Instrumentation of an Automatic Capsule-Filling Machine

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Abstract ☐ Techniques similar to those used in instrumenting tablet presses were applied to an automatic capsule-filling machine. The dosing unit was modified to allow the bonding of strain gauges to the compression piston. The gauges formed the arms of a Wheatstone bridge circuit. Thus, compression and ejection events were monitored by measuring the bridge unbalance voltage using a suitable amplifier–recording system. The instrumented piston was calibrated in a physical testing machine. Dosing unit rotation required the interposing of a mercury contact swivel between the amplifier and instrumented piston. The instrumentation system required only one minor, permanent modification to the machine, a cut in the dosator tube. Since the same dosator piston sensed both compression and ejection, only one of the two dosing units was instrumented and the other was removed from the machine. A solenoid switching system was devised which only permitted the feeding of empty gelatin shells into the filling cycle for the instrumented piston. Representative fillers were run at constant powder bed and piston heights. Oscilloscope tracings showed two stages in slug formation: (*a*) "precompression," representing the force sensed during dipping of the dosator into the powder before actual compression, and (*b*) actual piston compression. Generally, the maximum slug compression force fell to zero rapidly on retraction of the piston, but in some cases a retention force was noted, possibly due to elastic rebound of the slug against the retracted piston. A negative deflection due to binding of the piston also was observed in tracings of one material. Lubricated batches exhibited ejection forces of less than 1 kg.

Keyphrases ☐ Capsule-filling machine, automatic—instrumentation for monitoring compression and ejection forces described ☐ Instrumentation—described for monitoring compression and ejection forces in automatic capsule-filling machine ☐ Compression forces—in automatic capsule-filling machine, instrumentation described ☐ Ejection forces—in automatic capsule-filling machine, instrumentation described ☐ Technology, pharmaceutical—instrumentation described for monitoring compression and ejection forces in automatic capsule-filling machine

One significant advance in pharmaceutical technology in recent decades was the application of instrumentation techniques to monitor the forces developed in the formation and ejection of tablets. Applied first to single-punch presses and later to high-speed rotary presses, this instrumentation has brought about great insights into the fundamentals of tablet compaction, facilitated product formulation, and permitted continuous in-process monitoring and control of tablet weight (1–4). In light of the successful application of instrumentation to tablet formulation and production, the application of this technology to modern capsule-filling equipment should be of equal value.

Modern, fully automatic, capsule-filling equipment, employing filling principles similar to tablet compression, appeared uniquely suited to the application of instrumentation techniques. Although both the traditional semiautomatic and the newer fully automatic capsule-filling machines generally require that formulations have good flow properties and be lubricious, the machine used in this study[1] required that formulations also be compressible enough to form slugs sufficiently cohesive to be transported within the machine and ejected into open capsules.

The similarity of this filling mechanism to tablet compression suggested that slug compression force and ejection force would be meaningful parameters that could be monitored in a manner similar to that presently used in tableting. Therefore, the specific aim of this research was the development of an instrumentation system capable of monitoring the compression and ejection forces developed during the filling cycle of this capsule filling machine.

A literature review revealed only two references related to the instrumentation of capsule filling machines. Cole and May (5), in a short article, noted the instrumentation of the same model automatic capsule filling machine[1] using strain gauges but gave no details regarding the method of instrumentation. They did, however, report forces ranging from 5 to 350 N (0.5–35 kg) required for compression and ejection of the powder slugs.

Coinciding with the completion of the present work, Cole and May (6) reported in detail their method of instrumentation. A size No. 00 piston was fitted with strain gauges. The rotating dosator head was modified by incorporating a planetary gear system, which prevented the continuous twisting of the cable connecting the gauges with the monitoring equipment. Compression, retention, and ejection forces of representative capsule fillers were reported. However, as will be pointed out, several important differences exist between the methodology and results of Cole and May and those reported here.

EXPERIMENTAL

A primary concern throughout the design process was to keep the modification of the machine to a minimum. The attachment of mounting brackets or guides should be by existing hardware. The system should not alter the normal functioning of the filling process nor reduce normal operating speeds. Finally, the machine should retain the capability of operating uninstrumented, and restoration to this mode should be easily accomplished.

Modification of Dosator Piston—The dosator piston of this capsule filling machine is analogous to the upper punch of a single-punch tableting machine and also to the lower punch in both single-punch and rotary machines because the piston is responsible for both compression of the powder slug and ejection of the slug from the filling head. Since the piston must, therefore, sense the forces generated during compression and ejection, it provided the logical site for bonding of the strain gauges used to detect these forces.

