IAEA-TECDOC-1230

Reference manual on the IAEA JRQ correlation monitor steel for irradiation damage studies

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

July 2001

The originating Section of this publication in the IAEA was:

Nuclear Power Engineering Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

REFERENCE MANUAL ON THE IAEA
JRQ CORRELATION MONITOR STEEL FOR IRRADIATION DAMAGE STUDIES
IAEA, VIENNA, 2001
IAEA-TECDOC-1230
ISSN 1011–4289

Printed by the IAEA in Austria
July 2001

FOREWORD

The reactor pressure vessel (RPV) is a key component in most nuclear power plants (NPPs) and since it is usually considered to be impossible to replace, its operating life can therefore determine the lifetime of the NPPs. It is therefore necessary to understand those mechanisms which affect the mechanical properties of the component in order to be able both to follow the current status and to predict the remaining lifetime.

One of the major mechanisms affecting the RPV material properties is radiation embrittlement due to the exposure of the RPV and its welds to neutron irradiation.

Information on irradiation effects on the mechanical properties of RPV steels is usually gained from research and surveillance programmes using fluence normalizing features taking also into account the neutron energy spectrum.

The effect of irradiation on the mechanical properties can be followed by irradiation of specimens taken from representative archive samples of an operational RPV (or research samples or candidate materials for future RPVs) under representative neutron fluences and irradiation temperatures.

The uncertainties resulting from calibration of fluence could be lessened by the use in the surveillance programmes of a 'standard' reference material, i.e. material which has a 'known' response in terms of its change of mechanical properties to neutron irradiation. A well characterized reference material may be used to provide a correlation between different irradiation rigs, material test reactors and power reactors. A standard reference material is generally included in irradiation capsule loadings in power reactors to aid in the interpretation of the results.

The IAEA has carried out a number of projects dealing with studies of RPV steel behaviour under neutron irradiation. At the very early stage of those studies it was recommended that the use of a 'reference steel' should be encouraged for a reliable comparison of results obtained during the studies.

This TECDOC serves as an initial description of such a reference steel, designated as 'JRQ', introduced by the IAEA in the Co-ordinated Research Project on "Optimizing Reactor Pressure Vessel Surveillance Programmes and their Analysis", which began in 1983. The use of JRQ material has since then been internationally recognized and explored by a number of Member States. This report represents a reference collection of available material properties for the JRQ material to aid in its use for both experimental and surveillance programmes.

The main contributor to the drafting of this TECDOC was M. Brumovsky and his work is greatly appreciated. The IAEA officer responsible for the preparation of the report was V. Lyssakov of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. Objective

The objective of this report is to provide information on the mechanical properties of the ASTM A533 grade B class 1 steel that was designated as 'JRQ reference steel' and for many years served as a radiation/mechanical property correlation monitor in a number of international and national studies of irradiation embrittlement of reactor pressure vessel steel. This report provides the most comprehensive listing of material test data obtained on the JRQ manufacturing history and material properties in the initial, and as delivered condition during the implementation of two IAEA co-ordinated research projects (CRPs) on behaviour of reactor pressure vessel steels under neutron irradiation.

1.2. Background

After completion of the two initial CRPs, the IAEA initiated the Co-ordinated Research Project on "Optimizing Reactor Pressure Vessel Surveillance Programmes and their Analysis" (CRP-3) with the aim of obtaining useful data on neutron irradiation embrittlement. For this purpose the IAEA requested Japanese steelmakers to provide materials of plates, forgings and welded joints. This request was strongly supported by the Atomic Energy Research Committee of Japan Welding Engineering Society and accepted by major Japanese steelmakers, resulting in the provision of 18 types of laboratory heats and steels for the study.

Among these, a large sample of 25 t of steel with sensitivity to neutron irradiation, later designated by the code JRQ, was provided by the Kawasaki Steel Corporation [1].

This report describes the manufacturing history and properties of JRQ plates in the unirradiated, as delivered conditions as they were received by the IAEA for use in the IAEA Co-ordinated Research Projects on "Optimizing Reactor Pressure Vessel Surveillance Programmes and their Analysis" (CRP-3) and "Assuring Structural Integrity of Reactor Pressure Vessels" (CRP-4).

1.3. Structure of the report

A description of the manufacturing history and overview of material preparation for testing, subsequent acceptance testing results, and results obtained during the Co-ordinated Research Projects are given in Sections 2–5. Section 6 gives conclusions and recommendations for further use of this reference material.

2. MANUFACTURING PROCESS

Table 2.1 shows the scheme of the manufacturing process of the plates. The steel was produced by the BOF-LRF process. After rolling, the plates were heat treated normalizing at 900°C, quenching from 880°C and tempering at 665°C for 12 hours, then stress relieving at 620°C for 40 hours.

TABLE 2.1. SCHEME OF MANUFACTURING PROCESS

Process	Manufacturing condition
Primary refining	180 t BOF
Degassing and final refining	Ladle refining furnace (ASEA-SKF Process)
Pouring	Bottom pouring, big end up ingot
Slabbing	Dimensions (mm):
	2 slabs – 340 × 2300 × 3430
Annealing	
Reheating	Batch type reheating furnace: 1200^{o}C
Plate rolling	Dimensions (mm):
	2 plates – 225 × 2500 × 3000
NDE	Ultrasonic tests (straight beam method)
Heat treatment	Normalising: 900^{o}C
	Quenching: 880^{o}C
	Tempering: 665^{o}C – 12 h
	Stress relief: 620^{o}C – 40 h
NDE	Ultrasonic tests (straight beam method)
Flame cutting	Each plate was gas-cut into 6 pieces (225 mm × 1000 mm × 1000 mm) and tests pieces
Acceptance testing	Chemical composition
	Tensile test
	Charpy impact test
	Drop weight test
	Hardness distribution
	Sulphur print and macrostructure
	Microstructure

3. CUTTING SCHEME OF TEST PLATES

Each plate (dimensions: 2000 mm × 3000 mm × 225 mm) was cut into test blocks with the dimensions 1000 mm × 1000 mm × 225 mm and sent to the Paul Scherrer Institute, Switzerland, where they were stored — see Table 3.1. One test block, 3JRQ made from Plate A, was cut into small test blocks with the dimensions of 150 mm × 150 mm × 225 mm and distributed to participants of CRP-3.

TABLE. 3.1. CUTTING DIAGRAM OF PLATES INTO TEST PLATES WITH DIMENSIONS 1 m × 1 m (PLATE A)

PLATE A

2000

1JRQ	2JRQ	3JRQ
4JRQ	5JRQ	6JRQ

3000

PLATE B

2000

7JRQ	8JRQ	9JRQ
10JRQ	11JRQ	12JRQ

3000

In 1995 all remaining material was transferred to the Nuclear Research Institute Řež plc, Czech Republic. One test block, 5JRQ, again from Plate A, was cut into small blocks with dimensions 150 mm × 150 mm × 225 mm and distributed to participants of CRP-4. All remaining material is still held in stock at Řež for further use.

The scheme of cutting the test block into smaller blocks is given in Table 3.2 — the blocks are designated according to the following code:

xJRQyz x = number of the test block (1 to 6 from the Plate A) as delivered

y = number of the row in the block

z = number of the column in the block.

The rolling direction of the plates is coincidental with the column direction.

TABLE. 3.2. CUTTING DIAGRAM OF TEST PLATES INTO TEST BLOCKS WITH THE DIMENSIONS 0.15 m × 0.15 m

XJRQ11	xJRQ12	xJRQ13	xJRQ14	xJRQ15	xJRQ16
XJRQ21	xJRQ22	xJRQ23	xJRQ24	xRQ25	xJRQ26
XJRQ31	xJRQ32	xJRQ33	xJRQ34	xJRQ35	xJRQ36
XJRQ41	xJRQ42	xJRQ43	xJRQ44	xJRQ45	xJRQ46
XJRQ51	xJRQ52	xJRQ53	xJRQ54	xJRQ55	xJRQ56

x = test plate number.

4. ACCEPTANCE TEST RESULTS

Acceptance test results were performed by the manufacturer in accordance with the scheme in Table 2.1 and were summarized in [1].

4.1. Chemical composition

Table 4.1 shows the chemical composition as from the ladle and from both Plates A and B.

TABLE 4.1. CHEMICAL COMPOSITION (MASS %)

	Location		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Al_{sol}
Ladle	–		0.18	0.24	1.42	0.017	0.004	0.14	0.84	0.12	0.51	0.002	0.014
Plate A	Top	0/4t	0.19	0.25	1.41	0.017	0.004	0.14	0.84	0.12	0.50	0.003	0.012
		2/4t	0.20	0.26	1.43	0.019	0.004	0.14	0.85	0.12	0.51	0.003	0.012
	Bottom	1/4t	0.18	0.25	1.39	0.017	0.003	0.14	0.83	0.12	0.50	0.003	0.012
		2/4t	0.18	0.25	1.38	0.019	0.004	0.14	0.82	0.12	0.49	0.003	0.012
Plate B	Top	0/4t	0.19	0.25	1.39	0.019	0.004	0.14	0.83	0.12	0.50	0.003	0.012
		2/4t	0.20	0.25	1.41	0.019	0.004	0.14	0.84	0.12	0.50	0.003	0.012
	Bottom	0/4t	0.18	0.25	1.37	0.018	0.004	0.13	0.82	0.12	0.49	0.003	0.012
		2/4t	0.16	0.25	1.35	0.019	0.003	0.13	0.80	0.12	0.49	0.003	0.012

t = plate thickness (225 mm).

4.2. Mechanical properties

Table 4.2 summarizes results from room temperature tensile tests (specimens according to ASTM E 370) of Plate A, while Table 4.3 gives similar results for Plate B.

TABLE 4.2. TENSILE TEST RESULTS (PLATE A)

Location		Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Reduction of area [%]
Top	0/4t	564	688	26	82
	1/4t	487	635	25	77
	2/4t	482	630	24	77
Bottom	0/4t	548	678	27	81
	1/4t	467	624	27	76
	2/4t	465	611	27	77

t = plate thickness.

TABLE 4.3. TENSILE TEST RESULTS (PLATE B)

Location		Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Reduction of area [%]
Top	0/4t	559	691	24	81
	1/4t	487	635	26	77
	2/4t	489	638	25	77
Bottom	0/4t	546	689	26	82
	1/4t	477	625	26	76
	2/4t	455	607	25	77

Tables 4.4 and 4.5 summarize the evaluated results — transition temperatures — from Charpy impact tests obtained for Plates A and B, respectively. Tests were performed with Charpy V-notch type specimens (ASTM E 370) in accordance with the ASTM E 23 procedure.

TABLE 4.4. CHARPY IMPACT TEST RESULTS (PLATE A)

Orientation	Location		$T_{41\ J}$ [°C]	$T_{68\ J}$ [°C]	$T_{50\%}$ [°C]	KV(–12°C) [°C]
Longitudinal	Top	0/4t	– 115	– 112	– 99	240
		1/4t	– 28	– 15	2	75
		2/4t	– 23	– 13	5	74
Transverse	Top	0/4t	– 53	– 46	– 36	176
		1/4t	– 23	– 13	2	69
		0/4t	19	– 8	8	60

TABLE 4.5. CHARPY IMPACT TEST RESULTS (PLATE B)

Orientation	Location		$T_{41\ J}$ [°C]	$T_{68\ J}$ [°C]	$T_{50\ \%}$ [°C]	KV(–12°C) [°C]
Longitudinal	Top	0/4t	– 115	– 97	– 83	221
		1/4t	– 28	– 21	2	87
		2/4t	– 14	– 4	7	76
Transverse	Top	0/4t	– 110	– 79	– 61	171
		1/4t	– 24	– 17	4	80
		2/4t	– 9	– 3	10	68

Results from drop weight tests of both plates are given in Table 4.6. Tests were performed in accordance with ASTM E 208 procedure, with P3 type of specimens; their orientation was in the transverse direction.

