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17 TESTING FACILITIES

In this Section details are given of various specialised test methods or testing facilities that may be needed in the design of fluidised combustors.

17.1 Feed-stock Performance Tests

The requirements of tests to ascertain the performance of particular fuels and/or sulphur absorbents in fluidised combustion units are outlined below. The figures quoted should not be regarded as applying to all possible feed-stocks presented for testing since unusual fuels may require specialised treatment. The size of sample required depends on the calorific value and is specified as a weight of carbon or calorific equivalent.

17.1.1 Atmospheric pressure tests; equipment at CRE

17.1.1.1 Initial fluidised combustion test for solid fuels

After a full physical and chemical analysis, initial fluidised bed combustion tests are carried out in a 0.15 m diameter open fluidised bed. The bed, which normally consists of ash or sand, is fired by pre-mixed gas and air. Samples of the fuel to be tested can be added to the bed either batchwise or continuously.

The test is used to:-

(i) give guidance as to the suitability of the feed stock for fluidised bed combustion and make a qualitative assessment of the burning characteristics of the fuel.

(ii) elucidate the problem areas which might arise in further larger scale tests, for example, problems in feeding and ability to maintain the bed.

(iii) to provide guidance as to the suitability of the mineral content of the fuel to form a satisfactory fluidised bed.

Size of sample required — 5 kg (11 lb) carbon or calorific equivalent

17.1.1.2 Fluidised combustion tests in the 0.3m square rig

The combustion rig consists of a 3 mm thick stainless steel body, 0.3 m square in section by 2 m high, surrounded by insulation. The effluent gases pass through a single low pressure drop cyclone. The rig can be run on either coal or gas and provision could be made for liquid fuel and additive feeds. Start up is by above bed gas burners. No provision is made for fines recycle or for in-bed cooling. Coal firing is by pneumatic injection to the bed.

The rig is particularly suitable for testing low grade fuel, but may be used for the assessment of most fuels in fluidised beds over an extended period. It establishes clearly whether the fuel being tested can be fed continuously and can sustain combustion. An initial assessment of materials handling can be made at this stage as a guide to larger plant design.

A minimum running period of 8 hours is assumed for each test with additional extensions of 8 hours each.

Size of sample required — basic test 200 kg (440 lb) carbon or calorific equivalent

additional, 100 kg (220 lb) carbon or calorific equivalent per 8 hours

17.1.1.3 Fluidised combustion tests in the 0.15 m diameter rig

The combustor consists of a stainless steel vessel 0.15 m diameter and approximately 2 m high with an expanded head 0.48 m diameter and 1.4 m high. The whole combustor can be heated electrically by external wall heaters which are used for start-up and to counteract surface heat losses. Coal and additives are fed pneumatically and are limited to a top size of about 1700 μm (0.07 in.).

The heat produced in the bed can be removed by an immersed coil of stainless steel tubing. Bed temperature can be controlled to ± 2°C.

Bed level is controlled automatically and fines recycle is possible. Full dust and gas sampling and monitoring is possible.

This rig can be used to determine the maximum practicable combustion efficiency, for testing various bed conditions and for assessing sulphur retention by different additives.

A minimum period of 3 days testing is assumed.

Size of sample required	240 kg (530 lb) carbon or calorific equivalent. For each additional 8 hours, 20 kg (44 lb) carbon or calorific equivalent.

17.1.1.4 Fluidised combustion tests in the 1.5 m dia. rig

This rig is 1.5 m (5 ft) in diameter and has been specially constructed for assessing the combustion characteristics of low grade fuels especially those fed as an aqueous slurry. It is fully instrumented but at present it is not equipped with any in-bed cooling surfaces.

On account of its size, test duration and sample size would be subject to individual negociation.

