TECHNICAL UNIVERSITY OF BUDAPEST

P R O C E E D I N G S

of the

ADVANCED STUDIES ON RELIABILITY ENGINEERING (A.S.R.E.)

Summer course at the Technical University of Budapest

3-7 September, 1990.

Organizers: the Institute for Precision Mechanics and Optics
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Invited Papers

Abstracts of contributed papers

The Organizing Committe of the course expresses its regrets for all papers and abstracts which could not be included in this volume due to missing the deadline, 31th July, 1990.

INVITED PAPERS

PROBABILITY ASPECTS OF LIFETIME PREDICTIONS

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PROBABILITY ASPECTS OF LIFETIME PREDICTIONS

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ABSTRACT. In this paper the scatter of the lifetime of components is discussed. Simple probabilistic models for fatigue crack initiation and crack propagation are presented. The relation between microstructural variation of material and the scatter in material properties is emphasised. Finally the practical application of a probabilistic approach including the problem of nondestructive evaluation of defects is discussed.

1. INTRODUCTION

A great amount of scatter in the lifetime of components at high temperatures is observed, both in laboratory tests and under conditions of service loading. To cope with this scatter large safety factors have to be applied or periodic inspections are necessary to detect damaged components. Another possibility consists in incorporating the scatter into the design, where the probability of a failure is predicted as a function of time. The probabilistic approach starts from a deterministic lifetime prediction model which is based on empirical relations and may include microstructural observations of the damage process. All the models developed so far /1/ lead to a relation between time to failure or number of cycles to failure, the stresses or the stress amplitudes, and a number of material parameters. The probabilistic evaluation of failure probabilities starts from the statistical distribution of the material properties, the loading parameters and the defect size and, in addition, can include the reliability of non-destructive inspection methods.

A sophisticated probabilistic failure model has to consider the different stages of the damage process and to relate the scatter of the material properties to the variation in the microstructure of the material.

In this paper some of these probabilistic aspects are discussed. It does not deal exclusively with the behavior at high temperatures, but is rather intended to explain the idea of a probabilistic approach in a general way and to show the trends in this relatively new field. Very often only the basic ideas of the probabilistic models are given. More detailed models can be found in the literature or have not yet been developed.

2. DETERMINISTIC AND PROBABILISTIC DESIGN

Design in mechanical engineering is usually performed in a deterministic manner, where a load parameter L (for instance the stress) is compared with a resistance parameter R (for instance yield strength). The load parameter L is a function of the external loads (for instance external forces, temperature gradients or pressure) and may depend on time. The resistance parameter is a material property or a function of material properties and may also depend on time. Failure occurs if

$$L = R \tag{2.1}$$

Where time dependence is involved this equation can be solved for the time to failure t_f:

$$t_f = t_f < L,R > \tag{2.2}$$

Three simple examples may illustrate the deterministic concept

a) A bar with circular cross section (radius r) is exposed to the load F. A useful loading parameter is the stress

$$L = \sigma = \frac{F}{\pi r^2} \tag{2.3}$$

If "failure" is defined as the onset of plastic deformation, the resistance parameter is the yield strength

$$R = \sigma_y \tag{2.4}$$

The failure equation then is

$$\sigma = \sigma_y \quad \text{or} \quad F = \pi r^2 \sigma_y \tag{2.5}$$

b) A bar with circular cross-section is loaded in tension at high temperatures where creep deformation is possible. The loading parameter again is the stress. If rupture is the failure event, the resistance parameter is the rupture stress σ_r which is a function of time. If the relation between time to failure and stress can be expressed by

$$t_f = A\, \sigma_r^{-n} \tag{2.6}$$

the failure equation $\sigma = \sigma_r$ leads to

$$t_f = A \left(\frac{\pi r^2}{F} \right)^n \tag{2.7}$$

where the time to failure is a function of the load applied, the radius r and the material parameters A and .

c) A component with a crack is loaded in tension. A useful loading parameter is the stress-intensity factor K_I, which is a function of stress and crack length a

$$L = K_I = \sigma \sqrt{a}\ Y \tag{2.8}$$

where Y is the linear-elastic correction factor.

The resistance parameter is the fracture toughness:

$$R = K_{Ic} \tag{2.9}$$

The failure equation then is

$$K_I = K_{Ic} \tag{2.10}$$

which can be written also as

$$\sigma = \frac{K_{Ic}}{\sqrt{a}\ Y} \tag{2.11}$$

If the crack is growing by fatigue the loading paramater K_I increases, because of the increase in crack length. Then from

$$K_I < \sigma , N > = K_{Ic} \tag{2.12}$$

the number of cycles to failure

$$N_f = N_f < K_{Ic}, \sigma > \tag{2.13}$$

can be obtained.

All the quantities entering a failure equation are no fixed values, but are exposed to scatter. In case a) the applied load, the radius r and the yield strength may vary among different components. In case b) the crack length, the fracture toughness and the stress may be different in different components.

To ensure a safe design two procedures are applied in a deterministic approach:

- Instead of mean values lower or upper bound values are used. These values are designed by a v: minimum yield strength σ_y, upper bound of load $\check{F}$

- Between the lower limit of resistance $\check{R}$ and the upper limit of load $\check{L}$ a safety margin $M = \check{R} - \check{L}$ is specified (Fig. 1).

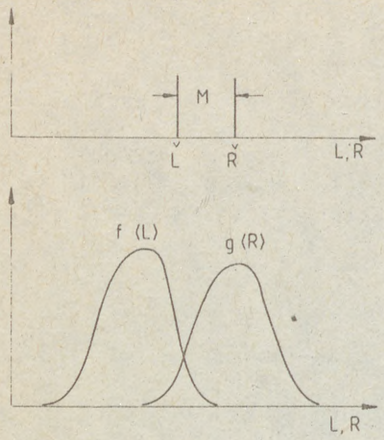


Figure 1. Density distribution of loading parameter L and resistance parameter R.

The safety margin or the corresponding safety factor $S = \check{R}/\check{L}$ is introduced for various reasons /2/:

- Variability of material resistance. There may be a chance that the material resistance is even lower than the assumed lower value
- Degradation of material resistance due to change in the microstructure at high temperatures or because of radiation damage. Such a degradation has to be taken into account in selecting the lower bound value. However, the uncertainties in the extent of degradation can be covered by a safety factor
- Variability in the primary sources of the stresses (or other quantities characterising the load parameter such as external forces, internal pressure, temperature transients)
- Inaccuracies in the transformation of these primary sources into stresses or stress intensity factors (e.g. thermal stresses)
- Uncertainties in the physical model describing the failure event

The safety factor chosen for a given component depends on the assessment of these uncertainties and variabilities, but also on the consequences of the failure of a component.

In a strictly deterministic design it is assumed that for large enough safety factors failure should be excluded. However, after selection of the safety factor two contradictory questions may arise:

- Is there still the possibility of a failure?
- Is the design too conservative?

No exact answer can be given within the deterministic approach. The probabilistic approach replaces the lower or upper bound values by distributed values which are described by distribution densities f<L> and g<R>, see Fig. 1. The probability of failure is the probability that the load parameter exceeds the material resistance and is given by

$$P(L > R) = \int_{0}^{\infty} \int_{R}^{\infty} f \langle L \rangle \, dL \; g \langle R \rangle \, dR \tag{2.14}$$

This simple relation can be extended to failure equations where more than two quantities are described by density functions.

3. SCATTER OF STRENGTH AND LIFETIME IN CERAMIC MATERIALS

As an example for the relation between the scatter of material properties and lifetime prediction ceramic materials are considered. These brittle materials fail from small flaws such as pores, inclusions, cracks or scratches of the surface. It is interesting to see that fracture mechanics methods can be applied successfully to relate the scatter of the lifetime to the scatter of the strength.

3.1 Deterministic relations

The flaws are described as cracks with a size parameter a. The extension of these cracks is governed by the stress intensity factor for mode I loading K_I, which is given by

$$K_I = \sigma \sqrt{a} \; Y \tag{3.1}$$

where σ is the stress at the location of the flaw and Y is the correction factor. For small semicircular surface cracks Y = 1.17 is independent of the crack size.

In most ceramic materials the cracks can extend subcritically under constant or slowly changing stress. The crack growth rate is a function of the stress intensity factor:

$$\frac{da}{dt} = f \langle K_I \rangle \tag{3.2}$$

This function can be approximated over a large range of K_I by a power law:

$$\frac{da}{dt} = A \, K_I^{\,n} \tag{3.3}$$

The time to failure then can be obtained by applying Eq. (3.1) and integrating between the initial crack length a_i and the critical crack length a_c:

$$t_f = \int_{a_i}^{a_c} \frac{da}{da/dt} = \int_{a_i}^{a_c} \frac{da}{A \sigma^n a^{n/2} Y^n} \tag{3.4}$$

Under the assumption that Y = const., Eq. (3.4) leads to

$$t_f = \frac{2}{A(n-2)Y^n\sigma^n}\left[a_i^{(2-n)/2} - a_c^{(2-n)/2}\right] \tag{3.5}$$

Because of the large exponent n (usually above 20) the second term in the bracket can be neglected.

Let us first assume that all components have flaws of identical size. Then the initial crack size a_i can be obtained indirectly by measurement of the so-called inert fracture strength. Under rapid loading in an inert medium (nitrogen, very often normal air may be sufficient) there can be no subcritical crack extension, and the stress required for unstable crack extension can be related to the fracture toughness K_{Ic}:

$$K_{Ic} = \sigma_c \sqrt{a_i}\, Y \tag{3.6}$$

Equation (3.6) can be used to calculate the initial crack size a_i from the measured inert fracture strength. Then Eq. (3.5) can be written as

$$t_f = \frac{B\,\sigma_c^{n-2}}{\sigma^n} \tag{3.7}$$

with

$$B = \frac{2}{(n-2)AY^2\, K_{Ic}^{n-2}} \tag{3.8}$$

Thus the time to failure can be predicted from the inert fracture strength, the fracture toughness and the subcritical crack growth parameters A and n.

3.2 Probabilistic relations

Due to the scatter of the initial flaw size a large amount of scatter is observed in the inert fracture strength and in the time to failure. The distribution of the most dangerous flaw in different components has to be considered. For a homogeneous stress distribution the distribution of the largest flaw $f\langle a_{i\,max}\rangle$ is responsible for the strength distribution $f\langle\sigma_c\rangle$ and the distribution of the time to failure $f\langle t_f\rangle$ (s. Fig. 2). It is difficult to obtain $f\langle a_{i\,max}\rangle$ and $f\langle t_f\rangle$ by direct measurements. Nondestructive methods for the determination of the size of the small flaws in ceramics are not precise enough. The distribution of the time to failure can be obtained only by testing many components over a long period of time. However, the inert strength distribution can be obtained easily by testing specimens. Then it is possible to calculate $f\langle a_{imax}\rangle$ from $f\langle\sigma_c\rangle$.

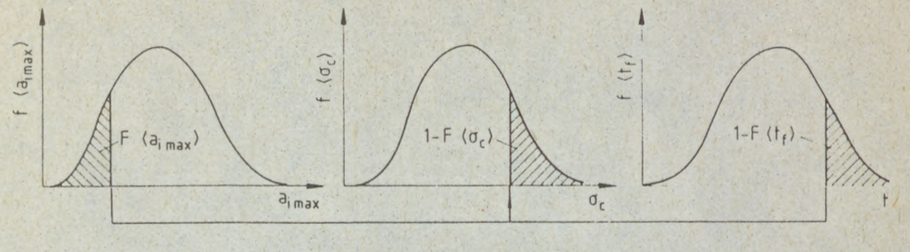


Figure 2. Distribution of maximum flaw size, strength and time to failure of ceramic materials.

It follows both from theoretical considerations and from experimental results that the strength distribution can be described by a Weibull distribution. The cumulative density (probability that fracture occurs at $\sigma < \sigma_c$) then is

$$F\langle\sigma_c\rangle = 1-\exp\left[-\left(\frac{\sigma_c}{\sigma_o}\right)^m\right] \tag{3.9}$$

The parameters σ_o and m can be obtained from experiments. The cumulative density distribution of the initial crack size a_{imax} can be obtained from the strength distribution applying Eq. (3.6), where now $a_i = a_{imax}$ (s. also Fig. 2):

$$F\langle a_{imax}\rangle = 1 - F\langle\sigma_c\langle a_{imax}\rangle\rangle$$

$$= \exp\left(-\left(\frac{K_{Ic}}{\sqrt{a_{imax}}\;Y\sigma_o}\right)^m\right) \tag{3.10}$$

The distribution of the time to failure can be obtained from

$$F\langle t_f\rangle = F\langle\sigma_c\langle t_f\rangle\rangle \tag{3.11}$$

where σ_c in Eq. (3.11) is replaced by

$$\sigma_c = \left[\frac{\sigma^n\, t_f}{B}\right]^{1/(n-2)} \tag{3.12}$$

from Eq.(3.7).

Thus, the distribution density of t_f is also a Weibull distribution:

$$F\langle t_f\rangle = 1 - \exp\left[-\left(\frac{t_f}{t_o}\right)^{m^*}\right] \quad . \tag{3.13}$$

with

$$t_o = \frac{B\,\sigma_o^{\,n-2}}{\sigma^n} \tag{3.14}$$

$$m^* = \frac{m}{n-2} \quad . \tag{3.15}$$

As an example results for hot pressed silicon nitride at 1000°C are shown in Fig. 3 /3/. It is interesting to see that the large amount of scatter in the time to failure could be predicted quite accurately from the scatter in fracture strength.

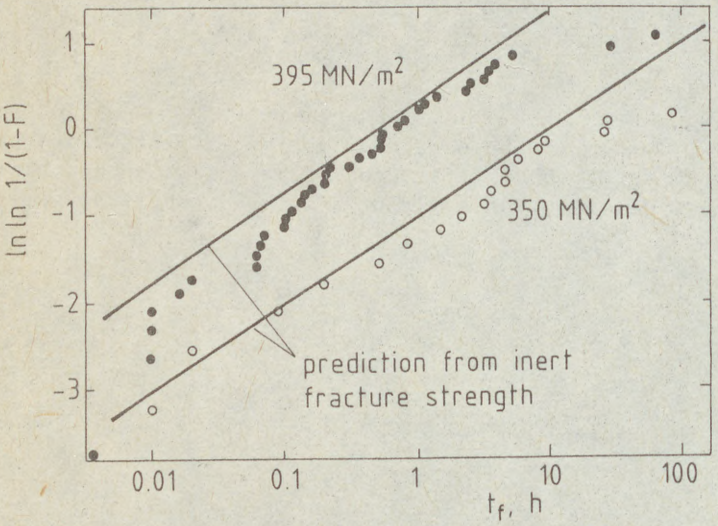


Figure 3. Measured and predicted cumulative density of time to failure for hot-pressed silicon nitride at 1000°C /3/.

Equation (3.15) is only correct if the sizes of the components for inert strength measurement and for lifetime prediction are identical. Both the fracture strength and the time to failure are dependent on size. The principle of the weakest link has to be applied to describe the size effect. For a stress distribution

$$\sigma = \sigma^* \cdot g \langle x,y,z \rangle \qquad (3.16)$$

in a component, where g <x, y, z> is a function of the geometry, Eq. (3.9) has to be replaced by

$$F = 1 - \exp - \frac{1}{V_o} \left(\frac{\sigma^*}{\sigma_v}\right)^m \int g^m \langle x,y,z \rangle \, dV \qquad (3.17)$$

where V_o is a unit volume.

The material parameters A, n and K_{Ic} are used as fixed values. The scatter of these parameters is a minor effect compared to the large scatter in the initial flaw size.

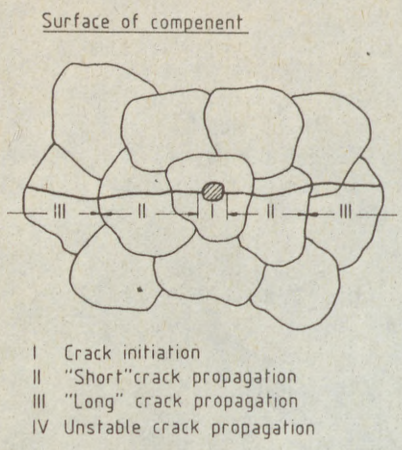
4. GENERAL FAILURE BEHAVIOUR AT HIGH TEMPERATURES

At elevated temperatures two main failure modes have to be considered:
- exceeding of a critical deformation of a component by creep or by creep-fatigue
- rupture of the component

In the first case "failure" is a functional failure due to a change of shape of the component. For this failure mode the global behaviour of the whole component or at least a rather large part of the component is responsible.

Rupture of a component in the final stage is always a local event, where one single crack is separating the component, whereas the first part of damage can be a more global or bulk event. If the failure is fatigue-dominated, the total failure is a local event. If the failure is creep-dominated, then most of the time to failure is spent within the bulk damage range. A more complicated situation is creep-fatigue-interaction, where a fatigue crack extends into a creep damaged region.

From these general considerations it can be concluded that much more scatter can be expected for fatigue-dominated than for creep-dominated failure. Therefore this failure mode will be treated in more detail. Four different regions have to be considered (Fig. 4).
- The crack develops from a local region in the order of the size of the microstructural constituents of the material (grains, phases, inclusions, pores). The number of cycles until crack initiation is strongly dependent on the type, size and orientations of these constituents and therefore cracks develop at different locations of the component after different number of cycles.
- During the first part of crack propagation the special arrangement of the microstructure surrounding the crack effects the crack propagation rate. Different cracks initiated at the same time may propagate at very different rates during the first part of extension.
- If the crack size grows larger, fatigue damage continues to be a local phenomenon. However, the crack growth rate is now controlled by the



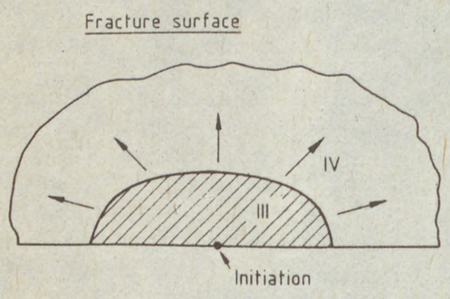


Figure 4. Four regions of crack propagation.

average microstructure along the crack front. The crack growth rate is still varying but to a lesser extent than for short cracks.
- Final failure occurs, if the crack reaches a critical size. This size is dependent on the maximum stress and a toughness parameter of the material. Again the toughness is sampled along the crack front and is varying through the material.

If many cracks are initiated, the linking of cracks, especially during the first part of propagation, may be an important event, which has to be considered.

5. A SIMPLE PROBABILISTIC MODEL

A probabilistic model for fatigue damage has to be developed in various steps. Here a simple crack initiation-crack propagation model will first be presented. This model will be refined in the next sections. The assumptions of this model are:

1) A crack is initiated after N_o cycles.
2) The crack size after initiation is a_i.
3) After crack initiation linear-elastic fracture mechanics can be applied to describe crack propagation.
4) Crack propagation is under mode I.
5) There is no interaction between individual cracks.
6) Final fracture occurs after a critical crack size a_c is reached which is a function of the maximum load.

If the definition of the initial crack size is based on microscopical observations, a_i has the size of grains or phases of the material. In this case assumption 3) might not be correct. If, on the other hand, a_i is a "technical crack" of a size on the order of one mm, assumption 3) may be reasonable, and the crack growth rate per cycle is a function of the range of the stress intensity factor ΔK:

$$\frac{da}{dN} = f \langle \Delta K \rangle \tag{5.1}$$

For simplicity the Paris-equation is used:

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{5.2}$$

ΔK can be defined as

$$\Delta K = \begin{cases} K_{max} - K_{min} & \text{for } K_{min} > 0 \\ K_{max} & \text{for } K_{min} < 0 \end{cases} \tag{5.3}$$

or, if crack closure is considered

$$\Delta K = K_{max} - K_{op} \tag{5.4}$$

where K_{op} is the stress intensity factor for which the crack is fully open. Here, for simplification (assuming R = - 1)

$$\Delta K = \sigma_a \sqrt{a}\, Y \tag{5.5}$$

is used, where σ_a is the stress amplitude. In addition, Y = const (independent of the crack length) is assumed. Then the crack length as a function of the number a cycles can be obtained in an analytical form by integration of Eq.(5.2):

$$\int_{a_i}^{a} \frac{da}{A\sigma_a^{\,m}\, a^{m/2}\, Y^m} = N - N_o \tag{5.6}$$

$$a = \left[a_i^{\frac{2-m}{2}} - \frac{m-2}{2} (N - N_o) A\sigma_a^{\,m}\, Y^m \right]^{\frac{2}{2-m}} \tag{5.7}$$

The number of cycles until failure N_f is obtained for $a = a_c$:

$$N_f = N_o + \frac{2}{A(m-2)\sigma_a^{\,m}\, Y^m} \left[a_i^{\frac{2-m}{2}} - a_c^{\frac{2-m}{2}} \right] \tag{5.8}$$

Equation (5.8) is the deterministic failure equation.

As a first step in a probabilistic approach the crack density z is introduced. If surface cracks are considered, z_S is the number of cracks in a unit area. If cracks in the volume of the component are considered, z_V is the number of cracks in a unit volume. The crack density is a function of the stress amplitude and of the number of cycles:

$$z = z \langle \sigma_a, N \rangle \tag{5.9}$$

As an example results of Ishihara et al. /4/ are mentioned. For a low-carbon steel, fatigued in 3% NaCl-solution the relation

$$z_S = z_{So} \left\{ 1 - e^{-\beta(N-N_c)} \right\} \tag{5.10}$$

with

$$\beta = C_1\, e^{C_2\sigma_a}, \qquad z_{So} = C_3\, e^{C_4\sigma_a} \tag{5.11}$$

was found.

Each crack grows after initiation according to Eq. (5.7). On account of the variability of the material the crack growth parameters A and m are varying. Two further assumptions are made:

- m is a fixed value and only A is a statistical variable described by the distribution density f⟨A⟩.
- A is constant for one individual crack

For f⟨A⟩ often a log-normal distribution

$$f\langle A\rangle = \frac{1}{\sqrt{2\pi}\, A\alpha} \exp\left\{ -\frac{1}{2}\left[\frac{\ln(A/A_o)}{\alpha}\right]^2 \right\} \tag{5.12}$$

has been used.

In contrast to this assumption, Tanaka et al. /4/ described experimental results with m and A as random variables, which are mutually dependent.

For a fixed number of cycles until crack initiation, N_o, the distribution density of the crack size for a given stress amplitude and number of cycles can be calculated as:

$$f\langle a, N_o, N, \sigma_a, a_i\rangle = f\langle A\rangle \cdot \frac{dA}{da} \tag{5.13}$$

In the distribution density relation A is replaced by its function of crack length a which is obtained from Eq. (5.7):

$$A = \frac{2(N-N_o)}{(m-2)\,\sigma_a^{\,m}\, Y^m}\left[a_i^{\frac{2-m}{2}} - a^{\frac{2-m}{2}} \right] \tag{5.14}$$

As a next step the continuous initiation of cracks has to be taken into account (s. Fig. 5). The contribution to the final distribution - called $f_1\langle a\rangle$ - of cracks initiated between N_o and $N_o + dN_o$ is given by

$$\frac{dz\langle N_o, \sigma_a\rangle}{dN_o} \cdot f\langle a\rangle\, dN_o \tag{5.15}$$

Therefore

$$f_1\langle a, N, \sigma_a, a_i\rangle = \frac{1}{z}\int_o^N f\langle a, N, N_o, \sigma_a, a_i\rangle \frac{dz}{dN_o}\, dN_o \tag{5.16}$$

To obtain a normalized distribution the integral has to be divided by the crack density. The cumulative density is

$$F_1\langle a, N, \sigma_a, a_i\rangle = \int_{a_i}^{a} f_1\langle a, N, \sigma_a, a_i\rangle\, da \tag{5.17}$$

To calculate the failure probability the number of cracks in a component has to be considered. For simplicity a homogeneous stress state is as-

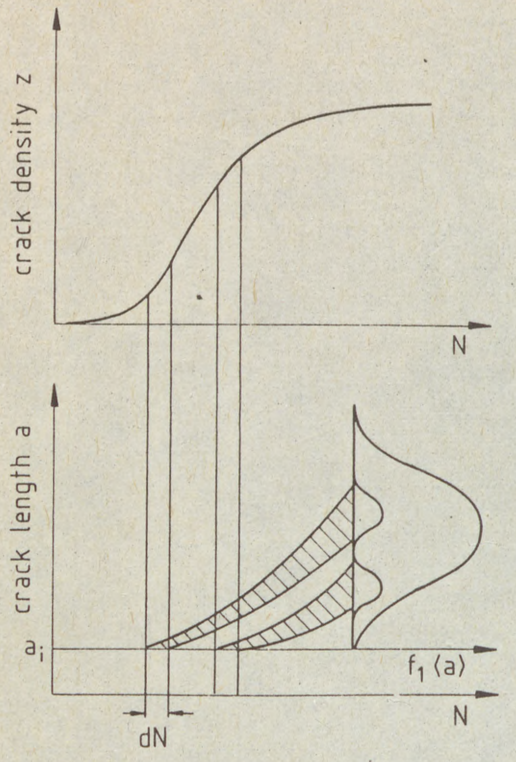


Figure 5. Crack size distribution after initiation.

sumed. The average number of cracks in the component is given by

$$Z_v = z_v V \text{ or } Z_s = z_s S \qquad (5.18)$$

where V is the volume and S the surface of the component. The probability of having k cracks in a randomly selected component is given by the Poisson-distribution

$$P \langle k \rangle = \frac{e^{-Z} \cdot Z^k}{k!} \qquad (5.19)$$

Then the probability of having at least one crack is

$$P = 1 - e^{-Z} \tag{5.20}$$

The probability that a randomly selected crack is larger than the critical crack is

$$P(a > a_c) = \int_{a_c}^{\infty} f_1 < a, N, \sigma_a, a_i > da \tag{5.21}$$

$$= 1 - F_1 < a_c, N, \sigma_a, a_i > \tag{5.22}$$

The number of cracks exceeding the critical crack length is given by

$$\zeta = Z\ (1 - F_1 < a_c, N, \sigma_a, a_i >) \tag{5.23}$$

The failure probability of the component is identical with the probability that at least one crack exceeds the critical length:

$$P_f = 1 - e^{-\zeta} \tag{5.24}$$

One important conclusion from these considerations is the existence of a size effect. For a given stress amplitude the failure probability increases with increasing size of the component. This follows from Eqs. (5.18), (5.23), (5.24), leading to

$$P_f = 1\text{-}\exp\ |- z_s\ S(1-F_1 <a_c, N, \sigma_a, a_i>)| \tag{5.25}$$

for cracks initiated at the surface.

So far we have been able to calculate the failure probability under the assumptions given in this section. As input information we need:

- the fixed material parameter m (from fatigue crack growth rate measurements);
- the distribution of the material parameter A (from fatigue crack growth rate measurements using different specimens);
- the fixed critical crack length a_c, which can be obtained from fracture toughness (K_{Ic} if linear-elastic fracture mechanics can be applied) and maximum load;
- the crack density as a function of stress amplitude and number of cycles

The information about the crack density has to be obtained from surface observations of fatigued specimens /5-7/. It is, however, desirable to relate the crack density to the microstructure of the material and to find general relations between microstructural features and the number of cycles until initiation of cracks.

6. RELATION BETWEEN MICROSTRUCTURE AND CRACK INITIATION

Fatigue crack initiation is caused by cyclic plastic deformation. This cyclic deformation is not homogeneous, not even in single crystals. It was shown that from a more or less homogeneous dislocation distribution in single crystals special dislocation arrangements develop locally in which cyclic deformation is concentrated. These fatigue slip bands are the regions where cracks can develop. In polycrystals inhomogeneous plastic deformation is further enhanced due to different orientations of the individual grains. Different orientation of the slip planes, dislocation pile-ups at grain boundaries and elastic anisotropy are effects which are responsible for crack initiation at some favourable locations within the material. Inclusions are further constituents of the microstructure which can be responsible for crack initiation. Different elastic moduli cause stresses, and dislocations can pile up at the inclusions. These effects can lead to inclusion cracking, debonding of the inclusion from the matrix or to cracks in the matrix, due to enhanced cyclic plastic deformations near the inclusion.

It is not intended to give a detailed description of the various mechanisms. Only some indications concerning the further refinement of the probabilistic model for crack initiation will be discussed.

