Development of a membrane switch-type full-travel tactile keyboard

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This paper describes the approaches to design and the rationale that successfully satisfied the requirements for a full-travel keyboard with usage exceeding 10 million actuations per character, satisfactory N-key roll-over, and phantom key control. Emphasis was placed on technical understanding of the effects of all material and design decisions. Interactions among design, material, and processing variables were revealed through statistical parameter modeling and environmental exposure studies. This knowledge facilitated the control of critical parameters to permit an order-of-magnitude reduction of actuation forces and tolerances. Product reliability was achieved through evaluation, environmental protection features, and stringent process controls. This paper highlights the design, materials, and processing aspects of the membrane switch developed for low-force keyboard applications. It also discusses effects of environmental factors on the individual components and overall system function.

Introduction

To reduce product cost in the area of keyboards, design concepts which would reduce part count, lower raw material costs, and lend themselves to automation were sought. Adaptation of membrane switch technology to a high-reliability keyboard design required changes to the available products. The industrial uses of membrane switches have predominately been in panel switches and no-travel, limited-tactile-feel data entry devices. Changes in materials, processes, and design were required to produce a typewriter keyboard with good tactile response. Force levels were lowered an order of magnitude from the 100–200-gram range commonly found. The force tolerance was reduced by a factor of five (±5 grams versus ±25 grams). This reduction was accomplished by critical controls on all variables affecting switch forces. Special equipment designed to measure switch forces to a tenth of a gram was used in the evaluations.

Many of the early material decisions were governed by existing membrane switch products available on the market. The visual simplicity of the system in no way reflected the complex array of variables present. Examples include

1. The effect on switch performance of the glass transition temperature of the polymer binder in silver compositions.
2. The effects of the polymer binder structure on flexural fatigue resistance.
3. The influence of residual solvents on silver particle mobility within the polymer binder matrix, leading to changes in electrical resistance.
4. The effect of substrate thickness tolerance on switch force.

Preliminary searches of published literature revealed that very little engineering data had been generated. As a result, only raw material data were readily accessible.

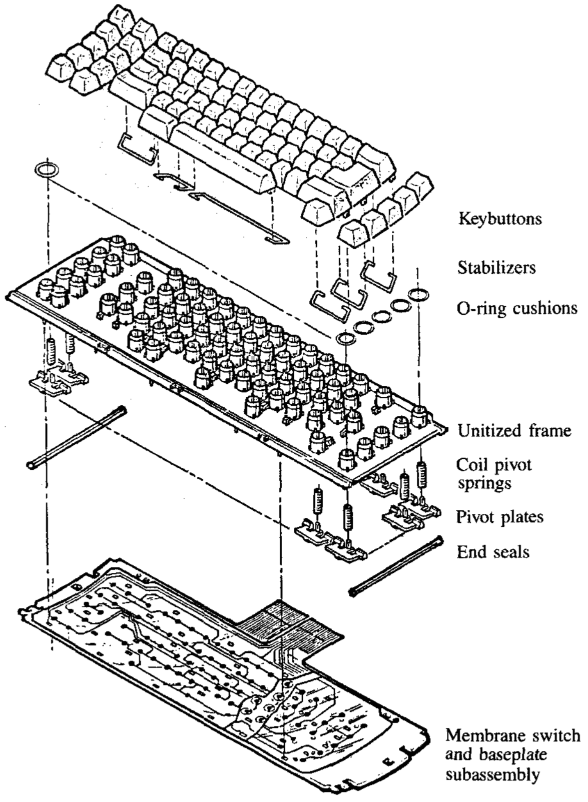


Figure 1

Exploded view of entire keyboard assembly (minus covers).

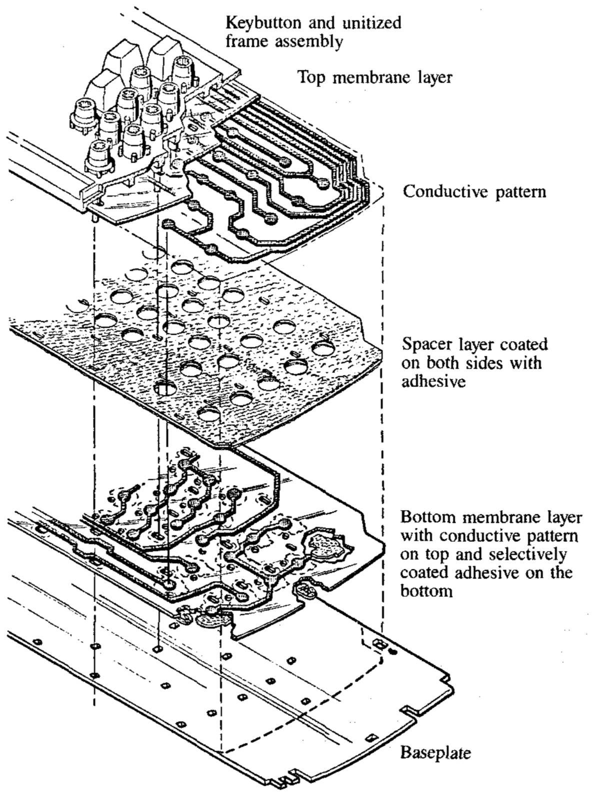


Figure 2

Exploded view of membrane switch layers with unitized frame, spacer layer, adhesive layers, and baseplate.