17.1.2 Atmospheric pressure teste; equipment at CURL

The shell boiler has a diameter of 1.2 m(3.75 ft) and can be used to study fluidised combustion on a slightly larger scale than is currently possible at CRE. This fire-tube boiler was originally equipped with fluidised combustion to demonstrate the use of this combustion technique for steam raising. It is fully instrumented and can now be used for combustion efficiency studies using either solid, liquid or gaseous fuels. Solids may be fed by both in-bed and above-bed techniques. The rig is described in reference (17.1). Other specific tests, such as sulphur retention or corrosion studies, may be carried out.

A minimum period of 4 days testing is assumed.

Size of sample required	18,500 kg (40,000 lb) carbon or calorific equivalent

17.1.3 Pressurised operation tests

17.1.3.1 0.3 m rig at CURL

Combustion studies at pressures up to 610 kN/m^2 (6 atm) absolute can be carried out using either a gaseous, liquid or solid fuel at fluidising velocities up to 3.7 m/s (12 ft/s).

A minimum running period of 4 days is assumed:

Size of sample required	7,500 - 30,000 kg carbon or calorific equivalent (16,000 - 64,000 lb) according to fluidising conditions

17.1.3.2 0.9 by 0.6 m rig at CURL

The combustion vessel of this rig is 1.3 x 0.6 m (4 x 2 ft) rectangular cross-section, 5.5m (18 ft) high, housed in a pressure shell. Water cooled tube banks can provide in-bed cooling but the rig may also be operated adiabatically if desired. The fuel may be solid, liquid or gaseous with provision for the use of sulphur retention additives if required. The operating pressure may be up to 610 kN/m^2 (6 atm) absolute, with fluidising velocities up to 3 m/s (10 ft/s) and bed depths up to 2.5 m (9 ft).

The rig is fully instrumented and is suitable for detailed studies of any aspect of fluidised combustion. On account of its size, test duration and sample size would be subject to individual negociation.

17.1.3.3 0.3 m rig at BP, Sunbury

This rig is very similar in design to the 0.3 m rig at CURL and can be used for combustion studies at pressures up to 610 kN/m^2 (6 atm) absolute.

The fuel may be solid, liquid or gaseous. Heat is removed from the bed either as sensible heat or through an in-bed cooling coil. The fluidising velocity can be up to 3 m/s (10 ft/s).

A minimum running period of 4 days is assumed.

Size of sample required	7 500 - 30 000 kg carbon or calorific equivalent (16 000 - 64 000 lb) according to fluidising conditions.

17.2 Corrosion/Erosion Tests

Facilities are available on most of the rigs described in Section 17.1 for studying the corrosion of heat transfer tubing or of other specimens immersed in the bed.

Additionally, the 0.3 m (12 in.) rig at CRE was built specially for the investigation of fire side corrosion in fluidised bed systems. This corrosion rig consists of a mild steel shell, lined with 0.1 m thick insulating blocks over which a 0.08 m lining of hard castable refractory has been placed. The internal dimensions of the combustor are 0.3 m (12in.) square in section by 2.4 m (8 ft) high. The rig runs on coal, fed pneumatically, while start-up is by a gas fired preheater. There is a facility for feeding various additives, such as limestone. The flue gases pass through two cyclones in series and provision could be made for fines recycle.

Four specimen tubes, which are comprised of rings of different alloys clamped together, can be installed within the bed where they form part of a pattern of four rows of 0.05 m (2 in.) OD tubes on a 0.15m (6in.) triangular pitch. Two further specimen tubes can be installed in the freeboard, 0.6 m (2 ft) above the nominal bed surface, while small plates of different alloys can be mounted in and above the bed.

The rig is fully instrumented and sampling equipment, for obtaining data on plant performance and environmental impact, are installed at various locations. In addition to materials testing, combustion tests on many fuels could be carried out over a wide range of conditions.

A minimum test period of 4 days is assumed.

Size of sample required	650 kg (1 420 lb) carbon or calorific equivalent. (For a test at 850°C, 0.9 m/s, and 20 % excess air.)