As a simple example crack initiation at inclusions is considered. The number of cycles for crack initiation should be a function of the stress amplitude and the size d of the inclusion:

$$N_o = N_o < d, \sigma_a > \qquad (6.1)$$

As a simple relation

$$N_o = C_o \, d^{-\alpha_1} \cdot \sigma_a^{-\alpha_2} \qquad (6.2)$$

with $\alpha_1 > 0, \alpha_2 > 0$ can be assumed. The correct relation may be found experimentally or by a more detailed model. Such a model was developed by Morris et al /8, 9/. They showed that N_o is a function of the inclusion size d and the largest possible slip distance w at 45^o to the principle stress axis (Fig. 6):

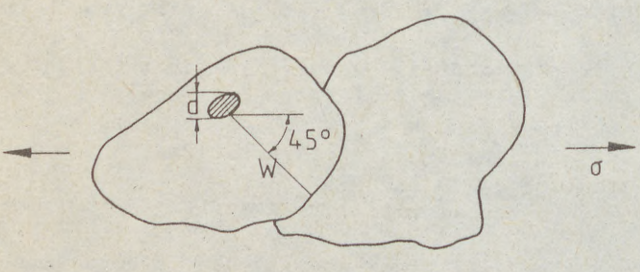


Figure 6. Microstructural parameters for crack initiation after Morris et al. /8, 9/.

$$N_o = \frac{C_o}{\sqrt{d}\; w(\tau - \tau_o)^2} \tag{6.3}$$

where $\tau - \tau_o$ is the effective shear stress. Later on this model was modified /10/. The probability density function of the number of cycles to crack initiation now can be related to the distribution of the inclusion size d and - if Eq. (6.3) is applied - to the distribution of w, which is dependent on the grain size distribution. The inclusion size distribution was described by the relation /11/ (s. Fig. 7)

$$f < d > = \frac{C^{\alpha-1}}{(\alpha-2)!} \left(\frac{d}{d_o}\right)^{-\alpha} \exp\left[-\frac{C}{d/d_o}\right] \tag{6.4}$$

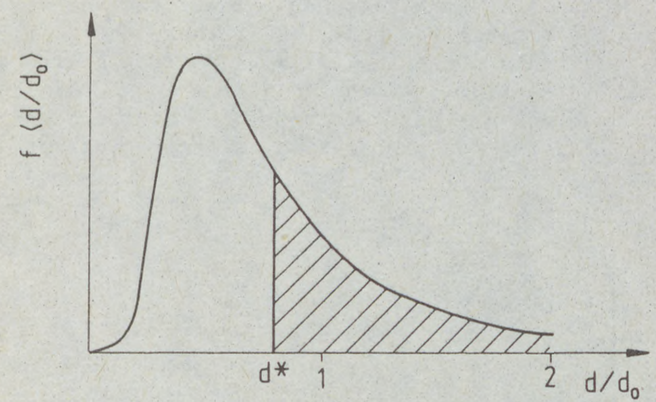


Figure 7. Inclusion size distribution

For the simple relation of Eq. (6.2) the crack density as a function of the number of cycles and of the stress amplitude then is given by

$$z < N, \sigma_a > = \eta_o \int_{d^*<N, \sigma_a>}^{\infty} f<d>\, dd \tag{6.5}$$

where η_o is the inclusion density (average number of inclusions per unit volume and per unit area, respectively). The lower integration limit is obtained from Eq. (6.2):

$$d^* = \left(\frac{C_o}{N}\right)^{1/\alpha_1} \sigma_a^{-\alpha_2/\alpha_1} \qquad (6.6)$$

If Eq. (6.3) is applied, then $z<N, \sigma_a>$ can be obtained from the distribution f<d> and f<w>.

For other crack initiation modes other crack initiation models have to be developed. Then it is possible to relate the crack initiation distribution to the distribution of the size and shape of the microstructural constituents of a material. With the methods of quantitative stereological characterization of the microstructure these distributions can be obtained /12/.

7. EARLY FATIGUE CRACK GROWTH

For cracks initiated at inclusions the first part of crack propagation within one grain and the transition into the neighbouring grains across the grain boundary is important. This early part of crack growth can span a large part of the life of a component. In recent years research has concentrated on the propagation behavior of these short cracks /13-15/. The main observation is shown in Fig. 8 as a crack growth rate (da/dN)-crack length(a)relation. For macrocracks a lower threshold exists below which no crack extension is possible. Microcracks are extending during the first part of propagation at decreasing rate. They

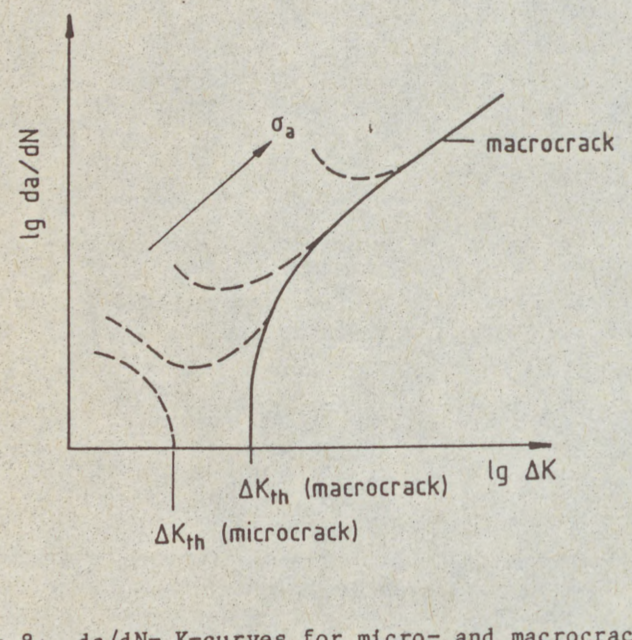


Figure 8. da/dN- K-curves for micro- and macrocracks

may get arrested for low amplitudes at grain boundaries or accelerated at higher amplitudes after crossing the grain boundary. Within this first part of crack extension a large amount of scatter is observed.

It is not intended to review here the different aspects and hypothesis of the extension of short cracks. Mainly three effects have been discussed: necessity of applying non-linear (elastic-plastic) fracture mechanics, crack closure and special microstruktural phenomena.

Two approaches will be mentioned briefly. Miller /15/ developed a dislocation model for the deceleration part of crack extension for a 0.4% C steel under torsion loading. This approach, however, can be generalised to include other materials and loading conditions. For the cracks initiated in ferritic grains the crack growth rate is given by

$$\frac{da}{dN} = \frac{0.1\ (0.5\ \tau_a - \tau_o)t}{\mu} \quad \frac{1 - a}{l} \qquad (7.1)$$

with τ_a: amplitude of torsion, τ_o: friction stress of dislocations, μ: shear modulus, t: ferrite plate thickness, l: ferrite plate length. This model offers a statistical evaluation of early fatigue crack growth incorporating the distribution of l and t.

Morris and James /10/ explained the deceleration and acceleration of short cracks by a change of crack closure stress and developed a model leading to

$$\frac{da}{dN} = A\ (\Delta K_{eff})^n \qquad (7.2)$$

with

$$\Delta K_{eff} = \Delta K \left[1 - \frac{\alpha\lambda}{a} \right] \qquad (7.3)$$

with α: material parameter in the range of 0.5 to 1.2, λ: distance of crack tip from grain boundary.

Again a statistical evaluation of crack extension is possible, where the distribution of crack size effects via λ the distribution of crack growth rate.

These are only two examples which show that a relation between scatter of the microstructural parameters can be related to the scatter of early fatigue crack growth rate.

8. FLAW LINKING

If many cracks are initiated a linking of individual cracks can occur during the extension /5, 7, 16/. The detailed process of crack-linking is complicated because of the interaction of the stress fields of the cracks. As a first step for a statistical treatment simple models can be developed. The simplest assumption is the random nucleation of cracks and a linkage without any interactions before linking. We are assuming surface cracks of the same length a, which are orientated perpendicular to the applied stress (Fig. 9). The surface area is divided into unit cells of length a and width b, where b may be equal to the grain size.

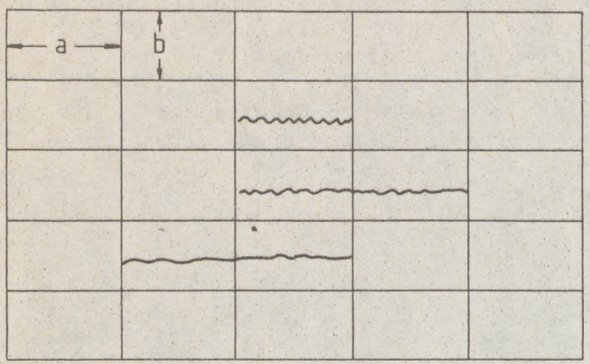


Figure 9. Crack linking (2 unit cracks combined).

The probability for a crack in a unit cell is given by

$$\lambda = \frac{z_s}{m} = z_s\,ab \tag{8.1}$$

where z_s is the density of surface cracks and m is the number of unit cells in the unit area. The probability of having a single cracks is given by the probability of a crack in a unit cell λ and the probabilities that the neighbouring cells are free from cracks:

$$P_1 = \lambda(1-\lambda)^2 \tag{8.2}$$

The probability of occurrence of two linked cracks is given by

$$P_2 = 2\,\lambda^2(1-\lambda)^2 \tag{8.3}$$

(There are two configurations starting from one crack). It can be shown /17/ that the probability of occurrence of r linked cracks is

$$P_r = r\lambda^r(1-\lambda)^2 \tag{8.4}$$

The number of coalesced cracks of length $a \cdot r$ in the unit area is

$$z\langle r\rangle = \frac{P_r \cdot m}{r} = (z_s ab)^r\,(1 - z_s ab)^2\,\frac{1}{ab} \tag{8.5}$$

The number of coalesced cracks of length a·r in a component of surface areas S is

$$Z\langle r\rangle = S\,z\langle r\rangle \tag{8.6}$$

In a complete probabilistic model the extension of individual cracks, crack linking and the growth of linked cracks have to be treated simultaneously /5, 17/.

For creep dominated rupture also flaw linkage is important. Flaws may be pores on grain boundaries or intercrystalline cracks. This problem was treated by Lindborg /18/ and by Hunt /19/. The model starts from two-dimensional flaws (Fig. 10). Also the nucleation of these flaws is a

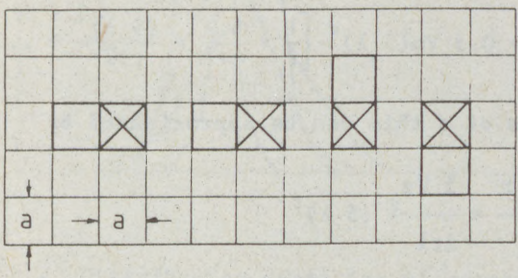


Figure 10. Flaw linking (2 unit areas combined).

statistical process. Therefore, the flaw size distribution and the flaw density may change with time. Similar to the crack linking model it is assumed in a first step that at a given time all flaws have the same size, which is described by a square unit of length a. The probability of occurrence of a flaw in unit cell λ is related to the volume flaw density z_v:

$$\lambda = \frac{z_v}{m} = z_v \cdot a^2 \tag{8.7}$$

where m is the number of flaws in the unit area. The probability of a single flaw occurrence then is

$$P_1 = \lambda(1 - \lambda)^4 \tag{8.8}$$

(four neighbouring flaw-free units). The probability of occurrence of exactly two linked flaws is given by

$$P_2 = 4\,\lambda^2\,(1-\lambda)^6 \tag{8.9}$$

(There are 4 possible configurations and for each 6 neighbouring crack free units). For r linked flaws Lindborg got the approximate relation

$$P_r = 0.5\,(5\,\lambda)^r \tag{8.10}$$

The number of flaws of size r in a volume V is

$$Z < r > = V \frac{P_r\, m}{r} \quad . \tag{8.11}$$

The number of flaws of size r or larger is

$$\zeta = \sum_{r}^{\infty} Z <r> = 0.5\ Vm(5\ \lambda)^r \left[\frac{1}{r} + \frac{5\ \lambda}{r+1} + \frac{(5\ \lambda)^2}{r+2} + \ldots\right] \tag{8.12}$$

For large enough values of r this can be approximated by

$$\zeta = \frac{5\ Vm(5\ \lambda)^r}{2r} = \frac{5\ Vz_v}{2r\lambda}\,(5\ \lambda)^r \tag{8.13}$$

Let us assume that final failure occurs if a critical flaw size corresponding to r* linked flaws is reached. Then the failure probability is given by the probability that at least one flaw is exceeding r*:

$$P_f = 1 - e^{-\zeta} = 1 - \exp\left[-\frac{5Vz_v(5\ \lambda)^{r^*}}{2r^*\ \lambda}\right] \tag{8.14}$$

These simple flaw-linking models can be refined. Instead of a fixed single flaw size a flaw size distribution can be applied and interaction of flaws can be included.

9. PROBLEMS IN THE DETERMINATION OF DENSITY FUNCTIONS

Two problems in the determination of density functions shall be mentioned briefly. The probability distribution of a material property is obtained by testing a large number of specimens applying statistical methods, e.g. the maximum likelihood method. The location and shape of the density function, which is reflected in the parameters of the distribution may depend on the sampling procedure. Let us consider a given material for which the composition and the heat treatment procedure is specified within given limits. If the specimens for measuring the property, e.g. strength, are fabricated from one plate a relatively small density function with the mean value μ_1 and the standard deviation σ_1 is obtained. Specimens from a second plate of the same fabrication lot may have a somewhat different distribution (Fig. 11) with μ_2 and σ_2, because of a systematic variation in composition or heat treatment parameters during fabrication.

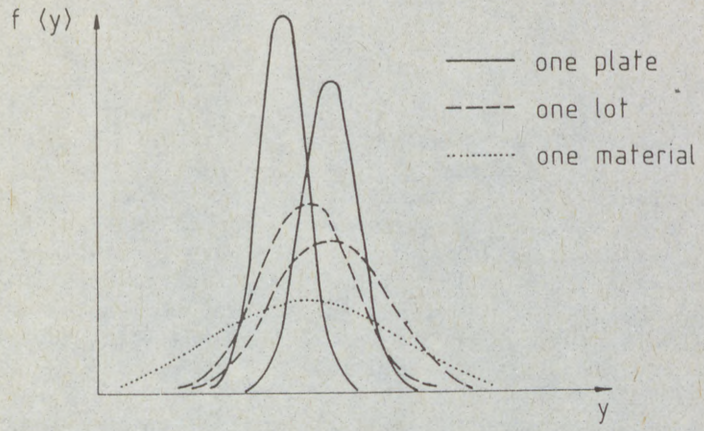


Figure 11. Distribution densities of material property Y.

If specimens of many plates of the same lot are tested a joint probability distribution is obtained with the mean value μ_I and the standard deviation σ_I. Testing specimens from another lot or another manufacturer may have a different joint probability distribution with μ_{II} and σ_{II}. Information about the possible scatter in the material property requires therefore to test specimens from different manufacturers or at least specimens from one manufacturer fabricated at different times. This leads to the final mean value μ and standard deviation σ. It is obvious that $\sigma_1 < \sigma_I < \sigma$. Therefore it may not be possible to characterize the variability of a material property by only testing many specimens from one plate or one fabrication lot.

Another problem in the evaluation of the scatter of material properties is the existence of a lower limit. Usually probability functions with a lower limit of zero are used (e.g. 2-parameter-Weibull or log-normal distributions). However, a lower limit should exist, taking into account fabrication specifications and quality control. Usually, the number of tested specimens is not large enough to furnish reliable lower limits. It is also often not possible to describe the tails of the distributions correctly. The problems of lower limit and lower tail behaviour is important if the reliability of a component has to be very high, for instance in nuclear power plants. The failure probability then is strongly dependent on the lower tail behaviour of the material properties. It is not possible to solve this problem by testing more and more specimens. The only possible solution seems to find correlations between the microstructure of a material and the material properties. If, for instance, a relation exists between the inclusion size and the number of cycles for crack initiation, then the inclusion size distribution has to be measured. It should be possible to measure much more inclusions than specimens can be tested. If it is possible to specify a maximum inclusion size, a minimum number of cycles for crack initiation can be obtained.

10. PRACTICAL APPLICATION OF A PROBABILISTIC APPROACH

10.1. General remarks

The aim of a probabilistic treatment of the failure can be threefold:

1. General understanding of the causes of scatter in the lifetime.
2. Quantitative evaluation of the main causes which are responsible for the scatter of time to failure. Even if the absolute failure probabilities may be wrong, a sensitivity study may lead to special actions to reduce the scatter (for instance: control of the inclusion size).
3. Probabilistic design according to an allowable failure probability and definition of inspection intervals.

The necessary accuracy of the probabilistic evaluation increases from 1) to 3). The microstructural models described in sections 6 and 7 are especially important for 1). For 2) and 3) often empirical distribution densities have to be used as input data for a probabilistic calculation.

In this section the main principles for a probabilistic design and a probabilistic determination of inspection intervals are outlined briefly, without development of all quantitative relations.

A crack initiation-crack propagation failure is considered. In a deterministic design a component has to be retired without any inspection if an initiated crack reaches a fixed value a_r which is smaller than the critical crack length. The ratio a_c/a_r is a safety factor.

Instead of retirement a nondestructive inspection is possible. If all cracks larger than a* can be detected than the inspection period is the time necessary for a crack growing from a* to a_r (s. Fig. 12). A probabilistic evaluation has to take into account:
- the developing crack size distribution,
- the crack detection probability,
- the probability of incorrect sizing of a crack.

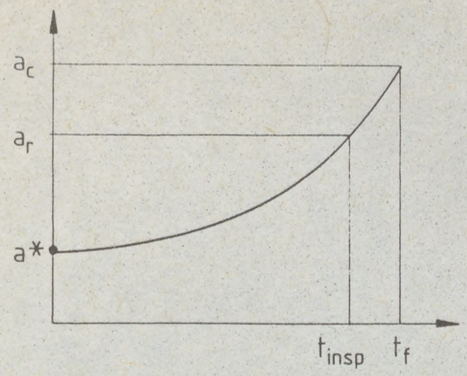


Figure 12. Crack size versus time (a^*: maximum crack size after inspection, a_c: critical crack size a_r: maximum crack size before inspection.

10.2 Inspection uncertainty

Ideally, non-destructive inspection of a component should result in the size, shape and location of all flaws above a given size. Then it can be decided that all components with flaws above a critical size have to be rejected. In reality, not all the cracks are detected and the detected cracks may be sized incorrectly. The number of rejected components depends on the inspection sensitivity. Regarding ultrasonic inspection, for instance, it may be stated that all components are rejected if a flaw leads to a pulse echo greater than 50% of a drilled hole of a given size. For a fixed inspection sensitivity then two types of error are possible /20/.

- False acceptance of a component, because flaws are not detected or incorrectly accepted.
- False rejection because a small detected flaw is oversized.

To illustrate the situation, flaw size distributions before inspection and after inspection and rejection are shown in Fig. 13. The flaw size distributions after inspection are dependent on the probability of detecting a flaw $p_D \langle a \rangle$, which is a function of the flaw size. In case a) a correct sizing of the flaws is assumed. All flaws above a critical size a^* are rejected. The shaded areas are showing the correctly rejected flaws and the undetected flaws with $a > a^*$.

In case b) and c) the detection probabilities are given for two different fixed inspections sensitivities. All detected flaws are rejected. In addition to the shaded areas for correctly rejected flaws and undetected flaws with $a > a^*$, there is now an area with flaws of the size $a < a^*$ leading to a false rejection. It can be seen by comparing cases b) and c) that increasing the inspection sensitivity leads to a decrease in the number of undetected dangerous flaws but to an increase in the number of rejected, not dangerous flaws.

Quantitative relations can be obtained if the flaw size distributions before inspection $f\langle a \rangle$ and the flaw detection probability is

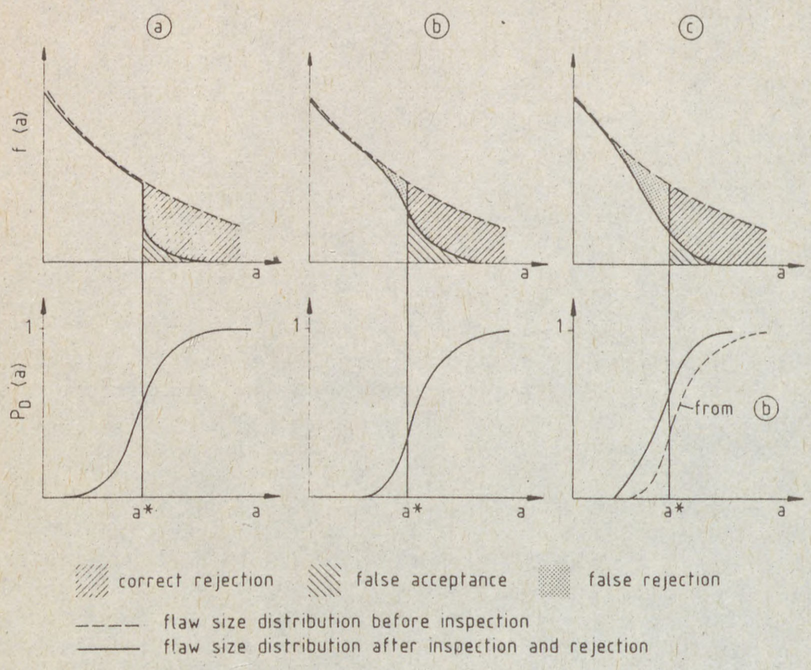


Figure 13. Flaw size distribution before and after inspection a) correct sizing and rejection of all flaws with a > a*, b) and c) all detected flaws are rejected.

known. The average number of dangerous flaws in a component before inspection is given by

$$Z_D = Z \int_{a^*}^{\infty} f \langle a \rangle \, da \qquad (10.1)$$

where Z = zV is the total number of flaws in a component. The (not normalized) distribution of undetected cracks is given by

$$f_1 \langle a \rangle = f \langle a \rangle \, |1 - P_D \langle a \rangle| \qquad (10.2)$$

Then the average number of dangerous flaws in a component after inspection (the number of undetected dangerous flaws) is

$$W_D = Z \int_{a^*}^{\infty} f\langle a\rangle \, |1-P_D\langle a\rangle| da \qquad (10.3)$$

The average number of detected dangerous flaws is

$$U_D = Z \int_{a^*}^{\infty} f\langle a\rangle \, P_D\langle a\rangle \, da = Z_D - W_D \qquad (10.4)$$

The probability of false acceptance P_{FA} is the joint probability of occurrance of undangerous detectable flaws in a component and at least one dangerous, not detectable crack in a component:

$$P_{FA} = e^{-U_D} \left[1-e^{-W_D}\right] = e^{-U_D} - e^{-Z_D} \qquad (10.5)$$

For case b) and c) the average number of detected cracks with $a < a^*$ (detected not dangerous flaws) is important:

$$U_{ND} = Z \int_{o}^{a^*} f\langle a\rangle \, P_D\langle a\rangle \, da \qquad (10.6)$$

The probability of false rejection P_{FR} is given by the joint probability of occurrance of at least one detected crack in the component with $a <$ a^* and no dangerous crack (detected or not) with $a > a^*$:

$$P_{FR} = \left[1 - e^{-U_{ND}}\right] e^{-Z_D} \qquad (10.7)$$

The probability of correct rejection P_{CR} of a component is given by the probability that there is at least one detectable dangerous flaw in the component

$$P_{CR} = 1 - e^{-U_D} \qquad (10.8)$$

Finally, the probability that a component is correctly accepted, P_{CA}, is given by the joint probability that there is no dangerous flaw in the component and the probability that there is no detected undangerous flaw:

$$P_{CA} = e^{-Z_D} \cdot e^{-U_{ND}} \tag{10.9}$$

The probabilities of both false acceptance P_{FA} and of false rejection P_{FR} are dependent on the detection probability P_D which effects the average number of detected cracks with $a > a^*$ (U_D) and with $a < a^*$ (U_{ND}). If the inspection sensitivity is increased, U_D and U_{ND} increase, leading to an increase in P_{FR} and a decrease in P_{FA}. Fig. 14 shows schematically the number of detected and not detected dangerous and undangerous flaws.

A cost optimized inspection sensitivity can be obtained /21, 22/.

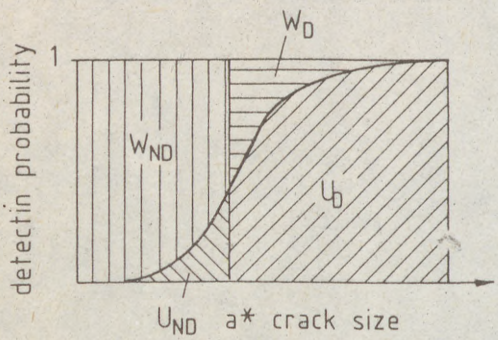


Figure 14. Probability of flaw detection versus crack size (areas correspond to number of detected and not detected dangerous and not dangerous cracks for a constant probability density function of crack size.

If C_F is the cost of a failed component and C_M the cost for manufacturing the component the effective cost of an accepted component is given by

$$C = \frac{C_M + P_{FA}\, C_F}{1 - P_{CR} - P_{FR}} \tag{10.10}$$

8.3 Periodic inspection

A periodic inspection leads to a reduction in the failure probability compared to only a pre-service inspection /23, 24/. After each inspection and rejection of components with detected flaws a new crack size distribution is obtained:

$$f_{POST\ INSP}\langle a\rangle = f_{PRE\ INSP}\langle a\rangle\ |1 - P_D\langle a\rangle| \qquad (10.11)$$

The post inspection distribution is the starting distribution for calculating failure probabilities until the next inspection. It is thus possible to calculate the failure probability for different inspection intervals. A cost optimisation is possible taking into account the costs of inspection, the costs of manufacturing (for a replaced component) and the costs of a failure.

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THE CALL EFFECTIVENESS PROCESS:
A MODEL FOR A TECHNICAL AND ECONOMICAL ANALYSIS

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The Call Effectiveness Process: a model for a technical and economical analysis.
by dr. Flavio Riciniello (SIP, ITALY)

Abstract.

This paper presents an analysis of the call completion process, and proposes a model for an overall characterization of the network performance and customer behaviour.

The results presented in this paper are useful for network planning, through the determination of the traffic demand and of the "repeated" traffic, for the analysis and monitoring of the network capability in handling call attempts (with the introduction of appropriate parameters); moreover these results constitute the means to determine the goals for the network effectiveness related to the evaluation of the costs/benefits, including the lost traffic.

1. Introduction.

The interpretation of the field data, the evaluation of the traffic demand and of the "repeated" traffic, related to the effectiveness of the network and to the customer behaviour (both calling and called) are considerable issues in traffic engineering, measurement and control.

In the dimensioning of network resources(nodes and links) and in the evaluation of the costs associated to a poor network performance, the analysis of this phenomenon is of great interest.

In the past, several studies have been carried out with the aim of evaluating the characteristics of customer behaviour related to a previous unsuccessful call attempt (due to congestion and failure, busy called party or no answer). The main results, contained in the reference [1,2,3,4,5], indicate clearly the fundamental elements of the phenomenon and the great influence of the above-mentioned elements on:

- the call setup delay;
- the probability of the call completion;
- the customer behaviour (dialling delay, probability of abandoning, answer delay).

The same studies have shown the great dependency of the phenomenon to the traffic classes (local, national, international) and to the subscriber categories (residential, business).

The Italian network has carried, in 1989, 24 billions of communications (local:16.26 billions; long-distance:7.50 billions; international:0.24 billions).

As a matter of fact, a user does not always communicate with the desired subscriber at the first attempt; in general several attempts are needed and the last may be followed by a conversation or by an abandon. The fact that a call attempt is followed by a conversation depends not only from the network, (for example, the dimensioning of the circuits, the alternative routing) but also by the customer's behaviour.

Therefore, the problem should be dealt globally, taking into account all the different aspects.

The results presented here are the outcome of a wider activity in progress at SIP, aiming to refine the existing quality indexes and to propose more efficient solutions, if appropriate. The main objective of the work presented in this paper is to develop a model allowing:

1) the possibility to analyze the various aspects of the phenomenon;
2) the specification of indexes or parameters more oriented to the customer perception;
3) the identification of specific indexes or parameters for each aspect;
4) the identification of the elements for the analysis of the costs associated to the call attempt completion process;
5) a more efficient interpretation of the collected data.

The model proposed in this work is an extension of the model contained in the Racc. E.501, Blue Book of CCITT for the estimation of the offered traffic. For the validation of this model, were useful the data presented in [5], related to a field trial carried out in the USA by Bell Telephone Labs. in 1976.

2. Characteristics of the proposed model.

The model, and all its variants, proposed in this work are based on an appropriate composition of the characteristics of the network performance and of the subscriber behaviour.

In the following analysis we will leave aside all the mathematical aspects (described in the Appendixes).

The reference scheme is presented in Fig. A-I-1.

The parameters of the model can be distinguished in two classes:

a) external parameters;

b) internal parameters.

The number of first call attempt (Nf), the number of conversations (Nc) and the number of abandoned call attempts (Na) belong to the first class; the number of call attempts offered to the network (No) and the number of repeated call attempts (Nr) belong to the second class.

The distinction reflects the fact that the external parameters are more related to the ultimate successful probability (how many conversations/call demands), while the internal parameters are more related to how easily a conversation is obtained (how many attempts per first call attempt).

Usually, we have information only on No and Nc (easily obtained), but it can be very useful to have the information on Na, Nf and Nr. This can be possible only with a field trial especially dedicated to this purpose and this is very costly.

The model of Figure A-I-1 shows the relationship between the internal and external parameters, and allows the identification of the indexes for the network and indexes oriented to the customer perception. The above issue has been investigate and the first results are given in the Appendix IV.

These are some of the reasons for which this model can be useful either for traffic forecasting and dimensioning of the network resources or for the evaluation of Na,Nf and Nr.

Nevertheless the main issue consists in the equivalence between the model 1 (Fig. A-I-1) and the model 5 (Fig. A-I-5).

The importance of this last issue is that all the study can be developed taking into account only two equivalent parameters (R and C). R represents the equivalent retrial probability due to a inefficient call attempt and C represents the equivalent ASR (Answer Seizure Ratio); used together they give the same results, in terms of external and internal parameters.

The model, and its variants, permits a great quantity of applications, and some of them are:

- the evaluation of the number of first call attempt, of the number of repeated call attempts and of the number of abandoned call attempts;
- the evaluation of the lost traffic, of the repeated traffic and of the traffic demand expressed in terms of Erlang (by introducing the delays associated with the call processing);
- the specification of indexes oriented to the subscriber;
- technical and economic evaluations;
- a better interpretation of the field data.

In the following we will present two examples of applications.

3. Validation of the proposed model.

As an example of the application, we will chose the results from field trial measurement carried out by Bell System in 1976 in the USA and quoted in [4].

In this field trial, 12658 call attempt have been registered and of these 10672 were judged first call attempts, on the bases of the identity of the calling party and of the called party.

In Tab. 1 are presented the main results from the 10672 call attempts.

Attempt level	Number of attempts	Completion probability	Retrial probability
1	10672	0.755 ± 0.015	0.665 ± 0.042
2	1749	0.510 ± 0.051	0.743 ± 0.067
3	636	0.415 ± 0.061	0.793 ± 0.081
4	295	0.377 ± 0.052	0.871 ± 0.069
≥5	386	0.119 ± 0.017	0.957 ± 0.028

Average retrial probability = 0.719 ± 0.020
Average attempts/initial attempt = 1.29 ± 0.04
Ultimate success probability = 0.885 ± 0.009

TABLE 1. Results from measurements in USA [5]

From the analysis of these results it becomes evident that with the increasing of the attempt level the completion probability decreases , and the retrial probability increases. Therefore it seems necessary the analysis presented in Appendix V.

