2.4.

DEVELOPMENT OF A CLOSED-END BURST- AND CREEP-TEST FOR IRRADIATED CLADDING MATERIALS

H. Kostecka and E.H. Toscano

Commission of the European Communities, European Institute for Transuranium Elements, Postfach 2340, 76125 Karlsruhe, Federal Republic of Germany.

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1. INTRODUCTION

In a nuclear reactor the cladding material of the fuel rods is subjected, during operation, to complex biaxial stresses imposed by the internal pressure due to filling gas and fission gases and, additionally at high burnup, by fuel swelling. Considering also the external stresses imposed by the pressurised coolant, the actual longitudinal to tangential stress ratio may locally vary depending on the fuel rod design as well as the axial linear power distribution.

Biaxial stresses resulting from the internal gas pressure have also to be considered for storage licensing of spent fuel to confirm the reliability of dry long-term storage of Zircaloy clad fuel rods. In this context it is important to determine the mechanical properties which describe the ductility of highly irradiated cladding materials, in particular the creep phenomena that may occur due to post-pile heat generation.

A device, able to operate under remote handling conditions, has been developed to evaluate the mechanical properties of closed-end samples, taken from irradiated cladding materials, by performing burst- or long-term creep-tests. Closed-end mechanical testing produces a longitudinal to tangential stress ratio of 1:2 and thus is considered to simulate the stresses occurring in fuel rods under the in-pile and dry storage conditions previously described.

2. EXPERIMENTAL

2.1. General description of the equipment

The system is based on the internal pressurisation of a cylindrical sample. Oil (stiff system) was preferred to gas (soft system) pressurisation because its stored energy is intrinsically lower. In Fig. 1, a schematic diagram of the apparatus and a general view of the equipment are shown.

The equipment was designed for samples (normally 10.75 mm in diameter) up to 150 mm in length which, taking into consideration the grip length, ensures an unsupported length of about 10 times the average outside diameter, as recommended in the ASTM - Norm B 353.

2.2. Pressurisation system

The dual piston pump allows a smooth pressure increase and is able to maintain a constant rate of volume increase in the specimen throughout the test, except in the final stage of a burst test. The pumping rate can be varied in order to avoid a pressure surge during a pump stroke or the overloading of the sample due to the inertia of the system. The pressure system allows pressures up to about 200 Mpa to be reached and is located outside of the hot cell. A pipe-line system connects the pressure system, through the α-containment walls, to the sample. During a creep test, the pump is controlled by a computer; an ad-hoc software compares the actual value with the default value established, maintaining it during the whole test. During this creep operation mode, the pumping rate is set to the minimum and the software assures a constant pressure to within $\pm$ 1 bar during the whole test.

As pressurisation fluid a silicon oil (Dow Corning 200) was used, having an expansion coefficient of 1.34 x 10^{-3} ml/ml °C and a compression coefficient of about 0.2 at room temperature. In the closed system used, the stability of the oil was not affected by the temperature and no cracking or oxidation phenomena were observed. The maximum temperature allowed is about 400 °C

2.3. Furnace

An electrical furnace, provided with three heating zones and an internal double wall lining containing caesium, allows homogeneous heating of the sample to the test temperature, minimising the temperature gradient along the sample. During the tests it was established that the heat transfer by conduction through the grips and pipes to the ambient contributed significantly to the formation of temperature gradients. Therefore, to reduce this effect, the diameter of the oil inlet was reduced to a minimum. With an appropriate configuration, gradients over the whole sample length as low as ± 0.2 °C were achieved.

The temperature gradient was checked by means of two thermocouples attached to the upper and lower grips (located inside the furnace during the test) and a third positioned close to the centre of the sample. In order to avoid cooling of the specimen during the burst-tests, an oil preheating chamber was included in the lower grip. The temperature regulation system allows the target temperature to be obtained with a precision of ± 2 °C.

2.4. Data acquisition

A data acquisition system allows simultaneous recording of the specimen pressure as measured by a pressure transducer located near to the sample, the oil volume input to the specimen obtained from the piston travel with a potentiometric transducer and the temperature. At pre-set time intervals the instantaneous values of pressure, temperature and piston displacement can be recorded during the whole test

In Figs. 2 and 3 the sample fixing and a sample mounted on the apparatus are shown.

2.5. Ancillary equipment

Three devices had to be developed in order to: 1) retrieve the fuel, 2) tighten the specimen grips and 3) measure the sample diameter before and after the testing.

2.5.1. Fuel retrieval and sample preparation

Based on a commercial drilling machine, able to hammer while drilling, a device was developed to retrieve the fuel from the segments of fuel rods irradiated in nuclear power plants. The device utilises a concrete drilling tool, fixed during the operation while the samples rotates. The system allows a smooth vertical displacement through counterweights which keep the sample in quasi-equilibrium during the drilling operation, permitting the operator to control and maintain the applied load at a minimum.

