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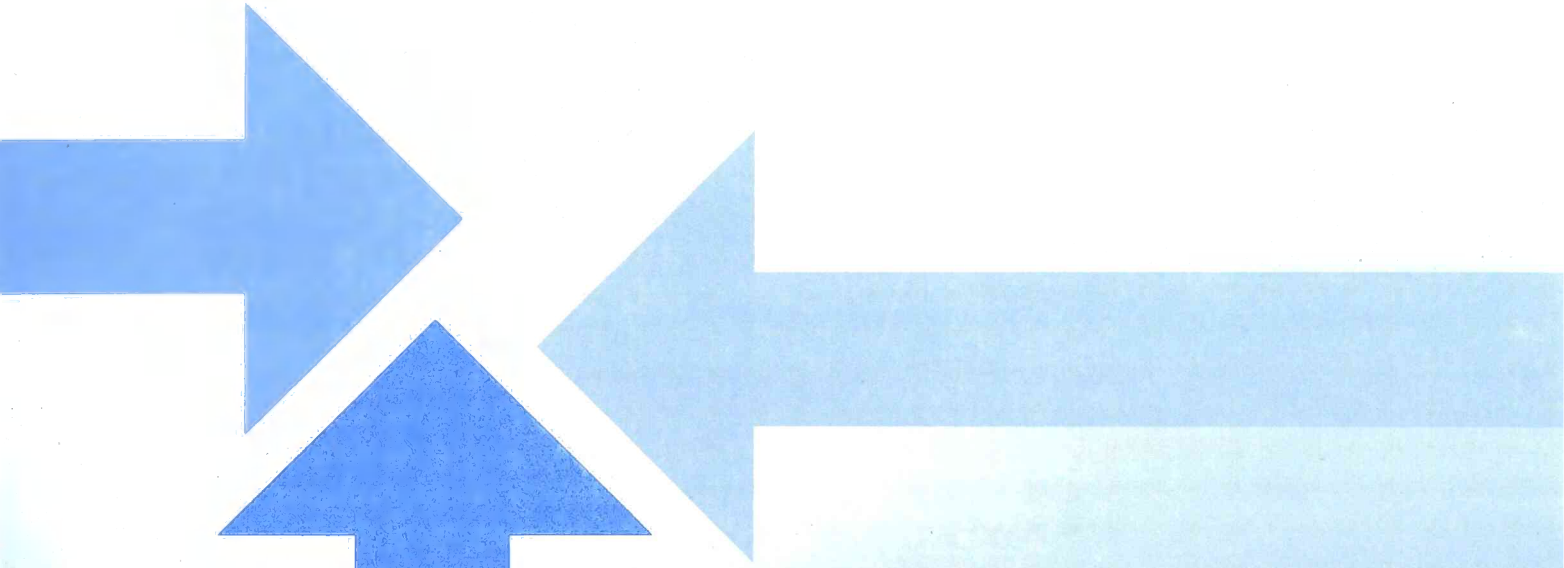
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

ENHANCED SURVEILLANCE OF NUCLEAR REACTOR PRESSURE VESSELS



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Current reactor pressure vessel surveillance practice relies heavily on the Charpy-V Notch (CVN) impact test, to which actual fracture toughness bounds are indexed. This methodology entails significant uncertainties susceptible to penalize operation flexibility and to adversely affect plant life management decisions of ageing reactors.

The enhanced surveillance strategy developed in Belgium allows to alleviate these drawbacks. The R&D effort to demonstrate this new capability encompasses tests on trepans from decommissioned vessels, like the Belgian Reactor 3 (BR3), and accelerated irradiations in the materials testing reactor BR2.

INTRODUCTION

The Reactor Pressure Vessel (RPV) is a crucial component whose integrity is of major concern to ensure the safety of a nuclear power station. The susceptibility of the RPV to irradiation embrittlement clearly constitutes a central material degradation issue for reactors. RPV failure is unacceptable at any time, vessel replacement is extremely costly and dry annealing is still in a demonstration phase for Western type reactors.

As the regulation to assess RPV embrittlement is based on empirical arguments, it is necessary to try to understand the underlying physical processes responsible for material degradation.

