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PROJECT PH8.01/99

Dissemination of the PHARE project descriptions and results
Technical assistance to the management of PHARE funded projects

PHARE PH2.01/95 Project
REACTOR PRESSURE VESSEL

EXTENDED PROJECT SUMMARY

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Summary

The VVER 440/213 RPVs (Reactor Pressure Vessel) have been produced using verified manufacturing technology based on common qualification programme between Izorsky and Skoda Factories according to Russian codes and standards. In this project the manufacturing technology used In Skoda Factories for the fabrication of VVER 440 type 213 Nuclear RPVs was described. At present there are 18 VVER 440/213 NPPs in operation in Eastern Europe, i.e. Dukovany (4 units), Paks (4 Units), Bohunize (2 Units), Mohovze (2 Units), Kola (2 Units) Rovno (2 Units) and Loviisa (2 Units). Skoda has provided totally 14 RPVs of type 213 for Check, Slovakia, Hungary and (East)Germany. As a part of this project the manufacturing technology of these RPVs at Skoda Factories has been described. In addition material properties of the RPV material has also been presented.

Russian design requirement include the determination of operation limits for the RPV as well as the demonstration of acceptability of cold overpressurisation and PTS (pressurized thermal shocks). By means of fracture mechanics assessments margins against initiation of predicted end of life reference defects have to be shown. The codified procedure used for the fracture mechanics assessment of VVER 440/213 RPVs is based on static fracture toughness of the materials and does not consider dynamic behavior of crack initiation or crack arrest, although these phenomena form an essential part of the western integrity evaluation codes. There is also very limited amount of dynamic fracture toughness and crack arrest data available for VVER 440 RPV steel. In order to homogenize various practices but taking also into account particular material behavior, the dynamic initiation due to rapid loading and crack arrest of the VVER 440/213 materials have been investigated in this project.

The RPV is the most important component in a NPP since it contains the nuclear core and is the basis for the energy production. Accordingly the integrity of the RPV must be guaranteed for the whole life time of the NPP. The VVER 440 RPV has a small diameter compared to PWRs in the western countries. The water gap between the reactor core and the RPV wall is thus narrow. Accordingly the RPV wall of a VVER 440 is exposed to a very high neutron fluence during its life time. The neutron irradiation bombardment on the RPV material induce disturbance in the microstructure of the material (vacances, interstitials etc.). As a result of this effect the material is getting brittle. The embrittlement is followed up by testing of surveillance specimens according to a certain schedule. The surveillance specimens opf a VVER 440 RPV are located in capsules in the RPV in the core region. The neutron fluence at the specimen position is much higher that at the RPV inner wall position. By testing the surveillance specimens one will get information on the embrittlement of the RPV material in advance. Based on surveillance tests important FT (Fracture Toughness) parameters is elaborated which will be used for assessing integrity of the RPV.

The fracture toughness of the RPV material is a most important parameter for evaluating the integrity of the RPV. In this project test results from a number of fracture toughness testing carried out in Check and many other countries were collected and a database was elaborated. Several fracture mechanics test were also carried out in this project to elaborate different fracture toughness results (static and dynamic crack initiation, crack arrest, etc.). Also large scale testing was carried out on material in original condition and on material which was artificially aged to correspond to end of life condition of the core region in the RPV. Finally a proposal for complementary fracture mechanics testing was elaborated for possible future activities.

Foreword

The safety of nuclear power plants is a primary concern of the European Union (EU) and its Member States. In the early 1990s, the European Union decided to take a prominent role in international efforts to help the New Independent States (NIS) and countries of Central Europe to ensure the safety of their nuclear reactors. The Commission's approach to nuclear safety in Central and Eastern Europe and the NIS is based on two main objectives, which are fully in line with the policy of the international community as decided by the G7 in 1992:

(i) In the short term, to improve operational safety; to make near term technical improvements to plants based on safety assessments and to enhance regulatory regimes;

(ii) In the longer term, to examine the scope for replacing less safe plants by the development of alternative energy sources and more efficient use of energy and to examine the potential for upgrading plants of more recent design.