TABLE 4.6. DROP WEIGHT TEST RESULTS

Location			Orientation	Test temperature [^{o}C]					T_{NDT} [^{o}C]
				– 5	– 10	– 15	– 35	– 55	
Plate A	Top	1/4t	T	○○	○○	☯●	●○	●○	– 15
		2/4t	T	○○	○○	●○	●●	●○	– 15
	Bottom	1/4t	T	○○	○○	○☯	●●	●○	– 15
		2/4t	T	○○	○○	●●	●○	●○	– 15
Plate B	Top	1/4t	T	○○	○○	☯☯	●○	●○	– 15
		2/4t	T	○○	○○	○☯	●○	●○	– 15
	Bottom	1/4t	T	○○	○○	○●	●○	●○	– 15
		2/4t	T	○○	○○	●●	●○	●○	– 15

○ – specimen was not broken.
● – specimen was fully broken.
☯ – specimen was partially broken.

4.3. Microstructure

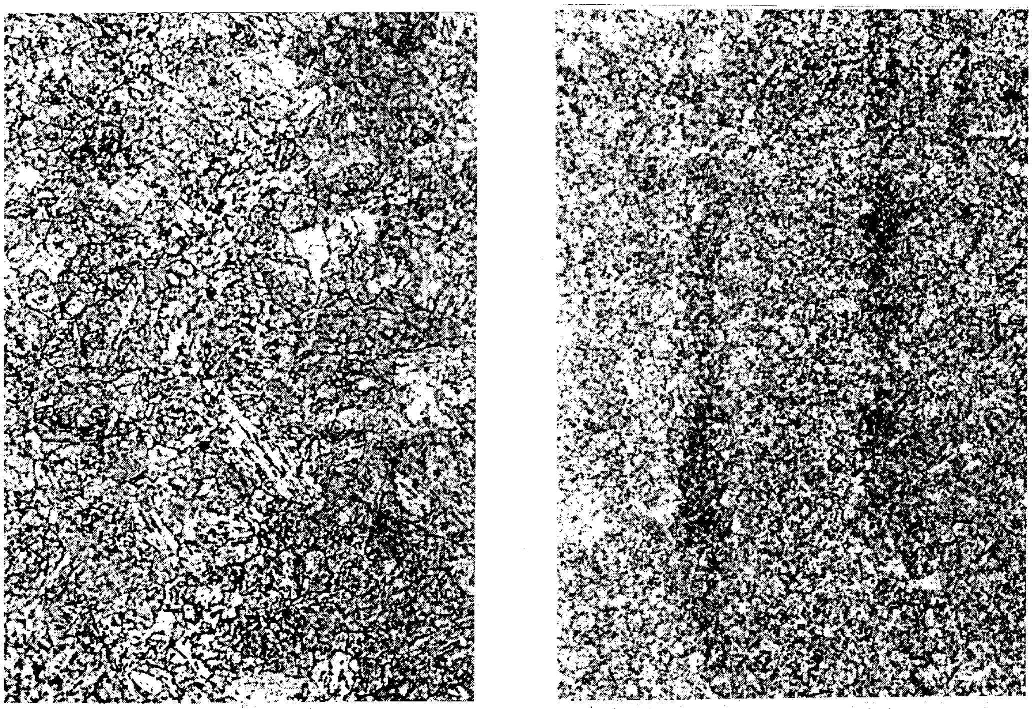
The microstructure of each plate was determined at three different depths, in accordance with mechanical testing, i.e. at the surface, at one quarter (t/4) and at the centre of the thickness (t/2). Typical microstructures are given in Fig. 4.1. It is noted that some “ghost lines” can be found within the plate thickness in each case.

4.4. Evaluation of acceptance tests

Evaluation of acceptance tests led to the conclusions that:

- plates were relatively homogenous with respect to chemical composition as well as mechanical properties,
- mechanical properties (and microstructure) depended on specimen orientation and mainly on specimen location in the plate thickness — t/4 depth was chosen as a characteristic in accordance with Nuclear Codes,
- the steel could be used as a reference material for the CRP-3 investigation if strong requirements to specimen location and orientation would be maintained.

Fig.4.1. TYPICAL MICROSTRUCTURE OF JRQ STEEL IN A QUARTER OF THICKNESS
(Places without and with ghost lines)



5. RESULTS FROM THE IAEA CO-ORDINATED RESEARCH PROJECTS

Both Co-ordinated Research Projects — CRP-3 and CRP-4 — were directed towards the mechanical testing of the reference material JRQ: Steel JRQ in CRP-3 was chosen as a strict reference material for comparison results from different laboratories in unirradiated as well as irradiated conditions. This steel has been chosen as the main material for the mandatory part of CRP-4. CRP-3 focused mainly on Charpy impact testing (and fracture toughness testing was only of the second priority for some participants), while CRP-4 was fully devoted to fracture toughness testing with Charpy impact tests being a comparative test. Thus, a large data set of material properties has been collected during a period of several years, based on tests from two test blocks — 3JRQ and 5JRQ. Relatively good homogeneity of results points to the fact that these data sets can readily characterize the reference material JRQ, as the differences with the acceptance tests are also small.

5.1. Chemical composition

The chemical composition was determined by several participants of CRP-3. All results, together with acceptance tests, are summarized as histograms of individual chemical element concentration in Figs 5.1 to 5.9. Mean values of individual element concentration together with their standard deviations are given in Table 5.1.

TABLE 5.1. MEAN VALUE OF CHEMICAL COMPOSITION OF ELEMENTS

ELEMENT	MEAN VALUE [mass. %]	STANDARD DEVIATION [mass. %]	FIGURE
C	0.070	0.010	5.1
Si	0.21	0.04	5.2
Mn	1.34	0.01	5.3
P	0.020	0.001	5.4
S	0.002	0.001	5.5
Mo	0.49	0.02	5.6
Ni	0.70	0.05	5.7
Cr	0.11	0.01	5.8
Cu	0.15	0.02	5.9

