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Material Properties Degradation Assessment of the First Generation WWER-440 RPV after Prolonged Operation

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ABSTRACT

As a result of electric power deficiency in the country one of the main tasks in the nearest time is lifetime extension of acting NPP of the first generation containing the WWER-440/230 reactors, their design service life is 30 years. This task is incorporated in the "Program of RF nuclear power engineering development for 1998-2000 and for the period up to 2010". The design service life of four units of nuclear power plants (3 and 4 units of Novo-Voronezh NPP, 1 and 2 units of Kola NPP), having the above stated reactors ends in 2001-2004. In order to extend lifetime of these power units the technical state of RPV, head and upper should be assessed for the period elapsed since electric power supply to the power system over a prolonged operation period (30 years). This will permit the prediction of the characteristics values determining service life for the operation time being extended considering degradation caused by influence of temperature, neutron fluence, cyclic loads and corrosive environment. This investigation was carried out for the last five-six years.

Using the experimental results as the base, it has been shown that thermal ageing after 30 years of operation and accumulation of fatigue damages in 15X2MFA steel and its welded joints do not result in a pronounced variation of properties. Therefore the ductile brittle transition temperature shift caused by ageing and cyclic damages for those reactor parts which are not subjected to neutron fluence effect were assumed equal to zero when assessing brittle fracture resistance. Taking into account, that the RPV of the first generation were made without anticorrosive cladding the examination of their inner surface was carried out and also the assessment of corrosion allowance for most unfavorable conditions for 15 years after the design service life completion.

Based on the investigation results the necessary information was given to the general designer of NPP with the WWER reactors (OKB "Gidropress") for conducting strength calculation and substantiating integrity of the main equipment (reactor pressure vessel and upper head) within 45 years of operation.

KEY WORDS: degradation, mechanical properties, reactor pressure vessel, base metal, circumferential weld, operation factor, neutron fluency, thermal ageing, cyclic damage, corrosive resistance, irradiation embrittlement, ductile-brittle transition temperature, service life.

INTRODUCTION

The reactor pressure vessels (RPV) WWER-440 of the first generation for 3 and 4 units Novo-Voronezh NPP and 1 and 2 units Kola NPP were manufactured at Izhora plant and put into operation in the early seventies. And in the early nineties the circumferential welds No.4 (weld joining core shells are subjected to maximum fluence neutron during the whole operation time) of these RPV were subjected to annealing for 100 hours at 475^{o}C. After recovering annealing these reactors are being under operation over a period of 10 years. Before the design service life (30 years) completion a problem of their further operation should be solved. First of all it is necessary to assess technical state of RPV itself. The present report is devoted to this issue: a technical conclusion about the technical state of RPV WWER-440 is made on the base of information about RPV materials, design and production technology as well as about the variation of material mechanical properties under the influence of operating conditions during the period of operation time and possibility of their further safe operation during 10-15 years.

The reactor pressure vessel WWER-440 consists of four parts: flange, two shells of nozzle zone (upper and lower), support shell, two shells of core zone (upper and lower) and elliptical bottom. These parts are joined to one another with six circumferential welds using submerged welding (filling wire Sv-10XMFT, flux AN-42). For submerged welding of root one uses wire Sv-08A and AN-42 flux.

All RPV shells (except elliptical bottom) are made of forgings produced from 15X2MFA steel. The thickness of core zone shells was 140 mm, the thickness of nozzles zone shells in region of weld No.6, joining these shells – 200 mm. Plates from the same steel were used to produce elliptical bottom, before plates forming they were welded using electro-slag welding (wire – Sv-13X2MFT, flux – OF-6).

The nozzle zone shells of RPV contain 6 nozzles each to which sleeves having an inner diameter 500 mm and a wall thickness 70 mm are welded up, they are made from the austenitic stainless steel 08X18N10T. When welding different steels (pearlitic 15X2MFA steel with austenitic 08X18N10T steel) the buttering cladding with EA-395/9 electrodes (the first layer – 4^{+2} mm thickness)and with EA-400/10Y electrodes (the second layer – up to the total thickness of clad layer equal to 9 mm). This procedure is carried out at the plant manufacturing reactors, because after the cladding production the high temperature annealing (670°C) for 15 hours is carried out. The joining of clad edges of nozzles with adapters from 08X18N10T steel (weld No.10) was carried out using manual arc welding (MAW) with EA-400/10Y electrodes with a subsequent heat treatment. The inner surface of RPV of the first generation is not protected with anticorrosive cladding against the coolant influence during operation.

