ZJE - 194 1976

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CS 7705212

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Reg. č. ÚVTEI 73 307

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A B S T R A C T

One of the most important task of present-day nuclear technology is to ensure the safety of operation of reactor pressure vessels. The crack--initiation approach and the crack-arrest approach are the two techniques nowadays most often used for evaluating the safety of pressure vessels. The former is based on the methods of Linear Elastic Fracture Mechanics and Fracture Toughness, while the Fracture Analysis Diagram and the Crack Arrest Temperature underlie the latter.

By introducing some formalism and the unified temperature (T_R), this paper tries to formally unify both the approaches mentioned above. Experimental data suggest using the Nil Ductility Temperature as a reference temperature for both approaches. Using the theoretical background of linear elastic fracture mechanics it is possible to construct the Defect Analysis Diagram which summarizes the dependencies of critical sizes of flaws. The dependence on the crack arrest temperature is also included, which seems to be highly advantageous.

Moreover, after extending the principles of Linear Elastic Fracture Mechanics to cover the elasto-plastic failure, this diagram may be made applicable also in other regions.

One of the most important requirements imposed on contemporary design and operation of nuclear power plants is to ensure operational safety of nuclear devices. This concerns mainly their pressurized components including pressure vessel. In the case of pressure vessels, these must be fully safe, i. e. no reference failure may lead to a loss of its integrity. Consequently, every effort is to be taken process of design, manufacture and operation to avoid any possibility of failure. Sudden brittle failure is considered as the most dangerous.

Pressure vessel safety analysis is performed in conformity with standards of nation-wide validity based on the theory of fracture mechanics. The contribution presented hereinafter analyzes this matter on the bases of two different approaches - the initiation and arrest of brittle fracture. In addition, a comparison and formal unification of both approaches is given, and their incorporation into the "Defect Analysis Diagram (DAD)" is described.

1. THEORETICAL BACKGROUND OF UNIFICATION

The analysis of pressure vessel safety necessitates to know, during both stationary and non-stationary modes throughout the whole operation, the values of L^i and L_c^i, which are described at some length hereinafter:

$$L^i = f(C, \sigma_{ij}, a) \qquad (1)$$

where L^i represents a chosen parameter of fracture mechanics (e. g. the stress intensity factor, K_I; crack opening displacement, δ; value of J-integral, J_I; further parameters are not excluded),

C (compliance factor) characterizes the geometry of both the flaw and the body under investigation,

σ_{ij} is stress tensor in the location of the flaw, and

a represents a characteristic dimension of flaw.

The second value, L_c^i, may be expressed in the following terms (2)

$$L_c^i = g(M, \vec{n}_i, x_i, T, \dot{\varepsilon}, t\ [illegible], \Delta\varepsilon, \Phi, \text{L-C-T}, \ldots)$$

where L_c^i is chosen characteristic parameter of the material (e. g. fracture toughness, K_{Ic}; critical crack opening displacement, δ_c; critical value of J-integral; and possibly further items),

M characterizes the material, its microstructure, etc.,

x^i denote the coordinates in the material under testing (they may depend, e. g., on the thickness, location in the weld, ingot, etc.),

$\vec{n}_i$ denote the orientation of the crack in tested material (e. g. in relation to the surface, etc.),

T is testing (operating) temperature,

$\dot{\varepsilon}$ is strain-rate during the test, t is time counted from starting the operation and characterises the material as a consequence of damage in the course od the operation; this degradation is due to thermal ageing (T), strain ageing ($\Delta\varepsilon$), radiation ageing Φ, low-cycle damage (L-C-F), etc.

It should be taken into account that both L^i and L_c^i are pseudo-vectors, because they depend not only on the coordinate in the body or material, but also on the coordination of the crack.

Safe operation requires that

$$L_c^i \geq \mathcal{F} \cdot L^i , \qquad (3)$$

$\mathcal{F}$ being linear operator of the safety coefficient. Its value is selected according to the degree of knowledge of fracture mechanics (or of its characteristic factor which has been used), adopted techniques of operational inspections and, finally, on the accuracy of determining the operational or transient (in other words, it requires to know the tensor σ_{ij} (t)).

The operator $\mathcal{F}$ may be usually expressed as

$$\mathcal{F} = \begin{cases} F^K & \text{for approach based on } K_{IC} \\ \Delta CAT_F + & \text{for approach based on CAT.} \end{cases} \qquad (4)$$

Owing to the character of the change of material characteristic parameter, L_c^i, due to operation (damage is usually reflected by transformation of temperature dependence of this curve consisting in its shifting towards higher values), the influence of operational damage may be formally expressed as

$$L_c^{\,i}\,(t,T) = \mathcal{L}\,.\,L_c^{\,i}\,(t=0,\,T) = L_c^{\,i}\,(t=0, T-\Sigma\Delta T_j) \qquad (5)$$

where $\mathcal{L}$ is the linear operator of operational damage and is reflected in the practice by shifting the original dependence $L_c^{\,i}$ - T by a value of $\Sigma'(\Delta T_j)$; ΔT_j characterizes the shift of transition temperature induced by the j-th manner of ageing or damaging (temperature-induced ageing, strain induced ageing, etc.).