The PHARE program, especially design safety projects aim at analyzing major safety concerns regarding soviet-designed reactors, formulating appropriate solutions, and supporting their implementation.

This Phare project was awarded to western European companies IVO Power Engineering and VTT (Technical research Centre of Finland), the former being the main Contractor with the EC. The Beneficiary of the project were the Check and Slovak utilities as well as authorities. The local sub-contractor was NRI Rez in Check Republic.

1 Introduction

The general objective of the work was to evaluate the applicability of dynamic fracture properties and criteria generally used in western codes for integrity assessment to the VVER 440 RPV. The specific objectives were the following:

- summarize and evaluate existing Charpy V and fracture toughness data for representative base material and welds
- define and realize complementary Charpy V and FT (Fracture Toughness) tests on typical archive materials in original and in simulated EOL (End Of Life) conditions.
- propose a set of curves defining FT (static and dynamic as well as crack arrest) as a function of temperature including selection of pertinent indexation parameters
- define and realize experimental tests to validate the proposed approach for static and dynamic crack initiation and arrest by means of series of adequate test specimens including representative defects to be tested in brittle regime
- define a standard procedure including simplified stress intensity factor calculations and adequate safety margins for fast fracture resistance assessment of VVER 440/213 RPVs in order to :
  - define operating limits (pressure-temperature limits for heat-up and cool-down)
  - evaluate cold overpressurisation and PTS (Pressurized Thermal Shock)
- define complementary experiments for validation under realistic thermal shock conditions the capability of the elaborated procedure to predict crack arrest
- present the results to the local safety authorities for approval of the elaborated standard procedure

2 Implementation

The project Kick Off Meeting was held the 24th of September 1997 at NRI Rez in Czeck republic. The duration of the project was 24 months. The project proceeded according to TOR and the Work Plan and no major difficulties cold be encountered during the project. At the end of the project a meeting was held in which the safety authorities of Czeck and Slovak republics took part and the overall output of the work was presented.

3 Presentation of the Tasks and results

3.1 Task 1; Summary and evaluation of existing Charpy-V and FT (Fracture Toughness) data

Existing data relating to validation of indexation curves of VVER 440 base and weld material were collected and summarized. Totally 81 different material heat treatment states were used. The number of experimental data on fracture toughness was:

- 840 static fracture toughness, K_{Ic}
- 278 dynamic fracture toughness
- 114 arrest fracture toughness

The materials testing was performed according to DIN (Tensile testing, Charpy-V impact testing), ASTM (crack arrest toughness, K_{Ia} , and partially static fracture toughness), CMEA (dynamic fracture toughness) and CSN (partially static fracture toughness) standards. The a.m. standards are very similar and do not give different test results.

All the test results data were saved in Windows Exel format in the NRI. (Nuclear Research Institute, Rez). Similar test result data obtained in this Phare project were later were also stored in the same database for further elaboration during this project.

3.2 Task 2. RPV manufacturing and material. properties

The first step in Task 2 was to elaborate a summary of manufacturing procedure and experience in Skoda Factories. The procedure contains an assembling scheme describing the different semi-products and sequence of welding the forgings, the nozzle regions and associated quality control. It also contain description of welding and cladding techniques for assembling and cladding VVER 440/213 RPV showing main parameters such as weld materials and fluxes, welding sequence indicating technique and intermediate operations, wire and strip data, welding energy and speed, pre- and post weld heat treatments and non destructive testing. Acceptance results including chemical composition, mechanical properties, results of NDT etc. were also elaborated.

In the second step of this Task 2 typical VVER 440 RPV materials were prepared at the manufacturing plant Skoda in Pilzen for testing. The programme included manufacturing both base and weld metal for the testing planned in Tasks 3 and 4 below. The material was produced for representing the "original" condition as well as artificially aged condition to simulate the effect of neutron embrittlement for EOL (End of Life) condition.

