/soft pigs at 3 months frequency. Pipelines cleaning must be immediately followed by high dosage of biocide treatment preferably while soaking the pipeline for 24 hours to allow biocides to interact with remaining (exposed) bacteria before a new biofilm layer is established.

2. Ensure that state-of-art Corrosion Monitoring/Testing techniques are applied which should satisfy current & future requirements.

3. Develop a Data Management System and establish traffic light indicators to allow easy and accessible tools to monitor the key parameters which ensure long term Operability, Functionality & Integrity of the entire Water Injections System.

4. Plan and schedule an on-line intelligent pigging program for selective pipelines to evaluate the effectiveness of the control measures and to provide management with evidence that appropriate mitigation measures are in-place.

5. Develop and document a reliable testing strategy for water injection chemical selection while improving the QA/QC methods and procedures to ensure that the supplied chemicals are in full compliance with the approved ones.

6. Introduce new techniques to allow measuring and recording the souring (H_2S) potential in the production wells while studying how the quality of the injection water may affect this potential.

7. Ensure that the Integrity Management System of the water Injection facilities from the water intake throughout into the well bore is applied, assessed and reviewed.

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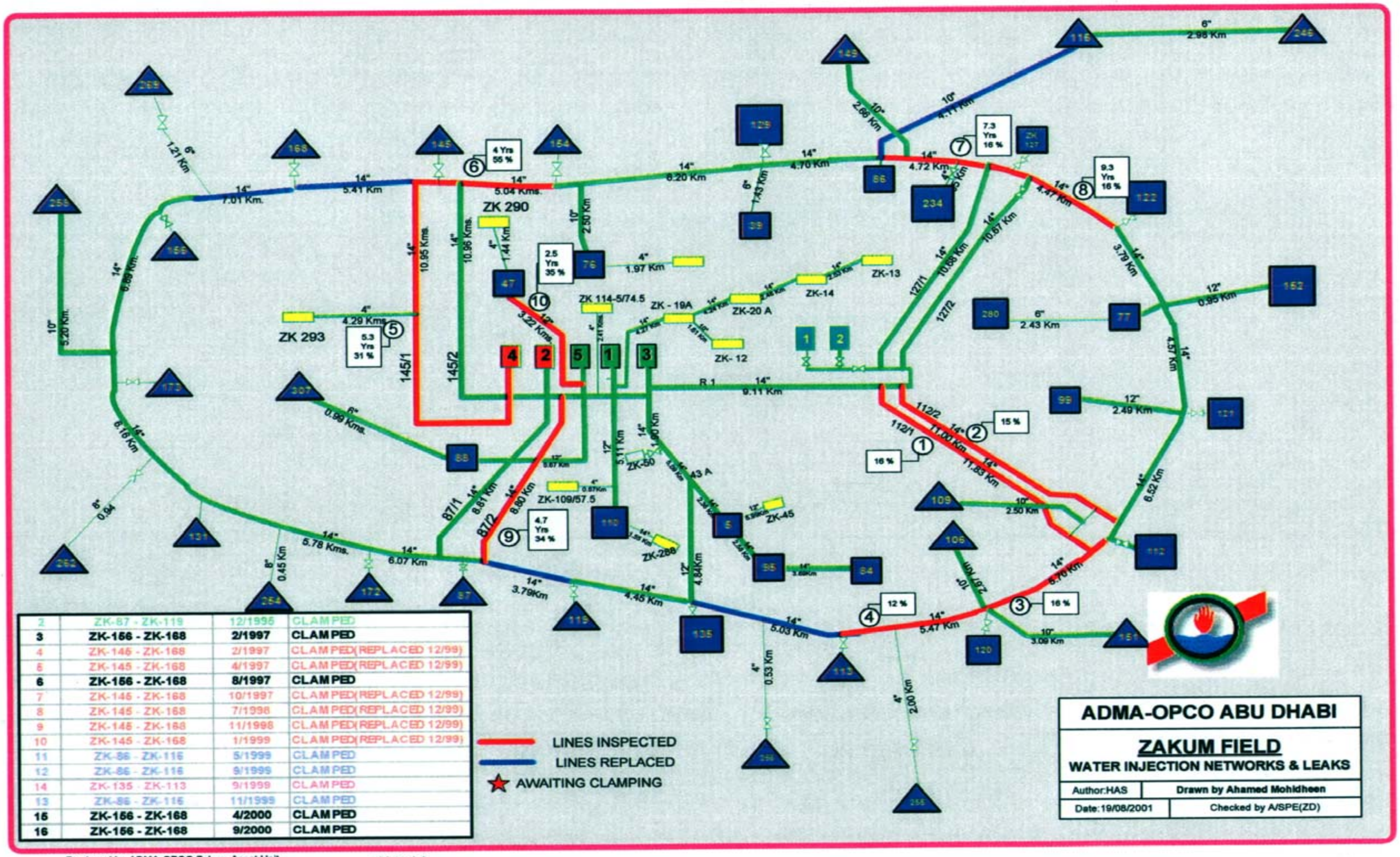
ZAKUM Water Injection

