16

European Working Group
"Hot Laboratories and Remote Handling"
Willigen, Switzerland
27-29 September, 2000

Review of methods used at SSC RF RIAR for mechanical testing of specimens made of VVER zirconium fuel rod claddings.

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Abstract

SSC RF RIAR uses and develops continuously the methods for investigating the different properties of fuel elements (FE) as well as their components irradiated in the VVER reactors. The methods for investigating the mechanical properties of zirconium claddings before irradiation, in irradiation and after it are of particular interest.

Considering the objectives of meeting, the given report reviews the methods of mechanical testing as well methods of corrosion and thermal treatment of samples made from irradiated fuel elements and their claddings. Presented here are the procedures and some results of their application.

1. Introduction

VVER fuel elements claddings are exposed to compound thermal, mechanical effects and corrosion attack. These effects continue for a long time in nominal operation condition. Their results are studied adequately and they can be allowed correctly for calculation of fuel element reliability and life time. As for transient and emergency conditions the effects are of short duration but their consequences are studied to a lesser degree. To calculate fuel element reliability under such kind effects and the remaining lifetime of fuel elements after the affecting, it is necessary to know the mechanical properties of zirconium claddings on their long-term exposure to the combined mechanical loadings, after rather short-term and high-temperature corrosion attacks and after high-speed thermal shock.

2. Methods of Mechanical Testing

2.1 Uniaxial Loading

Test devices provided with mechanical drive are used for uniaxial loading testing. Fig.1 demonstrates the most generally used shapes of the experimental samples.

These are ring samples (Fig.1a) that are cladding cutoffs designed for tensile testing in the transverse direction with the use of semicircular supports. The cutting-off is performed using the high-speed diamond cutting wheel.

These are longitudinal samples (Fig.1b) that are made with the use of electroerosion cutting and designed for tensile testing in the axial direction.

These are tubular samples (Fig.1c). They are cladding cutoffs provided with terminal parts that are welded on each end face and intended for axial tensile testing.

2.2 Biaxial Loading

2.2.1. For a long period of time the mechanical testing of claddings under biaxial loading was performed using samples (Fig.2a) sealed under the excess gas pressure. Sealing is followed by the sample exposure at high temperatures. The method is the simplest one but it makes the variation of tangential stresses in the cladding impossible at constant temperature.

Such variations are possible when the external source of the controlled gas pressure in sample is used that is exposed to heat (Fig.2b).

Fig.3 presents the schematic drawing of the in-cell test rig that is used for such kind of tests.

The engineering properties of the test rig:

- Test temperature- up to 1200°C;
- Internal pressure of the sample- up to 16Mpa;
- Sample length- 275mm.

2.2.2 The biaxial stress-strained state forming the different relation of hoop-axial stresses σ_θ/σ_z occurs in cladding as a result of thermomechanical UO_2 pellet-cladding interaction. This relation depends on the factor of UO_2 pellet-cladding friction. And in the general case it can change in the range from 2 (without contact) to 1 (full engagement and isotropic fuel extension). The test rig was developed to determine the failure parameters of tubular samples in conditions of biaxial stress-strained stress with the hoop-axial loading relation of $\sigma_\theta/\sigma_z = 1...2$. The facility is illustrated in Fig.4. The cutoff sample of VVER and RBMK fuel element becomes free of UO_2 pellets and it is sealed mechanically on each end face using the metal sealing bushings. The internal sample pressure is created by the external source of the controlled hydraulic pressure. The independent external source creates the controlled axial loads on the sample. The cladding diameter of central section, internal sample pressure and axial load are measured in testing.

The engineering properties of the test rig:

- Test temperature- up to 500°C;
- Rate of pressure increase inside the sample –0.01...1.0MPa/s;
- Internal sample pressure - up to 150MPa;
- Additional axial load- up to 10kN;
- Sample length- 275mm.

Results of mechanical tests conducted with non-irradiated and irradiated claddings of VVER fuel elements are given on Fig.5 [1] to show the significant effect of the additional axial loading.

2.2.3. A test rig pictured in Fig.6 is used for studying the effects of corrosion attack of fission iodine on the cladding. The source provided with coarse control of gas pressure creates the internal pressure in the sample that is the FE cladding cutoff. Another source of gas pressure is used for fine control of external pressure. As a result, the preset pressure is maintained inside the sample to high accuracy. The sample dimensions vary in the course of long-run testing.

The required quantity of iodine is in the glass capsule that breaks at a right time. The iodine is placed inside the sample being tested.

As this takes place, the corrosion damage of zirconium claddings is simulated when fuel element is operated in steady- state or power ramping conditions.

The engineering properties of the test rig:

- Test temperature- up to 500°C;
- Internal sample pressure - up to 100 MPa;
- External sample pressure- up to 1 MPa;
- Sample length- 275mm.

The results of irradiated cladding testing exposed for a long time to the internal gas pressure at 350°C are presented in Fig.7 to demonstrate the significant effect of iodine as a corrosive agent.

2.2.4. A test rig demonstrated in Fig.8 is designed for biaxial loading of claddings with internal gas pressure. Claddings can be loaded with hydraulic pressure on the outside that is capable of cycling with time. As an alternative to possible ways of testing the examples are plotted. This is the external hydraulic pressure cycling against constant internal gas pressure. Such kind of loading allows us to simulate the mechanical loading of FE claddings having high burnups and to study low-cycle cladding fatigue. The simulation is performed under power ramping conditions.

The engineering properties of the test rig:

- Test temperature- up to 500°C;
- Internal sample pressure - up to 100 Mpa;
- External sample pressure- up to 200 Mpa;
- Possibility of external hydraulic pressure cycling on a frequency of ≤1 cycle/min;
- Sample length- 275mm.

3. Methods of corrosion and thermal treatment.

3.1 Overheating of claddings and samples in water steam

The in- reactor superheating of FE claddings under emergency conditions was simulated with the help of local overheating stand [2] using muffle furnace (Fig.9). The sealed or unsealed fuel element cutoff (or FE cladding cutoff) is exposed to different temperatures (up to 1000°C) at different points as shown in the Figure. As a result of this, corrosion and thermal effects in the cladding material are distinguished by height. The differences are revealed in the course of mechanical testing of ring samples that are cutoffs of different cladding sections to be distinguished by height when the cladding is tested using the test rig.

The ring sample cutoff for mechanical testing of claddings exposed to active oxidation in heating may involve difficulties due to considerable reduction of zirconium plasticity. In such a situation, the sequence of operations was as follows.

