FAILURE CONTROL OF DRILL STRIYG COMPONENTS: NONDESTRUCTIVE INSPECTIONS

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ABSTRACT

Nondestructive inspections of dnll string components play a fundamental role in reducing failures. For this reason, ENEL S.p.A. dedicated special attention to the inspection of material in both the manufacturing and acceptance phases.
During the dnlling phase, adequate and constant control is the starting point for correct failure management. Since the inspection standards normally adopted are the ones prescribed by the API oil dnlling standards, ENEL thought it necessary, because of the particular use of the material, to prepare its own specifications for inspection standards and acceptance criteria. Although still satisfying the API standards, these specifications are specially tailored to geothermal drilling.
This, together with other measures for the handling and control of drilling fluids, helped to greatly reduce the number of failures. Just in the period 1988-1990, failures were reduced to a third.
This paper presents the procedures adopted by ENEL to guarantee lasting high quality performance and to minimize failures even in a field like geothermics, where the material is constantly subjected to severe stresses.

1. INTRODUCTION

Geothermal drilling is usually performed with the traditional rotary method used in oil drilling, which produces a rotation of the whole drill suing, from the surface tc wellbottom.
In this situation all the drill string components are subject to variable stresses depending on the position occupied in the string. The main stress on the string is due to its own weight and increases from the wellbottom to surface. Bending stresses are also present due to crooked holes.
The chief causes of drill string failures are cyclic bending and rotating bending stresses which can lead, in the presence of defects, to failure of a component from fatigue ir: a matter of hours.
Geothermal drilling, mostly done in dishomogeneous formations at a low drilling ratr. and in total or partial absence of circulation return at the surface, is performed in more extreme conditions than oil drilling. This is because it does not benefit from the damping effect of the fluid in the well, whose level is often several hundred meters from the surface.
Limiting the number of drill string failures brings not only considerable economic benefits due to shorter well construction times and fewer string components, but also leads to improved safety conditions because of the lower probability of component failure, which can have potentially dangerous consequences.
Since 1988, ENEL had felt a pressing need for a complete revision of its purchasing specifications, especially with regard to the quality of basic materials, production line controls, acceptance criteria and inspection methods for used msteriai. In that year, problems linked to some particular supplies, although not far from satisfying the **API** standards. and an increase of the average well depth and hence of the stresses acting on the material, resulted in a particularly large number of drill string failures.

2. DRILL STRING FAILURES

Failures of drill string components can be caused by problems connected with the well construction, especially when the well axis is particularly irregular, leading to increased tensile and bending stresses. They can be caused by problems connected with the fluids encountered during the drilling, which can lead to corrosion and corrosion fatigue phenomena. And finally, failures can be caused by an inadequate control system which fails to prevent defective components with potential crack initiations from being introduced into the well.

Table 1. Type of crack initiation in drill smng components.Year 1988

DRILL STRING COMPONENTS	FAILURES %		TYPE OF CRACK INITIATION		
			S.C.C.	CORROSION FATIGUE	MECHANICAL
DRILL PIPES	PIPE	88%	/	100%	/
	BOX	6%			
	PIN	6%			
HEAVY WALL D.P.	PIPE	38%	55%	45%	/
	BOX	62%			
	PIN	/			
DRILL COLLARS	PIPE	/	42%	4%	54%
	BOX	92%			
	PIN	8%			
SUB/ STAB.	BOX	94%	11%	33%	56%
	PIN	6%			

Table 1 shows the percentage breakdown of the failures that occurred in 1988 according to failure type and affected drill string component. The table distinguishes between drill pipes, heavy wall drill pipes and dnll collars, which are subjected to stresses of different kinds due to their different locations inside the well: the former are mostly located near the surface, the others in the terminal part of the well.
From the table we can see that the crack initiations can be traced to a cyclic stress component: a chemical component is always present as well due to the particularly aggressive geothermal environment.
The thicker drill string components working near wellbottom, on the other hand, are mostly affected by failures caused by crack initiations of a mechanical nature.
With the aim of reducing dnll string failures, ENEL took action on several fronts:

- Since the crack initiations always proved to be on the internal surface of the drill string components, we adopted systematic injection, through the drill pipes, of filming amines and H_2O + NaOH, or more effectively $Ca(OH)_2$, + scaling inhibitors in order to reduce the number of initiations due to corrosion by the endogenous fluid used for the drilling. This treatment helps to bring the pH of the fluid circulating inside the pipes in line with the 12.5 value our laboratory tests have shown to guarantee the best operating conditions, and also to prevent $CaCO_3$ precipitation in proximity to fractures producing CO_2.