The results obtained with the model compared with those measured in the USA (see Tab II), give a confirmation on the validity of the proposed model and the confirmation that we can describe the phenomenon with simply two parameter: R and C (or G).

Symbol	LIU	Model	Parameter
Nf	10672	-	number of first call attempts
No	13738	-	number of call attempts offered to the network
Nr	3066	-	number of repeated call attempts
Nc	-	-	number of conversations
ASR	not used	0.681571	Answer Seizure Ratio
G	not used .	0.223176	loop gain
R	0.719 ± 0.02	0.700865	average retrial probability = G/(1-C)
Pc	0.885 ± 0.09	0.8773	ultimate success probability = C/(1-G)
1/(1-G)	1.29 ± 0.04	1.28792	average attempts/initial attempt

TABLE II. Comparison of the proposed model and [5].

4.<u>Example of application: analysis of the benefits associated with the improvement of the effectiveness of the network</u>.

The method applied for the evaluation of the benefits associated with the improvement of the effectiveness of the network has been proposed from AT&T [6] and applies the relations obtained in this work (in particular those from Appendix II).

The evaluation is based on the calculation of the increase $\triangle$Nc of the number of conversations, consequent the improvement of the effectiveness of the connection accessibility, and on the calculation of the decrease $\triangle$Ni of the number of ineffective call attempts.

The calculation is made with the following assumptions:

a) the number of first call attempts Nf does not change varying the value of C;

b) the retrial probability for an attempt does not change varying the value of C.

R and C are the two parameters related to the model 5 described in Appendix I (Fig. A-I-1).

The assumptions a) and b) are a approximation of the reality, as with an increase $\triangle$Nc, there will be an increase of first call attempts Nf and an increase of the value of R, as the subscriber is induced in retrials, due to the higher probability of success related to the increase of C. This means that assuming points a) and b) we have an underestimation of the obtainable benefits.

If we assume that:

4.1 $\quad \Delta Ni = - Ni(C) + Ni(C_0) \Big|_{\substack{R=cost \\ Nf=cost}} \qquad \Delta Nc = - Nc(C) + Nc(C_0) \Big|_{\substack{R=cost \\ Nf=cost}}$

and indicating with C_0 the initial value we have:

$$\Delta Ni = \left[\frac{1-C_0}{1-R(1-C_0)} - \frac{1-C_0-\Delta C}{1-R(1-C_0)+R\Delta C} \right] Nf$$

4.2
$$\Delta Nc = \left[\frac{C_0+\Delta C}{1-R(1-C_0)+R\Delta C} - \frac{C_0}{1-R(1-C_0)} \right] Nf$$

$$Nf = Nc(C_0) \frac{1-R(1-C_0)}{C_0}$$

The above relations where obtained using the A-II-7 and the A-II-9. These can be written as:

4.3 $\quad \Delta Ni = \dfrac{\Delta C}{C_0} \dfrac{Nc(C_0)}{1-R(1-C_0)+R\Delta C} \qquad \Delta Nc = \dfrac{\Delta C}{C_0} \dfrac{Nc(C_0)(1-R)}{1-R(1-C_0)+R\Delta C} \qquad Nf = Nc(C_0) \dfrac{1-R(1-C_0)}{C_0}$

To be noted that in first approximation ΔNi and ΔNc are proportional to $\Delta C/C_0$. Moreover we can deduce that:

4.4
$$\Delta Nc = \Delta Ni(1-R)$$

Now is possible to evaluate the additional income AI due to the increasing of the conversations; that is:

4.5 $\quad AI = f\Delta Nc$

and the reduction of costs DC, due to the decreasing of the ineffective attempts:

4.6 $\quad DC = g\Delta Ni$

The values f and g should be distinctly evaluated for the incoming traffic and the outgoing traffic, differentiating, when appropriate the local,long distance,international traffic and also if necessary distinguishing the customer's class (business,residential).

Obviously the analysis should be made for various values of R. Studies made by others [1,2,3,4,5,6], suggested values between 0.50 and 0.80.

Considering the 4.4, 4.5 and 4.6 the total benefit BC is:

4.9 $\quad BC = AI + DC = \left(f + \dfrac{g}{1-R} \right) \Delta Nc$

References.

[1] - R.I. Wilkinson, R.C. Radnik: The character and effect of customer retrials in intertoll circuit operation, Bell Telephone Laboratories, Holmdel, New Jersey, USA.

[2] - F.P. Duffy, R.A. Mercier : A study of network performance and customer behaviour during direct-distance-dialing call attempts in USA, B.S.T.J., vol. 57, Jan. 1978, N° 1, pp. 1÷33.

[3] - J.W. Roberts : Recent observations of subscriber behaviour, ITC-9.

[4] - K.S. Liu : Direct-distance-dialing call completion and customer retrial behaviour, ITC-9.

[5] - L. Burkard, J.J. Phelan, M.D. Weekly : Customer behaviour and unexpected dial tone delay, ITC-10, paper 45,session 2.4.

[6] - J.H. Rosebluth : Payoff analysis for improved international call completion, ATT Technical memorandum 1984.

[7] - M. Decina, F. Riciniello, A. Roveri : Esercizi di sistemi digitali, ed. Siderea 1976.

Symbols and definitions.

K ≡ number of repeated call attempts (c.a.)
$P_L(K)$ ≡ probability of having at least K repeated c.a.
$P_a(K)$ ≡ probability of abandoning after the K repeated c.a.
$P_c(K)$ ≡ probability of success after K repeated c.a.
$P_1(K)$ ≡ probability of having exactly K repeated c.a.
Nc ≡ number of conversations
Nf ≡ number of first c.a.
Ni ≡ number of ineffective c.a.
Nr ≡ number of repeated c.a.
Na ≡ number of abandoned c.a.
No ≡ number of c.a. offered to the network
E[·] ≡ expected value of [·]
Pa ≡ abandon probability after any number of repeated c.a.
Pc ≡ ultimate success probability
Ni ≡ number of unsuccessful c.a.
Pc(K)1)≡ ultimate success probability with at least one repeated c.a.
SI ≡ probability of customer's incorrect or incomplete selection.
AC ≡ probability of a c.a. receiving intelligible information about the state the called user
CON ≡ probability of a successful c.a. being completed
OCC ≡ probability of a successful c.a. receiving the busy tone
LNR ≡ probability of a successful c.a. not receiving no the answer signal
C ≡ probability of a c.a. being completed
R ≡ equivalent probability of a ineffective c.a. being repeated
G ≡ equivalent probability of a c.a. being repeated
R_i ≡ probability of a c.a. to be repeated for i^{th} cause
H_i ≡ probability of a c.a. not being completed for i^{th} cause
Ni_i ≡ number of a c.a. not being completed for i^{th} cause
Nr_i ≡ number of a c.a. not being completed for i^{th} cause and being repeated
f ≡ incremental income per conversation
g ≡ incremental cost reduction per not completed c.a.
AI ≡ additional income corresponding to an increase of C
BC ≡ total benefit corresponding to an increase of C
DC ≡ cost reduction associated with a decrease of Ni

Appendix I

<u>Transformation of the model</u>

In figure A-I-1 is shown the diagram which describes the effectiveness of the network for the call handling.

From figure A-I-1, writing the expressions of Nc and Ni_i (i=1..4), we have:

A-I-1 $$Nc = C\ No \qquad C = (1-SI)AC\ CON$$

A-I-2
$$H_1 = SI \qquad H_3 = (1-SI)AC\ LNR$$
$$H_2 = (1-SI)(1-AC) \qquad H_4 = (1-SI)AC\ OCC$$
$$Ni_i = H_i\ No \qquad (i = 1..n)$$

Obviously the following condition is verified:

A-I-3 $$CON + LNR + OCC = 1$$

Thus model 2, presented in figure A-I-2 is equivalent to model 1; such models are shown for four different causes of noncompletion. Nevertheless it is possible the extension to n different causes. The equilibrium equations are:

A-I-4
$$Nf = Nc + Na$$
$$No = Nc + Ni$$
$$No = Nf + Nr$$

where:

A-I-5 $$Nr = \sum_{i=1}^{n} Nr_i \qquad Ni = \sum_{i=1}^{n} Ni_i \qquad Na = \sum_{i=1}^{n} Na_i$$

Now it is easy to verify that:

A-I-6 $$C + \sum_{i=1}^{n} H_i = 1$$

and

A-I-7 $$Ni = Nr + Na$$

The expressions A-I-4 ÷ A-I-7 define the equilibrium of model 2. From the following equations, that define the functional blocks of the model:

A-I-8
$$Nc = C\ No$$
$$Ni_i = H_i\ No \qquad (i=1..n)$$
$$Nr_i = R_i\ Ni_i \qquad (i=1..n)$$
$$Na_i = (1-R_i)\ Ni_i \qquad (i=1..n)$$

and the equilibrium equations we have:

A-I-9
$$\frac{Nc}{Nf} = \frac{C}{1 - \sum_{i=1}^{n} H_i R_i}$$

A-I-10
$$\frac{Ni}{Nf} = \frac{1 - C}{1 - \sum_{i=1}^{n} H_i R_i}$$

A-I-11
$$\frac{Na}{Nf} = \frac{1-C-\Sigma_i H_i R_i}{1 - \sum_{i=1}^{n} H_i R_i}$$

A-I-12
$$\frac{Nr}{Nf} = \frac{\Sigma_i H_i R_i}{1 - \sum_{i=1}^{n} H_i R_i}$$

Now using the first of A-I-8, we can obtain from A-I-9 ÷ A-I-12 the following equations:

A-I-13
$$\frac{Ni}{No} = 1 - C$$

A-I-14
$$\frac{Nr}{No} = \sum_{i=1}^{n} H_i R_i$$

A-I-15
$$\frac{Nf}{No} = 1 - \sum_{i=1}^{n} H_i R_i$$

A-I-16
$$\frac{Na}{No} = 1-C-\sum_{i=1}^{n} H_i R_i$$

The quantity

A-I-17
$$G = \sum_{i=1}^{n} H_i R_i$$

is the total loop gain, obtained by adding the individual loop gains and can also be written as follows:

A-I-18
$$G = R \sum_{i=1}^{n} H_i$$

where

A-I-19 $$R = \frac{\sum_{i=1}^{n} H_i R_i}{\sum_{i=1}^{n} H_i}$$

Through the expression in A-I-18, it is now possible to substitute every R_i with R in the A-I-9 ÷ A-I-16. This is shown in model 3 of figure A-I-3. Looking at the model 3 we note no indications of the quantities Nr_i and Na_i because the A-I-18 permits the equivalence only for those quantities that depend on Σ_i H_i and G and not on the single values of R_i. Still we can calculate the Ni_i as they depend on H_i. In figure A-I-3 bis and figure A-I-3 ter are shown equivalent variants to model 3. Looking at model 3 ter we can write:

A-I-20 $$Nr = R \sum_{i=1}^{n} Ni_i = R\ Ni$$

The A-I-20 enables to take into consideration the loops directly after the adder; thus now we can have a single loop as shown in figure A-I-4. A last transformation is possible substituting the parallel branches H_i in one transfer function:

A-I-21 $$\sum_{i=1}^{n} H_i = 1 - C$$

This brings us to model 5 shown in figure A-I-5.

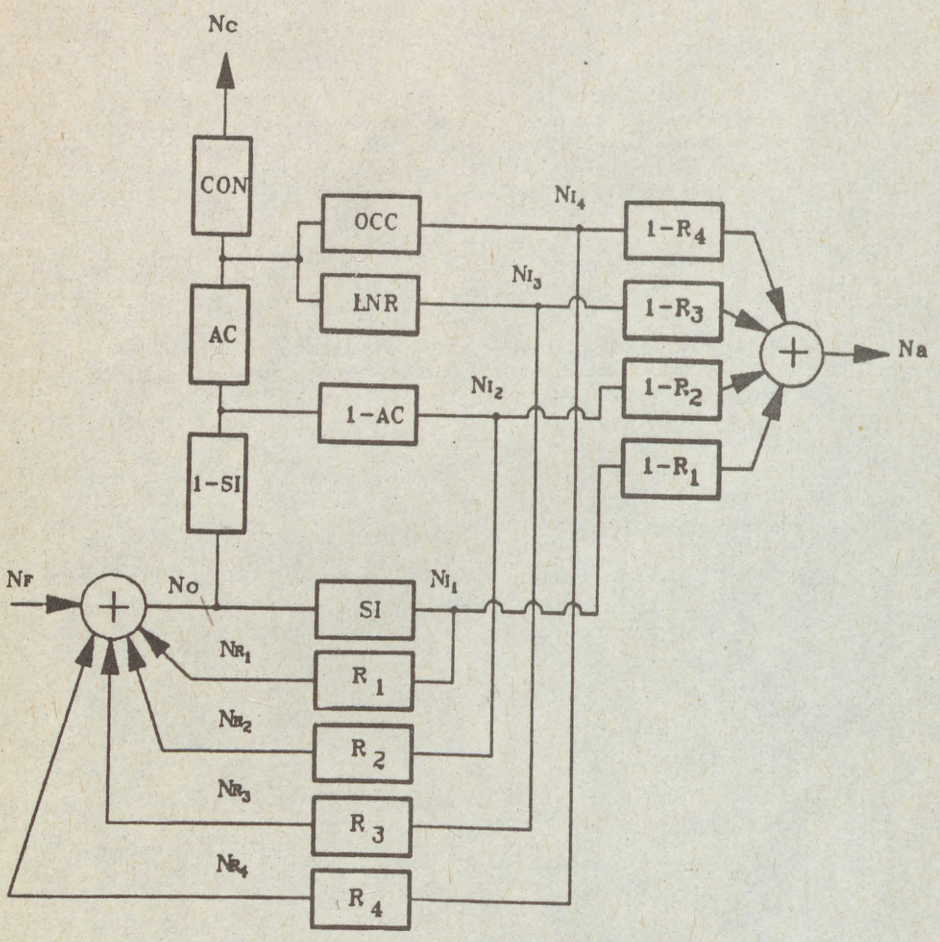

Figure A-I-1 Model 1

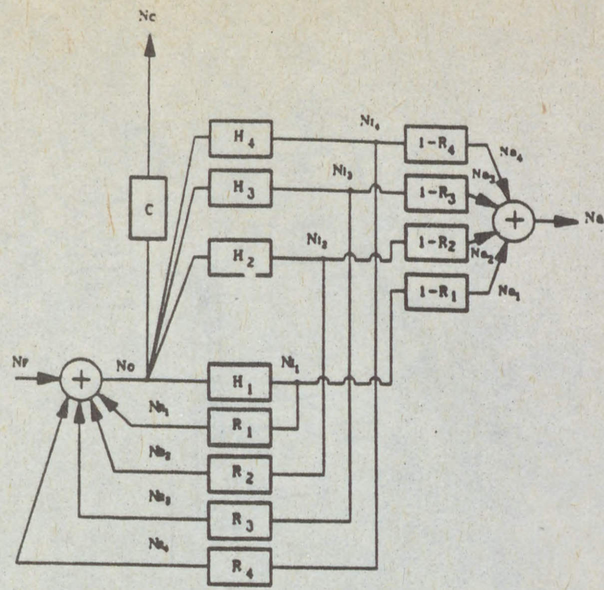

Figure A-I-2 Model 2 (for n=4)

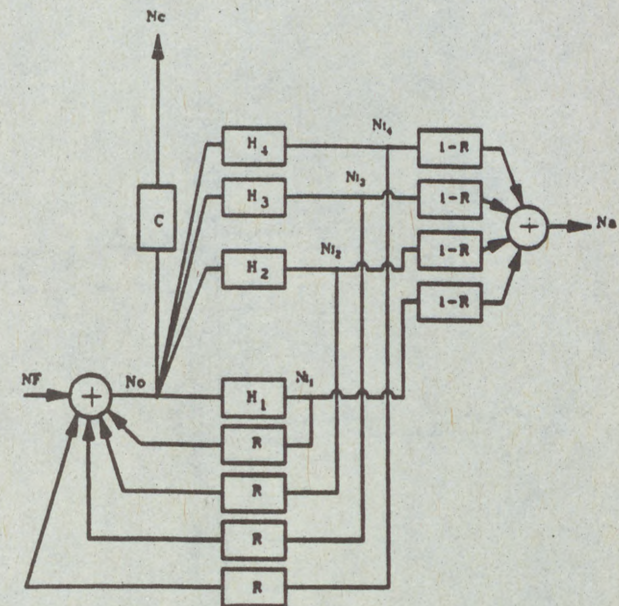

Figure A-I-3 Model 3 (for n=4)

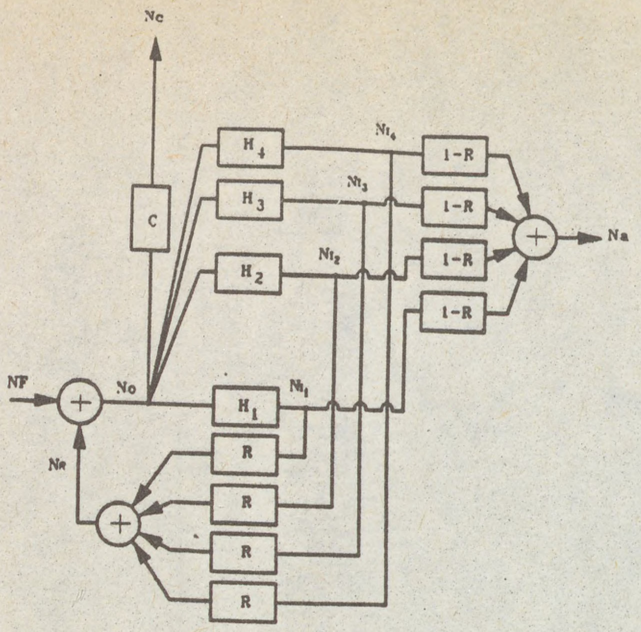

Figure A-I-3 bis Model 3 bis (for n=4)

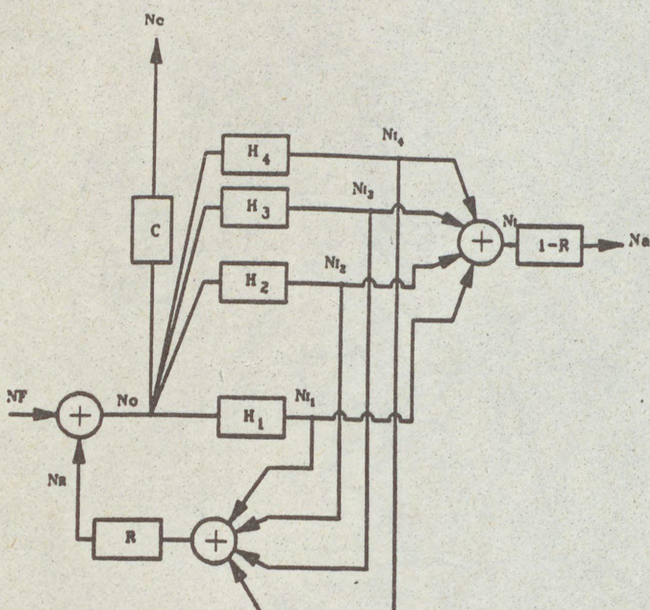

Figure A-I-3 ter Model 3 ter (for n=4)

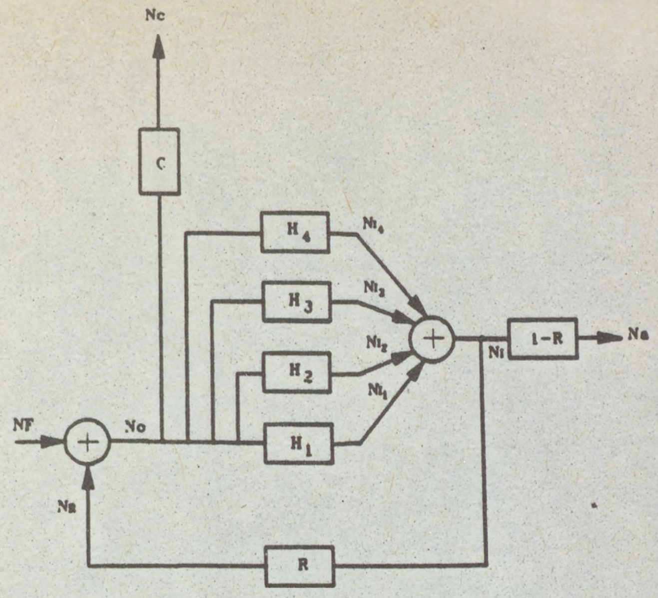

Figure A-I-4 Model 4

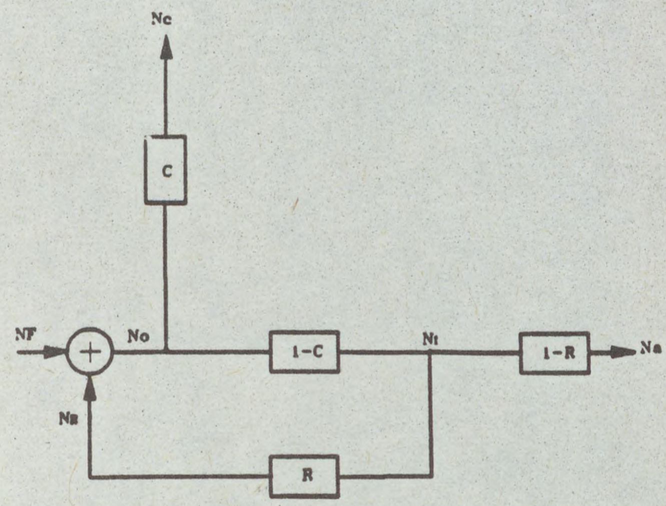

Figure A-I-5 Model 5

Appendix II

<u>Study of model 5</u>.

From figure A-I-5 we can derive the following equations:

A-II-1 $$Nf = Nc + Na$$

A-II-2 $$No = Nf + Nr$$

A-II-3 $$No = Ni + Nc$$

Subtracting term by term the A-II-2 and A-II-3 we have:

A-II-4 $$Ni = Nr + Na$$

Remembering the definitions of R and C we have:

A-II-5
$$\begin{aligned} Nc &= C\ No \\ Ni &= (1 - C)\ No \\ Nr &= R\ Ni \\ Na &= (1 - R)\ Ni \end{aligned}$$

If we define:

A-II-6 $$G = R\ (1 - C)$$

from the above expression we will write:

A-II-7 $$\frac{Nc}{Nf} = \frac{C}{1 - G}$$

A-II-8 $$\frac{Na}{Nf} = \frac{1 - G - C}{1 - G}$$

A-II-9 $$\frac{Ni}{Nf} = \frac{1 - C}{1 - G}$$

A-II-10 $$\frac{Nr}{Nf} = \frac{G}{1 - G}$$

A-II-11 $$\frac{Na}{No} = 1 - G - C$$

A-II-12 $$\frac{Ni}{No} = 1 - C$$

A-II-13 $$\frac{Nc}{No} = C$$

A-II-14 $$\frac{Nf}{No} = 1 - G$$

A-II-15 $$\frac{Nr}{No} = G$$

The quantity G is the loop gain and is equivalent to the probability of a call attempt being repeated. Taking into account the definitions we have:

A-II-16 $$P_L(k) = G^k \qquad K \geq 1$$

A-II-17 $$P_c(k) = C\,G^{k-1} \qquad K \geq 1$$

A-II-18 $$P_a(k) = (1 - C - G)^{k-1} \qquad K \geq 1$$

A-II-19 $$P_1(k) = (1 - G)^{k-1} \qquad K \geq 1$$

A-II-20 $$P_i(k) = (1 - C)^{k-1} \qquad K \geq 1$$

We can also note that:

A-II-21 $$P_1(k) = P_a(k) + P_c(k) \qquad k \geq 1$$

points the fact that the probability of having exactly k repeated attempts is equal to the sum of the probability of abandoning and the probability of completion.

Adding term by term the expressions in A-II-21 we have:

A-II-22 $$\sum_{k=1}^{\infty} P_1(k) = \sum_{k=1}^{\infty} P_a(k) + \sum_{k=1}^{\infty} P_c(k)$$

and if we consider

A-II-23 $$P_a = \sum_{k=1}^{\infty} P_a(k)$$ A-II-24 $$P_c = \sum_{k=1}^{\infty} P_c(k)$$

we have:

A-II-25 $$P_a + P_c = 1$$

Then using the A-II-17 and A-II-18 we can write:

A-II-26 $$P_a = \frac{1 - C - G}{1 - G} \quad \text{if } G<1 \qquad P_a = 0 \quad \text{if } G=1$$

A-II-27 $$P_c = \frac{C}{1 - G} \quad \text{if } G<1 \qquad P_c = 0 \quad \text{if } G=1$$

Since $P_1(k)$ is a probability density, we can write:

A-II-28 $$E[k_1] = \sum_{k=1}^{\infty} P_1(k)\ (k-1) = \sum_{k=1}^{\infty} (1-G)\ G^{k-1}\ (k-1)$$

therefore

A-II-29 $$E[k_1] = \frac{G}{1 - G} \quad \text{if } G<1 \qquad\qquad E[k_1] = 0 \quad \text{if } G=1$$

Appendix III.

<u>Calculation of the moments of the variable "number of repeated call attempts".</u>

The expression of the m^{th} moment of K_1 is:

A-III-1 $$E[K_1^m] = \sum_{K_1=0}^{\infty} K_1^m \, P_1(K_1) = (1-G) \sum_{K_1=0}^{\infty} K_1^m \, G^{K_1}$$

Taking into account the expression on page 40 of [7] we have:

A-III-2 $$E[K_1^m] = \frac{1 - G}{(1 - G)^{m+1}} \sum_{i=1}^{\infty} b_i^{(m)} \, G^i$$

In Tab. III-1, are presented the coefficients for $m \leq 11$. Furthermore it is possible to demonstrate that

A-III-3 $$b_i^{(m)} = b_{m+1-i}^{(m)} \quad i=1..m \quad ; \quad b_i^{(m)} = 1 \quad i=1..m \quad ; \quad b_1^{(m)} = 1$$

Concerning the central moments we have:

$$E[(K_1 - E[K_1])^m] = E[\sum_{i=0}^{m} \binom{m}{i} K_1^i (-1)^{m-i} E[K_1]^{m-i}] = \sum_{i=0}^{m} \binom{m}{i} E[K_1^i] (-1)^{m-i} \, E[K_1]^{m-i}$$

$$= (-1)^m \, E[K_1]^m + \frac{G}{(1-G)^m} \sum_{i=1}^{m} \binom{m}{i} (-1)^{m-i} G^{m-i} \sum b_j^{(i)} G^{j-1}$$

$$= (-1)^m \frac{G^m}{(1-G)^m} + \frac{G}{(1-G)^m} \sum_{i=1}^{m} \binom{m}{i} (-1)^{m-i} G^{m-i} \sum b_j^{(i)} G^{j-1}$$

Therefore the central moment expression can be written as follows:

A-III-4 $$E[(K_1 - E[K_1])^m] = \frac{G}{(1-G)^m} \sum_{j=0}^{m-2} G^j C_j^{(m)} \qquad \text{where} \quad C_j^{(m)} = \sum_{i=m}^{m-j} \binom{m}{i} (-1)^{m-i} b_{j+1+i-m}^{(i)}$$

$j=0..m-1$

The distribution of the number of repeated call attempts can be easily studied by means of the following moment coefficients:

A-III-5
$$K_m = \frac{E[(K_1 - E[K_1])^m]}{E[(K_1 - E[K_1])^2]^{m/2}} \qquad m \geq 1$$

and remembering the A-III-4:

A-III-6
$$K_m = \frac{\sum_{j=0}^{m-2} G^j C_j^{(m)}}{G^{m/2-1}} \qquad m \geq 1$$

In Tab. A-III-2 are presented the various quantities calculated for $m \leq 5$.

Moreover in Tab. A-III-3 are presented the values of K_m for different distributions. Various similarities can be noted between the distribution under examination and the Poisson, the Binomial, the Exponential and the Gamma distributions. We can also notice that for values of G close to 1 the distribution we are studying has a considerable similarity with the Gamma distribution.

m	i										
	1	2	3	4	5	6	7	8	9	10	11
1	1										
2	1	1									
3	1	4	1								
4	1	11	11	1							
5	1	26	66	26	1						
6	1	57	302	302	57	1					
7	1	120	1191	2416	1191	120	1				
8	1	247	4293	15619	15619	4293	247	1			
9	1	502	14608	88234	156190	88234	14608	502	1		
10	1	1013	47840	455192	1310354	1310354	455192	47840	1013	1	
11	1	2036	152637	2203488	9738114	15724248	9738114	2203488	152637	2036	1

Table A-III-1

m	$E[K_i^m]$	$E[(K_i - E[K_i])^m]$	K_m
1	$\frac{G}{(1-G)}$	0	0
2	$\frac{G(1+G)}{(1-G)^2}$	$\frac{G}{(1-G)^2}$	1
3	$\frac{G(1+4G+G^2)}{(1-G)^3}$	$\frac{G(1+G)}{(1-G)^3}$	$\frac{1+G}{\sqrt{G}} \geq 1$
4	$\frac{G(1+11G+11G^2+G^3)}{(1-G)^4}$	$\frac{G(1+7G+G^2)}{(1-G)^4}$	$\frac{G(1+7G+G^2)}{G} \geq 9$
5	$\frac{G(1+26G+66G^2+26G^3+G^4)}{(1-G)^5}$	$\frac{G(1+21G+21G^2+G^3)}{(1-G)^5}$	$\frac{(1+21G+21G^2+G^3)}{G\sqrt{G}} \geq 44$

Table A-III-2

COMPARISON WITH OTHER DISTRIBUTIONS

Distribution	Density function	Mean value	Root-mean-squarevalue	Variance	K_3(Skewness)	K_4(Kurtosis)	K_5
Repeated call attempts	$(1-G)G^K \quad K \geq 0$, $0 < G < 1$	$G/(1-G) = m$	$G(1+G)/(1-G)^2 = m^2(1+\frac{1}{G})$	$G(1-G)^2 = \frac{m^2}{G}$	$(1+G)\sqrt{G} \geq 2$	$(1+7G+G^2)/\sqrt{G} \geq 9$	$\frac{1+21G+21G^2+G^3}{G\sqrt{G}} \geq 44$
Poisson	$\frac{a^K}{K!} e^{-a} \quad 0 < a < \infty$	α	$\alpha(1+\alpha) = \alpha^2(1+\frac{1}{\alpha})$	α	$\frac{1}{\sqrt{\alpha}}$	$3 + \frac{1}{\alpha}$	$\frac{10\alpha + 1}{\alpha\sqrt{\alpha}}$
Binomial	$\binom{n}{p} p^K (1-p)^{n-K}$, $0 < p < 1$	$n\,p$	$np[1+(n-1)p]$	$np(1-p)$	$\frac{1-2p}{\sqrt{[np(1-p)]}}$	$3-\frac{6}{n}+\frac{1}{np(1-p)}$	not available
Exponential	$\frac{1}{\lambda} e^{-X/\lambda} \quad X \geq 0$, $\lambda > 0$	λ	$2\lambda^2$	λ^2	2	9	44
Gamma	$\frac{X^{\beta-1}}{\lambda^\beta \Gamma(\beta)} e^{-X/\lambda} \quad X \geq 0$, $\beta > 0$	$\lambda\beta$	$\lambda^2\beta(\beta+1)$	$\lambda^2\beta$	$2/\sqrt{\beta}$	$3 + \frac{6}{\beta}$	$\frac{20\beta + 24}{\beta\sqrt{\beta}}$
Normal	$\frac{1}{\sigma\sqrt{2\pi}} e^{-(X-\bar{X})^2/2\sigma^2}$, $-\infty < X < +\infty$	μ	$\mu^2+\sigma^2$	σ^2	0	3	0

Table A-III-3

Appendix IV.