Previous work using silver in electronic circuitry had resulted in serious corrosion and migration issues [1, 2]. Since silver-particle-filled polymer compositions are the materials used for membrane switch conductors, reliability testing was given high priority. Results from extensive exposure testing showed that the use of silver in this application does not present a risk. Comparisons with previous silver circuitry applications show why those earlier results do not apply to this system.

This article describes the design, the material systems, the processes, and the stressed exposure studies that were essential to membrane switch development. It is divided into three sections. The first section discusses hardware design, membrane switch physical attributes, and function. The second addresses processing and properties of the four main material groups: polymer film, silver conductor composition, structural adhesives, and passivations. The third section covers environmental exposure and includes a six-month study of the effects of high temperature and humidity on the strength and structure of synthetic-rubber-based adhesives, the effect of corrosive gas exposure on the conductor composition, and the influence of particulate contamination on switch performance.

Design

The two major subassemblies of the membrane keyboard are the actuation system and the membrane switch. These are shown schematically in **Figures 1** and **2**. Figure 1 shows how the keyboards are assembled, beginning with the mating of the keybuttons to the unitized actuator frame, which in turn fastens to the membrane switch and baseplate subassembly. Figure 2 shows the subassembly of Fig. 1 by component layers. **Figure 3** is a schematic cross section of a single keybutton assembly illustrating the relation of the membrane switch components to the keybutton assembly.

This section discusses the design of the keyboard system with emphasis on the mechanical and materials aspects of the membrane switch. Key components of the actuation system are discussed where they interact with or influence decisions on membrane switch parameters. The membrane switch is a three-layer design; a conductive silver composition is deposited on the facing sides of the top and

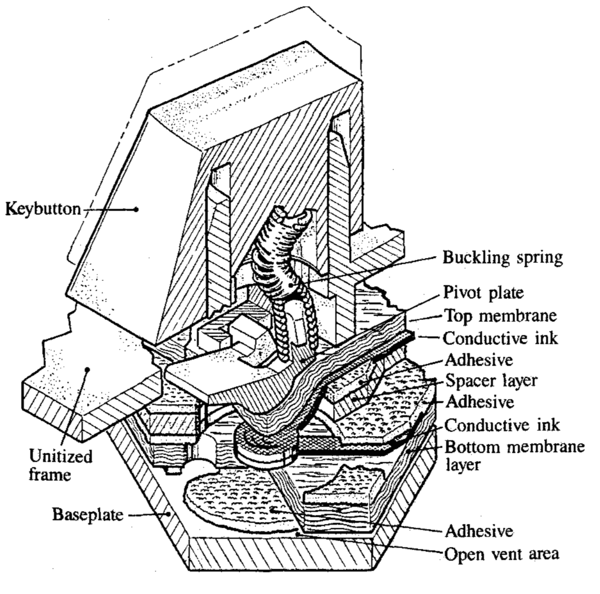


Figure 3

Cross section of one keystation during actuation (not to scale). Buckling spring applies a twisting movement on pivot plate, which rocks up on radius on bottom and closes switch gap to contact.

bottom layers prior to assembly. These conductive circuit patterns are the electrical contacts for each keystation and the electrical interconnections. The bottom layer is powered, the top layer electronically sensed. The spacer layer provides the gap between mating contacts via holes at each keystation. A switch closure is accomplished by deflecting the top layer enough for the contacts to touch (approximately 0.015 mm).

The three-layer switch subassembly is adhesive-bonded to a radiused steel baseplate which serves as the primary structural member of the keyboard assembly. By selective coating with the adhesive, openings are produced which allow air to escape via small holes in the bottom layer of each switch cavity. This technique is called "venting." Some method of venting is incorporated into most membrane switches used in keyboard applications. Equalizing the air pressure maintains consistency and the low-level actuation forces required for proper operation and rapid switch recovery.

A molded plastic unitized frame positions and guides the keybuttons and actuator mechanisms. It is fastened to the membrane switch by tenons on the underside of the frame which pass through clearance holes in the membrane switch and baseplate. These tenons are hot gas staked to form a permanent assembly.

The membrane switch actuator mechanism consists of a pivot plate and coil spring. The assembly is designed to deliver a force of 27 grams. The spring is guided by a molded detail in the keybutton, and the pivot plate is located and retained by details in the unitized frame. A cam surface is molded on the pivot plate at the point where it contacts the membrane switch. When a key is depressed, the spring buckles, applying the full downward component to the plate. The resulting reaction is a rocking or "pivoting" of the plate up onto the cam surface, which applies enough normal force to close the switch at that keystation (Fig. 3). Critical variables in maintaining uniform actuation forces are spring wire diameter, spring length, radial coil orientation, number of active coils, and presence of burrs.