For these materials both basic and advanced mechanical and fracture mechanics testing was carried out (including Charpy V, Pellini NDT and RT_{NDT}, K_{Ic}, K_{Ia} and K_{Id}). The same material was used for preparation of test specimens for the large scale tests in Task 4 (see below).

3.3 Task 3. Fracture toughness data

A set of fracture toughness envelope curves for static, dynamic and arrest toughness were elaborated in Task 3. The existing fracture toughness data base was upgraded and evaluated. Data was collected and analysed and design fracture curves were re-analysed. The output showed that the general static fracture toughness curve covers more than 99.9% of all data while specific design curves covers approximately 95% of data. New dynamic and arrest toughness curves were proposed. According to findings a shift of general design curve by +30 °C will be sufficient to reach a 5% tolerance bound and 60 °C for 1%. Finally, an attempt was made to replace the reference temperature T_{ko} by a temperature based on Master Curve RT_{To}. According to findings a suitable value for this comparison is $T_o - 25$ °C.

Based on the test results in this Task the following conclusions were made:

- Different toughness transition temperatures have no reliable correlation
- Crack arrest transition temperatures, determined either from standard arrest fracture tests or from instrumented impact tests are in good correlation
- The artificial ageing treatment caused a shift in transition temperature of about 100 °C
- Additional data on static, dynamic and arrest fracture toughness of the selected materials have been obtained, collected and evaluated
- Master curve approach can be applied for both static and dynamic fracture toughness determination
- Temperature dependence for FM parameters was better correlated based on T_o than on T_{ko}

Static fracture toughness can be relatively well correlated with RT_{NDT}

3.4 Task 4. Large scale specimen testing

The objective of this Task was to validate numerical methods for predicting static and dynamic crack initiation as well as specified envelope curves and transition criteria by means of large scale testing. The first part of the task was definition of the test program and creation of a predictive scenario by means of FEM (Finite Element Method) calculations. The real material properties from Task 2 and from additional tensile testing were taken into account in the definition of the testing program. The main aim of the testing was to generate controlled crack initiation toughness properties and also to accomplish crack arrest parameters. The results will be evaluated utilizing linear elastic plastic fracture mechanics calculations based on real material properties obtained from various calculation methods and compared with experimental results. The fracture mechanics methods used were compared and the effect of crack shape and cladding on crack initiation behavior was evaluated.

As testing material 15X2MFA type VVER 440 RPV material and weld produced by Skoda as mentioned above in Task 2 was used. The material was tested in 2 different conditions: initial conditions and in simulated EOL condition. The EOL irradiation embrittlement condition was elaborated by proper thermal heat treatment embrittlement. The dimensions of large scale four point bend specimens produced for the testing were 102*70*670 mm. A pre fatigue crack was manufactured by pulsation to reach the required size and semi-eliptical shape. In order to decide on a proper test temperature for the testing of the large scale test specimens smaller three point bend specimens were tested in various temperatures (Task 3). The large scale specimens were mounted on the testing machine and pre-stressed by a force of approximately 1% of the expected fracture force and it was equipped with all necessary monitoring elements. The test specimens were cooled to proper temperature gradually by liquid nitrogen. The test specimen temperature stabilization took about 3-4 hours to homogenize the temperature field in the specimens before testing. Finally the test specimens were tested in 4 point loading pattern until crack initiation.

For the FEM the Ormgen mesh generator was used for producing the FE mesh. Due to symmetry of the test specimen only a quarter of the specimen was modelled. The generated FE mesh included 1406 elements and 6535 nodes. The main goal of the FEM calculations was to predict the value of the total force for which the stress intensity factor will reach a 100 $MPam^{1/2}$ and to compare it with maximum force which was developed by the testing equipment. The maximum total force received was 510 kN and it corresponds to a LLD (Load Line Displacement) of 6,312 mm. It was shown, that the J-integral in nodes near the deepest point of the crack equals 60 kJm^{-2} which corresponds to 117.7 $MPam^{1/2}$.

