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RADIATION STABILITY AND RECOVERY OF WWER-440 MATERIALS

The main results of a complex investigation of radiation embrittlement of WWER-440 reactor vessel (RV) materials, carried out in Russia are presented. The object of the investigation was surveillance specimen (SS) evaluations of RV materials. It has been found that at the irradiation temperature of 270°C neither the base metal (steel 15Kh2VFA) nor weld metal exhibits saturation of radiation embrittlement in irradiation of specimens up to neutron fluences of 7.10^{20} n/cm^2 (E.0.5 Mev). Regularaties in the influence of impurity elements (copper and phosphorous) on radiation embrittlement of RV materials have been investigated. It is shown that radiation embrittlement of the weld metal is determined by at least four processes associated with the individual effects of copper and phosphorous, their joint effect and the mechanism of direct build-up of radiation defect in the metal. The effect of dependence of the radiation embrittlement characteristics of the WWER-440 materials on the neutron flux has been found. A tendency has been observed for the values of the radiation embrittlement coefficients A_1, characterizing sensitivity of the steel to radiation embrittlement, to reduce with an increase of neutron fluence in irradiation specimens with flux of 4.10^{11} n/cm^{2}s.

The main results obtained from studying recovery of radiation embrittlement of reactor vessel steels are presented. The effect of the annealing temperature and annealing time, neutron fluence, and phosphorous and copper impurity contents on recovery of the ductile-to-brittle transition temperature was studied. Recovery of the transition temperature depends mainly on the annealing temperature. At an annealing temperature 420 and 460°C , residual post-annealing embrittlement does not depend on neutron fluence.

Experimental results are presented from a study of changes in ductile-to-brittle transition temperature under cyclic irradiation and recovery. Specimen irradiation was carried out in a commercial reactor in three irradiation and recovery cycles.

Annealing of specimens was performed at 340, 420, 460°C. Change in the transition temperature as a result of annealing depends both on the intermediate annealing temperature and on the chemical composition of the metal, in particular, on the phosphorous content. It has been found that the greatest shift during re-irradiation corresponds to the highest temperature of annealing.

Features of the first generation reactor vessels.

1. Transportability by railway of ready-made reactor vessels.

2. Vessel welds are only circumferential; one of the welds (Number 4.) is situated in region nearby maximum neutron flux.

3. Some vessels have welds with a high content of impurities (P, Cu).

4. A number of vessels was produced without stainless steel plating.

5. Some of the vessels were produced without surveillance samples.

6. Neutron flux is by an order of magnitude greater in places where surveillance samples are irradiated than on vessel wall.

Table 1

Grade of vessel steel	Mass content of elements, %					
	C	Si	Mn	S	P	Cu
15KH2MFA	0,11-0,22	0,17-0,37	0,3-0,6	0,025	0,025	-
15KH2MFAA	0,11-0,16	0,17-0,37	0,3-0,6	0,015	0,012	0,10
Sv-10KHMFT	0,07-0,12	0,15-0,35	0,4-0,7	0,030	0,030	-
Sv-10KHMFTU	0,07-0,12	0,15-0,35	0,4-0,7	0,12	0,012	0,010
15KH2NMFA	0,13-0,18	0,17-0,37	0,3-0,6	0,020	0,020	0,20
15KH2NMFAA	0,13-0,18	0,17-0,37	0,3-0,6	0,012	0,012	0,08
Sv-10KHGNMAA	0,08-0,14	0,05-0,20	0,9-1,2	0,012	0,010	0,10
Sv-08KHGNMTA	0,05-0,10	0,22-0,37	0,7-1,0	0,012	0,010	0,10

Table 1 continued

Grade of vessel steel	Mass content of elements, %				
	Cr	Ni	Mo	V	Ti
15KH2MFA	2,0-3,0	0,4	0,6-0,8	0,25--,35	-
15KH2MFAA	2,0-2,5	0,4	0,6-0,8	0,25-0,35	-
Sv-10KHMFT	1,4-1,8	0,3	0,4-0,6	0,20-0,35	0,05-0,10
Sv-10KHMFTU	1,4-1,8	0,3	0,4-0,6	0,20-0,35	0,05-0,12
15KH2NMFA	1,8-2,3	1,0-1,5	0,5-0,7	0,1 -0,12	-
15KH2NMFAA	1,8-2,3	1,0-1,5	0,5-0,7	0,1 -0,12	-
Sv-10KHGNMAA	1,8-2,1	1,6-1,9	0,55-0,7	0,03	-
Sv-08KHGNMTA	1,55-1,85	1,1-1,4	0,5 -0,7	0,03	0,03-0,10

Note: For fabrication of VVER-1000 RV the steel is additionally alloyed with nickel in order to improve characteristics of strength and to reach the lower T ko.

Table 3

Limits of content of some impurity and alloying elements and the range of ductile-to-brittle transition temperature in vessel materials of VVER-440 reactors of first generation (production before 1980)

	Steel of grade 15KH2MFA	Weld metal of wire Sv-10KHMFT
P, %	0,010 - 0,019	0,013 - 0,040
Cu, %	0,09 - 0,15	0,03 - 0,21
C, %	0,13 - 0,17	0,05 - 0,06
Ni, %	0,13 - 0,31	0,11 - 0,18
Mn, %	0,38 - 0,69	0,65 - 1,24
Tk, °C max.	0	+60
Tk, °C min.	-50	-13