- In order to reduce the number of cracks occumng on drill collar threads, new stress relief groove profiles with a lower tension concentration have been adopted.
- To reduce failures due to weak mechanical characteristics of the material, the purchasing specifications for drill string components have been modified, focusing attention on the material's basic characteristics, on the manufacturing processes and on product quality control.
- To reduce the defects present on drill string components when they are lowered into the well, the inspection specifications have been modified. These specifications regard both the manufacturing phase and the final acceptance at our pipe shop as well as the subsequent periodic inspections on the used material, also performed in our pipe shop.
- Finally, to reduce the possibility of anomalous fatigue in drill string components due to lack of knowledge of their average life, a new pipe management system has been introduced. This makes it possible to use the pipes in different ways in accordance with the stresses and the safety factor requirements in the different well sections.

Limiting failures also means reduced costs and improved work safety.

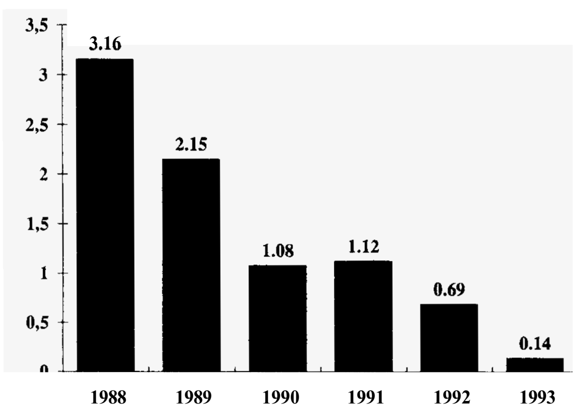


Figure 1. Histogram of failures/km since 1988

In 1988, the cost to ENEL of 3.16 drill string component failures per drilled km, including the time spent to recover the drill string, the loss in meters of well, and the **loss** of material in the well, was estimated, in 1994 currency, at over ME 4000. In 1990, when the treatment of drilling fluids, the modification of the stress relief groove profile of box connection, the improvement of the materials used, the improvements in stock management of the pipes and the new acceptance and inspection methods were in an advanced stage of implementation, the number of failures was reduced to a third.
Finally, in 1993, when all the new procedures were fully in place, the number of failures per km dropped to 0.14. **As** a result, in 1993 the costs for the above-mentioned items, in 1994 currency, fell to M£ 350.
The histogram in Fig. 1 shows the trend of the number of failures since 1988.

3. ACTIONS AIMED AT PRODUCT IMPROVEMENT

The APT standards satisfy quite completely the quality requirements for products for use in oil drilling. When applied to geothermal dnlling, however, they show some limitations, especially with regard to types of inspections and acceptance criteria.
The higher chemical aggressiveness of the fluids circulating in geothermal wells, the greater stresses due to low-permeability inhomogeneous formations, the low fluid level in the wells, which strongly limits the damping effect on vibrations, and the higher well temperatures, sometimes over 400°C, make for a much more extreme working environment. As a result, geothermal drilling requires components which are qualitatively better than the standard.

3.1 Product characteristics

Research was carried out by ENEL in collaboration with the University of Pisa on the fatigue behavior of drill string components in *air* and in a corrosive environment by means of nucleation tests on cracks in specimens with and without notching. Results indicate that in the geothermal environment, in spite of a reduction of the allowable tension, in 10^6 cycles, by about 50% on smooth samples and 40% on notched samples, the API ***G*** 105 and S 135 steels, those most used in the drill pipes, have a very similar fatigue strength.
For this reason, for several years now ENEL has been using only the **S** 135, which in many cases possesses the minimum characteristics needed to withstand the considerably high operating stresses. In this way there is no need to differentiate the drill string components, which is an advantage both at the drill site and in stock management.