The piston (Fig. 1A) can be conveniently divided into four areas: (1) an upper graduated shank, (2) a collar supporting a metal rod used to adjust the height of the piston in the dosator, and (3) a middle shank tapering to (4) a lower shank with a slightly flared, flattened end. To facilitate bonding of strain gauges and to increase sensitivity, a new piston was machined from No. 304 machinable stainless steel (Fig. 1B). The new piston is identical in all respects to the original, except that the normally cylindrical middle shank was altered to a rectangular cross-section 1.12 cm wide and 0.234 cm thick. In addition, part of this area was reduced to a 0.742-cm width, affecting a portion of the middle shank 1.89 cm in length.

This reduced area (1.89 × 0.742 × 0.234 cm) is the bonding site of the strain gauges. This reduction further increases sensitivity and provides clearance for connecting wires to pass to the reverse side of the piston

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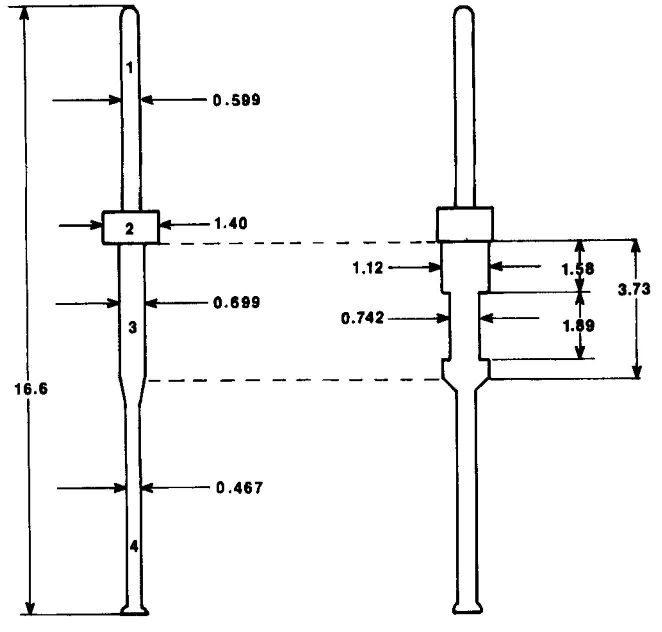
[1] Zanasi LZ-64 automatic capsule filling machine, USM Corp., Machinery Division, Beverly, MA 01915.



1A. ORIGINAL 1B. MODIFIED

Figure 1—*Sketch of original and modified pistons (all dimensions in centimeters).*

when in the dosator unit. A groove was also cut into the collar on one side of the piston, 3.18 mm wide, to allow passage of connecting wires. The plane of the modified rectangular cross section is parallel to the axis of the hole drilled in the collar. The piston, thus modified, is fitted in the dosator unit in the same fashion as the original piston.

Axial strain produced in the bonding area originates only from stress generated at the flared end of the lower shank. The piston is pushed downward, externally, at the tip of the upper shank. The flared, lower end presses on the powder sectioned by the filling head during compression and ejection. The piston is retracted to its original position by a spring acting on the base of the collar.

Installation of Strain Gauges—Two sets of strain gauges[2] were bonded to the reduced area of the modified piston, one set on each side. The strain-gauge configuration chosen for this project consisted of two grid elements, perpendicular to each other, mounted along the length of the gauge backing. The gauges were oriented so that the grid elements closest to the flared end of the piston were parallel to the axis of the piston.

Bonding of the gauges was carried out according to a standard procedure provided by the strain-gauge manufacturer (7). The gauges were mounted such that the center alignment mark of one gauge was perfectly matched with the center alignment mark of the gauge on the opposite side of the piston. A four-post terminal strip was bonded to the grooved collar side of the piston, midway between the collar and gauges (Fig. 2).

Circuitry and Connections—The gauge elements parallel to the axis of the piston serve as the active arms of a Wheatstone bridge. The gauge elements perpendicular to the piston axis serve as temperature-compensating gauges and complete the Wheatstone bridge circuit. The active gauges are connected in opposite arms of the Wheatstone bridge to double the sensitivity of the instrumented piston (Fig. 3).

To protect the bridge and eliminate strain on the gauges induced by the connecting wiring, the terminal strip was interposed between the bridge circuitry and connecting wiring. The connecting wiring was fed from the terminal strip through the groove in the collar and loosely wrapped once counterclockwise behind the upper shank of the piston. Narrow strips of plastic electrical tape secured the connecting wires on each side of the collar. The completed bridge was coated with a polyurethan preparation[3].

Assembly of Dosator with Instrumented Piston—The dosator was assembled in the same manner as an original piston. The retracting spring was fitted over the lower and middle shanks of the piston, coming to rest against the lower edge of the collar. The spring and piston were then inserted into the dosator tube. The piston was then manually pushed below the adjusting rings, the cross bar was inserted through the collar, and the set screw was tightened.