Fig.5.1. CHEMICAL COMPOSITION OF JRQ
C content

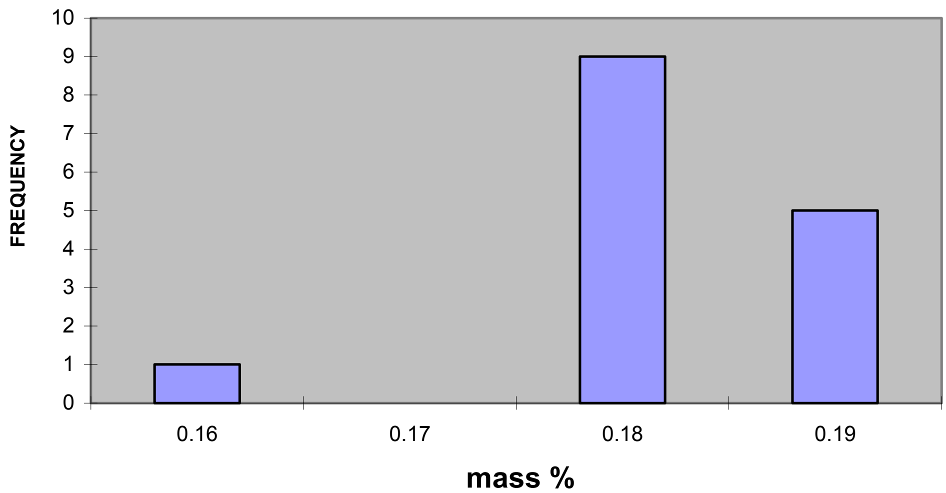


Fig.5.2. CHEMICAL COMPOSITION OF JRQ
Si content

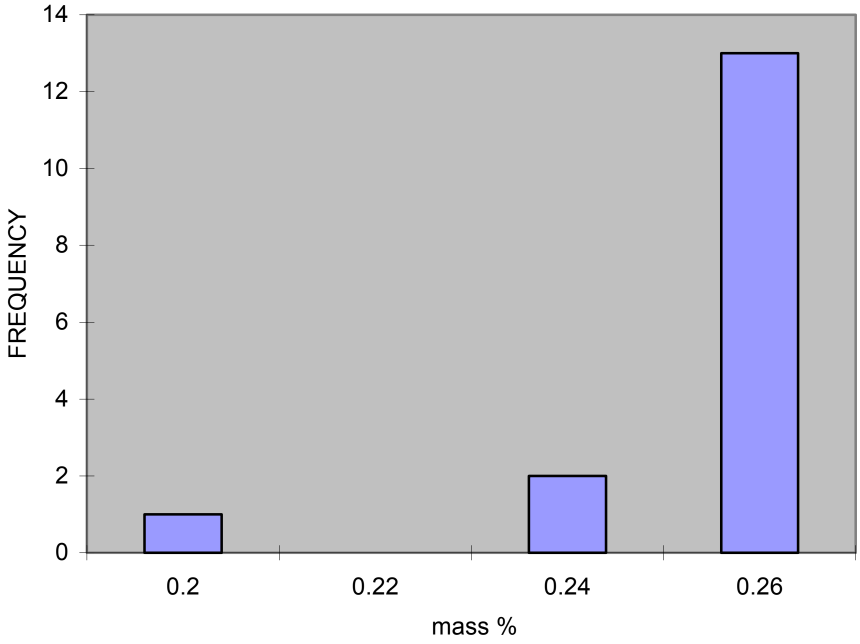


Fig.5.3. CHEMICAL COMPOSITION OF JRQ
Mn content

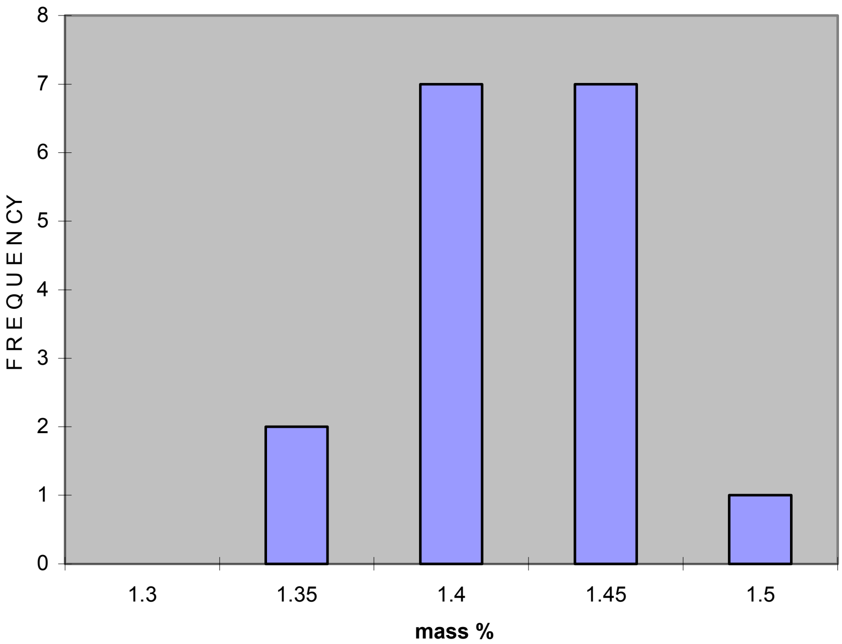


Fig.5.4. CHEMICAL COMPOSITION OF JRQ
P content

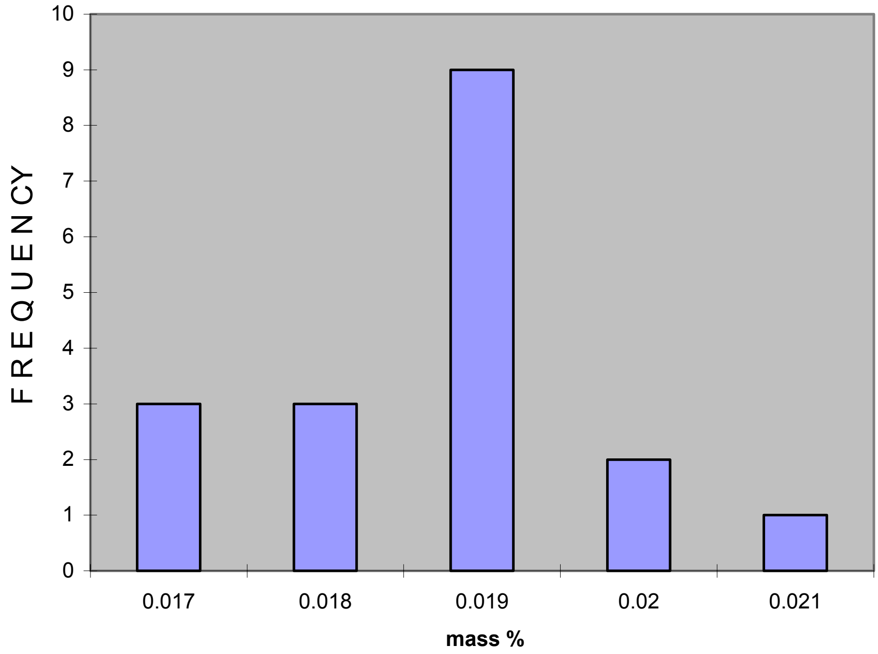


Fig.5.5. CHEMICAL COMPOSITION OF JRQ
S content

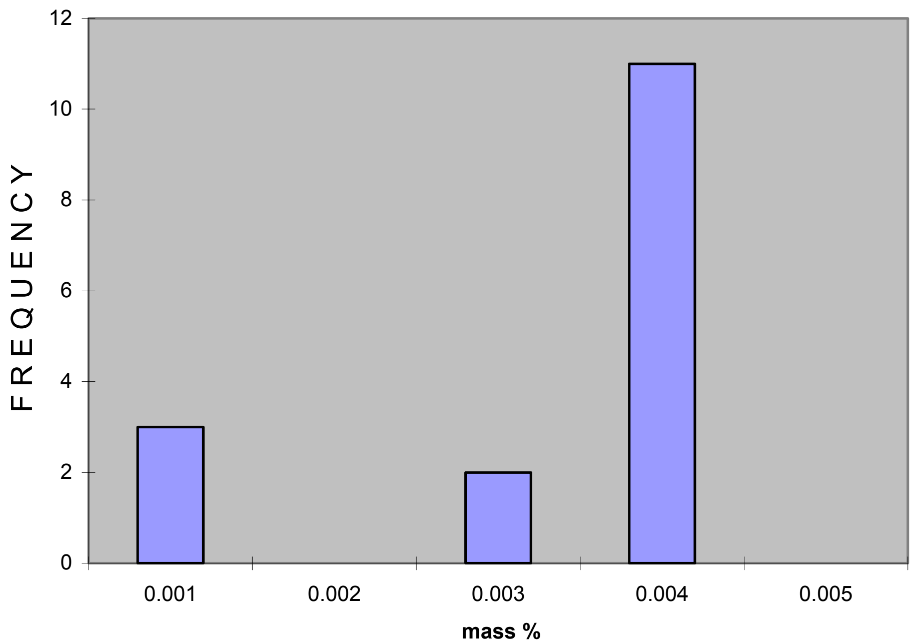


Fig.5.6. CHEMICAL COMPOSITION OF JRQ
Mo content

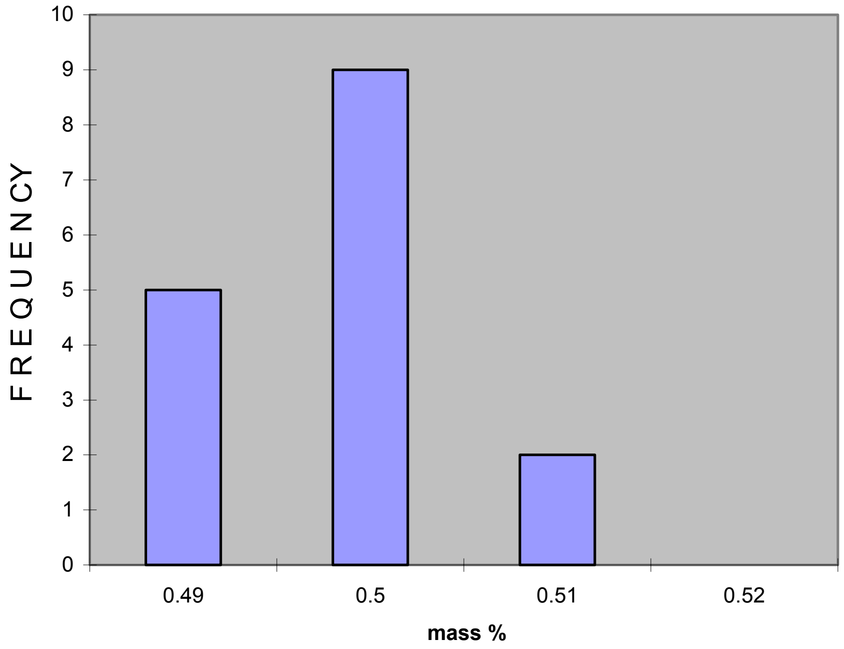


Fig.5.7. CHEMICAL COMPOSITION OF JRQ
Ni content

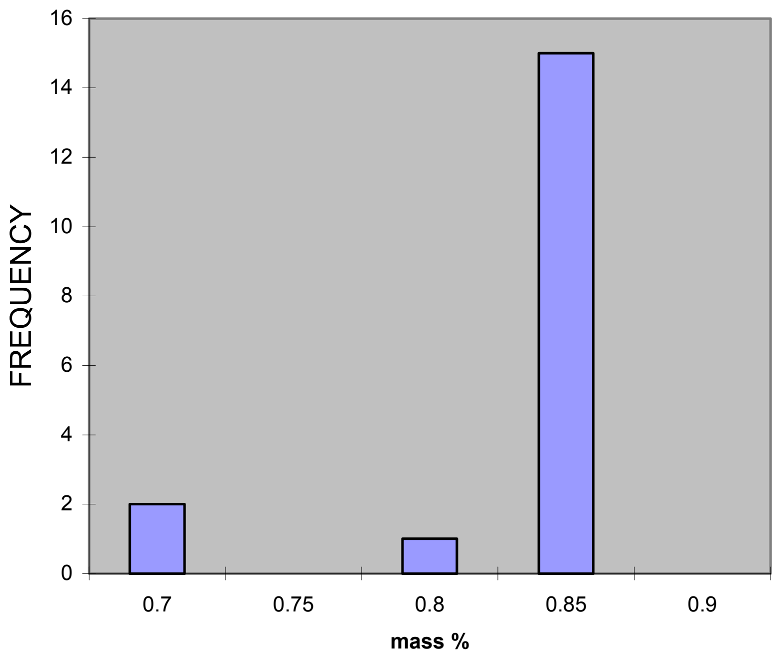


Fig.5.8. CHEMICAL COMPOSITION OF JRQ
Cr content

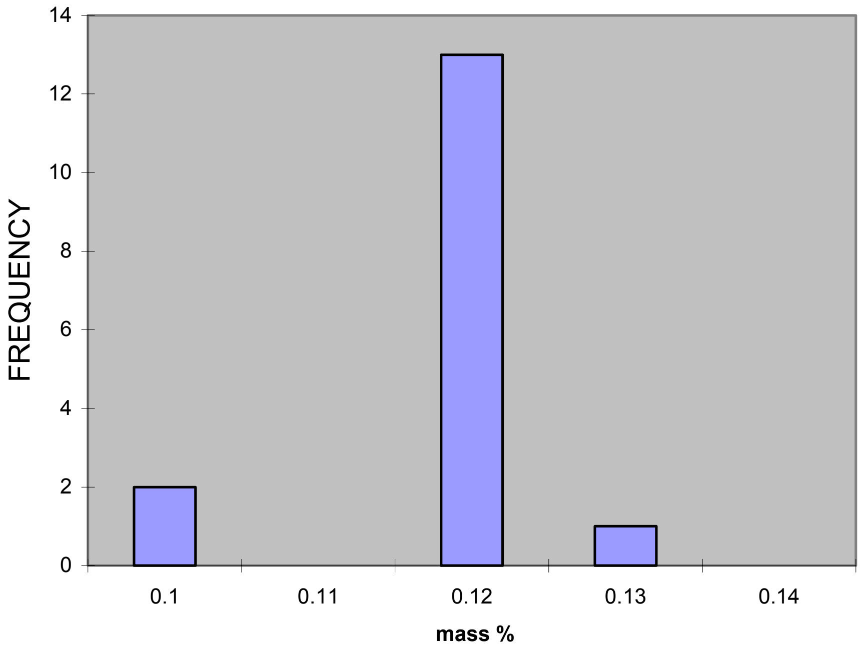
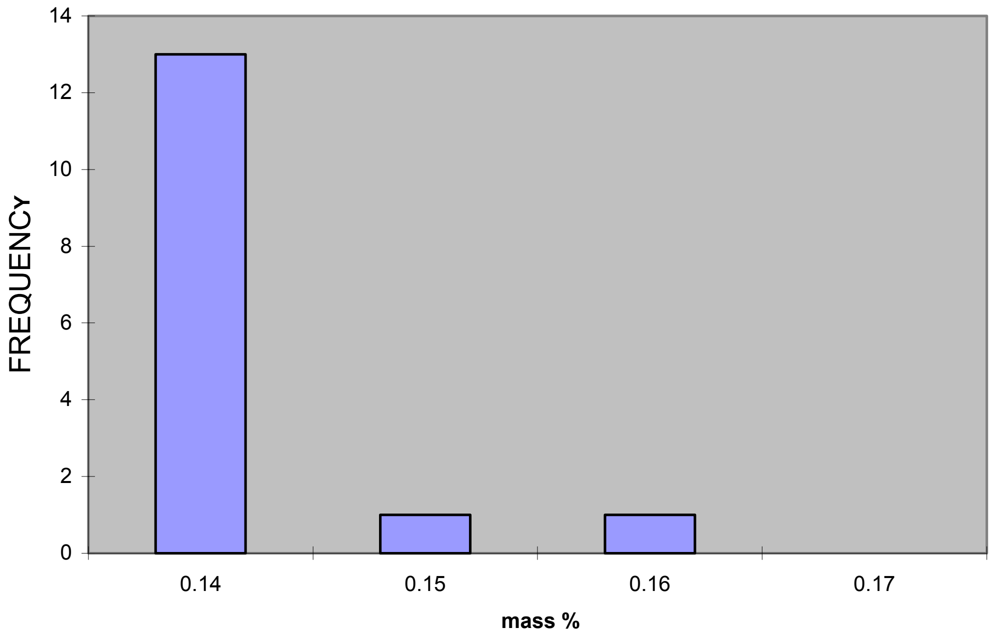


Fig.5.9. CHEMICAL COMPOSITION OF JRQ
Cu content



5.2. Tensile properties

Tensile properties, mainly on small size specimens (with diameters between 3 and 6 mm) have been determined in three ways:

- effect of specimen orientation on room temperature tests,
- temperature dependence of tensile properties,
- thickness effect on tensile properties, i.e. effect of specimen location in the depth of plate thickness even though one quarter of the thickness was chosen and strongly recommended for reference purposes.