Table 2. Mechanical characteristics of drill pipe body and joint

MECH. CHARACT.	PIPE	JOINT
Medium Stress of fatigue limit Wöhler (50% failure probability after 10^7 cycles)	50 kg/mm^2	40 kg/mm^2
Minimum Stress Wohler (10% probability)	45 kg/mm^2	39 kg/mm^2
Minimum Resiliency at room temperature (KV)	G 105: 150 J/cm^2 S 135: 120 J/cm^2	TJ: 90 J/cm^2
Maximum Transition Temperature (Fatt)	-40 °C	-40 °C

In order to guarantee that products of suitable quality are purchased, ENEL has placed special emphasis on the characteristics of the basic materials, on the manufacturing processes, and on controls.
In this regard the Wohler curves of the materials have been required from the manufacturer and resiliency and transition temperature values guaranteeing safe working conditions even at low temperatures and in the presence of accumulations of CO_2 near the surface have been established.
High critical stress intensity factor values have also been required, because research performed by ENEL indicates a sharp increase in crack propagation speed in the geothermal environment for K_{IC} values below 50 MPa*m^{½}. In setting the acceptance values for K_{IC} the production standards of the various manufacturers were also taken into consideration.
The mechanical characteristics required in the manufacturing phase are summarized in Table 2.
The manufacturing process of drill pipe bodies was also examined. It is now required that drill pipe bodies be made by means of a continuous rolling process, which guarantees high quality of the geometry and mechanical characteristics.
The upset zone of the drill pipes is a critical one as it is more subject than others to possible failure because it is a transition zone between two sections with quite different rigidity, the body and the joint.
For this reason, the manufacturer is required to produce pipes on which the upsetting is done with a hot forging process and without any subsequent machining *so* as to obtain a fiber trend that is as regular as possible and free of interruptions, as these are sometimes the cause of crack initiations, especially on the inside surface of the Pipe.
Studies and field tests were carried out to find the best shape for the stress relief grooves of the screw threads because of the high number of failures in the box connections of drill collars, particularly on the last threads.
The analysis was conducted, with the finite-element method, between the API standard profile and other profiles already in use in the oil industry. The load conditions were chosen to reproduce the stress states of the joint in high bending conditions, of instability

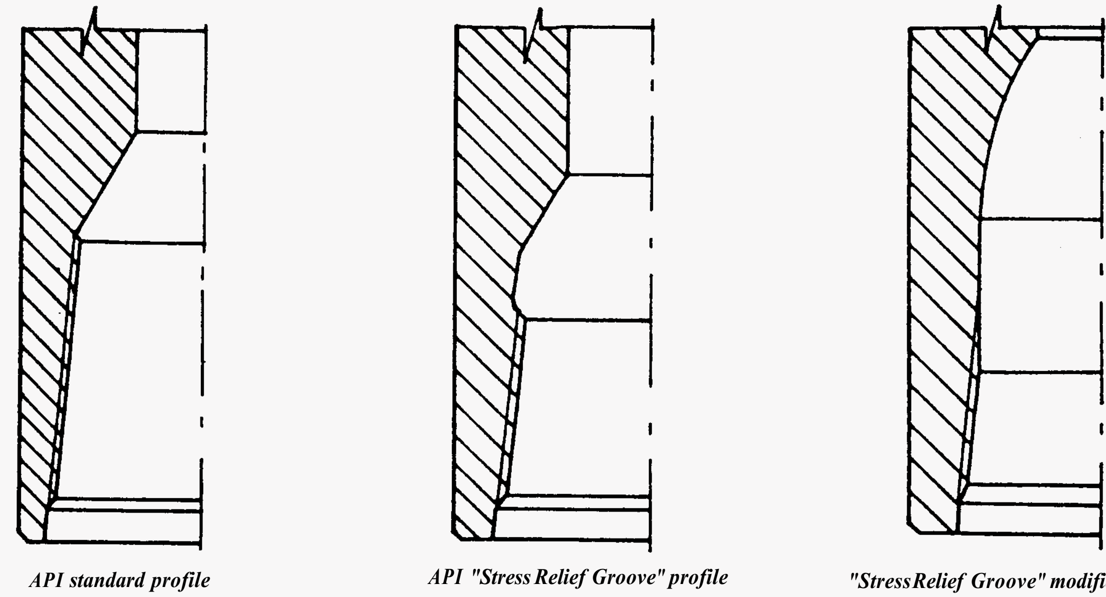


Figure **2.** Box connection profiles in use in ENEL geothermal drilling

phenomena (buckling) or vibrators.
With reference to Fig. 2, the profiles used until 1988 were the API standard type or the **stress** relief groove type. The adoption of themodified stress relief groove, which shifts the highest internal stresses away from the threads, led to a 30% reduction of the stresses acting on the last threads.
In this way, the number of box thread failures dropped from 2 per km in 1988 to less than 0.1 per km in 1993.