Main characteristic of the model 5.

In the following are presented the main characteristics of the model 5 in the form of diagrams. They can be easily derived from the expressions given in Appendix II.

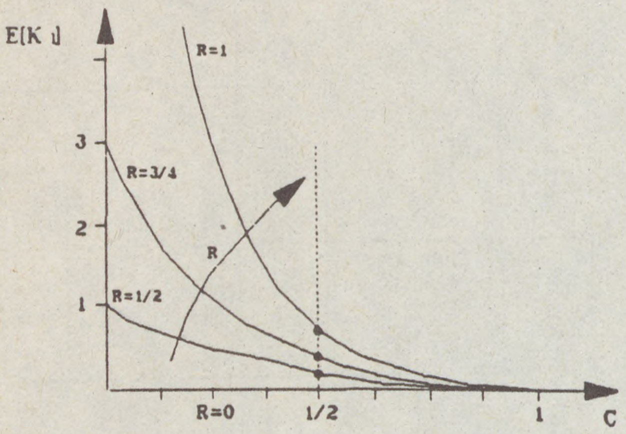

Figure A-IV-1

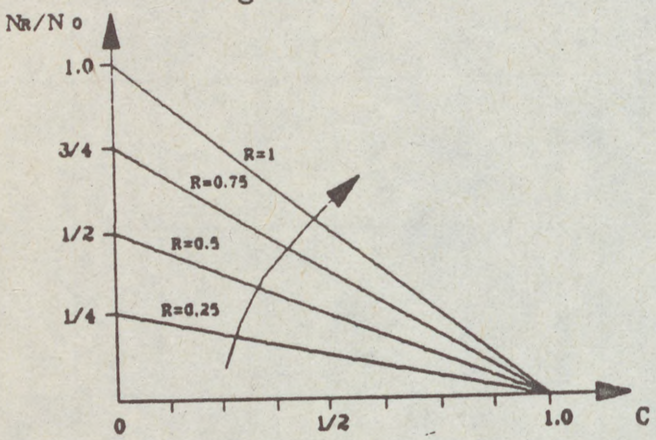

Figure A-IV-2

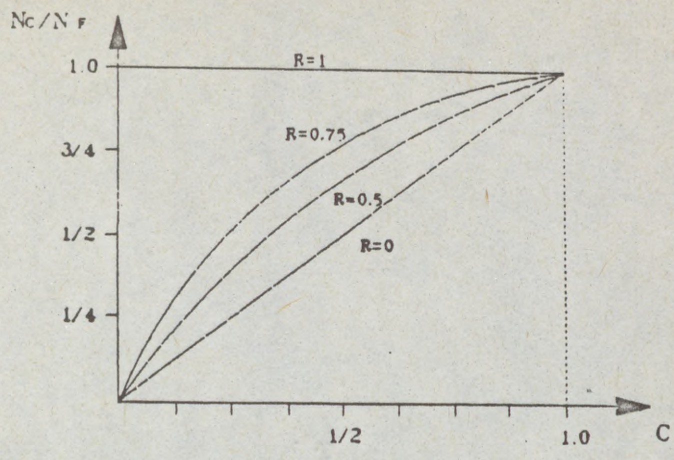

Figure A-IV-3

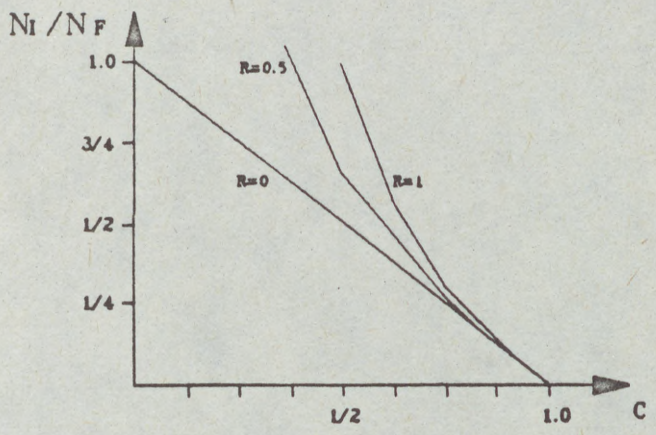

Figure A-IV-4

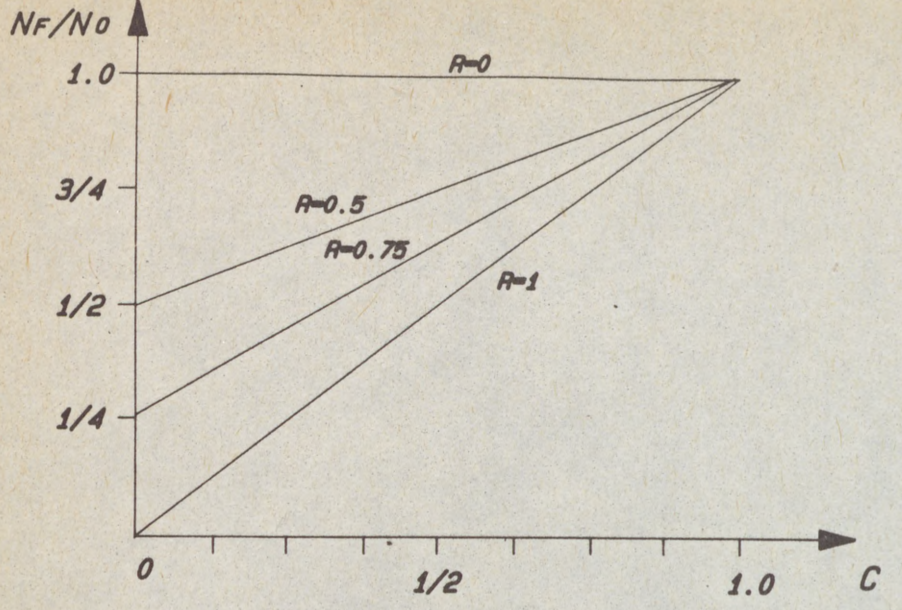

Figure A-IV-5

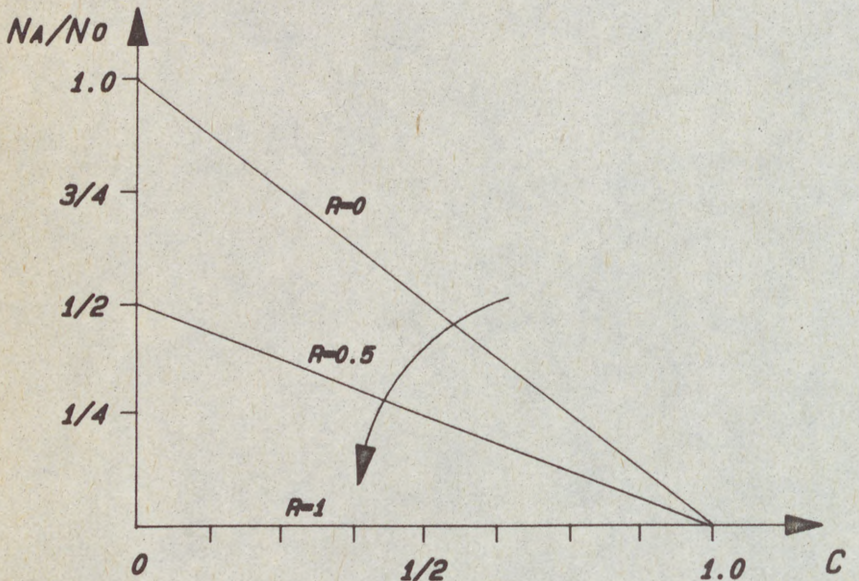

Figure A-IV-6

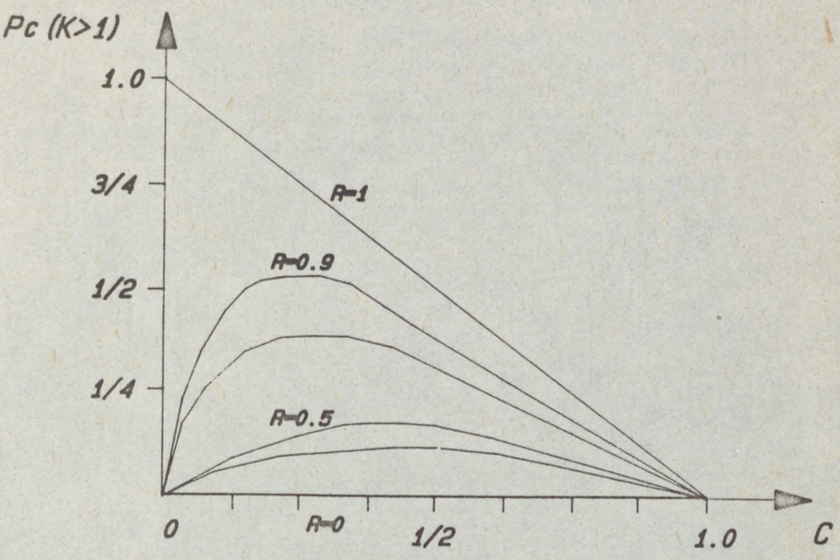

Figure A-IV-7

Appendix V

<u>Extension to the case of dependence from the level of attempt</u>.

Model 5 has been obtained with the hypothesis that C and R were independent from the value K of repeated attempts. In fact, the field trials have demonstrated that the parameters R and C are functions of K. Let us consider figure A-V-1. The cell presented in figure A-V-1 corresponds to a "open loop" version of model 5. The number Nr(K) is given to a new cell of the same kind, with the only difference in the substitution of K-1 with K. The system of figure A-I-5 (the "close loop model") is equivalent to a chain of infinite cells as illustrated in figure A-V-2.

From the equilibrium of a single cell we have:

A-V-1

$$Ni(K) = (1-C(K))\ Nr(K-1) \qquad K=1,2,\dots,\infty$$

$$Nr(k) = (1-C(K))\ R(K)\ Nr(K-1) \qquad K=1,2,\dots,\infty$$

$$Nc(K) = C(K)\ Nr(K-1) \qquad K=1,2,\dots,\infty$$

$$Na(K) = (1-C(K))\ (1-R(K))\ Nr(K-1) \qquad K=1,2,\dots,\infty$$

$$Nr(0) = Nf$$

From the equilibrium of the model of figure A-V-2 we can write:

A-V-2

$$Ni = \sum_{K=1}^{\infty} Ni(K) \qquad No = \sum_{K=1}^{\infty} Nr(K) + Nf \qquad Na = \sum_{K=1}^{\infty} Na(K)$$

$$Nc = \sum_{K=1}^{\infty} Nc(K) \qquad Nr = \sum_{K=1}^{\infty} Nr(K)$$

We can also write the expressions in A-V-1 as:

A-V-3

$$Nr(K) = Nf \prod_{i=1}^{K} a(i) \qquad Ni(K) = [1-C(K)]\ Nf \prod_{i=1}^{K-1} a(i) \qquad K=1,2,\dots,\infty$$

$$Nc(K) = C(K)\ Nf \prod_{i=1}^{K-1} a(i) \qquad Na(K) = [1-a(K)-C(K)]\ Nf \prod_{i=1}^{K-1} a(i) \qquad K=1,2,\dots,\infty$$

assuming that:

A-V-4

$$a(i) = [1-C(i)]\ R(i) \qquad i=1,2,\dots,\infty$$

$$a(0) = 1$$

From the expressions given in Appendix II we have:

$$E[K] = \frac{Nr}{Nf} = \frac{\sum_{K=1}^{\infty} Nr(K)}{Nf} = \sum_{K=1}^{\infty} \prod_{i=1}^{K} a(i)$$

A-V-5
$$Pa = \frac{Na}{Nf} = \frac{\sum_{K=1}^{\infty} Na(K)}{Nf} = \sum_{K=1}^{\infty} [1-a(K)-C(K)] \prod_{i=1}^{K-1} a(i)$$

$$Pc = \frac{Nc}{Nf} = \frac{\sum_{K=1}^{\infty} Nc(K)}{Nf} = \sum_{K=1}^{\infty} C(K) \prod_{i=1}^{K-1} a(i)$$

If a(i) = constant = a and C(K) = constant = C then we have:

$$E[K] = \frac{a}{1-a}$$

A-V-6
$$Pa = \frac{1-a-C}{1-a}$$

$$Pc = \frac{C}{1-a}$$

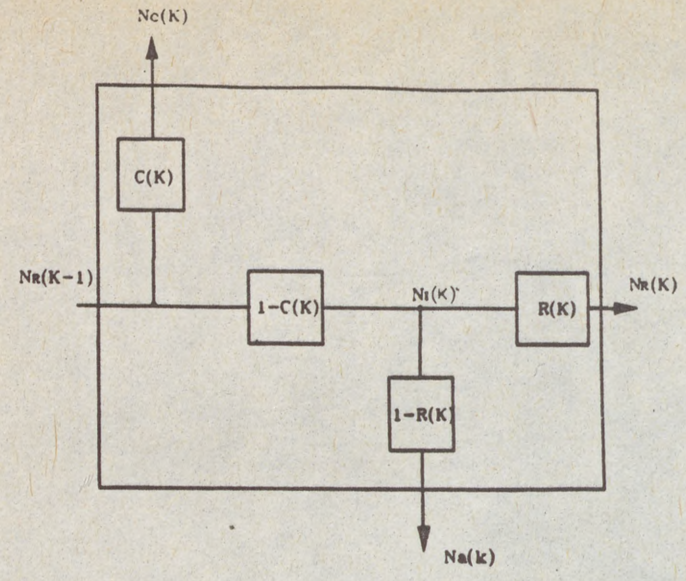

Figure A-V-1 Elementary cell of the "open loop" version of Model 5

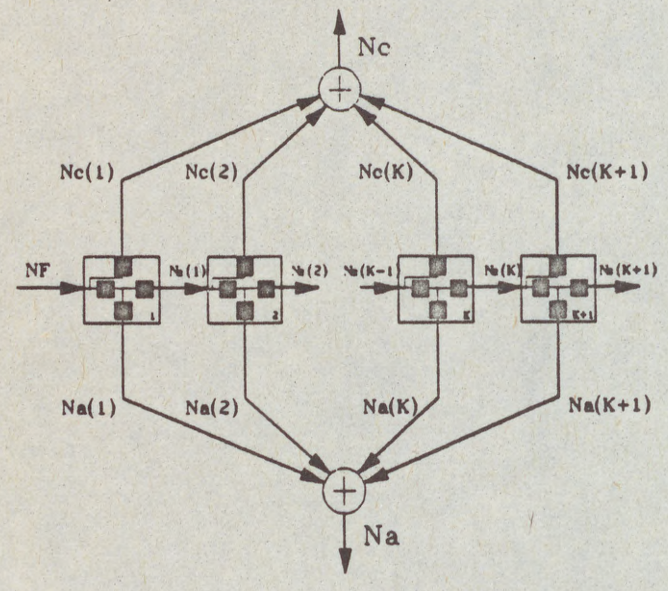

Figure A-V-2 "Open loop" version of Model 5

SOME ASPECTS OF EVALUATING THE GRADE OF SERVICE OF TELECOMMUNICATION NETWORK ELEMENTS UNDER FAILURE CONDITIONS

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SOME ASPECTS OF EVALUATING THE GRADE OF SERVICE OF TELECOMMUNICATION NETWORK ELEMENTS UNDER FAILURE CONDITIONS.

Lecture on the International Postgraduate Course "Advanced studies on Reliability Engineering" at the Technical University of Budapest.

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Abstract.

Two main aspects of the problem such as: a) methods of evaluating exchange service inaccessibility, b) methods of evaluating the grade of service after eliminating the total failure of network elements are given. A full accessible group of devices was used as an example. A group of devices is under monitoring.The system of monitoring has final reliability,i.e. errors in monitoring may take place.The tables are presented to simplify calculations.

1.Introduction.

Since the lecture deals with the problem of evaluating the grade of service of telecommunication network elements,it would be reasonable to fix the place of this performance in the hierarchial system of CCITT concepts,which determine the quality of service.Exchanges and circuit groups are considered to be the elements of the network.The system of concepts is shown in fig.1. The concepts introduced by me in addition to CCITT hierarchial system of concepts (Rec. E.800) are dotted.These include network accessibility as well as network elements service effectiveness.

The hierarchial system of concepts related to the effectiveness of network elements service accessibility is shown in fig.2.

Network elements service performance as well as its service retainability performance characterize the grade of service of a network element as serving system.

Network element service accessibility performance is effected by many factors such as:

-capacity of network element;

-traffic offered and its fluctuations;

-network element structure;

-algorithm of establishing connections;

-hardware and software failures;

-dependability providing technique,namely monitoring, redundancy,maintenance;

-repeated call attempts in cases of failure etc.

Therefore,to evaluate service accessibility performance of network elements it is reasonable to use characteristics which might take into account the effect of the factors mentioned.

CCITT Recommendation E. 550 suggests one of these characteristics,that is-exchange service inaccessibility.

Another characteristics that may be proposed is mean time Δt of network element traffic overload after removal of a total failure condition.This characteristic indicates that after abolishing the total failure condition of the network components call losses on a communication route exceed the permissible level.

In the lecture the simplified methods of evaluating these two characteristics are put forward for consideration.

2.Evaluation of network element service inaccessibility.

Grade of service without considerating network elements failures is assumed to be evaluated by call losses probability rather than by probability of the call being served.On analogy CCITT Recommendation E.550 suggests that the grade of service in an exchange should be evaluated under failure conditions by probability of exchange service inaccessibility.For a network element it is advisable to state the characteristic that is network element service inaccessibility.

The arriving call can not be served in the network element if there are either no free serviceable devices or it "has been served" by the device with undetected failure ("false service")

Provided the device failure is detected it is isolated and cannot be used for serving before it is repaired.This results in reducing the number of serving devices. Any failure in establishing a connection or"false service" results,as a rule, in repeated call attempts which,in turn,results in increasing the traffic. Consequences in equipment failures vary depending on the time of the day. Grade of service is mostly effected by equipment failure during busy hours.

Revised CCITT Recommendation E.550 suggests that the exchange service inaccessibility should be evaluated by two characteristics:

-by instantaneous exchange service inaccessibility,that is the probability that the exchange in question cannot perform the required function(successfully process calls) under stated conditions at the time a request for service is placed;

-by mean exchange service inaccessibility,that is the average of instantaneous exchange service inaccessibility over a prespecified observation period (e.g. one year).

In these definitions for common consideration of the question it is worth changing the term "exchange" into the term "network element".

Below,methods of evaluating these characteristics as far as possible accounting the mentioned above factors which effect the grade of service will be considered.

Problem statement.

Consider the evaluation of the network element service inaccessibility which takes full accessible group of V_0 devices as an example. A simple flow of calls,its intensity being $\lambda = f(t)$, comes to this group.Each device may fail at mean failure intensity ω and be repaired at mean repare rate μ .The monitoring spreads all over the group of devices in question.The monitoring may be continuous,cyclic or combined one,i.e. it may include both continuous and cyclic monitoring. The monitoring period may be either arbitrary with mean value of the period(γ^{-1}) or constant (τ).In the general case the monitoring system itself has final reliability,i.e. errors in monitoring may take place when a faulty device is marked as an operating one(conventional probability of an error β) and vice versa(conventional probability of an error α).The failure having been detected,the device is isolated and one can start preparation for its repairing and do repairing itself.We will mark the mean failure intensity of the monitoring system failures resulting in isolation of an operating device as ω_K.

Thus each device may exist in three states:1) operating, 2)non-operating and non-isolated(the device with undetected failure) when it can be used for service ("false service"), 3)non-operating and isolated(in the latter state it cannot be used for service). We mark probabilities of other states correspondingly:P_1 ;P_2 ;P_3 and mean times of these states correspondingly:T_1 ;T_2 ;T_3 .Mean time of occupation of an operating device and the one with undetected failure is different. We mark them ν_1^{-1} and ν_2^{-1} correspondingly.

Suppose that in a group of V_0 devices,V devices are non-isolated,including V_1 of operating and V_2 of non-operating devices (with undetected failures). $V=V_1+V_2$.

Evaluation of instantaneous network element service inaccessibility.

Instantaneous network element service inaccessibility under the state(V,V_2),i.e.when the group consists of V non-isolated devices including V_2 devices with undetected failure,can be expressed by the following probability

$$\pi(V,V_2)=\pi_b(V,V_2)+\pi_f(V,V_2) \quad , \qquad (1)$$

where $\pi_b(V,V_2)$-the probability that all V non-isolated devices are occupied including V_2 devices with undetected failure;

$\pi_f(V,V_2)$-the probability that the call having come to the group of V non-isolated devices has occupied a device with undetected failure.

If we mark $Y_1=\lambda/\nu_1$ and $Y_2=\lambda/\nu_2$ to calculate these probabilities one can use the formulae

$$\pi_B(V,V_2)=\frac{Y_1^{V_1}\,Y_2^{V_2}}{\sum\limits_{i=0}^{V_1}\sum\limits_{j=0}^{V_2} C_{V_1}^{i}\,C_{V_2}^{j}(V-i-j)!\,Y_1^{i}Y_2^{j}}\;; \qquad (2)$$

$$\pi_f(V,V_2)=\frac{\sum\limits_{i=0}^{V_1}\sum\limits_{j=0}^{V_2} j\,C_{V_1}^{i}\,C_{V_2}^{j}(V-i-j)!\,Y_1^{i}Y_2^{j-1}}{\sum\limits_{i=1}^{V_1}\sum\limits_{j=1}^{V_2} C_{V_1}^{i}\,C_{V_2}^{j}(V-i-j)!\,Y_1^{i}Y_2^{j}}\;; \qquad (3)$$

To simplify calculations the tables have been made up. According to these tables the probabilities $\pi(V,V_2)$ can be determined depending on traffic offered to a full accessible group of devices($Y= Y_1$ Erl);the ratio of mean times of occupating a serviceable device and the one with undetected failure ($H=\nu_2/\nu_1$) as well as the number of devices V and V_2
The tables have been calculated by the recurrent formulae:

$Q(0,0)=1$; $Q(V,0)=VQ(V-1,0)/Y+1$;

$Q(V,V_2)=(V-V_2)Q(V-1,V_2)/Y+V_2\,Q(V-1,V_2-1)\,H/Y+1$;

$\pi_B(V,V_2)=1/Q(V,V_2)$; $\pi_f(V,V_2)=HV_2\,Q(V-1,V_2-1)/Q(V,V_2)$

These tables are given in Annex 1.

Evaluation of mean network element service inaccessibility.

In compliance with the revised CCITT Recommendation E.550 in our case the mean network element service inaccessibility can be evaluated by the following probability

$$\pi=\sum_{V_1=0}^{V_0-1}\sum_{V_2=0}^{V_0-V_1} P(V_1,V_2)\,b(V,V_2), \qquad (4)$$

where $P(V_1,V_2)$-the probability of the state of a group consisting of V_0 devices including V_1+V_2 non-isolated devices;

$b(V,V_2)$-mean call loss probability due to the state(V,V_2) of the group of devices.

If we suppose that the moments of monitoring for different devices are independent,probability $P(V_1,V_2)$can be calculated by the formula

$$P(V_1,V_2)=\frac{V_0!}{V_1!\,V_2!\,(V_0-V_1-V_2)!}\,P_1^{V_1}P_2^{V_2}P_3^{V_0-V_1-V_2}, \qquad (5)$$

where probabilities

$$P_1=\frac{T_1}{T_1+T_2+T_3}\;;\quad P_2=\frac{T_2}{T_1+T_2+T_3}\;;\quad P_3=\frac{T_3}{T_1+T_2+T_3}\;.$$

Thus further calculation is reduced to calculating mean times T_1, T_2 and T_3. For some kinds of monitoring these values are calculated by the formulae, given in Annex 3.

To evaluate the value $b(V,V_2)$ it is reasonable to use the 24 hours traffic profile averaged over a long period of time T (e.g. one year). Let us divide this profile (fig.3) into short intervals t_j (for instance $t_j = 1$ hr) and define traffic intensity Y_j for each interval. Under this traffic intensity from the tables (Annex 1) we define call loss probability

$$\pi_j(V,V_2) = \pi_{Bj}(V,V_2) + \pi_{fj}(V,V_2).$$

Then probability

$$b(V,V_2) = \frac{\sum_{j=1}^{n} \pi_j(V,V_2) S_j}{S}, \qquad (6)$$

where S_j -part of the profile area related to interval j(in fig.3 it is shaded);

S -total area of the profile;

n -the number of intervals.

The same procedure should be done for the rest possible states of the group of devices.

It should be taken into account that probabilities of states of a group of devices when the number of non-operating devices $V_0 - V > 2$ and $V_2 > 2$ becomes as a rule negligibly small. Therefore, when evaluating the mean service inaccessibility the number of states can be limited.

3. Evaluation of mean time of network element traffic overload after removal of a total failure condition.

A failure in a given network element equipment for example in an exchange may cause blocking of all or some circuits on one, several or all routes. This, in turn, may cause either total route failure (when losses are 100%) or partial failure (when losses are below 100% but exceed the permissible level). During the total or partial failure condition, the number of subscribers making repeated attempts accumulates on the route, causing additional traffic after the route has been repaired.

Fig.4 shows the dependances of call losses π and the mean number K of subscribers who repeat the calls on the moment t. Up to the moment t_1,when the equipment fails which results in the route failure the values of π and K remain stationary.During the route failure time interval π and K gradually increase (in case of total route failure π =1,0) The moment t_2 the equipment has been restored,as a result of appearance of vacant circuits the losses are reduced to zero. Then they increase and upon reaching its maximum they are reduced to their stationary value.Upon reaching its maximum at moment t_3 ,K starts decreasing to its stationary value. During a certain period of time Δ t after the equipment restoration,losses π may happen to exceed the permissible value γ .This may be conventionally regarded as a route failure state.

It may thus be assumed that under certain conditions the route down-time T_{rd} (that is duration of the total or partial route failure condition) may exceed the equipment down-time(Ted) by period Δ t

$$T_{rd} = T_{ed} + \Delta t$$

This fact should be taken into account when calculating exchange reliability characteristics,the main task being to calculate the value of overloading time Δ t.

These studies have been done,the model being a full-accessible circuit group.Consider the following model(fig.5) A simple flow of primary calls with intencity λ =cV,as well as a flow of repeated attempts from the sources of repeated calls,arrive at the fully accessible group of V circuits. The incoming call with probability q occupies a vacant circuit during the time which is distributed exponentionally with parameter 1 and a source of repeated calls is formed with probability p=1-q.

A source of repeated calls appears if there are either no vacant circuits or in case the subscriber is "busy" or doesn't answer the call.

We will mark such a probability as P_B. A simple flow of repeated calls with intensity μ arrives from each souroe of repeated calls.The lifetime of a source of repeated calls is limited by a random value distributed exponentionally with parameter δ.

In order to simplify the model we assume that the time of establishing a connection is negligible as compared with the holding time and it can be neglected.

Moreover we assume that

1) after the moment of the route restoration its circuits will be serviceable;

2) probability of a circuit failure during the transition process is negligibly small.

When the mentioned above assumptions are made the state of a circuit group at any moment of time after restoration of the route may be characterized by two parameters (j, K).Where j - the number of circuits in a circuit group taken to serve the call; K - the number of sources of repeated calls.

We mark probability of a circuit group being in a state of (j,K) at the moment of time t as $P_{j,K}(t)$.

The following transitions from the state(j,K) are possible:

1) into state(j,k+1) when primary call arrives and the subscriber is"busy" or doesn't answer the call with the intensity λP_B if $j < V$,the intensity being λ if $j = V$ That is,the intensity of this transition

$$\alpha_1(j,K) = \lambda[1-(1-P_B)\varphi(V-j)] ,$$

where here and below

$$\varphi(X) = \begin{cases} 1, & X > 0 \\ 0, & X \leq 0 \end{cases} ;$$

2)into state(j-1,k) when call service comes to an end,if $j > 1$ with intensity

$$\alpha_2(j,K) = j\nu \ ;$$

3)into state(j ,k-1) when source of repeated calls are self-liquidated, if $k \geqslant 1$ with the intensity

$$\alpha_3(j,K) = K\delta \ ;$$

4) into state(j +1.k-1) when repeated call arrives and the subscriber being called is not occupied, if $j < V$ with intensity

$$\alpha_4(j,k) = k\mu(1-P_B)\varphi(V-j);$$

5) into state(j +1,k) when repeated call arrives with intensity

$$\alpha_5(j,k) = \lambda(1-P_B)\varphi(V-j):$$

The repeated call arrival, the subscriber being occupied at that, doesn't change the state of a circuit group and is not taken into account. Similar transitions are possible from different states into state(j ,k) as well.

