Technical Note

Aspects of lead/acid battery technology
2. Tubular positive plates

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Abstract

Various types and shapes of tubes are described. Suggested design parameters — specific formed material weight (g A^{-1} h^{-1}) and apparent formed material density (g cm^{-3}) — are given for long cycle life traction cell positives. The effect of deviations from a circular tube cross section are examined and how the tube material content and plate pitch are changed. It is shown how, in an optimized design using circular cross-section tubes, there is a clear relationship between pitch and tube diameter. Dry-powder filling methods are described together with the filling effectiveness of various powder blends and the bearing the filling method has on the reproducibility of density control. Reference is made to the importance of a firm operator discipline to ensure the health control equipment will maintain full effectiveness.

Background

The essential difference between a lattice-grid plate and a tubular positive plate is the provision in the latter of the active material in discrete pencils enclosed within cylindrical retainer tubes; a number of such tubes are connected in parallel, via a common top bar, to form a plate. The surrounding retainer tube can be either a single woven or nonwoven tube (in some circumstances supported by an outer perforated plastic tube) or a multiple tube arrangement with the individual tubes linked one to the other. The former are usually referred to as single tubes and the latter as multitubes or anode bags. Both designs perform satisfactorily in traction battery applications.

The single tube is made either as a woven tube (produced on high-speed knitting machines) or laid around mandrels using nonwoven fibre techniques. The woven tubes are fabricated from either glass or plastic filaments; the glass-woven variety is more common. Subsequently, the tubes are impregnated with starch or synthetic resins to provide the necessary rigidity for the powder filling operation.

The choice of the type of glass filament is important since a number of glass formulations denature in the presence of sulfuric acid and lead dioxide whilst others do not possess the necessary tensile strength to withstand the knitting operation. Various artifices have been adopted to impart to the glass tube the necessary strength and rigidity. The most common has been the addition of an outer perforated tube of

rigid poly(vinyl chloride) (PVC), although an admixture of polyester and glass filaments has been found to give an adequate strength for most battery applications. Less attractive are the use of polypropylene filaments or the enclosing of one glass tube in another outer glass tube with the inner tube finely woven to retain the active material and with the outer tube of a coarse weave.

The multitubes have been manufactured successfully from woven Terylene® and polyester yarns. The criticism made with regards to single tubes has usually centred around the difficulty of handling a large number of individual tubes compared with a considerably less number of multitubes. The composite type with an outer PVC tube enclosing the woven glass tube tends to be more expensive and poses an increased chlorine hazard during battery operation in terms of possible attack of the PVC by sulfuric acid. Despite these reservations, the composite tube has been very successful and has established a good life expectancy under onerous working conditions when used in conjunction with an effective microporous separator.

It is difficult to be critical of individual designs of tube (other than, perhaps, those woven from polypropylene yarn) on the basis of the nature of the weave or the material used. The latter are not the sole factors to be considered in any tube assessment. There seems reasonable agreement that polyolefin filaments are not as stable as glass, Terylene® or even polyesters in the presence of dilute sulfuric acid and lead dioxide. The degeneration in the burst strength is more rapid and splitting of the woven tube has not been uncommon. This does not mean that the other tubes are totally resilient. All tubes tend to split after periods of very heavy usage if the control of the filling powder densities is poor and there is a significant proportion of the filled densities at the upper tolerance level. Where woven glass filament tubes are used without an outer stiffening tube, it is unwise to exceed a filling density of 4.2 g cm^{-3}.

In the assembly process for single tubes, an individual tube is passed over each of the spines that comprise the conducting framework of a tubular plate. In the subsequent powder filling process, distortion can occur unless the tube/grid assembly is supported effectively. Without the latter, the spines can bow to such an extent that the spine metal is eccentric within the tube and, in service, stimulates localized corrosion and early failure.

The assembly of tubes on to the spines tends to be a slower operation than inserting a complete grid into a multitube design. Furthermore, the physical bond between the individual tubes of the multitube tends to impart a greater rigidity to the combination of tubes and spines during the filling operation; the lateral movement leading to the bowing of the spines is virtually impossible. For this reason, many manufacturers of traction batteries prefer to use the multitube system.

In the early days of multitubes, horizontally woven cloth in yarn of the copolymer of vinyl chloride and vinyl acetate was used. Two layers of the cloth were passed on either side of a row of cylindrical formers and the seam between adjacent formers was heat welded. Unfortunately, in the presence of sulfuric acid and lead dioxide, vinyl acetate degenerated to release acetic acid that, in turn, promoted spine corrosion and early battery failure. The heat sealing had to be accurately controlled and dimensioned. If the sealing pressure was too light, the seam was weak and soon came apart in service. Alternatively if the sealing pressure was too heavy, the sealed edges of the tubes were good but the actual seam was thin and soon came apart in service. Whilst this did not cause serious trouble in service, there was the tendency for the seam to part during the filling operation and the centre of the plate to bow. The latter created problems in the subsequent cell-assembly process, e.g., sometimes there was difficulty in inserting the plate into the cell container due to the oversize dimension.

Various artifices were introduced to replace the heat sealing. One involved the use of a composite weaving technique in which the tubes were woven in one operation with the filaments crossing over between tubes to form an integral seam.

Modern multitubes tend to revert to heat sealing or stitching using polyester filaments woven into cloths or nonwoven polyester cloths. The attraction of the nonwoven cloths lies in the lower basic material cost through the elimination of the weaving process. To attain the same order of burst strength, however, it is usual for the nonwoven tube to be thicker than its woven counterpart. This reduces both the working volume of electrolyte (due to the greater volume displacement of the nonwoven tube) and, usually, the volume of active material within the tube. The latter reduces marginally the capacity of the cell design.

Excellent plates can be made with either individual tubes or multitubes provided the yarn used in the making of the tubes is one which does not readily denature in service. Both specially formulated glass and polyester filaments meet this proviso.

Tube profiles

By far the majority of tube designs are based on circular sections with the tube diameters being varied to suit the plate pitch and the coefficient of utilization of the active material, i.e., the specific formed material weight. The design parameters common in the industry for positive active materials (formed) are: specific formed material weight 13.5 to 14.5 g A^{-1} h^{-1}, and apparent density of formed material 3.6 to 4.0 g cm^{-3}. These values assume that there is sufficient electrolyte to support the rated capacity requirement.

Consider the case of a plate rated at 63 A h ($C/5$) with a spine diameter of 3 mm (equivalent to 2000+ life cycles) and a total tube length per plate of 5.8 m, excluding the spine boss and the base plug intrusion.

If d (cm) is the internal tube diameter, than the cross-sectional area (A) of the active material will be the difference between the internal cross-sectional area of the tube and that of the spine metal, i.e.,

$$\text{material cross-sectional area, } A = \frac{\pi}{4} (d^2 - 0.3^2) \text{ cm}^2 \tag{1}$$

Thus, the volume of active material is 580 A cm^3, where 580 cm is the total length of the pencils of lead dioxide per plate.

