

ADVANCEMENT OF HOTLAB/RESEARCH REACTOR TECHNOLOGIES WITH PARTICULAR REFERENCE TO THE RPV MATERIALS SAMPLE PREPARATION TECHNIQUES AND POST-IRRADIATION EXAMINATION

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ABSTRACT

Paper reviews the advancement of the National Research Centre «Kurchatov Institute» Hotlab/Research Reactor technologies with particular reference to the reactor pressure vessel (RPV) materials post-irradiation examination and sample preparation techniques. As a main barrier against radioactivity outlet RPV is a key component in terms of power water reactor (PWR) safety. In Russia along with routine investigations, systematic research on actual radiation damage of the in-service and decommissioned RPVs has been carried out. Unique origin and value of these probe materials forced undertaking considerable efforts for hotlab techniques advancement. Sum of the measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the hotlab segment concerned with RPV materials study.

Particular and significant advancement have been made for the RPV steels behavior examination by means of the progressive methodology development for the primary irradiation, annealing and re-irradiation conducting. Transference of the centre of gravity to before- and after-irradiation stages leads to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall including ecological aftereffect.

1. Introduction

As a main barrier against radioactivity outlet reactor pressure vessel (RPV) is a key component in terms of PWR safety. RPVs are subject to multi-factor influence. It is practically impossible to reproduce some of this factors («long-time bias», e.g.) in the framework of experimental investigations including RPV surveillance specimens tests. At the same time, detailed information that can be obtained by means of taking of the through vessel wall probes (trepan) immediate from the ex-service (decommissioned) NPP RPVs is more representative than received by any another ways and therefore has the highest value.

2. Decommissioned RPV material actual properties study. HotLab specialization and modernization

Along with routine investigations in Russia systematic research on actual radiation embrittlement of the decommissioned PWR pressure vessel via trepan has been carried out. The earliest commercial PWR prototype unit Novovoronezh-1 (210 MWe) RPV after 20 years (1964-1984) of operation was trepanned in 1987. Then Novovoronezh-2 (365 MWe, 1969-1990), the oldest PWR type experimental reactor-prototype ERP (1956-1986) and, finely, nuclear icebreaker «Lenin» RPVs after shutdown were trepanned. List of these decommissioned units is present in table1.

Unit name	Output (MW)	Start of operation	Shut down	Operating temperature, °C	Max. neutron fluence, cm ⁻²
Novovoronezh Unit 1 (NV1)	210e	1964	1984	250	2,5×10 ¹⁹
Novovoronezh Unit 2(NV2)	365e	1969	1990	250	9×10 ¹⁹
Experimental Prototype (ERP)	<100t	1956	1986	275	7×10 ¹⁹
Nuclear icebreaker «Lenin»	159t	1970	1989	290	1,7×10 ²⁰

Table 1: List of the decommissioned units

Through-thickness RPV wall samples had been cut out remotely using trepanning tools such as boring machine with annular drill, anodic-mechanical and electric resistance cut machines. Typical dimensions of these probes were 120-140 mm in diameter, 120-140 mm lengthwise and up to 17 kg by mass. Schemes of the RPVs trepanning are presented in fig.1.

