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HOT EXPERIMENTAL FACILITIES AND METHODS EMPLOYED IN MECHANICAL TESTING PROGRAMS FOR PWR PRESSURE VESSEL STEELS

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ABSTRACT

Commencement of PWR pressure vessel manufacture at the Škoda Works and the start of operation of Škoda built WWER 440/213 nuclear units at NPS Jaslovské Bohunice and Dukovany in Czech republic led in the early 1980s to the design and construction of a hot and semi-hot laboratory for mechanical testing in the Nuclear Rasearch Institute Řež to participate in the development and surveillance programs for pressure-vessel steels. As described in this paper, the laboratory has all the necessary equipment and methods for post-irradiation tensile, impact, fracture toughness, hardness and fractography measurements.

1. INTRODUCTION

The hot and semi-hot laboratory of the Nuclear Research Laboratory Řež was designed and constructed during the 1980s to assist in the Institute's work in the (former) Czechoslovak programs of PWR pressure vessel steel development and surveillance.

As a part of the NRI Division of Integrity and Materials, the hot laboratories provides all the necessary mechanical tests, i. e. tensile tests, impact tests, hardness tests, dynamic and static fracture toughness tests, together with visual inspection, fractography and dimension measurements, required to establish the effects of irradiation on mechanical properties.

2. HOT CELLS LABORATORY

2.1. Technical description of hot cells

Hot cells laboratory carries out the pertinent preparatory and auxiliary operations, e. g. receiving of irradiated materials, unloading of containers (coming from the NRI research reactor or nuclear power plants), disassembly of capsules or irradiation rigs and recovery of their contents, sorting of specimens their inserting into containers used for internal transport and storage, as well as evaluation of detectors to determine the neutron fluence and irradiation temperature. Recently, this facility has been fitted with equipment for reconstitution of irradiated samples (welding, cutting and grinding machines).

Hot laboratory contains 20 hot cells, situated on two floors. They are mutually interconnected by two remotely operated horizontal conveyers and vertical lifts. The hot cell is in a principle a inside steel box with stainless steel bottom : width 240 mm, depth 1800 mm, height 3000 mm. Laboratory is equiped with the ventilation system ensuring underpressure and filtration against the surrounding atmosphere and at the same time the prescribed air exchange. Liquid radioactive wastes from hot cells are discharged into a special sewerage that collects these wastes for futher processing. All inlets into HCs are sealed. The technological inlet is secured by hanged door 660x1260 mm in the rear part of the cell. An insight into HC is enabled through a sight hole 800x800x1200 mm and consists of a reservoir filled with $ZnBr_2$ solution and of several layers of lead glass of 600 mm in diameter.

Tho total system of boxes, transport paths, insight holes and inlets is shielded with heavy concrete walls of 1100 mm thickness. Materials with the activity up to 10^{14}-10^{15} Bq (approx. 20 000-100 000 Ci) may be treated in these hot cells.

2.2. Radioactive material receipt in hot cells

Radioactive material receipt in hot laboratories may be accomplished through the reception hot cells. There are two inlet paths into each HC :

1. The inlet from the shifting chamber from the cell side-in this case, radiaoactive material is usually shifted out from the container (maximum container dimensions are 840x840x1300 mm, mass 10 t). Maximum dimensions of transporting box are 200x370 mm.

2. The inlet through a pool in the basement-pool depth is 4.9 m, its length 4m, and its with 2 m. Radioactive material is transported in a container above the pool and from the container it is submerged onto the pool bottom. From there, radioactive specimens may be transported through an inclined chute into the reception HC. The chute enables the transport of a box that has cylindrical shape of 125 mm in diameter and the length of 350 mm.

2.3. Hot cells machinery and devices

At present, the part of hot cells is used for the needs of research and for the evaluation of irradiated construction materials. In connection with the solution of these programs, Hcs are equipped with following remotely handled machinery and devices :

- Assembly for case or probe dismantling
- Cutting machine
- Device for specimen notch grinding
- Vacuum high-temperature furnace
- Electrospark cutter
- Electron beam welding unit
- Surface grinding machine
- Set of devices for measuring the dimensions

2.4. Possible operations in hot cells

The set of operation that may be carried out at present in HCs of Nuclear Research Institute is connected with the problems solved in the Division of Integrity and Materials, i. e. work with irradiated construction materials for nuclear power plant components.

