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# ACHIEVING RELIABLE FLOW FROM EXISTING HOPPERS: STRATEGY FOR SELECTING THE SOLUTION

# Obtaining Reliable Flow From Existing Hoppers: Strategy for Selecting the Solution[1]

Dr MSA Bradley
The Wolfson Centre for Bulk Solids Handling Technology
University of Greenwich, London SE18 6PF

## SYNOPSIS

It is common to have to deal with existing hoppers and silos which do not discharge reliably. The engineer faced with such a problem needs some sort of understanding of how to select the most appropriate of the many possible solutions available. The choice depends upon consideration of:-

- The material and its flow behaviour,
- The process requirements,
- The size of the installation,
- The capital available, and
- The prospect for future utilisation of the equipment.

The many types of mechanical extractors, vibrating flow aids, pneumatic devices and other options each have a place, but the selection of the wrong approach can lead to disappointment or even a worsening of the problem. However, even given the choice of the appropriate device, the way in which it is applied can make the difference between success and failure.

This paper seeks to give a general understanding of the principle of employing aids to flow, and develop some guidance to the engineer as to how to approach the problem, choose the solution most likely to be successful, and apply it in the best way.

## 1. BASIC PRINCIPLES

### 1.1 Core flow discharge and hopper obstructions

There are basically two possible flow patterns in hoppers, i.e. core flow and mass flow, as depicted below. Although mass flow has some useful advantages, the vast majority of vessels discharge in core flow. This is because achieving mass flow requires some very careful design, usually following flow testing of the product being stored; in practice this is not often done, consequently the "default" pattern of core flow is instead arrived at. The specific advantages of mass flow will be explored later in this paper.

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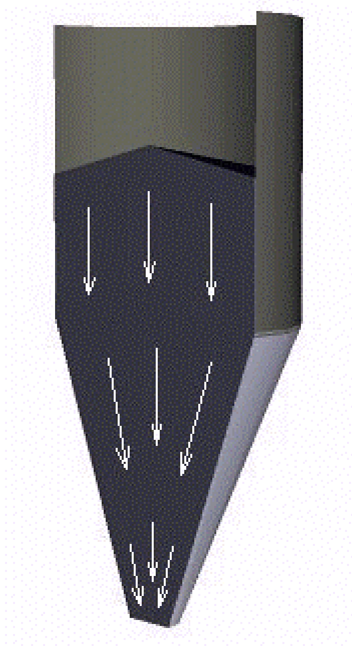

Fig. 1a
Mass flow
Material all in motion, sliding on the cone of the vessel and coming out in order of input

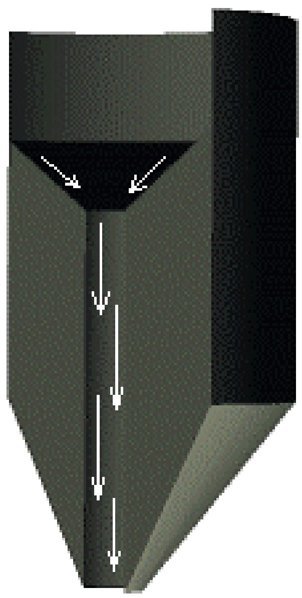

Fig. 1b
Core flow
Material sloughs off the top surface down an angle of repose and flows down through a central flow channel

## 1.2 Ensuring reliable core flow

Failures to discharge from core flow hoppers can occur as a result of two different types of blockage, the stable arch or the rat-hole as shown below.

Fig. 2a
Stable arch

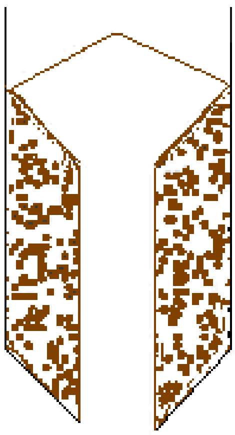

Fig. 2b
Stable rat-hole

These are both stable structures in which the strength of the bulk solid is higher than the stresses in the structure (from its self-weight), meaning that the structure will not collapse under its own weight. The stresses in the structures increase as the size of the structures (arch or rat-hole) increase; the size of the structure is dictated by the outlet size of the vessel, hence it follows that if the outlet size of the vessel is continually increased, there will eventually arise a situation where the stresses in the structure overcome the strength of the material and the structure collapses, allowing flow to occur.

Any given commodity has a certain strength characteristic, which effectively gives it a maximum dimension across which it can arch, and a maximum size of rat-hole which it can support. These dimensions depend to a degree on the size of the bin and hence the pressure applied to the material at the bottom to compact it, and also on the maximum time in residence between complete emptyings-out of the bin (this "time consolidation" effect can also strengthen the material).