Pipe lines ranking without inspection data considered

Pipeline WIN	Pipeline name	Average Velocity m/s	Remaining life TWI Model Jan '00	Rank TWI Model	Remaining life NDT Insp. Jan '00	Rank NDT Insp.	Comment	Operating Pressure
4493-0424	8" Water 86 To 149	0.5	-10.9	1				2300
4493-0419	10" Water 120 to 151	0.29	-10.9	2				2300
4493-0438	10" Water 112 to 109	0.11	-10.9	3				2600
4493-0436	10" Water 120 to 106	0.04	-10.9	4				2300
4493-0470	6" Water 77 to 280	1	-10.7	5				2600
4493-0460	6" Water Spur to to 269	0.64	-9.8	6				3200
4493-0415	14" Water 87 to 172	1.22	-9.1	7				3200
4493-0416	14" Water 172 to 131	0.87	-9.1	8				3200
4493-0434	14" Water 131 to 173	0.42	-9.1	9				3200
4493-0387	14" Water ZWRP-MH to 145E	1.23	-8.9	10				2300
4493-0427	14" Water 168 to 156	0.68	-8.8	11			Replaced 2002	3200
4493-0428	14" Water 156 to 173	0.38	-8.8	12				3200
4493-0422	12" Water 77 to 152	0.3	-8.7	13				2600
4493-0462	8" Water Spur to to 262	0.32	-8.1	14				3200
4493-0397	14" Water 154 to 129	0.79	-7.9	15				2300
4493-0388	14"Water ZWRP-M4 to 145W	1.38	-7.8	16	5.3	44	Insp. 5.00 mmWL (31%)	3200
4493-0383	14" Water 122 to 77	0.32	-7.7	17				2600
4493-0377	14" Water ZWRP-M2 to 87W	1.6	-7.1	18				3200
4493-0384	14" Water ZCCP-MH to 112E	0.98	-6.9	19	To be calculated	40	Insp. 3.05 mm WL (16%)	2600
4493-0381	14" Water 129 to 86	0.45	-6.9	20				2300
4493-0396	14"Water 145 to 154	1.23	-6.9	21	4.1	42	Insp. 8.80 mm WL (55%)	2300
4493-0379	14" Water ZCCP-WH to 127W	1.05	-6.7	22				2600
4493-0413	14" Water 119 to 135	0.77	-6.3	23				2300
4493-0414	14" Water 87 to 119	1.31	-6.3	24			Failed One clamp 12/95	2300
4493-0461	8" Water Spur to to 254	0.41	-6.1	25				3200
4493-0401	12" Water 121 to 99	0.09	-6	26				2600
4493-0386	14" Water 112 to 120	0.29	-5.9	27	To be calculated	39	Insp. 3.15 mm WL (16%)	2600
4493-0469	4" Water Spur to to 293	1	-5.8	28				3200
4493-0420	14"Water 112 to 121	0.61	-5.7	29				2600
4493-0423	8" Water 86 to 116	1	-5.3	30			Replaced 2002	2300
4493-0412	14"Water 135 to 113	0.94	-5	31			Failed One clamp 09/99	2300
4493-0459	6" Water Spur to to 256	1.15	-5	32				2300
4493-0411	14"Water 113 to 120	0.62	-5	33	To be calculated	38	Insp. 2.67 mm WL (17%)	2300
4493-0382	14"Water 127 to 122	0.66	-4.7	34	9.3	46	Insp. 2.60 mm WL (16%)	2600
4493-0360	14"Water ZWRP-MH to 87E	1.19	-4.3	35	4.7	43	Insp. 6.50 mm WL (34%)	2300
4493-0457	4" Water 116 to 246	1.46	-4.1	36				2300
4493-0425	10"Water 154 to 76	0.09	-3.4	37				2300
4493-0463	10"Water 173 to 258	0.52	-3.3	38				3200
4493-0466	4" Water 110 to 288	1	-2.7	39				2300
4493-0471	6" Water 88 to 96/52	0.52	-2.1	40				2300
4493-0464	4" Water 47 to 290	1	-1.5	41				2300
4493-0455	4" Water Spur to to 255	1.89	-1	42				2300
4493-0468	4" Water Spur to to 109/255	1	0.1	43				2600
4493-0456	4" Water Spur to to 234	0.65	0.3	44				2600
4493-0380	14"Water 86 to 127	0.17	0.3	45	7.3	45	Insp. 2.50 mm WL (16%)	2600
4493-0409	12"Water ZWRP-M5 to 47	0.09	2.5	46	2.5	41	Insp. 5.00 mm WL (35%)	2300

Table 1

ZAKUM FIELD
EXISTING WATER PIPELINE NETWORK



2	ZK-87 - ZK-119	12/1996	CLAMPED
3	ZK-156 - ZK-168	2/1997	CLAMPED
4	ZK-145 - ZK-168	2/1997	CLAMPED(REPLACED 12/99)
5	ZK-145 - ZK-168	4/1997	CLAMPED(REPLACED 12/99)
6	ZK-156 - ZK-168	8/1997	CLAMPED
7	ZK-145 - ZK-168	10/1997	CLAMPED(REPLACED 12/99)
8	ZK-145 - ZK-168	7/1998	CLAMPED(REPLACED 12/99)
9	ZK-145 - ZK-168	11/1998	CLAMPED(REPLACED 12/99)
10	ZK-145 - ZK-168	1/1999	CLAMPED(REPLACED 12/99)
11	ZK-86 - ZK-116	5/1999	CLAMPED
12	ZK-86 - ZK-116	9/1999	CLAMPED
14	ZK-135 - ZK-113	9/1999	CLAMPED
13	ZK-86 - ZK-116	11/1999	CLAMPED
15	ZK-156 - ZK-168	4/2000	CLAMPED
16	ZK-156 - ZK-168	9/2000	CLAMPED

