REMOTE CONTROLLED ROBOT FOR VISUAL INSPECTION AND SAMPLING OF THE INTERIOR SURFACE OF CANDU PRESSURE TUBES

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This paper describes a robotic equipment supposed to be integrated into the technology for the in-service investigation and/or the replacement of CANDU 600 reactor fuel channels. This equipment includes a robot part which is remotely operated and moves autonomously inside the pressure tubes.

The task of the robot part is to take samples for determining the Hydrogen concentration of the inside part of the pressure tubes.

The Differential Scanning Calorimetry method is used to estimate the amount of the hydrogen dissolved in the sample.

The advantages of using this equipment are discussed.

Keywords: pressure tube; CANDU; in-service inspection; autonomous robot; hydrogen concentration

1. Introduction

1.1 General considerations

The paper describes the development of new way (methodology and experimental facilities) in progress to investigate the CANDU pressure tubes in the shutdown periods in order to perform the structural integrity assessments. This consists of a robotic equipment that is supposed to be used to analyze the body of the CANDU fuel channels.

The main damaging phenomenon for CANDU pressure tubes (Zr-2.5%Nb alloy) is Delayed Hydride Cracking (DHC) that is following of deuterium increasing during of the normal operation conditions at 300 ºC temperature. Consequently, an important task for in-service inspection is to evaluate the equivalent hydrogen concentration in the pressure tube body.

The hydride concentration can be approximated through calculations with some errors according to the mathematical model but also based on the input data

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used. For precisely determining of the hydrogen concentration, one way is to sample micro-specimens from the inner pressure tube surface. However, the comparison of the calculated values versus the measured ones contributes to the improvement of the mathematical model.

The time increasing of deuterium concentration in the CANDU pressure tube body is mainly based on the hydrogen uptake rate in the normal operating conditions like as temperature, the inner oxide layer, and corrosion process. To manage equivalent hydrogen concentration during pressure tube life the experimental measurements should be quite accurate and sustainable with good results on the CANDU power plant safety.

1.2 Fuel channel assembly

The CANDU fuel channel assembly is composed of a pressure tube (PT) with two end fittings made of martensitic steel. The pressure tube is made of Zr2.5Nb alloy and placed inside the Calandria tube (CT) which is made of Zircaloy 2. The space between the CT and the PT (the annulus) is filled with an inert gas. In the annulus, there are Inconel spacers to prevent direct contact between the PT and the CT.

The fuel channel contains 12 fuel bundles and has a fixed end and a mobile end to allow for the axial thermal expansion and creep of the pressure tube.

The main cooling agent, heavy water, runs through the pressure tube, to which it is fed through feeders coupled to the end fittings. The cooling agent from the fuel channels has temperatures between 260ºC (111.4 bar pressure) at the entrance end fitting and 312ºC (102.1 bar pressure) at the exit end fitting.

The Zr2.5Nb alloy, from which the PT is made of, has a low neutron absorption section and a high mechanical strength, leading to a high-efficiency usage of fuel.

A few of the fuel channel assembly functions:

- supports and locate the fuel bundles
- ensures the undisturbed flow of the primary cooling agent and prevents leaking
- ensures a low neutron absorption
- ensures radioactive shielding
- ensures a tight connection to the fuel handling machine
- ensures freedom of movement caused by the thermal expansion and creep
- maintains an isolating gap between the cooling agent and the moderator

Taking all these into account, the analysis of the fuel channel behavior in reactor conditions is a central point in the research - development programs that have the security and safety of CANDU NPP as an objective.

1.3 The impact of hydrogen absorption on the mechanical properties of the pressure tube

During operation, the pressure tube undergoes hydriding which can lead to the deterioration of the mechanical properties with negative consequences to the nuclear safety. Laboratory and reactor test results have shown a strong dependence of the pressure tube quality as a function of the hydrogen concentration, reference [1].

