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Low-Cycle Testing of LWR Fuel Rod Cladding

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1 Introduction

The efficient utilisation of nuclear plant requires a load following capability together with automatic frequency control. These variations in power will result in fuel temperature changes and consequently introduce the cyclic stressing of the fuel rod cladding. In addition, there are varying thermohydraulics conditions within the core which can cause local pressure changes which influence cladding stresses. The fatigue properties of irradiated zircaloy cladding are therefore of interest with respect to assessment of fuel integrity and the achievement of maximum fuel irradiation.

Published information on the fatigue properties of irradiated zircaloy cladding is very limited. The low-cycle fatigue (LCF) properties of zircaloy-2 irradiated to fluences between 1.5 to 7.7E25 neutrons/m2 (E>1MeV) have been studied at reactor operational temperatures [1], although the test frequency of 0.5Hz represented a strain rate much higher than would be expected during service. Hourglass-shaped specimens were used made from 1.27mm thick sheet and were tested in fully reversed bending, R ratio = -1. The LCF life was found to be reduced by irradiation, although the effect was not large, the cycles to failure being reduced to about half that of the unirradiated material. Fatigue crack growth rate tests were also performed using compact tension specimens, but in this case irradiation was found to have no effect on crack propagation rate. The inference was that irradiation affects initiation but not propagation of fatigue cracks.

Repeated pressurisation fatigue tests have been performed on cladding specimens [2] irradiated to fluences of 4 to 10.7E25 neutrons/m2 (E>1MeV), although once again a high test frequency of 1Hz was used, which eliminated any creep contribution to the failure process. Most of the data presented were for stress-controlled tests and were in the form of stress/number of cycles to failure curves (ie high cycle fatigue tests). Irradiation was found to have a large effect on the stress for a given number of cycles to failure, especially in the region of the fatigue limit. Some data were also given for plastic strain range/number of cycles to failure, and here the reduction of endurance caused by irradiation was again about a factor of 2.

Since in power plant the cycling frequency for load following is typically about 1 cycle per day, fatigue tests at frequencies of about 1Hz do not represent actual service conditions, and at lower frequencies it may be expected that there will be a creep contribution to the deformation and failure process. There was consequently a requirement for LCF tests which were a closer simulation of the conditions experienced by the fuel cladding during operation. There was also a requirement to examine the influence of fission product species on the fatigue properties, since power ramp failures are usually attributed to stress corrosion caused by fission product iodine. Accordingly a LCF test programme has been undertaken in which test parameters more representative of service conditions are used and in which the effects of fission product iodine on failure can be assessed. In this paper some of the equipment developed for these tests is described.

needed
strain
displacement controlled / data
stress or load controlled

2 Fatigue Test Equipment

Repeated pressurisation was chosen as the loading system since this gives a reasonable simulation of the interaction between the fuel pellets and the cladding and maintains the plane-strain deformation condition. Normally such tests are done using oil pressurisation (as in ref. 2) but in the present case the requirement for the introduction of iodine vapour precludes this method and gas pressurisation must be used. The hoop stress developed in the cladding during power increases can be up to 500 MPa, and stresses of this level are known to be necessary for stress corrosion cracking to occur in unirradiated zircaloy [3]. Using the relation $\sigma = PD/2t$ where σ = hoop stress, P = pressure, D= tube diameter and t= wall thickness, a pressure of about 70 MPa will be needed to achieve the required hoop stress. This is well above commercial gas cylinder pressures which are around 17 MPa, and so a high pressure gas pump is needed.

Since the interaction between fuel pellets and cladding is essentially a strain-controlled process, it is essential to have a means of measuring the diametral strain for correlation with the cycles to failure. An optical method was adopted comprising a laser scanning micrometer with separate transmitter and receiver units which could be mounted either side of a split 3-zone furnace. The furnace was fitted with heat-resisting windows 40mm wide by 15mm high positioned at the centre point of the cladding specimen, to allow passage of the laser beam. This measuring system had a resolution of 0.1 micron, corresponding to a diametral strain of 1E-5.