Produced by ADMA-OPCO Zakum Asset Unit ah/wtraziz1

Figure 1 - Existing Field Map

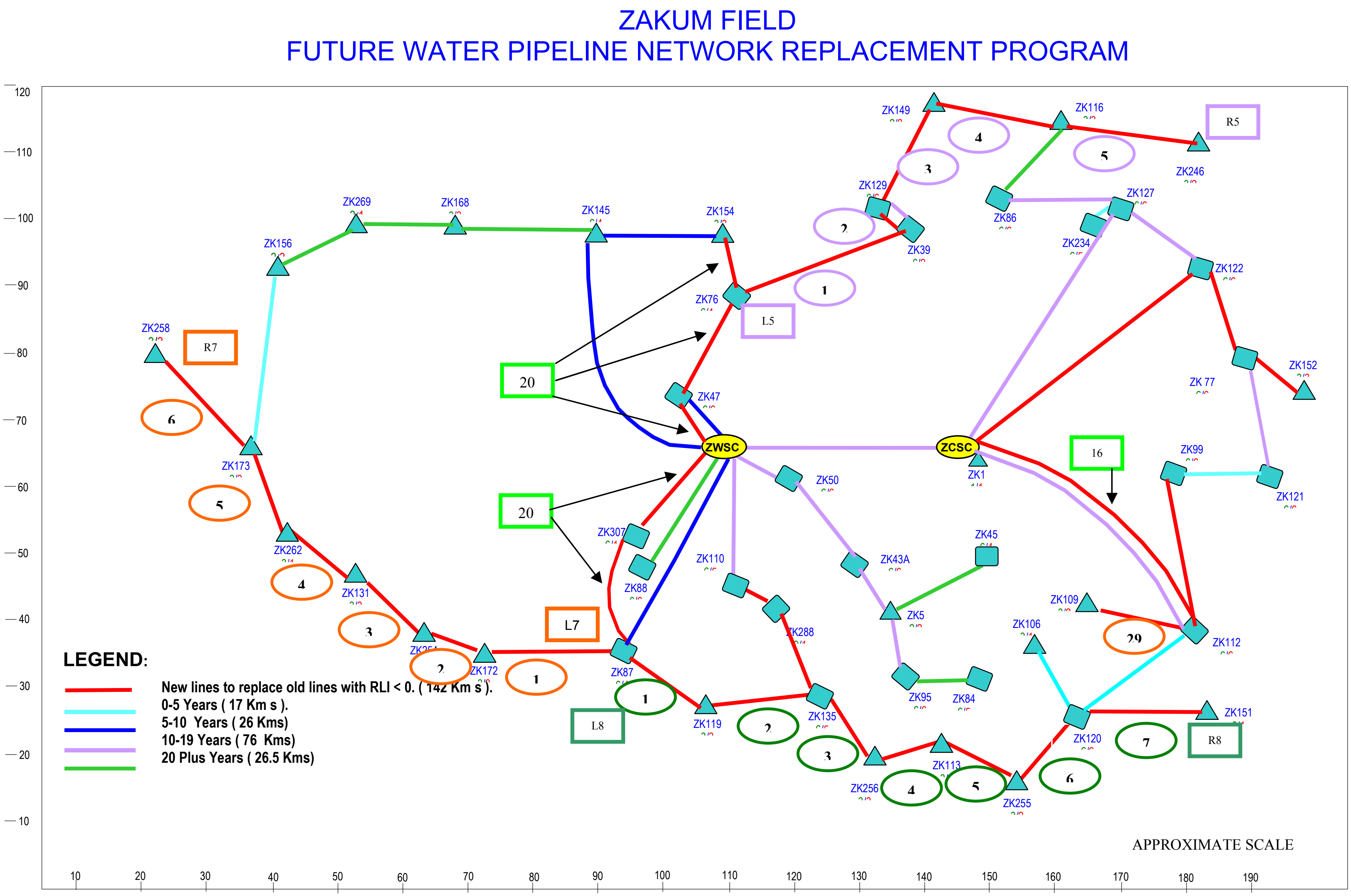


Figure 2 - Future Field Map

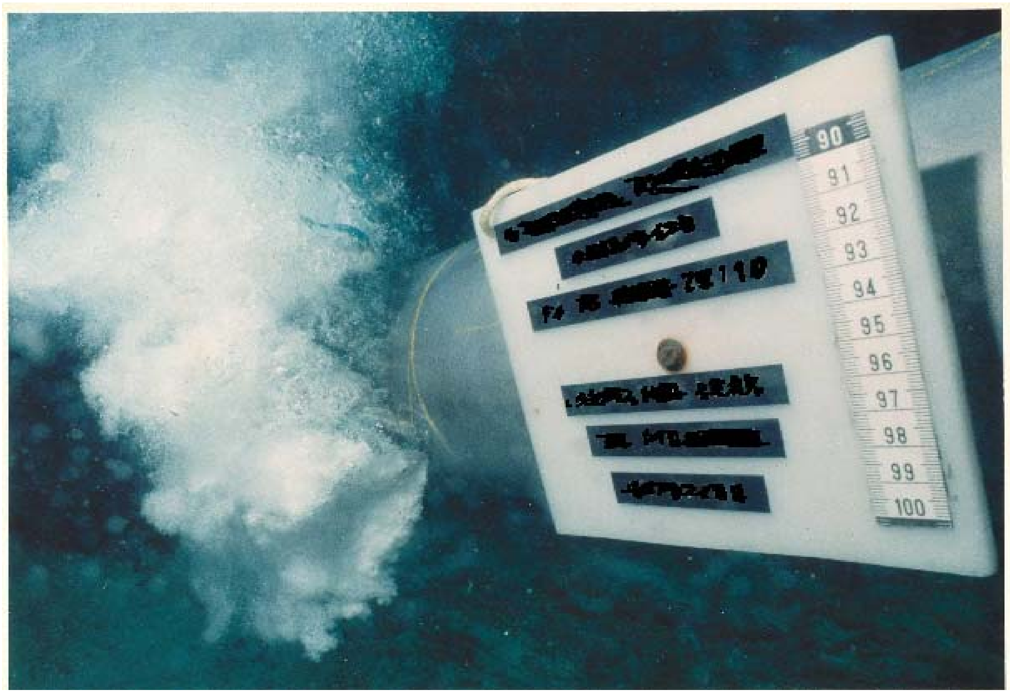


Figure 3 - Joint No. 155 from ZK 168

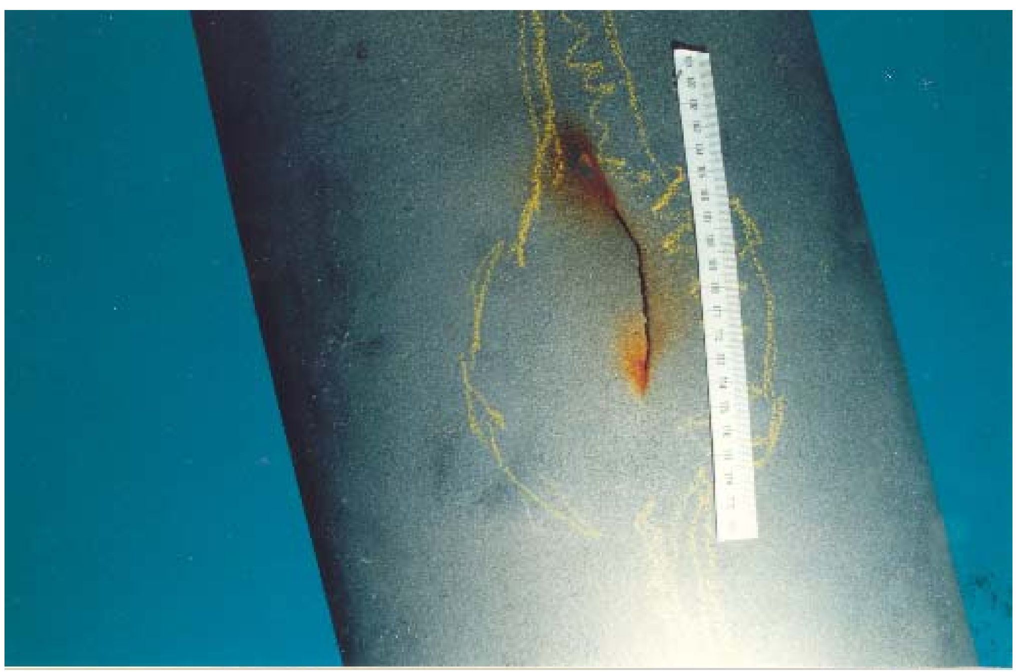


Figure 4 - Joint No. 155 from ZK 168

