C

CS81018409

ZJE – [illegible]

1979

[illegible]

SIZE EFFECT IN RADIATION DAMAGE

ŠKODA WORKS
Nuclear Power Construction Division, Information Centre
PLZEŇ, CZECHOSLOVAKIA

ZJE - 241 1979

M. BRUMOVSKÝ

SIZE EFFECT IN RADIATION DAMAGE

Reg. č. ÚVTEI 73307

ŠKODA WORKS
Nuclear Power Construction Division, Information Centre
PLZEŇ, CZECHOSLOVAKIA

ABSTRACT

Radiation embrittlement which is of great importance for nuclear reactor pressure vessel steels, is measured in most cases with the help of small standard specimens in dynamic bending. Their dimensions are much smaller than those of the reactor (this concerns first of all the pressure vessel thickness); there is usually no other possibility from the viewpoint of irradiation and testing conditions.

Increase in the critical temperature (transition temperature from brittle-to-ductile fracture) is normally measured using standard Charpy-V type specimens or small CT-type specimens. This increase is then used as the main parameter for both approaches to the pressure vessel safety evaluation, i.e. the temperature approach and fracture mechanics one.

This paper deals with the philosophy of experiments used for the unirradiated and irradiated states of pressure vessel steels. A comparison of the increase in transition temperature measured in different types of specimens with various testing methods (static and dynamic bending of specimens with notch or crack) is also made.

Results of this comparison as well as further study have shown a relatively good agreement of results within both static and dynamic tests. On the contrary, comparison of static and dynamic results have shown some differences, which the author tries to explain.

1. INTRODUCTION

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 vessels. These must be fully safe, i.e. no reference failure (MCA) may lead to a loss of integrity. Consequently, every effort must be made in design, manufacture and operation to avoid any possibility of failure. Sudden brittle failure is considered as the most dangerous type.

Because of the special conditions in the nuclear reactor active core, i.e. of the presence of an intensive field of nuclear radiation, it is necessary to include into this pressure vessel safety evaluation also the effect of radiation, especially the radiation embrittlement of pressure vessel steels, Moreover, these pressure vessels are manufactured with thick vessel walls; comparing their thickness with the size of normally used standard speimens, the problem of size effect in radiation embrittlement can arise.

2. THEORETICAL BACKGROUND OF THE PROBLEM

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 subsequently:

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

where L^i represents a chosen parameter of fracture mechanics (e.g. the stress intensity factor, K_I; crack opening displacement, δ ; temperature, T; value of J-integral, J_I; etc.),

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

σ_{mn} is the stress tensor in the location of the flaw, a represents a characteristic dimension of flaw.

The second parametr, L_c^i, represents the critical value of the chosen fracture mechanics parameter L^i for a given material (for example, it can be fracture toughness, K_{IC}; crack arrest temperature, CAT; critical crack opening displacement, δ_c; critical value of the Rice-integral, J_{IC}, etc.) Its value depends on microstructure and the orientation of the defect in the material, on temperature, strain rate or loading rate, on time (material can change its properties as a result of thermal ageing, irradiation, cyclic loading etc.). Both values, L^i and L_c^i , are pseudovectors.

Safe operation requires that

$$L_c^i \geq \mathcal{F} . L^i, \qquad (2)$$

$\mathcal{F}$ being the linear operator of the safety coefficient. Its value is selected according to the degree of knowledge of fracture mechanics (or of the characteristic factor which has been used), technique adopted for operational inspections and, finally, the accuracy with which the operational or transient states can be determined (in other words, it requires the tensor σ_{mn} (t) to be known).

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

$$\mathcal{F} = \begin{cases} F^K . \quad \text{or} \quad K^F + & \text{for the approach based on } K_{IC} \\ F^{CAT} = CAT + & \text{for the approach based on CAT.} \end{cases} \qquad (3)$$

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

$$L_c^i \ (t,T) = \mathcal{L} . L_c^i \ (t=0,T) = L_c^i \ (t=0,T - \Sigma' \Delta T_j) \qquad (4)$$

where $\mathcal{L}$ is the linear operator of operational damage and is obtained in 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, irradiation embrittlement, etc.).

Historically, and taking also into account current knowledge of fracture mechanics and its application to pressure vessel technology, two approaches (i.e. the selection of the characteristic parameters L^i and L_c^i) underlie the 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), transition temperature ($T_{50\%}$, $T_{50\ J}$, RT_{NDT}), and
- the stress approach, where plein strain fracture toughness, K_{IC}, is of the utmost importance.

