ON THE RISK OF FAILURE OF NUCLEAR PRESSURE VESSELS

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ABSTRACT

The fact that different ways of estimating the risk of failure of nuclear pressure vessels may lead to results of the same order of magnitude is not necessarily an indication of trustworthiness of the respective estimates. It appears that other factors than those normally considered might play an important role and, in particular, events or phenomena which may affect the quality of the materials used and the reliability of manufacture, operation and control procedures.

KEYWORDS

Quality assurance, unforeseen causes, inconceivable events, competence, workmanship, soft factors, outliers.

FRACTURE MECHANICS

The critical event in catastrophic failure of a pressure vessel is the fast, unstable propagation of a crack. This process can be treated theoretically by means of fracture mechanics, relating the size of the crack, a, to the stresses, σ, and the propagation resistance of the material, K_{IC}, in its simplest form according to the eguation: $\sigma\sqrt{\pi a} = K_{IC}$. The crack is postulated to exist as the result of fatigue, growing according to the equation: $da/dN = (\Delta K)^n$.

This fracture mechanical concept is classical and need not be elaborated in detail here. It is assumed that data on the respective variables are available with a certain accuracy. This is the first prerequisite for an assessment of assurance against catastrophic failure. One may then arrive at what is called a deterministic conclusion about the occurrence of failure. As will be explained in the next section, however, this is not sufficient for estimates of risks.

THE PROBABILISTIC APPROACH

Clearly the determination of risks is a probabilistic exercise. In principle the probabilities of the fracture mechanics parameters are coupled together in order to arrive at a probability of their critical combination according to the equations mentioned above. Graphically in two dimensions this is summarized in Fig. 1.

Several probabilistic analyses have been made in the last decade, yielding a number of different results depending on differences in the assumptions about statistical distribution of the parameters involved. Some factors are better known than others. The stress distribution is probably the variable which can be regarded as the most reliable one. The statistics of the toughness of the material are less satisfactory, in particular with respect to the lower end of the distribution, which is of interest from the point of view of failure.

As regards data for the presence of cracks this is a funcion of, among other things, the probability of not detecting defects and not determining their size and location properly. So far the input on this point has consisted of functions or curves, Fig.2, which have been obtained by asking the opinion of experienced inspectors. Obviously this is questionable as far as reliability of the final risk figures are concerned.

The figures for the rates of catastrophic failures arrived at by means of probabilistic fracture mechanics vary considerably depending on the data and the methods applied: from an order of 10^{-6} to 10^{-8} per vessel and year.

The relative importance of the uncertainties of data for the three major factors governing the risk of catastrophic failure can be assessed by a sensitivity analysis. This has been done as a project within the Swedish safety programme (Palm, Nilsson, 1980). Briefly the results indicate that the failure probability is very sensitive to the type of distribution function for the fracture toughness. As far as the risk of not detecting cracks is concerned, the most important crack sizes are between 10 and 15 mm.

At this point a further word of caution is warranted. It is a common saying that no statistical evaluation is better than the input data. But in addition to this one has to notice that also the choice or rather the restriction of variables limits the value of the results as a basis for decisions. A probablistic assessment of the risk of catastrophic failure using fracture mechanical concepts has naturally to be based on data which can be used for calculations according to the equations quoted above. This normally excludes so-called soft information which does not easily lend itself to quantitative treatment. Before dealing with such shortcomings of the probabilistic assessment a brief review of another statistical approach will be given.

A CASE FOR FAILURE STATISTICS

Risks under more conventional circumstances are usually estimated on the basis of statistics collected in the past from a large number of cases. This is not possible with the same accuracy for failure of nuclear pressure vessels, since - fortunately - no such events have yet been recorded.

There are, however, means of making use of information from failure statistics for other kinds of pressure vessels. This has been done several times. The first attempts were relatively primitive inasmuch as only little consideration was paid to differences between thickwalled nuclear pressure vessels and non-nuclear ones. In recent years there has been an improvement in the selection of data and their treatment.

