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IN-CELL FACILITY FOR PERFORMING MECHANICAL-PROPERTY TESTS ON IRRADIATED CLADDING

by

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FACILITY FOR TESTING IRRADIATED CLADDING

ABSTRACT

A new facility was developed in the AGHCF at ANL for testing cladding sections of LWR fuel rods. This facility and the accompanying test procedures have improved the level of in-cell mechanical-testing capabilities, making them comparable to existing capabilities for unirradiated cladding.

The new facility is currently being used to study the susceptibility of irradiated Zircaloy cladding from LWR fuel rods to iodine stress-corrosion cracking. Preliminary testing results indicate a systematic effect of temperature, stress and irradiation on the susceptibility of annealed and stress-relieved Zircaloy-2. Experimental data obtained to date are being used to develop a stress-corrosion cracking model for LWR fuel rod failure.

SEM examination of the undisturbed fracture surface of specimens that failed by pinhole leakage provides useful information on crack propagation and morphology.

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INTRODUCTION

Modeling Light-Water Reactor (LWR) fuel-rod cladding behavior during normal and off-normal operating conditions is an accepted means to identify reactor operating procedures which might adversely affect fuel-rod performance. Successful models can provide the understanding of cladding behavior that is needed to correct or alleviate fuel-rod problems which could restrict maximum reactor efficiency or operating maneuverability. A model based on mechanical-property data and post-test fractography information from irradiated cladding is expected to have greater relevance to in-reactor fuel-rod performance than a similar model based on unirradiated cladding properties. The former model will inherently account for the synergistic interactions between the material and environmental parameters and the irradiated state, whereas the model based on unirradiated cladding will not.

This report describes the recent development of a testing facility in the Alpha-Gamma Hot Cell Facility (AGHCF) at Argonne National Laboratory (ANL) which permits gas-pressurization tests to be conducted remotely on irradiated fueled and unfueled cladding. This test facility was developed within the past 12 to 14 months, and is currently being used to study

fission-product induced stress-corrosion cracking (SCC) in LWR fuel-rod cladding caused by fuel pellet-cladding interaction (PCI). These tests use iodine (I_2) as the corrosive fission product. Fuel-rod failures believed caused by I_2 SCC have been experienced in Boiling-Water Reactors (BWR) and Pressurized-Water Reactors (PWR) during power-ramp conditions, indicating that this type of cladding failure may be generic to both types of LWR's.

The philosophy underlying the development of in-cell equipment and test procedures was to recognize and deal with the many equipment and specimen-related problems normally encountered in a remote-testing operation. These include the physical limitations of mechanical manipulator operations with regard to manual dexterity and maximum force capability, the large ovality and considerable surface oxidation of irradiated cladding, the difficult problem of achieving a pressure-tight seal for biaxial tests, and the usual problems of close pressure and temperature control. For biaxial tests the specimen seals must withstand argon or helium pressures up to 137.9 MPa.

The design of all in-cell equipment permits movement and operation within the 9.1-kg force capability of standard master-slave manipulators. A 25:1 mechanical advantage is provided by a lead-screw operated fixture which is used to insert the end plugs into the specimen under a compressive load. Likewise, a 12:1 mechanical advantage is provided by a gear-driven mechanical wrench which is used to tighten the mechanical specimen seal. A mobile, low-rpm, high-torque motorized drive can be used to operate both pieces of equipment to save time and minimize mechanical wear on the manipulators. Both pieces of equipment can also be operated by normal manipulator movements with a ratchet drive. Torque, force, pressure and displacement are measured as an emf in the 0- to 100-mV range, permitting the standardization

of specimen preparation and testing procedures. The result is cost-effective generation of mechanical-property data for irradiated materials. Both the mechanical wrench and the end-plug inserting fixture are used in post-test operations to undo the pressure seal and remove the seal body from the failed specimen for reuse on subsequent specimens. The cost benefit of this procedure is threefold: a significant saving in time and in number of seals required per specimen tests, and a reduction in the volume of radioactive debris that must be removed from the AGHCF for burial at a later date.

MARK-I TEST APPARATUS

CONTROL FEATURES

Figure 1 shows the control sonsole for the Mark-I biaxial test apparatus that is used to test irradiated cladding in the AGHCF at ANL.

The Mark-I test apparatus is similar in design to the Mark-II biaxial creep apparatus used in testing unirradiated stainless steel cladding for the Liquid-Metal-Cooled Fast Breeder Reactor (LMFBR) and the Gas-Cooled Fast Reactor (GCFR).[1,2]

Specimen-temperature control within ± 1 C is achieved with three proportioning controllers and accompanying SCR power supplies which operate a three-zone furnace. The control thermocouples in the end zones of the furnace are connected in an electrically opposing manner to establish a master-slave relationship with the main center zone.

Specimen-pressure control and automatic test termination are achieved with three potentiometric control (PC) boards which compare a set reference millivoltage with a mV signal from a pressure transducer (PT). Two PC boards are used to control the "on" and "off" functions of the low-volume, high-pressure compressor to maintain specimen pressure within ± 172 Pa at pressures up to 138 MPa. The PC board which performs the automatic test-termination function is normally set to actuate at a pressure of 206 Pa below the compressor "on" set point.

The regulated DC voltage input to displacement, pressure and torque sensors is provided by the two DC power supplies shown at the top of the relay rack in Fig. 1.

A 2-channel, calibration-quality DC voltage source is provided to check the accuracy and linearity of all electronic sensors and recorders on a routine basis. This DC voltage source has been certified as a secondary voltage standard by the ANL Electronics Division. When the proper channel and function keys are actuated, the same instrument can also serve as a digital temperature indicator or an mV-measuring device.

HIGH-PRESSURE SYSTEM

The high-pressure system of the Mark-I test apparatus is shown schematically in Fig. 2. The two-stage, air-driven diaphragm compressor receives argon or helium gas at inlet pressures up to 6.9 MPa. Although this compressor is a high-pressure, low-volume device, the volume rate can be changed somewhat by changing the inlet pressure. The maximum pressure capability of the Mark-I is 206.8 MPa.

In-cell tests can be conducted under either low or high gas-volume conditions by manipulating valves HV-6, HV-7 and SV-1. In all biaxial tests, the total system volume (V_T) is the sum of the equipment volume (V_e) and the specimen volume (V_s), and V_s is intentionally made very much less than V_e by displacing approximately 96% of the specimen volume with a close-fitting Vycor slug. In tests conducted under high-volume conditions when V_T = 1085 cc, valve SV-1 closes automatically with the termination of the test to conserve the high-pressure gas contained in the one-liter vessel.

To avoid actuating cell-pressure alarms, the flow-limiting orifice (FLO) restricts the flow of high-pressure gas into the AGHCF upon specimen failure by rupture. This is especially important when the system is operating under high-volume conditions.

SPECIMEN SEAL

The importance of a pressure-tight specimen seal in biaxial tests is illustrated in Fig. 3. The curves are based on a 325°-C test temperature and a 58.6-MPa initial pressure. The leak rate of a nonsealing area in either a mechanical seal or a welded seal can be expressed as an "equivalent orifice diameter" (EOD). The EOD is the diameter of a through-the-wall hole that will exhibit the same leak rate as the nonsealing area under comparable conditions of temperature, pressure and total volume.