When the hydrogen concentration is above the solubility limit, the zirconium alloys undergoes embrittlement. The embrittlement of the zirconium alloys represents the most important cause for material defects and for fuel channel behavior which can adversely affect the CANDU NPP safety. In order to fall within the solubility limit, technical solutions must be chosen to limit the hydrogen absorption. The replacement of the Zircaloy-2 alloy with the Zr2.5Nb alloy has been used as a solution for this, the Zr2.5Nb alloy having a much lower hydrogen absorption rate. Also, very important is the elaboration of predictive test methods and determination test methods, through sampling, for measuring the equivalent hydrogen content.

The main paths for hydrogen absorption in the pressure tubes are:

a) Initial absorption during the manufacturing process

b) Water corrosion which leads to the growth of the ZrO_2 layer and the release of deuterium, which can penetrate the layer of oxide and diffuse into the pressure tube material.

c) The diffusion of hydrogen from the exterior gas annulus, which can contain impurities.

d) Galvanic corrosion which occurs at the rolled joints between different materials (pressure tubes, Calandria tubes, spacers, and end-caps).

Also, an important extra source of hydriding is represented by the addition of deuterium in the cooling agent used to neutralize the oxygen produced by radiolysis.

The main phenomenon’s which appear are:

a) The Delayed Hydride Cracking (DHC) mechanism, which consists of slow under pressure cracking. The DHC mechanism is facilitated by a series of factors from which are: the presence of a surface defect, time, tension, thermal cycles, hydrogen concentration, temperature and also the manufacturing process used.

b) The formation of hydride blisters at the contact zones between the PT and the CT when the annulus spacers are moved from their initial position. The contact between the PT and CT leads to the development of a local cold spot in the PT wall and a corresponding hot spot in the CT. As the hydrogen tends to migrate across the temperature gradient, it accumulates in the cold region leading to hydride blisters.

Apart from the cracking that can appear, the presence of hydrides has an important influence on the elastic properties of the pressure tube. The pressure tube is stressed both thermo-mechanically and under creep.

In order to determine the defect variables, the hydride concentration in the PT walls must be known.

According to research at The Institute for Nuclear Research Pitesti (INR), reference [2] made on Zr2.5Nb alloys we can specify the following:

- The main negative effect of the hydride zirconium alloys is their embrittlement;
- The effective deformation grows over time in hydride alloys;
- The possibility of cracking and ruptures goes higher in the hydride alloys;
- Notable differences appear between the value of effective stresses generated in alloys with nominal concentration (<10ppm) and those with higher concentrations;
- The axial elongation is higher for alloys hydride over the nominal values;
- The values of maximal deflection are higher for alloys hydride over the nominal values.

From those specified above we can conclude that the hydriding of zirconium alloys has a negative effect on the structural and functional integrity of the fuel channels, and implicitly on the safety of Cernavodă NPP, that is why this occurrence should be rigorously controlled and diminished. The periodic measurement of the hydrogen concentration is a must for determining the moment when the maximal safe concentration is reached.

Of course, an easy and low-cost technique must be developed. One possibility was the sampling of a small piece of the material of the pressure tube for chemical analysis. This small sample was not to affect the integrity of the tube but also to permit the chemical analysis to be performed.

In the last years, this technique was enhanced so much so that this became a routine work with high-cost reduction and low levels of radiation exposure for the personnel, and also with precise results, reference [1] and [2].

1.4 Considerations about the micro-sampling technique

The main geometric nominal data and normal operating parameters of the fuel channel, according to reference [3] are:

- Pressure tube length: 6.136 m
- Pressure tube inner diameter: 103.85 mm;
- Pressure tube outer diameter: 112.42 mm;

From experimental measurements coordinated with similar measurements made outside the reactor, it is concluded that the thickness of the oxide layer on the inner surface of the pressure tube is increasing by 2 μm/year according to reference [2], [4], and [5].

According to the reference [1] pressure tube forms a thin oxide layer with a higher concentration of deuterium than the tube body. So in order to be representative for the pressure tube, a sample for chemical analysis should be free of oxide.