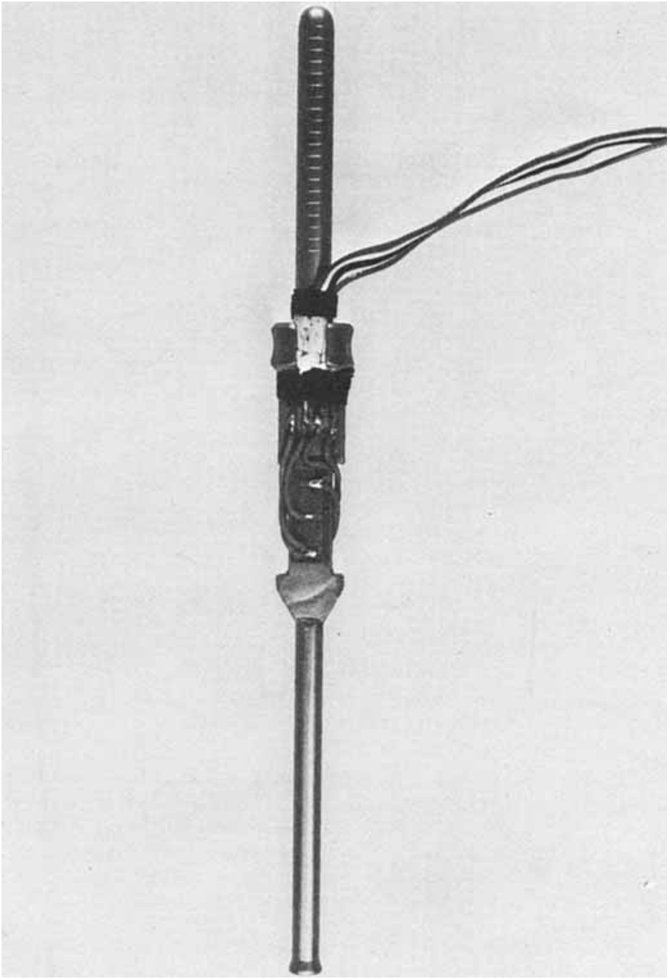


Figure 2—*Overall view of instrumented piston.*

The adjusting rings thread onto the outside of the dosing tube. The ends of the cross bar in the collar of the piston protrude from the dosing tube through slots, cut on a quarter-turn, extending most of the threaded length of the dosing tube. Since the rings function as a stop for the cross bar, the position of the adjusting rings determines the piston height. Thus, as the piston is pushed downward, it is caused to rotate a quarter-turn (or less, depending on the initial piston height) counterclockwise and then clockwise to its original position upon retraction. Since the connecting wire from the terminal strip through the groove in the collar was also wrapped counterclockwise, the piston unwraps the wire slightly as it descends and recoils the wire as it is retracted. In this manner, the required length of wire inside the dosing tube is held as compactly as possible to avoid damage.

To facilitate the installation and removal of the instrumented piston, one of the quarter-turn slots was continued vertically by making a cut in the dosing tube. This modification enabled the connecting wires to pass freely through the side of the dosing tube. This modification was the *only* permanent one made in the capsule filling machine.

The connecting wire was then supported at the upper end of the dosing tube by an auxiliary set of adjusting rings and a wire brace. The wire brace around the dosing tube was held securely by tightening the rings, one on either side of the brace. A cap, which centers the upper shank of the piston, was then screwed in the top of the dosing tube. The assembled dosator was then mounted, with the filling head, to the dosator arm.

The completed assembly is depicted in Fig. 4. The graduated shank of the piston (A) can be seen projecting from the dosator (B) mounted to the dosator arm (C). As the cable passes through the quarter-turn slot in the dosator, it is supported by the wire brace (D).

Mercury Contact Swivel—One problem inherent in the instru-

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[2] Type EA-06-125TF-120, MicroMeasurements, Romulus, MI 48174.

[3] M-Coat A, MicroMeasurements, Romulus, MI 48174.