The information in Fig. 3 supports the following conclusions:

1. A useful specimen seal must have an EOD $< 5 \times 10^{-4}$ cm.
2. The use of argon instead of helium as the pressurizing gas provides greatest benefit when the nonsealing condition compares to an EOD $\leq 5 \times 10^{-4}$ cm.

The above considerations were the basis for choosing the mechanical seal in preference to a welded seal for biaxial test specimens. Other considerations included the capital cost of automatic welding equipment and electrode-positioning fixtures, space limitations outside and inside the AGHCF, the need to protect the specimen from the nitrogen cell environment during welding, the long setup time involved in remote welding procedures, and the difficulty of obtaining repeatable pressure-tight welds on irradiated cladding containing implanted helium.

TEST CAPABILITIES

The mechanical test capabilities of the new facility are illustrated in Fig. 4. These capabilities are described primarily in terms of the I_2 SCC tests on irradiated Zircaloy cladding currently being conducted at ANL.

The threshold-stress test and the high-stress test in Fig. 4a are used to determine the "S"-shaped I_2 SCC curve. The cumulative-damage test is used to establish whether the cladding damage leading eventually to I_2 SCC failure is accumulated in a linear or nonlinear manner during the upward and downward pressure (stress) ramps sustained by the cladding.

The pressure-ramp test illustrated in Fig. 4b is essentially a biaxial version of the uniaxial tensile test. The specimen diameter is initially determined at ambient cell temperature with a motor-driven diameter-measuring device, and is subsequently measured after ramps at successively higher pressures. The experimental data are used to construct a biaxial stress-strain curve which reflects the cladding response to the biaxial loading mode and to the material texture developed during the tube-fabricating process.

The biaxial creep test shown in Fig. 4c provides strain-time information for irradiated cladding under constant load (pressure) conditions. Strain-hardening information can be obtained for irradiated cladding by comparing the initial portion of two biaxial creep curves conducted at a constant temperature and different pressures. Because the biaxial creep test is difficult and time-consuming, strain-hardening information is usually obtained from a uniaxial tensile test.

The uniaxial tensile test shown in Fig. 4c is not conducted in the new facility, but on an in-cell Instron machine. However, the stringent requirements for gripping irradiated tubular cladding have been satisfied by the sealing techniques developed for the biaxial tests.

PROCEDURES FOR TESTING IRRADIATED CLADDING

Figure 5 is a flow diagram showing the steps involved in the testing of irradiated cladding in the AGHCF.

PRETEST FUEL-ROD INSPECTION

A fission-gas analysis is performed on most fuel rods entering the AGHCF to obtain information pertinent to the ongoing interest in fuel-rod performance.

An eddy-current inspection will be performed on a fuel rod when requested by the interested party. If a failed fuel rod is to be sectioned to provide specimens for biaxial testing, an eddy current inspection will be performed to locate the cladding breach. Regions of cladding showing eddy-current indications of defects are avoided when the fuel rod is sectioned into specimen lengths for subsequent mechanical testing.

A profilometry inspection of the fuel-rod OD is always performed when the cladding is to be used for biaxial tests.[3] The information provided is necessary to determine the dimensional requirements of the mechanical seal components, the maximum cladding ovality, and the average pretest diameter (which is used to calculate the dimaetral strain after failure). The profilometer inspection also provides information about the surface oxide on irradiated cladding. A smooth trace indicates a uniform surface-oxide layer which will not affect the integrity of the mechanical seal. A jagged trace indicates a nodular oxide of variable thickness which could affect the integrity of the mechanical seal.

SPECIMEN PREPARATION

The specimen ends are deburred in a rotating chuck after the fuel has been removed from the 152.4-mm-long specimens. The OD surface at the specimen ends is given a thorough cleaning with emery paper over a distance of 2.54 cm to remove the rough oxide that could compromise the pressure integrity of the mechanical seal. Measurements of the specimen ID are made with an inside micrometer, "Intermik", after the cladding is cleaned with a nylon tube brush. End-plug dimensions are determined from the ID measurements.

SPECIMEN SEALING

The mechanical seal is made from a "Swagelok" fitting that has been modified to improve its sealing properties on a rough and oxidized surface. The nature and extent of the modification depends upon the properties of the cladding to be sealed and the surface condition.

The bottom seal is made first, by inserting and seating the bottom end plug with a compressive load in a fixture developed for this purpose. The bottom end of the specimen is then placed in a properly modified Swagelok fitting and tightened in a mechanical wrench. The specimen is then oriented vertically and the bottom half of a Vycor volume-displacement slug is inserted, followed by a sealed ampule containing 25 mg of iodine. The ampule is broken with a metal rod and the top half of the Vycor slug is inserted, followed by the top end plug. After the end plug has been seated as described above, the top mechanical seal is placed over the specimen and tightened in the mechanical wrench. The torque force applied to the mechanical seal is recorded on a strip-chart recorder and simultaneously viewed on a DVM as a mV output from a reactive torque sensor. Pressure-tight seals are obtained at torque values between 45 and 50 mV (150 and 165 ft.-lbs.).

If the cladding ovality is less than 0.075 mm, the specimen can be sealed without special treatment of the ends. However, if the ovality is greater than this amount, the specimen ends must be annealed and rounded before a pressure-tight seal can be made. In the annealing procedure, approximately 2.54 cm of the specimen end is inserted into a massive nickel heat sink at 565°C and held for 1200 s (about 20 min.), while the remainder of the specimen is protected in a massive copper chill block. The annealed specimen ends can then be rounded within $\pm$ 0.015 mm in a modified "Jacob" chuck. From this point on, the sealing of the specimen proceeds in the normal manner.

PRETEST LEAK RATE DETERMINATION AND SPECIMEN PURGE

An 1800-s leak-rate test is performed on the sealed specimen at ambient cell temperature and 13.8 MPa pressure to check the tightness of the seals. The leak rates obtained are usually below an EOD of 5×10^{-4} cm, which is well below the volume capacity of the 2-stage diaphragm compressor. The leak rate obtained includes leaks in in-cell line connections.

The specimen is purged 4 or 5 times with the pressurizing gas to remove the cell nitrogen before the I_2 SCC test is begun. Specimen purging is accomplished between 3.4 and 8.3 MPa pressure to reduce the I_2 vapor pressure and minimize iodine loss during the procedure.

IODINE SCC TEST

The I_2 SCC test is conducted in a flanged chamber which has been purged of residual iodine from previous tests. Flowing helium is used as a cover gas during the test.

The specimen with 10-MPa pressure and the chamber are brought to the test temperature in 7200 s and allowed to equilibrate for 1800 s. The specimen pressure is then increased to the desired level to start the test.

When an I_2 SCC failure occurs, producing a leak rate comparable to an EOD of 10.2×10^{-4} cm or greater, the test is automatically terminated by the appropriate PC board. At this point the specimen leak rate exceeds the volume capacity of the compressor.