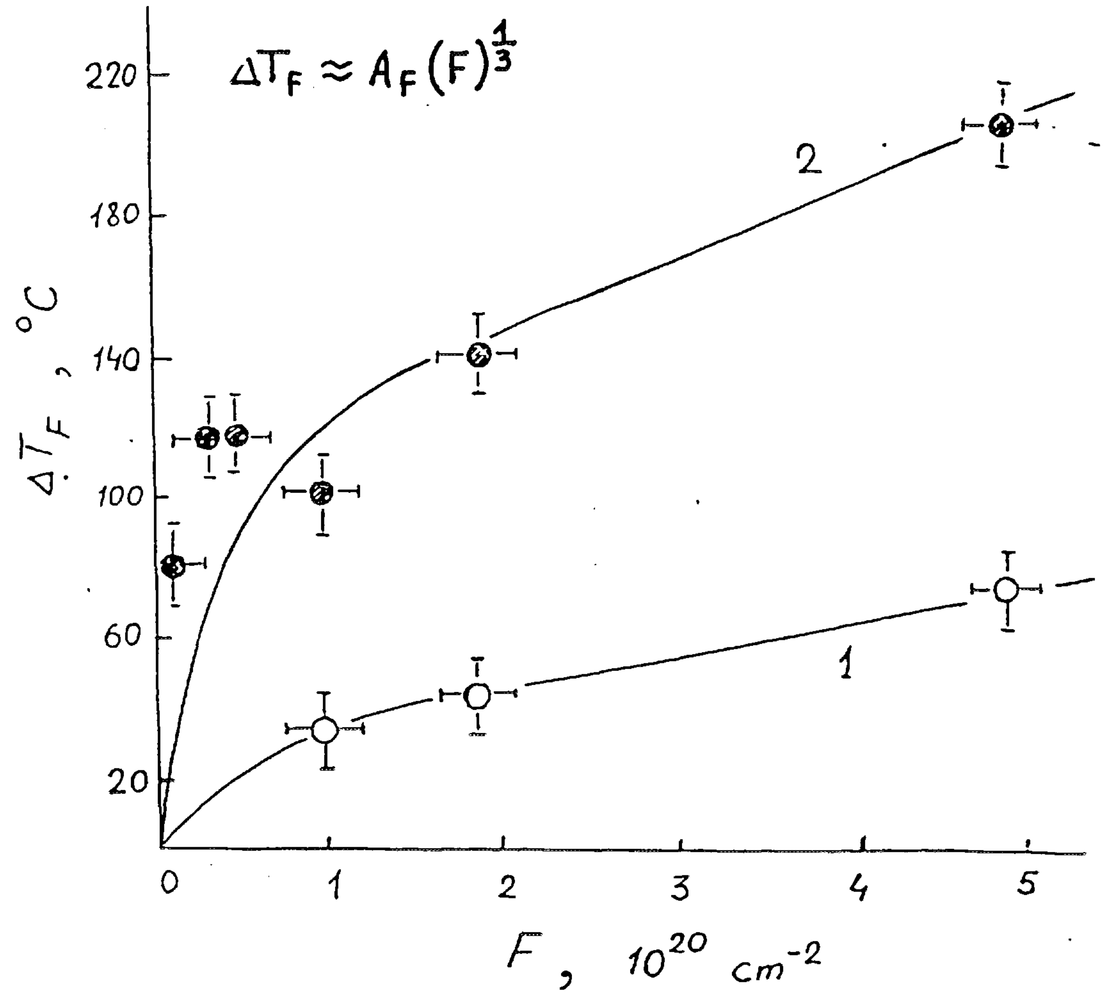

Fig.3 Dependence of shift in transition temperature as a function of fast neutron fluence for surveillance specimens of base and weld metal.
1 - base metal
2 - weld metal

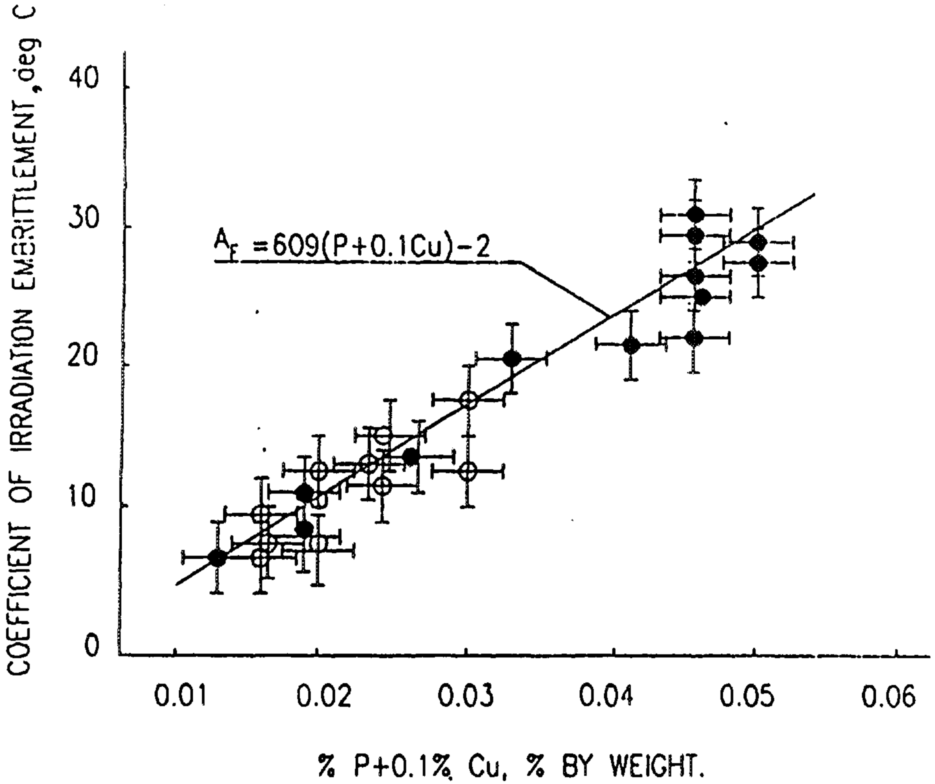

Fig.4 Coefficient of irradiation embrittlement Af as function of content of phosphorus and copper in base metal (o) and its weld metal (●) at irradiation temperature 270°C.

