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COMPARISON OF TRANSITION TEMPERATURE SHIFTS FROM STATIC AND DYNAMIC TESTS

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ABSTRACT

Paper summarizes results from surveillance specimens programmes of VVER-440/V-213C type reactors. Comparison of transition temperature shifts, induced by irradiation, and determined from impact Charpy V-notch toughness as well as from static fracture toughness tests on pre-cracked Charpy size specimens (COD) is given. Two methods have been used for determination of static fracture toughness shifts - standard COD type specimens from a standard surveillance programmes and reconstituted COD type specimens from broken halves of Charpy V-notch specimens.

Results obtained are discussed from the point of view of irradiation conditions as well as of different type of testing.

MAIN PROBLEM OF THE TASK :

PRINCIPAL CONTRADICTION
BETWEEN
ACCEPTANCE/SURVEILLANCE MATERIAL TESTING
AND
RPV INTEGRITY ASSESSMENT APPROACH.
i.e.

CHARPY V-NOTCH IMPACT TESTS
vs.
STATIC FRACTURE TOUGHNESS APPROACH

MATERIAL TESTED :

RE-EVALUATION OF SURVEILLANCE SPECIMENS :

- **BASE METAL - STEEL 15Kh2MFA - FROM RPVs OF NPP DUKOVANY**

- **SURVEILLANCE SPECIMENS AFTER 1, 2, 3 AND 5 YEARS OF OPERATION**
  i.e.
  WITH FLUENCE IN THE RANGE (1 to 5)x10^{24}n.m^{-2} (En ≥0.5 MeV) (high lead factor in standard surveillance programme) AT 270 C

EXPERIMENTAL PROGRAMME :

- **EXPERIMENTAL HEATS FROM 15Kh2NMFA TYPE STEEL (OF VVER-1000 TYPE) WITH DIFFERENT Cu AND P CONTENTS WITH FLUENCE EQUAL TO 2.6x10^{23}N.M^{-2}**
  (EN ≥0.5 MEV) AT 288 C

CHEMICAL COMPOSITION OF TESTED MATERIALS:

TYPICAL CHEMICAL COMPOSITION OF SURVEILLANCE MATERIALS:

Alloy	Cr-Mo-V-BM
C	0.13
Mn	0.40
Si	0.25
P	0.009-0.012
S	0.012
Cr	2.77
Ni	0.16
Mo	0.62
V	0.30
Cu	0.08-0.10

CHEMICAL COMPOSITION OF EACH EXAMINED EXPERIMENTAL HEATS IS GIVEN IN TABLE 2.

	1	2	3	4	5	6
C	0.15	0.15	0.15	0.15	0.16	0.16
Mn	0.48	0.48	0.34	0.34	0.34	0.34
Si	0.17	0.17	0.21	0.21	0.20	0.20
P	0.012	0.018	0.015	0.021	0.014	0.021
S	0.010	0.010	0.009	0.009	0.009	0.009
Cr	2.06	2.06	1.89	1.89	2.14	2.14
Ni	1.28	1.28	1.28	1.28	1.27	1.27
Mo	0.56	0.56	0.55	0.55	0.58	0.58
Cu	0.30	0.30	0.52	0.52	0.08	0.08
V	0.10	0.10	0.09	0.09	0.10	0.10

Table 2: Chemical composition of examined steels Cr-Ni-Mo-V

TESTING METHODS:

RE-EVALUATION OF SURVEILLANCE PROGRAMME:

- STANDARD CHARPY V-NOTCH SPECIMENS FOR IMPACT TESTING

  located in containers No.No.7 - 12

  = neutron flux plateau

  transition temperature = $T_K = T_{40J}$

- PRE-CRACKED CHARPY SPECIMENS FOR STATIC FRACTURE TOUGHNESS TESTING

  located in containers No.No. 1 - 6

  = neutron flux steep gradient

  transition temperature = $T_{KJC} = T_{100MPa.m0.5}$

- **RECONSTITUTED CHARPY STANDARD SPECIMENS INTO PRE-CRACKED CHARPY FOR STATIC FRACTURE TOUGHNESS TESTING**

  from specimens located in containers No.No.7-12

  = neutron flux plateau

  transition temperature = $T_{KIC}^{REC} = T_{100MPa.m0.5}$

  I.E. **THE SAME FLUENCE** OF CHARPY-V AND PRE-CRACKED CHARPY-V SPECIMENS WAS OBTAINED!

EXPERIMENTAL PROGRAMME :

- **STANDARD CHARPY V-NOTCH SPECIMENS FOR IMPACT TESTING**

  transition temperature = $T_k = T_{40J}$

- **PRE-CRACKED CHARPY SPECIMENS FOR STATIC FRACTURE TOUGHNESS TESTING**

  transition temperature = $T_{KJC} = T_{100MPa.m0.5}$

- **PRE-CRACKED CHARPY SPECIMENS FOR DYNAMIC FRACTURE TOUGHNESS TESTING**

  transition temperature = $T_{KId} = T_{100MPa.m0.5}$

PREVIOUS RESULTS FROM STANDARD SURVEILLANCE PROGRAMME :

COMPARISON OF CHARPY IMPACT AND STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURES WAS DETERMINED - Fig.1
but

CHARPY IMPACT TRANSITION TEMPERATURE WAS DETERMINED FROM SPECIMENS IRRADIATED IN SIMILAR CONDITIONS = FLUENCE + TIME

and
STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE WAS DETERMINED USING SPECIMENS FROM DIFFERENT CONTAINERS IRRADIATED FOR DIFFERENT TIME TO REACH APPROXIMATELY SIMILAR NEUTRON FLUENCE
(reason :steep neutron flux gradient in containers set with
these specimens
only two specimens are in one container,
i.e. six containers are necessary for one curve

PROGRAMME OF RE-EVALUATION OF STANDARD SURVEILLANCE PROGRAMME :