3.2 Inspections and tests

Since the failure of just one drill string component can cause sizable economic losses and has safety implications, ENEL decided to extend the main nondestructive inspections to 100% of the components.

Inspections and tests during the purchasing phase

The reliability of a component is determined right in the manufacturing phase. A component that has been designed and manufactured under quality conditions gives greater guarantees in terms of performance and service life.
For this reason, ENEL concentrated its attention on the purchasing specifications for dnll string components, particularly on tests of the material's characteristics, on the inspections on the production line, and on the final acceptance inspections on the material that ENEL performs in its own pipe shop.
In the purchasing phase the supplier is required to carry out inspections on the production line using not only the electromagnetic system, which detects mainly the superficial external defects, but also continuous ultrasonic inspection, which evidences defects located in the "end area," in the metal thickness and on the internal surface. The latter are mainly responsible for the failures in our wells.
In order to guarantee good visualization of the defects, it is also required to the manufacturer, in agreement with the ASTM standards and in addition to what is foreseen by the API standards, that the background noise of the material be significantly lower than the calibration level of the US and electromagnetic inspection equipment.
This not only guarantees good visualization of defects and high reliability of the readings made with these instruments but also ensures a good degree of finishing of the material in all zones, indicating good quality of the production plants and work cycle.
Because of the importance of the quality of the basic material in failure occurrence, ENEL requires the supplier to perform fatigue and transition temperature tests for each casting. Controls on the geometry of the upset zone are implemented by setting limits on the eccentricity, the maximum taper of the upset and its length in order to make the passage between areas of differing rigidity as smooth as possible.
The roughness of the internal surface of this zone, measured in any direction, is required to be no more then 3 µm *so* as to reduce the likelihood of crack initiation.
Drill smng components suitable for the extreme conditions of geothermal wells have to be of good quality at the moment they are used to avoid all the trouble caused by the presence of initial defects. For this reason, the inspections described below are more stringent than the API standards with regard to product type and acceptance criteria.
The pipe body is continuously monitored for longitudinal and transversal defects with the US and electromagnetic methods by means of automatic control systems. This avoids errors due to operator distraction and fatigue and offers the advantage of inspection record availability. The US system features very accurate detection of defects in the material's thickness and on the internal surface, defects responsible for many of the failures in our wells.
Since it is impossible to apply the electromagnetic method on pipe ends, these are inspected by magnetic particle testing, which evidences superficial external defects.
Since many failures are due to defects in weld zones, ENEL requires the manufacturer to carry out US and MS inspections to detect any lack of fusion, inclusions or cracks in the welded zone, both in the thickness and outcropping at the surface. The US system must be able to detect discontinuities within the thickness, defined by an equivalent surface parameter deduced from the lower limits contained in the API standards. This value has been chosen to ensure that all the main defect types encountered in past years on drill suing components from various supply sources will be detected.
With regard to acceptance criteria, more stringent limits are set than those of the API standards for US and MS inspections because they must detect the defects on the pipe body and on the upset, which are responsible for most of the drill pipe failures. The limit for material acceptance corresponds to a maximum 40% of the sample defect defined by the API standards. This criterion is based on a statistical analysis of the defects which have been encountered in various production standards and accepts the best quality standard existing on the market.