In the latest contribution to the analysis of failure statistics, data from England and USA have been used (Smith, Warwick, 1981). With due consideration to the particular character of the vessel population examined with respect to size, wall thickness, welding, inspection, age, etc, the conclusions that can be drawn from this study appear to be trustworthy. One finds that the rate of catastrophic failure at 95 % confidence level is 2×10^{-5} per vessel and year. The probability that defects will be formed which would need repair is 4.5×10^{-4} per vessel and year.

Obviously there is a discrepancy between these figures and those quoted above from probabilistic analyses. The sensitivity analysis referred to (Palm, Nilsson, 1980) indicates possible reasons why there might be such a difference. More recently a revision of one of the early probabilistic calculations has been made in order to find out whether figures of the order produced by failure statistics could possibly be arrived at using the probabilistic approach (Harrop, 1982).

Two important parameters, the incidence of cracks and how they grow, were arbitrarily adjusted to obtain a fit with the empirical evidence. Justification of the sense of these changes was given a posteriori. It was found that the theoretical probabilistic model can give results consistent with the main features of empirical evidence from a population of non-nuclear vessels. It was even possible to change the rising trend of the failure rate with age, which was typical of the original probabilistic model, into the reverse, which is true of failure statistics.

AN INDEPENDENT VIEW

While it is true that probabilistic assessments based on fracture mechanics may be made to fit failure statistics evaluation, this appears too schematic to be the last word about the risk of catastrophic failure of nuclear pressure vessels. For those familiar with the complexity of design, manufacture, control and operation of such a component the procedures for analysing this risk seems too little sensitive to influences from soft factors which are wellknown to occur in practice.

matically as a consequence of ambitions or directives. Manufacture of pressure vessels, for instance, might appear to be a relatively straight forward activity, but the troubles and delays experienced even by companies of high reputation in this field tell another story. The same is true also of control, which has to be performed according to schemes that cannot simply be copied from other types or scales of production.

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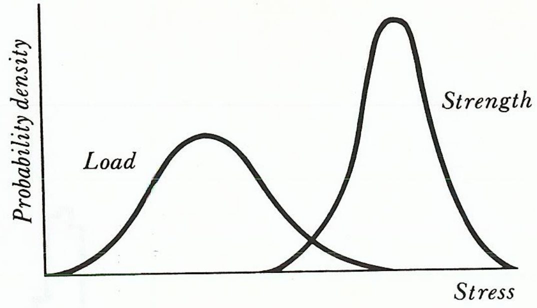

Fig. 1. Distribution of load and strength.

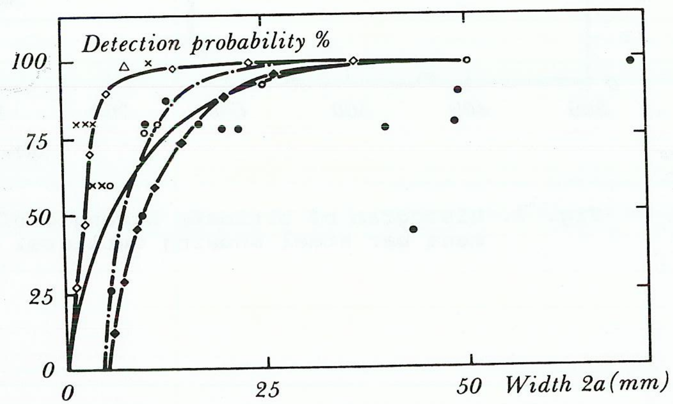

Fig. 2. Reliability of non-destructive examination (Dufresne, 1981).