At first the ring samples were cut out from the FE cladding cutoff. These samples were stringed using suspension rod. The suspension rod was placed at the specified section of the furnace. By this means the ring samples made in advance were exposed to overheating in water steam at produced temperature gradient inside the furnace. The specific mode of corrosion and thermal treatment is assigned to each ring specimen when the mechanical test data of these samples are analyzed.

The similar facility is illustrated in Fig.10. A smaller sample is exposed to uniform heating up to higher temperatures using this facility.

The engineering properties of the facility:

- Test temperature- up to 2000°C;
- Heating rate of sample in inert atmosphere- up to 100°C/s;
- Heating rate of sample in water steam and gas environment- up to 10°C/s;
- Sample length- 45mm.

3.2 Quenching of claddings and samples into water

The quenching of fuel elements after their emergency overheating in the nonuniform temperature field was simulated using the same facility (Fig.9). But some additional devices were used for this purpose. These devices made sample falloff into the water at the predetermined time period possible. The samples were after the corrosion and thermal treatment that was performed at the top end of the stand. Cutoffs of fuel elements, claddings as well as ring samples made beforehand were under mechanical testing (Fig.9a, 9b).

The similar facility is presented in Fig.11. The samples are exposed to uniform heating up to higher temperatures using it.

The engineering properties of the facility:

- Test temperature- up to 1300°C;
- Water temperature- up to 100°C;
- Sample length- up to 200mm.

4.Conclusion

The methods of corrosion and thermal treatment as well as methods for mechanical testing of samples made of claddings irradiated in the VVER reactors that have been developed and used in SSC RF RIAR provide the results required for calculation of VVER FE reliability operated in nominal, transient and emergency conditions.

References

1.L.Yegorova, V.Smirnov, S.Yeremin et al. "Mechanical Properties of Unirradiated and Irradiated Zr-1%Nb Cladding under Accident Conditions". Report presented on twenty seventh Water Reactor Safety Information Meeting, Washington, USA, October 25-27, 1999.

2. I.Golovchenko "Research Methodology and Equipment to Study Properties of Irradiated Fuel upon In-cell Local heating". Report presented on European Working Group "Hot Laboratories and Remote Handling", Petten, Netherlands, May 14-15, 1996.