Historically, and taken also into account the state-of-the-art in the domain of fracture mechanics as well as its application to pressure vessel technology, two approaches (i.e. selection of characteristic parameters L^i and $L_c^{\,i}$) underlie present-day-philosophy of pressure vessel safety, namely

- the temperature approach, characterized in the first place by the Crack Arrest Temperature (CAT), and sometimes also by the Nil Ductility Temperature (NDT), and
- the stress approach, where plane strain fracture toughness, K_{IC}, is of the utmost importance.

Further approaches, namely the strain approach (based on the critical crack opening displacement, and the energy one (based on J_{IC}) are not sufficiently mastered).

Historically most often used and in standards /1/ incorporated is the approach based on the Crack Arrest Temperature and the Fracture Analysis Diagram.

It should be added that this approach is somewhat more conservative, which, on the other hand, may be an asset in considering a higher danger of initiating and propagating a brittle fracture in gas-cooled reactors (as e.g. in Czechoslovak A-1 reactor) due to a high amount of energy accumulated in gaseous coolant. Practically, this approach neglects the conditions underlying the initiation of damage, i.e. the existence or the growth of flaws, and is based on finding such a temperature, at which (under given stress) the brittle crack arrests. If the operational temperature is higher than that so obtained, no catastrophic failure (explosion) of the pressure vessel can occure; the failure may be only reflected as a leakage resulting from subcritical fatigue-type growth of the flaw. The following relation underlies the temperature approach

$$T_{operat} \geq CAT\,(t,\ \sigma) = CAT\,(t=0,\ \sigma) + \Sigma(\Delta T_j, \text{damage}) + \Delta T_\sigma + \Delta T_\varepsilon, \qquad (6)$$

T_{operat} denoting the working temperature of the equipment,

$CAT\,(t=0,\ \sigma)$ is the initial crack arrest temperature determined on material of given thickness under given stress,

$CAT\,(t,\ \sigma)$ is the crack arrest temperature after operating period t,

$\Sigma \Delta T_j$, damage is the summation of this change caused by reactor operation (eq.5), i.e. CAT,

ΔT_σ is the safety coeficient (reflecting transients etc.),

ΔT_ε is the CAT increase owing to the accumulated energy (see, e.g. /2/).

The second approach is based on the linear elastic fracture mechanics, offers (against the former) an advantage of a lesser conservatism, for it deals in the first place with the conditions underlying the initiation of brittle fracture. Another advantage consists in the possibility of determining the critical size of flaw in the material under consideration. It requires, however, to carry out also in-service inspections with the aim of ascertaining the flaws in the pressure vessel material. The program with test surveillance specimens, intended for determining $\Delta T_{\not{z}}$, is to be performed in conjuction with an expensive and demanding program of in-service defectoscopic inspections. These inspections may be also done after reactor shut-down. Though, it can in some case markedly enhance the safety and reliability of the reactor. This approach underlies some standards /3/, sometimes in combination with Nil Ductility Temperature.

Generally,

$$K_{IC} = \alpha \cdot \sigma \cdot (\pi a_c)^{1/2} \qquad (7)$$

where α (the compliance factor) reflects the geometry of both the flaw and body,

σ represents design stress in the point in question,

a_c is critical size of the flaw.

It should be taken into consideration that the static fracture toughness, K_{IC}, depends in the first place on the state of the material and the testing temperature. In conformity with (5), the operation--induced changes may be expressed in the following terms

$$K_{IC} \quad (t \geq 0, T) = K_{IC} \quad (t=0, T - \Sigma \Delta \bar{T}_{j, \text{damage}}) \quad (8)$$

$\Delta \bar{T}_{j,\text{damage}}$ represents the amount of shift of the K_{IC} - T curve resulting from the operation, or, in other way $\Delta T_{K_{IC}}$.

The knowledge of $\Sigma \Delta T_{j,\text{damage}}$ enables then to find the value of fracture toughness in the time instant involved, and so to find the critical size of the flaw. It is also possible to proceed vice-versa, and to decide on the basis of results obtained during the in-service operational inspection, whether found flaws may be tolerated or not. Using this approach enables to avoid any damage of the vessel, so that even small leakages may be prevented. This, of course, requires to know well the field of stresses in any time instant, with the transients playing the most important role.

2. UNIFIED PARAMETER

Comparing of both approaches shows that they resemble each other in having a common parameter consisting in the change of characteristic temperature, i.e. either

$\Sigma(\Delta T_{j, \text{damage}})$ for the CAT approach, and

$\Sigma(\Delta \bar{T}_{j, \text{damage}})$ for the K_{IC} approach.

