STRUCTURAL MODELS FOR THE ANALYSIS OF STRESSES IN THE CASINGS OF GEOTHERMAL WELLS

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ABSTRACT

This paper illustrates an exacting work undertaken by ENEL to gain greater insight into the behavior of geothermal wells, seen as a structural element subject to thermal and mechanical stresses. The stresses that occur in the casing in connection with temperature variations due to well operations are examined after the development of suitable structural models. These models take into account the presence of defects in the cementing of the casing annulus which are related to the way the casing has been set and cemented.
Such stresses are also used as input for design and strength verifications, as well as for fatigue analysis.
Finally, comparison is made with the results of statistical research on damage that has occurred in the wells drilled by ENEL in the last five years. Agreement with the conclusions drawn from the above-defined models is excellent.

1. INTRODUCTION

ENEL has a geothermal tradition extending back over a century. This tradition also includes well drilling operations, and a few figures will give a precise idea of its scope. Taking into account only wells drilled from 1926 to the present, we have a total of 872 wells for a total length of 1014 km.
Naturally, since that date great progress has been made to cope with the increasingly difficult problems involved in drilling wells to increasing depths. In this regard it is enough to consider that while the average well depth up to 1946 was less than 350 m, this figure rose to around 700 m in the period 1946-1961, about 1000 m between 1961 and 1975, approximately 1900 m from 1975 to 1988 and finally over 2800 m in the period 1988-1994. Note, too, that many wells have been drilled to depths over 4000 m, the maximum being Torre Alfina 15, depth 4826 m.
This evolution necessitated a corresponding improvement in drilling and cementing techniques and in the materials used.
Over the years the areas of interest also became larger. Starting from the traditional Larderello area, they extended to the neighboring areas until, in the early 1970s, they were including other areas such as the Amiata and Latium fields. It became necessary to tackle new sets of problems connected with the different geological situations and the more extreme conditions of the fluids contained in the formations crossed by the drilling.

For all these reasons, the well projects implemented directly by ENEL specialists have evolved over time: new types of casing have been selected, and the use of special equipment has become quite common.
In the course of time many efforts have been made to increase the number of tools suitable for use in specific geothermal applications when required by circumstances. By way of illustration, we can cite special cementing equipment (multiple stage cementers, packers, liner hangers, etc.), mud motors, special high temperature muds and cements, light fluid drilling, instruments for in-hole measurements, etc. Italian geothermal wells are characterized by extreme thermal conditions, with local geothermal gradients over 0.3°C/m and temperatures above 350°C at 3000 m. Moreover, they are characterized by high risk fracture areas (lost circulation is frequent) and the presence of aggressive fluids.
Therefore, an analytical theoretical well model must be made available to the designer to allow him to integrate his knowledge and develop a synthetic explanation capable of describing what happens in the various drilling phases and in the functioning of the well.

Such a model has to include the casings, the wellhead, the cemented annulus and the formation, as least in *so* far as it influences the behavior of the installation.

2. PURPOSE OF THE WORK

In order to better accomplish the above task, ENEL realized several years ago that the theoretical well model on which the design considerations rested was inadequate to satisfactorily explain many events that occurred during the drilling and/or operation of the well, such as the damage sometimes caused to the 13 3/8" and 9 5/8" production casings.
It was also necessary to define an up-to-date model in order to ensure safe well operation for the ENEL Exploitation Unit for the planned lifetime of the well and to supply adequate information to the Mining Authority.
These requirements concern the state of the cementing, since it is well known that a complete interspace filling with cement **of** suitable strength and characteristics is of capital importance for correct casing functionality. This is particularly important for the verification of wellhead and casing behavior, especially of those portions that we refer to as the casing "cooperating depth."
In connection with the opening and closing cycles of the well the analysis must also include an assessment of the fatigue behavior.
In the ENEL Drilling Unit the integration of new elements of knowledge into an organized picture is seen as desirable and necessary. This will lead to a new "Method for Geothermal Well Casing Design" including a technical/economic optimization procedure, to be used both in the design phase preceding the drilling and for recalculating the casing in connection with new elements that come to light as the work progresses.
For all these reasons, a highly qualified engineering firm was charged with developing a structural model suited to take into account the various situations occumng in the work, on the basis of precise inputs provided by the ENEL Drilling Unit engineers, who assisted the assigned specialists through all the phases up to the final verification.
This paper describes the main results of the study and a first comparison with the results of a statistical research on casing damage in production wells drilled during the last five years.