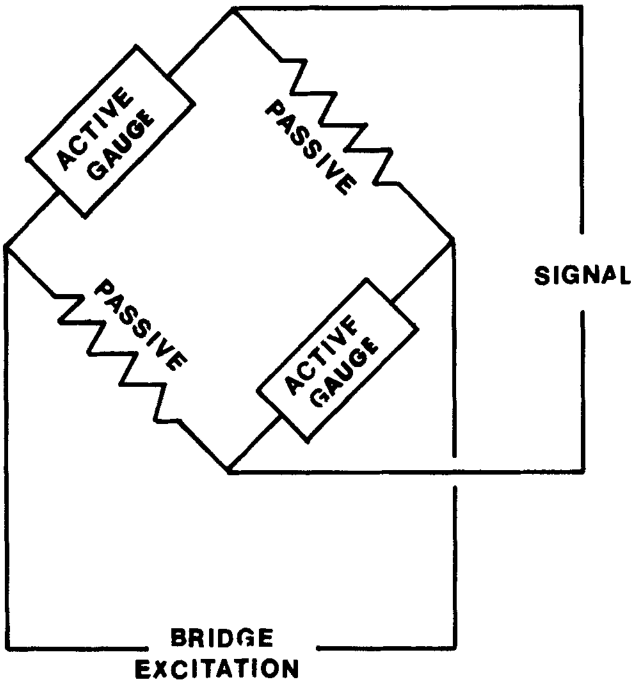

Figure 3—*Diagram of Wheatstone bridge circuit for the instrumented piston.*

mentation of this capsule filling machine was that the dosator arm, carrying the instrumented dosator, continuously rotated through 360°. To prevent the continuous twisting of the connecting cable, it was necessary to interpose a slip ring or swivel between the instrumented dosator and monitoring equipment. A mercury contact swivel[4] was selected in lieu of the usual mechanical type to minimize the possibility of noise in the output.

Figure 4 shows the swivel (E) mounted on the bracket (F) fashioned from 0.48-mm thick, 3003-H14 aluminum. The bracket is bolted to the machine by the existing mounting bolts of the capsule hopper. The swivel is supported by the bracket level with the top of the capsule hopper and directly over the dosator arm.

The swivel consists of a stationary plate and a rotating wheel. The upper cable connects the stationary plate to the monitoring equipment. The lower cable connects the piston with the wheel, which moves freely with the rotation of the dosator. Electrical continuity is maintained through the swivel by means of platinum-tipped electrodes, mounted on the stationary plate, which dip into mercury-filled annular canals cut into the rotating wheel. Additional electrodes passing through the bottom of each canal are connected to a standard connector by wires passing through the hollow axle of the swivel. Figure 4 shows the lower cable extending from the dosator to the standard connector.

Since the dosator arm not only rotates but also moves up and down to position the dosator, slack must be provided in the cable between the dosator and the swivel. To prevent the slackened cable from being snagged by the compression and/or ejection knobs, a wire guide was fashioned and mounted, using existing bolts, to the compression–ejection arm (Fig. 4G).

The compression and ejection events, detected by the instrumented piston, are monitored by measuring the bridge unbalance voltage using a carrier preamplifier[5], which also serves to activate the bridge. The compression and ejection events are recorded continuously on an oscillographic recorder[6] or displayed on an oscilloscope[7].

Calibration of Piston—Calibration was necessary to convert microstrains to kilograms of force. The associated monitoring equipment was capable of directly measuring the strain on the gauges during compression and ejection. The instrumented piston was calibrated statically by applying known loads to the piston in a physical testing machine[8].

Two trials were run, and the observed microstrain readings, resulting from the applied loads, were noted (Table I). Linear regression analysis, using data from both trials, revealed excellent linearity over the range of forces tested (correlation coefficient = 0.999). The slope was 3.96 microstrains/kg. The internal calibration of the recording system, determined by the gauge factor and the gain set on the galvanometer pen, set each millimeter of deflection equal to 1.60 microstrains. Dividing the internal calibration factor by the slope of the regression line resulted in the calibration factor of 0.404 kg/mm for this system.

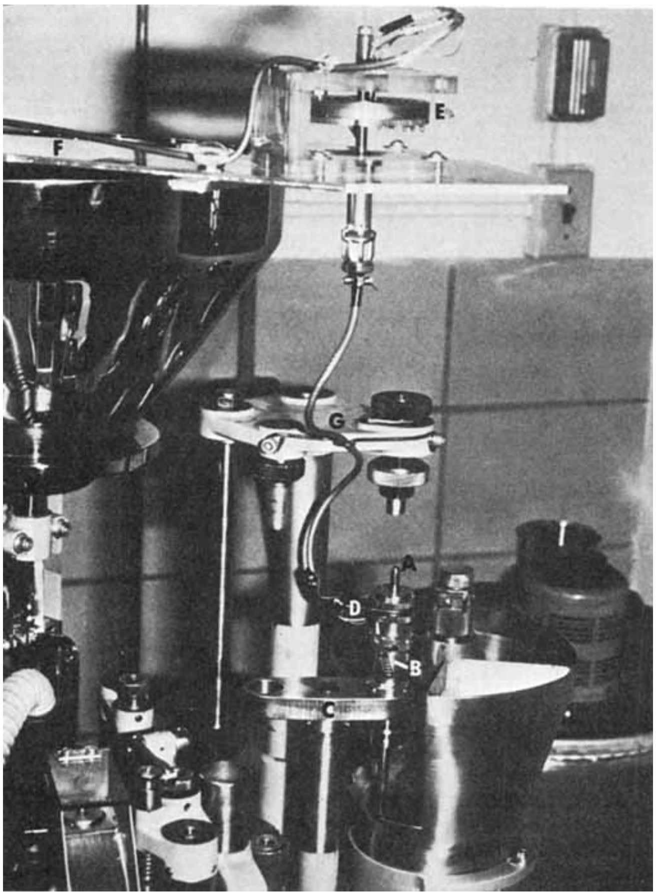

Figure 4—*Perspective view of instrumented dosator, cable, and swivel. Key: A, piston; B, dosator; C, dosator arm; D, wire brace; E, mercury contact swivel; F, swivel bracket; and G, compression–ejection arm.*

Alternate Feeding of Capsule Shells—Since the same dosator was used to monitor both compression and ejection, only one dosator was instrumented. This procedure also eliminated errors that could occur because of possible differences in piston height adjustment. This filling machine was designed to operate with two dosators in place. Thus, for every capsule that was filled, the machine ejected one empty capsule that had gone through the filling cycle but had not been filled because of the missing dosator.