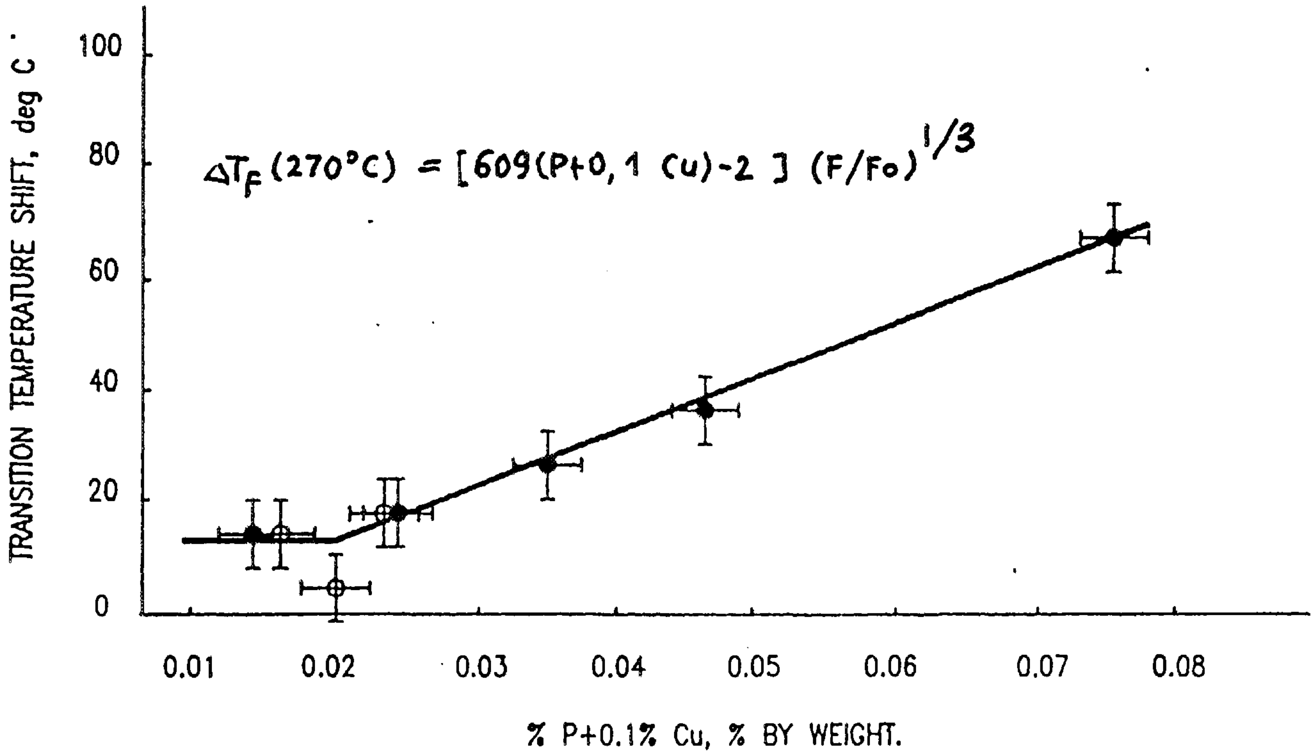

Fig.5 Dependence of shift in transition temperature at irradiation temperature 270°C of base metal (o) and of weld metal (●) as function of content of phosphorus and copper, irradiation in Rovno Unit 1. $F=1.1\times10^{19}\ n/cm^2 > 0.5$ Mev.

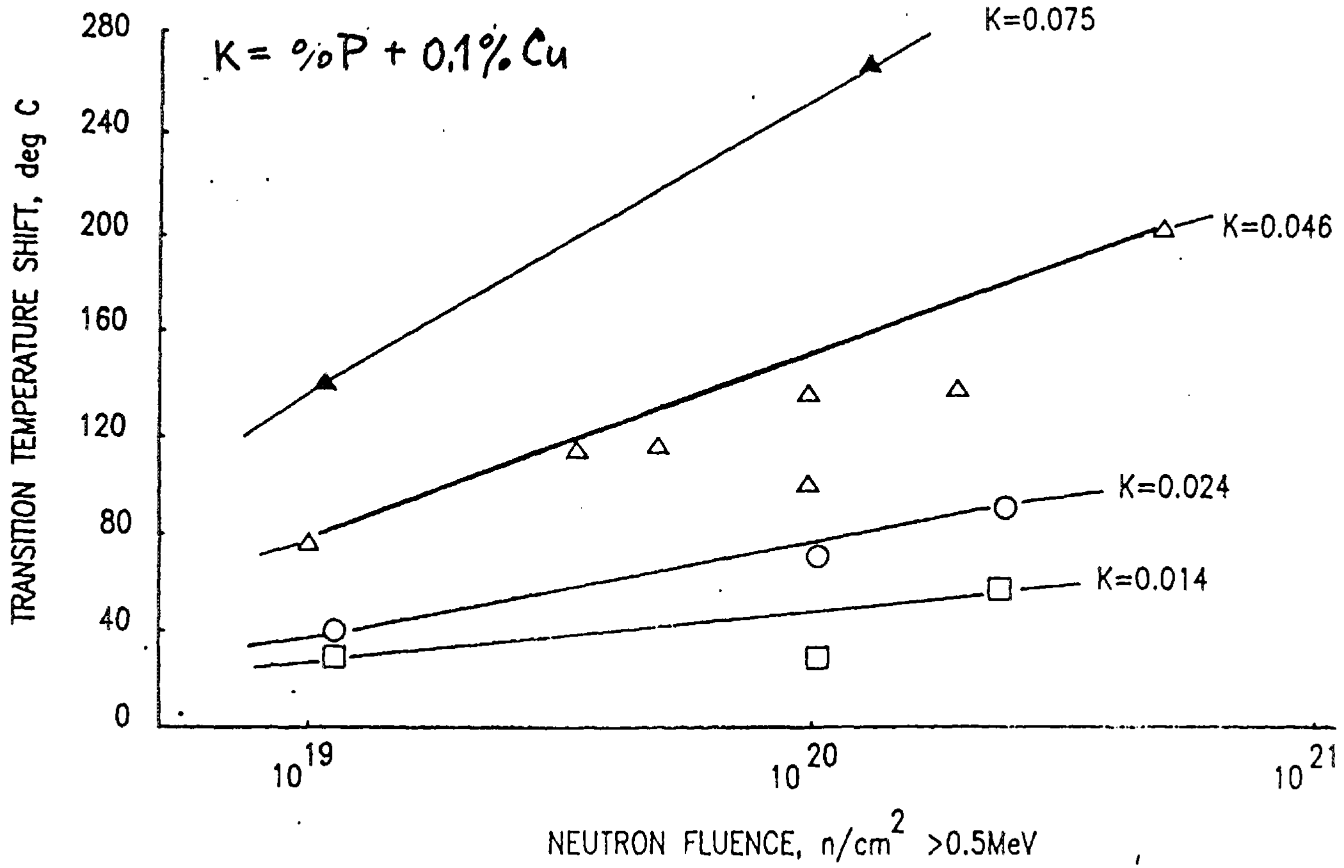

Fig.7 Dependence of shift in transition temperature at irradiation temperature 270°C of base metal and of weld metal as function of fast neutron fluence as characterised by different values of "K"