3. WORK DESCRIPTION

Developing a structural model to optimize the planning of a casing installation requires thorough analysis of all the major factors that concur in achieving safety, reliability, functionality and economy of a geothermal well.
The aspects to be included in evaluating the dimensioning and

realization of a casing installation can be divided into the following two main categories:
- aspects connected with the geomorphologic and geophysical characteristics of the formations (formation pressure, fracture gradient, etc.);
- aspects regarding the casing's structural features, with reference to the stresses applied during the setting, execution of the cementing, drilling progress and well operation.

In this paper the latter aspects have been given special emphasis, in relation to possible casing cementing defects.
Such defects are usually due to:
- insufficient mud displacement by the cement slurry;
- inadequate control of the "free water" and "fluid loss" values in the slurry at high temperature;
- difficulty of filling up highly fractured zones;
- "gas migration".

In particular, the analysis considered:
- imperfectly cemented portions of casing in the presence of thermal stress and axial action;
- imperfectly cemented portions of casing in the presence of water and gas pockets subject to thermal action as a consequence of the well's operation;
- fatigue problems in a casing installation.

In what follows we have tried to summarize an extensive work whose theoretical and fundamental calculation aspects are contained in the four proprietary reports cited in the references written by "Sistemi Dinamici S.r.l.".
Given the necessity of limiting this paper to six pages the details of the calculation and the related mathematical formulas have been omitted.
For its presentation, use has chiefly been made of synthetic diagrams chosen among the many possible, with the intention of giving an idea of the reasonings developed.

3.1 ANALYSIS OF IMPERFECTLY CEMENTED PORTIONS OF CASING IN THE PRESENCE OF THERMAL STRESSES AND AXIAL LOAD

The analysis is performed by considering the instability phenomena the elastic equilibrium of the plant undergoes due to thermal stresses and a possible axial load, and by taking into account the variations of the mechanical characteristics of the material the casing is made of.
In order to define the thermal stresses it is necessary to make two prudent hypotheses:
- the cement setting temperature of the annulus betwen the internal and the external casing (or the formation) is between the circulating and the static temperature;
- the casing temperature value after the production test depends ot the production fluid temperature, which in our case was assumed equal to the bottom hole static temperature.

From Fig. 1 it is possible to obtain, for each depth, the casing temperature increase under the hypotheses made.

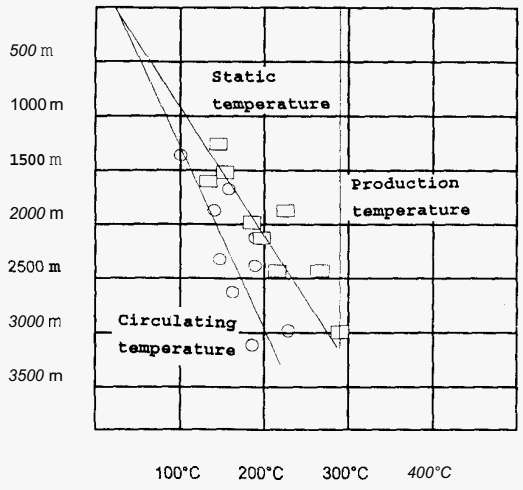


Fig. 1

Such a temperature increase causes stress due to hindered thermal expansion of the casing, partially offset by a possible state of traction that may have been produced during the hardening of the cemented annulus.

This stress in imperfectly cemented zones can lead to structural collapse which can be traced to one of two causes:
- collapse due to instability in elastic field;
- collapse due to yielding by post-buckling.

In cemented zones, on the other hand, there is a possible degradation of the material's strength characteristics due to the fact that its yield stress has been reached.
Such phenomena, however, do not cause geometrical deformations affecting the profile and the cross section through which the casing goes and it is analyzed in the following in connection with the effects of oligocycle fatigue produced on the casing by repeated thermal cycles.
In the case of collapse due to Eulerian instability in the elastic field, not considering, for the moment, the effects due to the pressure of the fluids in the casing, it is possible to evaluate, by using parameters for each of the casing types (diameter and thickness), the critical length of the uncemented section (maximum length above which the collapse of the structure occurs due to instability in the elastic field) dependent on the preexisting traction axial load and on the temperature increase as a function of the depth.
Examples of such relations are given in Figs. 2, 3 and **4.**