A radiused base plate was selected to minimize the number of different keybuttons and to maintain a contoured typing surface profile. The unitized frame was designed with a nonuniform cross section to allow a segmented deflection by keyrow and approximate conformance to the baseplate radius. All single-unit keybuttons are the same; only the special function keys such as "shift" and "return" are unique. Keybutton graphics are applied by a sublimation dye process. This technique has eliminated the need for two-color double-shot molded buttons and allows fully automated assembly. (In double-shot molding, two polymer resins, different either in color or in chemical type, can be molded into one part by successive molding operations. The first shot serves as an insert or outsert around or into which a second shot is injected.)

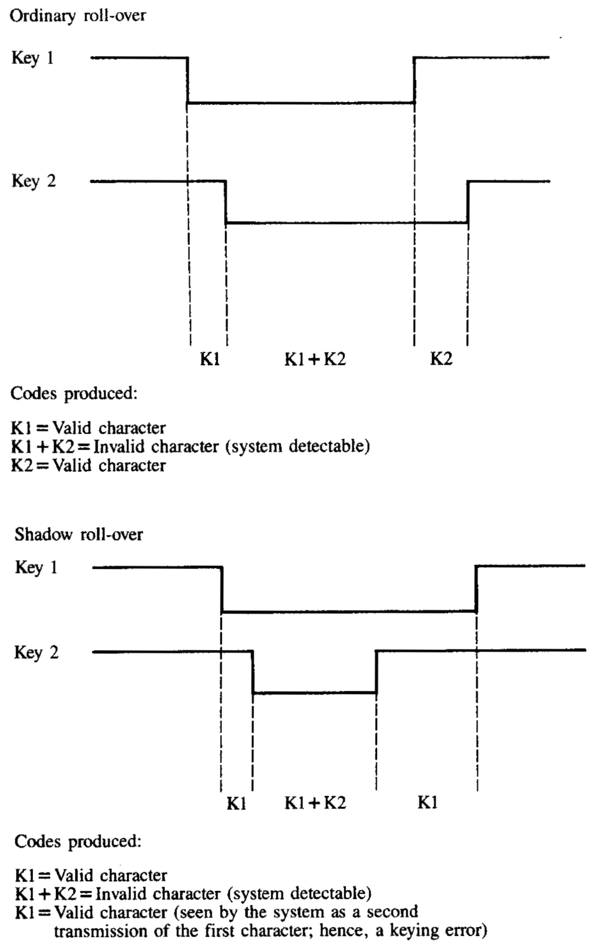
The following is a summary of design guidelines established for membrane switches used in keyboards:

1. The maximum allowable membrane switch actuation force should equal the keybutton force multiplied by 0.5 for actuation efficiency multiplied by 0.5 for bounce reduction. (Bounce is the unwanted opening and closing of the switch contacts after the initial making or breaking of the switch, primarily caused by oscillation of an undamped pivot plate assembly.)
2. Membrane switches to be used on a radiused surface should be constructed in a radiused position, not constructed flat and subsequently formed.
3. All layers of the membrane assembly should be structurally bonded.
4. Switch cavities should be vented to allow equalization of air pressure upon actuation.
5. Thickness of top and spacer layers is critical to maintaining uniform actuation force and should be toleranced accordingly.
6. A class 100 000 clean room or the equivalent should be used for component manufacturing with an assembly area of class 10 000. All operations should be grounded, and pure deionized air should be used to prevent static attraction of particulates on the film layers.

- *Membrane switch layout*

The *key "roll-over" capability* of a keyboard refers to its ability to process multiple key depressions without loss of key entry data. Generally, *"N-key" roll-over* refers to the ability to produce valid key data when a key is depressed or released regardless of the number of other depressed keys. *Two-key* or *"shadow" roll-over* means that a second key depressed will not produce electrical key data until the first key is released. Data for the second key are lost if the second key is released before the first key. The above are the two forms of roll-over most widely encountered (**Figure 4**).

Membrane switch keyboards produce invalid or "phantom key" outputs unless specific scanning techniques are employed. Phantom output exists because unwanted signal paths are created when two switch closures on the same row or column react with a third closure on another row or column to produce a signal from an open contact on that second row or column (**Figure 5**). Therefore, any time three contacts are closed that form corners of a rectangle in the scan matrix, the fourth corner will be a phantom key.



Codes produced:

K1 = Valid character
K1 + K2 = Invalid character (system detectable)
K2 = Valid character

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K1 = Valid character
K1 + K2 = Invalid character (system detectable)
K1 = Valid character (seen by the system as a second transmission of the first character; hence, a keying error)

Figure 4

Ordinary and shadow roll-overs.

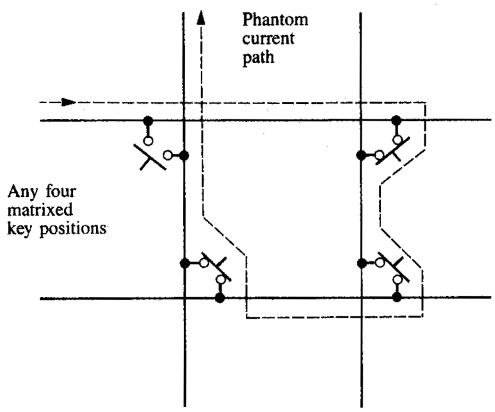

Figure 5

Phantom key signal path created when two key signals from one row or column react with a third key on a second row or column, which produces a false signal from a fourth key on that second row or column.