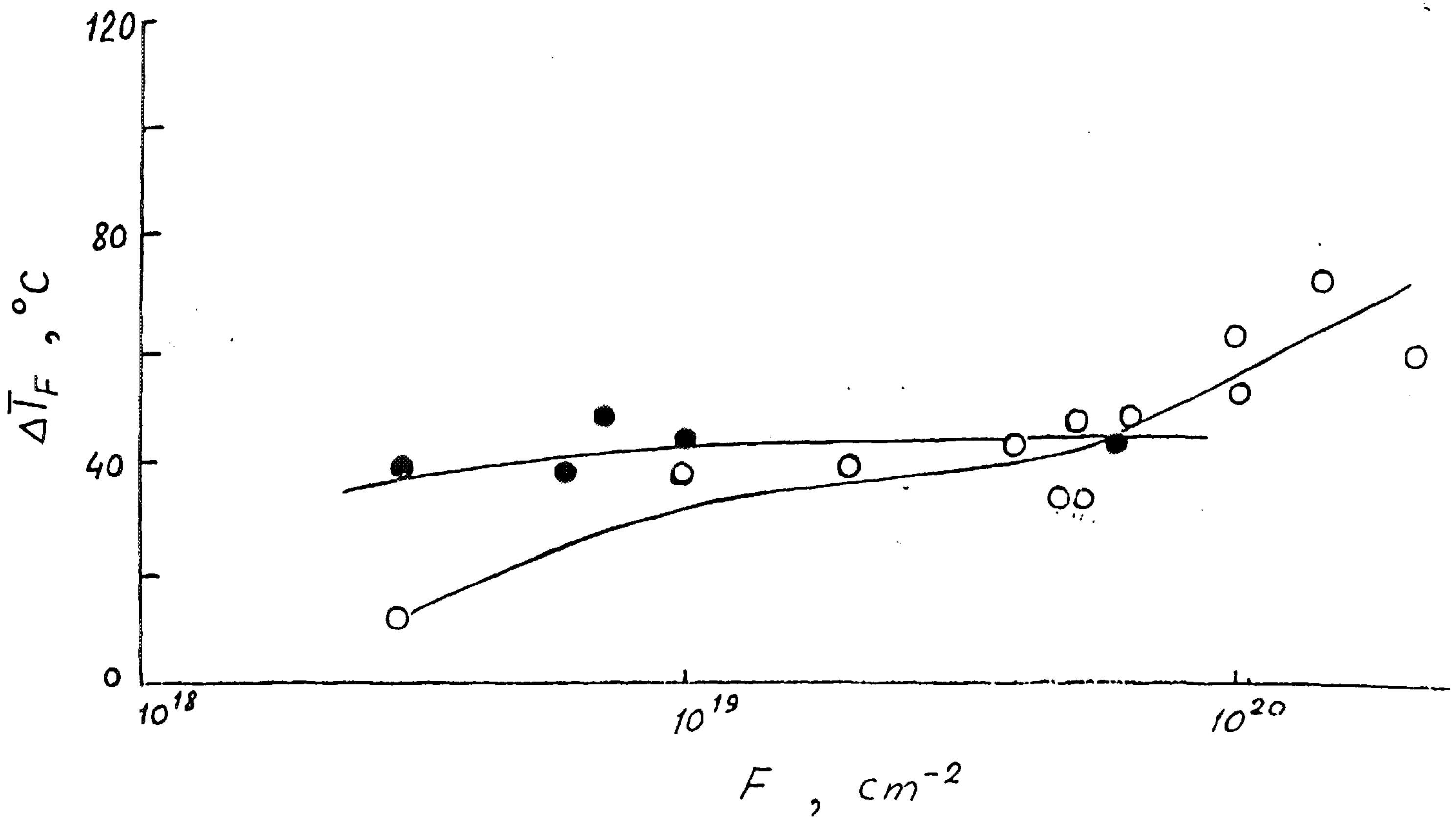

Fig.13 Radiation embrittlement of base metal at irradiation temperature of 270°C.
P = 0.020%; Cu = 0.11%
○ - φ = $1.5 \div 4 \cdot 10^{12}$ $cm^{-2} \cdot s^{-1}$
● - φ = $2 \div 8 \cdot 10^{11}$ $cm^{-2} \cdot s^{-1}$

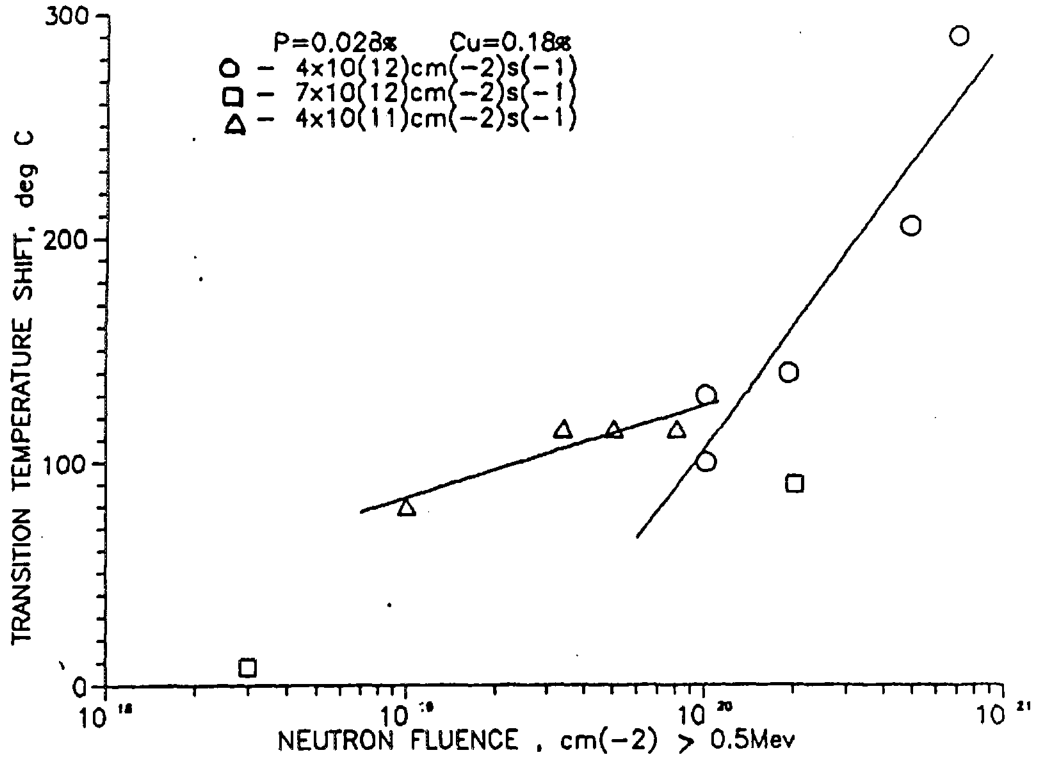

Fig.14 Radiation embrittlement of weld metal at irradiation temperature of 270°C.