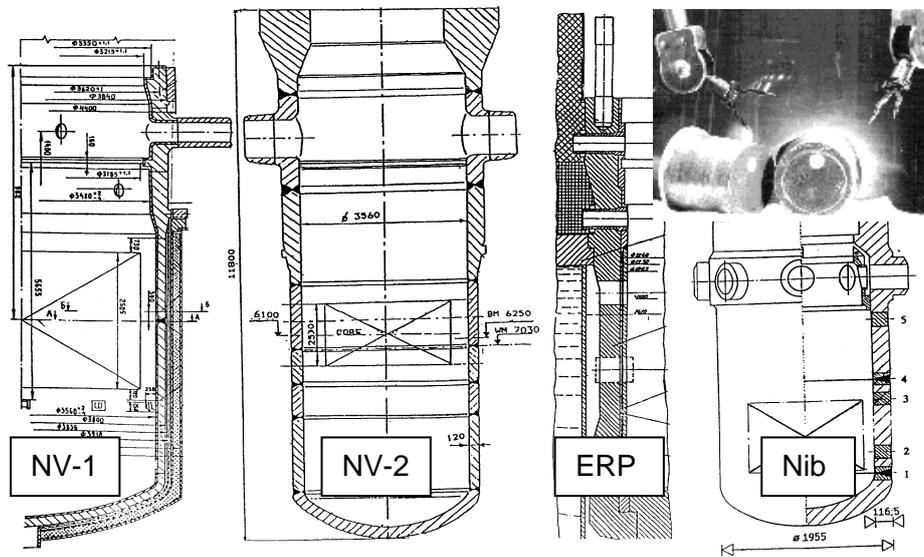


Fig.1. Schemes of the RPVs trepanning (NV-1, 2: Novovoronezh-1 and 2 units; EPR – experimental prototype reactor; Nib– nuclear icebreaker)

Through-thickness RPV wall samples had been cut out using trepanning tools such as boring machine with annular drill, anodic-mechanical and electric resistance cut machines.

Mechanical technique is the most advanced one, but the use requires periodic presence of a man in the reactor for inspections and adjustments. Thus, the use of a heavy protection cabin is necessary.

Anodic-mechanical cutting and contact arc cutting are fully remote technologies. However, each of them has a set of disadvantages, which eliminate this convenience.

Anodic-mechanical cutting requires liquid glass as a technological substance with following utilization of this radioactive waste.

Electric resistance cutting use water as a technological substance but is a very rough cutting method. The main disadvantage is a significant size of the heat-affected zone, therefore trepan material cannot be completely used. The emission of hydrogen is a potentially dangerous factor.

Typical dimensions of trepans were 120-140 mm in diameter and 120 mm lengthwise (fig.2).



Fig.2. Novovoronezh-2 NPP RPV trepan

Unique origin and value of these materials forced undertaking considerable efforts for hotlab techniques advancement:

- 1. introduction of the electro discharge machines (EDM) as tools for trepans and their fragments processing to diminish volume of wastes sharply;
- 2. EDM equipment application for precise manufacturing of the test specimens with low tailings;

Test pieces and specimens have been manufactured from trepans by means of wire cutting EDM (figs.3).

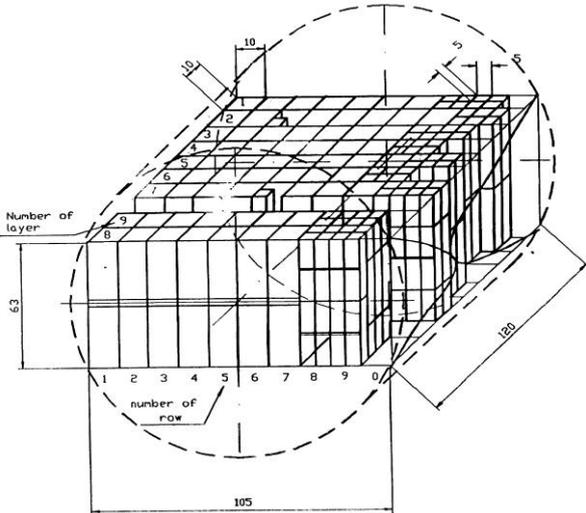


Fig.3. Typical scheme of the trepan cutting by EDM machine – up to 10 standard Charpy specimens have been manufactured from the disk 120 mm in diameter

EDM techniques came to change such routine methods of metalworking as milling and lathe approximately as it shown in fig.4 [1].

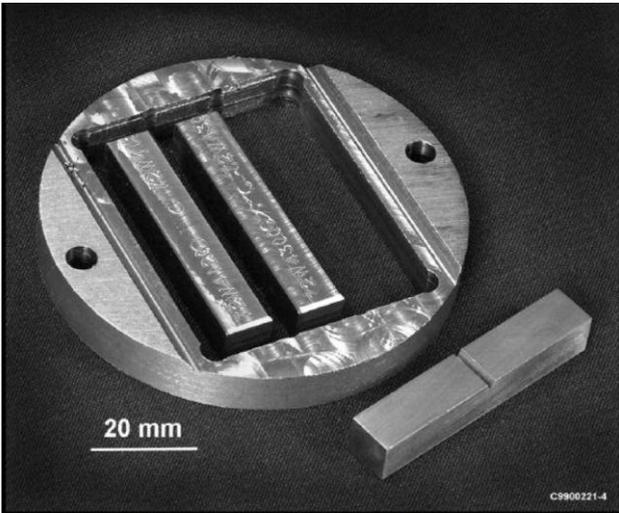


Fig. C.4. The three Charpy specimen blanks have been milled to final thickness and parted from the disk.