A flow diagram for the test system is shown in Figure 1. Argon from a 15-bottle gas pack flows via a regulator valve to a high pressure gas pump which is driven by a compressed air supply. Argon at up to 70 MPa pressure is delivered to an accumulator, the pressure being controlled by adjusting the compressed air supply pressure with a regulator valve. The pressurisation rate is controlled by two capillary tubes of different bore diameters each fitted with a solenoid valve. By switching between the two capillaries using a Eurotherm controller the gas flow rate can be closely controlled, and thus the rate of pressure rise in the specimen. The gas pressure is measured by a transducer in the inlet pipe to the specimen and is fed back to the controller. In this way the pressure can be smoothly ramped up to 70 MPa. On the downward pressure part of the cycle the inlet valves are closed and the argon is exhausted to atmosphere by another twin capillary tube and solenoid valve arrangement which controls the rate of depressurisation. The pressure, diametral strain, temperature and elapsed time are recorded by a data logging computer. A general view of the test equipment prior to hot cell installation is shown in Figure 2.

3 The Specimen

The specimen is 150mm long and has stainless steel pressure fittings of special design which are swaged on, giving a high quality seal up to pressures of 140 MPa in hydraulic burst tests,

Figure 3. The specimen is inserted into a pressure head located in the upper part of the furnace and a small diameter metal O-ring seal is used to achieve gas-tightness. The iodine crystals, where used, are weighed on a microbalance and placed in a glass capsule, then glued to an

alumina "Sintox" pellet using a halogen-free adhesive [3]. The Sintox pellets are of approximately the same dimensions as fuel pellets and are used to fill the bore of the specimen. On the iodine capsule Sintox pellet the adhesive degrades at the test temperature and opens the capsule allowing the iodine vapour to escape. Temperature measurement is by means of a sheathed Type K thermocouple inserted through the bottom end fitting and brazed into position.

4 Burst Testing

Some fatigue tests are not taken to failure but are fatigued for a predetermined number of cycles, then burst tested to assess the presence of damage in the form of fatigue or creep-fatigue cracks. The burst testing is performed using hydraulic pressurisation with silicone oil, at operational temperatures of around 300C. The diametral strain is not measured. Pressurisation is obtained from a pneumatic-hydraulic intensifier with an output to input ratio of 10:1. The input stage to the intensifier is connected to a standard gas bottle supply through a flow control capillary pipe.

5 Experimental Procedure

The specimen was brought up to the working temperature before starting the pressure controller. The pressure cycle profile consisted of a linear ramp at 0.4 MPa/s from a minimum value of 5 MPa up to a maximum of 50 MPa. The maximum pressure was then maintained constant for a period of 1 minute before being reduced at a rate of 0.4 MPa/s back to the minimum value, where again the pressure was maintained for 1 minute, Figure 4. During a test the furnace is maintained at a constant temperature but the flow of cold argon into the specimen during the pressurisation cycle caused a temperature drop, leading to temperature cycling of approximately 40C. A data logging system recorded pressure, specimen diameter, and temperature at intervals of 5s.

Where burst tests were performed the specimen was pressurised to a nominal pre-test pressure of about 1.4 MPa before being heated to 300C. During the heating stage the specimen pressure increased due to thermal expansion and was reduced by manual control to around 3.4 MPa once the required temperature had been achieved. After a short stabilisation period of 2 minutes the testpiece was pressurised at a rate of 13.8 MPa/minute until failure occurred. Pressure measurements were recorded at 1 second intervals using a computer data logging system.

6 Illustrative Results

A typical low cycle fatigue record is shown schematically in Figure 5. It is apparent that the tension-tension cycling at the relatively low strain rates involved leads to a significant creep contribution to the deformation, as shown by the steadily increasing strain with time. However, in unirradiated cladding specimens the overall level of diametral strain accumulated before rupture was small, showing that fatigue crack initiation and propagation were the principal causes of failure. The failure site itself consisted of a longitudinal crack.

The record of a burst test on a pre-fatigued unirradiated specimen is shown schematically in Figure 6. The trace is initially fairly smooth but there is a region of small pressure fluctuations before failure occurs. This phenomenon is not present in the trace for a non-fatigued unirradiated specimen, Figure 7. Metallographic examination is required to establish the reasons for the differences in behaviour, which may be associated with microcracking.

7 Conclusions

LCF testing of LWR cladding has been demonstrated using a gas pressurisation technique which allows stresses and strain rates typical of service conditions to be obtained.