- PRECISION OF NEUTRON FLUENCE DETERMINATION AND VALUES

- **RECONSTITUTION OF BROKEN CHARPY IMPACT SPECIMENS INTO PRE-CRACKED CHARPY SIZE SPECIMENS FOR STATIC FRACTURE TOUGHNESS TESTING**

thus

- BOTH TYPE OF TESTS IS REALIZED IN THE SAME SET OF SPECIMENS,
  i.e. SPECIMENS WHICH WERE IRRADIATED IN THE SIMILAR CONDITIONS = FLUENCE + TIME

DIRECT COMPARISON OF OBTAINED TWO MATERIAL PARAMETERS FROM THE SAME SET OF SPECIMENS
i.e. NO EFFECT OF DIFFERENT IRRADIATION CONDITIONS COULD AFFECT THE RESULTS

RECONSTITUTION OF SPECIMENS IS PERFORMED USING ELECTRON-BEAM WELDING TECHNIQUE, WHICH WAS CHECKED ACCORDING TO ASTM METHOD AND WITHIN ASTM ROUND-ROBIN PROGRAMME
insert length = 14 mm

RESULTS FROM SPECIMENS RECONSTITUTION :

- **RESULTS FROM RPVs OF UNITS 1 - 4 ARE SHOWN IN FIG.2**

COMPARISON OF TRANSITION TEMPERATURE SHIFTS IS USED, as

both transition temperatures cannot be taken as representative for tested materials in the level of acceptance tests,
because

transition temperature T_K ("critical temperature of brittleness) is determined on a small quantity of specimens, while only KCV criterion for mean values is used

transition temperature T_{KIC} is determined on small size specimens which direct applicability to RPV integrity assessment are still under discussion and needs some re-evaluation

- DIFFERENT TREND LINES OF CHARPY IMPACT AND STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS ARE MOSTLY SEEN
- LARGE DIFFERENCE IS SEEN BETWEEN TREND LINES OF STANDARD AND RECONSTITUTED STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS

- RECONSTITUTED STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS ARE, IN GENERAL, HIGHER THAN CHARPY V-NOTCH IMPACT TRANSITION TEMPERATURE SHIFTS

RESULTS FROM EXPERIMENTAL PROGRAMME :

- COMPARISON OF STATIC AND DYNAMIC TEST RESULTS IS GIVEN FOR TESTED EXPERIMENTAL MATERIALS - Fig.3
  (DIFFEREMT TRANSITION TEMPERATURE SHIFTS ARE OBTAINED EVEN FOR ONE NEUTRON FLUENCE DUE TO DIFFERENT Cu+P CONTENTS IN INDIVIDUAL HEATS)

- COMPARISON OF TWO DIFFERENT DYNAMIC TESTS RESULTS - CHARPY V-IMPACT AND DYNAMIC FRACTURE TOUGHNESS - IS ALSO SHOWN - Fig.4

DISCUSSION OF RESULTS :

RE-CONSTITUTION OF SURVEILLANCE PROGRAMME:

- **STATIC FRACTURE TOUGHNESS SHIFTS ARE, PRACTICAL IN ALL CASES, HIGHER THAN OF CHARPY IMPACT TOUGHNESS TESTS- Figs. 1, 2, 6**

- **RECONSTITUTED STATIC FRACTURE TOUGHNESS SHIFTS ARE, IN GENERAL, LOWER THAN FROM STANDARD SURVEILLANCE PROGRAMME TESTS - Fig.1**

- **THESE DIFFERENCES BETWEEN STANDARD AND RECONSTITUTED STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS -**
  i.e. dT(KIC) - dT(KCV)

  can be caused by :

- **uncertaintities in neutron fluence** determination in containers located in a steep neutron flux gradient (containers No.No. 1-6 with pre-cracked Charpy specimens)
- **scatter of neutron fluences** in individual containers, as 6 containers had to be tested for one curve
- **effect of flux rate**
  as
  specimens in one tested set were chosen from three or four different containers sets,
  i.e. irradiated for different time

- **DIFFERENCES BETWEEN CHARPY AND RECONSTITUTED STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS - Fig.5 -**

  i.e. $\underline{dT(K_{IC}^{REC})}$- $\underline{dT(KCV)}$

CANNOT BE NEGLECTED, AS

IN ALL CASES (WITH ONLY ONE SMALL EXCEPTION) STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS ARE LARGER THAN CHARPY IMPACT SHIFTS

especially when taking into account accuracy in transition temperature (shift) determination which can be equal to

$$\delta T_K = \pm 10\ ^\circ C$$

THESE DIFFERENCES CAN BE PRACTICALLY NEGLECTED ONLY FOR FOR NEUTRON FLUENCE UP TO ABOUT 2 X 10^{24} $n.m^{-2}$

which is equal to an end-of-life neutron fluence for VVER-440 type reactor pressure vessels !

HIGHER DIFFERENCES - UP TO + 50 ^{o}C - HAVE BEEN FOUND FOR NEUTRON FLUENCES UP TO ABOUT 5 X 10^{24} $n.m^{-2}$

trend in these differences is probably close to a linear dependence on neutron fluence applied

EXPERIMENTAL PROGRAMME :

- STATIC FRACTURE TOUGHNESS TRANSITION SHIFTS ARE LARGER SHIFTS FROM BOTH EDYNAMIC TYPE TESTS - CHARPY IMPACT AS WELL AS DYNAMIC FRACTURE TOUGHNESS ONES - FIG. 3, 4
- BOTH DYNAMIC TYPE TESTS - CHARPY IMPACT AND DYNAMIC FRACTURE TOUGHNESS - SHOW PRACTICALLY SIMILAR SHIFT VALUES - Fig. 7
- DIFFERENCE BETWEEN STATIC FRACTURE TOUGHNESS SHIFTS AND CHARPY IMPACT SHIFTS ARE MORE PRONOUNCED THAN IN SURVEILLANCE PROGRAMME, EVEN FOR LOWER SHIFT VALUES (AND MUCH LOWER NEUTRON FLUENCE) - FIG.8

CONCLUSIONS :