The graph of transitions for a circuit group being considered is given in fig.6.

Therefore the system of differential equations which describes the states of a circuit group may be written in the following way

$$\frac{dP_{j,k}(t)}{dt} = -\sum_{i=1}^{5}\alpha_j(j,k)P_{j,k}(t) =$$

$$= \alpha_1(j,k-1)P_{j,k-1}(t) + \alpha_2(j+1,k)P_{j+1,k}(t) + \alpha_3(j,k+1)P_{j,k+1}(t) +$$

$$+ \alpha_4(j-1,k+1)P_{j-1,k+1}(t) + \alpha_5(j-1,k)P_{j-1,k}(t) = L(j,k)[\bar{P}], \quad (7)$$

where $\bar{P} = \| P_{j,k}(t) \|;$

$$\sum_{k=0}^{\infty}\sum_{j=0}^{V} P_{j,k}(t) = 1.$$

The system of differential equations(7) is to be solved by means of power series expansion of the unknown functions:

$$P_{j,k}(t+\Delta t) = \sum_{n=0}^{\infty} P_{j,k}^{(n)}(t)\frac{\Delta t^n}{n!} \quad (8)$$

By differentiating each equation of the system (7) n times we obtain the following recurrent correlations for calculating the derivatives at the moment of time t:

$$\frac{d^{(n)}P_{j,k}(t)}{dt^n} = L(j,k)[\bar{P}^{(n)}].$$

Thus proceeding from initial conditions $P_{j,K}(0) = P_{j,K}^{(0)}$ $(j=0,1,\dots V;$ $K=0,1,2,\dots)$ one can calculate the derivatives of all orders and applying (8) calculate the values of unknown functions at the moment of time $t_l = t + l\Delta t$. If the value Δt is chosen rather small for approximate calculations one can limit the order of derivatives, that is

$$P_{j,K}(t+\Delta t) = \sum_{n=0}^{n_{max}} P_{j,K}^{(n)}(t)\frac{\Delta t^{(n)}}{n!} + R_{n_{max}}$$

Moreover it is sufficient to calculate those state probabilities k<n for which $k < k_{max}$, where k_{max} is found from condition

$$R_K^{(t)} = \sum_{j=0}^{V} P_{j,K}(t) < \varepsilon_0 \quad (K \geqslant K_{max}),$$

where ε_0 is a permissible error.

Since parameters of the transition process have little effect on the character of distribution of sources of repeated calls the initial value of $P_{j,K}(0)$ can be selected in the following way:

$$P_{j,K}^{(0)} = \begin{cases} 1 & j=V, \ K=\bar{K}, \\ 0 & j\neq V, \ K=\bar{K}, \end{cases} \qquad (9)$$

where $\bar{k}$ - the number of sources of repeated calls at the moment of equipment restoration.

To calculate the initial values of $P_{j,K}^{(0)}$ (9) it is necessary to find the mean number of sources of repeated calls at the moment of restoration of the equipment. For $\bar{k}$ one can have the integer value of the mean number of sources of repeated calls being accumulated during the downtime of a network element.

Since during the total failure of a network element any call becomes a source of repeated calls one can use the system of differential equations (7) assuming V=0 to calculate the mean number of sources of repeated calls which have been accumulated during the downtime of the network element.

Having multiplied the equation (k) of the system by k and having added all the equations we obtain the following equation for calculating mean number of sources of repeated calls

$$\frac{d\bar{K}}{dt} = \lambda - \bar{K}\sigma \qquad (10)$$

Taking advantage of the fact that at the moment of failure the mean number of sources of repeated calls agrees with the stationary one $K(0) = K_0$ We obtain specific solution of the equation (10) in the form of

$$\bar{K} = \sigma^{-1}[\lambda - (\lambda - K_0\sigma)e^{-\sigma t}] \qquad (11)$$

In case the subscriber is absolutely persistent (σ =0) the following specific solution will be as

$$\bar{K} = K_0 + \lambda t \qquad (12)$$

Application of the Ionin-Sedol method for calculating stationary values of sources of repeated calls.

Thus to calculate mean number of sources of repeated calls accumulated during restoration of the equipment one should know the stationary value of K_0 . The approximate method is based on replacing the given system by the one which neglects the time of establishing a connection with the following application of Ionin's and Sedol's tables[5]

Analysis of the results of the studies.

In general case the value of Δt depends on the following values:

γ -permissible level of call losses;

λ -intensity of the flow of primary calls;

μ -intensity of the flow of repeated calls resulted from one source of repeated calls;

σ -intensity of self-liquidation of source of repeated calls;

$\bar{K}$ -initial number of sources of repeated calls;

ν -intensity of the circuits release;

V -capacity of a circuit group

Therefore

$$\Delta t \nu = F(\gamma, \bar{K}, V, \lambda/\nu, \sigma/\nu, \mu/\nu) \qquad (13)$$

We consider the dependance of function (13) on γ and $\bar{k}$. Further on, to simplify the case we won't mark the rest arguments in the list of them, assuming that they remain constant. As a result of comparison of probabilities of the circuit group occupation under different values of $\bar{k}$ it turned out that the function of $F(\gamma, \bar{K})$ can be presented in the form of the difference of two functions. The first one doesn't depend on the initial number of sources of repeated calls $\bar{k}$, while the second one doesn't depend on permissible level of losses γ that is

$$F(\gamma, \bar{K}) = F_1(\gamma) - F_2(\bar{K}) \qquad (14)$$

Graphically it is shown by the shift of the part of the graph of losses along the time axis (fig. 7)

Simplified method of evaluating the mean time Δ t.

At the initial number of sources or repeated calls($\bar{k}$) the following equality results from (14):

$$\Delta t(\bar{K}, \gamma) = \Delta t(\bar{K}', \gamma) - a_K ,$$

where $\Delta t(\bar{K}, \gamma)$ - the function of argument γ at sufficiently large present number $\bar{k}'$;

a_K -the function of argument $\bar{K}$

Let us mark as a a random value which at the initial moment of time, i.e. the moment of eliminating total failure state (j =0) has the value a_K with probability $P_{0,K}$ Mean value of a random value a will be

$$\bar{a} = \sum_{K=0}^{\bar{K}'} a_K P_{0,K} .$$

We assume that when $\pi_{max} < \gamma$

$$a_K = \Delta t(\bar{K}', \gamma) ,$$

that is

$$\Delta t(\bar{K}, \gamma) = 0 .$$

Mean time of exceeding permissible threshold of losses is calculated by

$$\Delta t = \sum_{K=0}^{\bar{K}'} P_{0,K}\, \Delta t(\bar{K}, \gamma) = \Delta t(\bar{K}', \gamma) - \bar{a}, \qquad (15)$$

The distribution $P_{0,K}$ of a number of sources of repeated calls at the moment of eliminating the state of failure depends on duration of a total equipment failure in a circuit (T_{ed}) and is well approximated by Poisson distribution

$$P_{0,K} = \frac{\bar{K}^K}{K!} e^{-\bar{K}},$$

where $\bar{K}$ is found from (11) and (12).

The values of functions $\Delta t(\bar{K}', \gamma)$ and a_K have been tabulated (Annex 2) which makes it possible to calculate the value of Δt.

Since $P_{0,K}$ becomes rather small when $K_H > 6$ while tabulating the functions $\Delta t(\bar{K}', \gamma)$ and a_K, $\bar{K}' = 6$.

Note, that to have Δt in minutes one should divide the result obtained by formula (15) by ν.

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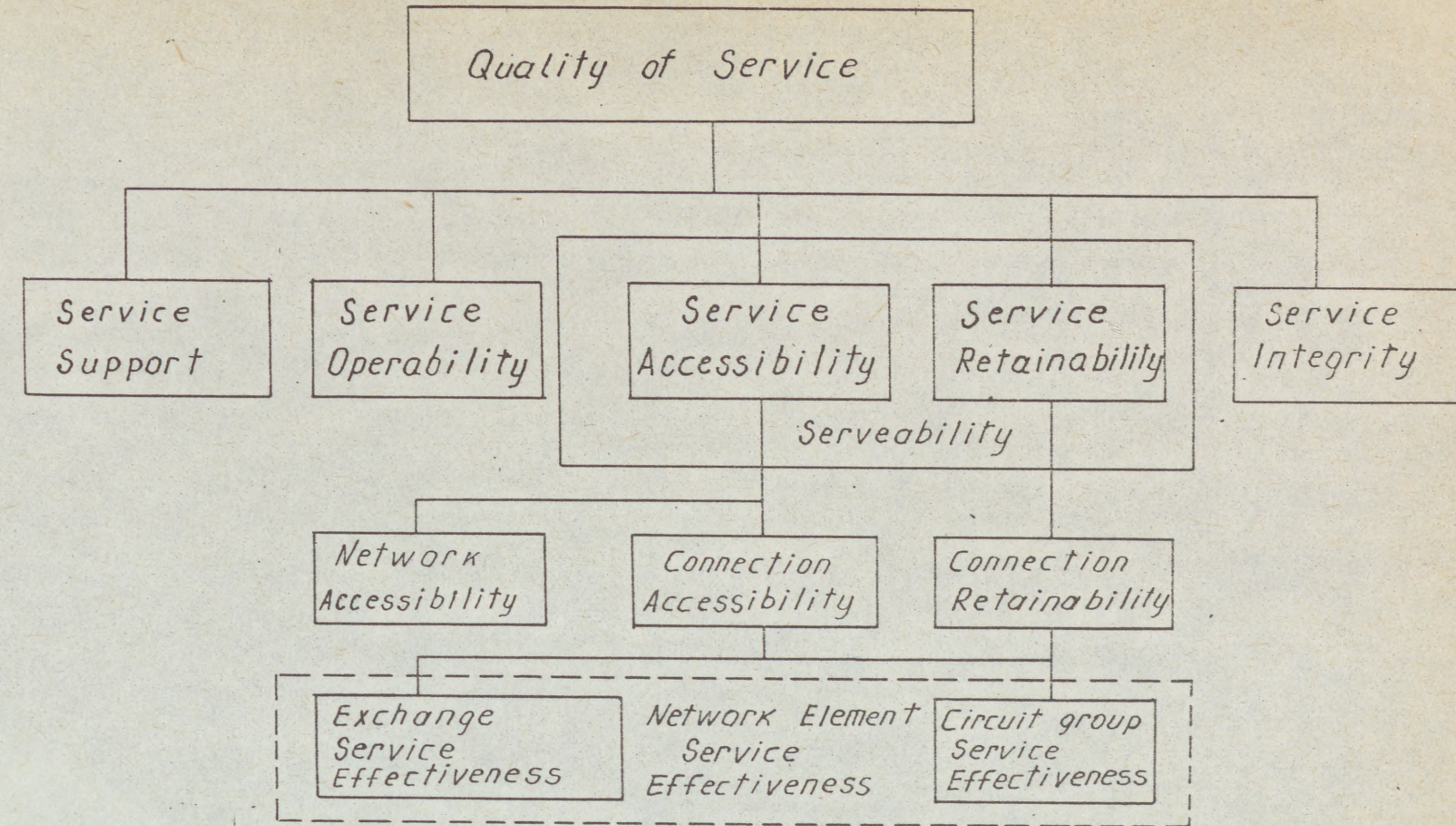
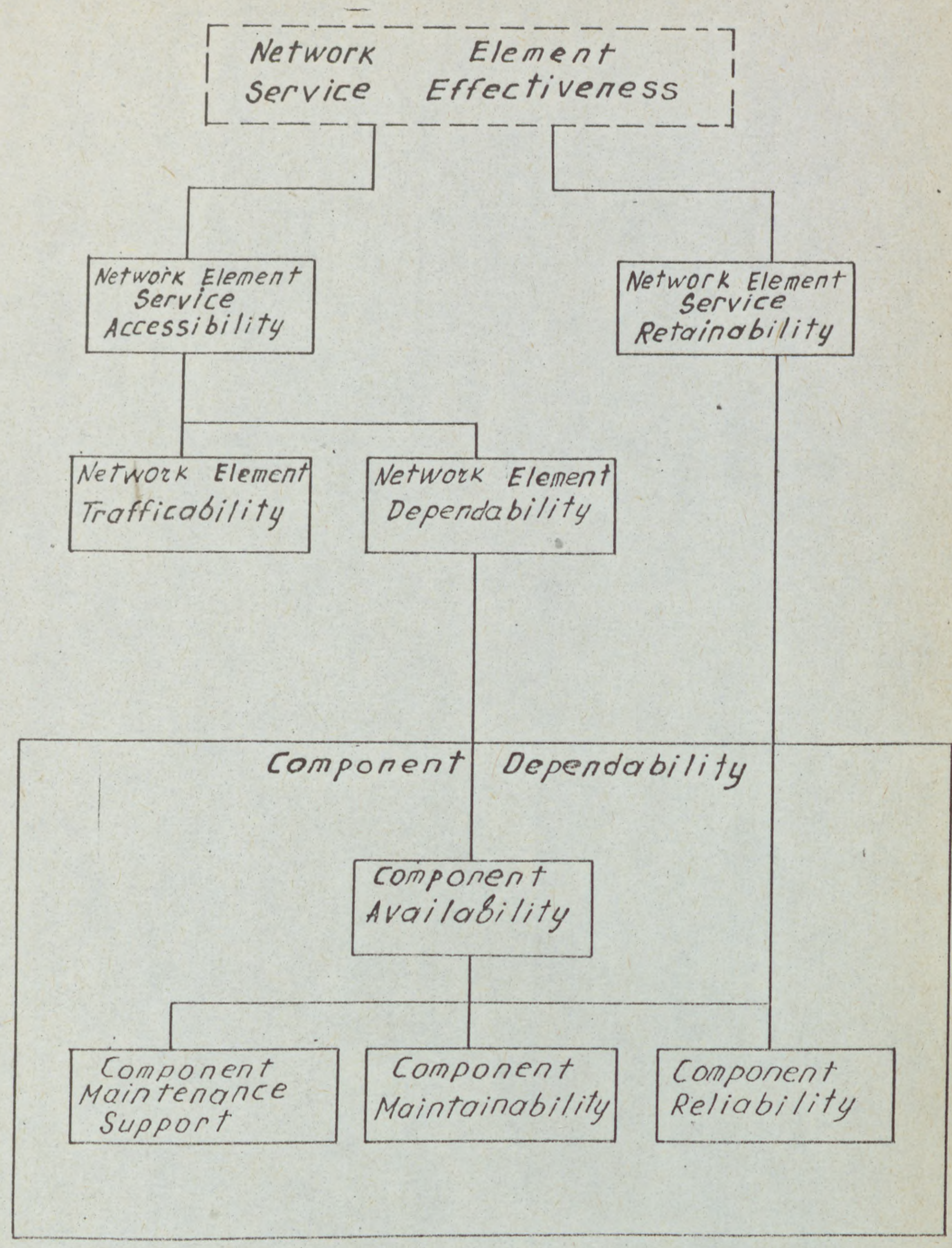

Quality of Service
Service Support
Service Operability
Service Accessibility
Service Retainability
Serveability
Service Integrity
Network Accessibility
Connection Accessibility
Connection Retainability
Exchange Service Effectiveness
Network Element Service Effectiveness
Circuit group Service Effectiveness

Fig. 1


Network Element
Service Effectiveness
Network Element
Service
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Network Element
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Network Element
Trafficability
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Dependability
Component Dependability
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Maintenance
Support
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Maintainability
Component
Reliability

Fig. 2

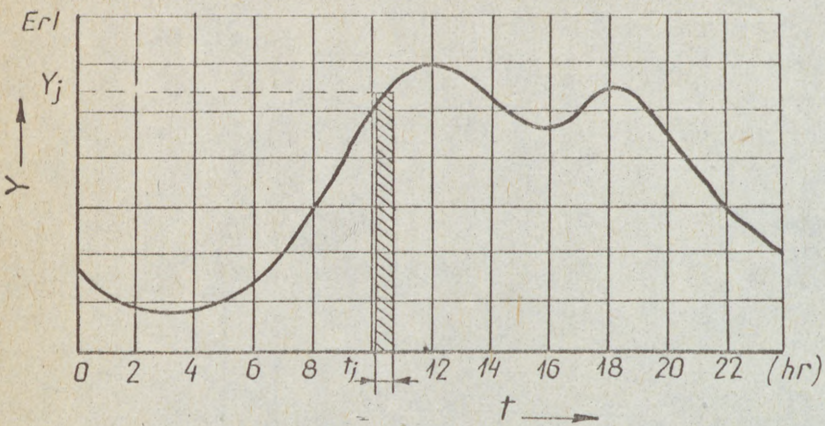

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Fig. 3

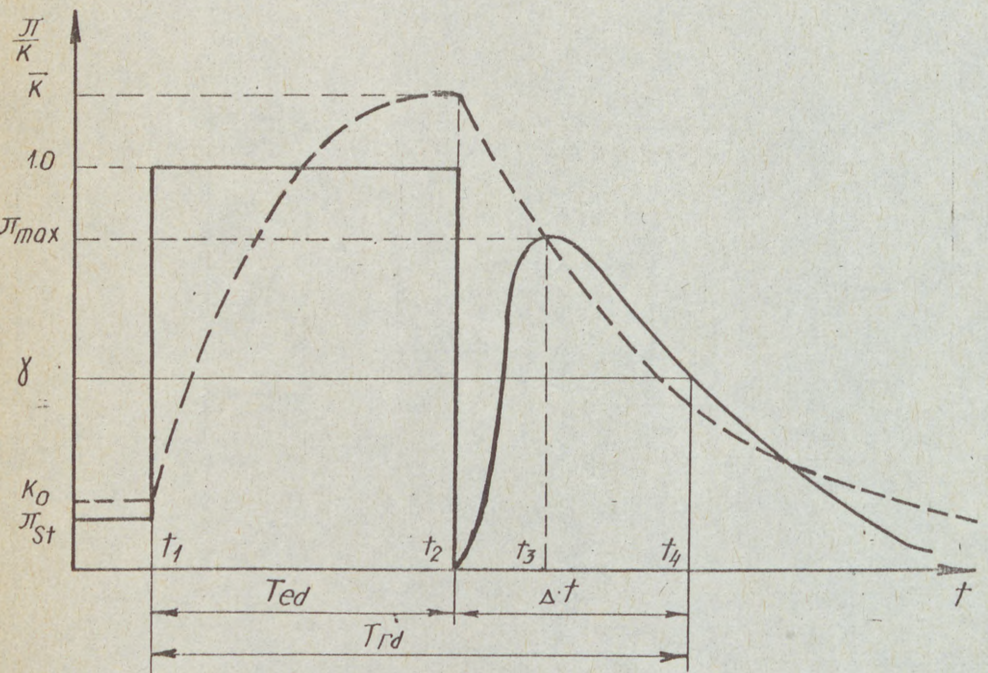

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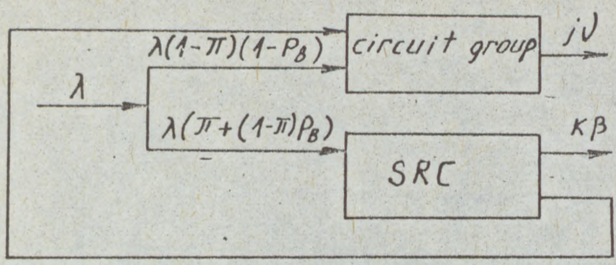
Fig. 4



$\lambda(1-\pi)(1-P_B)$
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Fig. 5

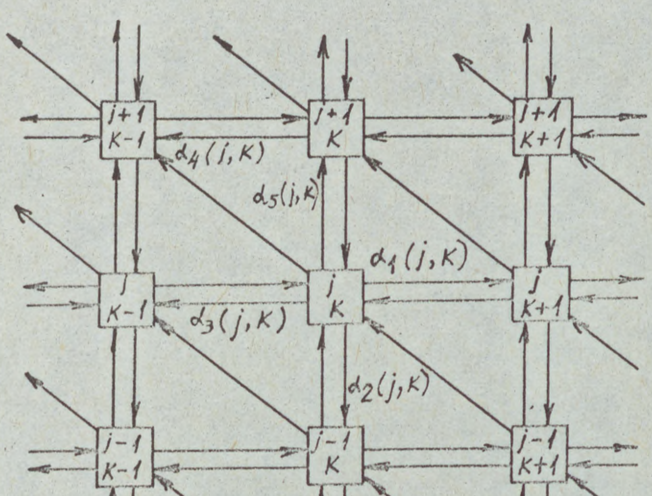

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Fig. 6

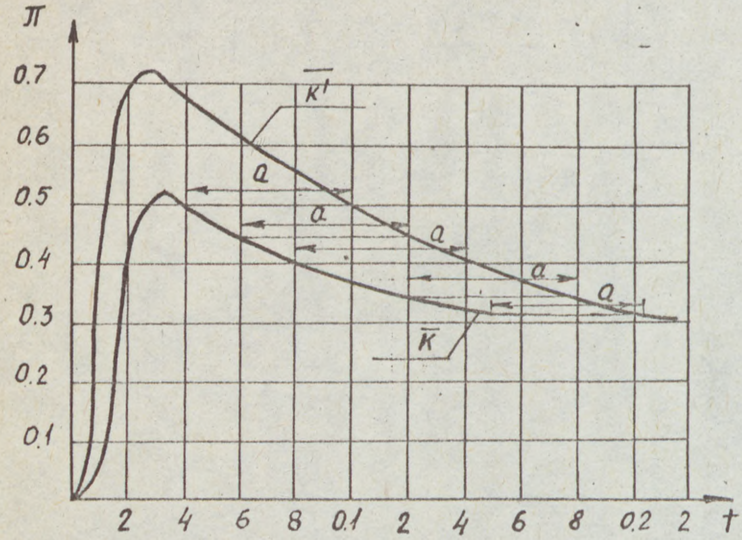
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Fig.7

HUMAN RELIABILITY AND INTERFACE DESIGN

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Human Reliability and Interface Design

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1. Introduction

System reliability, i.e. the functioning of a system according to requirements during a certain period of time, depends on the reliability of separate system components and system architecture. In a great number of complex systems, e.g. transportation, manufacturing, or medical systems, there is a human component (humanware) in addition to hardware and software components. Typically human tasks relate to process control, such as monitoring and setting values, and the human operator has the ultimate responsibility for proper system functioning under conditions of technical failure. This gives sufficient reason to examine human reliability within a system context when studying the functional safety of complex systems.
Questions to be addressed in this paper are the following:
1. what type of errors do human operators make?
2. how can one find out where human errors come from?
3. how can human reliability be improved, particularly by interface design?
First a brief discussion will be devoted to the issue of modeling the human operator.

2. Modeling man

When studying human reliability it is necessary to adopt an appropriate model of man. This is particularly important since the type of model that has traditonally been employed by system engineers seems less suitable for this purpose. This type of model, which can be characterized as 'mechanical', depicts man as the 'operator' of a technical system whose role consists in the fulfilment of a number of objective tasks, which for technical or economical reasons cannot be performed by hardware or software components. Task

fulfilment means carrying out well described operations such as handling, feeding, tending, manipulating, driving, controlling, etc. Relevant human resources are perceptual, psychomotor, memory and simple decision making capacities (cf the Fitts' list, e.g. Mackay & Whittington, 1983). The operator is assumed to behave in a reactive mode: signals, signs and symbols, whose appearance he should passively await, are thought to tell him what to do when.

This model can be contrasted with a more comprehensive 'psychological' model in which man is seen as a 'user' of the system, who is doing a job within the context of an organization. His role consist in the fulfilment of (subjective) duties, some of which relate to the technical parts of the system, and some of which do not. His activity is more than a mere execution of prescribed operations; it includes getting motivated, interpreting duties, setting goals, preparing action plans, and executing these plans. Relevant resources are problem solving, decision making, planning, and communicating, as well as perceptual and psychomotor capabilities. The most conspicuous dif

Figure 1: Models of man

	Mechanical	Psychological
Man	operator	user
Context	system	organization
Role	fulfilment of objective tasks by prescribed operations	fulfilment of subjective duties by getting motivated, interpreting, setting goals, preparing for, and executing action plans
Resources	perceptual psychomotor memory simple decision making	problem solving decision making memory perceptual psychomotor
Activity mode	reactive	proactive

Errors

Definition	non-fulfilment of prescribed operations	non-attainment of goals
Nature	random phenomenon (or gross neglect)	partly random, conditioned by: causal and contributing factors
Features	error types probabilities	error types frequencies causal factors contributing factors
Prevention	division of tasks systems architecture selection etc.	training motivating job design etc.

ference to the mechanical model is that man is assumed to operate in a proactive mode. His activity is thought to be goal-directed: cognitive plans tell him what to do next, coming steps of action are anticipated and perception takes place actively rather than passively.
These two models, which are summarized in Table 1, have clear implications for the study of human error. The mechanical model leads to a 'probabilistic approach' (e.g. Swain & Guttman, 1980; Raafat, 1983), in which errors, being defined as violations of prescribed rules of operation, are seen as random phenomena that should be classified and quantified according to such parameters as Fail-Safe Probability, Fail-to-Danger Probability, Mean-Time-Between-Unsafe-Failures. The main avenue to the improvement of reliability is seen to lie in the systems' architecture, i.e. the division of tasks between hardware, software, and humanware, and in similar and diverse redundancy arrangements (e.g. Turner et al., 1987). The psychological model opens the way to a 'causal approach' (Rouse & Rouse, 1983). Being defined as non-attainment of goals or frustration of action plans, errors are seen as partly random, but also partly determined by causes and contributing factors. Opportunities for reliability improvement are seen to lie in operator selection, training, job design, etc. The difference between the two approaches can be illustrated by an example: whereas the probabilistic approach would result in an estimate of the probability that an operator would fail to observe a given signal, the causal approach would identify the conditions (such as contrary expectations, distraction, haste, irritation) under which such failure occurs.
It is the author's opinion that the mechanical model of man, and the probabilistic approach to error analysis associated with it, are of very limited value. The neglect of relevant conditions not only produces unreliable probability estimates, more importantly it impedes the improvement of human and overall system reliability. The psychological model and the causal approach seem to be more fruitful for this purpose and will therefore be further considered here.

Without going into detail now, it is important to note that the psychological model covers at least the following 'human functional properties':
1. principles of motivation
2. principles of human information processing
   (including perception, memory, cognition, operation)
3. structural features of goal-directed action

(including action preparation, hierarchical-sequential action execution under cognitive supervision)
4. action regulation mechanisms;
5. the phenomena of mental and physical load, and action efficiency;
6. performance dynamics
(including learning, variability, and performance decline)
7. interindividual differences.

These functional properties are largely dealt with by McCormick & Sanders (1982), Wickens (1984), and Hacker (1986).

3. Human error

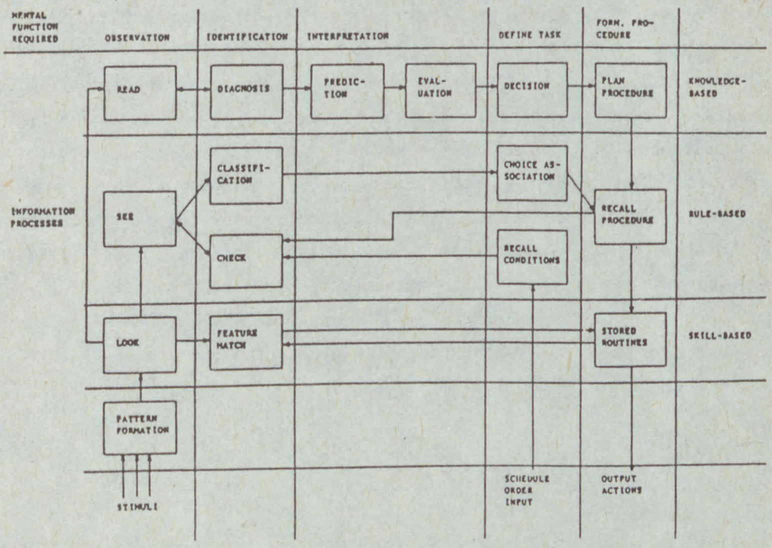
A major distinction in the field of error research is that between slips and mistakes (Reason, 1982,1983). Slips are errors that result from non-intended activity. Usually they can be attributed to a lack of attention during the execution of familiar operations. Examples are typing errors, and involuntary reversals of operations or exchanges between sequences of operations. Mistakes are errors that result from intended, but inappropriate actions. The person is well aware of his activity, but he is making errors because he draws false inferences, makes incorrect predictions, takes wrong decisions, develops inadequate plans, etc. Well known examples are design errors in programming, or the unwarranted deletion of computer files.
For a proper analysis of errors more refined distinctions of error types are called for. In fact, a psychological model of human action is needed. A useful model that fits the theoretical notions of action theory (Hacker, 1986) has been developed by Rasmussen (1982, 1983b). It can be designated as a 'multilevel model of human information processing'. The model, which is summarized in Figure 2, has two dimensions. Along the first dimension one finds stages of human information-processing in goal-directed action; the second dimension distinguishes levels of information processing, or action regulation.

The highest, knowledge-based level, is the one at which programming and modification of action plans take place. The input from the perceptual system is examined at its semantic value. The cognitive activities include problem solving and decision making. After the system's state has been diagnosed (identification), and hypotheses have been brought forward about causes of the present state and future developments (interpretation), a target situation is identified (task definition) and an action program is developed (procedure formation). The execution of the procedure is delegated to lower levels of regulation. The supervision of the execution, which includes anticipation of coming steps, status assessment, and feedback evaluation, takes place at the knowledge-based level, however.