Dismantling of specimens carriers in rigs irradiated in the NRI's research reactor LWR-15 is mastered with skill. Further, operations are currently carried out with chains of surveillance specimens from power reactors VVER-440, i. e. cutting of chains and opening of cases with surveillance specimens.

Construction materials may be cut up to the total mass of 5 kg, the dimensions are limited by both the transport paths between Hcs and by the technical possibilities of machines.

In the field of thermal treatment, even prolonged experiments may be carried out in a protective atmosphere with specimens up to the temperature of 1300 °C.

2.5. Reconstitution of Charpy-type specimens

The reconstitution of surveillance specimens of the Charpy-V type is possible in hot cells laboratory. New test specimens are expected after its disruption during mechanical test and subsequent welding of inactive ends.

Reconstitution of Charpy type specimens (impact, dynamic and static fracture toughness testing) from inserts of standard dimensions (10x10x14 mm) is carried out using electron beam welding machine. Reconstitution method and welding machine are shown in Figs. 1 and 2. The system consists of the high vacuum part with welding chamber, the electron beam device, the samples positioning part and special TV system for direct observing of the welding process. The main parameter, the beam power of about 5 kW, is suitable for reconstitution of all types of specimens used in NRI hot laboratories.

3. SEMI-HOT EXPERIMENTAL FACILITIES AND METHODS

3.1. General layout

The semi-hot cells laboratory is situated close to hot cells facility. The general layout of the semi-hot metallurgical laboratory can be seen from Fig. 3. The laboratory consists seven semi-hot cells

The face wall of the cells is shielded by 100 mm of lead for handling of specimens with an assumed activity of 3.7 GBq. All the cells are linked by a cable belt conveyer and equipped with tongs manipulators, and cells 5 and 6 have manipulators of master-slave type (cells for static fracture toughness and tensile properties measurement). The ventilation system ensures permanent underpressure of 50 Pa and exchange of air up to 20 times per hour.

3.2. Basic testing equipment and methods

3.2.1. Impact properties and dynamic fracture toughness

For impact testing, cell 4 has been equipped with a Tinius Olsen Model 74 Universal Impact Tester, instrumented with DYNATUP GRC Model 730-1 data acquisition and analysis system. The equipment has been fitted with a resistence furnace and a cooling box working with liquid nitrogen for test temperatures from -190 °C to +300 °C.

The impact tester has been mostly applied for notch ductility measurements on standard Charpy-V specimens according to the Czech standard ČSN 420381 (equivalent to ISO/DIS 148-76 Steel-Charpy impact test, V-notch). Actual research program have also included dynamic fracture toughness measurements.

Results from reactor WWER 440/213 pressure vessel surveillance specimen program are given in Fig. 4 for base material in unirradiated state and irradiated state after from one to five years of reactor operation. Impact energy temperature dependance is presented as measured on 10x10 mm Charpy-V type specimens.

3.2.2. Tensile properties and static fracture toughness

Instron 1342 servohydraulic 100 kN capacity tensile testers have been installed i cells 5 and 6, their function is controlled by PC control stations using Instron software. This standard equipment was tailored for hot-cell operation by adding stainless steel pull rods and openable furnaces and cooling boxes (operated by manipulators) of NRI's own design. The heating/cooling system covers test temperatures from -190 °C to +300 °C. During the tests, the load point displacement is measured by LVDT transducer gauges mounted on pull rods outside the furnace or cooling box.

Tensile test are performed according to the Czech standard ČSN 420310 (equivalent to ISO 86-1974 Steel. Tensile testing) mostly 3 mm and 4 mm diameter specimens.

Static fracture toughness measurements are conducted in accordance with the Czech standard ČSN 420347 (similar to ASTM E 399-81, ASTM E 813-81 and ASTM E 1290-89). Because of limiting number and dimensions of the specimens and the need to determine the fracture toughness charcteristics especially in the transition temperature regioon, the single specimen unloading compliance method has been adopted in the whole range of test temperatures.

For the above mentioned reasons, the specimens used for fracture toughness tests are generally of a smaller type (10 mm thick three-point-bend, 12.5 mm thick RCT, 12.5 and 25 mm thick CT specimens).

