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HTR Vessel Materials

Specification of the sample selection, irradiation and PIE of mod. 9Cr steel

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Summary

This report describes the test-matrix and the irradiation specifications for the HTR-M project. The aim of the HTR-M project is to obtain the mechanical properties of the reactor pressure vessel welds of the High Temperature Reactor (HTR) pressure vessel under End-Of-Life conditions. The integrity of the welded joints is seen as a critical feasibility issue and information is needed on the behaviour of welded joints under the influence of the HTR environment. The programme on the vessel material is therefore focused on qualification through a series of mechanical tests to look at the integrity of welded joints under irradiated and non-irradiated (reference) conditions. The 'LYRA rig', which allows accurate control of the specimen temperatures during irradiation and use of a helium atmosphere, will be irradiated in the high flux reactor in Petten. Post irradiation and reference tests will include tensile, creep, impact energy (KLST type specimens or bending bar) and CT toughness tests.

1 Introduction

The development of Advanced High Temperature Reactor (HTR) concepts requires material data and an understanding of the material behaviour under reactor operating conditions and environment. For components important to the safety and feasibility of designs, such as the main steel structures (vessel, internal structures, turbine) and the graphite structures (core), investigation of the behaviour of the different materials in the reactor environment is a necessary requirement. This work identifies and investigates the candidate materials and provides an HTR database of properties for the materials of the key components that can be used by designers for feasibility investigations of the most promising options for future application. This part of the project mainly focuses on the Reactor Pressure Vessel (RPV) for the HTR.

The reactor pressure vessel in the high temperature reactor will be irradiated with neutrons, which causes damage within the material and will result in a change in mechanical behaviour of these materials. Depending on the operating conditions of the HTR, this irradiation takes place at temperatures between 120°C and 450°C. In accidental conditions the temperature might increase up to 600°C. At the lower temperatures the embrittlement of the RPV-material and welded joints should be studied and at the higher temperature the creep behaviour of the RPV material and the weldments is an important factor in determining the lifetime of the HTR and the vessel behaviour under abnormal conditions. The objective is therefore to confirm the choice of material for different HTR concepts, in relation to both normal and accident conditions, and compile their design properties.

Overall Project Objective

- The main objective of the project is to improve the reactor pressure vessel of the HTR by design, structural integrity analysis and provide the materials properties currently lacking.
- Develop HTR vessel materials and data in the areas of design analysis, structural integrity analysis and materials properties under HTR conditions including testing on welds for cold and hot vessel options.

2 Specification of mechanical tests and testmatrix

2.1 Specimen selection

Specimens for mechanical testing will be selected from a welded-joint produced by Framatome ANP. The weldment was produced by narrow cap TIG welding on modified 9% Chromium steel (P91). The plate is 150 mm thick and the weldment has a length of approximately 1 m. In order to study the mechanical behaviour of such a weldment the following assessment was made: The heat affected zone (HAZ) and the weld metal are identified as critical zones, i.e. those regions are most susceptible for crack initiation and growth. The specimens should be tested in the main stress direction.

In figure 1, a schematic drawing of the weldment is given and in figure 2, a macrographic cut of the welded joint is shown. In the schematic drawing, the rolling direction of the plates is indicated. In order to qualify P91 as a vessel material for high temperature reactors, which may operate at relatively high temperatures (up to 450°C), the welded joint will be tested for the mechanical properties in reference condition and in End-Of-Life (EOL) condition.

The following mechanical tests are foreseen: instrumented impact tests (sub-size Charpy), tensile tests, creep tests to rupture and fracture toughness tests. In section 2.2, the test-conditions will be discussed and in chapter 3, the irradiation conditions to achieve EOL dose of the HTR will be described. In this programme, the specimens will be taken from the thick section by cutting plates with a thickness of approximately 15 mm parallel to the weld direction as shown in figure 3. Three of such plates are required to accommodate the test-matrix. Two of them will be taken at the same distance from the mid-plane, i.e. mirrored around the centre-line, to obtain similar material conditions for all fracture toughness and impact specimens. The third plate will be used for tensile and creep specimens. The root, bottom and top of the weld will be avoided in order to get well-specified and homogenous material (see also ASTM E 185). Framatome ANP will document the location of the plates within the thick welded joint.

The material will be cut in plates with a thickness of 15 mm as shown in figure 3. The plates will then be inspected by Framatome ANP for (welding) defects using an ultrasonic device. A detailed map will be made with the defect identification in order to select defect free specimens. The final specimens cutting scheme will be sent to the project partners for approval.

2.2 Specification of the post-irradiation examination and reference testing

Four material conditions are selected for the mechanical testing: plate material, in parallel and in perpendicular direction with respect to the rolling direction, the heat affected zone (HAZ) and the weld metal. For each specimen type a detailed description will be given on the orientation and the test conditions. The specimen geometry for reference testing and for post irradiation examination will be the same for all the specimen types to enhance the comparison between the EOL condition and reference condition.

Tensile testing

In figure 4 the geometry of the tensile test specimen is shown. The gauge length is 20 mm, the distance between the shoulders S=23.5 mm, and the diameter of the reduced section is 4 mm. The specimens will be taken in the L and T direction of the plate. Also cross-weld specimens will be taken with the heat-affected zone (HAZ) in the middle of the gauge length and additionally full weld specimens will be tested parallel to the weld direction (L). See also the recommendations from the ECCC [1] and ASTM E 185 [2]. The specimen orientations and cutting scheme are demonstrated in figure 8.