Human factors data show an insignificant error rate of 0.009% for roll-overs caused by the simultaneous depression of three or more keys.

Three-key roll-over provides valid data for two sequentially depressed keys. A third key depression does not produce an output until one or the other of the first two keys is released. Three-key roll-over ability can be implemented with a microprocessor controller to minimize problems with phantom keys. In addition, proper membrane layout can provide the capability of allowing certain simultaneous three-key depression combinations without phantom key exposures. Layout of the membrane can minimize roll-over and key phantom key problems encountered by skilled typists. Each key is depressed by a given finger (excluding special function and outboard keys). By assigning each key struck with a given finger to the same drive line, the phantom key problem is essentially eliminated.

Force parameter modeling

Switch actuation force was experimentally modeled on the following five variables: 1) sense or top layer thickness, 2) spacer thickness, 3) spacer hole diameter, 4) ink thickness, and 5) curvature. Only the ink thickness was found to be an insignificant contributor to the actuation force. Increasing the sense layer thickness and the spacer thickness increased the actuation force. Increasing the spacer hole diameter decreased the actuation force. Assembling the membrane on a curved baseplate increased the force and the variance. By using regression analysis, the following first-order equation was derived for predicting the actuation force:

$$F = 250.0S + 285.3L - 3.82H, \qquad (1)$$

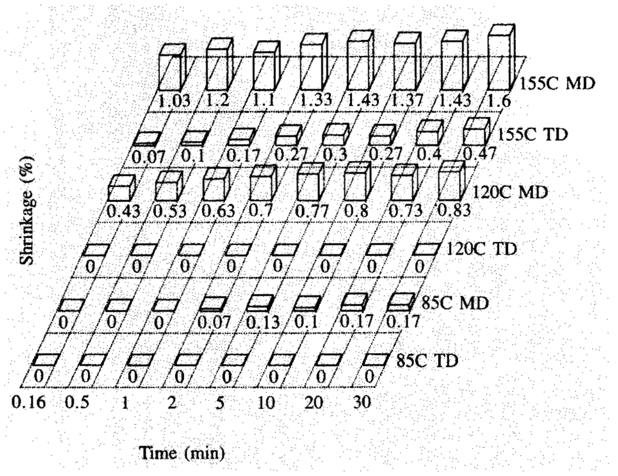

Figure 6

Polyester film shrinkage—the effect of temperature and time on the dimensions of 0.12-mm polyester film (unstabilized) in the transverse and machine directions.

where F is the actuation force in grams, S is the spacer thickness in millimeters, L is the sense layer thickness in millimeters, and H is the spacer hole diameter in millimeters. This is for a radius of curvature of 280 mm, which matches the radius on IBM ®SELECTRIC System/2000 keyboards.

Given an actuation force range of 13.5 ± 3.5 grams, membrane switches were constructed to the dimensions indicated by Eq. (1). Experiment had also indicated that the force range could be achieved by using a sense layer either 0.075 or 0.1 mm thick. The 0.075-mm thickness was chosen because the thickness tolerance had less effect. The other variables S and H were balanced to levels where the variance was lowest. This resulted in a design with a 0.075-mm sense layer, a 0.15-mm spacer thickness, and an 11-mm spacer hole diameter. Since the film substrate is only available in increments of 0.025 mm, the actuation force predicted by the model for the best combination of the three variables was 14.9 grams. A top layer of 0.069 mm would have been required to produce the target force. This was compensated for by increasing the spacer thickness slightly via the adhesive coat weight. The force on membrane switches made with these parameters correlated with the predicted force within experimental error. Measurements were made on a force/deflection tester designed using a proximity probe and a strain-gauge actuator.

Materials and processes

• *Film substrates*

Of the film substrate materials available for use in membrane switch construction, PET (polyethylene terephthalate) was chosen on the basis of its flexural fatigue resistance, good overall physical properties, and relatively low cost. In addition, PET is resistant to a variety of chemicals and environmental aging, and it is bondable with many common adhesives. PET does, however, have some limitations which have an influence on membrane switch applications. The biaxial orientation induced during the initial processing of the film results in shrinkage during any subsequent thermal processing (**Figure 6**). Control of this shrinkage is important for proper registration of the conductor pattern. Relief of biaxial orientation by a process called "stabilization" prevents excessive dimensional change during secondary thermal processing. Stabilizing is generally done at a temperature 10–20°C higher than the maximum expected process temperature. If close registration of coatings is not required or if a low-temperature-curing (<100°C) conductor is being used, stabilization may not be necessary. Even though PET film is biaxially oriented with on-line stretching equipment, there is still greater orientation and therefore shrinkage in the extrusion direction. It is beneficial to lay out the membrane pattern with the longest dimension in the transverse direction of the film to minimize the effect of any dimensional changes. Standard grades of PET have a thickness or gauge tolerance of ±10%. This can cause a difference in switch actuation force of up to 30%.