Regarding the chemical analysis techniques available the acceptable weight of a sample was determined within 80 ÷ 90 mg. A smaller weight decreases the confidence and a higher weight produces unnecessary pressure tube degradation and increases the radiation field of the sample.

Laboratory tests showed that the cutting methodology (scraping) in axial tandem is very effective in obtaining an adequate sample for analysis. Since CANDU pressure tubes are designed with a tolerance of corrosion, the total cutting depth acceptable for pressure tube was set at less than 0.15 mm. In view of this, the geometry of cutting allows a sample of the oxide of about 12 mm long, 9 mm wide and 0.06 mm thick and a sample for the analysis is about 10 mm long, 9 mm wide and 0.06 mm thick as shown in Fig. 1.

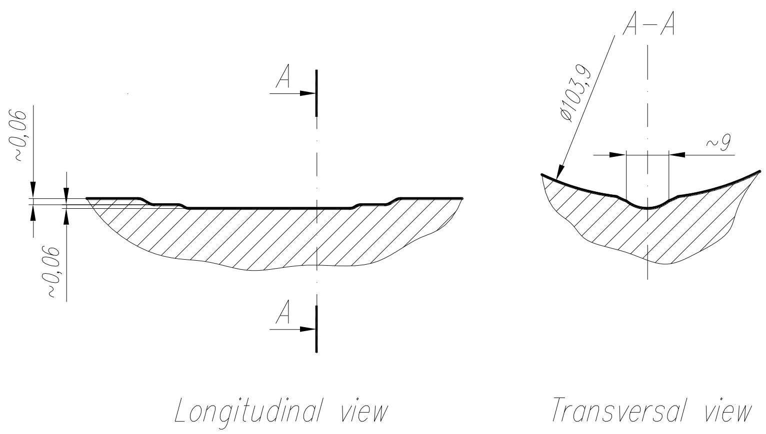

Fig. 1 - Sample dimensions (scrape)

1.5 Materials and methods

Some modules will enter inside pressure tube filled with coolant and therefore they should have a structure with a sealed outer surface and made of materials resistant to radiation and flux of neutrons which easily can be decontaminated. We used mostly duralumin (AlMg3) and stainless steel (AISI 304L).

Two methods for determining the concentration of Hydrogen equivalent (H_{eq}) of PT from a sample are Hot Vacuum Extraction Mass Spectrometry (HVEMS) and Differential Scanning Calorimetry (DSC).

Differential Scanning Calorimetry measures the final solubility of the solid on a sample that is related to the concentration of Hydrogen in the sample. This is a not - destructive analysis method. The principle of the DSC method consists in measuring the difference between the amount of heat required to raise the temperature of a sample and a reference to a certain value.

The pressure tube is made of Zr2.5Nb alloy. This alloy has a low neutron absorption section and a high mechanical strength.

2. Mobile remote sampling equipment

2.1 Terms, general requirements, and sampling operations

The equipment will be positioned to the work platform which will be installed on the bridge machine for loaded - unloaded fuel before terminal channel fitting which will be sampled under relatively restrictive space (terminals fittings are arranged on the front face of the vessel reactor in a square grid with up to 286 mm), reference [6].

Sampling is done on the inner surfaces of the pressure tube, anywhere over a length of approximately 2 m from the end (it was found that in the rolled joint zone, the hydriding is stronger according to reference [7]) with reactor under shut down condition, after minimum 24 hours from stopping.

2.2 Constructive structure and functional requirements of the equipment

In developing the overall concept of a model of sampling of the pressure tube equipment was started from main technical conditions imposed as follows: dimensions, environment (heavy water), temperature, pressure, radiation level , the possibility of sampling in any section of the pressure tube, the thickness of oxide layer, amount of samples, facile operation with automatic and manual control with distance supervision.

The development of the design solution concerned a modular structure with modules located within the fuel channel and others outside the channel on the mobile temporary platform and biological protection or, for example, in the control room.

