Application of Annealing for WWER Vessels Life Extension

Vladimir I. Badanin
Tznii Km "Prometei", Leningrad, USSR
Yuri G. Dragunov, Valentin G. Fedorov
OKB "Gidropress", Moscow, USSR
Igor V. Gorynin, Vladimir A. Nickolaev
Tznni Km "Prometei", Leningrad, USSR

ABSTRACT

Safe operation of NPP is greatly dependent on the guarantee of reactor vessel brittle failure strength with account for the effect of radiation embrittlement of vessel material.

Recovery of irradiated material properties is principally important way to extend radiation life of reactor vessel.

The aim of this report is to demonstrate the efficiency of annealing for recovery of vessel material properties and extension of its service-life.

Substantiation method is the investigation of effect of annealing temperature and time, fast neutron fluence and metallurgical factors (impurity element content) on recovery of irradiated metal properties, investigation of laws of radiation embrittlement at repeated irradiation after annealing.

The investigation results made it possible to substantiate the expediency of application of annealing to extend vessel service life.

In May,1987, the first pilot-commercial annealing of reactor vessel of Novo-Voronezhskaya,III,NPP was performed.

Carried out set of investigations and developed equipment allowed to create and test the process of reactor vessel annealing with the aim of improvement of reactor vessel safe operation and extension of service life.

INTRODUCTION

Safe operation of nuclear power plants is greatly dependent on the guarantee of reactor vessel brittle strength with regard for the effect of steel radiation embrittlement.

Processing the available data on radiation strength of 15X2MΦA steel and weld metal allowed to set an empirical relation of radiation embrittlement factors against impurities content.
For base metal : $A_F = 1100\ \%P - 2$
For weld metal : $A_F = 300\ (\%P + 0{,}07\%\ Cu)$, where %P and %Cu -

percent of phosphorus and copper content in weld metal.

The analysis of radiation embrittlement factors,assumed on the basis of the given relations, has shown that for the base metal A_F values do not impose restrictions on reactor vessel radiation life, values of radiation embrittlement factors of weld metal exceed those accepted in the design.

With regard for the analysis results more strict requirements were introduced into the normative-technical documentation with respect to copper and phosphorus content in metal ($Cu \leqslant 0,10\%$, $P \leqslant 0,012\%$) for vessels being manufactured. As to reactor vessels in operation a shift of critical brittle temperature of weld metal due to irradiation, for a number of vessels designed prior to putting in force "Norms for strength calculation" in 1972, may impose a restriction on reactor vessel operation and were recommended measures realization of which permits to ensure reactor safe operation from the point of view of brittle strength assurance/1/.

EXPERIMENTAL STUDY RESULTS

Thermodynamic instability of various radiation defects on heating up **irradiated** metal results in elimination of these defects and recovery of mechanical properties of irradiated metal. In such a manner radiation embrittlement effect may be completely eliminated or remarkably mitigated at irradiated metal annealing. This provides pricipal scope for improvement of steel brittle strength and, therefore, allows to ensure reactor vessel operation without reaching potentially dangerous boundary of metal embrittlement permitting to improve remarkably NPP safe operation during the design service life and to open an opportunity for extension reactor vessel operation beyond the design service life.

Studies on substantiation of temperature-time conditionsof reactor vessel annealing involved the following:
-establishing general laws of metal radiation embrittlement depending on metallurgical considerations, first of all, content of impurity elements and coolant effects;
-substantiation of temperature-time conditions of annealing by means of study of effect of annealing temperature and time, fast neutron fluence upon recovery of material properties;
- study of effect of impurity content in metal on recovery of irradiated metal properties;
- study of embrittlement laws at repeated irradiation after annealing.

Studies were carried out on materials produced according to standard process used for manufacturing reactor vessel shells located opposite the core (15X2MФA steel grade and weld metal performed with Cв 10XMФT welding wire).

To provide for irradiation conditions being controlled irradiation was implemented in NPP reactors in places of surveillance-specimens location.

Fig.1 represents the results of experimental studies on the effect of temperature difference in annealing ($T_{отж}$) and in irradiation ($T_{обл}$) upon the degree of critical brittle temperature recovery /1/.

