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Surveillance Specimen Programmes for WWER Reactor Vessels in the Czech Republic

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ABSTRACT

Continuous monitoring of properties degradation for the whole life time is one of important elements of safety and reliability of nuclear units. Paper describes a present state of material degradation in reactor pressure vessels of WWER type reactors manufactured in Czech Republic. Standard surveillance program for WWER-440/V-213 type reactors is described and its deficiencies together with main results obtained are discussed. New, supplementary surveillance program was developed and started; it fulfils all requirements for PWR type reactors. Quite new design was chosen for surveillance programme of WWER-1000/V-320 type reactor pressure vessels. Description of material selection, containers design and location as well as withdrawal plan connected with ex-vessel fluence monitoring is described.

KEY WORDS: nuclear reactor pressure vessel, radiation damage, material degradation, monitoring, neutron fluences, surveillance specimens, embrittlement, remnant life assessment.

INTRODUCTION

Surveillance specimens programmes from reactor pressure vessel materials are one of the most important parts of in-service inspection programmes that are necessary for realistic and reliable assessment of reactor pressure vessel residual lifetime.Structure, volume, type of specimens, withdrawal schedule and testing procedures depend, first of all, on time when reactor was designed, and also, on volume and other possibilities of reactor pressure vessel construction. Thus, these surveillance programmes represent, on one side, knowledge (state-of-the-art) of assessment of resistance against failure and of irradiation embrittlement, and on the other side, possibilities of individual pressure vessel internal part locations.

Reactor pressure vessels of WWER-440/213 type reactors are characterized by small diameter that enable them to be transported by train. This advantage brings with smaller diameter also smaller thickness of water reflector and relatively high neutron fluxes and fluences on inner vessel wall.This type of reactor was primarily designed in late sixties, even though some of them (for NPP in Czech and Slovak Republics as well as in Hungary) were manufactured in ŠKODA Nuclear Machinery, Plzen, Czech Republic as a modification V-213C only in late seventeenth or even in beginning of eighties. Thus, their design does not satisfy nowadays requirements. Wide and detailed analysis was performed in our Institute that finished in a elaboration of a project for "Supplementary Surveillance Programme", as an addition to the Standard Surveillance Programme.

Original Standard Surveillance designed by Soviet organizations for WWER-1000/V-320 type reactors used the same type of capsules but located over the reactor active core where temperature, neutron spectrum as well as neutron flux were not well known and determined. Thus, in the early stages of the design of RPV-1000 in SKODA Nuclear Machinery, a decision was made that a new Modified Surveillance should have to be developed and incorporated.

WWER-440 SURVEILLANCE PROGRAMMES

Description of a Standard Surveillance Programme

Test materials

Test specimens were manufactured from the following materials used in pressure vessels :

- base metal (steel 15Kh2MFA) from a ring used for beltline region,
- weld metal (submerged arc weld - Sv-10KhMFTA) from a welding coupon represented the weld in the lower part of beltline region (weld 0.1.4),
- heat affected zone from this welding joint;
  all materials are of Cr-Mo-V type.

Test specimens

Three type of specimens are part of the programme :

- static tensile (dia 3 mm x 30 mm)
- Charpy V-notch for impact testing
- COD (pre-cracked Charpy) type for static fracture toughness testing

In all cases specimens were cut from the central part of material thickness not closer than 1/4 of thickness to pressure vessel surface.

Neutron flux monitors
Fast neutron flux (and fluence) measurements are based on measurement of the following activation monitors (which are used according to their lifetime):
^{54}Fe (n,p), ^{63}Cu (n, alpha), ^{93}Nb (n,n`)
There are 18 containers with neutron flux monitors in each set irradiated up to two years, and 6 containers for sets that are irradiated longer. Monitors are made from thin foils that are put into aluminum tubes and located in upper part of specimen container.

Temperature monitors
Powder natural diamond is used as a temperature monitor. Principle of its use is given by the fact that :

- crystal lattice parameters are increased by irradiation,
- this change can be removed by following annealing at temperature higher that was the irradiation one.

Thus, using X-ray diffraction method, change in crystal lattice parameters is determined just after irradiation, and consequently after annealing performed at several temperatures higher than the supposed one.