Fig.4. The three standard Charpy specimens have been milled and parted from the disk 87 mm in diameter (ORNL) [1]

- 3. using a fully automatic optical emission spectrometer to provide fast and exact simultaneous elemental analysis for both alloying and trace elements with minimum material losses (fig.5).

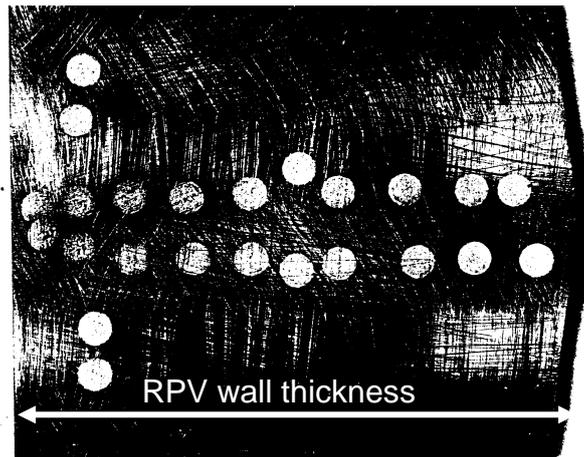


Fig.5. Using of the optical emission spectrometer for elemental analysis of both alloying and trace elements and their bulk distribution (white spots – places of analysis)

4. application of the reconstitution technique achievements (arc stud and laser welding) to use the RPV materials as efficiently as possible («materials recycling») (fig.6).

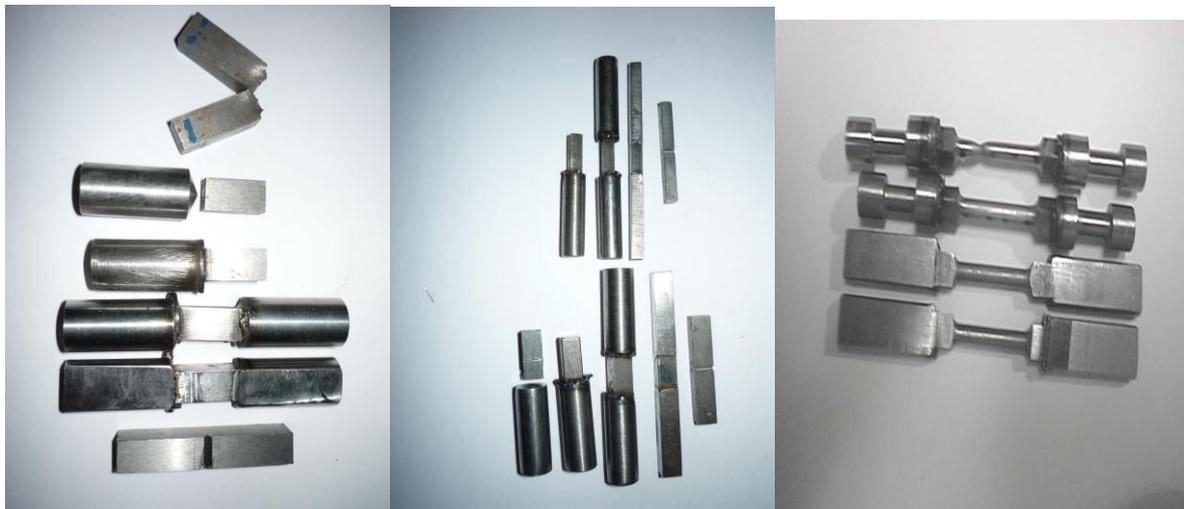


Fig.6. Examples of the reconstitution technique application (arc stud welding) for materials recycling. Left: standard Charpy $10 \times 10 \text{ mm}^2$; in the middle: subsize Charpies $5 \times 5 \text{ mm}^2$ and $3 \times 4 \text{ mm}^2$; right: tensile specimens. посередине

Sum of these measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the hotlab segment concerned with RPV materials study.