Both specimen orientations — longitudinal (L) as well as transverse (T) — were tested, mainly in the CRP-3. Test temperature dependencies of tensile properties (from one quarter of the thickness) are shown in Fig. 5.10 (yield strength and ultimate strength properties — Rp0.2 and Rm, respectively) while Fig. 5.11 shows results from plasticity properties (elongation and reduction in area – A5 and Z, respectively). Tests were performed with specimens of both orientations – L and T; there is no statistical difference between these orientations. Scatter of the data is within a standard test distribution.

Fig.5.10. TENSILE PROPERTIES OF JRQ
DEPTH = 56 mm = T/4

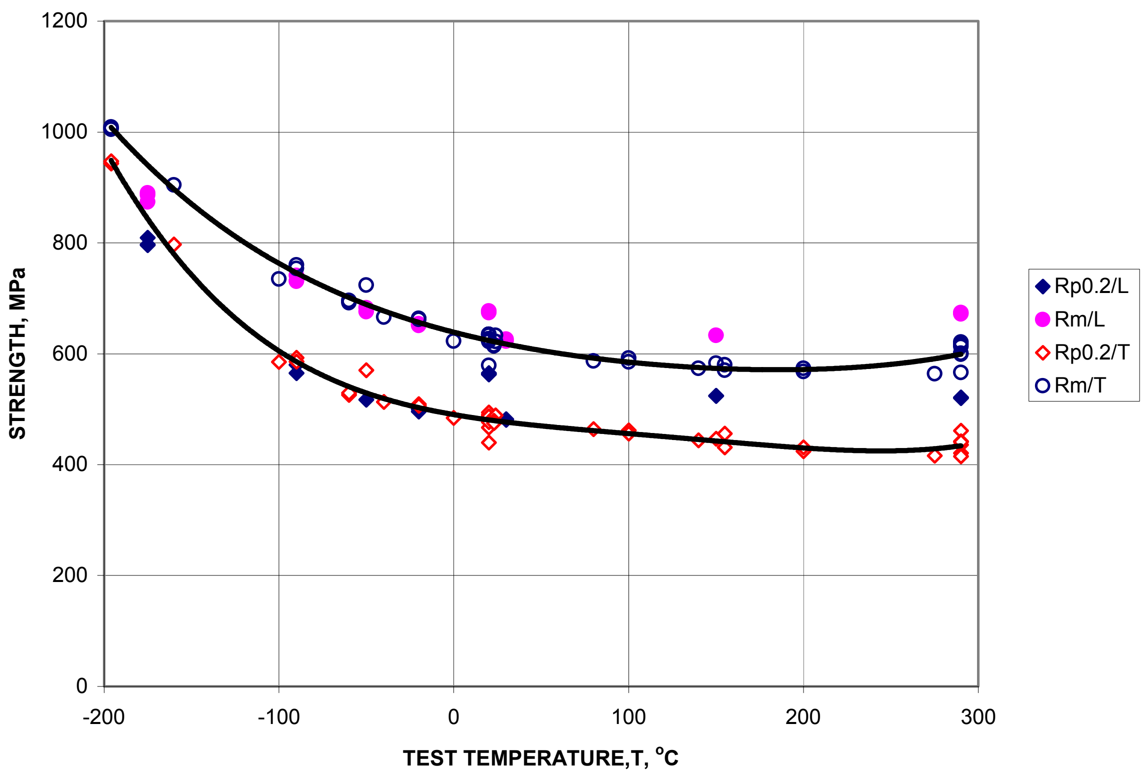
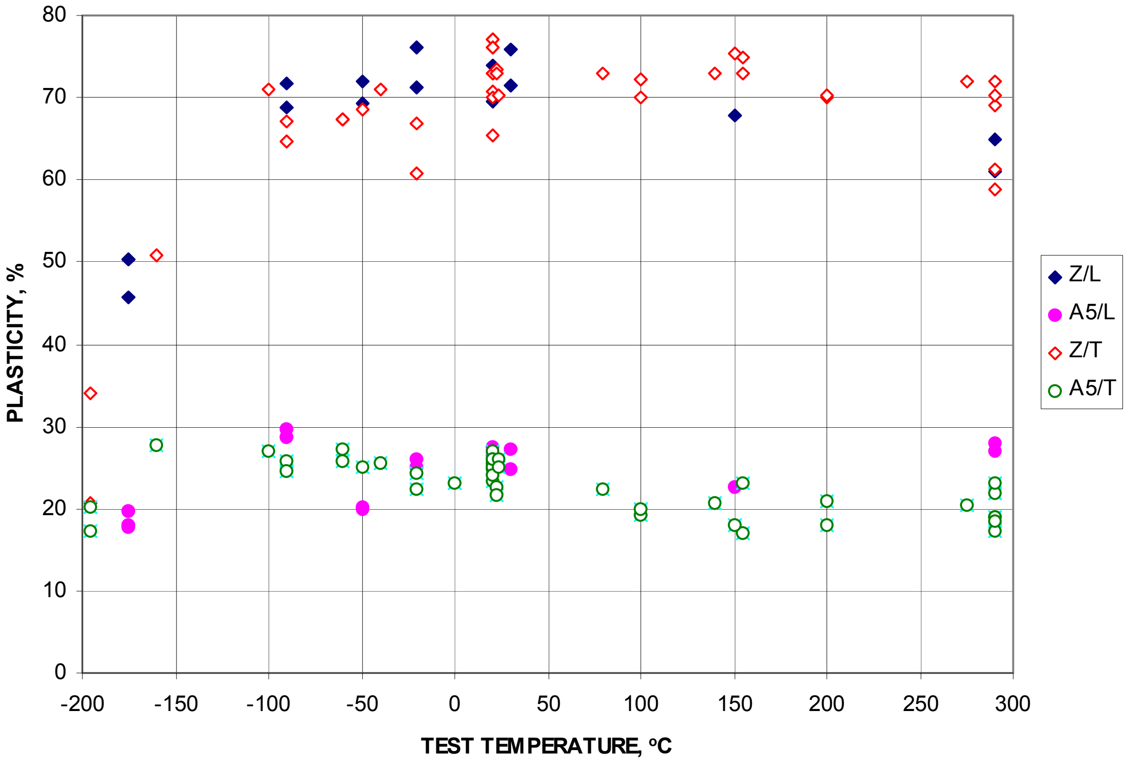


Fig.5.11. TENSILE PROPERTIES OF JRQ
DEPTH = 56 mm = T/4



Statistical evaluation of tensile properties (in depth equal to T/4 = 55 mm) gives the following relationship for yield strength (with a correlation coefficient $R^2 = 0.9875$):

$$Rp0.2 = 4 \times 10^{-8}\, T^4 = 2 \times 10^{-5}\, T^3 + 0.0036\, T^2 - 0.543\, T + 490.29$$

Where yield strength Rp0.2 is in MPa and temperature T in °C.

Location of specimens in the plate thickness is very important for a precise and reproducible test results. Figs 5.12 to 5.15 summarize results from this effect. While Figs 5.12 and 5.13 give results from one laboratory only, Figs 5.14 and 5.15 show results obtained in several laboratories within the projects. In all cases it is clearly seen that results obtained from specimens located within the outer one quarter of the thickness (i.e. between 0 and t/4 and between 3t/4 and 4t/4) are strongly affected by the quenching effect of the steel. Strength properties are increasing in the direction to the surface, while plasticity is decreasing. Thus, the recommendation of testing specimen only from t/4 is strongly supported. In general, location of t/4 and two layers of Charpy size specimens in the direction to the plate centre are accepted.