The diameter of the drilling tool was normally around 1 mm smaller than the nominal internal diameter of the sample. Considering that the fuel-cladding interaction at the burnups of interest (more than 40 GWd/tU) can be large, additional techniques were developed to remove partially the interaction layer. To this goal a lathe, modified for operation under remote controlled conditions, and provided with special grinding tools, was used. In figs. 4 and 5, the lathe and the fuel retrieval device are shown.

2.5.2. Tightening device

Mechanically attached end-fittings were used to seal the specimen. In order to screw the fittings to the specimen, a special device was developed on the basis of a commercial pneumatic wrench, able to perform a smooth tightening of the fittings, avoiding impacting or pulsing tightening cycles which could lead to the damage of the samples. The torque can be controlled to within ± 5% of the envisaged target by regulating the gas pressure. The samples were strengthen by inside mandrels in order to counteract, at least partially, the external forces applied during the tightening of the metallic seals. The mandrels are provided with a groove to facilitate movement of the fluid within the specimen.

2.5.3. Sample measurement

A displacement transducer has been mounted on a floating head to measure the relative movement of two knives which perform the measurements using, as reference, calibrated standards. The device is able to detect variations of ± 0.1 µm in the diameter. The same device permits the simultaneous measurement of the axial displacement (± 1 µm), allowing correlation of the diameter measured with the axial position on the sample. A similar device is also use to measure the length of the specimens after a creep test.

3.- TEST SCHEDULE

Previous to the installation of the equipment in the hot cell, several tests were performed using non-actives samples. Under remote controlled conditions, several samples, taken from a 4-cycles PWR (about 50 GWd/t[U]) irradiated fuel rod, were tested. As an example, the schedule of a typical creep test is described below.

3.1. Sample preparation

Special care was exercised during the drilling operation to avoid damage of the sample wall or to cause deformation of the sample. Drilling periods were alternated with inactive intervals, allowing the sample to cool down. The remains of the fuel and part of the interaction layer were removed by grinding, using a lathe previously installed in the hot cells. The latter operation was conducted in such a way that part of the interaction layer remained attached to the wall, ensuring that the cladding was not affected during the operation. Hence, the fuel segments were externally "decruded" with fine emery paper and the samples visually inspected to ascertain that neither undercuts nor scratches were present on the surface.

Afterwards, the internal diameters of the sample at both ends were measured using calibrated gauges. Then, internal mandrels were manufactured, with a typical tolerance of about - 20 μm. Finally, previous to the tests, the samples were measured, usually in five axial positions, at four azimuthal positions each, to determine possible eccentricities.

3.2. Creep Tests

A precise schedule was established for the development of a test. This included: a) pre-loading of the sample, in order to avoid bubble formation during the heating phase; b) complete elimination of occluded air to keep the stored energy low and to have a reliable measurement of the diameter increase through the amount of oil pumped into the sample; c) pressurisation of the creep sample after the test temperature was achieved and had established; and, d) preheating at low pressure lasting for a few hours was used as standard procedure.

3.3. Post-test evaluation

After the tests, the samples were measured every 5 mm along the axis, again at four azimuthal positions, and its length determined. From these data the total strain was calculated. Good agreement with the deformation predicted from the continuous measurement of the amount of oil pumped into the sample was generally found.

4.- RESULTS

As an example the creep results of a sample, taken from the plenum position, are presented. In Fig. 6 the creep hoop strain as function of time is shown. The three typical creep stages are clearly defined. In Fig. 7 the measured hoop strain as a function of the axial position on the sample is depicted. The influence of the neutron flux is clearly seen.

5.- CONCLUSIONS

A burst- and creep-test apparatus has been developed which has low stored energy, provides good control over the oil volume pumping rate, produces a smooth pressure/volume curve and works reliably under remote controlled conditions. The future work foresees the testing of samples from 4 and 5 cycles LWR fuel rods. The influence of increasing radiation damage, oxide layer thickness and hydrogen pick-up will be studied.

