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FLUIDIZED BED COMBUSTION 1000 HOUR TEST PROGRAM

Volume IV—Engineering Details and Post Test Inspections

By
A. G. Roberts
S. N. Barker
R. N. Phillips
K. K. Pillai
P. Raven
P. Wood

September 1981

Work Performed Under Contract No. AC01-78ET10423

NCB/Coal Utilization Research Laboratory
Leatherhead, England

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Prepared For

UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia

Under Contract
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The principal members of staff involved were: A.G. Roberts (Planning & Coordination); P. Raven (Project Leader); R.N. Phillips (Project Engineer); R.V. Wardell, J. Curtis & S.N. Barker (Plant Operation); D. Crawford (Design); K.K. Pillai & P. Wood (Data assessment); and K. Cox, W.A. Gearing, R. Keating, A.W. Lindsay, R. Lowman, L.E. Mummery.

The following organisations, in addition to the Department of Energy, took part in the planning and execution of the programme: Electric Power Research Institute (EPRI); American Electric Power Corporation (AEP); Stal-Laval Turbin AB; General Electric (GE); Combustion Systems Ltd. (CSL) and Babcock International Ltd. The assistance of all who were involved, either directly, or indirectly, is gratefully acknowledged.

ABSTRACT

Volume IV of the report on the 1000 hour programme consists of three appendices giving details of the engineering/construction aspects of the plant and reports from Stal-Laval Turbin A.B.

CONTENTS

VOLUME IV

APPENDIX L : ENGINEERING DETAILS

APPENDIX L. CONTENTS

List of Tables

List of Diagrams and Photographs

Inspections

1. INTRODUCTION

The 1000 hr test programme carried out in the pressurised fluidised-bed facility at Leatherhead during 1979 had three main objectives which were to assess:

(i) the performance of alloys which may be suitable for fabrication of the tube bank

(ii) corrosion/erosion/fouling of candidate gas turbine alloys

(iii) the performance of gas cleaning equipment, together with comprehensive techniques for assessing particulate concentration in the combustion gases.

To carry out the programme major modifications and additions had to be made to the Leatherhead PFBC Test Facility. These broadly involved,

(i) Installing a new combustor in the existing pressure vessel.

(ii) Providing an additional cyclone, a Stal-Laval cascade and associated ductwork and ancillary equipment on one stream from the combustor (Stream 1).

(iii) Providing a new clean-up train of three cyclones on the second stream (Stream 2), a GE cascade of airfoils, and associated ductwork and ancillary equipment. This stream incorporated some existing equipment.

(iv) Providing additional lock hopper systems for dust removal from the cyclones and modifying the existing ones.

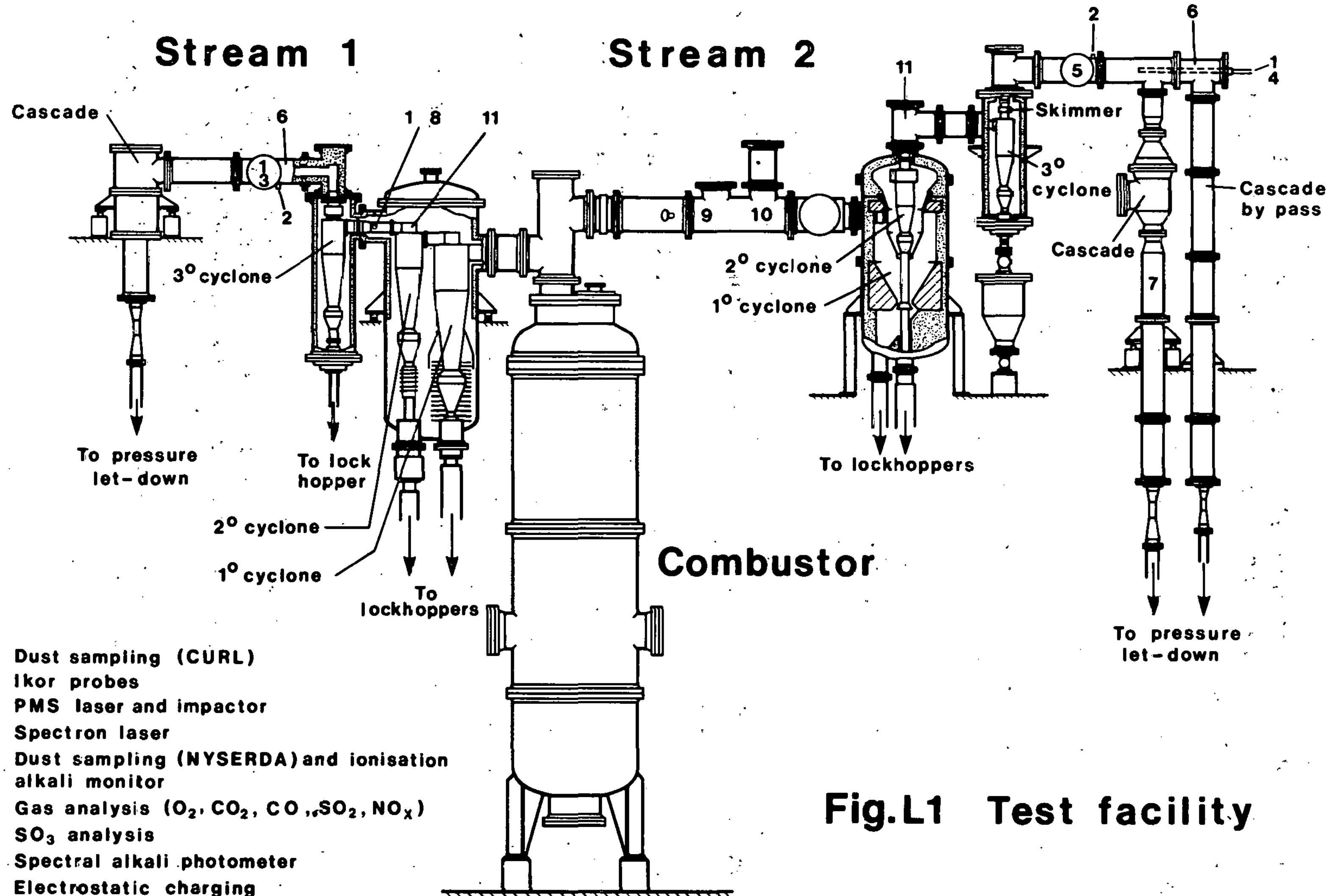
(v) Replacing the Petrocarb coal flow feed control arrangements by rotary valves.

(vi) Installing special cooled and uncooled corrosion specimens in the combustor.

All site installation work and the greater part of the design and construction work associated with the hot gas ductwork, and hot gas clean-up systems was carried out by Leatherhead personnel. The arrangement of the plant is shown diagrammatically in Fig. L.1.

The major part of the work was carried out under Contract ET-78-C-01-3121* but a number of other organisations contributed to and participated in the programme.

* From US Department of Energy



1. Dust sampling (CURL)
2. Ikor probes
3. PMS laser and impactor
4. Spectron laser
5. Dust sampling (NYSERDA) and ionisation alkali monitor
6. Gas analysis (O_2, CO_2, CO, SO_2, NO_x)
7. SO_3 analysis
8. Spectral alkali photometer
9. Electrostatic charging
10. Electrostatic charge sampler
11. Propane injection (reheat)

Fig.L1 Test facility

Organisation		Contribution
(i) Electric Power Research Institute	:	via Contract with Fluidised Combustion Contractors Ltd. (i) special cooled and uncooled specimens for materials evaluation in the combustor. (ii) alternative refractory materials for the combustor walls. (iii) tertiary cyclone and associated duct work for Stream 1.
(ii) Combustion Systems Ltd.	:	via Babcock, Renfrew, the tube section of the combustor.
(iii) Stal-Laval Turbin AB	:	Cascade of turbine blades including supervision of testing, between-test and post-test evaluation.
(iv) General Electric	:	via contract from US DOE (i) cascade of airfoils, supervision of testing, between-test and post-test evaluation. (ii) coordination of initial test programme planning. (iii) design data for Stream 2 hot gas clean-up system, Nyserda sampling equipment, equipment for providing and for measuring electrostatic charging, and operator training for the latter.
(v) American Electric Power	:	Supply of coal and dolomite.

Appendix L describes the engineering of the rig in more detail than hitherto and comments upon the operational behaviour of the important components.

2. DESCRIPTION OF THE TEST FACILITY

2.1. The Combustor

General

The combustor (Fig.L.2) consisted of a refractory-lined casing situated within a vertical pressure shell of 6 ft internal diameter. Air compressors supplied the fluidising/combustion air which entered through a connection at the top of the pressure shell. The air flowed downwards around the outside of the combustor (cooling the casings in the process) and then upwards through the distributor plate and into the bed. Thus the walls of the refractory-lined casings had to withstand only the pressure differential due to the pressure drop imposed by the distributor plate and the fluidised bed.

Tube Bank and Containment

The containment tapered from the distributor plate to the level of the top of the tube bank. The metal casing was of 3/8 inch thick carbon steel and was lined with insulating and hard refractory (see P. 6 for refractory details). The cross-section inside the refractory was 2 ft x 2¼ ft at the top (Figs.L.2 and L.3).

The tube bank extended from 2 ft to 8 ft above the distributor plate. The general tube geometry was representative of that being considered for the design of the AEP/Stal Laval Engineering Test Facility (The Tidd Plant). The tubes were of 1½ inch o.d. heat-resisting steel on a 6¼ inch horizontal pitch and a 3¾ inch vertical pitch. Alternate rows were displaced to give a pattern which, while it was staggered, was not uniformly triangular throughout the tube bank. The proportion of bed volume (within the tube bank) occupied by tubes was about 15%.

The tubes were formed in the shape of single hairpins. The feed and return pipes passed through the sloping end walls of the tapered section of the casing, being welded in position from the outside and set in the refractory on the inside. Alternate rows were mounted from opposite ends so that half the tube bank was mounted from one end wall and half from the other. This contruction can be seen in Fig. L.44 a photograph of one half of the tube bank taken after dismantling the combustor at the end of the programme.

In the upper part of the combustor, each hairpin formed an individual water circuit. In the lower part of the combustor, two hairpins at the same level were connected in series, external to the casing, to form a single water circuit.

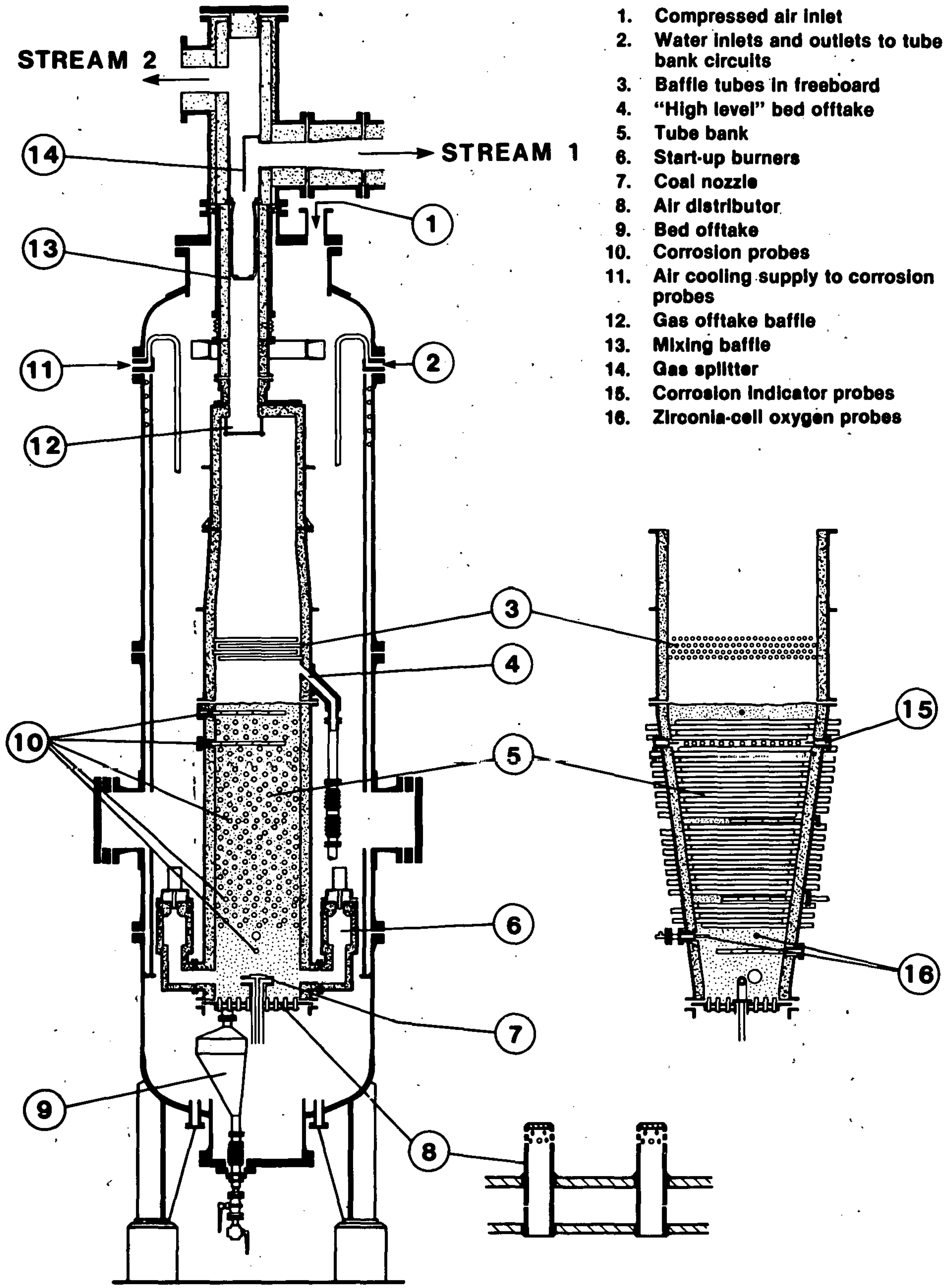


Fig. L2 ARRANGEMENT OF FLUID BED COMBUSTOR Mk VI

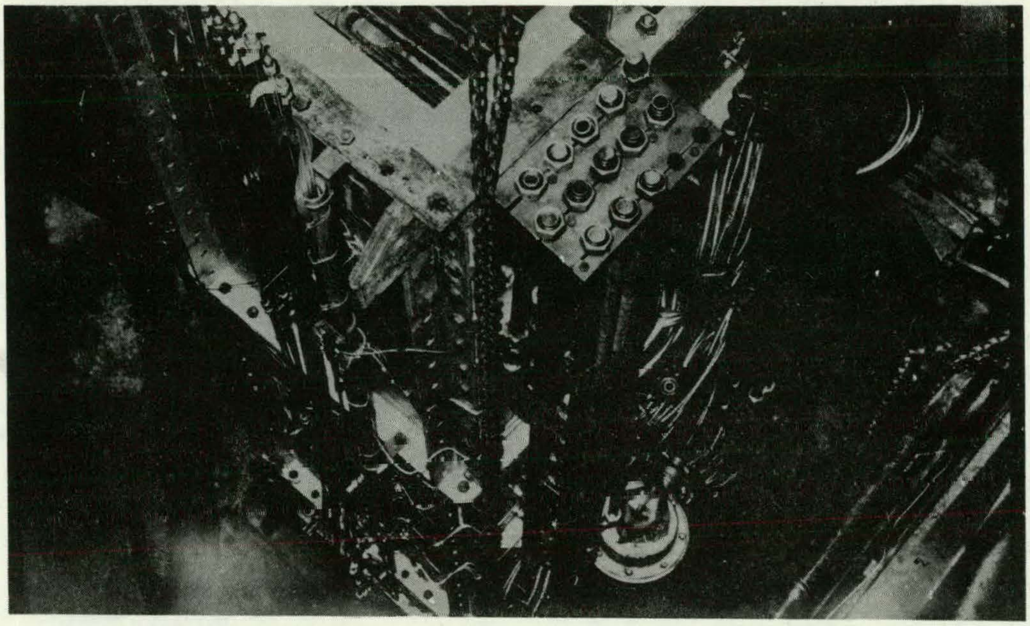


Fig.L3 "Tapered" Combustor casing before lowering into pressure vessel

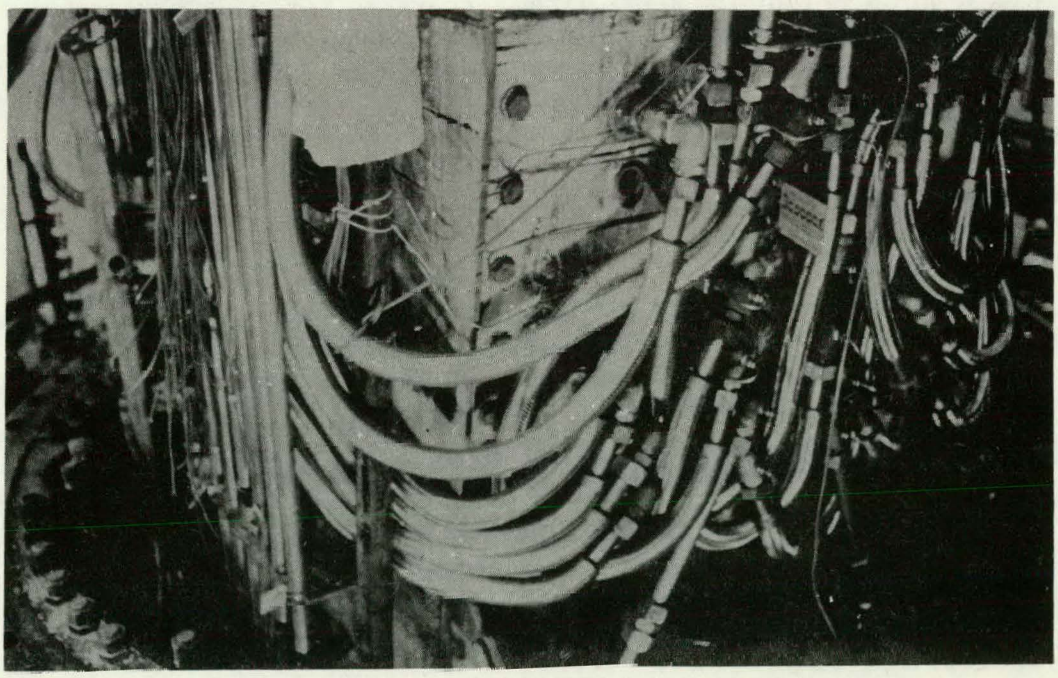


Fig.L4 North End wall showing tube bank water connections

Becuse water at low temperature was the cooling medium on the Leatherhead rig, only a part of the tube bank was cooled, the remaining tubes operating at bed temperature. The cooled tubes were distributed more or less evenly throughout the tube bank. Each cooled circuit had a separate water inlet and outlet with thermocouples to measure the temperature rise so that the heat flux to each circuit could be accurately monitored. (Fig. L.4). The circuits were of differing lengths, but no circuit included tubes at more than one elevation.

Baffle Tubes and Freeboard

The casing section above the tapered part of the combustor constituted the lower of the two freeboard casings, and contained the baffle tubes. These started 110 inches above the distributor plate (i.e. about 14 inches above the nominal bed level) and were in four rows on a triangular pitch of 2 inch vertical and 2 inch horizontal centres. They were constructed of 1 inch o.d. heat-resisting steel tube and were welded at one end to pegs attached to the casing and protruding through the refractory. Alternate tubes were attached to opposite sides, and the free ends were supported by brackets fixed to adjacent tubes. The baffle tubes were at right angles to the tubes in the tube bank.

The total freeboard height above the nominal bed level was 8 feet. 10 inches above the baffle tubes the casing section converged slightly (over a height of 2 ft) from 4 ft x 2¼ ft to 3 feet 11 inches x 1 foot 11¾ inches. This was necessary in order that the topmost freeboard casing and suspension steelwork from previous forms of the combustor could be re-used. Gases left the freeboard through a 9 inch diameter exit in the roof of the combustor. In the upper part of this gas offtake the gas flow was split into the two streams (Fig. L.5).

Corrosion Specimens

Inserted into the bed, mostly within the tube bank, but some below the tube bank and some in the freeboard were corrosion specimens manufactured from alloys that might be used in a commercial plant. There were basically four types of specimen:

1. Cooled corrosion probes. These were made up of four tubular specimens, 1¼ inches in diameter and approximately 4½ inches long, welded together to form a probe approximately 22 inches long and cooled internally by an air supply which was controlled to give a specified metal temperature on one of the specimens. A thermocouple was embedded in the wall of each specimen to monitor its temperature. Cooling air for the probes was

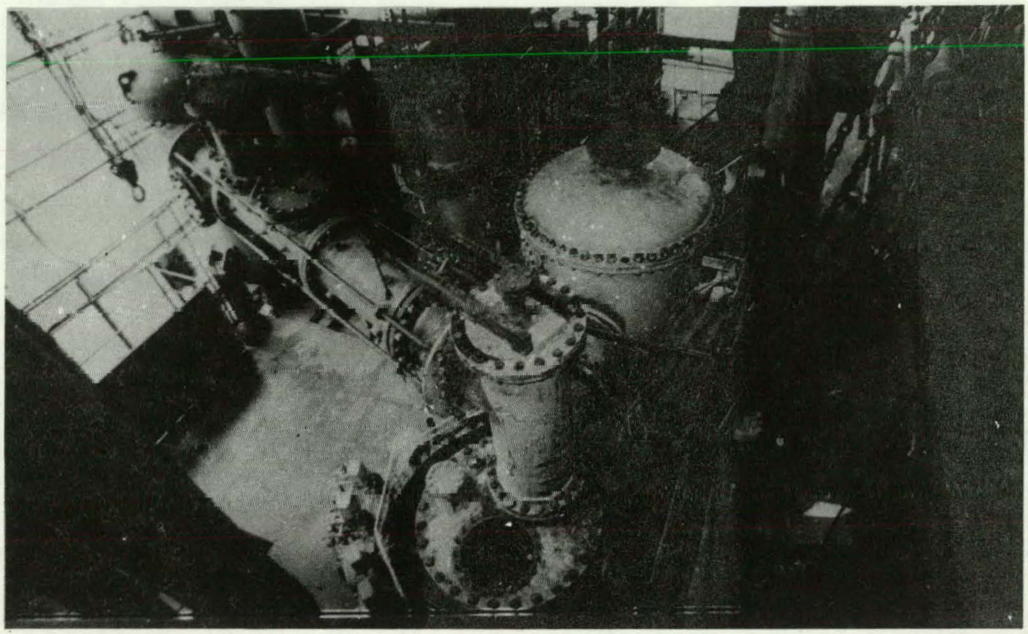


Fig.L5 General view of facility showing Streams1 and 2.

diverted from the main combustion/fluidising air downstream of the pressure and flow controlling elements. The air exhausting from the probes was piped to a position below the distributor plate where it mixed with the main fluidising air.

2. Uncooled corrosion probes. These were of a similar construction to the cooled probes, but had no cooling air supply. The specimens were made of two materials - Incoloy 800 H and Inconel 617. Previous experience had shown that these alloys could be used to indicate the corrosion potential in different parts of the bed.

3. Uncooled corrosion rods. A number of ¼ inch diameter rods, of various materials, were inserted through the combustor casing to a depth of 3 inches at various positions. These rods were drilled axially to take a thermocouple.

4. Corrosion indicators. A number of rods were hung from two of the uncooled tubes in the tube bank. These rods were made of two materials - Incoloy 800 H and Inconel 617.

A full description of the corrosion investigations will be given elsewhere*. The general location of the specimens is shown in Fig. L.6.

Distributor Plate

A cross-section of part of the distributor plate is illustrated in Fig. L.7. Passing upwards through two mild steel plates were 70 heat-resisting steel tubes on a 3 inch x 3 inch square pitch. The upper ends of the tubes were closed off. The tubes were ¾ inch O.D. and each had fourteen 1/8 inch diameter holes in two rows drilled through the walls so that the fluidising air emerged approximately horizontally into the bed. The bottom row of holes, which was 1 inch above the top plate of the distributor, defined the start of the fluidised bed. Six of the nozzles were made from different materials for investigating corrosion behaviour and were fitted with thermocouples. Two of the six nozzles extended a further 2 inches into the bed (the air inlet holes remained at the same level) so that additional information on corrosion behaviour at higher metal temperatures could be obtained.

The chamber between the mild steel plates was internally divided into a number of sections from which propane could be fed into the air nozzles via small holes. The propane was used to heat the bed during start-up. Each section had an individually controlled propane

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* The corrosion investigations within the combustor are covered by a separate contract between EPRI and Fluidised Combustion Contractors Ltd. (a joint venture company of Babcock International Ltd and British Petroleum). The results will be reported by FCCL to EPRI.

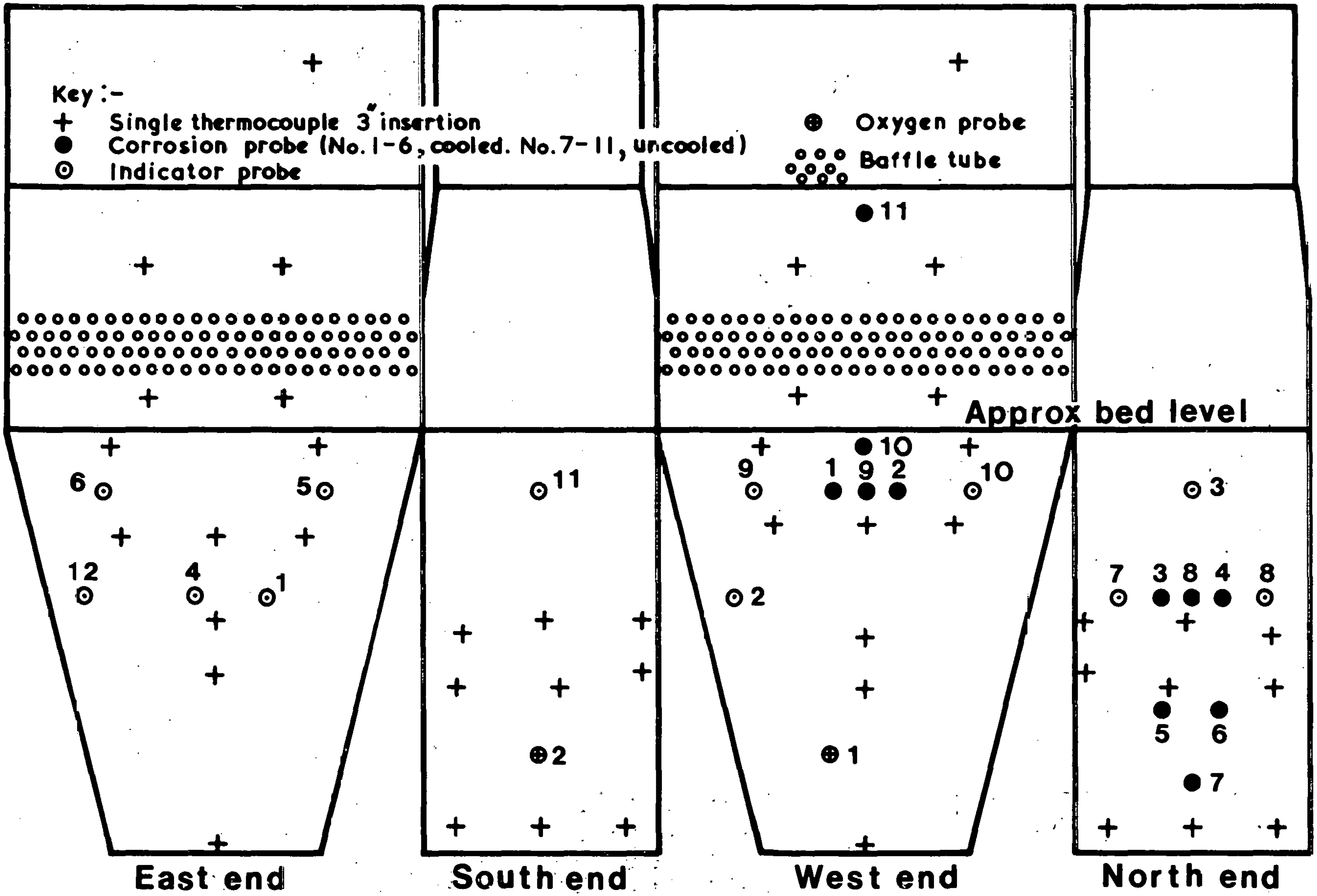

Fig.L6 Location of thermocouples and corrosion probes

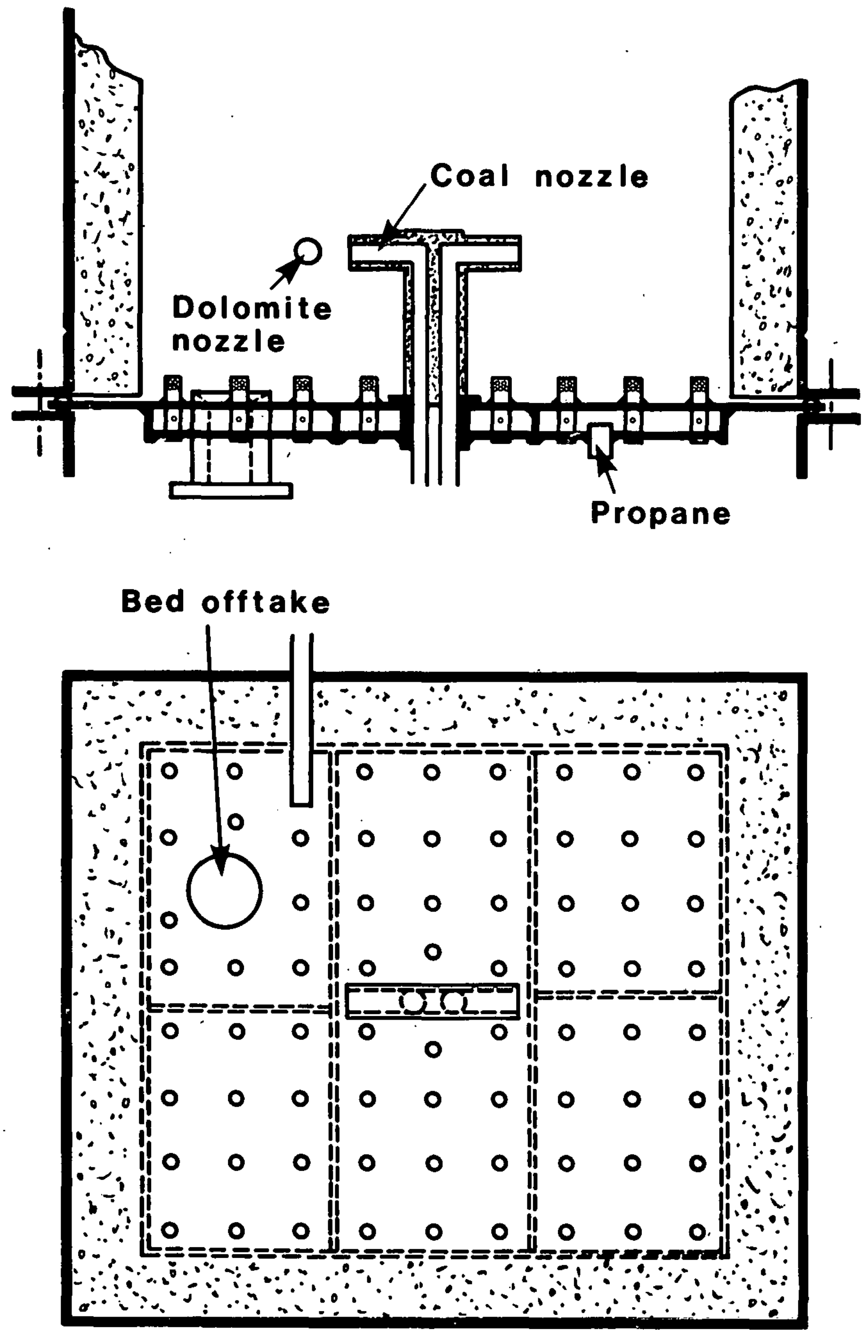

Fig. L7 Diagram of distributor and coal/dolomite nozzles supply and propane was fed first to those air nozzles closest to the start-up burners. Cold flow measurements of distributor pressure drop together with pressure drop measurement during combustor operation provided a relationship between p and a flow parameter F* which, for the distributor plate used in this programme, is shown in Fig. L.8. The pressure drop during normal operation, was about 20 inches w.g.

Refractory lining

The whole of the combustor and freeboard was lined with a 2-inch thick layer of hard-face refractory backed by a 1-inch thick layer of insulation refractory (thermal conductivity approx. 1.5 Btu/ft^2.h.^{o}F/inch). As part of the contract with EPRI, different faces of the combustor were lined with different refractories so that a comparison of suitability could be made. The types of hard-face refractory on the various faces are shown in Fig. L. 9. The refractory and insulation layers were secured by two-piece, stainless-steel 'Y' type anchors welded to the mild steel side and end plates. The tubes of the tube bank and the baffle were fitted to their respective casing sections before refractory was placed.

Tube Bank Services

Thermo-wells, pressure taps, corrosion probes, coal and dolomite nozzles and start-up burner combustion chambers were all bolted or screwed externally on the casings and were fitted as the sections were assembled. Thermowells were open ended of 5/16 inch o.d, 16 gauge heat-resisting steel, projecting approximately 3 inch in from the refractory wall of the casings. Pressure tappings finished flush with the wall. Positions of the thermocouples, corrosion probes, indicator probes, and Zirconia-cell oxygen probes can be seen in Fig. L. 6.

All connections to the bed casings were made either from the top or bottom of the cylindrical pressure casing or from one of the two 20-inch diameter manways on each side. Both the side manways and the top head connection incorporated sandwich ring flanges with radial tappings through which connections were made. The top dome flange ring also supported the steel frame from which the whole of the combustor casing assembly was suspended. Most water circuit connections to the tube bank were made through the tope dome flange ring, via vertical tubes fitted to the outside of the combustor casings (see Fig. L.4) connected to their respective bed tubes by corrugated stainless-steel flexible hose. Pressure tap impulse lines and thermocouple connections

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* F = (air mass flow)^2 x absolute temperature/pressure = constant x air density x velocity^2.

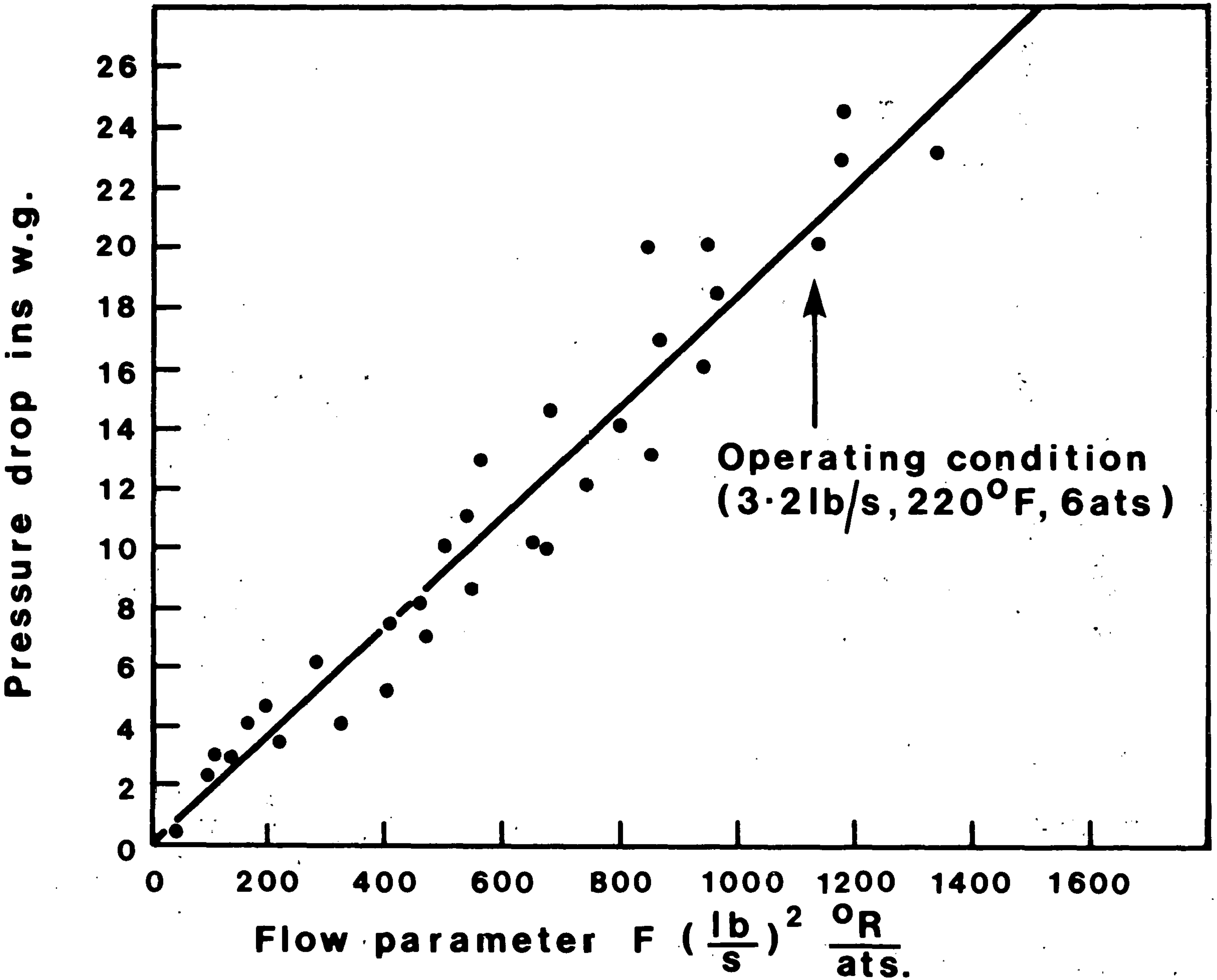
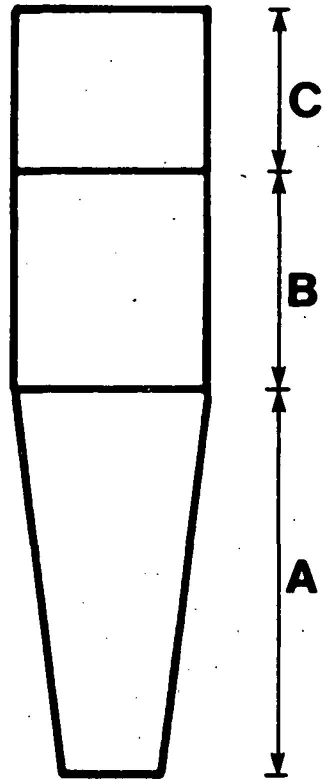


Fig.L8 Distributor plate pressure drop characteristic

D504



2 inches of refractory

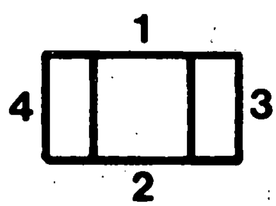
1 inch of insulation

<u>Refractory</u>:

Mid cast : Morgan refractories.

Mizzou
KS4
Bromcast 80

} A. P. Green



level \ side	1	2	3	4
A	Mizzou	KS4	Mid cast	Mizzou
B	KS4	Bromcast 80	Mid cast	Mizzou
C	Mid cast	Mizzou	Bromcast 80	KS4

Fig. L9 Details of refractory on combustor walls were made via multiple gland assemblies fitted to nozzles on the top dome of the pressure vessel. Thermocouple cables between measuring points and these glands were of standard compensating cable laid in conduit fitted to the outside of the combustor casings. The rest of the water circuit connections were made through the side manways together with supplies and controls to the two natural-gas-fired start-up burners, and cooling air supplies to the corrosion probes.

Coal and Dolomite Feed Nozzles

Two coal feed nozzles were sited 6½ inches above the base of the fluidised bed as shown in Fig. L.7. The nozzles projected vertically upwards through the distriubtor plate and ended with horizontal pipes so that the whole assembly simulated a single coal feed nozzle ending in a Tee in the fluidised bed. The nozzles had an internal diameter of 0.82 inches (¾ inch nominal bore pipe) and were thermally insulated from the fluidised bed to reduce the possiblilty of caking of the coal. Dolomite was fed through the side of the combustor casing via a separate, uninsulated nozzle as shown in Fig. L.7.

Start-up Burners

The combustor was equipped with two gas-fired burners for initial bed heating (item 6 of Fig. L.2). These burners also acted as a source of ignition for propane vapour, supplied via the air tubes in the distributor, which augmented the heat output from the burners once a bed temperature of 400 - 600 ^{o}F had been reached.

Each burner consisted of a commercial air/natural gas burner, with integral flame failure control, firing into a small refractory-lined combustion chamber into which dilution air was added to reduce the gas temperature to about 1600 ^{o}F. Each burner had a normal heat input of 0.2×10^{6} Btu/h and the combustion gases were emitted into the bed at a velocity of about 50 ft/s through 4 inch diameter holes in the wall of the main combustor, sited approximately 8 inches above the distributor.

Removal of Bed Material

During normal operation, bed height increased due to the release of ash from the coal and to the accumulation of dolomite used for the retention of sulphur. Bed depth, which was monitored by differential pressure readings, was maintained at the required level by periodic removal of bed material via a small hopper and an ash off-take tube (item 9 of Fig. L.2). This passed down through the space within the pressure shell below the distributor to be discharged to atmosphere through two manually operated 1-inch diameter full flow valves (one a Neles and the other a lubricated plug valve with a cooled base).

2.2. Solids Preparation and Feeding

Coal Preparation and Storage

The coal was supplied, crushed and dried by an outside contractor to the desired specification. It was delivered by sealed road tankers which were discharged pneumatically into silos. The silos were purged with nitrogen to reduce the risk of overheating and condensation.

