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Zircaloy fuel clad ballooning tests at 900-1070K in steam

Preliminary results

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NORTHERN DIVISION

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ZIRCALOY FUEL CLAD BALLOONING TESTS AT 900-1070K IN STEAM
Preliminary results

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SUMMARY

Zircaloy-4 clad specimens filled with alumina pellets and tested in steam under conditions relevant to those expected in a Pressurised Water Reactor (PWR) loss-of-coolant accident (LOCA) developed a variety of clad shapes. Failure during temperature ramping resulted in localised balloons whereas failure under approximately isothermal conditions could result in large circumferential strains extending over long lengths of cladding.

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United Kingdom Atomic Energy Authority
Springfields Nuclear Power Development Laboratories

CONTENTS

1. INTRODUCTION

The majority of Pressurised Water Reactors (PWR) now contain UO_2 pelleted fuel rods, Zircaloy-4 clad, which have been filled with helium gas at high pressure during manufacture to prevent collapse of the clad under the high coolant pressure.

If a loss-of-coolant accident (LOCA) occurs, coolant depressurisation can take place in about 20 s, depending upon the break size. This rapid depressurisation creates an increasing internal to external pressure differential which gives rise to an increasing biaxial stress in the clad. Concurrently the decreased heat transfer caused by loss of coolant causes the clad temperature to increase. Soon the stress-temperature combination reaches a point where the clad begins to deform and increase in diameter. The nature and extent of this deformation influences the flow of emergency core cooling water between the pins in the reflooding phase.

This Report presents the results of an investigation of how Zircaloy-4 clad behaves when subjected to temperatures and differential pressures appropriate to postulated loss-of-coolant accidents in a Pressurised Water Reactor.

2. EXPERIMENTAL

2.1 CLAD SPECIMEN PREPARATION

The 470 mm long specimens were made from nuclear grade Zircaloy-4 clad (9.5 mm o.d. 0.575 mm wall), supplied by a leading manufacturer. Diameter and wall thickness measurements were made at 2.5 cm intervals along the specimens which were selected at random. The wall thickness variation was typically 2-3%.

Each tube was degreased before welding an end-cap at one end. A Pt/Pt 13% Rh thermocouple was then welded to the centre of the specimen with the wires 1 mm apart so that the hot junction was the specimen.

The specimens were mounted vertically in the specimen environmental chamber, Fig. 1, with the welded end dipping into a pool of molten metal which formed an electrical connection for heating by direct electrical resistance. The open end was sealed by a hollow plug, one end of which was pressed tightly onto the stack of pellets in the specimen and the other end against the upper electrical connection which also served as a specimen clamp. The actual pressure seal was made by a tight fitting 'O' ring which was capable of withstanding at least 13.8 MN/M^2 (2000 lb/in^2).

The pressurising gas was supplied through a capillary tube welded into the end plug and passed into the specimen via holes in the plug. The experimental arrangement is shown schematically in Fig. 2.

2.2 PROPAT* TESTING

The experimental facility developed at Springfields for this

*PROPAT: Programmed Pressure and Temperature

investigation is known as the PROPAT since it provides both independent pressure and temperature programming. A schematic arrangement is shown in Fig. 1.

2.2.1 Temperature programming

The Temperature Programme Unit, Fig. 3, is designed to produce controlled temperature variations in a directly heated specimen. Any temperature variations within the range 873-1473 K (600 to 1200°C) can be generated, with an accuracy of ± 2.5 K against a base of time, variable from 50 s to 500 s maximum.

Programming is accomplished manually by a 120 x 100 way Programme Board, the desired profile being created by the insertion of plugs into the matrix. Thus, a permanent display of the programme is retained in the form of temperature (y) against time (x).

The programmed emf's (temperature) are outputted sequentially to produce a "demand" signal representing the desired profile. This "demand" signal provides an input to the 3-term controller representing the desired value, and is continuously compared with the "follow" signal (measured value) derived from the thermocouple mounted directly on the specimen. A d.c. output from the 3-term controller regulates the temperature of the specimen via a drive unit and thyristor unit in the primary circuit of the step-down power transformer which provides the low voltage high current supply for the specimen heating.

The basic timescales are switch selected at 50, 100, 200 and 500 s, intermediate values being obtained by means of the programme board. A digital display indicates the elapsed time increments, each increment representing 1% of the basic timescale.

The signals representing "demand" and "follow" are available for use with a two-pen chart recorder.

2.2.2 Pressure programming

The equipment, Fig. 4, is designed to produce a controlled pressure variation, within a small volume specimen, to a base of time. To allow complete flexibility, the pressure programme is loaded into the unit on punched tape which permits up to 256 discrete pressure values to be selected during the cycle time. Any programme can be produced by the operator, provided a teletype is available, and no "program language" is involved.

In operation, pressure values are read consecutively from the tape at intervals of 0.5 to 4 seconds, giving minimum and maximum cycle times of 128 to 1024 seconds; the maximum pressure limit is 13.8 MN/m^2 (2000 lb/in^2).

Output signals from the unit are suitable for application to an X-Y recorder to provide records of the pressure transient against time.

A gas bottle and pressure regulator provide the supply to the specimen under test. A motorised needle type control valve regulates the gas flow

into the sytem, with a transducer mounted adjacent to the specimen to monitor pressure variations.

2.2.3 Strain measurement

Two methods of strain measurement are used: post-test measurement and photographic recording during testing which was developed by Mowat in 1971 at Springfields. The limitation to this method is that only part of the specimen is photographed, so that extensive visual observations were made in addition to the photography.

2.3 TEMPERATURE MEASUREMENT

It is recognised that a thermocouple attached to the surface of a specimen can cause localised cooling so that the indicated temperature does not represent the true temperature of the surface. Also with a directly heated thin walled tubular specimen in a steam environment there is likely to be a temperature gradient across the wall. An additional complication arises when such a specimen is filled with alumina pellets. However, a thermocouple placed in the centre of such a specimen should experience virtual black body conditions so that it can be used to calibrate an external thermocouple welded to the clad surface. Such calibrations were carried out with thermocouples placed as shown in Fig. 5 under isothermal and temperature ramping conditions. These showed that in the range 900-1100 K (627-827°C) the accuracy was ± 5 K. During ramping, the temperature at centre of the pellet lagged behind that at the clad exterior surface by about 80 K. Local variations in temperature around and along the clad were observed presumably caused by variations in the degree of pellet clad contact but after 10-15 seconds of isothermal conditions the clad temperature was apparently uniform over most of the heated zone.

The temperature of the inner surface of the clad was 8-10 K higher than that of the surface. This has been taken into account in the temperatures quoted in this Report which are those of the mid-wall. The temperature variation along the specimens unstrained was ± 2-5 K at 970-1070 K ~ (700-800°C) over 370 mm.

2.4 TEST PARAMETERS

2.4.1 Temperature

The time-temperature history i.e. transient, of the clad during a LOCA varies according to the nature and size of the breach in the circuit and where it occurs. Typical transients have been published;[1] the most severe, such as reproduced in Fig. 6, is used for a design basis LOCA, whilst Fig. 7 is an example of a less severe breach.

The published transients such as Figs 6 and 7 are usually those for the peak rated fuel rod. However the remainder of the rods in the core will experience a transient similar in shape but with overall lower temperatures. These transients can be inferred from Fig. 8 which shows how the clad temperatures in the lower rated rods relate to that of the peak rated rod.[2]

2.4.2 External pressure

The maximum differential pressure across the clad only applies after the core has "blown down", so that during the first peak in Fig. 6 little if any clad strain occurs. Thus the test programme was based on the post blow-down region of the transient and assumes that the external pressure variations can be discounted.

2.4.3 Axial restraint

The rods were filled with dished alumina pellets made to UO_2 pellet dimensional specifications to simulate the fuel stack and produce axial restraint which has been found to reduce the circumferential strain during ballooning.(3)

2.4.4 Axial gas flow

Restriction of the gas flow from the plenum to the swelling balloon may reduce the internal pressure thus causing a significant reduction in strain rate which previous work has shown is an important factor in determining the shape of the balloon. For this work a capillary tube of length equal to the distance between the plenum and the mid-point of a fuel rod and a bore equal in cross sectional area to the annular gap in a cold new rod was used. The resistance so imposed is less than that of the cold or hot fuel/clad gap.

2.4.5 Internal gas volume and pressures

The increase in volume as the clad swells reduces the internal gas pressure of a closed system and hence the clad strain rate which is a significant factor in determining balloon shape. Thus the gas volume in the plenum and specimen used in the present work, (17 cm^3), was estimated from published information on PWR fuel and dimensions.(4) The pressure in the plenum was monitored during the tests.