- **RECONSTITUTION TECHNIQUE WAS PROVED** AS A VERY EFFECTIVE AND VALUABLE METHOD FOR RE-EVALUATION OF SPECIMENS FOR STANDARD SURVEILLANCE PROGRAMMES

  USE OF THIS METHOD IS VERY IMPORTANT MAINLY FOR DETERMINATION OF DIFFERENT MATERIAL PARAMETERS FROM THE SAME SPECIMENS
  which means that fully similar initial as well as irradiation conditions can be assured

- DIFFERENCES BETWEEN STATIC FRACTURE TOUGHNESS TRANSITION TEMPERATURES CAN BE DESCRIBED AS A LINEAR DEPENDENCE ON NEUTRON FLUENCE OR ON TRANSITION TEMPERATURE SHIFTS VALUES - THE HIGHER IS TRANSITION TEMPERATURE SHIFT, THE HIGHER

IS A DIFFERENCE BETWEEN STATIC AND DYNAMIC TRANSITION TEMPERATURE SHIFT even though quite different fracture mechanisms are present in these different tests :

- static vs. dynamic
- initiation load for un-stable crack growth vs. work necessary for crack initiation, propagation and arrest

- THESES DIFFERENCE CAN BE PRACTICALLY NEGLECTED UP TO VVER-440 EOL DESIGN NEUTRON FLUENCE (approx. $2x10^{24}$ n.m^{-2})

- THESE DIFFERENCES CAN REACH VALUES UP TO ABOUT 50 ^{o}C FOR NEUTRON FLUENCES EQUAL TO ABOUT 5×10^{24} n.m^{-2}, i.e. for double RPV design lifetime

- THESE DIFFERENCES CAN BE OBTAINED EVEN FOR LOWER NEUTRON FLUENCE, IF SIMILAR TRANSITION TEMPERATURE SHIFTS ARE OBTAINED,
  I.E. IT SEEMS, THAT DIFFERENCE BETWEEN STATIC AND DYNAMIC TEST SHIFTS DEPENDS MAINLY ON THEIR VALUES

- DIFFERENCE DYNAMIC TYPE TESTS RESULTS IN SIMILAR TRANSITION TEMPERATURE SHIFTS

- CHARPY IMPACT TRANSITION TEMPERATURE SHIFTS CAN BE PROBABLY USED FOR RPV INTEGRITY ASSESSMENT UP TO EOL NEUTRON FLUENCE

STILL OPENED QUESTIONS :

- **POSSIBLE EFFECT OF FLUX RATE ON TRANSITION TEMPERATURE SHIFTS AND THEIR DIFFERENCES**

- BOTH SHIFTS ARE PRACTICALLY IDENTICAL FOR FLUENCES UP TO DESIGN EOL LIFETIME
  WHILE DIFFERENCES UP TO ABOUT 50 °C FOR DOUBLE EOL FLUENCE ARE FOUND

- CHARPY IMPACT TRANSITION TEMPERATURE SHIFTS CAN BE APPLIED AS A REPRESENTATIVE RPV MATERIALS PARAMETERS USING STATIC FRACTURE MECHANICS APPROACH

FUTURE PROGRAMME CONTINUATION:

- RECONSTITUTION OF CHARPY IMPACT SPECIMENS FROM WELD METAL INTO PRE-CRACKED FRACTURE MECHANICS TESTS

- TESTING OF RECONSTITUTED SPECIMENS FOR STATIC AS WELL AS DYNAMIC FRACTURE TOUGHNESS TRANSITION TEMPERATURE SHIFTS DETERMINATION