This procedure presented a number of problems. The empty capsules had to be manually separated from the filled capsules for economic reasons and simply for ease of handling the filled capsules for further study. However, even when the capsules were separated, they risked being contaminated by the formulation used. Furthermore, damage to the capsule may have occurred during a previous run, which could cause the machine to stop during a subsequent run.

To eliminate these problems, a means to feed the capsules alternately into the filling cycle was devised. A standard 120-v solenoid[9] (Fig. 5A) was mounted and connected to the rod (Fig. 5B) controlling the position of the metal shoulder (Fig. 5C), which lifts the rocker arm assembly to allow one capsule to feed into the turntable bushings. Again, mounting was accomplished using existing hardware. The solenoid, energized by house current, was connected in series with a microswitch mounted on the support rod of the orientating block so that the lever of the microswitch rode on the edge of the turntable.

When the lever was tripped, the solenoid was activated to retract the

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[4] Technical Concepts, Bronx, NY 14063.
[5] Model 8805A, Hewlett-Packard, Palo Alto, CA 94306.
[6] Model 7702B, Hewlett-Packard, Palo Alto, CA 94306.
[7] Oscilloscope system 5103N, Tektronix, Beaverton, OR 97005.
[8] Instron model TM-M, load cell CCTM, Instron Corp., Canton, Mass.

[9] Trible's and Associates, Baltimore, Md.

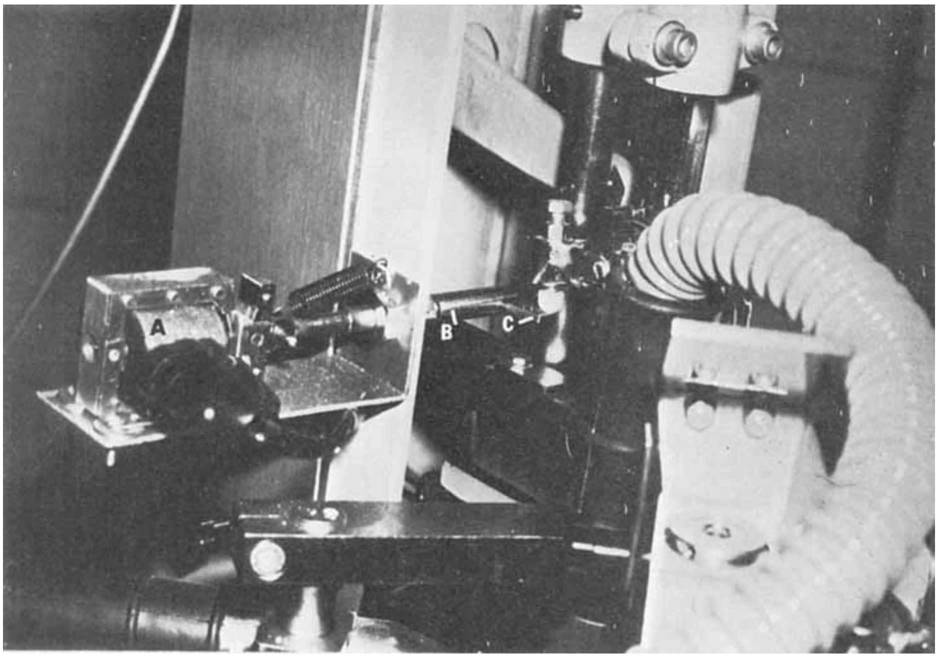

Figure 5—*Solenoid mechanism for alternate capsule feed. Key: A, solenoid; B, rod; and C, metal shoulder.*

metal shoulder, thereby preventing capsule feed. The tripping of the microswitch was timed so that omission of a capsule feed coincided with the missing dosator cycle by causing the lever to ride over hex nuts strategically fixed to the turntable edge. A return spring caused the metal shoulder to return to its original position, which permitted capsule feed for the instrumented dosator.