For a lower specific formed material weight of 13.5 g A^{-1} h^{-1}, a density of 3.8 g cm^{-3} for the particular active material, and a rated capacity of 63 A h:

$$\text{weight formed active material} = 13.5 \times 63 = 830.5 \text{ g} \tag{2}$$

$$\text{volume formed material} = 830.5 \times \frac{1}{3.8} = 218.6 \text{ cm}^3 \tag{3}$$

it follows that:

$$580 \times \frac{\pi}{4} \times (d^2 - 0.3^2) = 218.6$$

and this gives a value for the tube internal diameter of 0.75 cm. In other words, a tube of 0.75 cm internal diameter would be required to satisfy the stated design requirements, i.e., a plate containing 5.8 m of active material pencils with spine diameters

of 0.3 cm for current collection using an active material density of 3.8 g cm^{-3} and fulfilling the criterion of formed material utilization of 13.5 g A^{-1} h^{-1} and a plate capacity of 63 A h.

This design approach assumes that there are tube-making facilities available in which the tube diameter can be varied to optimize plate performance. Such a facility can exist where there is an on-site tube production or where the supplier can readily vary the diameter parameter. This is not often the case and reliance has to be placed on suppliers where the standard diameter is that of the largest demand. This can be slightly different to the optimum figure and can cause the total length of the pencils of active material to fall away from the optimum value.

Take, for example, the case where the standard tube from an outside supplier has a diameter of 0.8 cm instead of the desired 0.75 cm. Assume the spine diameter remains at 0.3 cm. The required volume of active material remains at 218.6 cm^3, as derived from material density, specific formed material weight and plate rated capacity. From a consideration of the tube dimensions:

$$\text{volume of formed material} = \frac{\pi}{4} \times (0.8^2 - 0.3^2) \times L \text{ cm}^3 \tag{4}$$

where L(cm) is the total active material length. This gives a new total active material length of 506 cm (instead of 580 cm) with the assumption that in the cell assembly there is no reduction in the electrolyte volume in moving away from the 0.75 cm to the 0.8 cm tube, i.e., the pitch of the plates is increased.

This simple relationship between tube diameter and material pencil length holds good only whilst the formed active material density remains within a comparatively narrow range from ~3.6 to 4.2 g cm^{-3}. Where, either by design or accident of design, the active material density is greater than 4.2 g cm^{-3}, there is always the danger of incomplete penetration of the mass of the material by the electrolyte, particularly in the early part of the battery life, and the specific formed material weight criteria no longer applies.

Mention has been made of the need to maintain the electrolyte volume to ensure the material provided can be utilized to deliver the capacity. In those cases where only standard diameter tubes are available, as opposed to those of optimum diameter, a shorter plate has to be adopted and there is no freedom to increase the plate pitch to obtain the requisite volume of electrolyte. This, in turn allows no alternative other than to increase the head of electrolyte over the element. It is normal to omit the volume of electrolyte under the element in deriving the specific electrolyte volume for a particular cell design since this bottom electrolyte contributes little to creating the capacity. Using the specific electrolyte volume parameter in both examples with 7.5 and 8 mm tubes, the excess height requirement for the latter can be calculated.

At first sight, there appears to be virtue in the designer aiming to use the largest diameter tube possible. The plate pitch, however, puts a restraint on how large that diameter can be, since space has to be left between the adjacent positive and negative plates to accommodate a separator of adequate back-web thickness to guarantee the order of expected life the market requires. In examining what this means, it has to be appreciated that the larger the tube diameter employed, the greater will be the thickness of matching negative plates and the smaller will be the reservoir between the plates for electrolyte where the latter is the most effective.

Some stationary cells with tubular positive plates do use tubes with diameters as high as 10.5 mm, instead of the traction tube diameters of 7.5 to 8 mm. In such

stationary cells, the plate pitch is increased beyond the traction range of 15.6 to 19 mm to ensure that the electrolyte balance is maintained.

Rectangular and elliptical tubes

Circular tubes provide the maximum cross-sectional area for a particular tube perimeter. They also provide the greatest support, or restraint, on the active material with little tendency for distortion. There is an increasing difficulty in filling tubes with powder as the diameter is reduced below ~7.5 mm. This creates voids within the bulk of the powder as well as varying filling weights. Tubes with a diameter of 6 mm can be filled with a reasonable consistency provided small numbers of tubes are processed simultaneously and a continuous weight monitoring system is applied conscientiously. These requirements tend to slow down filling and increase the production costs for smaller diameter tubes compared with those of 7.5 mm diameter and upwards. Whilst it is advantageous to have the filling powder thoroughly dry and free from aggregates, it does not cause too much trouble if some moisture is present or if there is some aggregation in the case of the tubes of diameter 7.5 mm and upwards, but is can be disastrous in tubes of smaller diameter.

Where the tubular positive plates are required to exhibit good voltage performances at relatively high-discharge rates (e.g., 15 to 30 min rate) smaller diameter tubes than the traction standards of 7.5 to 8.0 mm are necessary, as long as it is necessary for the tube to be circular. Some designers have adopted a distorted circular tube, ranging from roughly elliptical to roughly rectangular, to avoid the production difficulties and high costs of the small diameter tubes. By distorting a standard circular tube in this manner, a thinner plate is formed with less filling problems and retaining the tubular feature. Much depends on how thin the plate has to be to provide the necessary high-rate voltage performance and this, to a great extent, dictates the degree of distortion to which a standard diameter tube has to be subjected.

To illustrate the effect of distorting a standard tube, consider one of 8 mm internal diameter used in conjunction with a spine of 3 mm diameter. Although the tubes after distortion are described as roughly elliptical or rectangular, in practice it is difficult to pass the initially circular tubes over elliptical formers and distort them by the application of heat and afterwards to retain the elliptical shape. It is easier to produce and retain a shape nearer to two semicircular ends joined by parallel sides. Figure 1 shows the variations possible within the limitations of a plate 135 mm wide (suitable for a cell of 160 mm width), and the influence the degree of distortion has on the number of tubes per plate and the effective plate thickness. In arriving at these configurations, allowance has been made for the inevitable space between adjacent tubes that is demanded by the tube-making process.

The deformation from circular shape is accompanied by a reduction in the cross-sectional area and the number of tubes forming a plate. Table 1 summarizes the dimensions of the tubes so formed and, after allowing for a spine cross-sectional area equivalent to that of a 3 mm diameter circular section, the percentage of active material contained in a plate compared to that of a plate with circular tubes.

The substitution of an elliptical or rectangular tube for a circular one, whilst reducing the effective plate thickness, also reduces the plate capacity. There is usually a cost increase per effective ampere-hour of capacity as the labour element in the plate-making cost remains substantially constant, irrespective of the plate configuration. In the case of a 12-tube plate corresponding in width to that of a 15-circular tube
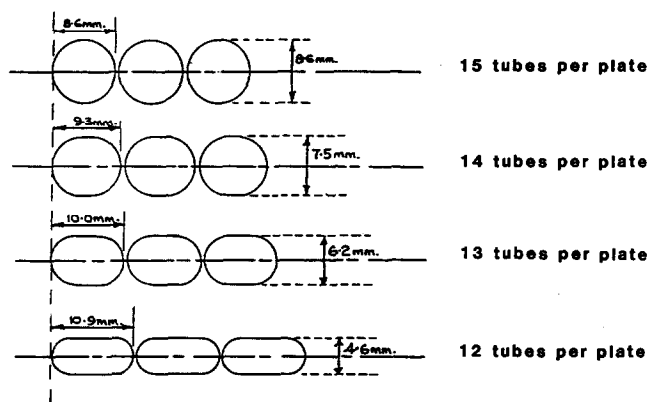
Fig. 1. Variations in the shape and number of tubes arising from distorting a standard tube of 8 mm internal diameter for use in a plate of 135 mm width.