The results to date indicate that deformation consists of both creep and fatigue components. The small diametral strain prior to failure in unirradiated specimens indicates that fatigue is the dominant mechanism.

8 References

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2 Soniak A, Lansiart S, Royer J, Mardon J P and Waeckel N. Zirconium in the Nuclear Industry, 10th Int. Symp. ASTM STP 1245 pp.549-558.

3 Dakin J S. Proc. 1994 Int. Topical Meeting on LWR Reactor Fuel Performance, American Nuclear Soc. April 1994. pp.601-608.

9 Acknowledgement

Development of the fatigue rig described here was undertaken on behalf of the UK Nulear Industry Management Committtee (IMC) and their support is gratefully acknowledged.

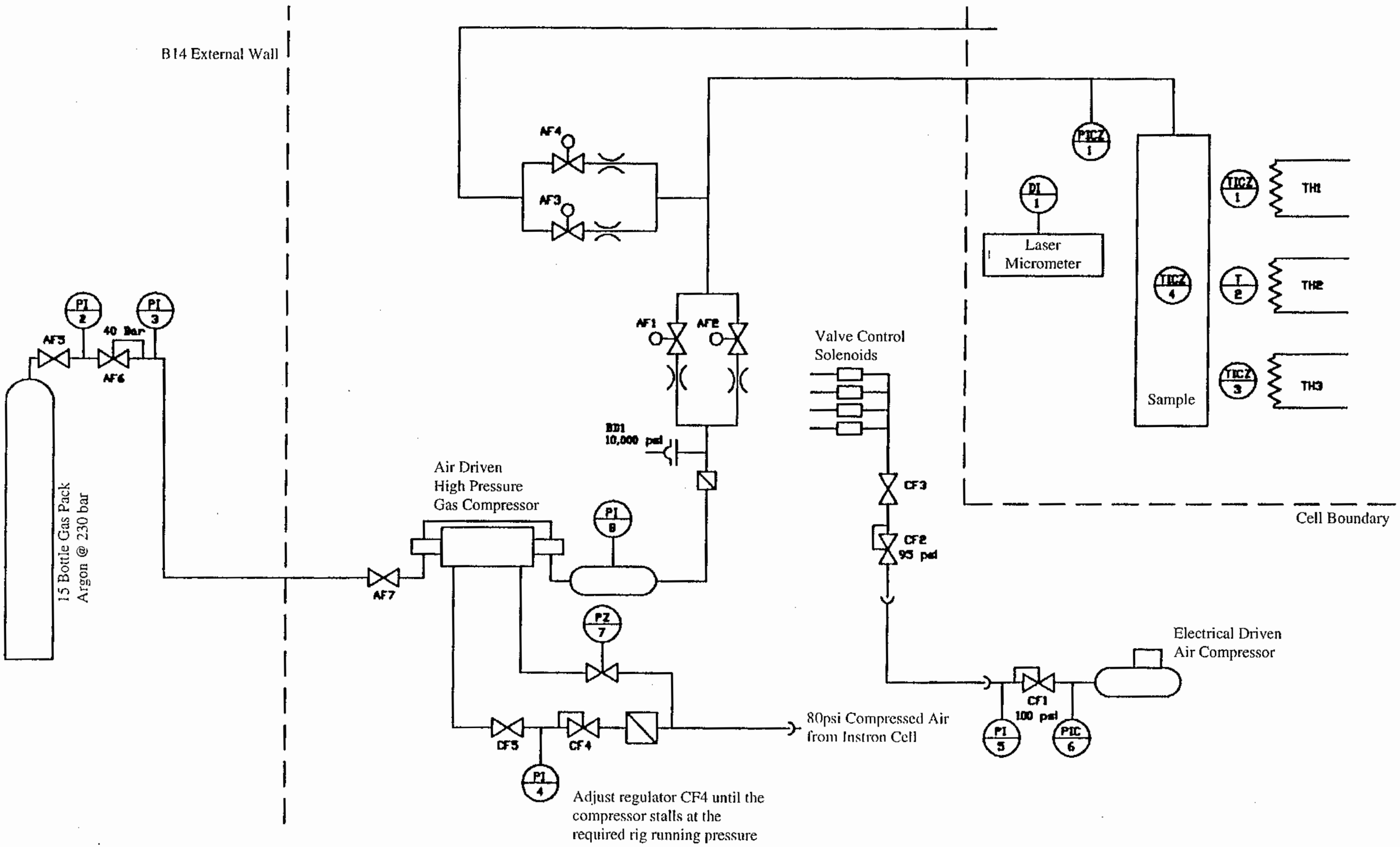

Figure 1: Flow diagram for LCF Rig.