For the first one, the temperature based approach, equation (4) is modified into

$$CAT\ (\sigma,\ t \geq 0) = CAT\ (\sigma,\ t=0) + \Sigma \Delta T_j \qquad (5)$$

while for the second one, based on the fracture toughness,, it is changed into

$$K_{IC}\ (t \geq 0,\ T) = K_{IC}\ (t=0,\ T - \Sigma \Delta \bar{T}_j) \qquad (6)$$

where ΔT_j represents the changes in CAT caused by reactor operation, i.e. CAT,

$\Delta \bar{T}_j$ represents the amount of shift of the K_{IC}-T curve resulting from the operation, or, expressed otherwise, $\Delta T_{K_{IC}}$.

3. THE EFFECT OF RADIATION EMBRITTLEMENT

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

$\Sigma\Delta T_j$ for the CAT approach, and

$\Sigma\Delta T_j$ for the K_{Ic} approach.

In both cases, these increases or shifts of temperature dependencies, caused by the operational regimes, are usually considered equal to the transition temperature increase, T_K, as obtained by notch toughness tests with Charpy-V specimens.

As regards feasibility, i.e. operations with specimens, the accurate application of either approach involves problems, e.g. whether.

$$\Delta CAT = \Sigma\Delta T_j \overset{?}{=} T_K \qquad (7)$$
$$\Delta T_{K_{Ic}} = \Sigma\Delta\bar{T}_j \overset{?}{=} T_K$$

If relations (6) are valid, then it is possible, and only in such a case, to write

$$\Delta CAT = \Delta T_{K_{Ic}} = \Delta T_K \qquad (8)$$

Even though there is a lack of data verifying the validity of Eq. (8), it is widely employed and in practice it is one of the fundamental tools used in the application of surveillance specimen programmes to the evaluation of the pressure vessel lifetime.

This means that Eq. (9) is the most important one for the nuclear reactor pressure vessel safety correct evaluation.

Let us discuss some factors which can affect the correctness of this Eq. (8):

/a/ - Standard Charpy-V specimens have small dimensions (10x10 mm), and pressure vessel wall thickness is at least by one order larger (100 mm and more), i.e. Charpy specimens do not include the size effect;

/b/ - notch toughness tests on Charpy specimens are made by dynamic bending; on the contrary pressure vessel failure is more initiated by static mode;

/c/ - notch toughness tests on Charpy specimens are made with V-type notches, and pressure vessel failure is in most cases initiated from the fatigue crack, i.e. from the concentrator with substantially smaller tip radius;

/d/ - notch toughness value characterizes first of all the conditions of the initiation of the failure /from the sharp notch/ and its further propagation and/or arrest, while K_{IC} represents only the conditions of brittle fracture initiation;

/e/ - on the other side, crack arrest temperature characterizes the conditions of the crack arrest, independently on the initiation and propagation of the crack;

/f/ - irradiation in substantial way increases the yield strenght of the material and by that way the conditions of the transition from the plane strain to the plane stress conditions are also changed; this effect can be expressed namely in the case of notch toughness tests in the transition region, but it can manifest itself substantially less in the case of pressure vessel wall.

From this small, short discussion, it is clear that the correctness of Eq. (8) is not possible to accept without any experimental approval.

Some experimental study in this field has been made recently. In this paper some results from the study of Czechoslovak State Standard ČSN 13 030 (type ASTM A 212-B) steel are used and discussed. Independently on the type, chemical composition and irradiation conditions it can be supposed that received results can be used as an illustration also for the solving of the whole problem, i.e. of Eq. 8.

4. ANALYSIS OF EQUATION (6)

From the general point of view, several dependencies among individual parameter changes can be studied, let us use only some more important:

/a/ - $\Delta T_K = \Delta T_{NDT}$ (9)

this equation had been examined several times several years ago, for example in the NRL /1/; received results show good agreement;
in both cases tests are characterized as dynamic bending, even though with other type of crack initiator

/b/ - $\Delta T_K = \Delta T_{DT}$ (10)

this equation was also studied using specimens with thickness of 5/8 in. = 16 mm and 1 in. = 25.4 mm /2/; received results show a good agreement, too;
in both cases tests are provided by dynamic bending and the measured value is absorbed energy or fracture surface appearance; on the contrary in these tests are used specimens with different type of initiator;

