19. METAL WASTAGE

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19.1 Introduction

The term metal wastage is used to describe any process that results in a reduction in the thickness of any metal component used in the construction of a fluidised bed combustor. The term is used without reference to the underlying causative mechanism, which may be erosion, abrasion, particle impingement, corrosion or any other process acting either separately or together, for it is the final result, the metal wastage, that is of primary concern in the design of the combustor.

Because of the particle movement during fluidisation it is likely that metal wastage is an inherent factor in the operation of fluidised bed combustors although the degree of wastage may not become significant until some threshold fluidising, or particle, velocity is exceeded. It may well be, however, that any threshold velocity is uneconomically low so that metal wastage must generally be anticipated to some extent during normal operation.

Guidelines to designs and operating conditions appropriate for minimising metal wastage are given in this Section. The number of factors that can influence metal wastage is large and the optimum design will generally depend on the economics of the application. As an aid in interpreting the guidelines therefore, this section also includes background information on the effects, as far as is known, of the parameters that influence metal wastage rates and on the phenomenon generally.

Metal wastage is a topic of ongoing research by CSL and its Partners. The monitoring of existing industrial installations is continuing with a view to identifying those conditions and designs that minimise metal wastage. Cold models are in use for assessing metal wastage rates over a wide range of operating conditions and combustor designs. Such models can be used to advise on designs or conditions that will result in least metal wastage. Research is also in progress to elucidate the basic mechanisms causing the metal wastage, to identify more wear resistant materials for component manufacture and to find suitable bed solids materials that give reduced rates of metal wastage.

Metal wastage on associated equipment such as air distribution nozzles and oil feed nozzles is also being studied using cold model techniques for the assessment of alternative designs and a programme for monitoring metal wastage in the smoke tubes of fluidised bed boilers is being carried out.

19.2 Metal Wastage Phenomena

19.2.1 Occurrence

Any area where metal has been removed is described as an area of metal wastage. The worst affected areas are always localised, sometimes extremely so, but are often surrounded by a region of reduced wear. Under adverse conditions the localised rates of wear can be quite unacceptably high. At a particular site the rate of metal loss may fluctuate but over an extended period consistent trends in loss are observed.

The pattern of metal wastage on the combustor walls is somewhat different from that found on tubes immersed in the bed. On the walls wear appears to occur preferentially at sites where the wall surface is rough or uneven. Typical sites are seam welds, the heads of stay bars and regions where in-bed tubes are welded to the walls. For static bed depths in the range 100-300 mm (4-12 in.) the wear is concentrated in a band located in the expanded bed and splash zones about 50-150 mm (2-6 in.) above the static bed surface. Areas of maximum metal loss are located in the middle of this band with regions of lesser wear on either side (19.1).

Tube wear seems to be caused more by a rubbing action than does wall wear and does not generally show the rippled, gouged appearance that is characteristic of wall wear. Metal wastage on tubes is also more variable in its location than wastage on the walls. Wear does not occur evenly either around the tube periphery or along its length. Usually the area of worst wear is on the tube undersides in the 135° and 225° positions with a lesser degree of wear in between at 180° but sometimes the worst wear occurs a little higher around the 45° and 315° positions. (The 0° position is situated at the top of the tube.) If there is more than one row of tubes in a triangular pitch tube bank the uppermost row is the worst affected. If the tubes enter the bed horizontally and then turn upwards to leave through the freeboard these areas of worst wear are commonly sited on the horizontal parts of the tubes some 50-300 mm (2-12 in.) from the wall while when the tubes are inclined the worst affected areas may be sited towards the upper ends of the tubes (19.1).

A few instances of metal wastage have also been observed which can be attributed to specific causes. Examples are,

(a) Pitting of combustor walls when air distribution nozzles are located close to the wall with the air jets directed towards the wall.

(b) Mechanical deformation and wear of tubes sited immediately below a drop tube of a coal feed point.

(c) Jet erosion if a tube bank is located too close to the return of a bed solids pneumatic transport line.

19.2.2 Causes

Many forms of wear have been identified but two, abrasion and erosion, appear relevant to wear in fluidised bed combustors (19.2). These processes are defined as follows.

Abrasion is the displacement or loss of material from a surface brought about by pressure contact with hard projections on a contacting surface, or with hard particles that are in intimate contact with, and moving in a direction approximately parallel to, the abraded surface.

Erosion is the displacement or loss of material resulting from particle impacts. Unlike abrasion, particles impinge on the eroding surface at an angle and remain in contact for only a short while.

Either of the above processes may be coupled with corrosion if the metal temperatures are such that oxide scales can form readily. The effect may be synergistic, that is the degree of material wastage could appreciably exceed that expected by summing the individual material losses caused by abrasion/erosion and corrosion acting separately.

The precise causes of metal wastage in fluidised bed combustors are not yet fully understood. It seems likely, however, that wall wear is associated more with abrasion while erosion plays a greater part in tube wear. Tentative reasons are as follows.

During the fluidisation process solids are transported upwards in the bubble wakes and deposited on the bed surface. Solids equilibrium is maintained by compensating down flows of close packed solids. Such flows are particularly strong at the walls and could possibly provide conditions favourable for abrasive wear on them.

Away from the walls, in mid-bed, the presence of in-bed tubing will obstruct the upward bubble flows. Bubbles may be deflected, deformed or broken up and the solids in their wakes could then impinge on the tubes. The solids velocities would be in excess of the mean fluidising velocity as the bubbles rise faster and could encourage erosive wear. It is also known that particles can be accelerated as bubbles explode at the bed surface.

It is not known to what extent corrosion contributes to the metal wastage process but it is considered that corrosion alone is not a likely cause of the metal wastage observed. Firstly, in many industrial fluidised bed boilers the metal temperatures of water-cooled walls and in-bed surfaces are in the range 200-260°C (390-500°F); such temperatures are low for significant corrosive attack. Secondly, it has been shown that cold model studies can simulate qualitatively some patterns of wear (19.3) which would be unlikely if corrosion alone were the cause.

19.2.3 Effect of system variables

This section is included to provide background information and explanations of the reasons for the recommendations made for minimising metal wastage.

19.2.3.1 Factors involved

A comparatively large number of factors may affect the rates of metal wastage. They are listed in Table 19.1 under the three categories of operational, design and materials parameters. Although all the factors listed in Table 19.1 can, under appropriate conditions, affect metal wastage rates their precise roles and relative importance are not entirely clear. The elucidation of their exact roles is currently a subject of ongoing research by CSL and its Partners.

The relative importance of the main parameters has been identified using the results of a programme for the systematic monitoring of metal wastage in over 30 industrial fluidised bed combustion units up to 30 MW (1×10^8 Btu/h) in thermal output (19.1) and from cold model experiments using a multi-layer paint technique (19.3, 19.4).

The single most important factor that influences the metal wastage rates is the fluidising velocity. For many fluidised bed combustor designs wear rates may be marginally acceptable at a fluidising velocity of 1.8 m/s (5.9 ft/s); at higher velocities the wear rates increase rapidly. It is not yet clear whether a threshold fluidising velocity exists, below which metal wastage does not occur, but it seems likely that any such threshold value will be too low for economic operation.

Table 19.1

Factors that may affect Metal Wastage Rates

1.	Operating Parameters	
	Total operating time	
	Fluidising velocity	(actual, not nominal, value)
	Bed depth	
	Metal surface temperature	
	Frequency of start-up	
2.	Design Parameters	
	Combustor walls	Surface finish
	In-bed tubing	Tube outside diameter
		Tube inclination to horizontal
		Type of tube pitch (triangular, square, etc.)
		Number of tube rows
		Tube/wall junction design (wall weld, etc.)
	Air distribution	Preferential air flows
3.	Materials Parameters	
	Bed solids	Composition
		Susceptibility to fracture (thermal shock)
		Particle hardness
		Particle shape
		Particle size, size range
	Metal components	Composition
		Hardness
		Surface finish (polished, rough, work-hardened, oxide film, etc.)
		Use of coatings

The detailed effects of the parameters are outlined below. Wall wear and tube wear are considered separately since different basic mechanisms are suspected to be responsible. See Section 19.2.

Equations for correlating and predicting the extent of metal wastage on both walls and tubes of fluidised bed combustors have been derived from the results of the programme of monitoring industrial fluidised bed installations (19.1). The wear parameter correlated is the maximum, localised, metal thickness loss likely to occur anywhere on either the walls or the tubes of the combustor. It is this parameter that will determine the component life. Such localised losses are generally, but not invariably, found at one particular site in a particular combustor.

These correlating equations are given in the appropriate sub-sections below. They are a useful aid in identifying the effects of the principal parameters causing metal wastage and in predicting the likely effects of changes in operating and design parameters. However, it must be stressed that these equations should be used with caution for the following reasons.