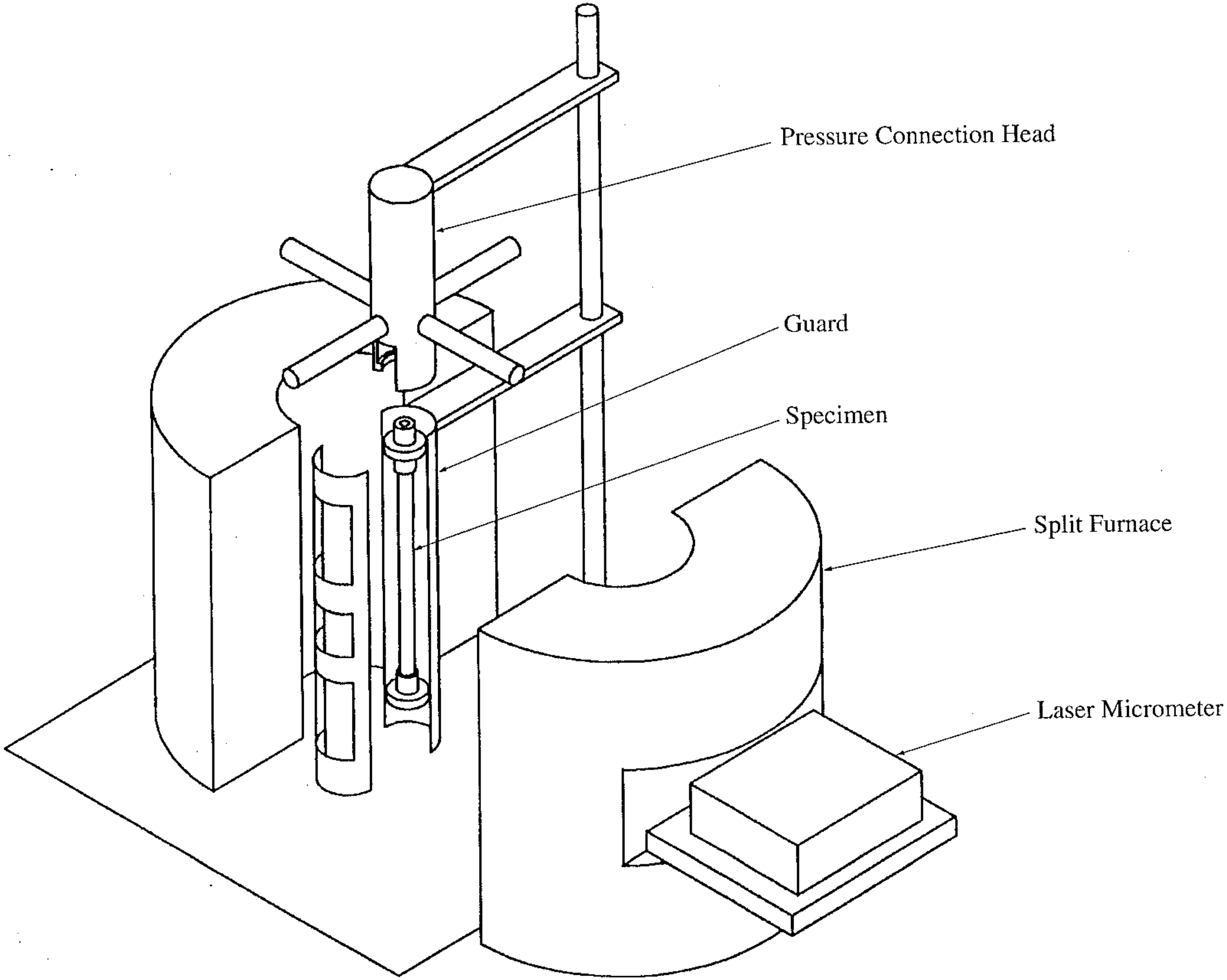

Figure 2: Test LCF Arrangement.