SCK•CEN and Tractebel Energy Engineering have developed an Enhanced

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Surveillance Strategy encompassing upgraded fracture toughness mechanics testing, microstructural interrogation and advanced modeling. This methodology is the result of more than 20 years of research and development.

CLASSICAL SURVEILLANCE

The actual surveillance of the vessel is accomplished by means of surveillance capsules, irradiated to different fluences near the inner side of the RPV wall at beltline height. At these positions the capsules experience accelerated exposure, relative to the RPV wall. The capsules are loaded with test specimens (CVN, Tensile and Compact Tension) prepared from surveillance blocks representative of the vessel materials. The capsules contain moreover temperature monitors and extensive dosimetry to determine the neutron fluence received by the specimens.

Mechanical tests are usually limited to tensile tests and CVN impact tests. These tests are performed in the initial and irradiated material conditions. Tensile tests are usually performed at two temperatures. The test indicates the increase of the yield stress and the loss of ductility of the RPV material after irradiation.

The bulk of the information used for the RPV surveillance programme comes from the CVN impact tests that reveal, as a function of irradiation fluence, the evolution of the RPV transition curves (energy, lateral expansion, shear fracture appearance (SFA)). As is well known, two effects due to irradiation occur. The transition curve shifts to higher temperature and in the US regulation applied in Belgium, this shift is measured at the 41 Joule energy level. The second phenomenon on the Charpy plot is a lowering of the upper shelf energy: here regulation requires that this energy value does not decrease under 68 Joule throughout the vessel lifetime.

As defined in Reg. Guide 1.99 Rev. 2, regulation also empirically predicts the irradiation shift of the ductile-brittle transition temperature by the product of a "Chemistry Factor" CF and of an unique fluence factor.

The safety evaluation of pressure vessels makes, however, use of the fracture toughness K, which is the actual resistance of the material against crack initiation and propagation. Regulation uses empirically fitted lower bound K_{Ic} initiation and K_{Ia} arrest fracture toughness curves, as defined in the ASME XI code. These curves are shifted with irradiation according to the CVN 41Joule shift. Limits are imposed on the CVN shift in order to ensure that the fracture toughness of the RPV materials remains adequate throughout the life of the NPP.

WHY ENHANCED SURVEILLANCE?

Current RPV surveillance and regulatory practice has various deficiencies:

1) the fracture toughness is indexed empirically;
2) the irradiation effect on the strain rate sensitivity is neglected;
3) complex damage mechanisms are lumped into generic trend curves.

The methodology entails significant uncertainties, and these are taken into account by imposing conservative bounds on toughness estimates. This tends to penalize plant operation and life management decisions. It can lead to premature shutdown, especially when surveillance results exceed the upper bound of predictive regulatory correlations.

Indexing toughness

The controversial embrittlement of the Yankee Rowe vessel plate, as indicated by Steele and Serpan (1) and Biemiller (2), will serve as illustration. The Yankee upper shell A302-B plate and the Yankee/BR3 surveillance plate have the same fabrication and chemical composition as the well-known ASTM reference A302-B plate. However, former two plates have been austenitized at higher temperature than usual, causing unusual coarsening of their microstructure. As a consequence, there is a difference in grain size: i.e. ≈ 36μ for Yankee/BR3 and ≈ 15μ for the ASTM plate.

The 41 Joule CVN shift of the surveillance plate is much larger than the shift of the reference plate and lies well above the uncertainty band of the regulatory prediction for these plates, leading to the conclusion that the Yankee/BR3 plate displays "outlier" behaviour. Can such small difference in microstructure have such large, detrimental effect on the embrittlement shift? It was shown by Fabry et al (3) that the anomaly is not seen in the CVN 50% SFA shift (the so-called FATT shift): there the Yankee/BR3 surveillance plate is no longer an outlier.
So, does the FATT shift better represent the actual fracture toughness shift or, does the index at 41 Joule introduce a distorsion of physical reality? We claim the indexation procedure must be questionned. To confirm this, the BR3 vessel was sampled.

Neglecting the irradiation effect on strain rate sensitivity

For some steels, the static fracture toughness shift is larger than the dynamic shift, but for other steels the reverse is true: regulation is not always conservative to this respect. Can one predict when this effect will happen and how large it will be? Enhanced surveillance aims to address this question.