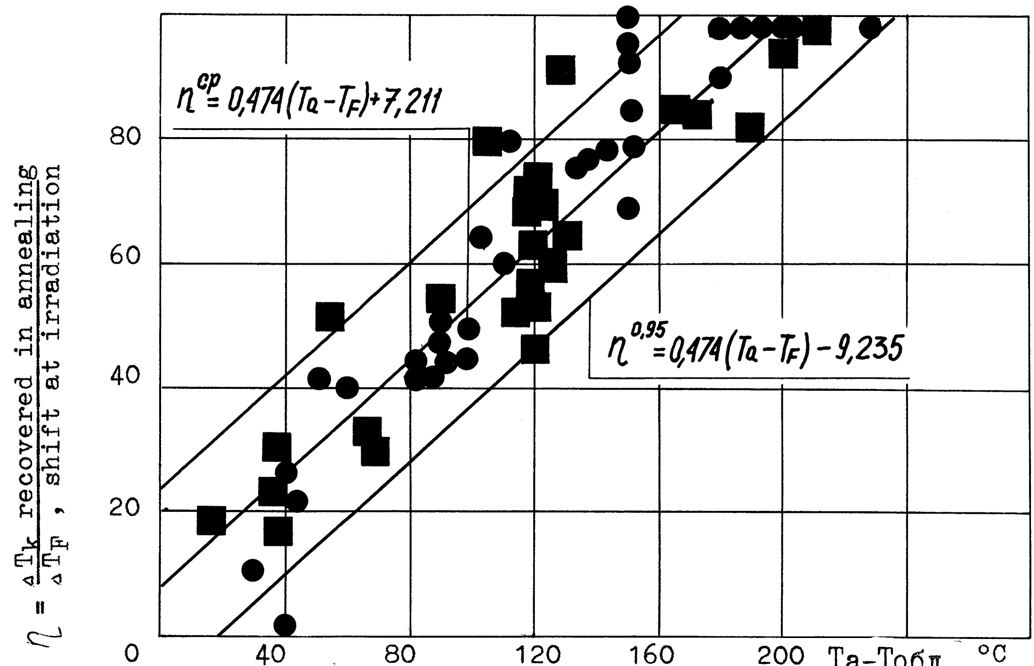

Fig.1 Effect of difference in annealing and irradiation temperature on recovery degree of critical brittle temperature

The investigations were carried out on specimens of 15X2MФA steel grade and of weld metal, phosphorus content in weld metal being varied from 0,012% to 0,055%, copper content - from 0,08 to 0,22%. Values of fast neutron fluence were within the range from 3.10^{19} to $4,9.10^{20}$ I/cm2.

The band of experimental data spread is caused by a wide range of irradiation temperature and by significant variation interval of impurity elements content in metal; nevertheless, the data given in Fig.1 show the general tendency to increase the degree of recovery of critical brittle temperature of irradiated metal at increase in difference of irradiation and annealing temperatures. From these data it also follows that depedence of degree of metal properties recovery upon difference between annealing and irradiation temperatures is approximately the same irrespective on the content of alloying and impurity elements.

Studies of neutron fluence effect on recovery of critical brittle temperature of weld metal were performed, phosphorus and copper content in metal was 0,028% and 0,18%, respectively, neutron fluence - $1,0.10^{19}$, $1,0.10^{20}$, $1,9.10^{20}$ and $4,9.10^{20}$ cm^{-2}, i.e. fluence values differed almost by 50 times.

Study results are given in Fig.2. For the investigated material annealing results in one and the same residual embrittlement of metal, i.e under the given heat treatment conditions metal critical brittle temperature after annealing does not depend on neutron fluence /1/.

Fig.3 represents experimental data on the effect of annealing time on degree of recovery of material critical brittle temperature. These results show that increase of annealing time above 100 hours practically has no effect on the degree of properties recovery.