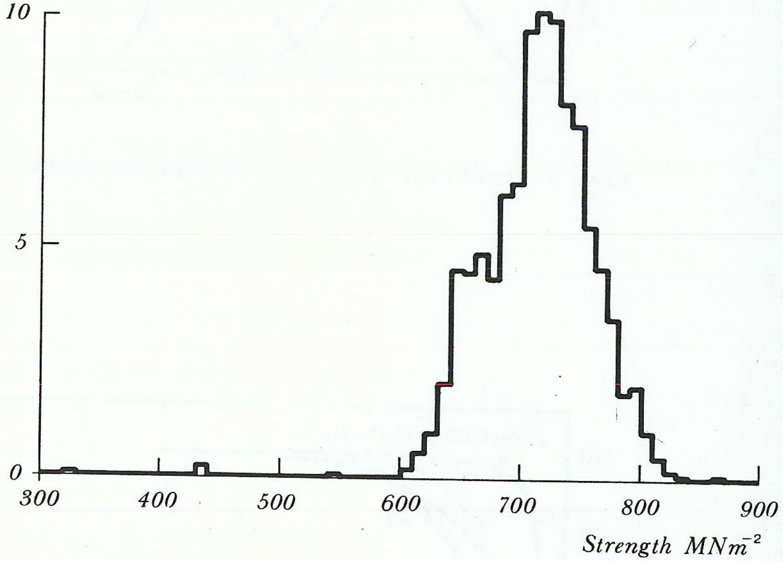

Fig. 3. Histogram of ultimate strength of reinforcement bar steel showing outliers.

SHORT CRACK PROBLEMS IN GAS TURBINE DISKS

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ABSTRACT

Gas turbine disks operating under low-cycle fatigue conditions represent typical machine parts with short crack systems. Herewith, the authors aim at presenting some methods being good for solving real problems with short cracks in the process of disk airworthiness certification.

KEYWORDS

Mechanical systems; machine parts; gas turbine disks; low-cycle fatigue; crack detecting and development; short crack problems.

BACKGROUND

Němec, Drexler (1984) stated that there is no universal method which would enable solving short crack problems in machine parts under all possible varieties of structural configurations and corresponding operational conditions. Obviously, the engineering solutions of the mentioned problems are to be searched for a specific machine type and a representative sample of its working field characteristics, only. In these relations, short crack problems in gas turbine disks involve the following typical subproblems of

1. detecting a short crack at its first occurence,
2. an adequate description of a short crack system aiming at the relation of short crack characteristics to disk reliability parameters,
3. estimating the safe life or life to safe crack occurence in the worst damaged fir-tree blade attachment on the disk taken for being the least reliable disk in the whole envisaged production series.

In this relation, it is the authors' task to present some possible solutions of the subproblems mentioned above.

PROBLEM OF DETECTING A SHORT CRACK AT ITS FIRST OCCURENCE

The main problem in examining a disk under test - should any of the known detection method be used - is the human operator taking the following two final resolutions:

i) the crack is (is not) present in the investigated zone,
ii) if present, the crack length estimation is L mm.

The presence of the human operator in crack detecting procedure forces the necessity of carefully verifying outside reference data on crack detecting probability before applying them to one's own purpose. One of the reliable (robust) methods often used independently on others under laboratory conditions is visual detection supported by several component penetrants and a microscope. In this connection, a method is necessitated how to quantify the crack detection ability level of a human operator: such quantification is required by Civil Aviation Authorities when an airworthiness certificate is applied.

First, let us examine the information structure of the results of human operator's activity in detecting cracks: these results are in form of registered crack length data referring to critical zones, e.g. edges of disk blade attachments, see Fig. 1. Such a crack length datum forcibly involves the following information :

a) the one of the type of critical machine part under investigation,
b) the one of the type of the detection method used, i.e. on human ability (one operator or operator group) to crack detection,
c) the one of a finished programme test unit number,
d) the one of crack trace length as accessible to visual investigation,
e) the one on all other operating conditions which were not explicitely mentioned.