An indication of the range of internal gas pressures and how they vary during reactor service(4) is shown in Fig. 9. Accordingly, pressures in the range 6.21 MN/m^2 to 12.0 MN/m^2 (900 lb/in^2 to 1740 lb/in^2) were used in the present work.

2.5 TEST CONDITIONS

2.5.1 Stylised transients in steam

The temperature in the post blow-down region of the design basis transient shown in Fig. 6 continually changes, so a rate of 10 K/s which approximates to the steeper part of the curve was adopted as a standard for the stylised transients which comprised a temperature ramp followed by a constant temperature, see Fig. 6. The alumina pellet-filled specimens were heated to 873 K (600°C) and held for about 30 s so that the temperature of the alumina pellets equilibrated with that of the clad. Then the system was pressurised to the chosen value and the clad temperature ramped at 10 K/s to a set temperature which was held until rupture. The object of this treatment was to simulate the post blow-down portion of a family of

transients, based on the published peak clad transient shown in Figs 6 and 7. Some of the stylised transients in the lower part of the shaded region on Fig. 6 also have relevance to Fig. 7.

2.5.5 Simulated transients in steam

Experiments using stylised transients are convenient for analysis but in view of the sensitivity of the results to temperature, tests were also run with temperature transients following the predicted shape for a peak rated pin, but having peak temperatures representing some of the lower rated rods. These are indicated as dashed lines on Figs 6 and 7.

3. RESULTS

3.1 STYLISED TRANSIENTS

The shape of specimens after stylised transient testing in the region indicated on Fig. 6 can be classified into two distinct categories depending at what point on the stylised transient failure occurred, see Fig. 10.

3.1.1 Failure during temperature ramping

Specimens which failed during the temperature ramping portion of the stylised transient exhibited localised ballooning, see Fig. 11. Rupture followed almost immediately after the bulge became noticeable and there was little internal pressure drop before rupture.

3.1.2 Failure during isothermal conditions

The specimens which survived the ramp portion of the stylised transient and deformed under isothermal conditions for more than about 40 s exhibited long balloons, see Fig. 12, and there was considerable decrease in pressure. The deformation developed slowly over most of the heated length. When the uniform axial balloons reached 30-50% strain, noticeable localised bulges often began to form which then appeared to darken progressively relative to the other parts of the axial balloon. Later a final superimposed balloon developed and failed quickly i.e. within a few seconds.

After rupture the alumina pellet stack usually remained intact with a uniform annular space between it and the deformed clad. Some of the specimens kinked at the point of rupture causing the pellet at that point to chip. Specimens which survived the ramp portion of the stylised transient but ruptured in less than about a further 40 s had shapes which were intermediate, either developing several localised balloons, Fig. 13a, or much less pronounced axial ballooning, Fig. 13b.

3.2 AXIAL BALLOONING DURING SIMULATED TRANSIENTS

3.2.1 Design basis LOCA (cold leg break)

Specimens with initial pressures 6.21-4.51 MN/m^2 (900-1380 lb/in^2) were subjected to simulated transients for the design basis accident shown as broken lines on Fig. 6. They failed after various times as shown in

Table 1, with the lower pressurised specimens lasting longer and producing greatest axial ballooning which developed slowly over most of the hot zone. The diametral strain, temperature and pressure time relationships are shown in Fig. 14 for test 81 which had an initial pressure of 9.51 MN/m^2 (1380 lb/in^2) and peak temperature of about 973K (700°C), the position at which the continuous strain measurements were made is shown on Fig. 15a. Fig. 16 shows the results of test 78 with an initial pressure of 7.86 MN/m^2 (1140 lb/in^2).

3.2.2 Pump suction leg break

The peak clad transient for this accident lies in the region where analysis of the stylised transients suggests that long axial balloons would be expected so here the peak transient was also programmed in addition to several simulated transients. The results, given in Table 1, show that axial balloons can be produced even with initial pressures as high as 10.34 MN/m^2 (1500 lb/in^2). The strain and pressure time relationships for an initial pressure of 10.34 MN/m^2 (1500 lb/in^2) and peak temperature of 953K (680°C) test 77 are shown in Fig. 17. The specimen is shown in Fig. 15b. The maximum strain did not occur within the length covered by photography during testing.

4. DISCUSSION

The high ductility of Zircaloy-4 in the temperature range used in this study results from a fine grain size ($\approx 6\mu m$) rapid recovery of work hardening and the absence of premature failure mechanisms such as cavitation. Lee and Backofen[5] obtained values of over 100% total elongation using tensile specimens and their results fit well on the correlation curve[6] between strain rate sensitivity and total elongation. However, total elongation can be affected by specimen geometry as shown by Avery and Stuart.[7] If their analysis is applied to the present specimens, total elongations of at least $\approx$ 60% can be expected. Thus the circumferential strains obtained in this study are consistent with other materials property data.

The shape of some of the specimens after testing was unusual in that the expected high circumferential strains were present over considerable axial distances so that they are similar in shape to those which are known to have deformed superplastically.[8] However the strain rates are several orders of magnitude higher and the strain rate sensitivity m is 0.15-0.2[9] compared with ≥ 0.3 usually associated with superplastic deformation,[10] so an alternative explanation must be sought.

The shape of specimens, Fig. 11, which failed during or within a few seconds after temperature ramping was similar to those found in other studies,[12-15] and is the norm for high strain rate tube burst tests. Once deformation starts, stress intensification occurs rapidly as the wall thins so that all that is required for local bulges to form are perturbations in strain rate. These can be provided by a small change in temperature along the specimen since the strain rate $\dot{\epsilon}_T$ is markedly affected by temperature as shown by the following equation,[16] for secondary creep of α phase Zircaloy.

$$\dot{\epsilon}_T = 2511\ \sigma^{5.0} \exp\left(\frac{-287000}{8.314T}\right) \quad \ldots (2)$$

where $\dot{\epsilon}_T$ is true strain rate

T is the absolute temperature
σ is initial hoop stress in MN/m^2

Thus in the high α phase region a temperature increase of about 20K doubles the creep rate and Chapman[17] has clearly demonstrated that small temperature variations along internal heaters correlate with clad deformation during ramp testing at 28K/s.

Similar perturbations are present in this study caused by a combination of the alumina pellets lagging behind the clad during temperature ramping and chance variations in pellet-to-clad gap around the circumference of each pellet. Thus the specimens which failed during the ramp, or shortly after, before the differences in temperature disappear exhibited localised bulging. But the whole of the hot length of specimens which after ramping change temperature very slowly or are at near isothermal conditions will strain fairly uniformly whilst instability develops. Thus provided the overall strain rate is reasonably slow a bulge will slowly form. A bulge, because of its increased surface, can lose heat more rapidly than the remainder of the tube. Since the creep rate of Zircaloy is markedly affected by temperature the creep rate of a local "cooling" bulge then decreases. Thus a balance may be achieved between the enhancement in creep rate caused by the local stress intensification and the decrease caused by the local cooling. The balance between continued local deformation and overall axial deformation depends upon:

i. the strain rate, because if this is too high then there is insufficient time for local cooling to change the strain rate.

ii. the heat transfer between clad surface and environment because this controls the rate at which the bulge decreases in temperature.

There is evidence of a localised temperature decrease when bulging occurs in the present work in steam using direct resistance heating, also in the work at ORNL[17] in steam and at GFK[18] in air, both of which use internal rod heaters. The ORNL tests do not produce axially extended ballooning but the GFK tests do. It is suggested that in the former the 28 K/s ramping causes such high strain rates that there is insufficient time for the cooling effect to dominate the straining behaviour of a bulge, whereas in the latter which are initially ramped at 11 K/s, cooling effects are becoming significant.

In most of the GFK tests the clad bows, probably as a result of anisotropy, so that one side remains in contact with the heater. The other side heats up less quickly because of the increasing radial gap and surface area and differences of 100 K can develop around the circumference, this limits the strains to 22-30%.[19,20] However, in several of the GFK tests there was less clad/heater contact and circumferential strains of 40-52% resulted.[19,20]

It is suggested that the present work and that at Karlsruhe demonstrates that large strains could occur in some LOCA transients over a length equal to many rod diameters. The LOCA transients which produce long balloons are

those where the diametral strain rate is low enough to allow short bulges to cool below the temperature of the neighbouring cladding. The transients simulated at Karlsruhe have been different from those of the present work as were the methods of heating. At Karlsruhe the internal heater tests produced clad diametral strain rates $\dot{\epsilon}_m = 1.9\text{-}4.0 \times 10^{-2}$/s and failure occurred at 22-30% strain at a short bulge superimposed on the general expansion.(18) However several of these tests which fortuitously did not have close enough contact between heater and clad during ballooning to maintain the temperature ramp(19) and so approximated to a transient with a short post-ramp region, failed at 40-52% strain.(19,20) In the PROPAT tests which simulated reactor transients extending well into the post-ramp region, lower strain rates i.e. $\dot{\epsilon}_m = 0.5\text{-}1.4 \times 10^{-2}$/s were produced and the failures came at 60-90% and occurred over greater axial distances. Both methods of simulation have limitations but suggest that in a LOCA some rods would fail only when diametral strains in the range of these results i.e 40-90% were reached. There is some support for this view from an in-reactor ramp burst test(20,21,22) at Karlsruhe with fresh fuel which produced a circumferentially symmetrical bulge with a maximum strain of 65%. The deformation extended axially for 65 mm but the conditions, i.e. ramp test without ECCS steam flow, were not conducive to axially extended ballooning.