Occasionally during the programme excessively fine material reached the combustor. This was mainly due to poor quality control by the supplier but it is probable that some segregation did occur in the silos despite them being equipped with anti-sgregation bases.

Coal Pressurising

The equipment was generally as shown in Fig. L.10. It was originally supplied by Petrocarb Inc. but had been modified substantially by CURL over a period of several years. The storage and feeder vessels formed a lock-hopper feeding system. The system was provided with instrumentation for automatic sequencing, but, as the capacity of the vessels was such that the cycle time was about 10 hours, the valve sequence was operated manually. The normal interlocks were included to ensure safety in the event of human or mechanical error.

When a low level was indicated in the feeder vessel, nitrogen was blown into the storage vessel until its pressure equalled that of the feeder vessel. The interconnecting valves were then opened and material allowed to flow by gravity. Displaced gas from the feeder flowed through a balance pipe to the storage vessel. After transfer, the vessels were isolated and the storage vessel was vented to atmosphere. Re-filling from the silos was via a dense phase pneumatic conveyor, the coal having been first screened to remove oversize and tramp material.

The feeder vessel pressure was automatically controlled at approximately 7 psi above the combustor casing pressure to provide the pressure head necessary to transport the coal and to minimise the risk of reverse flows owing to pressure fluctuations in the combustor. The control of this pressure difference was accomplished by injecting a constant flow of nitrogen into the feeder vessel and throttling the flow through the vent line to atmosphere.

The weight of coal in the system was measured by two sets of load cells, one on each of the vessels. To allow independent weighing, the vessels were mechanically isolated from each other by flexible bellows. These flexible sections were normally vented to atmosphere to eliminate errors in load cell readings caused by a variable pressure in the bellows leading to variable thrusts on the valves on either side.

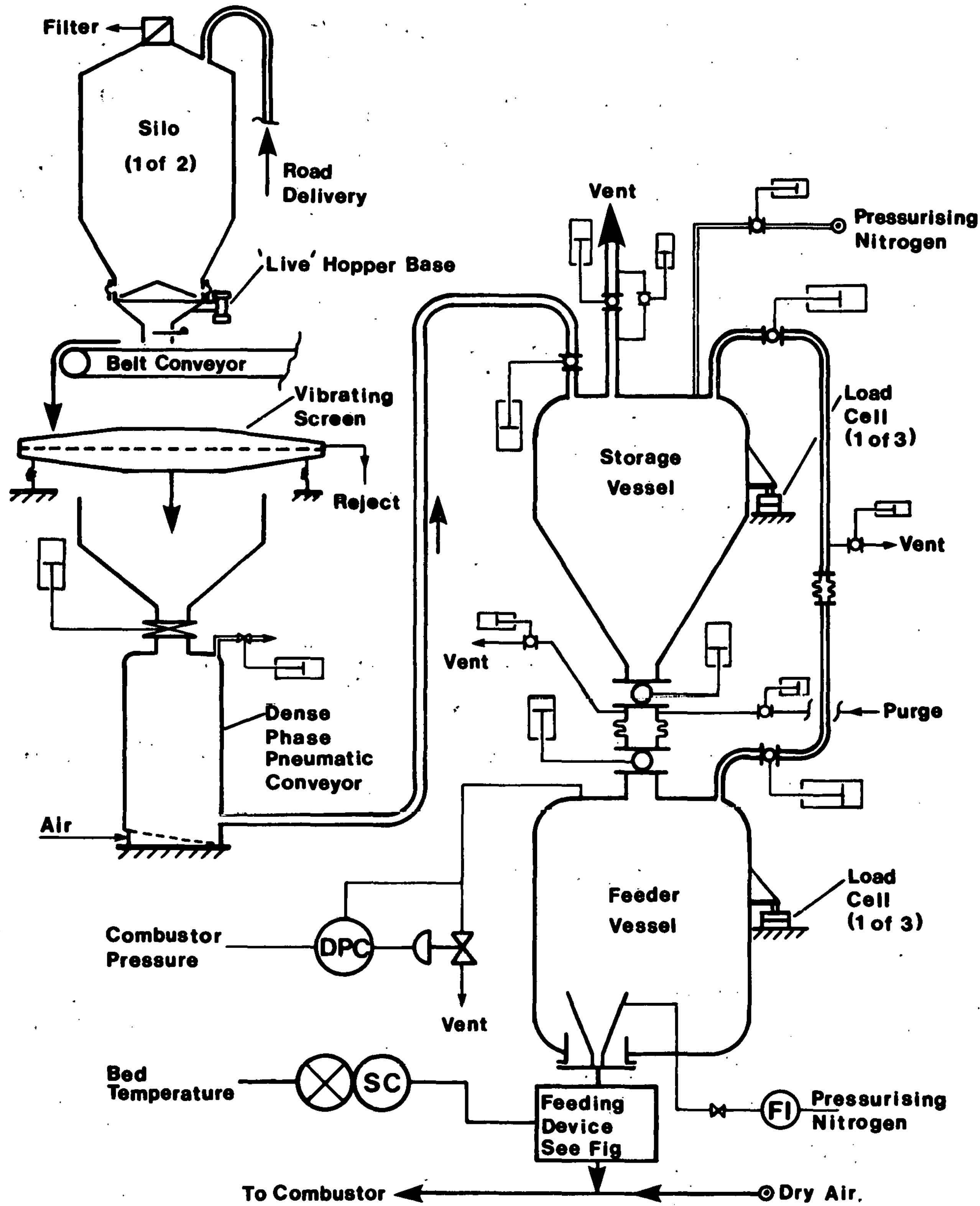


Fig. L10 Coal Storage and Lock Hopper

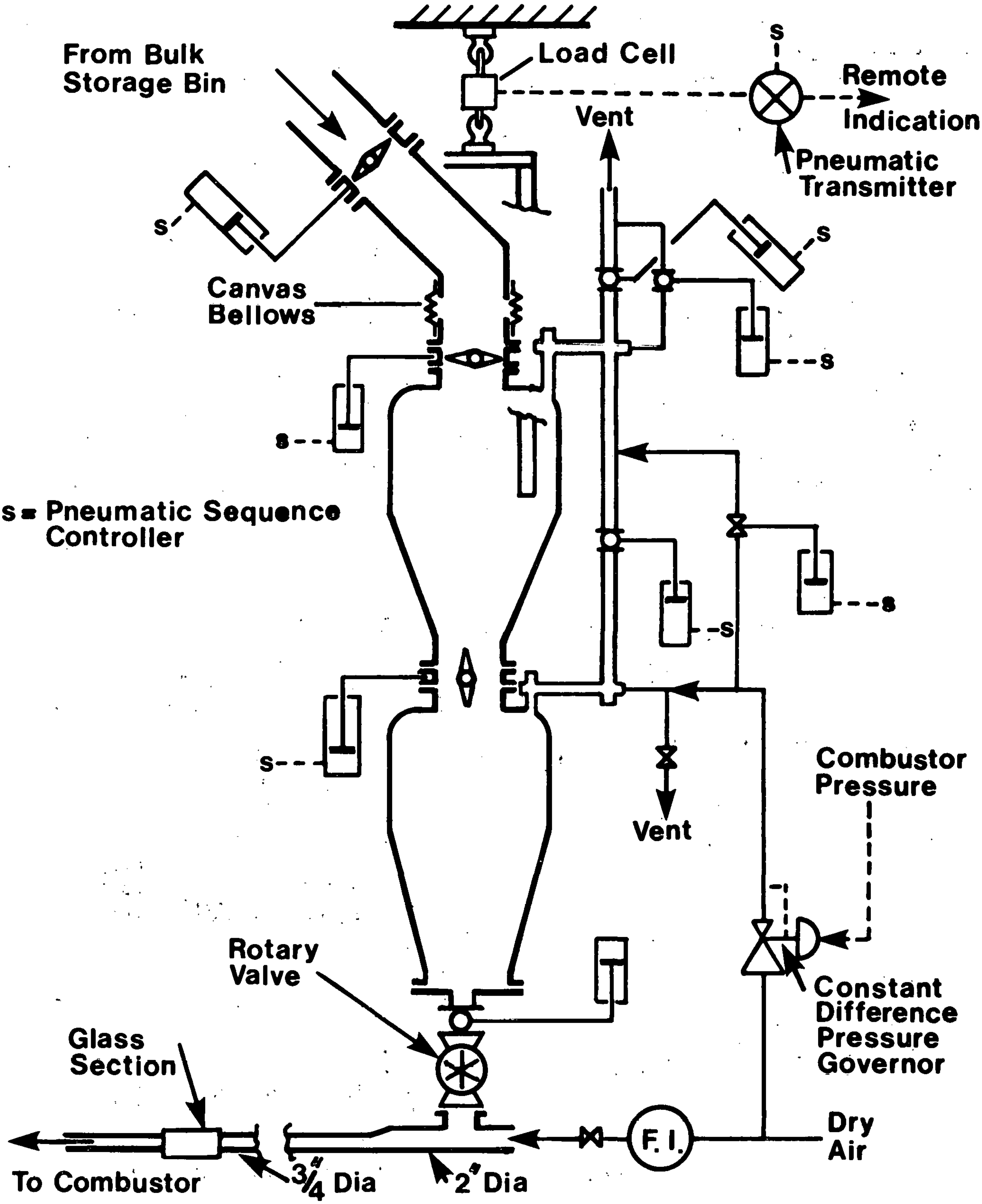


Fig. L11 Dolomite Feeder

Coal Feeding

The Petrocarb vessel was equipped with six offtakes. Three types of feed control device were installed:

two rotary valves
two 'L' valves
two modified Petrocarb offtakes.

Only the rotary valves were used - the others were 'back-up' arrangements in the event of rotary valve failure. The rotary valves were built specially for the programme by the manufacturer* whose design was developed in consultation with CURL. Features of the design of the rotary valves and comments on their performance are given in Section 3.

Dolomite Storage, Pressurisation and Feeding

The equipment used was generally as shown in Fig. L. 11. The sorbent, delivered in paper sacks, was first screened from tramp material and oversize before being conveyed pneumatically to a bulk storage bin. From this bin the material flowed by gravity into a lock hopper system, thence to the combustor via a rotary valve and a dilute phase pneumatic conveying line. Feed rate was manually controlled by varying the speed of the rotary valve drive.

The weight of material in the feeder was measured by a hydrostatic load cell. A pneumatic transmitter fitted to the cell gave signals for recording and sequence control.

The lock hopper valves were operated in sequence by a system of moving-part pneumatic logic elements. This system was entirely automatic and did not require manual interruption during normal operation. A series of interlocks was provided to prevent depressurisation of the feeder and to isolate it from the combustor in the event of malfunction.

During the final 150 hours of the programme, the sorbent was fed for part of the time using a pulsed 'L' valve. Features of design and operation of this and the rotary valve are given in Section 3.

---

* Westinghouse Brake & Signal Co, Controls & Automation Div, Chippenham, Wiltshire, England.

3. DESIGN AND OPERATION OF SOLIDS FEEDING SYSTEMS

3.1. Rotary Valves

The arrangement of the coal feed rotary valves beneath the feeder vessel with their associated equipment is shown in Figs. L.12 and L.13 and details of the valves themselves are shown in Fig. L.14.

CURL were aware that attempts to use rotary valves with coal at high pressures elsewhere had been unsuccessful due to leakage from the shaft seals and abrasion of the body and blades. Measures were therefore taken to minimise these problems as follows:

(a) The shaft seals were chevron gland packs which provided a perfect gas seal with no "pulling-up" needed during use.

(b) the seals were purged with clean, dry air to prevent dust and grit working into the packing.

(c) the bores of the valves were plasma sprayed with tungsten carbide and the blades manufactured from hardened steel.

(d) the rotor speed was kept low (typically 3 1/3 rpm).

(e) The pressure difference across the valve was kept low (about 4 psi) and the valves were used as simple volumetric meters, and not as airlocks.

The motor drives were shunt wound D.C. with solid state controllers. The set points of the controllers were adjusted either manually, or more usually, by a signal from the combustor bed temperature controller in the main control room.

The valves performed satisfactorily throughout the programme. The bed temperature was maintained very close to its desired value for virtually the entire running period. The few irregularities in coal feeding that did occur were a consequence of (a) excessive fines content of the fuel and (b) the impedence to flow of coal with high fines content caused by the small apertures at the bases of the Petrocarb offtakes. Automatic control of bed temperature was found to be feasible, and it was possible to maintain the bed temperature to within $\pm$ 10^{o}F over a test period of typically 200 hours. A typical set of operating conditions is given in Table L.1.

There was no leakage from the glands of the valves. However, on inspection after the first 250 hours operation the shafts were found to be grooved in the seal areas. These areas were hardened and reground after which the problem did not reappear. Failure to harden the shafts initially was an error on the part of the manufacturers. Blade wear was minimal (Figs. L.15 and L.16) and no wear of the body could be detected.

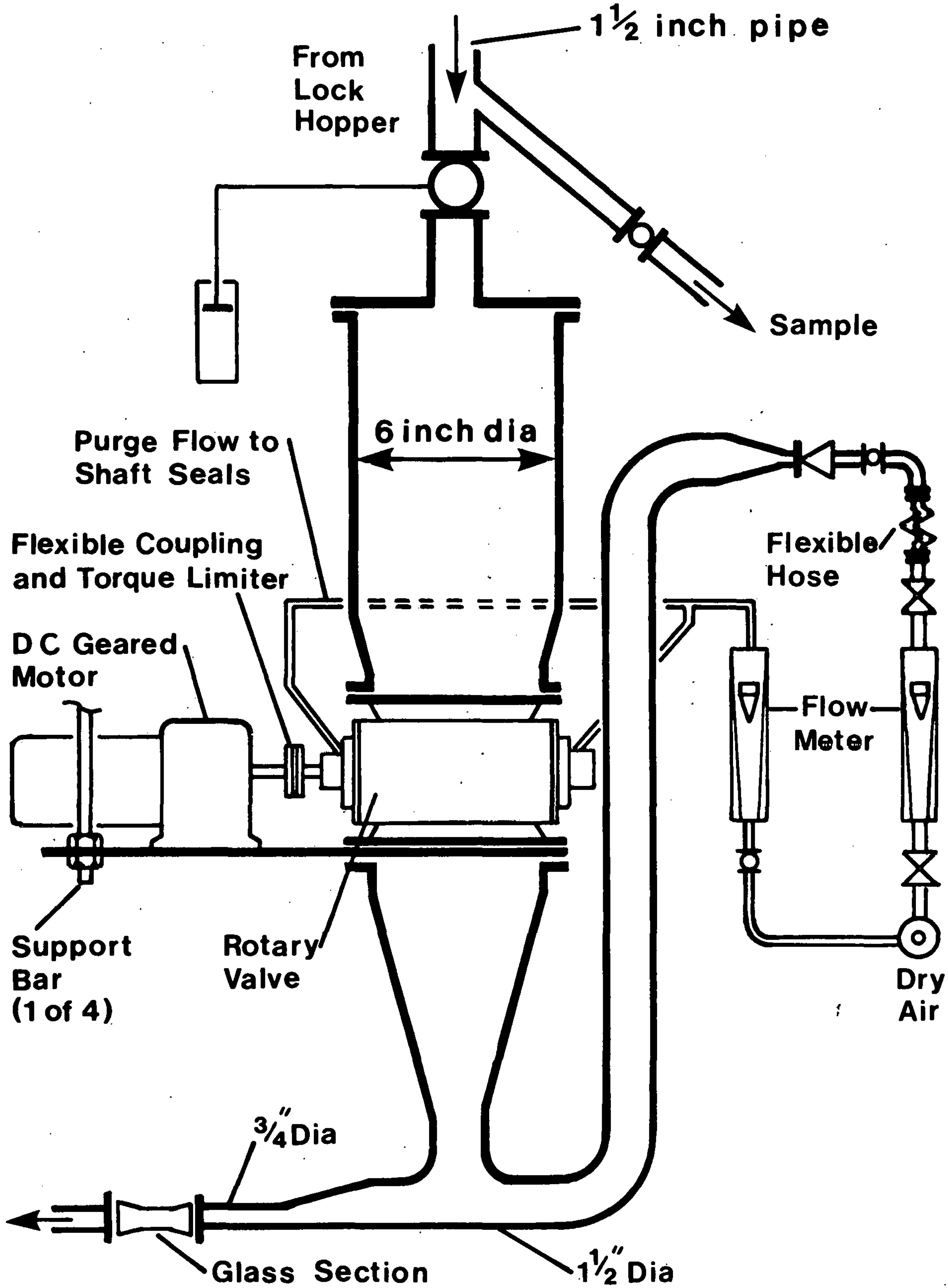


Fig.L12 Arrangement of Rotary Valve Under Lock Hopper

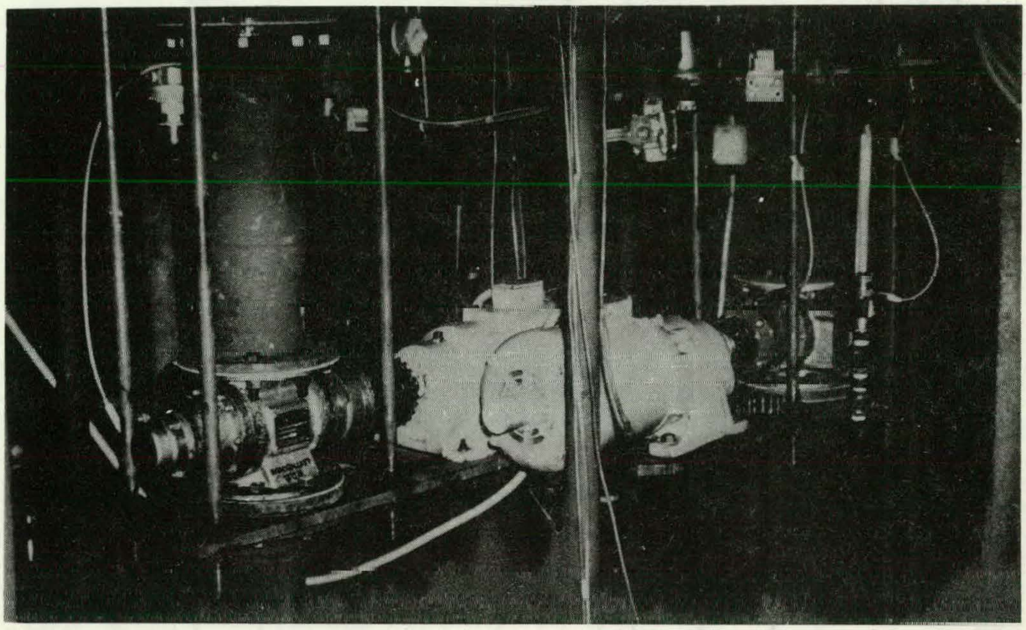


Fig. L13 Rotary valves on coal feeding system

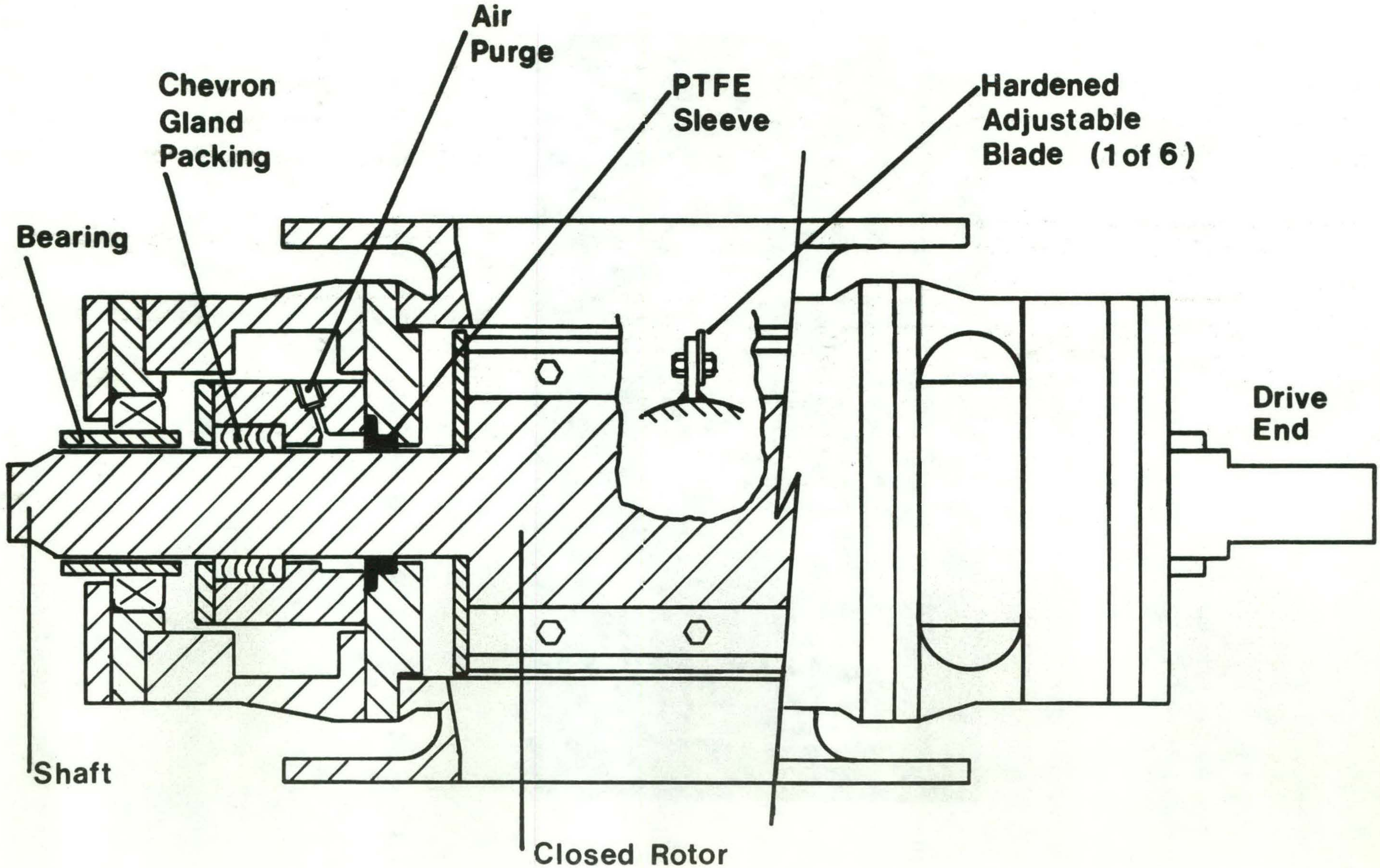


Fig.L14 Details of Coal Feed Rotary Valve

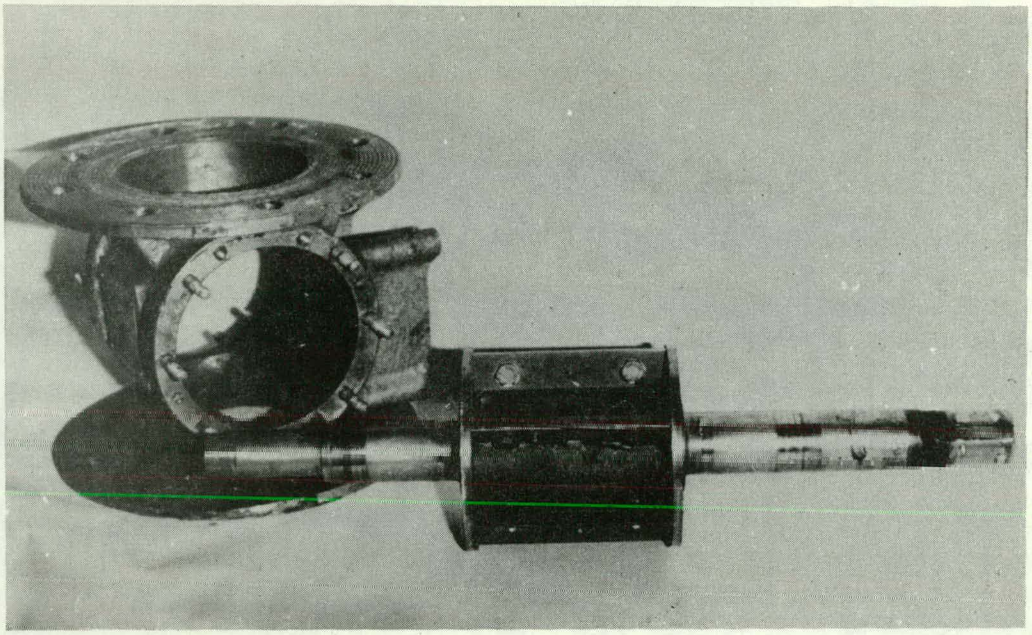


Fig.15 Coal feed rotary valve – Casing and rotor

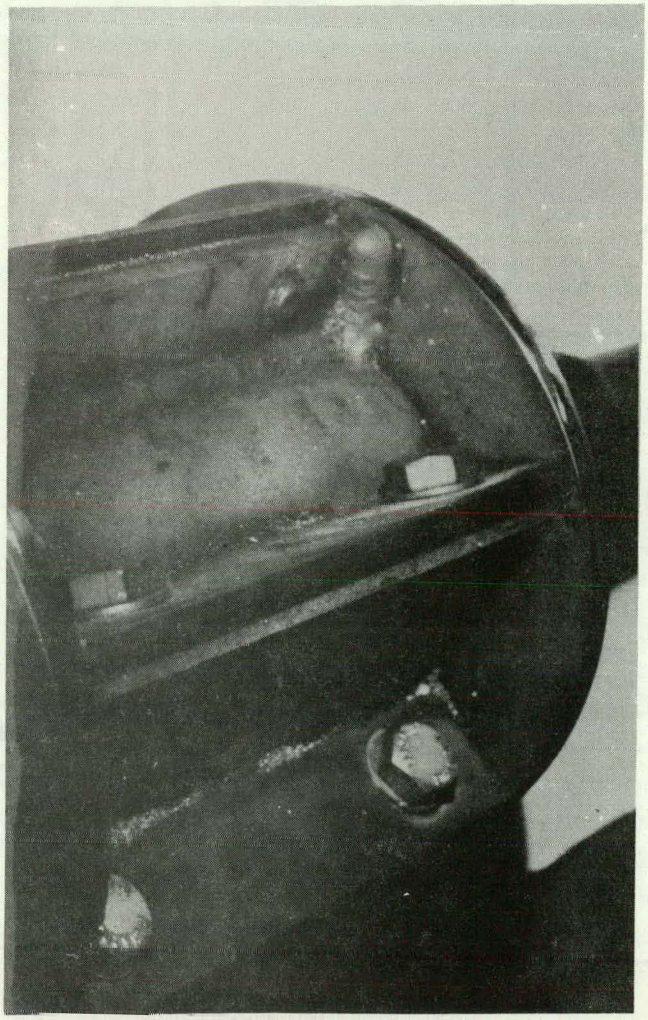


Fig.L16 Coal feed rotary valve rotor

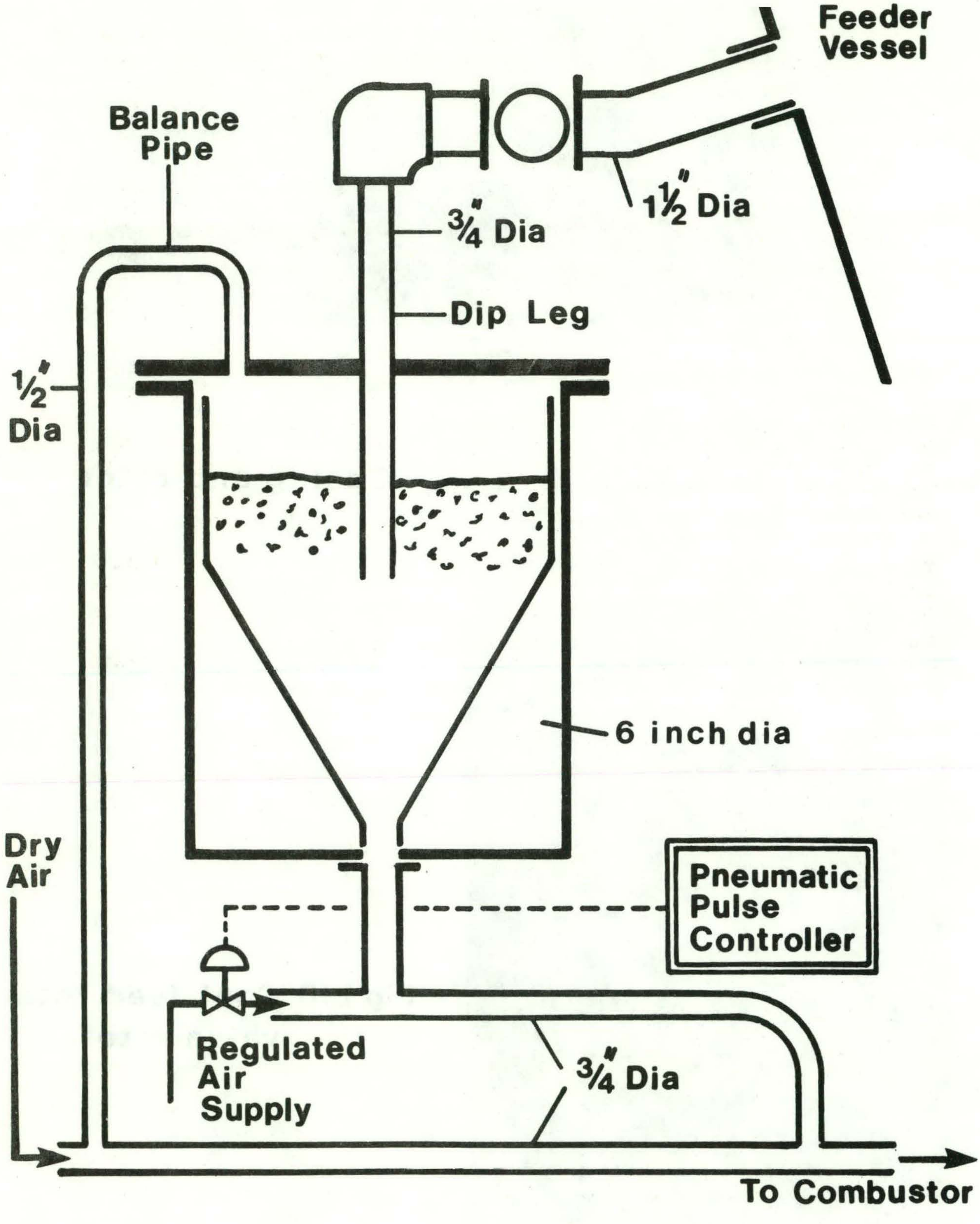


Fig. L17 Dolomite 'L' Valve Feeder

The rotary valve on the dolomite feeder was a standard (2 inch) model modified for high pressure use by the manufacturer*. The modifications consisted of installing a chevron packing in the shaft seals and strengthening the end covers. It was not possible to purge the shaft seals because of the small size of the valve.

The valve performed satisfactorily through the test. Some leakage was found through the drive end shaft seal of the rotary valve after 850 hours. This was probably due to the lack of an air purge. The gland packing and shaft were replaced between tests. A typical set of operating conditions is shown in Table L.2.

3.2. <u>'L' Valve</u>

The 'L' valve used on the dolomite feeder was generally as shown in Fig. L.17 and was based on the work carried out at Argonne National Laboratories. A small pressure vessel of approximately 2 lb. capacity was fed from a side arm on the main dolomite feeder vessel. The dip leg seal and balance pipe were found to be necessary to prevent flow around the 'L' when the aeration gas was off. This is a consequence of the free flowing nature of the material.

The device worked satisfactorily. It showed promise as a potential feeding device and has the advantage of being without moving parts in the feed line. The feed rate was not as repeatable or consistent as with the rotary valve, but with further development satisfactory operation can be anticipated. A typical set of operating conditions is shown in Table L.3.

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* Westinghouse Brake & Signal Co., Controls & Automation Div., Chippenham, Wiltshire, England.

Table L.1 COAL FEEDING - TYPICAL OPERATION CONDITIONS

Feeder pressure	:	83 psig
Combustor pressure	:	76 psig
Conveying air velocity	:	30 ft/s
Solids/gas mass ratio	:	1.4/1
Lock hopper cycle time	:	10 hours
Feed rate	:	580 lb/h
Conveying line diameter	:	¾" (Sched 40)
Conveying line length	:	30 ft
Rotary valve speed	:	3.3 rpm

Table L. 2 DOLOMITE FEEDING - TYPICAL OPERATING CONDITIONS

Rotary Valve Operation

Feeder pressure	:	81 psig
Combustor pressure	:	76 psig
Conveying air velocity	:	30 ft/s
Solids/gas mass ratio	:	1.2/1
Lock hopper cycle time	:	90 mins
Feed rate	:	240 lb/h
Conveying line diameter	:	¾" (Sched 40)
Conveying line length	:	30 ft
Rotary valve speed	:	6 rpm

Table L.3. 'L' VALVE OPERATING CONDITIONS

As above except:-

Rotary valve speed	:	not in use
'L' valve pulse rate	:	19 pulses/min
Pulse duration	:	0.2 sec
Pressure of pulse air	:	100 psig.

4. DESIGN AND OPERATION OF COMPONENTS EXPOSED TO HOT COMBUSTION GASES AND SOLIDS

4.1. Hot Gas Path

Gas Flow Splitter at the Combustor Outlet

The arrangement by which combustor gas flow was split into two streams of 2 and 1.2 lb/s flow can be seen by reference to Fig. L.18 which shows the position of the mixing baffles and splitter insert. The purpose of this arrangement was to provide streams of similar solids concentration by splitting the combustor gas flow isokinetically.

Fig. L. 19 shows the construction of the combustor outlet duct in which the splitter was mounted. In order to allow for differential expansion with respect to the pressure shell, the outlet duct consisted of two parts: (i) an outer casing of mild steel which was bolted to the pressure shell at the top 20 inch diameter nozzle with the small expansion being taken up by a set of bellows at the bottom and (ii) an inner refractory-lined duct (item A of Fig. L.19). The latter sat on top of refractory cast in the combustor outlet and was free to expand upwards. Resting on top of this refractory-lined duct was a duct cast in refractory (item B of Fig. L.19) which had side holes to line up with the two stream branches. Dimensions were such that holes and branches were in alignment at operating temperatures. The splitter was mounted in the side hole to Stream 1.

This upper refractory duct was set in ceramic fibre packing in its pressure casing and relied on this to prevent gas tracking between sliding refractory joints to the casing. On previous PFBC layouts, with only a single stream, this system worked adequately but with two streams - and two refractory-lined nozzles for the sliding duct to seal against - it was not so successful. Considerable difficulty was experienced during assembly and evidence of gas tracking behind refractory was seen during Test 1.

Subsequently the ceramic fibre packing was replaced by a refractory "grout" and the construction gave no further trouble during the 1000 hrs.

Stream 2 Expansion Joint

The provision of a sufficient length of ducting for dust sampling, electrostatic charging, and sampling on the inlet duct to the cyclones of Stream 2 meant that the primary/secondary stage vessel was mounted about 20 ft away from the gas off-take of the combustor. The expansion of this length of duct (about ½ inch) at operating temperatures was compensated for by the compression of a 20 inch diameter bellows unit at the combustor end, the total length of the duct being restrained by four tie rods.

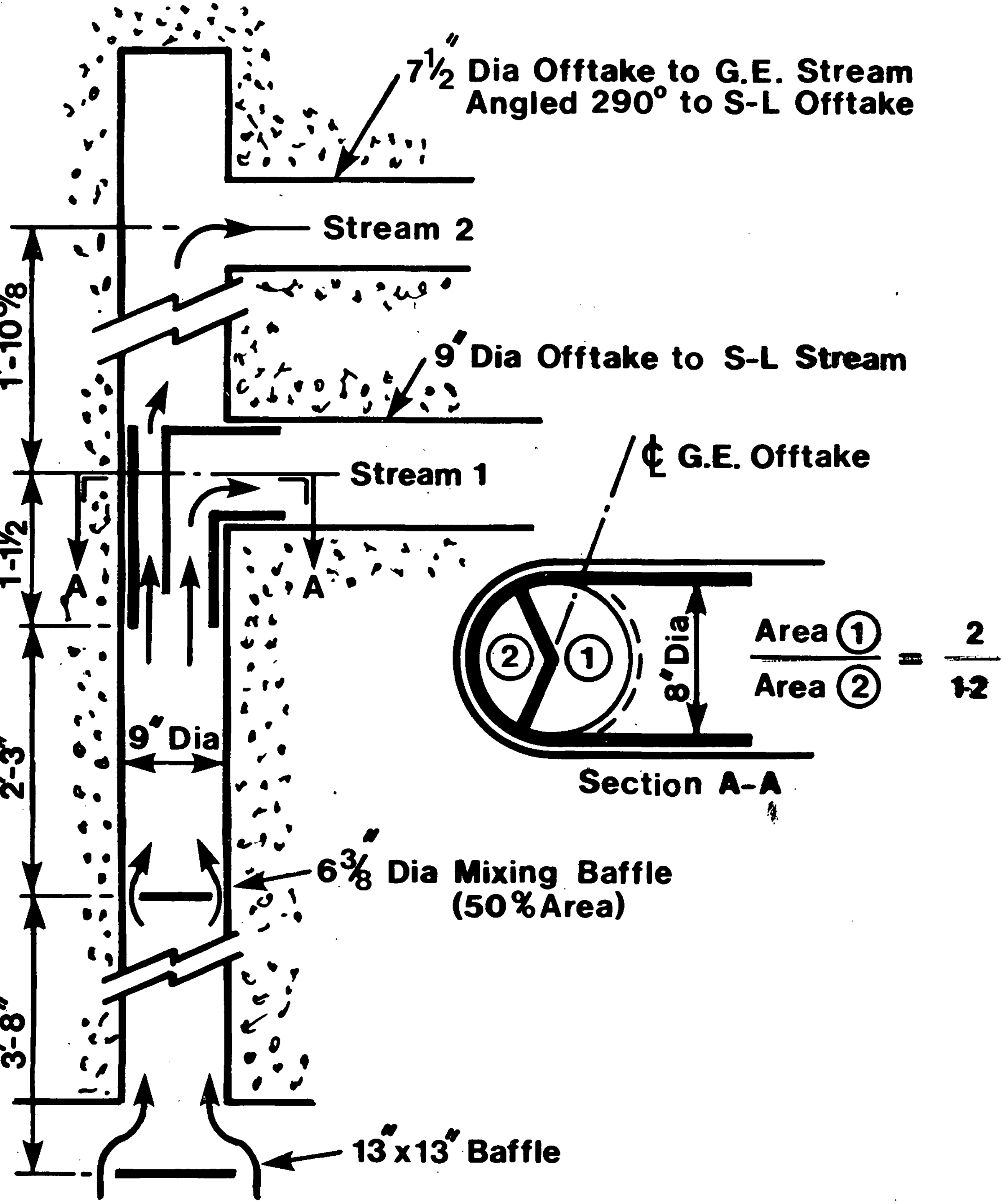

Fig. L18 Flow Splitter

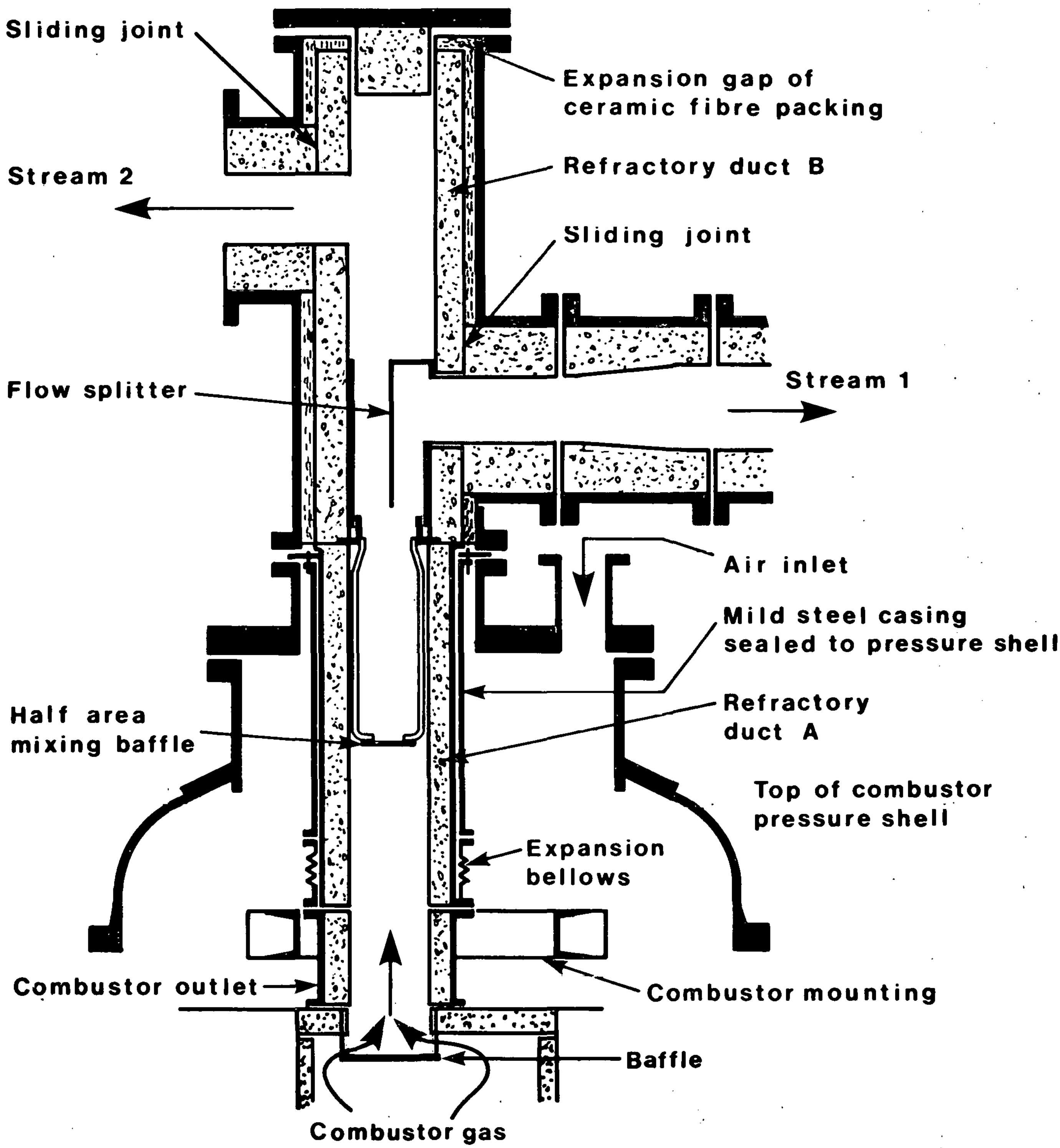

Fig. L19 Arrangement of combustor outlet and flow splitter

Fig. L.20 shows the final arrangement of the bellows. The two-ply corrugated section of 321 stainless steel was welded to mild steel stubbs with flanges for mounting in the duct. Originally, the unit had a mild steel liner mounted from one end and a two-layer refractory liner, mounted on a sandwiched flange from the other. This construction, used during a previous programme (G.E. Tests 8 and 9) in the same situation had suffered severe local stress corrosion of the 321 stainless steel with the result that longitudinal cracks appeared in two places across the corrugations, forcing a plant shut-down.