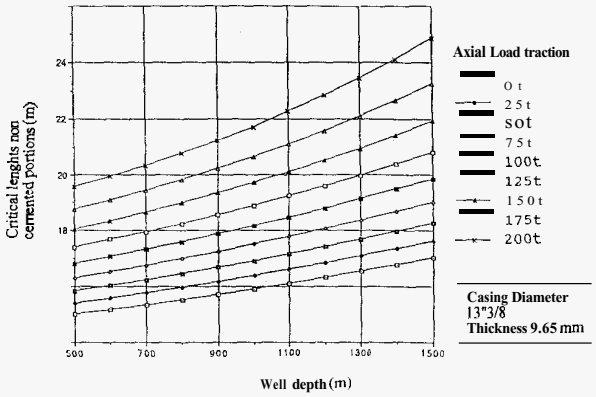


Fig. 2

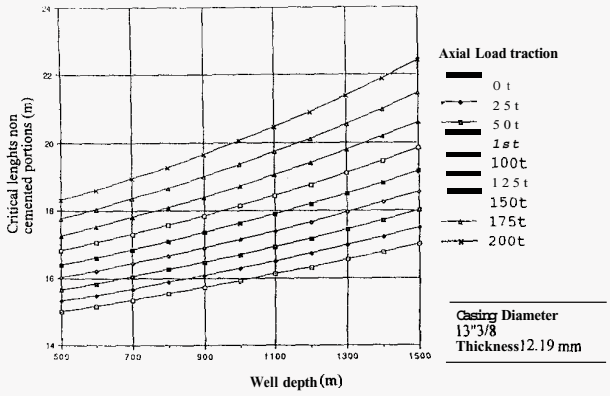


Fig. 3

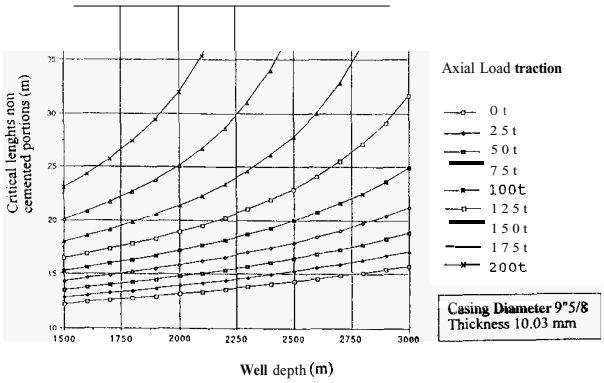


Fig. 4

Clearly, an increase in the outside diameter of the casing, thickness being equal, has a positive effect on stability, while at equal outside diameter, an increase in thickness has a slight negative effect.
These conclusions are conditioned by the fact that, in first analysis, the effects of the fluids pressure on the casing have been neglected.
It can also be observed, for example, that for 13 3/8" casing 12.19 mm thick, in the well section near the surface, the critical length for uncemented sections is 15 m.
A critical length of the uncemented section about 20% greater could be attained by applying a pretensioning of 200 memc tons, but these benefits are difficult to achieve because the necessary preloads are too large and because of the practical difficulty of applying them.

In the post-buckling case the analysis starts from the hypothesis that the casing, once the critical Eulerian load has been overcome, comes to rest upon the uncemented wall of the hole, with an f value of the casing displacement depending on available gap between the casing and the hole.
The goal of the analysis is to deduce the conditions which make the piping plastic.
The stress on the casing is considered to be the sum of the axial stress of thermal origin, corrected for the effect of the possible traction preload, and the bending stress due to deformation of the casing. Therefore, it is possible to estimate, by using parameters for each casing type (diameter and thickness), the critical value of the casing displacement (above which the material becomes plastic) in the above-defined conditions, depending on the depth and on the pretensioning axial load. Such relations lead to the results summarized in Fig. 5.