Preliminary Experience with Instrumentation System—To evaluate the system and to obtain force–time traces, No. 1 capsules were filled with representative fillers. The fillers were microcrystalline cellulose[10] NF, lactose[11] USP, pregelatinized starch[12] USP (compressible starch), and dibasic calcium phosphate[13] NF (unmilled). Fifteen hundred-gram batches of these materials were lubricated with 0.5% magnesium stearate[14], 80 mesh, by mixing in a twin-shell blender[15] for 15 min. The intensifier bar was run during the final 2 min to ensure efficient distribution of the lubricant. Abbreviated runs with unlubricated materials were also made.

The two piece star-wheel, which rotates at the bottom of the hopper, was adjusted to yield the maximum powder bed height of 49.4 mm. This was the height of the bed into which the dosators dipped. Then, with the star-wheel rotating and the dosators removed, powder was gradually added and allowed to come to an equilibrium bulk density at a hopper reservoir powder height of 25 mm. To prevent any possible change in powder bulk density due to changes in reservoir powder weight, care was taken to maintain this reservoir bed height to within approximately ±12 mm during all runs.

The dosator was then fitted to the dosator arm, and the instrumented piston was set to a height of 18.7 mm. This piston height, representing a setting of 9.5 graduated divisions on the upper shank of the piston, was the highest setting that would allow the apparent complete fill of the capsule at zero compaction at the maximum powder bed height regardless of the material being filled. The powder bed height and piston height were then kept constant throughout the evaluation.

The Zanasi filling principle includes compression of the dosed powder prior to ejection into the capsule. The degree of compression or the compaction level is controlled by the extent of displacement of the piston. This, in turn, is regulated by the length of the compression knob located on the compression–ejection arm. The length of the compression knob was adjusted such that it just touched the tip of the upper shank of the piston when the compression–ejection arm was at the lowest point of its downward stroke. At this setting, no displacement of the piston would occur for this piston height. This setting was taken to be the zero reference for compaction. Batches were run first at this setting and then, starting from this point, at knob length increments of 1.27 mm until the final free displacement of the piston was 6.35 mm.

Free displacement is, however, a theoretical displacement because, under filling conditions, the piston may or may not actually be displaced the full adjusted distance due to an overload relief mechanism. Much like the overload mechanism in a rotary tablet press, the compression knob is equipped with a spring in its support to prevent damage to the machine. Care was taken not to exceed the limits of this system.

DISCUSSION

Analysis of Force–Time Trace—Study of the force–time trace yields information about the forces generated during the filling cycle and the

Table I—Calibration of Instrumented Piston

Trial 1		Trial 2	
Applied Load, kg	Resulting Strain, microstrains	Applied Load, kg	Resulting Strain, microstrains
0	0	0	0
1.0	4.0	1.0	4.0
2.0	8.0	2.0	8.0
4.0	16.0	3.0	11.0
5.0	20.0	4.0	15.0
8.0	32.0	5.0	20.0
10.	40.0	6.0	24.0
15	60.0	7.0	27.0
20.	80.0	8.0	32.0
25	99.0	9.0	36.0
30.	119	10.	40.0
35	136	12	48.0
40.	158	15	60.0
45	179	18	72.0
50.	199	20.	80.0
		25	99.0
		30.	118
		35	135
		40.	156
		45	178
		50.	197
		60.	235
		70.	279
		75	299

Correlation coefficient = 0.999
Intercept = −0.0352 microstrain
Slope = 3.96 microstrains/kg

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[10] Avicel PH101, FMC Corp., American Viscose Division, Marcus Hook, PA 19061.
[11] Fast Flo, Foremost Dairies, San Francisco, CA 94104.
[12] StaRx 1500, A. E. Staley Manufacturing Co., Decatur, Ill.
[13] Stauffer Chemical Co., Industrial Chemical Division, Westport, CT 06880.
[14] Ruger Chemical Co., Irvington-on-Hudson, NY.
[15] Liquid solids blender P-K LB5695, Patterson-Kelly Co., East Stroudsburg, Pa.

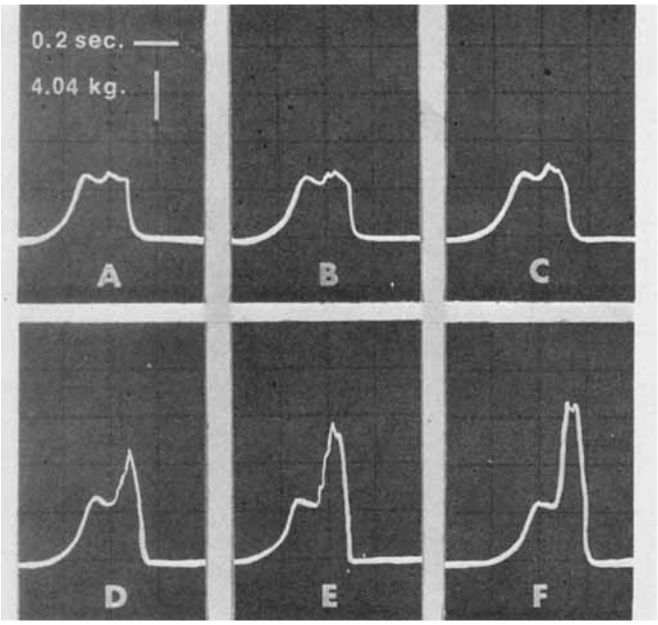

Figure 6—*Progressive changes in the force–time trace of lubricated microcrystalline cellulose.*