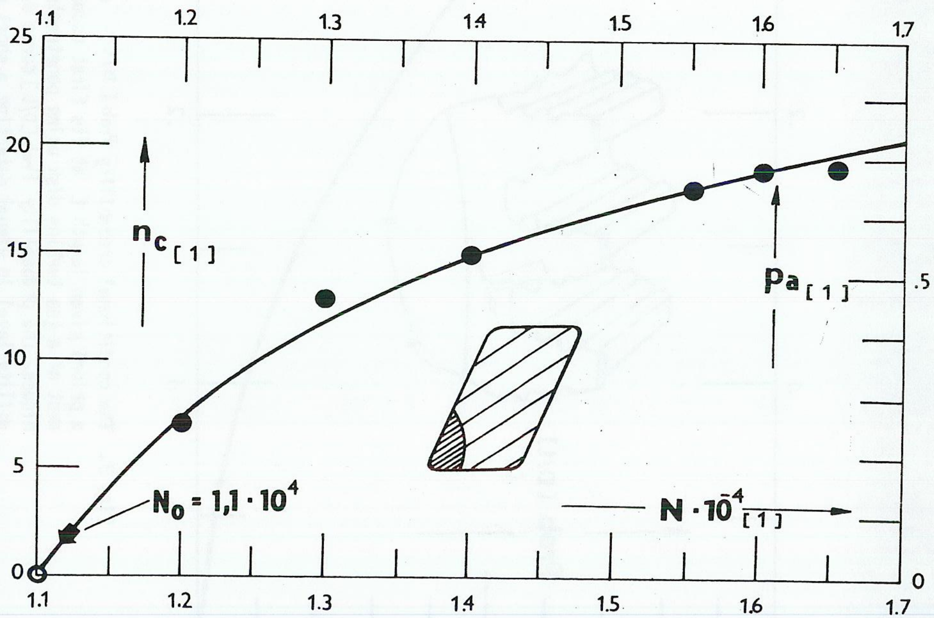

Fig. 1. Crack number n_c in function of the programme test unit number N as found on disk blade attachment edges, back side (Němec, Drexler, 1984). p_a - crack occurence probability in a fir-tree blade attachment.

The whole information content of a crack length datum may be depleted by the following elementary statement definitions :

C : " The critical machine part under investigation is a gas turbine disk "
N : " The programme test unit number finished by the disk up to this inspection time instant is N "
D : " Cracks are visually detected by a selected human operator whose ability level is to be quantified "
L : " The crack trace length is L mm "
O : " Other operating condition present when detecting cracks "

In our case, we have limited considerations of a specific machine part (disk), of an a priori agreed programme test unit number and of standard laboratory conditions. Hence, the fact that a crack length datum involves information expressed through statements C to O can be registered by a composed statement (D. L/C.N.O) being of random character due to the problem nature.

Therefore, our task to quantify the operator's ability level in respect to crack detection is transferred to that one of establishing an adequate probabilistic characteristic. Using the product rule, we may write

$$\mathrm{Prob}\,[D.L/C.N.O] = \mathrm{Prob}\,[D|L.C.N.O]\,.\,\mathrm{Prob}\,[L/C.N.O] \qquad (1)$$