Because of strong nuclear radiation fluxes and radioactive contamination danger, the concept of the equipment is to work with manual and automatic control, both under human operator supervision, reference [8].

2.3 The general concept of equipment

Equipment is designed with dual command, so start can be made both from a desktop locally on the temporary platform working and biological protection placed on the bridge of the Fuel Handling Machine, close to the channel fitting which must be analyzed and also from a desk located in outside area in front of Calandria where the radiation level is low and staff standing is allowed a long time, reference [9], [10], (Fig. 2).

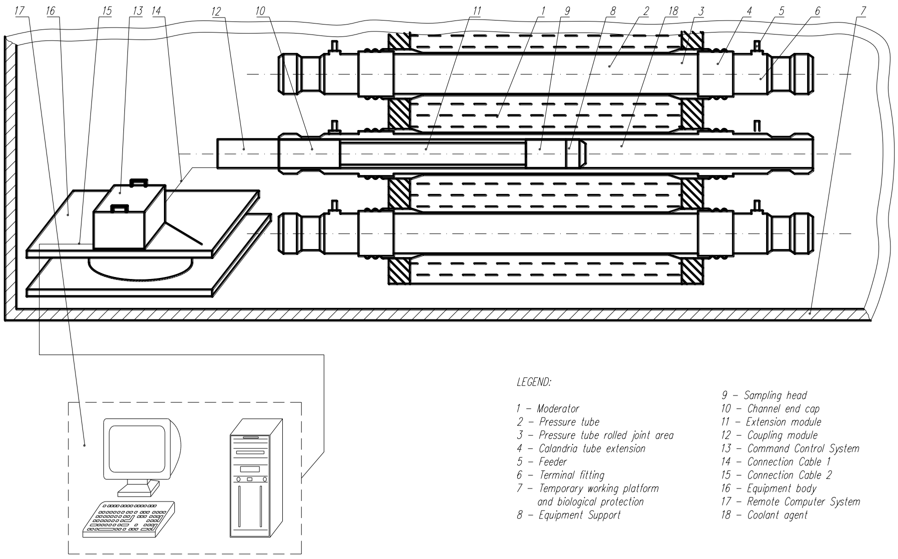

Fig. 2 – General view of equipment

The equipment must be able to accommodate over any terminal fittings on both sides of the reactor vessel, reference [10].

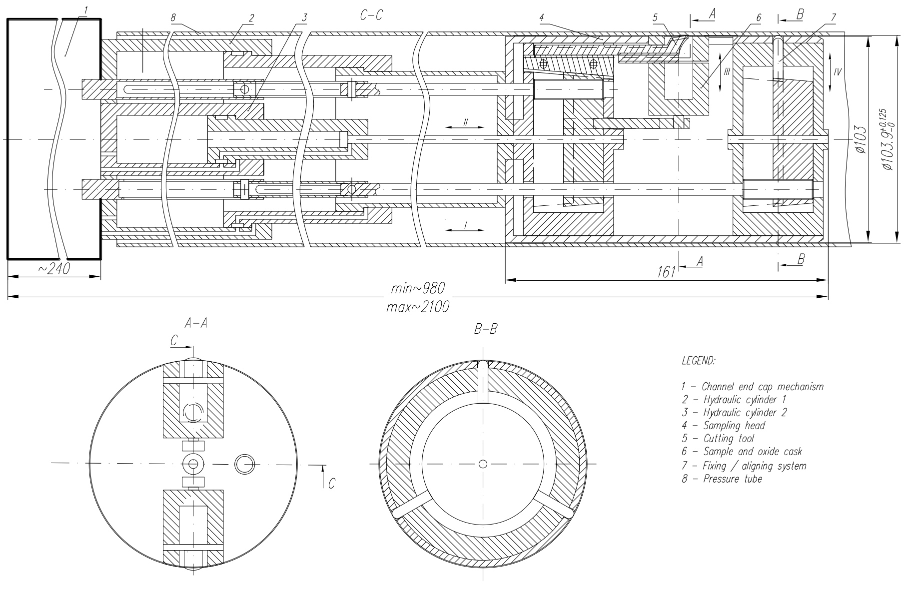

Fig. 3 – Mechanical structure of the robot

The equipment body (16) and command control systems (13) (Fig. 2) will work under the environmental conditions presented in Table 1.