In particular, following results were obtained:

- controlling radiation embrittlement by means of RPVs thermal annealing was substantiated providing vessels «recycling»;
- annealing conditions for the first generation of Russian NPP with PWRs were optimized;
- taking templates and using for in-service escort of WWER-440/230 units instead cancelled surveillance programmes was grounded, also absence of hydrogen-assisted degradation for unclad RPVs was confirmed;
- as applied to WWER-1000 surveillance specimens program deep modernization was carried out: additional standard Charpy-V specimens were reconstituted from a broken

specimens halves and, as a result, extended experimental data availability allowed to satisfy and conform the Guide requirements concerning the test specimens quantity and quality;

- data on actual radiation stability and through the RPVs thickness embrittlement change taking into account chemical factor and neutron flux level were obtained.

Thus, examination of the specimens manufactured from templates and trepans presented a unique opportunity for qualifying the effects of long-term irradiation and multi-factor influence on actual RPV properties.

3. Innovative methodology for the primary irradiation, annealing and re-irradiation development

Particular and significant advancement have been made for the RPV steels radiation stability examination by means of the progressive methodology development for the primary irradiation and re-irradiation conducting.

The main idea consists in utilization of the Unified Radiation-Reirradiation Specimen (URRIS) for experimentation. URRIS represents metal block of the simplest form e.g. cylinder or parallelepiped. It undergoes irradiation, annealing and reirradiation as a hole, and test specimens are manufactured later to satisfy the present-day requirements *immediately* before testing and examination. Inasmuch as metal under irradiation-annealing-reirradiation treats as monolithic piece the gradients of neutron flux and/or temperatures during irradiation and/or annealing are as small as possible. Moreover, simple form of the blocks give a chance to simplify rigging strongly.

Reconstitution application is the midpoint of the technology proposed. Damage zone (plastic deformation zone) at mechanical tests occupy no more then 25-30% of the specimen volume. Therefore, according to routine technology basic part of the specimen is irradiated uselessly. According to new technology, only useful volume of the metal are under irradiation and ballast parts of the specimen have to be welded to the irradiated one later, before tests. At the same time, small target dimensions lead to high uniformity of the temperature field during irradiation. So, as a result target material, reactor space, neutrons and nuclear fuel use more effectively. In addition, the quantity of the wastes decreases radically.

Transference of the centre of gravity to before- and after-irradiation stages leads toward to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall.

Prototype version of the abovementioned technology successfully was tested in the commercial and research reactors during composite multi-aspect reactor experimentation:

- cylinder-type fragments of the nuclear icebreaker «Lenin» RPV trepans were extra irradiated in the WWER-440/213 immediately in contact with coolant (fig.7) to provide data for functioning nuclear-driven icebreakers RPVs lifetime prolongation.

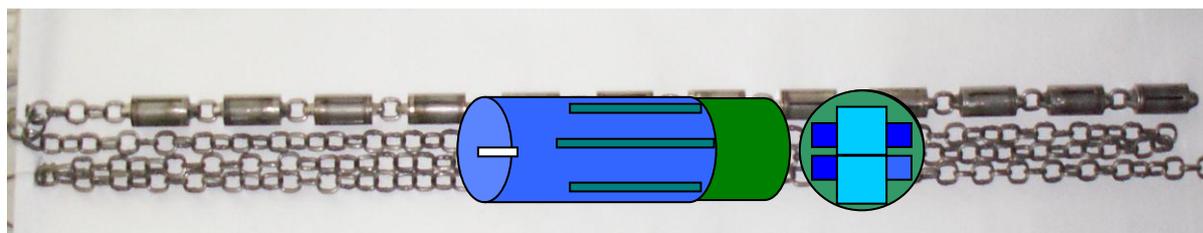


Fig.7. Set of the perforated capsules with cylindrical billets inside before reirradiation and sketch of the specimens by EDM manufacturing after reirradiation

As an example of the URRIS techniques potentiality, experiment on so-called «wet» annealing effectiveness of the reactor vessel was conducted. Pre-irradiated in WWER-440/213 SS channels immediately in running water up to $9 \times 10^{19} \text{sm}^{-2}$ at 270°C base metal billets of the cylindrical shape were additionally irradiated in test reactor IR-8 at 330°C and neutron flux level of $3 \times 10^{11} \text{sm}^{-2} \text{s}^{-1}$ during 87 hours. Fig.8 shows the experimental device. One can see and understand that simple forms of the billets and device components allows providing the possibility of operative and inexpensive irradiation process.