5. CONCLUSIONS

1. In tests which simulated transients relevant to a PWR LOCA Zircaloy-4 clad specimens filled with alumina pellets exhibited circumferential strains which, if they occurred in a reactor, would cause adjacent rods to touch over considerable axial distances.

2. The conditions which encourage the formation of axially extended ballooning are near isothermal temperatures coincident with cooling of developing bulges to reduce their creep rate to that of the neighbouring cladding which was generally $\dot{\epsilon}_m = 0.5\text{-}1.4 \times 10^{-2}$/s.

3. The highest initial pressure which produced axial ballooning with 60-65% circumferential strain was 11.17 MN/m^2 (1620 lb/in^2) at 933 K (660°C). This extended continually for 250 mm along the specimen and failure occurred 66s after ramping.

4. Localised balloons 2-3 rod diameters long were formed when the specimens failed during temperature ramping at 10 K/s.

5. Axially extended ballooning is not restricted to the direct resistance heating technique used in the present work.

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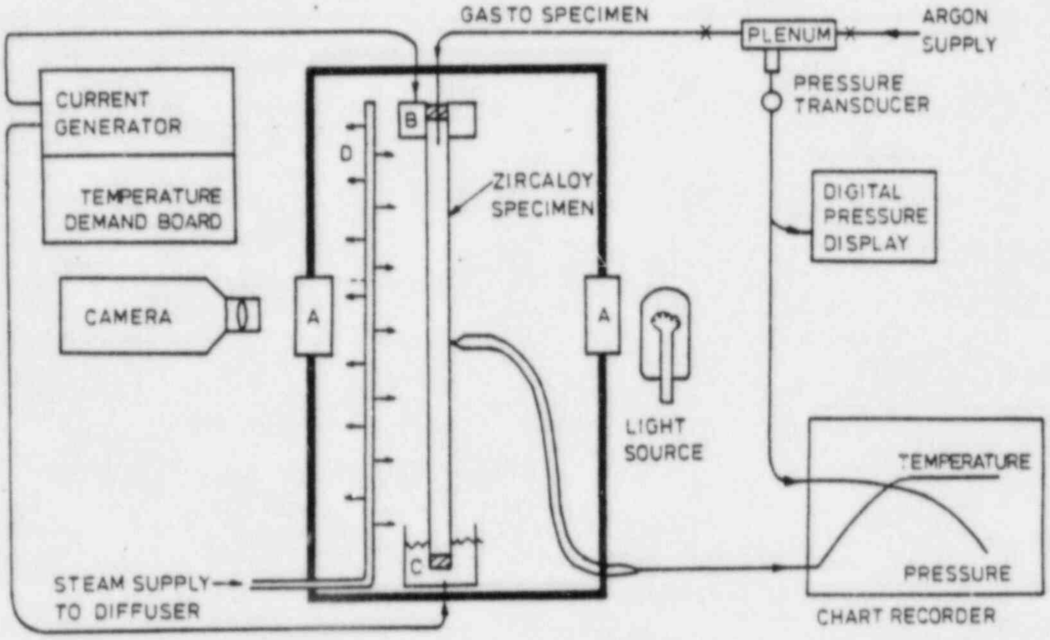
TABLE I

Results of simulated transient tests in steam

Transient type		Peak temperature reduced to		Initial pressure		Time to rupture from 873K	Diametral strain		
							Strain range of main ballooning region	Axial length ≥ 33%	Axial length ≥ 60%
Test No.	Tube No.	°C	K	MN/m²	lb/in²	S	%	mm	mm
Fig. 6 Cold Leg Break									
55	22H	773	1046	6.21	900	102	80-103	340	324
58	22C	"		7.03	1020	64	40- 80	325	135
59	25F	"		6.21	900	95	35-107	330	210
60	23C	"		6.21	900	107	60- 75	330	270
61	22F	"		7.03	1020	71	20- 40	155	43
78	1C	725	998	7.86	1140	113 (see Fig. 16)	50-100	320	270
79	38G	"	"	8.69	1260	47	17- 40	140	18
80	9H	"	"	8.69	1260	61	20- 50	140	20
81	18C	700	973	9.51	1380	102 (see Fig. 14)	40-100(Fig. 15a)	310	165
82	30G	"	"	9.10	1320	89	30- 70	285	85
83	9A	690	963	9.10	1320	145	30- 70	225	145
Fig. 7 Pump Suction Leg Break									
46	29B	760	1033	6.21	900	134	60- 80	335	320
47	13F	"	"	7.03	1020	98	35- 50	330	0
48	29D	"	"	7.86	1140	81	5- 40	15	0
*50	11I	"	"	6.21	900	118	40- 70	330	80
51	23F	"	"	6.21	900	112	60- 75	335	300
52	23B	"	"	7.03	1020	89	45- 75	330	220
*53	4H	710	983	7.03	1020	262	43- 47	330	0
54	13E	710	"	7.86	1140	143	27- 50	280	0
77	1D	680	953	10.34	1500	88 (see Fig. 17)	45- 90(Fig. 15b)	330	140
74	9C	660	933	10.34	1500	122	45- 70	330	310

* Failure which was affected by the thermocouple was probably premature



A VIEWING PORTS

B SPECIMEN CLAMP AND UPPER ELECTRICAL CONNECTION

C LOWER ELECTRICAL CONNECTION (LIQUID METAL)