POST-TEST SPECIMEN EXAMINATION

FAILURE LOCATION

Very small I_2 SCC pinhole failures with leak rates less than an EOD of 2×10^{-4} cm will retain a 6.9-MPa specimen pressure at ambient cell temperature. A pinhole failure of this size is impossible to locate by visual inspection because of the rough surface topography of an irradiated specimen. However, the pinnole site is easily located by applying kerosene to the specimen surface in a dropwise manner while the specimen pressure is increased to 17.2 MPa or above. The pinhole is clearly indicated by an atomized kerosene stream as shown in Fig. 6 for specimen 190D2-5. This specimen is irradiated stress-relieved Zircaloy-2 tested at 325°C and a stress of 183.9 MPa.

Post-test specimen diameter and ovality are measured by a motorized LVDT diameter-measuring device which has an 0.01% resolution and an 0.1% accuracy, and is calibrated with a diameter standard. The post-test diametral strain of specimen 190D2-5 was 0%.

EXAMINATION BY OPTICAL MICROSCOPY

Figure 7 is a metallographic section of specimen 190D2-5 showing the I_2 SCC failure which resulted in the pinhole leak seen in Fig. 6. It is apparent that the crack was initiated at the ID surface and began branching about midway through the specimen wall. Figure 8 shows a second crack in the same

specimen located 90° from the principal failure shown in Fig. 7. This crack was also initiated at the ID surface and only partially propagated through the well of the cladding.

EXAMINATION BY SCANNING ELECTRON MICROSCOPY

Figure 9 shows SEM macrographs of the I_2 SCC failure in specimen 190D1-2. The crack is shown from the ID surface before and after ultrasonic cleaning in Figs. 9a and 9b, respectively. Figure 9c is an SEM macrograph of the fracture surface, showing crack initiation at the ID surface; this was due to chemical attack by iodine.

Figure 10 is an SEM fractograph of the area of specimen 190D1-2 delineated by the vertical lines in Fig. 9c. It shows the change in the morphology of the fracture surface as the crack propagated from the ID to the OD surface.

COMMENTS

The in-cell facility described in this report has been shown to be suited to the performance of sophisticated mechanical-property tests on irradiated cladding. Data obtained to date indicate a systematic effect of temperature, stress and irradiation on the I_2 SCC failure susceptibility of irradiated Zircaloy.[4] The small scatter in the experimental data proves the reliability of the test facility and the test procedures. The test data are being used to develop an SCC model for pellet-cladding interaction failures in LWR fuel rods.[5]

ACKNOWLEDGEMENTS

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Fig. 1. Control console of the Mark-I biaxial testing apparatus for performing mechanical-property tests in the AGHCF at ANL.

Fig. 2. High-pressure system of the Mark-I biaxial testing apparatus.

Fig. 3. Loss of specimen pressure as a function of time, caused by a leak in a seal.

Fig. 4. Mechanical test capabilities of the AGHCF at ANL.

(a) Threshold-stress, high-stress and cumulative damage tests.
(b) Pressure-ramp test.
(c) Biaxial creep test.
(d) Uniaxial tensile test.

Fig. 5. Flow diagram of procedures for performing mechanical-property tests on irradiated cladding.

Fig. 6. Pinhole failure in specimen 190D2-5 of irradiated Zircaloy-2, tested at 325°C and a stress of 183.9 MPa.

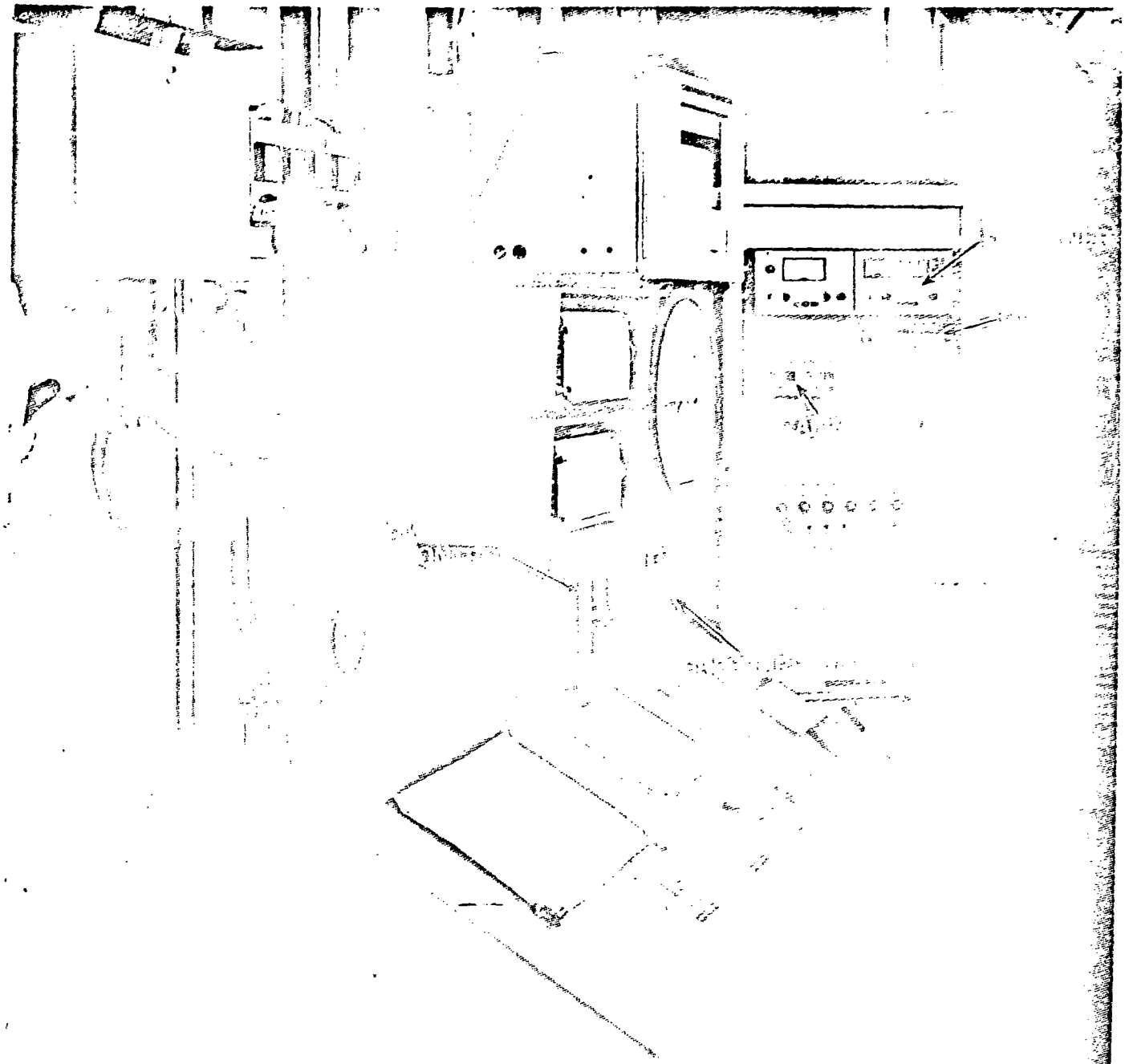
Fig. 7. Metallographic section of specimen 190D2-5 showing a through-the-wall SCC failure.