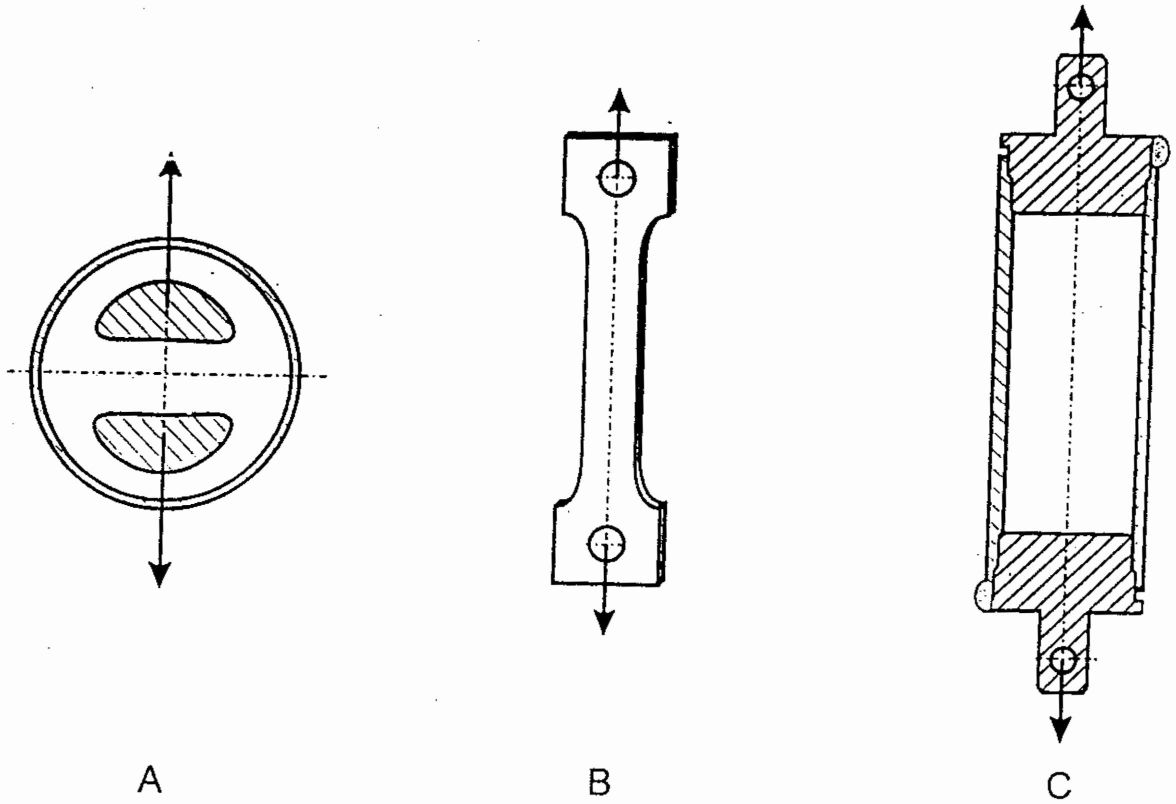


Fig.1. Samples for uniaxial tension

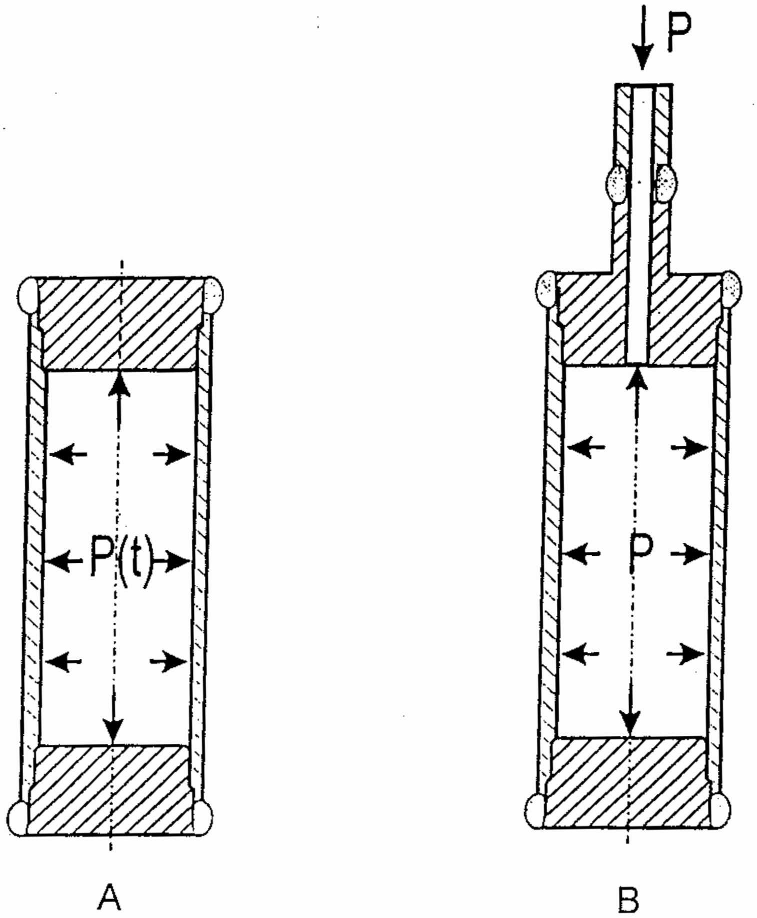