From the viewpoint of feasibility (this concerns mainly the operations with specimens), accurate application of both approaches involves problems, i.e. whether

$$\Delta CAT = \Sigma(\Delta T_j, \text{damage}) \overset{?}{=} \Delta T_K \qquad (9)$$

and

$$\Delta T_{K_{IC}} = \Sigma(\Delta T_j, \text{damage}) \overset{?}{=} \Delta T_K \qquad (10)$$

where ΔT_K is the change of transition temperature caused usually by damaging the material in the course of operation and determined by a notch toughness test using Charpy-V specimens.

If the relations (9) and (10) are valid, then it is possible to write

$$\Delta CAT = \Delta T_{K_{IC}} = \Sigma(\Delta T_j, \text{damage}) \qquad (11)$$

There is lack of data to verify the validity of equation (11), this being so due to the difficulties involved in irradiating the test specimens of heavy thickness and dimensions, or in accomplishing strain ageing and other ageing accompanied with a subsequent testing to find CAT. The validity of the above equation has been supported lately by the test carried out in the framework of a more extensive program of testing for the pressure vessel of the Czechoslovak A-1 nuclear power station /4/. These tests have been accomplished by ŠKODA WORKS, Nuclear Power Plant Division. In addition, further supporting findings have been also obtained in the framework of Heavy Section Steel Technology Program (HSST) /5/. It should be also taken into account the validity of equation (11) is not evident at first sight, for it involves several types of tests with specimens having different dimensions (including thickness); moreover, the rates of loading also differ (ΔCAT and ΔT_K being determined by means of dynamic testing, while $\Delta T_{K_{IC}}$ has been obtained by static testing). Nevertheless, all the analyses take the validity of relation (11) as granted and the same is valid for planning and executing the programs of testing and periodic inspections.

It is seen, therefore, that both the approaches have an important and common parameter, the change of the characteristic temperature, on which depend both fundamental parameters of fracture mechanics - the crack arrest temperature and fracture toughness.

This reasoning would suggest as suitable to find a similar common relation not only for the change of the characteristic temperature, but directly for the characteristic temperature.

2.1. Crack Arrest Temperature

Searching for a characteristic temperature which could be used in comparing both approaches, should be more simple, because the temperature is expressed in an explicit fashion,

A number of dependencies between CAT and σ have been determined for different steels on specimens with a thickness ranging between 120 and 200 mm in the course of many years in the ŠKODA WORKS. The test have been accomplished on the ZZ 8000 testing machine (maximum force 80 MN) using the ESSO technique to find the crack arrest temperature. Tested steels for pressure vessels are presented in table 1. The comparison suggests that by a suitable shift, a unified CAT-T dependence may be obtained for all types of steels. In doing so it is necessary to transform the curves into the coordinates

$$T_R = T - NDT \qquad (12)$$

and, similarly

$$CAT_R = CAT - NDT, \qquad (13),$$

T_R denoting a unified temperature, and NDT standing for Nil Ductility Temperature.

Using this diagram (it is shown in fig. 1) it is then possible to determine the crack arrest temperature for all types of used steels, independently on initeal value of NDT. The diagram incorporates also the results obtained in the framework of HSSTP with the ASTM steel A 533-B. These results have been found by the Dynamic Tear Tests. In spite of this, they are in conformity with the general trend.

Furthermore, the diagram shows that the difference FTE (Fracture Transition Elastic) - NDT depends on the type of the material (see the arrows at the coordinate T_R). In addition, for steels of medium strength (which is the case of most steels), it is higher than that suggested by Pellini, i.e. 66 °C (120 °F). This difference ranges between + 64 and + 92 °C, with the only exception of steel ČSN 13030 (type ASTM A 212-B) which is in the region originally proposed, i.e. + 42 °C. It should be of course mentioned that this steel ranks among those with a low yield point. Similarly as the relation between

CAT and T_R, this dependence is practically linear and is presented in fig. 2.

This comparison suggests that increasing the yield point of the material (and thereby also of the design stress) increases also the difference FTE-NDT, and, beyond this, that this difference is to be taken into account when formulating the relation (6) for the CAT approach: this value determines the value of the ΔT_σ factor, which characterizes the coefficient of safety. It therefore implies that the selection of the value + 30 °C has been justified only in the case of steels with low yield point (steel ČSN 13030), but not for steels of medium strength (as e.g. ASTM A 543).