/c/ - $\Delta T_K = \Delta CAT$ (11)

this equation is very difficult to study and verify on the basis of the irradiation embrittlement. From this reason, similar type of damaging, i.e. artificial strain ageing was chosen and tests on plates with thickness of 150 mm on ZZ-8000 equipment have been made /3/;
received results approved very well Eq. (11) and thus also Eq. 7; i.e. no size effect in these type of tests is expressed similarly as the difference between the measured characteristics - temperature of crack arrest and absorbed energy by crack initiation and propagation has no observable effect on Eq. (11);
both tests are of dynamic mode;

/d/ - $\Delta T_K = \Delta T_{1/3}$ (12)

this Eq. is recommended in standard /4/; the increase in the transition temperature, $\Delta T_{1/3}$, is determined using static bending of specimens with sharp notch. Critical temperature is then determined as the temperature at which the fast decrease (pop-in) from the load P_F to the P_A is equal to the 1/3 of the P_F. Characteristic results for both type of tests are shown in Fig.1. It is seen that the increase in the transition temperature $T_{1/3}$ is lower than the ΔT_K approximately by 40 % (unfortunately, the determination of the $T_{1/3}$ is very simple because of very sharp brittle-to ductile transition of steel).

In this case, two types of tests are used - static and dynamics ones - even though both are bending tests. The most different is the model of result evaluation. In the case of notch toughness tests only the absorbed energy for the initiation and propagation of the crack is measured; in the case of static bending only the pop-in in load is determined, i.e. the pop-in in load caused by the rapid propagation and arrest of the crack. That is, temperature $T_{1/3}$ is determined from the characteristic change in load, and temperature T_K is determined from the whole absorbed energy.

On the contrary to the afore mentioned dependencies, Eq. (12) has not been approved;

/e/ - $\Delta T_K = \Delta T_{FM}$ (13)

where ΔT_{FM} means the increase in the temperature dependence (curve) of a chosen fracture mechanics parameter, e.g. K_{IC}, δ_C, J_{IC}, etc.

Eq. (13) has been also analysed, first of all from the point of view of the linear elastic fracture mechanics, i.e.

$$\Delta T_K = \Delta T_{K_{IC}} \qquad (13a)$$

Experiments made in the framework of the HSSTP (5) have shown the relatively good agreement between both increases, even though not fully clearly.
On the contrary, /6/ shows that both shifts are not equal; shift in ΔT_K is larger than $\Delta T_{K_{IC}}$.
It can be said that Eq. (13a) is the most important equation for the whole pressure vessel safety evaluation and also it is the basis for the planning and use of the surveillance specimens programmes for the reactor pressure vessel materials.
The effect of the non-equality of both increases (or also of $T_{1/3}$) on the final evaluation is shown in Fig. 1: for these small fluences the difference in transition temperature shifts reaches only approximately 25 %, but finally, in the critical defect value, it represents a change equal to 60 %, which is not neglectable;

/f/- further possibility is the summary equation for all fracture mechanics parameters:

$$\Delta T_K = \Delta T_{1/3} = \Delta T_{K_{IC}} = \Delta T_{J_{IC}} = \Delta T_{\delta_C} \qquad (14)$$

Study of this equation has been made on base material, manual arc and electroslag welding joints using specimens with sharp notch and with fatigue crack. Example of received results are shown in Fig. 2. Criteria for the determination of individual temperature dependencies were chosen in such a way as to receive approximately the temperature of $T_{1/3}$ in all cases in non - irradiated material, e.g. 35 J. cm $^{-2}$ for T_K, 100 MPa. m$^{1/2}$ for $T_{K_{IC}}$, 0.05 MJ.m^{-2} for $T_{J_{IC}}$ and 0.1x10^{-3} m for T_{δ_C}. Determination of the K_J has been made in accordance with ČSN and ASTM standards, values of J_{IC} using for example /7/ and values of δ_C

using /8/.
From Fig.2 it is seen that the increases of individual temperature dependencies are also different - all parameters have been measured in one specimen at the same time, during one static bendig test. It is seen that these increases are not equal, as they reach the following values:

ΔT_{δ}	ΔT_J	ΔT_K	$\Delta T_{1/3}$	
+ 54	+ 42	+ 76	+ 38	(°C)

From this short summary it can be concluded that the smallest increase is received for the temperature $T_{1/3}$ which is not based on the fracture mechanics. Increases in parameters δ_c and J_c are close one to another - likewise the measured values, or types of loading diagram, even though different initial measured values are used, i.e. crack opening and absorbed energy, see Fig. 3. The largest increase, practically twice higher, is observed in fracture toughness dependence. It shows that during irradiation the conditions for the brittle crack initiation are markedly changed, unlike the crack tip deformation in the quasi-brittle type of failure.