Fig.2. Samples for biaxial tension when $\sigma_\theta / \sigma_z = 2$

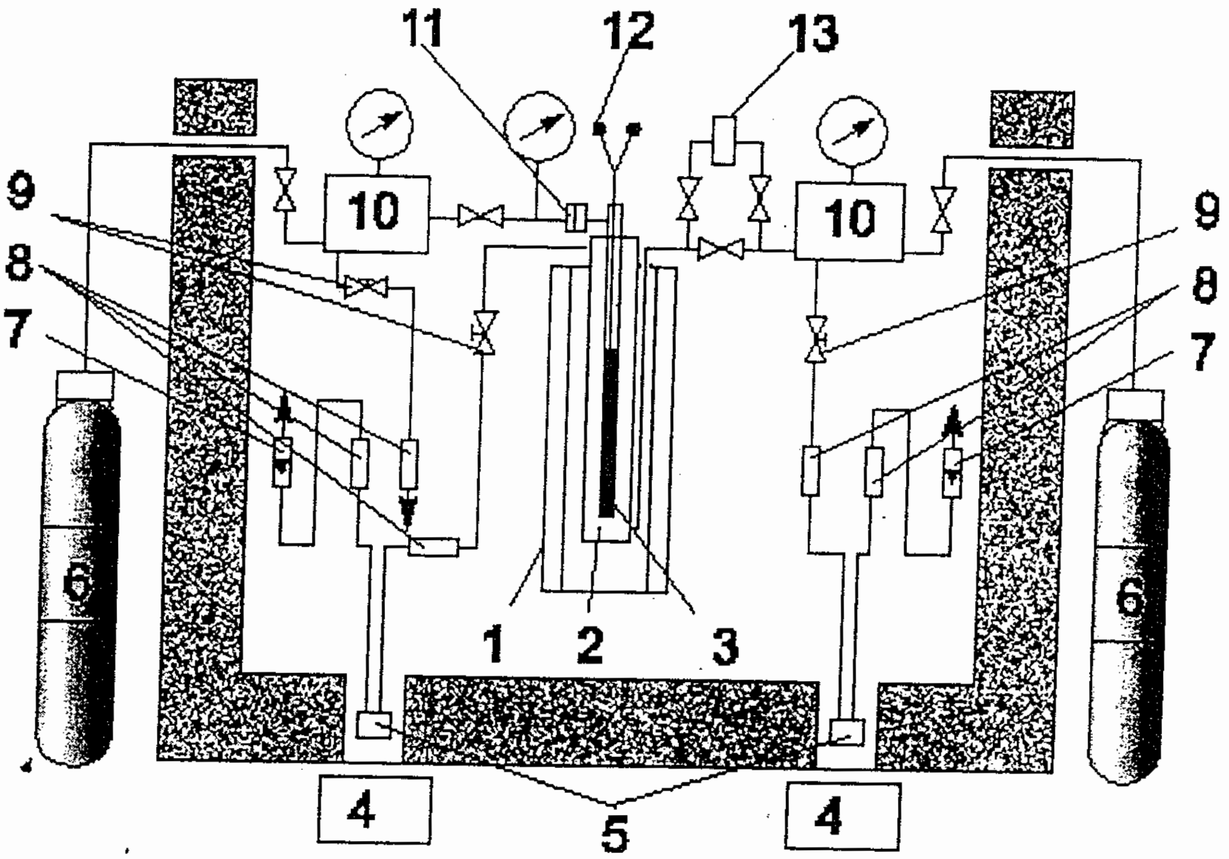
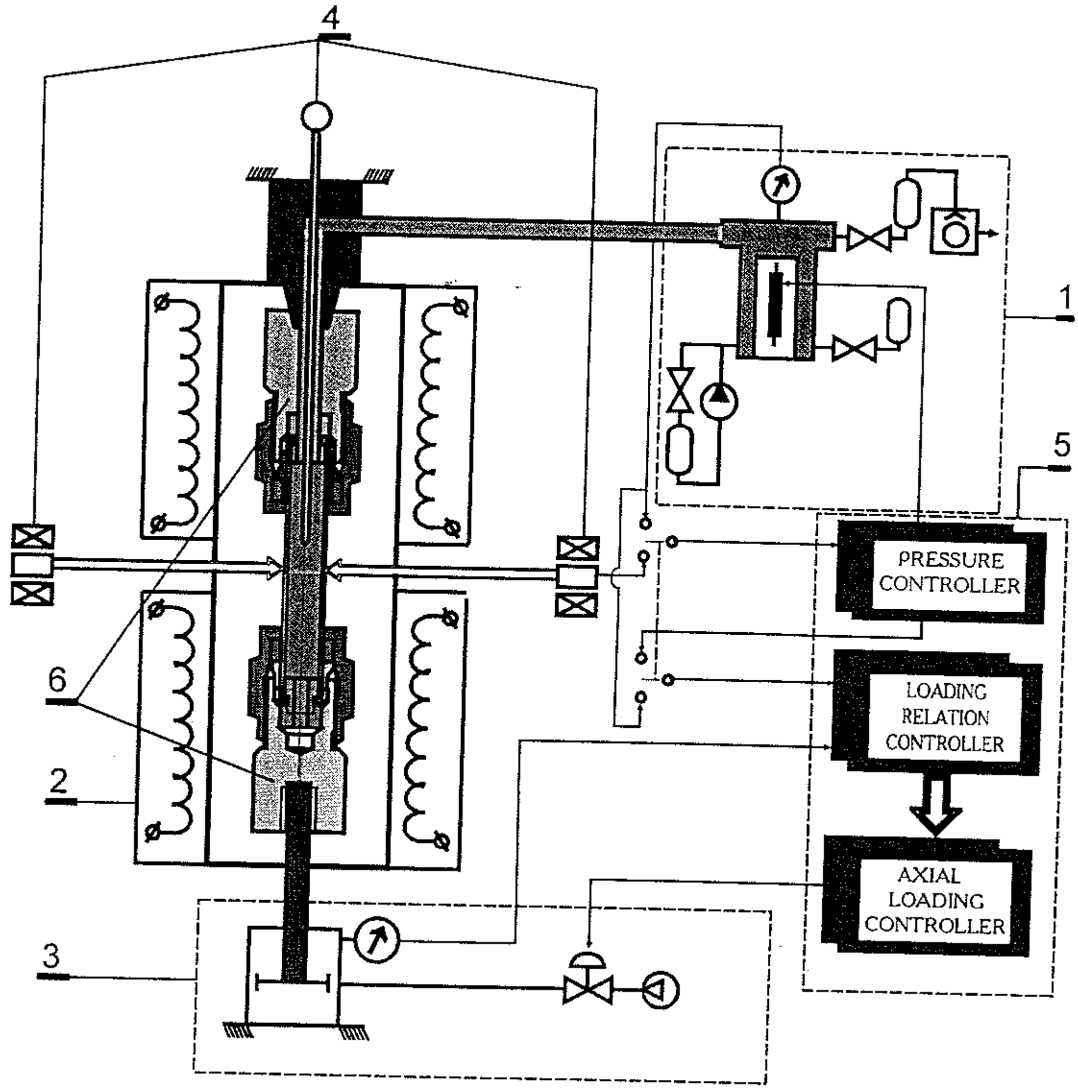