An example of static fracture toughness temperature dependance obtained from surveillance specimen program of WWER 440/213 reactor pressure vessel steel is given in Fig. 5. Results of 10x10 mm three-point-bend specimens, fatigue precracked, with side grooves are presented in unirradiated and irradiated state after from one to five years of reactor operation.

3.2.3. Specimen visual inspection and dimension measurement, fracture examination

To improve the precision of visual inspection and the accuracy of dimensions measurements on irradiated specimens, as well as to processing and storage of the data thus obtained, e. g. for fractography purposes, an image analysis system is used. The system enables measurement and evaluation of all the pertinent dimensional data connected with tests of notch ductility, static and dynamic fracture toughness, tension, etc. namely the basic specimens dimensions, necking, lateral expansion, share of ductile fracture, length of fatigue or ductile cracks. The system permits storage of the image on magnetic media and redisplay if necessary.

4. APPLICATIONS

During its existence (30 years), the hot and semi-hot laboratory has carried out mechanical tests within the reactor pressure vessel surveillance program of WWER 440/213 type nuclear units at Jaslovske Bohunice and Dukovany in Czech republic. These tests have included tension, notch ductility, fracture toughness and hardness measurements on base metal, weld metal and weld heat-affected zone samples before and after irradiation in core region during 1, 2, 3, 5 and 10 years of reactor operation.

At present these programs in their original version are terminating. Futher continuation of the reactor vessel steel surveillance is carried out on reconstituted specimens, to provide both the reactor manufacturer and the utilities with more data carrying out their QA programs and for vessel life assessments.