Fig. 8. Metallographic section of specimen 190D2-5 showing a secondary SCC crack located 90° from the principal crack in Fig. 7.

Fig. 9. SEM macrographs of the SCC failure in specimen 190D1-2.

(a) View from the ID surface before ultrasonic cleaning.
(b) View from the ID surface after ultrasonic cleaning.
(c) View of fracture surface between the ID and OD.

Fig. 10. SEM fractograph of the area of specimen 190D1-2 delineated by the vertical lines in Fig. 9c.



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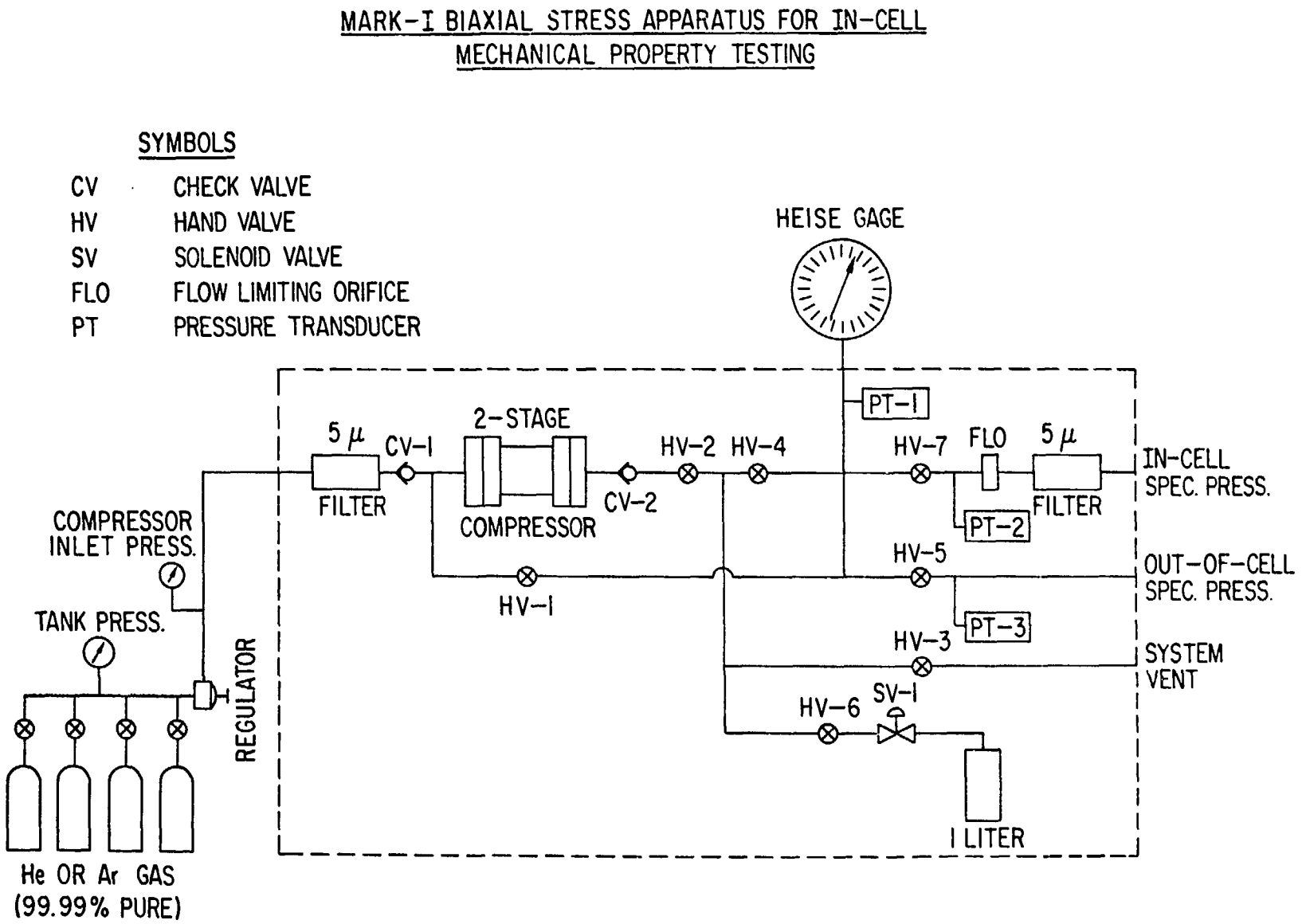


Fig. 2. High-pressure system of the Mark-I biaxial testing apparatus.