Further test facilities are available on the 1.3 x 0.6 m pressurised rig at CURL. The gases leaving the second stage cyclone of this rig can be passed through a horizontal, pressurised section in which specimens, such as

turbine blading, can be mounted for corrosion, erosion and deposition assessment.

17.3 Coal Ash Suitability Test

If a coal is to be used in a fluidised combustor without the use of an additive or other inert bed material, the ash from the coal will very often be suitable for maintaining the bed. The ash content of a washed coal is insufficient to make up for elutriation from the bed and generally only unwashed coals can be used without the need for bed make-up material. The three parameters which determine whether or not a coal will sustain the bed are (i) the ash content, (ii) the size distribution of the ash produced on combustion, and (iii) the resistance to abrasion of the ash. The abrasion resistance may be quantified by a Degradability Number found from the empirical test described below. The test procedure also generates information on ash content and size distribution and the results enable a preliminary assessment of the suitability of a coal to be made.

17.3.1 Degradability Number

The abrasion resistance of the ash may be assessed using the test described in the following steps.

1. Prepare a 1 kg sample of the coal to the following size specification:

+ 10 BS mesh	- not more than 1%
- 10 + 30 BS mesh	- 30 to 40%
- 30 BS mesh	- remainder

This specification should be met simply by crushing; none of the sample should be screened out and rejected.

2. Ash the sample in a furnace at fluidised bed temperature, stirring occasionally to promote oxidation.

3. Weight the ash and calculate the ash content of the coal.

4. Determine the size distribution of the ash.

5. Perform a degradability test using the -10 +30 B.S. mesh fraction of the ash as follows:

i Weigh out 10 g of the -10 +30 B.S. mesh ash fraction.

ii Place in a 1 oz. glass narrow-necked sample bottle, together with 10 steel balls, 4.75 mm diameter.

iii Mount in a laboratory shaker and shake for about 5 minutes. (The actual time required for the particular shaker in use should be determined such that the correct Degradability Number is obtained for a standard material).

iv Sieve the product on a 30 B.S. mesh screen by hand for one minute.

v Weigh the +30 mesh material remaining.

vi Calculate a "Degradability Number" as the percentage of the ash remaining +30 mesh.

vii Repeat for two further 10 g samples of -10 +30 mesh ash and take a mean value.

Values of ash content, percentage of the ash in the size fraction -10 +30 BS mesh, and the Degradability Number are shown in Table 17.1 for 31 unwashed British coals.

It should be noted that the values of Degradability Number given in Table 17.1 refer only to the particular sample of the coal used in the test and in practice it is necessary to ensure that the sample is typical and that large variations are unlikely to occur as between one sample and another. For example, while values for two coals used in the experimental programme. (Babbington and Newstead) remained approximately constant over about two years, two batches of Goldthorpe coal taken six months apart had Degradability Numbers of 15 and about 60, respectively. Since the values quoted in Table 17.1 were determined some years ago they could be very misleading if applied to coals of the same description in production today.

Table 17.1

Ash Contents and Degradability Numbers of Various British Coals

Name	Ash content %	Ash in size fraction −10 +30 B.S. mesh %	Degradability Number	Suitability Index
Midland Area				
Babbington	28	33	66	1850
Bentinck	20	34	44	880
Bolsover	36	27	8	290
Cotgrave	19	27	7	130
Cresswell	19	29	60	1140
Goldthorpe	17	18	15	260
Hem Heath	17	31	45	760
Hucknall	22	28	51	1130
Lea Hall	17	16	38	650
Moorgreen	15	21	29	430
Newstead	22	24	54	1190
Renishaw	29	28	58	1680
Shirebrook	26	28	54	1400
Silverdale	13	21	25	325
Teversal	22	31	40	880
Theresby	23	21	41	940
Northern Area				
Brenkley	22	27	58	1270
Vane Tempest	25	30	54	1350
Scottish Area				
Monktonhall	22	28	59	1300
Seafield	24	30	72	1730
Yorkshire Area				
Askern	21	32	33	690
Brodsworth	16	26	53	850
Cortenwood	20	20	3	60
Dodsworth	19	23	47	890
Frickley	21	26	47	990
Kellingley	27	21	39	1050
Lofthouse	20	23	45	900
Park Mill	22	26	42	930
Rockingham	19	21	48	910
Sharlston	22	31	43	950
Walton Kent	27	30	55	1480