Fig.3. In-cell test rig for gas loading

1 - electric furnace
2 - capsular
3 - sample
4 - detector
5 - accumulative chamber
6 - gas-cylinder
7 - rotameter
8 - filter
9 - reducer
10 - container
11 - demountable connector
12 - thermocouple
13 - steam generator



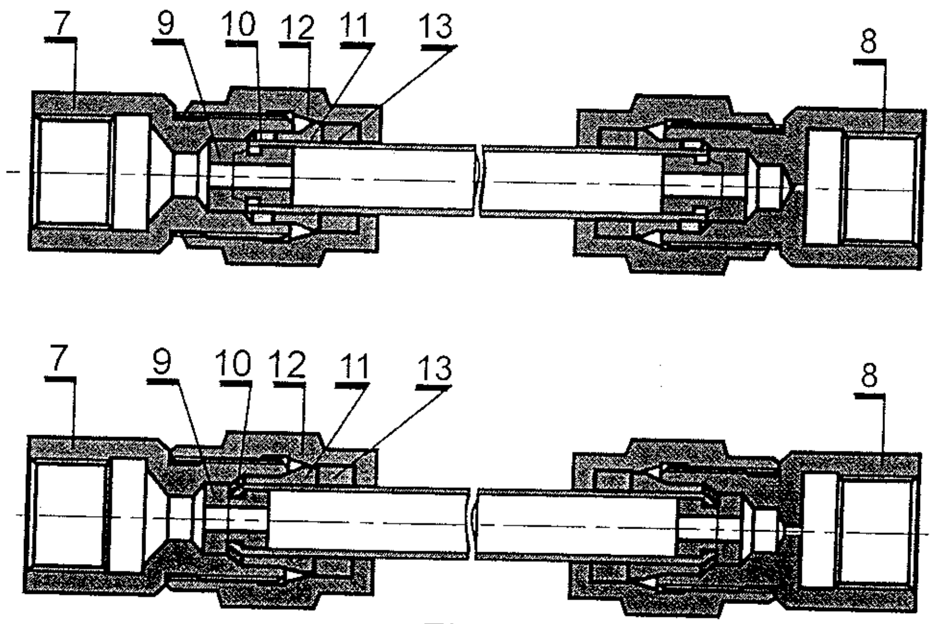


Fig.4

Rig for tubular sample testing when $\sigma_\theta/\sigma_z=1\ldots2$

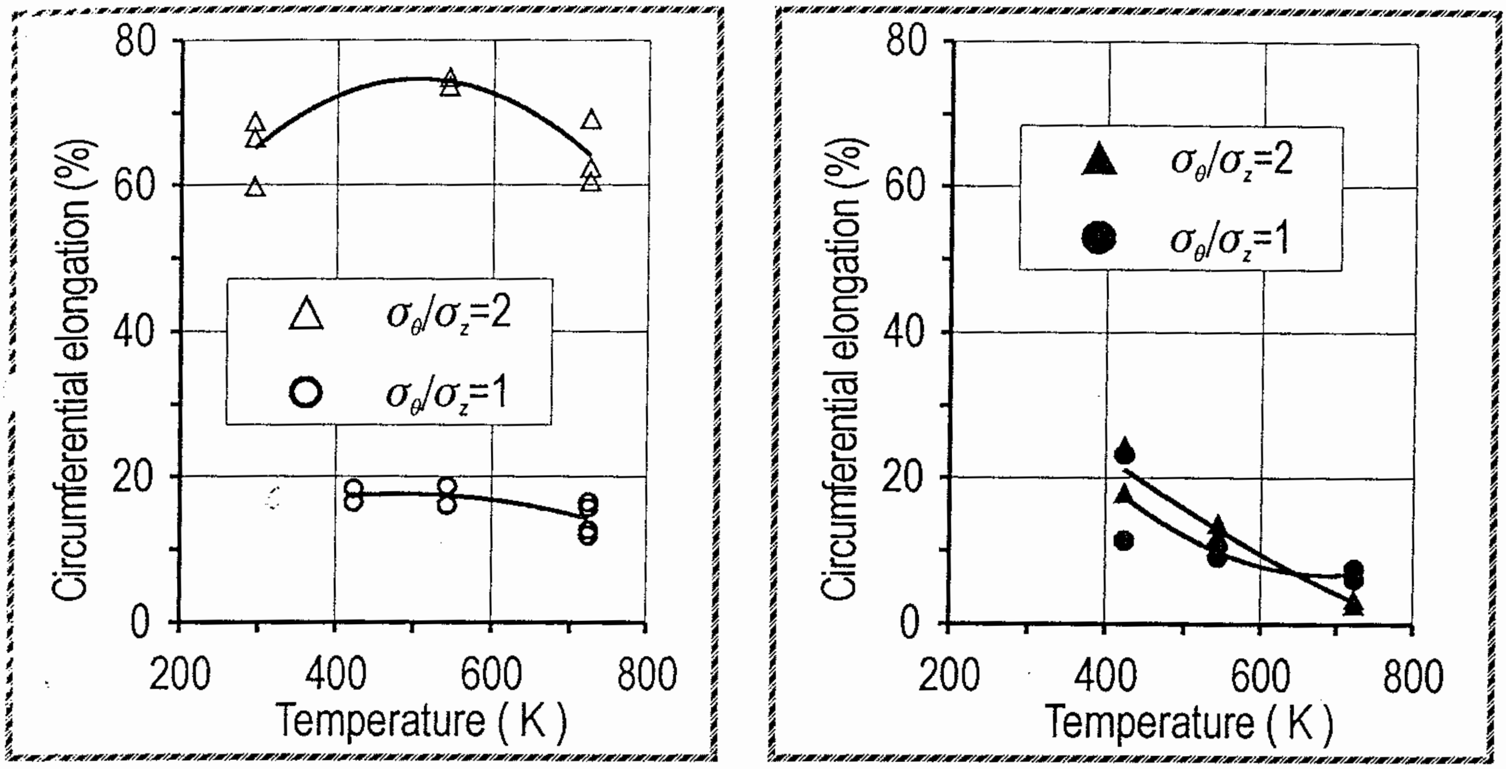


Fig.5 The influence of σ_θ/σ_z relation on hoop strain of non-irradiated and irradiated VVER FE claddings

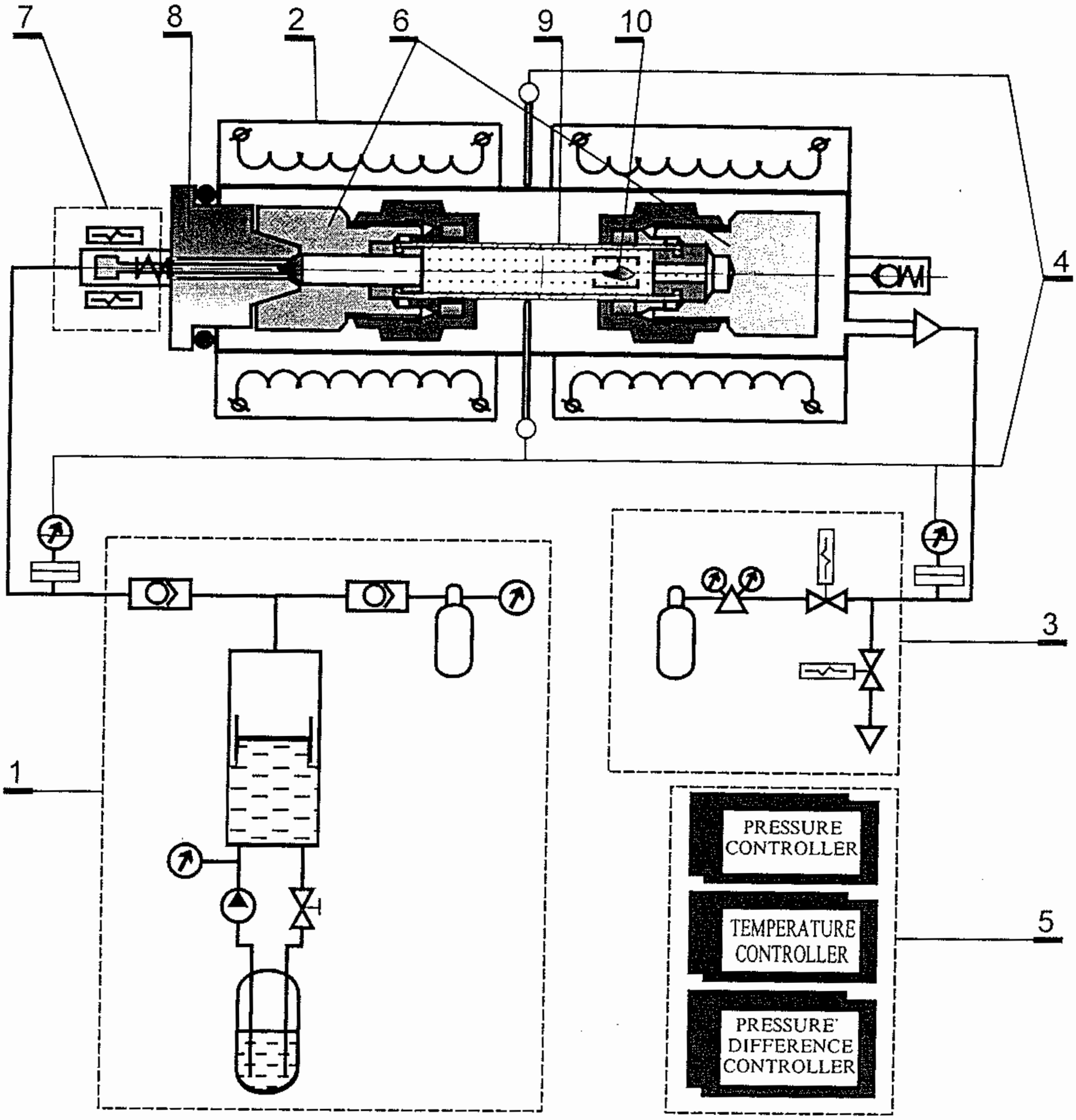


Fig.6
Rig for tubular sample testing under iodine corrosion attack

1 - high gas pressure generator
2 - electric furnace
3 - system for pressure difference keeping
4 - instrumentation sensor
5 - controlling system
6 - final elements
7 - electromagnetic valve
8 - sealing unit
9 - sample
10- corrosive agent