D STEAM DIFFUSER

FIG. 1. SCHEMATIC ARRANGEMENT OF SPECIMEN MOUNTED IN ENVIRONMENTAL TEST CHAMBER

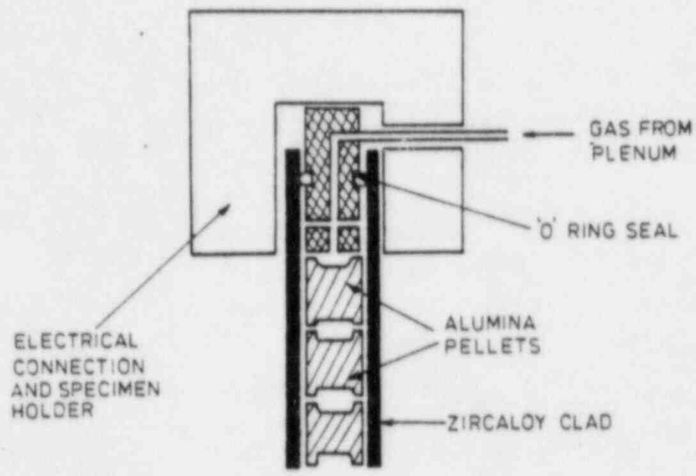


FIG. 2. SCHEMATIC ARRANGEMENT OF SPECIMEN TOP END SEALING

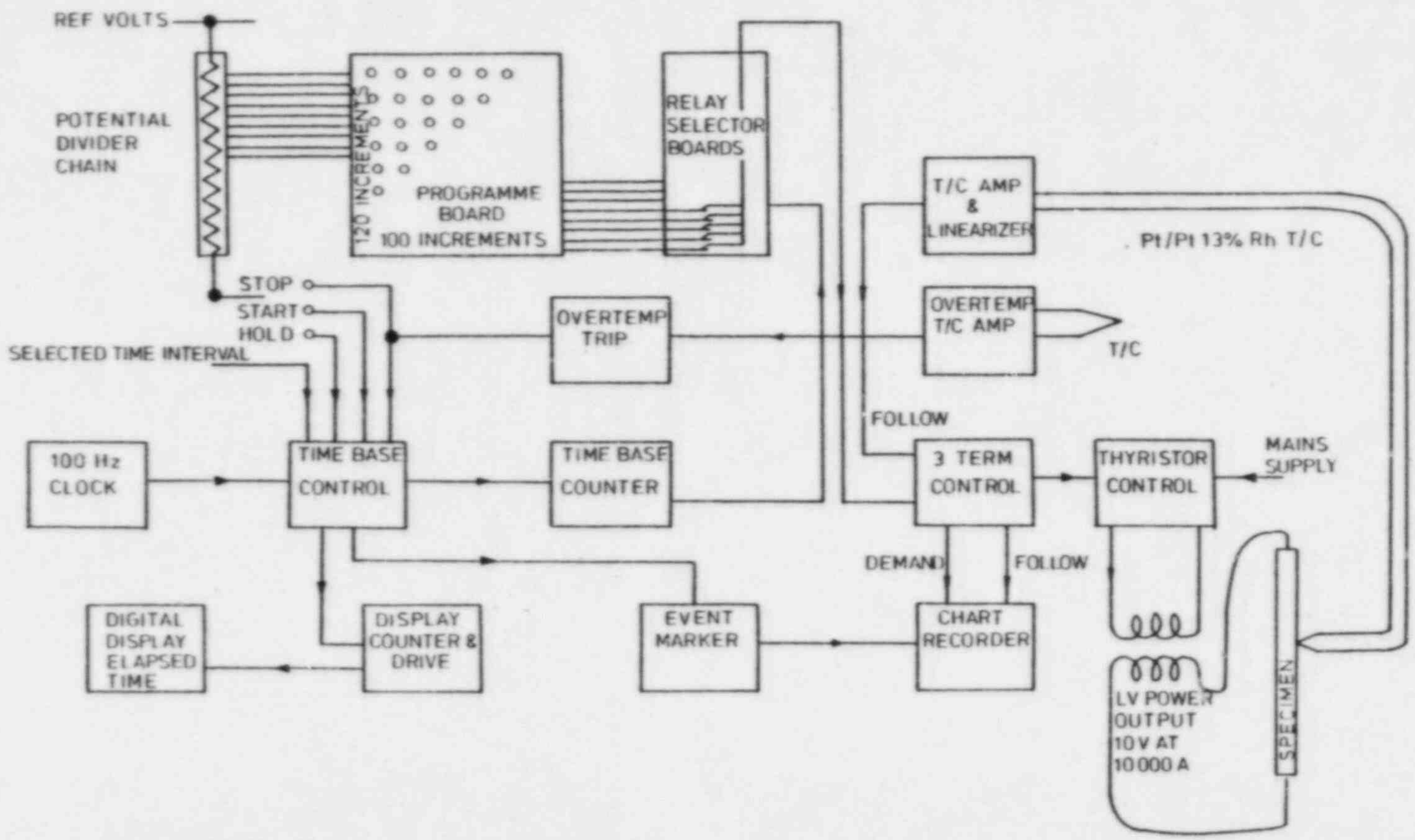


FIG. 3. SCHEMATIC DIAGRAM OF TEMPERATURE PROGRAMME UNIT

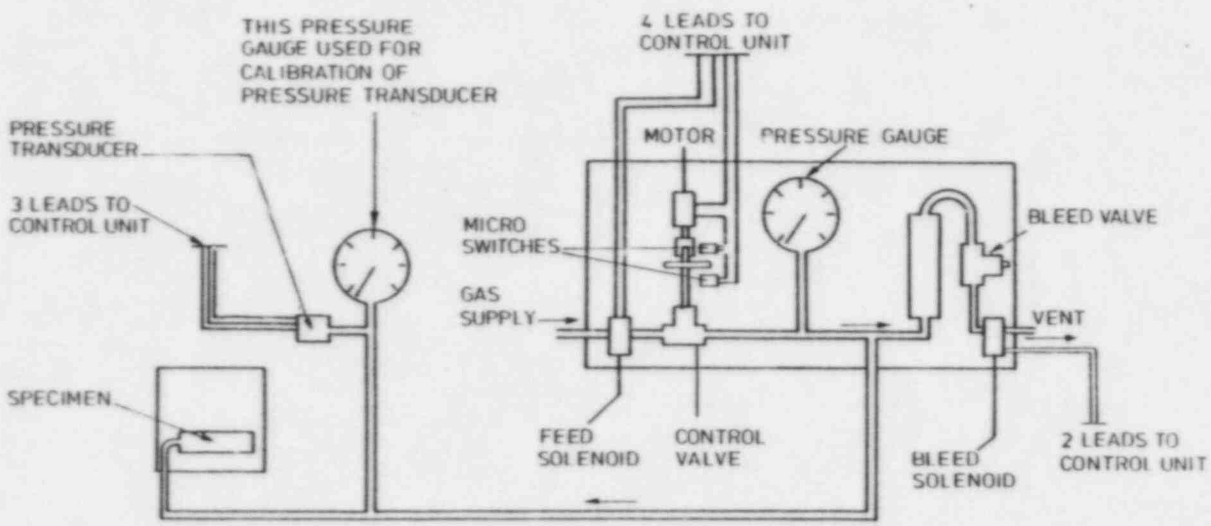
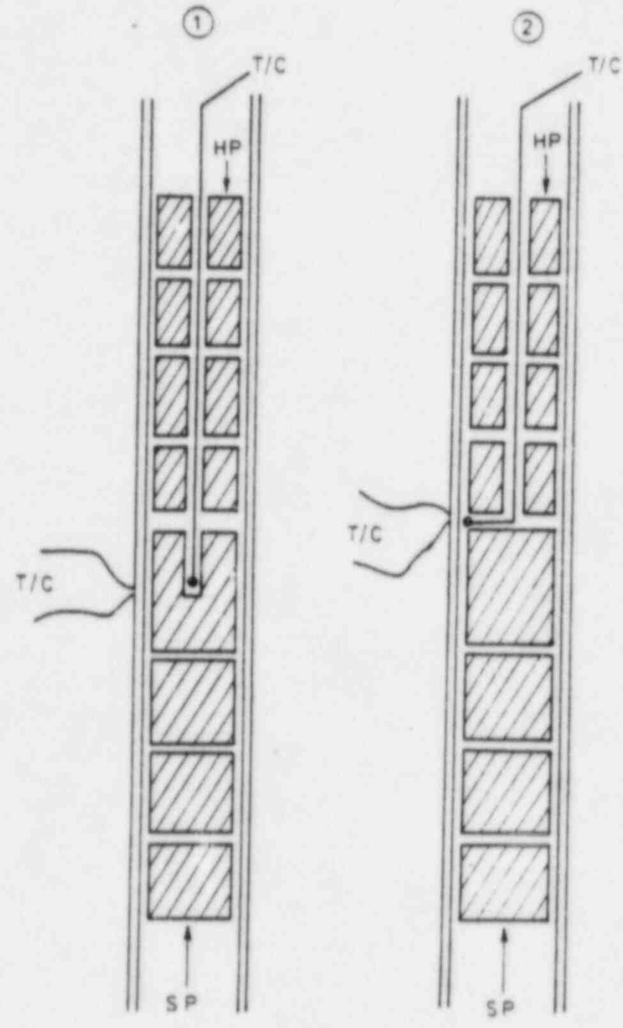


FIG. 4. GENERAL CONTROL LAYOUT OF PRESSURE PROGRAMME UNIT



HP - ALUMINA PELLETS WITH
A DRILLED CENTRAL HOLE

SP - SOLID ALUMINA PELLETS

T/C - Pt/Pt 13% Rh THERMOCOUPLE

FIG. 5. CROSS SECTION OF ZIRCALOY-4 SPECIMENS SHOWING SCHEMATIC ARRANGEMENT OF THERMOCOUPLES FOR TEMPERATURE CALIBRATIONS