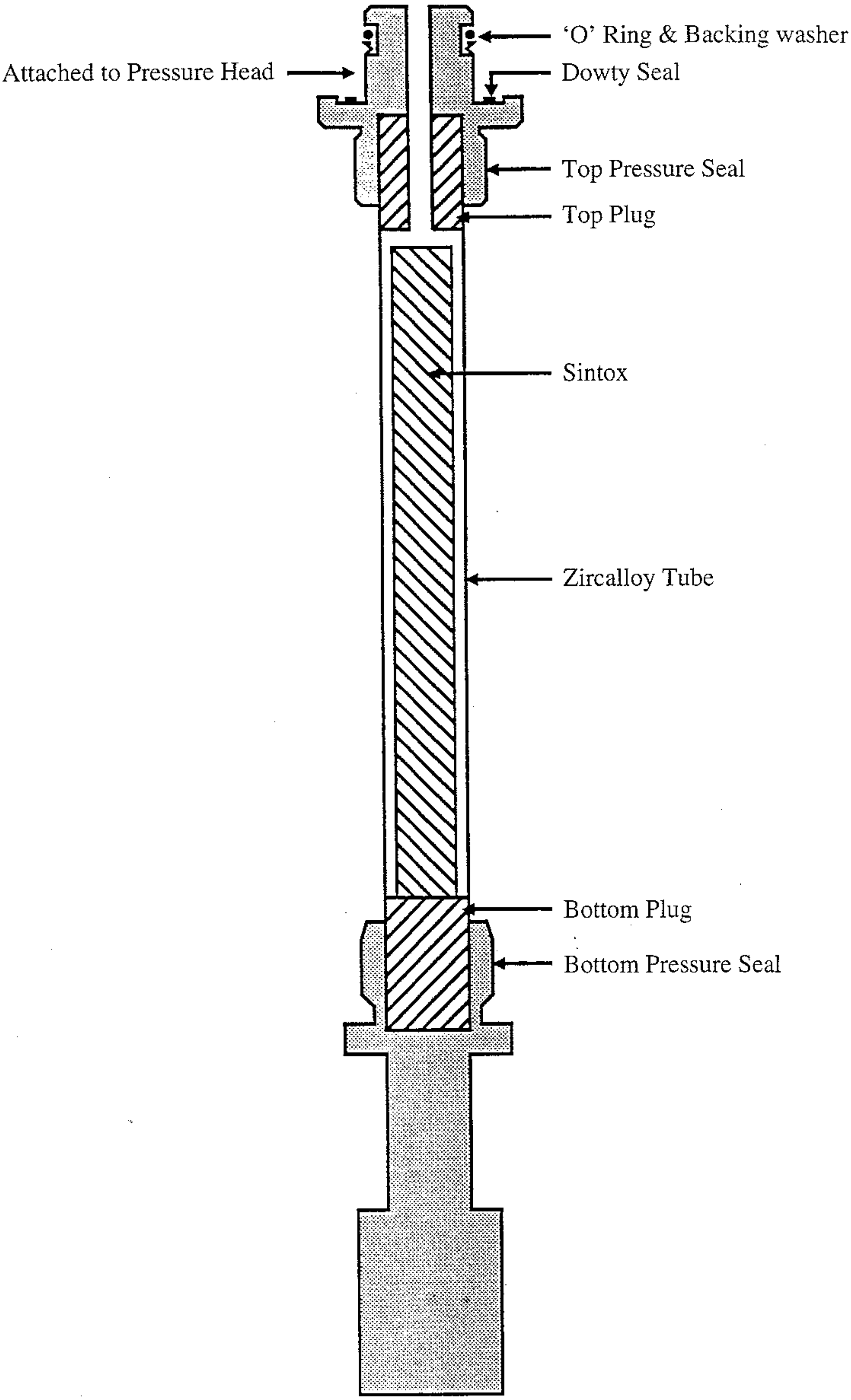

Figure 3: Specimen Design.