1. They are based on data obtained from a restricted range of designs of fluidised bed combustors. The units were predominantly boiler installations with heat outputs up to 30 MW (1×10^8 Btu/h) and using the bed expansion method of turn down. The bed depths used in consequence were relatively shallow - typically 130 - 200 mm static (5 - 8 in static) - with fluidising velocities generally in the range 1 - 3 m/s (3.3 - 9.8 ft/s) - but up to 6 m/s (19.7 ft/s) in a high velocity experimental rig. The in-bed heat transfer tubing was arranged, typically, in two rows with the underside of the lower row near the static surface.

2. In all the installations the bed material was graded silica sand without any addition of solid sorbents for sulphur retention and the metal components were made from boiler grade mild steel.

3. The effects of some parameters suspected of influencing metal wastage are omitted from the correlations because their values were either constant or varied over such restricted ranges that no conclusions could be drawn; e.g. bed temperature.

4. The metal wastage results from bubble and solids flow processes that are partly random in nature and partly influenced by combustor geometry and fluid flow conditions that are imperfectly understood. As a result predicted and measured values of metal wastage can differ by a factor of 2 or more.

19.2.3.2 Wall wear

Metal wastage on the walls appears to occur at a rate that accelerates with increasing operating time. The maximum cumulative metal loss, y,[†] has been correlated by the following equation,

$$y = \Theta \times \left[t \, U_f^{2.4} \right]^{1.8} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \; 19.1$$

where t is the total operating time in hours and Θ equals 6.38×10^{-9}, for U_f in m/s and y in mm or, 1.486×10^{-12}, for U_f in ft/s and y in inches.

Equation 19.1 indicates that the metal thickness loss varies with the 4.32 power of the fluidising velocity. Figure 19.1 shows predicted values of y plotted as a function of operating time for various constant values of fluidising velocity. The very wide range of operating times needed to produce a given thickness loss is supported by operating experience. For example, a loss of 3 mm (0.12 in.) was experienced on the high velocity rig at CRE (19.5) in only 1200 hours of operation at a mean fluidising velocity of 5.5 m/s (18 ft/s) while a similar loss of 2.7 mm (0.11 in) was monitored on an industrial unit (19.1) after 17000 hours operation at a mean fluidising velocity of 1.8 m/s (5.9 ft/s). The

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[†] Symbols are defined in Section 1 of this Manual.

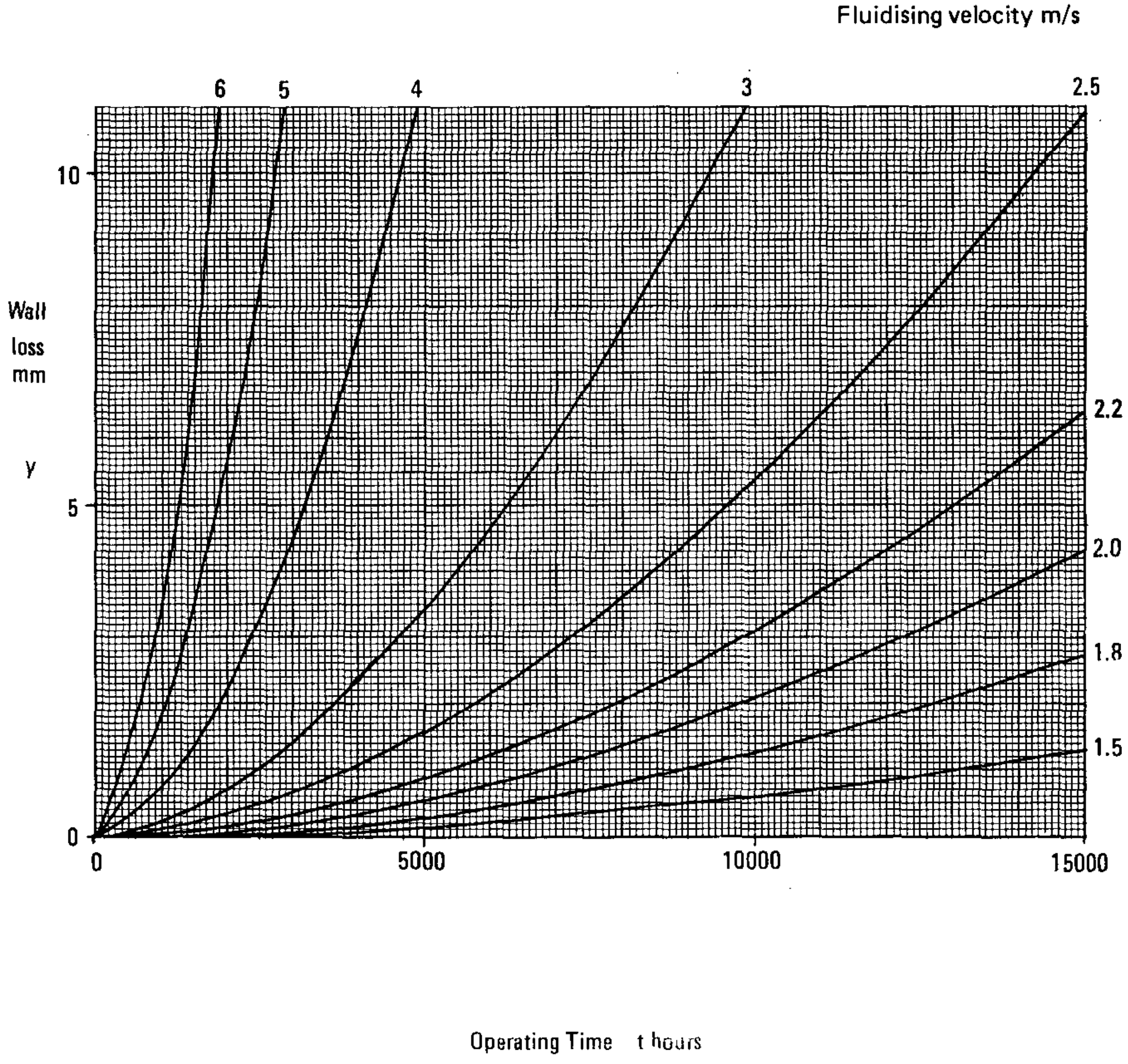


Figure 19.1 (SI Units)
Predicted Variation of Wall Loss with Operating Time.