Summarized results are shown in Fig. 4. In this diagram the increases in transition temperature, T_K, measured on Charpy-V type specimens by noth toughness tests, and increases in other fracture mechanics parameters are shown together. It is clearly seen that the increase in $\Delta T_{1/3}$ gives the smallest values. Further results also confirmed /6/, which means that increase in temperature dependencies of K_{IC} and J_{IC} are also smaller than the shift in transition temperature, T_K. It means that the notch toughness tests, even though there are some critical notes to them, give the most appropriate results from the viewpoint of the following reasons:

- these shifts are the largest, i.e. from the viewpoint of the highest safety they are most suitable, because they give the largest safety factor with respect to the fracture mechanics values,
- this type of tests is very simple, cheap and small-size, which is important first of all for the surveillance specimens programmes.

Increase of the transition temperature, T_K, is aproximately equal to the increase in temperature dependence of δ_C; it can be explained probably by the fact that both increases are measured in the transition region of failure, i.e. in elastic-plastic conditions.

Comparison of different conditions for the determination of individual studied parameters is shown in Fig.3. There are shown different types of diagrams and first of all different measured characteristic values that determine the resulting value. While fracture mechanics tests cover only the conditions of initiation /I/, Charpy notch toughness tests cover also the propagation /P/ and arrest /A/ of crack initiated from a sharp notch. In the first two tests (K_{IC} and δ_C) load and crack opening are measured, the last two tests measure the absorbed energy. Moreover, K_{IC} is determined only for fully brittle failure, while other three values can be determined also in elastic-plastic or in fully plastic regions.

These differences in measured characteristics and type of diagram used in analysis mean that each change in the ratio between the conditions of crack initiation, propagation and arrest can substantially change the values of their temperature dependencies. This fact is fully supported by the known changes in irradiation-induced mechanical properties: increase in yield strength and decrease in toughness, elongation and absorbed energy.

On the basis of known mechanism of crack initiation and propagation in the polycrystalline solid it is real to suppose that irradiation-induced changes in structure can also influence the ratio between the resistance of material against crack initiation and arrest: the arrest of a running crack becomes more difficult than in the unirradiated state. This fact has two implications:

- absorbed energy in notch toughness tests will decrease more rapidly than the temperature shift would suggest; the temperature dependencies become less steep and upper shelf energy decreases,
- temperature shift between Charpy notch toughness values and fracture toughness values is equal only in the brittle region, i.e. for small notch toughness values only.

5. IMPLICATION TO SURVEILLANCE SPECIMEN PROGRAMMES

The most important application of this theory can be found in the surveillance specimen programmes as it is the only real possibility of the determination of the pressure vessel material changes (changes in the resistance against brittle fracture).

From the point of view of both used approaches, it is necessary to know increases in both temperature dependencies - crack arrest temperature and fracture mechanics (K_{IC}) tests, caused by the irradiation and other operational effects.

On the basis of received data as well as literature results it can be recommended as the most safe (with the largest safety margin) to use Charpy specimens for notch toughness tests. Moreover, these tests are very cheap and simple and necessitate small quantity of material and small volume in irradiation capsules, and involve a small induced activity after irradiation.

With respect to the widely used application of fracture mechanics, first of all of linear elastic fracture mechanics, it is also important to include some quantity of Charpy - sized specimens (10x10x55 mm) with fatigue crack, tested by dynamic bending (K_{ID}) or static bending (δ_C or J_C) . The first parameter gives values very similar to the reference values of fracture toughness, K_{IR}, used in ASME Codes, thus the exact knowledge of its change should be very important and by this way it could be possible to substantially increase the pressure vessel safety and reliability.

To receive full information about the changes of material properties in the VVER type pressure vessels, their surveillance specimen programmes include also some part of specimens with fatigue crack; these specimens are used for the determination of fracture mechanics parameters - K_{ID} and/or δ_C.

6. CONCLUSIONS

Analysis of received results and references suggests some principle conclusions:

/a/ - determination of the transition temperature increase or the increase of the temperature dependence of individual characteristic parameters is necessary for use of fracture mechanics methods;

/b/ - the most appropriate method for the determination of this increase is the notch toughness test made by dynamic bending of Charpy specimens (cheap, simple, small volume, small induced activity);

/c/ - increase in transition temperature, ΔT_K, determined on Charpy specimens during notch toughness tests, is not dependent on the size effect; this conclusion is valid also for the increase in other characteristic temperatures - NDT, DT, and CAT;

/d/ - increase in transition temperature, $\Delta T_{1/3}$, is smaller than in ΔT_K;