Capsule assemblies
The test specimens are placed into capsules made from austenitic stainless steel that prevents corrosion effects on specimens. Scheme of such capsules is given in Fig.1. Each capsule contains either 6 tensile specimens or 2 specimens of Charpy type. Some of them contain also neutron flux monitors. Capsules are assembled into chains - each contain 19 or 20 capsules in active core position. Two chains contain also another 13 capsules that are located in upper part of reactor pressure vessel, out of neutron field, and these specimens are determined for determination of thermal ageing affect.

Two chains of capsules represent one set of specimens, that is located on outer surface of active core basket, symmetrically to the corner of hexagonal active core structure. Thus, six sets of chains are placed into each pressure vessel. Capsules with the same type of specimens are located in chains in such a way to reach approximately the same neutron fluence - in some cases they are located in one chain in one row - compartment, in other way in two chains in the same location.

Removal schedule
Removal schedule is given by operation schedule of reactor, i.e. by fuel elements reloading. Interval between these changes is approximately one year, thus modified schedule of withdrawal with respect to lead factors are as follows : 1, 2, 3, 5 years of operation + 1 set for 10 to 20 years, one set is withdrawn after 5 years of operation, annealed and then tested.

Reactor pressure vessel integrity assessment is fully based on fracture mechanics, i.e. on knowledge of fracture toughness of RPV materials and their changes due to irradiation damage. Nevertheless, the most importance in old surveillance programmes has been concentrated in testing of Charpy V-notch specimens for determination of impact notch toughness, KV or KCV, and its transition temperature. In the standard surveillance programme for these RPVs specimens for static fracture toughness (or COD) determination were planned, but their location is fully unfavorable for such determination : specimens were located in periphery of chains - see Fig.3. Thus, each set of two specimens (located in one container) received different neutron fluences, even in one chain. Grouping of these specimens into one testing set in quite impossible. To overcome this problem a modified procedure has been applied - specimens with similar neutron fluences, but from chains irradiated by different time are grouped together to obtain one transition curve.Halves of broken Charpy specimens were reconstituted and tested for static fracture toughness. Comparing transition temperature shifts from both static fracture toughness testing shows a substantial difference : reason for this difference can be given either by uncertainties in neutron fluence determination or by neutron flux effect. Thus, in the supplementary programme a modified design of capsules is used - each capsule contains twelve inserts for further reconstitution of one set of specimens to cover the whole transition curve.

Using an experience from a standard surveillance programme, requirements for reliable assessment of reactor pressure vessel residual lifetime, as well as requirements, given by a trend of harmonization of WWER standards and procedures with PWR ones, the following requirements for a supplementary surveillance programmes has been established.

Supplementary Surveillance Programme Design and Planning

Supplementary surveillance programme has been designed taking into account requirements as well as the experience from the verification programme :

- monitoring of RPV during the rest of lifetime, i.e. not only of material degradation but also of neutron field on RPV,