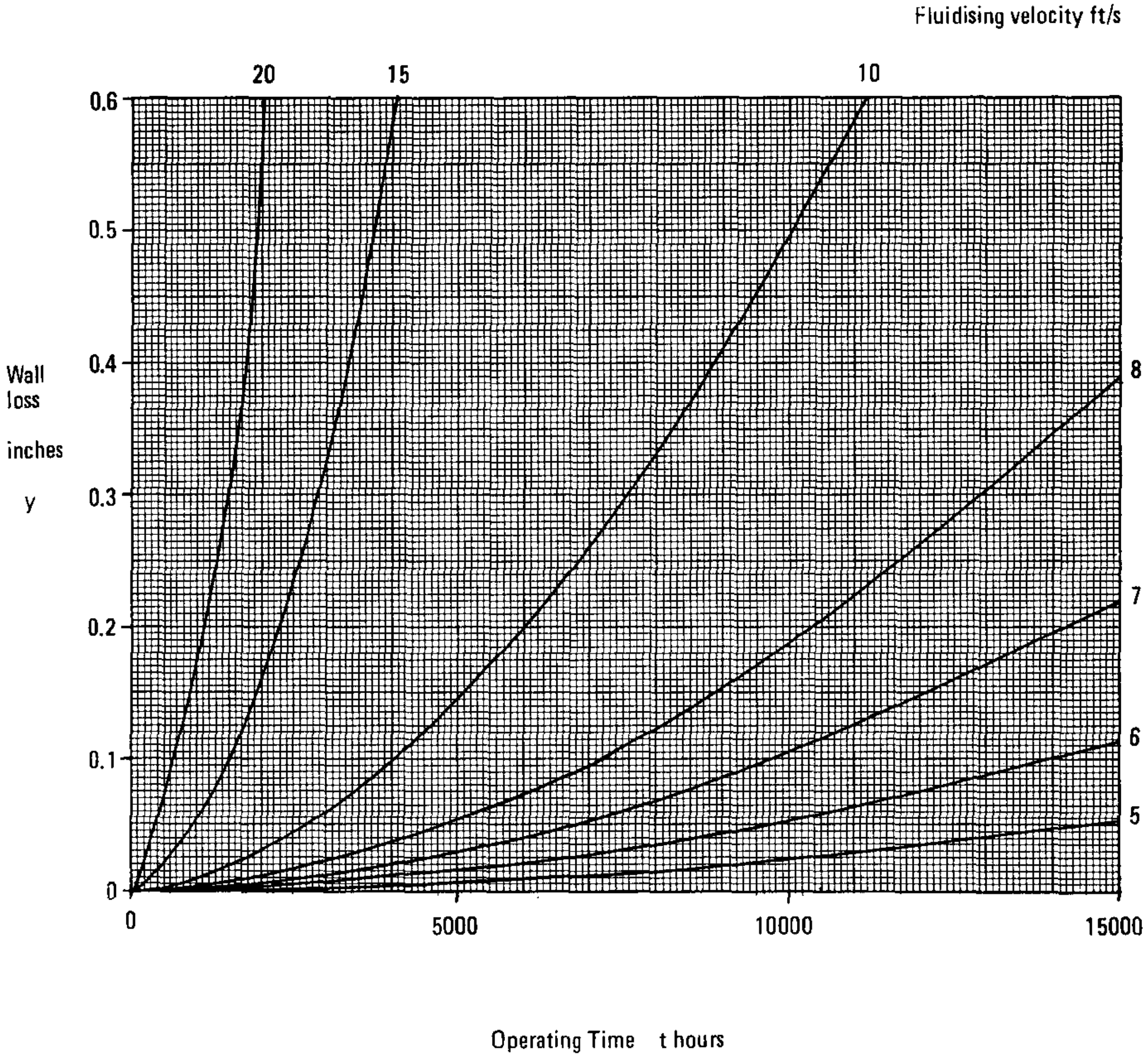


Figure 19.1 (British Units)
Predicted Variation of Wall Loss with Operating Time

sensitivity of wall wear to changes in fluidising velocity is such that the rate of wear is doubled by only a 17% increase in fluidising velocity (ie by an increase of 1.17 times).

The only other factor known so far to influence wall wear is the surface finish of the metal. The effect of the wall wear process is to produce a rippled, roughened or gouged surface and areas with a similar rough finish, like seam welds, or with protuberances, like the ends of stay bars, have been found to be attacked preferentially. Such attack may be connected with the accelerating nature of the process. In this connection it should be noted that the use of a hard weld overlay as a protective coating has not been found to be successful. The rate of wear on the areas of weld overlay is increased, presumably because of the rough surface finish of the overlay.

19.2.3.3 Tube wear

Tube wear, like wall wear, also increases with increasing operating time. Data for tube thickness losses experienced on various industrial units are shown plotted as a function of operating time in Figure 19.2. The precise form of the relationship between loss and time is difficult to determine for two main reasons. Firstly, the range of loss values is restricted and varies only between 0.3 mm, which is the smallest loss measurement that is considered to be significant, and 4 mm, which is about the largest thickness loss that occurs before a tube must be replaced for safety reasons. Secondly, the parameter of importance to the designer - the localised maximum tube metal thickness loss, y_p - is necessarily a single value at any operating time so its experimental error is relatively large.

Two possible forms of relationship between loss and time, which could be used to represent the data, are shown at the bottom of Figure 19.2. The data points for all the units could be fitted using relationship A, which gives straight lines through the origin. However, the data for some units, particularly those operating at the lower fluidising velocities, could be fitted equally well using relationship B which involves a delay or induction period before significant wear begins. Because the experimental errors are relatively large it is not possible to distinguish between the two relationships statistically but Figure 19.2 has been included so that the possibility that some kind of induction period occurs may not be overlooked.

Relationship A is the simpler and has been used as the basis of a correlation for predicting y_p for plain tubes. The correlation was derived using a least squares analysis and is as follows.

$$y_p = m \, \Theta \, t \qquad \dots \dots \dots \dots \dots \dots \dots \qquad 19.2$$

where t is the cumulative operating time in hours and Θ equals 1.0 for SI units to give y_p in mm, and 0.0394 for British units to give y_p in inches.

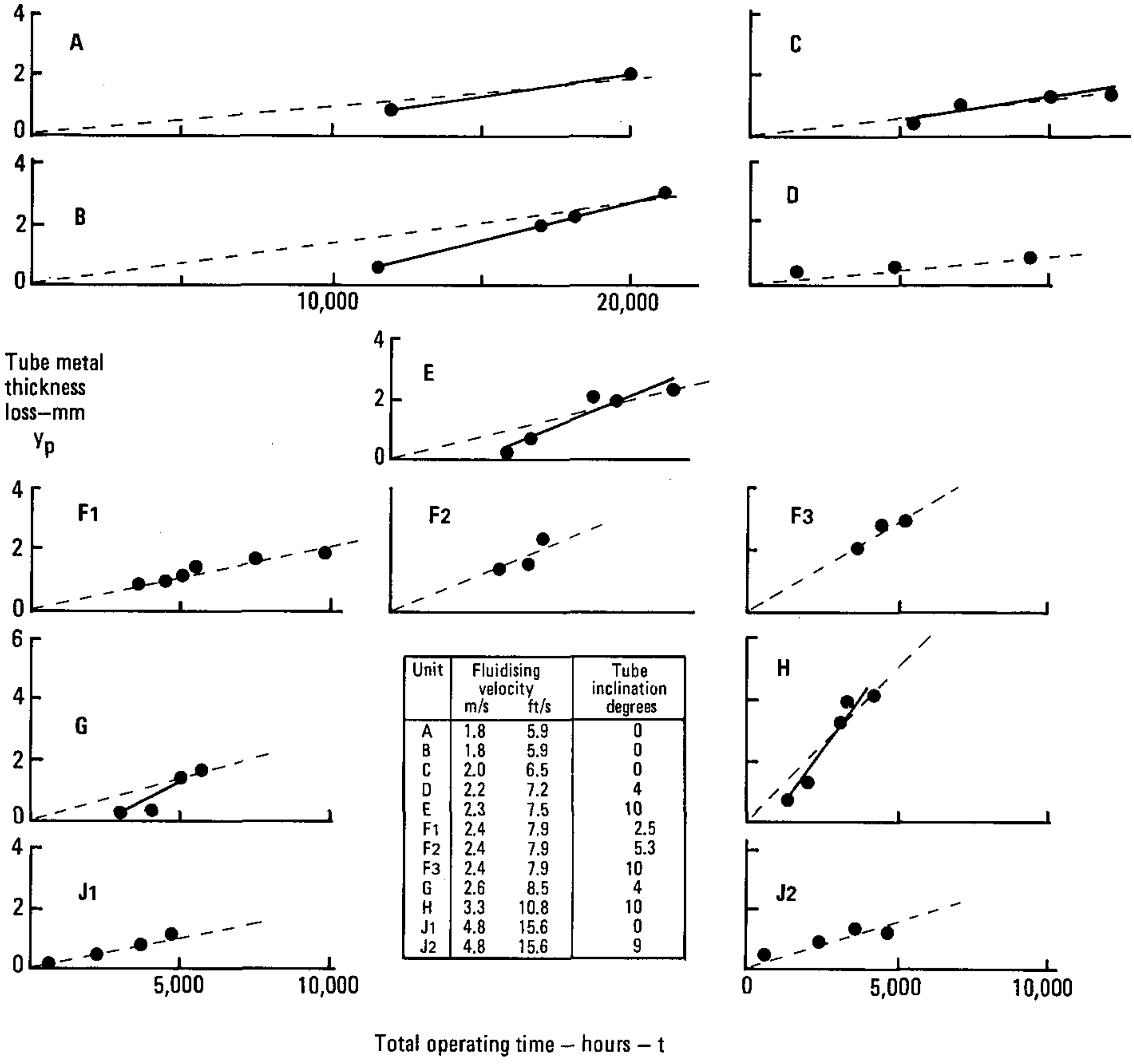
The loss rate, m, has been shown so far to be affected by the tube inclination and diameter, the fluidising velocity and the static bed depth and is correlated by,

$$m = \Theta_2 \, (1 + 0.1 \, \Theta_i) \, U_f^2 \, D_o^{0.6} \, L_s^{1.33} \qquad \dots \dots \dots \dots \; 19.3$$

where Θ_2 equals 1.873×10^{-9} for SI units with U_f in m/s, D_o in mm and L_s in mm, and 8.963×10^{-8} for British units with U_f in ft/s, D_o in inches and L_s in inches.

It is evident from equations 19.2 and 19.3 that the rate of metal wastage on tubes will be minimised by using horizontal tube banks of relatively small diameter tubes and by operating with a fluidising velocity and static bed depth that are as low as economically possible.