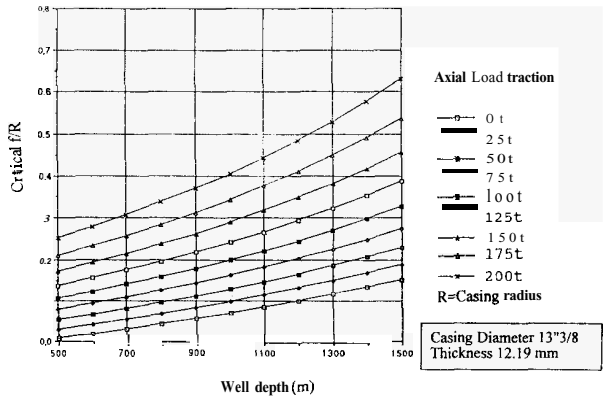


Fig. 5

It can be observed that, for the casing type already considered, in the well portion near the surface the material becomes plastic as soon as the critical Eulerian load has been overcome; however, when a preload of 200 metric tons has been applied the material becomes plastic with a displacement of 70 mm.
Finally, it can be stated that the preload produces tangible effects, relative to the applicable amount, only in protecting the casing from plastic deformation, hut not from elastic instability.

3.2 ANALYSIS OF IMPERFECTLY CEMENTED CASING PORTIONS IN THE PRESENCE OF WATER AND GAS POCKETS, SUBJECT TO THERMAL ACTION AS A CONSEQUENCE OF WELL OPERATIONS

In order to evaluate the action of water and gas pockets existing in imperfectly cemented portions, a model has been specifically developed which allows one, knowing the outflow rate and the thermodynamic state of the steam/gas, to evaluate, instant by instant, the following quantities:
- time variation of the well temperature at the considered depth;
- unitary thermal conductances of the well's side and pocket;
- thermodynamic state of the fluid in the pocket;
- total and partial pressure for each component in the pocket.

To carry out the analysis of the adopted model some remarks must be made on the way the well portion was schematized. The system is assumed to be formed by a casing situated at a certain depth "H", of external diameter "D", surrounded by an uncemented ring-shaped space, filled with water and/or gas, as represented in Fig. 6.
In the shallowest zones of the well (<500 m) where the thermal stresses take on the highest values and where statistically the greatest number of failures occur, the most harmful pockets are those between the production casing and the external casing.
Starting from this observation it is hypothesized that the surface of the pocket is completely impermeable to the fluid under pressure contained inside it. In any event this hypothesis is a cautious one in case the pocket comes into contact with the external formation since any formation permeability or the fracture pressure value can only attenuate the pressure peaks reached by the fluid in the pocket.

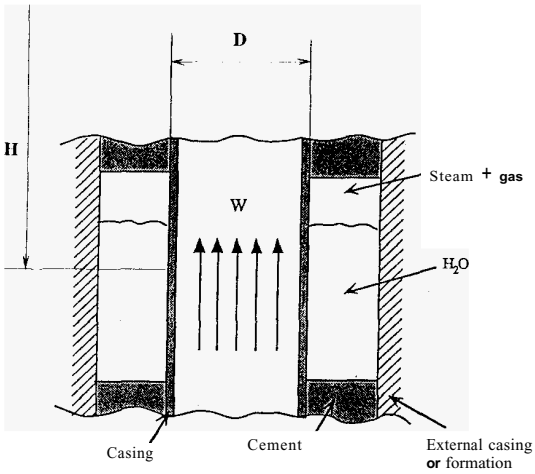


Fig. 6

As a consequence of a well temperature increase which may be due, for example, to a production test, the casing is run through by the outflowing fluid, at the temperature of the endogenous steam, with a speed depending on the flow rate and on the thermodynamic conditions of the fluid. For the above-described system it is hypothesized that there are no thermal exchanges with the external casing or with the formation; this hypothesis is conservative since the heat which should be absorbed by the formation is stored completely by the fluid in the pocket.

From the mechanical standpoint this system is similar to a thin-walled cylinder with the upper and lower rims constrained, subjected to a pressure ΔP (obtained as the difference between the pressure of the pocket and the pressure of the fluid inside the casing) and to a stress due to hindered thermal expansion.
Obtaining, as a function of the geomeuy of the system:
- the critical stress ocr of axial instability due to axial load, assuming ΔP=O;
- the critical pressure of collapse ΔPcr, the axial stress assumed to be nil;
- the pressure ΔP obtained by the difference between the pressure in the pocket and the pressure inside the casing;
and applying the criterion for determining the collapse due to instability of the system under the combined effect of the axial compressive stress oa and the pressure P (H. Baker, L. Kovalvski, F.L. Rish, 1972), "Structural analysis of shells," McGraw-Hill):

