WHAT AN ORGANBUILDER SHOULD KNOW ABOUT SOLID-STATE

The advent of solid-state technology has transformed our technical world and made electronic devices come of age to stand beside other technology in reliability and endurance. In the organ world there was perhaps less need for it than elsewhere, especially in organs restricted to mechanical action. However, the use of solid-state in most organs today is no longer an adventuresome option -- it is now a necessity, especially for the builders of electric-actioned instruments. The reason for this is two-fold: It is no longer possible to obtain good quality switches, relays and contacts of older design because of the greatly increased manufacturing costs of these labor-intense components and the workers skilled in making these intricate devices have largely retired or passed on (with the newer generation being trained only in solid-state and disdaining work of the older generation's). OSHA requirements imposed on older plants who used to make all this equipment as well as the high cost of importing certain materials (and even the unavailability of vital material such as ARMCO iron needed for organ magnets) have forced manufacturers to resort to cheaper and less reliable designs and methods to keep the costs within reason. Solid-state has become the only solution for continuing quality organ construction at affordable costs. A still further justification for solid-state in a pipe organ is the dramatic and noticeable improvement in the precision and attack of electric action on pipe speech and tone of the organ which was never attainable previously.

Just as the responsible organbuilder must know something about pipemaking (though he may not be able to make pipes himself), something about wood technology (though he may not have academic training), something about chest engineering and pneumatic technology (though he may not be a degreed engineer), he should not flinch from the now obvious necessity to know something about the measures of quality of solid-state (though he may not be an electronics designer or experienced with semi-conductor technology). In using solid-state in an organ the organbuilder assumes responsibility for it to his customer who rightfully expects the same levels of quality that have been a hallmark of respected organbuilding for the past several centuries. Like with everything else, there are amateur, sloppy, mediocre and high quality methods of creating solid-state equipment. People who have failed to satisfy other industries with their work may find the organbuilder gullible "prey" to use up obsolete components and other poor practices which can be of great financial advantage to themselves. The organbuilder should establish the level of acceptable quality for his solid-state and learn the landmarks to identify this quality. This discussion attempts to provide some of that insight.

Three Basic Levels of Solid-State Quality

Most development of solid-state has occurred with government financing of research and support of initial production of various solid-state devices. This early production has always been costly and out of reach for other industries until lower-cost versions of each new development were found. As time has gone on, cheaper and cheaper means have been found to make various items: some of the older items are now inexpensive because more efficient means have been found to produce high-quality production runs but sometimes the lower cost has been brought about simply by relaxing tolerances or specification requirements or, even, thoroughness of inspection methods. This has brought about a gradation of general quality levels of solid-state equipment into approximately three categories:

1) Amateur, hobby and unprofessional level work using mostly mail-order or surplus parts.

2) Commercial and entertainment industry level work using only price-competitive, lowest-cost parts and assembly practices.

3) Military standard and computer industry level work using only high quality parts and long term proven assembly techniques with cost considerations secondary to maximum reliability and endurance.

Unfortunately, much of Category 2 started off in Category 1, somewhat understandably, so there is a great range of quality within Category 2. This includes everything from inexpensive home appliances through automobiles, TV sets, stereo systems, games and home computers -- even electronic "organs"! In all of this work, a life beyond 10 years is not anticipated and arguments to improve quality beyond that durability level are considered only to raise the cost of the item and decrease the volume of sales. A certain expected level of maintenance and unanticipated parts replacement is also considered acceptable for this type of equipment.

Since the pipe organ is expected to last at least 50 to 75 years before major maintenance is necessary and eventually to last a lifetime with only a reasonable amount of such maintenance, the philosophy of Category 2 is obviously inconsistent with that traditionally used by organbuilders for other components of the instrument. In the opinion of the writer, organbuilders must seek and insist upon only Category 3 level quality to insure that solid-state used in an organ is truly within the expected reputation of organbuilding. There are a number of important differences between Category 2 and Category 3 levels of quality as will be henceforth discussed in this article. Not all Category 3 equipment is economically practical for the organbuilder but an adequate amount is to pursue its use uniquely.