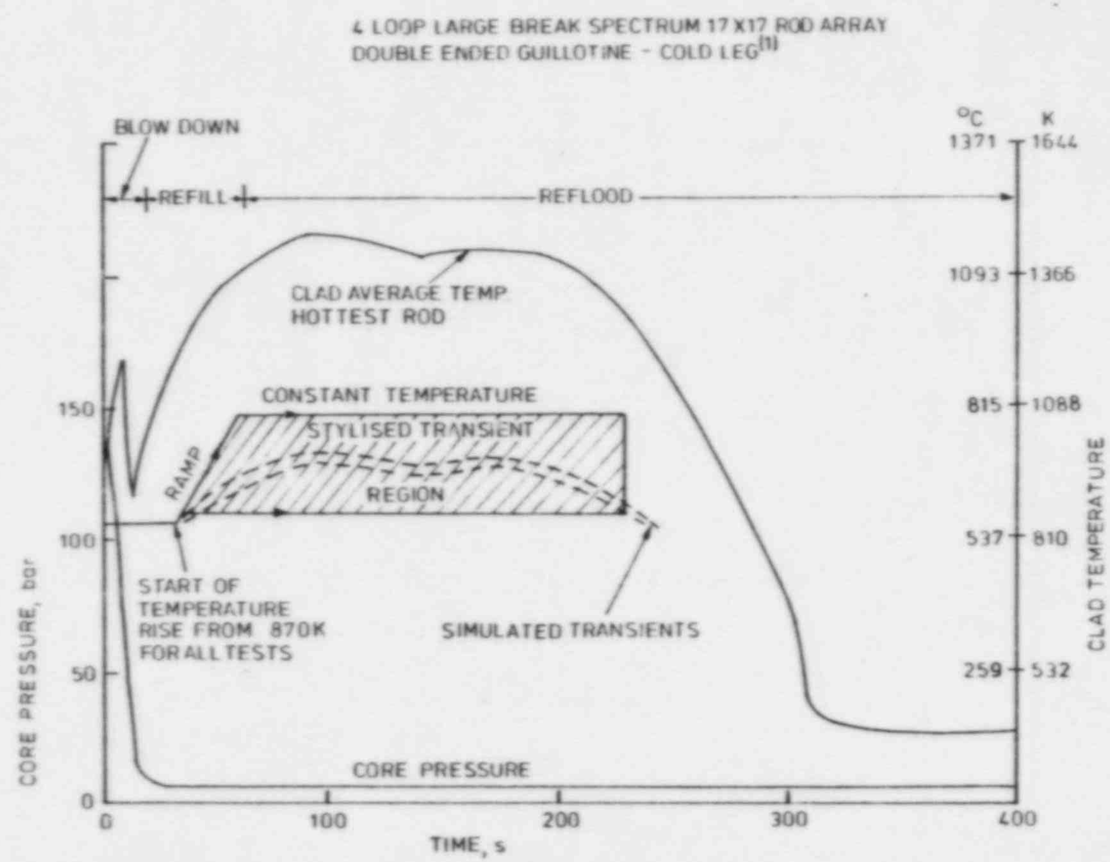


FIG.6. DESIGN BASIS LOSS-OF-COOLANT ACCIDENT

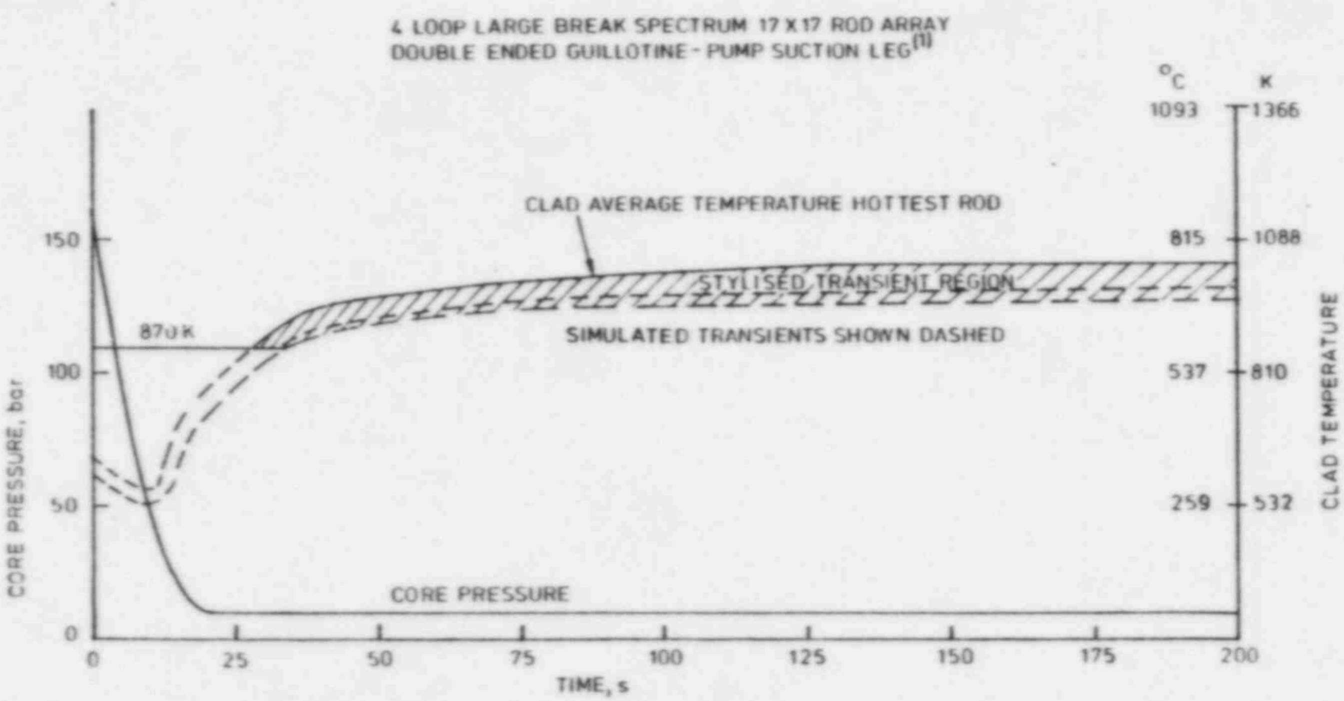


FIG.7. PUMP SUCTION LEG ACCIDENT

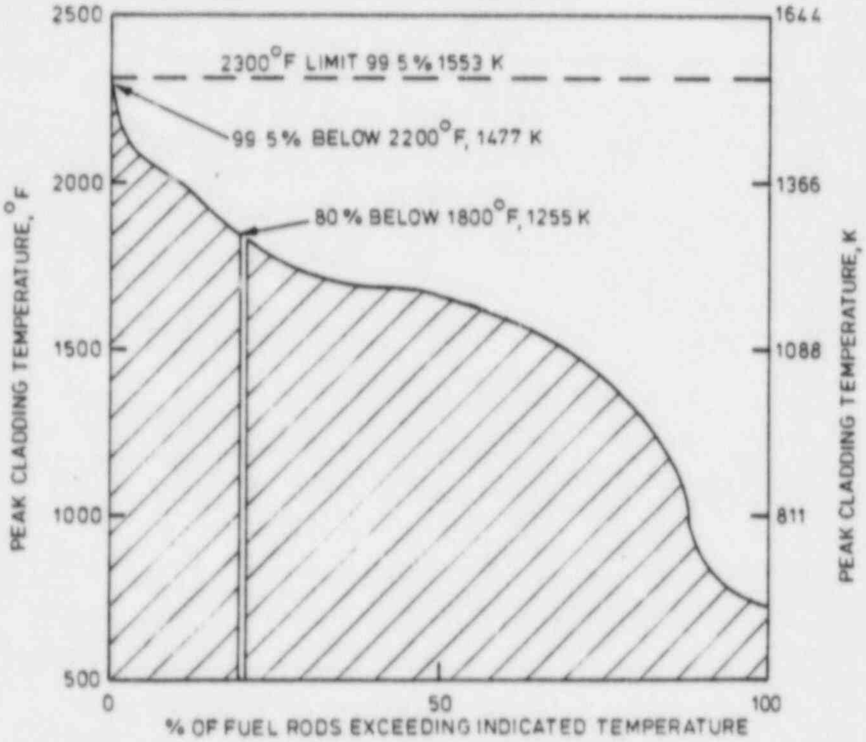


FIG.8. PEAK FUEL ROD TEMPERATURES REACHED IN DESIGN BASIS LOSS-OF-COOLANT ACCIDENT (2)

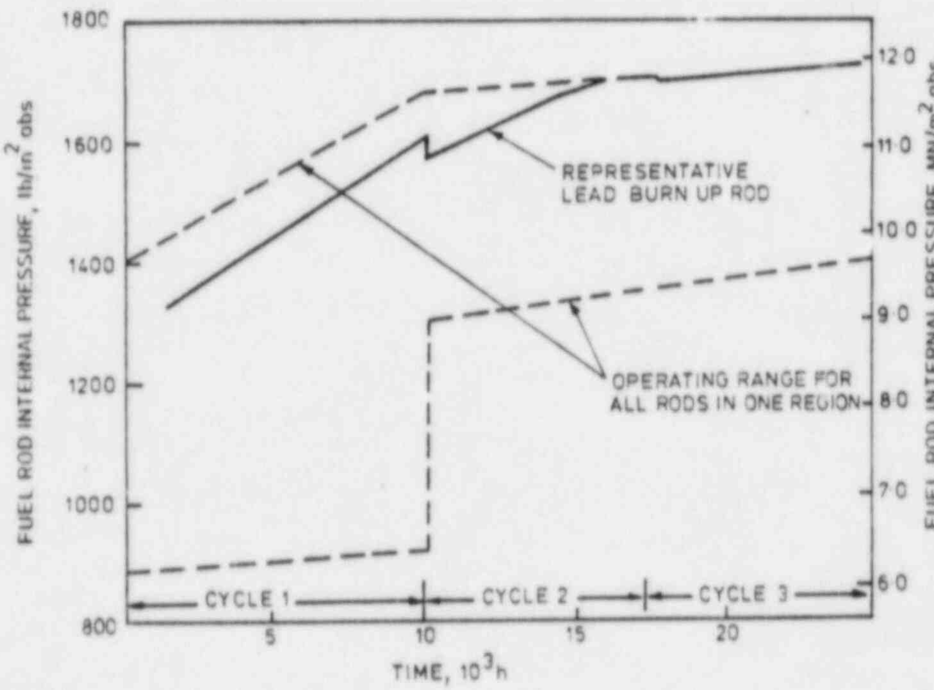


FIG.9. REPRESENTATIVE FUEL ROD INTERNAL PRESSURE[4]