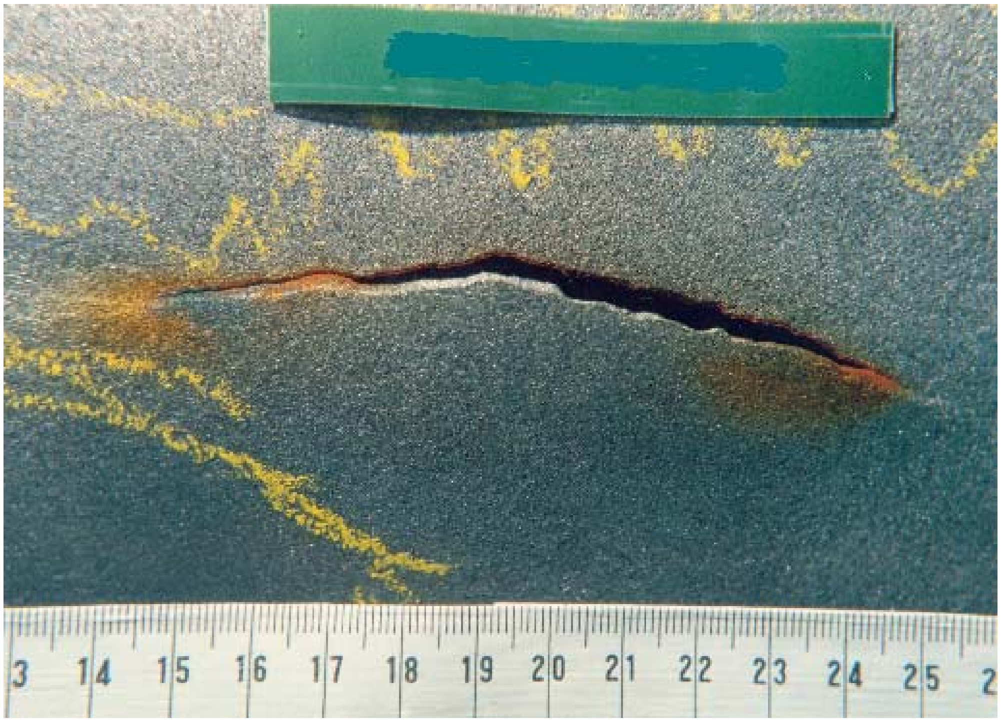


Figure 5 - Field Joint No. 155 from ZK 168

Figure 6 - Field Joint No. 451 from ZK168

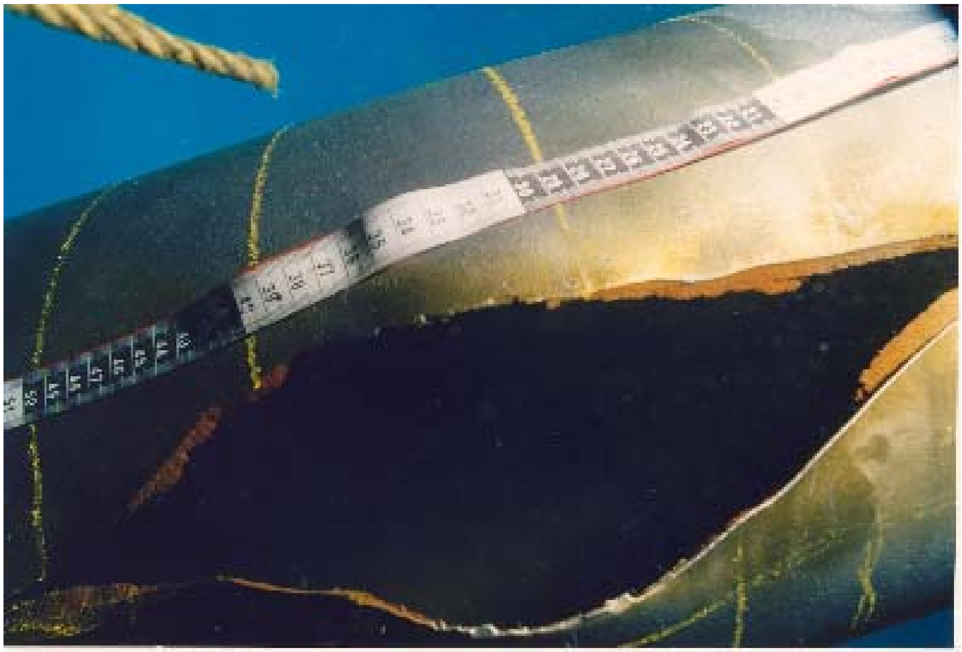


Figure 7 - Field Joint No. 451 from ZK168

Figure 8 - Field Joint No. 301 from ZK 168

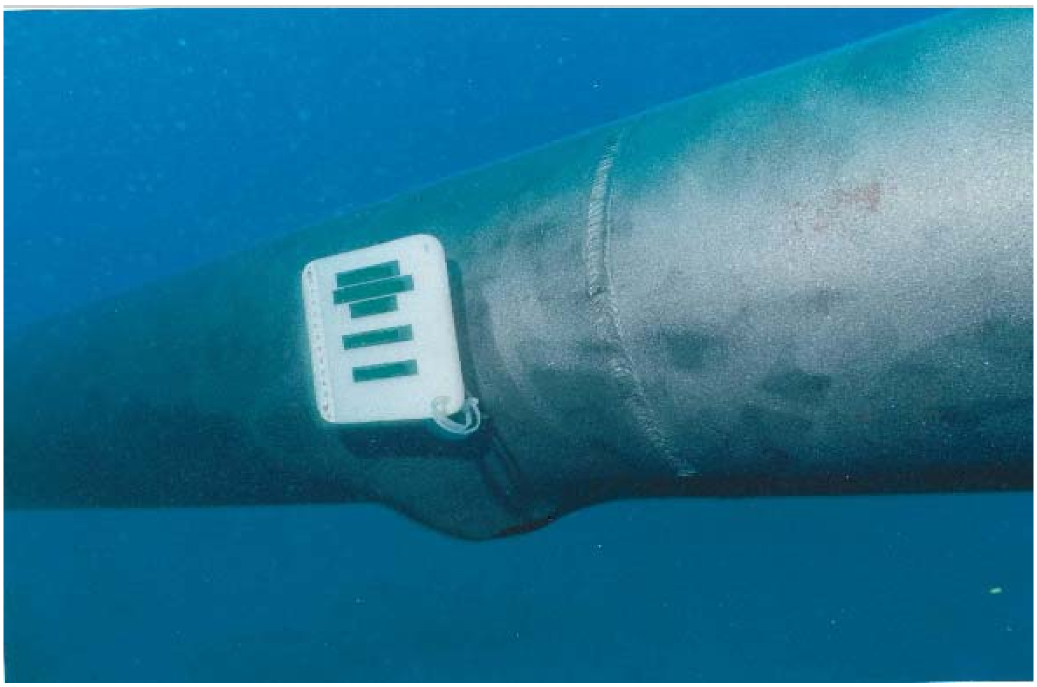


Figure 9 - Field Joint No. 301 from ZK 168