A small concentration of chlorine in the combustor off-gas condensing on the relatively cool corrugations was identified by inspection and analyses carried out by the manufacturers as being the most likely instigator of the corrosion. Consequently, a change in the material of construction of the corrugations was recommended for the 1000 hour programme. Incoloy 825 was thought to provide more resistance to such attack . However the extremely long delivery of a replacement set of corrugations in this material and the small possibility that similar, albeit less rapid corrosion may still occur, because of the sub-dewpoint operating temperature, prompted a small modification to the design of the unit which is shown in Fig. L.20. This took the form of a gland assembly welded to the free end of the existing mild steel liner, and bearing on the inside surface of one of the stubb ends, thus providing a sealed cavity around the inside of the corrugations. The gland packing was not expected to form a gas tight seal but merely to provide sufficient restriction to allow the cavity to be filled by a small flow of nitrogen. In practice a very efficient seal was provided by the gland once the unit had reached operating temperatures and marking of the inside surface of the bellows stubb end, seen on inspection after 265 hours operation, indicated that the packing had compensated well for lack of concentricity of the pipe whilst allowing bellows compression of about half an inch. This marking, and the very clean conditions of the inside surface of the corrugations (321 SS), can be seen in Figs. L.53, a photograph taken after 1000 hours of operation. A spare bellows in Incoloy 825 was delivered part way through the programme, but was not used.

Duct work upstream of cascades

It was essential to avoid material break-away from the walls of the duct between the final cyclone stage and the cascade. This precluded the use of refractory or ceramic materials and hence a metal lining within castable insulation refractory was used. Two considerations arose: compensation for the differential expansion involved and avoidance of material likely to suffer from serious 'spalling' of the oxide film. Final choice of material, however, was influenced as much by availability and workability as by theoretical requirements.

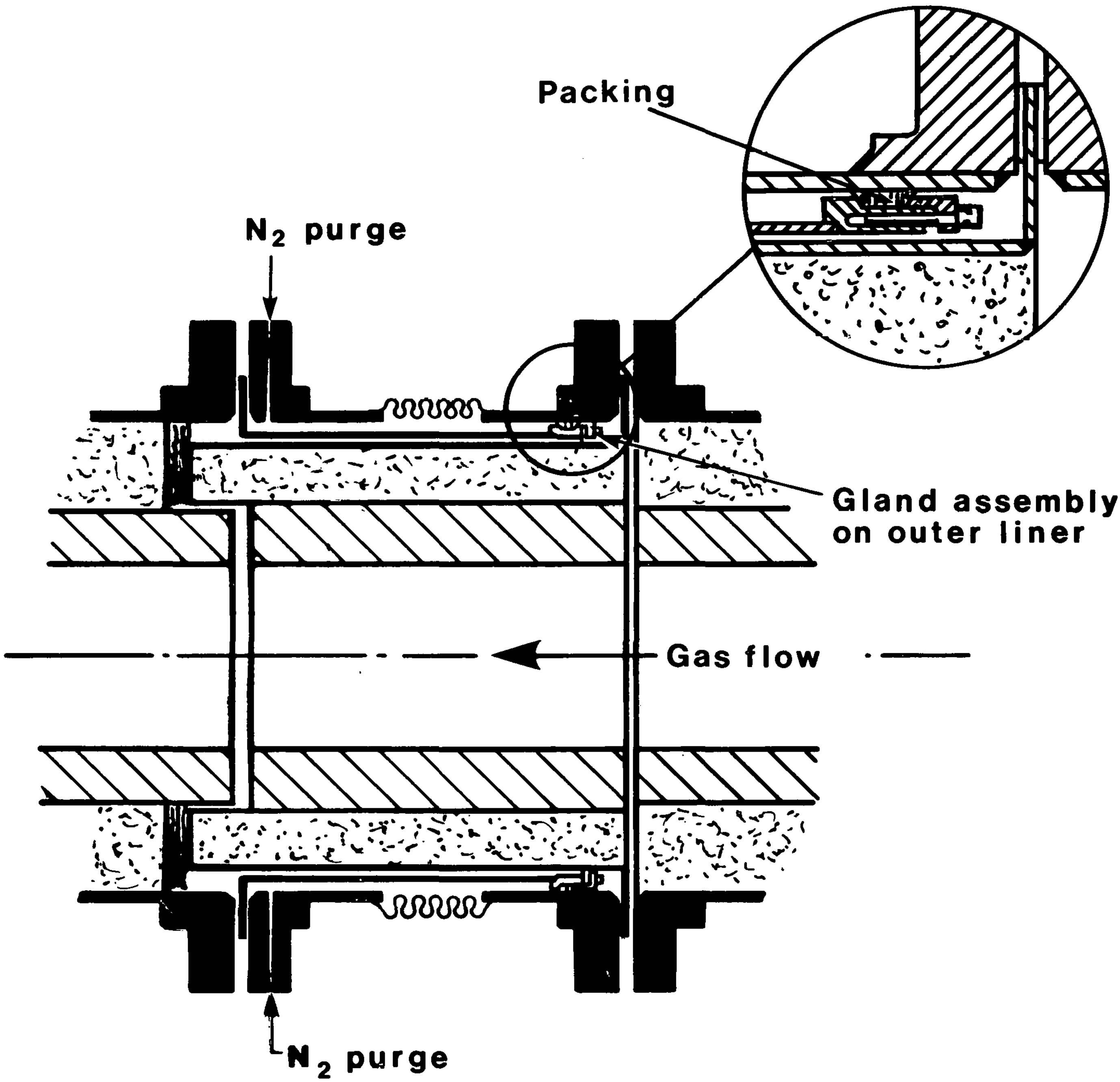

Fig. L20 **Stream 2 500mm pressure casing bellows**

An example of the detail design of the metal-lined ducting is shown in Fig. L.21. Apart from the size (5 inches I.D. in Stream 1 and 4 inches I.D. in Stream 2) the only differences between the Stream 1 and 2 liners were materials of construction, (310 grade SS in Stream 2 and 316 grade SS in Stream 1), and the fact that the liners (not the joints) were rolled and seam welded in the case of Stream 2, and were thin-walled seamless tube in Stream 1.

Fig. L.21 shows how the liners were located in the insulation refractory at a single plane in a way that minimised conduction to the casing and which allowed longitudinal expansion in both directions from that point. Male and female sliding joints were fitted at the ends of each section of duct and the whole liner wrapped in ceramic paper insulation before insulation refractory was cast around it. The interlocking points protruded beyond the ends of each section and lugs and sockets were added on the casing to provide more accurate alignment.

Flow measuring elements were built into the ducts to monitor hot gas flow in each stream. These took the form of a venturi in Stream 2 and a nozzle in Stream 1, and used similar sliding joints to connect to adjoining duct sections (see Fig. L.22).

Inspection of the ducts between tests and after 1000 hours showed no sign of malfunction or damage even though parts of the Stream 2 duct had undergone long periods of operation at up to 880°C when propane was burned to compensate for heat losses. The duct walls were, in the main, coated with fine easily removable dust, particularly in the case of Stream 2 where the coating thickness was 3-4 mm in many places. There were some bare areas in Stream 1 however, notably on the ducting at the entry to the Stream 1 cascade.

Local build-up had occurred on the upstream facing edge of the branch for the GESRI dust sampling probe at its intersection with the main duct on Stream 2 and thickness here was 6-10 mm. Although the type of dust associated with PFBC systems is normally non-abrasive it is possible that over a long period of exposure to hot gases interspersed with periods of shut-down in conditions where moisture absorption can occur, hard agglomerates might form. Avoidance of aerodynamic conditions conducive to the formation of large dust deposits between the final gas clean-up system and the turbine is therefore desirable.

Spalling/exfoliation of oxide films on alloy ducting walls is also a potential risk to turbine blades. Examination of the cascade on Stream 1 showed some scale to be embedded in the surface coating. This was not so on the cascade on Stream 2, where the ducting was more heavily coated with dust.

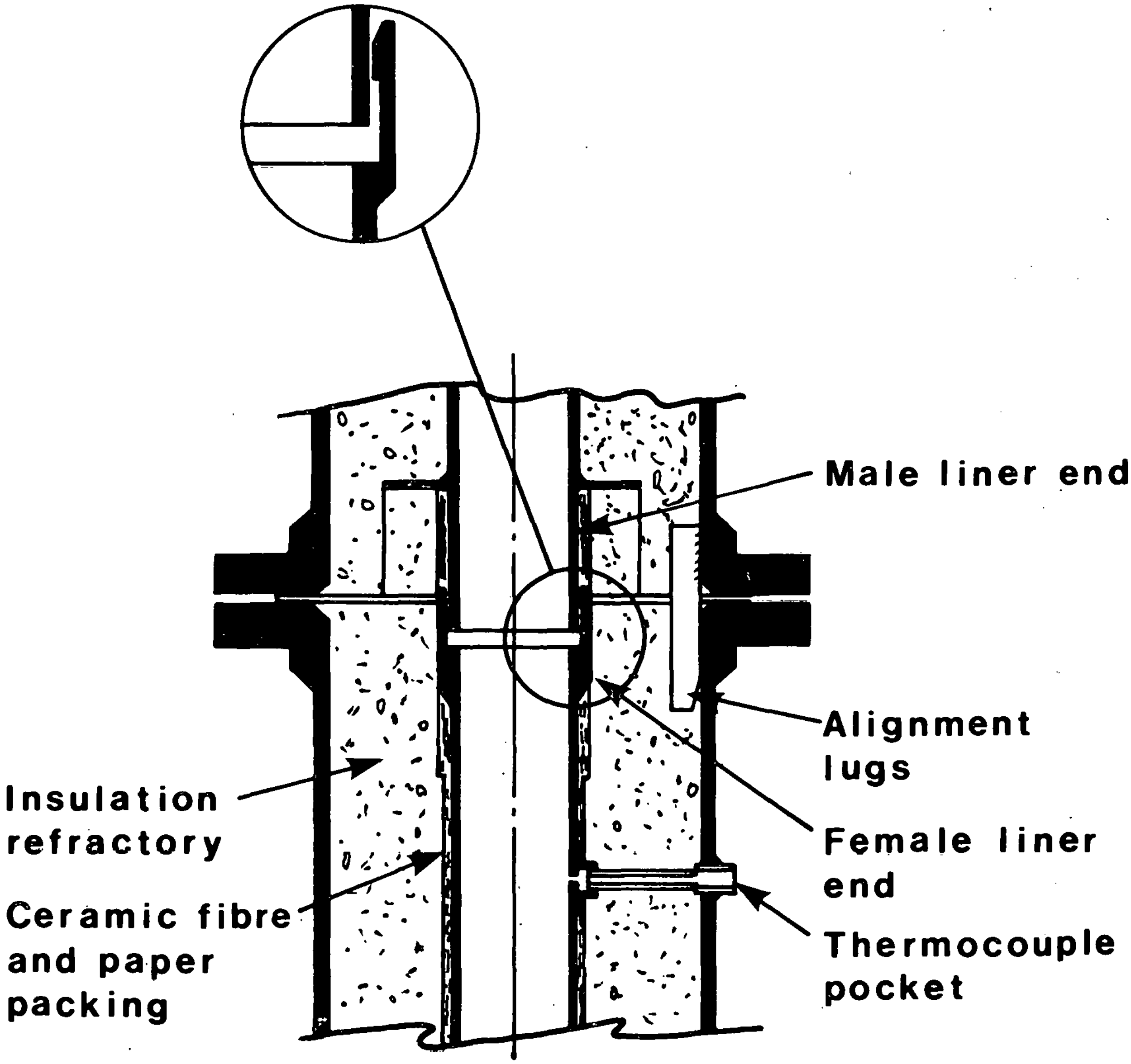

Fig.L21 Typical sliding joint in metal-lined ducting up to cascade test section.

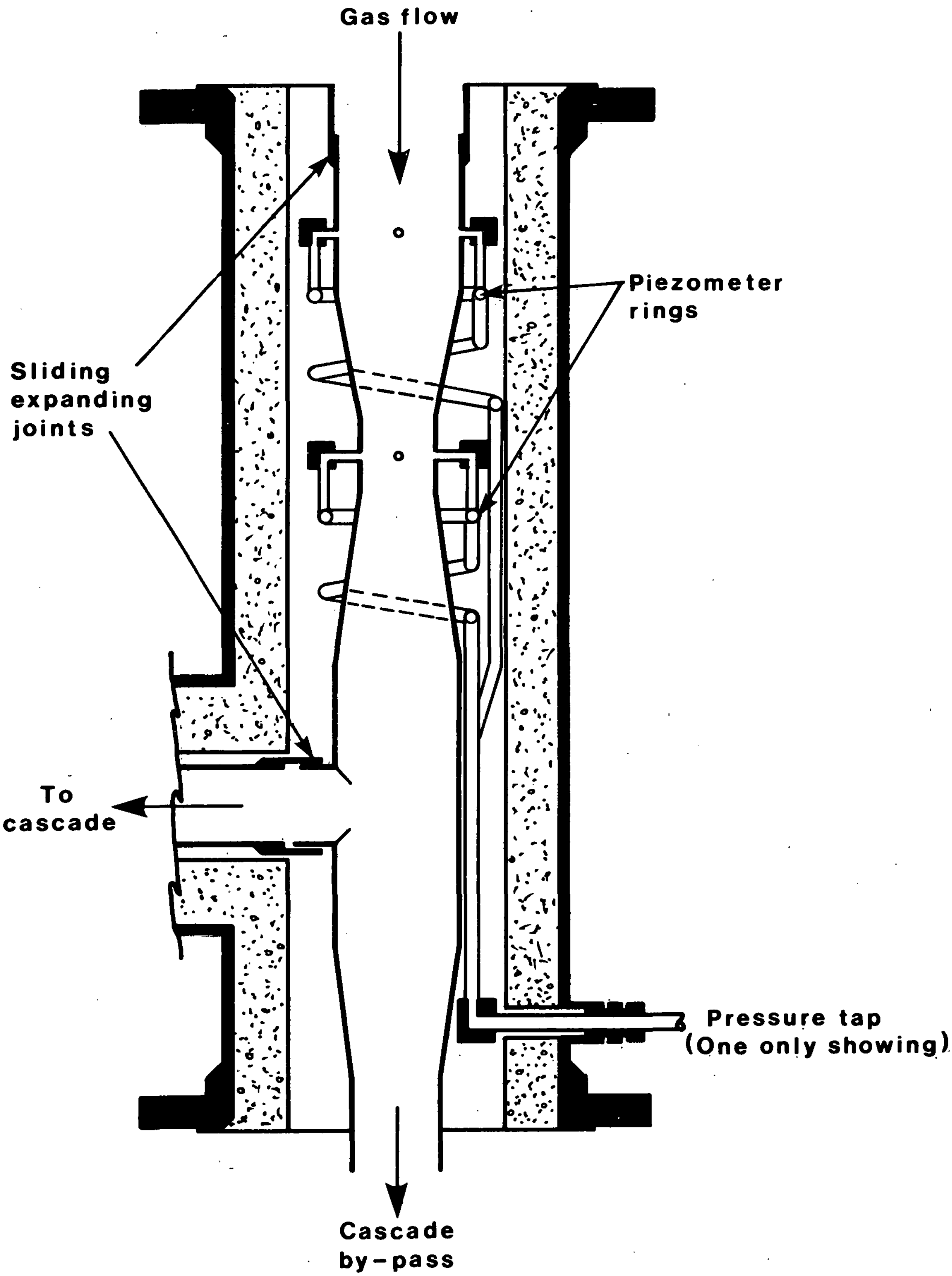

Fig. L22 Stream 2. Hot gas flow measurement venturi

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It is possible that spalling/exfoliation of the oxide layer during cooling on the 316 alloy used for the ducting on Stream 1 led to the smaller accumulations of dust as well as to greater risk to the turbine blades. On Stream 2 the combustion gases were by-passed until full operating conditions were reached, hence if spalling of the oxide layer on the 310 alloy did occur the material would be discharged through the by-pass on start-up.

Viewing window for the electrostatic charging system: Stream 2.

A sight glass (Fig. L.23) was installed in the duct ahead of the primary cyclone on Stream 2 to enable the corona discharge from the electrostatic charger to be viewed. The unit was installed on a 2-inch branch welded to the duct upstream of the charger and at an angle of 45° to the axis of the duct.

To provide isolation in the event of window breakage and to facilitate cleaning, the body of a "Worcester Series 44" ball valve was installed between the windows and the process stream. Double windows were provided as a safety measure, together with a wire mesh screen on the outer window. The sight glasses were made from Corning "Vycor" silica glass and the housing was constructed from grade 321 steel.

Nitrogen purges were provided to the inner face of the inner window in order to prevent particle deposition. It was also supplied to the space between the two glasses and the pressure there controlled to approximately 40 psig by restricting the vent flow. Plant pressure was therefore dropped in two stages and the resultant thrust on each sight glass was only half of that which would have been taken by the glass in a single window unit.

The unit operated satisfactorily throughout the 1000 hour programme. No sight glass breakages occurred and, although a slight deposit accumulated on the inner glass face, cleaning of the window was never required.

4.2. Hot Gas Clean-up

Stream 1 Cyclones

All three cyclones in this stream were of conventional design. The primary and secondary cyclones were of similar proportions and were supplied by Van Tongeren (U.K.). Their dimensions are shown in Fig. L.24. Salient features are volute inlets and outlets and tapered vortex finders. (Not shown in Fig. L.24). The primary unit was 20 inch diameter with a design inlet velocity of 60 ft/s and the secondary unit was 15½ inch diameter with a design inlet velocity of 100 ft/s.

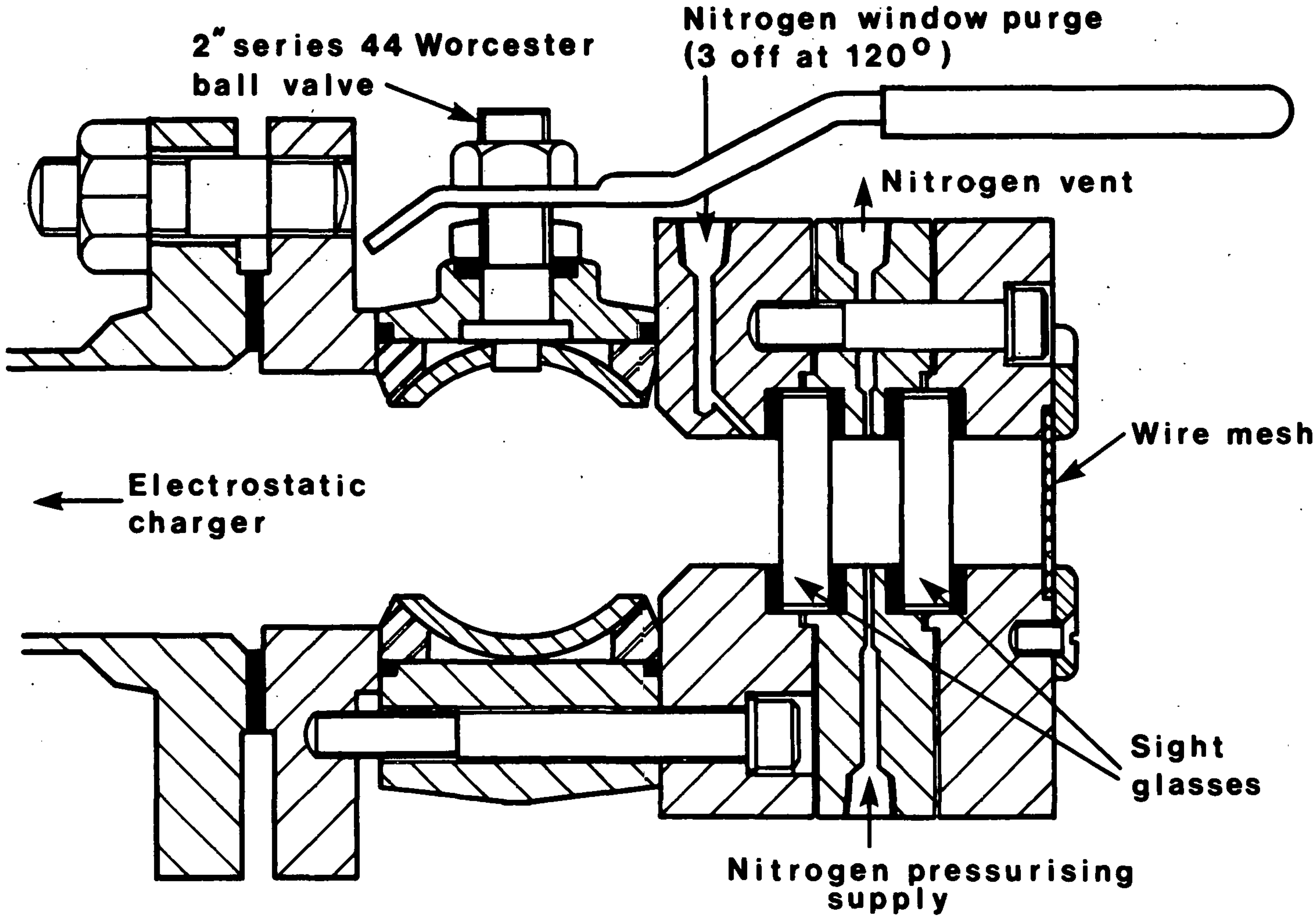
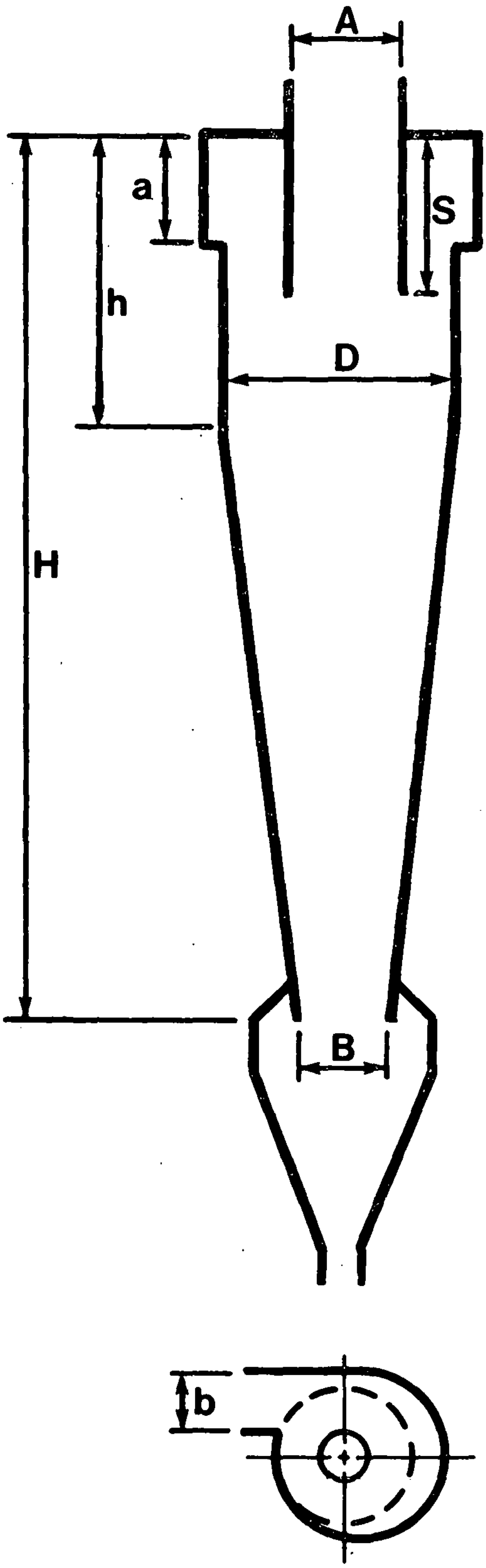


Fig.L23 Sight glass for electrostatic charger



Primary Cyclone

Mass flow	= 2·0 lb/s
Inlet velocity	= 60 ft/s
Body diameter	= 20 inches

a/D = 0·46
b/D = 0·21
A/D = 0·30
S/D = 0·90
h/D = 1·32
H/D = 3·80
B/D = 0·40

Secondary Cyclone

Mass flow	= 2·0 lb/s
Inlet velocity	= 100 ft/s
Body diameter	= 15·4 inches

a/D = 0·46
b/D = 0·21
A/D = 0·19
S/D = 0·90
h/D = 1·32
H/D = 3·80
B/D = 0·40

Fig. L24 Dimensions of Primary and Secondary Cyclones on Stream 1 (Van Tongeren AC 850 Design)

These units were mounted side by side from water-cooled support frames in a 4 ft 6 inch diameter pressure vessel (see Figs. L.25 and L.30). So that expansion movement could take place, the inlet to the primary cyclone was not positively sealed to the pressure vessel casing. Gas and dust bypass of the cyclone (i.e. into the pressure vessel) was minimised by a labyrinth type design of the duct lining (see Fig. L.26). Expansion of each cyclone and its ash leg downwards from the mounting point, (which was at the level of the primary cyclone inlet) was taken up by bellows units mounted in the ash legs.

The separation hopper of the primary cyclone was fitted with a steam-heated coil to reduce the effects of condensation during start-up and also to provide a heat sink should mal-operation result in combustion in the cyclone hopper.

The outlet from the secondary cyclone was connected via another set of expansion bellows to the tertiary cyclone which was mounted, again on water-cooled supports, in an adjoining 2 ft diameter pressure vessel. The tertiary unit was of the Stairmand "High Efficiency" design and had a tangential inlet with a gas velocity of 145 ft/s (see Fig. L.27). The outlet continued vertically on the axis of the vortex finder and was sealed at the top flange of the containing pressure vessel. Expansion downards and upwards from the mounting point (again, at the level of the cyclone inlet) was absorbed by bellows in the ash leg below the cyclone and in the gas outlet above the vortex finder.

The containing vessel for the primary and secondary cyclones was lined in its upper half and top dome with approximately 4 inches of vermiculite/Cement-Fondue insulation on the walls and the remaining spaces around the cylones filled with loose vermiculite granules to provide a barrier to heat loss from the cyclones. The adjoining tertiary cyclone vessel was similarly filled with vermiculite granules, the walls being lined with 2 inches of castable insulation. The effectiveness of this method of insulation can be seen in Fig. L.28 which shows average values of pressure vessel skin temperatures taken during Test 4. Only on the tangential inlet nozzle on the 24 inch diameter tertiary vessel, where insulation thickness was limited to about 1½ inches by the geometry of the cyclone inlet, was heat loss appreciable.

Stream 2 Cyclones

The arrangement of primary and secondary stage cyclones in this stream was unusual in that they were mounted concentrically. Fig. L.29 shows the arrangement of the three cyclone stages and much of their constructional detail. The configuration was suggested by GE in order to form a large volume for the first stage to assist electro-static enhancement whilst at the same time making use of an existing pressure vessel.

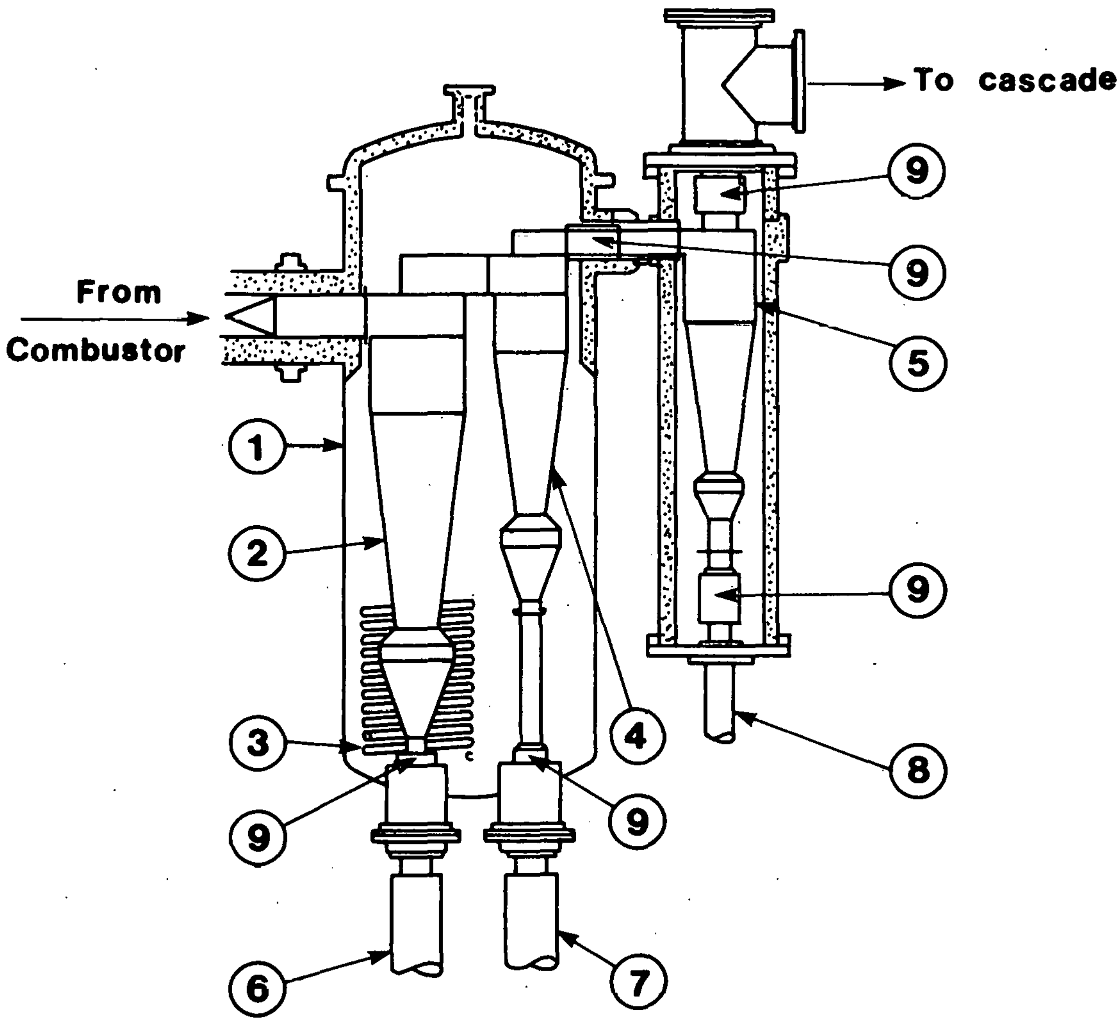


Fig.L25 Arrangement of Stream 1 cyclones.

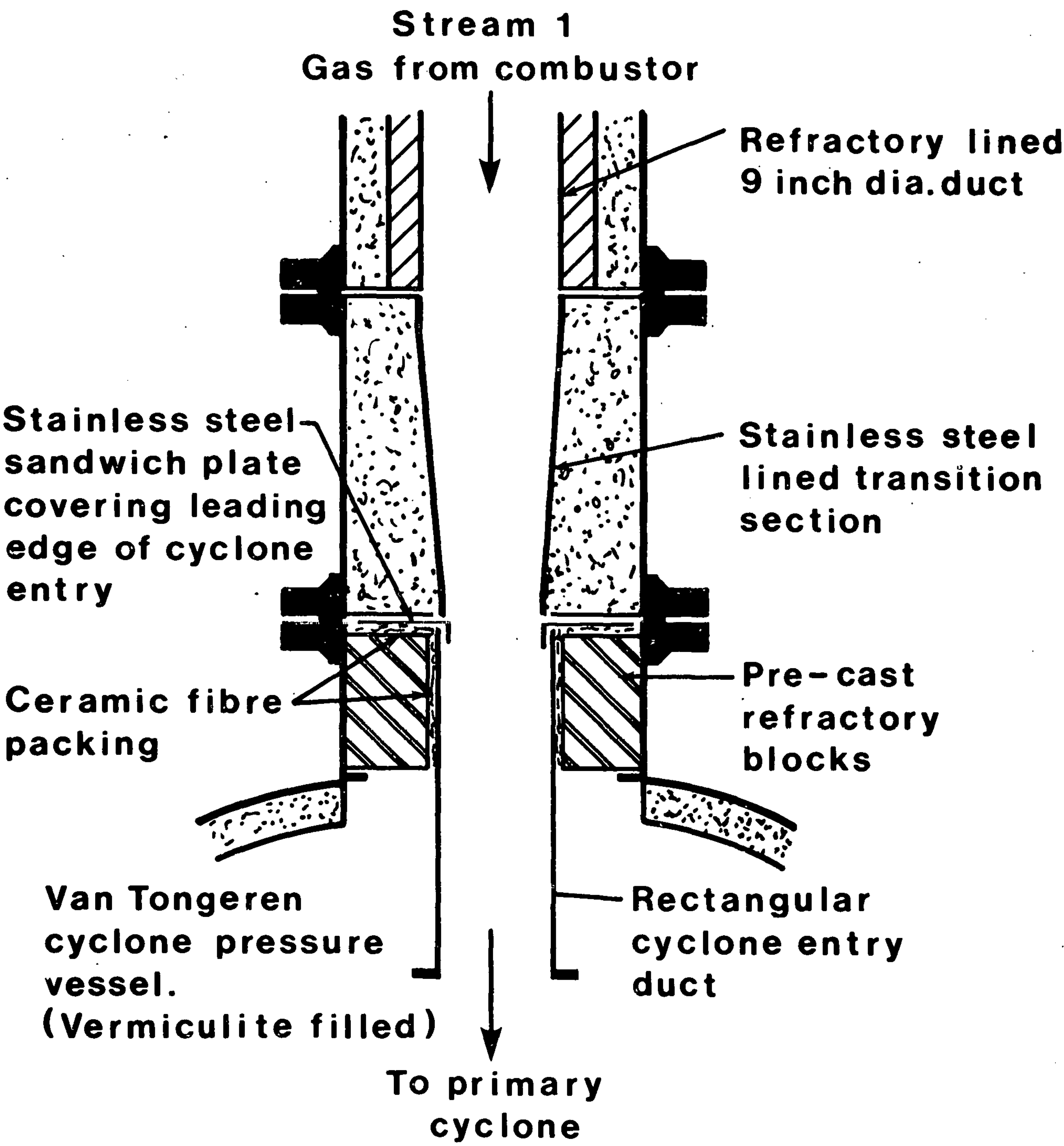


Fig. L26 Sealing arrangement at entry of stream 1 primary cyclone

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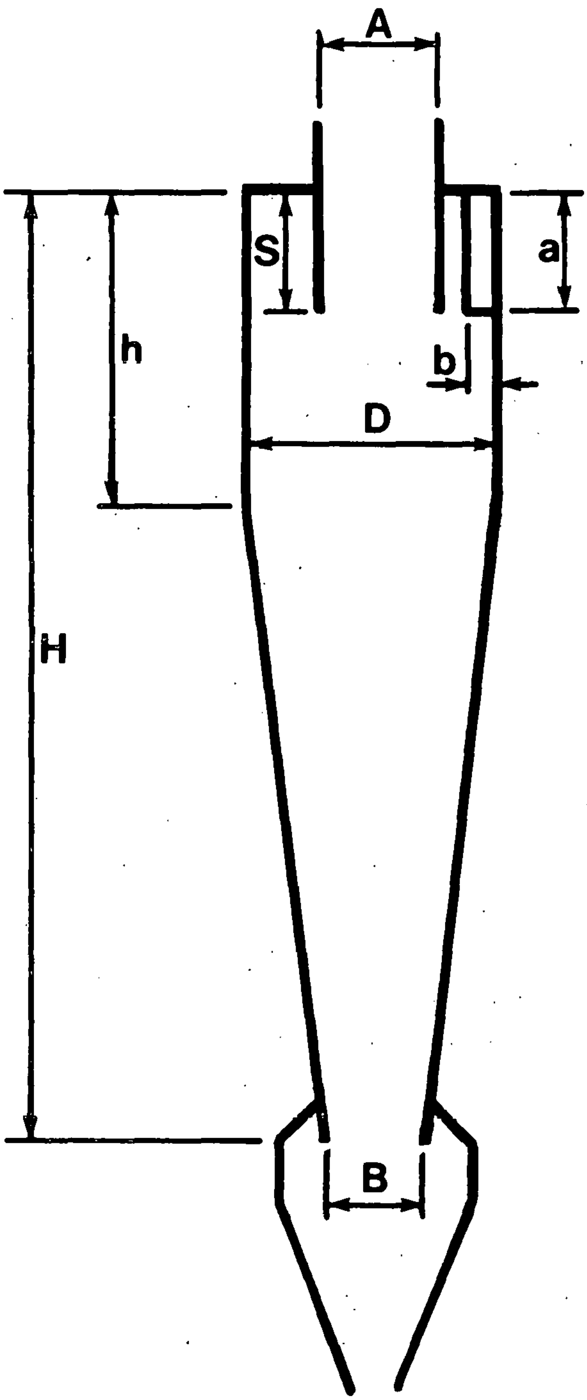


Tertiary Cyclone

Mass flow	= 2·0 lb/s
Inlet velocity	=145 ft/s
Body diameter	= 13 inches

a/D = 0.5
b/D = 0.19
A/D = 0.5
S/D = 0.5
h/D = 1.5
H/D = 4.0
B/D = 0.38

Fig. L27 Dimensions of Tertiary Cyclone on Stream 1
Stairmand High Efficiency

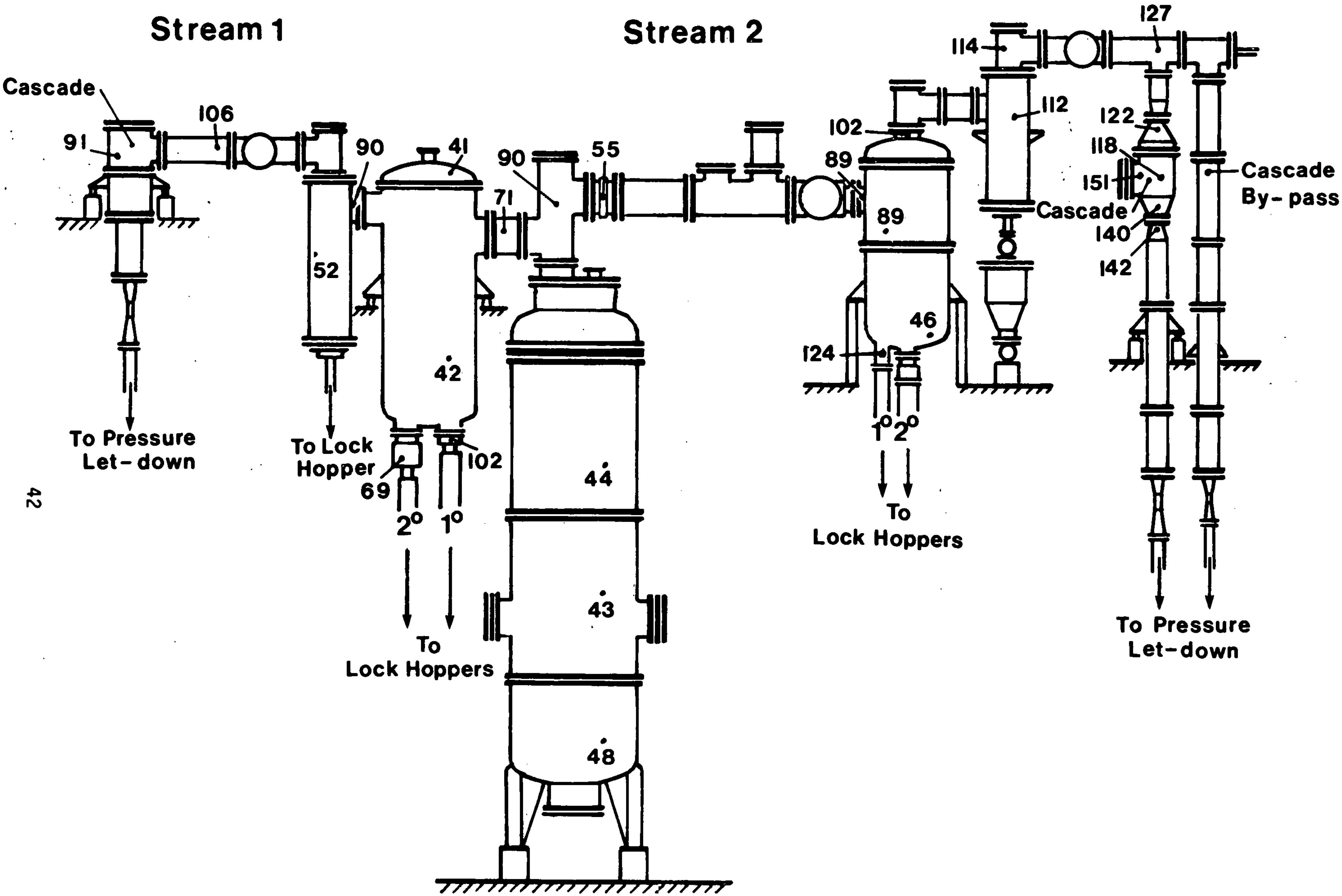


Fig.L28 Plant Skin Temperatures °C

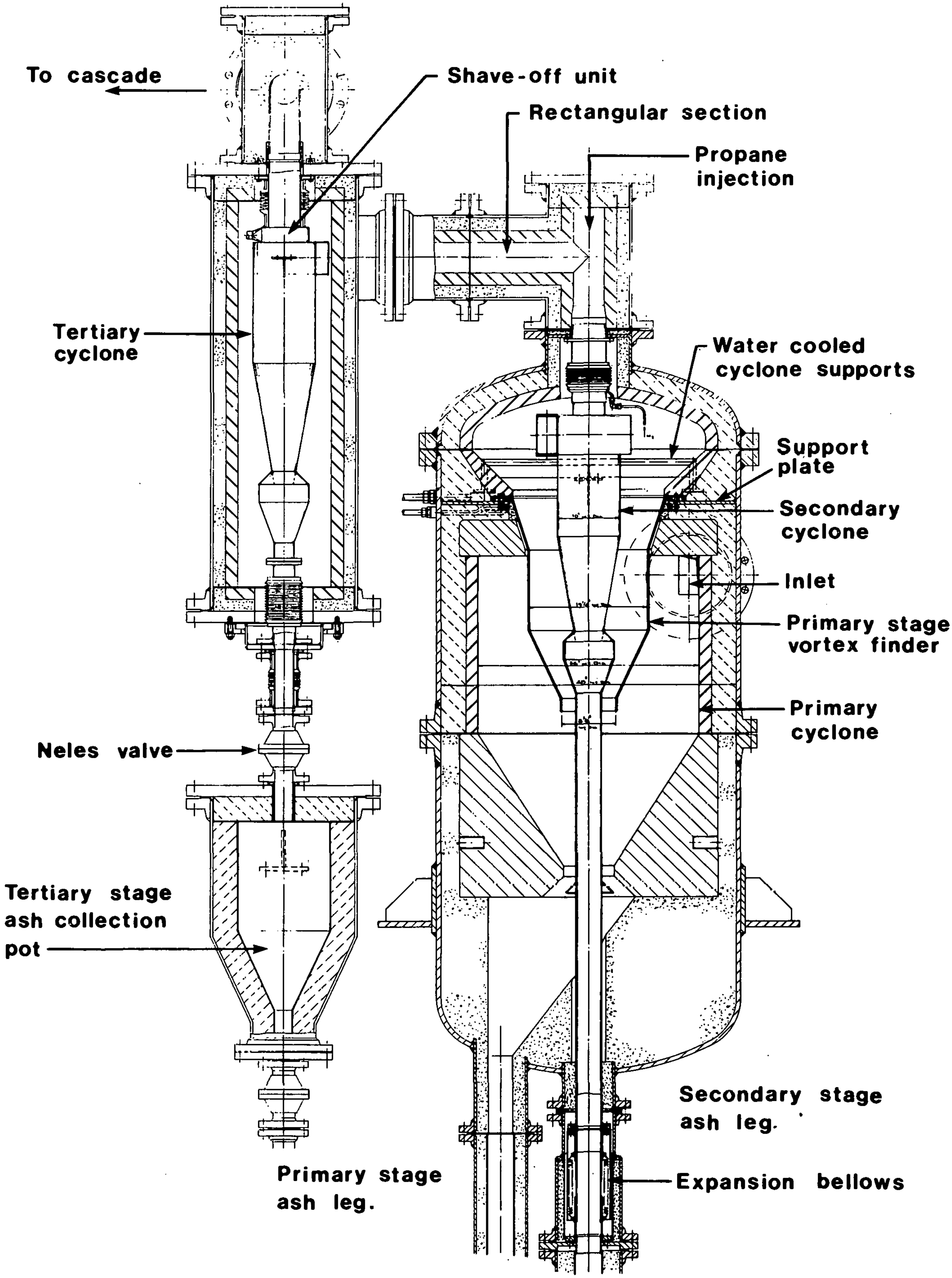


Fig. L29 Stream 2 cyclones.