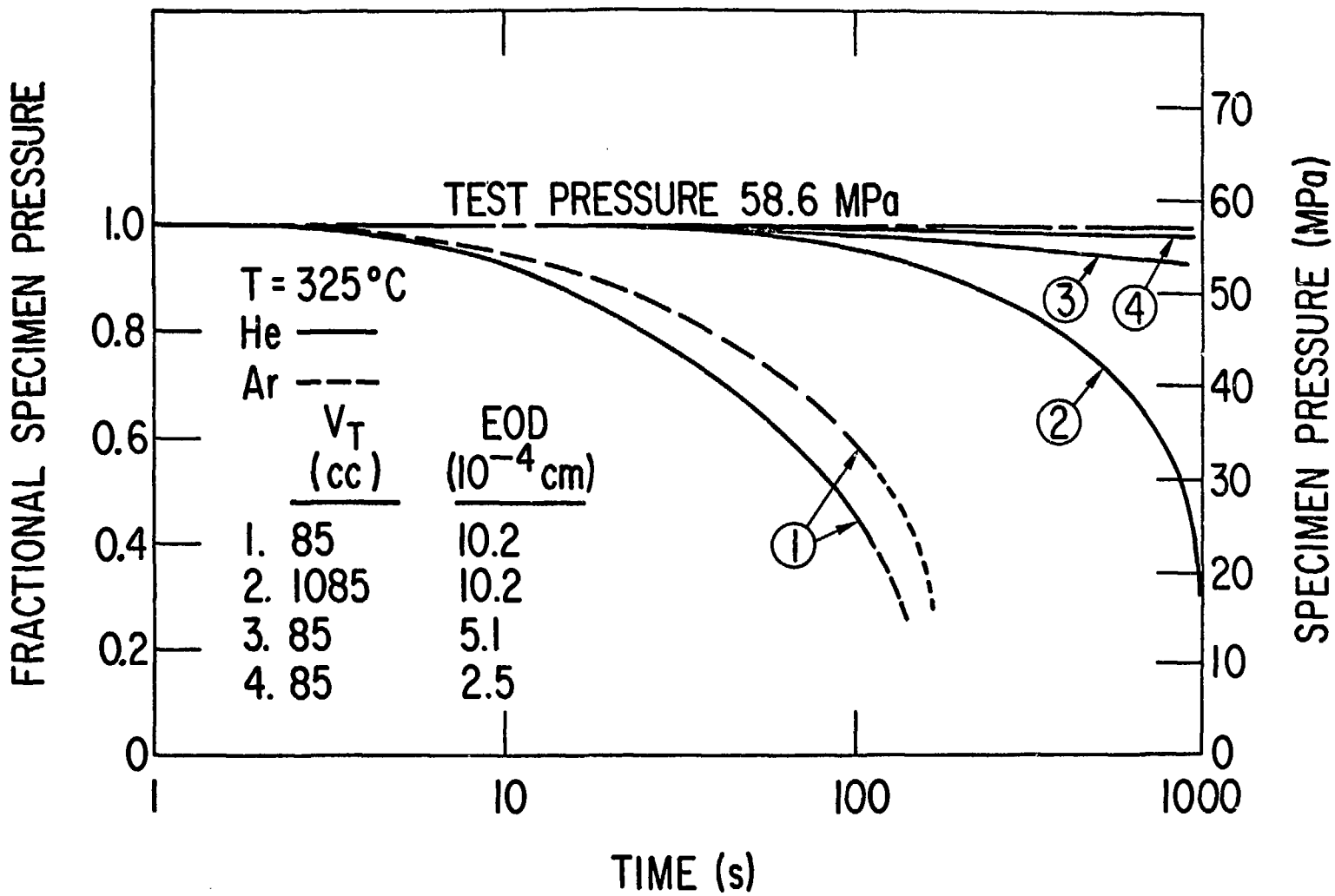
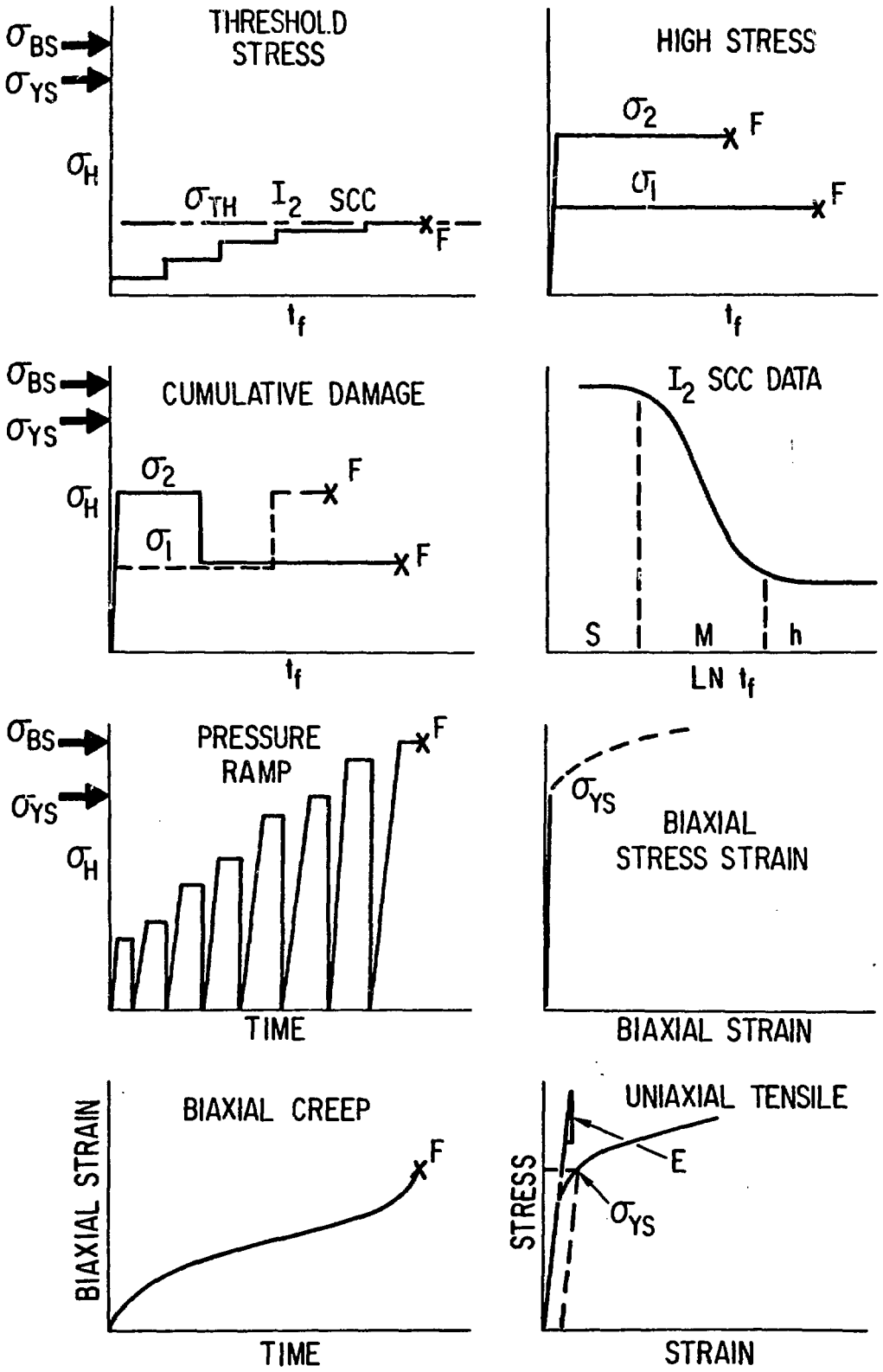


Fig. 3. Loss of specimen pressure as a function of time, caused by a leak in a seal.