Three Aspects of Quality Definitions

Generally, most manufactured items have three traditional aspects of quality: Design, Materials and Workmanship. Materials and Workmanship, the usual factors included in a warranty, are most often inspectable or observable in some manner, particularly when trouble occurs. Design is somewhat more obscure and a certain faith must be put in the manufacturer for the integrity of his design. Usually, if a product operates as specified and expected, it is assumed that the design is adequate. Since product design generally requires a professional effort, a certain reliance might be placed on the fact that most professional people will not intentionally do inadequate work--although this is certainly not guaranteed! We do not propose to dwell in this article on the myriads of design arguments about organ solid-state, but we will mention two or three important areas where well-meaning designers have slipped up when trying to apply their experience to pipe organs, or where cost factors have been held in too great a priority:

First, the pipe organ is somewhat unusual in that electronic control for this instrument uniquely deals with large numbers of inductive circuits (circuits with magnetic coils and relays). Electronic organs have no inductive circuits worth mentioning except the final amplifier stage which runs the loudspeakers, a well-known and thoroughly solvable problem. Therefore, pipe organ electronics must allow for unusual voltage "spikes" or surges through its circuitry as these inductive circuits are activated under playing conditions. The components must be over-rated and designed to withstand these inductive spikes with additional filters and suppression equipment added to further protect critical transistors and IC's (Integrated Circuits). While this inductive circuitry is an unusual condition for solid-state, it is easily and responsibly handled by the knowledgeable designer who properly takes it into account.

The second peculiarity of pipe organ electronics is its susceptibility to electrical noise or static, which comes from vehicular ignition, furnace oil burners, fluorescent lights, CB radio signals and miscellaneous other RFI* producing devices often found around public buildings. The reason pipe organ circuits are particularly susceptible is that the voltage and current levels in organ solid-state, particularly in integrated circuits, are often lower than the noise that may be picked up by the long cables involved in organ wiring (which act like antennas) and the generally unshielded equipment. For this reason, designers should avoid things like "TTL" integrated circuitry which is particularly susceptible to noise--unless very thoroughly filtered which adds, unnecesserily, to the complexity and cost of the equipment. The more recently developed C-MOS componentry is far more practical for the pipe organ as is the older, "discrete" component systems. Further, in any circuitry, suitable filters should be included in certain critical areas to prevent noise from interfering with legitimate organ signals from the console.

Another factor in organ solid-state is its exposure to possible inept service technicians or local amateurs attempting to perform emergency service. The majority of solid-state failures to date in organs has been due to this unwitting damage where low-resistance voltmeters or make-shift trouble-shooting techniques or even accidental shorting out of circuits has occurred. This type of problem will probably continue for at least another decade or two until organ technicians become more accustomed to solid-state. In the meantime, a clever, responsible designer can avoid many potential jeopardies by including certain protective devices and circuits in his equipment.

*RFI= Radio Frequency Interference (noise)

Materials

All solid-state circuitry is mounted on some kind of insulation material, such as various kinds of plastic, bakelite, phenolic (cloth embedded) or epoxy-soaked fibreglass, usually sheets 1/16" to 1/8" thick. On this material are very thin strips of tin-plated (solder) copper constituting the interconnecting "wiring" between the components. These strips are called "etches" and the insulation material is called the "board", "card" or "PC Board" (printed circuit board). Through the board are drilled numerous holes through which various pins and other electrical conductors pass because the components (diodes, resistors, capacitors, transistors, etc.) are mounted on the opposite side (usually) from the etches which electrically connect them. Some place on the board must be either a terminal strip to which wiring or cabling is connected to convey signals in to the board and outputs off the board, together with power supply connections, or "fingers" along one edge of the board which allow the board to be plugged in to a female, multi-pin receptacle. The board must have sufficient substance to physically mount and support the components.

The material out of which the board is made is of paramount importance. It has been customary in commercial and entertainment equipment to use a form of plastic or phenolic but this material has never been accepted by high-quality producers of solid-state because of its susceptibility to temperature variations and humidity effects. Temperature variations, particularly extreme temperatures, cause the boards to change dimensions, cracking and breaking the etches, sometimes the components themselves and even the board itself! Where there are fingers used for a plug, the fingers can go out of alignment with the female connectors and effectively miswire the circuitry. Humidity creates the same effect and worse. Moisture seeps into the pores of many materials, expanding the material, causing warpage and breakage of etches and contacts. Often these effects do not occur for some time, even years, after manufacture.

Fibreglass-epoxy boards are far superior and do not suffer from temperature or humidity effects as they are inert, non-organic and absolutely stable with very low coefficients of expansion. Only this board material can be relied on for long and indefinite periods. The material is usually a green translucency but can be other pastel shades.

It is designated as "G-10" or "FR-4" quite universally. It looks and feels like glass and is glass, but it is rugged and strong. All organ solid-state should employ this glass material in the opinion of electronic engineers experienced with long-life equipment.

Another important characteristic of board material is its ability to withstand reheating of soldered joints when repairing circuits and replacing parts. Most board materials start to disintegrate, de-laminate or melt when being repaired. Etches "lift-off" the board and become very fragile. Glass boards will tolerate considerable abuse and allow local repairing to components without weakening their structure or causing etches to "lift". This can be important where the boards often cannot be removed from the organ easily for repair or modification and must be serviced in place.