Figure 19.3 shows the predicted tube thickness loss as a function of operating time for various constant values of fluidising velocity. The other relevant parameters have been assumed to remain constant at values that will minimise tube metal wastage. That is, Experimental Results for Plain Tubes



Unit	Fluidising velocity m/s	Fluidising velocity ft/s	Tube inclination degrees
A	1.8	5.9	0
B	1.8	5.9	0
C	2.0	6.5	0
D	2.2	7.2	4
E	2.3	7.5	10
F1	2.4	7.9	2.5
F2	2.4	7.9	5.3
F3	2.4	7.9	10
G	2.6	8.5	4
H	3.3	10.8	10
J1	4.8	15.6	0
J2	4.8	15.6	9

Possible forms of relationship

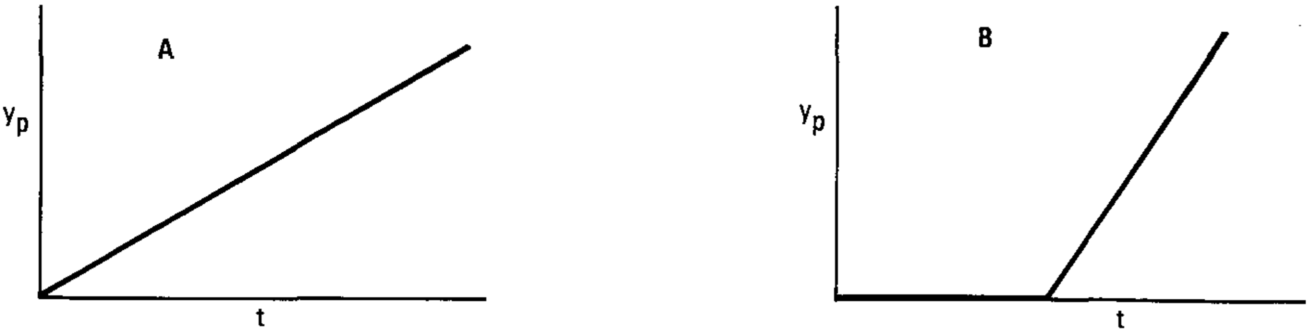


Figure 19.2

Variation of Tube Metal Loss with Operating Time

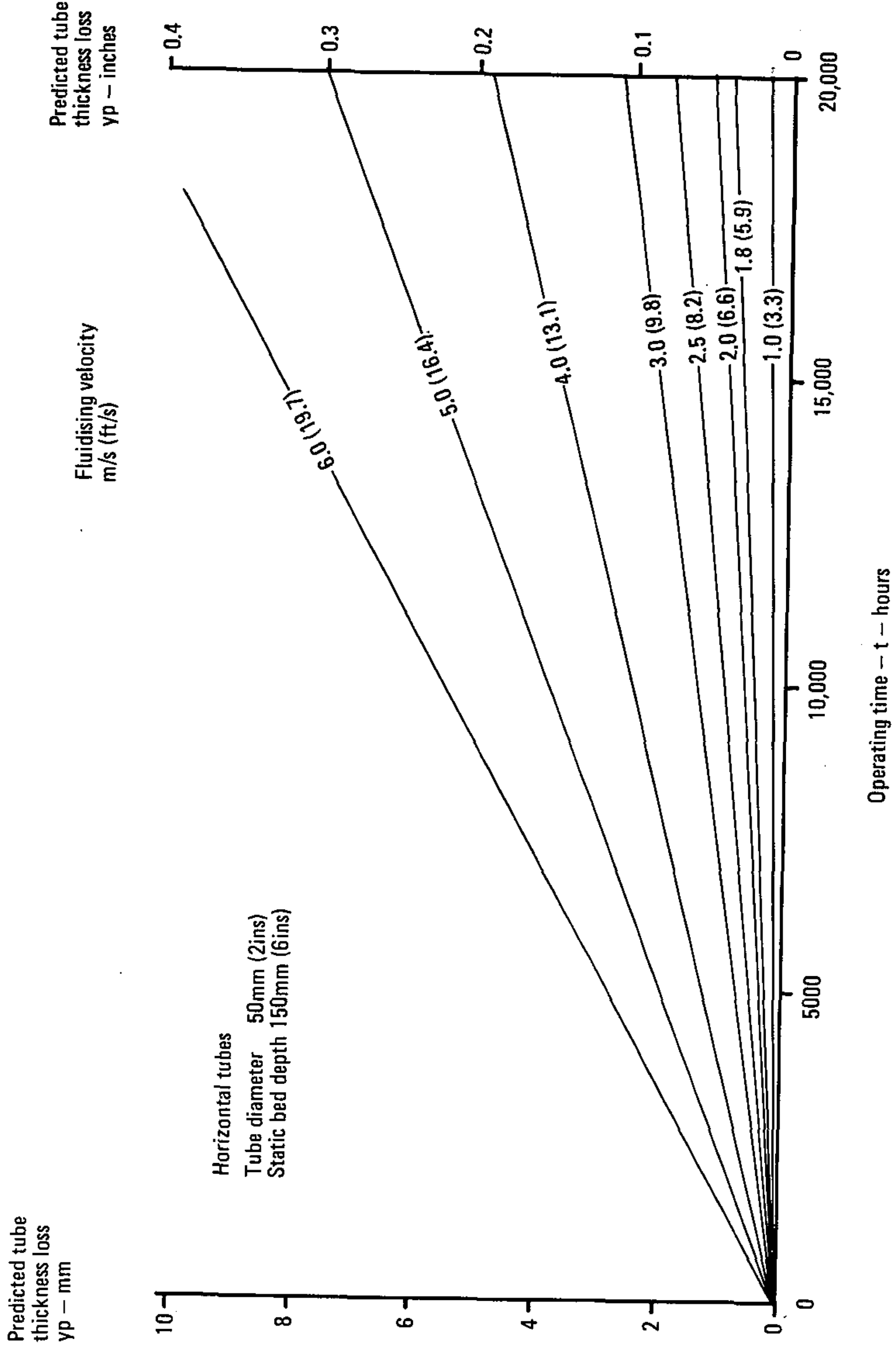


Figure 19.3
Variation of Predicted Tube Thickness Loss with Operating Time

horizontal tubes, $\theta_i = 0$

relatively low tube diameter, $D_o = 50$ mm (2 in.)

relatively low bed depth, $L_s = 150$ mm (5.9 in.)

The rates at other conditions can readily be found by scaling using equation 19.3.

The range of parameters on which equation 19.3 has been based are,

Fluidising velocity	1.5 - 6.0 m/s (4.9 - 19.7 ft/s)
Tube diameter	50 - 114 mm (2 - 4.5 in.)
Static bed depth	90 - 300 mm (3.5 - 11.8 in.)
Tube inclination	0 - 13 degrees

Caution should be used in extrapolating equation 19.3 to conditions outside these limits.

19.2.3.4 Uncorrelated factors

A comparison between Table 19.1 and equations 19.2 and 19.3 shows that several parameters are not included in the equations. The omission of these parameters does not necessarily imply that they have no effect on tube metal wastage as their effects may not yet have been positively identified. See section 19.2.3.1. Also some parameters have shown influences during cold model studies (19.4) that require further corroboration on the industrial scale. Some possible effects are outlined below.

Tube bank location. In the cold model studies a distinction was made between changes in static bed depth and changes in tube position relative to the static bed surface. Wear was greatest when the tubes were close to the static bed level and reduced as the tubes were raised. Most of the industrial units monitored for metal wastage used the bed expansion method of turndown. The lowest tubes were positioned, therefore, a short distance above the static bed depth irrespective of the actual value of that depth.

The bed depth term in equation 19.3 is likely, therefore, to be representing the effect of bed depth variations and not those of tube position. In units operating with beds deeper than 1 m (3.3 ft), wear was increased as the height between the air distributor nozzles and the lowest tubes in the tube bank was increased.

Tube bank pitch type. Cold model studies indicated that the wear on the upper tubes in a tube bank with a triangular pitch was greater than that on similarly placed tubes in a tube bank with square pitch. Comparative results for this effect on industrial units are scanty but do not indicate a strong effect. Equation 19.3 is considered as representing a triangular pitch arrangement and may overestimate the rate of metal wastage for a square pitch tube arrangement but this point requires further confirmation.

Tube metal temperature. Most of the industrial units monitored for metal wastage operated with tube surface metal temperatures varying from 210 to 260°C (410 to 500°F) but a few results have suggested that wear rates may increase as the tube surface metal temperature increases within the range 150 - 350°C (300 - 660°F). Equation 19.3 is based on the bulk of the data obtained at temperatures in the middle of this latter range. Further data is required before the correlation could be modified to include such an effect. It should also be noted that for still higher metal temperatures in the range 400 - 600°C (750 - 1110°F) there is some evidence that the wear rate may reduce as the metal temperature is increased (19.12). This effect might be attributable to the formation of a protective oxide layer.

19.2.3.5 Materials factors

Equations 19.1 to 19.3 have been derived from data obtained on combustors made from boiler grade mild steel operated with beds of silica sand containing traces of coal ash derived from the fuel. It would be expected that metal wastage, on both walls and tubes, would be influenced by the properties of both the bed solids and the materials of construction of the combustor. Unfortunately, no data from large scale operation is currently available but laboratory studies on the subject have been undertaken at CRE (19.6, 19.7).

In the laboratory apparatus the erosivity of candidate bed materials and the sensitivity to erosion of candidate materials of construction can both be measured. The principle of the tests is that a jet of bed particles is fired at a controlled particle velocity onto a target. The loss of weight of the target in a known operating time is measured. If the target is a standard material then the relative erosivity of candidate bed materials can be assessed. If the targets are made of different metals then the sensitivity of candidate materials of construction can be measured.