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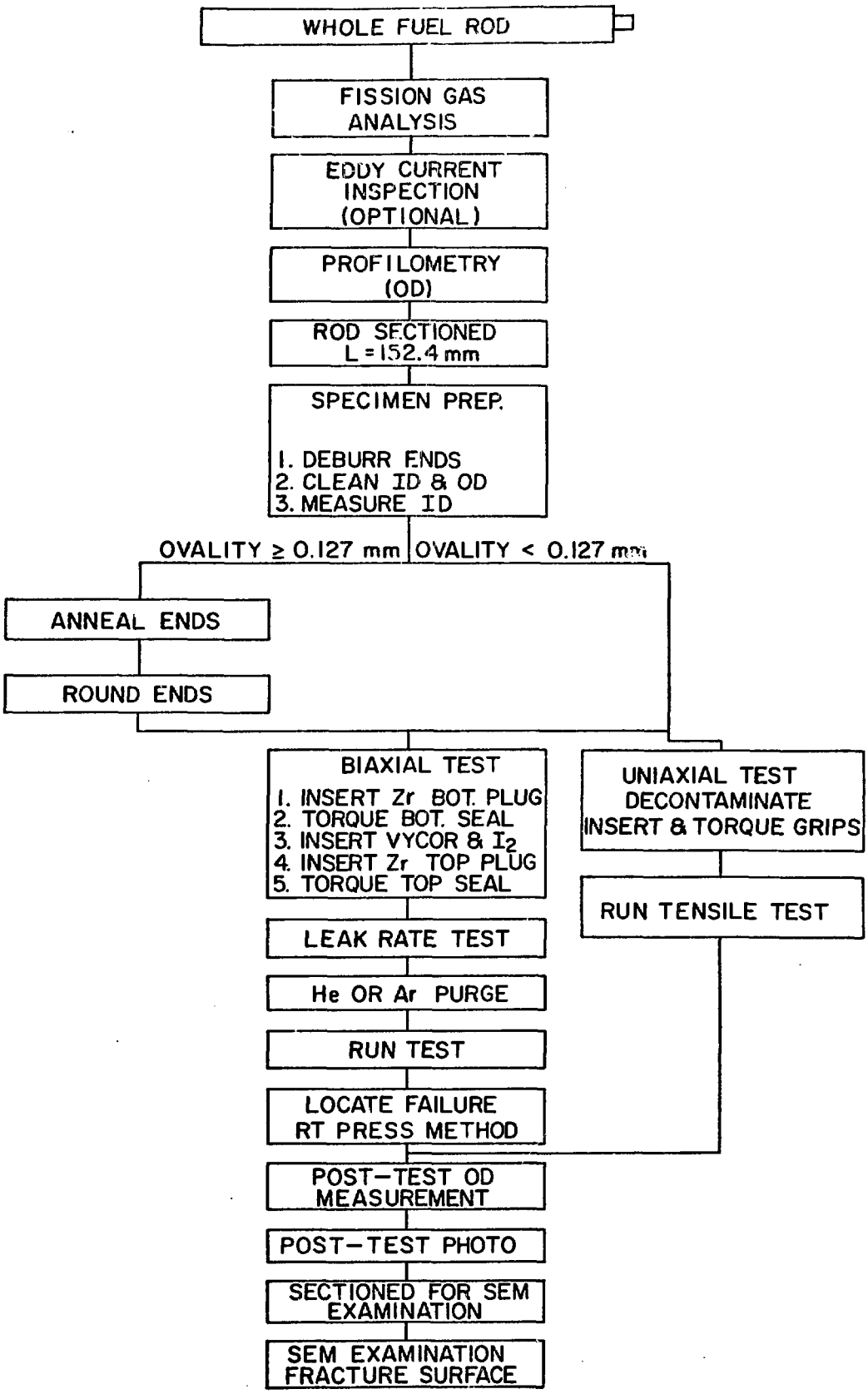
(d) Uniaxial tensile test.



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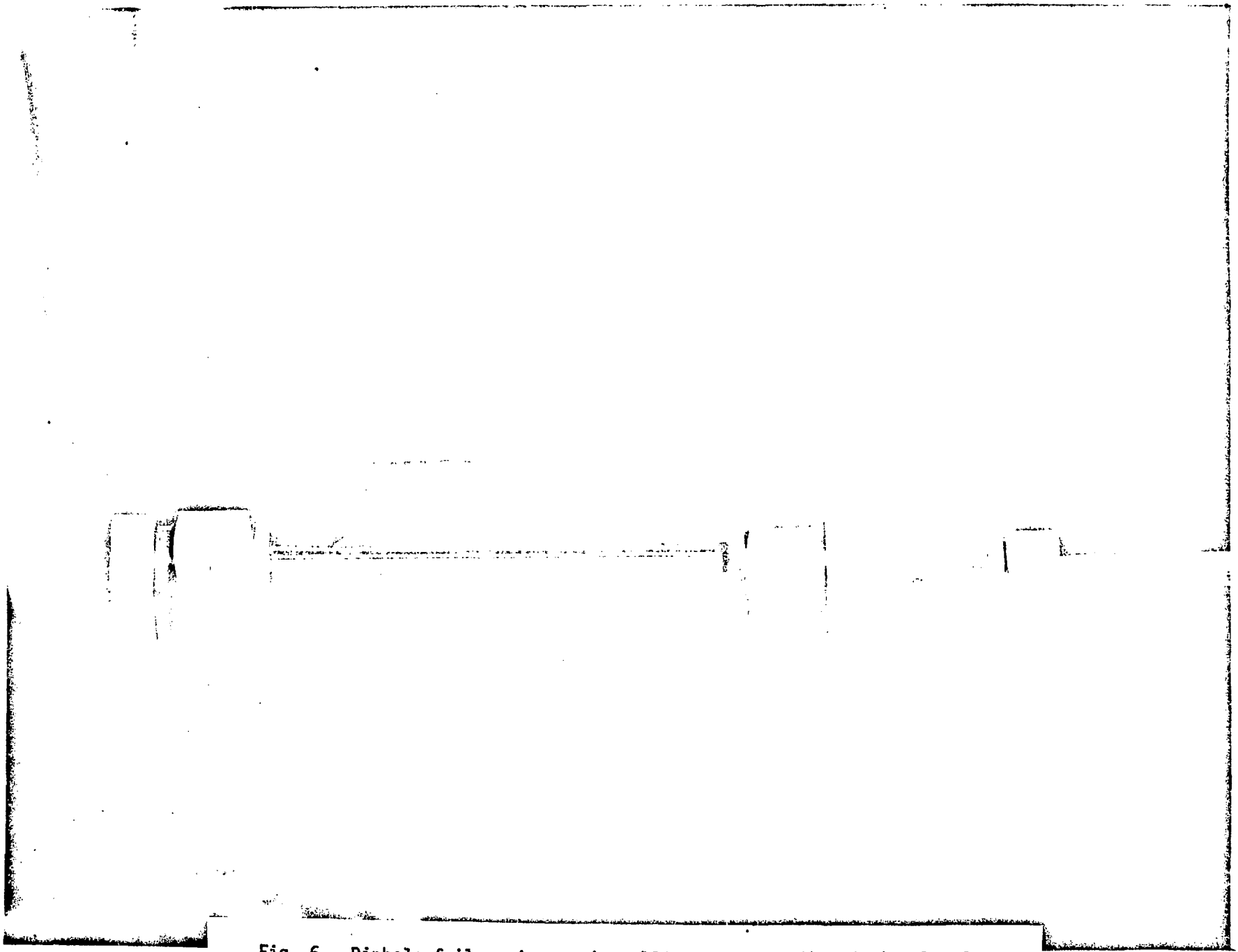