Lumping complex damage mechanisms

In the U.S. Regulation, partly applicable in Belgium, the chemistry factor CF is tabulated as a function of the Cu and Ni content of the steel; differentiation is made between weld and base metal. Phosphorus effects are neglected, although they become significant if Cu is less than 0.1%. This influence is not ignored in other regulations, like the French and Russian one.

In reality, depending on the steel, up to five distinct damage mechanisms can cause embrittlement and each has a distinct fluence dependency. Micromechanical modeling and microstructural research try to determine the origin of these mechanisms. Besides effects of Cu precipitation, two of these damage mechanisms, that contribute to the temperature shifts and whose origin are not known, are referred to as 'matrix damage'.

ENHANCED SURVEILLANCE

The 'Enhanced Surveillance' concept is synthetized by the block diagram on Figure 1.

'Classical' surveillance contains more information than has been exploited so far: we refer to the load-time traces from instrumented CVN tests, which allow to construct load-temperature diagrams and to directly integrate the tensile test data (3, 4).

Reconstitution technology - see the review article by van Walle (5) - allows to prepare new test specimens from CVN remnants. In particular, welding of end tabs to cubes of 10x10x10 mm is used to make precracked Charpy specimens (PCCV). These PCCV samples can be impact tested to obtain K_{Jd} or can be tested quasi-statically (by 3 point bending) to obtain K_{Jc}. New ASTM standards are in final preparation for the conduction and interpretation of such tests in the critical transition temperature range.

Microstructural interrogation of irradiated steels is essential to characterize both the fracture process and the in-service damage mechanisms. More direct visualization techniques as Scanning and Transmission Electron Microscopy are complemented by indirect methods such as Positron Annihilation, Internal Friction and Mossbauer Spectroscopy.

Advanced modeling is the analytical 'cement' of the preceding experimental building blocks of enhanced surveillance. It combines two main disciplines:

1) *Damage modeling*, primarily aiming at quantifying irradiation effects on the flow properties (yield stress, work hardening) and on the microscopic fracture stress of the material;
2) *Micromechanics modeling*, relating the microscopic information to fracture toughness, using critical stress or triaxiality-modified critical strain criterions.

THE MAXIMIZATION OF INFORMATION

The CVN load-temperature diagram approach developed in Belgium for the ductile-brittle transition temperature regime allows to put classical surveillance data in a modern fracture mechanics perspective.

Clearly, the CVN load-deflection traces and the corresponding fracture surfaces are correlated, as has been mathematically quantified (4). Two characteristic temperatures of the load diagram can be defined: T_I, the temperature above which ductile initiation occurs (i.e.when the SFA ≠ 0) and T_O, the temperature at onset of the CVN upper shelf (i.e. when the SFA reaches 100%).These temperatures are adequate for a physically more meaningful indexing of fracture toughness: T_I for the dynamic toughness K_{Id} and T_O for the crack arrest toughness K_{Ia}.

The shift of these two temperatures upon service exposure is in general similar and may be approximated by the FATT- shift. In many cases, these three shifts differ little from the 'Regulatory 41 Joule' shift. However, this is not true for outliers such as the Yankee/BR3 plate (3), the Doel-I,-II welds (see Gérard et al (6)) and numerous Linde 80 low shelf welds,...

Combined evaluation of CVN and tensile flow properties allows to predict irradiation effects on the strain rate sensitivity of fracture toughness. This is done using an engineering-oriented micromechanical model. This prediction allows to estimate an indexation temperature for the static fracture toughness K_{Ic}. The prediction is refined and finalized by 3 point slow bend tests of a small number of PCCV specimens. Figure 2 illustrates the method. Here, the K_{Jc} data and their 5%-95% confidence intervals pertain to CVN-PCCV size specimens. Size and statistical effects are accounted for through the 'master curve'-Weibull slope procedure of Wallin (7). Validation of the procedure for reconstituted PCCV specimens of HSSI weld 73W is shown in Figure 3.