The important point to understand from the above is this: *For a given commodity in a given vessel, there is a certain maximum arching dimension and a certain maximum rat-hole dimension which the commodity can support.* As it happens, the maximum rat-hole dimension is usually much larger than the maximum arching dimension. If the outlet of the vessel is below the arching dimension of the material, an arch will result when material is withdrawn; if the outlet of the vessel is above the arching dimension, but below the rat-hole dimension then a stable rat-hole will form once the material in the centre of the bulk has flowed out (unless the bin operates in mass flow in which case a rat-hole cannot form).

Thus, for a core flow bin to discharge successfully by gravity, without flow aids, the outlet size would need to be above the maximum stable rat-hole dimension of the commodity being stored. In bins where there is not a problem with flow, this is the case. However where there is a flow problem, clearly it is not.

One option is to enlarge the outlet dimension above the maximum stable rat-hole dimension. If this is too big to connect directly to the equipment under the vessel, then a mechanical feeder of some kind is needed to take the commodity from this large hopper outlet and feed it into the smaller equipment underneath. This approach, whilst workable, is not always possible or desirable, especially as the stable rat-hole dimension of the commodity can often be several feet with cohesive materials.

## 1.3 Successful application of flow aids

The objective of a flow aid is effectively to turn the lower section of the hopper into a feeder, by artificially encouraging flow of the contents where such flow would not occur under gravity alone. *An effective flow aid must therefore encourage flow down to the mouth of the hopper, and all the way up to a diameter above the stable rat-hole dimension of the commodity.*

One point to note is that if the commodity has a high tendency to "time consolidate" (i.e. gain strength with time) then the maximum stable rat-hole diameter will be very large, sometimes even as large as the vessel containing it. This is a particular problem with a core flow hopper, since with this flow pattern, the material around the hip will remain static all the time until the hopper is actually emptied right out. In such a case, for a flow aid to be successful, it has to activate the entire height of the converging section. However, for materials with such a high tendency to time consolidate, it is probably more economic in the long term to change to a mass flow hopper for reasons which will become apparent later.

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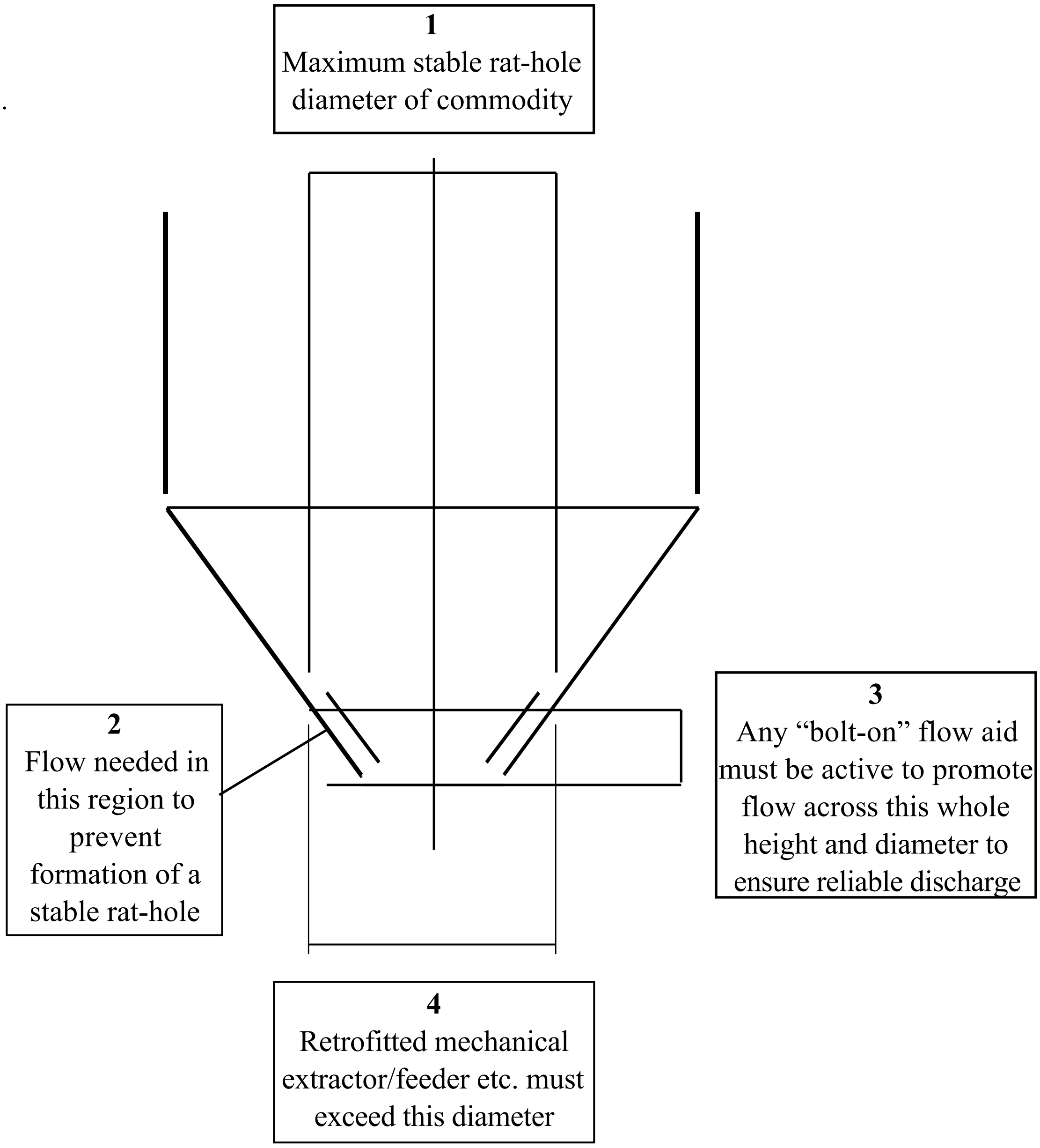