TABLE 1

Tubular plate design

No. tubes per 135 mm wide plate	Tube dimensions (mm)		Cross-sectional area of active material (cm^2)	Percentage active material per plate
	Length	Width		
15	8.6	8.6	0.43	100
14	9.3	7.5	0.42	91
13	10.0	6.2	0.39	79
12	10.9	4.6	0.31	58

plate, the thickness is reduced to ~54% and the active material content to ~58% of the circular tube plate. Provided the negative grid design permits a similar reduction in the plate thickness, it is possible to obtain an equivalent capacity per unit cell volume with an appreciable increase in the high-rate voltage performances. This is because a 12-tube plate matched to a negative plate 2.5 mm thick will give a working pitch of 10 mm compared with the commercial pitches of 15.6 to 18 mm of circular tube plates.

As the number of tubes per plate is reduced, it becomes more unrealistic to try and retain a circular section spine. For example, in the 12-tube plate, the clearance between a circular spine of 3 mm diameter and the parallel sides of the distorted tube would only be 1.6 mm if the spine was accurately located in the tube. In practice, this rarely occurs and the danger exists that the spine surface is very near the outer periphery of the pencil of active material on one side and this promotes the possibility of increased spine corrosion. It has been suggested that a spine in the form of two small diameter wires spaced approximately on the middle thirds of the major axis and held parallel by short tie sections will provide better conductivity than a single spine. Such spines tend to be more difficult to cast free-of-surface defects than a single spine. In addition, the greater surface area exposed to the active material and the electrolyte favours increased oxidation corrosion. In most applications, it is preferable to adopt a single spine with its profile cross section reflecting to a limited extent that

of the surrounding active material. Such a spine casts more readily with a good surface finish and has a long corrosion life under regular deep-discharge conditions.

The examples of noncircular tubes discussed above presuppose the deliberate distortion of standard diameter tubes. In some applications where previously the flat plate cell design has had a monopoly, some manufacturers have found it advantageous to adopt other tube sizes to optimize the plate performance. In one application for diesel-engine starting, a plate comprising an assembly of 6 mm diameter tubes has been used as well as a competing design with positive plates with 11 elliptical tubes. Larger diameter tubes have been adopted for stationary cells.

A criticism raised against the use of elliptical tubes has been their propensity to return to their original circular shape wherever there is dimensional freedom within the cell element assembly. With well-controlled components held to reasonable dimensional tolerances in manufacture and with the cell elements shimmed to take up the negative tolerances, the degree of freedom within the cell container is very limited and only a small movement away from the original shape is possible. This movement towards the circular shape is accompanied by a small increase in cross section. This results in a small decrease in the positive material density and an improvement in the capacity. Such a shape change, far from being an adversity, can conceivably be an advantage in the long run.

Filling powders

Three basic filling methods are in common use: (i) dry powder; (ii) pelletized powder, and (iii) extruded paste. Of these, dry-powder filling is the most widely used. The pelletized powder is derived from dry powder filling; the initial dry powder is subjected to a degree of sulfation and controlled drying to produce a standardized free-flowing material not unduly affected by climatic conditions. This pelletizing process can have a beneficial effect later by simplifying the formation process which is often carried out in the cell container.

The idea of extruding a mainly grey oxide paste into the tubes has been viewed as an ideal method as the environmental hazards arising from the escape of dry powder into the operator's breathing zone are eliminated. The main difficulty with the use of prepared pastes has been the difficulty of equating good extrusion qualities with a relatively high paste density so that, in the setting process, the cured paste density is sufficiently high to preserve the density and integrity of the formed material throughout the full-guaranteed life of the battery. Too often, in order to obtain good extrusion characteristics, the water additions to the paste are relatively large and the subsequent material density is below the safe minimum for long cyclic life. The addition of small amounts of a thixotropic material to the paste can ease extrusion and allow the wet-paste density to be adjusted to a sufficiently high value to produce formed densities of the order of 3.6 to 3.8 g cm^{-3}.

Two basic filling techniques with wet paste have been developed. In one, the tubes are filled with the paste and the spines introduced into the wet paste afterwards. In the alternative method, extrusion nozzles are passed into the assembly of tubes and are withdrawn steadily as the tubes are filled. Synchronized with the withdrawing nozzles is the entry of the spines into the individual tubes so that the paste is extruded around the tip of the advancing spine. Irrespective of the method used, the technique calls for specialized equipment. Full consideration of the economic situation involved

is recommended as there are some doubts as to whether the problems introduced may not be as troublesome as those of dealing with the environmental hazards.

There is a wide variation in the filling powders. Some idea of the extent of the variation can be obtained from the following list:

(i) battery-grade red lead (usually 26 to 32 wt.% PbO);

(ii) blends of red lead and ball-mill oxides;

(iii) blends of red lead, litharge and ball-mill oxides;

(iv) dried and pulverized sulfated pastes based on (i) and (ii);

(v) ball-mill oxide;

(vi) Barton-pot oxide;

(vii) dried and pulverized sulfated pastes based on (v) and (vi), and

(viii) as (vii) but with the addition of red lead.

With such an assortment of filling powders, one instinctively feels that there must be some basic parameters governing the choice of the most suitable powder for any particular factory, although the list would make it seem that any type of powder can be used without too much difficulty. Before a choice is made it is as well to consider the filling system. Two main systems are in use. They can best be described as (i) vibratory and (ii) tamping.

(i) The vibratory system depends on the use of a halfwave rectified a.c. supply to an electromagnetic field that lifts a heavy table against the constraint of springs so that, when the impulse is removed, the table is rapidly pulled back to its original position against a bottom stop. The reversal of direction at each halfwave impulse, together with the effect of the spring system, produces acceleration forces within the mass of the active material causing the powder to shake down into the tube. These acceleration forces can be modified by altering the stiffness of the springs and by altering the loading of the table. Most of the commercially-available vibrators used for tube filling were originally developed for the consolidation of concrete in the casting of shaped blocks or slabs. These vibrators have only one frequency i.e., that of the mains supply, either 50 or 60 Hz according to the country in which the equipment is operated. This restriction means that the choice of powder is dictated by the filling equipment, i.e., the powder that flows most readily under the conditions set up by the acceleration forces in the equipment. This limits the choice and the final filling density range. For all powders and blends, there is an optimum frequency that gives the widest range of density control and flow consistency. In most cases, this does not agree with the frequency of commercially-available vibrators. For example, a standard red lead supplied for tubular-plate filling behaves more consistently and over a much wider range of filling densities with input supply frequencies in the range of 3 to 10 Hz using a halfwave rectified voltage to the electromagnetic system.