Fig.5.12. TENSILE PROPERTIES OF JRQ
ROOM TEST TEMPERATURE

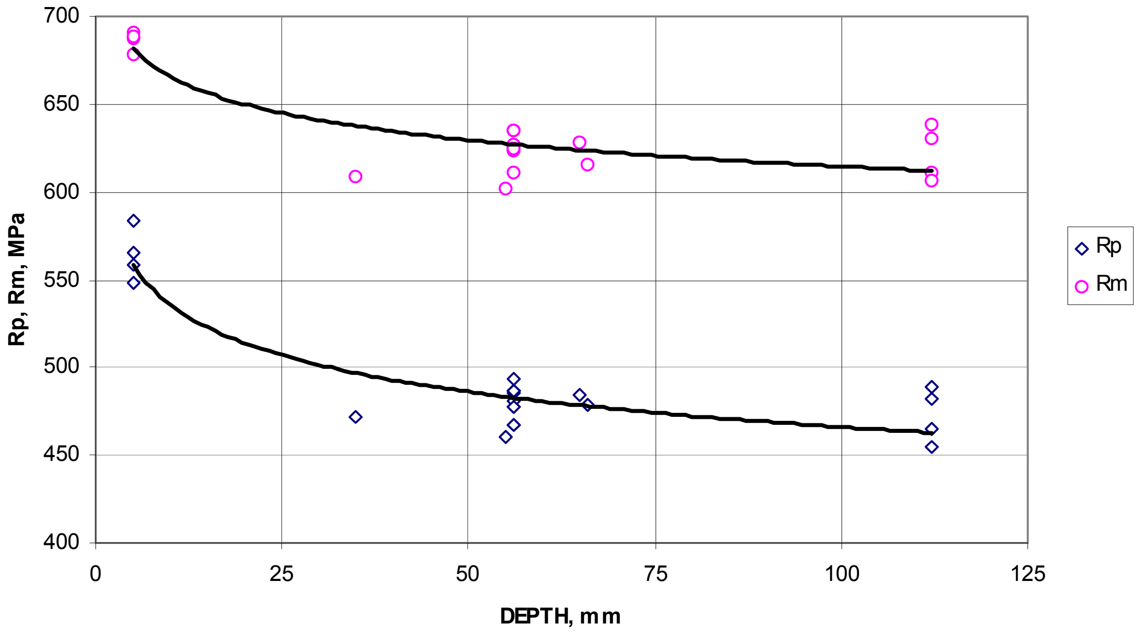


Fig.5.13. TENSILE PROPERTIES OF JRQ
ROOM TEST TEMPERATURE

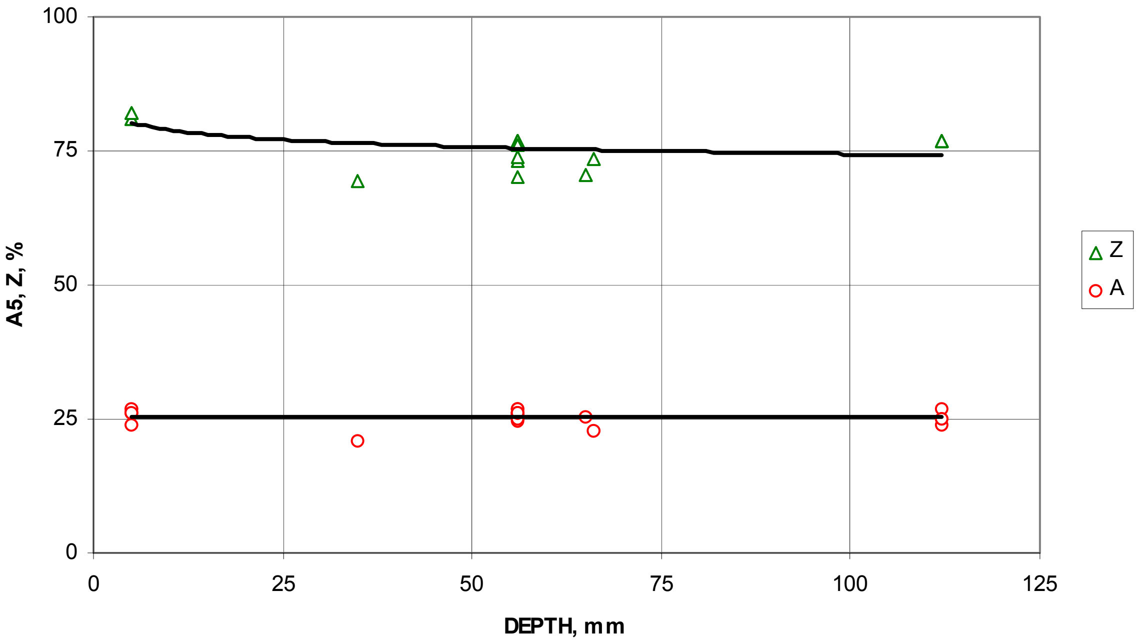


Fig.5.14. TENSILE PROPERTIES OF JRQ
ROOM TEST TEMPERATURE

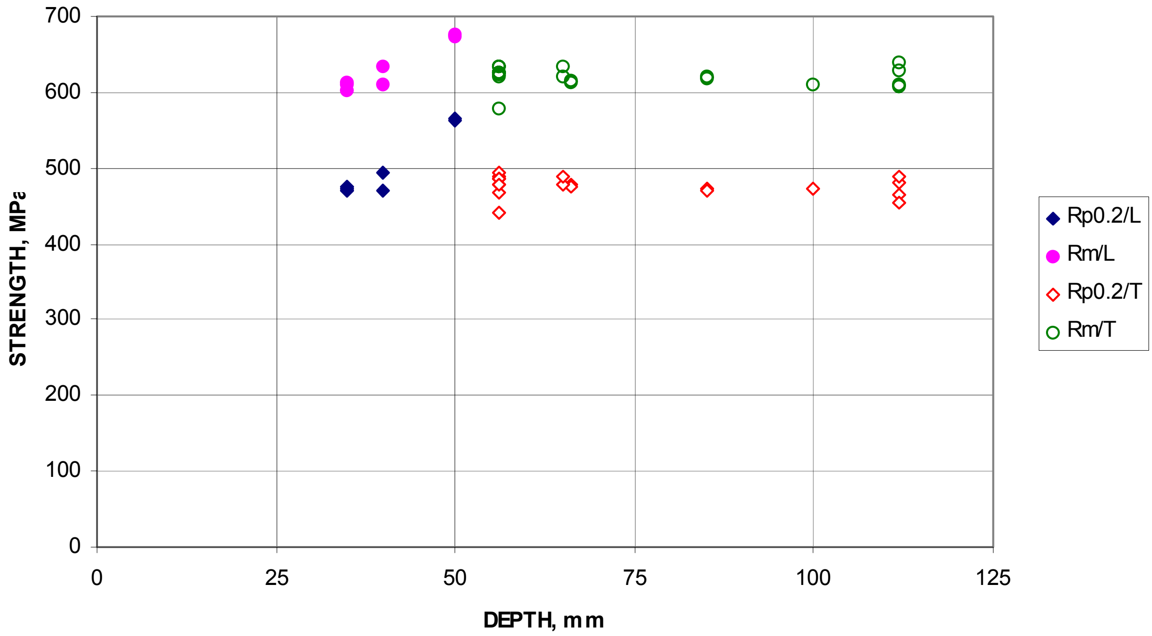
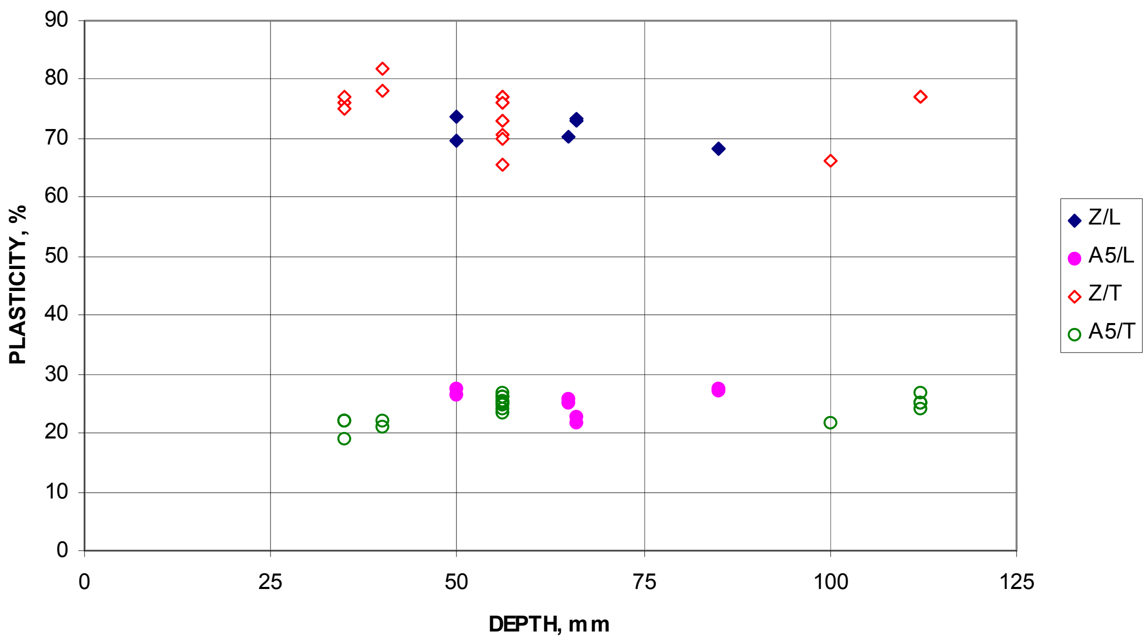


Fig.5.15. TENSILE PROPERTIES OF JRQ
ROOM TEST TEMPERATURE



5.3. Impact properties

Impact properties, mainly Charpy impact test results as raw data as well as their evaluation as transition temperatures, are of main interest to the current reactor pressure vessel materials evaluation in unirradiated as well as irradiated conditions.

Thus, similarly to tensile properties, Charpy impact tests were performed to determine different effects on transition temperatures:

- effect of specimen orientation,
- effect of specimen location in the plate thickness.

Figures 5.16 to 5.21 summarize test results obtained by CRP-3, i.e. on test block 3JRQ. Raw data of notch toughness (absorbed energy), KV, fibrous fracture, FA, and lateral expansion, LE, are given for both specimens orientations — T-L and L-T. Test results for orientation T-L were obtained in both CRPs, while data for orientation L-T come from CRP-3, only.