The requirements of chemical composition and mechanical properties of base materials, welds and buttering cladding for all materials used for manufacture of RPV WWER-44-0 of the first generation are given in Tables 1 and 2.

Table 1. Requirements for chemical composition of different units of the first generation RPV WWER-440

Unit	Material	Element content, %									
		C	Si	Mn	Cr	Mo	V	Ni	Cu	S	P
Reactor	15X2MFA	0,13-0,18	0,17-0,37	0,30-0,60	2,50-3,00	0,60-0,80	0.25-0,35	≤0,40	≤0,30	≤0,020	≤0,020
	Sv-10XMFT	0,04-0,12	0,20-0,60	0,60-1,30	1,20-1,80	0,35-0,70	0,15-0,30	≤0,30	≤0,25	≤0,015	≤0,042
	Sv-13XMFT	0.10-0.16	0,17-0,37	0,30-0,60	2,00-3,00	0,35-0,70	0.25-0,35	≤0,30	≤0,25	≤0,020	≤0,020
Sleeve	08X18N10T	≤0,08	≤0,8	≤1,5	17,0-19,0	-	-	10,0-11,0	≤0,30	≤0,020	≤0,035
	EA-395/9	≤0,11	≤1,20	0,8-2,0	12,5-17,0	4,0-6,5	-	20,0-26,0			
	EA-400/10У	≤0,10	≤0,60	1,1-3,1	16,8-19,0	2,0-3,5	0,30-0,75	9,0-12,0		≤0,025	≤0,030

Table 2. Requirements for mechanical properties of different units of the first generation RPV WWER-440.

Unit	Material	At 20 °C					At 350 °C			
		UTS, kg/mm^2	YS, kg/mm^2	δ, %	ψ, %	KCU, kgm/sm^2	UTS, kg/mm^2	YS, kg/mm^2	δ, %	ψ, %
Reactor	15X2MFA	58	50	14	50	8	50	40	14	50
	Sv-10XMFT	55	44	14	50	6	48	38	12	45
	Sv-13XMFT	58	44	14	50	8	50	40	12	45
Sleeve	08X18N10T	50	20	38	45	—	32	18		
	EA-395/9	60	37	13	15	—	50	35	15	30
	EA-400/10У	55	35	18	30	—	44	30	15	35

ASSESSMENT OF BASIC OPERATING FACTORS INFLUENCE ON MECHANICAL PROPERTIES

It is important to know material mechanical properties not only in as-produced condition but also with consideration of their variation in the process of operation (temperature, time, cyclic and radiation damages, etc.) in order to solve a problem of a possible lifetime extension of NPP RPV. The level of mechanical properties of a base metal and weld metal (which is determined in accordance with material certifications – Table 2) is preliminary taken into account at the design stage by selecting basic sizes. In the process of manufacture this level of properties is provided and as a rule the material properties as higher and stored (safety margin). Nevertheless in the process of operation due to a prolonged material being under conditions of elevated temperatures, influence of cyclic loads and radiation a remarkable decrease of properties take place and this requires an obligatory checking of properties after a prolonged operation above 10^5 hours. These checks are carried out at NPP by the usual maintenance of the main circulating piping after 100000 hours operation time according to the normative documentation [1].

However for the other equipment elements including reactor pressure vessels such checking was not foreseen. Subsequently, six complements of surveillance specimens made from base metal and weld metal (weld No.4) were set in RPV opposite and above the core zone in special containers and withdrawn in 1, 3 and 5 operation years. Each complement contains 12 Charpy specimens, 12 COD specimens and 6 tension specimens from each material investigated. By testing surveillance specimens one can judge of the variation of RPV material properties in the process of operation. Unfortunately, this information is absent for RPV of the first generation because surveillance specimens are lacking. Nevertheless in the early nineties while annealing RPV the templets were cut out and specimens were fabricated in order to determine metal mechanical properties, including the ductile-brittle transition temperature (DBTT) T_{KO} for base metal and metal of weld No.4.