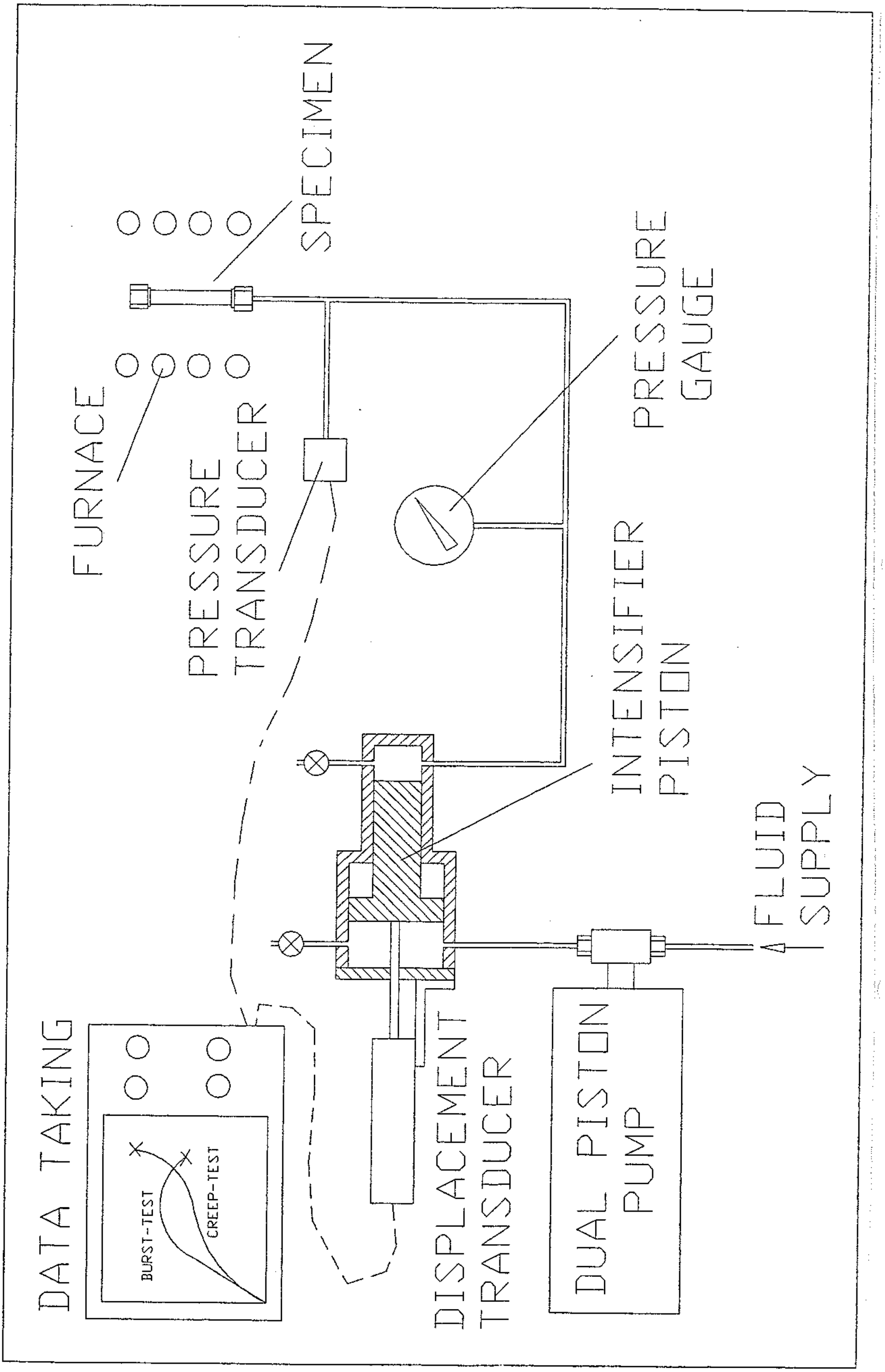


Fig. 1. a): Schematic diagram of creep- and burst-test device

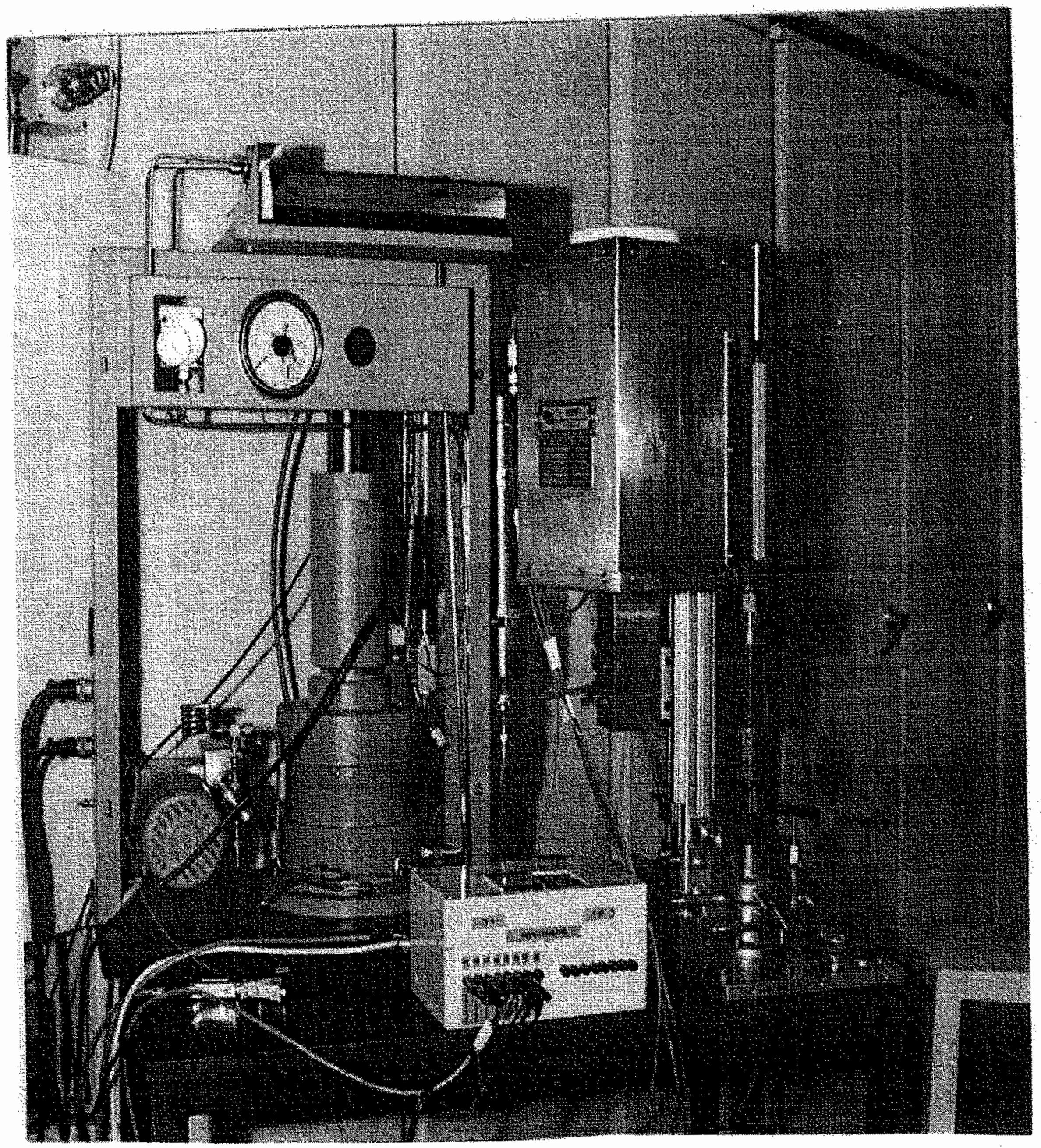