The test results from the large scale testing showed the following:

- fracture toughness with surface cracks are in good agreement with results from standard size specimens as well as with the FEM calculations
- fracture toughness from large scale specimens with under clad cracks on the contrary do not show a good agreement. Testing of this type of specimens gives problems as no COD (Crack Opening Displacement) could be measured. Furthermore these specimens showed pop-in behaviour and thus no correlation with the FEM calculations could be made. The FEM model should have been updated simultaneously with crack growth. Furthermore the results for underclad cracks were underestimating the fracture toughness values considerably (below 99% curve).

3.5 Task 5: Elaborating of standard procedure proposal

A standard procedure for fast fracture resistance assessment of VVER 440 RPVs was prepared on the basis of existing codes and results from the study in this project. The procedure is based on Soviet Code: “Standard for Stress Analyses of Components and Piping in NPPs”, from 1989. The approach was to cover for NOC and hydro-test conditions only. For upset and emergency conditions the Soviet Standard was under modification with respect to IAEA Guidelines.

3.6 Task 6: Complementary testing program

In Task 6 feasibility of a complimentary testing program for supporting further RPV Integrity evaluations was elaborated. The Experimental programme of complementary tests should support the proposed Proposal for RPV integrity assessment. To reach this task, the following tests would be useful to realize:

3.6.1 Static fracture toughness tests of large scale specimens with underclad cracks

Main purpose of testing the large scale specimens in this project (Task 4) has been accented in checking calculating/computing procedure results with real behaviour of specimens as well as in comparison of these results with resu1ts from standard size (thickness of 25 mm) specimens. Experience with these large scale specimens -with dimensions of 70 * 100*670 mm - with "real size" cracks of surface as well as underclad type has shown to the following conclusions:

- testing specimens with surface type cracks (both through as well as semi-elliptical) bring no problems in testing as well as in an evaluation of results
- testing of underclad type cracks initiates some problems in test evaluation as no crack opening displacement can be measured. Eventually, if some pop-in of defects occurs (as some of diagrams probably shows), thus FEM models crack front size and shape should have to be modified in accordance with possible crack growth. This fact must be verified by a detailed fractography of fracture surfaces (by electron scanning microscope) and some additional test analysis
- results from testing specimens with surface type cracks are in a good agreement with standard size specimens results while calculated static fracture toughness of specimens with underclad cracks has shown mostly too low values of static fracture toughness. This can be explained by the fact that linear elastic fracture mechanics equations are inappropriate for cases with a relatively large plastic deformation before final failure occurs. Moreover, a moment of possible pop-in has not been easy to define
- tests have been carried out only at one temperature for which static fracture toughness close to 100 MPam^{0,5} was predicted on the basis of standard specimens results

As elastic-plastic behavior is characteristic for testing specimens with underclad cracks up to relatively high temperatures, complementary tests will be useful for better understanding the behavior of underclad cracks in the elastic- plastic region of loading.

The tests should cover the following parameters:

- test temperature in the region close to lower shelf of bainitic material, as austenitic cladding will still exhibit relatively high fracture toughness and high margin of plasticity
- test temperature in the region close to or in ductile tearing preceding final failure when both type materials will exhibit good elastic-plastic behavior.

In both cases, improved instrumentation for better characterization of crack front behavior like acoustic emission monitoring, could bring some important information. Crack sizes and their location can be similar to this Project to extend the existing data base.