According to PNAE G-7-002-86 brittle fracture resistance is considered to be provided for selected calculated crack like defect in operation regime considered $K_I \leq [K_I]_i$, where $[K_I]_i$ is the permissible value of stress intensity factor. According to Strength Calculation Norms [2] in this case T_K is determined by the formula:

$$T_к = T_{ко} + \Delta T_{ag} + \Delta T_N + \Delta T_F,$$

where T_{KO} - initial ductile-brittle transition temperature;

ΔT_{ag} – shift of DBTT due to thermal ageing;

ΔT_N – shift of DBTT due to cyclic loading;

ΔT_F - shift of DBTT due to neutron irradiation.

THERMAL AGEING OF MATERIALS

The issues of thermal ageing of 15X2MFA steel and its welds are given in detail in [3, 4]. However the base of these tests by material certification is limited in time and as a rule does not exceed 10^4 hours. Therefore to as certain material behavior on a more prolonged time base is important to possess information obtained by material properties inspection directly at NPP after 100000 hours operation according to [1]. At present such investigations are not enough. In [5] the information of real properties of austenitic piping of the primary circuit of four units Novo-Voronezh NPP with WWER-440 is given. It has been shown that the mechanical properties degradation of materials (08X18N10T steel and its welds produced by MAW using with EA-400/10Y electrodes) does not take place. The same result was obtained by the other investigators [4, 6, 7] as applied to pipe-lines from steels 20 and 22K and also their welds. Fig.1 also shows the variation of mechanical properties of 15X2MFA steel by thermal ageing under various operating conditions (time). As can be seen the thermal exposures at temperatures close to operating temperature having a duration above 10^4 hours do not result in variation of mechanical properties of steels and their welded joints. This conclusion also corresponds to the variation of DBTT. Nevertheless for weld metal (SAW wire Sv-10XMFT, flux AN-42) a tendency to some increase of after thermal ageing is observed.

The investigations [6-7] determining thermal ageing effect on impact energy temperature dependence for base metal and weld metal of welded joints from 15X2MFA steel show that by the exposure at 350°C for 50000 hours practically there is no changes as compared with the initial state (τ=0) in these materials (Fig.2). As after the thermal ageing at 350°C for 50000 hours the DBTT shift is less than 10°C, and the actual operating temperature of RPV of the first generation did not exceed 300°C a conclusion was drawn in the mutual investigation with the Finnish specialists [6-7] that the value ΔT_{ag} is equal to 0 for base metal of 15X2MFA steel and its circumferential welds, produced by SAW (wire Sv-10XMFT, flux AN-42) as specified in PNAE G-7-002-86 [2]. It should be noted that it is very difficult to determine experimentally the shift ΔT_{ag} due to thermal ageing, because it is based on test results of Charpy specimens by various duration and ageing temperature. Using the Kholomon parameter and available test results of Charpy specimens it is possible to predict DBTT shift absence due to thermal ageing both 15X2MFA steel and its circumferential welds by the lifetime extension of RPV of the first generation by 10-15 years.

As to higher alloyed materials, namely 08X18N10T steel, the metal of buttering cladding and welds, joining adapters with cold and hot nozzles of nozzle zone shell, at the operating temperature of the LWR WWER-440 which does not exceed 300°C, their thermal ageing does not occur during the whole service life (30 years) and this was demonstrated in investigations on standard mechanical properties [8]. The same results were obtained by determining brittle fracture resistance of buttering cladding metal and weld metal. In this research of two compositions of clad metal (04X19N11M3 and 08X16N25AM6) the J-R curves in as- produced condition and after thermal ageing at 350°C for about 10000 hours are practically the same.

ACCUMULATION OF CYCLIC DAMAGES

The reactor pressure vessel is subjected to the influence of cyclic loads by various operating conditions. At normal operating conditions for 30 years we can see the next regimes:

- start from cold condition – 300 cycles;
- semi-hot start – 700 cycles;
- normal stop with cooling – 1000 cycles;
- emergency stop – 600 cycles;
- hot start – 600 cycles;
- complete discharge – 90 cycles;
- rapid start from 10% to 1005 – 90 cycles;
- step by step loading from 50% to 100% - 200 cycles;
- step by step reduction from 100% to 50% - 200 cycles;
- switching-off of pressure transducer of steam generator operation under power 200 cycles;
- separate hydro-testing of the primary circuit on density 14 MPa – 70 cycles;
- separate hydro-testing of the primary circuit on strength 17.5 MPa – 70 cycles.

In total the number of cycles during the whole service life exceeds 4000.