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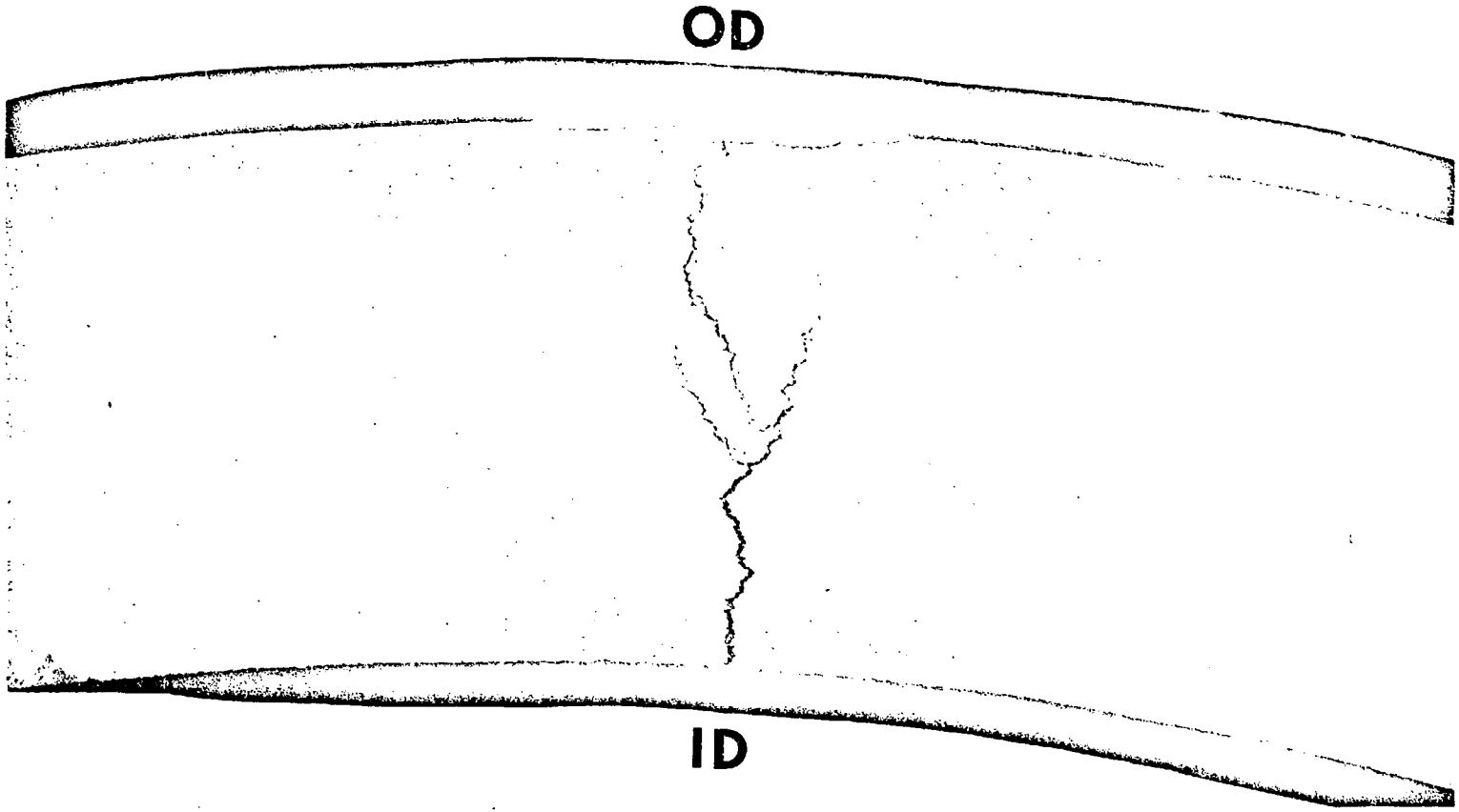


Fig. 7. Metallographic section of specimen 190D2-5 showing a through-the-wall SCC failure.

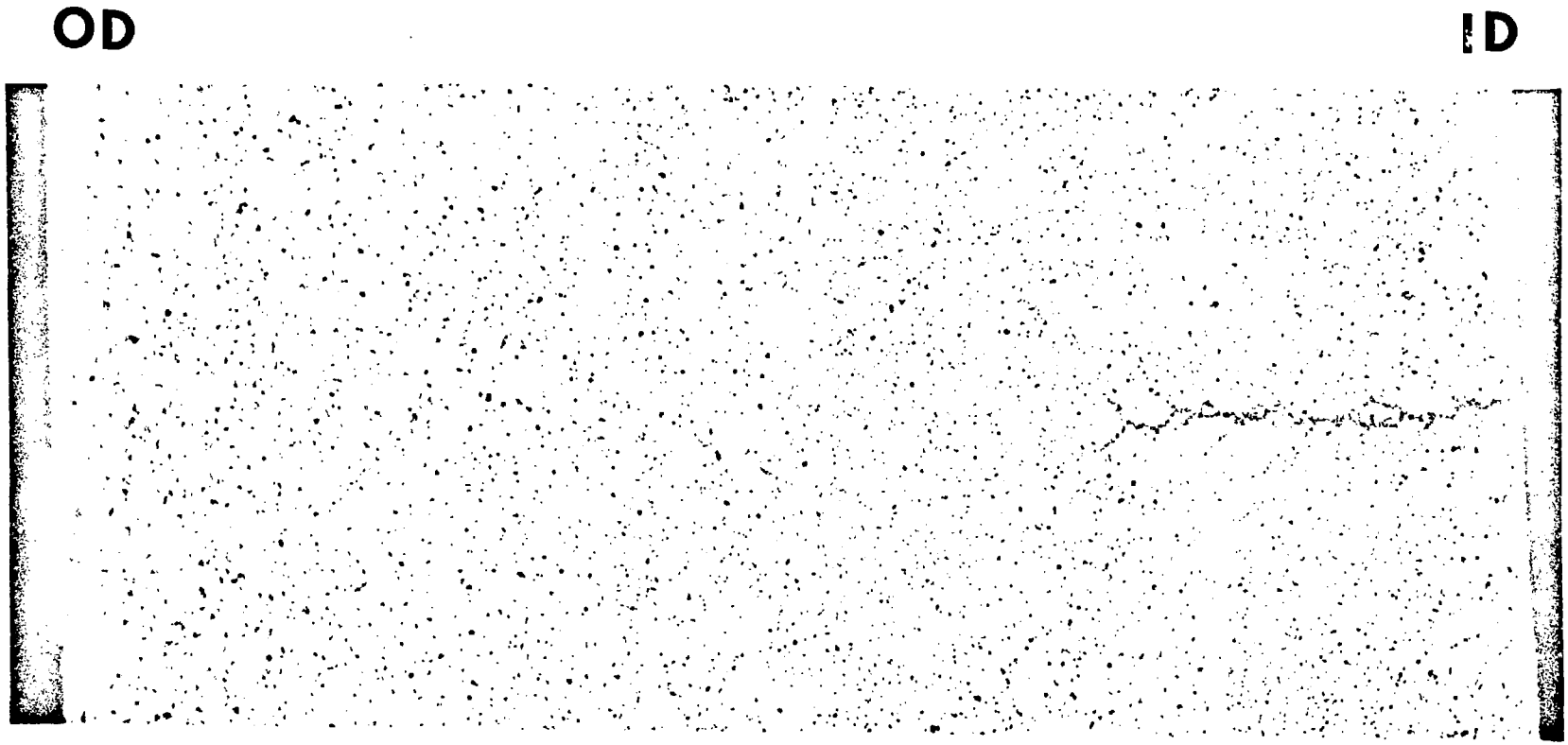
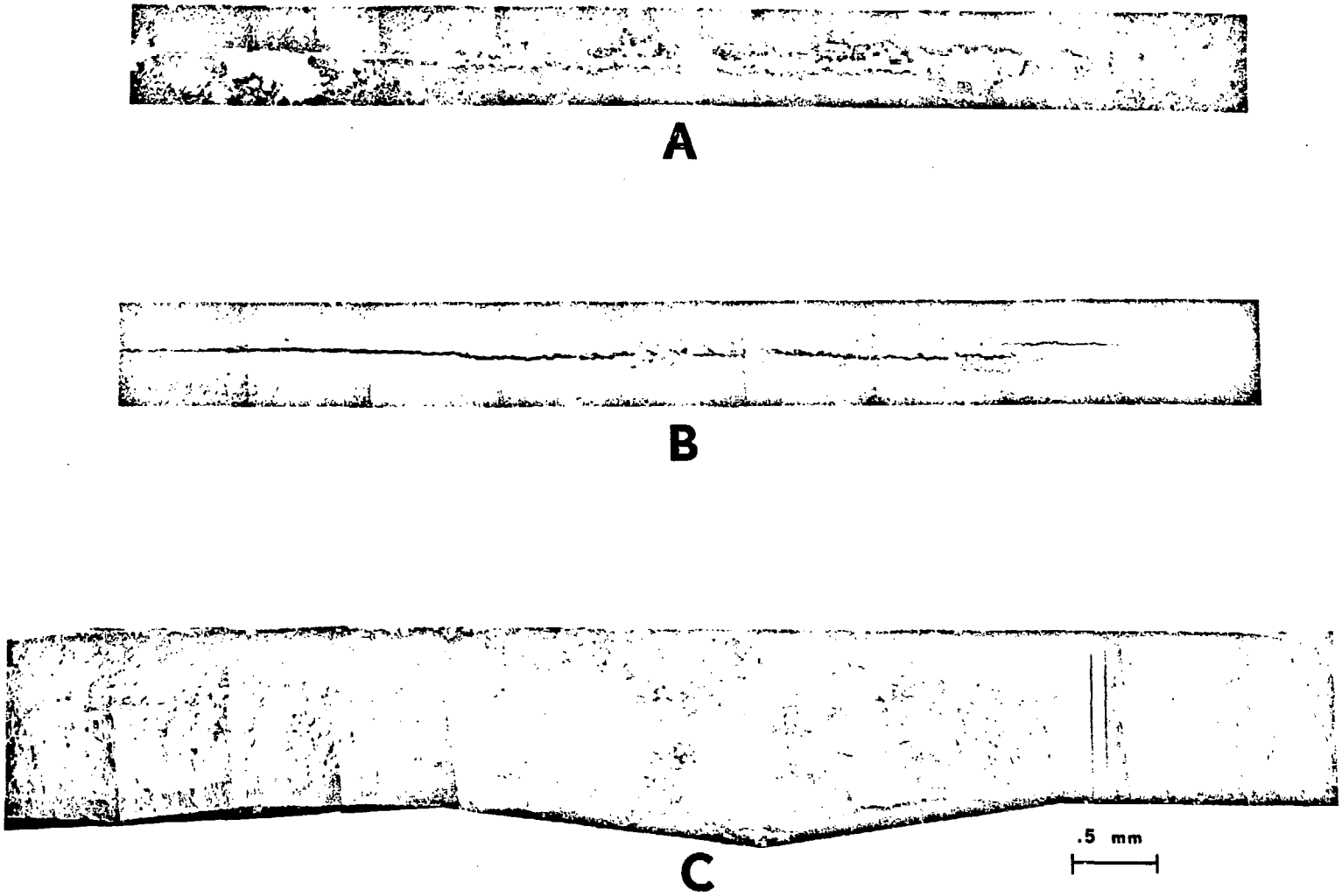