2.2. Fracture Toughness

Comparison of a large volume of results obtained from fracture toughness tests (static - K_{IC}, dynamic - K_{ID} and possibly also arrest - - K_{IA}) suggests that also in this case the Nil Ductility Temperature may be taken as the characteristic value /3/. For calculating the critical states of pressure vessels it is recommended to take the so called reference value of fracture toughness, K_{IR}, which is the lowest of all the results obtained and should be practically equal to the values of K_{IA}. The following relation is given

$$K_{IR} = K_{IA} = 29.37 + 1.223 \exp[0.0261(T.NDT+110)] \; ; \quad [MPa.m^{1/2}] \qquad (14)$$

which, after combining with (12), may be expressed as

$$K_{IR} = K_{IA} = 29.37 + 1.223 \exp[0.0261(T_R + 110)] ; [MPa.m^{1/2}] \qquad (15)$$

The possibility of using the same characteristic temperature (T_R) for both approaches enables to use this temperature as a unified parameter.

3. THE DEFECT ANALYSIS DIAGRAM - DAD

Introducing a unified characteristic parameter (T_R) for both approaches makes it possible to get a relation between both parameters (K_{IC} and CAT) of the material. The following two dependencies may be obtained ($CAT_R - T_R$, $K_{IR} - T_R$) and, by combining them, it is also possible to find the dependence between K_{IR} and CAT_R. This is made possible by the fact that both are related to one common temperature (T_R), practically independently on initial properties of the material (i.e.on NDT).

Taking advantage of the relations of linear elastic fracture mechanics enables to construct for various values of fracture toughness (K_{IR}) the dependence between flaw size (a_c) and stress (σ). Fig. 3 presents a general diagram of this type in log-log coordinates. Linear elastic fracture mechanics is valid in region "E", elasto-plastic mechanics is denoted as "E + P". As usual, the following limiting relations are made use of:

$$\text{"E"} \quad : \quad a, B \geq 2.5 \left(\frac{K_{IR}}{\sigma_{0.2}} \right)^2 \qquad (16)$$

$$\text{"E + P"} \quad : \quad a, B \geq 1.0 \left(\frac{K_{IR}}{\sigma_{0.2}} \right)^2 \qquad (17)$$

The curves corresponding to equal values of fracture toughness (K_{IR}) are limited from above by the ultimate strength of material.

The relations important for calculation are accurately valid only in the region "E" where plane strain condition occurs. For higher stresses - - i.e. in regions "E + P" or "P" they hold true only approximately and the critical fracture stresses seem to be somewhat underestimated . As a consequence, the calculated results are more conservative.

The diagram also presents the dependence CAT_R - T_R, which enables to evaluate directly from the diagram whether a crack (originating from a critical flaw) will propagate further: if the temperature T_R in the given point is below CAT_R, then the crack will continue growing, otherwise it arrests. Broken line indicates in fig. 3 the boundaries of both regions. As distinct from others, this dependence is not linear, for the dependence K_{IR} - T_R is not such.

This Defect Analysis Diagram may serve for evaluating the safety od pressure vessels both prior to and during operation, because for the NDT may be inserted (into the unified temperature T_R) both starting data, and data corresponding to some time of operation.

On the basis of fig. 3 it is also possible to decide whether the sizes of flaws are critical and whether (under a given temperature) a crack may be arrested or will propagate futher in a brittle manner. In the region where the linear elastic fracture mechanics is not valid, this diagram offers a higher safety.

Practical use of the diagram necessitates its precise construction for e.g. surface flaws (considered as most dangerous) of a given configuration (e.g. a : 2 c = 1 : 5) and for a given thickness of pressure vessel wall. In conformity with /3/ it is necessary to do a correction for the effect of the other surface, therefore the dependence $\sigma - a_c$ (for constant K_{IR}) is no more linear for increasing a_c. Fig. 4 demonstrates an application of the Defect Analysis Diagram for a pressure vessel wall with a thickness of 200 mm and steel 15Ch2MFA (yield strength 600 MPa, ultimate tensile strength 700 MPa). The calculation has been carried out for semielliptical surface flaws with a:2c = 1 : 5. It is seen that the region of design stresses occurs in the region of failure "E + P" or, another way, in the region of higher safety (in comparison with direct calculation). It should be also mentioned that the boundaries of the region "Arrest - Non - Arrest" are situated in the range of very low fracture toughness (practically below 75 $MPa.m^{1/2}$, i.e. at temperatures below T_R = NDT + 50 °C). This implies that above the value of NDT + 50 °C no catastrophic fracture can occur even in the presence of large flaws, because the properties of the material ensure arresting of the brittle crack.

An additional advantage of the Defect Analysis Diagram consists in the fact that it is practically independent on the material; material manifests itself only by the values of yield strength and ultimate tensile strength and by the regions of validity of linear elastic fracture mechanics. Concerning all other parameters the diagram is the same for all steels.

The diagram, as shown in fig. 3 or 4, may also reflect desired values of the safety coefficient. This may be done either in the form of F^K or ΔCAT_K by shifting the scale of stress or temperature CAT_R by the needed amount. Both these transformations have been found to lead to the same effect (in dependence on their absolute value).