SPECIMENS HEATED AT 10K/s IN STEAM FROM 873K TO SET TEMPERATURES AND HELD AT CONSTANT TEMPERATURE UNTIL RUPTURE. THE RUPTURE TIMES AT CONSTANT TEMPERATURE ARE GIVEN ALONGSIDE THE KEY SYMBOLS

KEY
● LOCALISED BALLOON MAXIMUM CIRCUMFERENTIAL STRAIN AT BURST
▲ LONG AXIAL BALLOON GENERAL STRAIN RANGE OVER SPECIMEN
□ INTERMEDIATE BALLOON MAXIMUM CIRCUMFERENTIAL STRAIN AT BURST
R FAILURE OCCURRED DURING THE TEMPERATURE RAMP

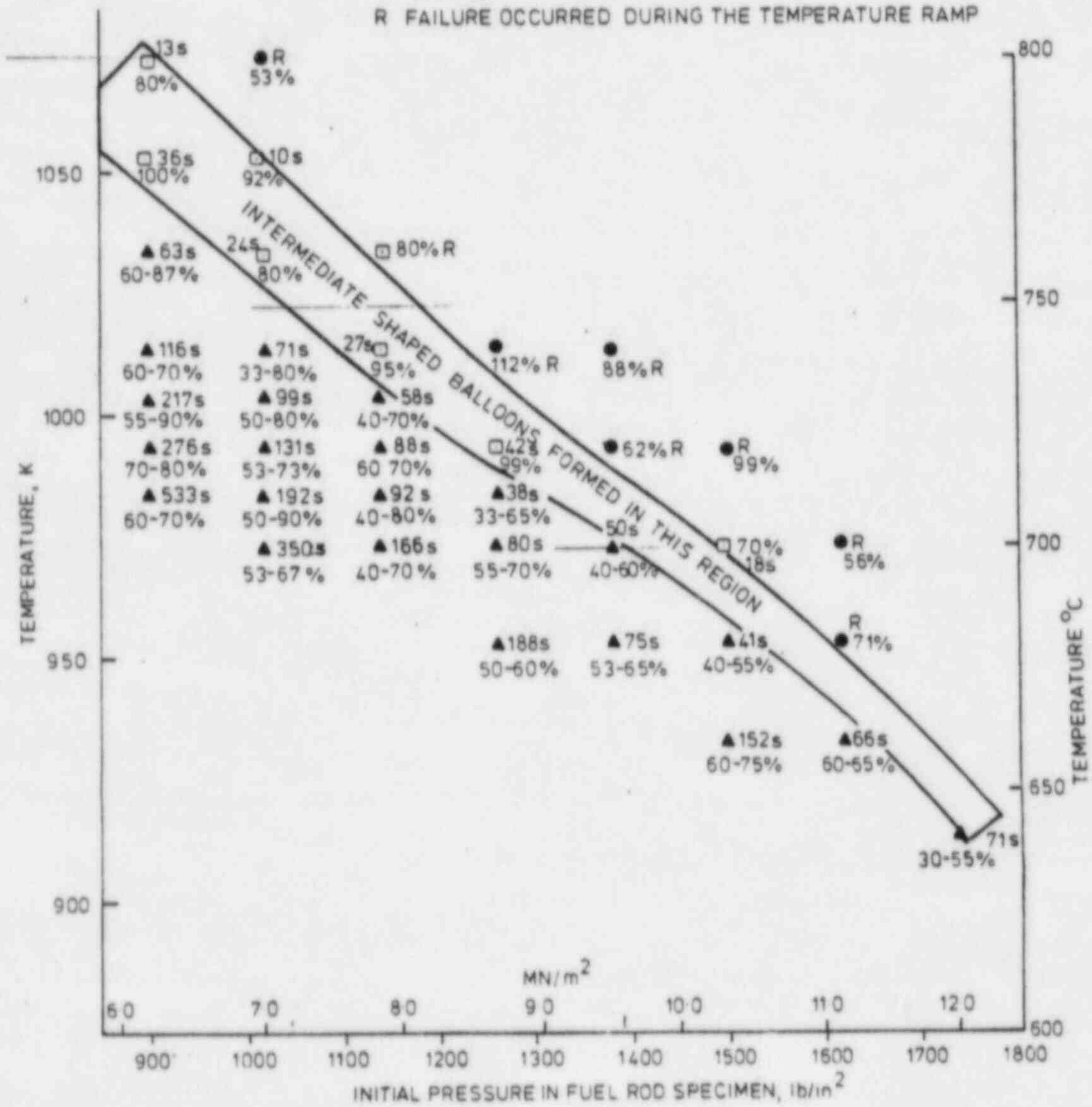
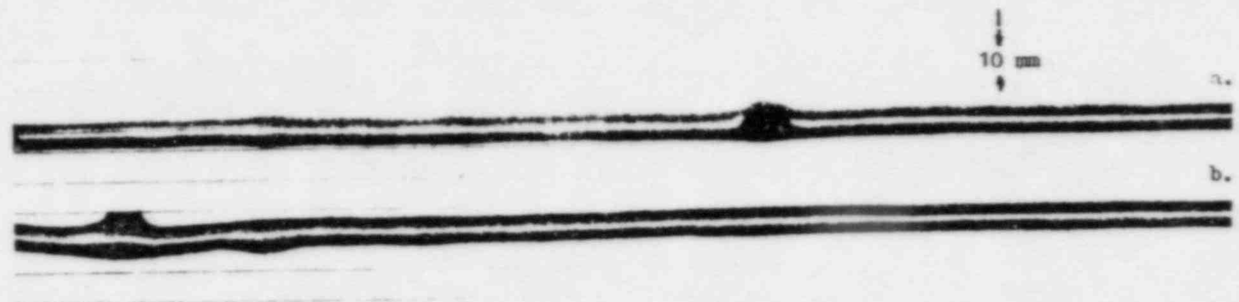


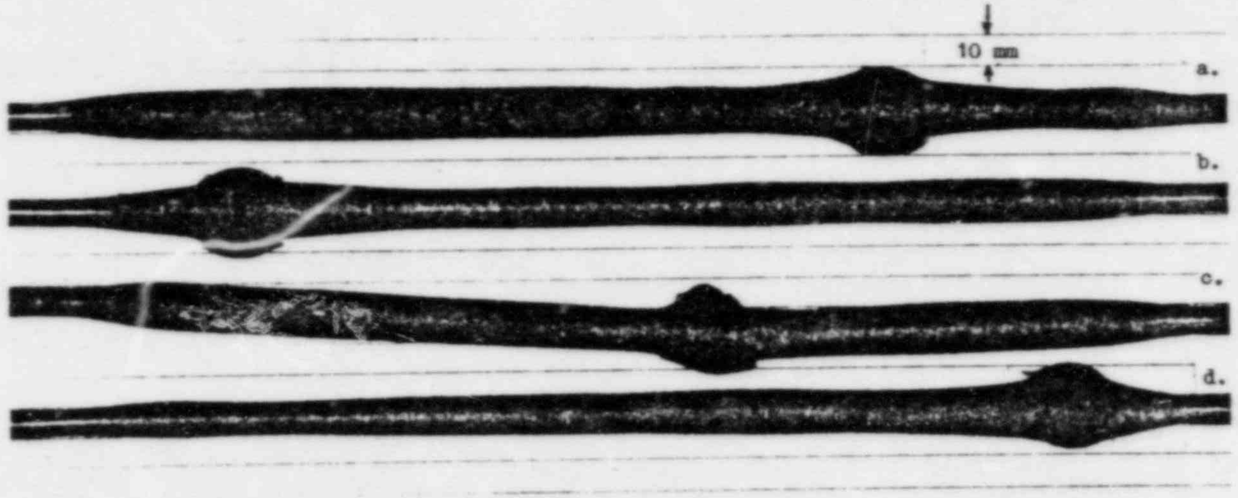
FIG.10. RESULTS OF STYLISED TRANSIENT TESTING IN HATCHED AREAS OF FIGS 6 & 7



HFL 7216

Fig. 11 Specimens failed during temperature ramping 10K/s (see Fig. 10)