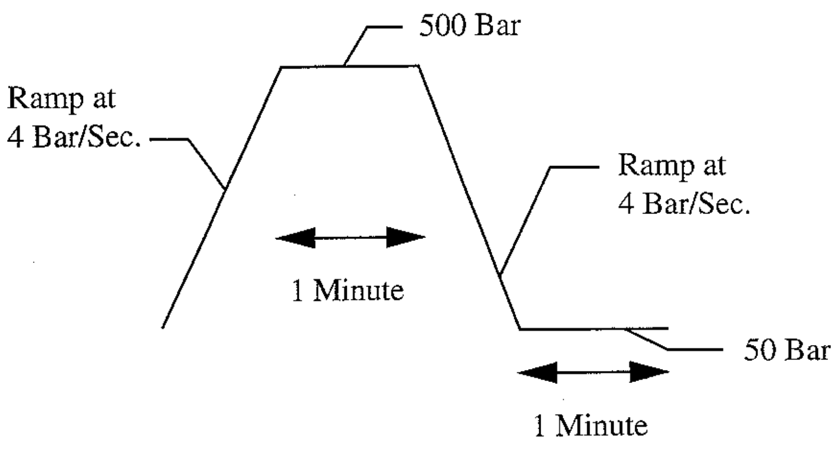

Figure 4: Pressurisation Cycle.

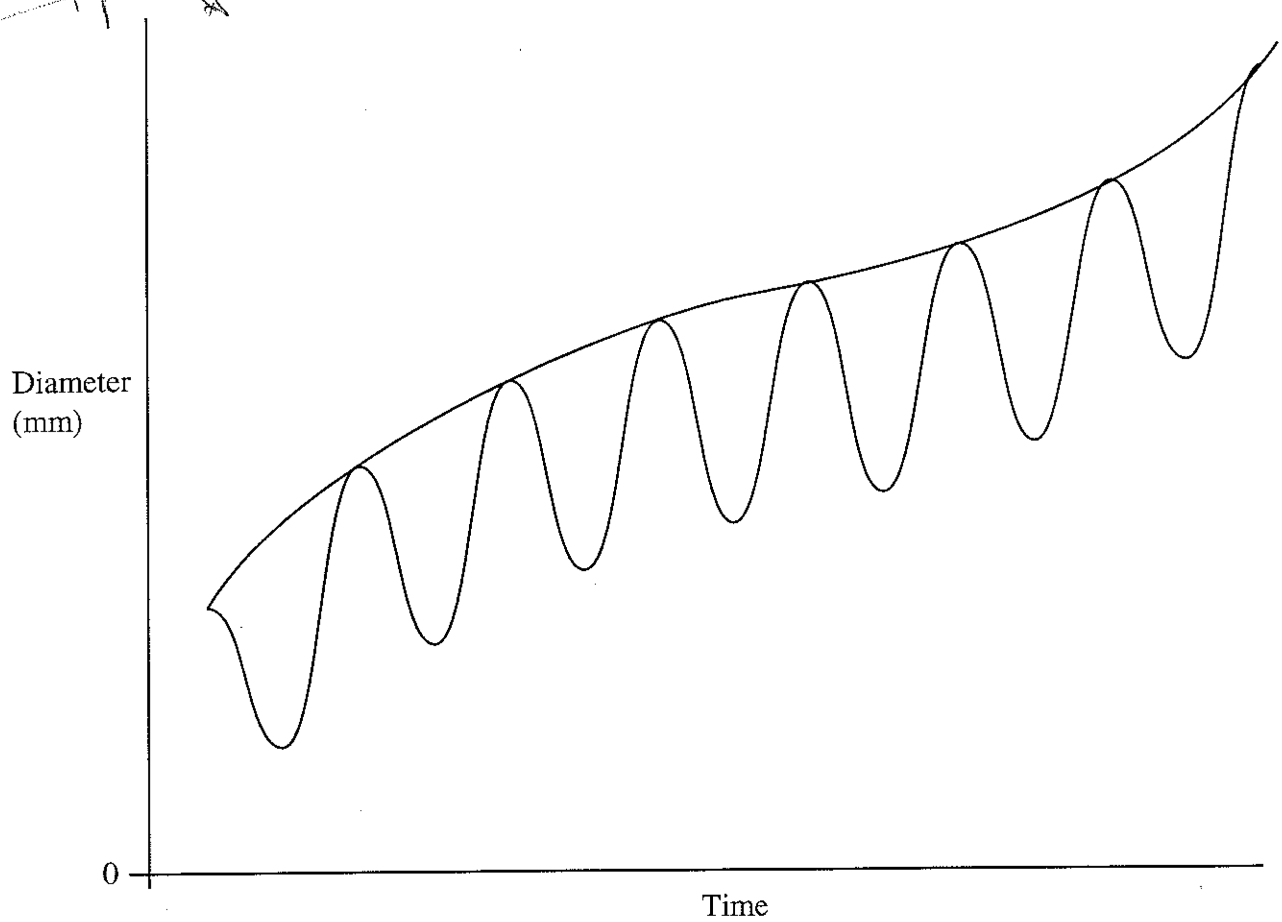

Figure 5: Schematic LCF Test Record.