In general, for medium to high Cu steels, irradiation increases predominantly the athermal part of the flow stress. This reduces the strain rate sensitivity and K_{Ic} tends to shift more than K_{Id}. The difference between these shifts depends on the unirradiated load diagram of the steel. In contrast, the less stable component of 'matrix damage' appears to primarily affect the thermally activated part of the flow stress. In certain cases, it can cause the shift of K_{Id} to equal or exceed the shift of K_{Ic}.

In conclusion, advanced modeling uses the load-temperature diagram, obtained from CVN and tensile specimens, to estimate the fracture toughness and to help quantifying the role of distinct damage mechanisms that cause RPV embrittlement.

ENHANCED SURVEILLANCE DEMONSTRATION

Belgium conducts an extensive R&D program to demonstrate and improve the 'Enhanced Surveillance' strategy. Two projects - the BR3 Vessel Sampling and Testing and the BR2 Chivas Irradiations to Investigate Incubation Effects - will be summarized.

The BR3 vessel sampling and testing

The BR3 vessel, manufactured by Babcock and Wilcox in 1958, is of particular interest in terms of the fracture toughness indexation issue. As stated before, the BR3 plate is similar to the Yankee Rowe lower shell plate: it has been austenitized at 950-980°C, was operated at a (detrimentially low) temperature of 260°C and is nickel-modified. In 1984, this vessel was successfully wet-annealed at 343°C during one week, after receiving a maximum neutron fluence of 3.3 E19 cm-2 (>1MeV) in 72000 EFPH. The operation license was renewed. The plant was shutdown in 1987 at 86000 EFPH and at a maximum neutron fluence of 4.0 E19 cm-2. The BR3 plant is one of the benchmarks selected in the frame of the research program on the Decommissioning of Nuclear Installations of the Commission of the European Communities.

In fall 1994, SCK•CEN decided to sample and test the BR3 vessel. This was accomplished in January 1995 in cooperation with PCI Energy Services. The Electron Discharge Machining technique was used to remove 14 samples weighing approximately 10 kg each. The cuts, in the shape of boat samples extending to a depth of 7.4 cm in the 11 cm thick wall, were performed at vessel midplane and at nozzle elevation. In latter location, the neutronic exposure is negligible. Moreover, this material can be considered to be an adequate baseline, as a careful evaluation has demonstrated that thermal ageing effects are negligible as well. The beltline specimens are labelled here "IAR" - irradiated, annealed and reirradiated. "IARA" specimens have also been prepared by furnace anneal (one week at 343°C) of IAR specimens. Preliminary CVN test results are shown on Figure 4. The 41Joule shift is 124°C, and the anneal recovery seems very poor.

The load diagram approach, Figure 5, gives a value of 29% recovery for the yield stress and of 21% and 28% recovery for, respectively, T_I and T_O. As for the Yankee/BR3 surveillance plate, the FATT shift is significantly less than the 41 Joule shift, and this will also be true for the K_{Id} and K_{Ia} shifts: the physical reason is simply that after irradiation, the 41 Joule level cannot be triggered anymore by initiation energy alone (3), as can be seen from Figure 4. The K_{Jc} shift has not yet been measured, but the 1T-equivalent 100 Mpa.m$^{1/2}$ temperature for the nozzle (baseline) condition is -55°C (Figure 2 shows the 0.4T data), significantly lower than the NDT estimate of -12°C: it can therefore be concluded that the toughness of the BR3 plate is adequate and that the wet anneal treatment was neither needed nor efficient.

It is interesting to compare the 41Joule shift results to previous experiments and evaluations in Figure 6. The plate designated as YA9 (2), was specially produced and heat-treated to simulate the Yankee Rowe A302-B upper shell plate (Yankee/BR3 surveillance). The plate YA1 was similarly designed to represent the Yankee Rowe nickel-modified lower shell plate and thus the BR3 vessel plate. Furthermore, fine grain versions of both YA9 and YA1 were also investigated, as well as versions corresponding to vessel surface conditions. Finally, the plate PT-A has the same chemistry as the BR3 plate, but has fine grains. All these plates were irradiated at 260°C in test reactors, and all the results are gathered on Figure 6. The full curve on the figure is a 1991 SCK•CEN evaluation (3), considered to be an upper bound for the K_{Jc} shift, and the 'star' is a similar ORNL/UCSB evaluation by Nanstad and Odette(8). The BR3 plate embrittlement is less than predicted, and most importantly, the lack of Ni influence for all these plates (3) is confirmed.