Tables 19.2 and 19.3 show preliminary results using this apparatus at ambient temperatures. Table 19.2 shows the relative influence of particle type on erosion. Used sand is about four times more erosive than the unused sand. This change is probably connected with the greater proportion of angular particles in used sand because of fracture during operation. (See also Section 9.) The pronounced erosivity of molochite is probably associated with its angular shape and apparent resistance to fracture. In similar experiments no significant influence of particle size was noted for particles in the size range 500 - 2000 microns (0.02 - 0.08 in.) which is of interest for fluidised bed combustion.

Table 19.3 shows the sensitivity of various alloys to erosion by unused silica sand. Stainless steels are apparently about twice as resistant to erosion than is mild steel. The nominal hardness of the alloys tested is also shown in Table 19.3 and it appears that wear resistance increases with increase in alloy hardness.

It should be noted that the trends outlined in the paragraphs above have not yet been confirmed by tests carried out under actual operating conditions in industrial scale units.

19.2.4 Remedial measures

Remedial measures to reduce metal wastage may be required for the following reasons,

Table 19.2

Relative Erosivity of Candidate Bed Materials

Material	Mean target weight loss *1 mg	Erosivity relative to unused sand
Unused silica sand	1.8	1.0
Used bauxite	4.1	2.3
Unused bauxite	4.4	2.4
Coal ash	6.5	3.6
Used bed sand (B)	6.7	3.7
Used bed sand (A)	7.4	4.1
Molochite *2	9.2	5.1

*1 For 2 kg of particles and test duration of 15 minutes (target material PVC)

*2 Trade name for alumina-silicate refractory aggregate of English China Clays Ltd., St. Austell, Cornwall.

Table 19.3

Relative Sensitivity to Erosion of Various Metals

Material	Mean target weight loss *1 mg	Sensitivity relative to mild steel	Alloy hardness H_v
Mild steel	16.8	1.0	150
2.25 % Cr, 1 % Mo steel	10.2	0.61	170
Stainless steel, type 321	8.0	0.48	210
Stainless steel, type 310	6.5	0.39	220

*1 For 870 kg of particles and test duration of 20 hours. Estimated particle velocity 4 m/s. Material, unused silica sand.

1. To allow operation at conditions, and with designs, that otherwise would lead to unacceptable rates of metal wastage.

2. For retrofitting to reduce the rates of metal wastage to acceptable values with existing designs and operating conditions.

Information on remedial measures is given below separately for walls and tubes. A computer program is available as an aid in the economic assessment of suitable remedial measures (19.9, 19.10).

19.2.4.1 Walls

Three possible remedial methods have been tried to minimise or eliminate metal wastage on the walls; they are,

(a) The application of a hard weld overlay to the worst affected areas.

(b) The use of baffles or "shelves" to alter the solids flow pattern over the wall.

(c) Coating the walls with a refractory material.

Trials of method (a) showed it to be unsatisfactory and it is not recommended (19.1). Surfaces treated with a hard metal overlay were found to give rates of metal wastage similar to, or greater than, those of untreated surfaces. It is possible that the rough surface finish of the overlay allowed the erosion process to continue unabated.

Method (b) is recommended for use with plain water-cooled walls. A number of industrial units have been fitted with "shelf" baffles and have operated subsequently for up to 12 000 hours without further metal wastage occurring on the walls (19.1).

For the membrane wall type of construction it is more difficult to fit shelves than on plain walls because of the undulating profile of the membrane walls. In these circumstances the application of a castable refractory lining, method (c), may be considered easier. Such linings have been in use successfully on a number of industrial units for up to 14 500 hours of operation. The lining should cover completely the combustion chamber walls from the distributor level up to a level above the splash zone at MCR conditions.

The following guide lines are suggested for the installation of metal shelves on plain walls of fluidised bed combustors.

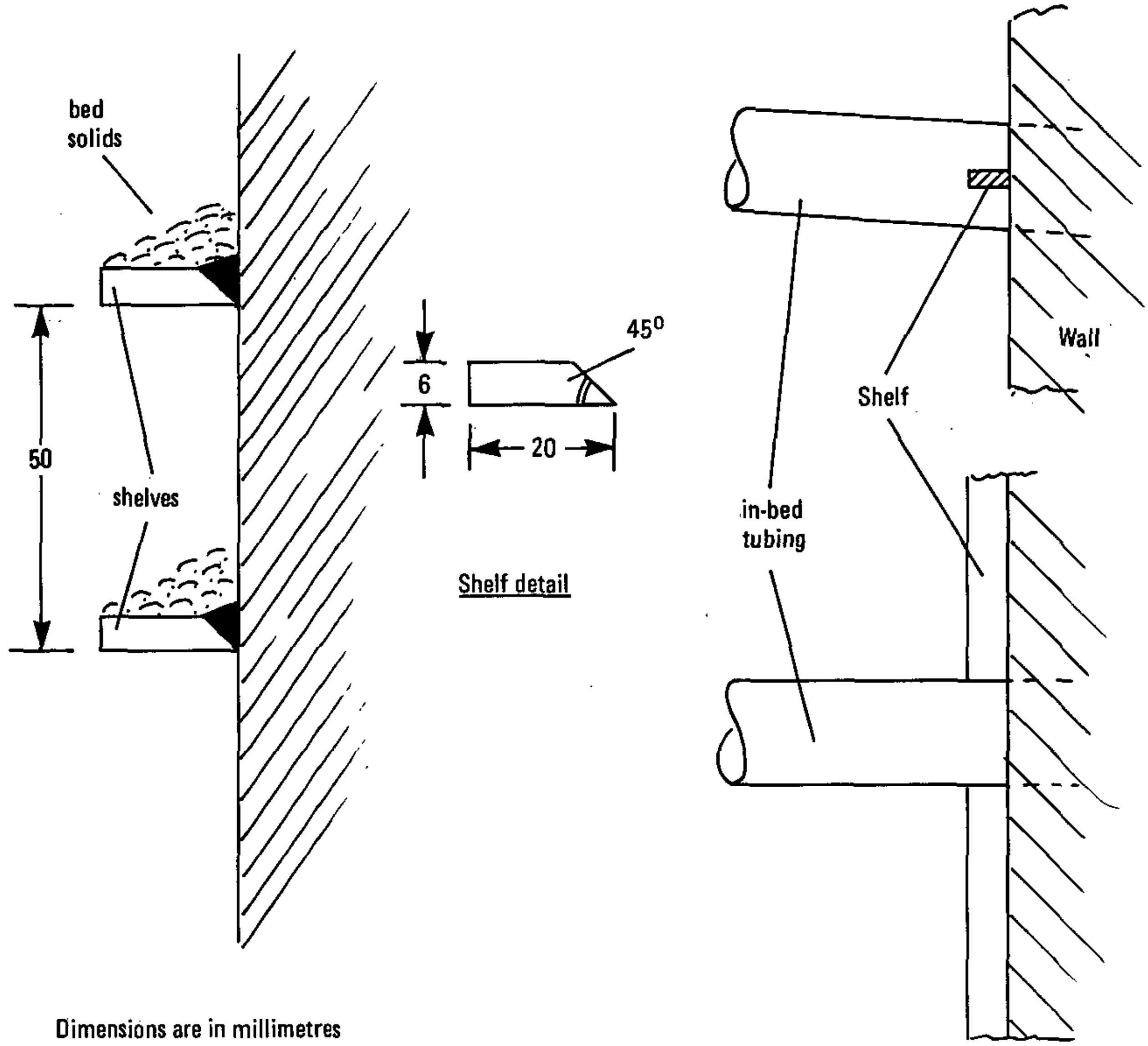
1. Shelves

(i) The shelves should be made from mild steel.
(ii) The shelves should be 20 mm wide and 6 mm thick.
(iii) Each shelf should be angled at 45° on the back edge to ensure a good weld contact.

Figure 19.4 shows a sketch of the suggested shelf design.

1a. Arrangement of Shelving

(i) The shelves should be as near to a 50 mm pitch as possible given the constraints imposed by the geometry of the in-bed tube bank.
(ii) One shelf should be at, or near, the static bed surface.
(iii) The shelving should cover a region extending from below the static bed level to above the expanded bed surface. To allow for the increasing magnitude of level fluctuations as beds become deeper it is suggested that the bottom shelf should be 50 mm (2 in.) below the static level in beds of less than 400 mm (16 in.) static depth or 100 mm (3.9 in.) below in beds with a static depth of 400 mm (16 in.) or greater. Also the top shelf should be located at a level at least twice that of the static bed surface. (Section 9 should be consulted for the estimation of bed expansion



Dimensions are in millimetres

Arrangement on plain walls

Arrangement with in-bed tubing

Figure 19.4
Details of Shelves

characteristics.)