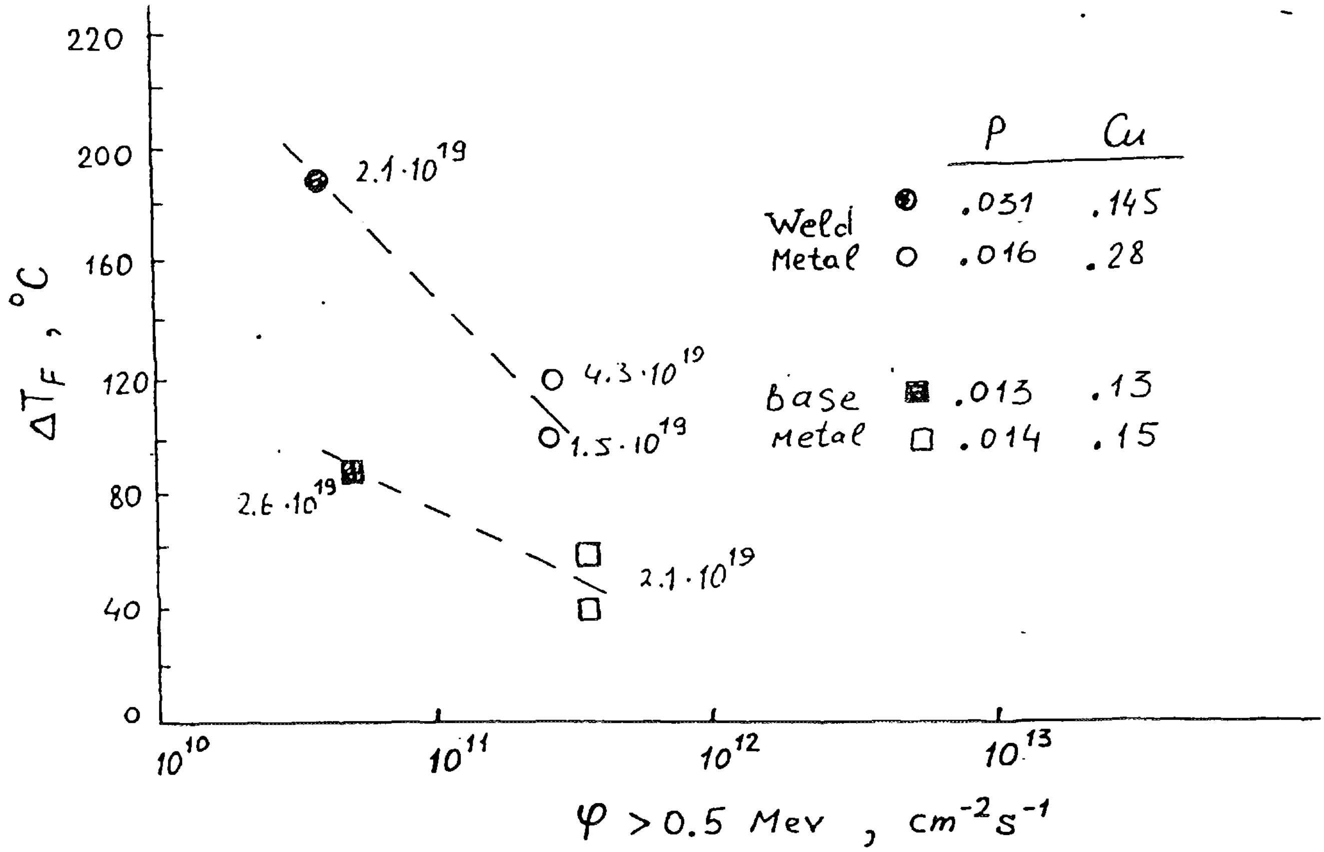

Fig.17 Radiation embrittlement of Novo-Voronezh unit 1 reactor vessel material (●, ■) and surveillance specimens (○, □ at irradiation temperature 250°C.

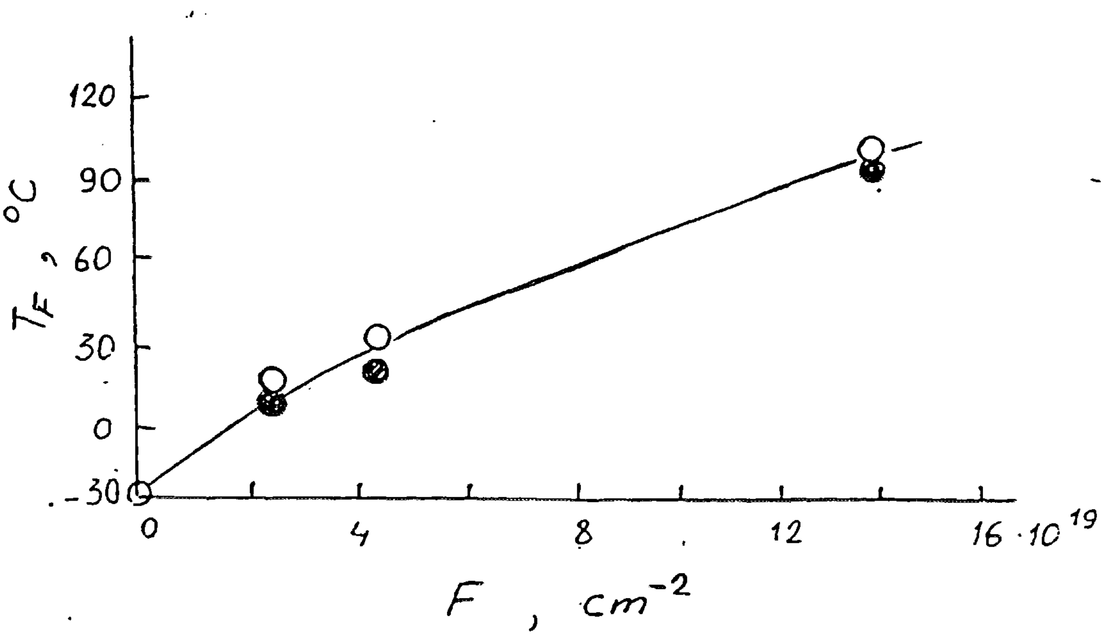

Fig.18 Change of the transition temperature of steel 15Kh2MFA under irradiation in shield (○) and without shield (●).