(ii) The tamping system employs equipment originally designed for the consolidation of sand in moulds for metal casting. Most of the equipment uses compressed air to lift a heavy metal table followed by a free fall when the air supply is cut off. The lift imparts potential energy to the table, and the assembly of tubes clamped to the table, so that when the table comes to an abrupt stop at the bottom register the powder accelerates downward into the tube. The supply of air and the cutting-off when the table reaches its top position is regulated by the motion of the table and is continuous. The frequency of operation is generally slower than the vibrator units and the optimum for consistency of filling. The slow frequency tends to allow time for the powder at the bottom of the tubes, as they are assembled on the table, to consolidate more than that at the top of the tubes. This difference between the top and bottom of the tube material is affected by the flow properties of the powder.

The more freely the flow, the less is the density differential. This tends to place considerable importance on the types of oxide, whether made by a ball mill or in a Barton pot.

Ball-mill oxides, formed by the rubbing action of pure lead nuggets tumbled in an oxidizing atmosphere, are produced in the form of platelets of sizes varying from 10 to 20 μm down to submicron size. The surfaces tend to be rough and jagged at the edges and this inhibits free flow. This can be demonstrated by reference to the angle of repose resulting from a relatively energy-free fall. Angles of repose of up to 60° are not uncommon. Because of this physical shape, it is not easy to compact the powder sufficiently so that an acceptable formed density can later be obtained. This does not mean that ball-mill oxides cannot be made to flow sufficiently to produce better than minimum filling weights, but rather that they are not very acceptable to proprietary vibrators or tamping equipment. If, when using tamping equipment, the frequency can be varied over a relatively wide range, it can be shown that, for a fixed amplitude of upward movement, the curve of filling weight versus frequency is approximately Gaussian with a relatively broad base but a distinct peak. If the frequency is set to that giving the peak-filling weight and the amplitude varied, the resulting curve is again roughly Gaussian. From such experiments, an optimum frequency and amplitude can be derived that will give maximum filling weights. The latter have been shown to exceed those generally required to produce formed densities within the range 3.6–4.0 g cm^{-3}. The fine control to bring the filling weights within the design range is usually an increase or decrease in the frequency.

The ability to control the filling equipment frequency calls for specialized equipment made to the customer's specification at higher costs than the proprietary equipment. Nevertheless, the greater control possible probably more than compensates for the cost difference. Many manufacturers adopt the principle that it is possible to modify the flow properties of the filling powders to the commercially-available vibrators or tampers and still not deviate too far from the optimum conditions for filling.

Barton-pot oxides are approximately spherical in form due to the method of manufacturer where molten lead is poured into a reaction chamber and is broken up into minute droplets by the impact of a slowly moving paddle with the stream of molten lead. These droplets are then oxidized. The oxides flow relatively well since the angle of repose is very much less than comparable ball-mill oxides.

Filling powders consisting mainly of the ball-mill or Barton-pot oxides tend to develop capacity slowly and, in order to build up the capacity to the rated value within the first few cycles, it is necessary to obtain an initial capacity as close as possible to the rated value. One method of achieving this is to insert in the formation regime a number of deep discharges, preferably at a low rate. The effect of these deep discharges is to produce an increased volume of lead sulfate with an increase in the material volume beyond that normally accepted in service. The increased volume physically spaces the particles of material farther apart than before the deep discharge so that on the recharge, when the lead sulfate particles are converted into dense lead or lead dioxide, the spaces between the particles are larger than before and more open to irrigation by the electrolyte.

The incorporation of a number of 'opening-up' discharges in the formation regime greatly extends the time taken for formation. Thus, to maintain a specified output of filled and charged cells, considerably more charging equipment is required. The use of blended filling powders can speed up the formation and the rate of charged cell production. The more customary blends are those with the addition of red lead and

litharge to either ball-mill or Barton-pot oxides. Some manufacturers have replaced the blend by red lead alone as this material requires the lowest formation input and gives the highest initial conversion into lead dioxide.

The level of free lead depends on the proportion of red lead in the blend; the lowest value occurs when the powder is all red lead. The presence of an appreciable free-lead component produces a situation similar to that of a pasted flat plate in which a curing reaction will occur if sufficient moisture and heat is present. In the case of a dry-powder filling, no curing reaction can take place and, dependent on the level of free lead, an equivalent reaction will occur when the cells are filled and charged. This shows up as an appreciable self-discharge after formation unless action is taken to contain the free lead conversion by a controlled discharge during the formation process. One reason for adopting red lead alone as the filling powder is the absence of any significant curing problem and a fast formation. The disadvantage of using red lead is the appreciably higher cost involved for that material compared with a ball-mill or Barton-pot oxide. When all the hidden factors such as the need for extended formation, depreciation of the extra charging plant to meet production output rates, etc., are fully evaluated, it is generally found that the true cost of cell manufacture does not differ much whether red lead or a blend of powders are used.

Typical red lead powders that have been found acceptable for tubular-plate filling have the properties shown in Table 2. Oxide A is more suited to vibrator filling and oxide B to tamp filling.

The method used to determine the tamp density is one developed for evaluating lead oxides for the paint industry. A 500 g sample of the proposed oxide is put into a glass measuring cylinder that is secured to a table lifted to a height of ~ 1 cm and allowed to fall freely on to a bottom register. The cam actuating the rise and fall of the table rotates at a speed of 3 to 4 rps. After 2000 strokes, the volume of the oxide in the measuring cylinder is recorded and the tamp density calculated. The equipment, marketed under the name JEL volumeter (Engelmann AG, Ludwigshafen, Germany), gives good reproducibility of results with all forms of lead oxide and the relatively slow frequency of operation of the device compares closely with the previous statement that maximum densities during filling tend to occur at frequencies around 200 tamps min^{-1}.

TABLE 2

Characteristics of red-lead powders

	Oxide A	Oxide B
Oxide content (%)	96	88
Scott apparent density (g cm^{-3})	2.1	1.6
Tamp density (g cm^{-3})	4.5	3.8
Particle size analysis (μm)		
< 50	35	87
< 25	33	75
< 20	20	70
< 15	16	63
< 10	11	52
< 5	5	37
< 2.5	2	25

Oxide B, with a tamp density of 3.8 g cm^{-3}, would produce a filling density of 3.8 g cm^{-3} if the filling system frequency matched that of the test equipment. Oxide A used on a tamp-filling system would settle more readily and compact; the formed density of the lead dioxide would be higher than that of oxide B and the initial capacity would inevitably be poorer.

Effect of filling powder blend on initial capacity

Tubular positive plates behave in much the same manner as pasted plates. Up to a point, the lower the formed density, the higher is the initial capacity. Similarly, as with pasted plates, the life decreases rapidly with regular deep cycling below a particular formed material density.

It is common practice to add a proportion of red lead to positives where a high initial capacity is a market requirement. There is a limit to how much red lead can be accepted in flat-plate positives as the shape of the red-lead particles tends to be more spherical than ball-mill oxides and the particle-to-particle cementation is reduced. Material silting becomes a significant problem. In pasted plate positives with or without glass-wool retainer mats, it is recommended that the amount of red lead is kept below 30 and 20 wt.%, respectively.

The material in tubular positive plates is fully supported within the external tube throughout life and there is no restriction on how much red lead is used, except that very fine material should be avoided as this can percolate through the tube pores and silt down to the bottom of the cell container. The silted material in its progress through the tube and downwards can be thrown upwards by gas bubbles to lodge on the top edges of the plates and separators, or lodge on the vertical edges of the plates to form side short circuits, or get caught up on the underside of the cell element. The result, irrespective of where the material lodges, can lead to a reduction in cell life.