The tensile specimens will be tested at 4 temperatures per material condition, i.e. room temperature, irradiation temperature (350°C), vessel operating temperature (450°C) and accident temperature (600°C). Per condition 2 specimens will be tested and hence in total 32 specimens for PIE and 32 for reference testing. The tests will be performed in accordance with the ASTM standard for tension testing of metallic materials (E8M) [3].

Creep testing

The geometry of the creep specimens and the orientations of the specimens with respect to the welded joint are the same as for the tensile specimens shown in figure 4 and figure 8. Creep tests will only be conducted at 1 temperature, the transient vessel temperature (550°C). 4 Creep specimens per material condition will be tested, i.e. in total 16 specimens. The creep tests will be performed to rupture according to the ASTM standard for creep testing E139 [4]. For the 6th FP it is foreseen that additional creep tests have to be performed at different temperatures in order to determine the temperature with negligible creep i.e. the creep threshold temperature. Therefore 16 additional creep specimens will be included in the irradiation (5th FP), which allows the start of the extra creep tests with long rupture times at the beginning of the 6th framework programme.

Instrumented impact testing

Miniaturised impact specimens, KLST type specimens shown in figure 5, will be used to determine the shift in DBTT, the lower and the upper shelf energy. Specimens will be taken from the plate material in the T-L and L-T direction and for testing the HAZ and weld; specimens will be taken in the T-L direction, i.e. with the crack running into the weld direction. The cutting scheme, including the orientation of the specimens is shown in figure 9.

For each full transition curve up to irradiation temperature, it is expected that 15 sub-size specimens are required. In total 60 sub-size specimens will be tested. The PIE tests will be performed with a small, instrumented Instron-Wolpert pendulum machine, with a maximum capacity of 50 J, in accordance with the ISO standard [5].

The reference-testing programme will also include full size Charpy specimens, shown in figure 6, in order to study the size effect of the impact properties. Only three materials conditions are selected for those tests: plate material in the L-T direction, HAZ in the T-L direction and the weld metal also in the T-L direction. 12 specimens and 3 conditions require 36 full size Charpy specimens. Also in the irradiation, full-size Charpy specimens will be included. The manufacturing costs of the full size Charpy's are originally not included in the 5th Framework HTR-m Programme. Therefore, these additional specimens will be produced from the limited budget in the 5th FP and will affect the manpower that can be spent on mechanical testing. The testing of the full size Charpy's in reference condition (36 specimens) and irradiated Charpy tests (36 specimens) will be performed in the 6th Framework Programme. The (irradiated) Charpy tests can either be 3 point bending static fracture toughness at NRG and/or impact tests at an Eastern European institute (Hungary or Czech Republic).

Fracture toughness CT-tests

CT-specimens, figure 7, will be used for fracture toughness testing. The orientation is the same as for the impact specimens and hence the crack extension is into the same direction as for the impact specimens, as shown in figure 10. The crack is running in the longitudinal direction of the weld and runs therefore in a relatively homogeneous direction, avoiding the deflection of the crack from a straight path. The fracture toughness will be tested at minimum vessel operating temperature (350°C) with an Instron servo-hydraulic mechanical testing machine using the Direct Current Potential Drop (DCPD) method for monitoring the crack growth. This method is very effective considering the required number of specimens for a full J-R curve. The displacement will be measured by an averaging load-line displacement bridge mounted to the CT-specimen. The fracture toughness tests will be performed in accordance with the ESIS procedure [6], which is similar to ASTM E1820 [7]. 5 specimens are intended for each condition. However, it might be that only 2 to 3 specimens are needed per condition using the DCPD method. When this is the case, the leftovers will be used for fracture toughness tests at a lower temperature (e.g. room temperature).

The test matrix is summarised in table 1 and the detailed cutting schemes for specimen retrieval are shown in figure 8 to figure 10. The identification number of the specimen will be related to its location within the welded joint and plate. The total number of specimens is limited (budget) and additional mechanical tests are required (6^{th} FP) for the qualification of P91 and the welded joint as a possible pressure vessel steel for the HTR.

table 1 HTR-m test matrix for reference and irradiation testing

Specimen type	#	conditions	Temp.	**sub-total**	6^{th} FP	irr/ref	**total**
Small size Charpy (KLST)	15	4		**60**		irr & ref	**120**
Tensile	2	4	4	**32**		irr & ref	**64**
Creep	4	4	1	**16**	16*	irr & ref	**32 (32*)**
Fracture toughness (CT10)	5	4	1	**20**		irr & ref	**40**
full size Charpy	12	3		**36**		irr & ref	**72****

* 16 specimens will be irradiated in LYRA but tested in the 6^{th} framework programme, also 16 additional creep specimens will be prepared for reference testing in the 6^{th} FP.

** 36 additional full size Charpy specimens will be included in the irradiation rig (6th FP bending or impact tested in Eastern Europe through JRC.IE) and 36 specimens for reference testing.