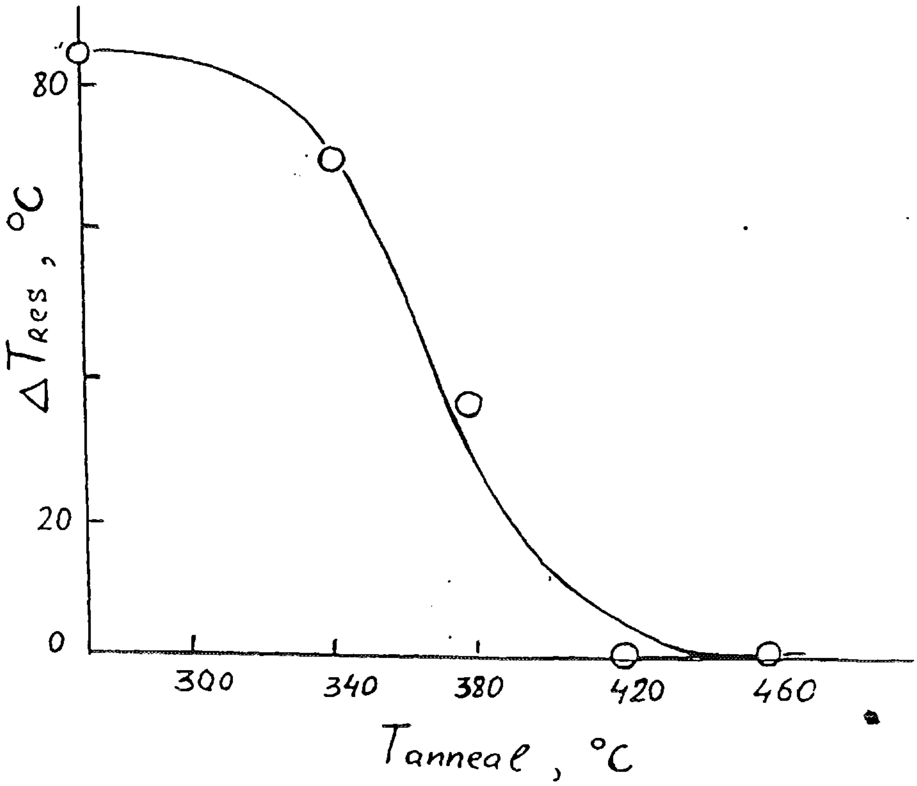

Fig.25 ΔT_F recovery of irradiated weld metal vs. anneal temperature. Annealing duration is 150 h.

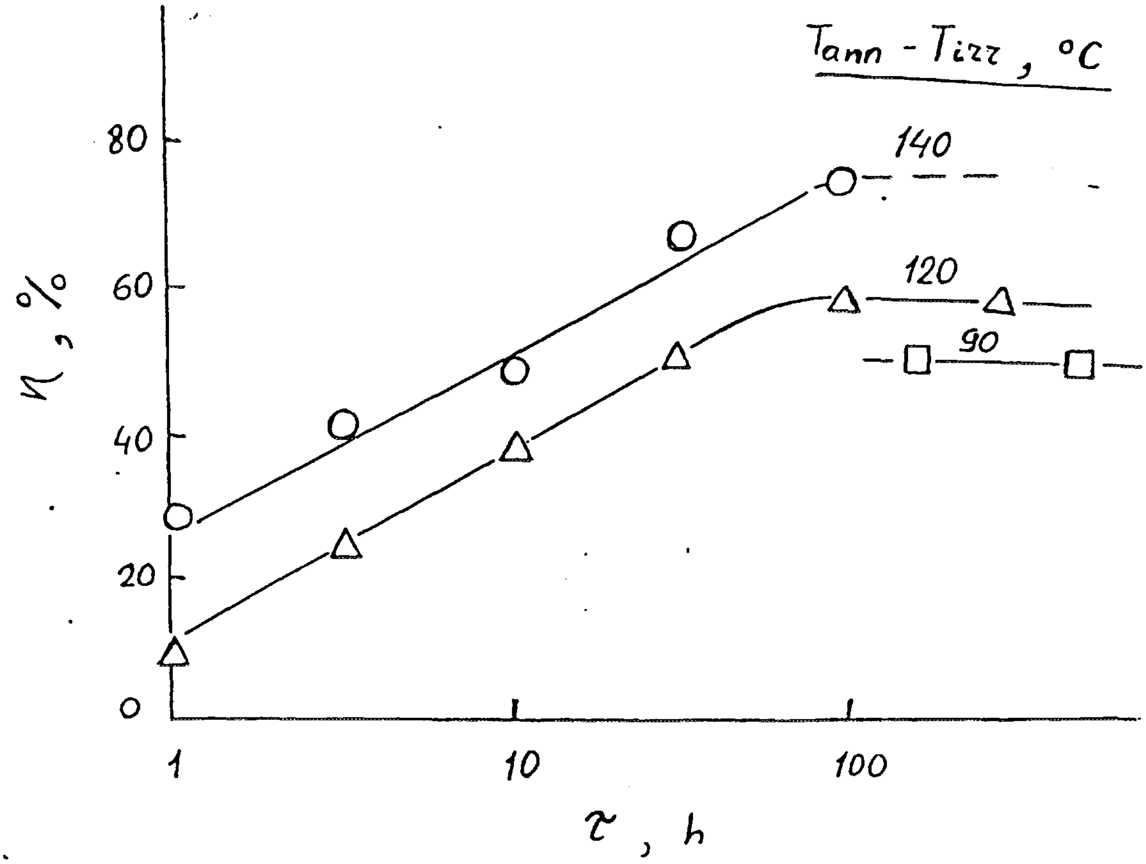

Fig.26 Degree of ΔT_F recovery of reactor pressure vessel materials vs. annealing duration.