Table 1

Environmental conditions 1

Operating conditions	Value
Temperature	~ 40 °C
Pressure	Atmospheric pressure
Humidity	~ 80%;
Radiation	~ 490* mR/h

*assessed value after a period of about 10 years of operation

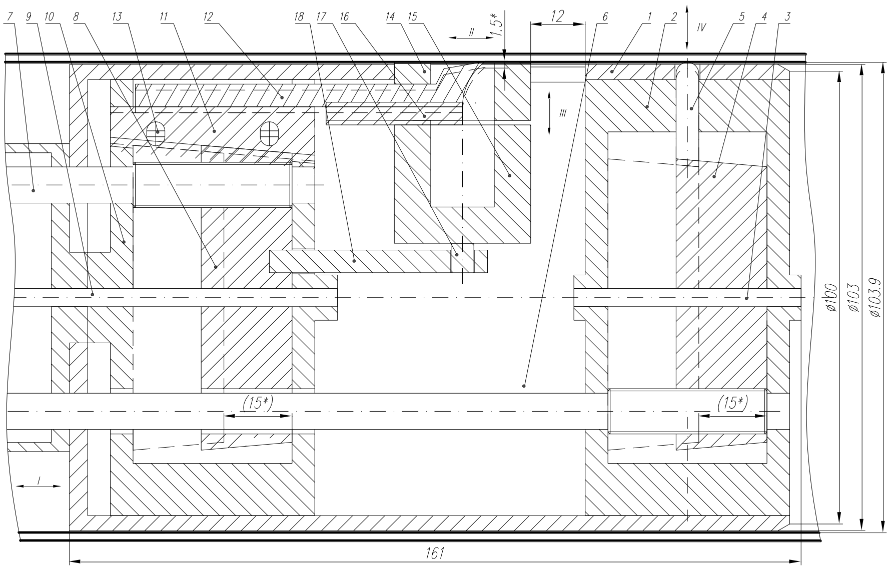

Fig. 4 – Sampling head

Head, end cap and expansion module (Fig. 3, 4 and 5) which penetrate inside the pressure tube (reactor stopped after at least 24 hours), will work under the environmental conditions presented in Table 2.

Table 2

Environmental conditions 2

Operating conditions	Value
Environment	Heavy water coolant (pH 10)
Temperature	max. 60 - 65 °C
Pressure	max. 1.5 MPa (200 psi)
Radiation	~ 10^6 R/h(γ) and $3 \cdot 10^9$ neutrons/cm$^2 \cdot$s neutron flux

A minimum quantity of substance is taken from the inner surface of the pressure tube for determination of hydrogen and deuterium concentration. The samples are approximately 80-90 mg weight.

Coupling/uncoupling operations and insertion/removal of the head inside the channel with closing/opening of the channel are adequate with the Fuel Handling Machine, reference [6], [7], [8].