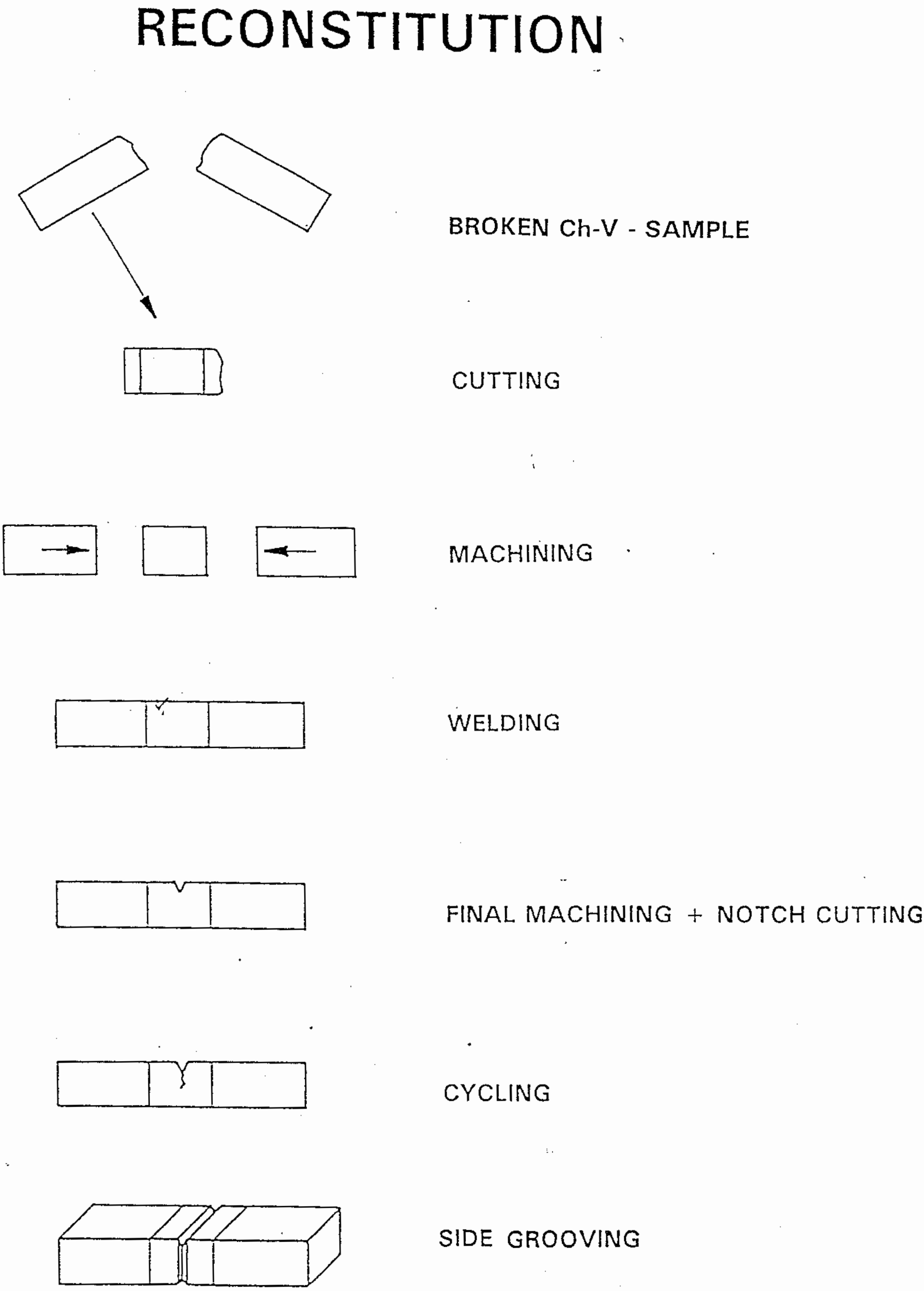

Fig. 1 Reconstitution of Charpy-V type surveillance specimens

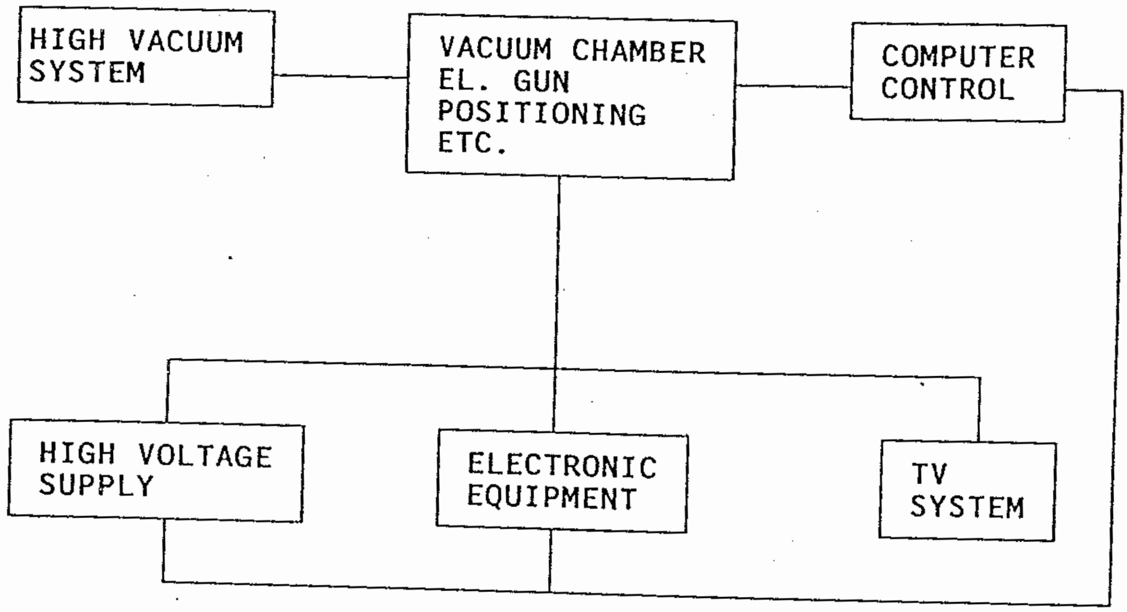

Fig. 2 Electron beam welding machine

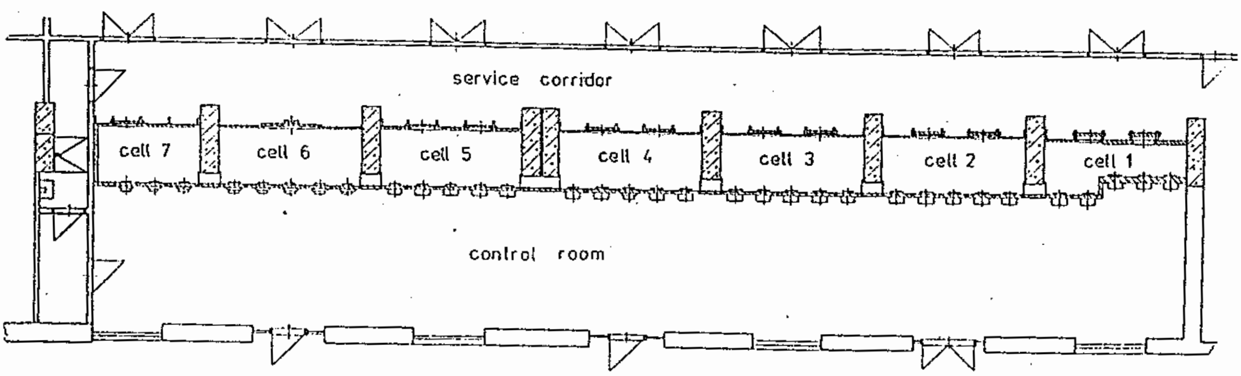