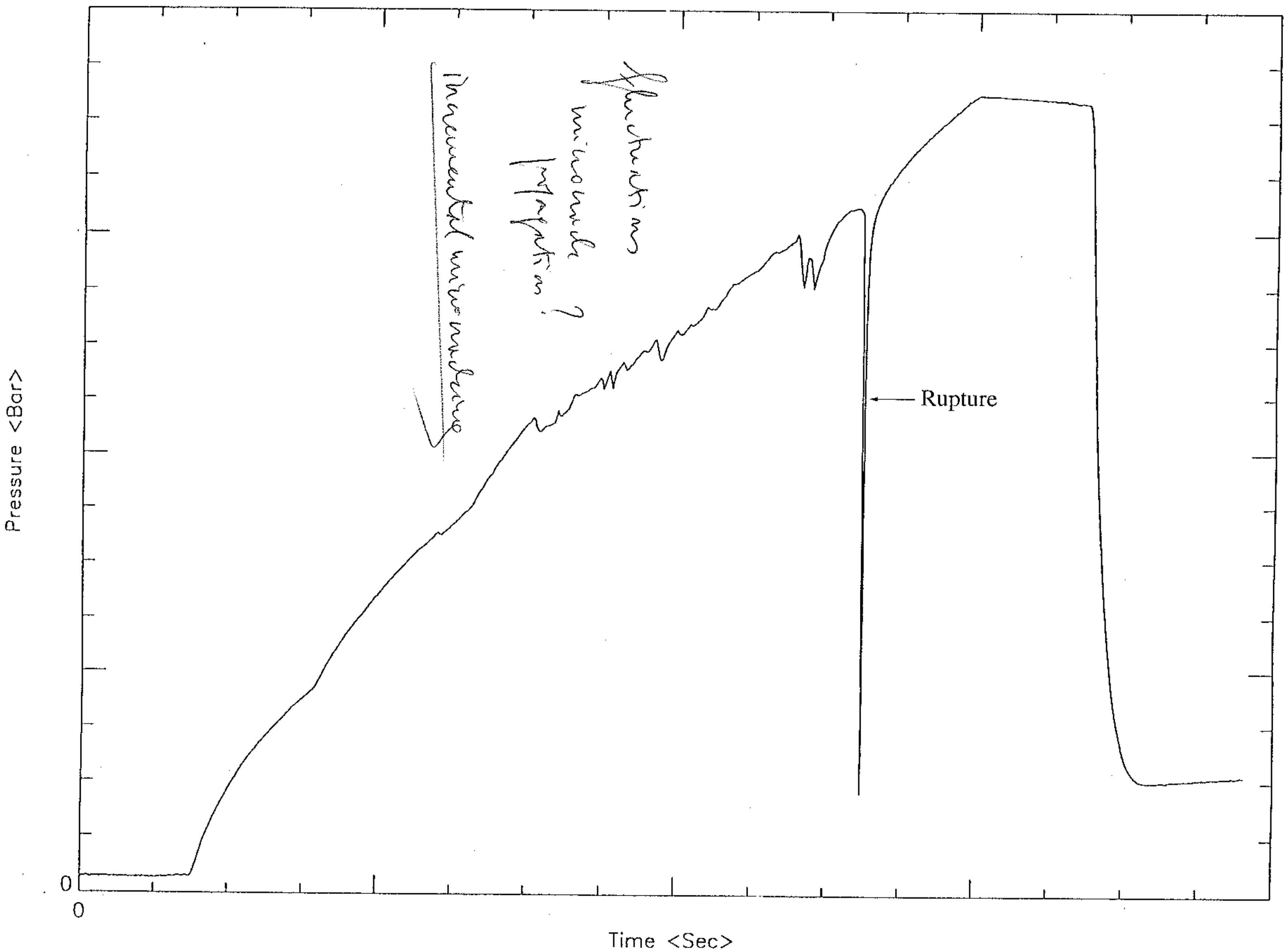

Figure 6: Burst test on fatigued specimen (unirradiated).