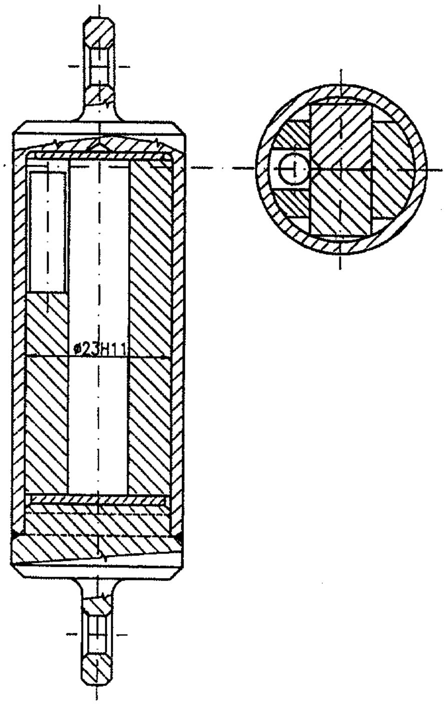

Fig. 1 Scheme of a container from the Standard Surveillance Program

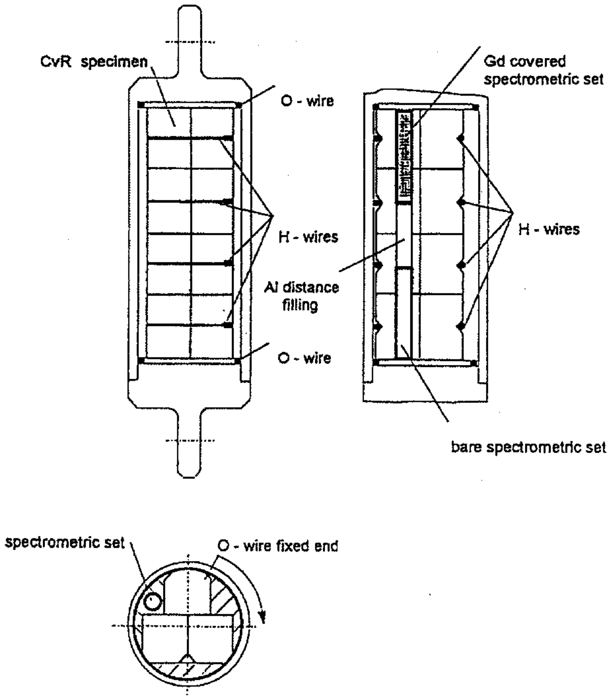

Fig. 2 Scheme of a container from the Supplementary Surveillance Program

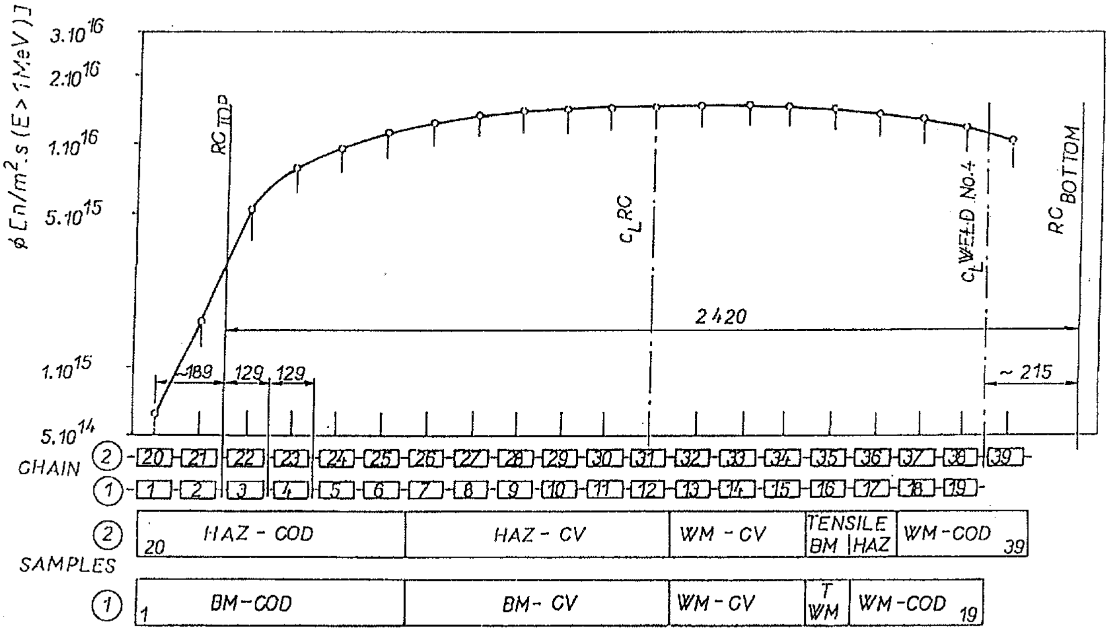

Fig. 3 Typical distribution of neutron flux along irradiation chain with containers

- use of only archive materials, each container contains twelve inserts for further reconstitution either to Charpy V-notch toughness or static fracture toughness type specimens (see Fig.2),

- irradiation with a low lead factor to be able to fully apply results from surveillance to RPV embrittlement assessment,
- irradiation of cladding materials as this material was not inserted into the standard surveillance programme and its behaviour is important for RPV integrity assessment during PTS regimes ,
- determination of an annealing efficiency and a re-embrittlement rate of real RPV materials after annealing as a useful and effective tool for potential Plant (RPV) Life Extension,
- use of IAEA reference JRQ material for qualification of irradiation conditions - these specimens are placed in one container in the central part of each chain (i.e. in the same irradiation conditions). Charpy impact tests will be performed to compare irradiation conditions in individual chains - neutron fluences and irradiation temperatures. Thus, this material will serve as a reference solid state neutron monitors, too.