At the second, rule-based level, activity is controlled by earlier stored rules or procedures. These rules associate incoming information, organized in 'signs', with complex operations. Information coming from the perceptual system (observation) is checked, and signs are classified (identification). Next, an appropriate procedure is chosen by applying a relevant rule (task definition), and this procedure is recalled from memory (procedure formation). The execution of the procedure is delegated to the lowest level. At this skill-based level of regulation the input (observation) is directly scanned for 'signals', given sets of features that are learnt to be associated with stored routines. When a signal fits a related stored routine (identification), this routine is triggered (procedure formation). When no fit is possible, the higher levels of regulation are activated. The execution of routines takes the form of muscular activity, performed under direct kinaesthetic, as well as more indirect types of feedback.

Figure 2: Model of action regulation

Adapted from Rasmussen, 1982



This model helps us to understand what can go wrong in the execution of human tasks. Errors can occur in all stages of information processing. In fact, every single part of the process can either be absent, incomplete, incorrect, or unnecessary (Rouse & Rouse, 1983):
Observation may be defective because the user is distracted, i.e. pays attention to the wrong input, fails to observe the right variables, or misreads appropriate variables, e.g. confuses signals having a similar appearance. Observation failure may lead to non-activity or to correct actions under the wrong conditions, like operating the wrong controls. Inadequate matching, checking, classification or diagnosis may produce faulty identifications. A well known example is the 'mode error', where the user confuses the actual mode (e.g. setting-up, editing) of the system with another (e.g. command) mode, and therefore performs inappropriate operations. Interpretation failures are present when the user comes up with a false hypothesis, makes incorrect predictions of the system's future state, evaluates information incorrectly, or draws false conclusions. 'Inconsistency errors' may be mentioned as an example: users tend to assume that different system parts should be operated in an identical or an analogous way, while this may not be true. Another example is the 'stereotype error': here the user acts on the basis of stereotyped knowledge, e.g. of the effects of turning knobs, setting switches, etc. Task definition may fail when goals are badly specified, no goals are set, or the wrong goals are set. Faulty procedure formation occurs when the user draws up an inadequate action plan, or when he recalls the wrong plans or subroutines. He may be activated by an inappropriate signal, and therefore call a wrong subroutine, a sequence of operations that he is executing may be taken over by a more familiar sequence of operations ('capture error'), or he may forget remaining parts of an incompleted action. It should be noted that errors take different forms at each of the three levels of processing. Errors at the knowledge-based level are 'mistakes': incorrect reasoning, planning, etc. At the other levels one finds various kinds of slips. Typical for the rule-based level are e.g. wrong classifications of system states, wrong associations, memory slips, etc. Skill-based level slips relate to variability as well as inadequate time-space coordination in perceptual and motor activities (Rouse & Rouse, 1983). Examples in keyboard operation are the type writer addiction error, the one-place off error, the missing target error, etc. (Galambos, 1984).

Figure 3 gives a classification scheme specifying the inadequacies that can be present at the distinctive stages and levels of the model. This scheme has been developed by Arnold & Roe (1987) on the basis of work by Hacker (1986), Rasmussen (1982), Reason (1982, 1983), Rouse & Rouse (1983).

Figure 3: Error classification scheme

Required mental functions	Levels of regulation: Skill-based	Rule-based	Knowledge-based
Observation	**inadequate pattern formation:** **- stimuli not perceived** **- misperception** **looking errors:** **- patterns overlooked** **- inadequate looking**	observation errors: - information not seen - information skipped - inadequate information reduction - patterns not recognized - insufficient information observed - inappropriate information observed	reading errors: - no reading by lack of information - inadequate reading - incorrect reading
Identification	**feature match errors:** **- false match** **- false mismatch**	checking errors: - inadequate check against conditions - no check classification errors: - stereotype error - stereotype fixation - classification criteria not recalled	diagnosis errors: - misinterpretation of correctly read data - no interpretation
Interpretation			prediction errors: - goal errors * insufficient specification * counter productive * non-production * goal not chosen - incorrect hypotheses * inconsistent * unlikely * too expensive * functionally irrelevant * side-effects and conditions not considered evaluation errors: - erroneous hypotheses * stopped before reaching a conclusion * wrong conclusion * not considered and tested * false acceptance * false rejection
Task definition		choice errors: - stereotype take over condition recall errors: - conditions not recalled - inadequate recall	decision errors: - choice would not attain goal - choice would attain incorrect goal - choice unnecessary for goal
Procedure formation/ execution	routine errors: - routine not available - inadequate routines triggered execution errors: - spatial misorientation: * stumbling * misgrasping * spilling - motoric variability errors - slips: * slip of the tongue * slip of the pen	recall errors: - forgotten isolated action - inadequate alternative procedure chosen procedure formation errors: - action-sequence(s) exchanged - required step skipped - unnecessary step inserted	planning errors: - computation error

3. Analysis of errors

In order to find out where human errors come from, one should not only consider failures at the level of behaviour outcomes and underlying mental processes, but also causal and contributing factors (cf. Rouse & Rouse, 1983; Rasmussen, 1982); see Figure 4.

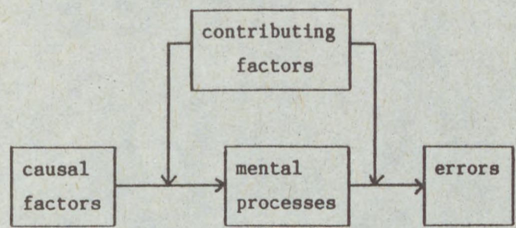


Figure 4: factors in error analysis

Errors tend to be caused by a number of factors that operate simultaneously in the course of a sequence of events. These factors can be divided into two classes:

1. internal factors: limited perceptual or mental capacity, knowledge and expectations, fatigue, sickness, variability of attention or motor operations, etc.
2. external factors: climate and physical environment, distractors, task demands, working time characteristics, hardware and software properties.

It is important to recognize that isolated internal or external factors seldom constitute sufficient conditions for error, even if they are necessary conditions. As a rule, it is the interaction of factors, showing up at the interface between man, the technical parts of the system and the system's environment, that creates such a sufficient condition, e.g. fatal interactions may occur between low capacity and high task demands, between distraction and fatigue, inadequate working times and high vigilance demands, or between user expectations and actual systems functioning. Generally speaking one might state that the predominant type of error cause is a misfit between man, the technical parts of the system, and the environment (Arnold & Roe, 1987).

Contributing factors produce neither necessary nor sufficient conditions for the occurence of an error, but they may be conducive in the sense of enhancing the likelihood of error. These factors may be divided into internal and external factors as well:

1. internal factors include: confusion, affective states such as frustration, anger, embarassment, subjective intentions, misunderstanding.
2) external factors include: distraction, noise, excessive work load, equipment breakdown, lack of communication.

An analysis of errors starts with the collection of performance data. Several techniques are available for this purpose (cf. Arnold & Roe, 1987), including:

- performance recording
- interaction logging
- video recording
- communication recording
- verbal protocols
- stimulated recall
- user questionnaires on problems and satisfaction
- interviews

Once the data have been collected, errors should be identified by evaluating the performance results using task prescriptions and user opinions. Next, mental failures as well as underlying causal and contributing factors should be identified (Rouse & Rouse, 1983). For this purpose one may employ checklists, classification schemes, as well as (quasi)experimental and statistical methods.

4. Improving human reliability by interface design

Human reliability in a systems context can be improved in several ways. Rouse (1985) distinguishes between:

1. user and/or system selection
2. user training
3. system (re)design
4. job (re)design
5. aiding.

Here the focus will be placed on systems (re)design, because this sets the limit to what can be attained by the other measures, and determines the financial and psychological costs associated with them. As the interplay between internal and external factors that takes place at the interface seems to be of crucial importance in causation of errors, the design of the interface deserves special attention. Preferably, the interface should be designed as an independent part of the system at an early stage of the total design process (Roe, 1985a), in order to make necessary adaptations of other systems components feasible. It should be noted that interface has a broad scope, as it covers aspects ranging from physical display and control characteristics to the meaning of commands and the flexibility of the dialogue. In fact, it covers all technical, syntactical, semantical and pragmatic aspects of the system that affect the user's performance (Roe, 1985b).

The basic objective of interface design should be: adaptation to the human functional properties mentioned before, as well as to user knowledge and expectations. There seem to be two major appproaches for realizing this objective, i.e. an empirical and a theoretical approach.

The empirical approach is based on observations made during actual use of the system, once this has been put into operation, or observations of prototype use during the design phase. Errors and other aspects of performance are recorded and analyzed, and problems as well as possible improvements are identified (Norman, 1983; Arnold & Roe, 1987). When 'mode errors' are found, one may choose for such design options as: doing away with modes at all, improving distinctions between modes, or giving continuous information on the actual mode and on admissable commands. When 'activation errors' are found one may think of introducing memory aids such as auditory signals, or overlapping windows, or of offering a facility that recalls interrupted action sequences (cf. Norman, 1983).

An analysis of user experiences based on systems use can yield additional information. Dzida et al. (1978) have described a method that can be used for identifying interface features requiring improvement.

A limitation of the empirical approach to interface design is that the results are task and equipment specific. This poses a problem of generalizability: e.g. observations about errors and improvement possibilities in aviation cannot be readily transfered to the domain of power plant control. Another limitation is that this approach does not lend itself to preventive design, i.e. avoiding interaction problems and errors from the start. The

- make the dialogue partly reversible (e.g. by an undo-command)

The foregoing has pointed out how errors can be studied and along which lines they can be prevented when designing user interfaces. It should be noted that the improvement of reliability cannot be set equal to the prevention of errors. It should be recognized that errors will always be made. Therefore interfaces should be built in such a way that they are error tolerant (Rasmussen, 1982; Rouse, 1985), which means that errors can be observed and corrected for. This implies that users should be given informative error messages, as well as adequate correction facilities.
Finally, it should be noted that while interface designs should be considered of primordeal importance, the other measures that were mentioned before can play a role as well in improving human reliability in a systems context.

THE BRADFORD DISASTER SCALE

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THE BRADFORD DISASTER SCALE

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ABSTRACT:

In order to compare different disasters, quantitative measures are necessary. A classification system based on The Bradford Disaster Scale (BDS) is presented here. The proposed scale is a logarithmic one and is based on the number of fatalities involved in the event of a disaster. It is shown that the method is particularly useful for hazard identification and quantification and can be used as a tool for structured and strategic planning.

1. INTRODUCTION

Hillsborough, Locherbie, Herald of Free Enterprise, Clapham Junction are some of the more notable disasters that have occurred within Europe over the past few years. The Armenian earthquake, Bangladeshi floods and the Sudanese famine and subsequent cholera outbreak have all claimed numerous lives outside Europe. Studies based on historical data covering a range of major incidents can be found in the literature typical of these is the work carried out by Fernandes-Russell [1], Grist [2], Griffiths and Fryer [3,4].

The Oxford English Dictionary [5] states that the word "Disaster" comes from the 16th century French word "desastre". The definition given by the O. E. D. is as follows;

"Anything that befalls of ruinous or distressing nature; a sudden or great misfortune, mishap or misadventure; a calamity"

The Bradford Disaster Scale

We suggest that a "disaster" may be defined as:
"An event which afflicts a community the consequences of which are beyond the immediate financial, material or emotional resources of the community". For the purpose of the present study a disaster is defined as "an event where ten or more fatalities result from one event over a relatively short period of time."

Disasters may involve man-made events such as rail or air crashes or may be natural occurrences such as violent storms. There may also be a combination of man-made and natural events e. g. a combination of an inadequate dam design and abnormal weather conditions resulting in the collapse of the dam.

The event may be localised in geography and time as in the Clapham Common rail crash or it may involve a large part of a nation such as the Ethiopian famine, or the Bangladeshi floods.

Because of relatively large financial and material resources of the Western World, many after affects and suffering can be ameliorated. However, despite significant assistance from the developed nations, mainly because of the relative underlying poverty of the country, the effects of the Ethiopian famine are still felt today.

What factors are required to enable a community to cope with a disaster?

An organised infrastructure involving emergency services, medical care and some form of after-care are obvious candidates. Less obvious factors are community spirit, degree of acceptance of events and initial quality of life within the community.

Within the Western World, the emergency services are generally highly developed , the same can be said to hold for the transport infrastructure. This allows a fast response to a disaster and rapid transfer of the injured from the site to the medical care centres. These facilities are seldom available in the under-developed nations, and, if available, are seldom able to cope properly with the situation as it develops.

The under-developed nations, however, tend to have a more localised well developed community spirit which is sometimes lacking within the more developed nations.

The threshold of acceptance of events in the developed nations is lower than in the under-developed nations. A mother in Ethiopia may expect to lose many of her children before they reach their teenage years. This is not a situation that a mother in Europe or the U. S. A. would tolerate. This does not imply, however, that the Ethiopian mother's grief is any less real or intense.

The Bradford Disaster Scale

To compare disasters of like occurrence or similar fatality rate requires that each disaster be quantified numerically before such a comparison is made. The Bradford Disaster Scale and Classification System sets out a methodology for the quantification of disasters based on the number of fatalities involved. This allows disasters arising from differing sources and causes to be compared.

In the analysis which is now presented, information with regard to disasters prior to 1976 have been extracted from Nash [6], and after 1975 from The Times.

2.PRIMARY CLASSIFICATION OF DISASTERS.

Disasters can be categorised into three classes,

2.1. Natural Disasters.

Natural disasters generally are beyond the ability of man to produce, influence or prevent, e. g. earthquakes, volcanic eruptions, cyclones etc... The scale of loss of life from natural disasters can range from a few individuals to several million.
Examples are, the Armenian earthquake, Krakatoa and the many cyclones and hurricanes that afflict the Philippine Islands.

2.2. Man-Made Disasters.

These are the disasters that are of anthropogenic origin. Examples are rail and air crashes, mining and marine disasters, large scale deaths due to the action of fires or explosions. The associated loss of life due to this type of disaster seldom exceeds several hundreds.
Examples of these are, Clapham Common, Herald of Free Enterprise, Piper Alpha.

2.3. Hybrid Disasters.

These arise from a concatenation of anthropogenic (man-made) and natural events. Man and his associated activities can produce natural disasters that would not otherwise occur, or significantly aggravate the effects of a natural disaster.
Examples of these are; the spread of disease from a community within which the disease is endemic to a community with no natural immunity to that disease, such as, the introduction of European influenza to the Eskimoes; the wholesale destruction of the Himalayan rain forests and consequent reduction in evapotranspiration which has intensified the annual flood occurrence of Pakistan and Bangladesh; the large scale deaths in the early 1950's due to smog

production in London and other major U. K. cities. The loss of life due to this type of disaster can be, and usually is, extremely large.

For the purposes of this paper, disasters have been classified by type into 17 categories and in Table 1 these have been referenced by the degree of man's involvement.

TABLE 1. DISASTER CLASSIFICATION and PREDOMINANT AGENT

Disaster Type	Natural	Man-Made	Hybrid
Avalanche/Rockfall	Yes	No	Yes
Landslide/Mudslide	Yes	Yes	Yes
Air Transport	No	Yes	Yes
Climatic	Yes	No	?
Drought	Yes	Yes	Yes
Famine	Yes	Yes	Yes
Epidemic	Yes	No	Yes
Plague	Yes	Yes	Yes
Earthquake	Yes	No	No
Fire	Yes	Yes	Yes
Explosion	No	Yes	Yes
Flooding	Yes	No	Yes
Marine Transport	No	Yes	Yes
Mining	No	Yes	Yes
Rail Transport	No	Yes	Yes
Volcanic Activity	Yes	No	No
Miscellaneous	No	Yes	Yes

For the purposes of the analysis, some of above categories have been grouped together as they can present difficulties in classifying source data. The differentiation between fire and explosion or avalanche and landslide is problematical and consequently fire and explosion will be referred to throughout the study as fire and avalanche and landslide as avalanche.

Drought, famine, plague and epidemic similarly present classification problems. For example, the large scale loss of life in Ethiopia is reportedly due to famine but the underlying cause of the famine is a long term drought within the region. The majority of fatalities within the region was not due to famine but to epidemics and plagues which readily spread through the under-nourished populace. Consequently for this presentation, these four sources are referred to together as D. F. E. P.(Drought, Famine, Epidemic, Plague)

The query against Hybrid Climatic disasters is that although the activities of man can influence climatic effects no disaster that can be completely classified this way has yet been identified.

The Bradford Disaster Scale

3. THE SCALE OF THE PROBLEM.

Within the last century over 400,000 people have lost their lives in disasters that have occurred within Europe. 31,500 of these fatalities occurred within the United Kingdom.

The total number of incidents occurring within Europe during this period is 1140, and within this period 270 incidents have occurred within the U. K.,i. e. 24% of the European total. However, disasters occurring within the U. K. in general were smaller in scale.

Figure 1 gives a frequency curve for the 10, ten year intervals of the last century , 1888-1988, for disastrous occurrences within Europe. There was a gradual increase for the first eighty years followed by a much more rapid increase over the last two ten year periods. Figure 2 gives the corresponding figures for the U. K..The plot here is more erratic but shows a decline over the first 50 years to 1936 after which there has been a general increase especially over the ten year period covering 1978-1988.

Figure 3 gives the total number of fatalities for these ten year periods for Europe. Apart from two major peak periods, 1908-1918 and 1918-1928, the number of fatalities are reasonably consistent through out. The 1908-1918 peak was due to the Italian earthquake in Sicily in 1918 and later on in that year, again in Italy, a massive flood. The 1918-1928 peak was due to a series of avalanches in the Italian Alps which caused many fatalities amongst troops stationed in that area.

The 1908-1918 peak in Figure 4 for the U. K. was due to a large number of civil marine incidents that occurred throughout that period whereas the peak period 1948-1958 was due to the large number of deaths that resulted from the high level of smog in the winter of 1952.

3.1 Frequency of Disasters by Type

The annual frequency of disasters that have occurred over the past one hundred years by type are shown in Figures 5 and 6 for Europe and the U. K. respectively. The major difference between the two sets of results is that the U. K. suffers fewer natural disasters than Europe. The frequency of man-made and hybrid disasters is greater than that of purely natural disasters. Air, marine and rail being the most frequent type of disaster incident.

Although man-made and hybrid disasters are more frequent than natural disasters the number of lives lost in Europe in the latter is far greater.(Figure 7

1898-1908 and 1908-1918 results are reduced by a factor of ten for both categories).The results for the U. K. are the reverse of what has happened on the European mainland, man-made and hybrid deaths far exceeding those occurring in natural disasters,(Figure 8). This is due to the fact that the U. K. is relatively immune from many major natural disasters such as earthquakes, avalanches and landslides.

3.2 The Bradford Disaster Scale and Classification.

Due to emotional and other factors, there is often difficulty in comparing one disaster with another. Magnitude of fatalities is obviously an important factor, and to a lesser extent the type and origin of the cause. Because of the large variation in numbers of fatalities that can occur in a disaster, this range is typically 10 to 1,000,000, the human mind has often difficulty in the perception of the magnitude and scale of disasters.
For this reason the following Scale of Magnitude is proposed

TABLE 2. Bradford Disaster Scale

No. of Fatalities	Magnitude
10	1
100	2
1000	3
10000	4
100000	5
1000000	6

Intermediate values of magnitude are given simply by the common logarithm (base 10) of the number of fatalities.
This scaling method based on common logarithms has been previously used by Richardson [7]. A reference of this method can also be found in Marshall [8,9].

One can establish absolute limits of the proposed scale by observing;

TABLE 3. Absolute limits of the Bradford Disaster scale

Fatalities	Nature	Magnitude
10^{10}	Destruction of entire planet	10
10^{20}	Destruction of entire galaxy	20
10^{30}	Destruction of entire universe	30

The Bradford Disaster Scale

Complimentary to Table 2 a classification scheme can be introduced such that,

TABLE 4. Classification

Fatalities	Class
$10 - 10^2$	1
$10^2 - 10^3$	2
$10^3 - 10^4$	3
$10^4 - 10^5$	4
$10^5 - 10^6$	5

In Table 5, examples are presented using this scale for some disasters that have occurred recently ,

TABLE 5. Notable Disasters By BDS Magnitude and Classification

Disaster	Fatalities	Magnitude	Class
Clapham Common	36	1.56	1
Hillsborough	95	1.98	1
Piper Alpha	166	2.22	2
Herald of Free Enter.	188	2.27	2
Armenian Earthquake	24000	4.38	4
1988 Bangladeshi floods	2000000	6.3	6

Using the Bradford Disaster Scale and Classification one can now analyse the frequency of disasters that have occurred in the U. K. and on the European mainland over the last one hundred years.

TABLE 6. Frequency of Disasters by BDS Class 1888 - 1988

BDS Class	Europe	U.K.
1	901	237
2	217	44
3	19	1
4	4	1
5	1	0

Hundred year frequencies of magnitudes of disaster that have occurred within Europe is presented in Figure 9, which has been derived from Table 6. The majority of disasters are of a magnitude less than 3

(Table 6),the pattern is similar for the U. K..As is shown in Figure 10.

The results of plotting the logarithm of the frequencies of occurrence of disaster in the last one hundred years for Europe and the U. K. against the class are shown in Figures 11 and 12 respectively. Both plots result in approximately straight lines of similar slope.

4. PROBABILITY OF OCCURRENCE.

For emergency planning purposes it would be useful to know not only the probability of a disaster occurring in a given time interval but also the likely magnitude of that disaster.
The Figures given in the appendices show the probability of certain numbers of disasters occurring in a given year for class 1 and 2 disasters for Europe and the U. K. respectively. For class 1 European disasters, Figure 13, the probability of no disaster occurring within a particular year is extremely small. The most likely scenario is that within any year Europe will experience between 5 and 11 class 1 disasters. For disasters of class 2 the highest probability is that at least two incidents will occur each year which will claim between 100 and 1000 lives.(Figure 14)

In Figures 13 and 14, observed frequencies are compared with those predicted using Poisson distribution.

Within the U. K. for class 1 disasters there is a high probability that there will be at least two class 1 disasters each year and there is a reasonable probability that there could be three or four ,(Figure 15).For class 2 disasters the probability is that one such incident will occur every three to four years.(Figure 16)

TABLE 7. Summary of Disaster Frequencies

BDS Class	Europe Frequency p.a.	U.K. Frequency p.a.
1	9	2
2	2	0.33
3	0.2	0.04
4	0.05	0.0067
5	0.01	0.001

4.1. Frequency Analysis by Type of Disaster

As discussed earlier, Europe and the U. K. differ in that the U. K. has a low rate of natural disasters, which cause the greatest loss of life, compared to Europe generally.

Within Europe the disasters with the highest probability of occurrence are those of man-made origin, i. e. air, rail, marine and fire. The cumulative frequency of these four types is approximately 0. 7 per year.

Two periods have been analysed, 1938 - 1963 and 1963 - 1988, for Europe and the U. K. to see if any change in the pattern of frequencies of occurrence has taken place; results are given in Figures 17 and 18 respectively.

The largest change is in those disasters that have occurred within Europe (Figure 17) resulting from mining incidents where the frequency has dropped by over 75 %.The frequency of marine disasters has dropped by around 50% due to the shift away from passenger sea travel to air travel. The small increase in the frequency of air disasters when compared to the considerable increase of usage of this means of travel clearly demonstrates the very large advances in air safety that have occurred over the last fifty years. The numbers of fatalities per disaster for air disasters has however dramatically increased due to the much larger aircraft now in use and the greater seat capacity. However, this is more than balanced by the dramatic drop in the frequency of accidents per flight and better designed aircraft operating within much improved flight rules and regulations.

Natural disasters have maintained a reasonably constant frequency over the two periods of analysis.

A similar analysis has been carried out for U. K. disasters for the same periods, Figure 18. The frequency of air disasters has remained constant whereas marine and mine disaster frequencies have dropped dramatically. Marine travel has decreased very significantly as a form of transport over the past forty years. The decrease in mine related incidents has occurred from the greater use of safety technology and a much reduced manpower levels within the industry. The frequency of fire related disasters has increased by 100% and the climatic disasters have risen by a factor of four. Large increases in frequencies have occurred within the DFEP and Miscellaneous groupings. Over the past twenty five years there has been a doubling of the number of small scale infectious outbreaks, especially within residential homes for the elderly. The Miscellaneous group contains those elements due to road transport accidents and within the past ten years there has been an increase in the number of large group fatalities especially on the motorways.

4.2. Fatalities by Disaster Type Analysis

For the period 1963 - 1988 the average number of fatalities for different types of disaster which have occurred within the U. K. have been analysed and the results presented in Figure 19. Only one major landslide, Aberfan, has occurred during this period and which claimed a total of 144 lives. The others are more representative of their groups.

Marine and air disasters have produced the largest number of fatalities over the last twenty five years although the marine results are distorted due to the large number of lives lost with The Herald of Free Enterprise. The marine fatalities would have been in the region of 20 for the above period of time. Air disasters average around 75 and rail disasters around 35 fatalities per disaster.

4.3 Fatalities per Incident

In this section an analysis of average fatalities are studied as a function of disaster magnitude of disasters occurring within the U. K..

Class 1 European disasters, Figure 20, show that the highest probability is that between 10 - 30 lives will be lost per disaster. For Class 2 European disasters, Figure 21, 6 out of every ten disasters will claim 100 - 200 lives and 9 out of every 10 will result in the loss of between 100 and 400 lives.

For class 1 disasters occurring within the U. K. the probability of number of fatalities is highest between 20 - 30 fatalities per disaster and for up to forty fatalities per disaster the probability rises to 0. 7. (Figure 22)

There is a probability of just below 0. 8 that any European disaster will be of class 1 - 2, Figure 23, and a probability just greater than 0. 2 that it will have a magnitude greater than 2.

For the United Kingdom, on the occurrence of a disaster, the probability of the number of fatalities being of magnitude 1 - 2 is about 0.83 and for a class 2 disaster the probability is around 0.16. (Figure 24) leaving a probability of 0.01 for disasters of class 3 or greater i. e. more than 1000 deaths.

Although emphasis has been placed on the number of fatalities that occur in a disaster, the number of injured involved can be an order of magnitude higher.

For planning purposes it is suggested that further research be carried out to establish the likely numbers of injured in a disaster of particular magnitude and type.

Statistics giving the number of injured survivors are not readily available and those that are often do not lend themselves to easy interpretation.

As a general rule for each fatality there are between 3 and 10 injured survivors with differing degrees of severity of injuries. A rail crash seldom kills all on board, the injured are mainly in the same carriages where the fatal injuries occurred. An air disaster occurring during mid flight, which is a relatively rare occurrence, produces no survivors whereas disasters occurring on take off or landing have about a 25% survivor rate with another 25% suffering severe injuries.

5. DISCUSSION.

The problem of classification of disasters to allow comparisons between different types has been studied and some key factors identified. These key factors are, number of fatalities, type of disaster and the degree of man-involvement.

Within Europe there is a high expectation that between 5 and 11 class 1 disasters will occur each year. Each of these class 1 disasters is likely to produce between 20 and 50 fatalities. Furthermore, there is a high likelihood that they will arise from man-made sources and will involve either air , rail or marine transport or be the result of the effects of a major fire.

The frequency of class 2 disasters will be around 2 to 3 per annum with an equal probability that it will result from natural or man-involved sources.

Class 3 or above disasters can be expected to occur once in every 3 years and will be of a natural origin.

For the United Kingdom the scenario is somewhat different in that two class 1 incidents can be expected to occur every year and there is a significant probability that this number could increase to up to five in any one year. Class 2 disasters can be expected once every 3 years, although in the last two years in the U. K. there have been three class 2 disasters. Pure statistical analysis at present is unable to establish whether the higher number of class 2 disasters which have occurred within the last two years are random rare events or are the beginning of an upward trend arising from some yet unidentifiable structural societal change such as undermanning

As regards overall planning strategies the present study suggests that emergency planning could perhaps mainly concentrate on preparing for disasters of man-made origin and in which fatalities are between 20 and 40 with up to 100 survivors with severe injuries requiring immediate medical treatment. These estimates are of necessity of a very approximate nature. However, it is believed that the present study does provide a methodology and a classification system for analysing disasters so that planning on a regional or national basis regarding provision of necessary and relatively scarce resources can be made on a quantitative judgemental basis.

6.CONCLUSIONS

1. A quantifiable system of classification has been demonstrated.

2. There has been an increase in the U. K. in the number of disasters over the past ten years of over 30% .

3. There is a high probability that a U. K. disaster will be either of transportation or fire origin.

4. The likelihood of a major natural disaster occurring within the U. K. is small.

5. The majority of disasters that occur in the U. K. are of anthropogenic origin and in principle are preventable.

7. RECOMMENDATIONS.

1. That the usefulness of the method for emergency planning purposes be assessed.

2. That the method be extended to include incidents that could have resulted in potential disasters.

3. That the method be used for initial hazard identification and risk evaluation and as a tool for strategic planning.

4. That the scale when combined with the probability of occurrence be developed as a tool for resource allocation and level of response planning.

5. That the research be extended to include factors in the scale other than fatalities; i. e. injuries, economic and long term effects etc..