Figure 10

Figure 11

Figure 12 - Riser Tubeturn
Oxygen Induced Corrosion & SRB Pits at 6 o'clock position

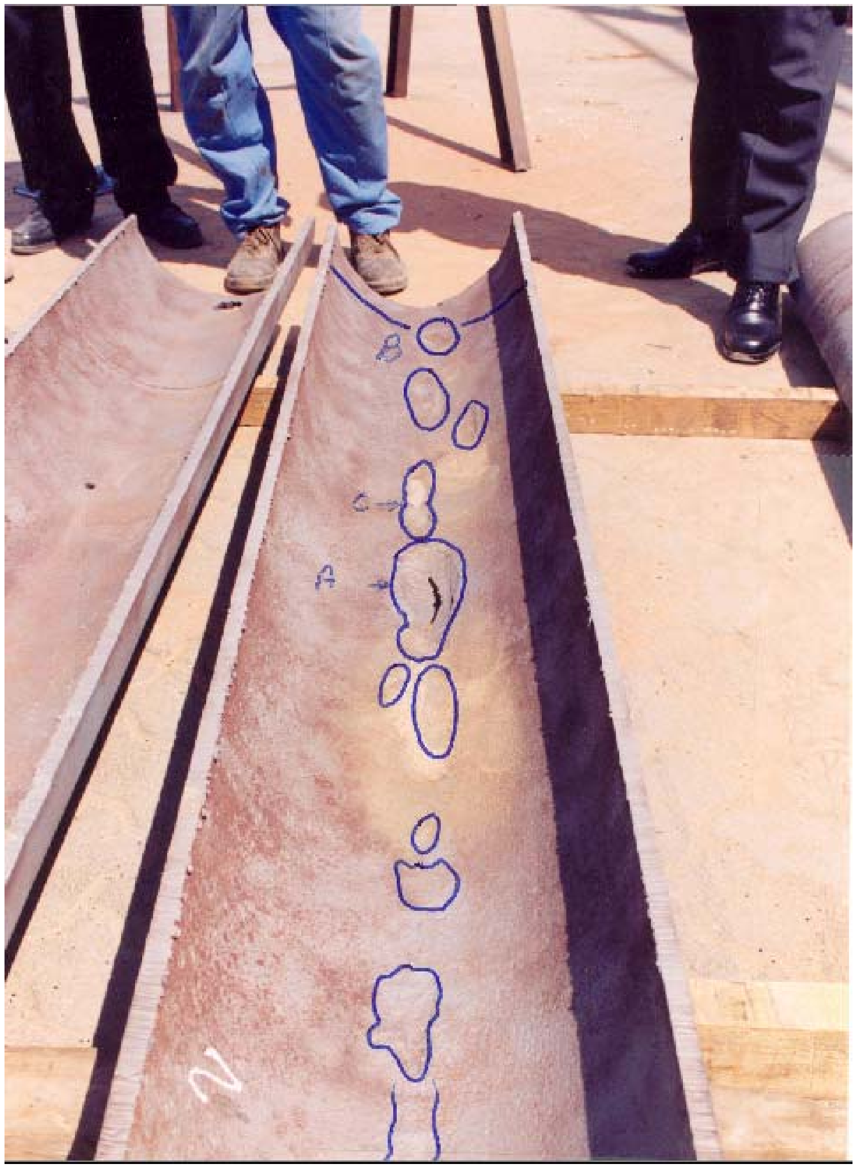


Figure 13 - Failed pipe section recovered with leak clamp
Interconnected Corrosion Pits at 6 o'clock position
Max. thickness at burst location 2 mm