/e/ - increases in temperature dependencies of fracture mechanics parameters (K_{IC}, J_{IC}) are the smallest ones, smaller than ΔT_K; it secures largest safety margin and high operational safety; this relation merits to be studied at full lenght;

/f/ - increase in the temperature dependence of critical crack opening displacement, δ_C, is in the first approximation equal to the increase of ΔT_K. Their widest use in surveillance specimen programmes should be based on further supporting evidence;

/g/ - during static bending tests several parameters of fracture mechanics can be determined at the same time: fracture toughness, crack opening displacement; J - integral, and transition temperature, $T_{1/3}$. In all cases a decrease of all fracture mechanics parameters has been observed, this decrease necessitates a more precise analysis of the operational effects which are included into the pressure vessel safety evaluation.

LIST OF REFERENCES

1./ - Steele L.E. - "Neutron Irradiation Embrittlement of Reactor Pressure Vessel Steels", At. Energy Review, 7, (1969), p.2

2./ - Loss F.J., Hawthorne J.R., Serpan C.Z., Jr.- "A Reassessment of Fracture-Safe Operating Criteria for Reactor Vessel Steels Based on Charpy - V Performance", NRL Report 7152 (1970)

3./ - Brumovský M., Filip R., Červášek J., Vacek M. - "Surveillance Programme Prepared and Carried Out during Production and Exploitation of the A - 1 Nuclear Reactor Pressure Vessels", IAEA Specialists Meeting on Surveillance of Nuclear Reactor Steel Pressure Vessels, Plzeň, May, 1976
Report ŠKODA - ZJE - 190 (1976)

- Brumovský M., - "Safety of Pressure Vessels of Light - Water Reactors Against Brittle Fractures", ŠKODA - REVIEW, 2 (1978) p.5

4./ - Standards for Calculating the Strength of the Elements of Reactors, Steam Generators, Vessels and Piping of Nuclear Power Plants, Experimental and Research Nuclear Reactors and Other Devices /original in Russian/,
Metallurgiya, Moscow, 1973

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

6./ - Haramia F. - private communication

7./ - Loss F.J., Gray R.A., Jr. - "J-Integral Characterization of Irradiated Stainless Steels", NRL Report 7565 (1973)

8./ - Elliott D., May M.J. - Crack Opening Displacement Inferred From Plasticity Phenomena", BISRA Report MG (C) 86/ 68 (1968)