Under cyclic stress loading, polymers relax. Test results have revealed that under normal switch actuation, relaxation is slight and does not affect proper switch function. Certain situations where excessive relaxation has occurred need to be guarded against. "Latchdown" designs can decrease a switch contact gap to unacceptably small clearances in a relatively short period of time. *Latchdown* refers to the conditions in which switch contacts are held closed to maintain the alternate operational mode on dual-function key positions. Any situations which unintentionally create latchdown, such as a stuck button or excessive dirt buildup in the actuator mechanism, introduce the potential for failure.

PET has limited temperature stability (although the service temperature of 150°C is more than adequate for most membrane switch applications). Second-generation applications with direct attachment of electrical components, wire bonding, or soldering may require higher-temperature substrates. Also, the inherent flammability of PET is a potential safety exposure. Polyimide, polyethermide, polyethersulfone, and polyetherketone are under evaluation for membrane switch use. Polyester film, however, presents the best cost per performance ratio of commercially available films. Most of its undesirable properties either are inherent in all films or can be compensated for without major cost or design penalties.

• *Adhesives*

In most membrane switch designs, adhesives are used for construction in two locations. Adhesive applied to both sides of the spacer layer provides proper registration of the top and bottom layers. Another layer of adhesive is generally used to fasten the switch assembly to some type of structurally supporting member, such as a baseplate. Depending on the particular design, the requirements for these adhesives may vary.

The family of keyboards used on the IBM SELECTRIC System/2000 Typewriter consists of a spacer coated on both sides with an acrylate pressure-sensitive adhesive (PSA). The major requirements are stability, strength retention, and the ability to maintain concise registration of the circuit layers in the X, Y, and Z directions. The adhesive layer used to hold the switch assembly to the baseplate also forms the network of passages for venting.

The majority of the development activity on adhesives was dedicated to the vent-layer adhesive. The requirements of good resolution and tight thickness control greatly limited the material options. Other requirements included processability, good adhesion, temperature stability, and resistance to environmental degradation. Silk-screening proved to be the most versatile and economical processing method, but it eliminated many candidates. Screen clogging and stringing created problems. Certain formulations of two groups of pressure-sensitive adhesive were identified which offered the right balance of properties and processing. One group was based on styrene-butadiene rubber (SBR); the other was a blend of a synthetic elastomer and acrylate. Both are supplied as approximately 50% solids in aromatic solvents.

- *Silver conductor composition*

Silver conductor materials, often referred to as silver inks, are commercially available for semiautomatic and automatic silk-screening of circuit patterns. Although limited by moderate line spacing and resolution, silver inks provide an economical alternative to etched metal and hard wire for low-cost, low-duty-cycle PTF (polymer thick film) applications. Key properties for silver inks include 1) uniform silver particle size and distribution, 2) homogeneous dispersion in the polymer binder, and 3) high glass transition temperature (T_g) of the binder. Low-T_g (40°C) binder materials exhibited certain reactions to the stress of switch actuation which sharply decreased their life expectancy and reliability. Nonhomogeneous areas in the contact pads rich in resin tended to stick, creating a permanently closed switch [**Figure 7(a)**]. Phase separation of the binder and the silver particles, occurring due to switch cycling, led to resinous interfaces which prevented electrical contact of the silver [**Figure 7(b)**]. Cyclic bending of the input/output (I/O) flextails even over a moderate radius resulted in unacceptable increases in line resistance, again due to separation in the silver binder matrix [**Figure 7(c)**]. These phenomena were not experienced with ink 55–60°C in T_g [**Figure 7(d)**]. In this family of thermoplastically bound inks, increased T_g is attributed to a higher ratio of aromatic/aliphatic chain sections of the binder. Most ink binders are aliphatic polyesters synthesized from diacids and glycols. The higher-temperature inks have an aromatic diacid structure (terephthalic and isophthalic acids). The aromatic segments allow much less molecular mobility due to their bulkiness, and this leads to the higher T_g. This more stable structure also leads to better flex resistance and a generally tougher product.

A major factor in developing proper ink properties is the residual solvent level. High electrical resistance and the failure modes discussed earlier can occur if the residual solvent level is too high. Process time and temperature control residual solvent and also affect adhesion to the substrate. Optimizing these parameters has produced adequate adhesion without any special surface preparation of the substrate.

- *Circuit passivation*

Sandwiched between layers of film and adhesive, the conductive ink is adequately protected from physical abuse and most environmental influences. However, where the I/O lines on the flextails leave the assembly, two types of protection are provided. A permanent coating is satisfactory for all but the area where electrical connections are made. For permanent protection, either film lamination or conformal polymer coatings may be used. Both methods have been shown to produce an adequate level of protection, i.e., scratch penetration and resistance from corrosion. For the contact area, a solvent-based paraffinic contact lubricant was selected. It is displaced under connector insertion, yet offers environmental protection in the unconnected state.