3 Specification of the irradiation

The objective of the irradiation experiment on the HTR pressure vessel steel is to achieve the HTR EOL neutron dose with a relevant neutron spectrum for the HTR pressure vessel at the normal operation temperature. The EOL neutron dose and fluence levels depend on the HTR design and type of the core. Therefore, the EOL neutron dose is estimated from PWR, LWR, BWR fluences [8] and by Buenaventura [9].

- The peak Neutron fluence $8 \cdot 10^{22}$ n/m^2 (E>0.1 MeV).
- Nominal irradiation temperature will be 350 °C ±10°C.
- Irradiation will take place in the Pool Side Facility (PSF) of the High Flux Reactor (HFR).

3.1 Materials & specimens

The materials (RPV steel and weldments of P91) selected for the HTR-m project will be supplied by FRAMATOME ANP. The nominal chemical composition can be found in table 2. The material properties are listed in table 3 and the HTR irradiation test matrix is listed in table 4.

table 2 Nominal chemical composition (wt%) of the P91 welded joint [10]

	C	Mn	P	S	Si	Cr	Mo	V	Nb	N	Al	Ni
P91	>0.08	>0.30			>0.20	>8.00	>0.85	>0.18	>0.06	>0.030		
	<0.12	<0.60	<0.020	<0.010	<0.50	<9.50	<1.05	<0.25	<0.10	<0.070	<0.040	<0.40

table 3 Material properties of the HTR pressure vessel candidate material P91

Property	**P91 ferritic/martensitic**
density	7.77 g/cm^3
linear CTE (RT-350°C)	11.8 10^{-6} K^{-1}
Thermal conductivity	26 – 28 $Wm^{-1}K^{-1}$

table 4 Minimal number of specimens for HTR-m for the LYRA irradiation

Specimen type	**material**	**number**	**dimensions**
KLST	T91 & weld	60	27 x 3 x 4 mm
Tensile/Creep	T91 & weld	64*	Ø12 x 45 mm
CT-10 FTT specimen	T91 & weld	20	29 x 27 x 10 mm

* Including 16 creep specimens to be tested in the 6th EU-framework programme

3.2 Design

The design of the irradiation experiment can be based on previous PSF irradiations like LYRA, which allows accurate control of the temperatures in an inert atmosphere (see figure 11). Tungsten plates will shield the specimen holder for gamma-irradiation to avoid a high gamma heating. Heaters in the rig will be used to maintain the nominal temperature levels.

3.3 Temperatures

The rig design should allow a nominal temperature of 350°C with a maximum temperature gradient of ±10°C The difference in temperature from specimen to specimen should be kept as low as possible, i.e. be smaller than 15 degrees (this can be achieved by external heating). It is very important to know the actual temperatures of the specimens during irradiation because of annealing effects. The temperatures will be measured by a set of 24 K-type thermocouples at different levels within the irradiation rig.

3.4 Nuclear characteristics

The required target dose is approx. $8 \cdot 10^{22}$ n/m^2 (E>0.1MeV). The dose can be achieved in one or two cycles in the Pool Side Facility (PSF) of the High Flux Reactor in Petten. The neutron fluences will be monitored by pieces of nickel-cobalt, titanium, iron and niobium. After irradiation the neutron detector sets will be analysed for fast fluence, thermal fluence divided in four energy groups. The fluence gradients, due to the flux buckling and self-shielding (thermal flux), will be determined using the neutron monitor sets. The specimen fluence gradients will be kept as low as possible (<5%), i.e. with the notch axis parallel to the HFR core box.

3.5 Environment

Pure helium should be used providing an inert environment and to simulate the HTR environment.

4 Conclusions

This report summarises the test matrix for the mechanical testing of the reactor pressure vessel materials for HTR in the frame of the HTR-M project. Because of the limited irradiation volume and budget and hence a limited number of specimens, the test programme should be considered as a survey study of P91 as a HTR reactor pressure vessel material. The programme on the vessel material is focussed on the qualification through a series of mechanical tests to study the integrity of welded-joints under irradiated and non-irradiated conditions. The test-matrix comprises fracture toughness-, impact-, tensile- and creep tests. The irradiation will simulate the end of life condition of a HTR pressure vessel, where reference tests are included for comparison. In the 6^{th} framework programme, new filler metal becomes available in order to avoid hot cracks during welding with a much wider margin for welding parameters. Also additional creep tests are foreseen in the 6^{th} framework programme.

References

[1] ECCC Recommendations 1999 - Volume 2 Part IIb "Terms and Terminology for Weld Creep Testing", Volume 3 Part II "Data Acceptability Criteria and Data Generation: Creep Data for Welds".

[2] ASTM standard practice for conducting surveillance tests for light-water cooled nuclear power reactor vessels, E185 (1996).

[3] ASTM standard for tension testing of metallic materials, E8M.

[4] ASTM standard test methods for conducting creep, creep-rupture, and stress rupture tests of metallic materials, E139-96.

[5] ISO standard for steel -- Charpy V-notch impact tests -- Instrumented test method CD 14556:2000 (E).

[6] ESIS procedure for determining the fracture behaviour of materials, European Structural Integrity Society (ESIS), ESIS P2-91D, May 1991.

[7] ASTM Standard test method for measurement of fracture toughness, E1820-99a.

[8] L.M. Davies, International journal of pressure vessels and piping, 76 (1999) p.163.