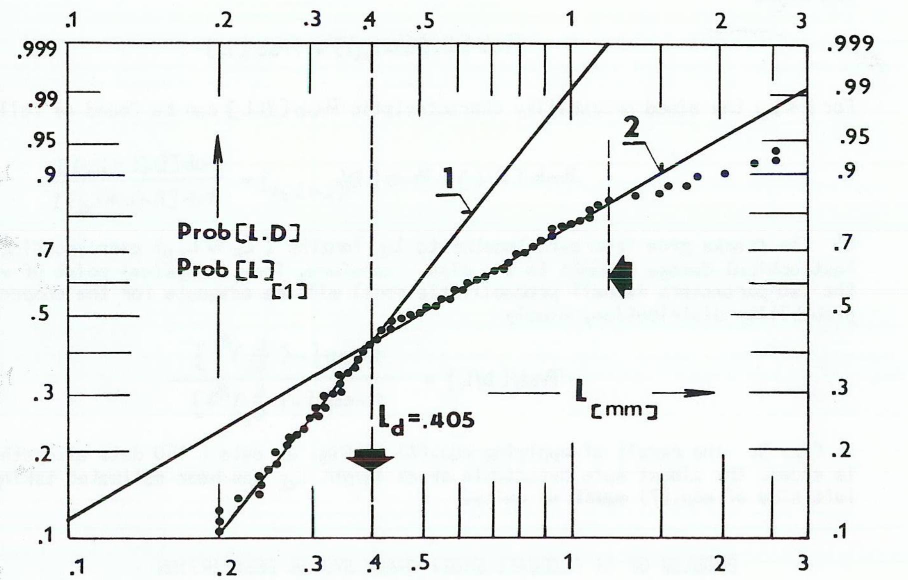

Fig. 2. Crack length first occurence experimental data L as investigated in Weibull probability paper in respect to human operator's ability to crack detection. 1, 2 component probability distributions (see right side of equ.(6), ⬍ sample upper limit due to an a priori agreed test unit number N .

Omitting - for brevity sake - the limitation symbols C . N . 0, we get

$$Prob\,[D.L] = Prob\,[D/L] \cdot Prob\,[L] \qquad (2)$$

where $Prob[D.L]$ is the joint occurence probability of the event that a crack is detected at its first occurence and has a length of L mm, $Prob\,[D/L]$ means the conditional probability of a crack being detected given its length L mm, $Prob\,[L]$ means the probability of a crack having a lenght $y < L$ mm independently of crack detection method used. It is evident that the conditional probability $Prob\,[D/L]$ presents an adequate characteristic to be found as qualifying the ability level of a human operator in respect to crack detection. From equ.(2), we obtain the basic formula

$$Prob\,[D/L] = \frac{Prob\,[D.L]}{Prob\,[L]} \qquad (3)$$

For estimating $Prob\,[D/L]$ from experimental crack length data, see Fig. 2., two basic physical boundary conditions are to be taken into account :

A) Given an almost sure detectable crack length L_d , then for all crack lengths $L \geq L_d$ (see straight line segment 2 in Fig. 2.) holds

$$Prob\,[D/(L \geq L_d)] = 1{,}0 \qquad (4)$$

and hence

$$Prob\,[D.(L \geq L_d)] = Prob\,[L] \qquad (5)$$

For $L < L_d$ the aimed probability characteristic $Prob\,[D.L]$ can be found as follows

$$Prob\,[D/L] \equiv Prob\,[D/(L<L_d)] = \frac{Prob\,[D.(L<L_d)]}{Prob\,[D.(L \geq L_d)]} \qquad (6)$$

B) The cracks grow from zero lengths to L_F lengths ($L_F \equiv L_{CR}$) corresponding to catastrophical damage brought to the disk. Therefore, from a physical point of view , the two-parameters Weibull probabilistic model will be adequate for the component probability distribution, namely

$$Prob[D/L] = \frac{1-\exp\{-(\frac{L}{\theta_1})^{\beta_1}\}}{1-\exp\{-(\frac{L}{\theta_2})^{\beta_2}\}} \qquad (7)$$

In Fig. 3. the result of applying equ.(7) to Fig. 2. data (160 data altogether) is shown. The almost sure detectable crack lenght L_d has been estimated taking the left side of equ.(7) equal to unity.

PROBLEM OF AN ADEQUATE SHORT CRACK SYSTEM DESCRIPTION

Drexler, Statečný (1983) presented one of the possible assessments of this problem using the quantile crack length L_Q for $Q = 0.05$ and the instantaneous total number of cracks n_c in the fir-tree blade attachments of the disk as parameters describing the short crack system as a whole. In Fig. 1. , the n_c total number of cracks is referred to the programme test unit number by the following formula