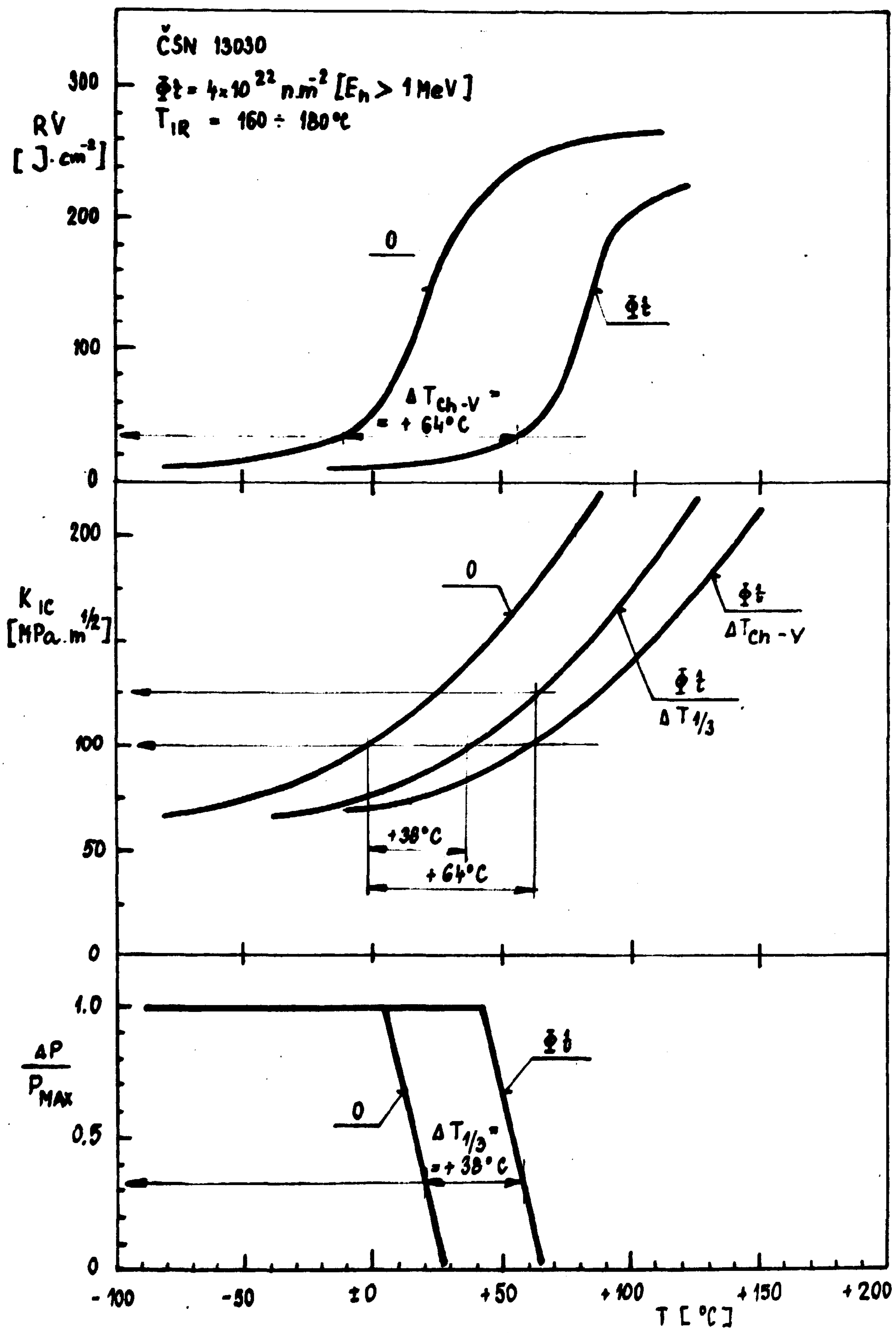


Fig. 1. Comparison of shifts in transition temperature, T_K, temperature dependence of fracture toughness, K_{IC}, and transition temperature, $T_{1/3}$, after irradiation with fast neutron fluence of $4x10^{22}$ m^{-2}, steel ČSN 13 030 (ASTM A 212-B type).