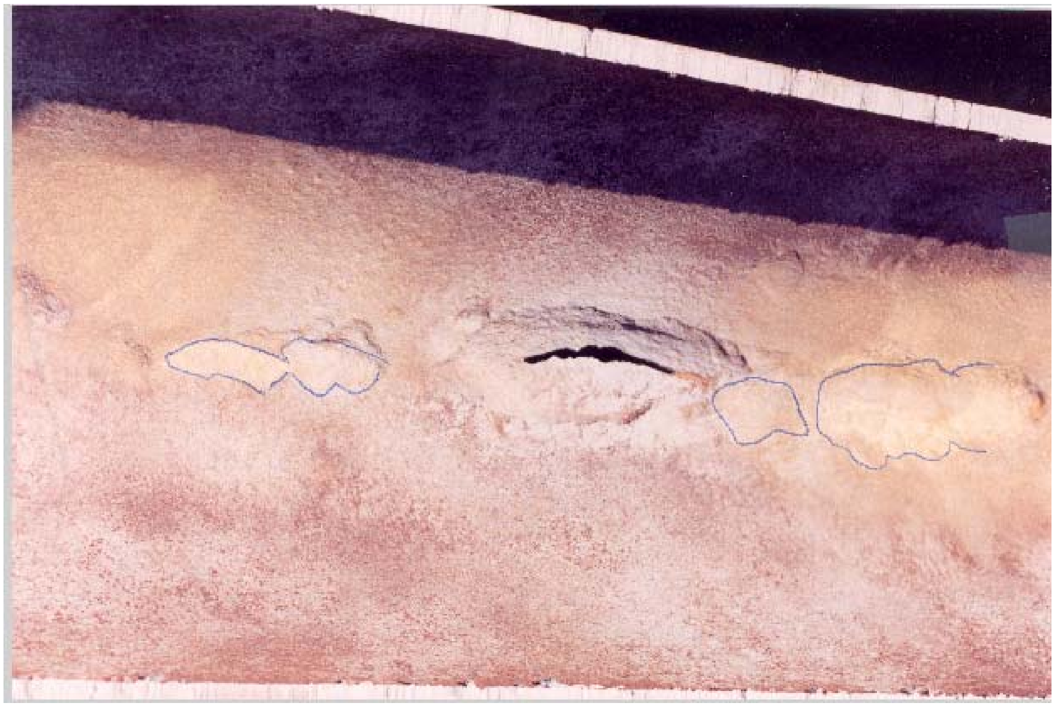


Figure 14 - Internal View

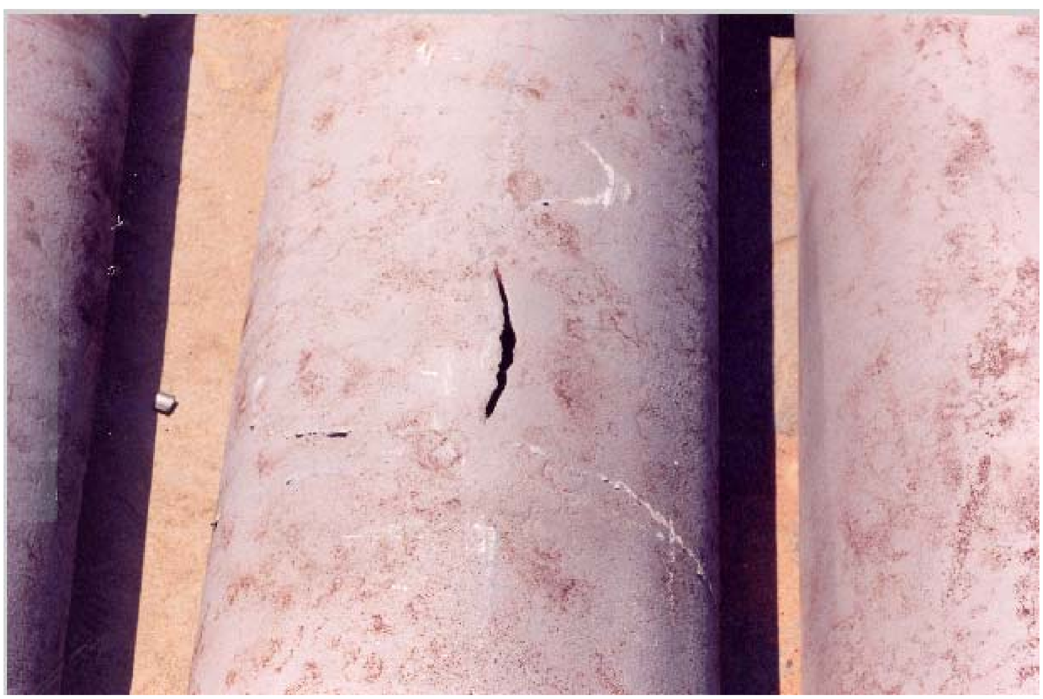


Figure 15 - External View

Figure 16 - Failed Joints recovered with Leak Clamp