BR2/CHIVAS: Incubation and kinetics of RPV damage mechanisms

For some PWR plants, long term life management or life extension may entail neutron fluences in the range of 5 to 8E19 cm-2 (> 1 MeV). There are very few surveillance data available at such large exposures. We have found (3) that for Western steels, a poorly characterized damage mechanism can cause a sudden increase of embrittlement, starting at an incubation fluence of 4.5E19 cm-2. This defect mechanism is rather stable, and is not affected by dose rate. It thus can be studied at the high flux materials testing reactor BR2, where the pressurized water loop Callisto is particularly suited for such task.

The Chivas 1995 program concentrates on 8 commercial steels of Belgian, French, German and US vintages. The main irradiations are done at 260°C: this is the operation temperature of the BR3 and Chooz-A vessels. Therefore, direct comparison will be possible, not only with surveillance results, but also with the tests being performed on trepans extracted from the vessels themselves. Most interestingly, Charpy and tensile specimens cut from the BR3 plate at nozzle elevation have been loaded in BR2, while for Chooz-A, archive samples, representative of the base and weld metals, are similarly investigated.

In order to modify the relative importance of the various damage mechanisms and to help separate their contributions, most of these steels have also been irradiated at 290°C and 150°C. It is planned to observe their annealing responses, using mechanical tests of miniature CVN samples, positron annihilation, internal friction and Mossbauer spectroscopy, complemented by TEM.

In the longer term, CVN remnants will be reconstituted for PCCV fracture mechanics tests. This will be done primarily in the cases where we will predict that the effect of irradiation on the strain rate sensitivity is sufficiently different to allow the most demanding and full validation of 'Advanced Modeling'.

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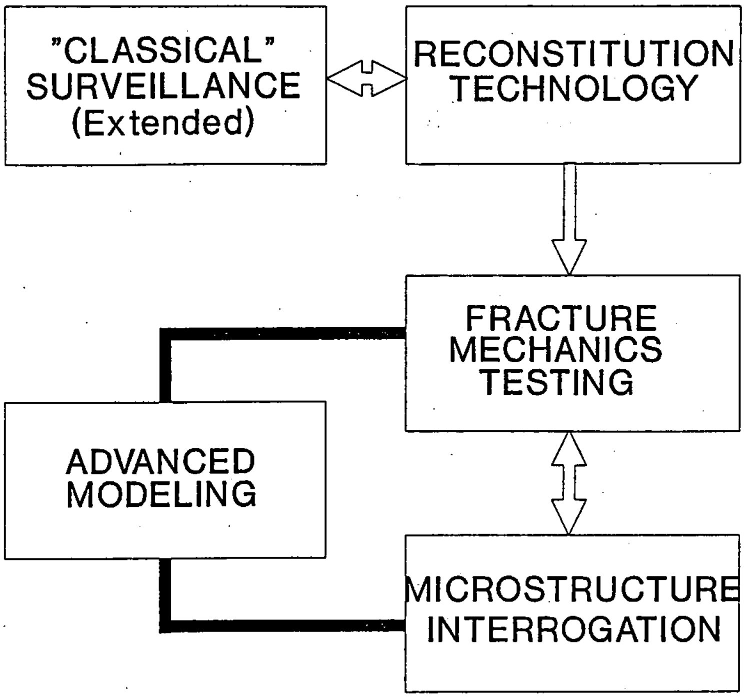