$$\frac{oa}{ocr} + \frac{\Delta P}{\Delta Pcr} = 1$$

it is possible to evaluate the axial compressive stress that leads to the collapse of the structure

$$\sigma a = \sigma cr \cdot (1 - \frac{\Delta P}{\Delta Pcr})$$

Indicated with:
- σt the stress that is generated in the system due to the hindered thermal expansion, a function of the differential temperature of the fluid produced by the well and the cement hardening temperature at the considered depth.
- of the "frozen tensile stress" which is the stress resulting from the weight load and the pretensioning load applied during the hardening of the cemented annulus.
In order to avoid collapse of the system must be:
$|\sigma a| > |\sigma t| - |\sigma f|$

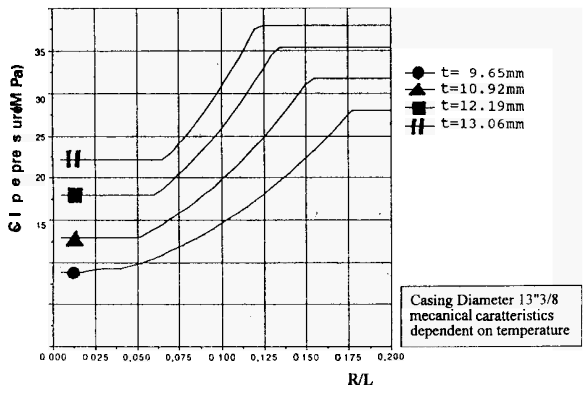


Fig. 7

Fig. 7 shows the values of the critical pressure of collapse ΔPcr for a 13 3/8" casing as a function of the thickness t of the casing and the length L of the uncemented section.
Fig. 8 shows the values of the axial compressive stress oa that lead to the collapse of a 13 3/8" casing 12.19 mm thick in the presence of a pocket of length L=3.4 m, as a function of the volume percentage of water and geothermal gas contained inside the pocket (obtainable by means of suitable logs such as USIT LOG*).
As said above, the value of σa has to be compared with the stresses of a thermal nature, whose magnitude is linked to the depth at which the pocket is located, and with stresses due to any preloading, as derived from the expected formula.

*USIT LOG is a trade name of SCHLUMBERGER INT.

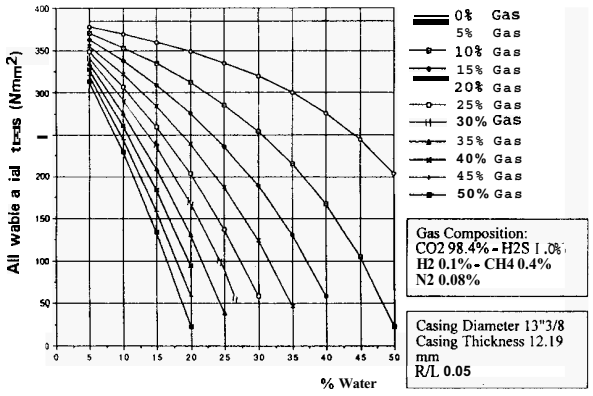


Fig. 8

From Fig. 8 one can see, for example, that an uncemented section of 3.4 m length, containing 50% of its volume in water and 10% in gas, is near to collapse due to the sole effect of the pressure ΔP, calculated for a temperature of 250 "C.
Such dependence has been derived by adopting different possible gas mixture types, especially the one gas mixture type most commonly encountered in the endogenous fluids.
The parameters which most influence the critical stress state for the uncemented pocket turned out to be:
- the volume percentage of the gases (higher percentages are detrimental);
- the kind of gases in the mixture (in the same thermodynamic conditions, low molecular weight gases have higher partial pressures);
- the volume percentage of H_2O if it is present together with other gases (higher H_2O percentages are detrimental);
- the casing thickness (lower thicknesses are detrimental).
The method used to open the well, on the contrary, does not have any influence under the hypothesis made, since the thermodynamic state of the fluid in the pocket and therefore its pressure on the casing depends only on the final (maximum) temperature reached as a consequence of the functioning of the well.
As an example of concrete application, Fig. 9 reports the preload values to apply to the 9 5/8" casing in the cementing phase in order to prevent collapse of the structure during the opening of the well (with fluid produced at 250°C) in correspondence to a possible uncemented section, as a function of the length L of the section and of the casing thickness, the composition of the fluid contained in the pocket and the depth at which the pocket is located being fixed.
The relations that led to the formulation of the graph in Fig. 9 are of considerable importance since they make it possible to define limiting values for the factors characteristic of the defects, beyond which an intervention becomes necessary in order to avoid collapse of the piping in the well opening phase.