17.3.2 Ash Suitability Index

It may be assumed that much of the ash in an unwashed coal arises from separate stone particles which have a size distribution similar to that of the coal, the remainder being fine interstitial ash from within the coal particles. Unwashed coals produce in general an ash having a similar, but somewhat finer, size distribution than the parent coal, and thus contain some coarse material suitable for bed maintenance. Clearly, if a coal did not produce any coarse ash on ashing it could not be burnt in a fluidised combustor without the supply of make-up bed material as used in oil or gas firing and/or additives for sulphur retention.

The resistance of the coarse ash to abrasion varies considerably from coal to coal. Thus, with ash from Seafield coal, 72% remained 'coarse' after the test, while with Cortonwood all but 3% was reduced to 'fines'. However, the importance of this degradation will be offset to some extent by a higher ash content of the coal. In order to make a preliminary assessment of the suitability of a coal for use in a fluidised combustor a "Suitability Index" has been defined empirically as:

Suitability Index = Degradability Number x Ash content (%)

Values of this index are given in the last column of Table 17.1; they range from 60 to 1850.

Provided that the coal feed size is appropriate to the fluidising velocity, it should be possible to maintain a bed by feeding a coal with an index greater than 1000 in any combustor. It will not be possible to maintain a bed using a coal with an index below 500 under any practical operating conditions. The suitability of coals with indices between 500 and 1000 will depend on the actual size distribution of the ash produced and on the proposed operating conditions.

Any of the coals could be made suitable for use by adding to the coal, or direct to the bed, a suitable amount of an inert material such as sand of the right size grading.

17.4 Abrasion Constant

The abrasion constant for a bed of particles is defined by the equation, †

$$K_A = \frac{(U_f - U_{mf})\ W_b}{G_{af}} \quad \ldots \quad \ldots \quad \ldots \quad 17.1$$

Values of K_A for beds of inert particles used in fluidised combustion have been calculated from computer studies of combustor operation (See Section 9.3). Values have also be derived more simply from attrition tests in a laboratory fluidised combustor.

The attrition test apparatus is described in detail in reference (17.2). It consists basically of a fluidised combustor 0.08 m (3 in.) in diameter, fired with propane and fitted with an external air cooled coil so that the combustor can be operated continuously at normal bed temperatures. The abrasion constant of a sample of bed material is found by the following procedure. Firstly the sample is sized to give a fraction within the limits < 14 > 25 BS mesh and the size distribution of this starting fraction is measured. The combustor is then charged with a known weight of this fraction sufficient to give a slumped bed depth of 0.08 m (3 in.). The bed is then heated to, and maintained at, a bed temperature of 850-900°C (1560-1650°F) using a fluidising velocity of 0.3 m/s (3 ft/s). At 25 hour intervals the combustor is shut down and a size distribution of the bed material is determined before it is returned to the combustor and the test continued. Normally the test continues for 200 hours but much shorter periods may be needed for particularly friable materials.

The results are expressed as graphs of weight % of particles in various size grades versus running time. Figures 17.1 and 17.2 show typical results obtained for a fairly hard material - sillimanite, Figure 17.1 - and for a fairly soft material - limestone, Figure 17.2.

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† Symbols are defined in Section 1 of this Manual.