The primary cyclone was formed in the pressure vessel by pre-cast refractory shapes which made up the roof and cone of the cyclone. These were cast onto insulating refractory. The middle section of the vessel was lined with 2 inches of hardface refractory to form the cyclone barrel, and the lower half was cast into an offset hopper shape to collect the primary dust and divert it to the ash leg. The outlet vortex finder had to accommodate the secondary cyclone in the upper part of the vessel and so was of somewhat unusual shape (see Fig. L.29). It was constructed of ¼ inch thick grade 310 stainless steel and had a ring flange on its top largest diameter which was clamped onto a ½ inch thick water-cooled mild steel support plate welded to the vessel casing. Ceramic fibre packing was then laid on top of the ring flange and clamp, (to allow space for expansion), before the conical refractory shape in the top of the vessel was cast in position on the support plate. Water connection blocks which supplied the water-cooled supports for the secondary cyclone were also mounted here. The top of the conical vortex finder of the 1st stage, clamped to the support plate, with the 2nd stage cyclone mounted from its water-cooled supports can be seen in Fig. L.31, a photograph taken before the conically shaped refractory lining was placed.

Dimensions of this first stage cyclone are given in Fig. L.32. The unconventional proportions and the intrusion of the second stage cyclone and ash leg on its centre line led to some uncertainty as to the performance and prompted cold flow testing by GE on a full size model.

These tests indicated a tendency for re-entrainment of dust from the collection hopper beneath the cyclone up the outside of the secondary stage ash leg which formed the core of the cyclone vortex. A simple conical skirt fitted to the outside of the secondary ash leg at the point where it passed through the bottom of the primary stage cone was found to reduce this tendency and was added in the later stage of assembly at CURL (see Fig. L.29).

The secondary cyclone, the dimensions of which are shown in Fig. L.33 was mounted above the outlet from the primary stage on water-cooled supports as can be seen in Fig. L.31, and was constructed from Incoloy D.S. It volute inlet had a slightly belled-out entry to reduce entry turbulence. The axial outlet from the cyclone - on the same axis as the containing pressure vessel - was flanged and bolted to a heat-resisting steel flange plate welded to the inside of the pressure vessel outlet nozzle. The large temperature gradient which existed along the radius of this plate under operating conditions was of some concern since any expansive forces great enough to distort the plate at its sealing face and cause leakage would result in bypass of the secondary stage cyclone. Hence, the temperatures of the pressure casing skin in this area, (see Fig. L.28), together with relevant internal skin temperatures were carefully monitored during the early stages of the programme. In the event the design performed satisfactorily and there was no evidence of dust and gases by-passing the cyclone.

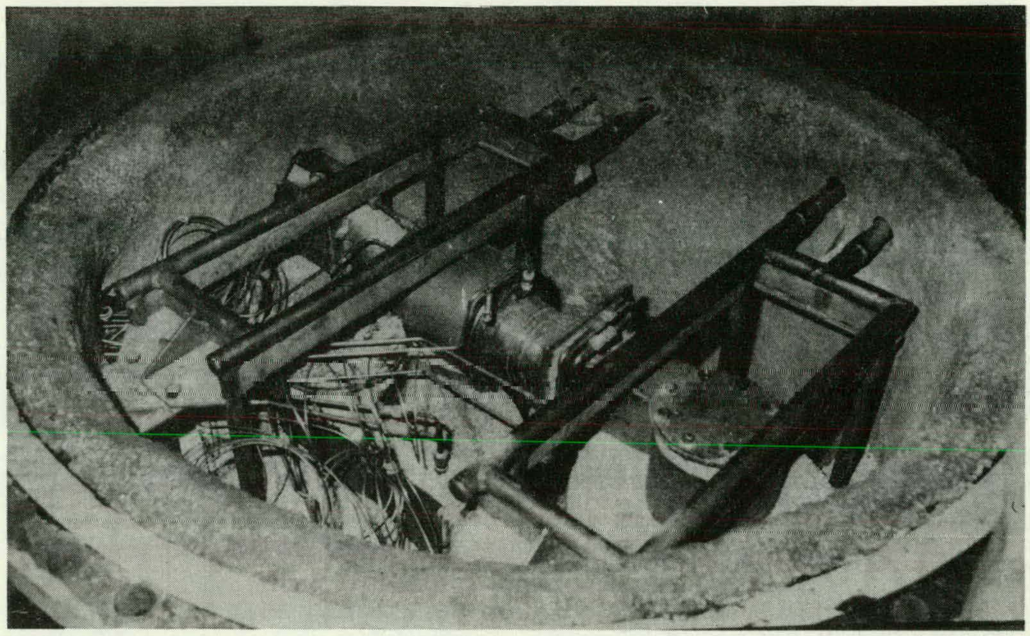


Fig.L30 Van Tongeren cyclones installed in pressure vessel, Stream 1.
Primary stage on left, secondary on right.

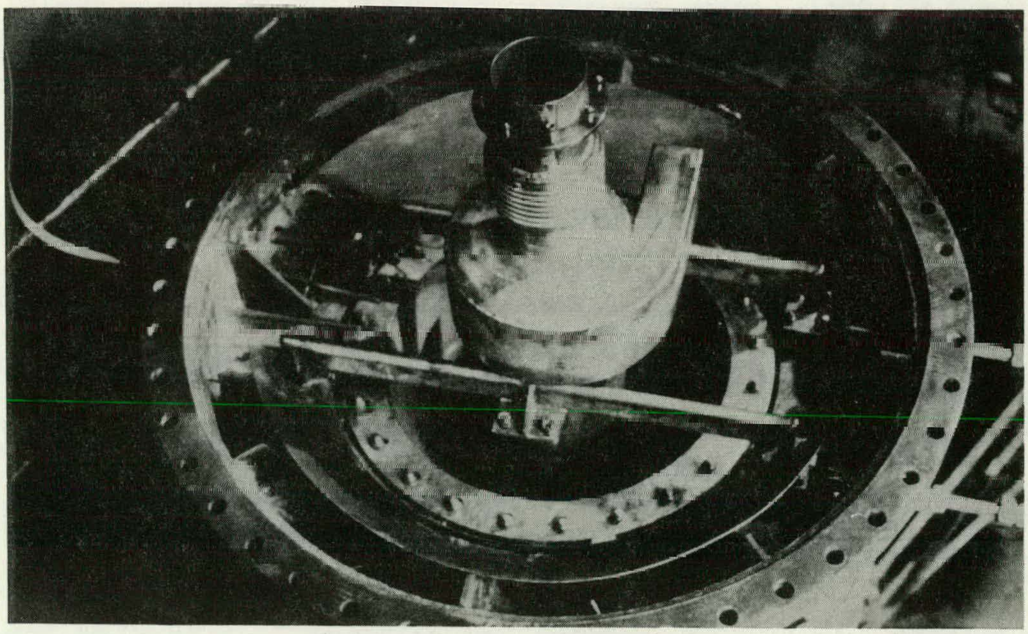
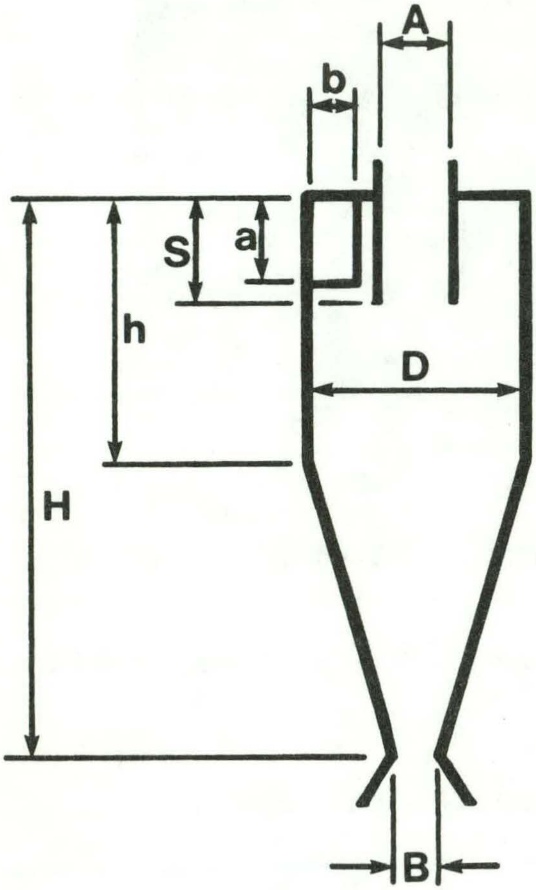


Fig.L31 Stream 2 Primary and secondary cyclones during construction



Primary Cyclone

Mass flow = 1.2 lb/s
Inlet velocity = 65 ft/s
Body diameter = 36 inches

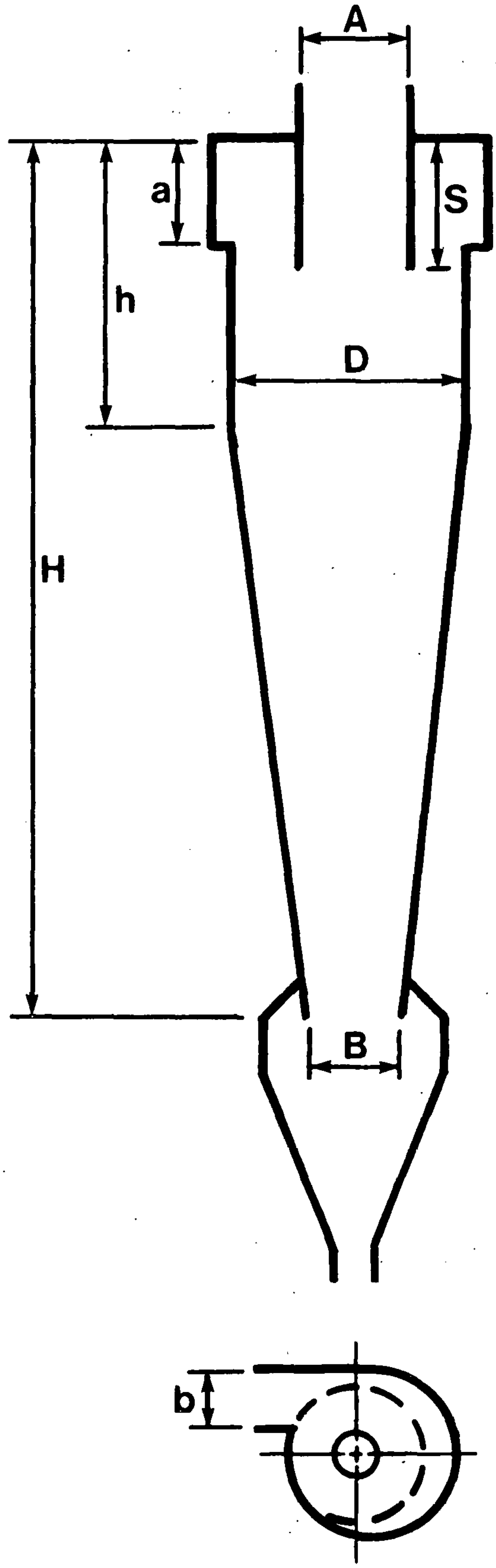
a/D = 0.18
b/D = 0.09
A/D = 0.24
S/D = 0.74
h/D = 0.83
H/D = 1.80
B/D = 0.22

Tertiary Cyclone

Mass flow = 1.2 lb/s
Inlet velocity = 110 ft/s
Body diameter = 10 inches

a/D = 0.5
b/D = 0.25
A/D = 0.4
S/D = 0.75
h/D = 2.0
H/D = 4.0
B/D = 0.4

Fig.L32 Dimensions of Primary and Tertiary Cyclones on Stream 2



Secondary Cyclone

Mass flow = 1·2 lb/s
Inlet velocity = 105 ft/s
Body diameter = 10 inches

a/D = 0·5
b/D = 0·25
A/D = 0·5
S/D = 0·75
h/D = 2·0
H/D = 4·0
B/D = 0·4

Fig. L33 Dimensions of Secondary Cyclone on Stream 2

The ducting between the secondary and tertiary cyclones was lined with a 2 inch thick layer of hard face refractory backed by a 2 inch thick layer of a vermiculite based insulating refractory with a conductivity of about 0.6 Btu/ft^2.h.^{o}F/inch. Despite its low mechanical strength and a quoted maximum operating temperature of only 800^{o}C (likely to have been exceeded in the section of the duct where propane was burned) the material behaved satisfactorily and the metal temperature of the casing of the duct did not exceed 200^{o}F.

The tertiary cyclone was supported, at the level of the centre line of the inlet, on water-cooled supports through the pressure casing in the same manner as for the Stream 1 tertiary cyclone. The cyclone was 10 inch diameter, constructed of 310 grade stainless steel and had a tangential inlet (Fig. L.32). A stainless steel section, leading into the cyclone entry, was cast into the refractory-lined inlet duct of the pressure vessel. A fourth stage of gas clean up, the shave-off unit, was mounted in the outlet of this cyclone about 1 diameter above the cyclone roof, (i.e. not exactly as shown in Fig. L.29). Fig. L.52, a photograph on dismantling after 1000 hours operation shows the position and the shape of the volute of the shave-off unit. Fig. L.34 shows the internal configuration of the shave-off vanes. 1-2% of the main stream flow was taken off through the shave-off vanes and via a steam-jacketed pipe to ceramic fibre filters where the dust was separated at about 400-500^{o}F and approximately 60 psig (see Fig. L.35).

The top of the shave-off unit was sealed to the cyclone vessel casing by means of expansion bellows, (thus preventing the passage of gas around the cyclone), and the cyclone outlet - an extension of the vortex finder - terminated in the first sliding joint in the steel-lined duct to the cascade section.

Pressure Sealing of Dust Discharge Legs. The method used to bring the cyclone ash legs through the bottom of their respective pressure vessels avoided the necessity of precise orientation of flanges in the ash leg and cyclone. A loose ring clamp was used on the pressure vessel closure, which took the form of a modified blind flange in the shape of an upside down "top hat". This "top hat" flange was sandwiched between the cyclone ash leg flange on the inside of the pressure vessel and the top flange of the ash leg to the collection-hoppers on the outside. This type of assembly can be seen in Fig. L.36 which shows the lower end of the pressure vessel containing the Stream 2 tertiary cyclone. Fastening was by means of bolts or studs seal-welded to the inside ash leg flange to prevent leakage down bolt holes. In one or two instances the residual stresses in this flange after welding caused slight distortion, sufficient to cause leakage at full pressure and temperature conditions. Further machining of the flange or replacement (by a thicker one) was carried out between test runs to obviate the problem.

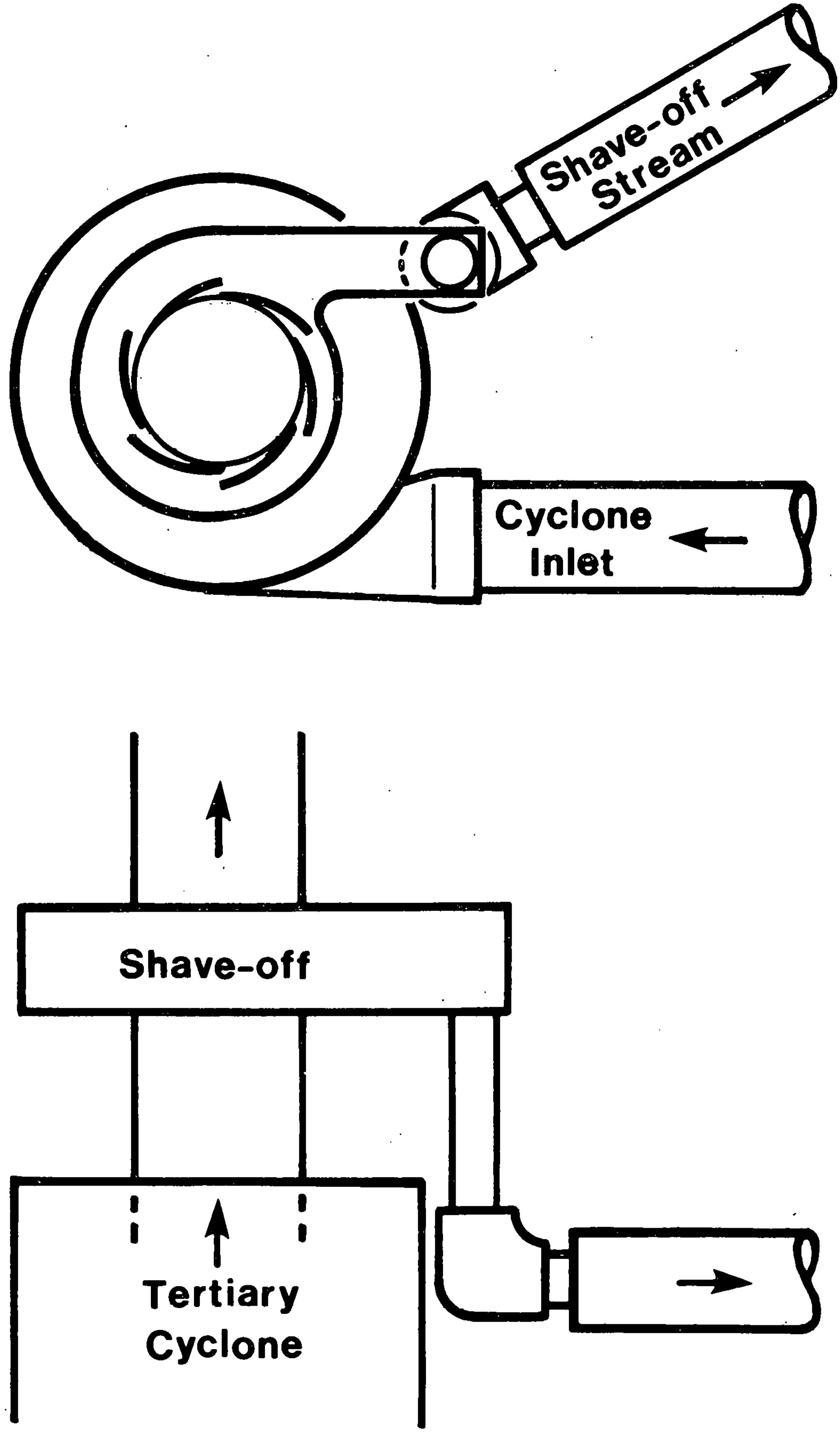


Fig. L34 Diagram of Shave-off Stream 2

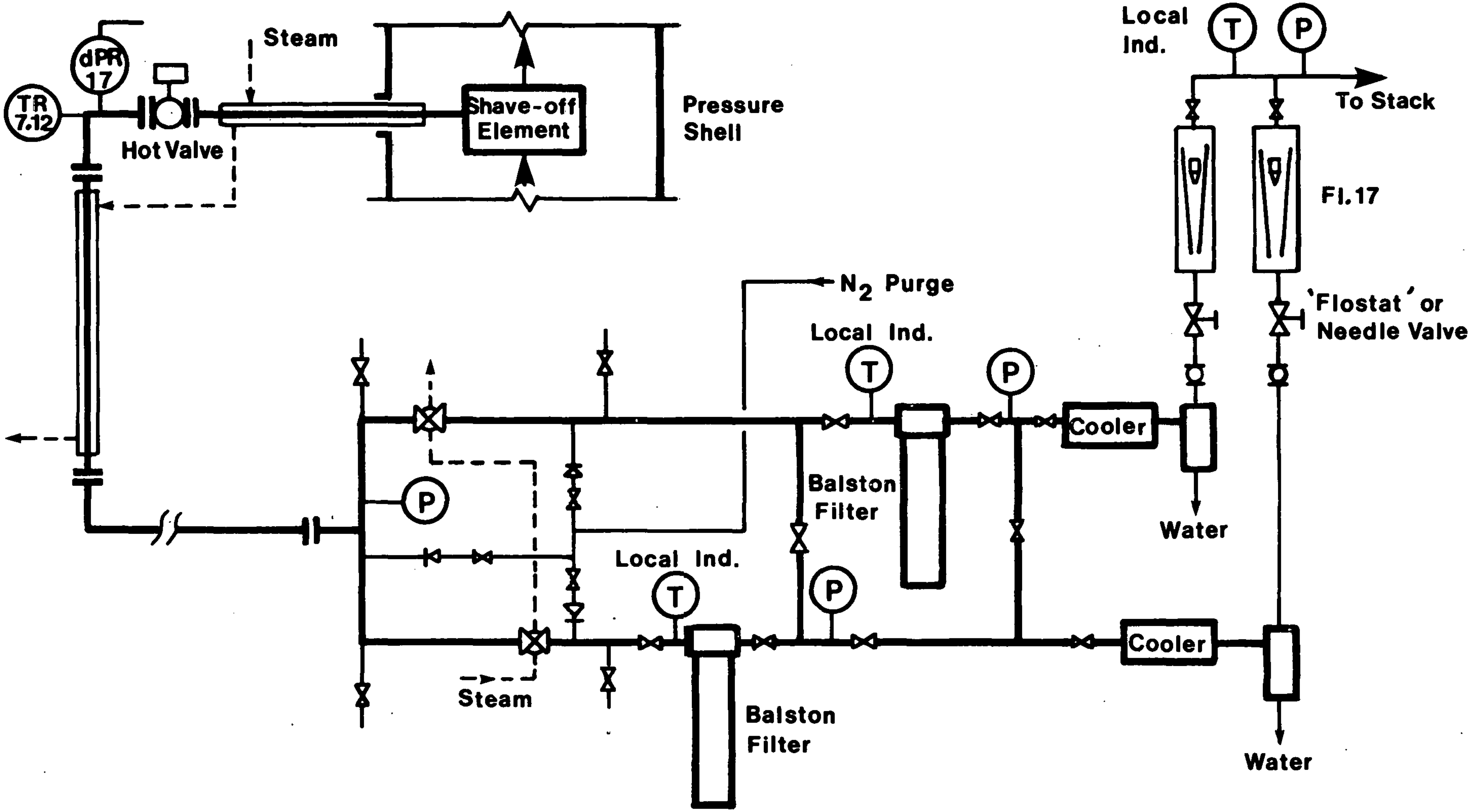


Fig. L35 G.E. Shave off Stream Pipework

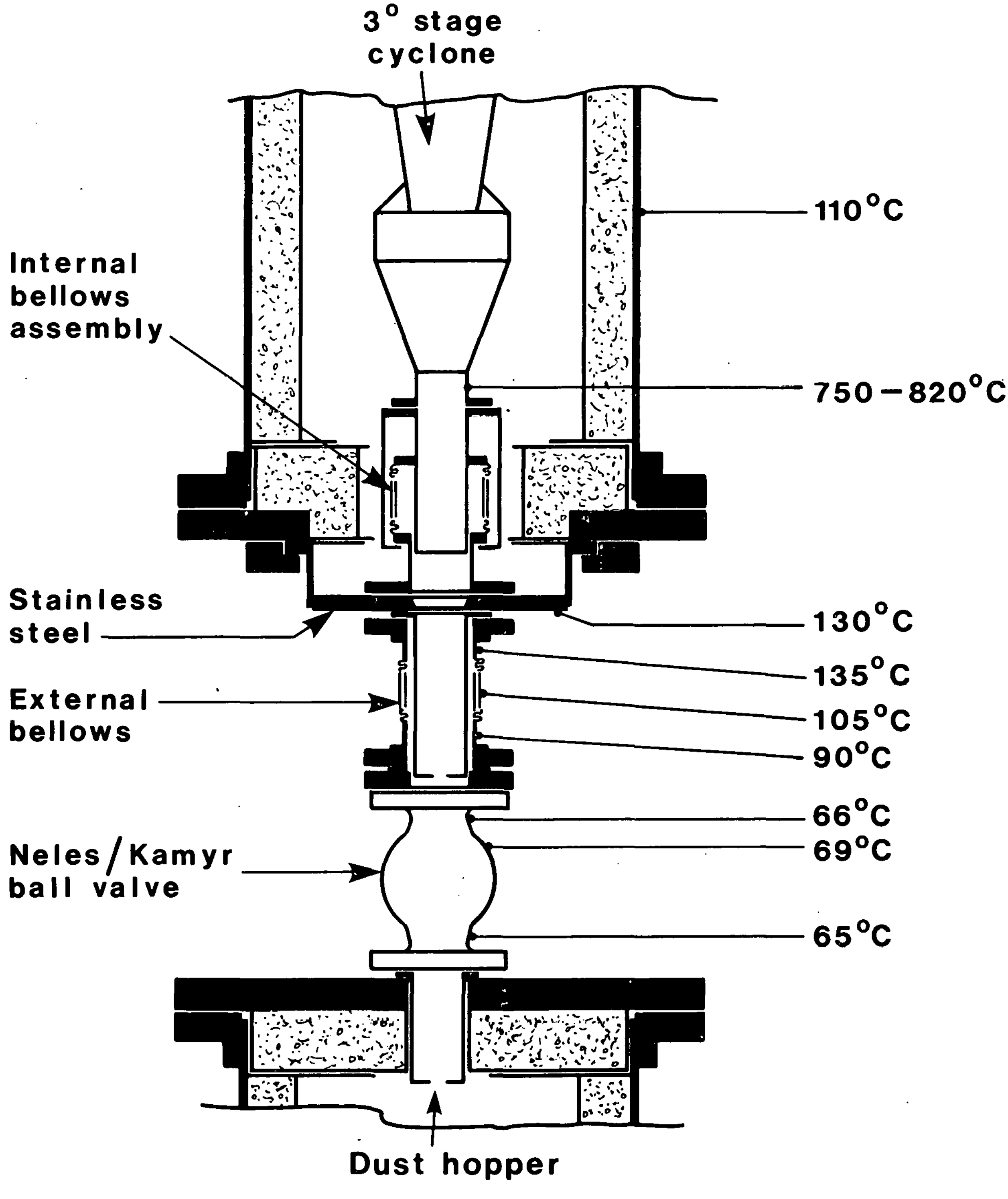


Fig. L36 Stream 2 tertiary dust leg showing skin temperature distribution

Mechanical Performance of Cyclones and Installation Arrangements

Performance of all cyclones relating to their dust collection efficiency is detailed in Volume 2. Only the performance relating to mechanical design is described here. Opportunity was taken during most of the shut-down periods between tests to visually inspect the cyclones internally. Apart from a partial blockage of the Stream 1 primary cyclone ash leg by a distorted expansion bellows liner there were no major mechanical failures in any of the hot gas clean-up systems. This bellows liner had buckled as a result of insufficient expansion clearance being allowed in the lower part of the dust discharge leg, and was replaced after Test 1. Ultrasonic thickness measurements were carried out on Stream 1 cyclones before and after the 1000 hours test programme and similar checks were done on the Stream 2 secondary cyclone after the test programme. These measurements are shown in Fig. L.37.

No abrasion was expected on the secondary and tertiary cyclones, but abrasion in the primary cyclone had seemed a possibility, even though the inlet velocity had deliberately been kept low. The lack of abrasion in this cyclone is encouraging and re-opens the possibility of using metal cyclones as the first stage in a commercial plant.

The inspections that could be carried out on cyclones between test runs did not show any excessive depositions of dust. However, inspection of the Stream 2 primary and secondary cyclones on dismantling at the end of the test series showed large quantities of dust to be "hanging up" on surfaces on and around the second stage cyclone in the top of the main vessel. A coating of dust 2-4 mm thick is quite normal on metal surfaces in secondary and tertiary hot cyclones but, as can be seen in Figs. L.46 and L.47, the amount of dust that settled out in this part of the system was excessive and can be expected to have influenced the performance of the secondary cyclone.

4.3. Performance of Expansion Bellows. Extensive use was made of a standard range of commercially-available bellows in the high temperature duct work in order to take up axial expansion and, in some cases, lateral misalignment. A standard "off the shelf" type was used because of advantages in delivery and cost despite lack of information as to their performance above 1100^{o}F. The material of construction was 321 S12 stainless steel to BS 1449 part 4. Consequently a fairly close inspection of these bellows assemblies was carried out to evaluate their performance at higher temperatures. Details of these inspections are reported in Section 5.

Only the corrugated parts of the bellows units were purchased. The design of the installations were carried out by CURL. A double internal liner was used, sometimes in conjunction with a nitrogen purge, to reduce the tendency for the corrugations to become packed with dust and to sustain suitable clearances to allow expansion movement to occur. Typical variations in this basic design are shown in Fig. L.38. Side 'A' shows a bellows with a nitrogen purge and Side 'B' shows a bellows without a purge and with an external shield.

Position	1	2	3	4	1	2	3	4
	Primary cyclone				Secondary cyclone			
Material loss $\frac{1}{(1000\text{th. inch})}$	1·9	1·1	1·5	0·9	—	2·8	3·3	1·6
	1·6	—	0·7	1·3	1·4	1·3	2·2	1·7
	0·2	1·0	1·1	1·3	1·0	2·0	1·9	2·5
	1·3	0·9	0·9	1·9	1·4	2·5	3·0	—
	1·3	1·1	0·6	0·9	0·8	2·8	3·9	1·5

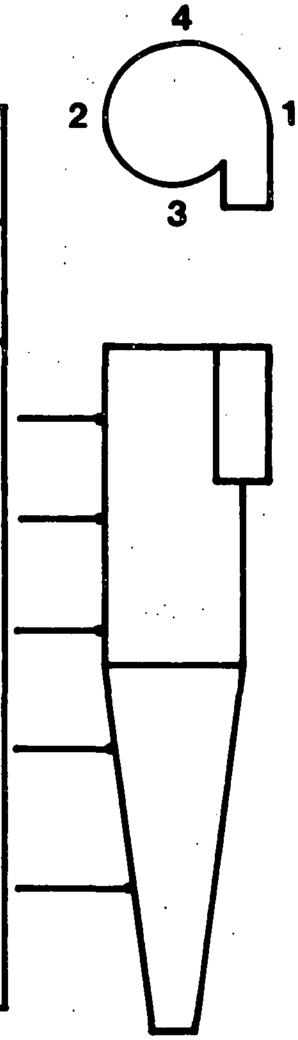


Fig. L37 Wall thickness measurements on Stream 1 Van Tongeren cyclones.

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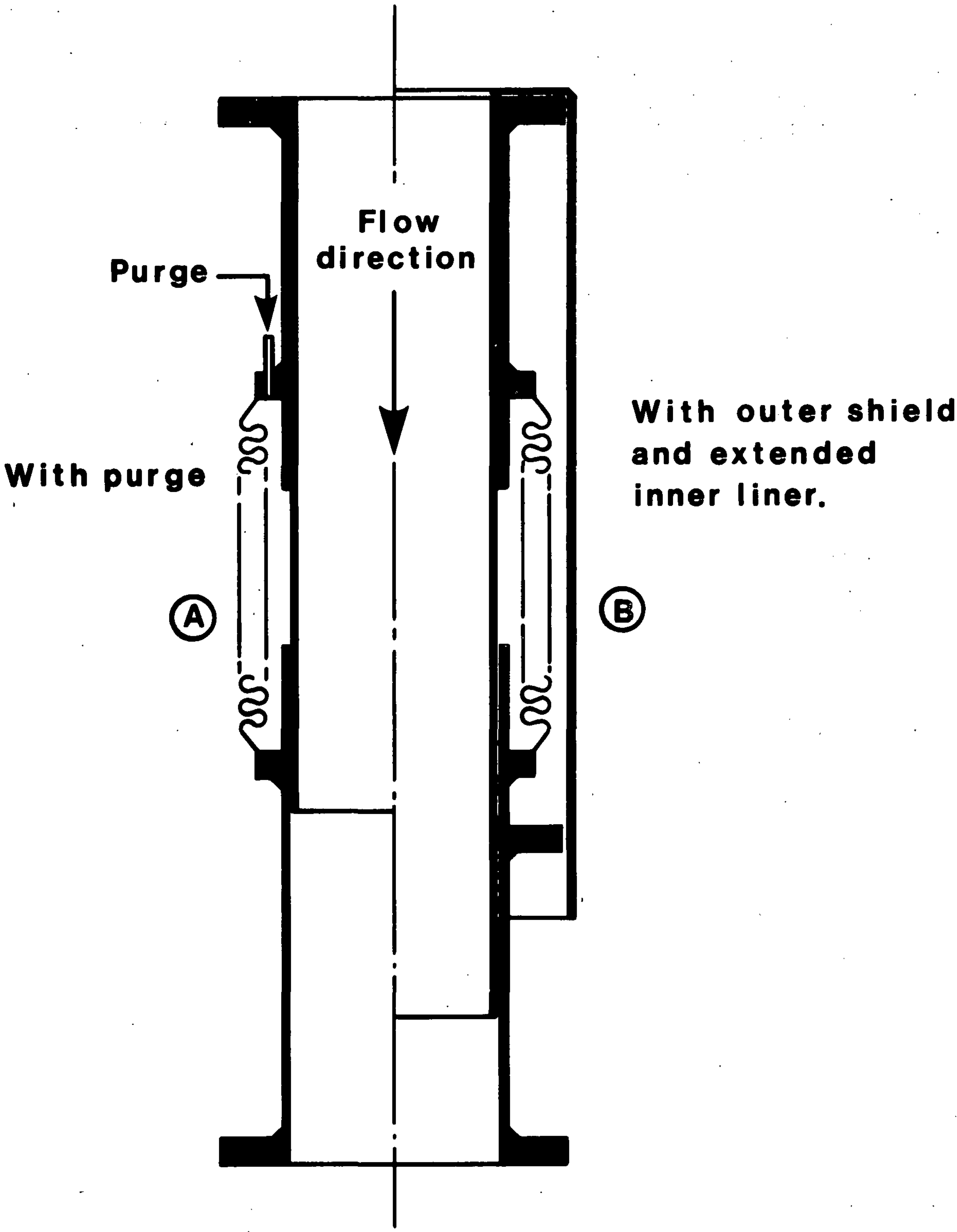


Fig.L38 Typical variations on standard expansion bellows design

In general the bellows assemblies used during the 1000 hour test runs on the internal hot duct work performed satisfactorily- there was no failure and in most cases the bellows could have continued in service. However, the inspections detailed in Section 5 have indicated scope for improvement in the design and installation procedures and in the materials used.

4.4. Dust removal from cyclones

General Design Features. Each of the cyclone dust removal systems contained a simple lock hopper system. No blowdown gas was taken from the cyclones and dust was allowed to fall under gravity from the disengagement pot to the point in the ash system from which it was discharged.

The detail design of the six systems differed, but all followed similar principles of depressurising and discharging batches of dust at regular intervals. Two types of lock hopper arrangement were used, one for the three larger capacity systems (Stream 1 primary, Stream 2 primary and secondary), shown schematically in Fig. L.39, and another for the smaller throughput systems (Stream 1 secondary and tertiary and Stream 2 tertiary) shown schematically in Fig. L.40.

In the larger systems, two hoppers were used. Dust was collected in the lower hopper with the isolation (top) valve open. The top hopper was used as a dust reservoir when the top valve was closed during depressurising and discharge operations. After depressurising the lower hopper, dust was blown into a sealed collection system comprising a combined collection bin and bag filter. From here it was normally dropped straight into a 45 gal. drum where it was weighed before being sealed, labelled and stored. Individual semi-automatic control was used on each of the three large systems. The valves were remotely operated in an interlocked sequence with local manual operation of a pneumatic fluid-logic control circuit. The hopper and ash leg temperatures were recorded in the main control room.

The small throughput systems used only a single hopper. The rate of dust collection was so low as to make a top hopper unnecessary, the volume afforded by the ash leg being sufficient to hold the quantity of dust falling from the cyclone during emptying of the collection pot.

In general these systems were only required to discharge dust every four hours and then in such small quantities as to make manual operation adequate. Key type valve handles were used, however, to prevent simultaneous opening of both lock hopper valves. Dust control during the emptying sequence was adequately effected through a vacuum cleaner filter.