Fig. 3
Application of flow aids to a core flow hopper for successful discharge

The many different types of flow aid work in different ways to achieve the same objective. Their ranges of applicability, and particular points to be watched when using them, will be explored below. Of course, the critical rat-hole dimension of the material in the hopper is often not known (although it can be determined by flow property measurement) but a general understanding of the above principle is necessary to ensure the successful use of discharge aids.

### 1.4 Available options

Briefly, the most commonly employed aids to improved flow are:-

Vibrating discharge aids (internal and external)
Aeration devices
Mechanical extractors
Mass flow
Inserts and linings
Altering the product

These will be taken in turn and their applicability examined.

## 2. VIBRATING DISCHARGE AIDS

Vibration is probably the most commonly-applied aid to discharge. It works extremely well to control the flow of free-flowing materials; ironically, discharge aids are rarely needed for such materials! However, they can be used for quite a wide variety of commodities provided the commodities are not either:-

(a) Highly cohesive, such that compressing them leads to a big gain in strength; Such materials like wet or damp sludges, or anything which forms a strong “snowball” when pressed in the hand, tend to be compacted by vibration; so applying vibration to such materials can frequently make the problem worse;

(b) Highly elastic, so that they just absorb the vibration instead of transmitting it through the bulk, such as bran, germ or wood chips; or

(c) Very fine (say 30 microns or less) which have a tendency to be very variable in their characteristics depending upon what state of settlement or aeration they are in; examples include cement, titanium dioxide or powdered carbon black.

### 2.1 External vibrators

Vibrators bolted to the outside of a vessel vibrate the wall, thereby reducing the friction between hopper and contents and (to a small degree) reducing the strength of the bulk. The reduced wall friction undermines any arch and puts an inwards pressure on any rat-hole, helping to collapse it.

To be effective, external vibrators must be applied in the right place, that is to vibrate the hopper wall in the region between the outlet and the critical rat-hole diameter, as shown in fig. 3 above. This presents something of a problem, since the area around the mouth of the hopper is its strongest part; frequently, it is bolted to a rotary valve or other heavy piece of equipment. Consequently, getting the vibration to transmit into this part of the structure is not easy. Nevertheless it is important that the vibration is carried as far down the wall towards the outlet as possible, as this is the most critical area for flow (being the smallest). If vibrators are fitted too high up, then flow will be encouraged high up which will simply serve to apply pressure to the material lower down near the outlet of the hopper and consolidate it, making it harder to discharge.

In general, it is best to start with vibrators low down on the hopper since the vibration will transmit upwards into the more flexible part of the structure, more readily than downwards.

Such external vibrators are usually installed as a first retro-fit option to a troublesome hopper; they are quite cheap, readily available and easy to install. Positioning has been mentioned; sizing is rather more hit-and-miss but suppliers can advise. Experience has shown that they are effective at overcoming slight flow problems (where discharge is mostly adequate but stops now and again and can be restarted with a bit of hammering). It can deal with more regular problems as long as the material is not highly cohesive. Often they do not need continuous running; just a fifteen-second period when flow is first initiated, or perhaps the same every minute during discharge. It is always better to start with too little vibration and increase it if necessary, to avoid the danger of compacting the material especially if the flow rate is limited under the hopper by a rotary valve or feeder.