4. CONCLUSIONS

When analysing the safety of pressure vessels from the viewpoint of brittle fracture it is possible, by introducing a formalism therein, to establish at least a formal linking of the two most important approaches of the fracture mechanics - that of Crack Arrest Temperature and that of Fracture Toughness. Application of this method to other approaches, subject to their being sufficiently mastered calculationally (J-integral, equivalent energy, critical crack opening displacement) is not excluded.

Formal unification is possible after introducing a unified parameter (the unified temperature T_R), in which case the Nil Ductility Temperature is used as reference temperature. Transforming the temperature dependencies of K_{IC} and CAT according to this temperature (T_R) enables to construct the Defect Analysis Diagram which icorporates critical sizes of flaws, crack arrest temperatures, and also the regions of validity of linear elastic fracture mechanics and regions of crack arresting.

The Defect Analysis Diagram can be extended to be applicable for determining not only critical, but also permissible sizes of flaws by introducing adequate safety factors concerning both fracture toughness and crack arrest temperature. In both cases, this coefficient of safety may be transformed into the unified temperature, T_R (by its lowering by the factor of safety).

The Defect Analysis Diagram proves itself to be useful not only in designing pressure vessels, but also in evaluating the pre-operational and operational inspections (irrespective of whether the results of defectoscopic inspection or of the tests of surveillance specimens are involved).

The diagram may be also modified into such a form as to express the assumed growth of critical flaws during planned operational modes. In this way it may be also used for predicting the lifetime of pressure vessels. Moreover, its applicability does not concern only pressure vessels - - generally speaking, it enhances any structure with heavier thickness where, at least in a certain region, the validity of linear elastic fracture mechanics may be ensured. Extending the validity of fracture mechanics into non-linear, elasto-plastic region, will make it possible to use the diagram also for higher operating temperatures or for heavier thickness of the material where the conditions of linear elastic fracture mechanics are not adhered to.

Table 1.

Dependence of the difference FTE-NDT on the yield point od steel.

Steel	FTE-NDT /°C/	yield strength /MPa/
ČSN 13030	+ 42	260
A-2	+ 64	420
15Ch2MFA (1)	+ 67	440
15Ch2MFA (2)	+ 78	510
ASTM A 533-B	+ 80	520
ASTM A 543	+ 92	610

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/5/ Berggren R. G., Canonico D. A., "Toughness Investigation of Irradiated Materials", ORNL-TM-5021, Vol. II, pp. 24-32 (1975)..