(iv) Where shelves are on the centre line of a thermosyphon tube they should be attached to the thermosyphon tube. See Figure 19.4.

1b. Installation details

The shelves should be welded to all four walls of a rectangular or square section combustor, or they should be installed around the entire circumference of a circular section combustor.

Any stay bar ends should be ground flush with the walls before the shelves are installed.

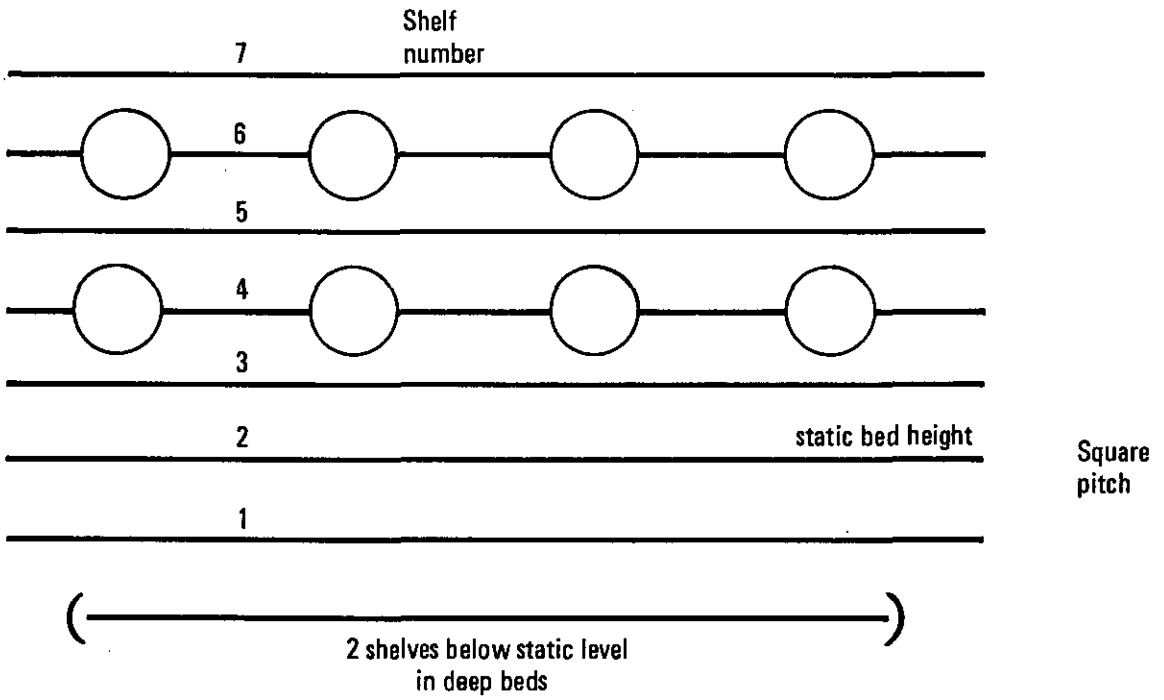
Figure 19.5 shows possible arrangements for shelves with tubing on both triangular and square pitch. For rectangular section combustors where shelves on adjacent walls do not meet at the front corners, appropriate overlaps should be employed. These overlaps should not be less than 100 mm in length.

For circular section combustors it is suggested that gaps should be left in each row of shelving to allow for expansion. It is important that these gaps should be staggered.

The weld between the shelf and the combustor wall should be of sufficiently high quality to ensure good heat transfer between shelf and wall.

2. Refractory coating

Two points require particular attention when a refractory lining is retrofitted as a remedial measure. Firstly, the refractory lining should be installed so as to increase the fluidising velocity as little as possible so that the rate of tube metal wastage is not unduly increased; see equations 19.2 and 19.3 for an estimate of the effect. The lining thickness



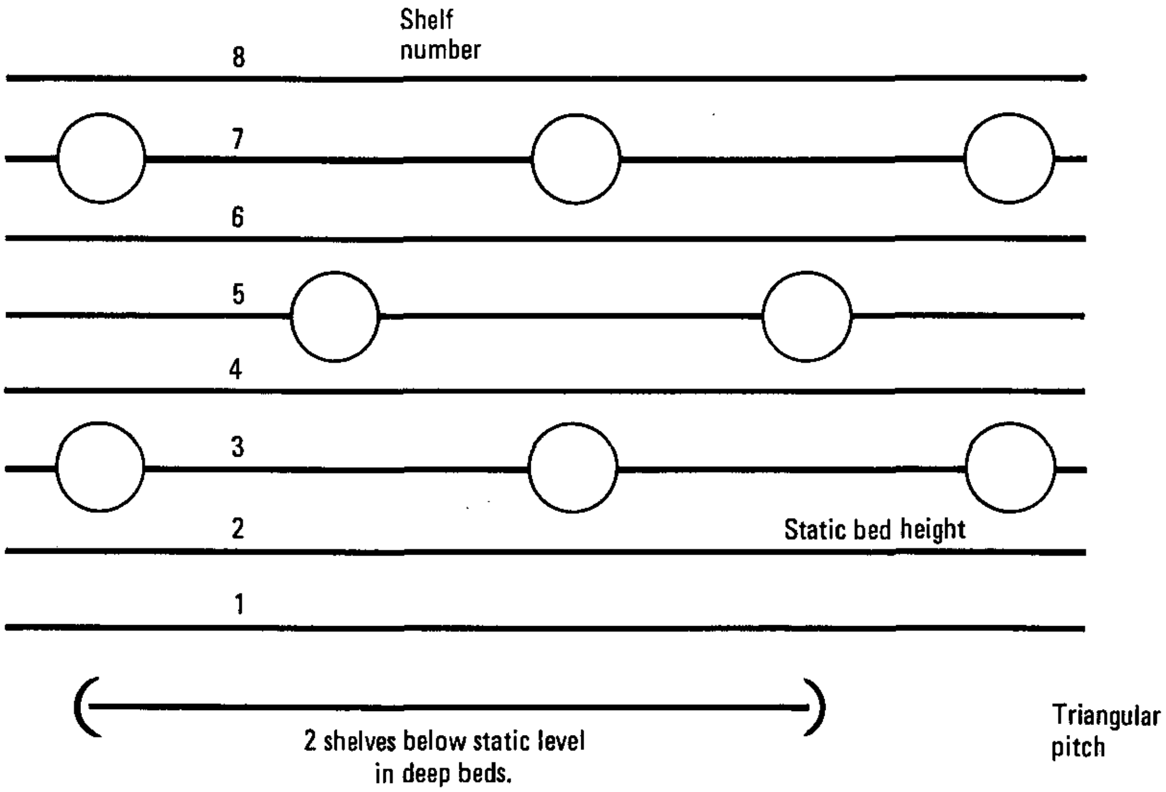


Figure 19.5
Details of Positioning of Shelves.

should, therefore, be kept to the minimum compatible with suitable mechanical strength. Secondly, the loss of heat transfer to the wall because of the lining will alter the bed heat balance. The changes that are likely to occur depend on the combustor size. Little noticeable change is likely for combustors with a heat release of 7.5 MW (25×10^6 Btu/h) and over. The loss of wall heat transfer in smaller combustors is most easily compensated for by small increases of bed depth (<20% of the original depth), provided the tube banks were not fully covered originally. Compensation can also be obtained by increasing the excess air level, but with the disadvantage of increasing the fluidising velocity, or by slight downrating of the combustor.