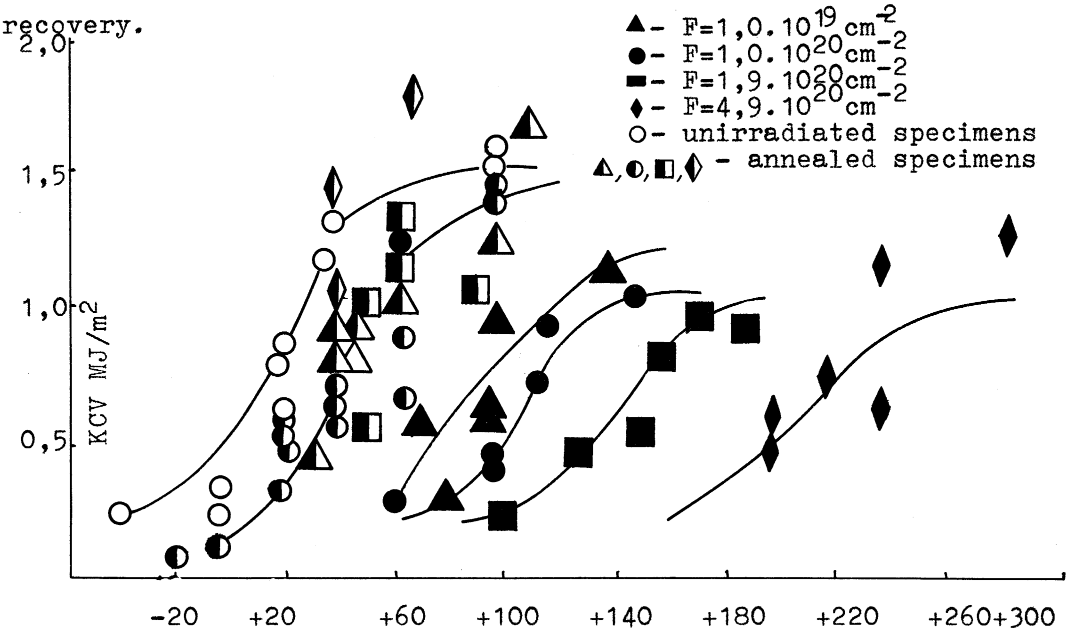

Fig.2. Recovery of weld metal properties against fast neutron fluence

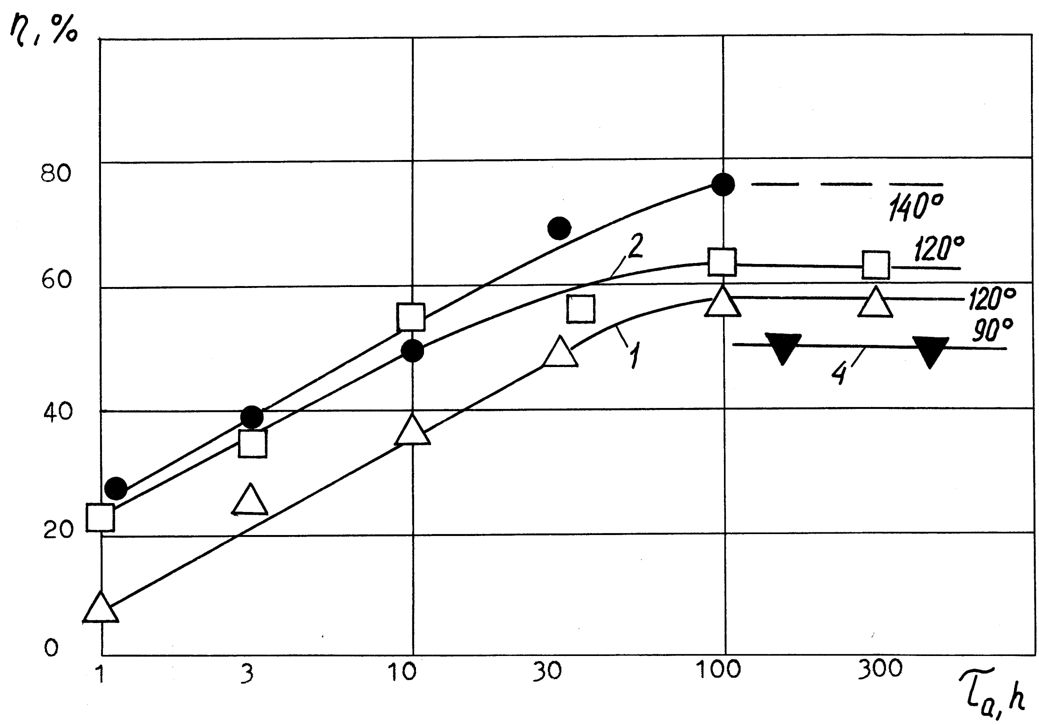

Fig.3. Effect of time of annealing on the degree of recovery T_k of vessel materials. Figures at the curves denote difference in annealing and irradiation temperature (Ta - Тобл),°C

When predicting reactor vessels radiation life determination of correspondence of estimation of degree of materials radiation embrittlement based on accelerated tests at high neutron flux and embrittlement degree at long-term operation of vessel is of great importance. To the same extent it is important to compare annealing efficiency by the test results of specimens irradiated at high neutron flux and specimens of reactor vessel metal after its long-term operation. With this aim tests of annealing efficiency on material of test coupon cut out of the reactor vessel of Novo-Voronezhskaya,I,NPP after 20 years of operation are envisaged /3/.

On practical application of annealing with the aim to extend the reactor vessel life it is very important to know the laws of radiation embrittlement of materials under conditions of repeated irradiation, annealing efficiency after repeated irradiation. Data on variation of critical brittle temperature of weld metal during irradiation-annealing-irradiation-annealing cycle are indicative of the fact that the rate of metal radiation embrittlement at repeated irradiation after annealing does not exceed the rate of embrittlement at initial irradiation. As to the efficiency of repeated annealing critical brittle temperature of metal is being restored to the value it has after initial annealing /2/.

PERFORMING WWER REACTOR VESSEL ANNEALING

On the basis of these study results in May 1987 was performed pilot-commercial annealing of the weld located in the core area of NVNPP, unit III, reactor vessel.