[9] M.T. Cabrillat and A. Buenaventura, WP1 Task 1.5: Design Rule check, HTR-M-02/08-D-1.1.40.

[10] The T91/P91 book, Vallourec & Mannesmann tubes, 1999.

appendix A Welded joint

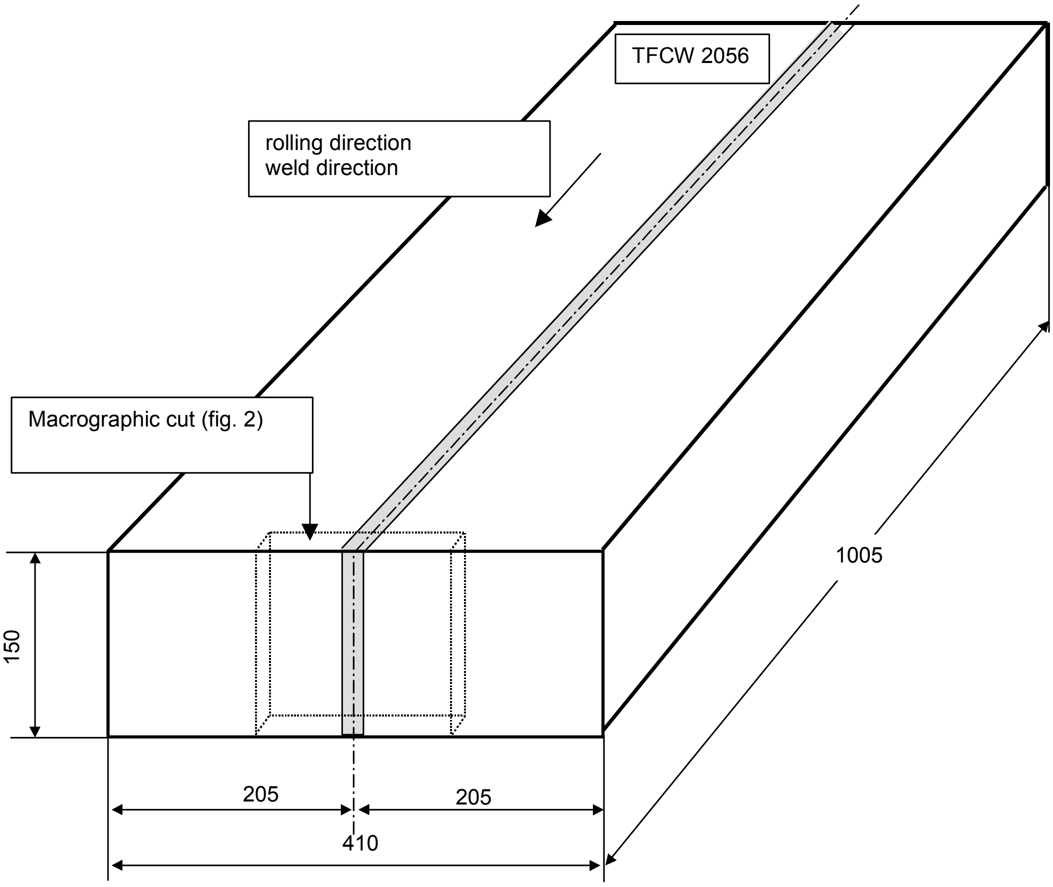

figure 1	Welded joint produced by Framatome ANP with reference TFCW 2056. The rolling direction of the P91 plates is indicated

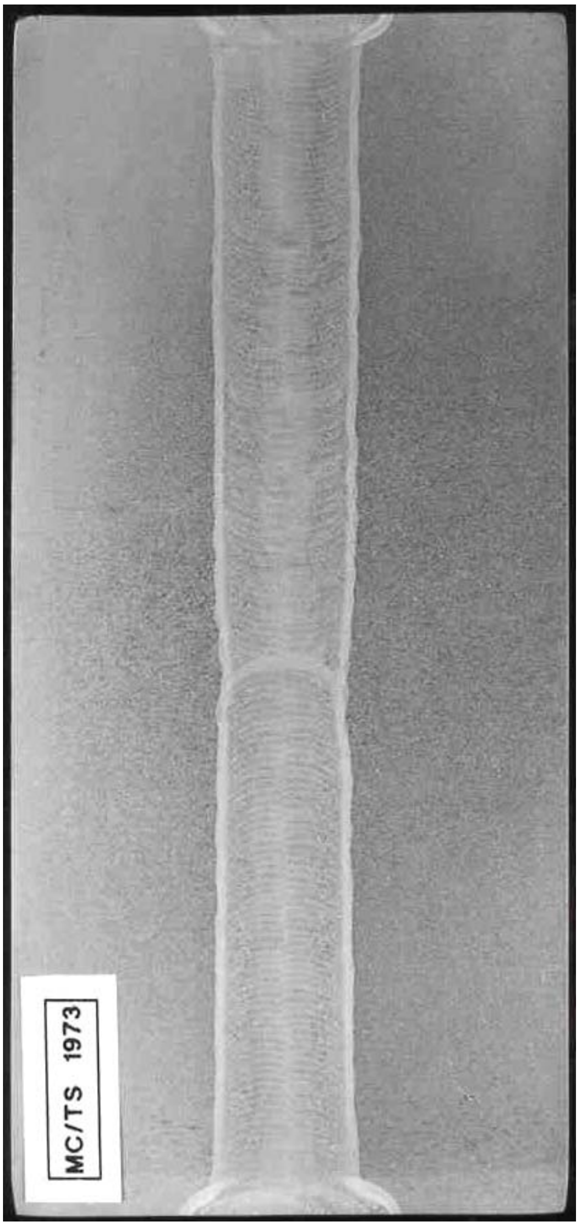

figure 2 Macrographic cut of the welded joint MC/TS 1973 obtained with the same welding conditions as the welded joint TFCW 2056 shown in figure 1