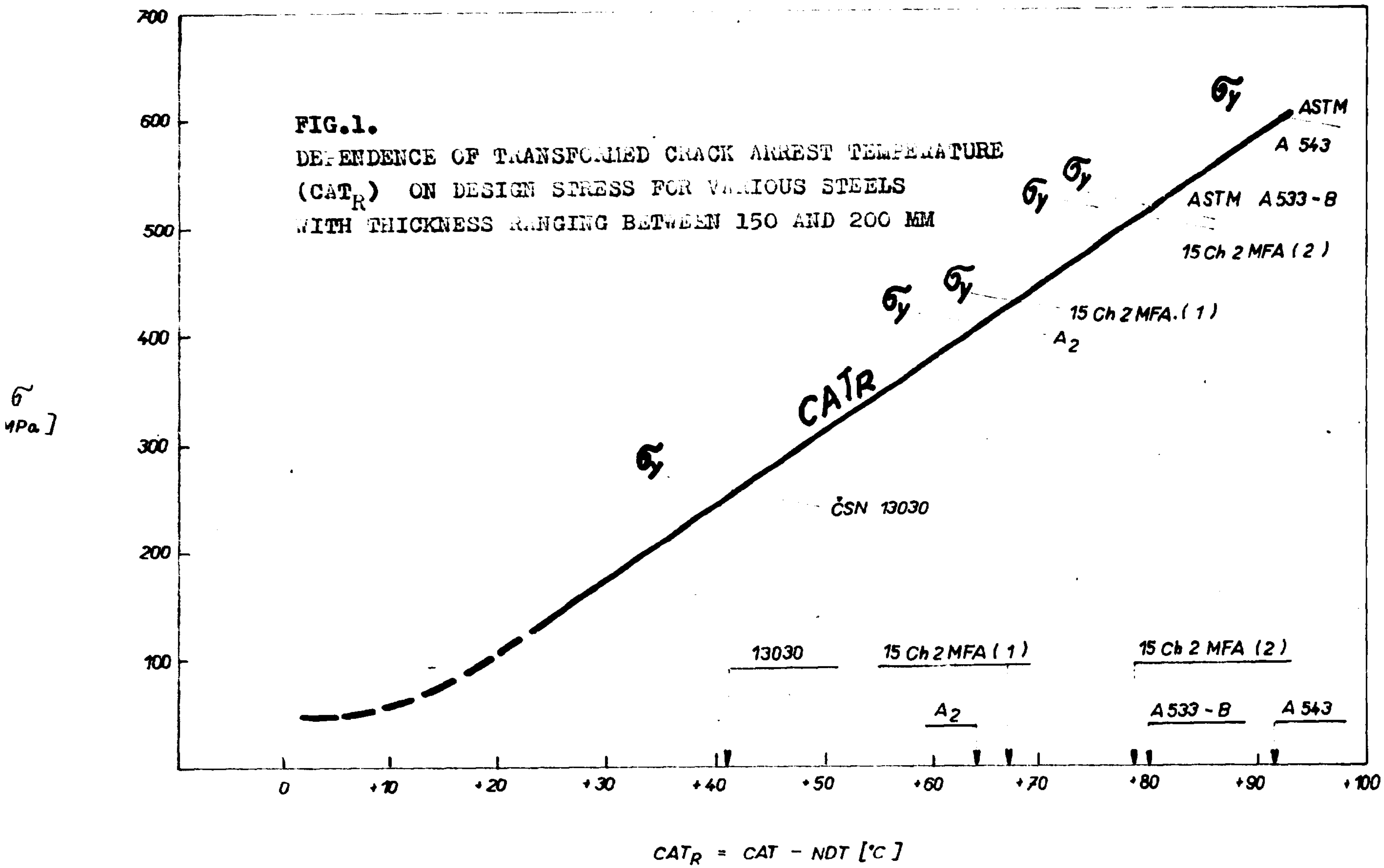


FIG.1.
DEPENDENCE OF TRANSFORMED CRACK ARREST TEMPERATURE (CAT_R) ON DESIGN STRESS FOR VARIOUS STEELS WITH THICKNESS RANGING BETWEEN 150 AND 200 MM

