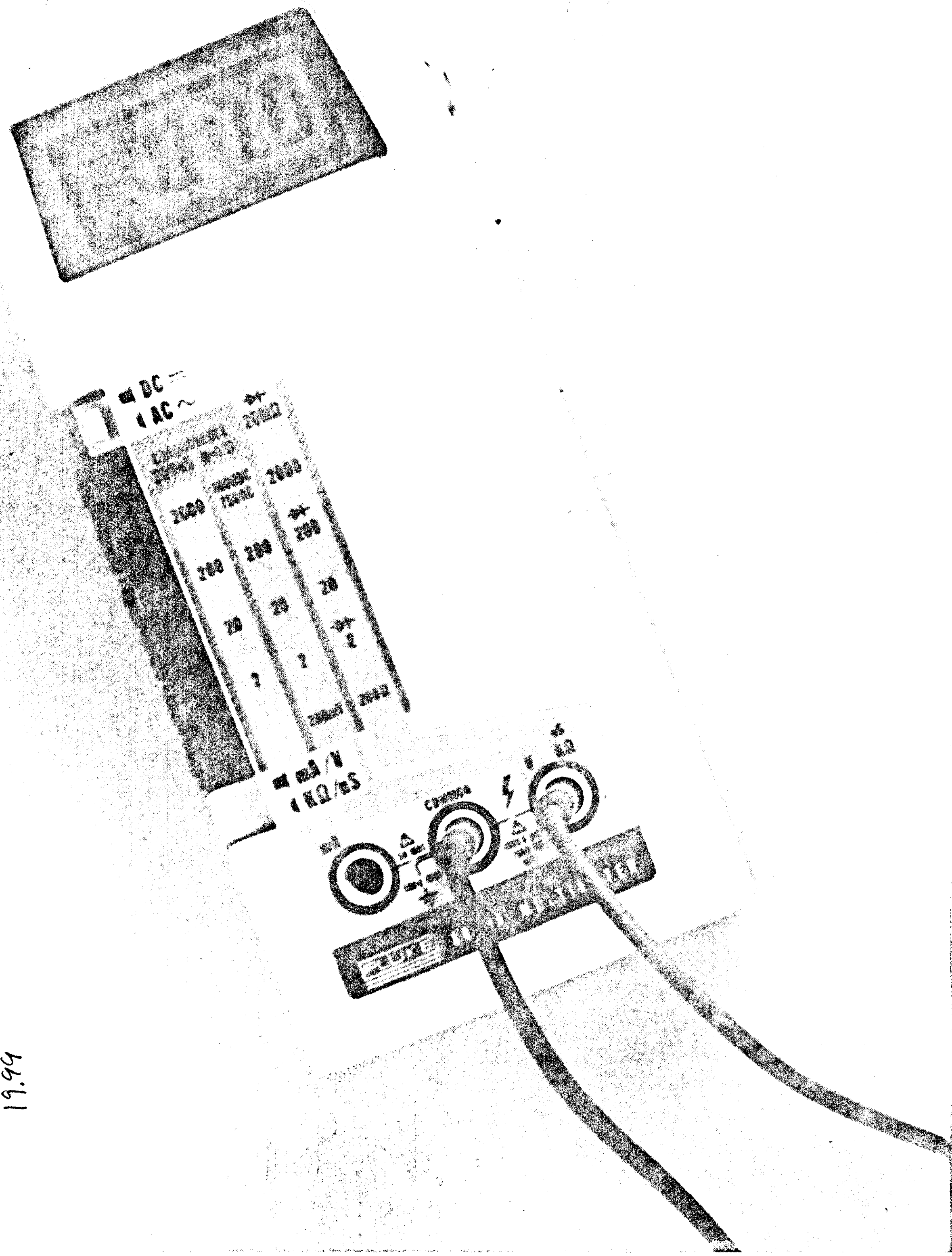
Product development profile

Rough life of digital multimeter puts tough demands on design

by Norman Strong, *John Fluke Manufacturing Co., Mountlake Terrace, Wash.*



Hand-held instrument has custom analog-to-digital converter chip, as well as a liquid-crystal display that is directly driven; combination reduces parts count and keeps power demand low

□ The hip-pocket life of a portable digital multimeter calls for a tough instrument. The portable DMM must put up with rough handling, electrical abuse, adverse environments, and long periods without calibration. The instrument also must be small, light, operate from batteries, and sell for less and work more easily than does its bench counterpart.