Inspections and tests during operation

The purchasing specifications guarantee the purchase of a quality product suitable for use in the geothermal field. The quality of the purchased components should always be kept as high as possible, even after use in the wells. ENEL therefore decided to build a special workshop to recondition drill string components; the shop has been in

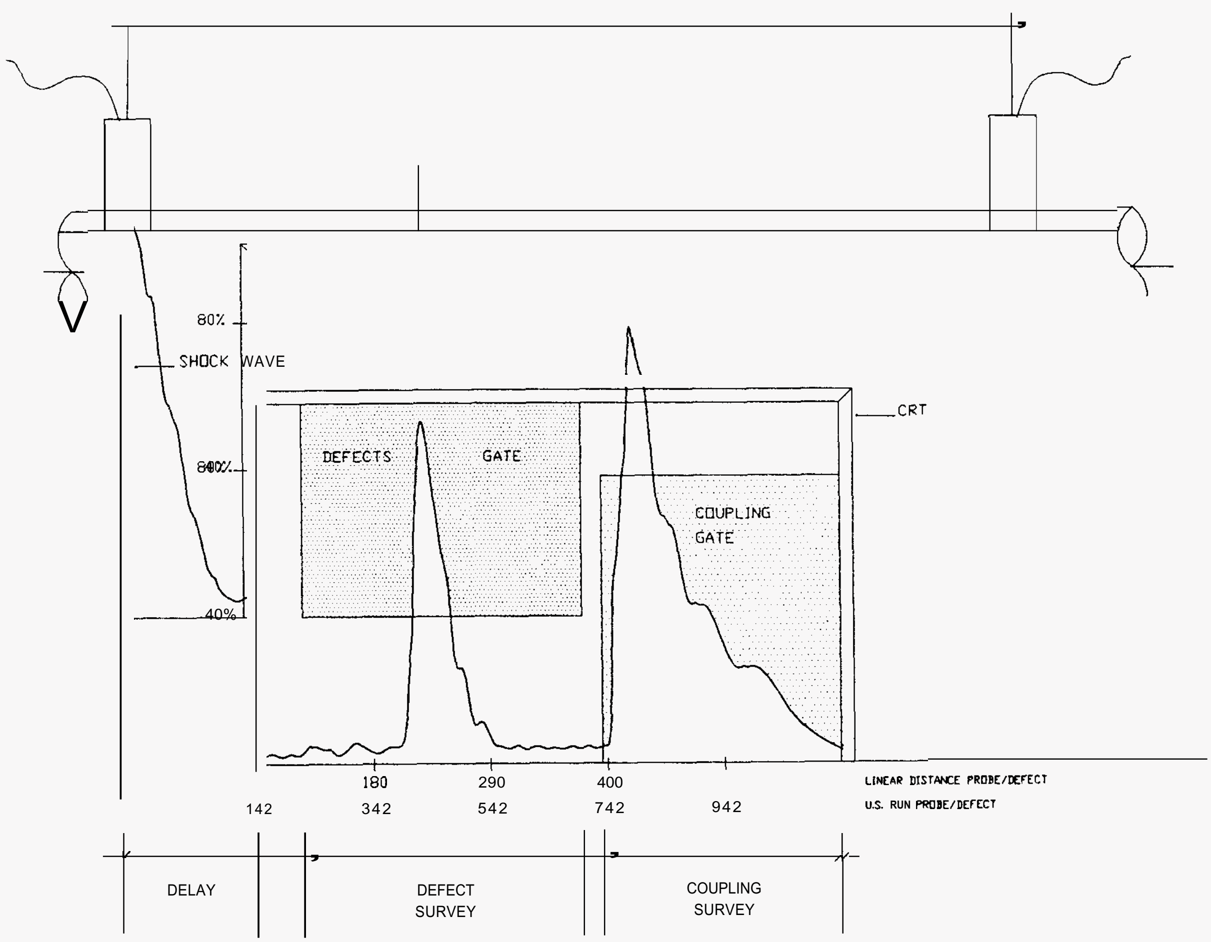
operation since 1989. Specifications have been drawn up for the inspection, testing and maintenance of the pipes when they return from the drilling yard.
The inspections on the used material have the twofold purpose of eliminating any defects that might cause failures in the wells later on and, no less importantly, of identifying and correcting any anomalous utilizations or severe stresses on the material inside the wells.
At present no inspections are performed on the material directly at the dnll site during the drilling, except in a very few special cases. The recent failure statistics, after adoption of the measures described in section 2, do not justify additional expenditures, in terms of rig stoppage and the allocation of workers and equipment, for intermediate inspections at the dril! site.
The specifications were drawn up bearing in mind the typical defects encountered on the used material and include stipulations for instrument calibration so as to guarantee repeatable and reliable controls.
In particular, attention is focused on the US inspections, which are performed automatically in our specialized pipe shop: the methods and times for probe calibration, sample defects and acceptance limits are precisely defined.
As far as drill collars are concerned, the failure statistics showed that 100% of the failures in these components occurred in the last thread of the box connection due to fatigue corrosion starting on the internal zone.
Therefore, two steps were taken: the first was to modify the stress relief groove profile of the screw threads, which greatly reduced failures in the welis; the second was to systematically rethread the box connections at every end-of-well control in the shop. This has almost completely eliminated the problem.
The decision to rethread the box connections was based on two main reasons:

- The first regards the analysis of the results of the nondestructive inspections performed on failures of box connections equipped with the new relief profile, which always revealed evidence of a certain number of cracks near the end of the thread. This means that the adoption of the new profile lengthened the life of the threads but did not completely eliminate the occurrence of cracks on them, Systematic rethreading of the box connection also has two advantages: it eliminates possible crack initiations which cannot be detected by means of NDI but can cause failures in the well, and it reconditions the material, canceling the history of previous fatigue cycles. The inspections had shown the material's average life expectancy to be only slightly longer than the life of a well.

- The second reason regards the statistical analysis of the wear of drill collars rejected because they were too short to be used. Because of the systematic use of the material in strongly abrasive formations, rejection for length coincided 90% of the time with rejection for diameter. The remaining 10% was close to this value. Given this situation, ENEL opted for systematic rethreading at the end-of-well control, since this guarantees the material used in the wells is free of defects and has a history of a low number of fatigue cycles and therefore a low probability of failure.

Main characteristics of the pioe reconditioning plant

Since inspections on drill string components, particularly drill pipes, have become a real necessity in order to help reduce failures in wells, ENEL decided to build an autonomous inspection plant. The decision was motivated in part by the expectation of a large work load in this area, and this has proved to be the case.



The plant was designed and built according to specifications drawn up by ENEL so as to guarantee material in complete conformity with the requirements of geothermal drilling as they evolved from analysis of the defects encountered in operation with the material to be inspected.
Besides fixing all the anomalies found on the pipes, such as restraightening, restoring the shoulder, rethreading and eliminating the external superficial defects, the plant is equipped with a modern continuous US inspection system, both for defect detection and thickness measurement.
The US equipment consists of a set of probes connected to the pipe surface by means of a trickle of water made up of two pairs of crystals, both transmitting and receiving, focused and arranged radially. The two pairs of crystals emit a US beam with a particularly high angle in steel. The reflected beam is received by each pair of probes, thereby revealing transverse defects of any orientation.
A schematic of the detection system for transversal defects is shown in Fig. 3.
Longitudinal defects are detected by means of special probes coupled by means of a column of water and mounted on the same probe holder.
The wide detection range of the probes enables continuous inspections and correct assessment of any defects that are found and allows them to be viewed from various distances.
The equipment can automatically adjust the US beam intensity to the distance of the defect from the probe and to the quality of the metal/probe coupling. This makes it possible to evaluate, with the same degree of precision, both defects very near the probe and defects at greater distances, which are sometimes at a more convenient detection angle because of their different orientation with respect to the beam, thereby enhancing inspection reliability.
The particular arrangement of the probes allows excellent detection of defects present in the upset zone and especially in the weld zone.
Since any inclusions or defects present in the basic metal are concentrated, during the manufacturing process, in the upset and weld zones, this equipment is vital for verifying the quality of the basic metal and for accurate detection of the main defects of the material being purchased.
Finally, the plant can acquire the data automatically, which is then stored in a data base. This aspect is very important in order to follow the evolution of the defects and to check for any reoccurrence of certain defect types.
The automatic MS equipment is divided into two sectors. In the first the magnetic inspection of the ends of the drill pipes is performed. It is extended to the whole end area, using both the continuous method and the residual method, by means of a coil for detecting transversal defects and direct current flow for detecting longitudinal defects. In the second sector, the drill collars are magnetized by means of equipment specifically designed by ENEL, capable of magnetizing and demagnetizing drill collars up to an outside diameter of 11½", to detect transversal defects, particularly in the screw thread zone and in the stress relief grooves.
For a control system to offer guarantees of reliability the calibration must be constantly verified. For this reason, the US system is recalibrated at set times during the day, making sure the working temperature has already been reached in order to avoid thermal drift of the system.
The calibration is performed on the sample defect as prescribed by the API standards and is achieved by means of electric discharge machining.
At the end of the inspection, the pipes are stocked in special containers, differentiated according to their hours of work and their use in the yard.
The maximum capacity of the shop is 50 pipes in an eight-hour working day. At present, 8000 pipes plus 1000 other components are reconditioned per year.