Environmental exposure

Silver, as an electrical conductor, has two well-documented problems: corrosion by the atmosphere, to form nonconducting reaction products; and migration of silver ions across voltage drops, causing short circuits [3–5]. Consequently, silver is not recommended for such low-voltage/low-current applications as logic circuits, or for high-voltage/high-power uses. There have been field problems from both conditions which have resulted in a cautious attitude toward the use of silver-based conductive species. Typically, the solution to both failure modes is to apply an overcoat to isolate the silver [6, 7], although there are cases where certain coatings such as polysiloxane have turned out to be a concentration medium for reduced sulfur vapors. Two corrosive atmospheres were used for accelerated testing: G1, which is based on concentrations of corrosives in an office environment, and G2, based on industrial atmospheres. For silver, there is a third possible test atmosphere known as flowers-of-sulfur vapor. The reduced sulfur concentrations are ranked as follows: G1 is less corrosive than sulfur vapor at 65°C, which is less corrosive than G2.

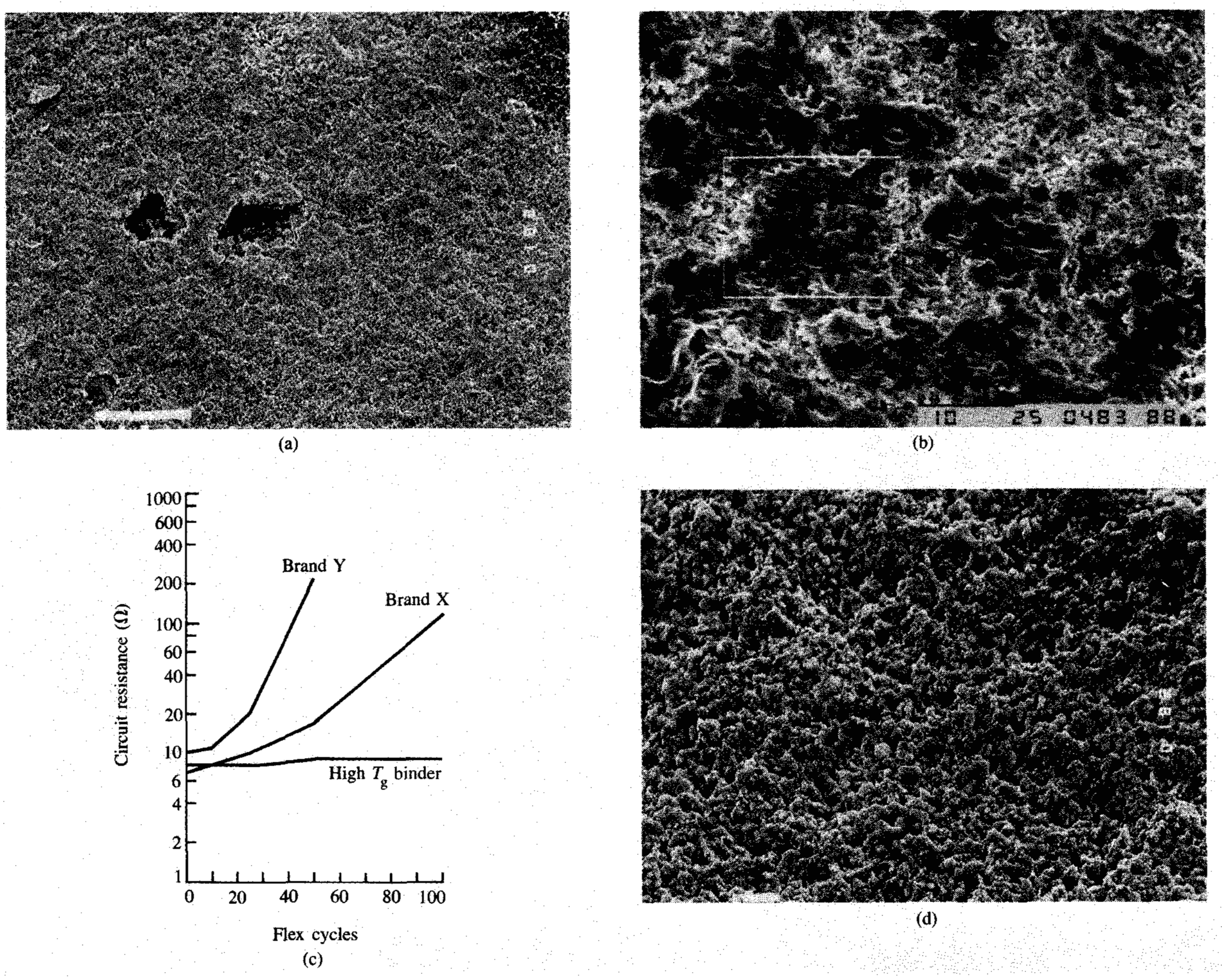

Figure 7

Failure mechanisms of conductive silver composition: (a) contact sticking due to low glass transition polymer binder—45 × magnification; (b) areas rich in polymer resin due to phase separation of binder matrix and silver particles—1000 × magnification; (c) electrical line resistance of three conductive compositions after 100 flexural cycles through 180° at a 1-mm bend radius; (d) high glass transition composition as processed—1000 × magnification.