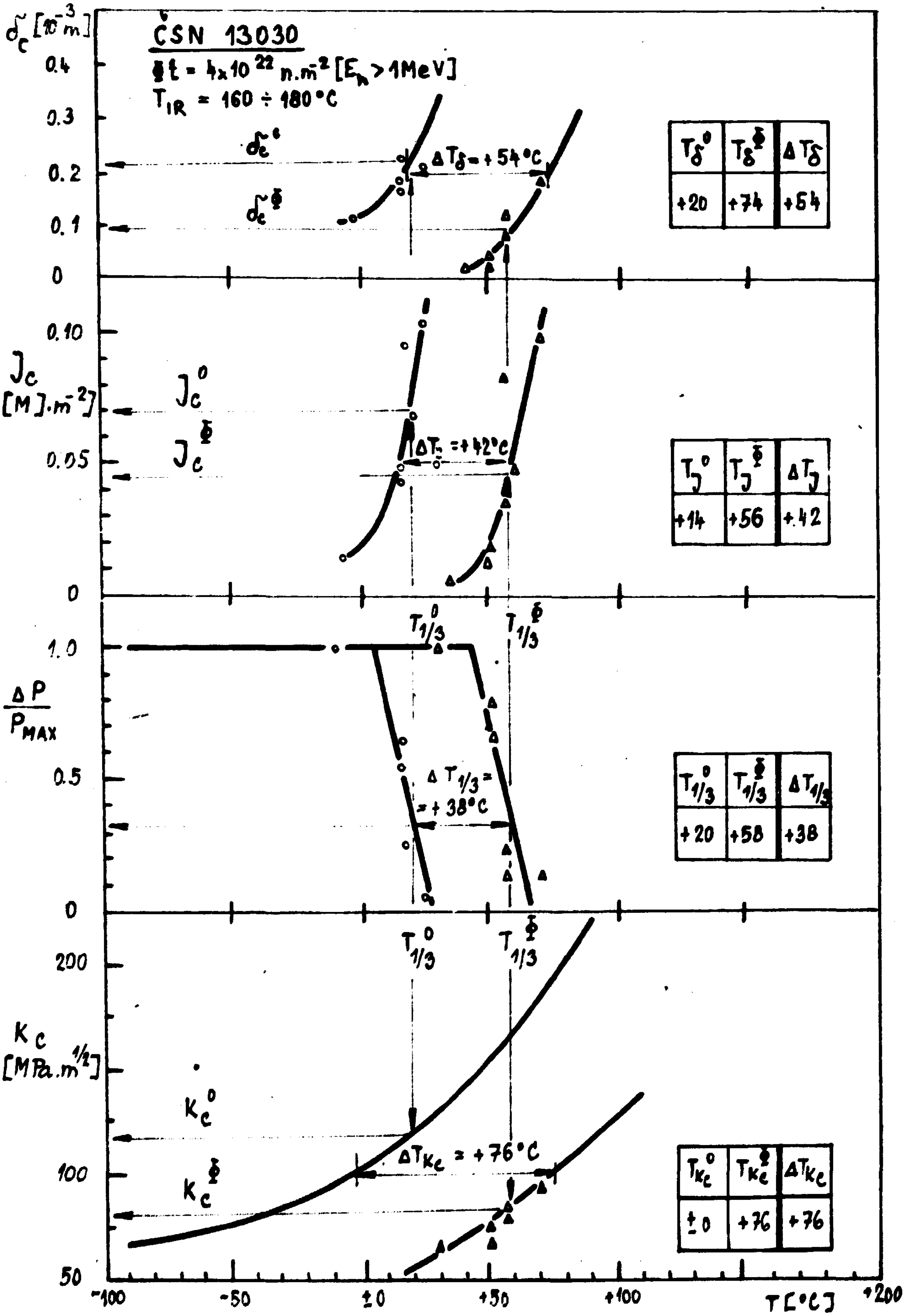
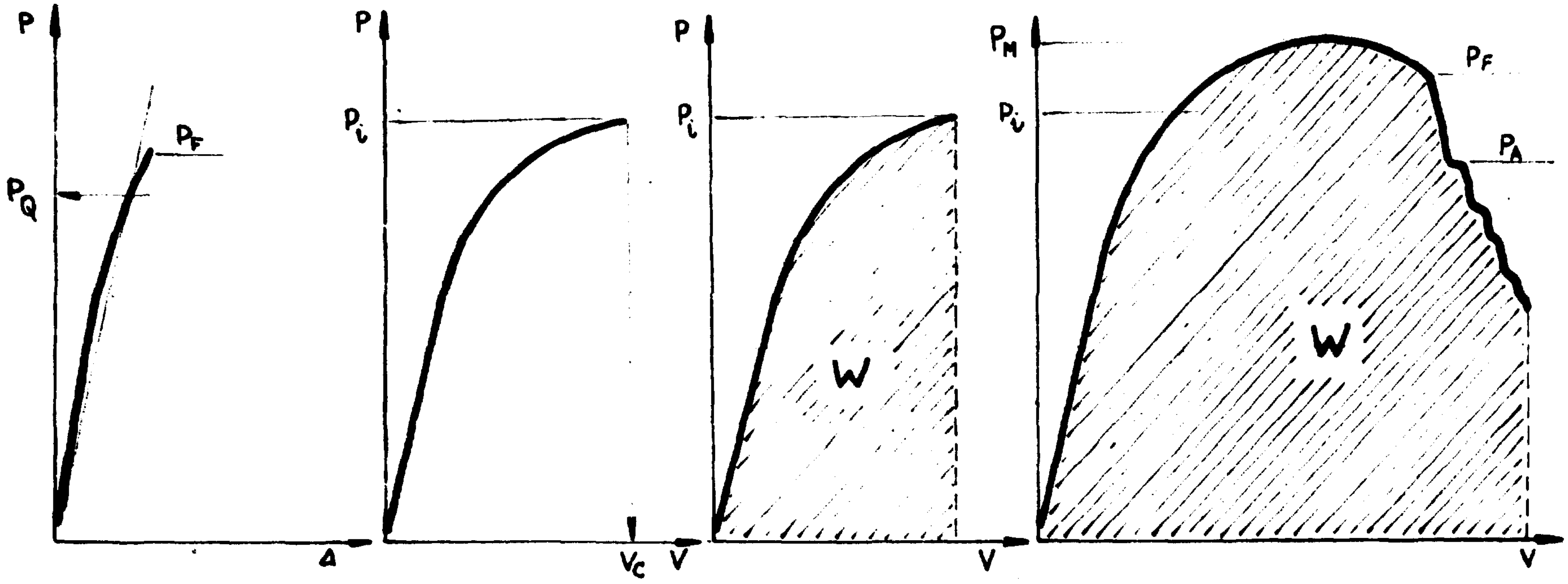


Fig. 2. Comparison of temperature dependencies of fracture mechanics parameters of ČSN 13 030 steel in non-irradiated and irradiated state; static bending tests of specimens with cracks.