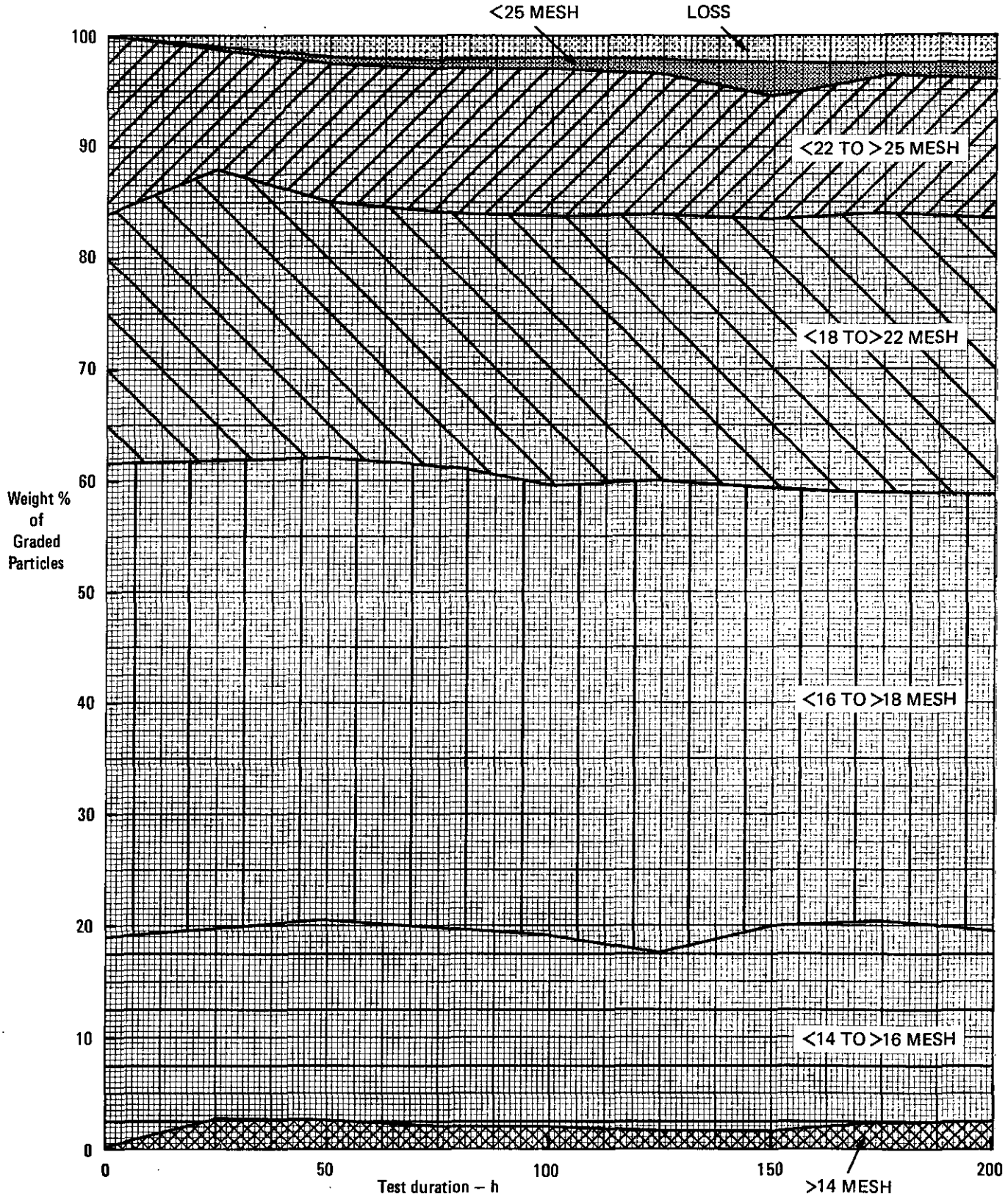

Figure 17.1

Attrition Test on Sillimanite

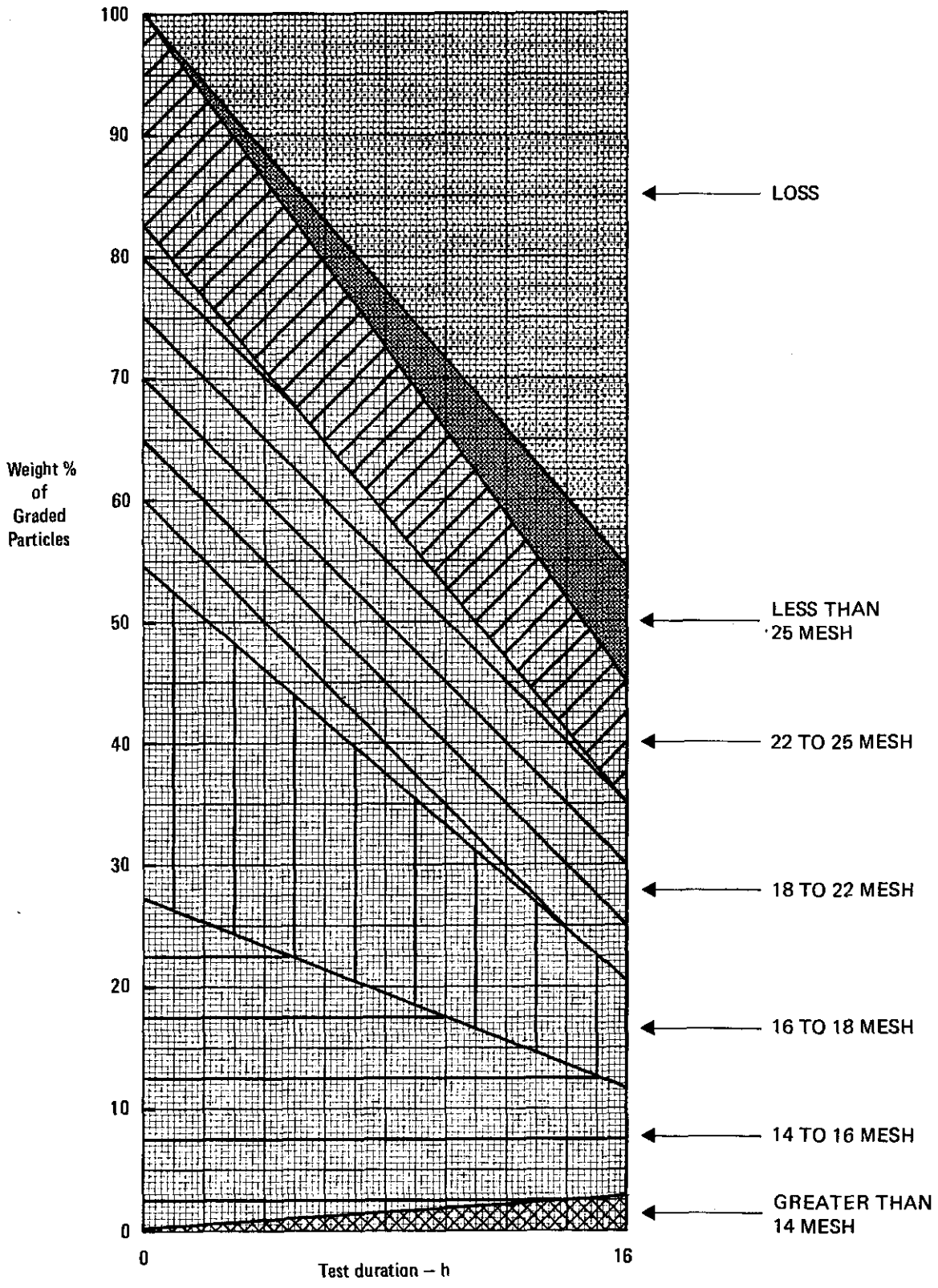

Figure 17.2

Attrition Test on Limestone

The uppermost line of each of Figures 17.1 and 17.2 shows the loss of fines during the test by elutriation. In general the rate of loss of fines from a previously unfluidised sample varies with time as indicated by the slope of the line shown in the diagram of Figure 17.3.