It is important to consider aspects of the hardware and design of these membrane switches that affect silver corrosion and migration. One aspect that tends to accelerate silver reactivity is filler loading above the critical pigment volume. This forces intimate particle contact beneficial for electrical conductivity, resulting in an open structure with higher gas porosity. Thus, bulk corrosion should be a greater exposure for silver ink than for solid silver. A second factor in the acceleration of silver reactivity is that the flextail mating area is exposed during inventory and partially exposed during installation.

Aspects that tend to inhibit silver interaction with corrosive species and moisture are the following:

1. The switch contact areas and the majority of the lines are enclosed by polyester film at least 0.75 mm thick. Gas exposure is limited by the permeation rate through the film and the small volume of air exchange through the vent system.
2. The electrical characteristics are favorable: 5 V dc nominal operating voltage, 0.1% voltage duty cycle (1 μs sweep per ms), and 75 Ω as maximum resistance for

sensing a closed circuit.
3. Gas-tight connectors are used.
4. The closest line spacing is 1.0 millimeters.

- *Atmospheric corrosion*

Unprotected membrane circuitry and completed membrane assemblies were exposed for 500 hours to G1 and sulfur vapor at 29°C and 65°C, respectively. No failures (defined as >75 Ω from drive line to sense line through a closed contact) were found in the G1 tests. Membrane assemblies, unprotected circuitry, and samples with various passivations were tested in the G2 environment at 29°C for 54 hours and at 70°C for 96 hours. Assembled membrane switches with flextail passivation, contact lubricant, and gas-tight connectors showed excellent resistance to the test environment. Open membrane layers were strongly attacked, having 8% failure in 54 hours at 29°C, and 100% failure under the more severe conditions. Comparison of eight contact passivation systems revealed the paraffinic contact lubricant to be superior. Even with the contact lubricant, sulfur attack was greatest in the flextail and connector areas.

- *Silver migration*

Sample configurations were clean bare lines, contaminated bare lines, and passivated lines (**Table 1**). The exposure sequence consisted of three ten-day cycles of Mil-Std 202F/106E with ten connector withdrawal/insertion cycles prior to each cycle [8]. (Note that Mil-Std 202F/106E has a freeze cycle which forces condensation.) The connector withdrawal/insertion cycling was used to demonstrate mechanical stability of the overcoats and conductive ink. Alternate lines were powered at 30 V dc during the 30 days of temperature/humidity cycling. No cleanliness precautions were used during the withdrawal/insertion cycle handling. The failure criterion for the testing was line shorting. Test conditions, compared to the nominal membrane switch exposure, were 6× over-voltage (30 V dc versus 5 V dc), closest actual line spacing, excessive connector handling, and 72× continual voltage bias (720 hours duty cycle versus 10 hours duty cycle. Eight hours per day × 250 work days per year × 5 years × 0.001 "current on" time per keystroke = 10 hours powered).

On bare conductors, migration was readily demonstrated. It was directly related to the quantity of ionic contamination present and could be prevented or promoted by cleanliness levels. The contaminated bare conductors failed. All other samples had no migration failures. These tests were run with membranes lying flat, and also suspended vertically to confirm that water bridges did not form across the contacts inside the membrane switch cavities.

- *Adhesive aging*

A six-month adhesive aging experiment was performed with peel strength as the dependent variable. The adhesive used was the synthetic rubber/acrylate-based PSA. Samples were prepared by screening 25 × 150-mm areas of adhesive on 0.12-mm polyester film. Peel strength values were determined using ASTM D3167, "Floating Roller Peel Resistance of Adhesives" [9]. Variations in adherent surface treatment and environmental test conditions were evaluated over 240-, 1020-, and 4056-hour test periods. The three surfaces evaluated were "dull" zinc preplated stock with and without a wax/oil corrosion inhibitor, and "glossy" zinc plating with yellow chromate coating. The environmental conditions were 23 ± 2°C/50 ± 5% relative humidity, 65 ± 1°C continuous, and Mil-Std 202F, Method 106E (minus freeze cycle).

The adhesive retained its peel strength in all environments and with all surface treatments for the 4056-hour test period. Infrared analysis of the chemical structure of the adhesive revealed a slight change in the carbonyl-to-methylene stretch bonds. This ratio is an indicator of oxidation of the double-bond sites, which leads to eventual breakdown of properties. There was no significant difference between the results for 22°C/50% R.H. and the two more hostile environments (**Table 2**). The test period of 4056 hours represents 10% of product life. The ability of the adhesive to resist this severe environmental stress (with no significant deterioration) should ensure lifetime performance under much less severe office or light industrial conditions. The resistance shown by the adhesive to environmental stress may be partially due to

Table 1 Passivations tested for silver corrosion and migration protection.

Type of passivation	*Summary*
Contact lubricant	Nine types evaluated Wiping-type connectors make good electrical contact Oil/grease-based coatings cause softening of conductor Most are effective in migration protection Polyphenyl ether oil/hydrocarbon wax—best sulfide and migration protection (material chosen)
Conductive overscreen (nonmigratory conductive fillers)	Copper, carbon fillers evaluated Copper—sulfide attack, delaminate from silver during insertion/withdrawal cycling Carbon—high and variable contact resistance (50–500 Ω)
Total encapsulation	Epoxy, silicone evaluated Nonreworkable Silicone acts as sulfur-attractor, accelerates tarnishing of conductor surface

Table 2 Adhesive aging experiment.