Figure 17 - Failed Joints recovered with Leak Clamp

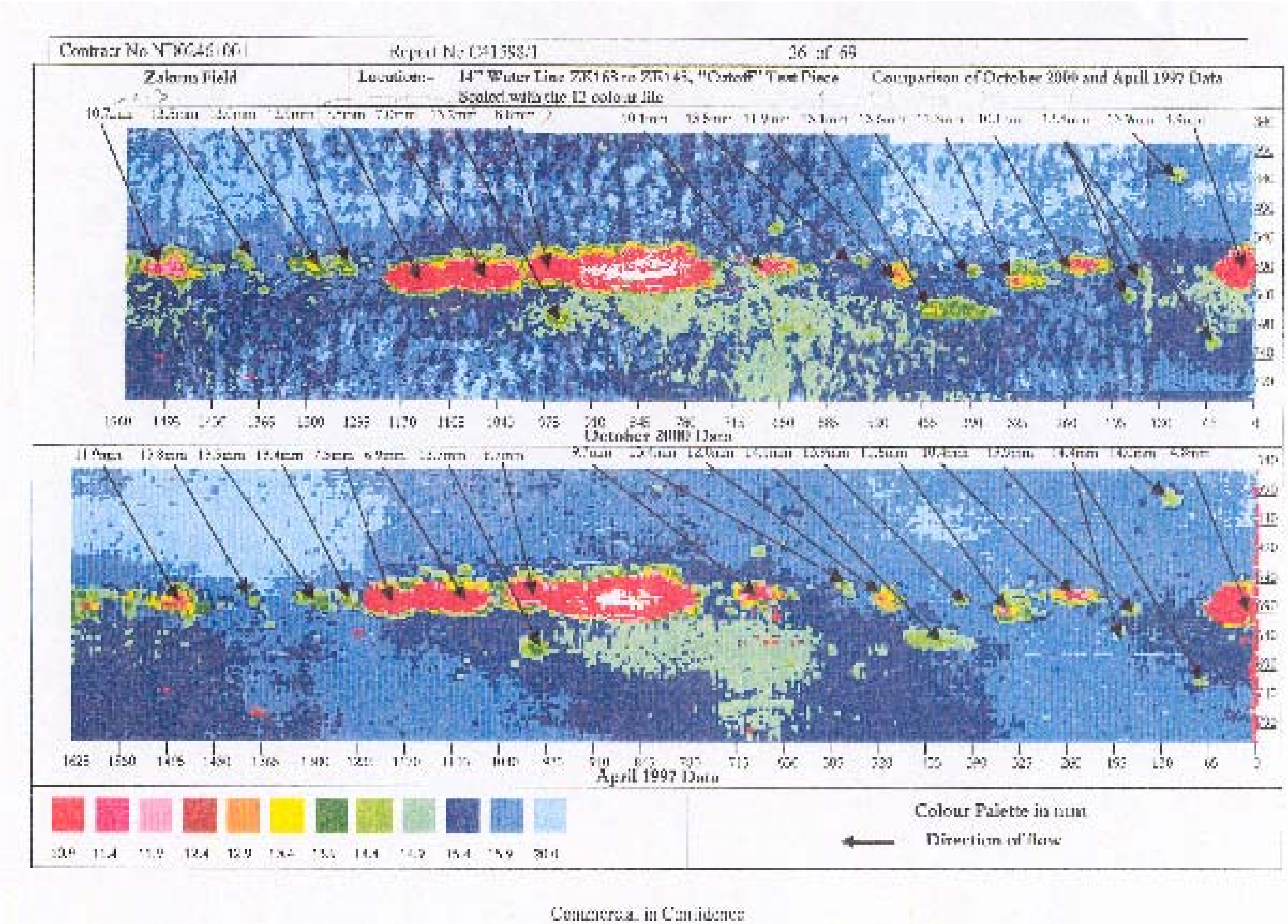


Figure 18

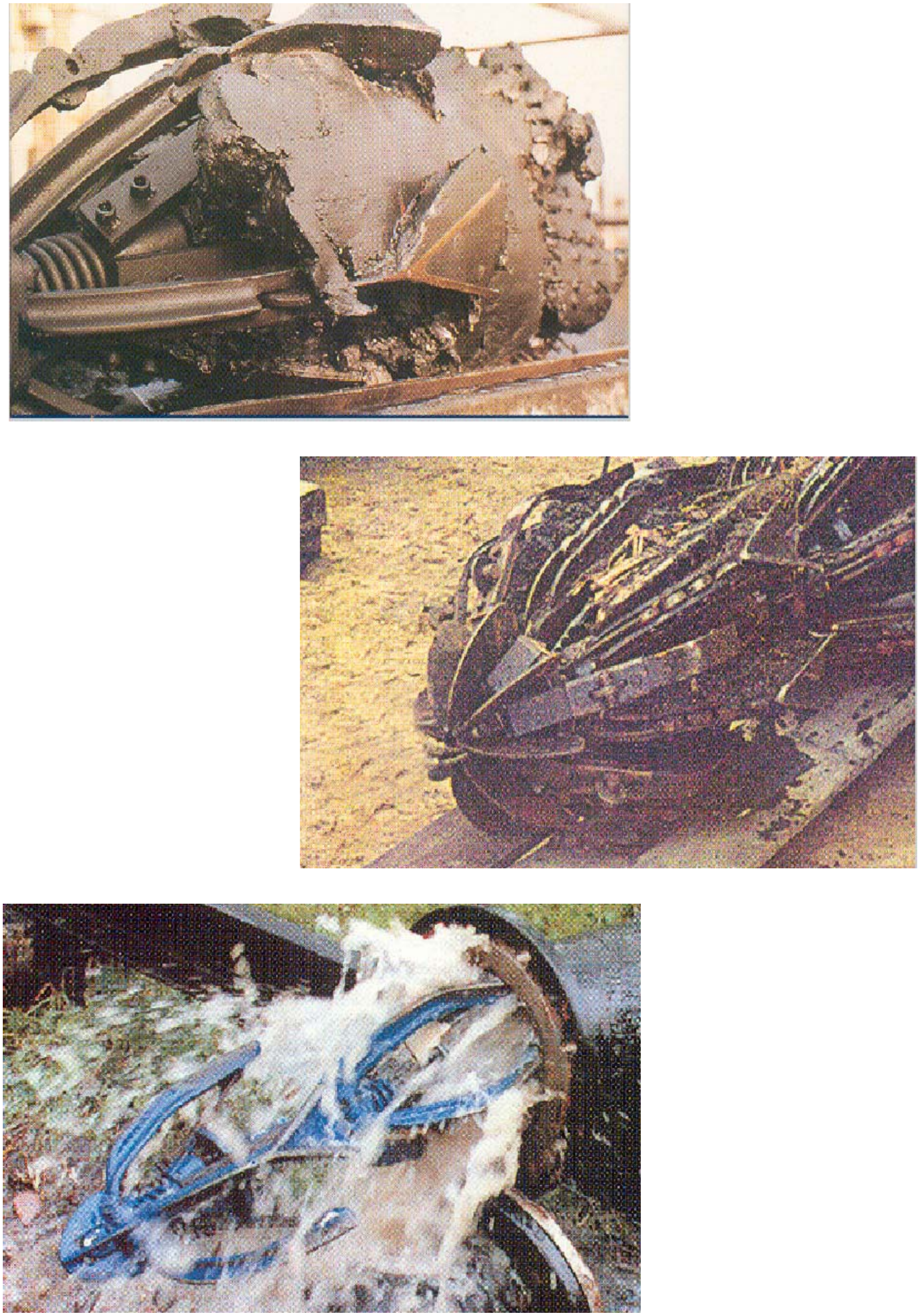
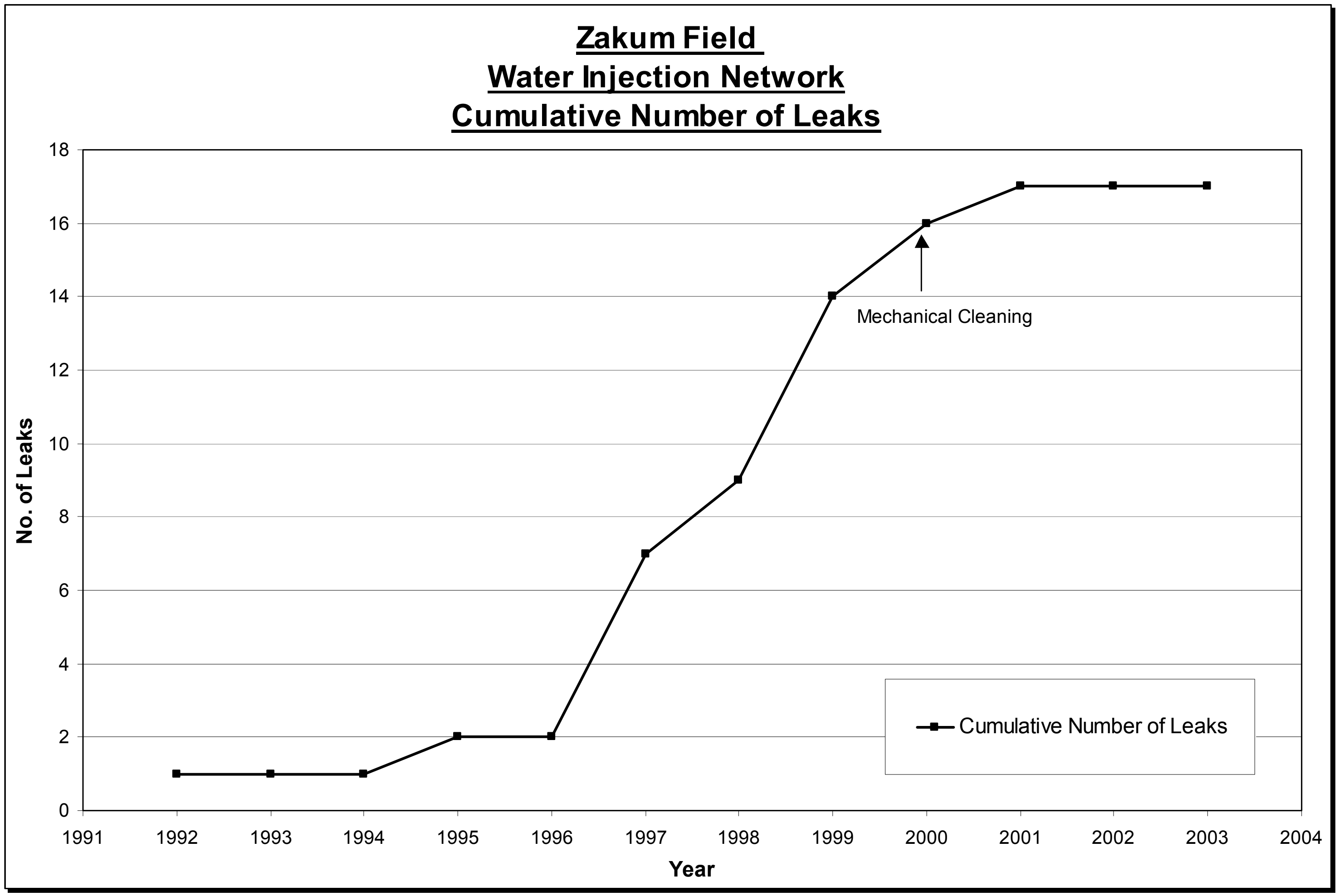