The effect of variation in the filling powder on the initial capacity of equivalent cells with the same negative plates and formation process is shown in Fig. 2. During the formation process, no opening-up discharges were incorporated, mainly because no such discharges were needed when red-lead powder was used.
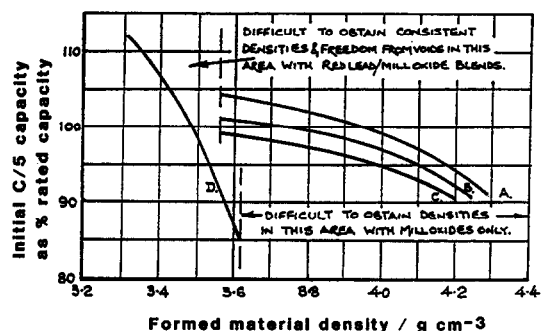

Fig. 2. Effect of powder type and formed density on the initial $C/5$ capacity after fixed container formation without opening-up discharges: (A) red lead; (B) 50 wt.% red lead, 50 wt.% ball-mill oxide (70 wt.% PbO); (C) 25 wt.% red lead, 75 wt.% ball-mill oxide (70 wt.% PbO); (D) ball-mill oxide (70 wt.% PbO).

The behaviour pattern with a typical ball-mill oxide with a Scott apparent density of 1.53 g cm^{-3}, a tamp density of 3.1 g cm^{-3}, and 70 wt.% PbO (curve D) differs considerably from that of the red lead and red-lead/ball-mill oxide blends (curves A to C). It is usually very difficult with ball-mill oxides alone to achieve formed material densities of the order of 3.6 g cm^{-3} or higher. Below 3.6 g cm^{-3} formed density, the capacity builds up rapidly but there is a great risk of voids developing in the filling and life tends to be short and erratic. At 3.6 g cm^{-3}, the life can be acceptable but the capacity is too low for despatch without recourse to a number of opening-up discharges. A major problem with densities below 3.6 g cm^{-3} is the lack of rigidity in the filled tube and the ease with which the filling powder can be displaced with handling before action can be taken by sulfating the powder to increase its volume.

A filling density tolerance of 0.1 g cm^{-3} is realistic when using red lead or red lead/oxide blends, i.e., operating with a formed density ranging from 3.5 to 3.7 g cm^{-3}. With ball-mill oxides alone, the realistic formed density range tends to be greater and the cost of attempting to hold the density range to that of a red-lead filling can be uneconomic.

Although the use of a Barton-pot oxide eases the filling control, the problem of a low initial capacity remains and the formation routine requires the inclusion of a number of opening-up discharges in order to produce cells with their capacities close to the rated value.

The differences between the initial capacities of cells with red lead filled positives and those with the red-lead/ball-mill oxide blends are not large, even when the blend contains up to 75 wt.% of the ball-mill variety. As a result, the most attractive economics tend to favour blend C in Fig. 2. The physical properties of the ball-mill oxide do play a part in determining the initial capacity levels and the oxides can be made to have better characteristics than those of oxide D. They generally demand a higher Scott and tamp density and a higher degree of oxidation. These oxides are more difficult to manufacture and cause most mills to become temperamental. Any plan to make them in bulk introduces mill-control problems and generally a reduced yield. Barton pots behave better with such oxides as they are often used to produce litharge and are preferred for filling tubular positive plates when blended with red lead.

Wherever a blend of red lead with a ball-mill or a Barton-pot oxide is adopted, there will always be a significant percentage of free lead present. This free lead needs to be oxidized (either by a curing reaction or by sulfation during a discharge reaction) before the completion of formation in order to stabilize the cell capacities. To eliminate either of these, some makers deliberately sulfate the filling oxide or blend and hammer mill the dry sulfated paste to form the filling powder. This process has a number of advantages. The addition of sulfuric acid produces an increase in the particle volumes through the formation of lead sulfate. The reaction and the presence of moisture causes agglomerates to form that, later in the pulverizing stage, break down into shapes that are less plate-like in character and have better flow properties than the original powder. During the drying operation following sulfation, the heat and moisture could be controlled to favour the conversion of the free lead as in the curing of flat plates. After pulverizing, the powder tends to have a greatly reduced free-lead content and the self-discharge and temperature rise associated with high free leads during/after rest periods in/after the formation are suppressed.

A typical presulfated mix is one made in the following manner using a normal ball-mill oxide with ~65 wt.% PbO:

(i) make a paste mix as for flat plates by adding 140 l of water to 1 tonne of oxide to which is then added 55 l of dilute sulfuric acid (1.400 sp.gr.); the rate of
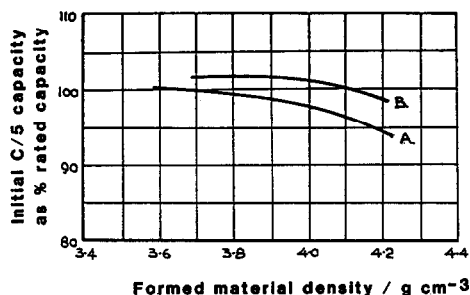
Fig. 3. Effect of sulfating and pulverizing the filling powder on the initial $C/5$ capacity after container formation without opening-up discharges: (A) 50 wt.% red lead, 50 wt.% ball-mill oxide; (B) blend A, sulfated and pulverized.

addition of the acid and/or the amount of mixer cooling must be adjusted to prevent the temperature of the wet mix from exceeding 60 °C;

(ii) turn out the wet mix into containers of ~ 500 kg capacity, cover with wet hessian or a plastic sheet and leave for 24 h;

(iii) spread the paste out on to trays to dry in the air for preference, or to dry slowly in a low temperature oven held at between 65 and 80 °C;

(iv) pulverize the dried paste in a hammer mill fitted with a 0.3 to 0.5 mm mesh sieve;

(v) dilute the pulverized powder with red lead (battery grade) in accordance with personal preference or experimental data.

Alternatively, the powder can be blended before sulfation and pulverizing and the water and sulfuric additions reduced in proportion to the ratio of ball-mill oxide to total powder.

Presulfation brings difficult environmental problems; pulverizers tend to lose their dust tightness very quickly and the atmosphere surrounding the pulverizers or hammer mills becomes a high health risk. The extraction of leaking dust by conventional equipment is virtually impossible; in some countries, the health authorities have banned the process.

The effect on initial capacity of presulfating the filling powder compared with that from a filling powder consisting of equal proportions, by weight, of red lead and an ball-mill oxide is shown in Fig. 3. The presulfated blend exhibits superior performance and this may be due to a lesser variation in particle size and, possibly, a more complete formation into lead dioxide arising from a more even distribution of lead sulfate throughout the mass of the material.

Plate filling

The cost of filling a tubular positive plate depends on: (i) the number of plates filled simultaneously by the operator; (ii) the number of times the operator has to extend the vibrating or tamping procedure to achieve the specified powder weight; (iii) the extent of check weighing needed to assure the bulk of the plates filled are, in fact, within the specified limits, and (iv) whether, or not, the operator is fully occupied with the specified sequence of events in the filling operation.