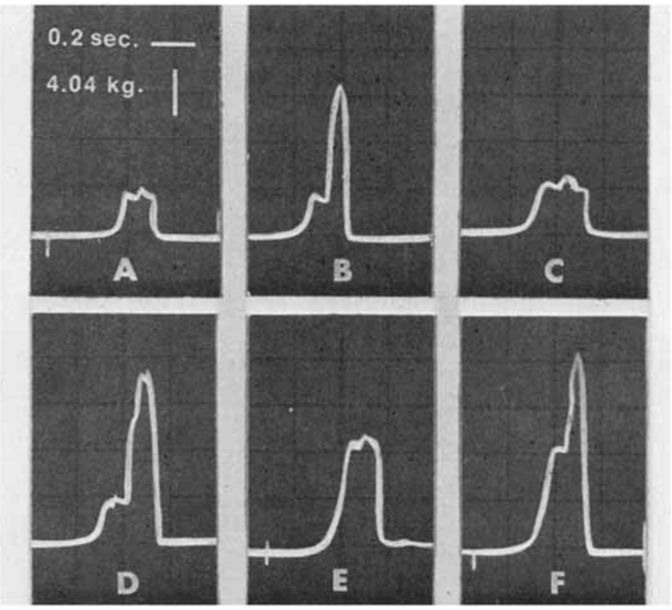

Figure 7—*Contrast of force–time traces of three materials (lactose, A and B; compressible starch, C and D; and dibasic calcium phosphate, E and F) at 0- (A, C, and E) and 6.35- (B, D, and F) mm compaction levels.*

sequence in which these forces occur. Figure 6 is a composite of single-compression force tracings of microcrystalline cellulose containing 0.5% magnesium stearate. Tracing A represents no compaction due to piston displacement (zero compaction level); tracings B–F represent the force trace changes as a result of continually increasing the compaction level with all other factors being held constant.

As the dosator dips into the powder bed, no force is recorded until the dosator penetrates the powder bed to a depth equal to the piston height. However, as the dosator continues its downward stroke, a force begins to be recorded and builds to a maximum at the maximum penetration of the filling head into the powder bed. At zero compaction level, this "precompression" force remains until the dosator is withdrawn from the powder bed (Fig. 6A). Since the powder bed height is greater than the piston height, it follows that the volume of powder sectioned by the filling head during the downward stroke of the dosing unit be either displaced or compressed into the adjusted volume of the filling head, resulting in the precompression force.

The pulse that appears to separate the wave form in Fig. 6A is not attributable to actual compression by the piston. This pulse coincides with the downward stroke of the compression–ejection arm which, when the compression knob is so adjusted, would ordinarily cause the piston to compress the sectioned powder. Because of the mechanical linkage between the compression–ejection arm and the dosator arm, some slight downward motion takes place in the dosator arm as the compression–ejection arm is in its lowest downward travel. Thus, the complete dosator unit essentially acts to compress the powder slightly at an adjusted zero compaction level.

As the compaction level increases, the second half of the trace begins to rise. This increase in compression force reflects the actual compression of the powder in the filling head. The rise in compression, to a maximum of 12.9 kg of force, is shown in Figs. 6B–6F.

The precompression force decays slightly in every case. After the dosator penetrates the powder bed and the precompression force is generated, there is a lag time (about 0.1 sec) that represents the travel time of the compression knob to the piston. During this period, the compressed powder probably undergoes some rearrangement or slight displacement of powder between the lower end of the filling head and the floor of the powder hopper.

Some slight decay also occurs in the compression part of the trace (Figs. 6D and 6E) during the short, but finite, dwell time of the maximum compressive force. As the compression knob lifts, the spring retracts the piston and the force trace drops rapidly to the zero baseline.

Figure 6F, for microcrystalline cellulose, and Figs. 7B, 7D, and 7F, for lactose, compressible starch, and dibasic calcium phosphate, respectively, depict the force responses generated by a constant piston displacement or compression of 6.35 mm. An evaluation of these tracings reveals the following decreasing order of compression forces developed under these circumstances: dibasic calcium phosphate, 16.2 kg; compressible starch, 14.8 kg; lactose, 13.3 kg; and microcrystalline cellulose, 12.9 kg.