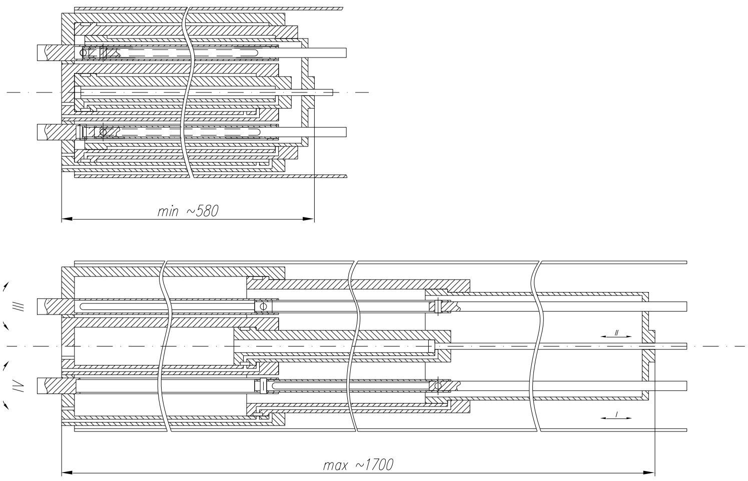

Fig. 5 – Expansion module

2.4 Kinematic description of equipment

Fig. 2 shows the general assembly of the equipment in the normal mode of working in a CANDU reactor, and in Fig. 3, the assembly which will function inside PT.

As shown in Fig. 2, the equipment consists of the following six distinct parts: sampling head module extension, end cap channel coupling mechanism module, the local command-control system and remote control and monitoring system, [8].

The main functions of the parts are:

- Sampling head that is mechanical and kinematic structure which remove the oxide layer and then the pressure tube sampling for determining the concentration of hydride;
- The end cap channel mechanism which provides sealing of the coolant channel at a pressure of 1.5 MPa and the maximum temperature of 65 °C;
- The expansion module ensuring the transmission of the translation movement (I and II) and rotation movements (III and IV) from the coupling module to the sampling head which moves inside the pressure tube;
- Coupling module performs the coupling of the free end of the end cap mechanism for supplying hydraulic cylinder (expander), and drive two screws;

- Local command - control system that provides command and control of the four degrees of mobility;
- Remote control and monitoring system that sets working to supervise and monitors the operation of the equipment, reference [10].

The mobility degrees of the robot are (Fig. 3):

I. - longitudinal displacement for pushing/pulling the sampling head inside the pressure tube (I);
   - Maximum race: about 1120 mm;
   - Maximum speed: about 60 mm/s.

II. - Longitudinal displacement for driving the turning tool - longitudinal advance movement (II);
   - Maximum race: about 12 mm;
   - Maximum speed: about 60 mm / s.

III. - Radial displacement for driving the turning tool - Crossing advance motion (III);
   - Maximum race: about 1.5 mm;
   - Maximum speed: about 10 mm / s.

IV. - Radial displacement of driving pins fixing/aligning (IV);
   - Maximum race: about 1.5 mm;
   - Maximum speed: about 10 mm / s.

Fig. 2 presents the six component parts of the sampling equipment in normal working mode, in front of the channel, on the temporary working platform and biological protection.

On equipment support - 16 which is placed on temporary work platform and biological protection - 7 stands the local command - control system - 13.

2.5 The mechanical and driving structure

The proposed mechanical and driving structure is composed of four distinct parts:

- Sampling with the head of the fixing / aligning system;
- Expansion Module.
- Channel end cap mechanism;
- Coupling module.

The first three modules enter inside pressure tube filled with coolant and therefore they should have a structure with a sealed outer surface and made of materials resistant to radiation and flux of neutrons, reference [9].

2.5.1 The sampling head

The mechanical structure is illustrated in Fig. 4. It is a complex structure with distinct and specific benchmarks (these are added to others unspecific). It consists of two parts: one is the actual body of the head and the other one is the fixing / aligning system.

It consists of a cylindrical body - 1 with Ø103 diameter and a length of about 165 mm beveled at the end to facilitate the insertion and movement into the pressure tube, provided with two lateral slots, wider than about 10 mm and about 120 mm long, depending on the size to be set for the sample.

At its end is situated the body of the fixing / aligning system - 2. Three fasteners (feet) are moving in one direction or the other - 5. The three legs are disposed at 120° one from another and are moving simultaneously by the same element performs a good aligning of the head and thus of the whole assembly on the pressure tube interior surface.

The head is provided with two diametrically opposite turning tools that work in tandem. According to reference [2], the laboratory tests have shown the feasibility of the methodology for axially cutting (scraping) in tandem is very effective in obtaining an adequate sample for analysis, and from a mechanical point of view, this assembly achieves a balance of the cutting forces.