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FIGURE 1

The Bradford Disaster Scale


UNITED KINGDOM DISASTERS
10 YEAR PERIOD ANALYSIS
No.of DISASTERS
50
40
30
20
10
0
1898
1908
1918
1928
1938
1948
1958
1968
1978
1988
10 YEAR PERIOD TO YEAR

FIGURE 2

FIGURE 2

EUROPEAN DISASTERS 1888 - 1988

FATALITIES WITHIN TEN YEAR PERIODS

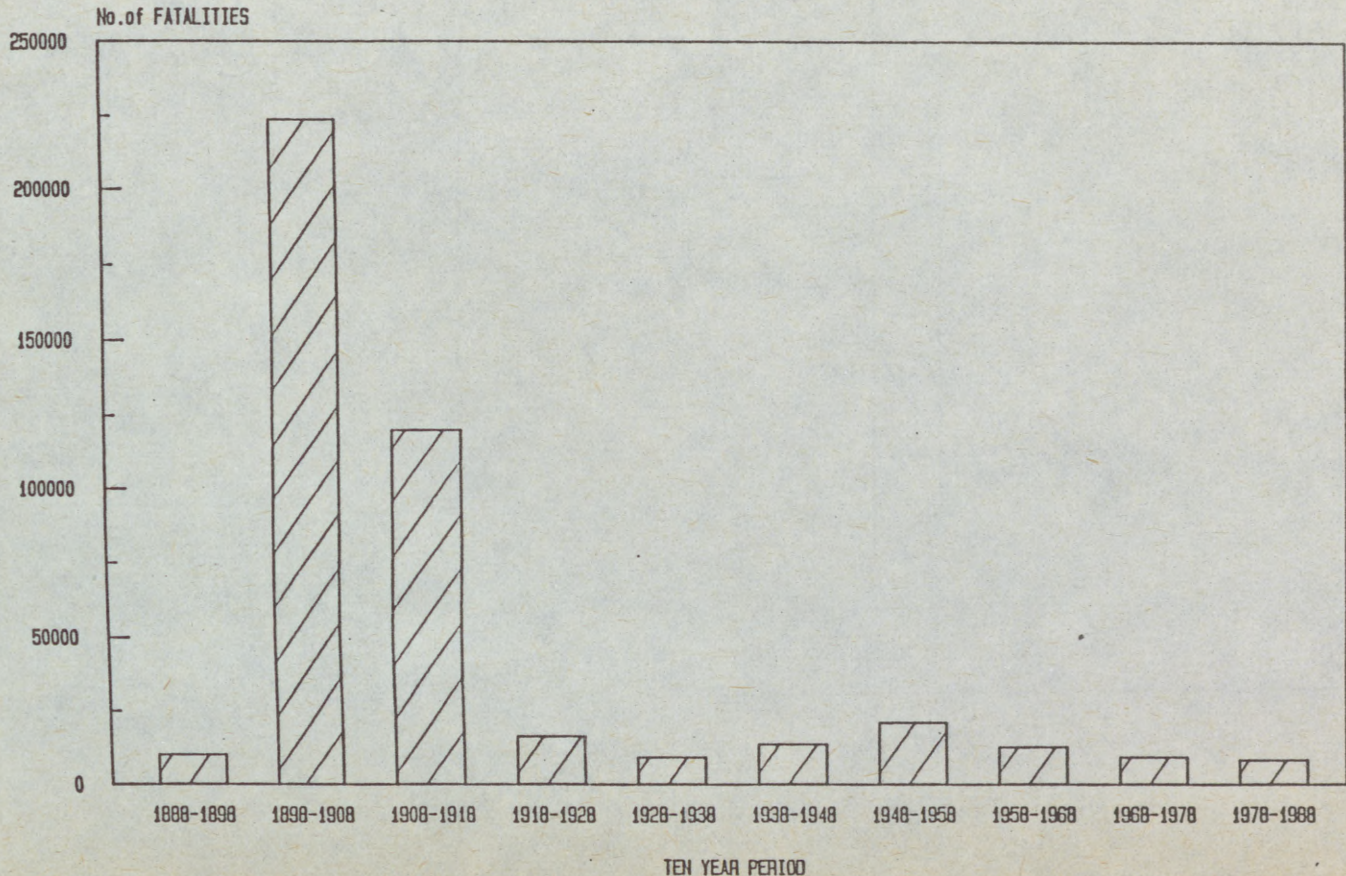


FIGURE 3

UNITED KINGDOM DISASTERS 1888 - 1988

FATALITIES WITHIN TEN YEAR PERIODS

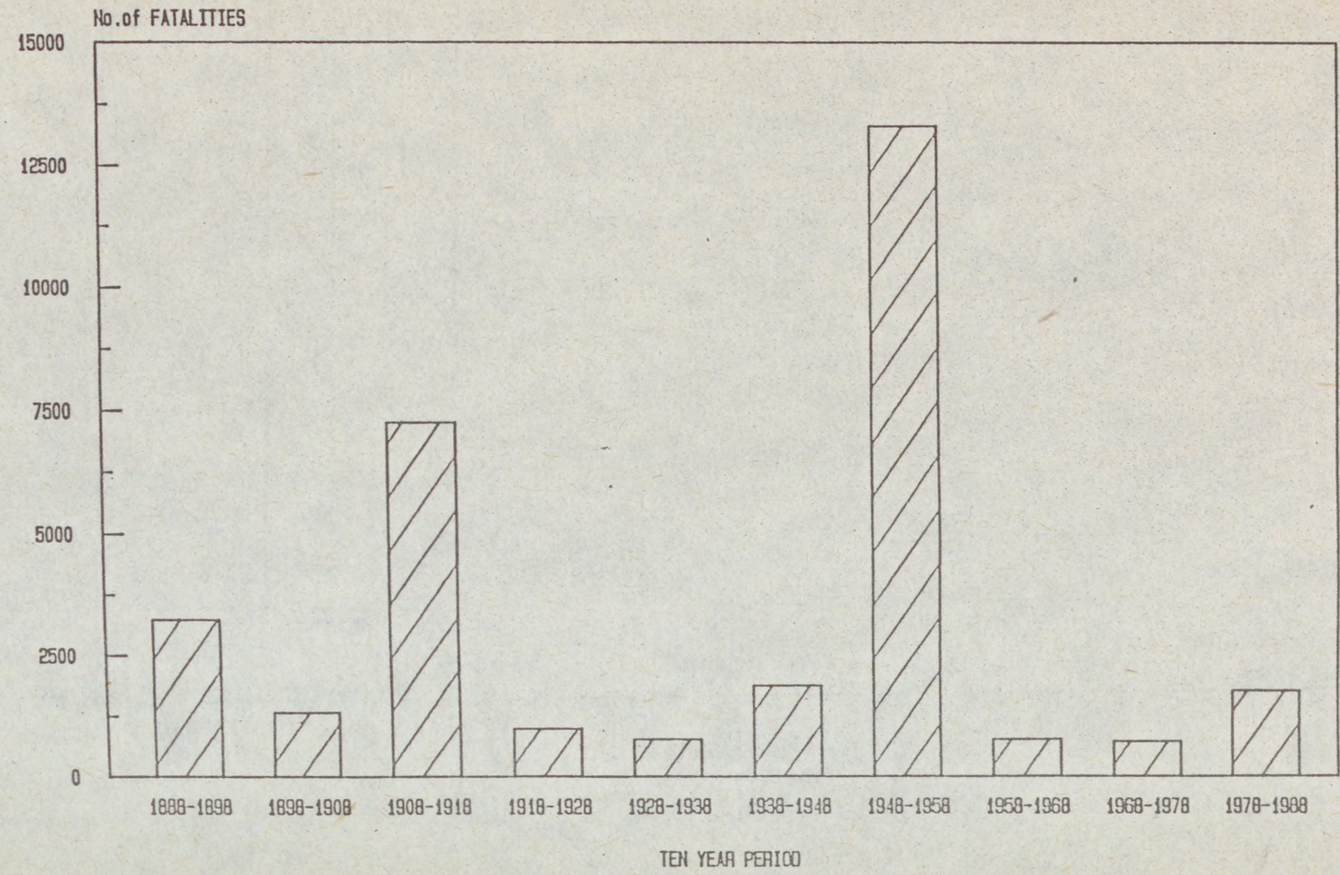


FIGURE 4

FIGURE 4

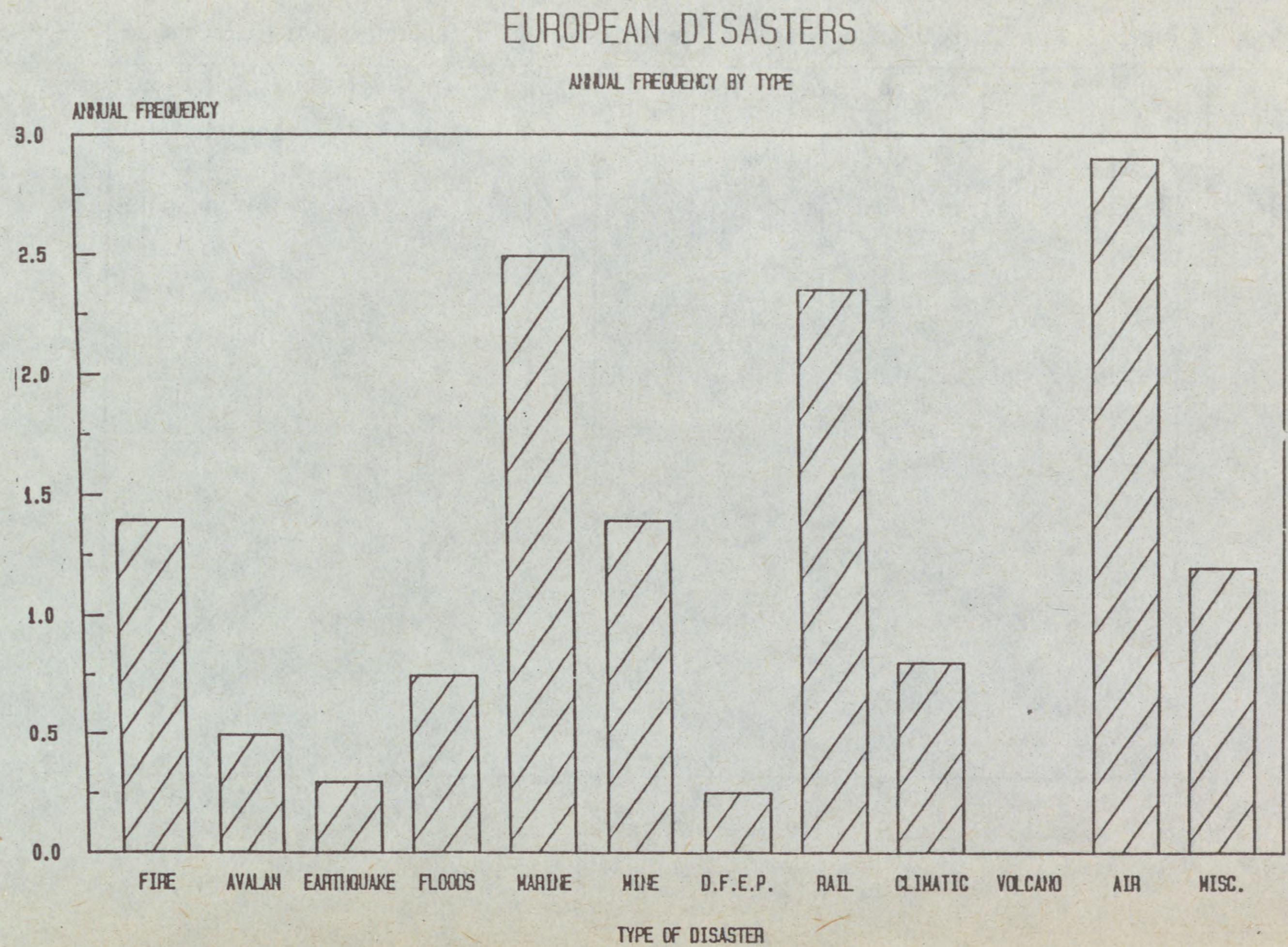


FIGURE 5

UNITED KINGDOM DISASTERS

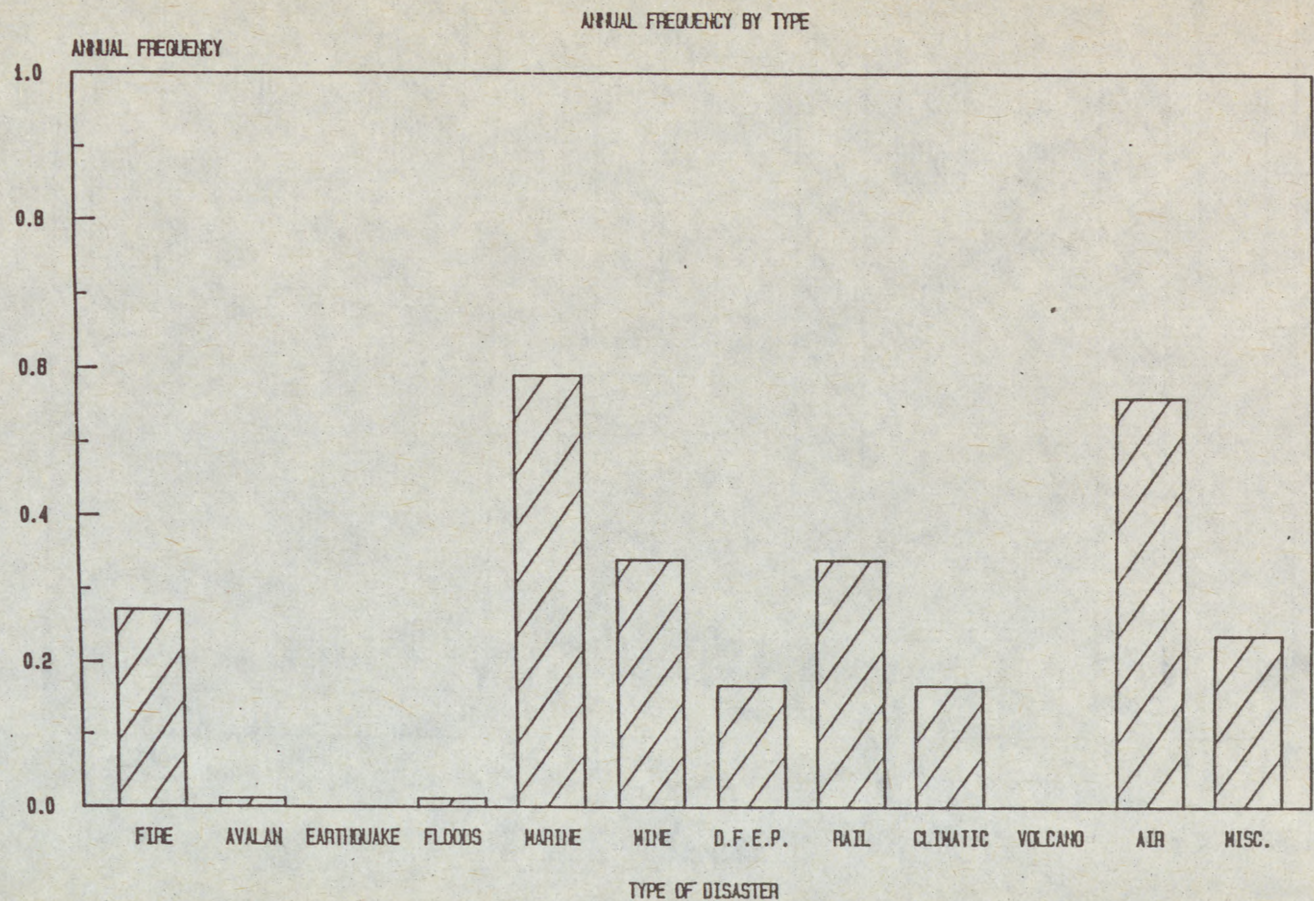


FIGURE 6

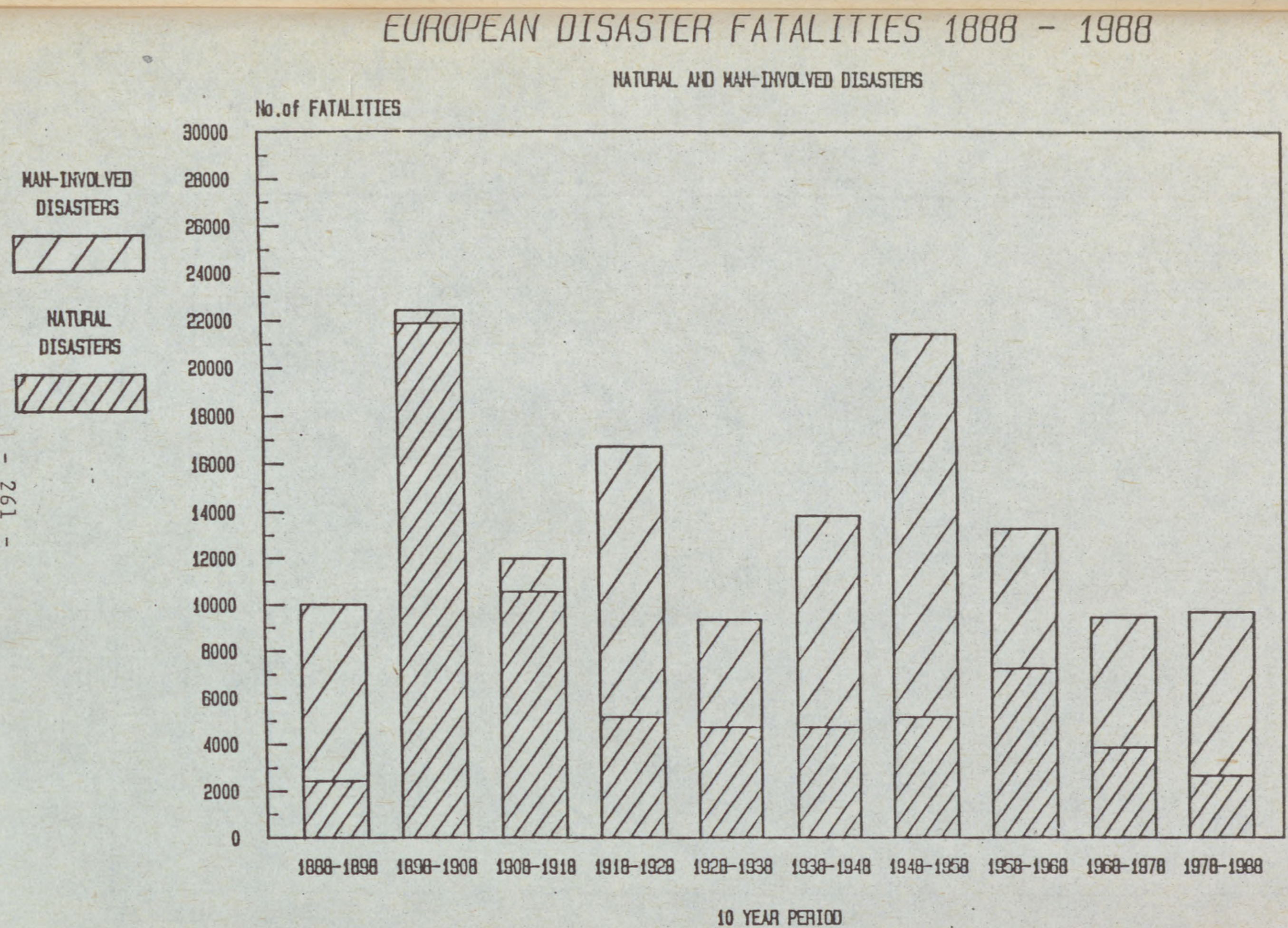


FIGURE 7

1888-1898 1898-1908 1908-1918 1918-1928 1928-1938 1938-1948 1948-1958 1958-1968 1968-1978 1978-1988

10 YEAR PERIOD

FIGURE 8

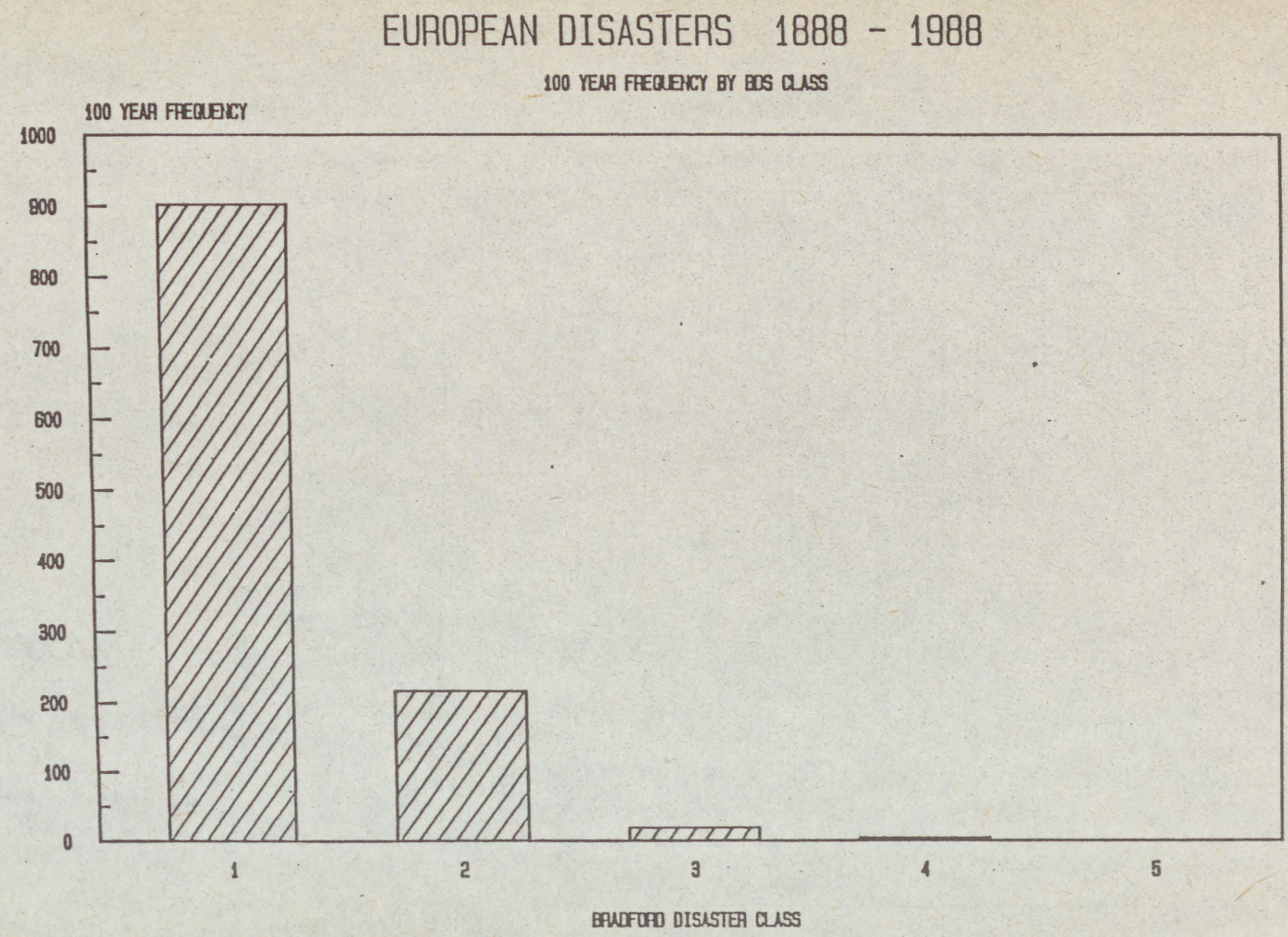

EUROPEAN DISASTERS 1888 - 1988
100 YEAR FREQUENCY BY BDS CLASS
100 YEAR FREQUENCY
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
BRADFORD DISASTER CLASS

FIGURE 9

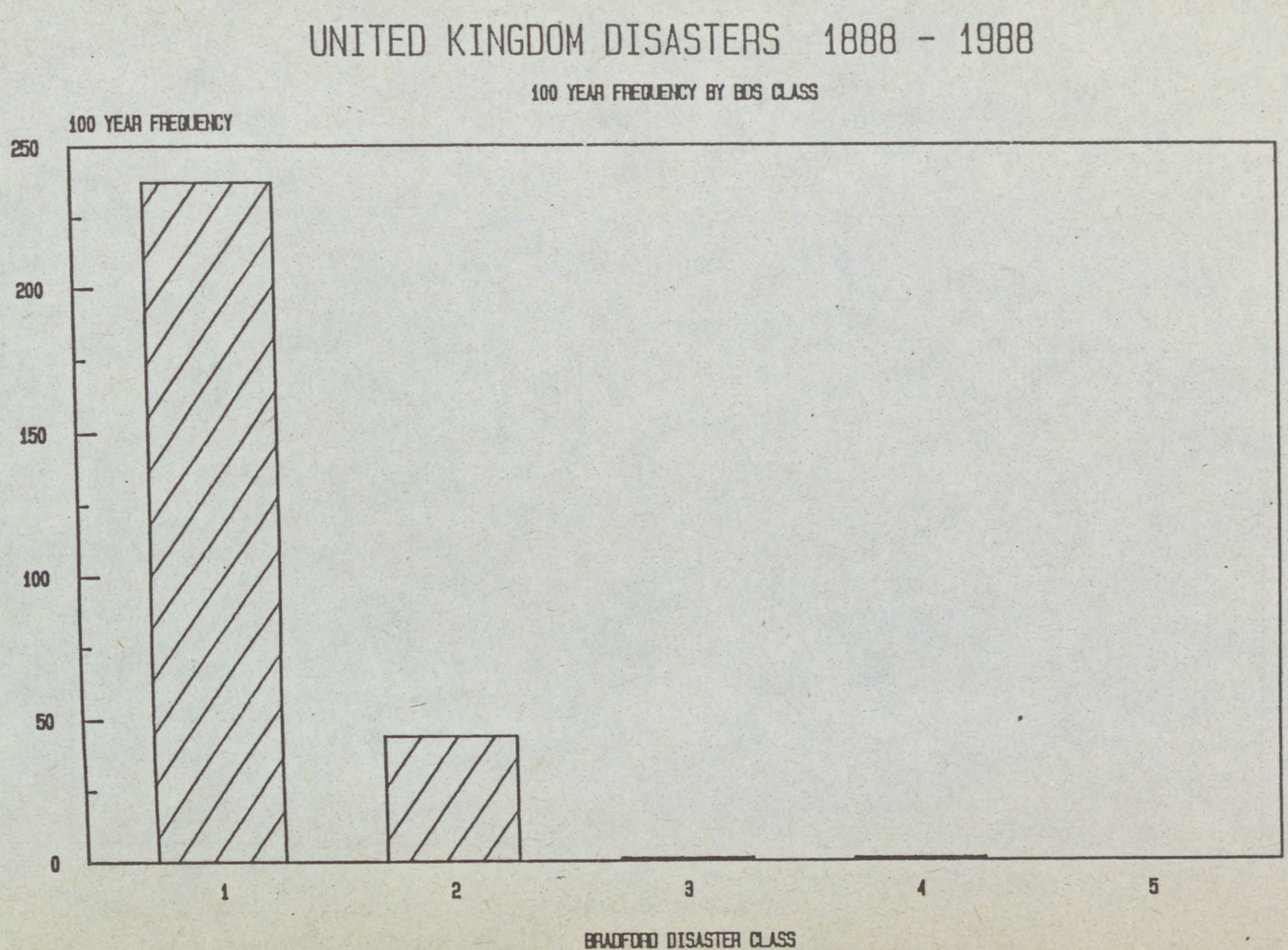

UNITED KINGDOM DISASTERS 1888 - 1988
100 YEAR FREQUENCY BY BDS CLASS
100 YEAR FREQUENCY
250
200
150
100
50
0
1
2
3
4
5
BRADFORD DISASTER CLASS