Fig.5.16. NOTCH IMPACT TOUGHNESS OF JRQ DEPTH=T/4=55 mm
ORIENTATION T-L

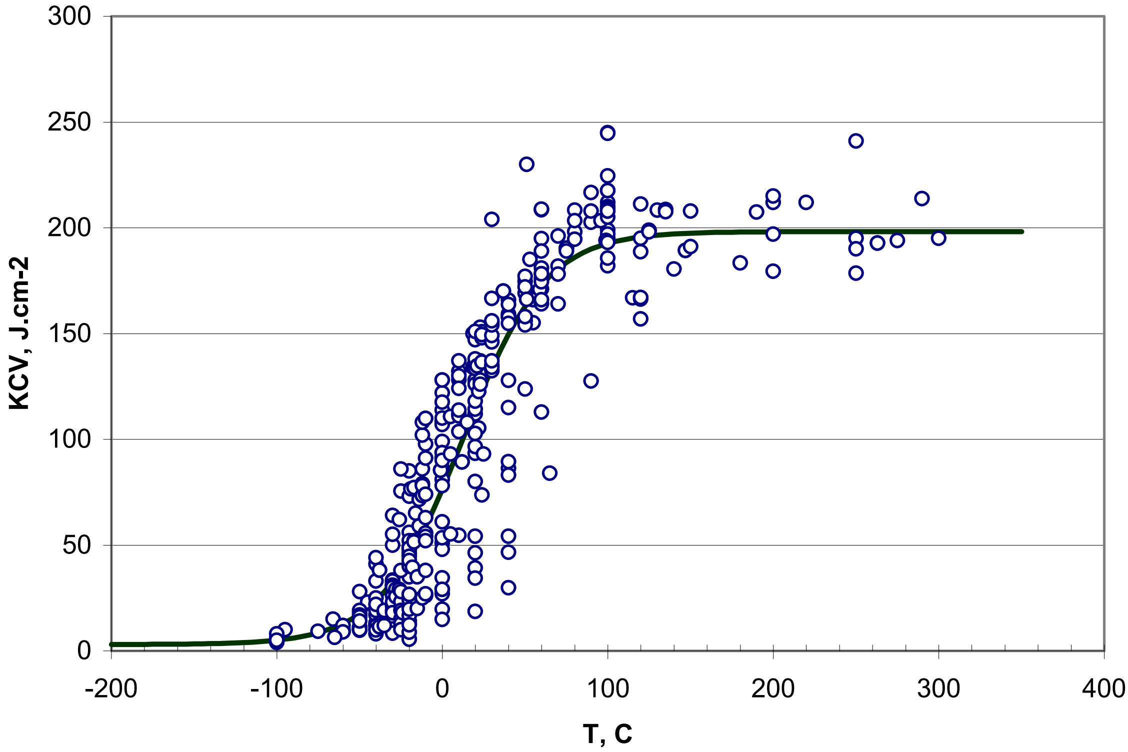


Fig. 5.17. LATERAL EXPANSION OF JRQ DEPTH=T/4=55mm ORIENTATION T-L

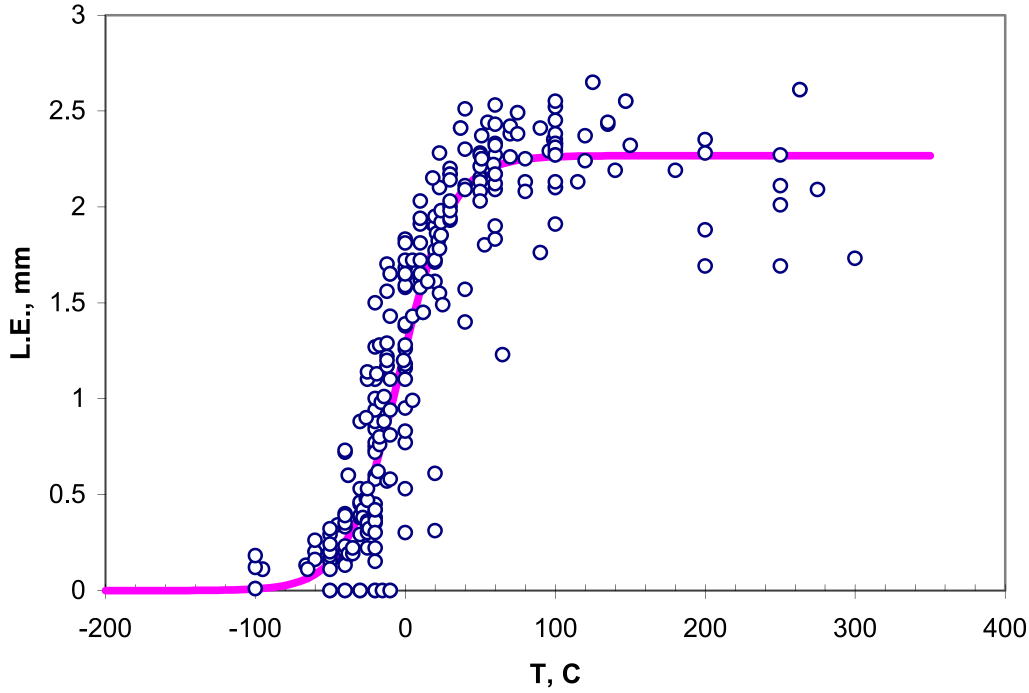


Fig.5.18. SHEAR FRACTURE OF JRQ DEPTH=T/4=55mm ORIENTATION T-L

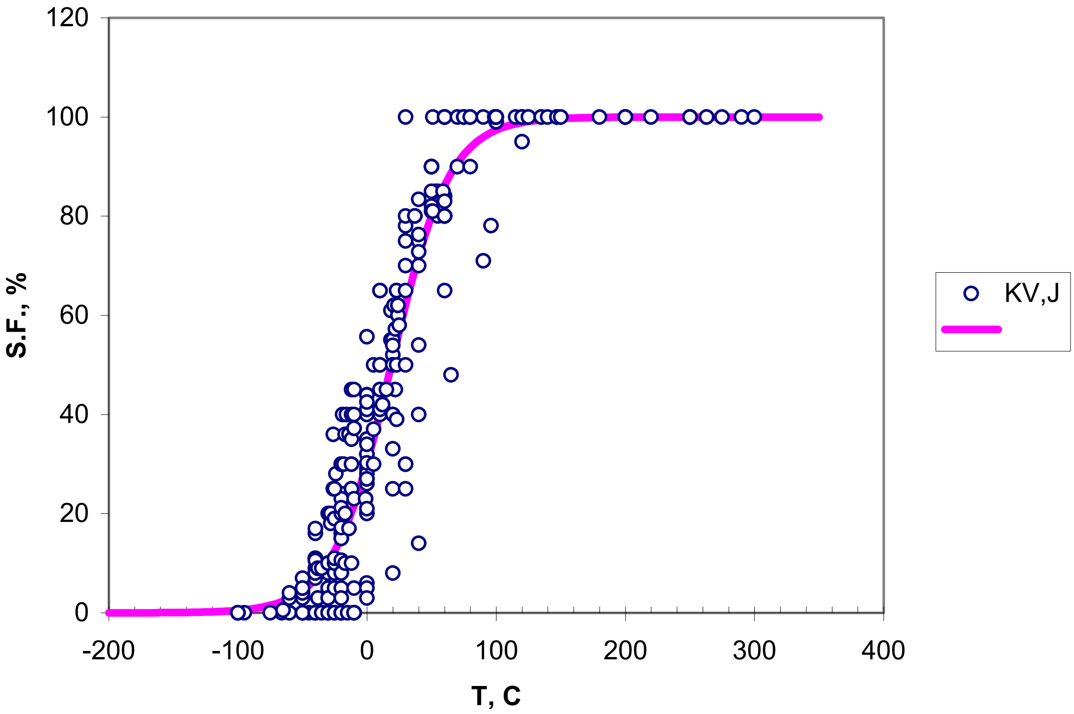


Fig.5.19. NOTCH IMPACT ENERGY OF JRQ DEPTH=T/4=55mm ORIENTATION L-T

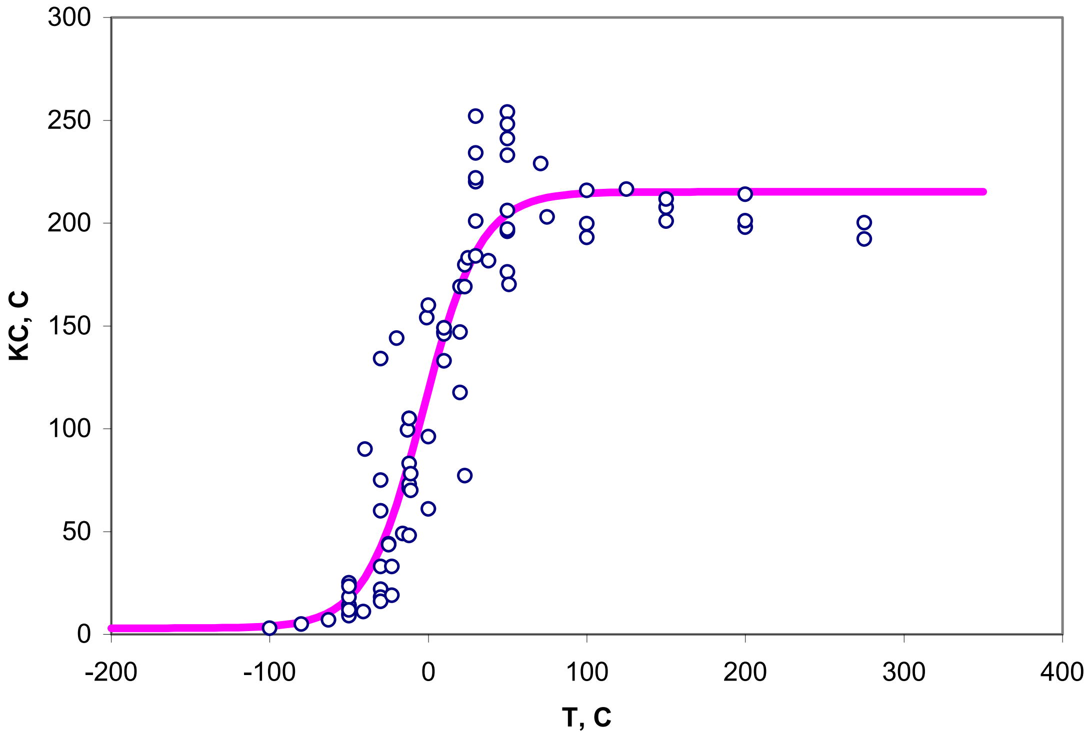


Fig.5.20. FIBROUS FRACTURE OF JRQ DEPTH=T/4=55mm ORIENTATION L-T

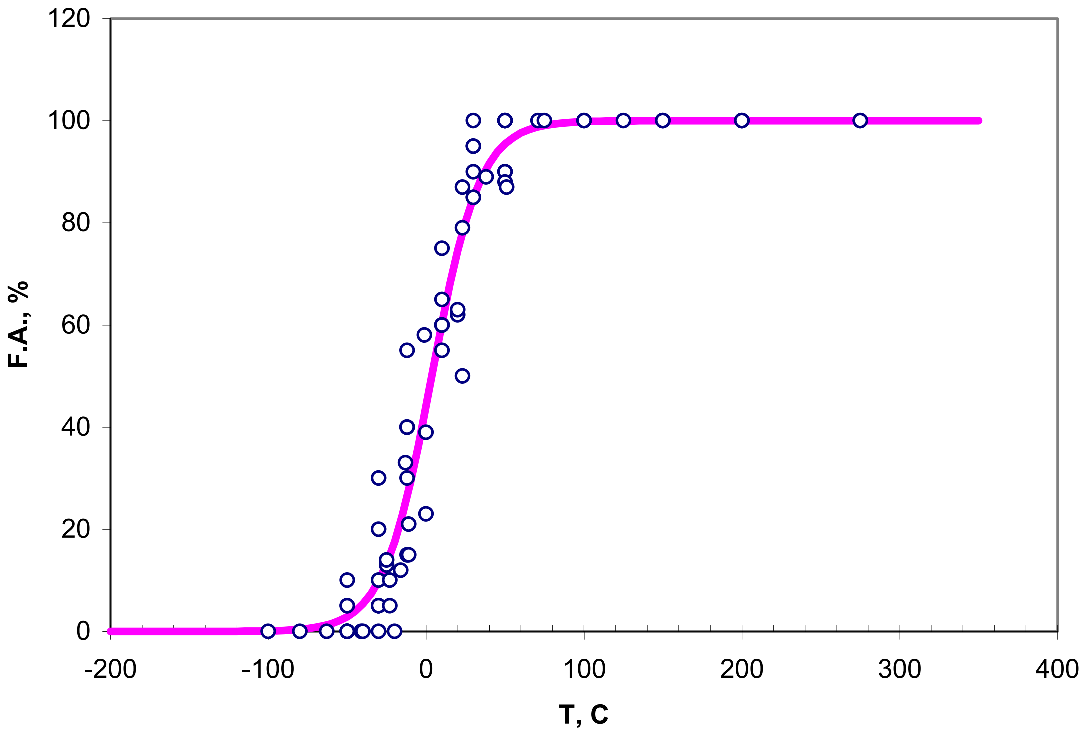


Fig.5.21. LATERAL EXPANSION OF JRQ DEPTH=T/4=55mm
ORIENTATION L-T

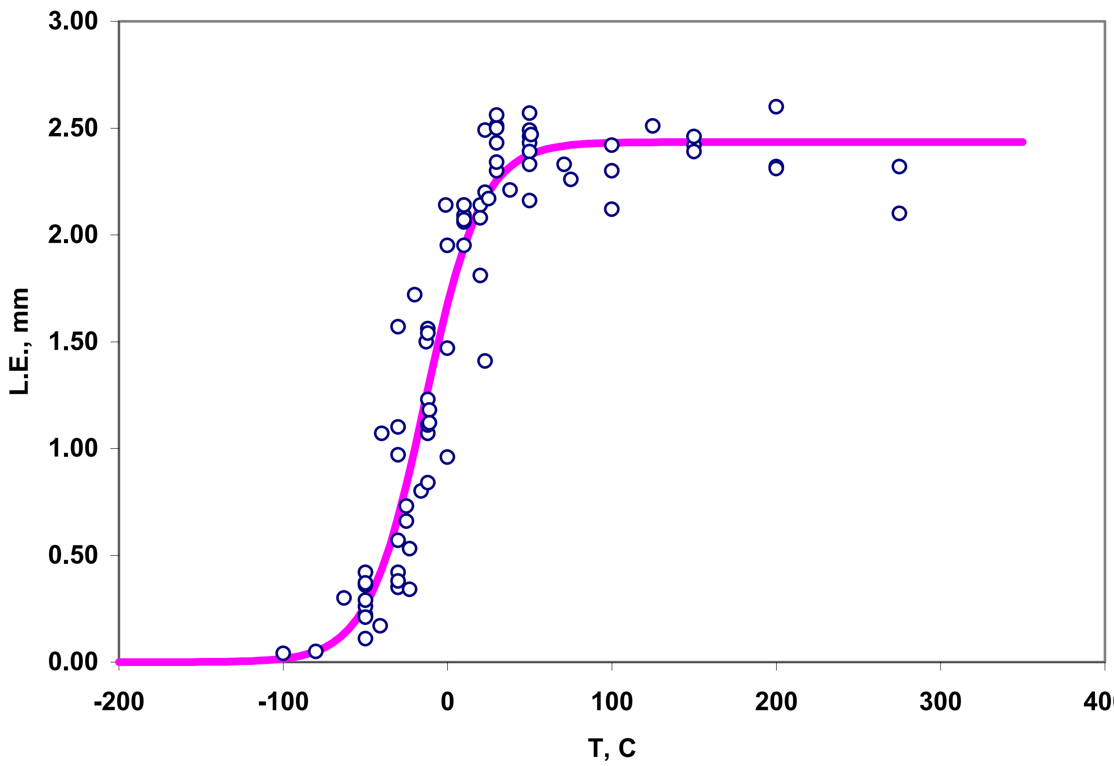


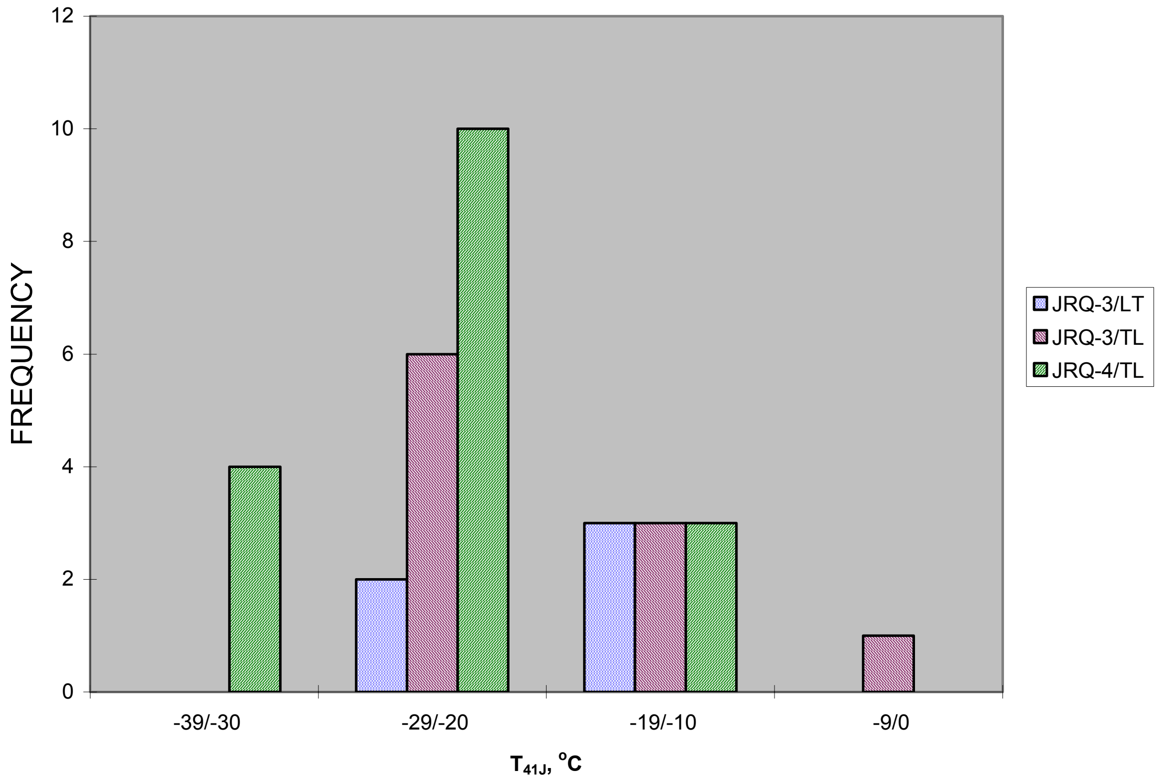
Figure 5.22 evaluates the effect of specimen orientation on transition temperature T_{41J} as a histogram where the scatter of results can be seen from the following mean values:

CRP-3	–	T_{41J} (T-L, 55 mm)	=	- 15.9 ± 8.2 °C
		T_{41J} (L-T, 55 mm)	=	- 23.7 ± 4.8 °C
		T_{41J} (55 mm)	**=**	**- 19.5 ± 7.8 °C**
CRP-4	-	T_{41J} (T-L, 55 mm)	=	- 23,8 ± 6,5°C

At the same time, the following upper shelf energies (USE) have been determined:

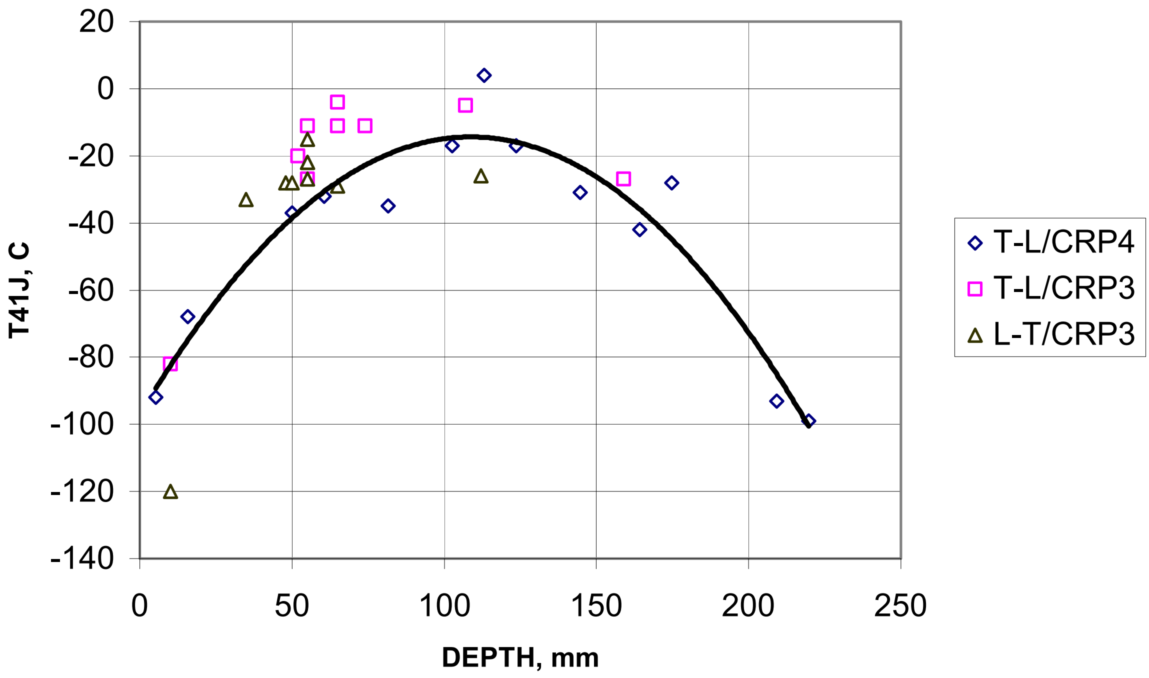
CRP-3	-	USE (T-L, 55 mm)	=	187.8 ± 11.1 J
		USE (L-T, 55 mm)	=	213.6 ± 12.2 J
		USE (55 mm)	**=**	**198.6 ± 17.2 J**

Fig.5.22. TRANSITION TEMPERATURES OF JRQ, DEPTH=55mm=T/4, ORIENTATION T-L



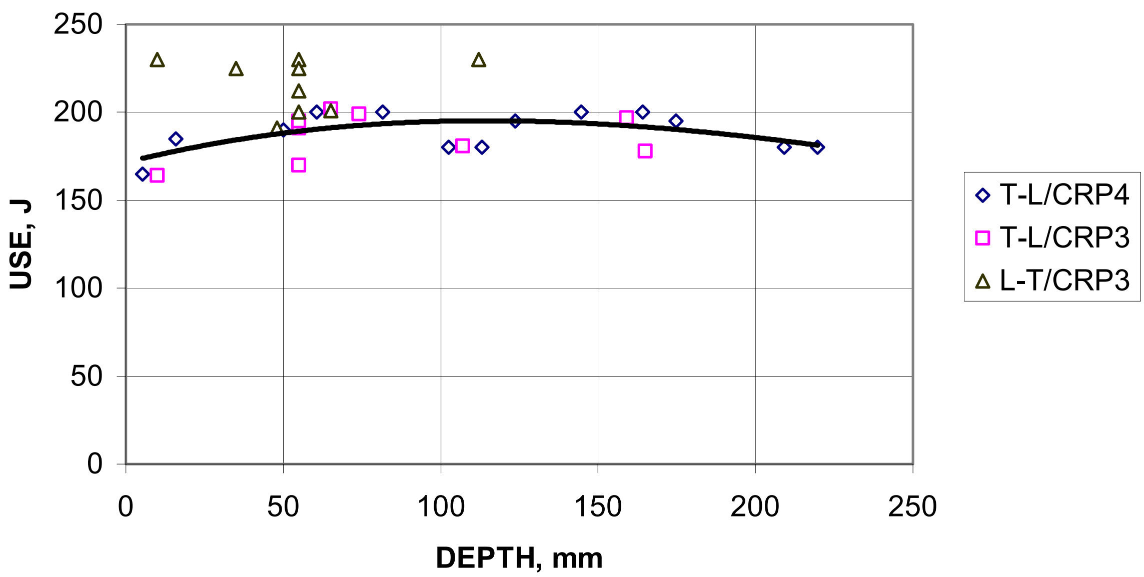
The effect of specimen location in the plate thickness was also determined. Figure 5.23 summarizes all the results of transition temperature T_{41J} from different depths of plate — both specimen orientations are mentioned. It is clearly seen that the depth dependence is much stronger in comparison with tensile properties – only results within the central half of the plate thickness show some relevant scatter of data. The transverse orientation (T-L) is less favourable in comparison with longitudinal one (L-T) which is in a good agreement with the aforementioned mean values of transition temperatures. Again, these results strongly support the recommendation for the use of specimen from one quarter of the thickness, only for reference use.