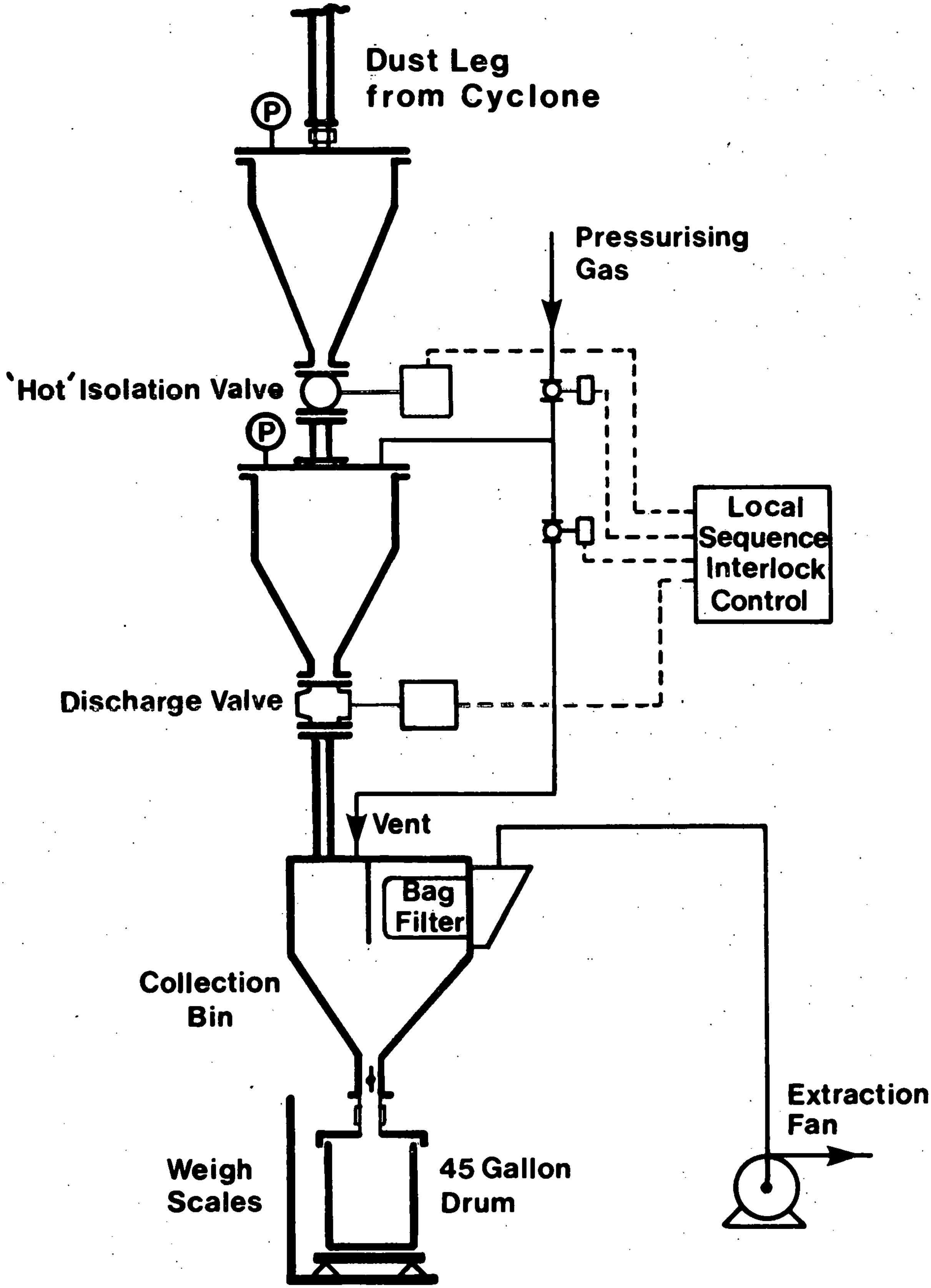
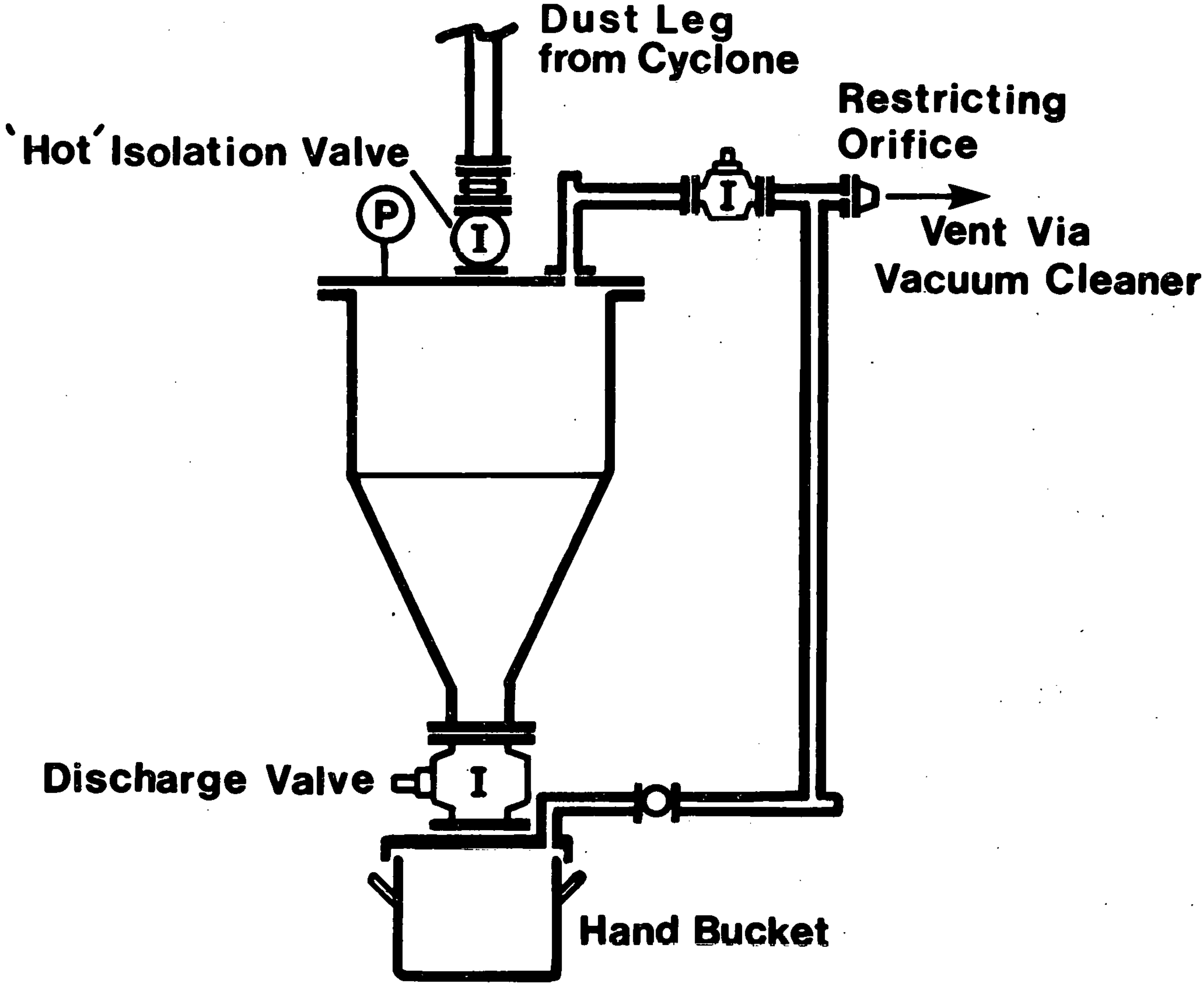


Fig.L39 Schematic of Large Capacity Dust Systems



Valves Marked I are Interlocked

Fig. L40 Schematic of Small Capacity Dust Systems

Stream 1 Primary Cyclone Dust Discharge System. Dust was discharged from the bottom of the primary cyclone through a 4 inch diameter leg about 30 inches long into the top hopper. This had a capacity of about 100 lb of dust (equivalent to about 2 hours operation) and was lined with a 3 inch layer of refractory. The bottom of the hopper converged at an included angle of about 45 deg.

The pipe connecting the upper to the lower hopper was steam traced and contained a 3 inch bore Kamyr valve. Valve performance is commented upon in Section 4.5.

The lower hopper was lined with a 1½ inch thick layer of insulating refractory and also had a heat-resisting steel lining. The hopper had been designed for use where headroom was restricted. The outlet cone was too shallow (90 deg included angle) for satisfactory flow of 'difficult' solids and the outlet was only 2 inch diameter. However, once the refractory had been thoroughly dried out and the steam tracing was fully effective, operation was reasonably satisfactory. A major factor was the favourable characteristics of the primary cyclone dust. This was relatively free flowing and in sufficient quantity to keep the temperature in the system above the dewpoint. The latter was probably aided by a decision to empty the lower hopper every half- hour.

Dust sometimes 'hung-up' in the discharge leg from the cyclone. Reasons for this were not obvious but unsatisfactory dust discharge from this and other causes could be corrected fairly easily by repeating the discharge valve operating sequence and by adjustment of the pressure in the lock hopper before opening the upper valve.

Stream 1. Secondary cyclone dust discharge system. The hoppers were initially identical in design to those installed in the primary system. The upper hopper was fed by a 4 inch diameter heat resisting steel leg about 5 ft long. A 3 inch bore Kamyr valve was bolted to a steam-heated flange at the base of the hopper, and the bottom hopper was fed by a 3 inch bore steam-jacketed pipe about 4 ft long.

The high efficiency of the primary cyclone resulted in only a small quantity of dust reaching the secondary cyclone and increased the problem of keeping the discharge system above the dewpoint temperature. Caking of dust in the Kamyr valve obstructed flow and caused it to fail to seal. There was serious build-up of dust in the cones of both hoppers, and discharge of dust from the system was only achieved with difficulty.

The shortcomings in the design of the lower hopper were largely rectified (after Test 2) by installing a steam-heated conical liner with an included angle of 30 deg and filling the space between the liner and the hopper walls with ceramic fibre. The problem with blockage in the Kamyr valve was largely overcome by replacing it with a steam-jacketed lubricated plug cock sited at the top of the receiving hopper instead of at the bottom of the upper hopper, (i.e. at the bottom of the 4 ft steam-jacketed line connecting the hoppers rather than the top). Cooling in the interconnecting pipe reduced the temperature of the dust and gases associated with it to an acceptable level for the lubricated valve.

In this form this dust removal system was able to operate successfully for the remainder of the 1000 hours. Plugging in the outlet from the discharge hopper was not totally eliminated but always cleared easily by repeating the discharge sequence.

Stream 1. Tertiary cyclone dust discharge system. The dust flow through this system was only about 500 lbs in total over its 665 hours of operation. The single hopper, similar to the lower hoppers of the primary and secondary Stream 1 systems was connected to the bottom of the cyclone by a 3 inch diameter, 4 ft long steam-jacketed pipe.

The problems experienced with the dust discharge system of the tertiary cyclone were of a similar type but of greater magnitude to those experienced with the secondary cyclone. After Test 2 the hopper was modified in the same way as with the lower secondary hopper on Stream 1 and the upper valve was replaced by a steam-jacketed Serck-Audco plug valve.

Dust removal thereafter was considerably more reliable but the discharge sequence was always repeated to ensure that dust was not left in the hopper.

Stream 2. Primary Cyclone Dust Discharge Systems. The concentric design of the first two stages of dust separation on this Stream (see Fig. L.31) led to configurations of dust removal systems that were less than ideal.

The offset cone-shaped section in the bottom of the pressure vessel containing the two stages constituted a disengagement pot for the primary separation stage. Dust fell into the dust leg proper along the line of minimum slope (53^{o} to the horizontal) of the hopper which was also interrupted by a secondary stage dust leg passing through on the centre line of the main vessel (see Fig. L.29). This was probably the main impediment to the flow of dust to the discharge point.

Below the disengagement hopper the dust fell vertically for about 12 ft into the top of the lock hopper system. The dust legs were lined with 4 inch diameter stainless-steel tubing cast into insulation refractory in a 10 inch diameter casing. The top hopper (as in the secondary system) was rigidly mounted and expansion of the dust leg was taken up by a 10 inch bellows unit with a refractory liner mounted on top of the upper hopper. The dust leg entry into this hopper was necessarily offset but the lower hopper was located centrally below, separated only by a short 4 inch diameter stainless-steel spool piece and a 4 inch full bore Kamyr "hot" valve. Both hoppers were metal lined and the linings were 'backed' by 4 inches of insulating refractory. The included angle of the cone was about 40^{o}.

It was difficult to avoid dust hanging up above the lock hoppers. It was apparent during one inspection that combustion had occurred in the neck of the disengagement pot. Lumps of lightly sintered material had formed on the refractory walls and some caked dust had also built up on the cone of the lower hopper. External steam trace heating fitted after Test 2 around hoppers, valves and pipework to minimise condensation resulted in generally satisfactory performance thereafter.

Stream 2. Secondary Cyclone Dust Discharge System. This system had smaller hoppers than the primary system (about 4 ft^3 capacity instead of 8.5 ft^3) and the dust leg had a 3 ft section at about 30° to the vertical. This was necessary because of the close proximity of the primary and secondary dust legs at their outlet from the pressure vessel (see Fig. L.29).

Dust 'build-up' on the cones of the hoppers that occurred during Tests 1 and 2 was eradicated with the installation of trace heating and lagging as on the primary system.

The dust 'build-up' in the leg that was noticed after Test 1 at a point about 8 ft below the cyclone was not noticed in later inspections and was thought to have been caused by condensation during the 'drying-out' of refractory early in the commissioning test.

Stream 2. Tertiary Cyclone Discharge System. This is shown in Figs. L.29 and L.36. The dust leg beneath the cyclone disengagement vessel included two expansion bellows, one inside the casing and the other outside, the latter being necessary because the dust hopper was mounted rigidly on its own supports. The hopper was of similar design to the others on Stream 2 and was stainless-steel lined. The isolation valve above the hopper was manufactured by Neles (a European version of the Kamyr valve). The discharge valve had a steam-heated jacket and was fitted to a steam-heated flange on the bottom of the hopper.

The very fine dust from the tertiary cyclone tended to stick and cake on any surface which was not steeply inclined or was slightly cooled.

The hopper was modified after Test 2 by the insertion of a steeper angled (30° incl. angle) steam-heated conical liner inside the existing hopper shape. This largely solved the problem in removing dust from the hopper but there was a continually recurring partial blockage higher up in the ash leg throughout the 1000 hours. This was close enough to the cyclone to affect its vortex and incipient blockage could be detected on the cyclone pressure drop indicator. With this early warning it was a simple exercise to free the blockage by going through the dust emptying sequence.

General

The experience gained during the 1000 hour test programme emphasized the following major points on the design and operation of PFBC dust discharge systems.

(i) Drying-out of Refractory Linings Must be Thorough. This may seem to be obvious but it is not easy to accomplish particularly when engineering work is being carried out against a tight time schedule, and where in many instances there are limitations on metal temperatures if distortion is to be avoided. Generally accepted dry-out procedures appeared to be inadequate for the hopper systems of the test facility.

(ii) Condensation of Products of Combustion Must be Avoided: This requirement is most onerous during start-up but continues to be a problem during operation where the quantity of dust carrying heat down into the collection system is small. Trace heating of discharge legs, hoppers, etc., in the dust path is essential if difficulties are to be avoided.

(iii) Exacting Design Requirements Need to be Adhered to: Reliable discharge of dust (and particularly of fine dusts), under gravity is most likely to be achieved (a) with discharge legs of 4 inch diameter or larger, (b) with corrosion-resistant metal-lined legs and (c) from hoppers with steeply inclined sides, (e.g. an included angle of about 30 deg), and with metal linings inside the refractory.

The above concepts do not represent a departure from those that have been successfully applied in the past, but a number of factors in both pilot-plant and industrial applications can lead to major departures from them. Factors such as lack of headroom, adaptation of existing vessels to save time and cost, previous experience of having successfully "taken liberties" with design, can lead, and has led, to operating problems.

4.5. Lock-Hopper Valves on Dust Discharge Systems

Isolation Valves

The isolation valves (upper valves) on the lock hoppers were Kaymr or Neles (European version of the Kamyr valve) and the discharge (bottom) valves were mainly lubricated tapered-plug valves (Fig. L.58) which were steam jacketed. Steam jacketed valves were used (a) to combat condensation and (b) to provide some protection against overheating.

The service histories of the dust discharge system isolation valves are shown in Table L.3 and leakage rates at the end of the test series are shown in Table L.4. Fuller details of servicing and inspections throughout the series are given in Section 5. The principal problem experienced with isolation valves was build-up of material between the seat and the ball. Fine dust entered the cavity between the ball and the casing and 'worked its way' between the ball and the seat. The tendency increased with finer dusts and was worse on the valves in the tertiary cyclone systems. The finer dusts were more cohesive and contained a significant amount of material similar in size to the working tolerances of the valves.

The Neles CDAHO3 valve on the Stream 2 tertiary dust removal system showed slight leakage during the run, but was virtually leak-tight when tested during the post 1000 hour inspection. This is attributed to the way in which the tertiary dust, which had collected in the body of the valve, packed and consolidated once the valve had cooled below the prevailing dewpoint.

In addition to causing the valves to leak, the dust entrained in the escaping gases caused local erosion on valves with chromium plated balls (see Fig. L.59) and indeed was the principal cause of erosion experienced. The two valves with stellited balls as well as seats showed no signs of erosion.

Ways of overcoming the problems were discussed with the manufacturers and other users. Purging of the space between the ball and casing with dry air could not be used (at least on the final gas clean-up stage) without risk of re-entraining dust separated by the cyclone. This expedient could however be envisaged where there was a continuous positive blow-down of gases through the dust discharge system.

Table L. 3 Service history of Lock Hopper Isolation Valves on Dust Removal Systems

Test History

Cumulative hours of plant operation.

Valve Type	Location	65	265	470	665	865	No. of Operations.
Kamyr * PD03	Stream 1 Primary Dust	Slight Leakage Not inspected	Inspected Rebuilt	Slight Leakage Not inspected	Slight Leakage Inspected Rebuilt	Slight Leakage Not inspected	1400-1500
Kamyr * PD03	Stream 1 Secondary Dust	very slight leakage Not inspected	Severe Leakage Replaced by Plug valve. System modified	No further leakage from plug valve			Kamyr approx 100 'plug' approx 200
De Zurick Permaseal	Stream 1 Tertiary Dust	No leakage	Leakage. Replaced by plug valve	No leakage	No leakage System removed		De Zurick approx 40 'plug' approx 60
Kamyr PD04 (Stellited ball)	Stream 2 Primary Dust	very slight leakage Not inspected	Significant leakage Rebuilt Installation modified	Slight leakage Not inspected	No. change Not inspected	No change Not inspected	1100-1200
Kamyr PD04 (Stellited ball)	Stream 2 Secondary Dust	No appreciable leakage Not inspected	Slight leak-age Rebuilt Installation modified	Slight leakage Not inspected	No change Not inspected	No change Not inspected	350-400
Neles CDAH03	Stream 2 Tertiary Dust	Slight leakage Not inspected	Severe Leakage Rebuilt	Severe Leakage New seats fitted Rebuilt	Slight leakage Inspected Rebuilt	Slight leakage Inspected Rebuilt	100-200

* These valves had seen approximately 100 hours of service in similar situations prior to 1000 hour programme.

Table L.4 Leakage rates of metal seat ball valves after 1000 hours operation

These measurements were done during the post 1000 hours inspection after the valves had been removed from the plant and before they were broken down for visual inspection. 100 psig air was the test medium and leakage rate was measured by small variable area flow meters ("Purge raters"). All the valves were operated several times before leakage rates were measured.

Valve	Seat	Ball	Duty/Location	No.of Operations	Leakage rate SCFH
Kamyr PD04 (4" port)	Stellited	Stellited	Stream 2. Primary dust system isolation	1100 to 1200	17
Kamyr PD03 (3" port)	Stellited	Chromium-plated	Stream 1. Primary dust system isolation	1400 to 1500	16
Kamyr PD04 (4" port)	Stellited	Stellited	Stream 2. Secondary dust stream isolation	350 to 400	10
Neles CD AH03 (3" port)	Stellited scraper type	Chromium-plated	Stream 2. Tertiary dust system isolation	100 to 200	1*
Neles CH AH01 (1" port)	Stellited	Stellited	Bed removal isolation	About 1000	15
Neles CH AH01 (1" port)	Stellited	Stellited	Dust sample system isolation	About 1500	1.5

* See text.

A potential solution for 'gravity' dust discharge systems would appear to be in the further development of scraper type seats (e.g. developments of those fitted to the Neles valve later in the programme) backed by means to ensure continuous contact between the scraper surfaces and the ball irrespective of temperature changes in the valve assembly. It appears to be essential that both the top and bottom faces of the ball should be 'clean' by the time the valve is in the fully open position. Avoidance of condensation by trace heating of the valves and associated ductwork is, of course essential.

From several points of view the isolation valve has the most critical duty in that:

(i) It is nearest to the hot gas flow path

(ii) It cannot be replaced or serviced without shutting-down the plant

(iii) In the (unlikely) event of failure of the system beyond it leading to depressurisation whilst it is in the 'open' position, it could conceivably attain a temperature close to the gas temperature.

Mitigating factors are (a) that it only needs to seal against plant pressure for the time needed to discharge the lock hopper and (b) that exposure to excessive temperatures in the event of (iii) can be avoided by automatically closing the valve when the temperature exceeds an acceptable working level.

Discharge Valves

Valves used on the bottom of the ash lock hopper system through which the collected dust was periodically discharged were of one design - the Serk-Audco tapered plug, lubricated-seal type (Fig. L.58). In most cases they were steam jacketed, thus providing heating during plant warm up and between ash system operation, and cooling protection during the actual discharge of dust. This type of valve does not have seats but relies on a renewable grease seal which passes from a supply in the stem along channels in the plug and body.

Some problems were experienced early in the test series, the grease channels becoming packed with dust, but when a more suitable high-temperature grease had been obtained and suitable service intervals for each valve had been ascertained, these units performed satisfactorily and provided a comparatively cost effective solution to the problem of discharging hot cyclone dust under the conditions prevailing in the pilot plant

4.6. BED MATERIAL REMOVAL

The system by which bed material was removed from the combustor and which enabled bed level to be controlled was simple and effective, relying on the skill of the operator for safe and efficient discharge of bed material.

The system consisted of a heat-resisting steel holding hopper, (item 9 on Fig. L.2) bolted directly onto the 2 inch i.d. insulated offtake through the distributor plate which is shown on Fig. L.7. A 2 inch diameter pipe ran from the bottom of the hopper via a connection through the casing to the isolating and discharge valves below the combustor. A set of expansion bellows, continuously nitrogen purged, was incorporated into the 2 inch pipe.

The isolation valve was a 1 inch bore Neles/Kamyr type metal-seated ball valve (type CDAH01) with stellited ball and seats. This was the only high-temperature rated valve in the system. Below this was a carbon-steel round port lubricated plug valve with a water-cooled base which was used to regulate the flow of hot bed material. Approximately 100 lb. of hot material was run out through the system into a specially designed hand bucket over a 2 - 3 min period every hour. The hopper was designed to hold about 100 lb. of material so that each batch discharge was held in dense phase below the combustor for about an hour before passing out through the valves. This provided a cooling period for the batch but preferential flow through the hopper meant that for the latter part of each discharge red hot solids flow was controlled by the plug valve. For this reason the valve was opened for only a few seconds at a time and then allowed to cool. This was done several times during a discharge period. The holding hopper contained a thermowell, and its temperature change and that of the skin temperature of the leg below the hopper was recorded and is reproduced in Fig. L.41 for a two-hour period during Test 4.

Valve Performance The duty required of the plug valve - to regulate and shut off solids flow, was an onerous one and an identical

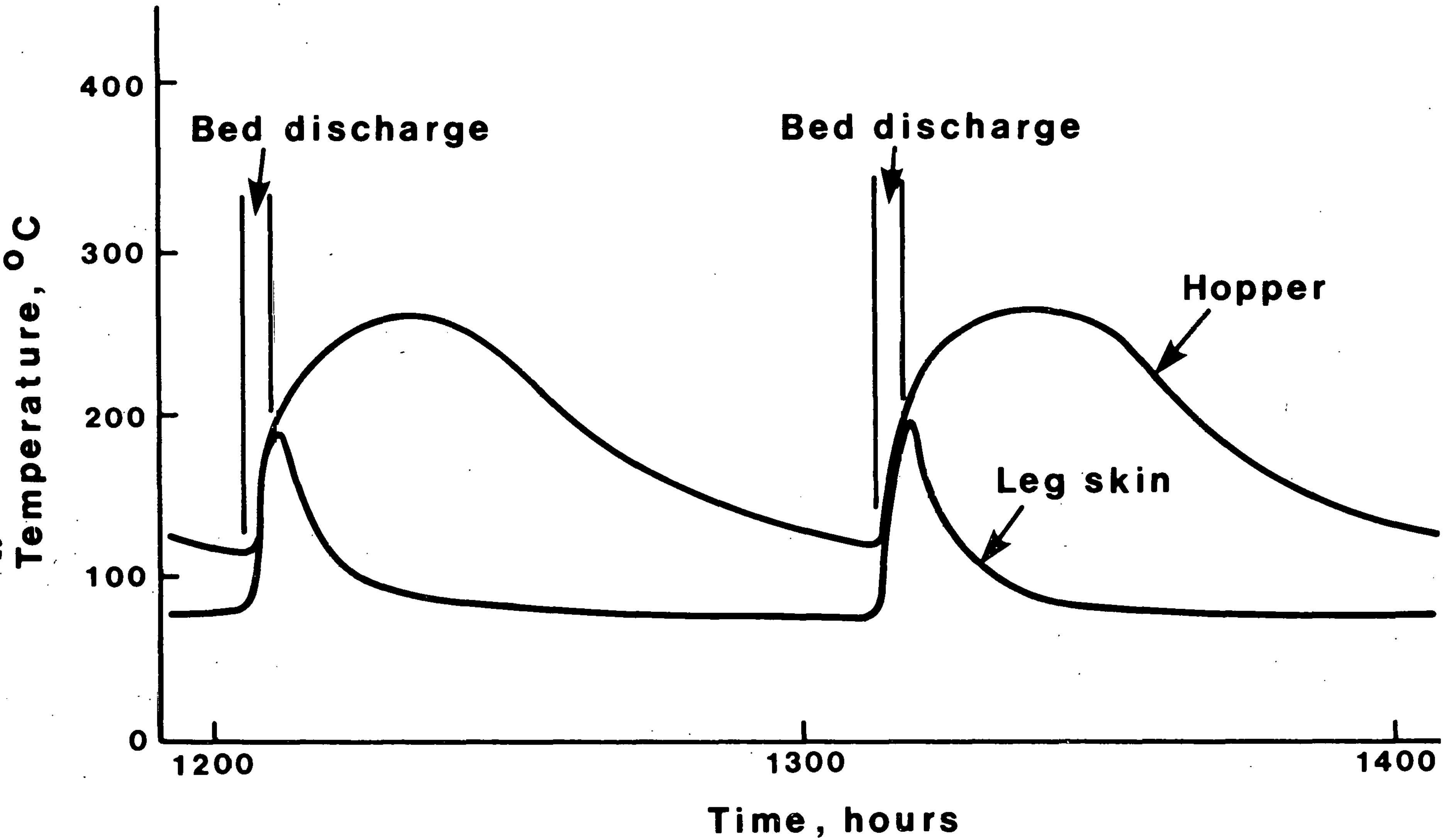


Fig. L41 Measured temperature variations in bed removal system during Test 4

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stand-by valve was fitted below the operational valve as a precaution. It was normally left in the open position and was, in fact, never brought into regular service.

The Neles/Kamyr valve was used primarily as an isolation valve. Attemps early in the programme to use the valve to regulate the solids flow by on/off action, (as used with the plug valve), were mostly unsuccessful. The differential expansion of the ball relative to the body together with the ingress of some bed material into the body cavity eventually caused the valve to seize and the extended manual actuator to fail. (All three valves were operated manually using extended handles). It was fitted with a body purge to help prevent material entering the body cavity and was subsequently used as an isolation valve. However, it usually failed to provide a gas tight seal and the regulating plug valve below was also closed. Checks after each test run showed excessive leakage through the valve, but the ball and seats had become scored, mostly as a result of its early use without a body purge. Fig. L.48 shows the condition of ball and seat after 1000 hours. The seats had also become loose in their sockets by this time. The leakage rate in the post-test inspection shown in Table L4, is high for a 1 inch valve. The data in the Table also show that a similar valve used on a dust sampling system was virtually leak-tight after 1000 hrs. This valve was used only for isolation purposes.

4.7. GAS QUENCHING AND PRESSURE LET-DOWN

This part of the test facility is the least relevant to large scale plant design but its description is included for completeness. No attempt was made to recover energy from the exhaust gases after they had passed through the two Cascade sections. Instead, each of the three exhaust streams, (Stream 1 cascade exhaust, Stream 2 cascade exhaust and by-pass stream), was quenched and scrubbed before being let down through the three pressure control valves. Two of these valves were used to set the pressure downstream of each cascade to a level which ensured choked operation, the third valve, on the Stream 2 cascade by-pass stream, being the plant pressure control valve.

In each case the gas streams were quenched by water sprays in the final refractory-lined section of duct to about 250^{o}F, the adiabatic saturation temperature, before passing through a conventional venturi scrubber. Water was supplied to sprays in the venturi throat at an approximate rate of 60 lb/1000 ft^3 saturated gas, passing through the throat at a design velocity of 300 ft/s. Water was then separated in wet cyclones (hydroclones) designed basically to Stairmand proportions with an inlet velocity of 45 ft/s in a rectangular tangential entry. On the outlet from these hydroclones were flow measuring elements (orifice plates) and pressure let-down valves. From here the three streams were combined and vented to the stack.

All quench and scrubbing water separated in the hydroclones was returned to settling points from where it was recirculated. Loss was made up from the mains water supply and pH in the system was controlled by injection of aqueous Ammonia.

One of the test programme requirements was that the Stream 2 (GE) cascade should be off-line whenever conditions in Stream 2 changed appreciably or when the dust loading in the stream exceeded 500 ppm (0.27 grains/ft^3). In order that this could be done without changing total mass flow through the plant or changing controller set points, it was arranged for the by-pass stream to handle either 0.2 lb/s flow (when the cascade stream was on-line) or 1.2 lb/s, the total flow in Stream 2 (i.e. when the cascade was off-line). The arrangement is shown in Fig. L.42. When the cascade was to be by-passed, which was only at start-up and shut-down since dust loadings never approached the limit of 500 ppm, a choked orifice was put in line and the cascade stream isolated downstream of the cascade. The orifice simulated the pressure drop of the cascade for a flow of 1 lb/s and enabled the cascade stream let down valve to continue controlling at the same set point (20 psig). A larger venturi scrubber and extra quench sprays were brought into operation in the by-pass stream to cope with the extra 1 lb/s of flow, the remaining 0.2 lb/s being handled as normal by the pressure controlling side stream.

5. DETAILS OF BETWEEN-TEST AND POST-TEST INSPECTIONS

5.1. Refractory lining of combustor

This inclusion of different types of refractory as a comparison of their suitability was part of the contract with EPRI. Visual inspection of the refractory surface condition showed no surface wear on any of the refractories apart from one patch between the coal nozzles and the start-up burner on the west side face. This can be seen in Fig. L.45, a photograph taken during dismantling. The cracks visible in the refractory surface were mainly caused by the separation of the four sides. In general the refractory surfaces had been roughened, but original trowelling marks could still be clearly seen.

It had been the intention to measure the thickness of the refractory at a number of positions before and after the 1000 hours operation. The pre-test measurements on the tapered section were made by the manufacturers (Babcock International Ltd.) before the ends and sides were assembled, and measurements at the end of the programme were done by CURL using calipers. The results and positions of these measurements are shown in Fig. L.43. However, dismantling of the ends and sides for measurement resulted in some disturbance to the refractory layers, lifting them in places from the mild steel walls. Uneveness in some places, due to the original casting of the refractory, made measurement difficult, so that the values given in Fig. L.43 do not have a high order of accuracy. For example, an independent (at a later date) inspection of the south section at point 5 of Fig. L.43(c) showed no signs of erosion but a considerable "rippling" of the refractory due to the initial "trowelling".

The thickness of the refractory in the freeboard was also determined at specific locations using calipers. Measurements before and after the programme were within ± 1/16 inch, indicating no measurable erosion. Because the refractory in the freeboard was not disturbed, and because access was easier, the accuracy was considerably greater than in the tube bank regions.

A full statement on the relative performances of the various refractories is being included in a report from Fluidised Combustion Contractors Ltd. to EPRI.

5.2. Internal expansion bellows.

Stream1 primary and secondary cyclone dust leg bellows

These were identical units with a similar duty, the only difference being in their positions within the cyclone pressure vessel. Both

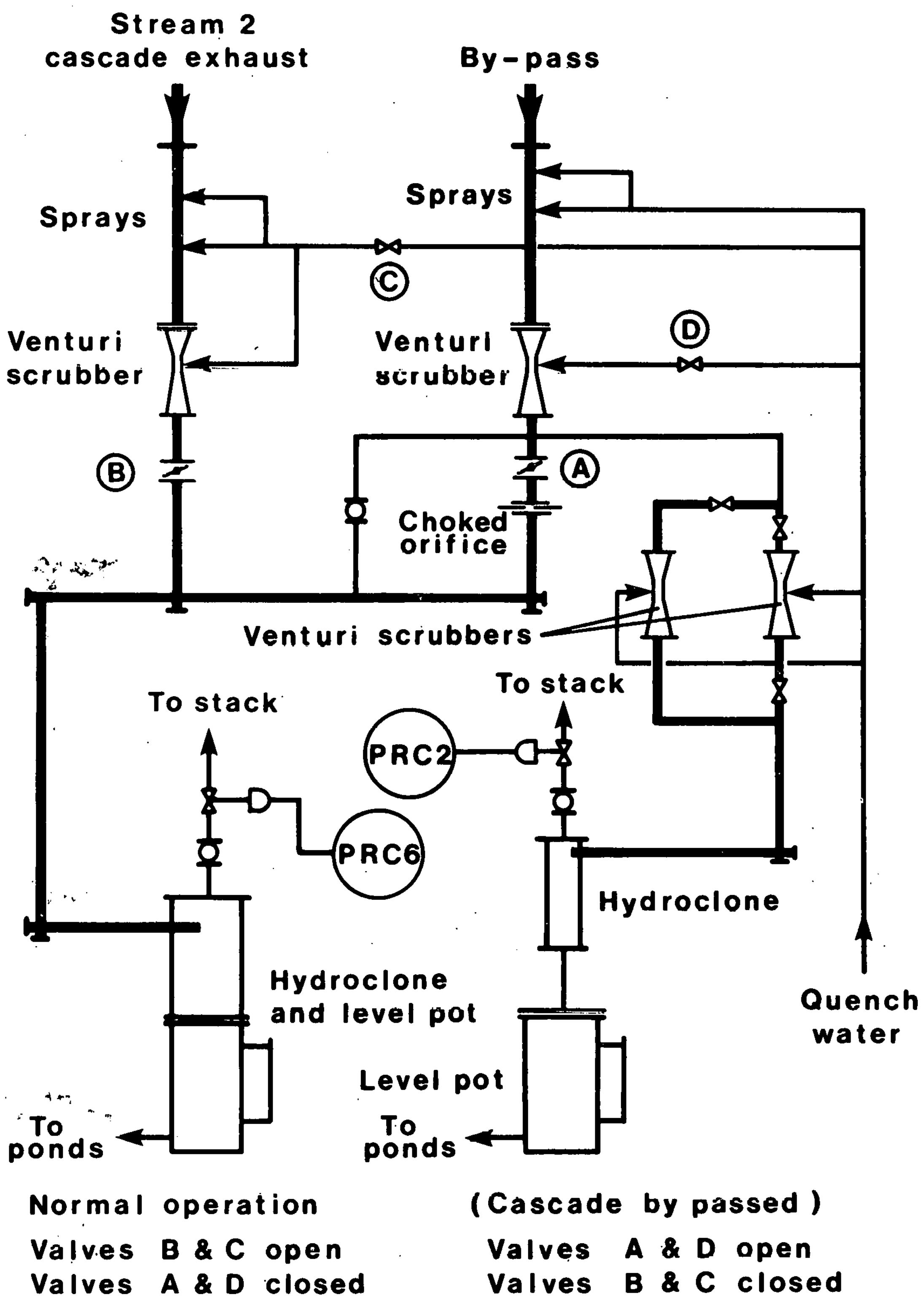

Fig. L42 Stream 2 cascade and by-pass scrubbing system

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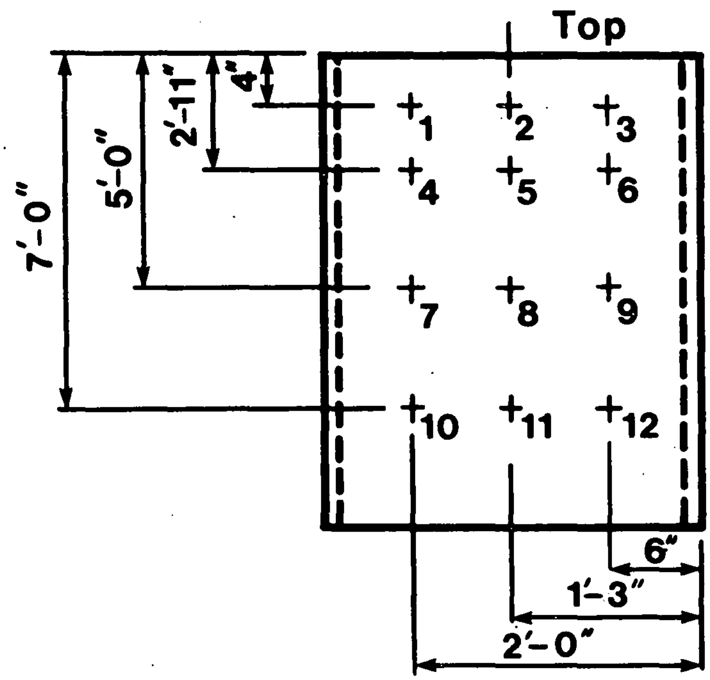


View on outside face 4
(North end)
Hard face material "Mizzou"

Point No	1	2	3	4	5	6	7	8	9	10	11	12
Measured thickness loss ($\frac{1}{1000}$ inch)	29	Gain	Gain	Gain	Gain	Gain	Gain	Gain	Gain	50	Gain	64

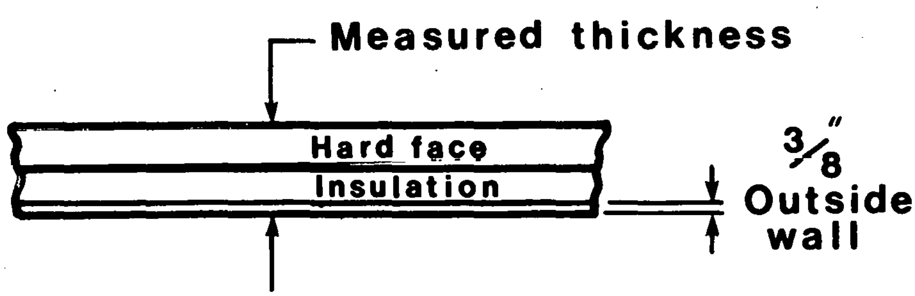
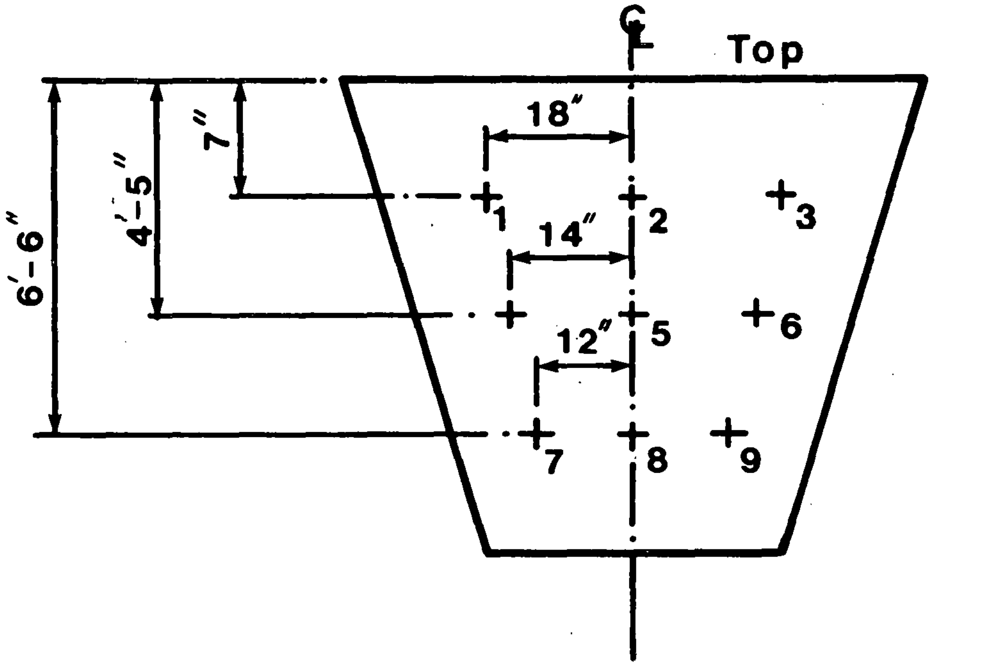


Fig. L43(d) Combustor refractory thickness measurements

D523



View on outside face 1
(East end)
Hard face material "Mizzou"

Point No.	1	2	3	4	5	6	7	8	9
Measured thickness loss ($\frac{1}{1000}$ inch)	50	50	87	54	34	61	Gain	103	177

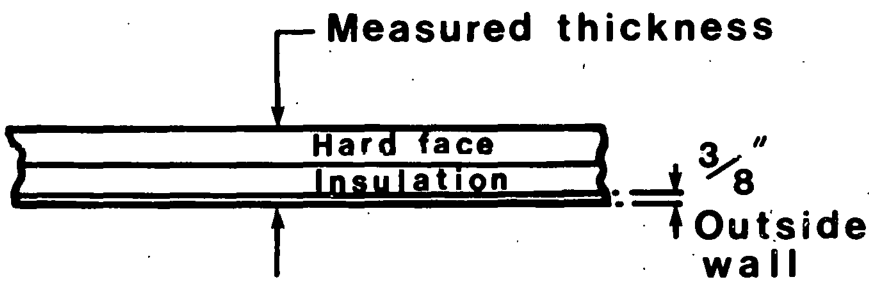
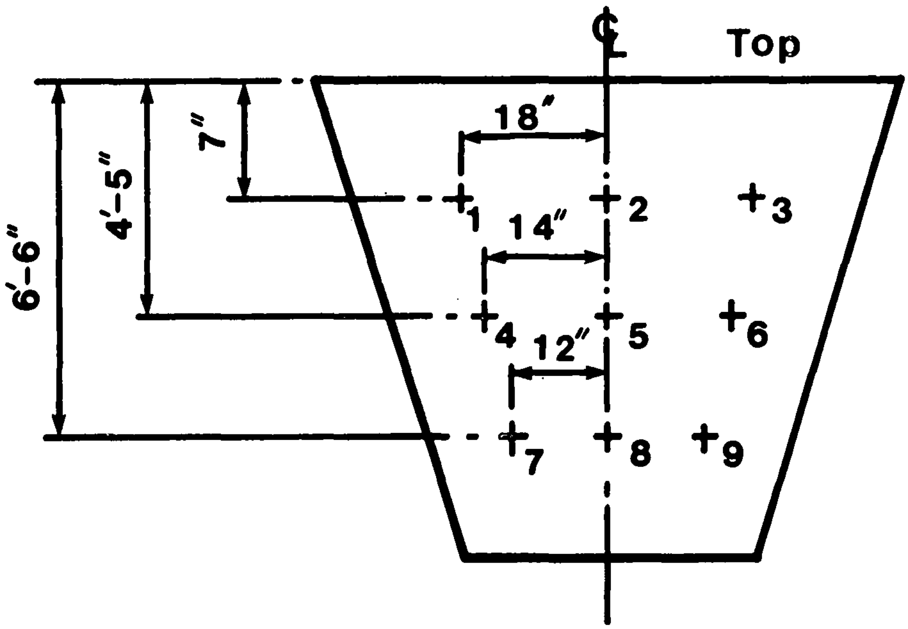


Fig. L43(a) Combustor refractory thickness measurements

D520



View on outside face 2
(West end)
Hard face material "KS4"

Point No.	1	2	3	4	5	6	7	8	9
Measured thickness loss ($\frac{1}{1000}$ inch)	105	250	Gain	Gain	Gain	Gain	30	27	98

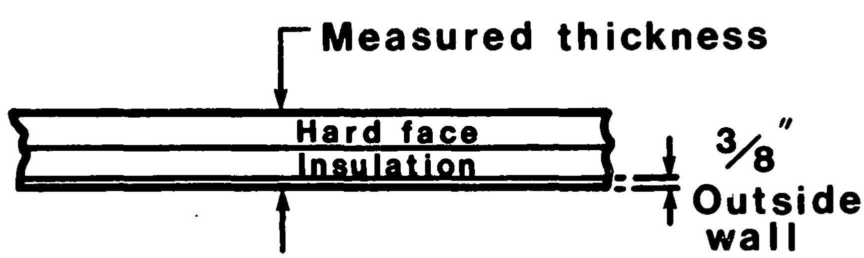
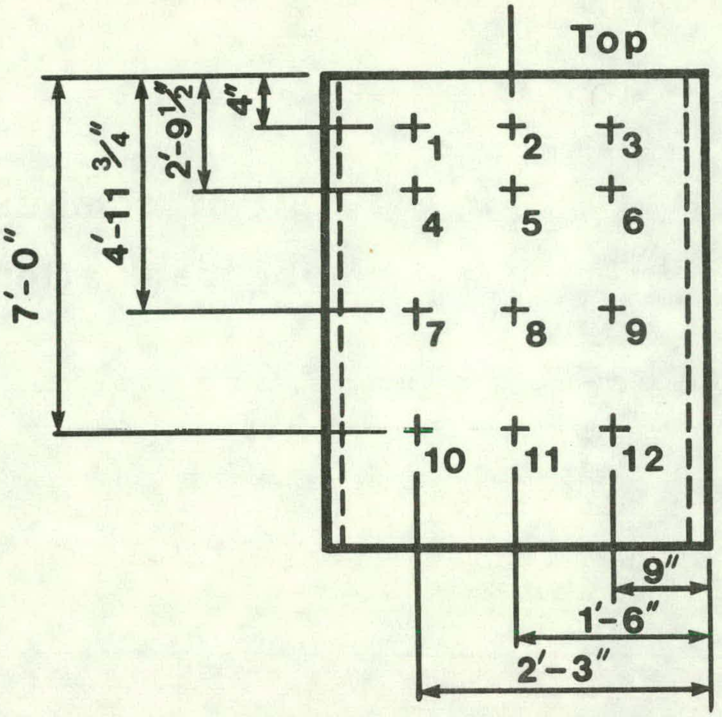


Fig. L43(b) Combustor refractory thickness measurements.