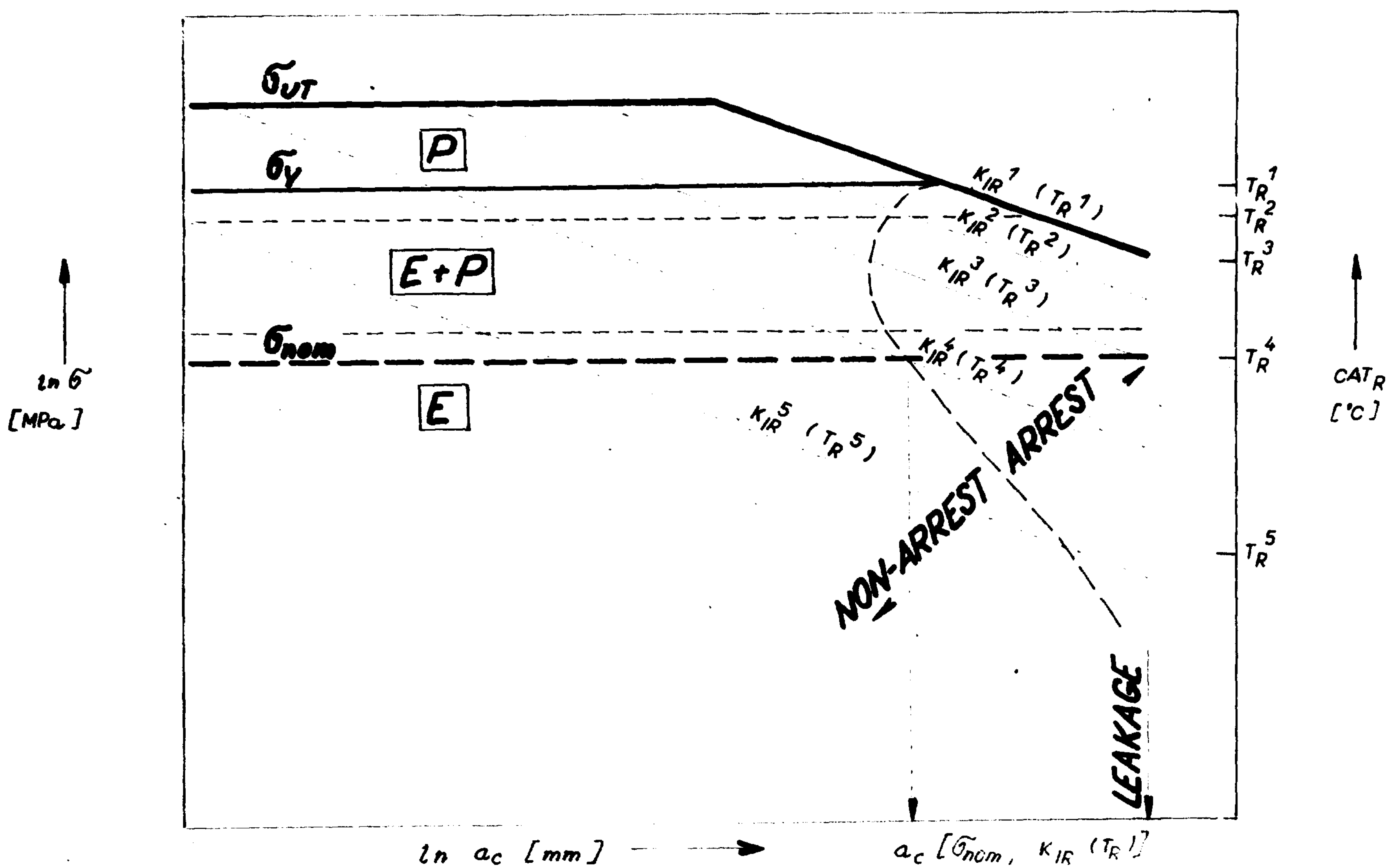


FIG.2. DEPENDENCE OF THE DIFFERENCE FTE-NDT ON YIELD POINT FOR VARIOUS TYPES OF STEEL (TESTS PERFORMED USING THE ESSO TECHNIQUE ON THICKNESSES 150 UP TO 200 MM)