Where the filling is carried out automatically at separate stations, the operator can be steadily filling small jigs carrying pairs of plates, whilst a second operator is removing the filled plates. This probably provides the best operating economics combined with the lowest spread of filling weights over a full shift. In these circumstances, the monitoring of plate weights can be on a truly random basis because of the inherent stability of the system. The system calls for several filling points in order to compete for output with an alternative arrangement where many plates are assembled in a single jig and the whole filled at a single filling point. In an automatic system with no more than two plates per jig, a preweighed amount of powder can be fed to each jig with the probability that the gross deviations between the proportion of the weighed powder accepted by each plate is small. In the case of jigs holding a relatively large number of plates, the powder can be preweighed but it is very difficult to ensure that the powder is evenly distributed across the tops of the plates and gross deviations can readily occur. In one particular arrangement, where 13 plates were filled simultaneously using an electromagnetic vibrator with time and amplitude control, the plates were assembled in a heavy section open-sided jig with the open ends of the tubes uppermost. The locating fins on the spine castings were used to maintain the plates in contact with each other without compression and to remain approximately circular. The filling powder was spread relatively evenly across the tops of the plates after the open side of the jig had been closed. Figure 4 shows the variations that occurred in the powder weights of each plate in the jig with varying vibrator amplitude setting. The filling powder was from the same bulk supply and the plate castings from the
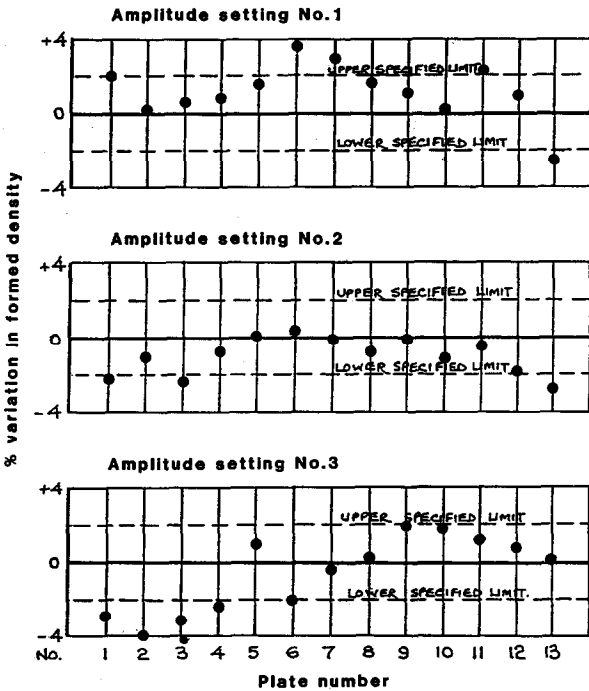

Fig. 4. Variations in the formed densities of consecutive plates in a multiplate jig with changes in the amplitude control settings of an electromagnetic vibrator.

same batch that produced during one shift. The variations in the filling weight are expressed in terms of the subsequent formed density since this is the material characteristic that controls the finished plate performance. The results indicate that:

(i) there are patterns of vibration that could produce relatively close density control, but with a large number of plates per jig, it is difficult to limit the variation between plates to less than $\pm 2\%$ of the specified density;

(ii) changes in the amplitude control of the vibrator can produce changes in density well in excess of $\pm 2\%$;

(iii) large differences can be experienced in density, even between adjacent plates, so that if checking is on the basis of random selection of individual plates from the jig, the results can be greatly misleading;

(iv) if the operator is given the freedom to adjust the amplitude control, or to extend the filling time, the system becomes unpredictable.

Wherever it is deemed expedient to adopt a multiplate filling jig (e.g., because of economic pressures) it is also important to maintain a rigid plate-weighing discipline. The latter should be extended to alternate plates of the jig assembly and should have a responsible official setting the vibrator amplitude and duration. The wide variability in filling weights when using multiple plate-filling jigs is reflected in variable capacities in the finished cells of the same type and size. Where a choice exists, it is always preferable to reduce the number of plates per jig and to concentrate on devising a process method whereby not more than two plates per jig can be filled with the same labour content per plate. Note, when using multiple plate jigs, the excess time required for correcting the filling weights should be taken into account.

The checking of the tamp density of the filling powder before use gives an indication of whether, or not, the attainment of specified filling weights will be troublesome. The tamp density will give an early warning that average plate-filling weights will tend to be higher/lower than the norm. Where a vibrator unit is used as a single unit on a discontinuous basis, it is helpful to maintain a constant load on the vibrating table, irrespective of the size of plates (i.e., add weights when short plates are being filled). The total table load, if variable, can modify the deceleration forces that assist the powder to enter and flow down into the tubes.

In incidences where there is difficulty in meeting the specified filling weights, there is a tendency to alter the amplitude considerably. This can often result in much poorer filling than was previously accomplished. This is due to resonance modes when standing waves are set up in the powder and the material remains almost stationary at the top of the filling jig. When changes are made, they should be in small increments and the change noted for future guidance.

Design parameters for tubular plates

In the design of flat-plate positives, it is relatively simple to determine the optimum dimensions to give specified formed material weights and densities since the production of the grid is not influenced by any bought-in item. This is not always the case for tubular plates since often the tubes are proprietary items and the standard sizes are not necessarily the best for the plate under design. Adoption of a nonstandard tube usually entails a premium price. In such cases, it is preferable to assess first the optimum tube diameter for performance and then estimate the cost per A h of capacity arising from material and labour costs. The latter should be compared against those equivalent costs using standard tubes, provided that the rated capacities can be obtained

using standard tubes. Frequently, the more expensive nonstandard tube is rejected purely on the basis of its cost, without conducting a proper design analysis and giving full value to the economics resulting from the usage of an optimum tube.

It is generally agreed that an acceptable life of four to five years under onerous working conditions requires a minimum formed density of ~ 3.6 g cm^{-3}. Whilst some success has been achieved with densities as low as 3.4 g cm^{-3}, the erratic incidence of premature life failures makes this value hazardous for commercial production without the use of bulking additives. A density of 3.6 g cm^{-3} becomes the minimum and some allowance is made to provide reasonable working tolerances. Even though the filling process is carefully controlled and the number of plates per filling jig is low, it is not uncommon for the variation in final formed density to be of the order of ± 0.2 g cm^{-3}. This indicates a prudent minimum design formed density of 3.8 ± 0.2 g cm^{-3}. Whether or not this can be maintained in practice depends on the flow properties of the filling powder and its tamp density. For example, an unhammered Barton-pot oxide will flow more readily than an equivalent ball-mill oxide, while a red lead, formed by roasting a Barton-pot oxide or litharge, will flow more readily than that produced by roasting the 'fines' from a ball mill.

Ball-mill oxides are rarely used on their own as: (i) their platelet form makes it difficult to reach even 3.6 g cm^{-3}, and (ii) the incidence of voids is high. In order to exploit the lower cost of ball-mill oxides, the material is usually blended with litharge and/or red lead produced in a Barton pot.