D521



View on outside face 3
(South end)
Hard face material "Mid cast"

Point No.	1	2	3	4	5	6	7	8	9	10	11	12
Measured thickness loss (1/1000 inch)	Gain	98	78	280	496	307	159	217	312	57	Gain	61

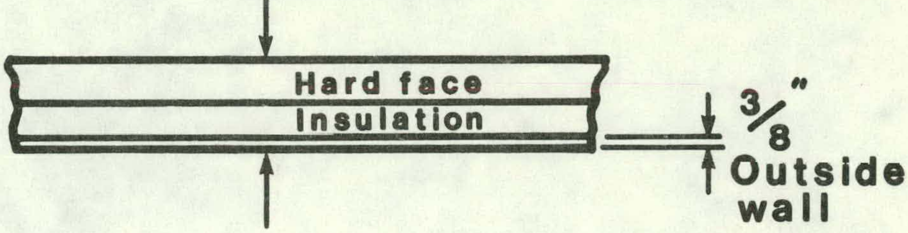


Fig. L43(c) Combustor refractory thickness measurement

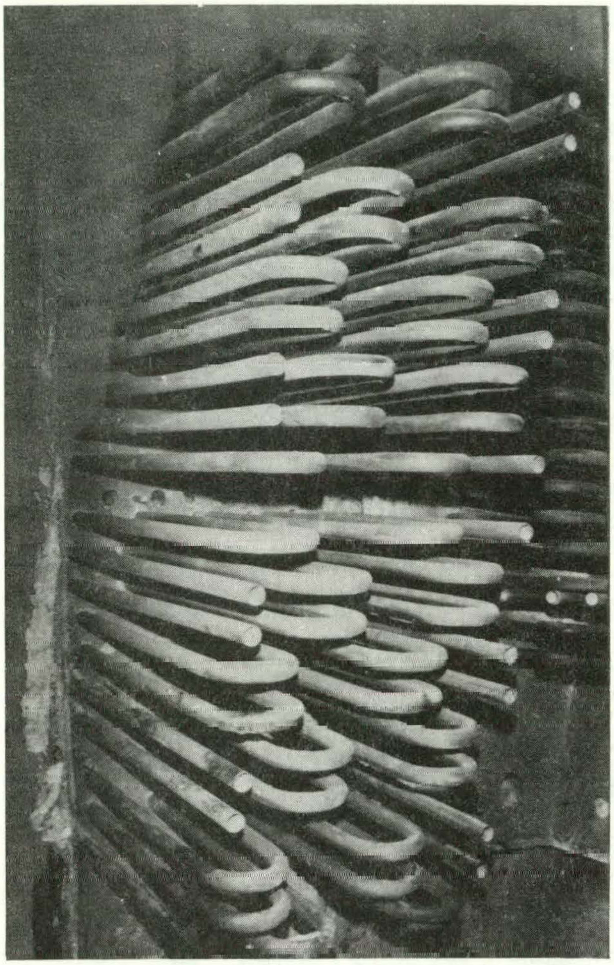


Fig.L44 Half of combustor tube bank after 1000hrs.

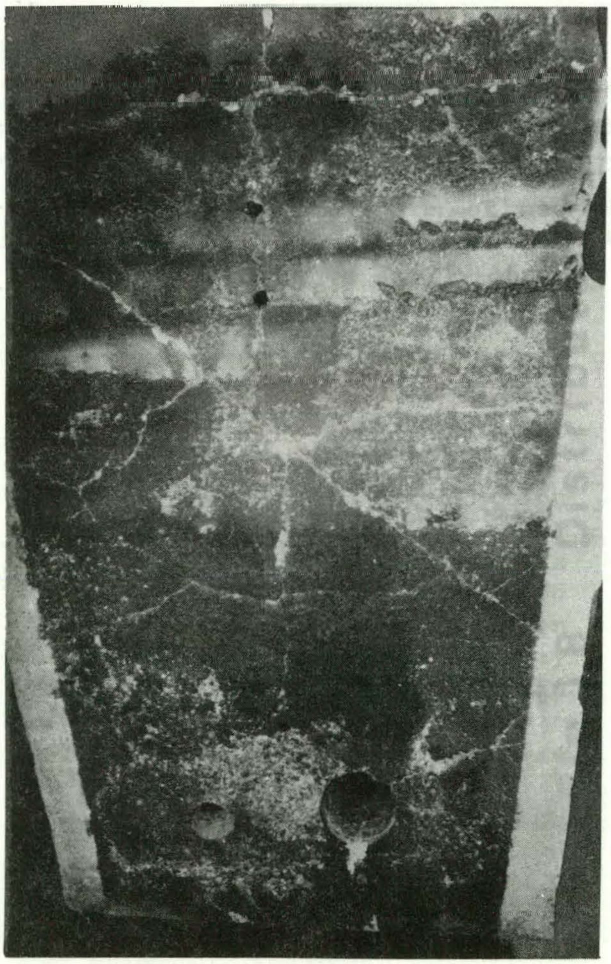


Fig.L45 East end refractory wall after 1000 hrs.

were positioned just below their cyclone disengagement pots so those on the secondary cyclone dust leg, (the secondary cyclone being shorter), were higher up in the pressure vessel. Both units included a surrounding water-cooled coil.

Inspection showed the corrugations of the bellows on the secondary cyclone dust leg to be deformed. They had annealed into a shorter overall length, about half being compressed and the rest stretched (FIg. L.49). The surrounding cooling coil had the appearance of not having been cooled at some stage and in their well-insulated position the bellows corrugations may have suffered temperatures up to 800°C. There was no indication of their movement being restricted by fouling of liners or shield. The corrugations were covered with a black, fairly coherent oxide layer on the outside surface. The corrugations on this unit, were sectioned and Figs. L.50 and L.51 show the slightly worse condition of the inside surface.

In the primary cyclone system, the skin temperature of the dust leg adjacent to the bellows ran at about 1200-1250°F throughout most of the 1000 hours. The bellows unit had returned to its normal length. Only at the outside edges of the corrugations was the oxide layer blackened: the rest was purple/blue. There was no discolouration on the cooling coil and it had apparently not been heated to greater than 220°F (Fig. L. 49).

Stream 1 tertiary cyclone dust leg bellows

This unit was removed with the Stream 1 tertiary cyclone after being in service for 650 hours. The corrugated section was similar to those in the primary and secondary legs but had been installed with a considerable amount of pre-stretch. Skin temperature records show temperatures of 1380-1430°F on the ash leg close to the bellows which were surrounded by Vermiculite insulation with no additional cooling. Some of the corrugations were still compressed when the unit was removed and the black/blue surface oxide was beginning to flake.

Stream 2 secondary stage ash leg bellows

The unusual concentric design of the 1st and 2nd stages of separation in this stream influenced the positioning of this bellows unit which was in an extension of the nozzle on the main pressure casing (see Fig. L.29). Quantities of dark grey ash were deposited on and around the bellows, obviously due to some leakage from the 1st stage dust hopper directly above these bellows and through which the 2nd stage ash leg passed.

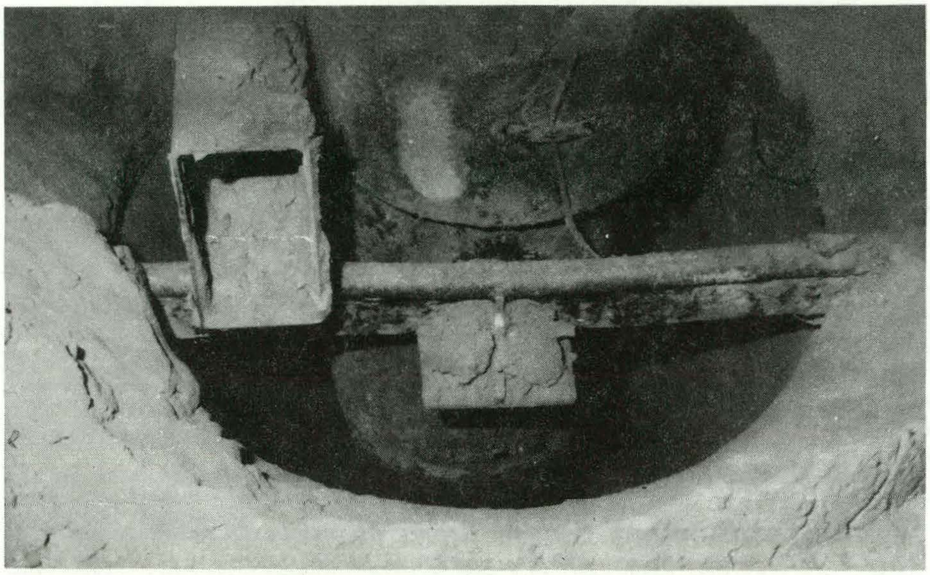


Fig. L46 Stream 2 secondary stage cyclone in primary stage outlet after 1000 hrs.

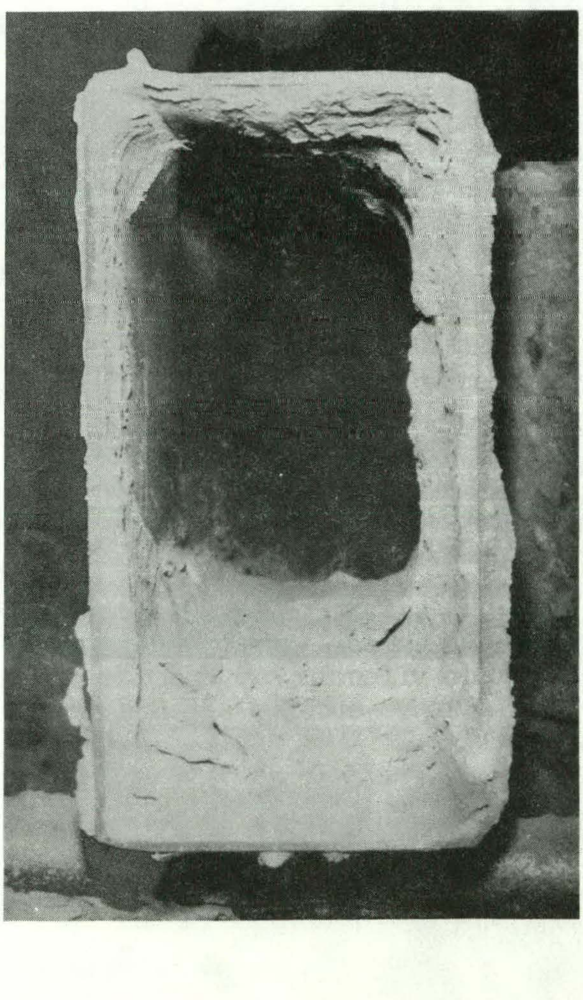


Fig.L47 Close up of secondary stage inlet.

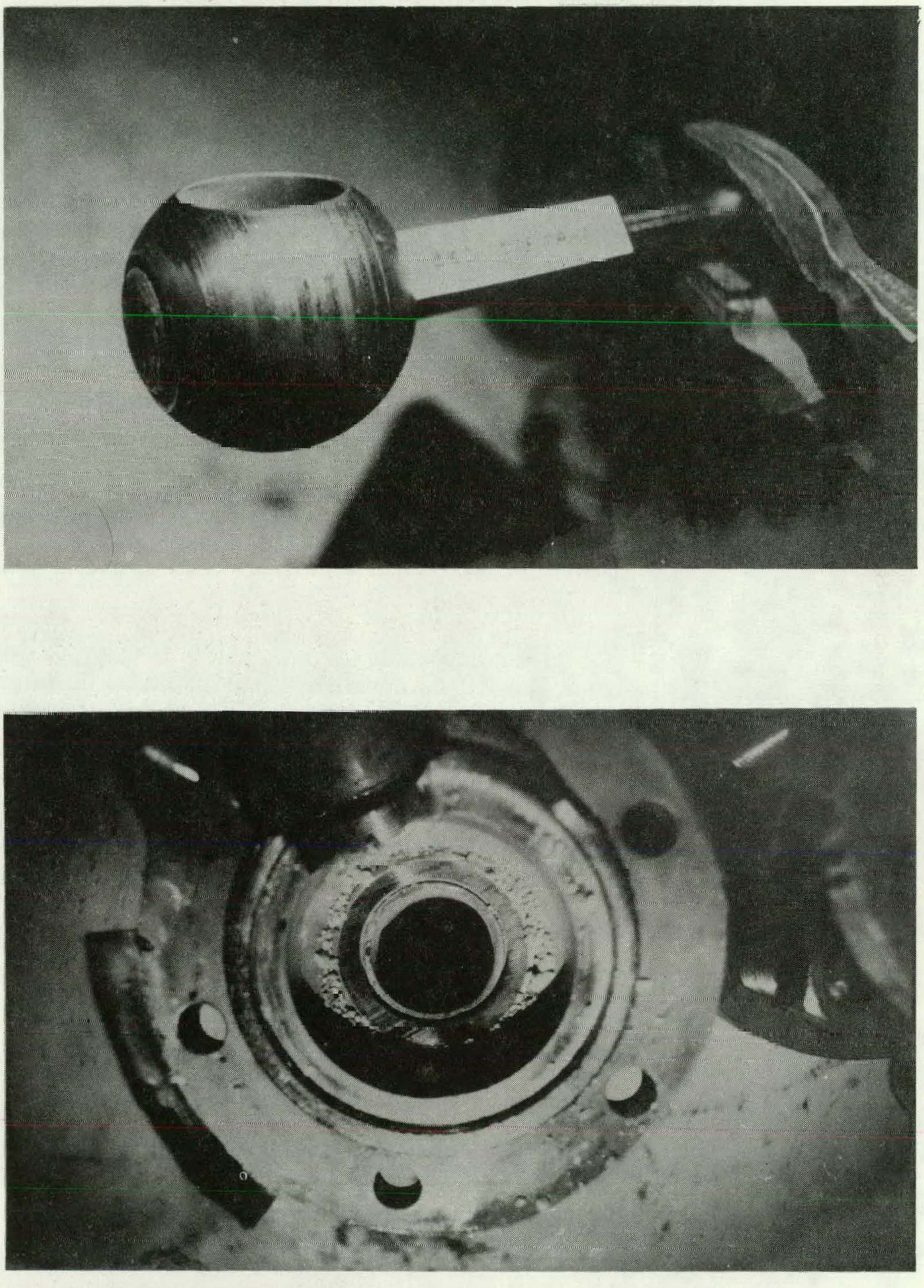


Fig.L48 Ball and one seat of 25mm Neles valve used on bed removal leg.

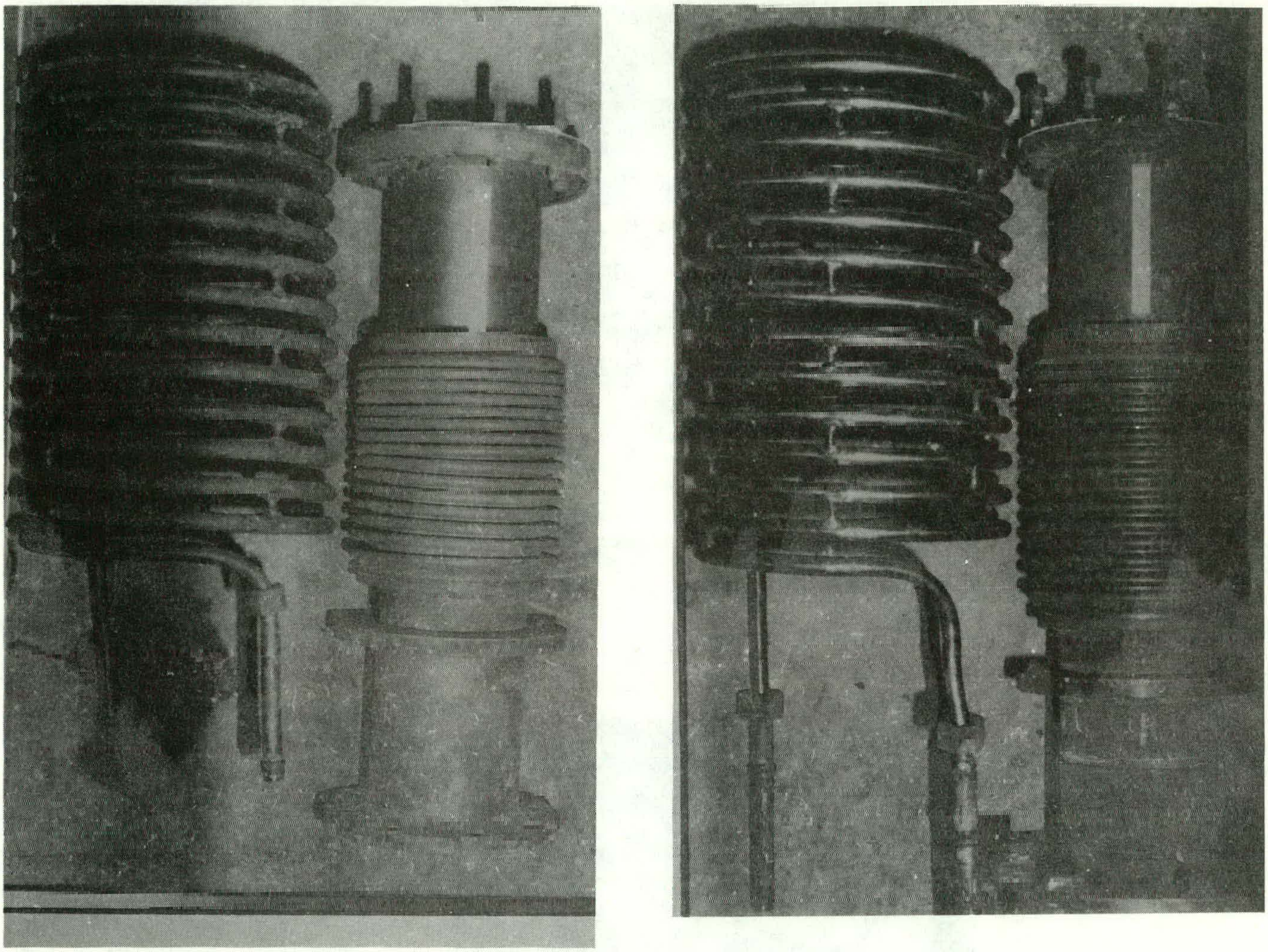


Fig.L49 Stream 1 primary (left) and secondary (right) dust leg bellows and their cooling coils.

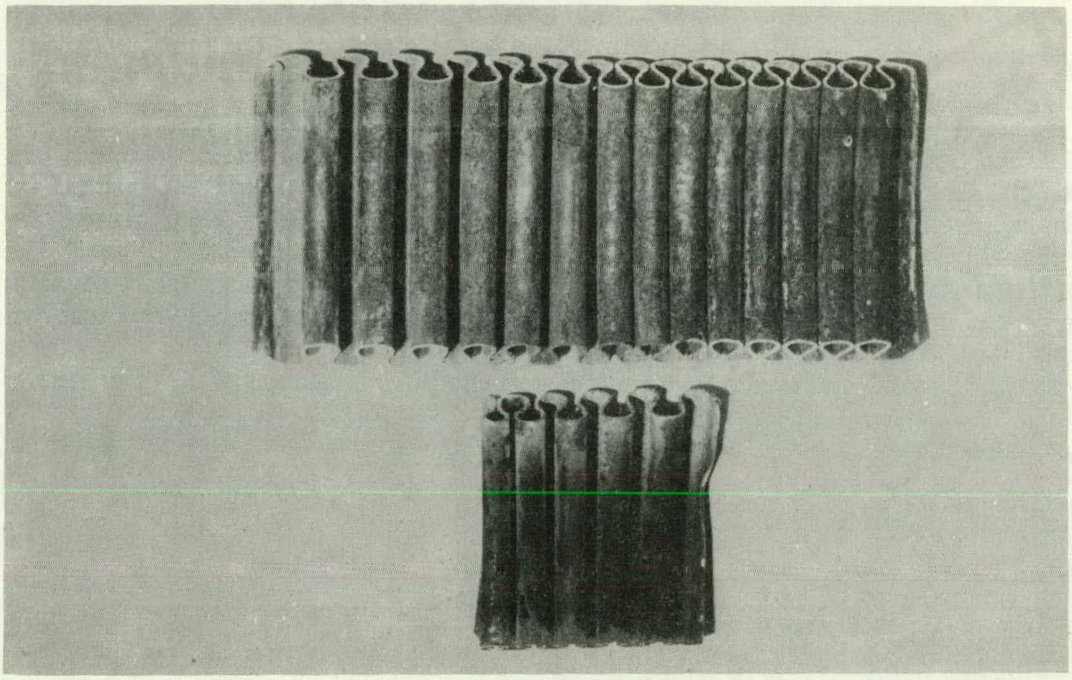


Fig.L50 Inside surface condition of ash leg bellows and gas path bellows (Top – Stream 1 secondary ash leg, Bottom – Stream 2 tertiary cyclone gas path.)

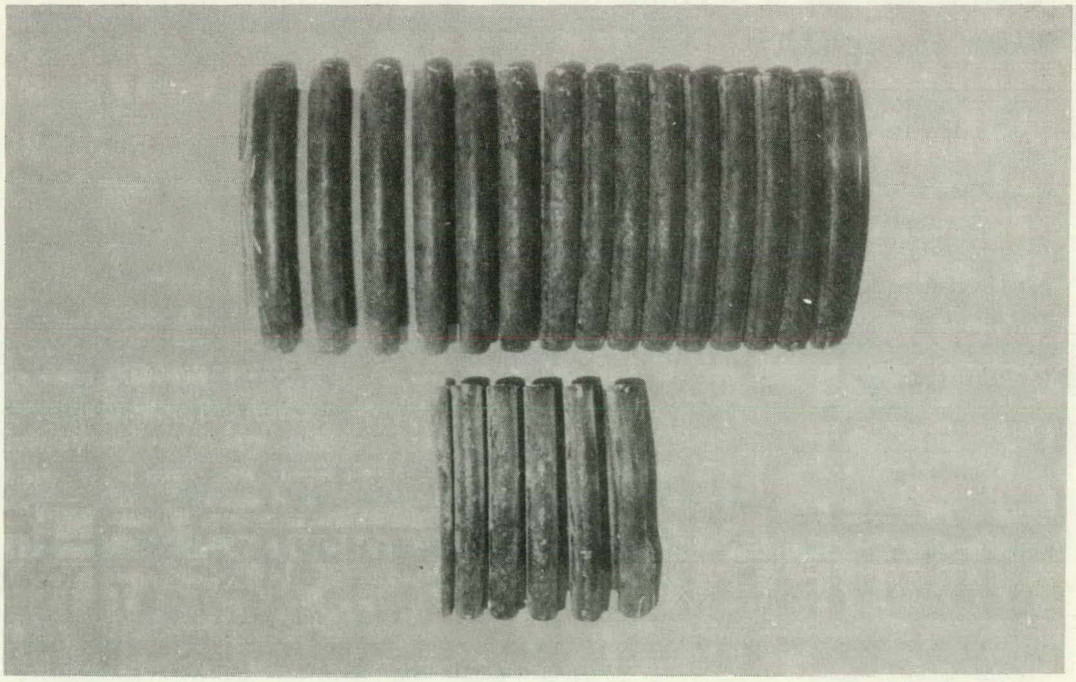


Fig.L51 Outside surface of sectioned bellows units as above

The surface colouration of the corrugation changed from purple on the inside (concave) part to light bronze on the outside (convex). There were signs of pitting corrosion around the welds which had probably arisen since plant shut down. Apart from this, the oxide film was complete and it was apparent from the general appearance of the bellows unit and adjoining part of the ash leg that the assembly had not reached temperatures much in excess of 500°F. Unfortunately the skin temperature thermocouple on this unit had apparently been damaged during installation and was never serviceable.

Stream 2 tertiary stage ash leg bellows

The appearance of this unit showed that a temperature gradient had existed along its length. The bellows unit, positioned just below the disengagement pot on the cyclone was effectively the lower connection between the cyclone and the ash outlet in the pressure casing. (Fig. L.29). The casing at this point was constructed of stainless steel. A skin temperature thermocouple just below the cyclone pot indicated between 1380°F and 1500°F during the test runs, whilst skin temperature surveys done on the pressure casing at this point showed about 200-300°F (Fig. L.36). Not surprisingly, the metal oxide on the upper end of the corrugation was black and not very coherent and some pitting corrosion was evident around the welds. Measurements of the corrugations showed them to have annealed in a slightly compressed state at this upper end. The lower end of the corrugated section appeared normal and was still springy. The oxide film on this part was bronze in colour.

Stream 1 tertiary gas path bellows

There were two units, one with its axis horizontal on the duct between the secondary and tertiary cyclones the other in the more normal vertical position on the outlet from the tertiary stage cyclone. There was some concern about this arrangement because the expansion and reaction forces involved were interactive at right angles. The spring reaction of the horizontal set would tend to misalign the vertical set possibly causing their movement to be restrained. However, there was not firm evidence on inspection to suggest that substantial problems of this nature had arisen. The horizontal bellows were annealed into an almost fully compressed position and the black oxide surface on both bellows had roughened and spalled quite badly.

Stream 2 secondary stage gas path bellows

This unit was positioned in the top (outlet) nozzle of the primary and secondary stage pressure vessel and as can be seen in Fig. L.29 was in that part of the vessel which constituted the outlet from the primary stage and inlet to the secondary stage. The hot gas duct skin temperature close to the bellows indicated 1400-1420^{o}F throughout the 1000 hours of operation. This can be taken as a fairly authentic operating temperature for the corrugated section since heat losses from the unit would be very small as it was surrounded by combustion gases from the primary stage. The bellows unit was lightly coated with dust on removal and showed no sign of disfigurement, oxide spalling or pitting corrosion. The nitrogen purge on this bellows unit, as with all the gas path units, probably contributed to its apparently good resistance to corrosion, by perhaps locally reducing the temperature of the corrugations as well as providing an inert atmosphere.

Stream 2 tertiary stage gas path bellows

Reheat propane was injected immediately upstream of the tertiary stage cyclone and heat loss between this cyclone and the cascade made it necessary for the gas temperature in the cyclone to be in the range 1560^{o}-1630^{o}F. Hence this set of bellows had the most arduous duty as far as temperature was concerned. Inspection showed that it had had to take up a considerable degree of misalignment between the cyclone centre line and the containing pressure vessel's centre line (about 3/16 inch over the corrugated length of 4 inches). The cyclone inlet was not sealed so that combustion gases filled the dead space around the cyclone in the pressure vessel. There was a light covering of dust on the outside of the bellows unit. The bellow unit, apart from being annealed into its misaligned position, was in relatively good condition (Fig. L.52). The oxide film was black, as would be expected, but seemed very smooth and coherent. The corrugations were sectioned to inspect inside as well as outside surfaces as shown in Figs. L.50 and L.51.

General

Loss of resilience was experienced on some of the units. These had obviously compressed to take up expansion as required but had not expanded again to their original cold length when the plant was cooled down. This was noticed particularly in bellows which had experienced high temperatures. Internal stresses of cold working, present in the bellows units and in the duct work at assembly are apparently relieved at a particular temperature and an annealing or normalising process occurs as the plant cools after shut down. This may severely affect the number of expansion and contraction cycles that such assemblies will withstand. The number of cycles experienced by the bellows assemblies during these test runs was very low (as few as 6 or 7 for some of the gas path bellows), compared with what might be expected in normal commercial use. The use of better materials should however obviate this problem.

Pitting corrosion around weld zones was most noticeable on ash leg bellows, i.e. those which operated at generally lower temperatures

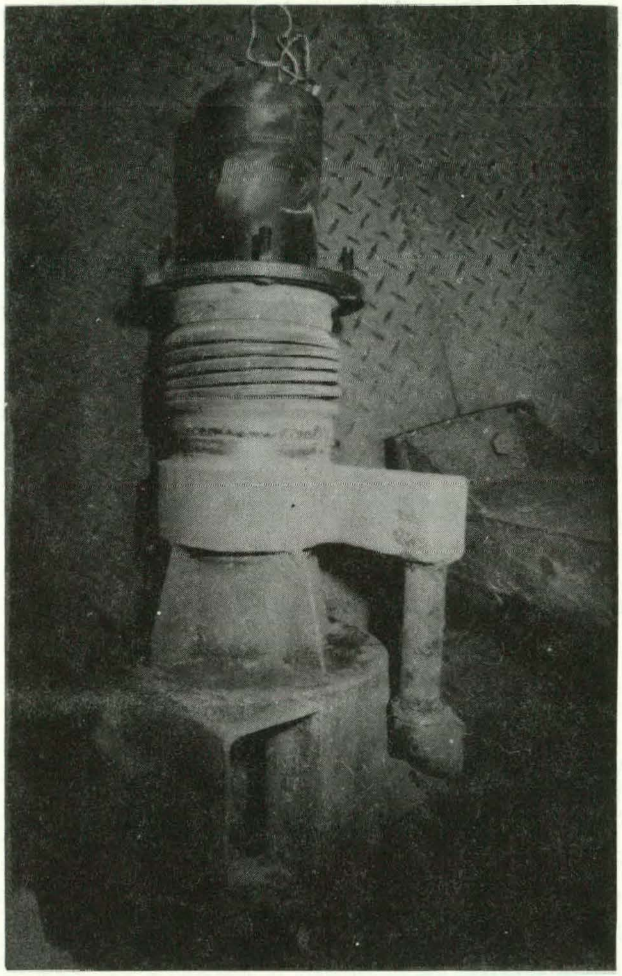


Fig.L52 Top of Stream 2 tertiary cyclone showing cyclone inlet, shave-off volute and expansion bellows after 1000 hrs.

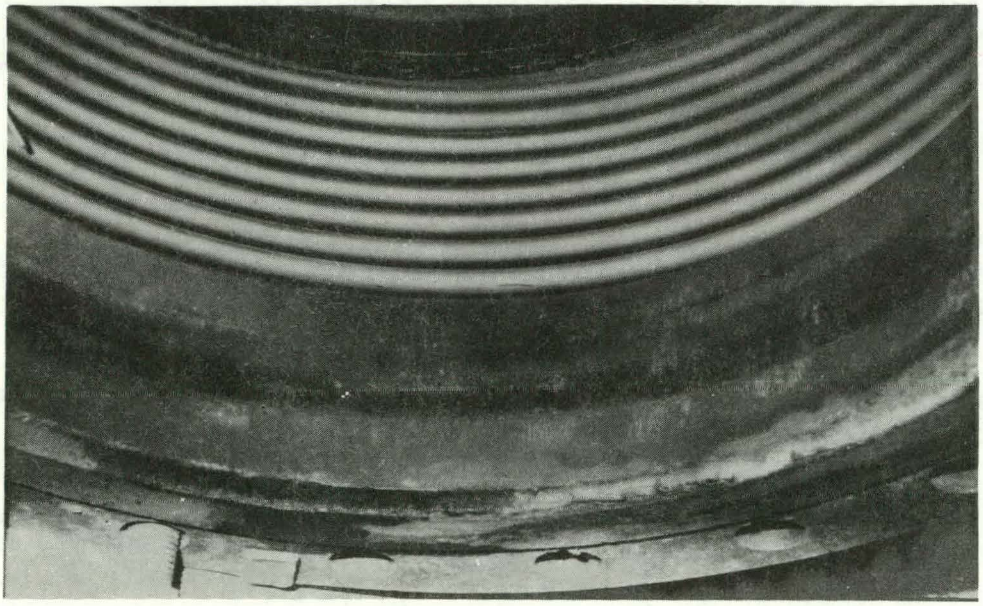


Fig.L53 Inside of 500mm casing bellows of Stream 2 showing gland sealing area.

but which underwent more frequent thermal and mechanical cycling and which had no nitrogen purge. On units which operated at higher temperatures the main corrosion evidence was lack of adhesion-cohesion of the oxide film. Both these corrosion problems can, no doubt, be eradicated by using higher-grade materials.

5.3. Isolating valves on dust lock-hopper systems

A synopsis of the history of operation and maintenance of the specialised high temperature valves used in the cyclone dust removal system is shown in Tables L.3 and L.4. (pages 27 and 28).

Primary dust system isolating valves

Stream 1. Kamyr PD03

This valve had been used in a similar situation on a previous PFBC test run of approximately 100 hours. It was not serviced prior to Test 1 but was leak tested.

Slight leakage between ball and seat after about 265 hours of plant operation warranted inspection of the valve, together with all other dust system valves, after Test 2. The body cavity was found to be full of loose free flowing dust but the ball and seats were clean and apparently undamaged. All parts were cleaned and the valve reassembled with an offset applied to the ball stem to provide a better seal on the bottom seat. This was not successful and the valve was re-installed although not being completely gas tight.

The valve continued to operate successfully but was removed for inspection again after Test 4. The ball and seats were then lapped together in order to try and reduce the leakage rate. Again, this was not completely successful, giving only a slight improvement.

The final inspection of the valve after Test 6 showed no major changes apart from slight discolouration or deposit on the polar region of the seats. The ball had slight discolouration of the edge of the port. (Fig. L.54).

Stream 2 Kamyr PD04

This was one of the two high-temperature valves on the dust system which had a stellited ball as well as stellited seats (all other Kamyr/Neles types had chromium-plated balls). No appreciable leakage between ball and seat was detected after Test 1 but by the end of Test 2 the leakage was significant. Inspection

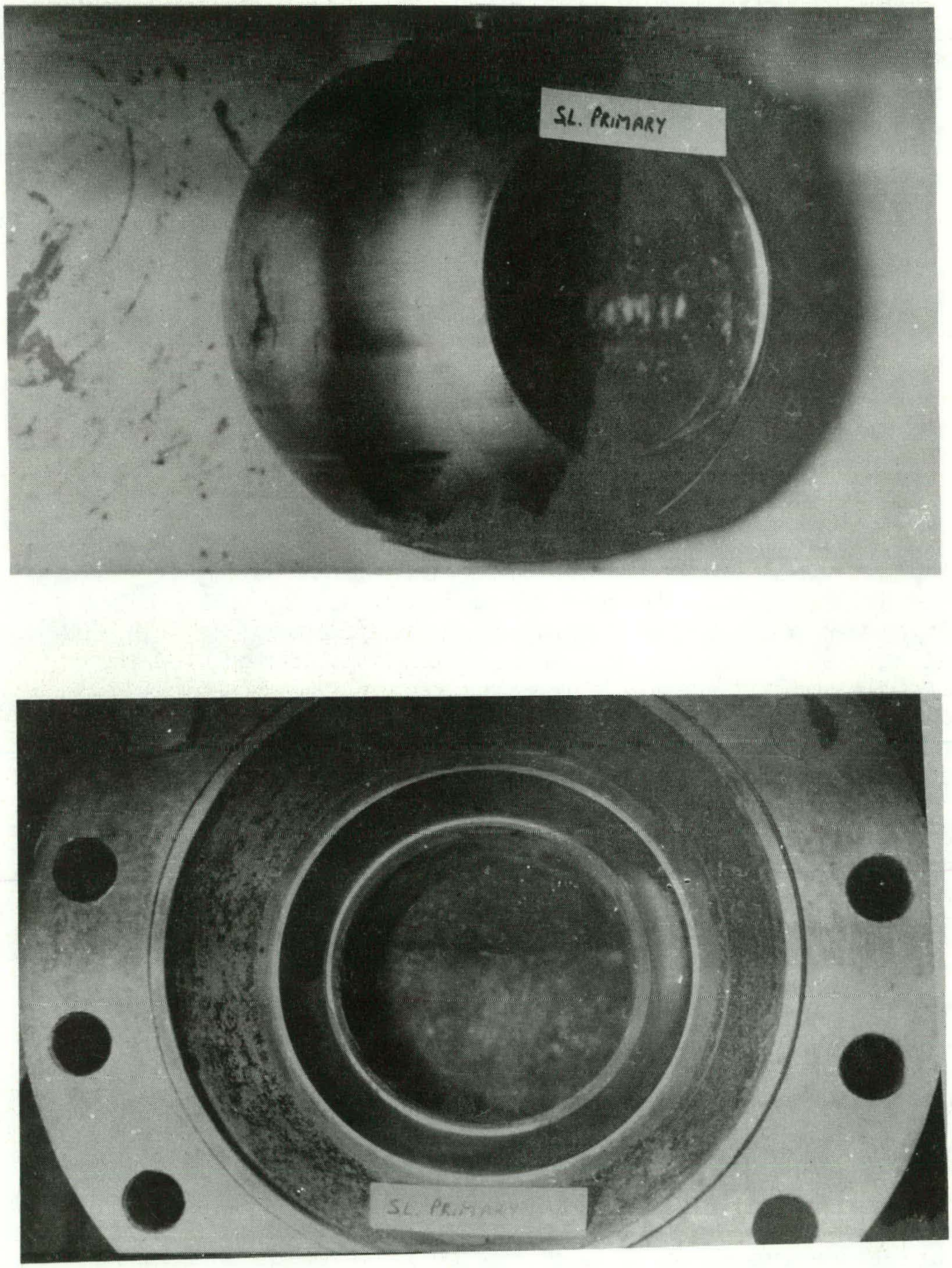
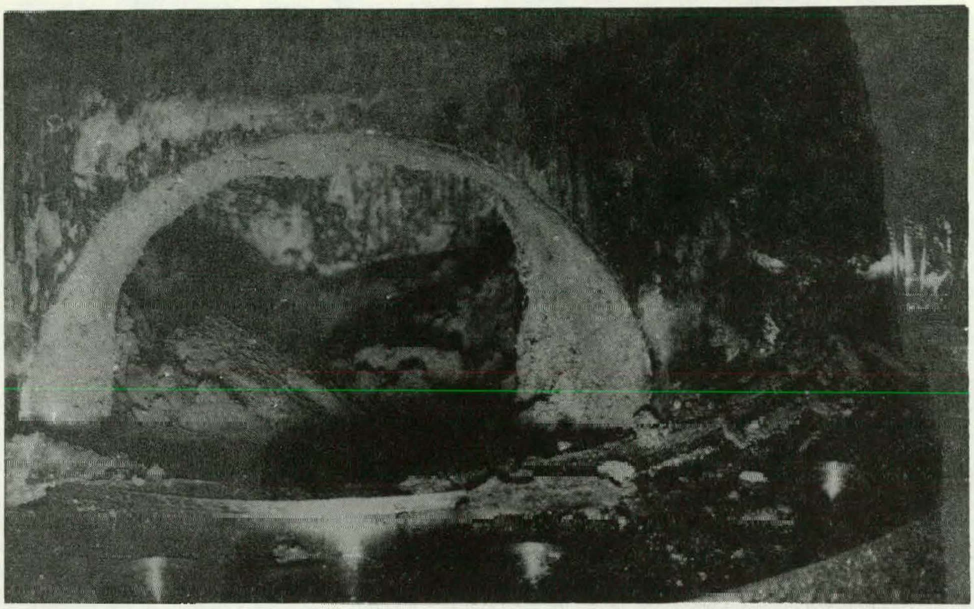


Fig.L54 Ball and seat of Stream 1 primary dust system isolation valve after 1000 hrs.