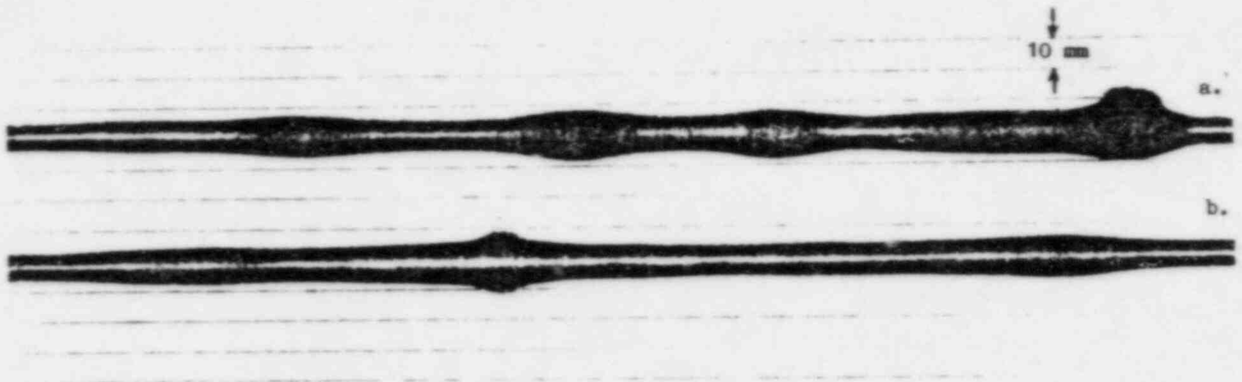
a. Initial pressure 7.03 MN/m^2 (1020 lb/in^2), ruptured at 1073K (800°C)
b. " " 11.17 " (1620 "), " " 973K (700°C)



RFL 7218

Fig. 12 Stylised transient specimens failed during isothermal conditions after ramping at 10K/s (see Fig. 10)

a.	Initial pressure	6.21 MN/m^2	(900 lb/in^2),	ruptured after 65 seconds	at 1033K	(760°C)
b.	" "	10.34 "	(1500 "),	" " 41 "	" 953K	(680°C)
c.	" "	11.17 "	(1620 "),	" " 66 "	" 933K	(660°C)
d.	" "	9.51 "	(1380 "),	" " 50 "	" 973K	(700°C)



RFL 7215

Fig. 13 Stylised transient specimens failed shortly after completion of temperature ramping 10K/s to a set temperature (see Fig. 10).

a. Initial pressure 6.21 MN/m^2 (900 lb/in^2), ruptured after 13 seconds at 1073K (800°C)
b. " " 10.34 " (1500 "), " " 18 " " 973K (700°C)

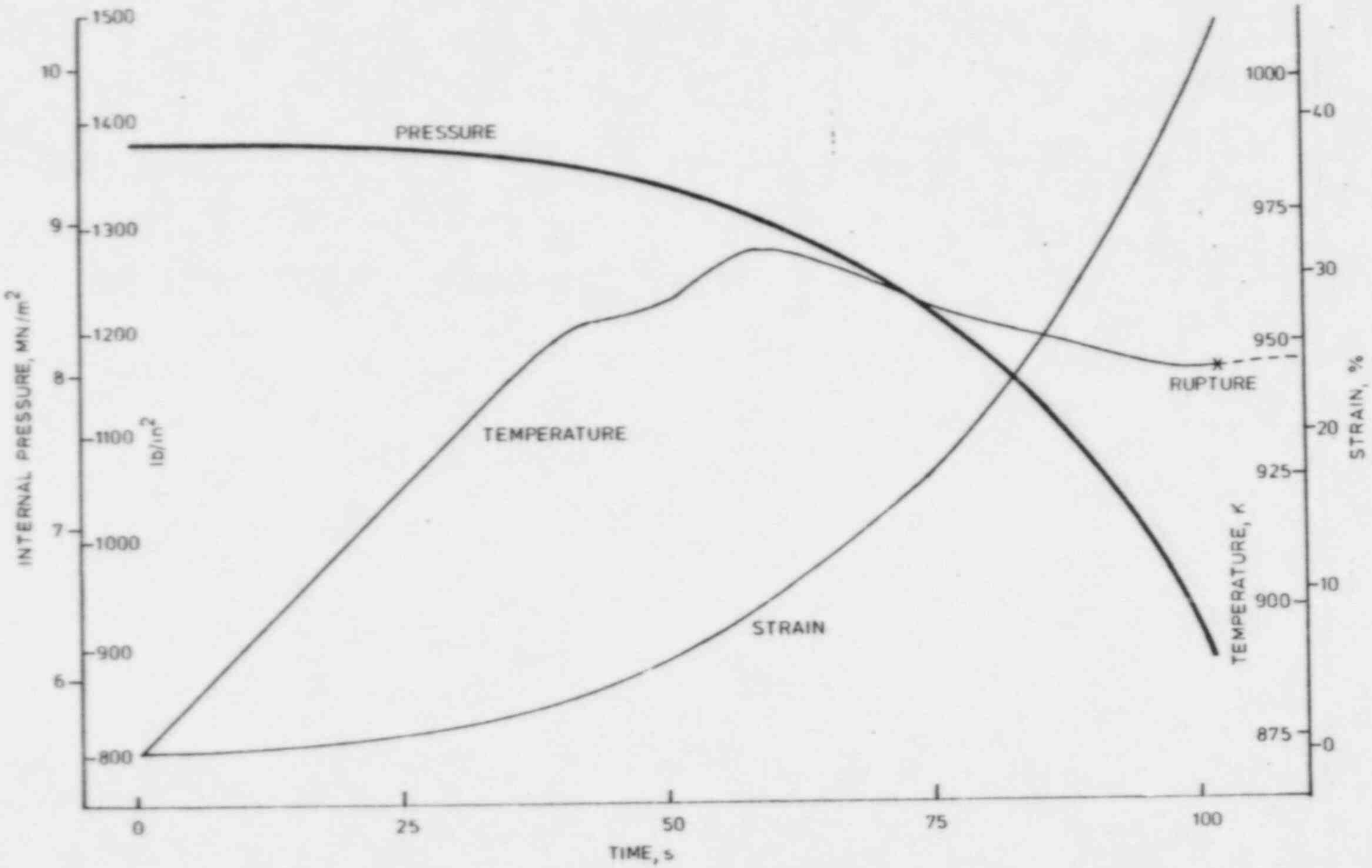
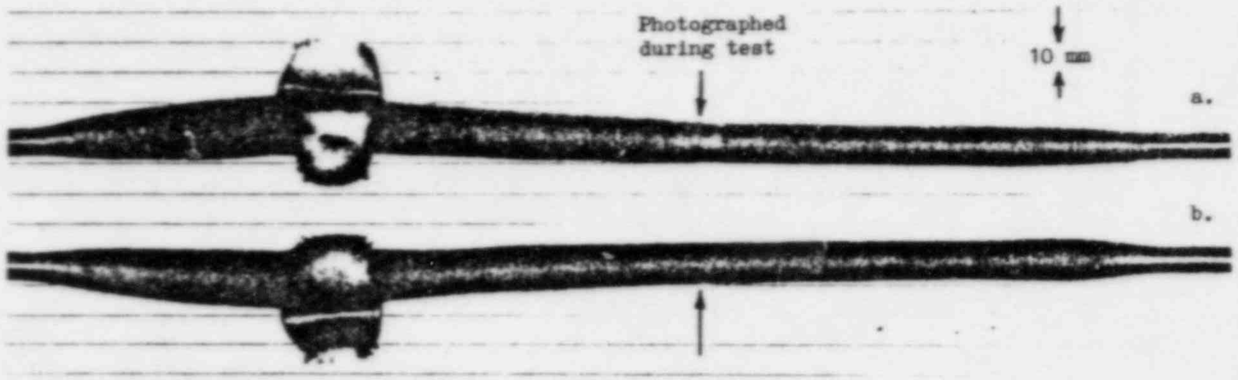


FIG.14. DIAMETRAL STRAIN TEMPERATURE AND INTERNAL PRESSURE AS A FUNCTION OF TIME DURING SIMULATEDTRANSIENT TESTING IN STEAM FIG.6. COLD LEG BREAK TEST 81 TABLE 1

N.B. STRAIN RECORDED AWAY FROM LARGEST STRAIN REGION SPECIMEN SHOWN IN FIG.15a



RFL 7217

Fig. 15 Specimens failed during transient testing

a. Fig. 6, cold leg break: peak temperature 973K (700°C). Initial pressure 9.51 MN/m^2 (1380 lb/in^2) (see also Fig. 14).

b. Fig. 7, pump section leg break: peak temperature 953K (680°C). Initial pressure 10.34 MN/m^2 (1500 lb/in^2) (see also Fig. 16).