Fig. 1. b): General view of the equipment

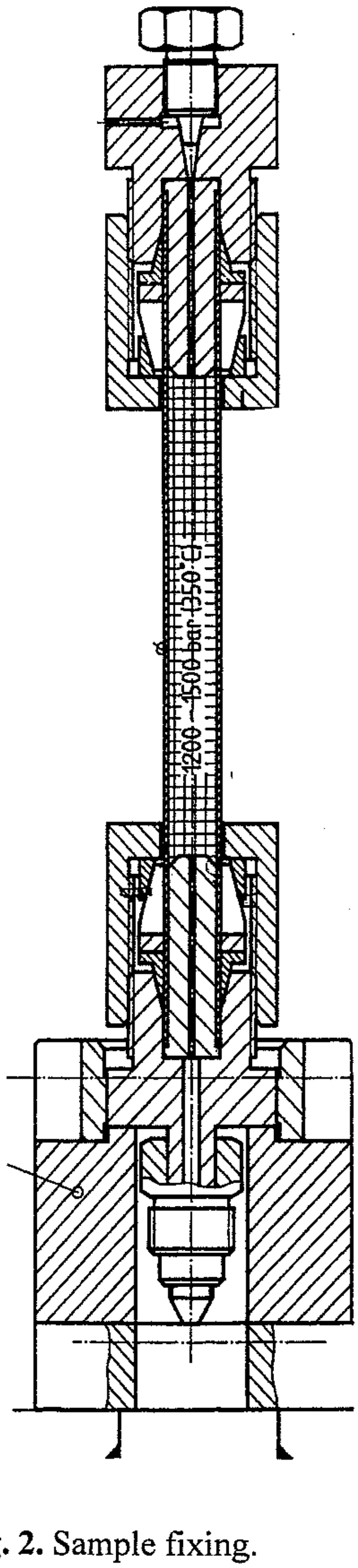


Fig. 2. Sample fixing.