Vibrators must always be sequenced so that they only come on when the material is being taken away from the hopper outlet; applying vibration to any material when it is confined will simply consolidate it.

Given the cheapness and ease of installation, the application of external vibrators is always worth a try unless the material is known to be highly cohesive or elastic or the discharge problem is extremely severe.

Some drawbacks are:-

- They can introduce quite substantial noise into the workplace;
- If oversized or badly installed, they can damage the hopper by metal fatigue;
- They are not good for overcoming severe problems of hopper blockage or rat-holing; trying to use a high level of vibration by this means will lead to damage to the hopper and often serve to settle and compact and long-term resident material in the hopper.

## 2.2 Internal vibrators

Where more severe flow problems occur it is better to install a well-designed internal vibrating flow aid. The most common include:-

### 2.2.1 Vibrating cones

In one realisation of these devices, the internal cone contains an air-driven vibrator and mounts inside the existing hopper cone on flexible mounts; examples include the well known “Soliflo” or “Matcon” devices. In other versions (e.g. the “bin activator”) the cone is mounted rigidly inside a conical or dish-shaped replacement hopper bottom, itself mounted on flexible mounts and driven by external vibrator motors. The first type can sometimes be retrofitted to an existing bin, whereas the second type requires the bottom of the hopper to be removed. Either can be designed in to new installation quite effectively.

In either case, the internal cone vibrates much more effectively than a hopper wall with a bolt-on vibrator. This promotes flow of the material right across the hopper from wall to wall, adjacent to the cone, by allowing flow down the surface of the cone and making it impossible for the material to arch between the hopper wall and the moving cone. Provided the diameter of the vibrating cone is nearly as large as the rat-holing dimension of the material, this will promote flow very well.

Vibration is applied continuously or intermittently all the time discharge is required, and when vibration is turned off the material arches between the static cone and the adjacent hopper wall. Again, vibration must not be applied unless the material can discharge freely beneath the cone.

These devices have been used very extensively for a wide range of materials, and found to be successful provided the material is not either highly cohesive or highly elastic, as described above. Sizing of such a device presents a challenge, as selecting too small a unit (below the stable rat-hole dimension of the bulk solid) will result in poor performance. Many suppliers of these units will size the unit in relation to the diameter of the hopper, which is not strictly correct as an approach but usually meets with success for the simple reason that their recommendations often result in the specification of quite large devices; not uncommonly two or three metres across, which is above the maximum stable rat-hole diameter of many bulk solids.

In general, the best advice with these devices is to accept the supplier's advice if they can show they have used one of the proposed size (or smaller) with the same bulk solid in the past, but be sure that the bulk solid is truly the same. If this cannot be shown, then it is better not to purchase the device until the supplier has proved its effectiveness with a sample of the bulk solid in a test set-up.

Again it is extremely important to ensure that the vibrator control is sequenced so that it cannot be run unless material is being taken away from the space underneath the device.

### 2.2.2 Internal screens

Some devices are available which consist of screens of perforated plate or similar, mounted parallel to the hopper cone surface on flexible mounts, and driven by an externally mounted vibrator. An example is the Mucon "Promo-Flow".

Experience with these devices is much less widespread, however they have been shown to be effectiveness with some materials. If contemplating the use of such a device then a trial with the bulk solid to be handled is an absolute necessity.

2.2.3 Outlet-plane grid devices

There are on the market several devices which are effectively square screens or grids of a "louvre" pattern which fit horizontally across the outlet of a hopper, and vibrate to encourage the bulk solid to flow through the grid into a short vibrating chute beneath (examples are the "Hogan bin discharger" and the "Siletta discharge aid"). These work in effectively a similar way to the internal cone devices, promoting flow across their entire upper surface. Similarly to conical devices, to be effective such a device must be above the maximum rat-hole dimension of the bulk solid. Retrofits involve cutting the bottom off the existing hopper. Again a trial is recommended to ensure success with the particular bulk solid to be handled by such a device.

## 3. AERATION DEVICES

These are probably the second most common flow aid device. In general, aeration is most effective for finer materials, say under 20 to 40 microns median particle size. However, the presence of larger particles in a commodity which consists principally of fines will not compromise the effectiveness of aeration.

Aeration works in three ways:

(a) At a low level, it can percolate through the bulk solid helping to overcome any partial vacuum tending to hold the particles together when flow stresses in the hopper tend to move them;

(b) At a higher level, it can cause the bulk solid to expand, reducing interparticle forces; and

(c) When it gets between the bulk of the material and the hopper wall, it can help reduce wall friction.