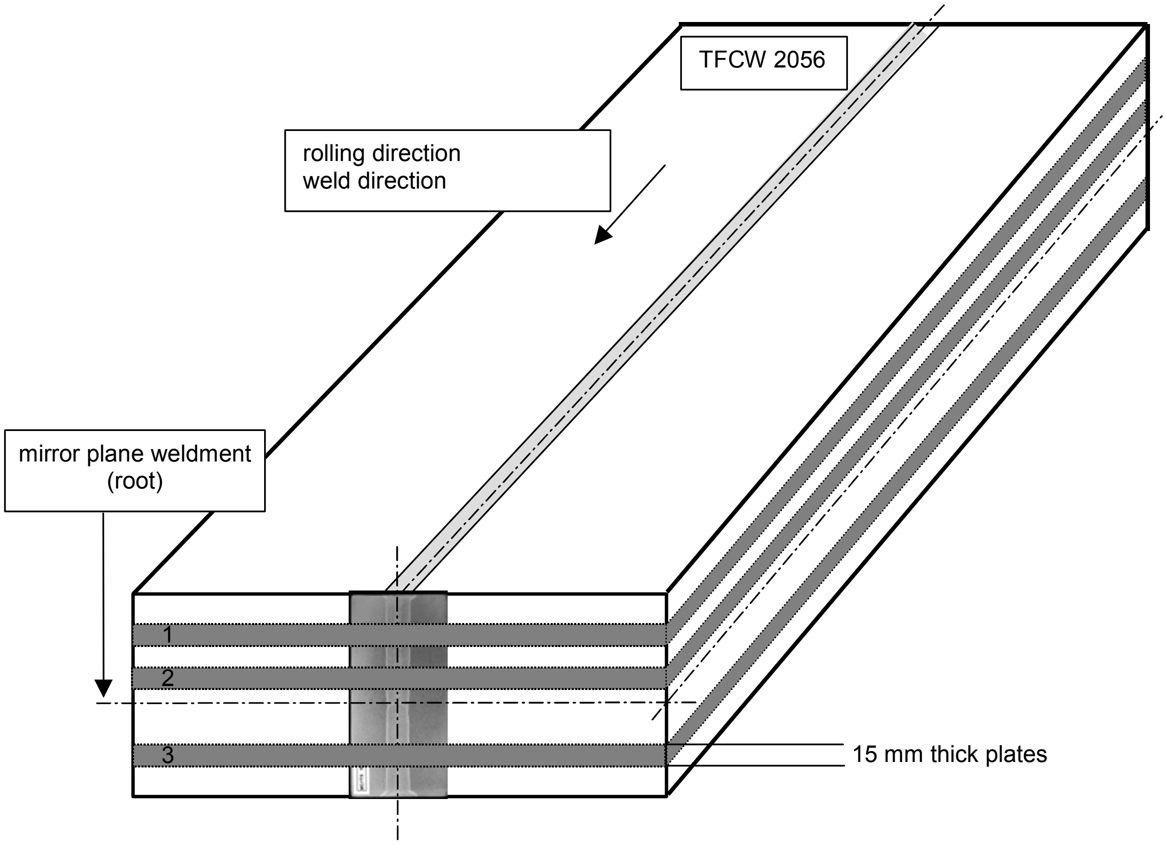

figure 3 Description of the plates that will be cut and used for mechanical testing

Plates 1 and 3 are located at the same distance from the centre plane and will be used for fracture toughness test specimens and for impact test specimens. Plate N^{o} 2 will be used for tensile and creep specimens.

appendix B Specimen types

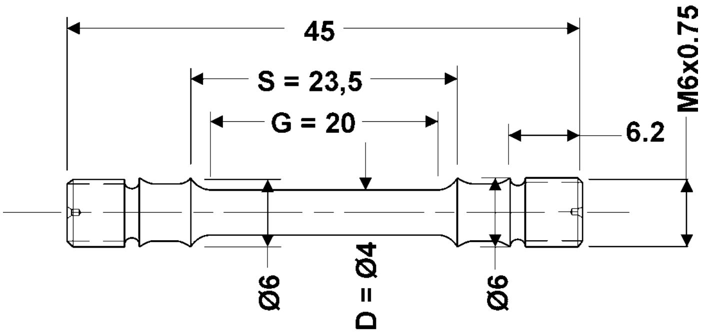

figure 4 Geometry of the tensile and creep test specimen (in mm)