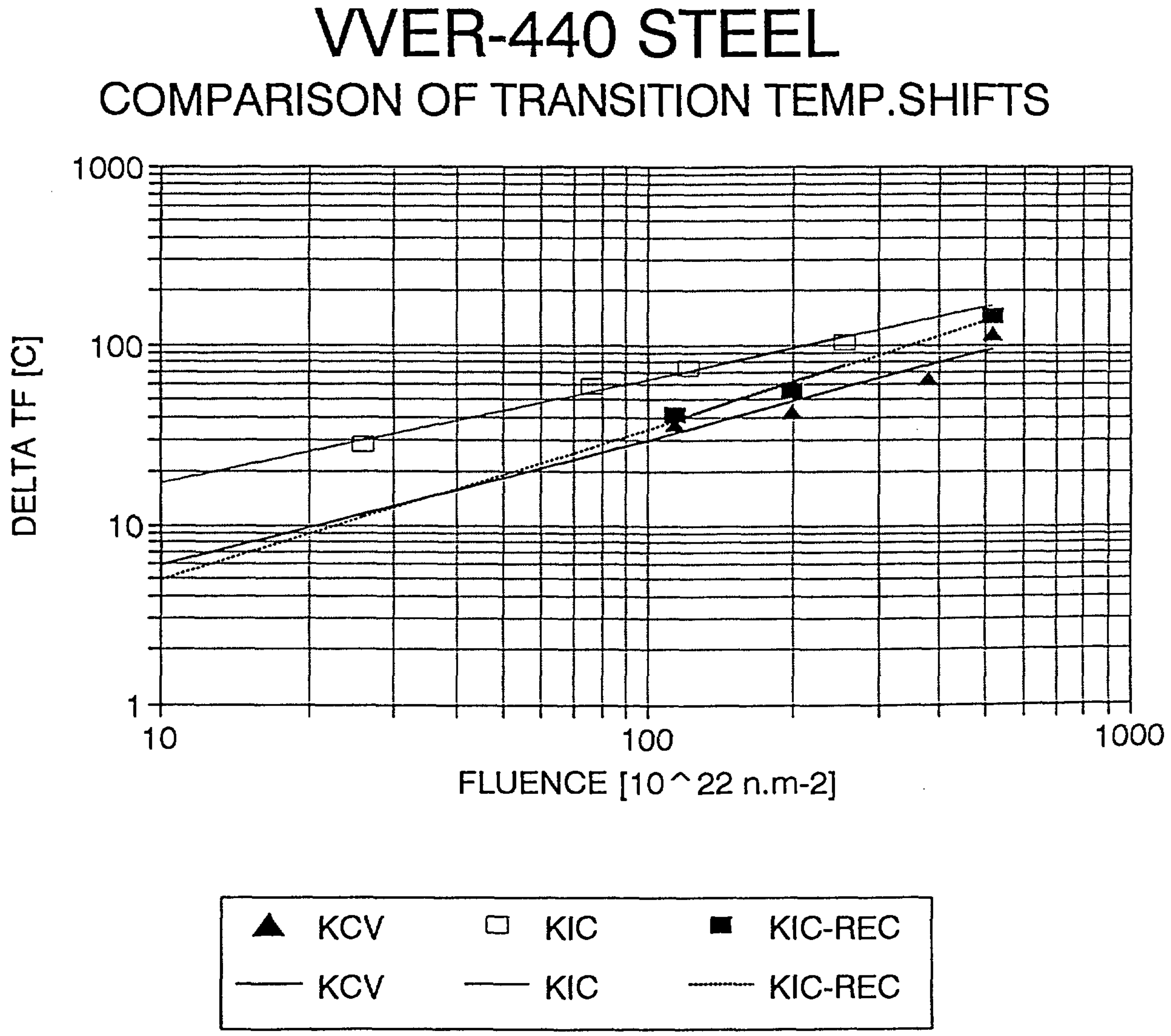

Fig.1 Comparison of transition temperature shifts from a standard and re-evaluated surveillance programme for one typical VVER-440/V-213Č type reactor pressure vessel

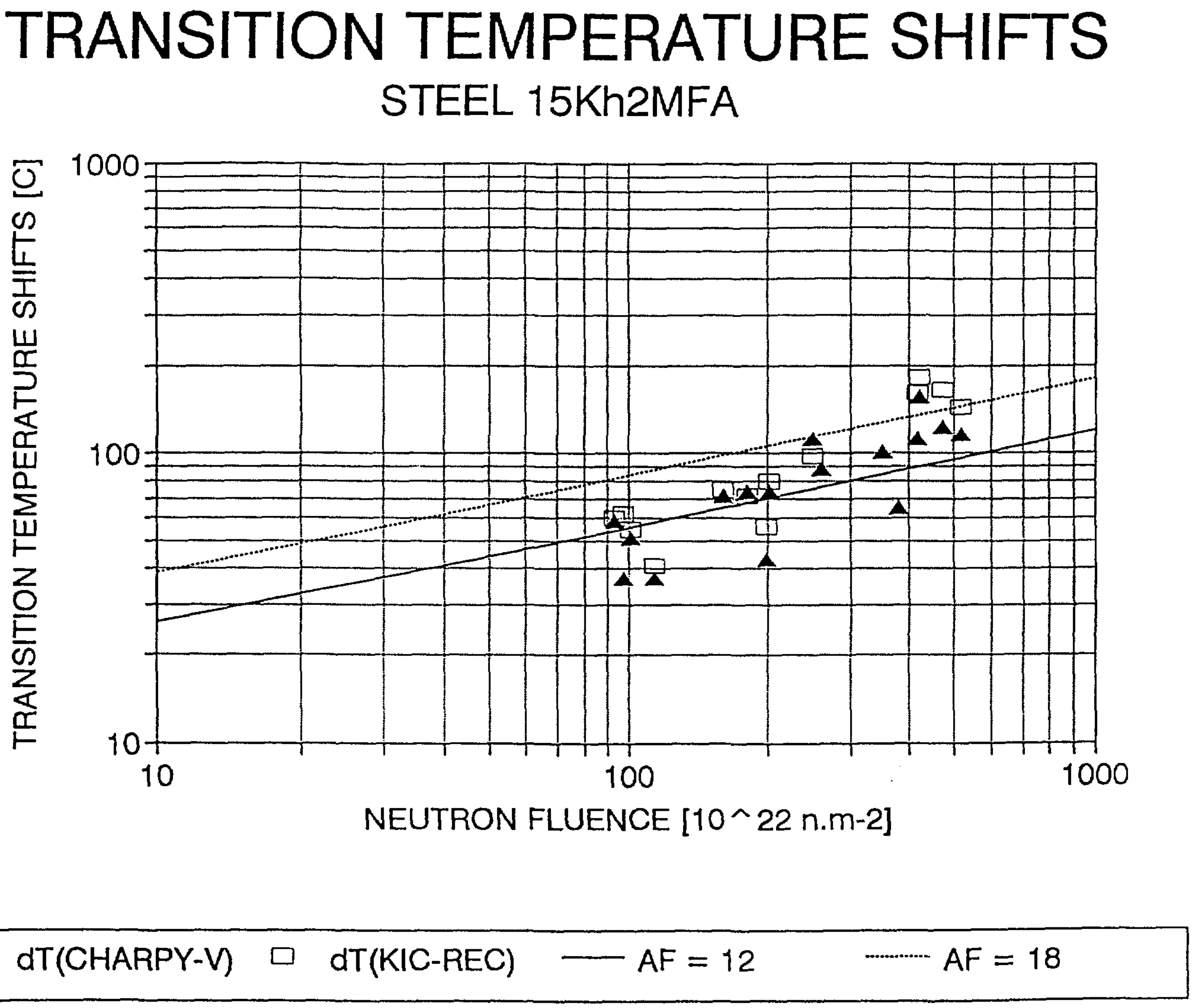

Fig.2 Comparison of transition temperature shifts for WER-440/V-213Č type reactor pressure vessels

dT(Charpy-V) - notch impact toughness
dT(KIC-REC) - static fracture toughness from re-constituted Charpy specimens
AF=12 - irradiation embrittlement coefficient for 15Kh2MFAA type steel
AF = 18 - irradiation embrittlement coefficient for 15Kh2MFA type steel