Monitoring individual containers has been modified with respect to the experience from the Standard Surveillance Programme:

- neutron fluence monitors :

  two spectrometric sets of monitors are placed in each container : Fe, Ni, Nb, Al-0.1%Co, Ti, Cu and Np - one set is inserted in Al-tube while the other in Gd-tube to be able to determine a correction factor for thermal neutrons;

  wire type monitors for determination of relative neutron field in each container and for each specimen - O-wire (in both ends of container) to determine azimuthal distribution (and also the orientation of container with respect to the reactor active core), and I-wire (in specimens corners) to determine an axial distribution of neutron flux ; wires are made either from Fe (for short irradiation) or Nb (for long irradiation),

- temperature monitors :

  two sets of temperature monitors are placed at least into three containers of each chain (upper, middle and lower part),

  one set is prepared according to ASTM standard (wires in quartz tubes) and contains (inlet water temperature is equal to 268 C) :

  Bi (melting temperature = 271 °C), Pb-12.5 In (280 °C) and Pb-10 In (291 °C),

  second set is prepared according to DIN standard (hollow rings located in Al-fillings of containers) :
  Bi (271°C), Pb-1.9 Ag-5 Sb (272 °C), Pb-12.5 Sn (278 °C), Pb-2 Ag-3 Sb (288 °C), Pb-10 In (291°C).

The supplementary surveillance programme is divided into four parts:

(1) irradiation with low lead factor:

irradiation of archive materials - base and weld metals - are prepared in all four units with such a schedule to cover the whole planned residual lifetime of RPVs; individual chains are prepared for base metals and other for weld metals- position of containers with base metals are slightly different than those with weld metals in such a way that their lead factors will be the same for both materials (fluence on weld metal is equal to about 70 % of base metal in beltline region),

the following locations of containers have been chosen :

- base metal : containers position 2 - Charpy impact
  4 - static fracture toughness
  6 - tensile
- weld metal : containers position 1 - Charpy impact
  3 - static fracture toughness
  5 - tensile
- reference steel JRQ : containers position 12 - centre of active core
  19 - weld No.4

this locations is used also in all parts of the programme,

principal time schedule for their withdrawal is as follows:

1, 2, 3, 5, 10 and some also 15 years of operation,

specimens will be tested for notch impact toughness as well as static fracture toughness determination (a limited number of tensile specimens is also included)

(2) determination of re-embrittlement rate:

portion of specimens from base and weld metals irradiated within the standard surveillance programme has been annealed by a standard regime (475 C-100 h) in laboratory and then inserted into RPV in similar positions as non-irradiated specimens, i.e. in positions with low lead factor (between 2 and 3) to be fully applicable to RPV embrittlement; irradiated and annealed specimens will be withdrawn in one, three and five years intervals to assess re-embrittlement rate of RPV archive materials in real RPV irradiation conditions,

both type of testing (notch impact as well as static fracture toughness) will be performed on both materials

(3) irradiation of cladding materials:

inserts cut from outer and inner cladding layers as well as from heat-affected zone in base metal are part of the programme,

this cladding material comes from an archive part of vessel - nozzle bottoms after their removal from vessel

cladding materials will be irradiated in two groups: one group in low lead factor position to obtain RPV end-of-life fluence (with similar schedule as base and weld materials, i.e. up to 15 years), the second group will be irradiated for 3 years in high lead factor, then it will be annealed and again inserted into the reactor. Further withdrawal is planned to cover an assessment of re-embrittlement rate after annealing for another 3 years of operation (represents more than 30 normal operating years),

only static fracture toughness tests will be realized for these materials

(4) neutron dosimetry chains:

even though some of chains within parts (1) to (3) will cover practically the whole remaining RPV lifetime, their long term irradiation will not allow to determine real neutron fluences in all operation years; thus, special chains with only a limited number of containers are inserted into reactors practically through the whole lifetime beginning five years from now; these chains for intermediate irradiation (for two years only, in principle) will contain only IAEA reference material (JRQ steel) and neutron monitors in position of maximum neutron fluence and weld metal locations - both reference material and neutron monitors will serve for determination/precisioning of neutron fluxes and irradiation temperatures.

JRQ specimens will be tested by notch impact method, only.

Thus, all four parts of the supplementary surveillance programme will ensure necessary and reliable information about RPV materials behaviour, mainly about their irradiation embrittlement under conditions very close to real ones - similar irradiation temperature as well as close neutron flux values. At the same time, information for potential RPV life extension - without and/or with thermal annealing - will be gathered well in advance till the designed RPV lifetime.