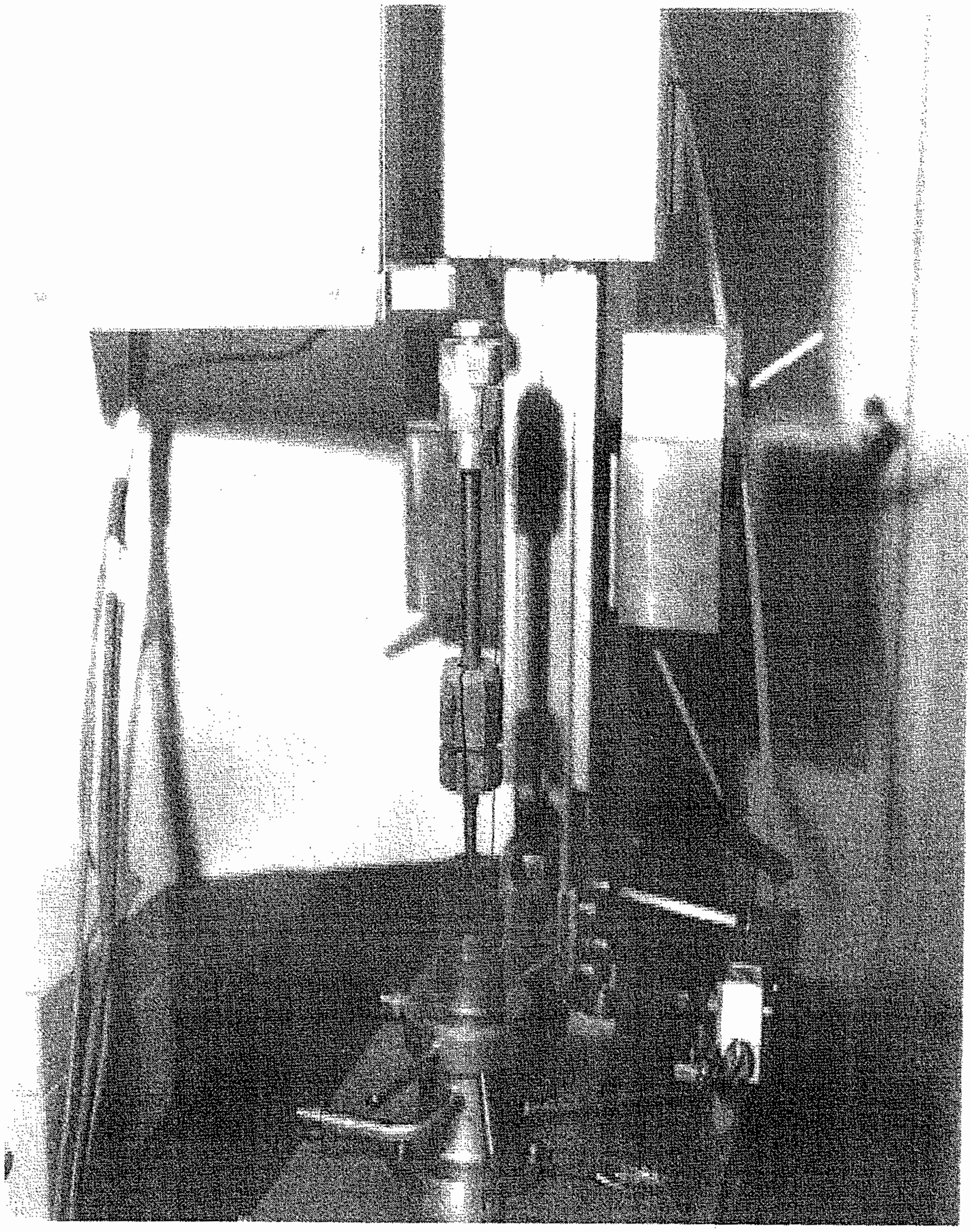


Fig. 3. Sample fixing.