Fig.8. Experimental device for RPV steel billets irradiation.
(1 and 2 – RPV metal billets, 3 - capsule for neutron monitors, 4 – heater)

As it follows from fig.9, where experimental results are demonstrated, 17°C recovery of the transition temperature shift (TTS) take place. This value is equivalent to 1,5 - fold neutron fluence reduction and therefore «wet» annealing technology has evident practical benefit.

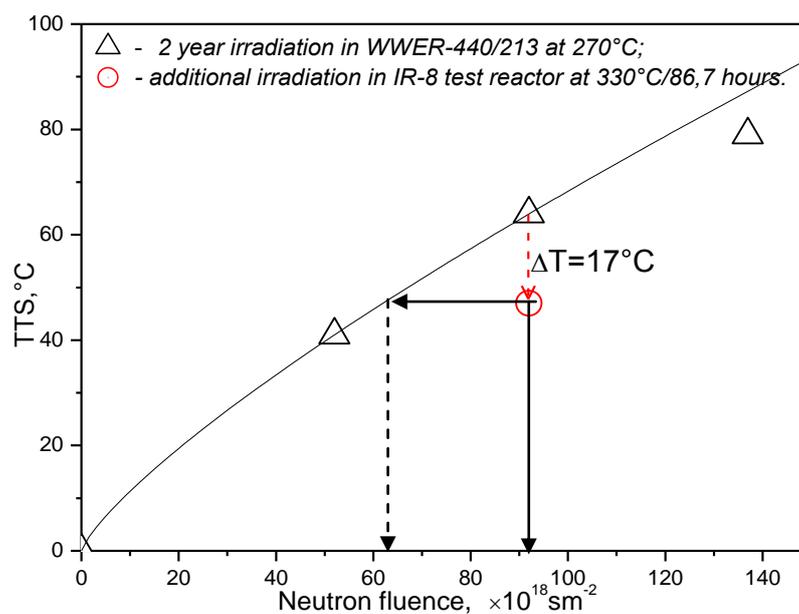


Fig.9. Results of the experiment on potential effectiveness of the RPV «wet» annealing study.

4. Advancements of sample preparation techniques as prerequisites for going to manageable RPV surveillance programmes

Routine RPV surveillance programmes (SP) are characterized by high laboriousness (fig.10 [2]) because call for precious rigging, containers pressurizing and tightening, necessity of the surveillance specimens (SS) temperature control, in case of depressurizing or temperature exceeding the SSs may be lost.