3.6.2 Static fracture toughness tests of large scale specimens in biaxial mode

Tests of large scale specimens have been realised by uniaxial loading (four- point bending). Results from the experimental programme realised on ASTM A 533-8 type steel have shown that relatively substantial decrease in static fracture toughness can be achieved if tested by biaxial type loading. This mode of loading is typical for reactor pressure vessels, especially for emergency cooling regimes, like "pressurised thermal shock", Some supporting results have been also obtained for 15Kh2MFA type steel with surface type cracks

Thus, additional tests with a different biaxility ratio are proposed with the aim to understand an effect of biaxiality in uniaxial static fracture toughness decrease

- These tests should have cover the following parameter testing:
- biaxility ratio ($\sigma 1$; σ 2) = 1:0,1:2,1:1,2:1
- test temperature close to uniaxial static fracture toughness equal to 100 $\mathrm{MPam}^{0,5}$
- specimens with surface- as well as underclad type cracks with a depth approximately 15 to 25 mm (cross section of 70 x 100 mm).

Results of these tests should answer a question if some correcting factor for biaxility effect would be necessary to implement into and integrity assessment procedure.

3.6.3 Effect of material degradation on "master curve" shape

"Master curve" approach suggested that its shape is not changed due to material degradation effects like thermal ageing and especially irradiation embrittlement. Many Experimental programs and their analyses supported the initial idea that “Master Curve” approach can be applied in many RPV steels of PWR as well as VVER type in their initial , unirradiated condition. Such results have been also within the project for static fracture toughness as well as for dynamic and arrest fracture toughness of tested materials.

A limited number of results exists also for irradiated materials, a few for WWER RPV materials, as no programme has been planned yet. Within the project, some results of the effect of simulated material degradation (by heat treatment) on "master curve" have been also obtained -no substantial effect has been found. Nevertheless, a programme fully concentrated in this effect is desirable, as the shape of fracture toughness curves plays an important role in an integrity assessment as a main parameter for calculation. In all existing procedures, no change in this shape is included into calculations, even though a change in temperature dependence of Charpy impact energy is usually observed.

The complementary programme should cover the following aspects:

- effect of neutron fluences close to and beyond the end-of-life design fluence on static fracture toughness temperature dependence; multitemperature "master curve" approach should be applied on two sizes of static fracture toughness specimens. In both cases, sufficient number of specimens should be tested to decrease the data scatter to a lower value.

3.6.4 Large scale experiments modelling "pressurised-thermal-shock" events

Existing approach for WWER RPV integrity assessment was based on "static initiation" -no static I (without or with a ductile tearing) of a calculated/postulated crack is allowed. Within this Project, a number of arrest fracture initiation toughness data of WWER-440 type materials have been collected and analysed Some additional data have been also obtained from the tests performed within the Project. Evaluation of these data into "design curves" has allowed to modify existing procedure by application of potential crack arrest material behaviour. This approach is used for PWR RPVs as it is shown in ASME Code, Section XI. Such modification of WWER procedure represents a harmonisation effort of WWER Codes with PWR Codes.

Crack arrest approach is applicable for emergency conditions, mostly like PTS (Pressurized Thermal Schock) events. Such situations are characterized not only by a steep temperature gradient through the RPV wall but also associated with high pressure. Unfortunately, standard type arrest fracture toughness tests are performed at constant temperatures, without any temperature gradient,

This is a reason why some programmes with PTS modelling are planned and carried out. Different type of tests can be realized: model pressure vessels (ORNL, USA), spinning cylinders (AEA, UK), hollow tensile specimens (MPA, Germany) etc. These programmes have been performed on models from PWR RPV materials only. WWER RPV materials have been tested only rarely -some model vessels in Prometey, Russia; and tensile type specimens in Czech Republic.
Realisation of such model type tests would check the "crack arrest" approach applicability to WWER materials and compare data from these tests with calculations

based on standard specimens test data (design arrest fracture toughness curve).