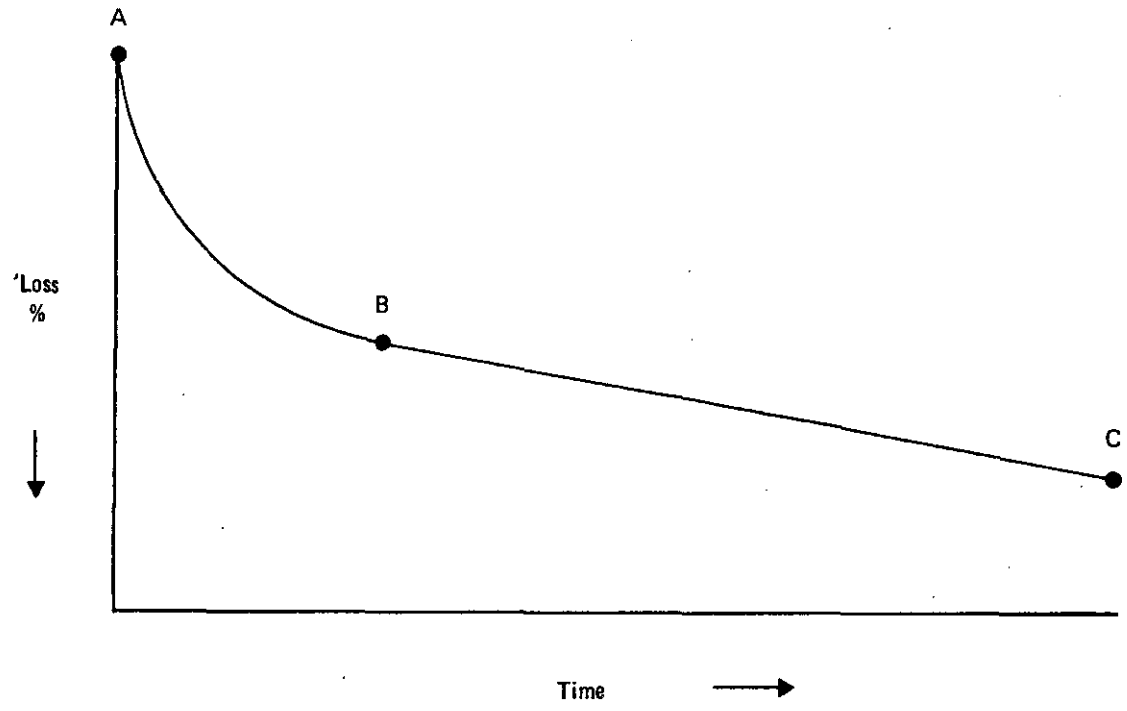

Figure 17.3
Variation of the Loss of Fines from a Fluidised Bed with Time

The high initial losses, portion AB of the curve of Figure 17.3, occur while sharp corners of the particles are being broken off and elutriated. As the test proceeds the particles become more rounded, abrasion occurs more through a grinding action between particles, and subsequent elutriation causes a lower but steady loss as represented by the portion BC of the curve. The time required to reach point B will vary with the hardness of the material and the particle shape as well as with the abrading forces in the bed characterised by the fluidising velocity. The test on sillimanite, Figure 17.1, shows that

over 50 hours were needed before the loss rate became constant. The test with limestone, Figure 17.2, suggests that the initial region AB is of quite short duration.

The residence time of the inert particles in a fluidised bed will be comparatively large and the make-up stream of fresh material will normally not contribute significantly to the bed inventory. The loss rate through abrasion would therefore be expected to correspond with the portion BC of the loss-time curve.