This programme started in 1997 but not all chains are inserted immediately - there is a time schedule prepared in such a way to cover their whole remaining design lifetime of reactor pressure vessels.

WWER-1000 SURVEILLANCE PROGRAMMES

Standard Surveillance Programme

WWER 1000 units of standard model V-320 comprising a RPV material surveillance programme with a standard number of various specimens sets described e.g. in the WWER 1000-SC-103.

Three types of materials were chosen for standard surveillance programme - base metal from central RPV ring, weld metal from the worse of weldments No.3 and 4 and apparent heat affected zone. Four type of specimens were machined (three types are the same as in a standard surveillance programme in RPVs of WWER/V-213 type) : tensile, Charpy impact and pre-cracked Charpy and additionaly also flat fatigue specimens. The sets denoted 1K and 2K are intended for determination of unirradiated properties.

Specimens of one type are put in stainless steel containers identical to the ones used in the standard surveillance programme in RPV of WWER-440/V-213 type, i.e. either two Charpy type (impact or pre-cracked), or six tensile,. resp. six fatigue type specimens, see Fig.1. Six, resp. twelve these containers are accumulated into assemblies with one, resp. two floors. Containers are pressed together by a special spring but they can practically freely rotate within an assembly (rotation of assemblies in their position is also permitted).

Five assemblies create one neutron embrittlement set, marked as 1L, 2L, 3L, 4L, 5L and 6L. One set of assemblies was planned to be withdrawn at the same time. These sets are located in the upper part above the active core shroud near its outer diameter, i.e. above reactor active core.

The neutron field in the location of neutron embrittlement assemblies in the RPV as well as containers within assemblies is very complicated. Due to their location above the reactor core, neutron flux gradient is substantial not only between upper and lower floor in assemblies but also between individual containers within the asseembly and also between individual assemblies within one set. Moreover, half of sets contains assemblies only with upper floor of containers, where neutron flux is even lower than in RPV beltline, i.e. lead factor is lower than 1.

The thermal ageing sets contain 30 containers in five floors and are located in the upper part of the reactor in front of head flange ring. These assemblies are marked as 1M to 6M.

The original withdrawal schedule, that proposed to take specimens out after 1, 4, 7, 10, x years and EOL irradiation periods was recently modified by the designer. The new programme proposed also by the Russian designer, requires evaluation after 5 (2 sets), 9, 17, x years and EOL irradiation periods (x... to be specified later).

General Problems in a Standard Surveillance Programme

The review of the existing surveillance programme of the WWER-1000/320 units confirmed the following deficiencies:

- design of assemblies and their positioning above the core result in nonuniform irradiation conditions and the number of specimens irradiated to similar neutron fluence is not sufficient for a reliable determination of the critical brittle fracture temperature shift;
- irradiation temperature of the surveillance specimens could be higher (up to 20 °C) than the RPV wall temperature;
- temperature monitoring by diamond powder is not adequate for determination of the irradiation temperature since the results show far too large scatter,
- the quantity of neutron fluence monitors (3 sets) and variety in individual assemblies is insufficient to characterize fully the distribution of the neutron flux within the assembly and in individual surveillance specimens;
- the choice of neutron activation monitors does not enable to monitor fluences on surveillance specimens throughout the entire reactor lifetime;
- the lead factor in surveillance specimens is mostly lower than one and therefore the results cannot be used for prediction of irradiation embrittlement of RPV;
- the design of surveillance assemblies and containers inside of the assemblies does not allow clear determination of their orientation (moreover, they can rotate during reactor operation) with respect to reactor core centre which, together with small number of neutron monitors, does not ensure a proper determination of neutron fluence in individual surveillance specimens without direct autodosimetry (gamma-scanning) on each specimen.

Modification of the Standard Surveillance Programme

Main disadvantage of the original surveillance programme is that it is not capable to provide the monitoring in a reliable way. Therefore, a modification of the programme was elaborated in SKODA Nuclear Machinery for NPP Belene and Temelin.