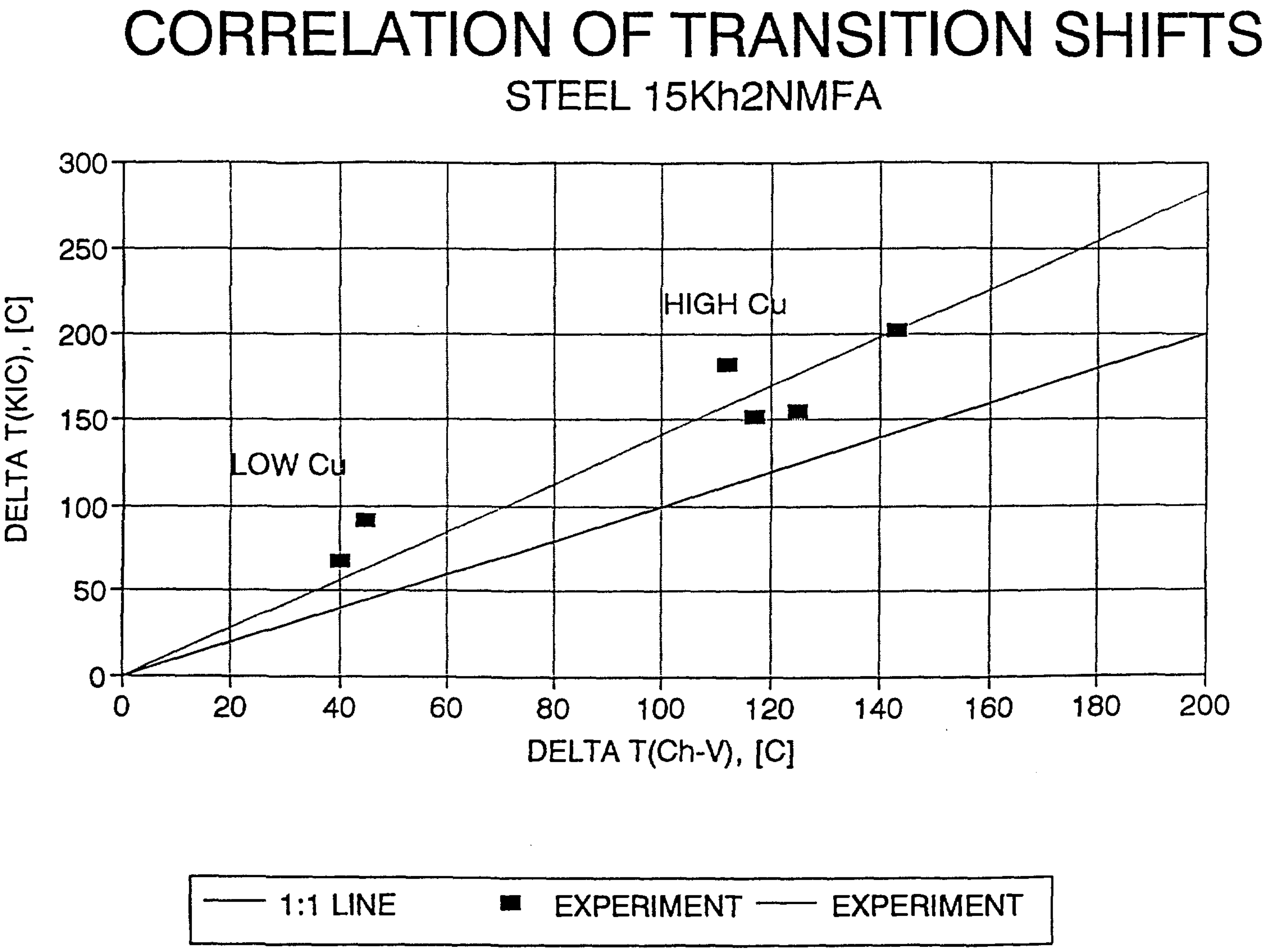

Fig.3 Correlation of static fracture toughness (KIC) and notch impact toughness (CH-V) transition temperature shifts for 15Kh2NMFA type experimental heats