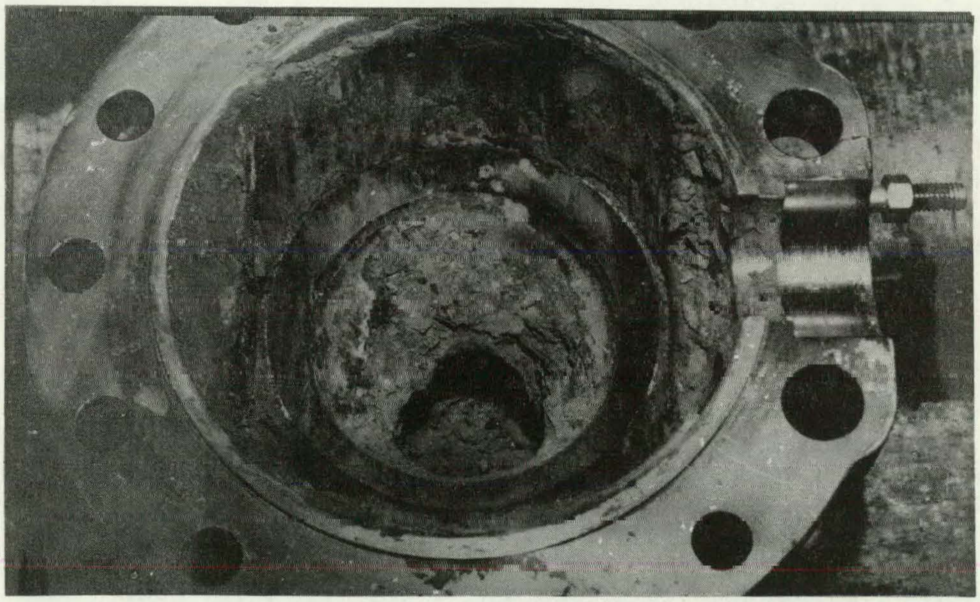


Fig. L55 Condition of Stream 2 primary and secondary dust system isolation valves after Test 2.
Top --Ball of primary system valve.
Bottom -Body and seat of secondary system valve.

showed the body cavity to be packed with damp compacted material (Fig. L.55). This had the effect of lifting the ball from its seat and allowing dust to compact in patches on the seat. After cleaning, no damage to the seats or ball could be observed. The valve was re-installed with an offset on the ball stem to assist sealing on one seat (the lower one) and with steam trace heating around the valve and adjacent pipework in order to obviate the apparent condensation problem within the valve.

Although some slight gas leakage through the valve was apparent after only a further 200 hours operation, its performance did not deteriorate further and was satisfactory for the rest of the 1000 hours.

Final inspection showed some discolouration of the top seat and slight scoring on the lower seat and ball. In general the valve was in good condition, this being only its second inspection (see Fig. L.56).

Secondary dust system isolating valves

Stream 1. Kamyr PDO3

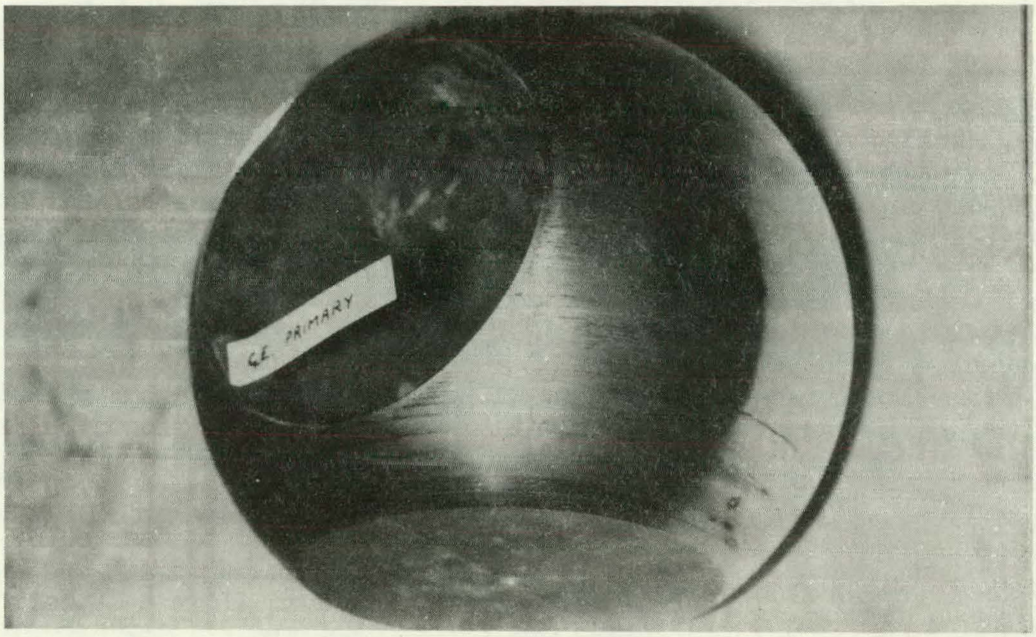
This was an identical valve to that on the primary dust system on Stream 1, and had also had about 100 hours of previous use. Again this showed some leakage after Test 1 but not enough to seriously affect the operation of the system. However, by the end of Test 2 the leakage rate was sufficient to severely restrict system operation. The secondary dust discharge systems were only operated once every two or four hours whereas primary systems were operated every hour.

On inspection, the body cavity of the valve was found to be packed with hard dry caked material and both seats and ball surfaces were scored. Some minute erosion patterns were visible on the ball at the edges of the seat contact area.

The valve was considered to be unsuitable for further use in this situation and was replaced by a jacketed tapered plug valve made by Serck-Audco Ltd. The valve was installed at a lower level in the dust leg, i.e. further from the cyclone (see Section 4.4.), where the gas and dust were somewhat cooler. Although the plug valve required frequent on-line attention, it performed satisfactorily for the rest of the 1000 hours programme.

Stream 2. Kamyr PDO4

This was identical to that on the primary dust system of Stream 2 and showed slight leakage between ball and seats after about 250 hours. On strip down after Test 2, it was found to be in



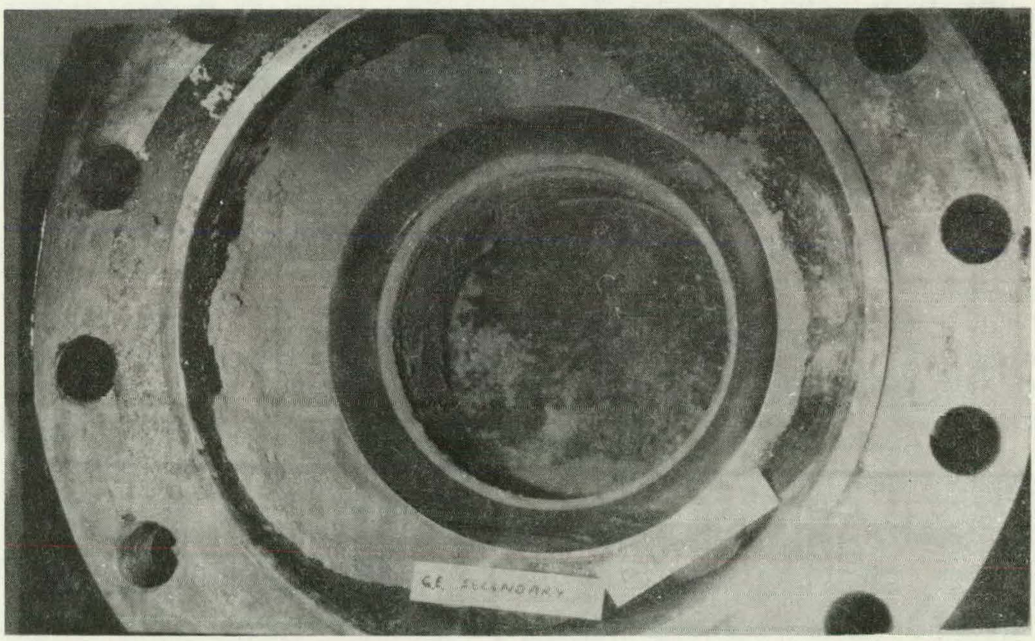


Fig.L56 Stream 2 dust system isolation valves after 1000h

Top - Ball of primary system valves.

Bottom - Lower seat of secondary system valve

a similar condition to the primary system valve. Dust had compacted in the body, apparently having been damp at some time, and again the ball was beginning to be separated from the seat by patches of compacted material, mainly around the polar region of the seats (see Fig. L.55). No damage had been incurred and the valve was reinstalled in a similar fashion to the primary valve, (i.e. with stem offset and steam trace heating).

Slight leakage through the valve showed up on leak tests at the end of following test runs but no serious deterioration was noticed and the valve did not receive further inpsection before the end of 1000 hours of operation.

After Test 6 the final inspection showed some considerable build up of material on the seats around polar regions and at edges (see Fig. L.56) The ball appeared to be in good condition.

Tertiary dust system isolation valves

Stream 1. De Zurik Permaseal plug valve

This was a tapered plug design of stainless-steel constuction, the plug being spring-loaded on to circular graphite seat inserts (see Fig. L.57). It gave a positive gas seal when first used, but was leaking after Test 2 and was removed for inspection with all other dust system valves. The valve was stripped down and showed serious scoring of the graphite ring seats. It had been feared that the graphite would not withstand high temperatures in what was a slightly oxidising atmosphere but there was no evidence to suggest that chemical reaction of the graphite alone had been the cause of failure. The condition of the seats suggested that most of the sealing action was being affected by packed dust in the body, making operation difficult. Since seats were not renewable the valve was replaced by a jacketed plug valve which performed satisfactorily until the cyclone and dust system were removed after Test 4.

Stream 2. Neles CDAHO3 valve

Supplied as a "standard" high temperature valve (950°F) with only minor differences from the Kamyr type valves, this probably had the most difficult duty to perform of all the dust system valves because it was located relatively close to the cyclone above and

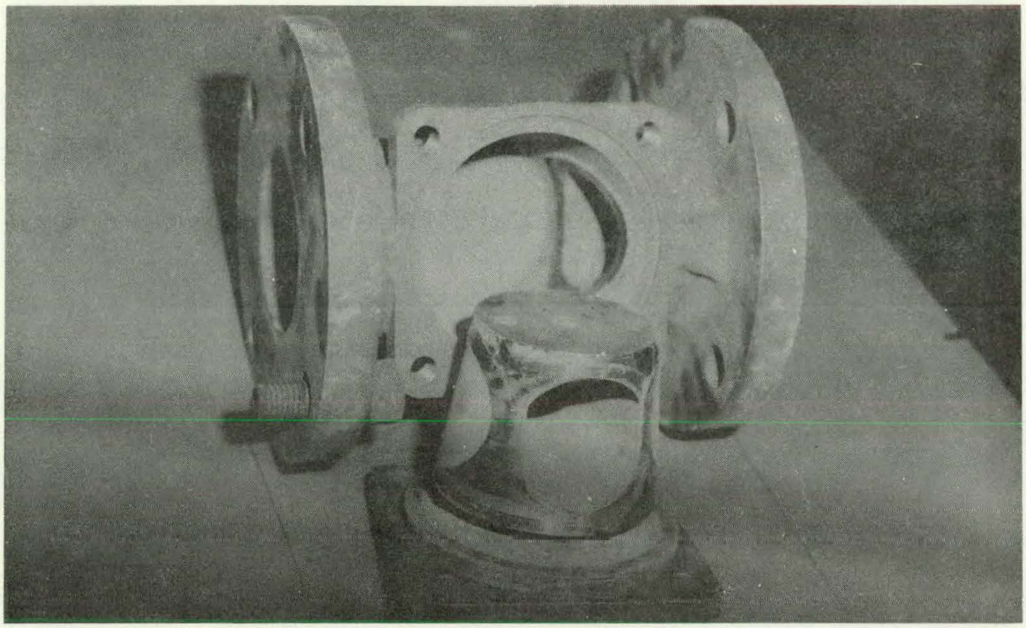


Fig.L57 De Zurik permaseal plug valve.

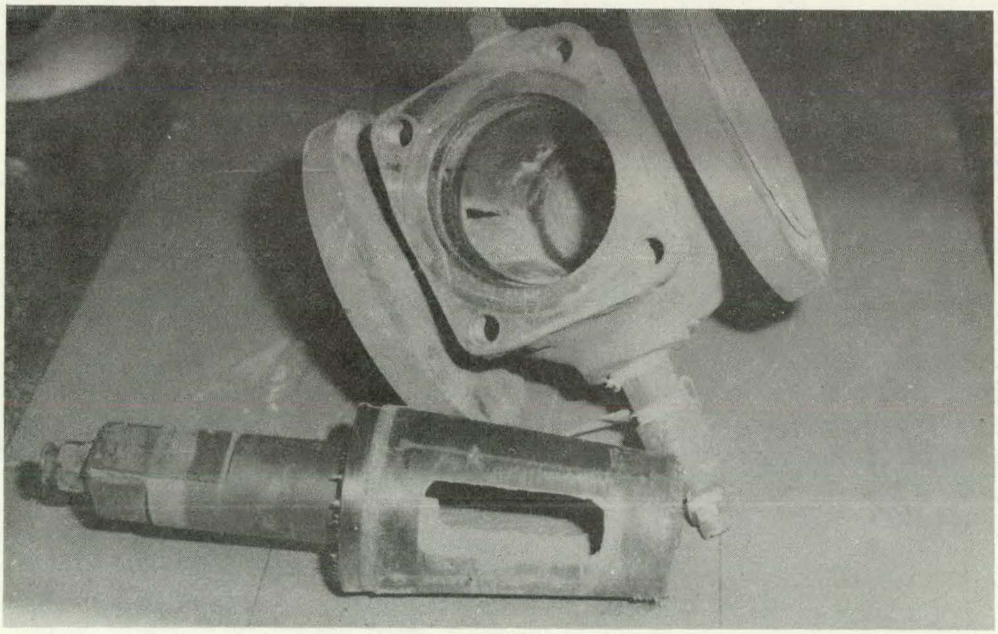


Fig.L58 Typical lubricated plug valve used as discharge valve on cyclone ash systems.

hence the operating temperature was high, though still below the design temperature. When the valve was closed the ball could "see" direct radiation from the cyclone (see Figs. L.29 and L.36).

By the end of Test 2 severe leakage through the valve made operation of the dust system very difficult. When stripped down, the body was found to be full of hard, dry, compacted material and this had lifted the ball clear of the seat. (as supplied the valve stem was already offset to push the ball on to the lower seat). Both ball and seat had sustained some scoring and there was marking of the ball surface. This marking (see Fig. L.59) was apparent also on other valves with chromium plated balls (viz Stream 1, Kamyr PDO3) and it is thought to have been caused by erosion when leakage occurred between the ball and seat. Some renovation of the ball was done by lapping with Boron Carbide paste. When tested after reassembly, the valve was still not providing a gas-tight seal, but the leakage rate was low enough to allow re-installation.

Considerable leakage through the valve developed again during Test 3 and on inspection it was found to be in a condition similar to that after Test 2. In an effort to reduce the build up of material between ball and seat, thin section "scraper" seats were fitted. Ball and seat were again lapped together and the increased clearance between ball and seat thus produced was reduced by fitting a thinner body gasket.

The valve was again not completely gas tight when re-installed for Test 4. Further leakage developed during this test but to a lesser extent. Again, inspection showed material build-up between ball and seat but this was easily removed. Ball and seat were lapped again, and the valve was cleaned and re-installed.

Inspection and cleaning was carried out again after Test 5, although the valve performed satisfactorily through this and the final test.

Inspection after 1000 hours showed material build-up still evident in the polar region of the seats. The ball seemed to have sustained no more damage than that noticed after 265 hours but there was some "blueing" of the surface of what was the top face of the ball in the closed position (Fig. L.60).

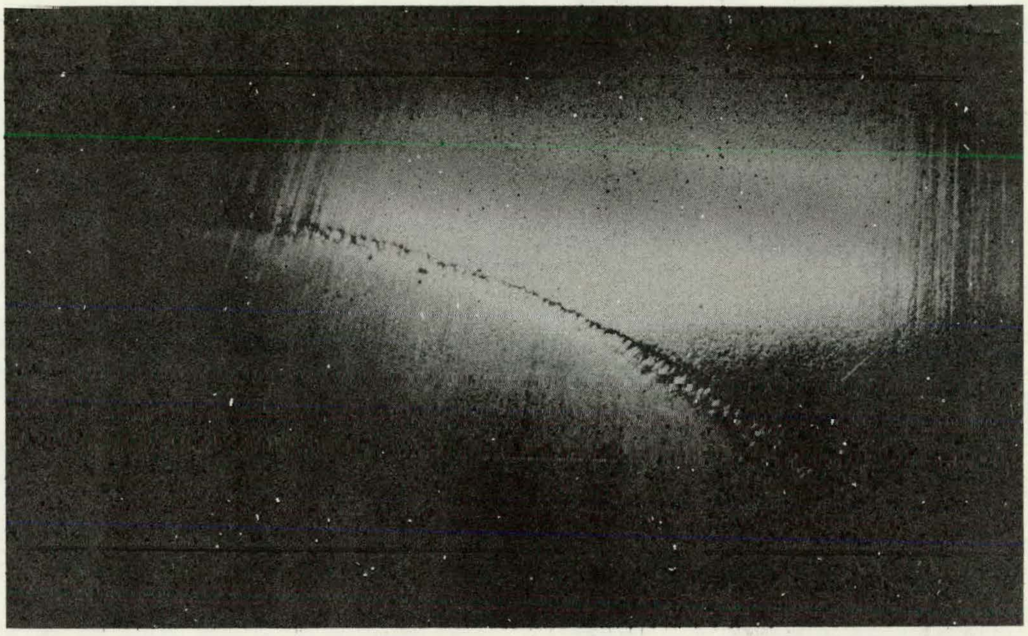


Fig.L59 Typical surface damage on Kamyr/Neles ball (chromium plated 316 ss)

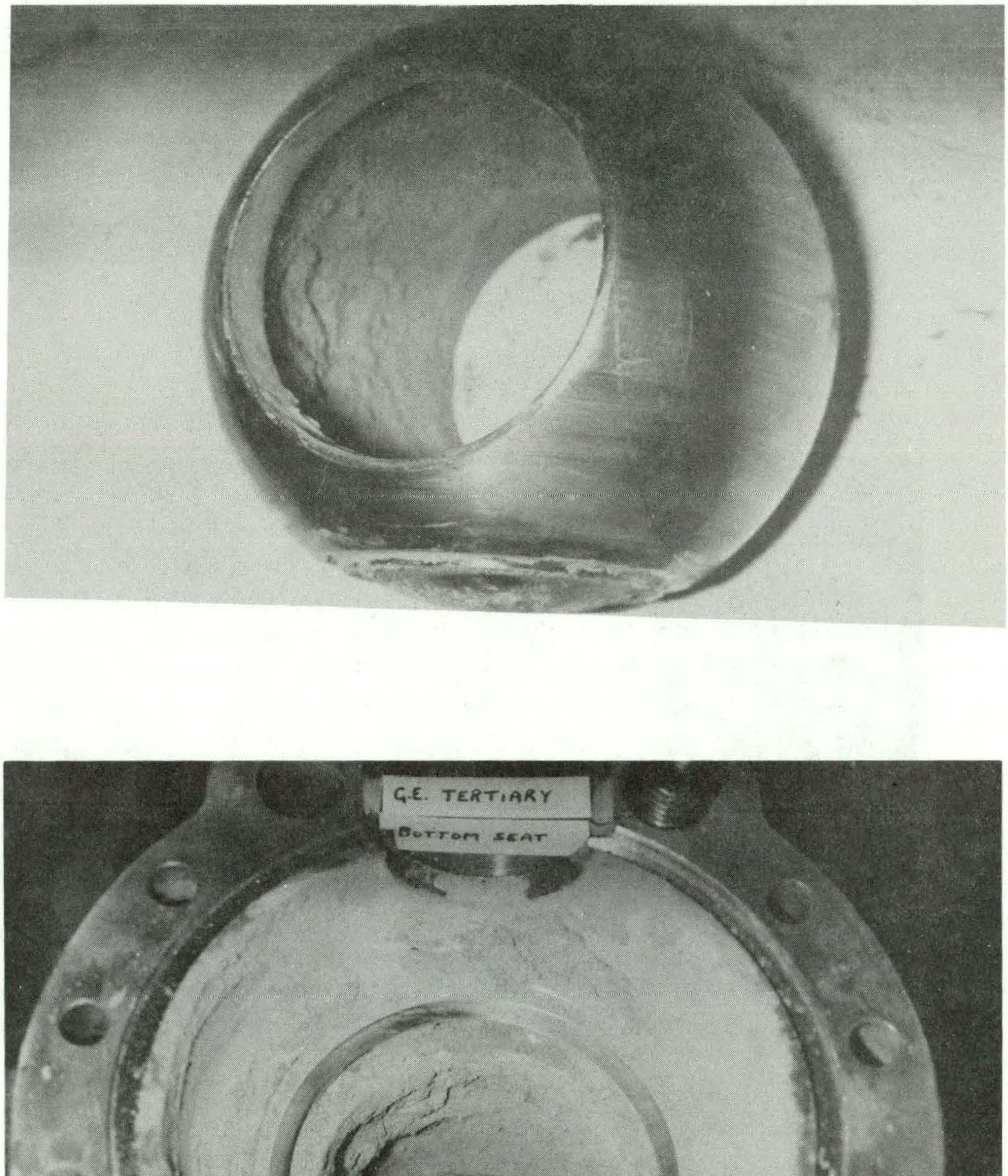


Fig.L60 Ball and lower scraper seat of Stream 2 tertiary dust system isolation valve after 1000 hrs.

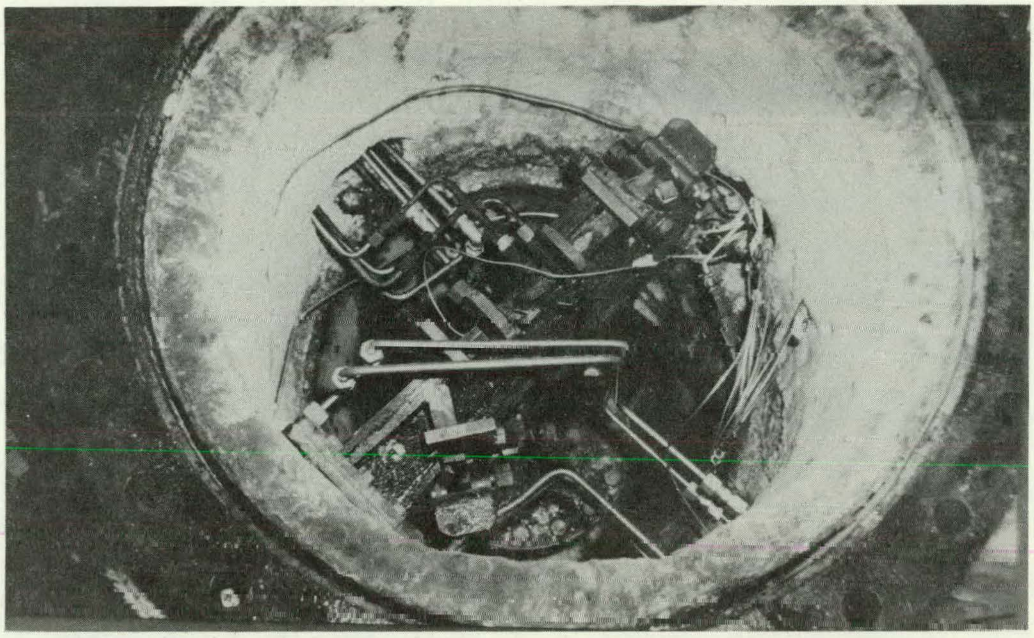


Fig.L61 Stream 1 cascade installation

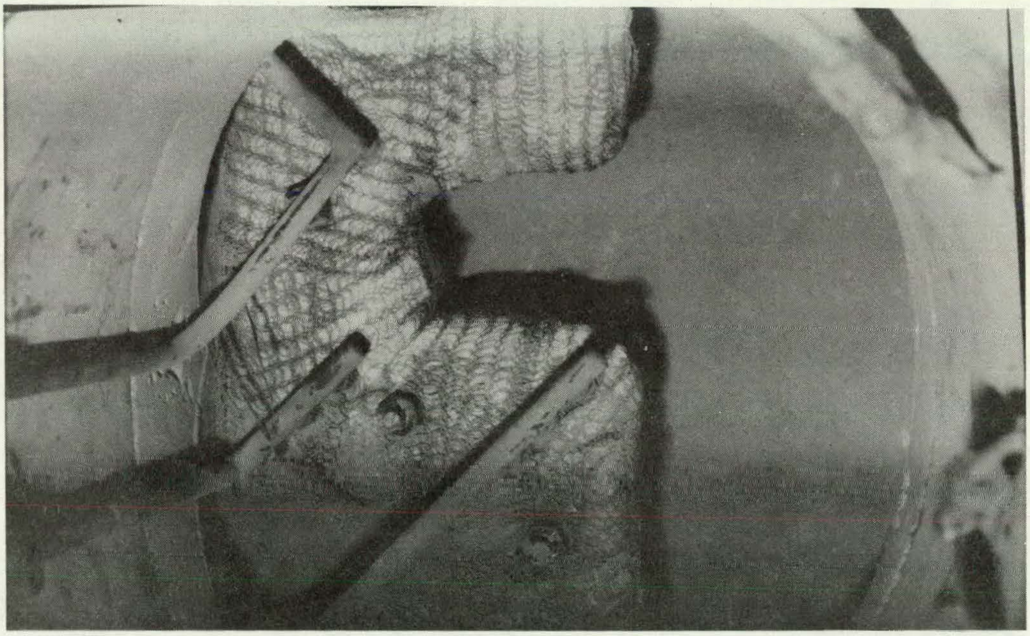


Fig.L62 Stream 2 cascade installation showing cooling air supplies and observation ports but not thermo-couples and pressure taps.

6. ENGINEERING DRAWING LIST

Some of the items were made to engineering drawings that are proprietary and therefore not generally available. The list of relevant drawings held by CURL is shown in Table L.5. In Table L.6. the more important of these drawings are cross-referenced to the relevant diagrams given in this report.

Table L.5 List of Engineering Drawings

COMBUSTOR

Drawing No.	
21732	Detail - Freeboard casing for tapered combustor
21733	" Baffle Tubes " " "
21830	Arrangement of bed off-take hopper and assembly, showing Neles (Kaymr) valve and plug valve
21828	Valve arrangement on bed off-take
21057	Combustor gas off-take (outlet duct external to main pressure casing)
RD 2381 (Proprietary.)	Woodhall Duckham - G.A. of Tapered Bed Combustor (Babcock & Wilcox)
	General Arrangement of Fluid Bed Combustor MK VI
21061	Detail - Start up burner chambers
RD 2420	Distributor Plate, tapered combustor - Woodhall Duckham

STREAM 2 - GENERAL ELECTRIC.

Drawing No.	
21574	Lock Hopper (Coarse) G.E. "Aerodyne" *
21575	Lock Hopper (Fine) G.E. "Aerodyne"
21576	Lock Hoppers - Top Flanges G.E. "Aerodyne"
21577	Lock Hoppers - Water Cooled Flange G.E. "Aerodyne"
21583/3	G.A. of Ducting from Aerodyne Outlet
21593/1	Details of Outlet Ducting from Aerodyne
21594	Details of Outlet Ducting from Aerodyne
21597	Details of Refractory Lining-inlet Duct to Aerodyne
21598	Arrangement of Ducting Downstream of G.E. Cascade
21599	Arrangement of Ducting Below Platform
21604	Detail Bellows Assembly in Stream 2 Ash Legs
21612	Detail Ash Legs on Stream 2
21618	Installation of Stream 1 Cyclones - Schematic
21619	Refractory for Tee Casing - Outlet from Combustor
21621	Detail of Cooling Coil for Tee Piece - (Outlet from Aerodyne)
21632	Assembly of Lock Hoppers and Down Legs from Aerodyne
21635	Corrosion Specimen - 12 Element Probes
21636	Proposed Layout of Stream 1 Cyclones in Vessel
21642	Arrangement of Cyclones in 4'6" Vessel - Stream 1
21650	Details of Rectangular Ducting (Van Tongeren Cyclones)
21661	Assembly of 20" Bellows in Stream 2 - original version
21662	Assembly of 12 Element Corrosion Specimens in Casing
21671	Coil for Primary Cyclone Disengagement
21675	Details of Flow Straighteners and Half Area Baffles.

* In this context "Aerodyne" refers to the pressure vessel used as the primary cyclone on Stream 2.

STREAM 2 - GENERAL ELECTRIC

Drawing No.	
21677	G.A. of Stream 2 2^{O} Cyclone & Bellows Unit
21679	Details of Bellows for Secondary Cyclone
21687	Detail - Connecting Ducting, Combustor/4'6" vessel
21688	Detail - 6 pass and 4 pass Tube Banks
21728	Proposed arrangement of Cyclones in existing Pressure Casing - Stream 2 (superceded by 21,755 and 21,759)
21731	Proposed arrangement of Cyclones in existing Pressure Casing and new 24" Casing - Stream 2 (superceded by 21,785)
21737	Detail - Additional Branch in Combustor Outlet Tee
21738	Details of Pre-cast Refractory Block for Aerodyne
21739	Detail - Combustor Outlet - Gas Splitter
21740	" " " - Refractory Lining
21742	Proposed Refractory Lining & Cyclone Support Aerodyne
21745	Arrangement and detail of 2^{O} Stage Cyclone - Stream 2
21753	Arrangement of Primary Cyclone Bellows Unit and Pipework
21755	Arrangement of Internals in 4' dia. Vessel - Stream 2
21759	Arrangement at inlet in 4' dia. Vessel - Stream 2
21762	Detail - Inlet and Outlet Duct Work for 3^{O} Stage Cyclone Vessel - Stream 2
21763	Detail - Shave off Element - Stream 2
21765	Detail - 3^{O} Stage Cyclone - " "
21767	Bellows Assembly for Secondary Cyclone Dust Outlet
21778	Lock Hopper for Secondary Cyclone Dust Outlet
21781	Cooled Outlet for Skimmer for Secondary Cyclone
21785	Assembly of 3^{O} Stage Cyclone, shave off and dust hopper
21790	20" Bellows Installation

STREAM 2 - GENERAL ELECTRIC

Drawing No.

21791	Proposed Cascade Outlet Sealing Arrangement
21827	Details of Ash Hopper for Bottom Ash Outlet
21834	Electrostatic Viewing Window - Stream 2
21841	Assembly of Sight Glass for Laser Particle Sizing
21849	Steam Heating Coil for 3^{o} Cyclone Hopper G.E.

Note:

1^{o}	Primary
2^{o}	Secondary
3^{o}	Tertiary

STREAM 1 STAL LAVAL

Drawing No.

R.D. 2398	Woodhall Duckham - Proposed modifications to existing plant to incorporate 3° Cyclone Vessel etc.
R.D. 2425	Woodhall Duckham - Assembly of 3° Cyclone Outlet to Water Sprays
R.D. 2427	Woodhall Duckham - Assembly of main vessel to tertiary cyclone vessel.

Table L 6 Engineering Drawings related to Report Diagrams

	Diagram	Drawing No.
Start-up burners	L.2 item 6	21061
Distributor plate	L.7	RD 2420
Bed offtake arrangement	L.2 item 9	21830 21828
Combustor outlet and gas splitter	L.19	21057 (1)
Stream 2 500mm pressure casing bellows	L.20	21,661 21,790
Typical sliding joint in cascade ducting	L.21	21,583/3
Stream 2 hot gas flow measurement venturi	L.22	21,583/3
Stream 2 cyclones	L.29	21,755 21,759 21,785
Van Tongeren cyclone installation, Stream 1	L.30	21,618 21,642
Typical expansion bellows design	L.38	21,767 21,785
Stream 2 cascade installation	L.62	21,583/3

(1) Drawing is G.A. from earlier programme. It shows typical construction, but has not been modified to include detailed modifications for the 1000 hr. run.

APPENDIX M

Examination of thermocouple from 1000 hour test at CURL by Stal Laval.

APPENDIX N

Examination of Stal-Laval cascade and interpretation of results

Note: This is a reprint of a paper presented by Stal Laval to the 6th International Conference in Atlanta, 1980. It is reproduced here as Stal-Laval's formal contribution to the report on Fluidised Bed Combustion.

TURBINE MATERIALS PERFORMANCE IN COMBUSTION GASES FROM A COAL-FIRED PRESSURIZED FLUIDIZED BED COMBUSTOR

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SUMMARY

Turbine blade sections and a number of alloy specimens were exposed in a turbine materials cascade during the recent 1000 hour PFBC test at CURL, Leatherhead, England. The material temperatures were 770 to 780 °C and the gas velocities over tested materials ranged from 180 to 520 m/s. Examination of the different components after the test showed no measurable erosive wear. However, oxide particles which according to their composition must have originated from steel surfaces in the system and most likely after the cyclones, were found to have impacted and become stuck in the coated blade sections. Proper system materials selection will minimize this "exfoliation" affects.

Udimet 500 blade sections coated with FeCrAlY and CoCrAlY exhibited very limited corrosion. An uncoated Udimet 500 blade section showed >100 μm hot corrosion after 950 hours exposure at crevice locations. Other specimens of the same alloy had <30 μm corrosion attack. Alloy 713 C was very little corroded. IN 671 showed severe hot corrosion after only 200 hours exposure. This attack was localized to the leading edge suggesting a strong erosion-corrosion interaction, even in this "non-erosive" environment.

Although the total exposure times are still relatively short as compared with expected component lives, the combined results from the study suggest that erosion, corrosion and deposition in the gas turbine will not be of serious concern in PFBC combined cycle systems.

INTRODUCTION

Participation in the 1000 hour test at the pressurized fludidized bed combustion (PFBC) facility at Leatherhead, England, is one of the activities within the current Phase II joint PFBC development program of the American Electric Power Service Corporation (AEP) and STAL-LAVAL Turbin AB. That program has been recently described in considerable detail by Markowsky et al.[1,2] This paper presents the results from exposing turbine blade materials in static cascades to the combustion gases from the Leatherhead PFBC unit.

GENERAL INFORMATION REGARDING THE TEST AND THE STAL-LAVAL TURBINE BLADE CASCADES

The 1000 hour test, described in more detail by Hoy and Roberts,[3] was divided into six shorter test sections, i.e., a 50 hour commissioning period (Test 1), followed by four 200 hour test periods of approximately (Tests 2-5), and concluded with a 150 hour test (Test 6).

Glen Brook (Ohio) coal and Plum Run (Ohio) dolomite were used throughout the test. The Glen Brook coal has a sulfur content of approximately 3.2 to 4.6 % and an ash content of 13 to 19 %. The Plum Run dolomite is a mixture of Tymochtee and Greenfield dolomites. The 1000 hour test generally went extremely well. Combustion efficiencies were 98 to 99 %. Sulfur retention was typically 90 % at a 1.8 Ca/S ratio. NO_x emissions were typically 180 to 190 ppm (i.e. about 0.45 lbs/10^6 Btu).

The bed temperature was approximately 860 °C throughout the test with only a few degrees variation within the bed at any time. Operational problems were relatively few. Compressor failures caused some interruptions. Coal feed disturbances did occur occasionally but were generally quickly corrected.

Figure 1 shows a schematic diagram of the combustor and the part of the gas cleaning system that provided a combustion gas flow (Stream 1) to the STAL-LAVAL cascade. Approximately two thirds (2 lbs/s) of the combustion gases from the combustor went through the STAL-LAVAL cascade. The remaining gases (Stream 2; 1.2 lbs/s) were guided, with the aid of a flow splitter at the outlet from the combustor, to another set of cyclones and a cascade provided by General Electric Company under contract to DOE.

A special STAL-LAVAL cascade was used during Test 1 only, with the purpose of providing early information about the performance of the fluidized bed and of the cleanup system (two Van Tongeren (UK) Ltd cyclones and one Stairmand High Efficiency cyclone in series). Here gas turbine components and other test specimens were exposed to the PFBC efflux at velocities up to 360 m/s. This cascade was dismantled after Test 1 for detailed examination.

A second cascade, schematically shown in Figure 2, was used for the remainder of the test. It contained three sections of GT 120 first stage turbine blades. The material in these blades is cast Udimet 500 with a nominal composition 19 % Cr, 19.5 % Co, 4.0 % Mo, 2.9 % Ti, 2.9 % Al, 0.01 % B and 0.08 % C, rest Ni. Two of the blade sections were coated by physical vapor deposition (PVD) techniques with FeCrAlY and CoCrAlY, whereas the third blade section was used in the as-received condition. As indicated in Figure 2 the gas velocities before and after the set of blades are 230 m/s and 380 m/s respectively. The nominal gas velocities before and after the first stage blade in a GT 120 gas turbine were 277 m/s and 330 m/s respectively, i.e., slightly higher than the corresponding velocities in the cascade. A considerable number of other test specimens were placed in the cascade at gas velocities between 180 m/s and 520 m/s. These included additional Udimet 500 specimens and also IN 671 (basically 50 % Cr, 50 % Ni) and Alloy 713 C (nominally 12.5 % Cr, 4.2 % Mo, 2.0 % Nb, 0.8 % Ti, 6.1 % Al, 0.012 % B, 0.10 % Zr and 0.12 % C, rest Ni) specimens.

All three cyclones were in use during Tests 1-4, providing a dust loading to the STAL-LAVAL cascade of approximately 100-120 ppm. Figure 3 shows a diagram where the dust loading/particle size relations are displayed for dust leaving the combustor, and the primary, secondary and tertiary cyclones respectively. The data presented in this diagram are based on Coulter Counter measurements in an aqueous electrolyte, using ultrasonics to break up aggregates. Results from such measurements at National Coal Board's Stoke Orchard Laboratories and at Exxon Research and Engineering Company, Linden, N.J., gave very similar results, which were also similar to results obtained by quite different techniques, i.e., optical and impactor techniques.[3] Figure 3 shows that the primary cyclone reduced both dust loading (from 10 000 to 800 ppm) and particle size very considerably. The secondary cyclone produced a further reduction in dust loading (from 800 to 200 ppm and in particle size, whereas the tertiary cyclone was effective in lowering the dust loading further (to approx. 100 ppm) but did very little to the particle size distribution.

After completion of Test 4, the tertiary cyclone was removed from Stream 1, and dust-laden gases from the secondary cyclone were passed directly to the STAL-LAVAL cascade during Tests 5 and 6. The purpose of this change was to get comparative data on cascade component performance at two different levels of particulate removal. Examination of cascade components during the test had up to that time shown no signs of erosive wear.

The temperature of the combustion gases at the inlet to the STAL-LAVAL cascade was approximately 750 °C during Test 1, due to air leakage into the freeboard. During subsequent tests it was between 770 and 780 °C, with the exception for Test 2 where propane was injected after the tertiary cyclone to produce an inlet temperature of 787 °C. These are slightly higher temperatures than are normally experienced by the first stage blades in a STAL-LAVAL GT 120 gas turbine.

RESULTS FROM INVESTIGATION OF THE CASCADE COMPONENTS AFTER EXPOSURE TO THE PFBC EFFLUENT

Examination of the vane and blade sections and other materials in the special cascade used during Test 1 revealed no measurable erosion or corrosion. Also, deposition was minimal. Accordingly, it was possible to state that the cyclone system had performed very well, and that the combustion products were not excessively corrosive. This latter observation was in good agreements with results from earlier tests within the AEP/STAL-LAVAL joint program.[1,2]

Figures 4 and 5 show photos of the blade assembly portion of the cascade used during Tests 2-6, after removing a lid that serves as one side wall of the cascade during operation. These photos show the exposed surfaces of the blade sections to have only slight deposits (on the suction side). No signs of major erosive attack are seen. Note the size of the components and the wide spacing between the blade sections (the chord of this blade is 80 mm).

Figures 6 and 7 show scanning electron microscopy (SEM) photos of the surface region of the FeCrAlY-coated blade before and after 950 hours exposure to the combustion gases. The areas of the blade where these photos were taken from are on the pressure side near the leading edge. The photos show two changes to have occurred during the test. First, the microstructure of the coating, and especially at the blade material/coating interface, had changed. Second, the outer surface of the coating had become slightly roughened, suggesting deformation due to particle impact or else loss of local portions of the surface. Special notice should be paid to the two deeper indentations, at top and center of Figure 7, which have a common "angle of impact" and which, as judged from the contrast in the SEM image, are partly filled with some non-metallic material. This direction corresponds to the path rather large particles would take through the blade assembly. This is further illustrated in Figure 8 where the locations and directions of such "impact craters" are summarized schematically. As shown in Figure 8, similar craters were also found on the CoCrAlY-coated blade.

Scanning electron microscopy energy-dispersive X-ray (EDX) analyses, showed the material in the craters to be rich in iron and sometimes in iron and chromium, and to be a multiphase material that in some instances also contain traces of aluminum, silicon, calcium and sulfur. Polarized light images of the material in the craters showed it to be metal oxide particles mixed in part with coal ash and sulfated dolomite dust from the combustor. (The PFBC ash appears red when viewed in polarized light.)