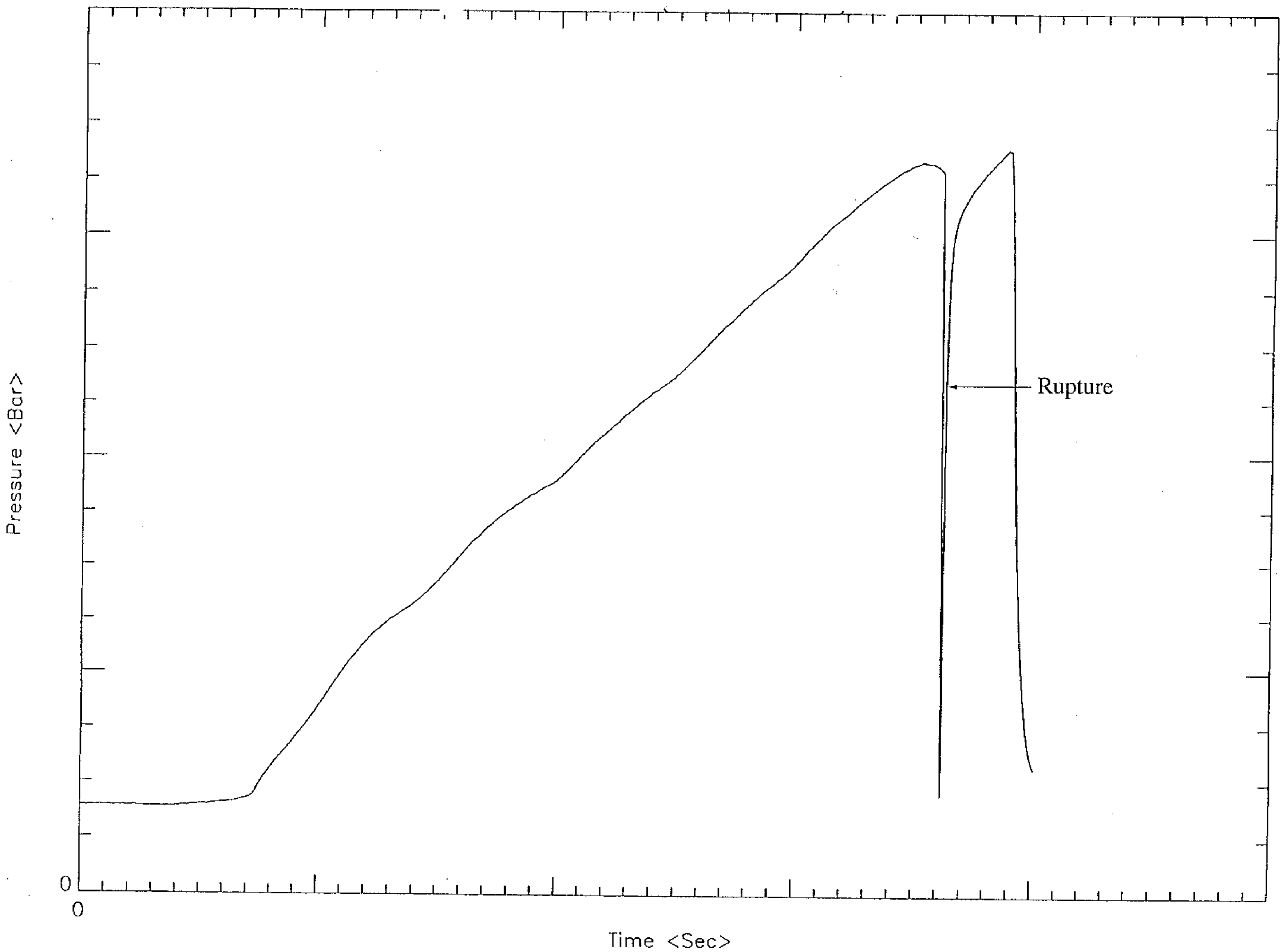

Figure 7: Burst test on non-fatigued specimen (unirradiated).