FIGURE 10

EUROPEAN DISASTERS 1888 - 1988

LOG FREQUENCY TO BDS CLASS

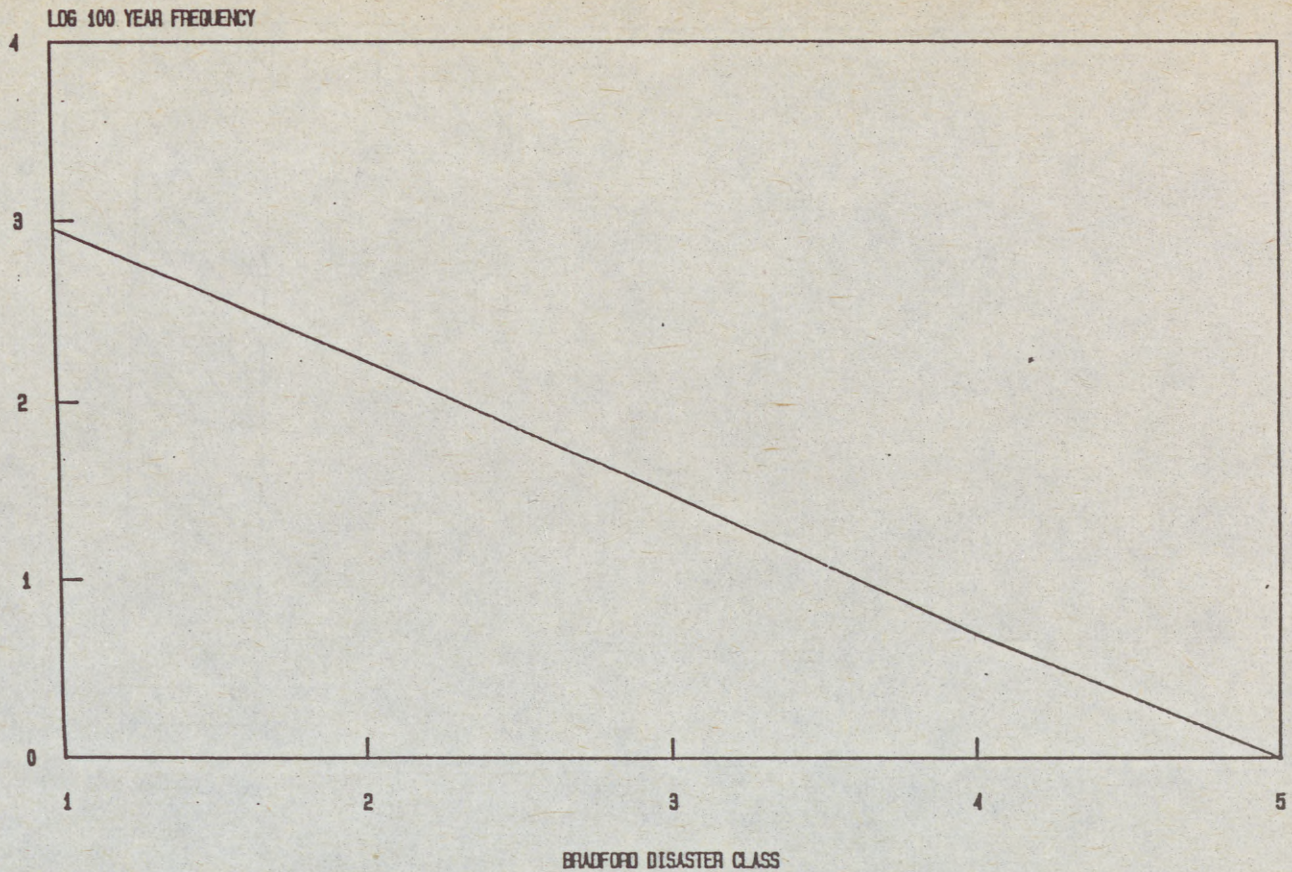


FIGURE 11

FIGURE 13

EUROPEAN DISASTERS   BDS CLASS 2

PROBABILITY OF FREQUENCY PER ANNUM

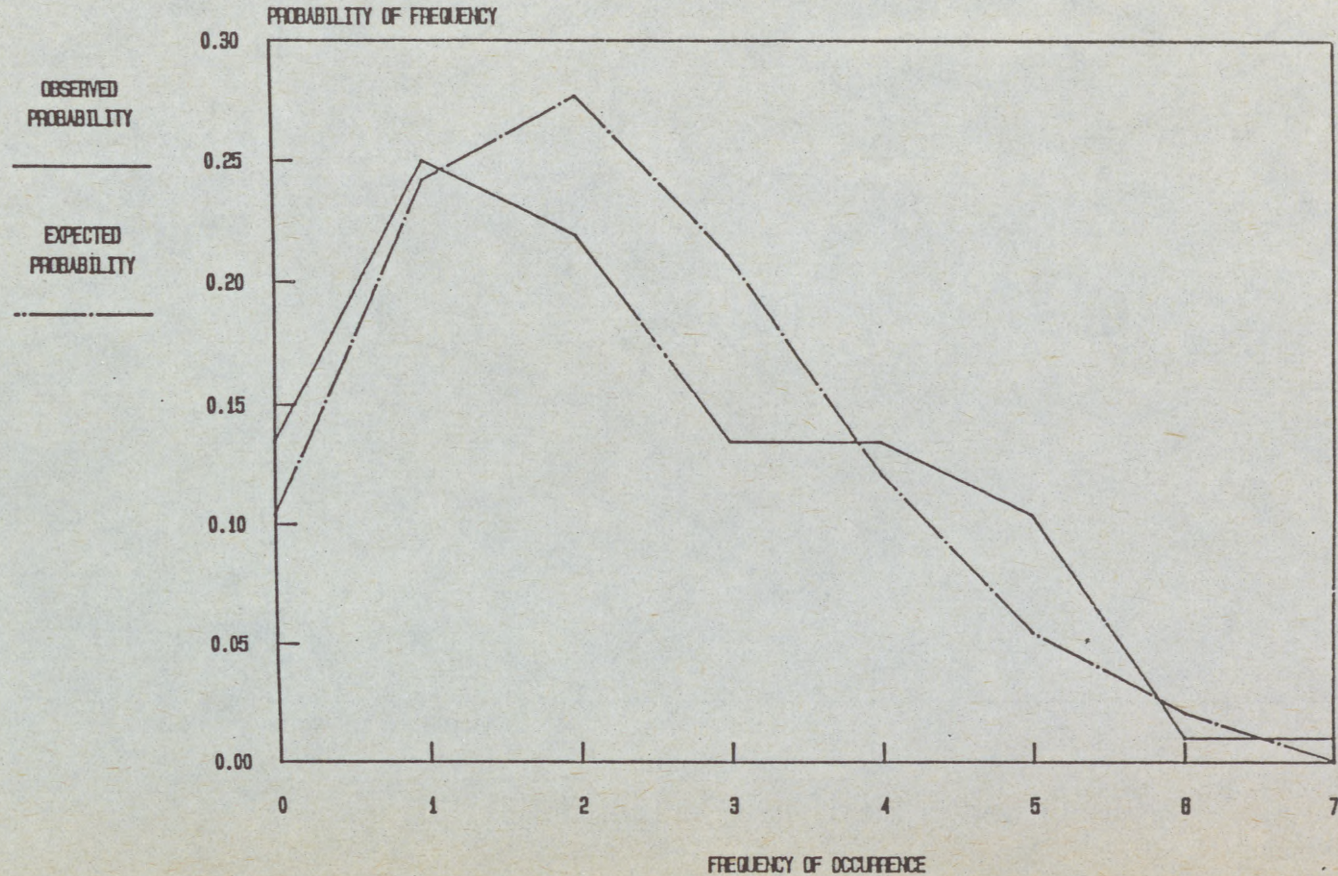


FIGURE 14

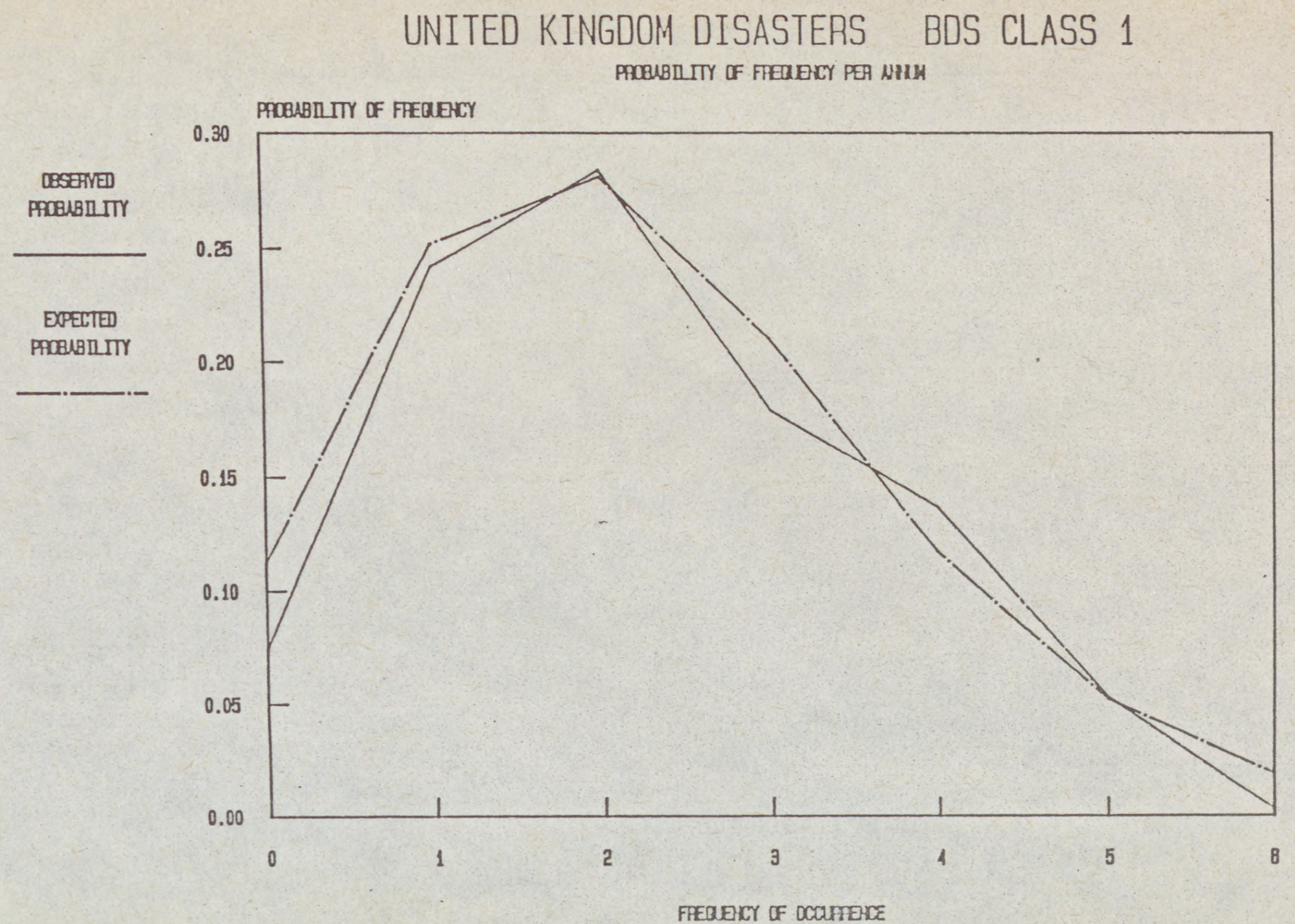

UNITED KINGDOM DISASTERS BDS CLASS 1
PROBABILITY OF FREQUENCY PER ANNUM
PROBABILITY OF FREQUENCY
OBSERVED PROBABILITY
EXPECTED PROBABILITY
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
8
FREQUENCY OF OCCURRENCE

FIGURE 15

UNITED KINGDOM DISASTERS   BDS CLASS 2

PROBABILITY OF FREQUENCY PER ANNUM

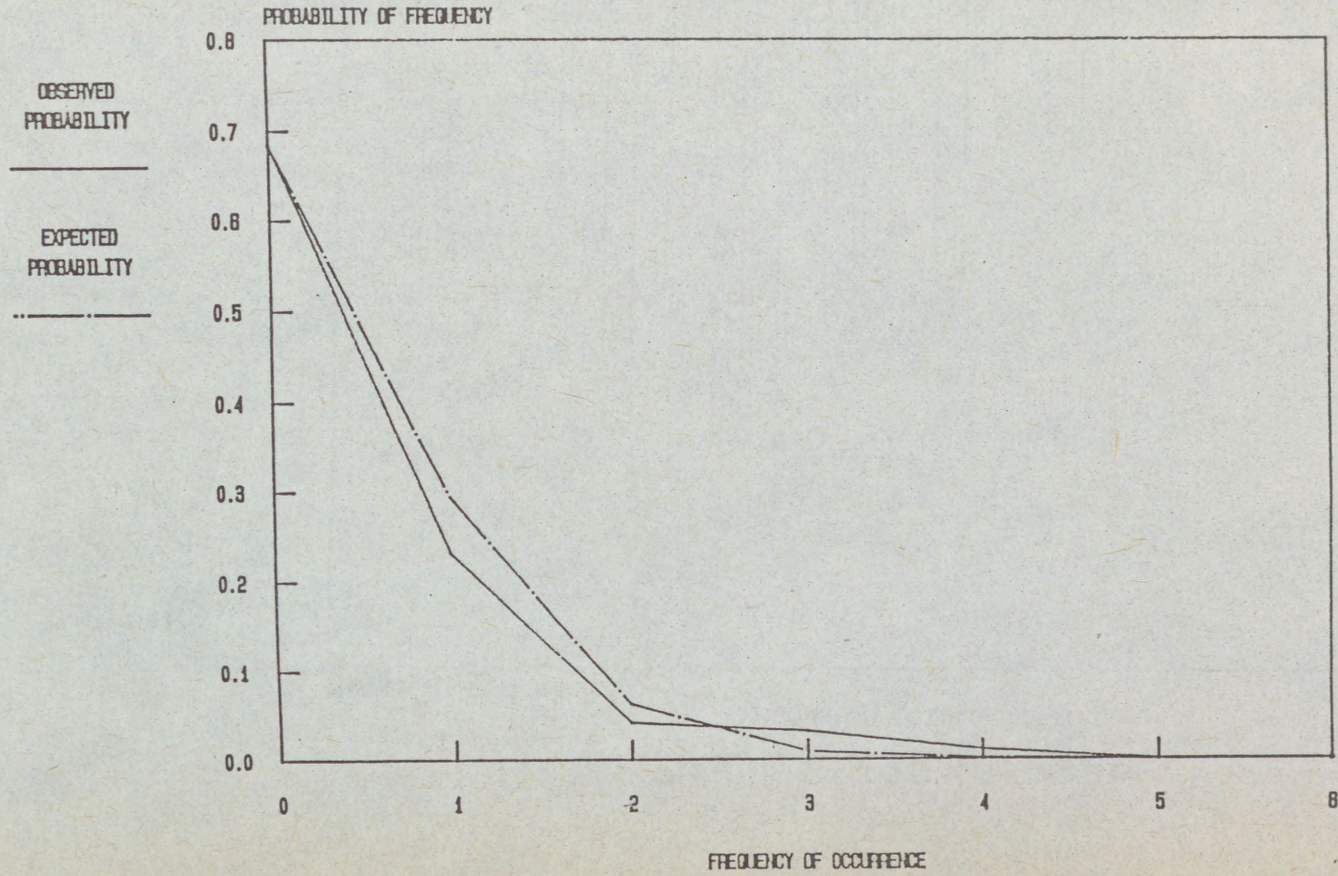


FIGURE 16

EUROPEAN DISASTERS BY TYPE

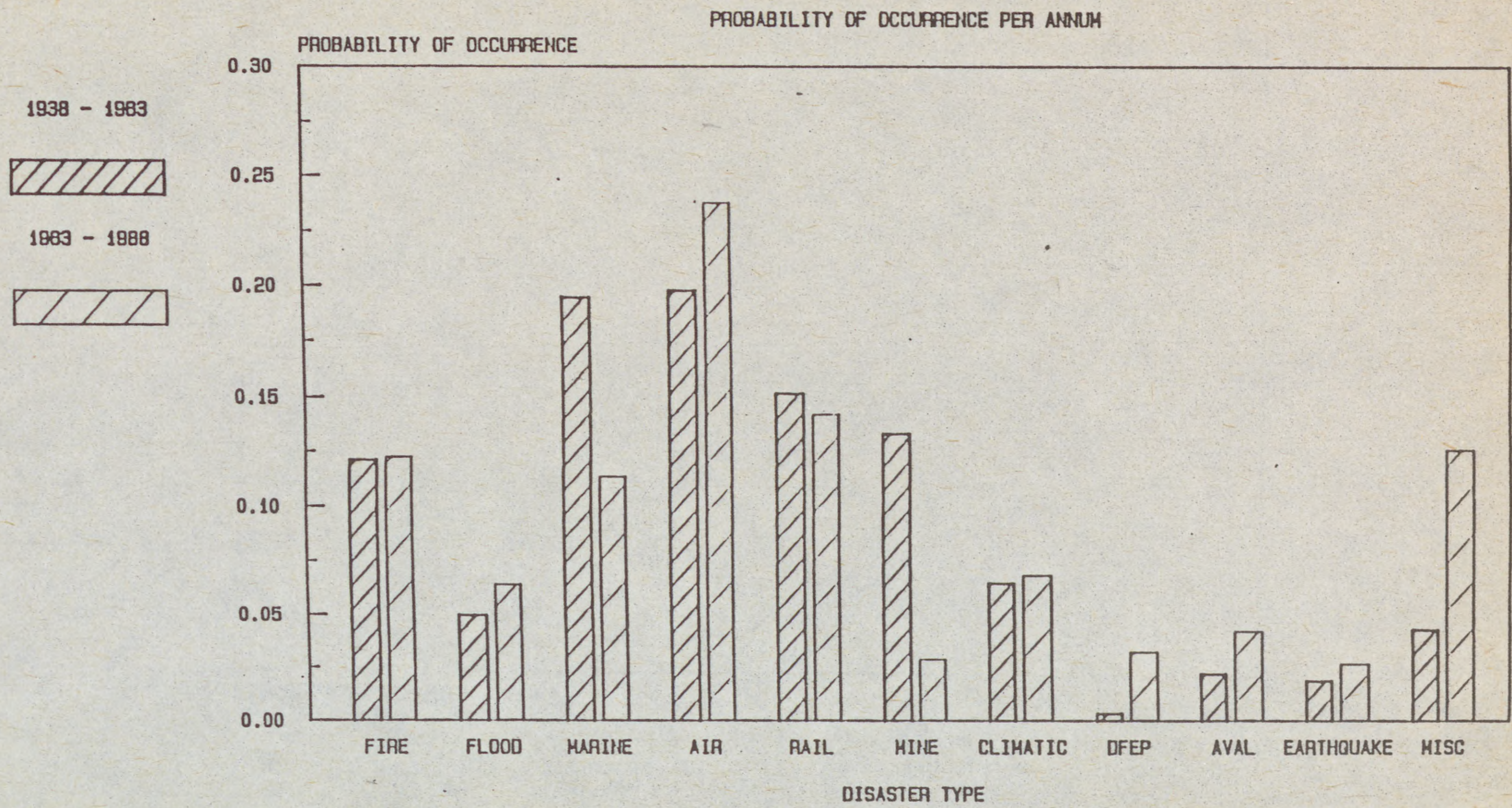


FIGURE 17

EUROPEAN DISASTERS CLASS 2

PROBABILITY OF FATALITY RATE

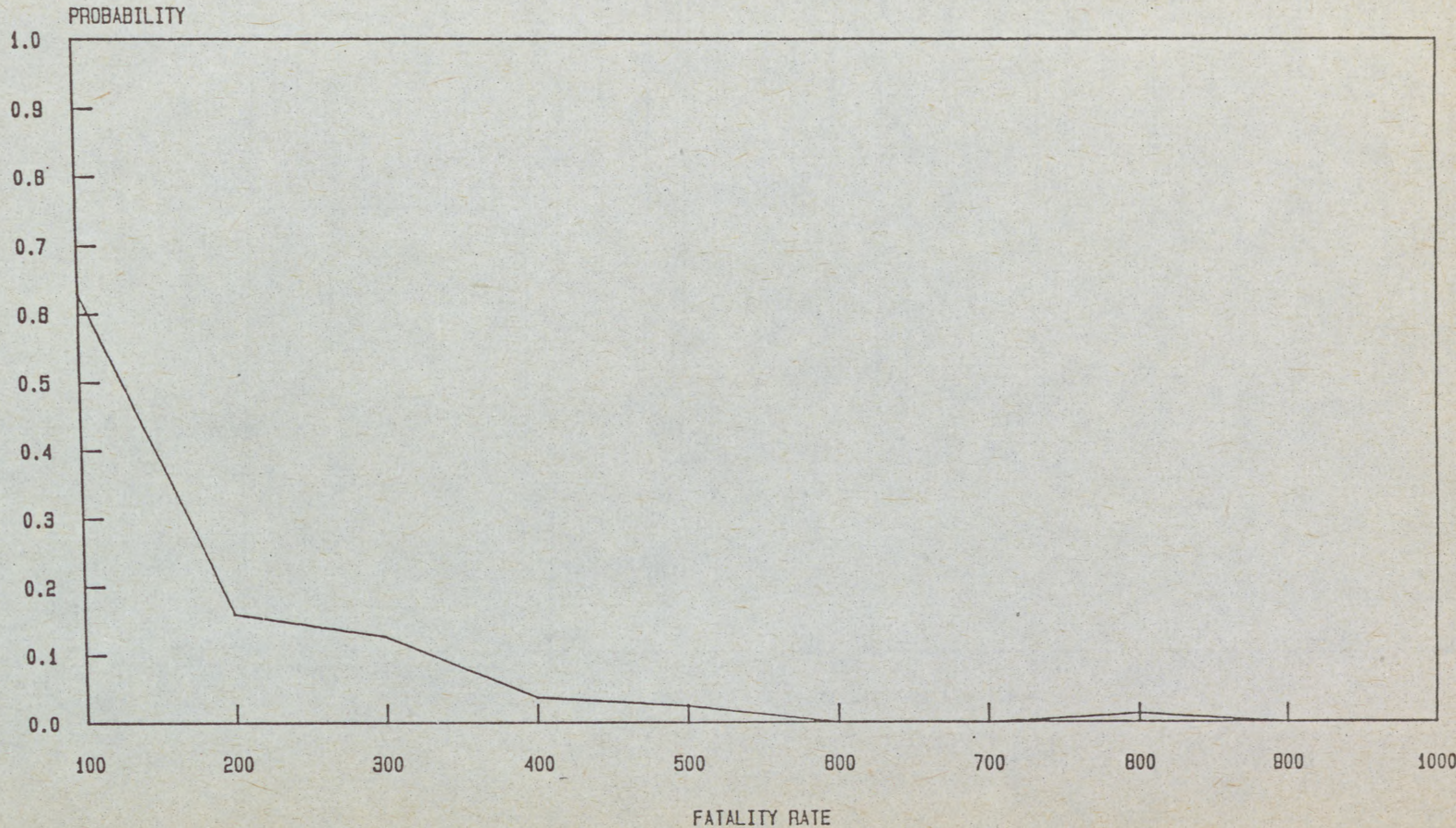
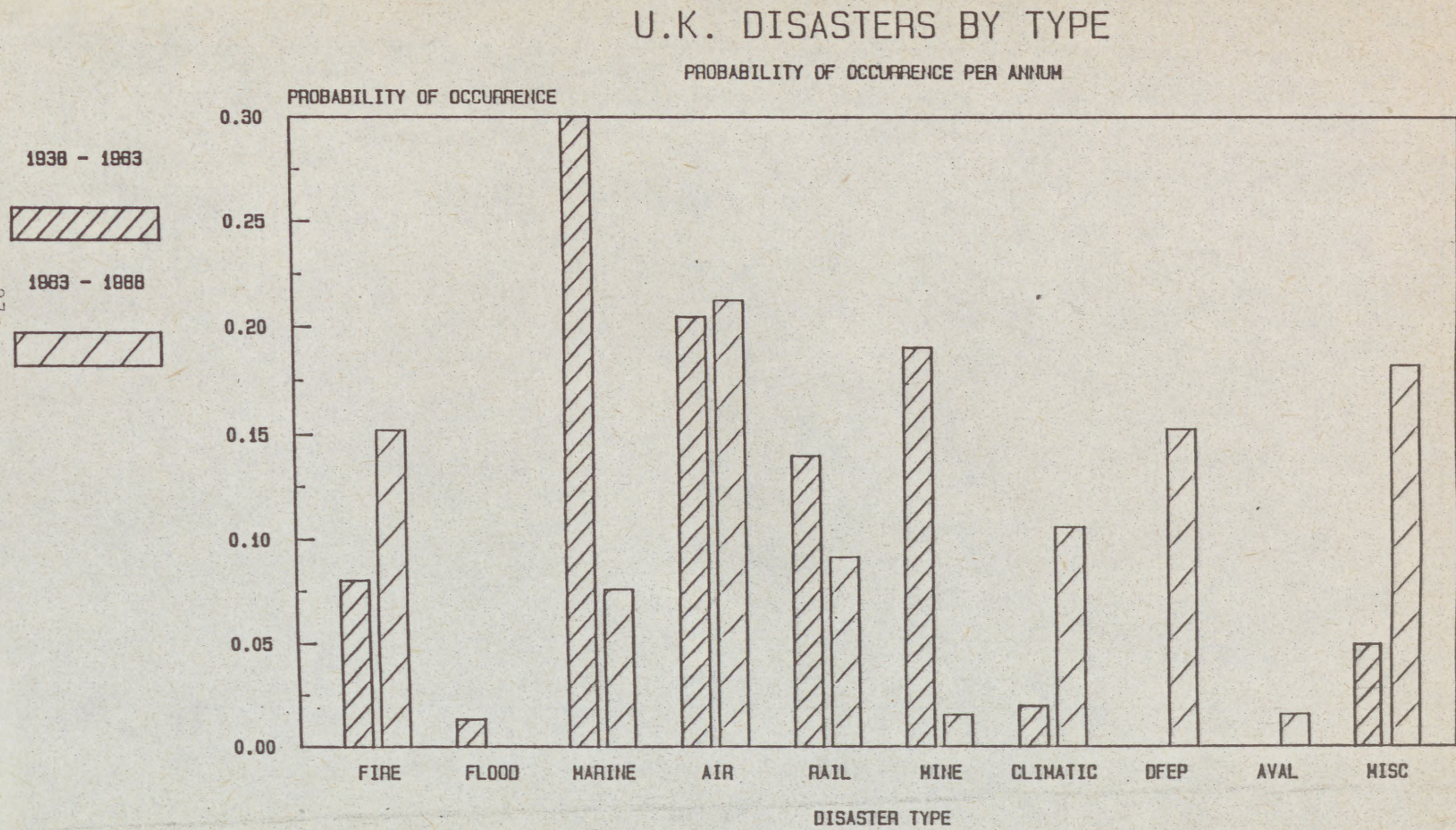


FIGURE 21



U.K. DISASTERS BY TYPE
PROBABILITY OF OCCURRENCE PER ANNUM
PROBABILITY OF OCCURRENCE
1938 - 1963
1963 - 1988
0.30
0.25
0.20
0.15
0.10
0.05
0.00
FIRE
FLOOD
MARINE
AIR
RAIL
MINE
CLIMATIC
DFEP
AVAL
MISC
DISASTER TYPE

FIGURE 18

ABSTRACTS OF CONTRIBUTED PAPERS

SIMULATION OF HEAT AND VIBRATION ACTIONS ON AUTOMOBILE ELECTRONIC SYSTEMS

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Application of various models of electronic devices on automobiles is one of the ways of development in automobile industry during the last ten years. The automobile electronic devices must guarantee the improvement of working characteristics (economy of fuel, reduction of air pollutions), extention of safety and creation the comfortable conditions for driver and passengers.

So the research of external actions on automobile electronic systems (AES) and the improvement of their reliability are very actual problems. In particular, the mathematical simulation of these actions has a special significance during design the electrical chart and construction of AES. Really, if one has the convenient tools for simulation of external actions on AES, he will be able to make some constructive decisions, which guarantee reliable work of automobile electronics.

The problems of creation of such tools for mathematical simulation of the main external actions of AES heat and vibration, are considered in this paper.

ASRE-TUB
3-7. Sept. 1990.
BUDAPEST

RELIABILITY in the FACTORY of the FUTURE

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SUMMARY

The FoF (Factory of the Future) is a greatly complex system, where the automation of physical and informational flows has a new quality level in comparison to the automation of the TF (Traditional Factory).

The availability and reliability problems of automation for different subsystems and production cells are discussed and realized in wide sortiment.

The reliability of complex automation in the FoF puts further problems with a new morphology and parameters, connected with:

- the physical and informational life of products and their parts with a wide mixed range of sortiment during the production,
- the functional availability and reliability problems of the highly complex and long flow chains and their mixtures,
- the role and qualities of man in the working staff for service and supervision.

Rihard Piskar, Iskra Delta Computers, Ljubljana

ZANESLJIVOST PARSIS ARHITEKTURE HIPERKOCKE IN TORUSA

PARSYS HYPERCUBE - TORUS ARCHITECTURE RELIABILITY

Abstract - The paper presents the combinatorial reliability model of a parallel computer PARSYS. The architectural design is based on 64 processor system with 64 memory modules, that are connected via network of routing nodes. The network is called 6-cube because 2^6 is the number of processors. At first there is derived the combinatorial reliability model of 6-cube architecture for 64 processors and memories connected in the hypercube. Then the reliability of the rerouting procedure is evaluated as the probability of the successful packet transfer from a processor to a memory. Further research showed that torus architecture is the enhancement of the packet transfer reliability because of redundant routing capabilities.

Shewhart Control Charts with Warning Limits

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8 May 1990

Abstract. In this paper we consider the control of a production process by measuring a dimension of interest X which has a normal distribution with known variance σ^2. We assume that the process can adopt two states, characterized by the expectation of X_i, which equals μ_0 in STATE I, the 'in-control' state, and which equals $\mu_0 + \delta\sigma$ with a known shiftparameter δ in STATE II, the 'out-of-control' state. Thereby X_i denotes the dimension of the i-th item produced, and it is assumed that the X_i are independent random variables. The process always starts in STATE I, a transition to STATE II happens randomly, a transition from STATE II back to STATE I is only possible by a renewal of the process. The aim is to recognize in due time a transition to STATE II. To this end regularly after h hours of production n consecutively produced items are drawn from the production line, their mean-value $\overline{x}$ is computed and the process inspected, if

$$\frac{\overline{x} - \mu_0}{\sigma}\sqrt{n} > k_1$$

with a constant $k_1 > 0$, called the control limit.

When using control charts with warning limits, an inspection is also performed, if

$$k_2 < \frac{\overline{x}_j - \mu_0}{\sigma}\sqrt{n} < k_1$$

holds for N consecutive sample-mean-values $\overline{x}_j$, where $k_2 > 0$ is called the warning limit.

A sufficient condition is derived, which assures that an additional warning limit improves the control chart result without warning limit. For most "optimal" control chart designs this condition is generally not fulfilled, and numerical examples indicate, that there is no improvement possible. The criterion for comparison is the average run length (ARL) of the chart in STATE II, which should be as short as possible.

Numerical results also show, that from a certain N_0 on the consideration of more than N_0 samples for the warning range only deteriorates the ARL.

Summer Course on Reliability Engineering ASRE '1990
Technical University of Budapest, 3-7 September, 1990

USE OF COMPUTER SIMULATION FOR RELIABILITY EVALUATION OF MAN-MACHINE INTERACTION IN INDUSTRIAL CONTROL SYSTEMS

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Abstract

Problems related to the reliability prediction of man-machine interaction in technological process control are discussed. Current design procedures, insufficiently including human impact on the system operation, are recognized as a significant contributor to the increasing human error rate in modern industrial control rooms. Necessity is stressed for the development of certain tools for the prediction of human reliability at the early stage of control room design.

Actual difficulties in human reliability analysis and prediction are discussed, relative to the problem of availability of human error data in various control room tasks. Practical use of existing human reliability data banks in performance studies is discussed.

Finally, a modified concept of human reliability in control room environment is presented. Together with the task-network simulation technique, it serves as a basis for the development of a computer-supported method for reliability evaluation of typical control room operations. A case study is presented and further possible applications of this method are discussed.

APPLYING SAFETY AND RELIABILITY METHODOLOGY FOR HIGH RISK INSTALLATIONS TO OTHER AREAS OF LIFE

-oOo-

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University of Bradford

1. ABSTRACT:

This paper discusses the application of risk, safety and reliability techniques to disaster prevention and limitation. Techniques such as Hazard Analysis, Preliminary Hazard Analysis, Failure Mode Effect and Criticality Analysis, Fault Tree analysis, Hazard and Operability Analysis, Cause and Consequence Analysis and Common Cause Analysis are described at length and their suitability for disaster prevention validated. Other characteristics of risk and reliability studies such as the importance of automatic and manual data collection and the advantages of warning devices are also discussed. The paper also addresses the benefits and needs of databases for emergency planning as well as the problems of fusing both soft and hard data together to arrive at an accepted level of system behaviour. Some available databases such as FINDS and CRISIS are reviewed. Finally, new developments, such as Expert Systems, already validated in the field of risk and safety studies are explored and extended to disaster management.