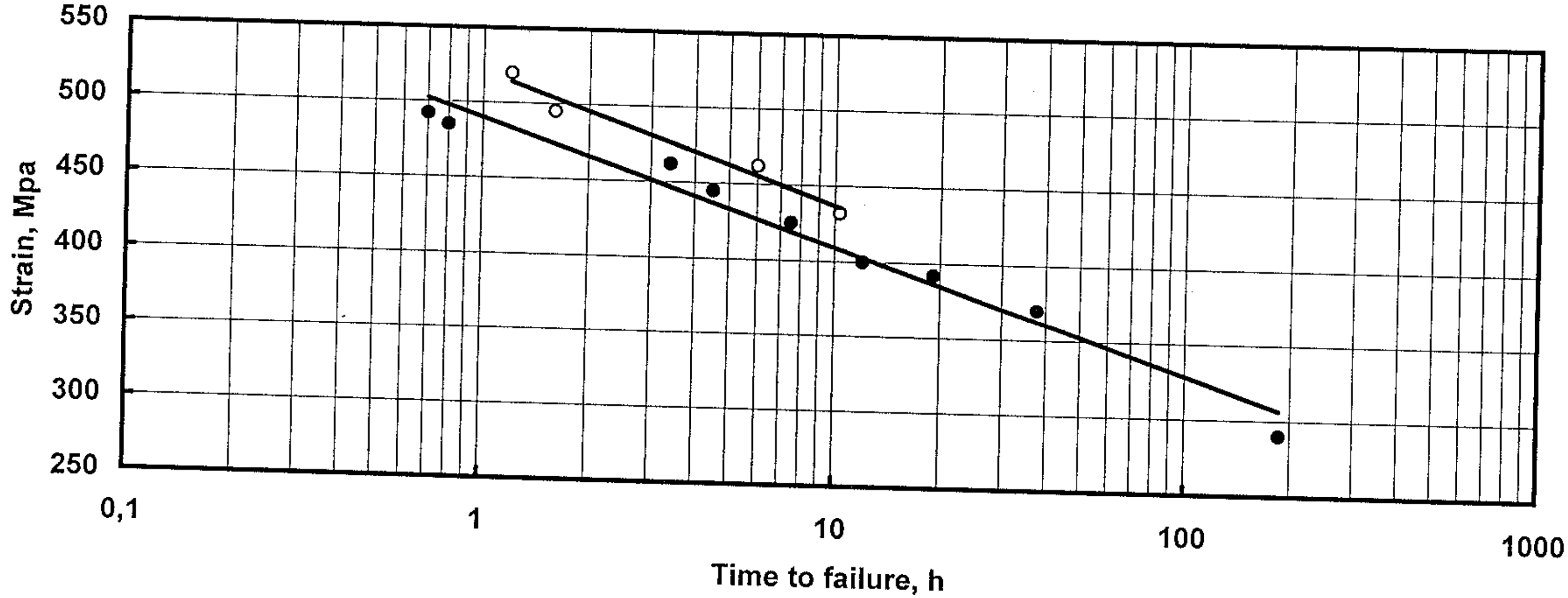


Fig.7. Iodine effect on long-term strength of irradiated VVER FE clading samples at 350^{0}C

○ Iodine-free samples;

● Samples with iodine;

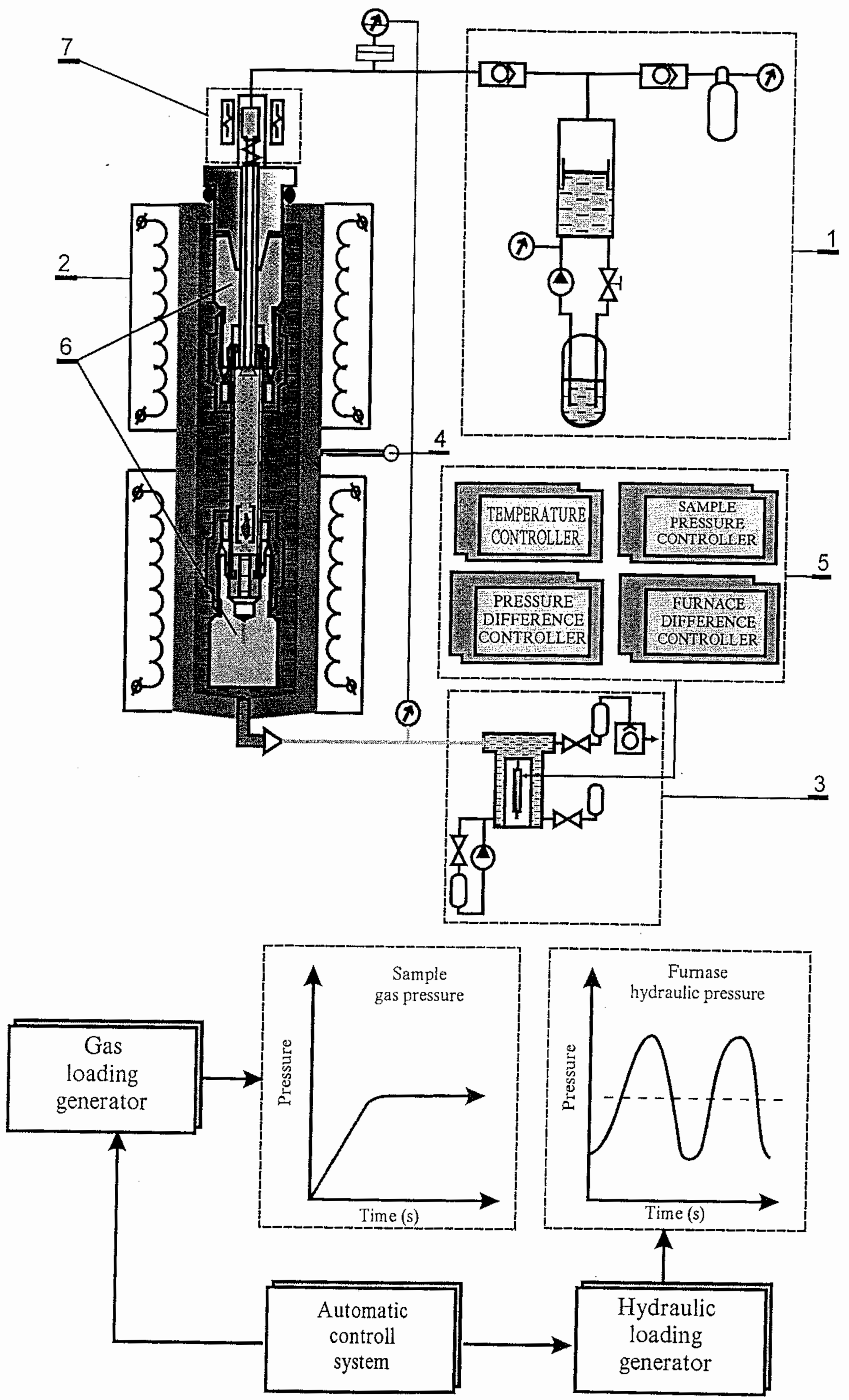


Fig.8. Rig for low-cycle fatique testing of tubular samples under iodine corrosive effect