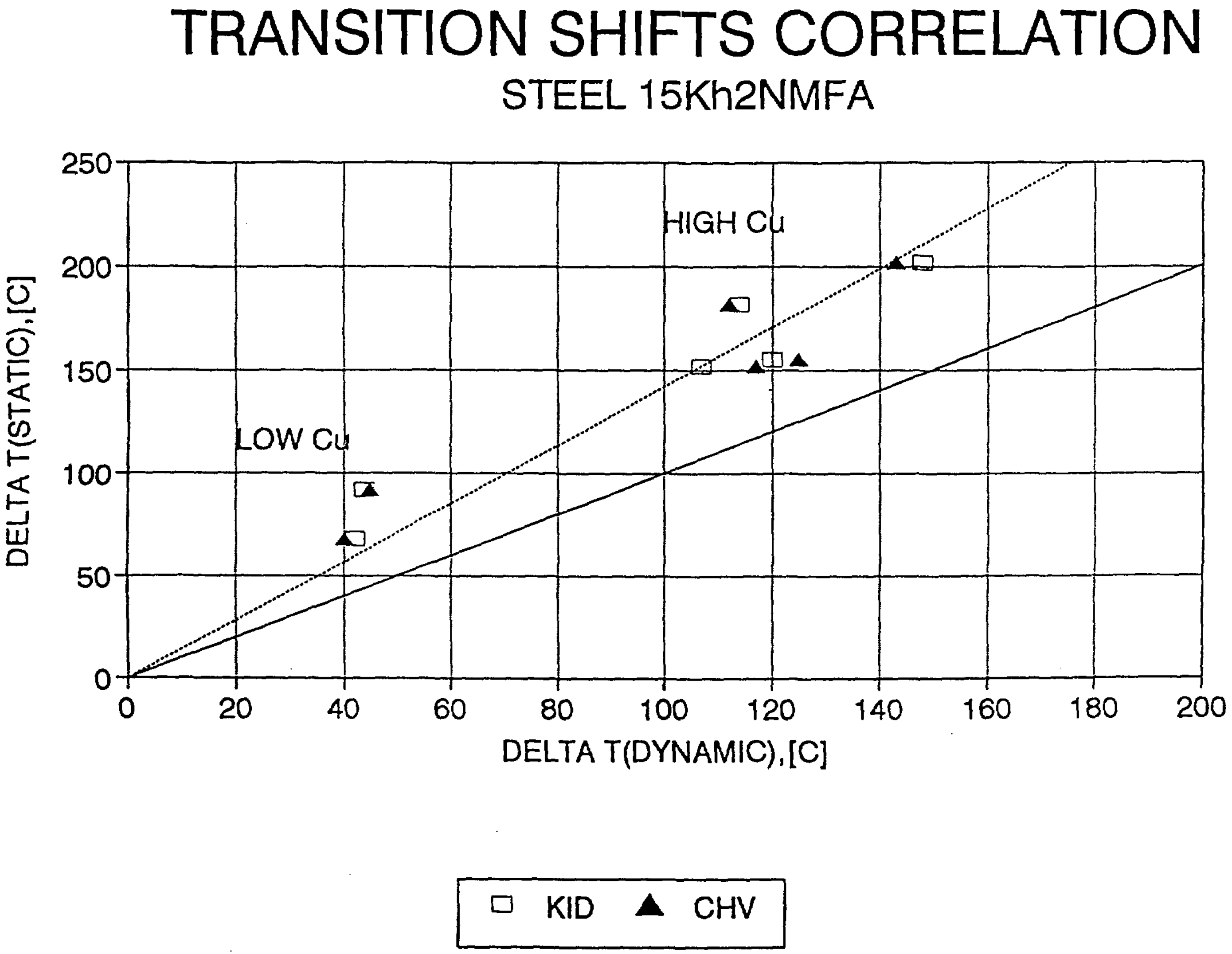

Fig.4 Correlation of static fracture toughness (KIC) and dynamic fracture toughness (KID) transition temperature shifts for 15Kh2NMFA type experimental heats

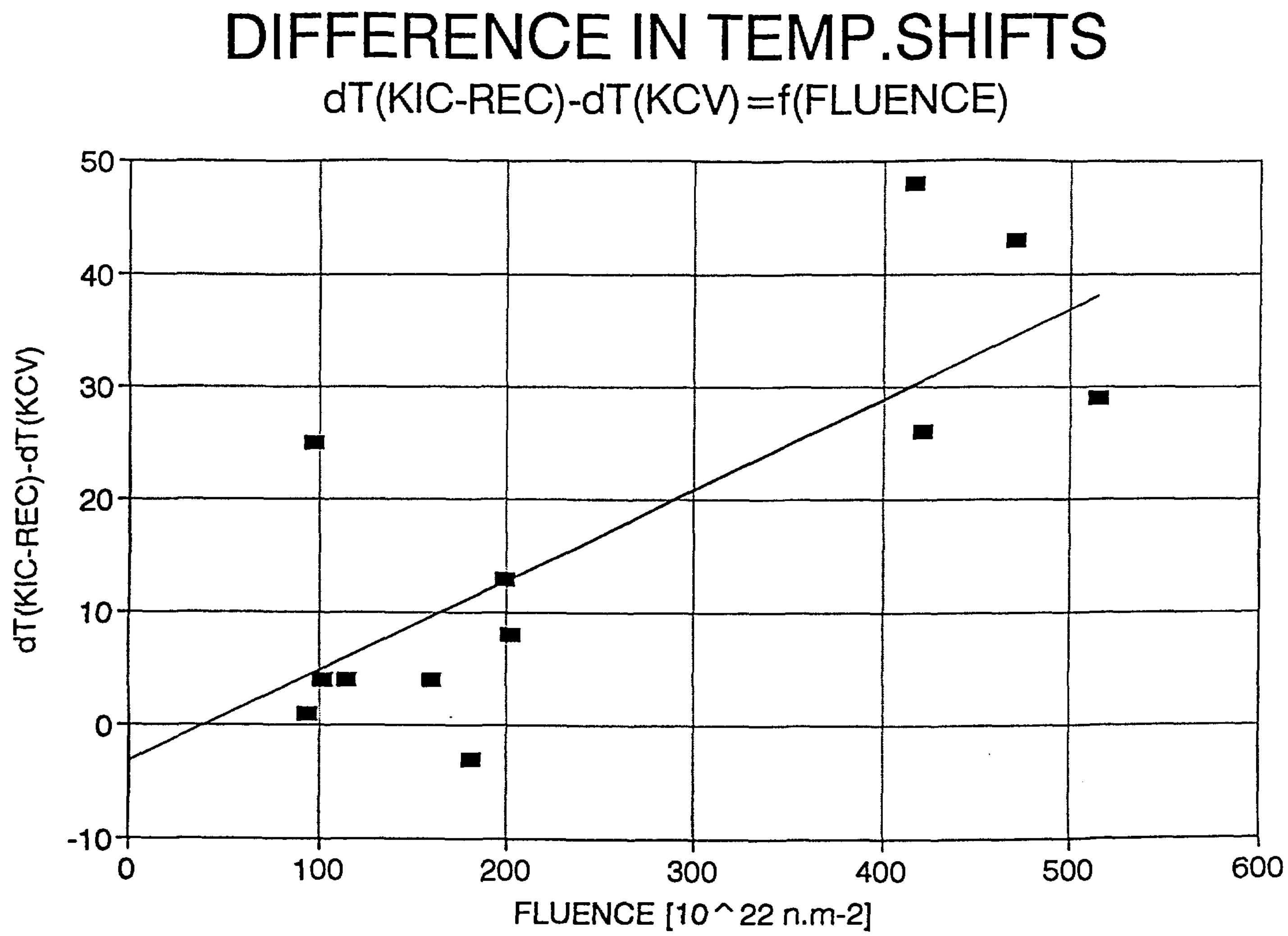

Fig.5 Difference between static fracture toughness (on re-constituted Charpy) and Charpy notch impact toughness transition temperature shifts for 15Kh2NMFA type experimental heats