19.2.4.2 Tubes

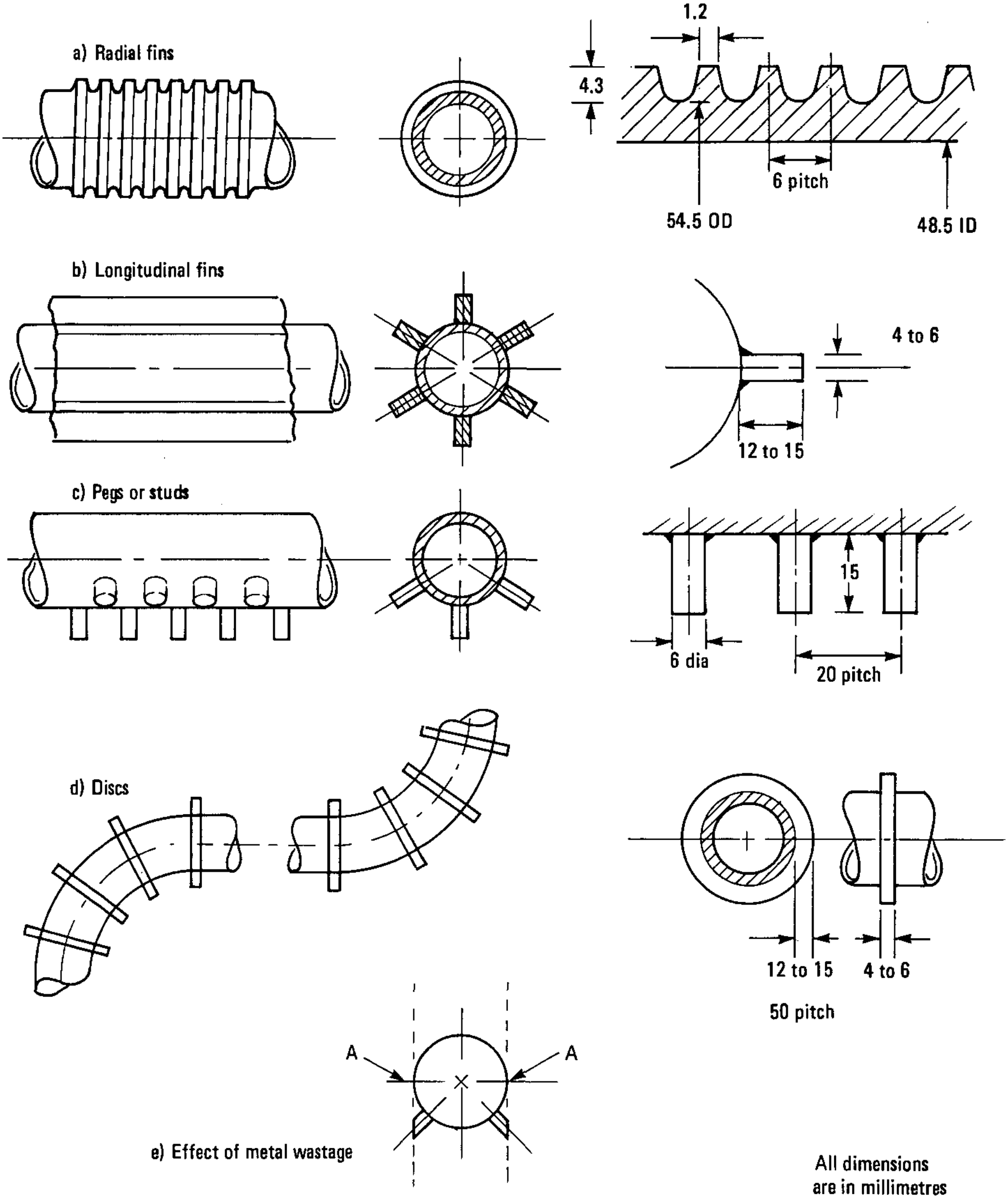
Two methods of protecting tube banks from metal wastage are currently undergoing trials; they are,

(a) to render the tube surface more wear resistant either through the use of coatings or of materials that have a better resistance.

(b) to attach flow spoiling devices to the tube surfaces to modify the bubble and solids flow patterns around the tubes without affecting the tube heat transfer characteristics.

The effectiveness of method (a) is being evaluated using tubes of various materials, tubes with metallic and ceramic coatings and tubes with a nitrided surface finish installed in various industrial units. No economic or effective coating or alternative material of construction can yet be firmly recommended although nitrided tubes have not shown any detectable wear after 1500 hours operation (19.8).

Limited reductions in metal wastage rates (by about 50%) have been obtained with method (b) using the arrangements shown diagrammatically in Figure 19.6. Straight sections of tubes have been finned (Figure 19.6(a)), or fitted with longitudinal fins (Figure 19.6(b)) or pegs (Figure 19.6(c)).



All dimensions
are in millimetres

Figure 19.6
Flow Spoiling Devices for the Reduction of Tube Metal Wastage.

Bends have been fitted with discs (Figure 19.6(d)). The dimension of the projecting portion of the devices was usually about 12-15 mm (0.5-0.6 in.). It is not yet clear which arrangement is the most effective. Reductions in wear rates by up to 50% have been obtained on different industrial installations using arrangements (a) and (b) of Figure 19.6.

The protection given by these flow spoiling devices is mostly sacrificial - the devices themselves wear in preference to the base tubing. In the case of the longitudinal finning (Figure 19.6(b)), it is noticeable, when the lower fins become so worn that the sides of the base tube can be "seen" by vertically rising bubbles, that wear then recommences on the tube sides as at A in Figure 19.6(e). If finned tubing like Figure 19.6(a) is used the fin profile and spacing should be such that bed particles cannot easily become lodged between the fins.

The heat transfer characteristics of the tubes fitted with any of the devices shown in Figure 19.6 do not seem to be impaired which is probably because the increased surface area that becomes available when the device is fitted compensates for any blanketting of the surface by static layers of bed particles on the tops of the tubes or baffles.

19.3 Design Recommendations

For operation at an economic fluidising velocity some metal wastage is probably unavoidable as a consequence of the process of fluidisation. Design and operating conditions should be chosen, therefore, to minimise metal wastage rates.

19.3.1 General operation

19.3.1.1 Fluidising velocity

The fluidising velocity is the single most important factor that influences both wall and tube wear. At relatively low velocities, less than 1.0 m/s (3.3 ft/s), the wear on both walls and tubes may occur at an acceptable level. With increasing fluidising velocities the wear rates increase rapidly. Wall wear increases with the 4.32 power of the velocity and tube wear is proportional to the square of the velocity.

For economic reasons operation may be required at higher fluidising velocities but it is recommended that the velocity should be kept below 2.2 m/s (7.2 ft/s) and preferably below 2.0 m/s (6.6 ft/s) to avoid excessive wear.

It is further recommended that non-uniform air flows in the combustor should be avoided. Preferential air flows can be caused by:

(i) poor plenum design
(ii) use of air distributors with too low a pressure drop
(iii) damaged standpipes
(iv) accumulations of oversize ash or sintered material in parts of the bed.

19.3.1.2 Static bed depth

Use a static bed depth as low as possible consistent with the type and quality of fuel to be used and any requirement for sulphur retention.

It appears that the effect of bed depth on wall wear is to move the band of metal wastage higher up the walls with increasing bed depth.

Tube wear is increased as the bed depth increases. The extent of the increase has been correlated by equation 19.3 and confirmed in cold model studies (19.4). If a bed deeper than 200 mm (7.9 in.) is needed it is recommended that all tube bank design parameters be chosen to minimise metal wastage.

19.3.1.3 Solids feeding

If coal particles are fed by gravity to the bed surface the feed tubes should be sited so that falling coal particles cannot impinge directly on any in-bed tubing. Particles falling through even relatively small distances have been shown to result in mechanical damage and wear on the top tubes.

For similar reasons, bed solids recycle or feed lines should not be so designed that they discharge solids directly onto in-bed tubing.

19.3.1.4 Air nozzle location

It is recommended that no air distribution nozzle should be sited closer than 50 mm (2 in.) to the wall to avoid wall wear. If a closer location is necessary then the nozzle holes facing the wall should be blanked off. See also Section 15.1.1.2.

19.3.2 Combustor wall design

The rate of metal wastage is normally acceptable on the combustor walls at fluidising velocities below 1 m/s (3.3 ft/s) but is markedly increased by increasing fluidising velocity in the range 1 - 3 m/s (3.3 - 9.8 ft/s); see Figure 19.1. Wear rates are not reduced by the use of hard weld overlay.

For plain walls it is recommended that mild steel "shelf" baffles should be fitted both on new equipment and as a remedial measure. Details of suitable shelving are given in section 19.2.4.1 and Figures 19.4 and 19.5. The shelves recommended are 20 mm (0.79 in.) wide, 6 mm (0.24 in.) thick welded to the walls on a 50 mm (2 in.) pitch. One shelf should be at, or near, the static bed level and the region from 50-100 mm (2-3.9 in.) (according to static bed depth) below, up to twice the static bed height, should be covered.

For membrane walls the installation of shelving may be too difficult or uneconomic because of the undulating wall profile. In that event it is recommended that the walls should be coated with a castable refractory lining both on new equipment and as a remedial measure. The combustion chamber should be lined from the distributor level up to a level above the splash zone. The height of the splash zone may be taken as 1.5 times the expanded bed height. The expanded bed height depends on the bed expansion ratio; see Figure 9.2 of section 9, issue 002.

When a refractory lining is installed as a remedial measure the thickness of the lining should be the minimum necessary to give the required mechanical strength so that the fluidising velocity is not unduly increased as a consequence of the reduction of bed cross-sectional area caused by installing the lining. The loss of heat transfer to the walls will alter the heat balance; the changes that are likely to occur depend on the combustor size. Little noticeable change is likely for combustors with a heat release of 7.5 MW (25×16^6 Btu/h) and over. For details of the effects, and methods of compensation for them, in smaller combustors see section 19.2.4.1 and reference (19.1).

It is recommended that the fluidising velocity for boiler applications be kept to below 2.2 m/s (7.2 ft/s) and the static bed depth be kept as shallow as possible consistent with the needs for satisfactory combustion for the type of fuel in use and any sulphur retention requirements. These recommendations will help to minimise tube wear. For hot gas generator applications, i.e. refractory lined combustors with no in-bed tubing, the fluidising velocity may exceed 2.2 m/s (7.2 ft/s).