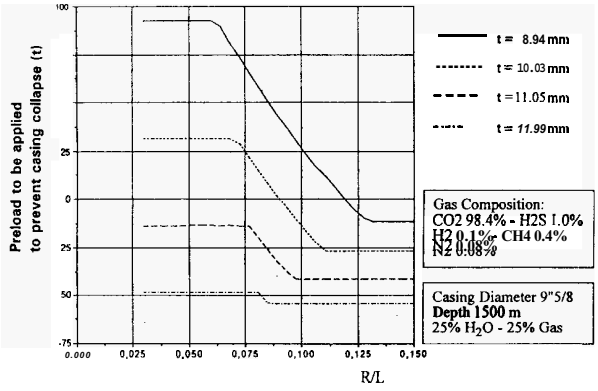


Fig. 9

From the graphs which have been analyzed in this section, it is evident that the main actions to be adopted in the construction phase, in order to reduce the negative effects of the fluids in the pockets, are the following:
- use of large thicknesses for the casing;
- adequate preload values to be applied in the cementing phase.

3.3 ANALYSIS OF THE FATIGUE PROBLEMS IN A CASING INSTALLATION

The problems connected with the fatigue phenomena for a casing installation are not easy to recognize due to the complexity of the structure. Despite this, in the analysis which the present paper is based on it has been attempted to identify the main aspects in order to give some indications.
The load cycle taken as a reference is the one corresponding to the opening and closing of the well.
It is a function of the pretensioning value and it is shown in Figs. 10 and 11.

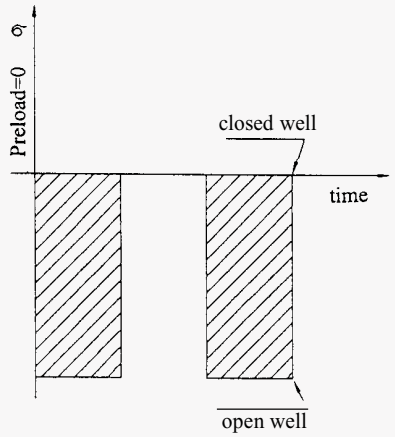


Fig. 10

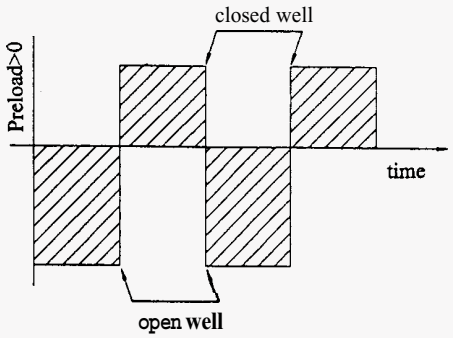


Fig. 11

It must be noted that the pretensioning modifies the mean value of the alternate stress.
In the fatigue evaluation the local defects are of considerable importance for their effects on concentrating the stresses.
The classic defects which can be found in a casing installation can be traced to punctual damages of the material due to pitting or to the presence of holes in the casing made by special equipment like "perforating guns" or to longitudinal damages due to the wear and tears caused by the rotation of the drill string and tools inside the casing.
Moreover, there are perturbations in the continuity of the casing caused by the presence of connections between the pipes. The first type of defect can be schematized by means of a radial hole of radius "r" on the casing circumference, as shown in Fig. 12.

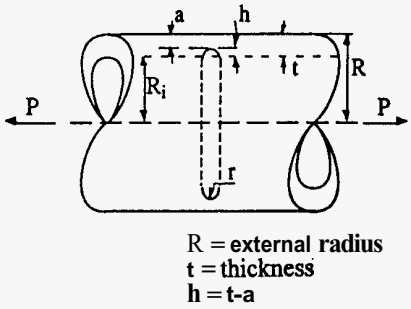


Fig. 12

The second type of defect is collectively analyzed by means of a cut of depth "h" and bottom radius "r" along the circumference of the casing internal surface (see Fig. 13).