Fig. 8. Metallographic section of specimen 190D2-5 showing a secondary SCC crack located 90° from the principal crack in Fig. 7.



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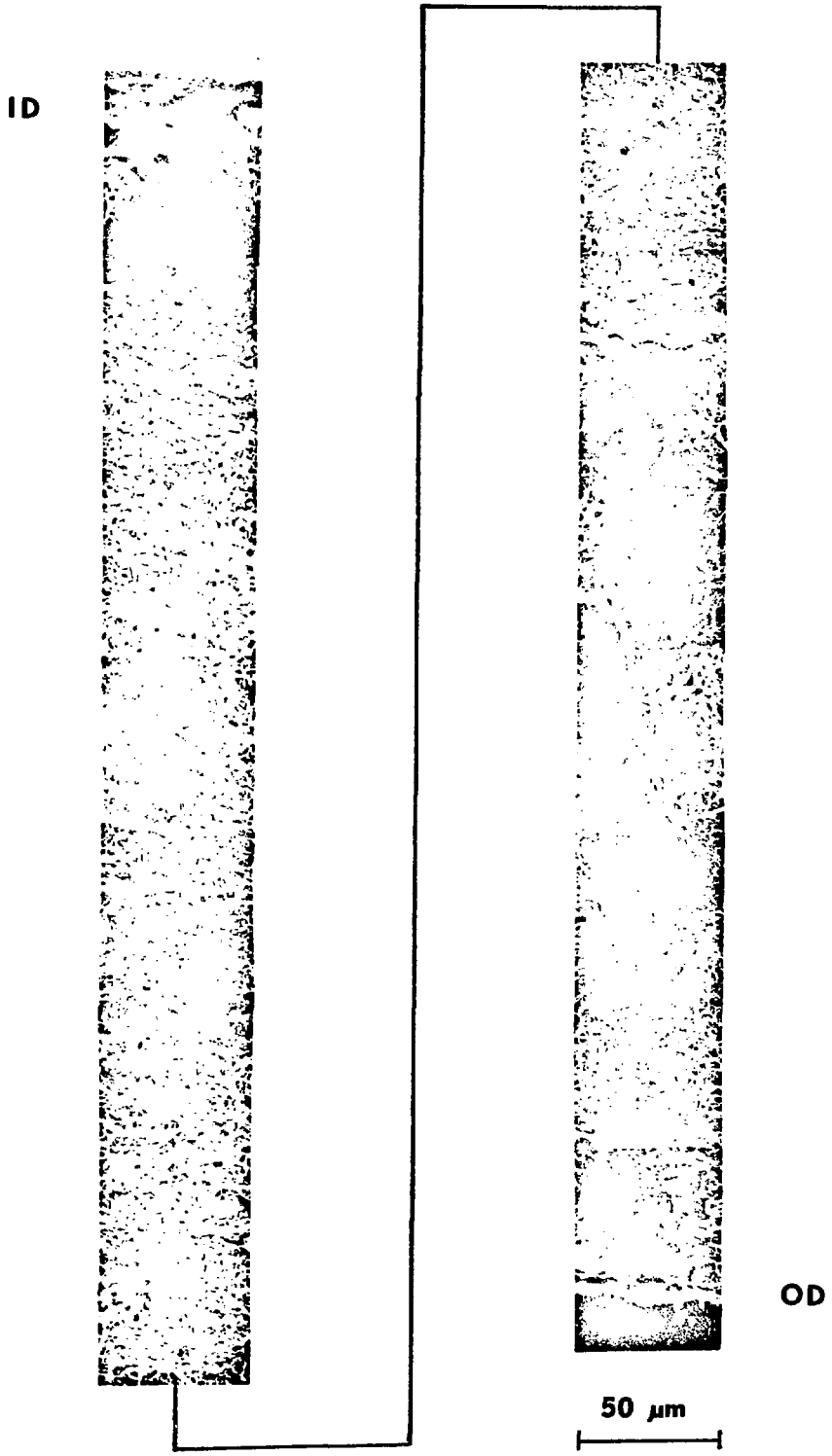

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