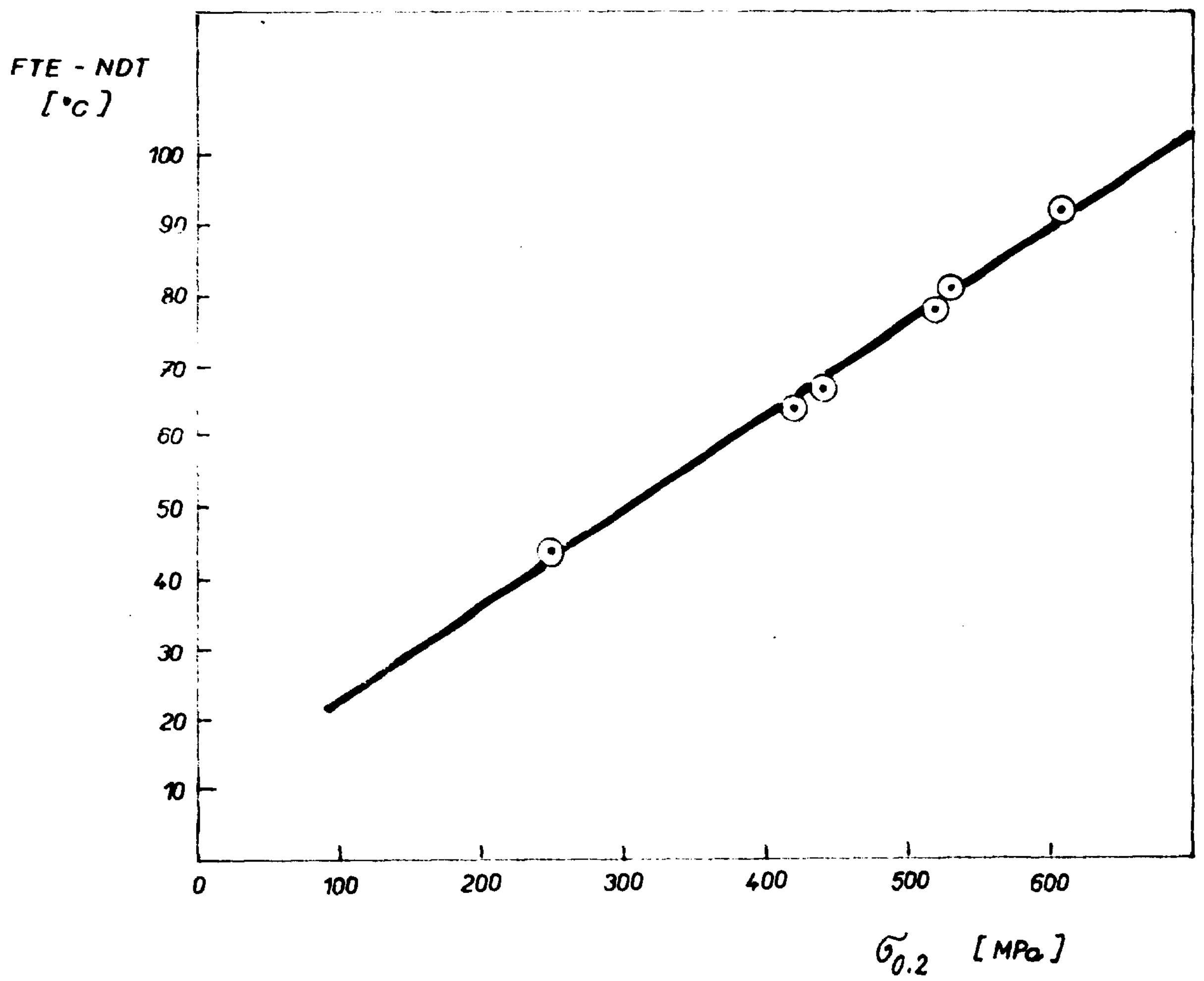
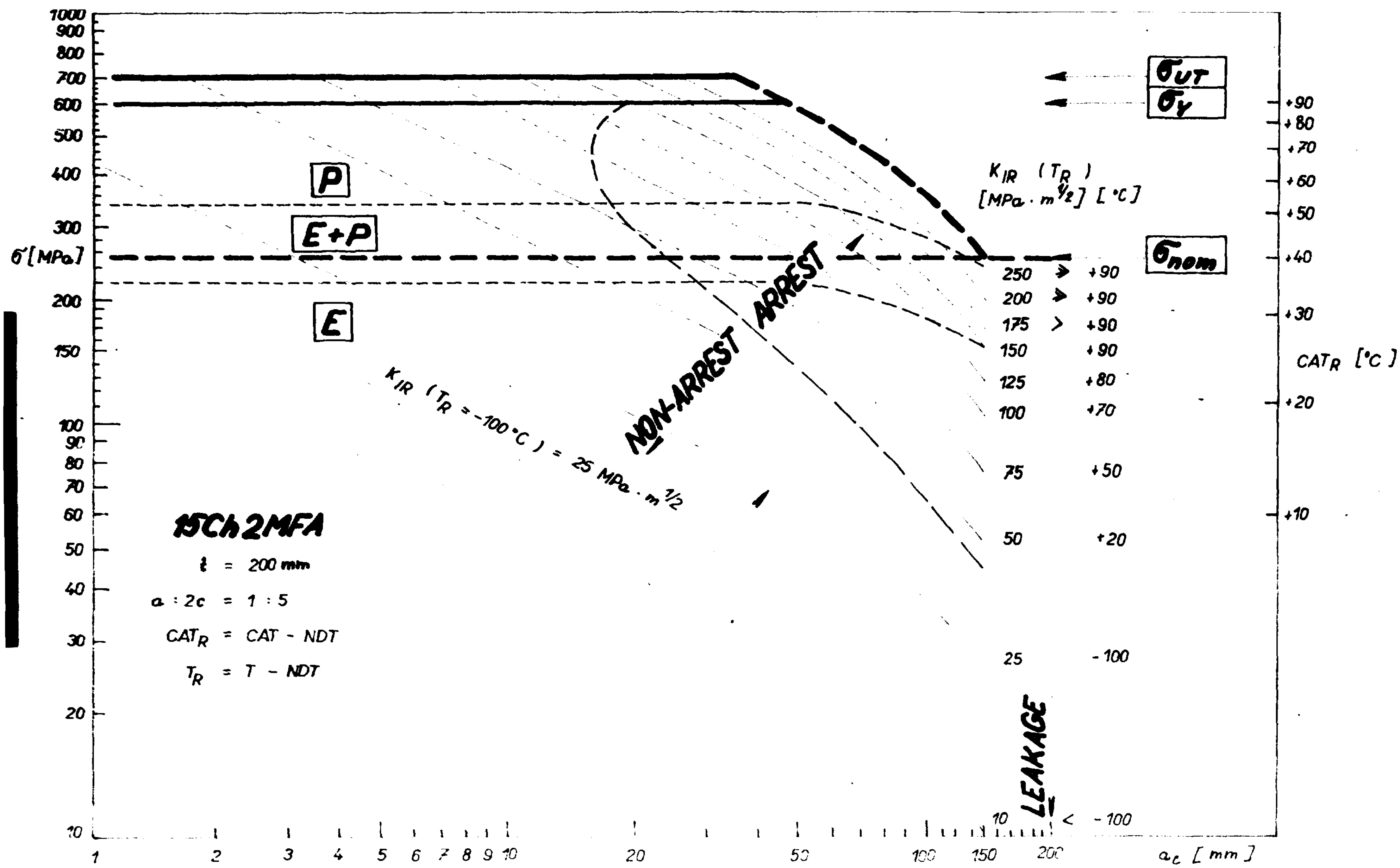


FIG.3. SCHEMATIC REPRESENTATION OF THE DEFECT ANALYSIS DIAGRAM FOR STEELS



σ [MPa]
σUT
σY
σnom
P
E+P
E
KIR (TR)
[MPa · m^1/2] [°C]
250 +90
200 +90
175 +90
150 +90
125 +80
100 +70
75 +50
50 +20
25 -100
10 < -100
CATR [°C]
ARREST
NON-ARREST
LEAKAGE
KIR (TR = -100 °C) = 25 MPa · m^1/2
15Ch2MFA
t = 200 mm
a : 2c = 1 : 5
CATR = CAT - NDT
TR = T - NDT
ac [mm]

FIG.4.