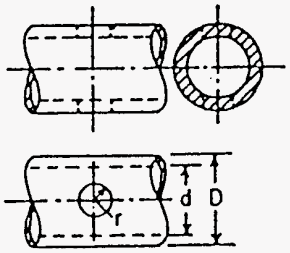


Fig. 13

This kind of defect simulates with good approximation also the local effects due to the presence of the connections.
The analysis is made for the two types of damage described above.
For each of them, it is possible to evaluate the well fatigue life, that is the maximum number of openings and closings allowed for the well. These results are presented in Fig. 14.

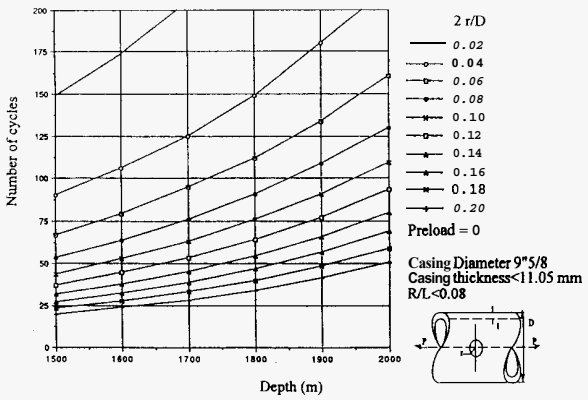


Fig. 14

In the case plotted in Fig. 14 it can be seen that, in the presence of a circular defect of radius r=25 mm located at a depth of 1500 m, the 9 5/8" casing has a fatigue life corresponding to about 20 opening cycles of the well.
The most important factors are:
- the length of the interval and the mean value of the characteristic stress of the loading cycles (it should be noted that the increase of the mean value as a consequence of the preloading has a negative effect on the fatigue strength);

- the geometrical form of the defects;
- the casing material;
- the casing geometry;
- the temperature at which the phenomenon takes place.

On this subject, further work is being carried out in order to make the analysis performed more usable.

4. COMPARISON WITH ENEL'S EXPERIENCES

ENEL conducted a statistical research which examined 8.5 wells dnlled in the last five years, with the aim of determining the factors that can be correlated with the casing damage. A large number of parameters were considered, some of which dimensional and geomemcal, others which concern the dnlling technologies. From this research the following main conclusions were drawn:

a) - the failures regard mostly the production casing (13 3/8", 9 5/8")
b) - they are more common in the zones close to the surface ($h \leq 250$ m);
c) - they are more common in the thinner casing portions;
d) - they are correlated with high "free water" and "fluid-loss" values in the slurry used for cementing the annulus;
e) - they are statistically more frequent in the casings subjected to multi-stage cementing, especially in the areas corresponding to lack of continuity in cementing.
f) - they are usually a consequence of a production test or of a temperature increase of the well, as in air drilling.

The above findings are in perfect agreement with the results of the previously described analysis.

It should be noted that the sample examined for the statistical research is made up of recently drilled wells, the majority of which are not in the production phase, but have been subjected to heating during production tests and/or air drilling. This excludes the possibility that the observed damage can be due to fatigue problems.

5. CONCLUSIONS

The analysis performed in this work evidenced the main factors that influence the structural stability of the casings of geothermal wells. in the presence of imperfectly cemented sections.

It turned out that:

- the casing's stress state, even when the cementing is not perfect, is a function only of the fluid temperature and not of the way the well is opened;
- the applicable preload in the cementing phase, even if it has a slightly negative effect on the fatigue life of the casing installation and a practically insignificant one on stability in the elastic field, produces strong positive effects when the material becomes plastic in the case of post-buckling;
- imperfectly cemented casing portions, especially if water and gases are present in the pocket, show a critical behavior even for lengths of less than 4 m; in this case pretensioning loads can have a positive effect and the casing thickness plays a fundamental role.

The above conclusion makes later interventions to restore the cementing particularly difficult, thus indicating that the maximum effort has to be made in improving cementing techniques and materials;

- the fatigue life of the well depends mostly on the presence of defects in the casing, while it is little influenced by cementing defects.

The results of the present work have already proved to be in excellent agreement with the conclusions drawn from the statistical research cited above.

However, further work is necessary to definitively validate the structural models developed through application to actual cases and to confirm the soundness of the hypothesis made.

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