The directional crater pattern suggests that particles that could cause deformation of the surfaces reached the blades during this test. There is, however, no evidence of any measurable loss of material from the surfaces of the FeCrAlY- and CoCrAlY-coated blades. This is illustrated in Figure 9 where coating thickness measurements around the periphery of the FeCrAlY-coated blade are shown. The different arrows, representing the points where the measurements were made, are connected to open and filled dots that show the coating thickness according to the scales at the left side of the figure. The open dots represent measurements before the test, with the definition given in the figure, and the filled dots represent measurements after the test. Clearly, the agreement between "before" and "after" measurements is excellent. We therefore conclude that no measurable erosion of the blades did take place during the test. Similarly, no measurable erosion of turbine component materials occurred elsewhere in the cascade, even at the highest velocity locations.

Examination of the uncoated Udimet 500 blade showed variable corrosion attack to have occurred after 950 hours exposure, whereas results from the 50 hour Test 1 and from previous 100 hour tests[1,2] had shown very little corrosion to take place. Figure 10 shows the maximum measured extents of attack, i.e., the combined oxide layer thickness and depth of subscale attack as measured around a section through the blade. It should be noted that maximum attack had occurred where a narrow crevice has existed, between the blade and the blade mounting device. The attack, Figure 11, is characterized by growth of an external oxide scale, internal oxidation in a surface layer, and the formation of subscale chromium sulfides, and perhaps some other sulfide phases in and just below the internally oxidized zone. It represents a type of hot corrosion attack. The bright appearance of the affected zone when the specimen is etched, Figure 12, suggests compositional changes in the alloy result from these reactions (chromium depletion is likely to have occurred).

Examination of all other Udimet 500 specimens exposed in the cascade showed a maximum corrosion attack after 950 hours of approximately 30 µm, including in some instances some very slight subscale penetration of sulfur with the formation of chromium sulfide precipitates.

Alloy 713 C was found to be nearly unaffected by the combustion gas environment. IN 671, on the other hand, exhibited severe oxidation-sulfidation (hot corrosion) attack at the leading edges of the specimens, Figure 13.

DISCUSSION

General implications of the test results

The lack of measurable erosion attack on the cascade components shows that erosion need not be a life-limiting factor for gas turbines which operate on combustion gases from PFBC units, and which rely on cyclone systems for particulate removal. Similarly, the absence of any significant corrosion attack on Udimet 500 blades coated with FeCrAlY or CoCrAlY makes it likely that acceptable component life, i.e., at least 8000 hours and possibly two to three times that figure, can be achieved through proper materials selection. Build-up of deposits also would seem to be no problem, based on the observations from this test and from earlier tests within the AEP/STAL-LAVAL program.[1,2]

Erosion

An outstanding feature from the present study is that measurable erosion of turbine materials occurred nowhere in the cascade, i.e., throughout the velocity range of 180 to 520 m/s. This implies that dust passing through the second (or third) cyclone in Stream 1, Figure 3, was essentially non-erosive to turbine materials at the test conditions. By comparison, considerable erosion did occur during the 117 hour shakedown test in the Exxon rig, whereas subsequent testing during 565 hours produced little or no erosion attack on FeCrAlY- and CoCrAlY-coated blades.[4,5]

With the assumption that PFBC efflux dust from the Exxon rig is similar in nature and properties to the corresponding material from the CURL rig it is of interest to compare the levels and particle size distributions of dust passing the cascades during the two tests. Figure 14 compares Coulter data from Test 3 at CURL (with three cyclones) to earlier data from tests performed in the Exxon rig.[4,5] It is clear from the figure that the dust through the STAL-LAVAL cascade had a lower concentration of particles >2 µm then any of the other two size distributions. Since it is very difficult to measure small amounts of larger particles in large amounts of finer dust, there is considerable uncertainty about the exact concentration/particle size relationships for particles larger than perhaps 3 µm in the curve that relates to the STAL-LAVAL cascade. Similar uncertainty should exist for the low concentrations ends of the Exxon size distribution curves, i.e., for particle sizes around 10 µm (565 hour test) and 20 µm (117 hour shakedown test) respectively.

In spite of these uncertainties it is tempting to attempt to correlate the absence or extent of erosive damage to turbine component materials in the different cascades with the level of large particles, say >5 µm, in the PFBC dust that reached the cascades. The data in Figure 14 would then suggest that if that concentration is close to 30 ppm (the 117 hour shakedown test) severe erosion can occur, whereas a 2- to 5-fold reduction of the concentration of particles >5 µm would eliminate the problem (the 565 hour test). If that is correct, and if the size distributions are very similar for larger particles than 5 µm, a threshold value for erosive wear would exist somewhere between 6 and 30 ppm >5 µm particles. (This way of rationalizing the problem is obviously too much simplified. In reality, the nature and shape of the individual particles must enter the picture. Accordingly, different coal and sulfur sorbents should in principle be capable of producing slightly different results. Also, the cyclone characteristics would have a very major impact on the concentration/size distribution relations for particles >5 µm and thus for the position of any threshold value.)

Clearly, for Test 3 at CURL the level of particles >5 µm would seem to be 20 to 30 times below that of the 117 hour shakedown test at Exxon. If the 565 hour test concentration/particle size relationship is taken to represent a "safe" relationship for cascades operating at close to 6 atm pressure, the Test 3 curve would represent an additional safety factor of approximately 4 to 6 times. The successful operation with only 2 cyclones, which approximately raised the concentrations of large particulates by a factor of 2, is then not surprising.

Oxide scale exfoliation

The chemical composition of the metal oxide particles found in "impact craters" on the coated blade sections in the STAL-LAVAL cascade suggests that these particles originated from oxide scales on low alloy and stainless steels upstream of the cascade. Spalling of such oxide scales is normally referred to as oxide scale exfoliation. It is a familiar phenomenon in steam turbine systems, with the oxide particles originating in the boiler tubing.

Oxide exfoliation occurs most readily on cooldown of oxidized steel surfaces due to differences in thermal expansion. Also, for alloys forming two-layer oxide scales it is mostly the outer oxide which will spall off. Spallation at temperature can happen but is less likely. It therefore seems probable that also the oxide found to have impacted the blade sections was released on cooldown.

Oxide that exfoliates upstream of the cyclones is likely to be caught by those. Therefore, the most likely source for the oxide particles found embedded in the blade surfaces are system walls from the outlet end of the tertiary cyclone to the cascade. Also in an actual PFBC system and with perfectly functioning cyclones, such exfoliation will provide a background level of oxide particles that will reach the gas turbine. To choose more exfoliation-resistant alloys is one way of lowering this "background". Another is to minimize the area of metal surfaces after the cyclones. A third method is to take steps for removing exfoliation-prone oxide in a controlled manner and possibly collecting it before entrance to the gas turbine. With such precautions, oxide scale exfoliation is unlikely to be important as an release mechanism for erosive agent that can reach the gas turbine components.

Corrosion

The very minimal corrosion attack on FeCrAlY- and CoCrAlY-coated Udimet 500 blade sections, the chemical composition of these coatings (FeCrAlY: 26.1 % Cr, 5.0 % Al, 0.19 % Y, rest Fe and CoCrAlY: 24.9 % Cr, 11.1 % Al, 0.34 % Y, rest Co), and the relatively small structural changes that occurred in the coating during 950 hours exposure to the PFBC efflux make it likely that acceptable life of coated turbine components can be reached with these coatings. Studies are underway to determine in more depth the extent of the structural changes.

Although coated turbine components should be preferred for use in a coal-fired PFBC combined cycle unit, the information obtained about corrosion of different alloys in the turbine cascade helps throw some light on the corrosion mechanisms, and also on the interactions of erosion and corrosion processes. Thus, the observed extent of corrosion on the uncoated Udimet 500 blade section in the cascade shows that the PFBC efflux environment is not innocuous. This is to be expected in view of the presence of sulfur, chlorine, sodium and potassium compounds in the coal and to some extent also in the dolomite. Upon combustion chemical and physical changes occur, causing the release of most of the sulfur, a considerable fraction of the chlorine and a small part of the alkali metals from the burning coal, the coal ash and the dolomite. Sulfur oxides, hydrogen chlorides, and alkali chlorides and hydroxides are among the prevalent gaseous reaction products.

Continued chemical reactions occur between these agents and the solid particles in the bed, in the combustion gas stream leaving the bed, and in deposits that form on system components, especially where a temperature drop enhances the adsorption and condensation of volatile reactive species. Much remains to be learnt about the actual chemical reactions that occur in the very complex ash/partially sulfated dolomite dust/condensed alkali chloride-sulfate system. It is especially important to recognize that the deposits form a partially reactive "sponge" that can affect the corrosion behaviour, both the mechanism and the kinetics, of the PFBC system component materials.

The observed differences in corrosion rate for the cast Udimet 500 blade section and for other Udimet 500 specimens in the cascade suggest that alloy pretreatment (mode of manufacture, microstructure, degree of cold work, etc) may be important. Longer term exposure is needed to determine the role of such factors during actual gas turbine operation.

The observation of maximum corrosion attack, with sulfur penetration of the scale, at narrow crevices between the blade and the blade mounting device suggests that the conditions for growing a protective oxide scale on Udimet 500 were less favorable there. One possible explanation for such an effect could be that the crevices filled up with dust already during the start-up of the PFBC system, and before the alloy came to such a temperature that a proper oxide film could form (this probably requires at least 550 to 600 °C). A change in the reaction mode to produce the structure seen in Figures 11 and 12 may not easily revert to the formation of a protective oxide layer.

The lack of significant corrosion attack on Alloy 713 C shows this alloy to have formed a protective surface oxide during the test. As far as IN 671, which is not a gas turbine alloy at all, is concerned, it was included in the cascade for two reasons. First, it has been shown to be very sensitive to hot corrosion attack within fluidized bed units burning coal with limestone or dolomite as the sulfur sorbent.[6] This type of attack has been suggested to result from a chemical reaction between the calcium sulfate (formed as the product of reaction between limestone or dolomite and sulfur oxides) and calcium oxide or calcium carbonate in the presence of reducing agents. These could be gaseous hydrocarbons or else char embedded into the deposit. Coexistence of calcium sulfate and calcium oxide (or carbonate) in a reducing environment will result in a high chemical potential for sulfur that can drive sulfur through the oxide scale and cause initiation of hot corrosion. IN 671 was now included in the cascade in order to examine whether it would be a hot corrosion indicator also at that location, where the presence of reducing agent would be much less likely to produce a low oxygen potential/high sulfur potential environment.

The other reason for including IN 671 in the cascade was that Mc Carron et al had tested blades clad with this alloy in the Exxon rig and had seen severe degradation of this alloy.[4,5] This observation was taken to show that the PFBC efflux was indeed a very severe corrosion environment, and the corrosivity of the environment was ascribed to the contents of alkali in the gas stream and the presence of significant amounts of potassium and chlorine.

The location of initial degradation of the IN 671 clad during the test in the Exxon rig was at the leading edge. This is the same location where hot corrosion occurred on the IN 671 specimens in the STAL-LAVAL cascade. Our interpretation of this observation, based also on other laboratory tests, is that the degradation of IN 671 occurs through an erosion/corrosion process, see further below. Basically, the oxide scale on IN 671, due to the two-phase nature and composition of this alloy, seems to be extremely sensitive to particle impact. The damage caused to the oxide upon impact of the PFBC dust seems to allow sulfur to penetrate the scale, react with the alloy, and then set up the conditions for a rapidly progressing hot corrosion attack. If this hypothesis is right, then it does not take a very corrosive environment to introduce sulfur to the alloy/oxide interface.

It is possible that the high sensitivity of this alloy to hot corrosion attack within fluidized beds is also, in part at least, due to an excessive sensitivity of the oxide scale to erosive damage.

Erosion/Corrosion

Turbine materials exposed to the PFBC efflux may suffer from erosion and corrosion separately or in combination. The latter case is called erosion/corrosion and implies that the kinetics and/or mechanism of attack differs from what it would be in the presence of either an erosive or a corrosive agent separately.

When "good" turbine alloys are exposed to complex high temperature combustion gas environments, protective oxides may form which are not damaged by particle impact or the presence of corrosive contaminants. This was basically the case for all turbine alloys in the STAL-LAVAL cascade during the test at CURL, with one exception, the uncoated Udimet 500 at narrow crevice locations. There, as outlined above, the corrosive environment and therefore the initial oxidation stage was probably effected by the deposition of dust into the crevices upon start-up.

Initiation of hot corrosion attack on the non-turbine alloy IN 671, on the other hand, seems to have been caused by the damage done to the oxide by impacting particles, even in this very non-erosive environment. If that is correct, then it follows that oxide scales on gas turbine alloys are less sensitive to particle impact. In other words, even the dust that passed through the STAL-LAVAL cascade had some erosivity, and the nature and properties of the oxide scale on the specimens determine whether erosive damage will occur or not.

It seems likely that erosion/corrosion will become the important process of gas turbine component materials degradation under conditions where the particulate cleanup systems malfunction. This conclusion points to the importance of securing good cyclone performance in PFBC plants. Although short term upsets can be tolerated, the surveillance system should be such that deviations can be rapidly noticed. This points to the need for on-line instrumentation to determine particle size distribution and concentration in the gases that will reach the gas turbine. The very successful results from the 1000 hour test at CURL give good hope about the possibilities of arriving at a workable solution, even with existing technology.

Use of cascade erosion data for turbine erosion estimates

Cascade studies give information about the performance of materials under well-known flow conditions. Particle concentration effects, such as may occur in actual turbines, may exist also in a cascade provided that the directional changes and the velocities are large enough. Secondary flow effects may also affect the local concentrations of particulates in a gas turbine. Other differences relate to angle of particle impact, effective velocities at impact (a result of blade rotation), and frequency of multiple impacts due to the differences in particle paths relative to the components. These differences affect the location and extent of a possible erosion pattern through a turbine compared with results from cascade experiments. Multiple impacts, due to bouncing off surfaces, are probably unimportant for particles <10 μm and therefore do not have to be considered for the levels of gas cleanup achieved during the PFBC test at CURL.

Although angles of impact differ, cascade results are relevant provided the specimens have a suitable shape. This was the case in the STAL-LAVAL cascade. Concentration effects are of two kinds, i.e., those that depend on pressure and those that relate to centrifuging and secondary flow effects. The effect of pressure is straightforward (the number of impacting particles per time unit is directly proportional to pressure; in this respect there is a direct analogy with increased velocity, otherwise erosion rate is normally assumed to increase with particle velocity to the second to third power.) Centrifuging and secondary flow effects are likely to be small for particles <5 μm. As a result cascade results will mainly have to be adjusted for concentration of particles >5 μm when used to estimate turbine erosion. In the STAL-LAVAL case the static pressure is 9.6 atm at the entrance to the first row of rotating blades in the GT 120, as compared with 6 atm in the cascade. An "effective" concentration increase of 1.6 results, i.e., very close to that factor which was imparted in the cascade tests simply by raising the velocity to 520 m/s from the velocity at the blade sections.

Based on these considerations it would seem that levels of particles >5 μm reaching the GT 120 gas turbine from a full scale PFBC unit can be allowed to be at least 2 to 3 times higher than what resulted from the Stream 1 cleanup system with two cyclones. Existing cyclone systems meet this requirement.

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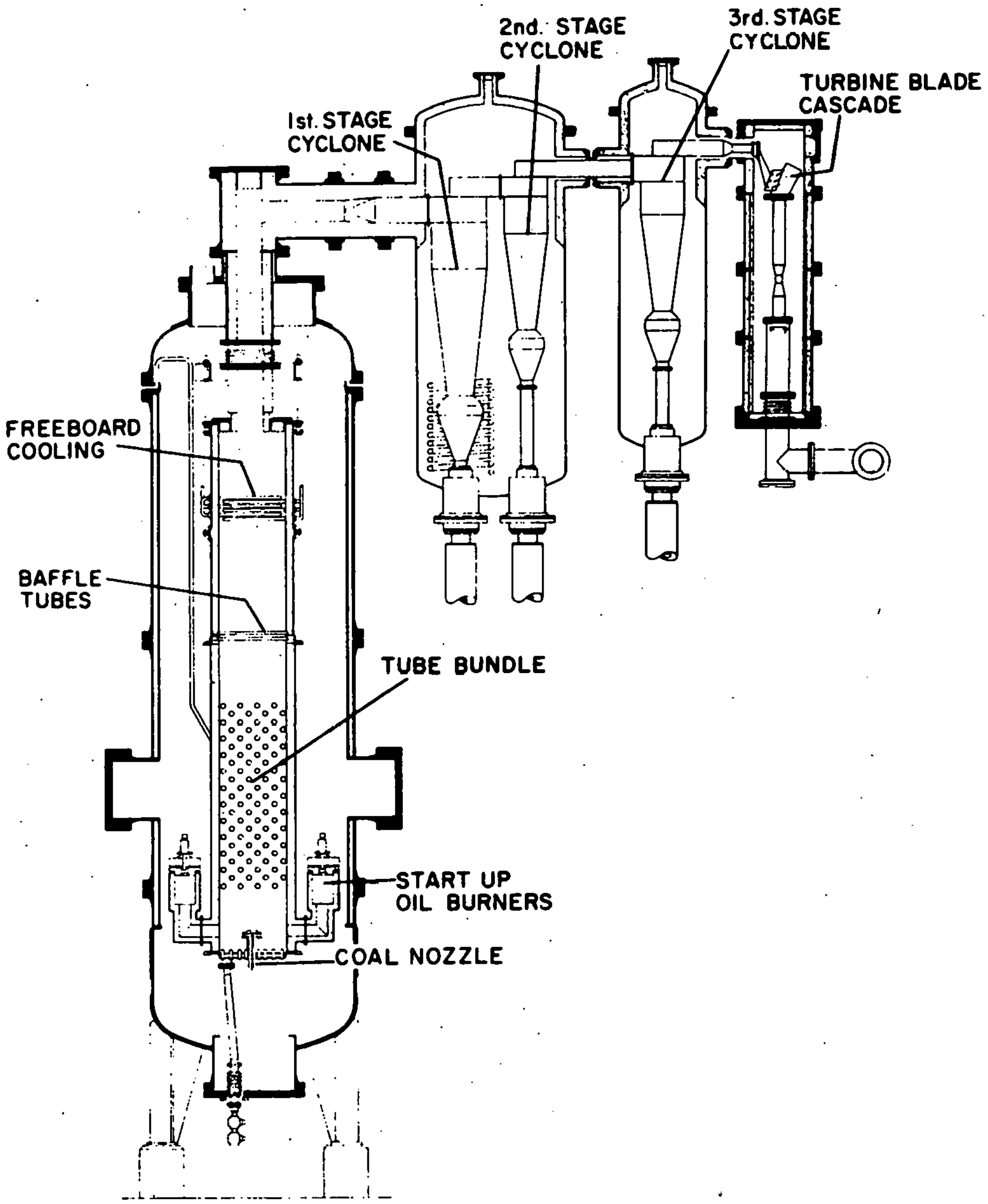


Figure 1. Leatherhead combustor configuration for the 1000 hour test. The Stroam 1 cyclone train and placement of the STAL-LAVAL cascade are shown.

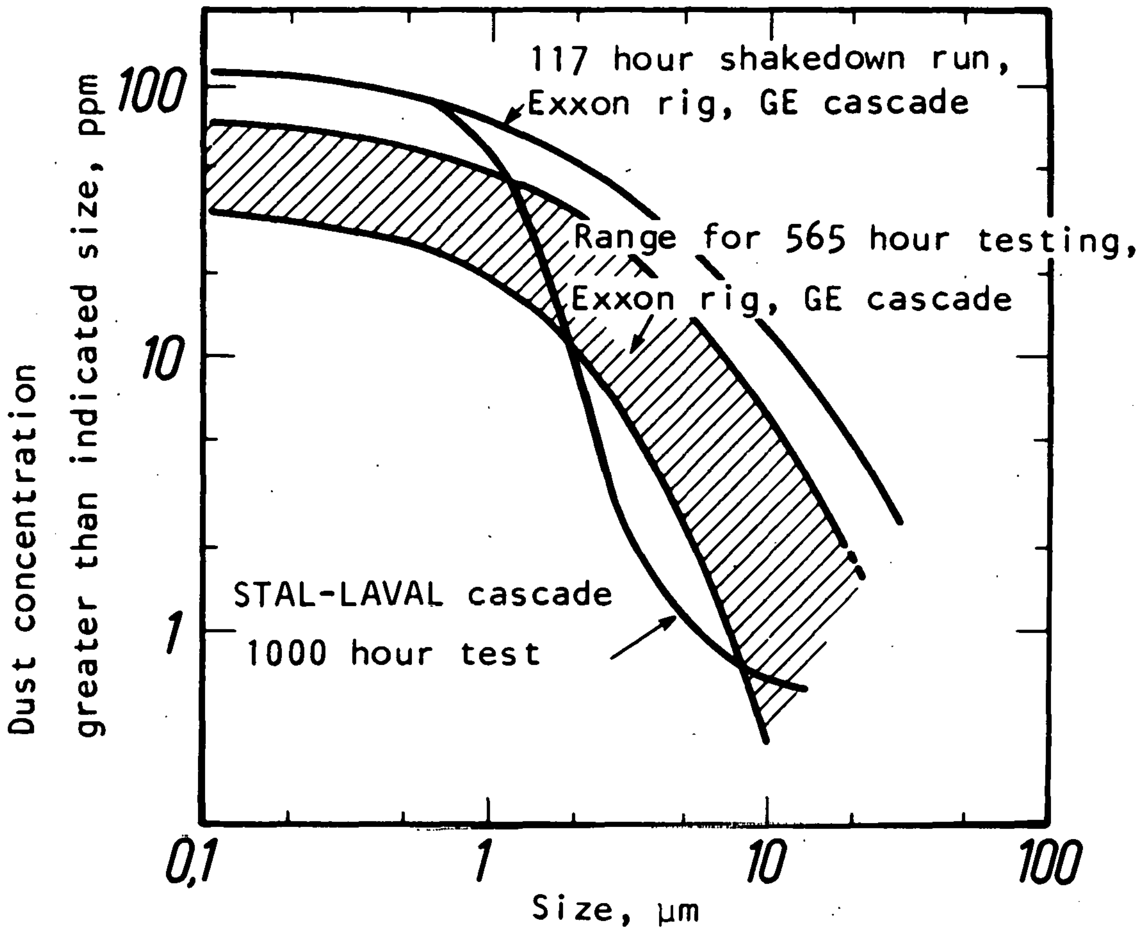


Figure 14. Comparison of concentration and size distribution for dust reaching the cascades during PFBC tests at CURL (Test 3 during 1000 hour test) and at Exxon.

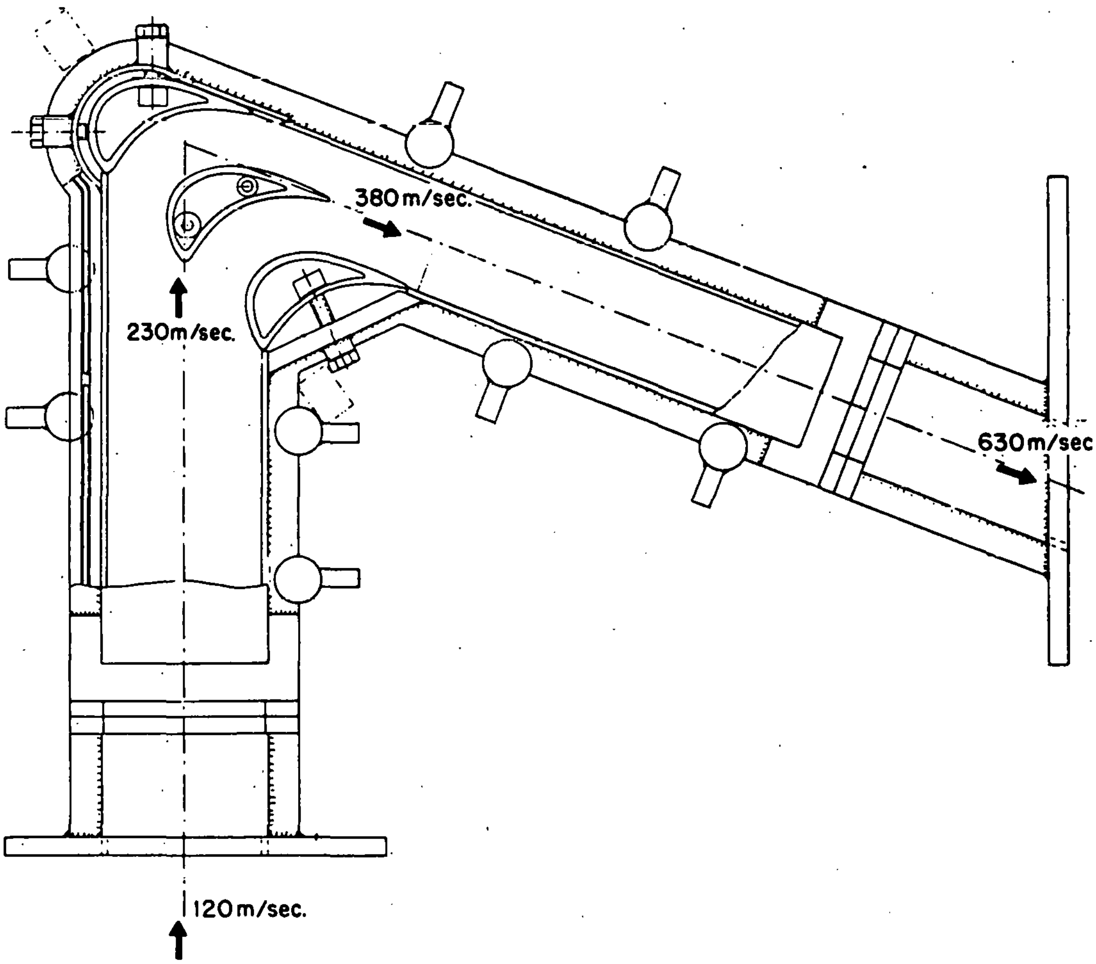


Figure 2. STAL-LAVAL turbine blade cascade.

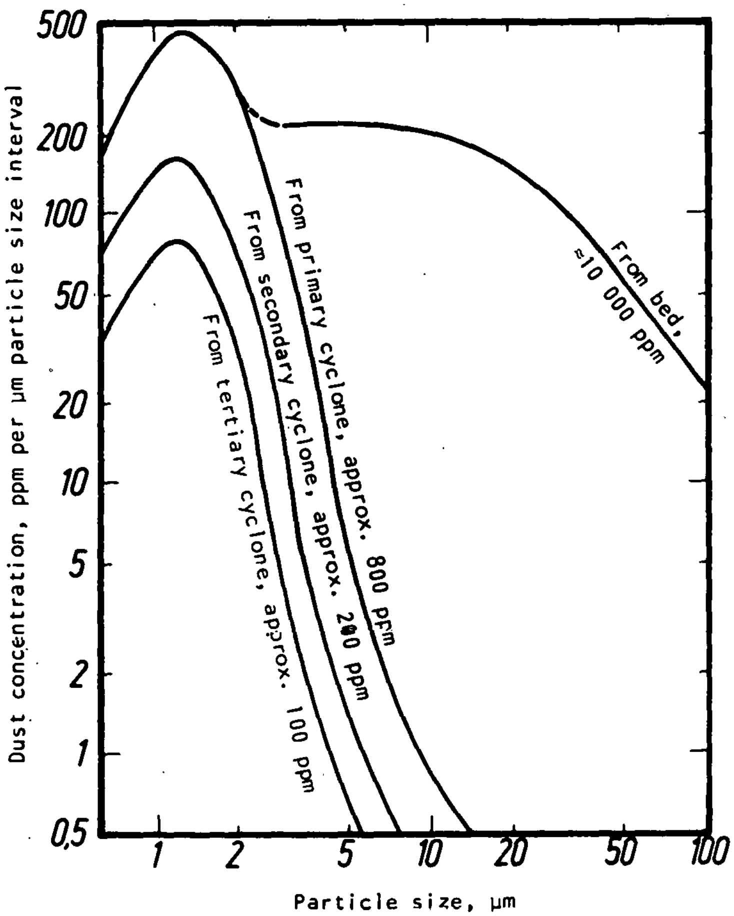


Figure 3. Particle size distribution in dust from PFBC combustor and in combustion gas flow downstream of the different cyclones in Stream 1.

Figure 4. Photo of cascade blade assembly at end of 1000 hour test.

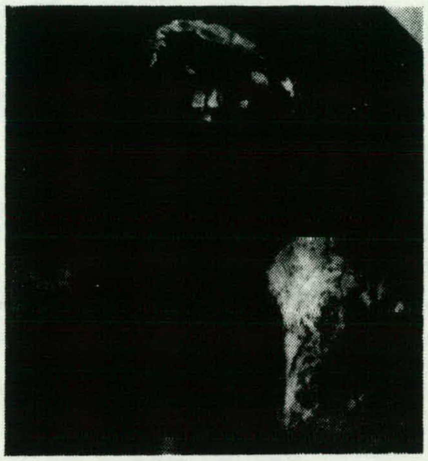


Figure 5. Other view showing also part of pressure side of FeCrAlY coated blade.

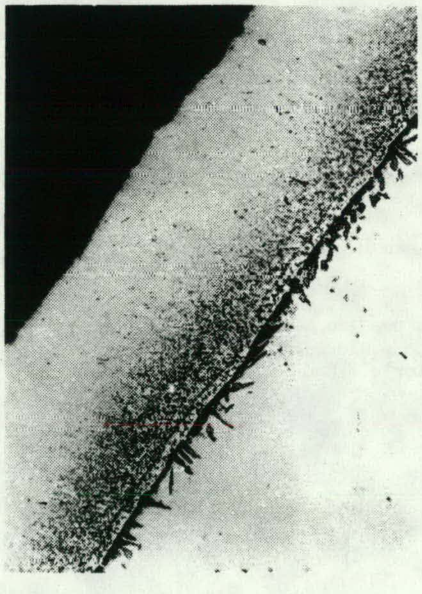


Figure 6. SEM-image of surface region (in cross section) of FeCrAlY-coated Udimet 500 blade. Coating thickness is approx. 100 μm.

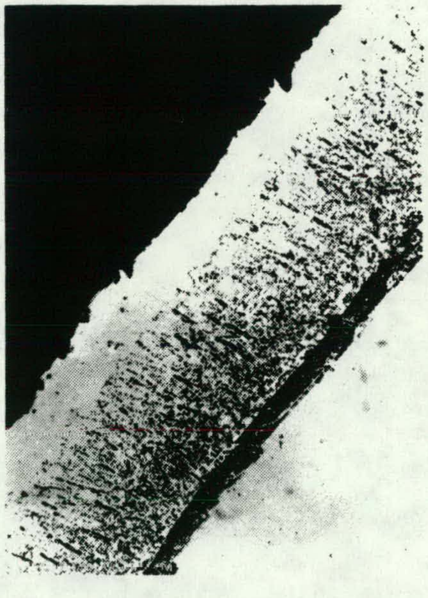


Figure 7. SEM-image of corresponding region after 950 hours exposure to PFBC combustion gases.

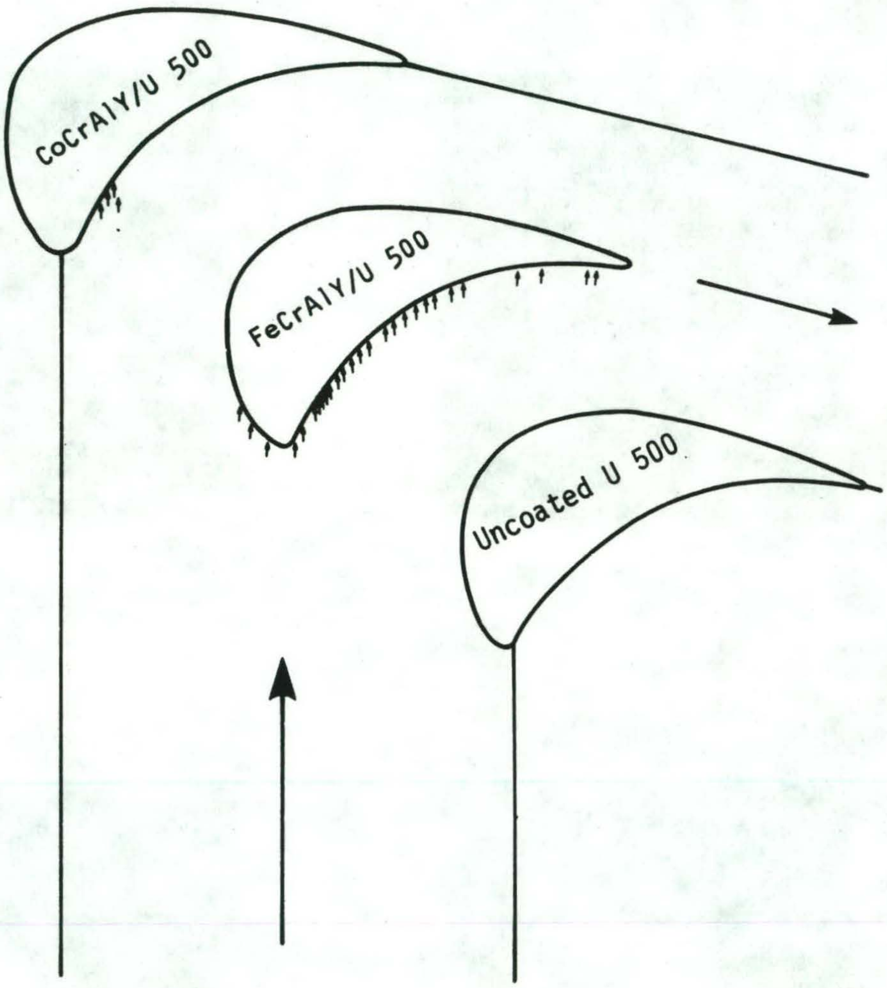


Figure 8. Distribution of sharp-edged particles at the surface of cascade blades. Composition of blade materials and direction of gas flow are shown.

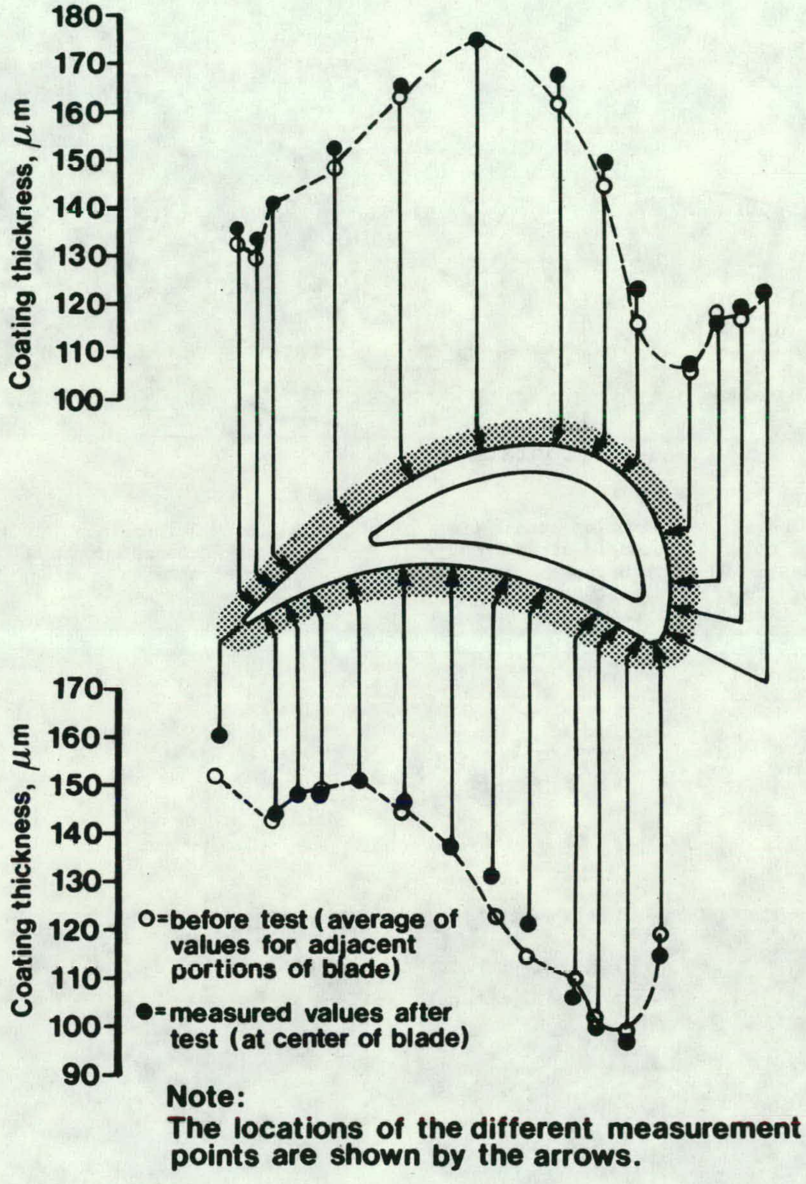


Figure 9. PFBC 1000 hour test. FeCrAlY coating thickness on cascade turbine blade.

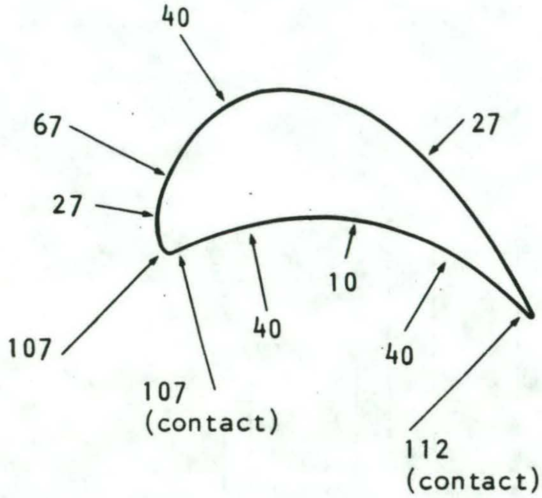


Figure 10. Maximum observed corrosion attack (in µm and including subscale attack) on uncooled U-500 blade after 950 hours exposure to PFBC combustion gases. "Contact" indicates point of contact with blade mounting device.

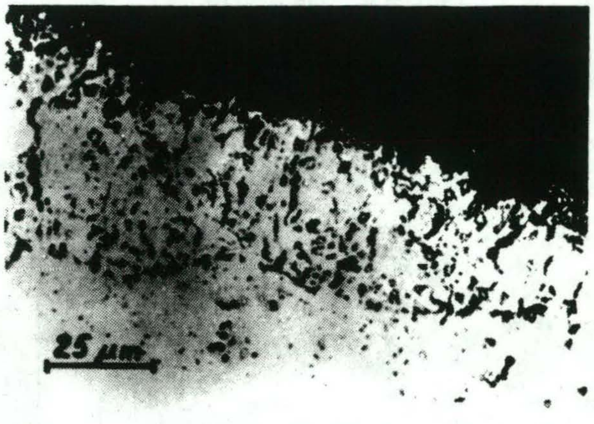


Figure 11. Light micrograph showing corrosion attack on uncoated Udimet 500 blade at point of contact with mounting device.

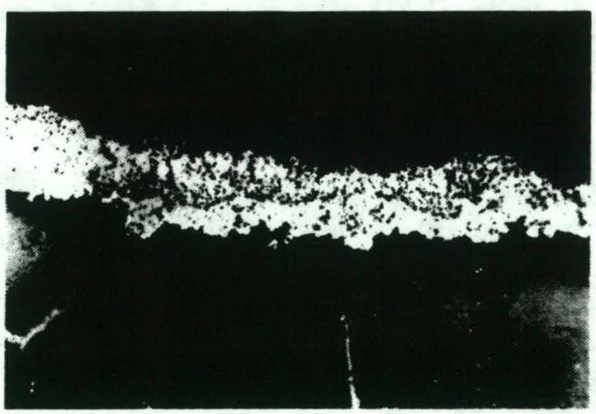


Figure 12. Light micrograph of the same part of the uncoated Udimet 500 blade. Electrolytic etching in oxalic acid shows a compositionally changed surface layer.

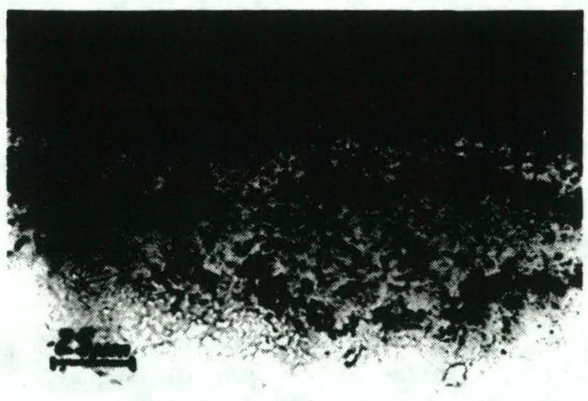


Figure 13. Light micrograph showing oxidation-sulfidation attack at leading edge of IN 671 specimen.

APPENDIX M

Examinations of Thermocouple positioned before cyclone on Stream 1

1 INTRODUCTION

Material: Probably some sort of INCONEL

Time of testing: 1000 hrs

Gas speed: 62 ft/s

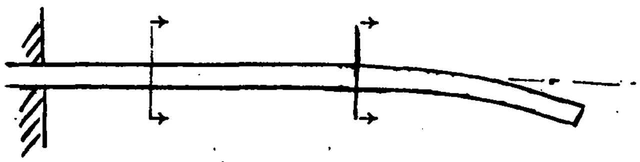
Temperature ~850 °C

Dust Loading: 7000-10000 ppm (most particles ~ 100 μm)

The thermocouple has belonged to the test plant at CURL. It was kindly received from CURL with wishes to take part of the result of the examination.

2 RESULTS

Two cuts through the thermocouple, according to the sketch below, have been examined microscopically (LM)



This examination shows the following:

- About half the circumference has an attack of a character similar to pure oxidation on INCONEL. No signs of sulphides are there. (LM) Before EDX-analysis which has not yet been done it cannot be fully explained. The maximum depth of the attack is in a cut ~< 54 μm

- The attack seems to be positioned on the trailing edge (back side) of the element.

- The result of both the cuts is the same.

- Measurements on the cut show no signs of descaling or erosion

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