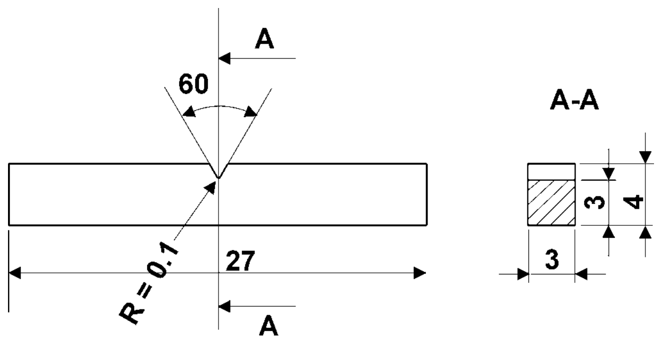

figure 5 KLST type (miniaturised Charpy) specimen for impact testing (in mm)

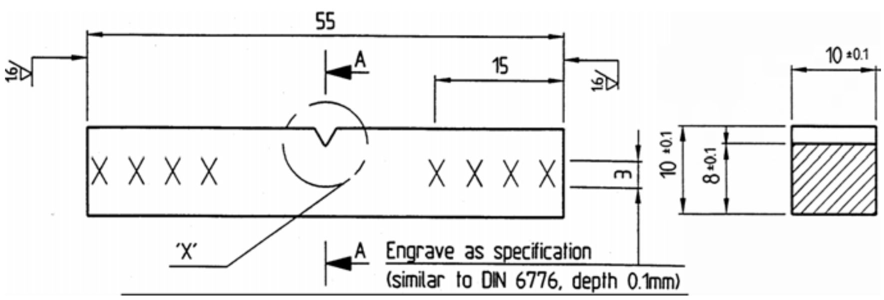

figure 6 Full size Charpy specimen for reference testing (in mm)

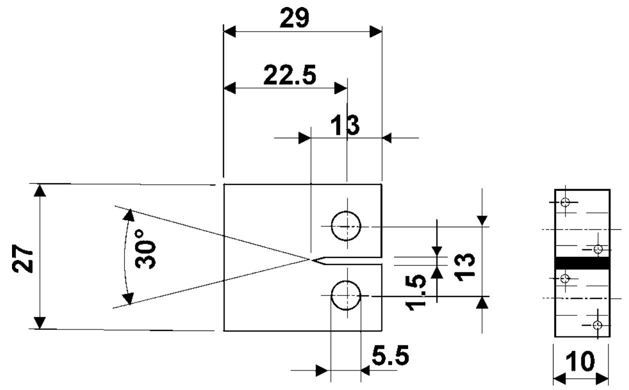

figure 7 CT-10mm/2 test specimen for fracture toughness testing (in mm)

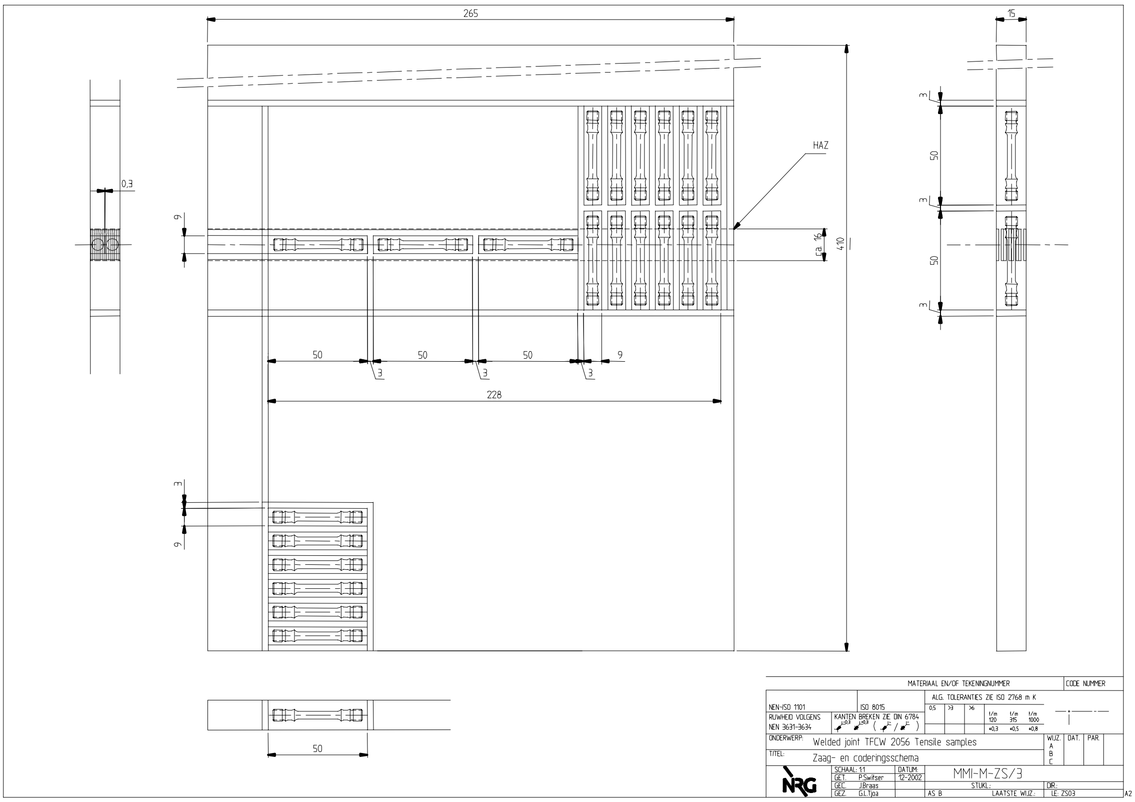

figure 8 Cutting scheme to obtain tensile and creep specimens from the welded joint