Fig. 3 General layout of the semi-hot metallurgical laboratory

Fig.4 Surveillance specimen program
Base material, 10x10mm Charpy-V samples

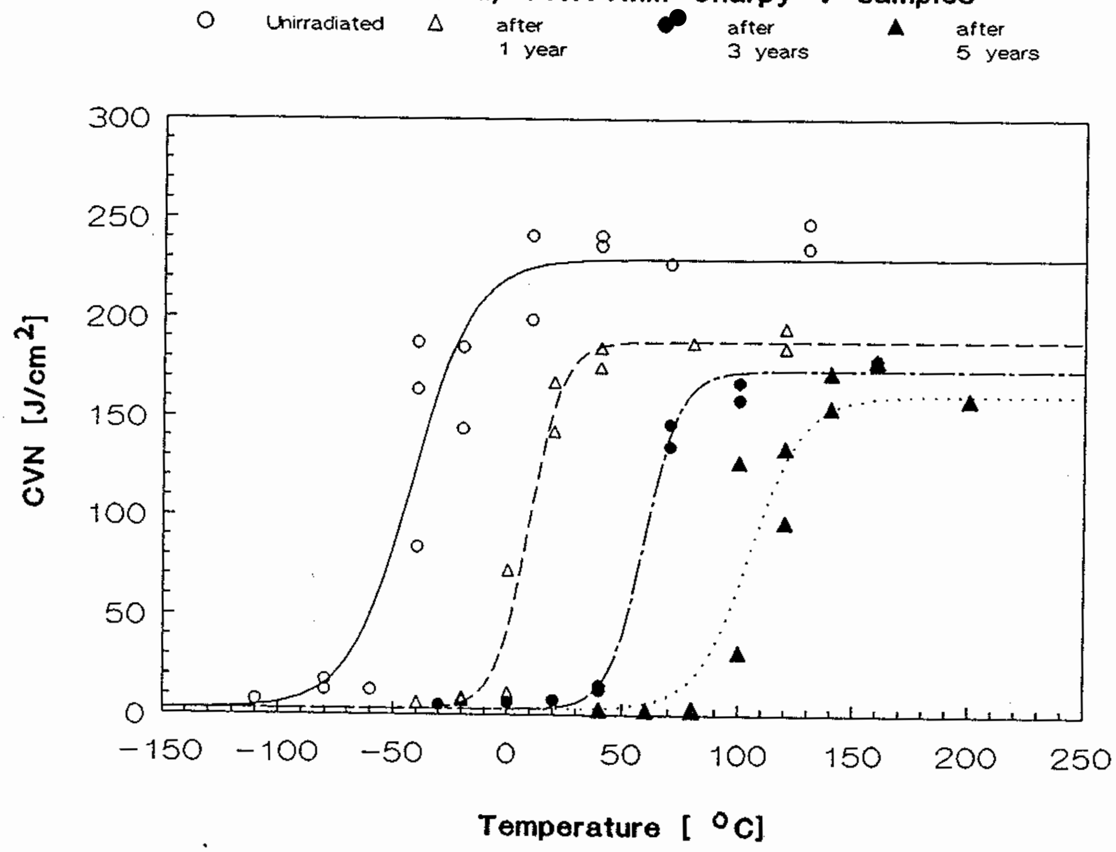

Fig.5 Surveillance specimen program
Weld metal, 10x10 TPB specimens