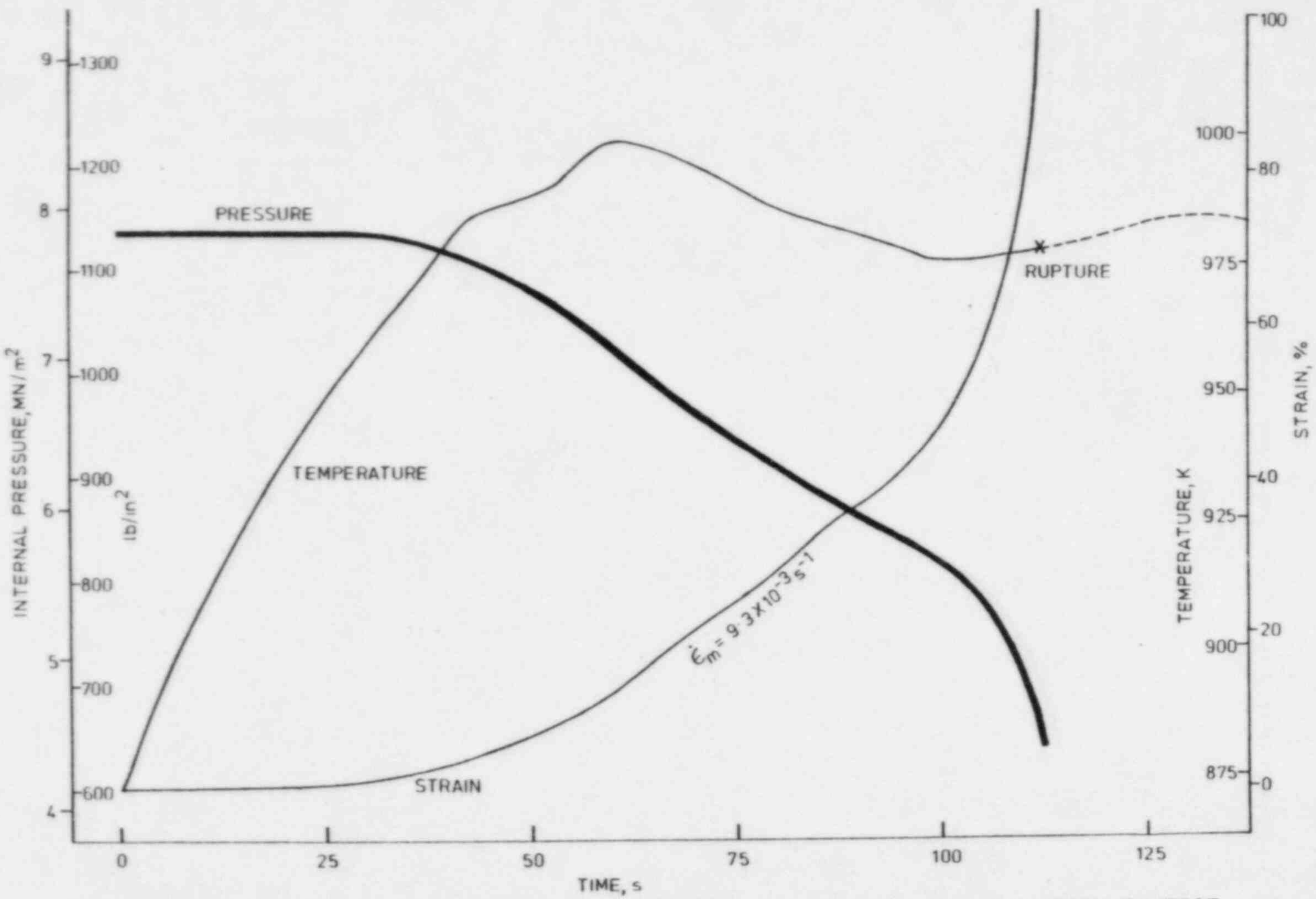


FIG.16. DIAMETRAL STRAIN TEMPERATURE AND INTERNAL PRESSURE AS A FUNCTION OF TIME DURING SIMULATED TRANSIENT IN STEAM FIG.6. COLD LEG BREAK TEST 78 TABLE 1

N.B. STRAIN RECORDED AT REGION OF MAXIMUM STRAIN

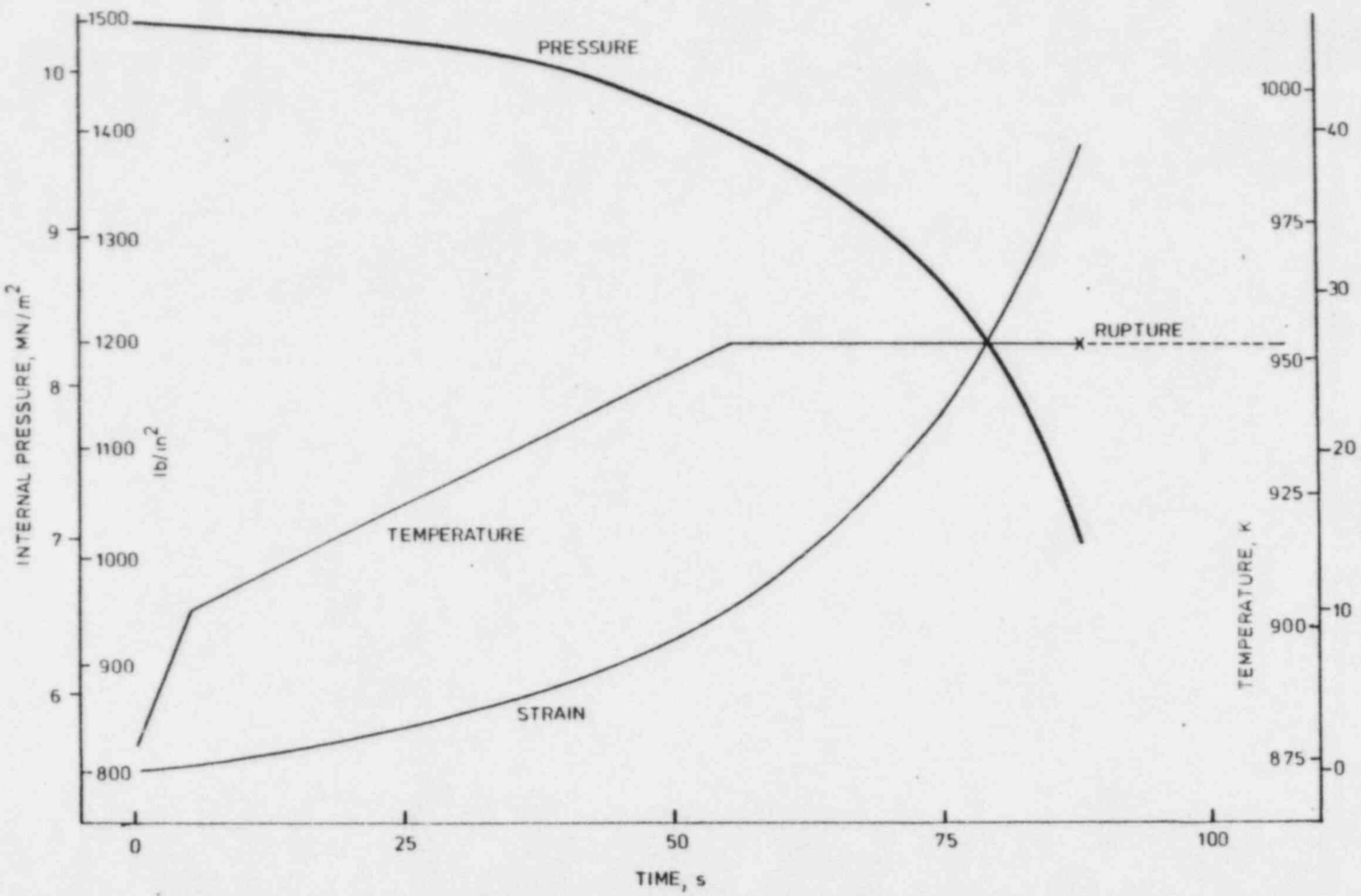


FIG.17 DIAMETRAL STRAIN, TEMPERATURE AND INTERNAL PRESSURE AS A FUNCTION OF TIME DURING SIMULATED TRANSIENT TESTING IN STEAM, FIG.7. PUMP SUCTION LEG BREAK TEST 77 TABLE 1

N.B. STRAIN RECORDED AWAY FROM LARGEST STRAIN REGION SPECIMEN SHOWN IN FIG. 15b