Accepting the minimum formed densities, the choice of tube internal diameter will dictate the excess of material (compare with the theoretical amount) that is required. This factor is important as it will determine the proportion of lead sulfate produced on discharge and the degree the conductivity of the active material is eroded by the near insulating sulfate. In addition, pores in the material will become clogged by the sulfate so that free access to electrolyte is denied to the unreacted lead dioxide. The presence of too high a proportion of lead sulfate after discharge makes recharging difficult and, in severe cases, almost impossible.

Where the capacity output of a cell is limited by the available electrolyte (and this invariably is the case with tubular positive traction cells), an active material utilization of 35% always keeps a cell free from recharging difficulties. This is equivalent to a minimum specific formed material weight of $4.46 \times \dfrac{100}{35} = 12.7$ g A^{-1} h^{-1} (where 4.46 g A^{-1} h^{-1} is the theoretical weight of lead dioxide to support 1 A h). This value of 12.7 g A^{-1} h^{-1} refers to the safe minimum formed density of 3.6 g cm^{-3}. When a manufacturing tolerance of ± 0.2 g cm^{-3} is allowed for the formed density, the mean specific formed material weight for design purposes becomes 13.4 g A^{-1} h^{-1}.

The designer has two problems to resolve: (i) to select the correct diameter tube to satisfy both the formed density and the specific formed material weights, and (ii) to ensure that the blended filling powder and the vibrator (or tamping) equipment are compatible. The latter is particularly important.

Where the competitive situation is difficult and the bulk of the production cells are not required to undergo regular deep discharge, some easement in the proportion of lead dioxide reacted, as used for design purposes, can be accepted. In such cases, the cell design can be based on a full discharge reacting up to 40% of the material provided. Nevertheless, the design must be optimized and the choice of filling powder is critical.

Figure 5 presents data of typical capacities per dm of formed material length for tubes of 8 mm internal diameter. The tubes are filled with red lead that, after formation
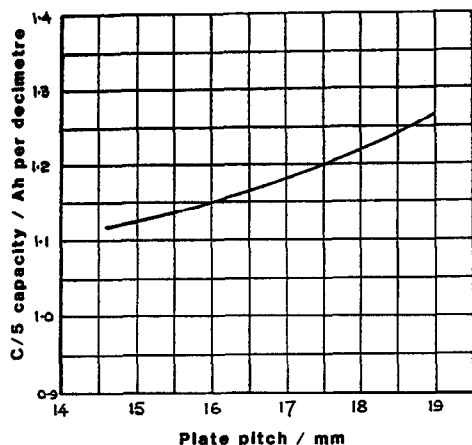
Fig. 5. Variation of capacity per dm of formed material of density 3.8 g cm^{-3} enclosed in tubes of 8 mm internal diameter.

and five initial discharges, had a density of 3.8 g cm^{-3}. The diameter of the central spine was 3 mm and the density of the electrolyte under fully-charged conditions was 1.280 g cm^{-3}.

The effect of decreasing the internal diameter of the tube is to reduce the amount of formed material, to increase the utilization of the material, and to increase the amount of electrolyte available per dm of tube length. Initially, the nett result is an increase in the capacity per unit weight of formed material up to the point where the proportion of lead sulfate formed as a result of discharge reduces the capacity through the greater loss of material conductivity and the more rapid clogging of the pores of the active material. It is difficult to be precise about the practical value of the proportion of lead sulfate which produces this loss in capacity but it appears to be when $\sim$40% or more of the initial lead dioxide has reacted.

To illustrate the effect of tube diameter on capacity take the case of a nominal four-year guarantee cell where the spine diameter is 3 mm and the limit of safe reaction of the active material is 40%. If d (cm) is the internal diameter of the tube, then:

- cross-sectional area of formed material, $A = \dfrac{11}{4} (d^2 - 0.3^2)$ cm^2
- volume of formed material per dm of tube length $= 7.854(d^2 - 0.3^2)$ cm^3
- weight of formed material per dm of average density 3.8 g cm$^{-3} = 3.8 \times 7.854(d^2 - 0.3^2) = 29.85(d^2 - 0.3^2)$ g

If the internal diameter of the tube is varied from 7 to 9 mm, the amount of formed material and the displacement of electrolyte will also vary. Above 8 mm diameter, the decrease in the volume of electrolyte available will reduce the cell capacity if the plate pitch remains constant. Initially, take the case of a pitch of 18 mm. Below 8 mm diameter, the volume of electrolyte will increase and there comes a point when there will be more than 40% of the material reacted if the full-capacity potential of the electrolyte is realized.

In order to estimate the effect of the electrolyte-volume changes, let the specific gravity change at 25 °C be 1.280 at full charge to 1.100 at the end of discharge. Over

this operating range, the capacity equivalent of the electrolyte is 0.087 A h cm^{-3} for the case of a tube of 8 mm internal diameter based on typical cell geometry.

Estimations of the capacity per dm for a pitch of 18 mm are summarized in the Table 3.

These data are plotted in Fig. 6, together with similar data for 15.6 and 19 mm pitches. The locus of the maxima of these curves defines the optimum internal diameters of the tubes for each pitch using spines of 3 mm diameter. The curves indicate that for every plate pitch there is an optimum tube diameter and, in order to make the most effective use of the active material, the option should be available to vary the tube diameter to obtain the most favourable cost figures in production.

The facility to manufacture tubes in-house is undoubtedly an advantage in such a situation to avoid paying a premium price if the optimum tube diameter should not coincide with a standard proprietary diameter. If the capacity rating of cells is to be

TABLE 3

Variation of capacity with tube diameter

Internal tube diameter (mm)	7	7.5	8	8.5	9
Volume of formed material per dm (cm^3)	3.14	3.71	4.32	4.97	5.65
Weight of formed material per dm (g)	11.9	14.1	16.4	18.9	21.5
Weight of PbO$_2$ equal to 40% reaction (g)	4.76	5.64	6.56	7.56	8.60
Capacity potential of 40% reaction (A h)	1.07	1.27	1.47	1.69	1.93
Volume difference in displaced electrolyte[a] (cm^3)	−0.48	−0.24	0.00	+0.27	+0.55
Estimated capacity equivalent of volume difference (−A h)	+0.04	+0.02	0.00	−0.02	−0.05
Estimated capacity equivalent per tube diameter per dm length (−A h)	1.07	1.24	1.22[b]	1.20	1.17

[a]Compared with 8 mm diameter tube.
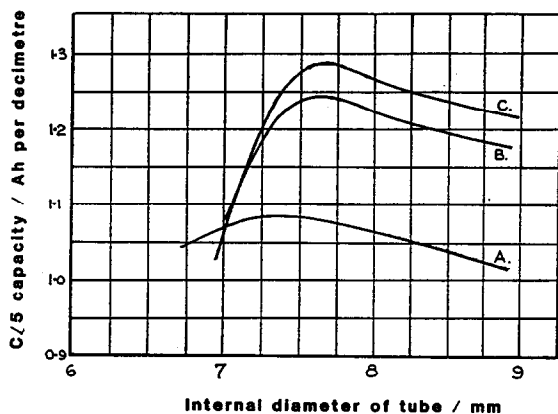[b]Capacity derived from Fig. 5.