Under the above stated operating conditions the level of acting stresses is different and at the design stage the chief designer estimates the accumulation of cyclic damages, which should be less than 1 for the whole set of operating conditions. As a rule the real number of cycles during the operation is less than specified in the design. It is reasonable that in case of lifetime extension by 15 years, the total number of cycles increases therefore it is necessary to assess the effect of cyclic damages on material brittleness. This assessment should be primarily carried out for those zones of RPV in which during operation the highest concentration of stresses is observed. These zones are shells of nozzles zone in the region of passing from Du-500 nozzle to the cylindrical part at the inner surface. As shown in [10, 11] the accumulation of fatigue damages in metal of this zone causes the change of brittle fracture resistance. In accordance with Strength Calculation Norms [2] by the determination of T_K the cyclic damage is characterized by the value ΔT_N which should be determined first of all for base metal. In [12, 13] the determination of ΔT_N was performed for 15X2MFA steel. For this purpose plane specimens (42x10 mm) were fabricated from this steel and cyclic loading tested on symmetrical cycle of the given strain $\varepsilon_a = 1.2\varepsilon_{0.2}$ (Fig.3). The cyclic test were carried out so that the accumulated damage was $n = N/N_{cr} = 0.1$ and 0.01. Since by testing these specimens by the strain amplitude equal to 1.2 from yield strain the number of cycles to a crack nucleation was 30000 cycles the ageing of specimens was carried out using 3000 cycles (n=0.1) and 300 cycles (n=0.01). The standard Charpy specimens (10x10x55 mm) were fabricated from two series of previously cyclic loaded specimens for base metal and weld (12-16 specimens from each) and they were impact bending tested at the temperature within range of –60 to +60°C. The test results after cyclic damages are given in Fig.3 in comparison with test results of specimens from the same material made from metal having n=0. As can be seen the accumulated cyclic damages do not influence the impact strength temperature dependence of this steel.

The similar tests of the other melt of 15X2MFA steel were carried out by a higher value of strain amplitude ε_a=0.61% and n=0.1, as well as a weld metal fabricated using SAW (Sv-10XMFT, AN-42) at two levels of strain amplitude ε_a=0.22% and ε_a=0.61 % by n=0.1. The test results of base metal and weld metal show that the shift ΔT_N=0 and cyclic damage may not be taken into account by determining the DBTT. Earlier the same result was obtained in [14] when assessing 15X2MFA steel damage in the absence of neutron irradiation.

RADIATION EMBRITTLEMENT

As shown above, the radiation embrittlement has a dominating influence on the degradation of pressure vessel material (base metal and weld) properties. In estimations of RPV brittle fracture resistance T_K to the EOL the DBTT shift due to neutron irradiation ΔT_F has the maximum value. It is defined on the formula

$$\Delta T_F = A_F (F_n / F_o)^{1/3},$$

where A_F is the coefficient of irradiation embrittlement; F_n - neutron fluence with E≥0.5 MeV, neutr/m^2; $F_o = 10^{22}$ neutr/m^2. The formula is true for the equipment at $10^{22} < F_n < 3\times10^{24}$ neutr/m^2.

The coefficient of radiation embrittlement depends on irradiation temperature, material alloying composition, content of harmful impurities (P and Cu). According in Russian Code [3] the A_F values are defined from the correlation's A_F=800(P+0.07Cu) at the irradiation temperature 270°C, A_F=800(P+0.07Cu)+8 at the irradiation temperature 250°C, where P and Cu - the content of phosphorus and copper in percent.

As was mentioned above, the service life of WWER-440 reactors is determined by brittle fracture, and is limited by a circumferential weld. The DBTT of this weld equals to 150-200°C after 10-15 years of operation, thus making a further operation of reactor impossible because of a danger of pressure vessel brittle fracture (Fig.4).

As this operation time is remarkably less than the design service life (30-40 years), special measures were necessary, especially the annealing of this circumferential weld. This procedure was successfully carried out on 15 reactors in Russia, Armenia, Bulgaria and Slovak Republic.