### 3.1 Low level aeration

The "vacuum-breaking" effect is beneficial in almost any situation where a fine powder is being discharged. Even when a mechanical extractor or a mass flow hopper with a large outlet is used, the introduction of a very small amount of air (say a quarter to a third of the volume flow rate of bulk solid) will help keep the flow consistent in rate and density. This should be introduced at a level perhaps a quarter of the way up the cone. However, this approach will not promote flow where the hopper outlet is less than the maximum stable rat-hole diameter of the bulk solid, so is hardly really a flow aid in the terms of this paper.

### 3.2 Aeration as an active flow aid

A higher level of aeration applied at the proper location (between the outlet of the hopper and the rat-hole dimension of the bulk solid) can be used to actively promote flow. With bulk solids which fluidise well (low cohesiveness, hard particles and not too fine a particle size, such as fly ash or cement) the exact means of air injection is less critical than the choice of location; even installations as crude as holes drilled in the wall of the vessel, covered with a disc of filter fabric and with compressed air applied, can be very effective as the air will tend to distribute itself through the bulk solid. Such a crude installation is a cheap emergency retrofit on an existing vessel, whereas in new or properly redesigned installations a more sophisticated approach (as will be described below) is preferable.

With more cohesive materials such as flour, the air tends to make cracks in the material and blow through these without helping promote flow, and such a crude approach does not work. In such cases, aeration pads of sintered metal or plastic, or (better still) flexible fabric are needed to ensure proper distribution of the air. For best effectiveness, these pads need to be mounted all the way down to the outlet of the hopper, and as far up as is required to prevent rat-hole formation. Often, four lines of aeration mounted at 90 degrees to one another in plan view are found to be most effective. On larger installations (perhaps more than a couple of metres across) it is preferable to "zone" the air flow with a timer and solenoid valves to ensure that all pads receive a fair share of the air flow in turn irrespective of how much material is above them and hence the local resistance to air flow.

With the sort of approach described and bulk solids with good fluidisation properties, it is possible to design very large vessels with almost flat cones (fifteen degrees to the horizontal, or less) making very good use of space. However, such installations need very careful design by experts, and are not really in the realm of "flow aids".

### 3.3 Very fine materials

For very fine materials such as titanium dioxide or similar, aeration cannot easily get in between the particles so the "reduced wall friction" effect is most effective, normally by lining the entire hopper cone with large segmented aeration pads. These aeration pads are best made from a good quality needlefelt fabric (as used for airslides) supported by perforated plate; sintered plastic or metal, or porous ceramics, have been used sometimes but tend to blind with the fine particles whereas fabric flexes and releases the particles. This approach is effective, but expensive not only in terms of equipment but also air consumption and maintenance. It can be retrofitted, at a cost. For new installations, the use of gravity-discharge mass flow hoppers is a more cost-effective solution.

### 3.4 Air blasters/air cannon

These devices are the exception to the general rule that aeration devices only work well with fine powders, since they are often used for coarser materials such as damp minerals. Firing an air cannon releases a small explosion locally to its injector point, dislodging bridged material. They have been used successfully to help move regular bridges of material from specific locations where flow is not reliable. General consensus suggests that they are best applied in situations where a hopper suffers only from local bridging, e.g. near an outlet. They are only really applicable to fairly large vessels where the energy released during firing can dissipate harmlessly, as if confined this energy can cause structural damage to the vessel itself. They can cause compaction of the bulk solid if applied incorrectly especially with fine powders; however their application is not well understood even amongst vendors of these units.

## 3.5 General comments on aeration devices

For any aeration system, quality of air is of paramount importance. Water in the air, high moisture content which will be taken up by the bulk solid (or for that matter excessively dry air which will dry out the bulk solid) will cause caking of the bulk solid and make the problem worse. Maintenance of water traps etc. is thus critical.

One drawback of using aeration as an active flow promotion device is that it will tend to expand the bulk solid to a low and somewhat variable density, and can lead to variations in discharge rate. Where the absolute value of discharge rate is not terribly important this is not likely to be a problem, but in instances where careful rate control is required, such as when interfacing to a metering feeder, this will cause difficulties in obtaining proper control. (This comment does not apply to the use of aeration at a low level for "vacuum-breaking" as first described, which will help keep the bulk solid to a more consistent density.)

A final point to bear in mind is that aeration (with the exception of blasters) is likely to fail completely when applied to wet, very sticky or coarse materials. In fact it can even make flow problems worse by encouraging drying-out or segregation of such materials.