Another important material used with printed-circuit boards is the surface of finger contacts or contacts for plug-in components. The common material to use is tin plate or solder. High-quality solid-state for low currents, such as organs use, always employs pure gold--only. The gold must have a nickel under-plating on top of the basic tin-plate or copper for stability reasons. Solder or tin plate on copper etches has been found by electronics researchers to "migrate" or "cold flow" with time, displacing the material and damaging the electrical continuity of the contact. Oxides also form on solder or tin which, in time, also interfere and reduce electrical conductivity. Thus, when tin or solder contact plugs are first installed, the circuit works perfectly but this can change with the passing of a few months or years--something that would be undesirable in pipe organs.

If the gold plating is too thin, porosity may allow atmospheric contaminants to still attack the material underneath, weakening electrical conductivity. A more important consideration is that gold has little strength and cannot resist migration of copper or tin-plate (solder) beneath by itself. Nickel plating over the tin plating or copper is necessary to combat migration and gold plating over the tin must be heavy enough to avoid porosity which allows the nickel plating to be attacked. To date, only the computer and military equipment industries have been disciplined to properly overplate the tinned or copper etches with nickel and then cover that with gold to create an inert, stable, trouble-free contact which will last indefinitely. We need the same disciplines if we are to see our solid-stated organs also "last" indefinitely without electrical malfunctions.

Other aspects include that organ circuits generally have very low currents much more susceptible to contact resistance than higher currents which often burn away accumulated oxides automatically. The gold-plated contacts are much more important in pipe organs, therefore, than in many other applications of solid-state where the life-expectancy is only ten years or less. Gold plating, however, does not last long if it is not underplated with nickel and is of sufficient thickness. The female connectors must also use gold-plated contacts.

Another materials problem usually ignored by the lower cost producers of solid-state is that of conductors through the PC board. A solid pin or plated-through holes are the standard high-quality method. But sometimes a convenient low-cost rivet-like device is used which is advertised to have a wicking action for solder to flow from one end to the other. Unfortunately, storage of these parts prior to use often results in oxides building on the tin-plated surfaces which when soldered hinder or prevent solder from flowing smoothly. Only cold solder, if any, reaches the other end--thus causing electrical resistance between.

Another important materials problem has to do with the covering or "packaging" of transistors and IC's. Many transistors popular for use in both entertainment equipment and pipe organ circuits have a less costly version which is encapsulated in plastic instead of a metal can. The plastic-packaged device cannot get rid of internally generated heat as fast as the metal packaged device. Therefore, at the same load, the plastic device runs hotter and, consequently, may have a significantly shorter life than the metal-encased version. The internal heat weakens the welded connections internally as well as attacking the semi-conductor materials. This is particularly true of the most common transistor output amplifier (driver) used in coupling and switching solid-state circuits. The metal encased transistor is designated 2N2219 but the same transistor is also available, at lower cost, in various plastic configurations such as 2N2222 and other designations. Since the 2N2219 version often barely gives a comfortable margin of operating temperature in many organ applications, the plastic versions are marginal and will sometimes fail after a relatively short period of time with the stresses of a pipe organ's inductive circuits. There are many other similar examples where the cheaper plastic versions of a transistor are inferior to the more expensive metal-encased styles. Again, the purchaser of solid-state equipment has to trust the manufacturer to have made proper temperature studies and life testing under realistic pipe organ-simulated conditions if the lower cost versions of some devices are employed. Mere experience with entertainment-type equipment is not enough to insure the reliability of a design.

Carbon resistors, often used with entertainment-grade construction, are not as reliable as metal-film resistors which all high-quality solid-state employs.

Capacitors have great ranges of quality and are one of the more susceptible of components in an assembly to premature failure. Only the highest quality capacitors should be used. "Entertainment grade" work often uses the least quality capacitors which are lower in cost.

C-MOS I.C.'s have a suffix such as "A" or "BE" after their identification number. The "A" suffix is usually the lowest-cost version, or a version which may have marginal ratings for the particular use employed, whereas later versions with higher suffix letters may have much more margin for a particular design. After the IC has been in use for a period, its manufacturers often find many ways to improve both the flexibility of the device and its reliability. Packaging is usually improved to ceramic or other materials, allowing it to operate cooler. The designation "BE" as a suffix usually indicates this improved version (various manufacturers will vary the suffix meanings and some suffixes are only for special-purpose uses). When these improved versions become available, the original "A" (or whatever) becomes cheaper and so is often purchased for entertainment level equipment. Organbuilders should insist on a grade of components for their equipment to insure the reliability and longevity appropriate for the craft. The greater cost components are usually only a few cents higher, in aggregate, an inconsequential cost increase for a pipe organ but a significant cost increase for a production device such as TV's or electronic organs. From force of habit, engineers accustomed to entertainment level solid-state may not bother to look for better grade components.