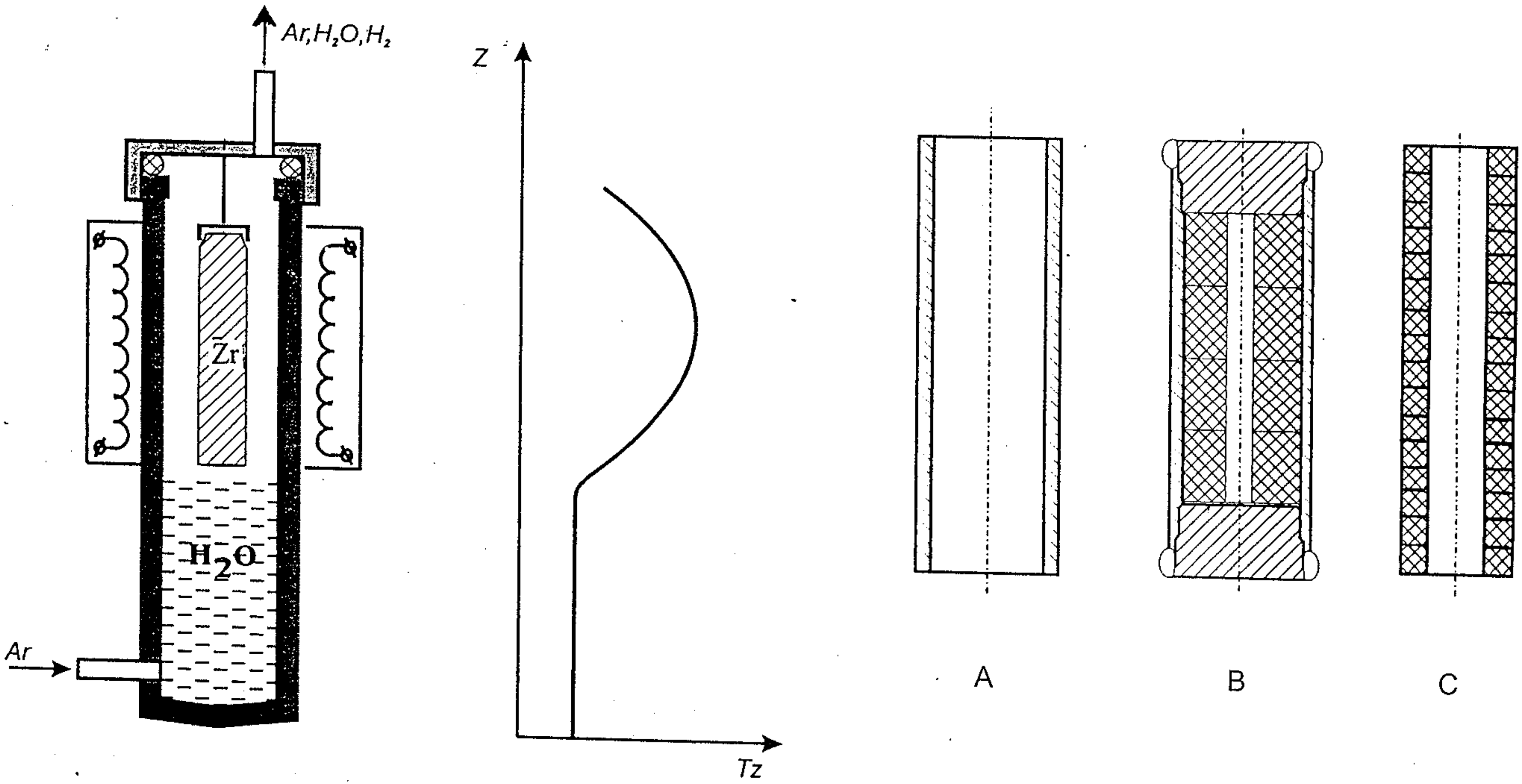


Fig.9 Facility provided with muffle furnace for corrosion and thermal treatment of zirconium samples
A- cladding cutoffs
B- sealed FE cutoffs
C- annular samples for mechanical testing