Fig.5.23. TRANSITION TEMPERATURES AS A FUNCTION OF SPECIMEN DEPTH



Similar, but less marked dependence has been obtained for USE values, as seen from Fig. 5.24. Again, an effect of specimen orientation (T-L vs. L-T) is seen, in that the T-L orientation produces results of somewhat lower energy.

Fig.5.24. UPPER SHELF ENERGY AS A FUNCTION OF SPECIMEN DEPTH,
DEPTH=55mm=T/4, ORIENTATION T-L



5.4. Fracture properties

Fracture properties, namely static fracture toughness, are of interest in the characterization of reactor pressure vessels structural integrity assessment and their operational lifetime evaluation.

A procedure for the determination of this material property has been under development for several years, especially its application to small scale specimens similar to those of Charpy size. Finally, the ASTM procedure [2] was issued and taken as the basis for testing within the CRP-4 mandatory part. Thus, a large set of data from testing 5JRQ block (as well as some from 3JRQ block) are available and can also be used for the JRQ material characterization.

Figure 5.25 shows all available raw data from Charpy pre-cracked specimens tested at different temperatures. These results are given even independently of the fact whether they are valid or not. All raw data were evaluated in accordance with [2] and adjusted to the thickness of 25 mm to allow the determination of transition temperature T_0. Then, Fig. 5.26 shows all these adjusted data as a function of relative temperature, $T-T_0$ together with tolerance bounds –1%, 5%, 95% and 99%. It is seen that tolerance bounds 1% and 99% are necessary to cover all the data points.