Figure 19 - Mechanical Cleaning Tools



Zakum Field
Water Injection Network
Cumulative Number of Leaks
No. of Leaks
0
2
4
6
8
10
12
14
16
18
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Year
Mechanical Cleaning
Cumulative Number of Leaks

Figure 20

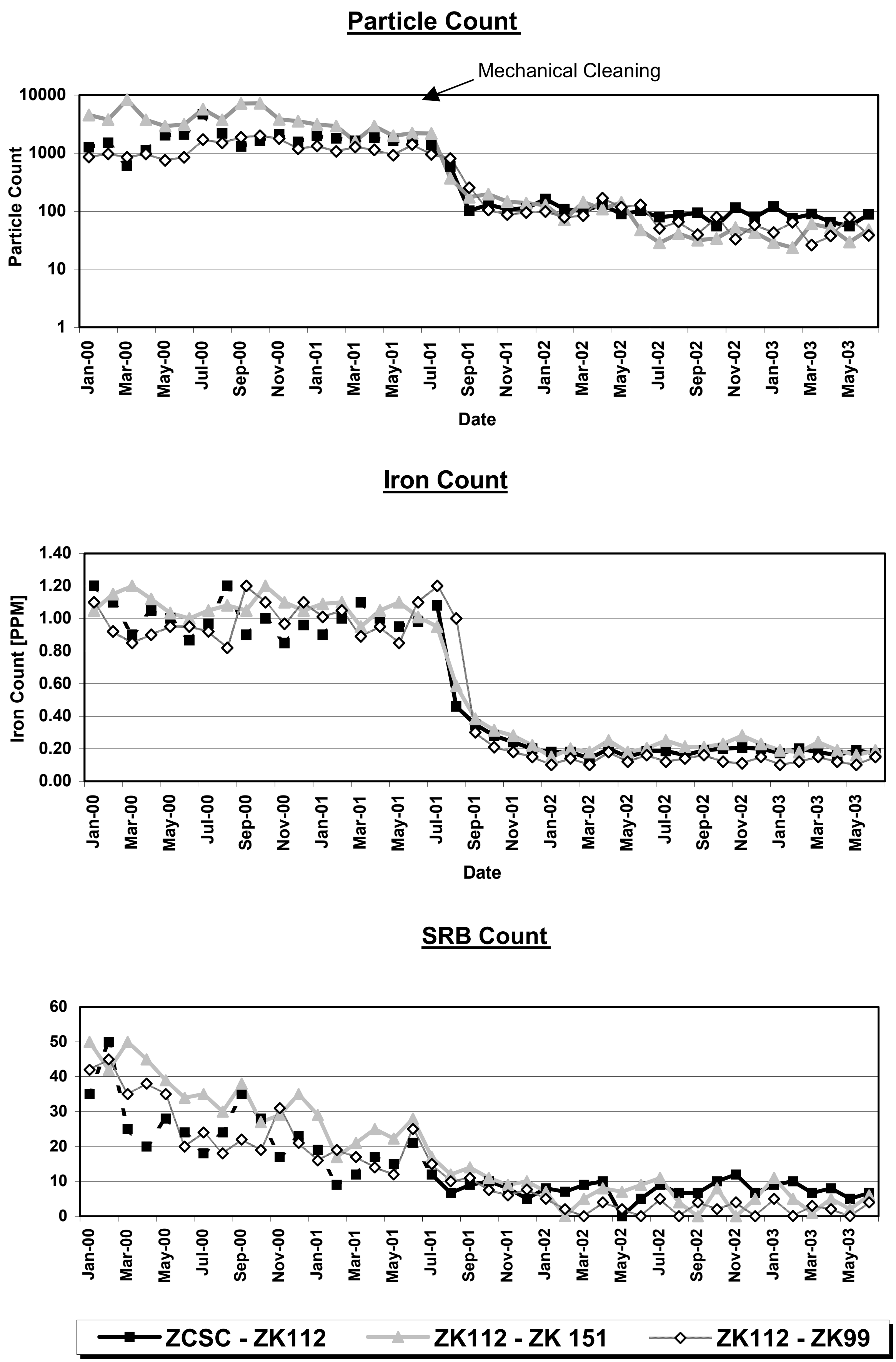

Particle Count
Mechanical Cleaning
Particle Count
10000
1000
100
10
1
Date
Iron Count
Iron Count [PPM]
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Date
SRB Count
60
50
40
30
20
10
0
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
May-03
ZCSC - ZK112
ZK112 - ZK 151
ZK112 - ZK99

Figure 21