Group	*Subgroup*	*Peel strength* (g/mm)
Exposure	23°C/50% R.H.	42*
	65°C	51
	Mil-Std 202-106E	48
Surface treatment	Paraffinic contact lubricant	53*
	Preplated zinc (dull)	43
	Zinc (glossy)	44
Time	10 days	44
	45 days	47
	169 days	49

* Significant deviations with 95% confidence level from the mean peel strength within each group.

the configuration in which it is used. The design protects the adhesive from the predominate degradation mechanism, oxidation, by limiting direct exposure to the edges, with the remainder subject only to gas diffusion.

- *Particulate contamination*

Keyboard membrane switches have several modes of failure due to particulate contamination. They include wear on mechanical parts, interruption of electrical circuits due to a nonconductive species between the switch contacts, and buildup of material in the actuator, preventing proper action of the pivot plate. Sources of debris include the manufacturing process, during which foreign matter becomes sealed within the membrane switch assembly, and the field environment, where particles can penetrate through the vent system into the membrane switch interior. A series of synthetic dusts were developed to study the effects of field contamination [10]. The dust was both shaken onto the keyboard assemblies and applied under pressure (80 psi) for about two minutes. Fifteen applications were made at intervals equivalent to four months' usage during accelerated life-cycling tests.

No keyboard, in either balanced or uniform usage testing, failed due to particles migrating into the switch chamber. Excessive wear was observed on all system components due to the abrasiveness of the particles in the synthetic dirt, especially Al_2O_3 and Fe_2O_3. This included pivot plates, springs, the unitized frame, and the top membrane layer. The observed relaxation in the substrate and ink fracturing were attributed to the excessive particulate buildup in the actuators. These two factors have developed only when cycling under severe contamination test conditions. Under these severe conditions, keyboards averaged 90% life, i.e., 9×10^6 cycles per key, in uniform usages and met life requirements, i.e., 43×10^6 total cycles, in balance usage tests.

Summary

A keyboard membrane switch was developed which demonstrated reliable switch performance and met the desired objective of ten million actuations per position. Extensive evaluations of materials, processes, and design were responsible for meeting this objective. The final design exhibited compatibility with the existing actuator system, with only minor modifications of the pivot plates.

Polyetheylene terephthalate demonstrated the best cost performance for membrane switch substrates. To meet quality and reliability requirements, emphasis was placed on prestabilization for dimensional control, substrate stress relaxation, and the use of thickness-consistent material. Two adhesive systems were required for construction. An acrylate-based pressure-sensitive adhesive was used to assemble the three switch layers. A modified acrylate was selectively silk-screened onto the bottom layer for attachment of the assembly to the base plate, and for creating vent openings. Six months of stressed exposure to hostile environments revealed no harmful effects on the adhesives.

Conductive inks with an aromatic polyester base proved superior to various other compositions on the basis of durability and overall service performance. An array of tests, under conditions at least two orders of magnitude more severe than service conditions, did not reveal silver migration problems. This is due to a low duty cycle (<0.1%), wide line spacing, low voltage, limited ionic contamination, and incorporation of passivation on the exposed conductor. I/O flextails were permanently coated up to the connector mating area, where a contact lubricant was used. These precautions, along with the inherent protection afforded the switch contacts by the design, satisfactorily inhibited corrosion and sulfiding. Particulate contamination testing revealed little risk of external particles entering the switch cavities and causing a problem. The greater exposure comes from "manufacturing" contamination, which can be maintained at suitably low levels by contamination control procedures.

The following are some of the advantages offered by the keyboard membrane switch over previous products: The low nominal actuation force and narrow range enable the use of conventionally styled full-travel actuators with the desired tactile response. Without actuation forces in the 10–15-gram range, the "touch" of an IBM keyboard would not be possible. Reliability has been improved by changes in two areas: the selection of a more thermally stable conductor composition, and stringent control to prevent dimensional changes and contamination during primary and secondary processing. Automation potential and low materials costs give membrane switches an economical advantage over other switch designs.

Acknowledgments

The authors would like to acknowledge the contribution of the following persons: J. G. Price, for his work on membrane switch parameter modeling and organization and support of the contamination studies; R. A. Christiansen, for his work on silver migration and corrosion and on circuit passivation; B. L. Beach, for his help with material failure analysis and chemical analysis of materials that were evaluated; W. C. Smith, for his work on conductive ink failure analysis and material characterization studies based on scanning electron microscopy; L. O. Aulick and F. M. Rose, for their help on procedure definition and testing of flexural fatigue resistance of conductive inks, environmental exposure effects on adhesive strength, and dimensional stability of film substrates; R. E. Henselman, for his analytic support on silver sulfiding and migration, and chemical characterization of the adhesives and conductor composition. The authors also thank M. T. Fazey for his help with the design and analysis of parameter modeling experiments; and A. L. Akers, E. T. Coleman, and M. L. Pawley, for the development of the data base used in the design section of this report.

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Received July 31, 1984; revised February 26, 1985

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