CRACK	CRACK	CRACK	NOTCH
$K_{IC} = f(I_S)$	$\delta_C = f(I_S)$	$J_{IC} = f(I_S)$	–
$K_{ID} = f(I_D)$	$\delta_{CD} = f(I_D)$	$J_{ID} = f(I_D)$	$RV = f(I_D, P, A)$

Fig. 2. Comparison of diagrams and parameters used for the evaluation of individual fracture mechanics values and notch toughness tests

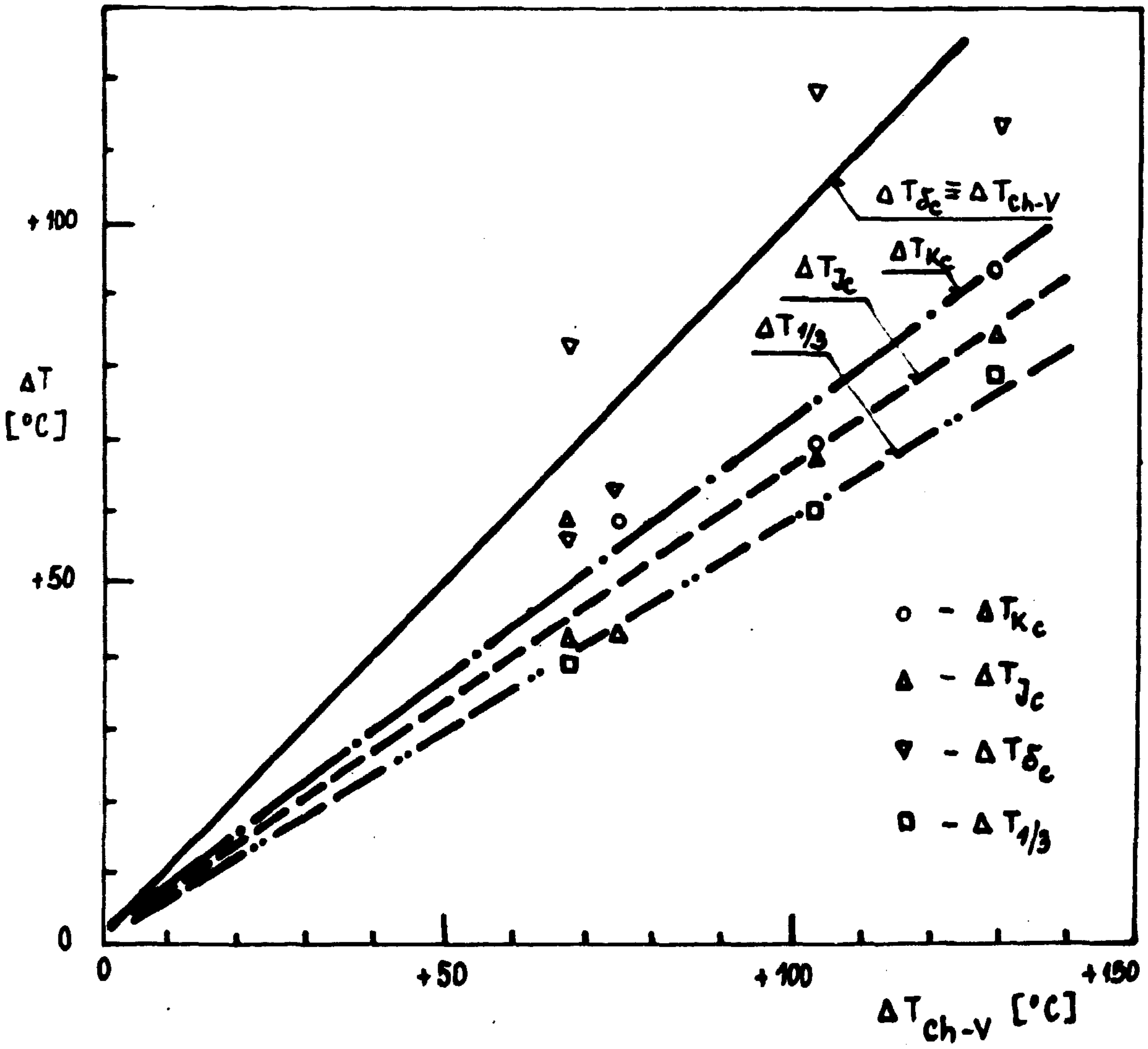


Fig. 4. Comparison of shifts in transition temperatures and temperature dependencies of fracture mechanics parameters, received by static bending tests of specimens made from ČSN 13 030 steel before and after irradiation.