FIGURE 1 Block diagram of Enhanced Surveillance

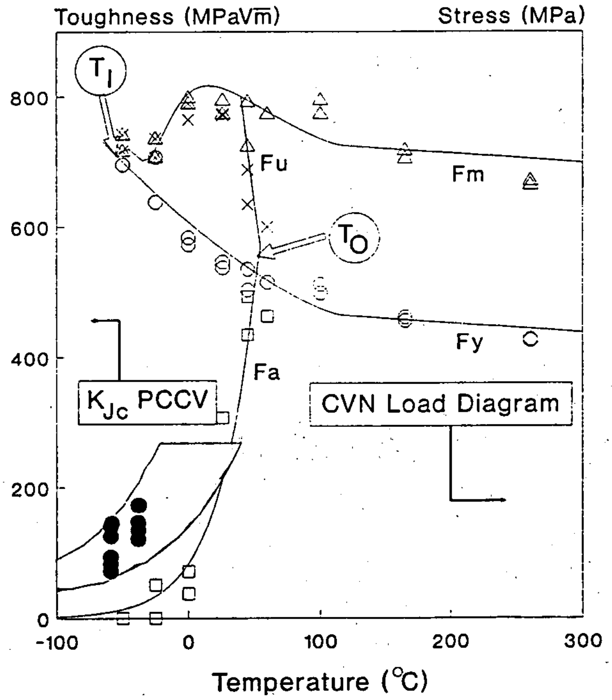

FIGURE 2 Fracture toughness indexing based on PCCV and CVN testing

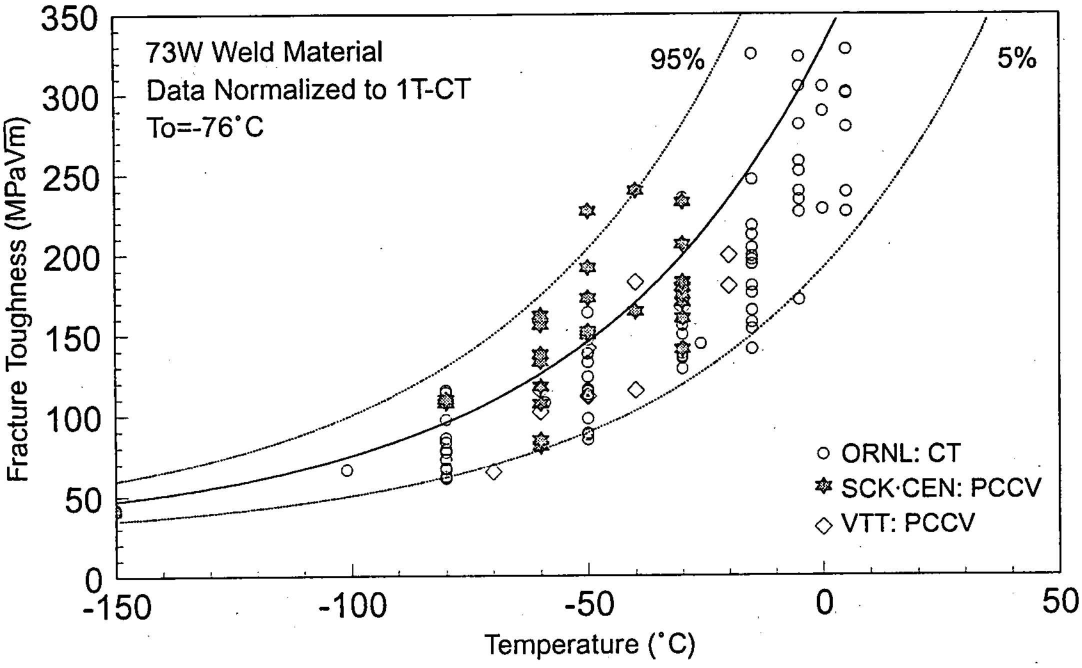