The abrasion constant is calculated as follows. Suppose a steady loss of x % $^{w}/_{w}$ occurs in y hours of operation in the BC region of the loss-time curve at a value of $(U_f - U_{mf})$ of z. If it is assumed that all the smaller particles produced by abrasion are sufficiently small to be elutriated and lost simultaneously then the abrasion rate, expressed as a fraction of the bed weight, equals the loss rate x/(100y).

$$\text{Thus} \qquad K_A = \frac{z}{x/(100y)} = \frac{100\ z\ y}{x} \qquad \ldots \quad \ldots \qquad 17.2$$

The values of abrasion constant shown in Table 9.4 of Section 9 were calculated from equation 17.2 using values of x and y derived from the final straight line approximation to the uppermost loss line of plots like Figure 17.1.

$$k_a = z \frac{w_0}{a_0} = {}^{2}/_{(a_0 w_0)}$$

17.5 Sulphur Acceptor Efficiency

The additives used for the retention of sulphur in fluidised combustors are naturally occurring carbonates of calcium (limestone) or of calcium and magnesium (dolomite). During combustion the sulphur in the fuel is converted to calcium sulphate so only the calcium is effective in retaining sulphur. The efficiency with which the calcium is utilised can vary for different samples and appears to be connected with the structure of the crushed rock. The variation may be considerable for limestones but is normally slight for dolomites. At present, a test in a fluidised combustor is the most reliable way of ascertaining the efficiency of any particular batch of stone. A small fluidised bed test apparatus is therefore being developed for the determination of the efficiency of additives for sulphur retention.

The test apparatus and method is described fully in reference (17.3). The apparatus is a 0.15 m (6 in.) diameter gas fired fluidised combustor with provision for the supply of a metered flow of sulphur dioxide gas to the base of the bed and for the analysis of sulphur dioxide in the combustor off-gas. The inert bed material is washed silica sand and the combustor is fired with natural gas at standard conditions thought to be reasonably representative of optimum conditions for sulphur retention.

The inlet sulphur dioxide concentration is approximately equivalent to that obtained by the fluidised combustion of a coal containing 2% w/w of sulphur.

When thermal equilibirium is obtained a test is begun. The procedure is to add at time zero an additive sample of weight equivalent to 22.5 g of CaO. The size specification of the sample is minus 600 plus 500 μm. The sulphur dioxide concentration in the off-gas is then analysed and recorded on a time base. The concentration drops to a minimum value and then slowly rises; the test is continued until the sulphur dioxide concentration has risen to 95% of the starting concentration at a time t_A (hours). From the area underneath the concentration time graph and the gas flow rate the weight of sulphur dioxide absorbed by the additive sample can be calculated.

Hence the weight fraction, κ_A, of CaO in the additive utilised during the test is calculated as follows.

$$\kappa_A = \frac{\text{wt. of } SO_2 \text{ absorbed}}{\text{wt. of } SO_2 \text{ absorbed for complete reaction}}$$

The weight of SO_2 for complete reaction is calculated using the chemical equation

$$CaO + SO_2 + \tfrac{1}{2}O_2 \rightarrow CaSO_4$$

For a sample of additive containing 22.5 g of CaO the theoretical absorption for the complete reaction is 25.7 g SO_2.

The additive sulphur retention efficiency is then found by relating the CaO utilisation to previous measurements with well characterised additives. Details of the experimental determinations of retention efficiencies, which were made using the 0.15 m (6 in.) diameter rig are given in reference (17.4). Alternatively the Reactivity Index of the additive may be calculated as described in Section 11.5.3.

17.6 References

17.1 NCB. Report No DHB : 010172 (Jan 1972)

17.2 Piper, D.S. "The Resistance of Alternative Bed Materials to Attritional Degradation". BP Report No. 31 841, (14 June 1977).

17.3 Anderson, J.S. "Characterisation of limestones using a 0.15 m diameter fluidised bed test rig". NCB, CRE Report No MP 88, (Nov 1976).

17.4 Holder, J.C. NCB, CRE Report No MP 75.