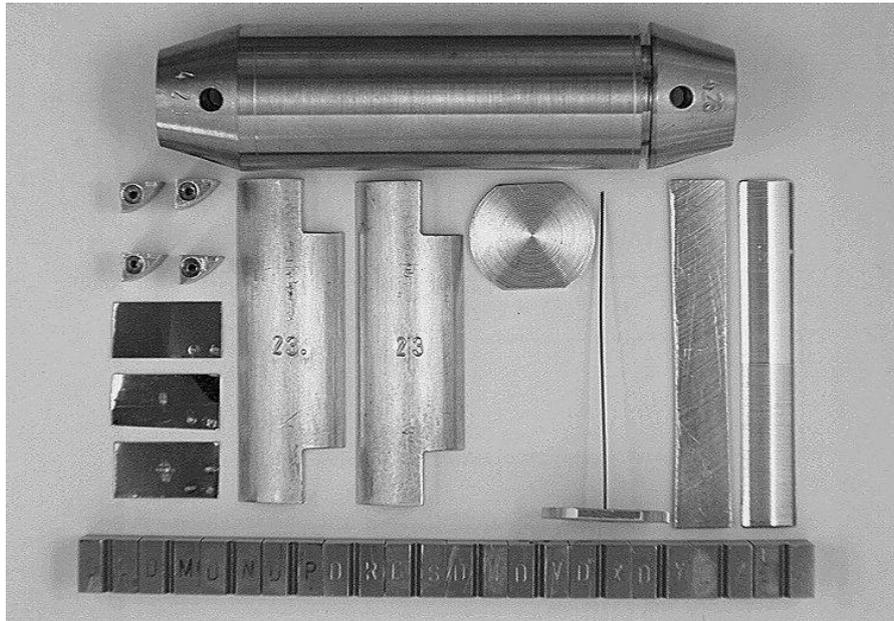


Fig.10. Set of modern SS capsule internals [2]

Using the above mention results and cumulative experience with particular reference to the reactor pressure vessel materials examination we have proposed [3] going from routine «hard» SPs to adaptable, «open» SPs that in potentiality allow the actualization and specialization of SPs and SSs types. These manageable SPs (MSPs) will be based on sets of archive material billets placed inside the RPV closely to wall and will cooled directly by primary circuit water.

It clears the way to a perspective in case of need put into practice an innovative MSP of anyone content and complexity, taking into account state-of-the-art of the safety standards, technical progress, level of science and technology.

Certainly MSPs development and application have to be based on disposable similar experience understanding and utilization. Let remember it.

It is known [4,5] that for the first generation of the Russian PWRs (WWERs) instead of the cancelled SPs just RPV (100% surveillance material) for a long time serve as billet for thin plates cutting and test specimens manufacturing as needed. As a matter, this practice is the first prerequisite of the proposed SP technology.

The second prerequisite is a worldwide experience on the through wall probes (trepan) of the ex-service RPVs using for actual metal properties examination [6-14].

The third prerequisite is our own long-term practice in SSs testing and long-term experience in decommissioned LWR pressure vessel material properties study [15]. Recently for the first time in the history of the RPV materials study set of the 1T-CT type specimens for fracture

mechanics tests was produced from 140 mm in diameter ERP RPV trepan. Fig.11 shows the steps of the 1T-CT type specimens manufacturing and testing.

In a certain sense, proposed MSP procedure (technology) is the closest analogy to trepans investigation with the exception surveillance billets (SB) in advance should be placed inside RPV and ready for examination in case of need without extra complex RPV cutting. SBs placement inside the RPV as close as possible to RPV wall should be the best decision in SP performance from all points of view.

In the upshot, one can say that the scientific and technological prerequisites to LWRs surveillance programme improvement by means of going to manageable SPs (MSP) exist.