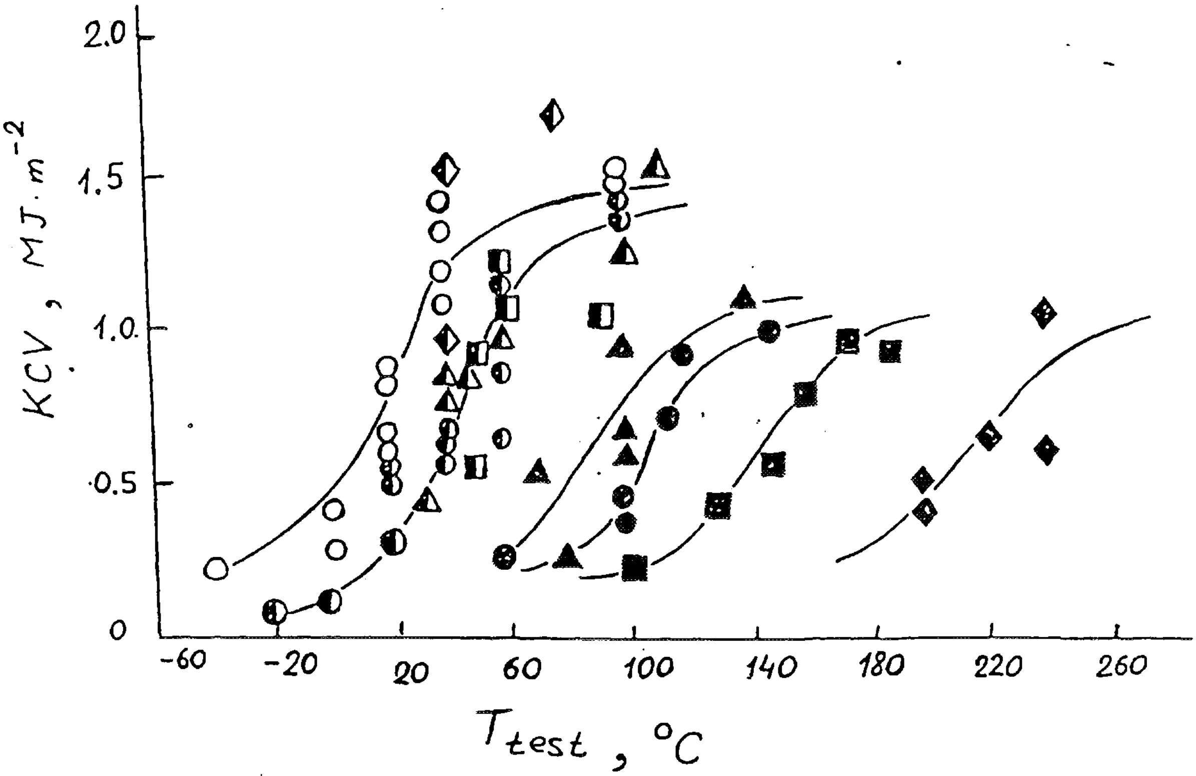

Fig.27 Impact energy of weld metal steel 15Kh2MFA at the different condition.

◭ , ▲ - F ≈ $1 \cdot 10^{19}$ cm^{-2}
◐ , ● - F ≈ $1 \cdot 10^{20}$ cm^{-2}
◧ , ■ - F ≈ $1.9 \cdot 10^{20}$ cm^{-2}
◈ , ◆ - F ≈ $4.9 \cdot 10^{20}$ cm^{-2}
△ , ◐ , ◧ , ◈ - specimens annealed at 420°C, 150 h
○ - unirradiated material

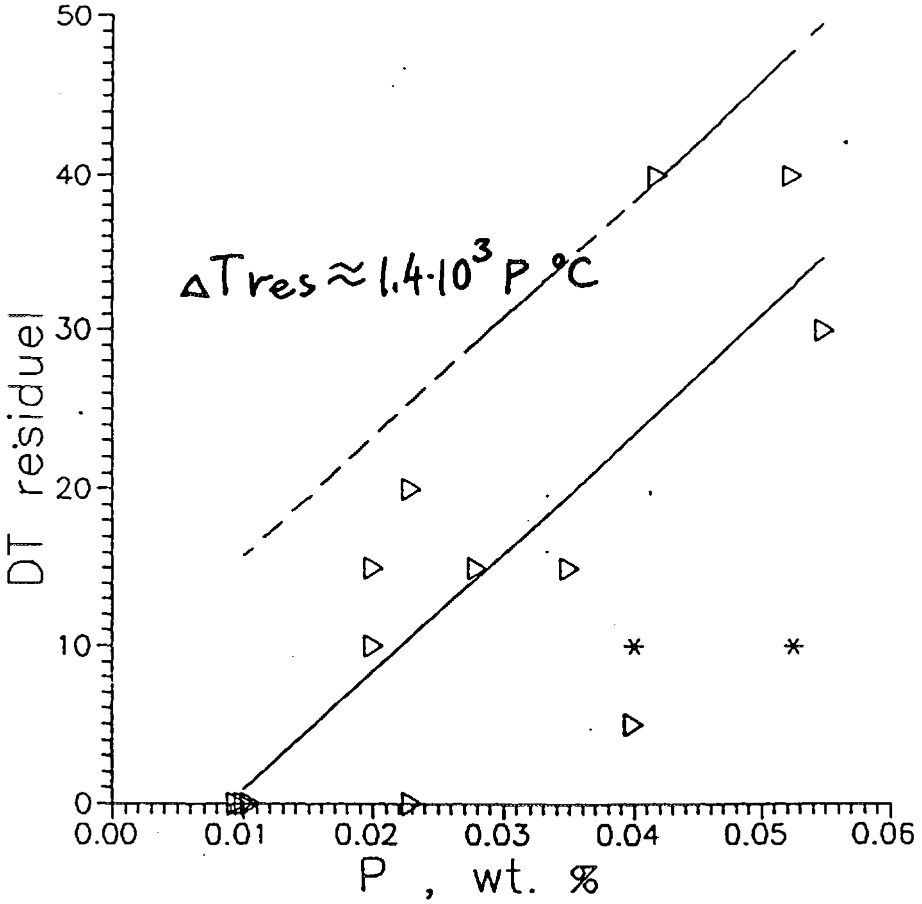

Fig.28 Dependence of the Δ Tres after annealing at 420°C 150 h of the pressure vessel steel 15Kh2MFA on their phosphorus content.