Before annealing weld metal was chipped in the depth of 2,5 to 4 mm to determine phosphorus and copper content in metal. The analysis results showed that the value of copper and phosphorus content in metal is below than those assumed in substantiation of reactor vessel radiation life. Measurement of weld metal hardness showed its variation by 50 units of HB.

Measurements of coercive force and residual magnetization also show remarkable variation of these characteristics in the course of annealing. On the basis of the analysis of investigations results of annealing efficiency, performed beforehand, was made a conclusion that critical brittle temperature of weld does not exceed 55°C after annealing.

In the course of annealing temperature of the cavity equipment and of structural concrete did not exceed the allowable values. With regard for adequate efficiency of metal properties recovery and positive results of metal ultrasonic inspection the reactor vessel was allowed for further operation.

In 1988 reactor vessel of Armyanskaya NPP,unit I, and GDR "Bruno Leuschner" NPP, unit I, were also subjected to annealing.

CONCLUSION

Thus, the conducted comprehensive studies and designed equipment allowed to develop and test the process for the reactor vessel annealing to improve the reactor vessel safe operation during the design life and extend its life.

REFERENCES

Amaev,A.D., Badanin, V.I., Dragunov,Yu.G.,Kryukov, A.M., Nickolaev,V.N.,Fedorov,V.G. Substantiation of application of annealing to improve safe operation of VVER vessels. Report at the French-Soviet seminar on reactor safety,1988,Sept.26-30, Avignon.

Amaev,A.D., Dragunov Yu.G., Kryukov,A.M., Lebedev,L.M., Sokolov,M.A. Investigation of irradiation embritttlement of reactor VVER-440 vessel materials. Proc. of IAEA Specialists' Meeting on Reactor Pressure Vessel Behaviour under Transient Conditions Caused by Thermal Shock, 1986, May 27-30 , Plzeň,Czechoslovak Socialist Republic.

Amaev,A,D.,Alexeenko,N.N., Dragunov,Yu.G., Krasikov,E.A., Kryukov,A.M., Morosov,A.M., Nickolaev,V.N. About the investigation program of test coupon materials cut out of NVVNPP unit I reactor vessel.