Fig. 6. Relationship between the tube capacity and the internal tube diameter for varying plate pitches: (A) 15.6 mm; (B) 18.0 mm; (C) 19.0 mm; spine diameter 3 mm; formed material density 3.8 g cm^{-3}; specific electrolyte volume for 8 mm tube 11.5 cm^3 A^{-1} h^{-1}), excluding electrolyte below cell element.

increased as a competitive weapon, then the ability to maximize outputs without incurring increased costs becomes a valuable asset.

The above data is based on a full-discharge reaction of 40% of the formed material wherever there is sufficient electrolyte to support that degree of reaction. There is always some risk of a poor response to recharging after regular deep discharging where the amount of material reacted exceeds 35%. Therefore, the wisdom of fully exploiting the optimum dimensions based on the figure of 40% has to be evaluated against the nature of the market to be served.

The customer is often informed that cells in normal service must not be discharged regularly below 80% of the rated capacity. This restriction is virtually impossible to enforce and some degree of overdischarging is inevitable with fixed operating routines such as delivery vehicles working to a nominal daily duty that is subject to fluctuation. Some variation between the individual cells comprising a battery is also inevitable. The maximum depth-of-discharge that an optimum tube would support without possible recharging problems would be 35%/40% × 100, i.e., 87.5%. If the difference between the worst cell's capacity and the rated capacity of a series assembly of cells exceeds 87.5%/80% × 100, i.e., 11%, the low performance cell will inevitably give early trouble. In such circumstances, it is prudent to increase the tube diameter marginally to ensure the worst cell is not subject to more than 35% reaction of its active material.

Recalculating the previous figures to limit the proportion of lead dioxide converted to lead sulfate to 35%, a new curve relating tube diameter to plate pitch can be derived. This is shown in Fig. 7 where the optimum tube diameter for each plate pitch is plotted for both 35 and 40% conversion of material. These curves indicate that:

(i) 40% conversion can be used where the discharge routine very infrequently exceeds 80% depth-of-discharge;

(ii) for onerous duties, it is prudent to accept the higher tube diameters based on 35% conversion;

(iii) where there is no control possible over the usage pattern of the cells, the larger tube diameter should be used.
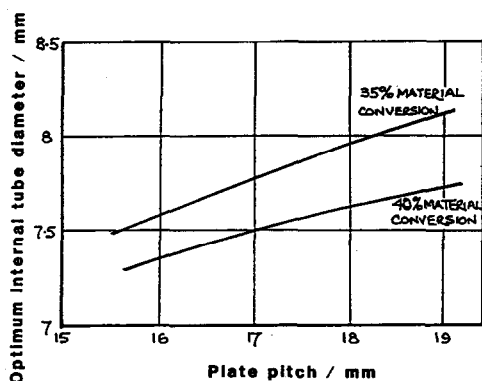

Fig. 7. Effect of active material conversion on the relationship between plate pitch and optimum internal tube diameter. Spine diameter 3 mm; formed material density 3.8 g cm^{-3}; specific electrolyte volume for 8 mm tube 11.5 cm^3 A^{-1} h^{-1}, excluding electrolyte below element.

The above sets broad guidelines for the initial design of tubular positive plates, but they have to be taken in conjunction with the negative plate and the availability of electrolyte that the cell geometry will permit.

Where facilities exists to deform standard diameter tubes into approximately elliptical or rectangular section to reduce the effective cross-sectional area (and the effective equivalent circular diameter), the ordinates of the curves in Fig. 7 are converted into effective cross-sectional area from which the dimensions of the major and minor axes of the deformed tubes can more easily be determined.

Environmental control of tube filling

The tube-filling areas can be a health problem since the raw material used in most cases is a toxic powder. The work area should be set apart from others and separated by solid walls or partitions extending from ground to roof. In the case of individual filling booths comprising a powder feed, a vibrator (or tamping) unit and a filled plate holding position, all these should be enclosed within the booth under negative pressure. The extraction velocity of the air should exceed the pick-up velocity of the particular filling powder.The extracted powder should be recovered by passing the extracted air through a plenum chamber where the air velocity is decreased to below the pick-up velocity. The deposited powder can then be passed back into the powder delivery store through a closed pneumatic system. The extraction air passes from the plenum chamber through ducting to the filter unit where the remaining powder can be removed before the air is allowed to pass out to atmosphere. A transparent shield should be interposed between the operating area of the booth and the operator's breathing zone. Preferably, the operator should be provided with approved respirators, although in certain circumstances, the extraction system can be sufficient to keep the lead powder level in the breathing zone below that required to meet statutory limits.

The free handling of the filling powder should be avoided wherever possible as there is no positive control on the operator's actions and, no matter how many times advice is given of the dangers of contaminating protective clothing and the outside of the booth, there will always be some operators who will ignore the advice and create their own personal contaminated atmosphere to the detriment of their health.

With the individual booth system using a dry powder, there is always the risk of some powder reaching the outside of the booth and falling on to clothing and the floor. The clothing should be such that trouser legs should be enclosed in protective footwear and operators required to walk through footbaths in their protective footwear to reach the filling booths. Safe storage cabinets should be provided for respirators adjacent to the booth so that the units can be kept, when not in use, free from the filling powder and not hung unprotected on a convenient projection near the booth. The respirators should be regularly cleaned by trained environmental staff and filter discs replaced frequently, where the operation of the respirator relies on such discs. Protective clothing should be changed before becoming visibly contaminated with powder. Operators should be instructed not to clap their gloved hands together as a means to remove accumulated dust, irrespective of the nature of that dust, as such an action produces a contaminated atmosphere close to the operator's breathing zone.

The enforcement of a clean and dirty clothes locker system interposed by wash facilities should be rigid and smoking allowed only after the operator has thoroughly washed and is completely clear of the work area.

Every effort should be made to encourage the use of fully enclosed protective clothing with the operator fed with clear air through a compressor system. This system has been criticized at times as it is not unusual for the air supplied to be oily, smelly and somewhat wet. It is rarely dusty. Unless the air is pleasant to breathe, the totally enclosed protective clothing will be resented. The air can be rendered more acceptable by passing it through a water separator and then activated charcoal. It is important when adopting the totally enclosed clothing to ensure the operator has clean hair and face before using the clothing. The helmets attached to the clothing should not be small as an unpleasantly large air-flow will be needed to avoid a negative pressure, noticeably on the eardrum when inhaling.

It is tempting to adopt respirators to avoid powder inhalation and economize on the installation and operation of adequate dust-elimination equipment. The latter is the only safeguard, and is not open to being ignored by the operator. The adoption of respirators or enclosed protective clothing should supplement, and not replace, dust control measures. Commercial respirators do not give perfect protection, nor is it likely that they ever will.

The adoption of individual booths for plate filling tends to call for a relatively high level of labour involvement. From the health viewpoint, if for no other reason, an automated or partially-automated filling system is to be preferred. The same health precautions need to be taken but, usually, the actual filling operation when there is dry powder falling on to the plates takes place within an enclosure away from the operators. The dust contamination problem is not so severe and the health risk reduced.

In either system of filling, it is often necessary for the dry powder-filled plates to be soaked in a dilute sulfuric acid solution to bulk up the powder. The act of transferring the dry powder-filled plates to a sulfating bath should be carried out within the booth or, with the automated or partially-automated filling system, through a transfer tunnel under extract. The soaked plate after sulfation does not present a health risk until it has been dried.