4. ECONOMIC ANALYSIS

Any requirements above and beyond the manufacturers' standards necessitate a benefit-cost analysis.
Improving the quality of the material entails an initial increase in the purchasing and management costs which must always be justified by a subsequent overall cost reduction.
The sharp drop in the number of failures in the years following the implementation of all the actions indicated in the preceding points testifies to the considerable economic advantageousness of improved component quality and from the better operating conditions. Failure-related costs have decreased from over M£ 4000 in 1988 to about M£ 350 in 1993. In order to facilitate comparison, these figures and the ones presented below are in 1994 currency.
In particular, as far as controls are concerned, compared with an annual expenditure just for US inspections of approximately *ME* 180, defects were found by US in about 90 used pipes, on the internal surface of the end area and in welds, which would probably not have been found with other types of inspection. It has been statistically demonstrated that in our wells. similar defects are the main sources of cracks in dnll pipes. Therefore, if these pipes had been used without US inspection, they would have caused failures in wells, with an estimated cost 20 times higher than the outlay.
Even more evident are the advantages derived from the reconditioning activities of the shop, where the yearly expenditures for complete reconditioning of the drill pipes, including rethreading, amount to M£ 1100. The savings achieved due to the salvaging of otherwise unusable material and the reduction in the number of failures were almost five times the expenditures just for the drill pipes. If we also include the drill collars recovered as a result of reconditioning, the savings are even greater.
Conversely, the extra costs for the higher quality material and the additional inspections during manufacture are fairly limited, less than M£ 200 per year.
The cost of carrying out the treatments of the fluid in the well is of the same order of magnitude, since it is performed with ENEL personnel and equipment.
The advantage of a lower number of failures in the wells, thanks to the better quality of the material purchased, cannot be directly quantified because it is closely connected with all the other precautions taken to improve the material and operating conditions. It is certainly far from negligible, and more than offsets the outlays for improved quality.
Finally, it must be mentioned that the costs outlined above are the average costs sustained in the last few years of activity.

5. CONCLUSIONS

Deep geothermal well dnlling is tough on drill string components.
This is attested to by the high number of drill pipe failures that occurred at ENEL, particularly in 1988. These failures have significant economic consequences and pose potential problems for the safety of the workers and of the well.
ENEL therefore decided to undertake a series of actions aimed at improving the quality of the material in the manufacturing and operation phases.
Examination of the causes of drill string failures pointed to the following areas where improvements had to be made. Experience in the field has confirmed them to be decisive in reducing failures:

- pumping of filming amines through the drill pipes to protect the pipe steel and control of the drilling fluid to reduce chemical attack, stabilizing pH values around 12.5 by injection of H_2O + NaOH or, more effectively, $Ca(OH)_2$, both accompanied by a scaling inhibitor

- modifying the stress relief groove profile of box connections, which led to a 30% reduction in stresses on the ends of the threads, where over 90% of the failures occurred in drill collars, subs and stabs

- systematic rethreading of box threads at wellbottom, to cancel the material's stress history

- developing specific purchasing techniques by redefining the mechanical characteristics of the material, the range of variation and the product acceptance criteria, especially for US inspections

- developing inspection specifications for used pipes and building a drill string component reconditioning plant equipped with inspection instruments, particularly US, built according to ENEL specifications to optimize defect detection

- developing in-hole pipe management and utilization system, forming a data base to reconstruct the history **of** the pipes, both on the level of utilization in the yard and from the standpoint of defects. The available data proved to be extremely useful for optimizing both the use of the material, differentiating its use in the wells, and the frequency of inspections
- systematic drill string inspection as a function of the working hours of the pipes

All the above actions, in which nondestructive inspections played a fundamental role, brought a 95% reduction in the number of pipe failures, per drilled km, in the space of *5* years, with a substantial yearly economic saving, based on the estimated failure costs.

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