## 4. MECHANICALEXTRACTORS OR DISCHARGERS

All the many types of mechanical dischargers have the same objective; to provide a physical gathering and pushing of bulk solid from across a large inlet dimension above, into a small outlet dimension beneath. This promotes flow very well across the inlet area of the device, and provided that the inlet is larger than the maximum rat-hole dimension of the bulk solid, reliable flow is assured.

With mechanical devices, large inlet dimensions can be achieved quite easily, albeit at a cost, so that even very cohesive bulk solids can be handled. In fact it is not uncommon to make the mechanical extractor the full diameter of the vessel so that no convergence is needed on the walls, and such an approach has the added benefit of giving effectively a mass flow discharge pattern in the vessel, thus promoting first-in-first-out storage, and eliminating long-term resident material which can go hard. This is practically a foolproof approach, as the bulk solid cannot hang up anywhere and will always discharge provided the extractor has the power to dig it out. It should be said that this extreme approach is not always required, and some systems work with mechanical extractors of more modest dimensions interfaced to core flow hoppers.

In either event, the point is that these devices can deal with highly cohesive materials which could not be moved by vibration, aeration or other less costly means. In general, they should only be considered where the flowability of the bulk solid is so poor as to make other options (including design for mass flow gravity discharge) impossible or uneconomic.

## 4.1 Sweep augers

These work by continuously undermining the inventory in the vessel ahead of the screw, and can cope with most bulk solids including damp materials unless they are either so sticky as to clog the screw flighting, containing long fibres which can wrap themselves around the screw, or lumpy and abrasive which would cause high wear.

They are subject to high forces so are strongly constructed with high-torque drives, hence are very expensive. One of the bigge*st potential problems with such devices is that they produce a rotating stress-field within the silo above, which can very easily destroy the silo unless it has been specially strengthened to an appropriate degree. This makes them almost impossible to retrofit. Screw breakages occasionally are a possibility especially if the screw hits some highly caked material, so it is worthwhile considering the pattern which allow for replacement of the screw without emptying the silo first, in a large installation.

A variation on the sweep augur which can be retrofitted to an existing vessel is the "circular bin discharger", with an arch-breaker arm inside the cone of the silo driven from a universal joint at the outlet. The length of the arm is almost equal to the slope length of the hopper cone, and rotates slowly, being free to move and undermine the bulk solid. These devices are still expensive, but sometimes can be applied to an existing silo without the need to cut the whole bottom off the vessel. Again they can discharge materials for which gravity-discharge hoppers would be impossible. If intending to use such a device, a trial is essential.

## 4.2 Ploughs

Plough dischargers are not commonly used in the UK; although they offer useful advantages, their relatively poor availability has limited the experience available. Recently the Portasilo "Rotoflow" device has been introduced to fill this gap but it will be some time before wide experience of application is available.

## 4.3 Walking floor and sliding frame dischargers

The "walking floor" discharger consists of a flat silo floor divided into several strips, which oscillate alternately to and fro alongside each other. At one end of the assembly there is a gap down which the bulk solid falls when the moving strip retracts, from which it is fed by a screw. The "sliding frame" device again consists of a flat floor, but this time static with a frame sliding backwards and forwards on top of it and encouraging the bulk solid to fall into a slot across the middle of the floor, where again it is taken away by a screw. In each case the discharger mechanism is invariably the full size of the silo plan so there is no converging section.

This type of discharger was mainly developed to deal with bulk solids of the most severe flow characteristics, such as high water content, compressible, highly cohesive materials (e.g. partially dewatered sewage sludge, paper pulp waste etc.) which cannot be handled by any other means. As such they are capable of dealing effectively with these materials, but the equipment cost is very high. These should be considered only when dealing with the most extreme cases of poor flowability.

## 5. MAKING BETTER USE OFGRAVITY

Gravity is very reliable in itself - it never breaks down or needs maintenance. However, the amount of work available from gravity is strictly limited according to the height available. That means that for bulk solids which are cohesive, and which hence require a significant work input to deform them in flowing down a hopper cone, some care is needed to ensure that gravity alone can overcome the strength of the material.

With relatively free flowing materials, the short height of a cone on a core flow hopper yields enough work to make the material flow reliably. However for materials which have significant internal strength, the outlet size needed for reliable gravity core flow usually becomes unacceptably large (usually half a metre or more, often over a metre). In addition, the last material to be discharged in core flow will have been in static residence since the hopper was first filled (first-in-last-out), so if the material has any tendency to gain strength with time, this last material out will have become very strong in the intervening period and thus very hard to discharge.