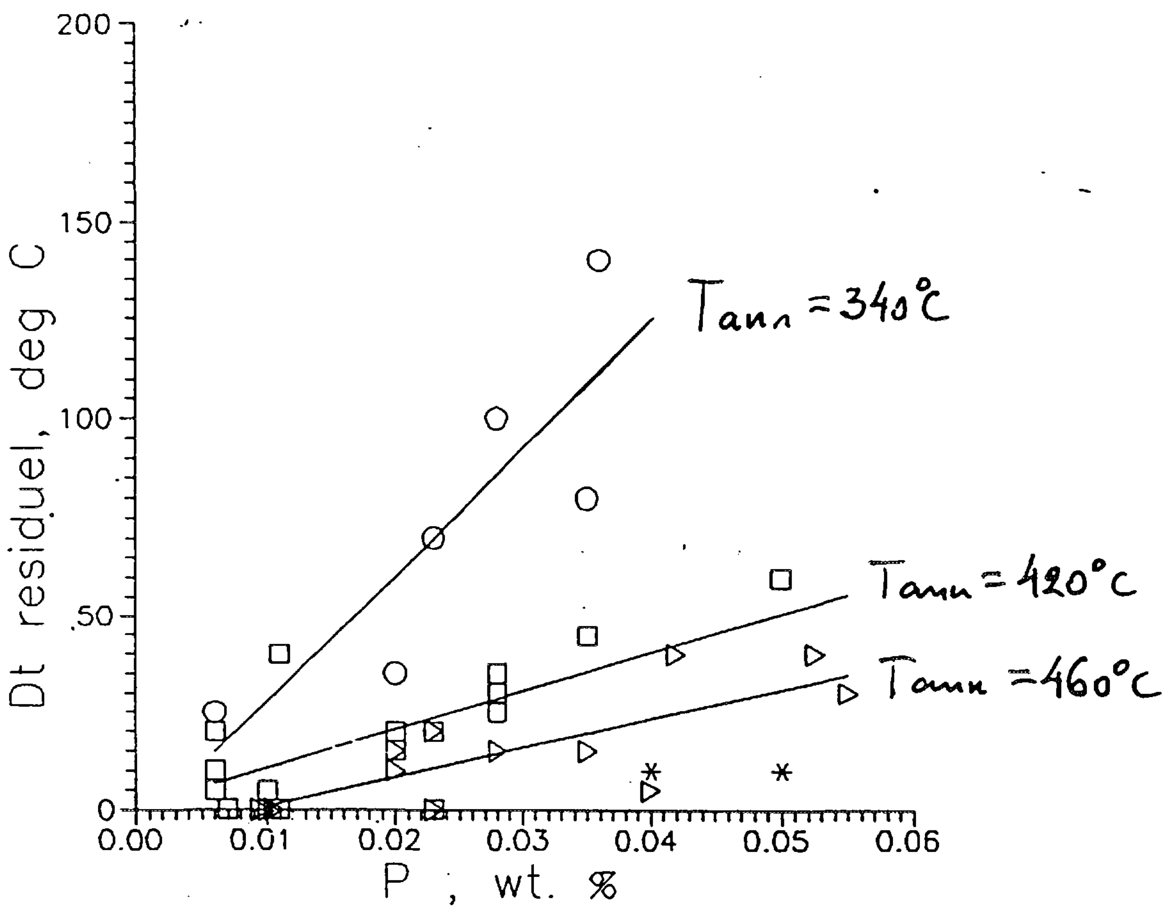

Fig.29 Dependence of the ΔTres after annealing at different annealing temperature (150 h) on phosphorus content in steel 15Kh2MFA.

O - Tann = 340°C

□ - Tann = 420°C

Δ - Tann = 460°C

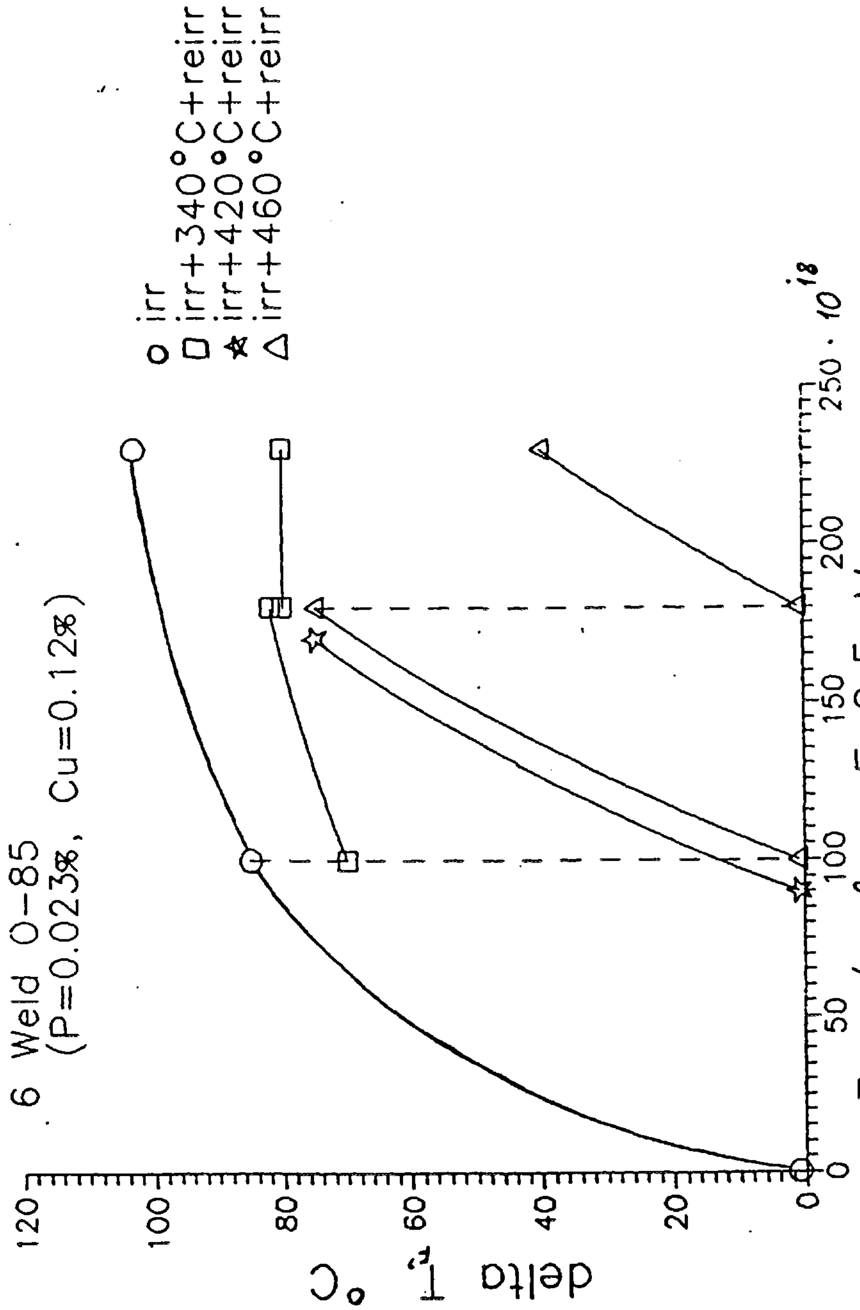

Fig. 31 Radiation embrittlement and post-irradiation annealing recovery of transition temperature vs. fast neutrons fluence at different annealing temperature.