19.3.3 In-bed tubing design

The rate of tube wear is generally acceptable if the fluidising velocity can be kept below 1 m/s (3.3 ft/s). Operation at higher loads, typically 2.2 m/s (7.2 ft/s) fluidising velocity, can result in severe tube wear; see section 19.2.3.3.

19.3.3.1 New equipment

It is recommended that the tube banks of new equipment should incorporate the following features to reduce metal wastage.

1. The tube diameter should be small; 50 mm (2 in.) OD tubes are recommended.

2. The tubes should be arranged on a square pitch in preference to a triangular pitch.

3. Where triangular pitch or cross-over arrangements are used some protection (in the form of studs or discs; see Figure 19.6) on the underside of the upper tubes may be required.

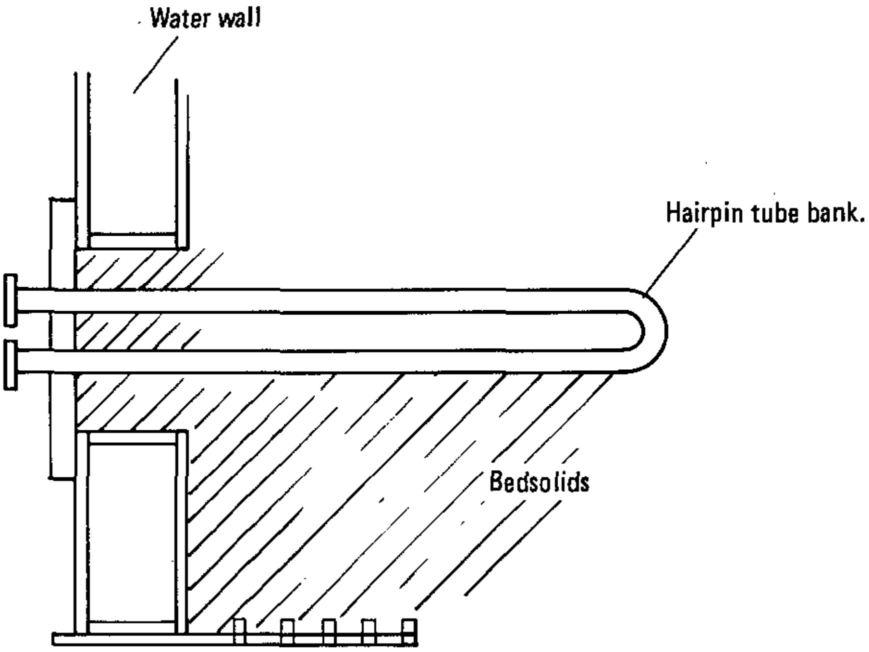
4. The tubes should be horizontal if at all possible. If not possible the tube inclination should not exceed 5°.

5. Tube banks are prone to wear at the weld with the wall where the tubes enter the combustion chamber. The design shown at Figure 19.7(a) where the entire tube bank passes through the combustor side and the gap at the wall becomes filled with static bed solids is strongly recommended as the only design where tube weld wear can be definitely avoided.

6. The use of extra heavy duty tubing with wall thicknesses in the range 8 - 10 mm (0.3 - 0.4 in.) should be considered for prolonging tube life.

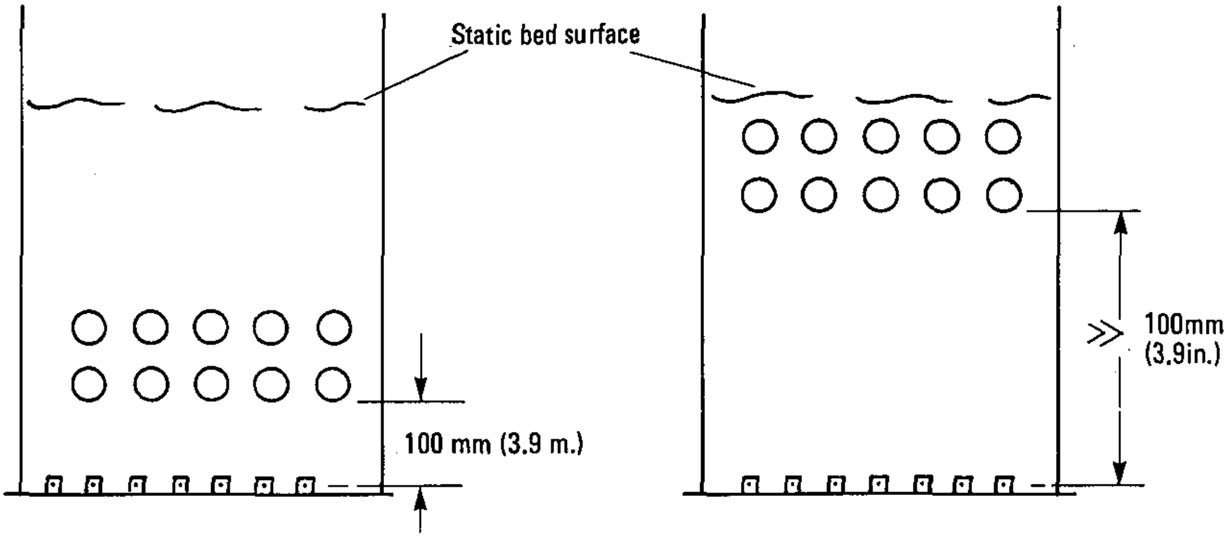
The tube bank should be designed for operation at a fluidising velocity below 2.2 m/s (7.2 ft/s) and preferably below 2 m/s (6.6 ft/s).

The design static bed depth should be as low as possible consistent with the type and quality of fuel to be used and any requirement for sulphur retention. There is evidence suggesting that wear rates are



(a)

Recommended tube entry design



Recommended

(b)

Not recommended

(c)

Tube bank location
in deep beds

Figure 19.7
Tube Bank Design Features.

increased on tubes located in the region between the static and expanded bed levels. Location of tubes in this region is unavoidable when the bed expansion method is used for turndown. If other methods of turndown are used then it is recommended that the location of tubes in that region be avoided. If the beds are comparatively deep it is better to locate tubes low down, as shown in Figure 19.7(b), rather than as shown in Figure 19.7(c).

19.3.3.2 Remedial measures

1. In designs where the tubes pass through a shell wall localised wear may occur at the wall weld. The use of fins on the tubes to protect this region is currently being evaluated at CRE but no firm recommendation can yet be made.

2. Bends susceptible to wear can be encased in refractory. Use of this measure should not be allowed to increase gas velocities significantly in other parts of the boiler.

3. The life of tubing has been extended by up to 50% through the installation of radial or longitudinal fins. See Figure 19.6.

4. The use of a nitriding treatment of the surface of affected tubes appears promising as a protective measure. However, longer term testing is needed before this measure can be fully recommended.

5. If the wear is sufficiently severe that retubing is required the replacement tube bank design should conform as far as possible with the recommendations for new equipment outlined above.

6. By far the most effective remedial measure is to lower the fluidising velocity provided the resulting reduced boiler output is acceptable.

19.4 Erosion on Associated Equipment

Instances of metal wastage have been recorded from equipment associated with the fluidised bed combustor.

19.4.1 Air nozzles

In one design of air nozzle the holes are tapered, the larger diameter being at the nozzle outer surface. Metal wastage was found to occur on the lower row of air holes; the resultant hole enlargement decreased the distributor pressure drop and caused uneven air distribution.

Cold model studies (19.11) showed that flow fluctuations associated with bubble formation allowed bed material to enter the lower holes periodically and cause erosive wear. Designs where the holes are parallel-sided did not show this phenomenon and are recommended as they gave negligible rates of metal wastage.

19.4.2 Smoke tube erosion

A programme of monitoring wear in a range of fixed bed and fluidised bed boilers is being carried out by CRE. In addition, testwork has been carried out at a selected site to measure solids loadings, temperatures and pressure drops through the smoke tubes.

It has been found that the erosion rates in the smoke tubes are proportional to the velocity of particle impact to a power greater than 2.0. Operation at gas velocities less than 22 m/s (72 ft/s) is, therefore, preferred but it is recognised that this is probably uneconomic as current design gas velocities range up to 36 m/s (120 ft/s). Similarly, it is also recommended that any boiler operating time at rates above MCR should be kept to a minimum to increase tube life.

The solids content of the gases should be kept as low as possible to minimise erosion. The implication of this finding for fluidised bed combustion is that an adequate freeboard height should be provided. See Section 9.5.1.

Ferrules for the protection of tubes at risk in 2nd and 3rd passes are recommended. Research into the most appropriate ferrule design is continuing. Work on the modelling of the aerodynamics of the combustion system is also in progress as designs in which the gas flow path is straightened before entry to the smoke tubes could assist in reducing erosion.

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