$$n_c = (m+1) \cdot (1-\exp\{-(\frac{N-N_0}{\theta})^{\alpha}\}) \qquad (8)$$

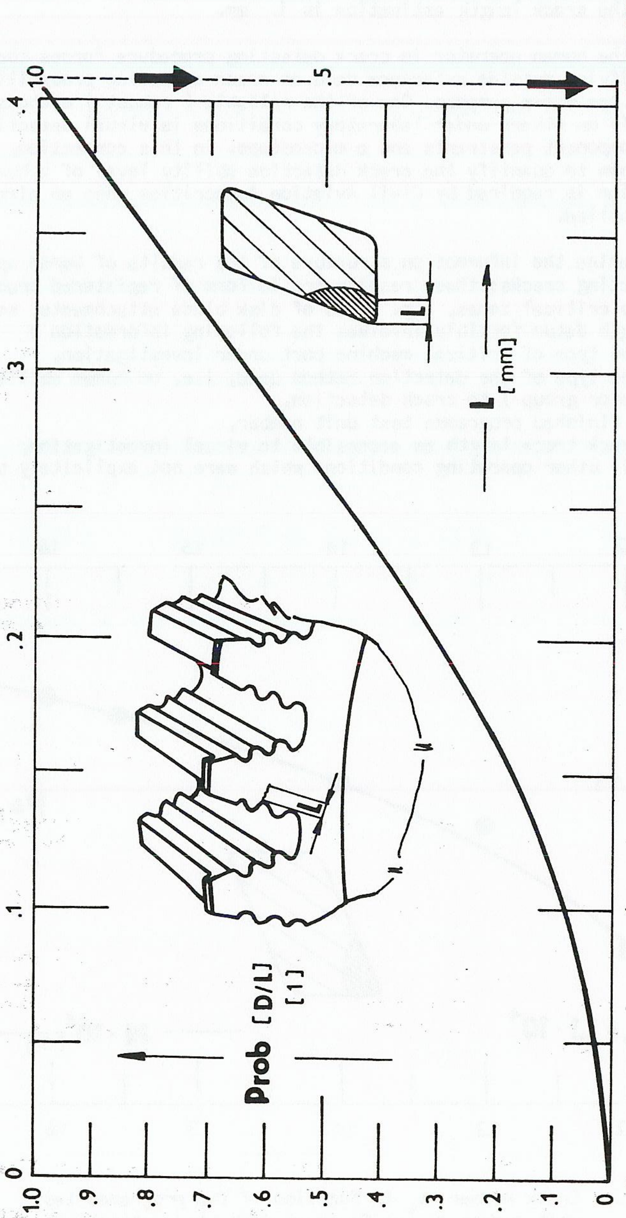

Fig. 3. The conditional probability $Prob\,[D/L]$ of detecting a short crack of an a priori given length L at its first occurence in a blade fir-tree attachment of a gas turbine disk using penetrants and microscope detection techniques. The probability $Prob\,[D/L]$ curve demonstrates the human operator ability level in visual detecting a short crack on basis of equ.(7) applied to Fig. 2. data.

m being the number of fir-tree attachments to the disk under investigation, whereby the crack occurence probability in one of the blade attachments is given by

$$p_a = \frac{n_F}{m+1} \qquad (9)$$

PROBLEM OF ESTIMATING LIFE TO SAFE CRACK OCCURENCE

Referring to airworthiness requirements for a hazard rate the life estimation in test unit number to safe crack occurence within a single disk has been derived by Němec, Drexler (1984) as follows

$$N_{FSC} \geq \Lambda^{-1} \cdot \{-\ln.(1-Prob[n_{FSC}/n_F; m; M=1])\} \qquad (10)$$

where n_F, n_{FSC} are total numbers of cracks in the disk blade fir-tree attachments up to the safe crack length L_{FSC} and to the critical length L_{CR} , M is the number of disks accounted for in the life estimation, whereby the conditional probability

$$Prob[n_{FSC}/n_F; m; M=1] = \frac{Prob[(x < n_{FSC}) \cdot n_F; m; M=1]}{Prob[x < n_F; n_F; m; M=1]} =$$

$$= \frac{\sum_{j=1}^{n_{FSC}} C_j^m \cdot p_a^j \cdot (1-p_a)^{m-j}}{\sum_{j=1}^{n_F} C_j^m \cdot p_a^j \cdot (1-p_a)^{m-j}} \qquad (11)$$