Main principles of the design was chosen in such a way to solve problems of the Standard Surveillance Programme, mainly:

- location of containers should well monitor the conditions of reactor pressure vessel wall in beltline region, i.e. specimens temperature should be as close as possible (containers must be washed by a cold inlet water) and lead factor should be less than 5,
- whole set of specimens for one testing curve should be located in identical neutron fluence position
- as much as possible sets of specimens should be located in similar/close neutron fluence to be able to compare behaviour of different materials
- withdrawal scheme of containers should assure monitoring pressure vessel material as well as neutron fluence during the whole RPV lifetime
- neutron monitoring should assure determination of neutron fluence to each of test specimens for every container
- temperature monitoring should be performed using melting temperature monitors with a appropriate range of melting temperatures
- cladding materials should be also included in the containers
- reference material should be added for an objective comparison of resuts
- spare containers should be added to monitor vessel annealing as well as further re-embrittlement if necessary.

Design of such a programme was performed and supported by a set of calculations (neutron physics, thermal-hydraulics) as well as experiments in a scale 1:1 (thermal-hydraulic characteristics measured in a hydraulic channel of a pressure loop in SKODA, thermal fatigue tests of container holders on pressure vessel wall).

Main characteristics of this Modified Surveillance Programme are as follows:

Containers

Containers are of flat type with inner dimensions approx. 200 x 300 x 25 mm, are made from austenitic stainless steels plates welded on a frame. They contain special holders for location on pressure vessel wall

All specimens for one withdrawal time are located in one irradiation container – specimens are in two layers, specimens of of type and one set are touched each other in layer, only

Location of containers

Containers are located in special holders that are welded on inner surface of reactor pressure vessel wall approx. 400 mm below the centreline of beltline region

Containers are located symmetrically in maximum neutron fluence on vessel wall, i.e. in hexagonal corner positions

Two additional identical containers are located between upper nozzles for monitoring possible thermal ageing effects

Specimen materials

RPV archive materials are used for specimens manufacturing

- base material from the more sensitive heat end from the three rings of the beltline region chosen in accordance with the criterion

  $CF = (10\,\%\,P + \%\,Cu)$
- weld metal from the special prepared welding coupon used the same welding consumables as the critical weld No.3 below the core beltline
- heat-affected zone from this welding coupon using the most sensitive base material

  all these materials were heat treated by the same regimes as the whole pressure vessel
- cladding materials
  - 1st layer – crack in both directions, i.e. from the surface and to the surface
  - 2nd layer - crack in both directions, i.e. from the surface and to the surface
  - heat affected zone in base metal - crack in both directions, i.e. from the surface and to the surface
- IAEA reference steel JRQ of ASTM A 533 B type
- V-1000 reference materials – both base metal and weld metals

Specimen types

- tensile specimens from base metal and weld metal (6 per set)
- Charpy V-notch impact specimens from base metal (24 per set), weld metal (24 per set), heat affected zone (24 per set), JRQ (32 per set) and reference materials (12 per set)
- static fracture toughness specimens of CT 0.5 type from base metal and weld metal (15 per set)
- static fracture toughness specimens of pre-cracked Charpy type from cladding, heat affected zone, JRQ and reference materials (14 per set)
- static fracture toughness specimens of CT 1 type from base metal and weld metal – only unirradiated conditions (15 per set)
- mostly, only “insert” type specimens are used for further reconstitution after irradiation to use the container volume more effectively

Neutron monitors

Two types of monitors are used-

- 5 spectrometric sets of monitors in each container located close to both surfaces of the container and in different ends for absolute dosimetry of the container

  activation monitors - Co, Nb, Ni, Fe, Ti, Cu and Mn as foils and
  fission monitors ^{237}Np a ^{238}U with and without Gd shielding
- two sets of wires – Cu and Fe – located on both surfaces in diagonal directions for relative dosimetry of each specimen
- scanning of specimens is prepared to check the neutron dosimetry
- continous measurement of neutron fluences on outer pressure vessel wall (in the cavity) is a mandatory part of the programme
- detailed calculation of neutron fields within assemblies and the reactor,

Temperature monitors

Several sets of melting temperature monitors are located either in specimens or in container filling:

Pb - 10% In	melting temperature	291°C
Pb - 8% In		300°C
Pb - 2,5% Ag		304.5°C
Pb - 1,75% Ag - 0,75% Sn		309°C
Pb		327°C

Withdrawal schedule

The following scheme is proposed:

2, 6, 10, 18, 26 + x years for radiation damage containers
14, 34 years for thermal ageing containers
one container for thermal annealing effect
one container for re-embrittlement rate effect

This programme has be loaded into both pressure vessels on NPP Temelin, and was also prepared for the pressure vessel of unit 1 in NPP Belene, Bulgaria.