Under the cutting tool is mounted a container - 15 whose cover - 16 is attached to the cutter body - 12. The container is able to collect the sample.

The sampling head could be replaced by a video camera or an endoscope for video examination of the interior surface of the tube.

2.5.2 Expansion Module

The mechanical structure is shown in Fig. 5. It consists of two hydraulic telescopic cylinders each of them is composed of three segments. The module is shown in two extreme working positions: raised with a length of about 580 mm and extended to a maximum length of about 1700 mm.

Three subassemblies constitute the first hydraulic cylinder, which is the one providing the positioning movement of device head (movement I) and other three subassemblies constitute the second hydraulic cylinder, which is the one who produces the longitudinal movement of the turning tool (movement II).

2.5.3 Channel end cap mechanism

The end cap mechanism for closing the channel will be a plug for closing the fuel channel, similar to those used in the operation of the reactor, adapted however with the passage for supplying the two hydraulic cylinders and transmitting the movement of rotation to the rods (Fig. 5).

The mechanism should allow a quick coupler on the other end (free end) with coupling module

2.5.4 Coupling module

Coupling module should permit rapid installation on the free end of the locking mechanism for the operation of the coupling channel to radiation to expose the human operator as little time as possible.

This module is designed to ensure the transmission of rotational movements and supply hydraulic cylinders and liaises with the control and device control.

3. Pressure tube sample analysis in the post-irradiation laboratory from Pitesti

Two methods for determining the concentration of H_{eq} (Hydrogen equivalent) of PT from a sample are Hot Vacuum Extraction Mass Spectrometry (HVEMS) and Differential Scanning Calorimetry (DSC).

Hot Vacuum Extraction Mass Spectrometry involves heating of the sample in vacuum at 1100°C for total gas extraction and their analysis by mass spectrometry. Isotope dilution technique is used to quantify the concentration of Hydrogen (H) and Deuterium (D) from pressure tube material (H_{eq}=H+0.5 D) and band spectrum of the substance is registered to seek other impurities and interference. Unfortunately, this method is very complex end difficult to apply especially for irradiated materials.

Differential Scanning Calorimetry is a thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. DSC measured the final solubility of the solid on a sample that is related to the concentration of Heq in the sample. This is a not - destructive analysis method, so, it can be used for several times on the same sample for greater confidence in results.