Workmanship

Workmanship can be translated into "assembly technique" in the solid-state industry. There are many assembly techniques in common use in entertainment and commercial type solid-state which may function satisfactorily for a time but have been found to cause unreliability after extended time periods. Some assembly techniques create unreliability after a short time!

One common practice to save space and cost is to mount components on end with one lead very short and soldered tightly to the board and the other lead draped over the other end to reach the board. This causes high stress to develop on the short lead which can break or crack the lead or the elements inside the component when temperature affects dimensions of the board (or humidity likewise). In the case of glass-encased diodes, the stress can craze or crack the glass, allowing the inert protective gas to leak out and slowly be replaced by contaminated air from the atmosphere, eventually causing deterioration of the electrical elements.

Components should always be mounted flat on the boards with both leads bent to allow a certain flexibility to accommodate slight dimensional changes with temperature or humidity. Transistors, similarly, should be carefully attached. Larger components should have special bracing to avoid strains on their electrical connections or the board itself!

Soldered connections abound on any solid-state PC board. These connections should be made with barely enough heat to insure a well-wetted connection but not so much heat as to burn the board material or to scorch the components as this weakens these items. Similarly, "cold solder" joints will eventually lose conductivity and cause circuit malfunction. Professional work will always look neat and consistent with no hint of questionable-looking connections. Flux should always be acid-free.

Finally, the boards should be washed in organic chemical cleaners to completely remove all traces of flux and tiny solder specks which can later cause partial and even full shorts when additional dust and foreign material also becomes stuck to the excess flux. The boards and the components should look absolutely clean in every respect and there should be no signs of extra wire or solder bits, plating "flakes", flux or oversized solder blobs. After cleaning, the boards should be sprayed with a lacquer or epoxy coating (cycle-bonding) to resist accidental shorting or damage to the board or its components. The boards should then be mounted in some sort of frame or means to protect them against accidental damage in the organ. If cables are to be attached by the organbuilder directly to the boards, a clear wiring "legend" should be provided and terminals of sufficient strength to allow inexperienced wirers to do a neat and reliable job. Attaching cables should always be independently supported and tied.

If the design of the equipment is such that the organbuilder plugs boards into other boards or plugs, the responsibility for malfunction of the circuit becomes that of the organbuilder rather than the solid-state supplier. Since plugs and connections have always been the primary cause of trouble with solid-state, the supplier thus neatly avoids this responsibility or warranty claims. The organbuilder should look for equipment where no plugging in is required - only soldered connections which are less susceptible to error, contact resistance or accidental damage. This is especially true when non-electronic-experienced technicians are to be installing equipment.

Testing

An important part of workmanship aspects is to be sure that a consistent and thorough testing program has occurred before installing the solid-state equipment in an organ. It is desirable to test each component separately before installing it on a PC board and then thoroughly test the completed board for each function to be certain the board is functioning within its proper specifications. The best and highest quality solid-state uses components that have been "burned in" prior to initial testing. Because of the nature of the rare flaw that occurs in the manufacture of semi-conductor devices, a failure will often not show up in initial testing but will after a short period of use. Therefore, to avoid these early failures, running the device under load for a few hours will isolate components which have early failure tendencies.

Purchasers of solid-state equipment should not hesitate to ask of their supplier what quality control procedures he will guarantee to follow and then to evaluate these procedures for their thoroughness. Sometimes the sources of solid-state components are of high enough integrity and reliability to responsibly omit some initial testing, but final thorough testing of the completed circuits should always be assured. This, of course, is impossible if the system is not purchased fully assembled!

If the equipment was never develop-tested under extreme conditions, such as low or high supply voltages, voltage surges (from lightning) on the line, very damp or dry conditions, summer heat or winter cold, the equipment is not to be trusted. It should be possible to request a copy of such a development test report from a reliable supplier. The integrity of the firm designing and producing the equipment is generally the controlling factor and such company's equipment will usually not be the most price-competitive.

Organbuilding demands a quality of solid-state design and construction above the level of generally accepted entertainment and commercial grade devices. One of the reasons the electronic "organ" has such a short life is the practice of using TV quality parts and components. Let us not accidentally and unintentionally degrade the traditional long-life qualities of the pipe organ by being ignorant of and inattentive to the important quality characteristics of solid-state control equipment!

David W. Cogswell, Registered Professional
Engineer (Massachusetts) and Master
Organbuilder

I am indebted to Mr. Roger A. Dame, Design Engineer from Digital Equipment Corporation, for making available various research reports and other experience data regarding the design and quality standards of solid-state. In addition, representatives of various manufacturers of equipment have given valuable information regarding quality practices and intents of their respective firm's products. Finally, various textbooks and quality control manuals furnished further information. Certain organbuilders have also learned much "the hard way" through their own experimentation.