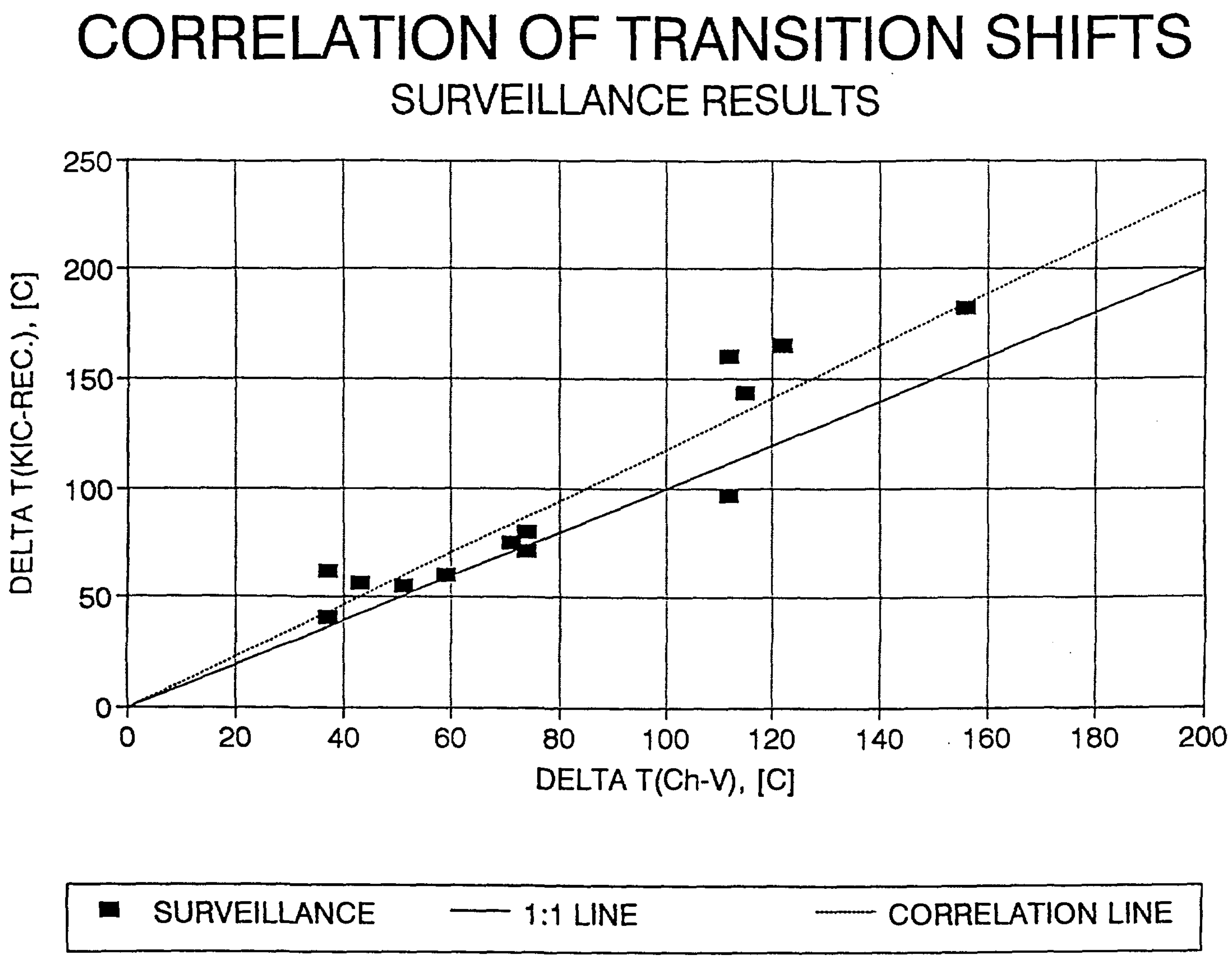

Fig.6 Correlation between static fracture toughness (on reconstituted Charpy) and Charpy notch impact toughness transition temperature shifts for surveillance specimens