Fig.5.25. STATIC FRACTURE TOUGHNESS OF JRQ DEPTH=T/4=55 mm ORIENTATION T-L

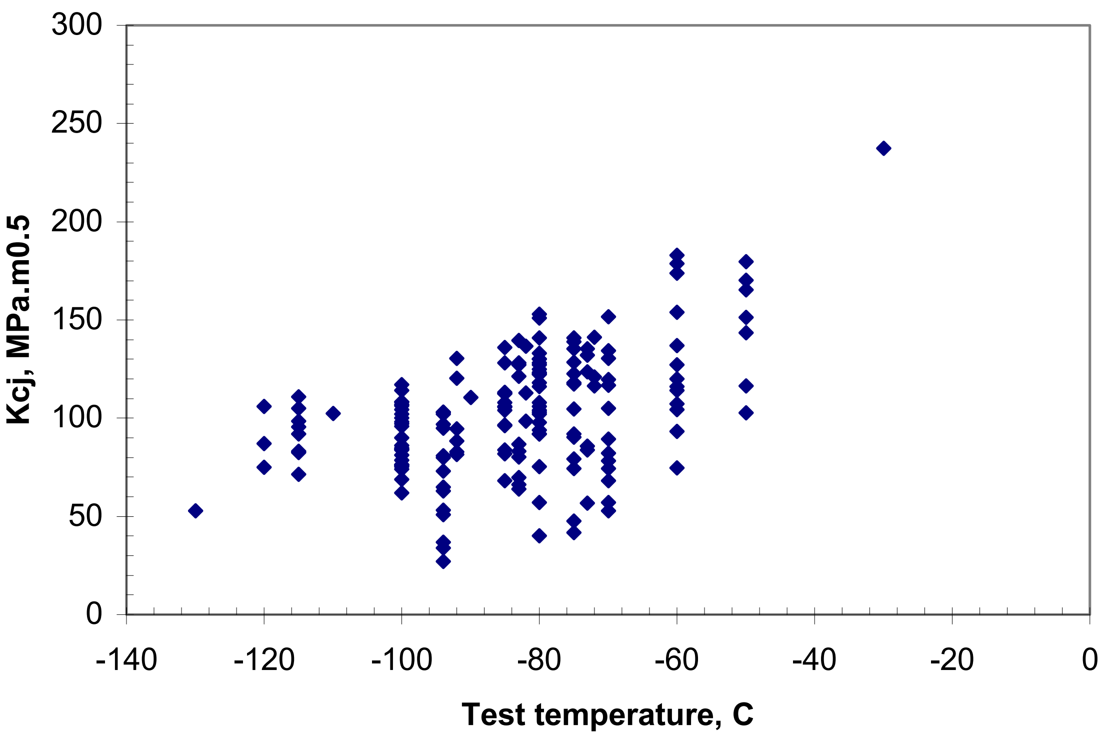


Fig.5.26 STATIC FRACTURE TOUGHNESS OF JRQ
DEPTH=T/4=55 mm, ORIENTATION T-L
SPECIMEN SIZE 10x10 mm

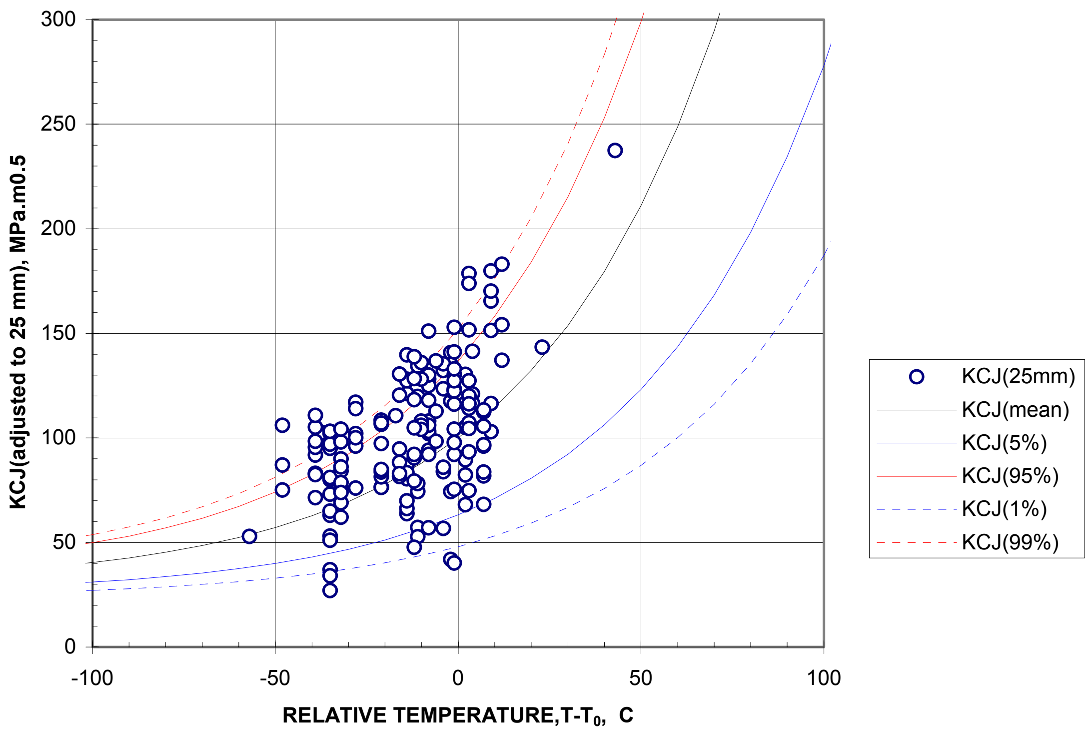


Figure 5.27 gives a histogram of all values of transition temperature T_0 – specimens have orientation T-L and were located in one quarter of the thickness, in both cases.

Mean value of all these tests is equal to $T_0 = 71 \pm 10^oC$.

Similarly to Charpy impact transition temperatures, Fig. 5.28 shows depth dependence of transition temperature T_0. The results show the same tendency, with some plateau in the middle part of the plate thickness.

Fig.5.27. REFERENCE TEMPERATURE T0 IN DEPTH=55mm=T/4,ORIENTATION T-L

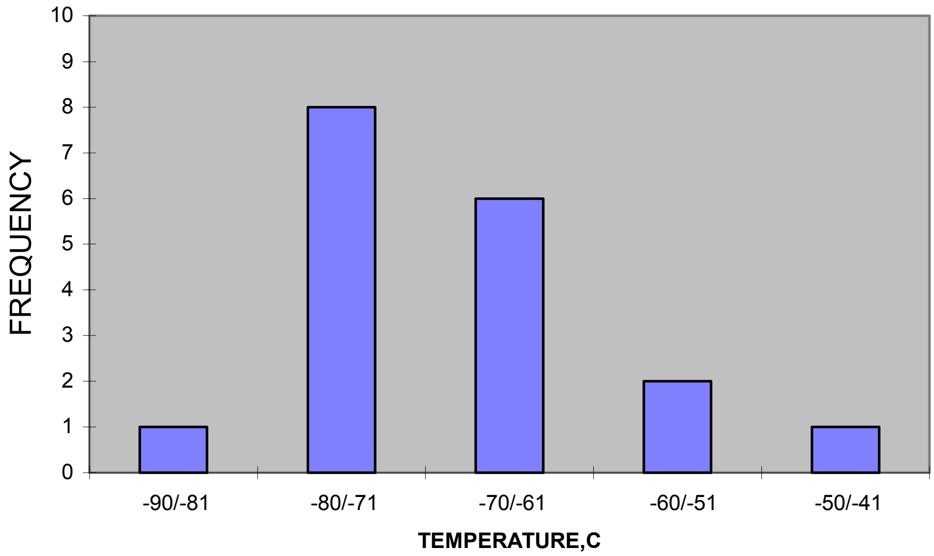
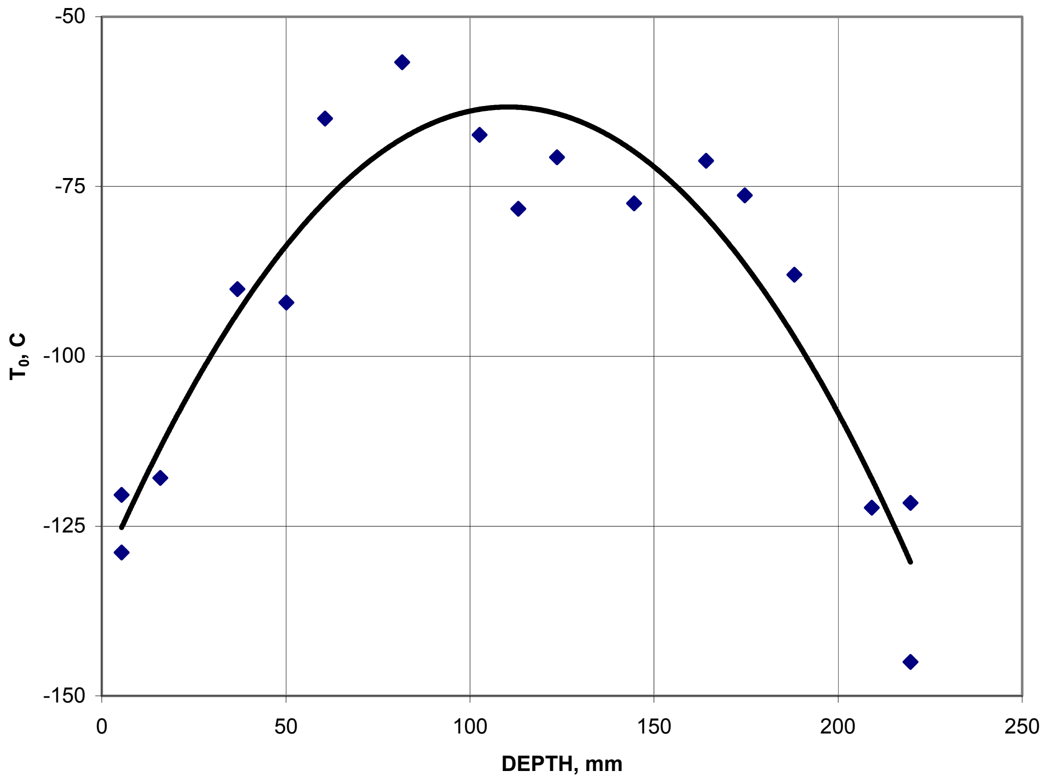


Fig.5.28. TRANSITION TEMPERATURE T0 AS A FUNCTION OF SPECIMEN DEPTH



6. CONCLUSION AND RECOMMENDATIONS

Results obtained showed that the JRQ plate is comparatively homogenous (difference between acceptance tests and results from two test blocks are small) and can be used as a reference steel, if the following requirements are fulfilled:

- specimen location must be at one quarter of the plate thickness (plus a maximum up to two layers for Charpy size specimens in the direction to the plate centre),
- specimen orientation must be standardized, T-L orientation is recommended (in accordance with Nuclear Codes as well as with the maximum amount of data collected),
- specimen preparation for Charpy impact tests must be done in accordance with a chosen standard, i.e. ASTM or ISO, as departure can produce different results,
- specimen preparation for fracture toughness tests must be done in accordance with a chosen standard, i.e. ASTM or ISO especially in fatigue pre-cracking and test temperature determination.

This report summarizes all the available data on manufacturing and properties of the reference steel JRQ which was chosen as reference material by the IAEA for use in co-ordinated research projects. The above results are not limited to the IAEA but could also be useful for national and international studies of reactor pressure vessel material behaviour – surveillance programmes, studies of radiation damage in these steels as well as for various round robin exercises, e.g. in fracture mechanics, etc.

REFERENCES

[1] Manufacturing History and Mechanical Properties of Japanese Materials Provided for the International Atomic Energy Agency, CRP Sub-Committee, Atomic Energy Research Committee, Japan Welding Engineering Society, October 1986.

[2] AMERICAN SOCIETY FOR TESTING AND MATERIALS, ASTM Standards Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in Transition Range, ASTM E-1021-97.

CONTRIBUTORS TO DRAFTING AND REVIEW

Brumovsky, M.	Nuclear Research Institute Řež plc, Czech Republic
Davies, L.M.	LMD Consultancy, United Kingdom
Kryukov, A.	Kurchatov Institute, Russian Federation
Lyssakov, V.N.	International Atomic Energy Agency
Nanstad, R.K.	Oak Ridge National Laboratory, United States of America