Considering the $M \gg 1$ disk production series, the probability (11) of meeting $x < n_{FSC}$ cracked ones of m fir-tree blade attachments in the least reliable one of M produced disks changes to

$$Prob[n_{FSC}/n_F; m; M \gg 1] = 1-(1-Prob[n_{FSC}/n_F; m; M=1])^M \doteq 1-\exp\{-M \cdot Prob[(x<n_{FSC}) \cdot n_F; m; M=1]\} \qquad (12)$$

whereby $Prob[x<n_F; n_F; m; M \gg 1]$ approaches unity. Hence, the life estimation $N_{FSC}(M)$ to safe crack occurence for the least reliable one of M disks is given by the formula

$$N_{FSC}(M) \doteq \Lambda^{-1} \cdot M \cdot Prob[(x<n_{FSC}) \cdot n_F; m; M=1] \qquad (13)$$

In our example case, we had $\Lambda = 1.10^{-8}$, $n_F = 24$, $m = 28$, $1 \leq M \leq 5000$ and for $p_a = 0.82759$. The result when applying equ.(13) to these data is shown in Fig. 4. Therefrom we see that production series increase in M from 1 to 5000 disks diminishes in our example case the possible programme test unit number gain $\Delta N = N_{FSC} - N_O$ to about a half, when $N_O = 1.1 \times 10^4$.

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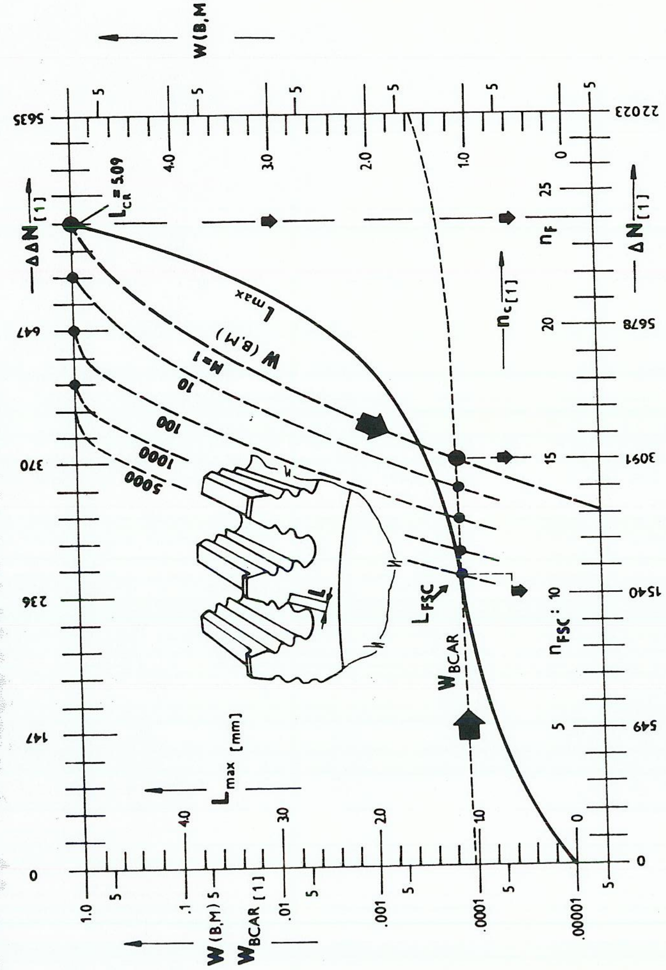

Fig. 4. Example of estimated life gain $\Delta N = N_{FSC} - N_O$ to safe crack ($L_{FSC} \doteq 1.1$ mm) occurence in the least reliable one of the M disks with short cracks according to equ.(13), given $\Lambda = 1.10^{-8}$, $n_F = 24$ ($L_{CR} \doteq 5.09$ mm), $m = 28$, $N_O = 1.1 \times 10^4$. $W(B,M)$ corresponds to equ.(12), W_{BCAR} is the BCAR admissible probability of catastrophical damage brought to the disk, $\Delta\Delta N$ being the test unit number between individual crack occurences.