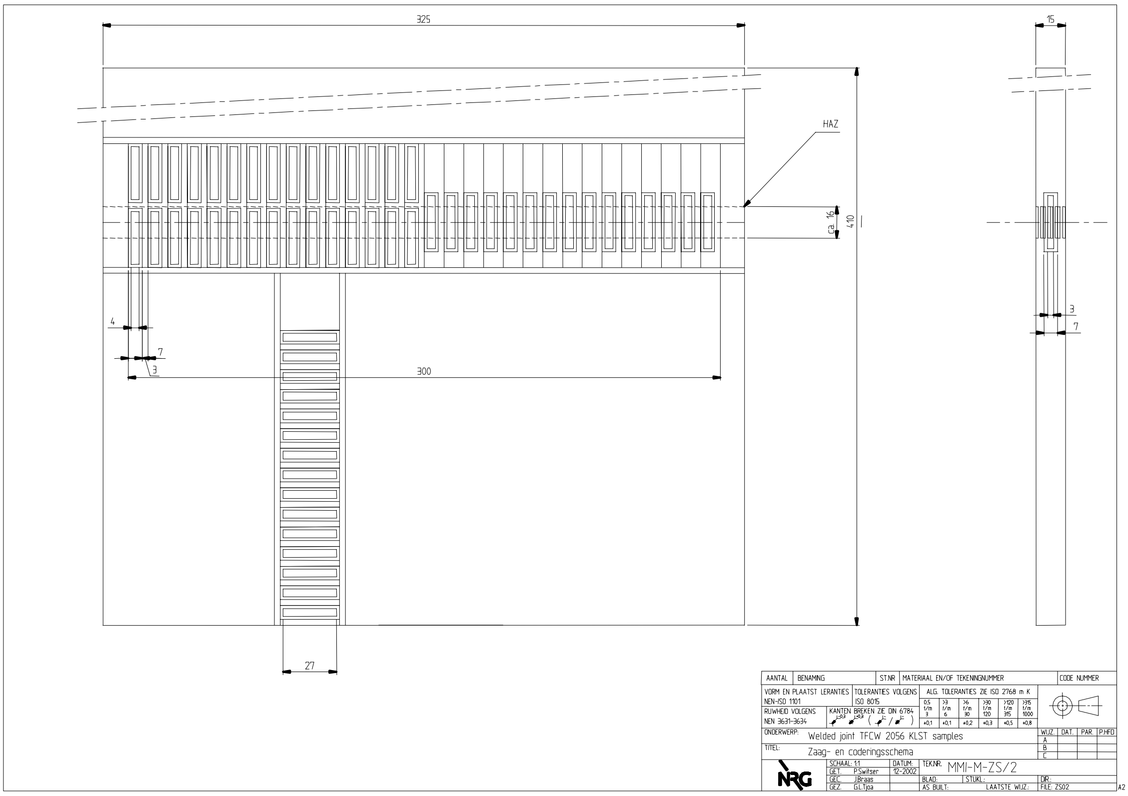

figure 9 Cutting scheme to obtain impact specimens (subsize Charpy and Charpy) from the welded joint