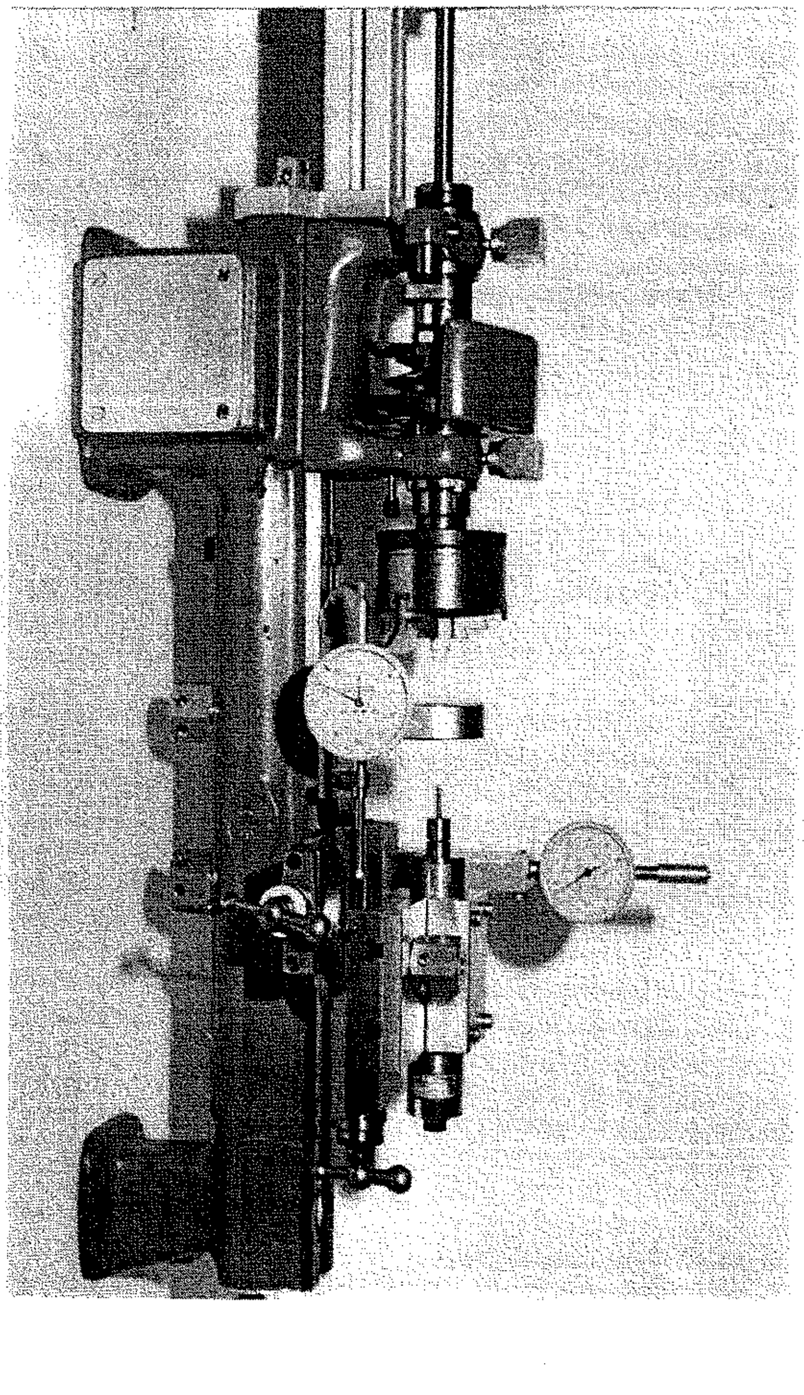


Fig. 4. Lathe.