### 5.1 Mass flow

It is in these two respects that mass flow comes into its own:-

(a) For a material of any given strength, that material will flow out of a much smaller outlet in mass flow than in core flow; and

(b) In mass flow, one has only to take a small amount of material away from the outlet and the whole contents is disturbed, preventing long-term gain in strength and spoilage.

Mass flow requires steeper and/or smoother walls in the cone of the hopper than does core flow. Just how steep, and what internal surface is best for the cone, depends on the frictional characteristic between bulk solid and hopper wall, so it is imperative to have flow tests undertaken with the bulk solid to determine the hopper geometry needed. In the absence of such flow tests, it is impossible to embark on the design of a suitable hopper, however once the flow characteristics are known the actual design procedure for mass flow is extremely reliable, and it is without doubt the most certain way to a reliable hopper.

There are sometimes other considerations which would lead to a preference for mass flow discharge anyway, principally:-

(a) A desire to avoid segregation of fine from coarse (or blend components) in a free flowing material;

(b) A desire for first-in-first-out ("FIFO") discharge for process reasons (e.g. to avoid ageing or cooling, or to enable proper stock rotation in foodstuffs); or

(c) Better control of very fine powders (to avoid flushing of aerated material through the bulk from the top surface)

However, setting those aside and looking at the problem purely from the point of view of reliable discharge, mass flow really comes into its own when dealing with *materials which have a significant gain in strength with time.* By disturbing the whole contents every time some material is discharged, and giving a "FIFO" discharge, such materials are handled far more effectively than any discharge aid on a core flow hopper ever could. In fact with highly time-dependent materials, it is probably futile to spend any significant amount of time trying out discharge aids. A decision to convert to mass flow will probably be the most cost-effective solution in the long term, even though it usually means cutting the cone off the hopper and fitting a new one, together with losing some vessel capacity to give the steeper cone walls needed.

There are two principal criticisms often levelled at mass flow:-

(i). The cone section will be taller than for core flow, meaning a reduction in capacity or increase in height; and

(ii). Mass flow hoppers are designed for a particular bulk solid and if the bulk solid changes, the hopper may not deliver mass flow any longer.

In practice, both of these can be overcome very effectively using "plane flow" (wedge-shaped) converging sections which do not require to be so steep, and are more tolerant of changes in bulk solid flow properties. One issue which is critical to obtaining mass flow is the interfacing of the feeder at the bottom of the cone; this must allow flow to take place right across the outlet area, which requires a degree of care in selection and interfacing of the feeder. More details of all these issues, together with a detailed analysis of mass flow, can be found in reference (1).

It will of course be appreciated that converting an existing vessel to mass flow can be an expensive exercise (often more costly than fitting discharge aids). However, engineering it into a new vessel is relatively cheap, and it is a very low maintenance option - for this reason it is especially worth looking at for new vessels, particularly for highly time-dependent materials as described above.

The ultimate limitation on mass flow is when the bulk solid is so poorly flowing as to require wall slopes near to vertical; in such cases a full-live-bottom with a mechanical discharger the width of the silo is indicated, as described in the section on mechanical devices.

## 5.2 "Low-friction" linings

Another way of giving gravity a helping hand is to reduce the amount of work it has to do on the bulk solid during discharge, by reducing the friction between the bulk solid and the hopper wall. Where a hopper is "nearly there" in giving mostly quite reliable flow, this can sometimes be an option, however the choice of lining material is not as straightforward as some vendors of linings would make out.

To take some examples, ultra-high-molecular-weight polyethylenes can be very good for some bulk solids (especially damp or wet ones) but bad for others (hard, angular ones); however the precise grade of polyethylene can make a difference and the grade which is best for some bulk solids will not be the best for others. In the same way, stainless steel can be very good for some bulk solids (not because it is inherently smoother than carbon steel, but because it doesn't rust and become rough when no flow is occurring) - however, choosing the grade of surface finish is extremely important as a mill finish (No. 1 finish) stainless is rougher than a mill finish carbon steel!

The important point is that to choose a "low friction lining" sensibly, some friction tests with the bulk solid against some different lining options are required. Fortunately the cost of wall friction testing alone is trivial compared with the cost of lining even a modest sized hopper, making it an economic exercise.

A word of warning is in order at this point however, regarding the limits of low friction linings; as stated above, they are at their best with "nearly there" hoppers. If a hopper is nearly mass flow, reducing friction will make it mass flow, likewise if it is firmly in the core flow region but almost self-drains then the lining will aid discharge of the last part of the contents. Remember, however, that installing a lining will reduce the transmission of vibration from the outer wall, thus reducing the effectiveness of any external vibrators.