FIGURE 3 Validation of the 'master' curve procedure for PCCV-specimens

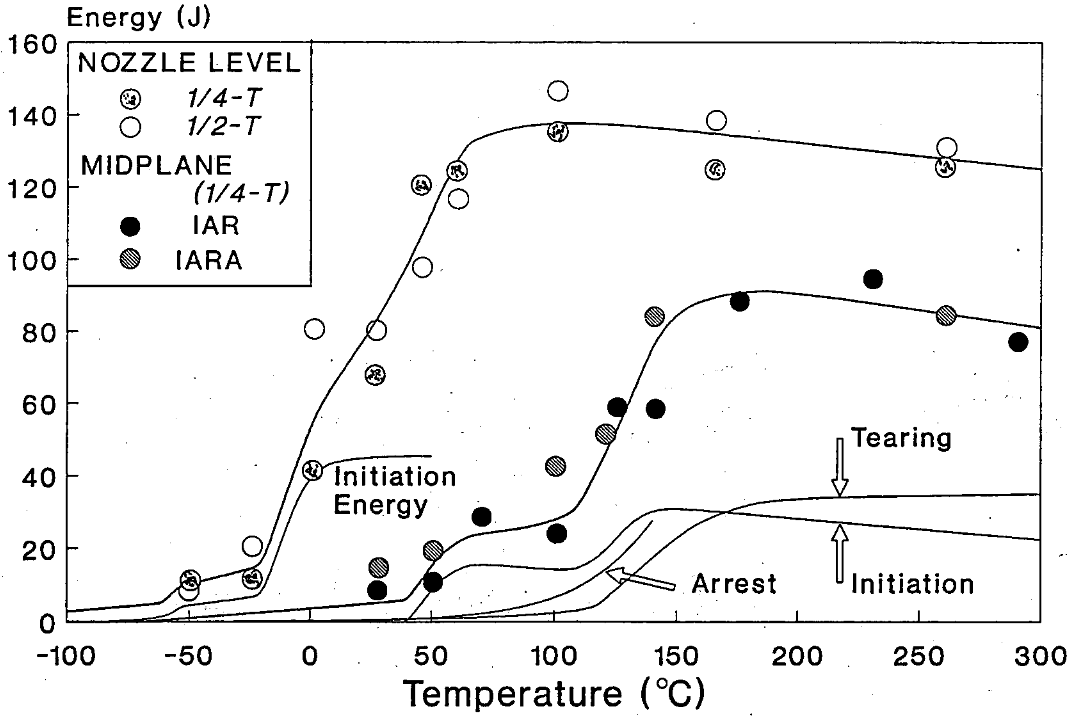

FIGURE 4 BR3 CVN testing results and energy partitioning

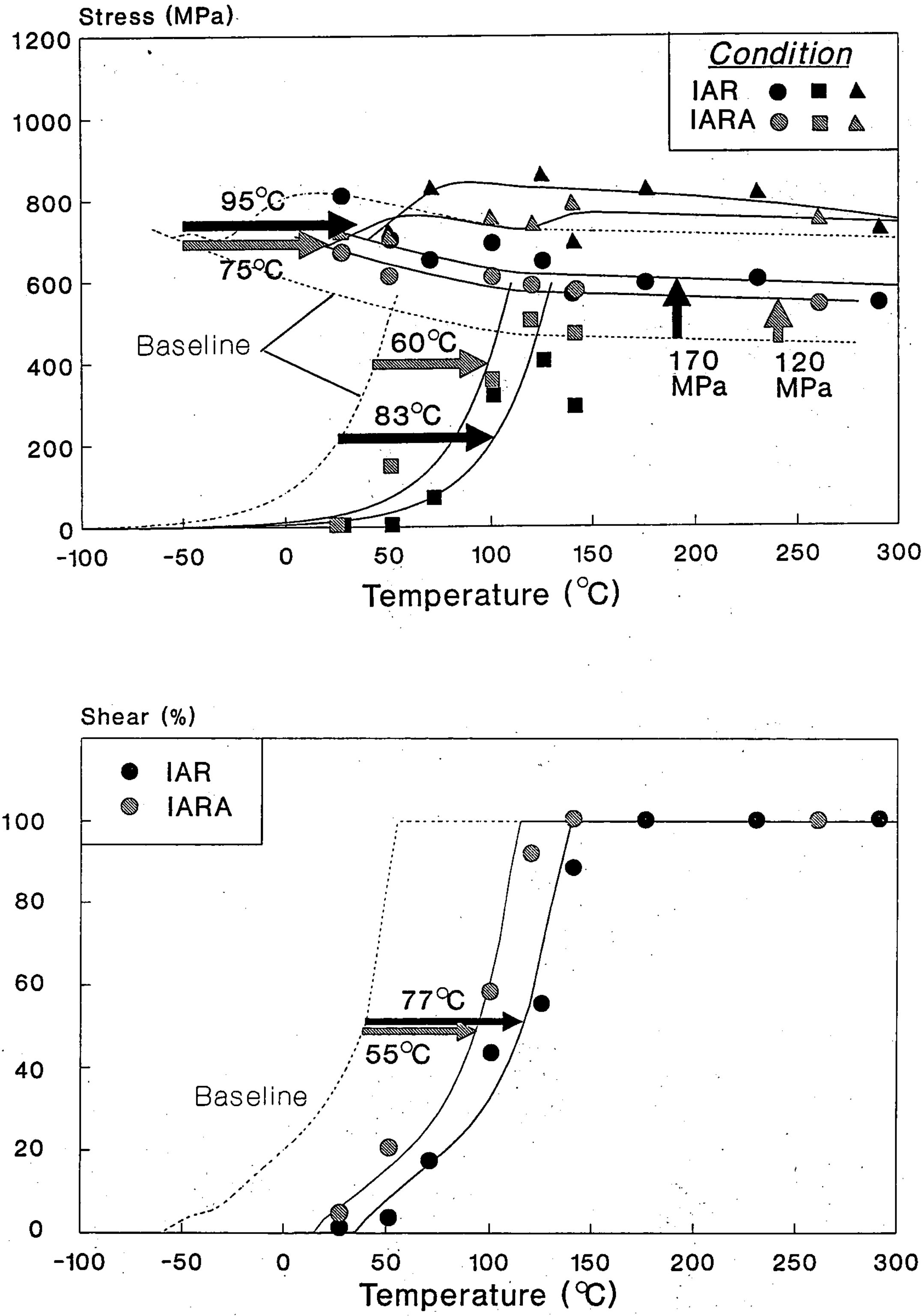

FIGURE 5 The BR3 vessel embrittlement is not large and