These differences are, no doubt, due to differences in initial packing densities as well as to differences in the relative ability of these substances to undergo further consolidation and voids reduction under the present experimental conditions. As previously noted, all samples were allowed to reach their own characteristic equilibrium packing density (due to the agitation induced by the star-wheel) at the same powder bed height prior to capsule filling. Under these relatively low compressive forces, such consolidation is likely mainly due to particle rearrangement with only slight elastic and/or permanent deformation.

Regardless of the material, all force tracings resemble one another in these runs. Also, all lubricated batches exhibit barely measurable ejection forces of less than 1 kg. This finding is surprising in view of the fact that these batches employ only 0.5% magnesium stearate. Stoyle (8), for instance, empirically determined lubricant requirements of up to 3% magnesium stearate for running lactose in a larger model of the same type of machine. Although there were no indications of poor lubrication in the small batches run here, lubrication requirements possibly would be greater under the stress conditions of a full-scale production run. For a given compression force, longer slug lengths may also increase lubrication requirements due to the increased area of contact with the filling tube.

Cole and May (5) made no mention of the compaction adjustment in their report, although the Zanasi filling principle clearly is based on the compaction of the slug prior to positioning over the capsule body. Also, the tracings published by Cole and May did not reflect the two stages, precompression and compression, as presented in this work.

Unlubricated Materials—The effect of varying levels of lubricant on the ejection force was not an objective of this work. However, the force–time traces of unlubricated materials were considered important, particularly since two fillers, microcrystalline cellulose and compressible starch, are self-lubricating when used alone as tablet fillers (9, 10). The force–time traces of these two materials are shown in Fig. 8. The compression event precedes ejection. The occasional small spikes appearing between the compression and ejection events are due to the cycling solenoid.

Figure 8A shows the usual compression trace (compression force = 9.7 kg) and the ejection event (ejection force = 5.5 kg) of microcrystalline cellulose. This trace contrasts markedly with the trace for the compressible starch (Fig. 8B), which exhibits a retention force (positive deflection of trace above baseline between compression and ejection) and a negative deflection just after ejection. Similar findings were reported by Cole and May (6).

The retention force noted in the unlubricated starch run (Fig. 8B) indicates a residual pressure on the end of the piston as the slug is trans-

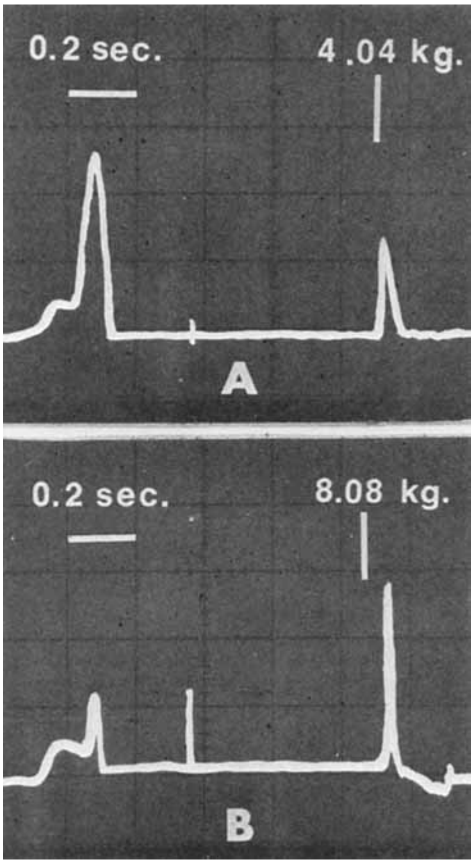

Figure 8—*Force–time traces of unlubricated materials. Key: A, microcrystalline cellulose; and B, compressible starch.*

ported to be ejected, possibly due to elastic rebound of the slug against the piston. This phenomenon occurs not only with compressible starch but also with unlubricated microcrystalline cellulose and lactose when run under conditions of relatively low compression force (*i.e.*, low powder bed heights and zero or low compaction levels). Apparently, under these conditions, bonding within the slug is insufficient to prevent expansion against the piston. However, unlubricated starch also produces a retention force when compressed at the maximum powder bed height and/or with a high compression force. This result is possibly due to a high modulus of elasticity in the case of starch. Lubricants presumably allow the slug to slip to relieve the residual pressure; this phenomenon was not observed in any lubricated run.

The negative deflection following ejection in Fig. 8B indicates tension on the piston as it is being retracted. A similar observation was reported by Cole and May (6), who suggested that this tension is likely to be caused by the adherence of material between the wall of the filling head and the piston. Under such circumstances, binding of the piston would be expected to occur, thereby leading to tension on the piston as it is being retracted by the spring. In the present study, particle adherence was observed in such cases, particularly on the piston. A similar phenomenon in tableting gives rise to a lower punch pulldown force (11).

Extreme care was taken when running unlubricated lactose and basic dicalcium phosphate. Very high ejection forces (up to 30 kg) developed after only 20–30 capsules had been filled, and the runs were terminated to prevent possible damage to the machine.

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