In principle, it exists a possibility to use this reactor as a “host” reactor for those V-1000 units that are supplied by the Standard Surveillance Programmes in two ways:

- for operating plants

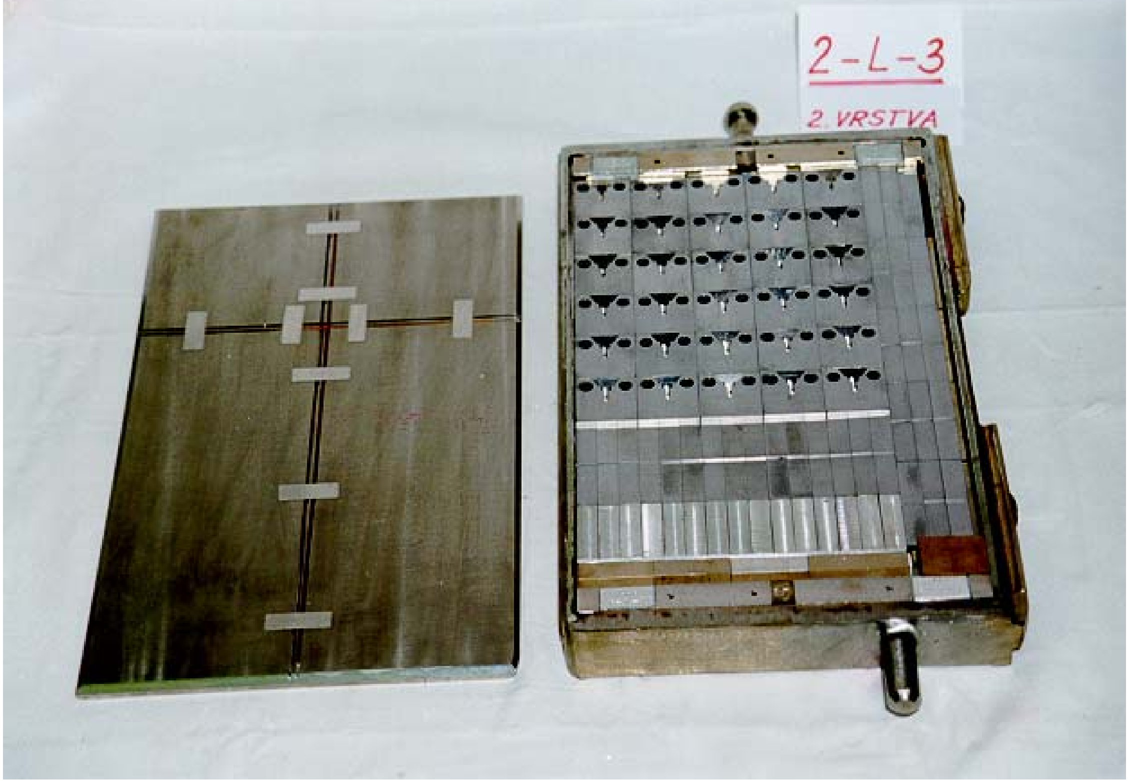

Fig.4. Picture of an opened container with specimens (right) and neutron wire monitors (left) for WWER-1000 RPV Modified Surveillance Programme

to manufacture specimens from unirradiated test/untest specimens using reconastitution technique

specimens can be located in new containers detailed calculation of neutron fields within assemblies and the reactor,

- for non-operating plants
  - either to change the Standard Surveillance Programme into a Modified one (based on SKODA or new Izhora design)
  - or to manufacture inserts from non-tested specimens from the Standard Programme and place them into new containers detailed calculation of neutron fields within assemblies and the reactor.

CONCLUSION

Paper describes Surveillance programmes for reactor pressure vessel of both VVER-440 and VVER 1000 types located in the Czech Republic.

Together with the description of Standard Surveillance Programmes their disadvantages are also shown that lead to their modification – Supplementary Surveillance Programme for NPP Dukovany with VVER-440 type and Modified Surveillance Programme for NPP Temelin with VVER-1000 type reactors.

A proposal is given to use the NPP Temelin reactor as a “host” reactor for an Integrated Surveillance Programme for VVER-1000 reactor pressure vessels, operating as well as non-operating, with the Standard Surveillance Programme.

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