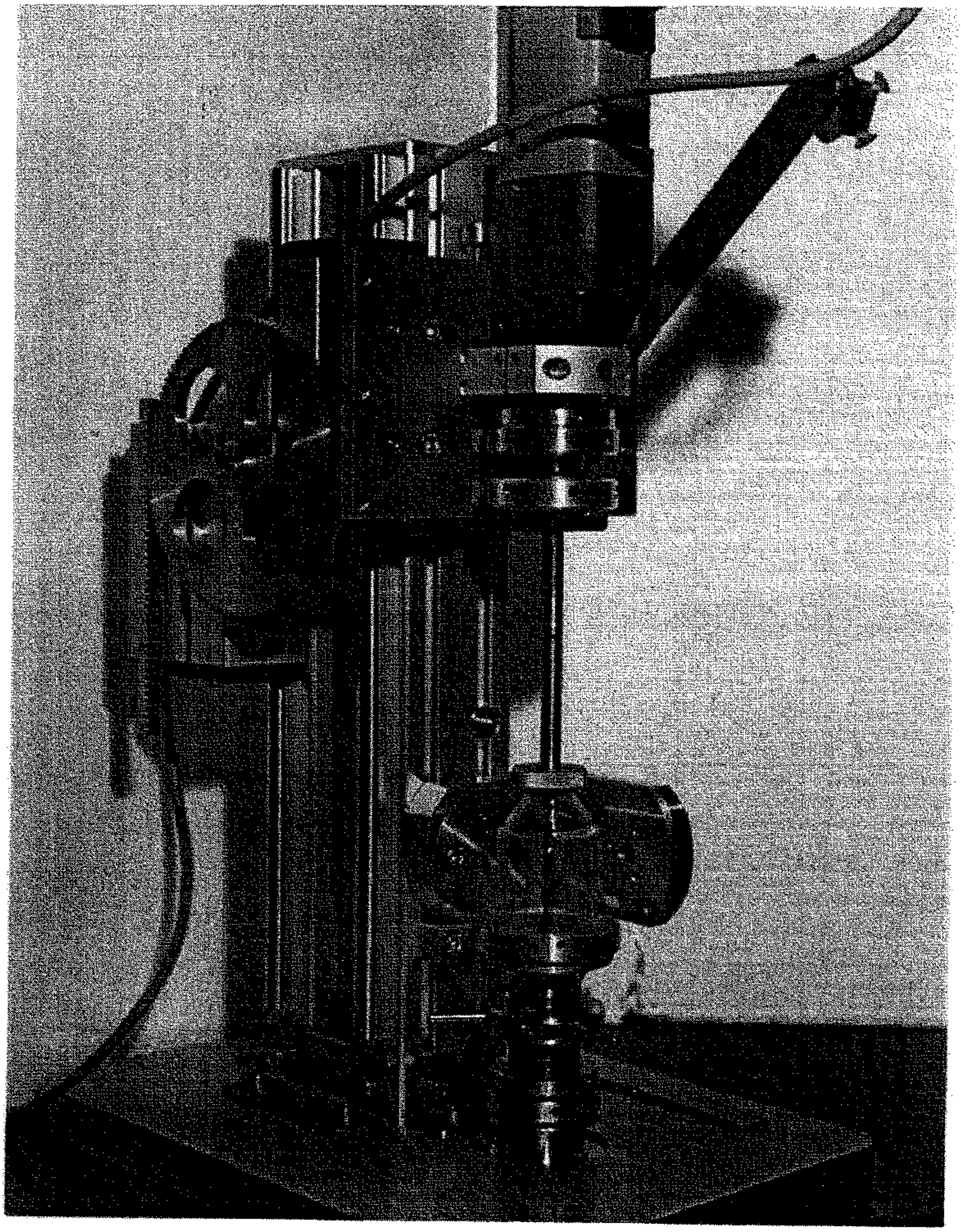
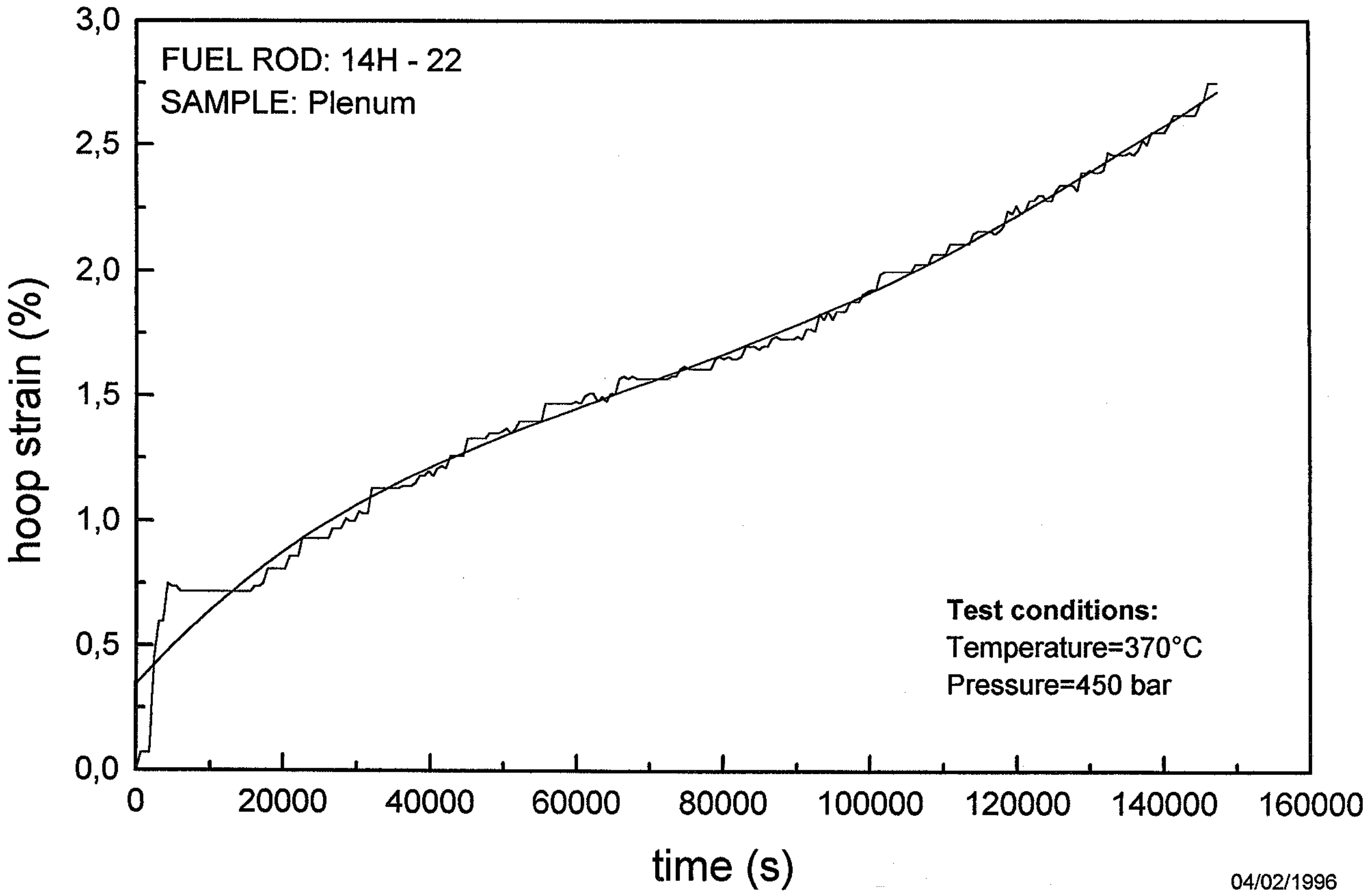
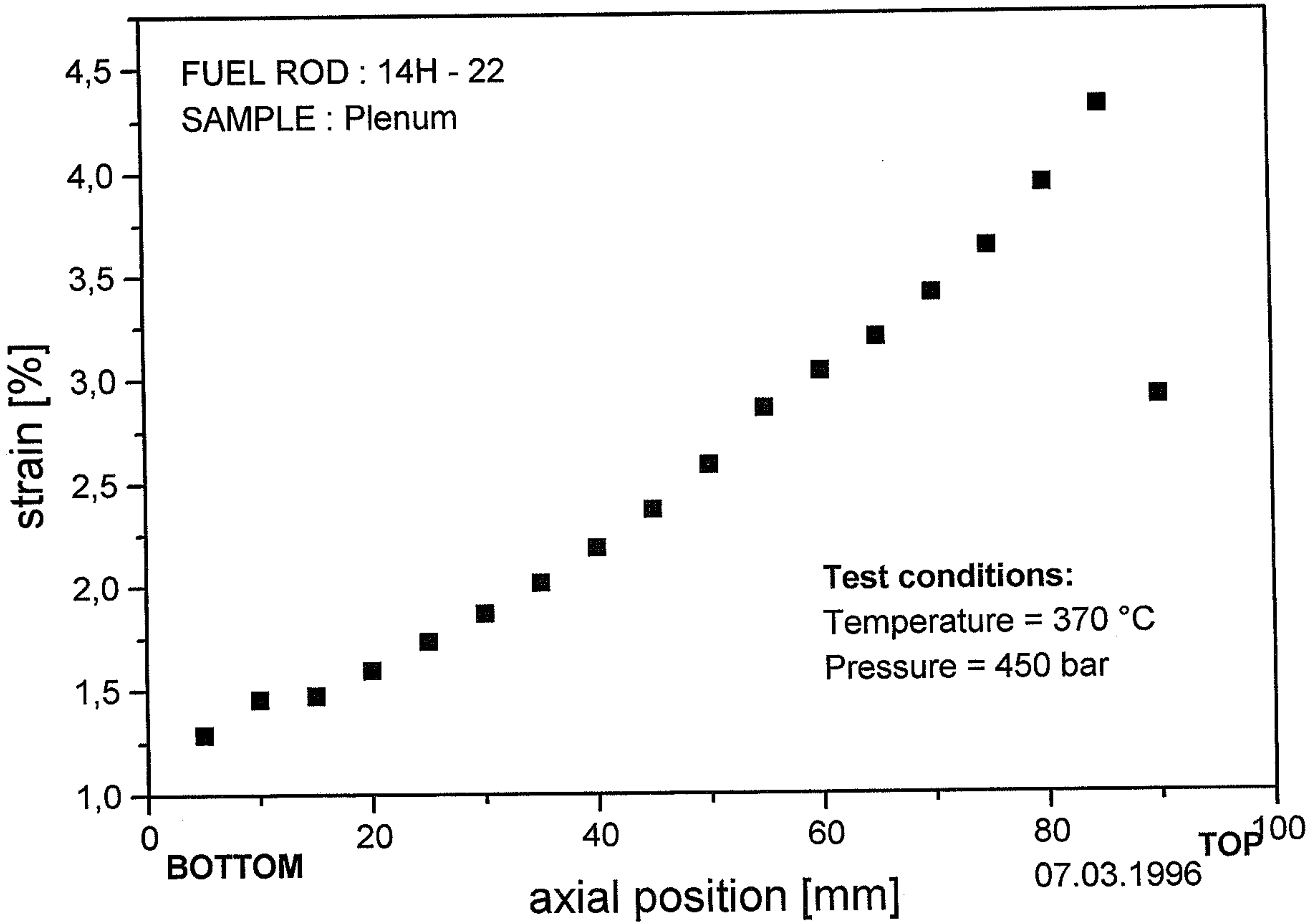


Fig. 5. Drilling machine.



FUEL ROD: 14H - 22
SAMPLE: Plenum
Test conditions:
Temperature=370°C
Pressure=450 bar
hoop strain (%)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0
20000
40000
60000
80000
100000
120000
140000
160000
time (s)
04/02/1996



FUEL ROD : 14H - 22
SAMPLE : Plenum
Test conditions:
Temperature = 370 °C
Pressure = 450 bar
strain [%]
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0
20
40
60
80
100
BOTTOM
TOP
07.03.1996
axial position [mm]