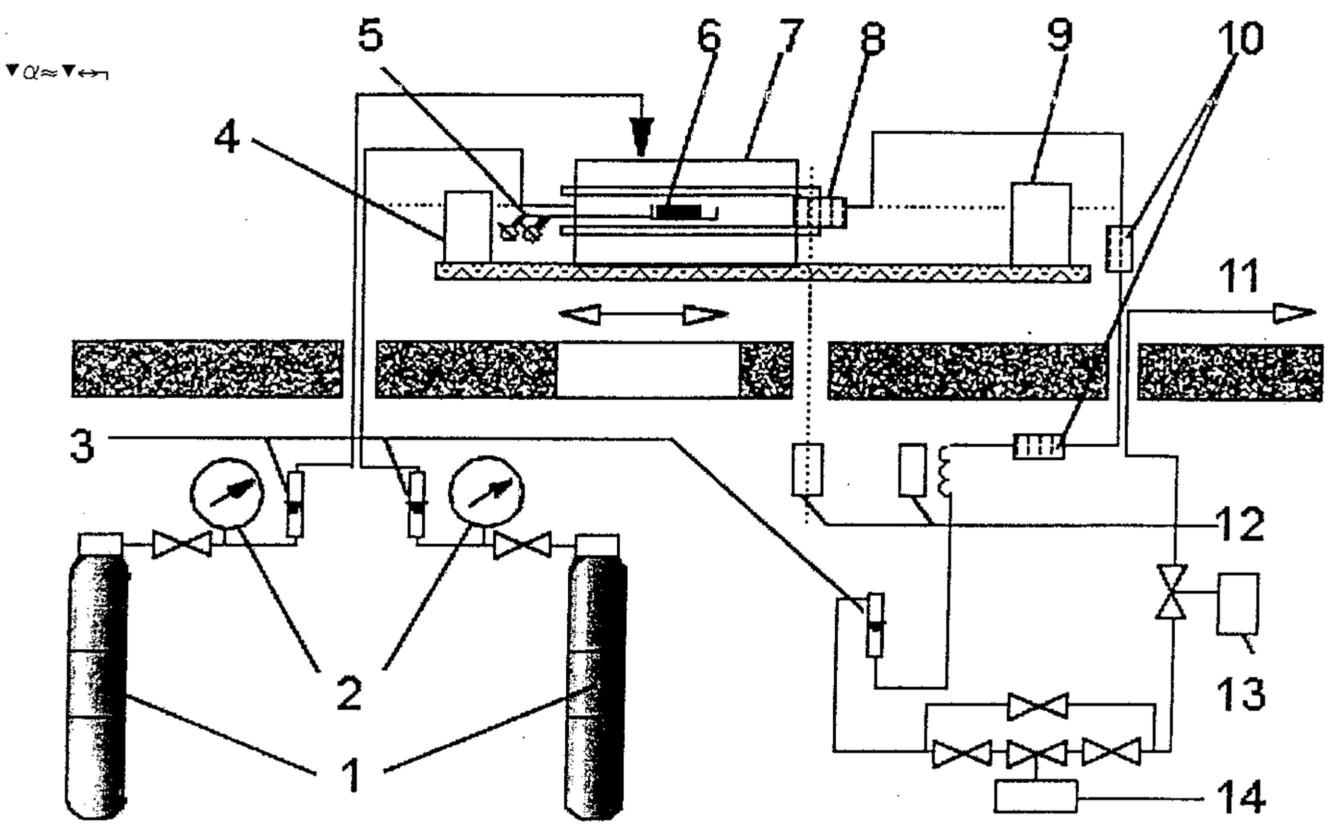


Fig.10. Experimental setup for sample oxidation study

1 - argon cylinder
2 - pressure gauge
3 - rotameter
4 - steam generator
5 - micro-thermocouple
6 - sample
7 - heater
8 - base filter
9 - condenser
10 - additional filter
11 - discharge to special ventilation system
12 - gamma detector
13 - gas-analyzer
14 - mass spectrometer

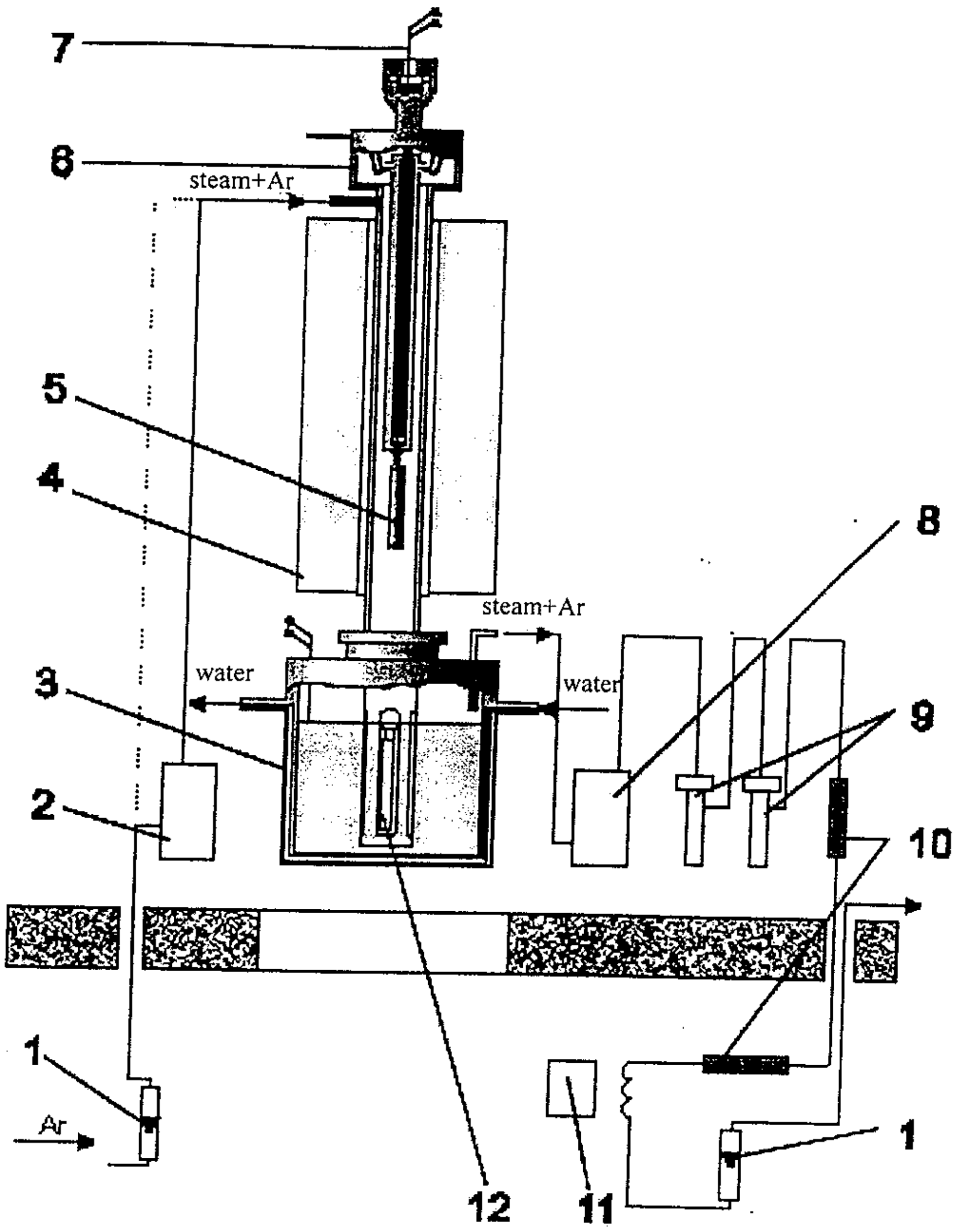


Fig.11 Experimental setup for cladding thermal stability study

1- Rotameter
2- Steam generator
3- Water tank
4- Heater
5- Sample
6- Device for sample falloff
7- Micro-thermocouple
8- Condenser
9- Bubbler
10- Filter
11- Semi-conducting detector
12- Sample after falling off