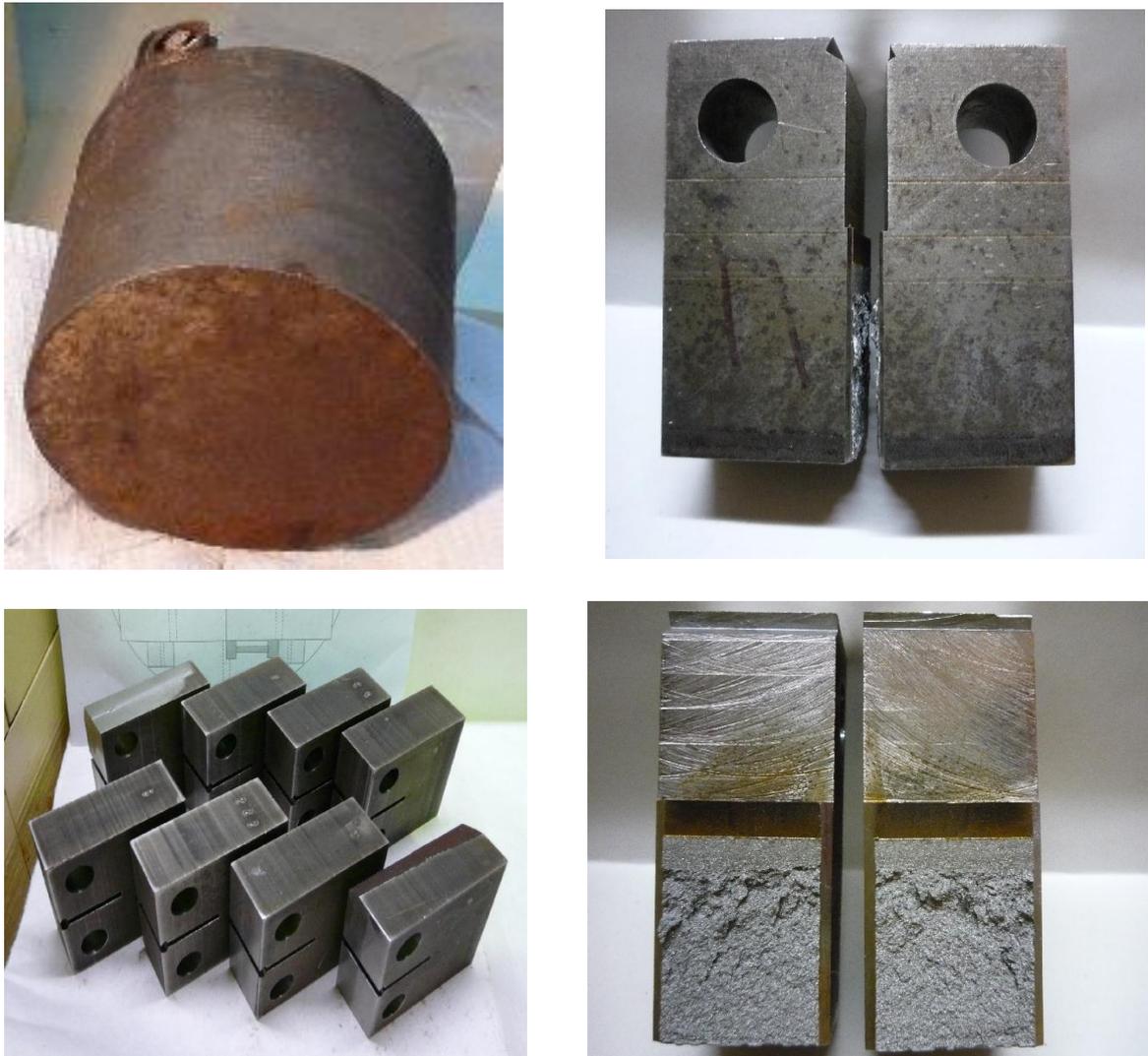


Fig.11. Steps of 1T-CT type specimens from 140 mm in diameter EPR RPV trepan manufacturing (left side) and testing.

5. Conclusion

Sum of the measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the HotLab segment concerned with RPV materials study.

Examination of the probe materials from ex-service RPVs presented a unique opportunity for qualifying the effects of long-term irradiation and multi-factor influence on actual RPV properties.

Particular and significant advancement have been made for the RPV steels behavior examination by means of the progressive methodology development for the primary irradiation, annealing and re-irradiation conducting. Transference of the centre of gravity to before- and after-irradiation stages leads to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall including ecological after-effect.

Prototype version of the abovementioned technologies was tested in the hotlab/research reactor/commercial reactor successfully.

Eventually, highly productive and the cost effective hotlab/research reactor/commercial reactor techniques for RPV materials examination is created and operated.

Advancement of hotlab/research reactor techniques with particular reference to the reactor pressure vessel materials examination allows proposing the new SP conception based on substitution of the surveillance specimens irradiation in sealed capsules by the surveillance billets irradiation in perforated containers with following test specimens manufacturing that can provide:

- strengthening the contribution of surveillance investigations to improve the safety and performance of PWRs;
- increasing the level of PWR type safety on account of more adequate conditions of the surveillance metal irradiation;
- improving the informativeness owing to carrying over the specimens of actual nomenclature manufacturing process immediately to moment of testing from initial stage of RPV producing;
- decreasing the laboriousness and specific quantity of rigging metal for surveillance metal irradiation and to reduce the quantity of radioactive wastes ;
- releasing funds and resources, to reduce the cost of the joint RPV metal surveillance programme execution;
- making better PWR's competitiveness.

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