### 5.3 Inserts

It seems strange to suggest that putting something in the way of the flow channel can actually improve flow, yet in some cases this can be so. The simplest insert is a plain "Chinese hat" suspended in the hopper cone above the outlet, reducing the consolidation pressure on the bulk solid near the outlet and hence making it more free-flowing. More sophisticated is a cone within the hopper cone and the same way up, but with walls somewhat steeper; this can promote mass flow in cones which otherwise would not mass flow. Other insert shapes have been used and shown to be useful.

However the reality of using inserts is that whilst they are often useful to improve the flow pattern in a bin discharging a fairly free-flowing material, they are of limited use with cohesive materials. Both academic research, and practical experience, have a long way to go before the use of inserts can be recognised as anything like a reliable solution to problems of unreliable discharge.

## 6. CHANGING THE MATERIAL

It is surprising how many cases actually offer the possibility of changing the flow properties of the bulk solid to ease a discharge problem in a hopper. In the food industries it is very common to add a "flow additive" to a product for retail sale in order to render it more free flowing, thus giving the consumer an easier material to handle and also easing problems in packaging machinery etc. Salt, grated cheese, flavourings etc. are often treated in this way and although the additives are quite wide-ranging, many act in the same way - to provide a coating of small, hard particles on the surfaces of the softer main particles, preventing the main particles from touching and sticking together. The levels of addition and distribution of the fine "flow additive" need to be very carefully controlled to get the best effect, and any chemical effects of the contamination caused by the flow additives must be considered.

Another approach is to control the moisture content. For example, sugar is "conditioned" (a slow, gentle but very searching drying process) to a low moisture content to prevent it from caking in storage. A further approach is to granulate the material (by spray drying, pelletising etc.) to reduce its surface area, thereby reducing its cohesive strength.

All these approaches are known technology, however their utility is usually dictated by the context. For example, if supplying a poorly flowing powder of high value to many customers who then have trouble in handling it, it will be economic for the producer to improve the flow characteristics of the powder. Likewise if reclaiming a blend of low-value mineral from a coarse stockpile, mixed with fines from screening together with ultra-fines settled from a lagoon, it may be worthwhile dumping the ultra-fines instead of reclaiming them, to make the balance of the reclaimed material easier to handle. By contrast, if the problem relates to one hopper in a process plant where the bulk solid is quite closely defined, it will probably be better to adjust the hopper to suit the bulk solid.

## 7. CONCLUSIONS

From the above it will be clear that the choice of approach to improving flow in hoppers is very much dictated by the circumstances. To sum up, the following table may be useful to indicate what approaches have proved, in the experience of the author, to be most successful in which circumstances:-

## Summary Guide to Selection of Hopper Discharge Techniques

| Generic approach | Specific types | Applicability |
|---|---|---|
| VIBRATORS | | Not usually good for very fine, wet or very sticky materials. |
| | External bolt-on | Good for hoppers which "nearly work", easy to retrofit. Not for severe flow problems |
| | Internal cone, screen or similar | More effective (& expensive) than external, especially for retrofit. |
| AERATION | | Works well with fine materials; not for coarse, very sticky or wet materials |
| | Local (pads) | Useful for many materials except extremely fine ones. Easy retro-fit |
| | Large area | Good for very fine materials e.g. pigments |
| | Blasters | For breaking specific areas of bridging; effects somewhat uncontrolled. Retrofit easy but unpredictable. Danger of structural damage to vessel |
| MECHANICAL | | Can give very large outlet dimensions or "full live bottoms". High maintenance |
| | Rotating ploughs | Quite economic, but have limited size availability |
| | Sweep augers and related types | Can handle a wide range of materials. Expensive, but some types can be retrofitted more economically than others. |
| | Walking floor or sliding frame | For the worst of the worst materials - even more expensive whether new or retrofit! |
| HELPING GRAVITY | Mass flow | Especially good for highly time-dependent materials. Very reliable design criteria, expensive to retro-fit but economic for new installations |
| | Low friction linings | Useful for silos which "nearly work". Economic to retrofit but critically important to choose the best lining material! |
| | Inserts | Few types well understood, so hard to plan; low maintenance |
| CHANGING THE MATERIAL | | Reduces handling problems in customers' premises; can be expensive |
| | Adding "flow aid" | Contamination considerations |
| | Controlling moisture | Can have other benefits (improving keeping qualities) or costs (reducing weight) |
| | Excluding fines | Can it be done? |
| | Increasing particle size | Economic and process considerations |