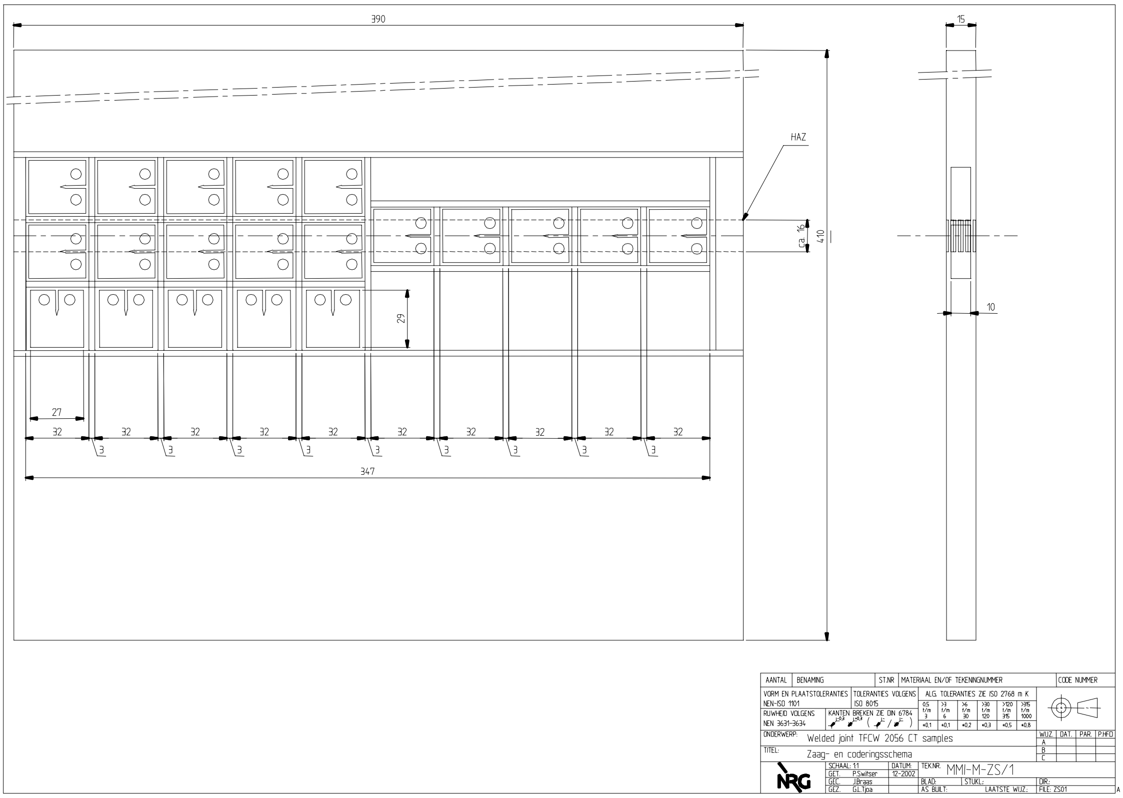

figure 10 Cutting scheme to obtain FTT specimens from the welded joint

appendix C LYRA irradiation facility

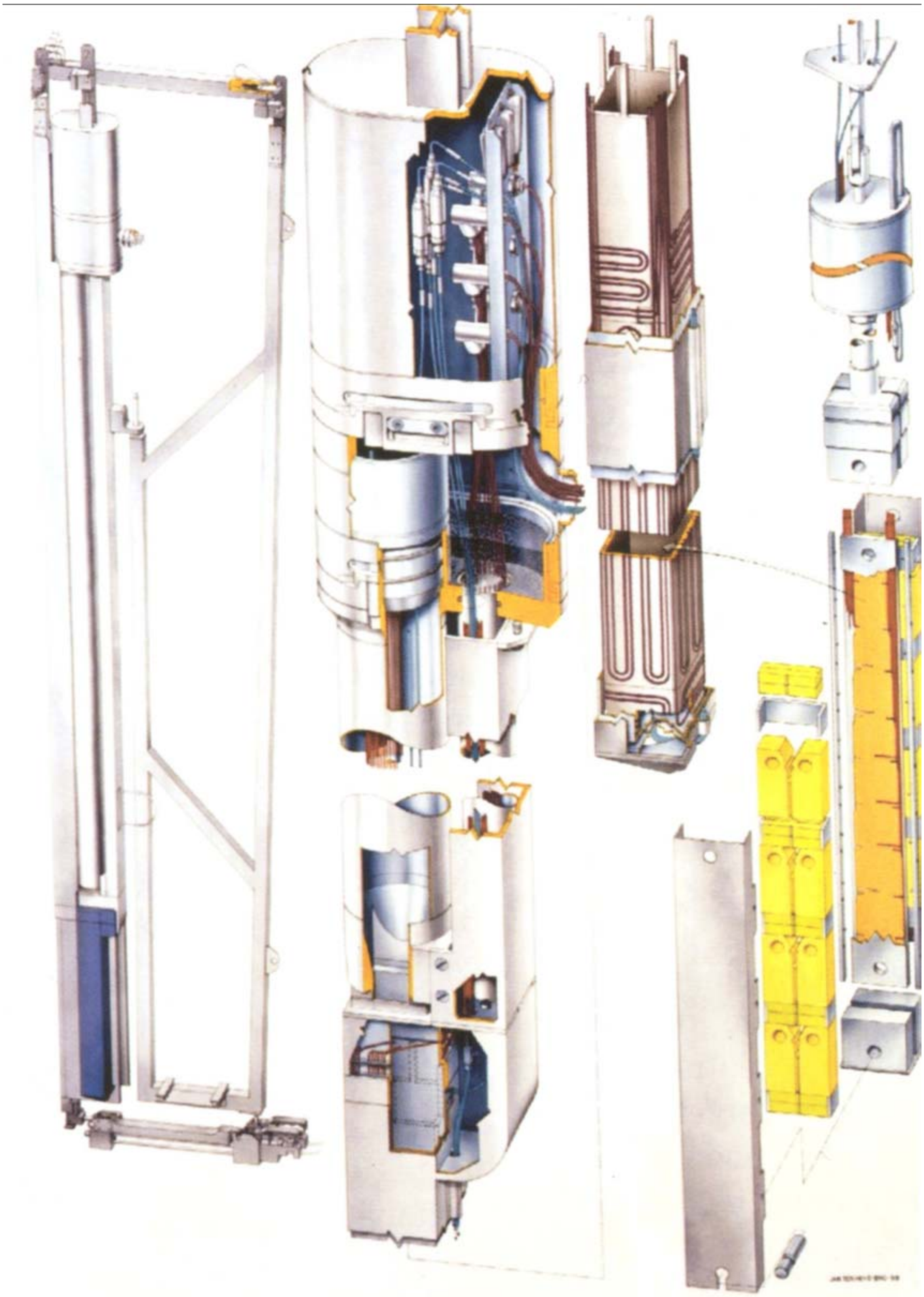

figure 11 Illustration of the LYRA irradiation rig (By B. Acosta and M.Beers, JRC-IE)