Programme of such model experiments can be planned as follows

- tests of flat tensile type specimens (test cross section 150 x 600 to 900 mm) with surface/underclad type defects with an easy unstable crack initiation (brittle bead),
- PTS regime is modelled by a pre-heating, constant tensile loading followed by pre-heating , constant tensile loading followed by a deep one-side cooling using cold water
- conditions for crack initiation as well as potential arrest are traced by a wide range instrumentation (strain gages, thermocouples, acoustic emission etc.)

Results of these tests will be would be a final checking of the crack arrest approach applicability to VVER RPV materials as well as of the validity and reliability of calculating methods.

3.6.5 Conclusions:

A complementary experimental programme of several type of fracture toughness tests of VVER RPV materials was proposed. This programme can be taken as an extension of the existing project 2.01/95, as such tests had not been assumed in the TOR of the Project. Their importance has risen during the Project realisation, mainly during the preparation of the "Standard Procedure for Fast Fracture Resistance Assessment of WWER Reactor Pressure Vessels"[4].

Project 2.01/95 has been concentrated only to materials of WWER-440 reactor pressure vessels. The same problems occur for materials of WWER-1 000 units but no similar project has been realised yet. Thus, extension of the 2.01/95 project to WWER- 1000 RPV materials is highly desirable, at least in its original volume.

3.7 Task 7: Presentation of results to the safety authorities

Task 7 included assistance to the Beneficiary for presenting the results and findings of this project to the Safety Authorities. A one day meeting was devoted for this task.

4 Overview of the project results

The specific technical TOR for the Phare Project 2.01/95 was realized and fulfilled in accordance with specification. A large amount of experimental data from former testing was collected into “design toughness curves” and new data was also created by carrying out comprehensive testing in this project. Large scale test specimens were prepared and tested simulating the original reference condition and the EOL condition of the RPV core region material. The testing was simulated in advance by calculating the testing situation by FEM methods. A standard procedure for fast fracture resistance of VVER 440 RPV was prepared and checked by practical experiments within this project. This elaborated procedure tries to harmonize VVER integrity assessment code with a general western PWR procedure mainly by incorporating crack arrest as well as Master Curve approach. Finally, a proposal for a complementary experimental program concentrating mainly on crack arrest behaviour in VVER RPV materials was elaborated.

Some of the main results of this project are still summarized in the following:

Based on the test results in Task 3 the following conclusions were made:

Different toughness transition temperatures have no reliable correlation

- Crack arrest transition temperatures, determined either from standard arrest fracture tests or from instrumented impact tests are in good correlation
- The artificial ageing treatment caused a shift in transition temperature of about 100 °C
- Additional data on static, dynamic and arrest fracture toughness of the selected materials have been obtained, collected and evaluated
- Master curve approach can be applied for both static and dynamic fracture toughness determination
- Temperature dependence for FM parameters was better correlated based on T_0 than on T_{k0}

Static fracture toughness can be relatively well correlated with RT_{NDT}

The test results from the large scale testing In Task 4 showed the following:

- FT elaborated on large scale specimens with surface cracks are in good agreement with results from standard size specimens as well as with the FEM calculations
- FT from large scale specimens with under clad cracks, on the contrary, do not show a good agreement. Testing of this type of specimens gives problems as no COD (Crack Opening Displacement) could be measured. Furthermore these specimens showed pop-in behaviour and thus no correlation with the FEM calculations could be made. The FEM model should have been updated simultaneously with crack growth. Furthermore the results for underclad cracks were underestimating the fracture toughness values considerably (below 99% curve).

5 Conclusions

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6 Recommendations

The recommendations elaborated in this project have been described under Task 6 “Complementary testing program” above.

7 Abbreviations

RPV	Reactor Pressure Vessel
EOL	End Of Life
FEM	Finite Element Method
PTS	Pressurized Thermal Shock
COD	Crack Opening Displacement
FT	Fracture Toughness
FM	Fracture Mechanics
TOR	Terms Of Reference
LLD	Load Line Displacement
IAEA	International Atomic Energy Agency
NPP	Nuclear Power Plant
NRI	Nuclear Research Institute

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