Since in the middle of nineties our Institute together with other organizations has been performing the work on the program of the validity of a possibility to extend lifetime of WWER-440/230 RPV units 3 and 4 Novo-Voronezh NPP and units 1 and 2 Kola NPP. According to this program the samples were cut out from the wall inner surface metal in the region of the maximum fluence attack on core zone shell and in the region of circumferential weld. Sub-sized Charpy specimens having dimensions of 3x4x27 and 5x5x27.5 mm were made from samples and tested on impact strength. This permitted to determine DBTT of base metal and weld metal after a prolonged operation. In the conduction of works the main attention was paid to material brittle fracture resistance to the end of designed service life and also after supplementary 10 and 15 years of operation. Taking into account that these RPV were subjected to intermediate recovering annealing, the assessment of radiation embrittlement kinetics of materials with consideration for this procedure was also carried out. The program also provides the use of alternative approaches to metal brittle fracture resistance assessment, based directly on fracture toughness tests of specimens having small dimensions (5x10x27.5 mm), fabricated from samples after their prolonged operation. These investigations are still going on and the final conclusion has not yet been drawn. The preliminary results show that these pressure vessels can be under operation above the designed service life and their brittle fracture resistance will be provided.

CORROSION RESISTANCE OF MATERIALS

The pressure vessels of WWER-440 reactors made of pearlitic steel 15X2MFA without anticorrosive cladding are subjected to corrosion in the coolant of the primary circuit in the process of operation. The following zones are most susceptible to damage: core zone shell, bottom, flange joint between pressure vessel and cover and also ranges of dissimilar welded joint between nozzles and adapters from the austenitic stainless steel 08X18N10T. In WWER-440 RPV of the first generation the area of dissimilar joint are protected from coolant effect with jackets made from stainless steels which are welded up to nozzle zone with welds.

The general corrosion rate of pearlitic and austenitic steels in reactor environment of the primary circuit (determined in CRISM "Prometey" in 1977-1980 on the base of stand test results of the duration 10000 hours) is within 0.001-0.002 mm/year. These test results fully conform with the similar characteristics obtained by other investigators [15]. With the availability of heat transfer or crevice gap 0.01+0.005 mm (in case of continuity disturb of weld No.11) the general corrosion rate of the type 08X18N10T steels increases by 2-3 times and this was also defined by stand testing for ≈ 10000 hours in water of the chemistry corresponding to the primary circuit water.

Besides under the above-stated conditions pearlitic steels show a tendency to pitting due to the reduction of break-down potential of surface protective film. The incubation period of pitting formation varies from 1 to 5 years. The number of pits over the area 1 m^2 is within 10-60 pits. The rate of local corrosion in pitting exceeds the general corrosion rate by 2-3 times under these conditions.

Thus while assessing RPV corrosion resistance, i.e. residual corrosion allowance for the next 15 years after exhausting design service life and lifetime of WWER-440 of the first generation, the corrosion influence is estimated proceeding from the fact that even under most unfavorable conditions the maximum general and local corrosion of materials contacting with coolant of the primary circuit will not exceed 0.002-0.006 and 0.01-0.02 mm/year, respectively.

PREDICTION OF MATERIAL MECHANICAL PROPERTIES AFTER A PROLONGED OPERATION

The above presented variation of mechanical properties of reactor pressure vessel materials under the influence of various operating conditions (thermal aging, radiation embrittlement, cyclic damages, etc.) permit prediction of actual characteristics (UST, YS, Z, DBTT) of materials for more prolonged operation time. The properties are given below in Table 3.

Table 3. Predicted mechanical properties of RPV components after operation for 45 years.

RPV components	Type of steel	UTS MPa at 350°C	YS MPa at 350°C	Z, % at 350°C	$\sigma_{в}$ MPa at 20°C	$\sigma_{т}$ MPa at 20°C	Z % at 20°C	DBTT $T_{ко}$ °C
Elliptical bottom	15X2MFA	490	392	55	589	432	55	20
Electro slag weld	Sv-13X2MFT	490	412	40	589	441	50	40
Core shell δ=140 mm	15X2MFA	490	392	55	589	490	55	0
Circumferential weld	Sv-10XMFT	470	372	50	539	441	50	40
Nozzle shell δ=200 mm	15X2MFA	490	392	55	589	432	55	0
Flange	15X2MFA	441	392	55	540	432	55	0
Adapter Du-500	08X18H10T	353	167	40	491	196	40	-
Buttering cladding	EA-395/9	490	343	40	588	392	35	-
Buttering cladding	EA-400/10Y	392	235	35	539	343	30	-

CONCLUSION

The metal state assessment of RPV of the first generation after a prolonged operation for 30 years has shown that:

1. The variation of actual values of mechanical properties of base metal, weld metal and cladding not subjected to the influence of neutron fluence is insignificant and while conducting strength calculations by chief designer is necessary to use guaranteed values of thermal-physical and mechanical properties.
2. When assessing RPV brittle fracture resistance with consideration of insignificant cyclic loading the DBTT shift ΔT_N may be assumed equal to 0.
3. The DBTT degradation of base metal and weld metal, produced by SAW and not subjected to neutron fluence effect is insignificant and therefore the value ΔT_{ag} may be assumed equal to 0.