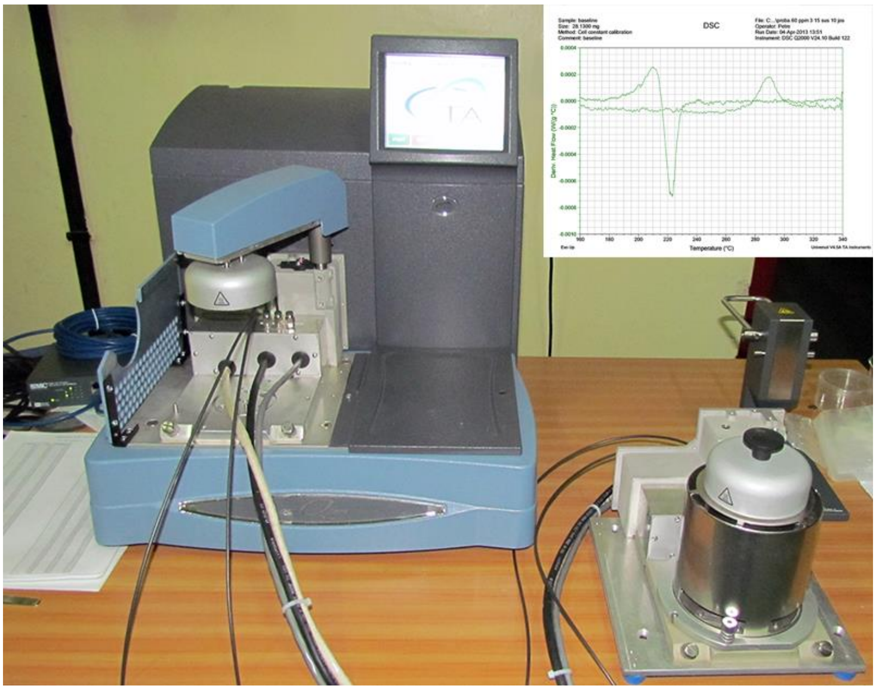

Fig. 6 - DSC Q2000 calorimeter

The simplicity of the H concentration determination procedure with DSC comparing with HVEMS method is an important factor in choosing DSC method for post irradiation laboratory because using the irradiated material it is an issue to protect the human operator. Also, it is more facile to implement DSC into a hot-cell or only its furnace. For these reasons, we have to use the DSC method in Post-Irradiation Examination. In the Post-Irradiation Examination Laboratory from Institute for Nuclear Research Pitesti, we are using a TA Instruments DSC Q2000 calorimeter (Fig. 6) to determine Hydrogen concentration from solid materials.

The DSC method is used to estimate the amount of the hydrogen dissolved in the sample, and also to estimate the precipitation temperature. As is presented in ref. [11], the terminal solid solubility of hydrogen in Zircaloy C_H has previously been measured and is given by the relation:

$$C_H = A \cdot e^{-\left(\frac{E_H}{T}\right)} \tag{1}$$

Where: A is a constant, equal to $1.2\text{x}10^5$ wt. ppm,

and E_H is the difference between the partial molar heat of solution of hydrogen in solid solution and partial molar heat of solution of hydrogen in hydrides.

The TA Instruments DSC Q2000 was specially designed with the detachable furnace in order to be used for radioactive materials.

A key contributor to the quality of DSC results is the sample preparation. The new Tzero® DSC Sample Encapsulation Press takes sample encapsulation to a higher level of performance and convenience in the conventional and hermetic sealing of a wide variety of materials. The press kit includes dying sets for the new Tzero aluminum and Tzero hermetic pans & lids (Fig. 7).

Fig. 7 - Tzero Sample Encapsulation Press

4. Conclusions

An original remote-controlled ROBOT for visual inspection and sampling from pressure tube of CANDU reactors was conceived and designed to take samples from the interior surface of PT. An overview of the equipment is given in the present paper. PT samples are useful for the determination of hydrogen and deuterium in the structure of the pressure tube because the hydriding of PT causes mechanical properties deterioration.

This manuscript has relevance by the fact that it is directly related to the safety of both personnel and the plant itself. The use of this remotely operated equipment for routine inspections will reduce the overall radiation exposure of the personnel working in a nuclear power plant. In addition, continuous monitoring of the hydrogen concentrations in pressure tubes is undoubtedly an important part of the overall maintenance of a nuclear power plant.

In the operating CANDU Nuclear Power Plants, in-service inspections of PT is regularly carried out to establish their integrity for continued plant operation reference [4]. These inspections are regulated by CAN/CSA N285.4. „Periodic Inspection of CANDU Nuclear Power Plants Components" ref. [5].

The construction and use of the visual examination and sampling equipment are important in the nuclear safety analysis of the reactor channels and CANDU fuel in general, and for comparing the measured values with those determined by calculation hydride, increases the mathematical models to estimate the behavior of the pressure tube during operation. Hydrides time control of the evolution of the pressure tubes depending on operational parameters of the reactor can improve reactor operation throughout his life.

If the hydrogen concentrations in a pressure tubes are above critical levels, that pressure tube must be closed and then replaced.

Taking all these into account, the analysis of the fuel channel behavior in reactor conditions is a central point in the research - development programs that have the security and safety of CANDU NPP as an objective.

The CANDU fuel channel assembly geometrical and mechanical characteristics, materials, and environmental conditions analysis were performed to establish the initial requirements for equipment.

After a preliminary study, the equipment was calculated, design and drawn.

The execution of the equipment is useful both in the mandatory analyze activity of the safety of the fuel channels and in the research and development activity.

The method used for sample hydrogen concentration determination is also described.

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