the wet anneal recovery is poor. Data taken at core midplane at 1/4 T and in the L-T direction.

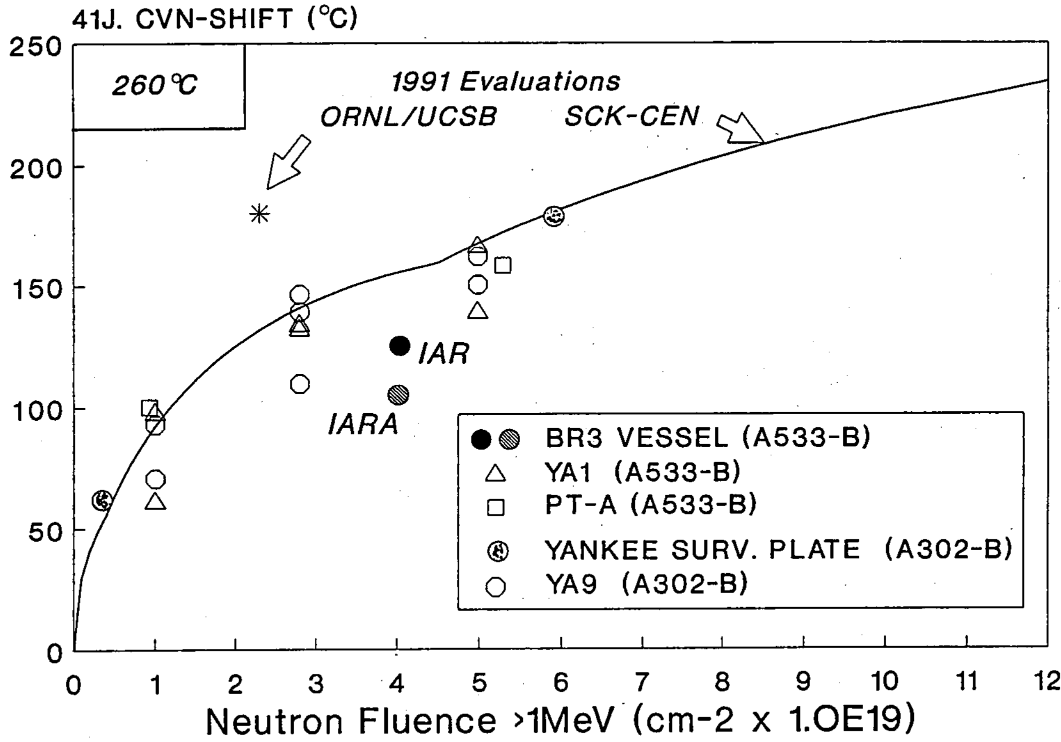

FIGURE 6 The BR3 plate embrittlement is less than predicted and lack of Ni influence is confirmed