4. Maximum DBTT shift is estimated by neutron fluence effect. For RPV the effect is connected with weld metal. The DBTT value for weld metal depends on the content of harmful impurities, first of all, on content of phosphorus and copper.
5. The corrosion allowance assessment under most unfavorable conditions by lifetime extension by 15 years after exhausting design service life will not exceed 0.006 and 0.02 mm/year for general and local corrosion respectively.

On the basis of performed analysis and conducted investigations the chief designer of WWER-440 RPV of the first generation was given guaranteed values of mechanical properties of separate parts of reactor pressure vessel (flange, nozzles zone shell, core zone shell, bottom, adapter). The same information about properties was also presented for welds and cladding. These properties including fracture toughness characteristics are necessary for Chief designer to carry out calculations of static, cyclic and brittle strength for the lifetime extended.

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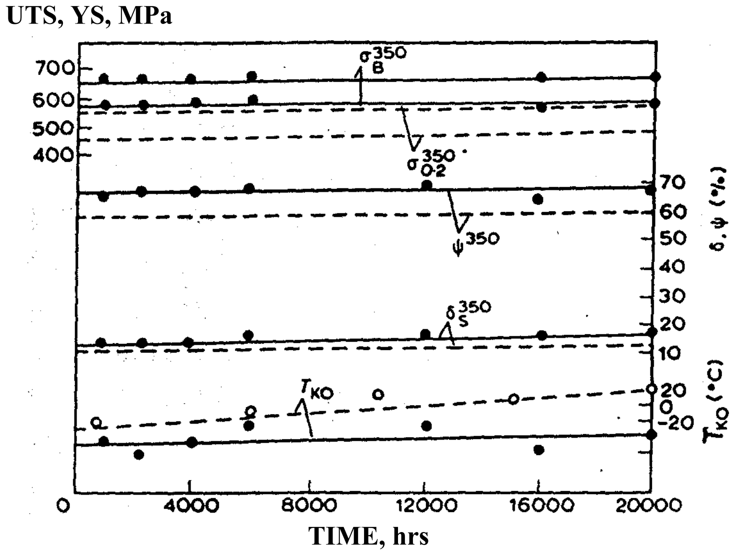


Fig.1. Dependence of the mechanical properties 0f 15X2MFA steel (—) and its weldments (---), produced by SAW under flux with Sv-10XMFT wire, on prolonged thermal exposure at 350°C.