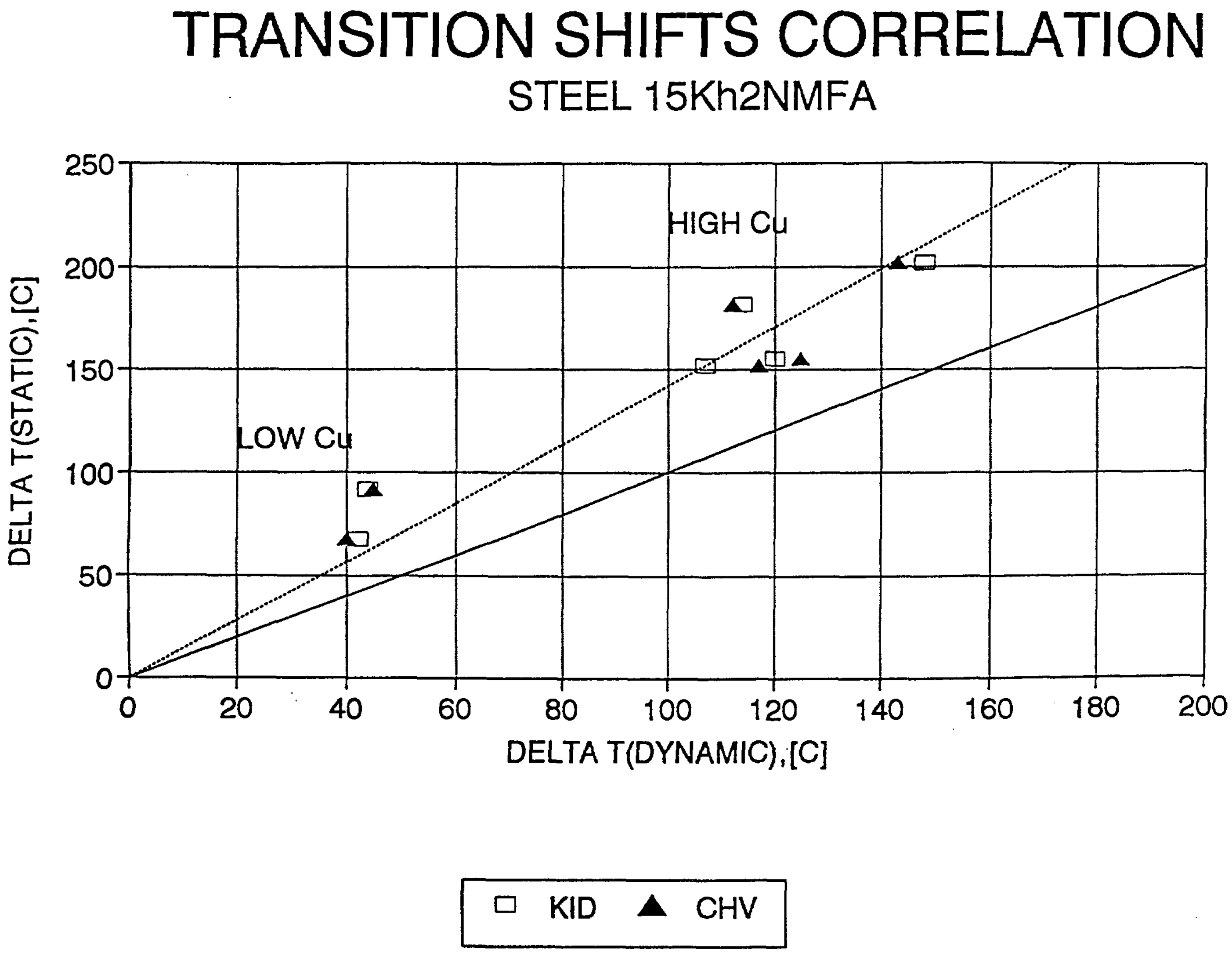

Fig.7 Correlation between static and dynamic fracture toughness transition temperatures shifts for 15Kh2NMFA type experimental heats

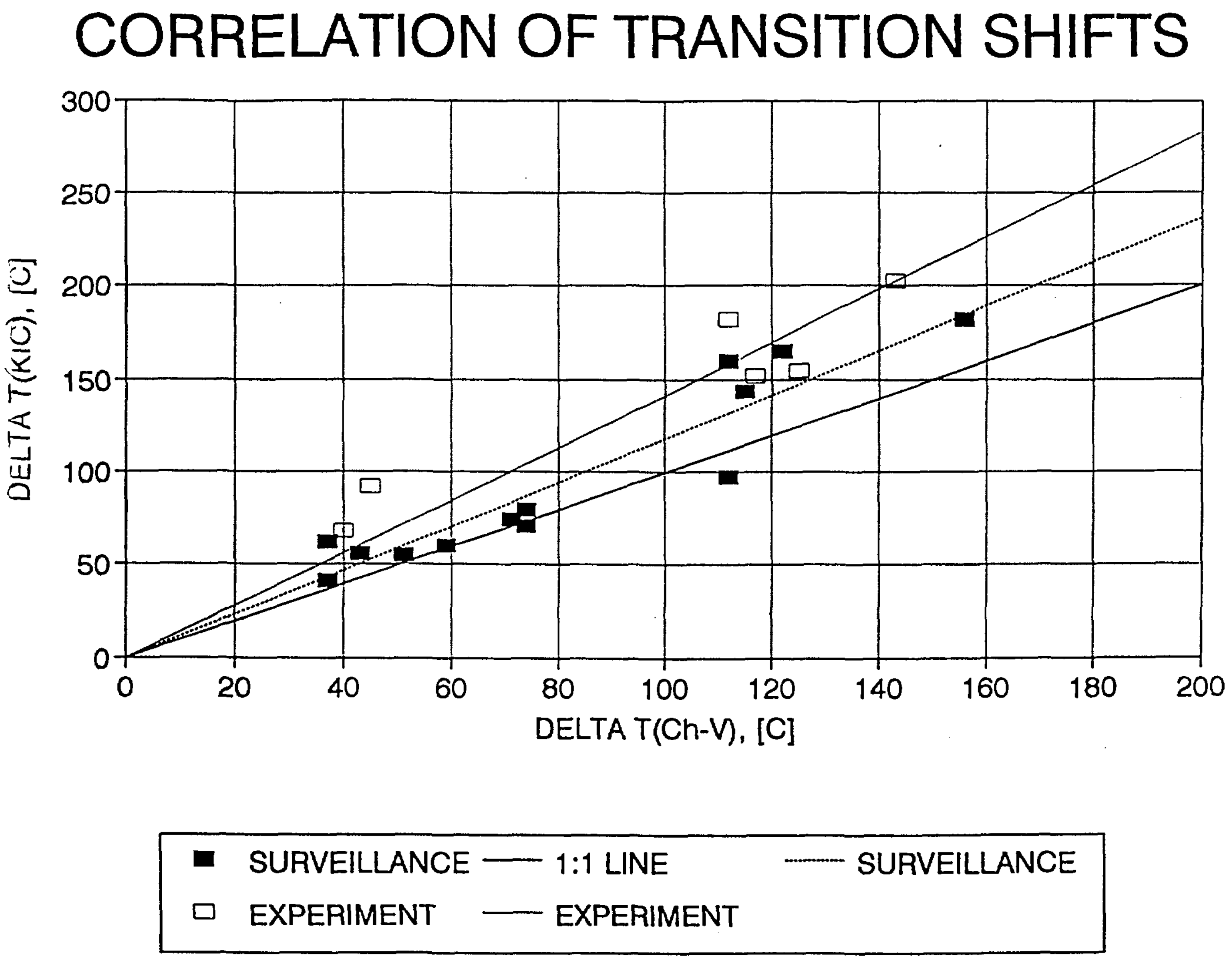

Fig.8 Correlation between static fracture toughness and Charpy notch impact toughness transition temperature shifts tested for VVER steels