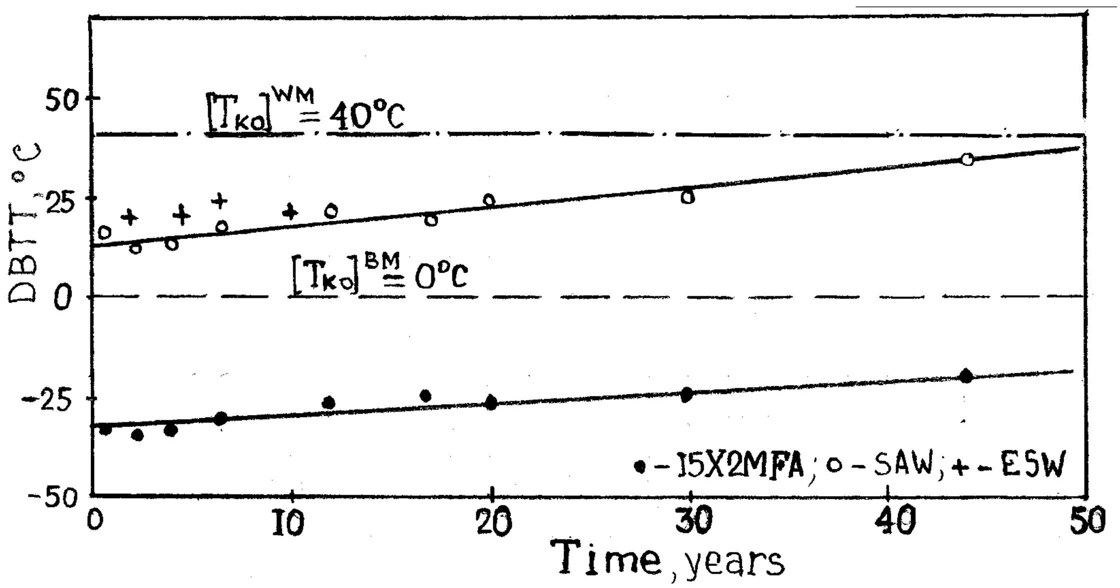


Fig.2. DBTT values variation for 15X2MFA steel and its welded joints after prolonged operation time.

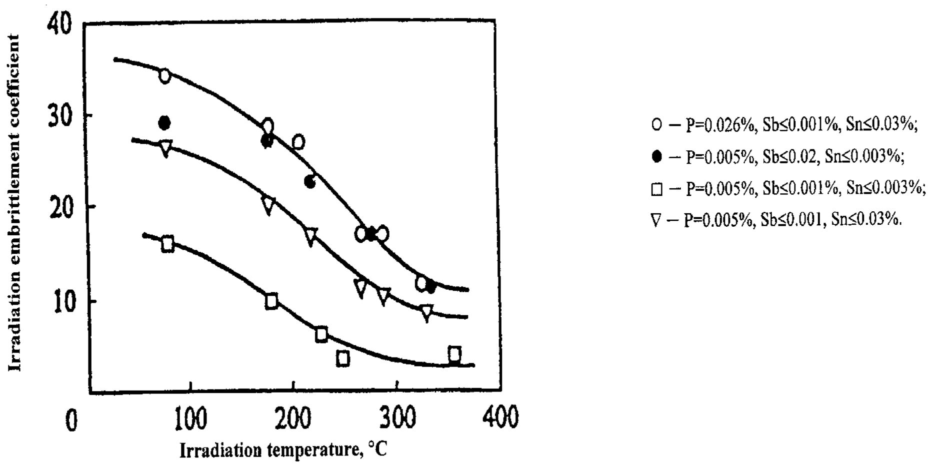
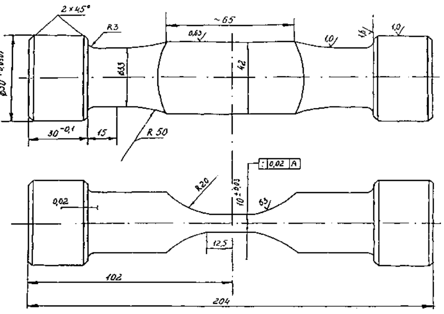


Fig.4. Irradiation temperature effect on irradiation embrittlement coefficient A_F of Cr-Mo-V steel with various content of harmful impurities.



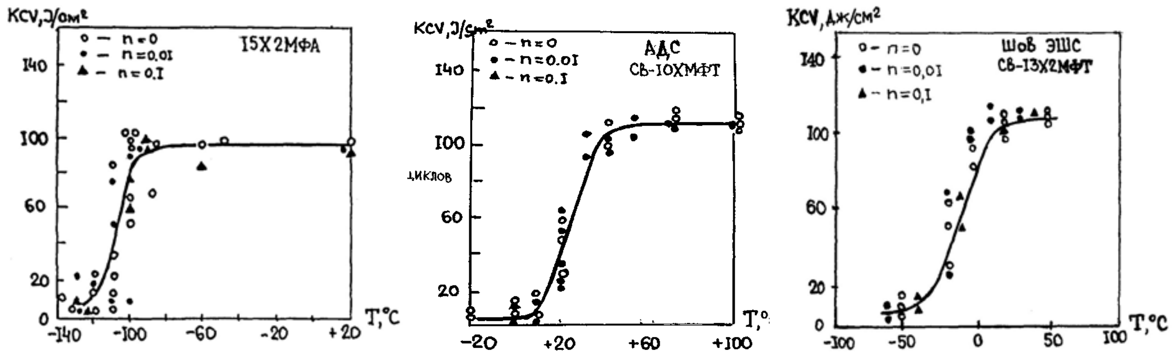


Fig.3. Effect of accumulated cyclic damages on impact strength temperature dependence for 15X2MFA steel and its welded joints, produced by SAW and ESW.