To meet these stringent demands was the goal of the designers of the 8020A. Long battery life immediately suggested a liquid-crystal display coupled to complementary-metal-oxide-semiconductor logic. Small size and low cost dictated a low parts count. And a tolerance for electrical and mechanical abuse required a sturdy plastic case and good input-protection circuitry.

A-d converter chip

Although there were several good one- and two-chip analog-to-digital converters on the market, with more to come, each one had drawbacks that made it unsuitable for multimeter applications—especially when used with an LCD display. Every general-purpose a-d converter required the addition of external display drivers, as well as dual power supplies and the usual passive components. These requirements largely vitiate the advantages of large-scale integration.

Fluke chose to simplify external circuitry by designing a custom C-MOS a-d converter chip capable of directly driving an LCD display and incorporating additional features useful in a multimeter application. The conversion technique chosen was a version of the familiar dual-slope converter; it has high accuracy, adequate speed, and enjoys general acceptance throughout the electronics industries. The design goals for the chip, built by Intersil Inc., Santa Clara, Calif., are:

- 2,000 count (±1,999) for higher precision than with 1,000-count instruments.
- Single 9-volt battery operation to keep size small and operating costs low.
- Direct LCD drive to simplify circuitry.
- Crystal-controlled clock oscillator for near-perfect rejection of line interference.
- Digitally selected 2-V and 200-millivolt ranges requiring no external components changes.
- True differential input for a simpler ac-to-dc converter.
- A single, floating, external reference voltage to simplify the ohmmeter protection circuits.
- Ratio accuracy to within one count when making measurements of high resistance.
- Near-zero bias current at all input terminals.

The inputs to the chip (Fig. 1) are routed through a series of switches (actually MOS transistors), which set up operations during different portions of the measurement cycle. Each measurement cycle is divided into automatic-zero, integrate, and deintegrate periods (Fig. 2).

During auto-zero, switches connect the buffer and integrator inputs to the internal common-voltage line. This closes a loop around the integrator and comparator to the auto-zero capacitor, C_2, removing the system offset voltage. The switches also connect capacitor C_1 to the 1-V reference, charging C_1 in preparation for the deintegrate period.

Because the 8020A is designed to operate from a supply as low as 6 V, the usual 6.4-V reference zener had to be replaced with bandgap type of reference, which operates at the bandgap voltage of silicon, (about 1.2 V) and has exceptional stability. A voltage close to the desired 1-V reference also makes for a much less critical voltage divider.

During integration, the unknown input voltage is connected to the noninverting inputs of the buffer and the integrator. These are both high-impedance inputs and allow a true differential measurement.

Two integration periods

There are two available integration periods. For the 2-V range (used for three resistance-range inputs), there is the 1,000-count period corresponding to one cycle of the ac 60-hertz line (which helps the meter to reject external 60-Hz signals). For the 200-mV range (used for all other inputs), there is the 10,000-count (10 60-Hz cycles), which increases the sensitivity by a factor of 10. A logic signal applied to the three-state range pin on the chip selects either integration period or a third choice in which the reference input is swapped with the unknown to allow inverse resistance measurements.

After integration, C_1 is connected to the buffer through the deintegrate switches in the opposite polarity from the unknown (which is determined by the output state of the comparator). When the integrator returns to the threshold, the comparator changes state and the count is transferred to the decoder and LCD driver for display. A new auto-zero period begins.

The reading rate is three per second, ideal for liquid-crystal readout, where faster rates might

Strong competition

The Fluke 8020A enters one of today's most competitive arenas in electronic instruments—3½-digit portable digital multimeters. There are at least nine other such DMMs on the market with prices ranging from approximately $100 to about $250. As with any instrument, potential buyers will have to size up the total specification package, along with convenience features.

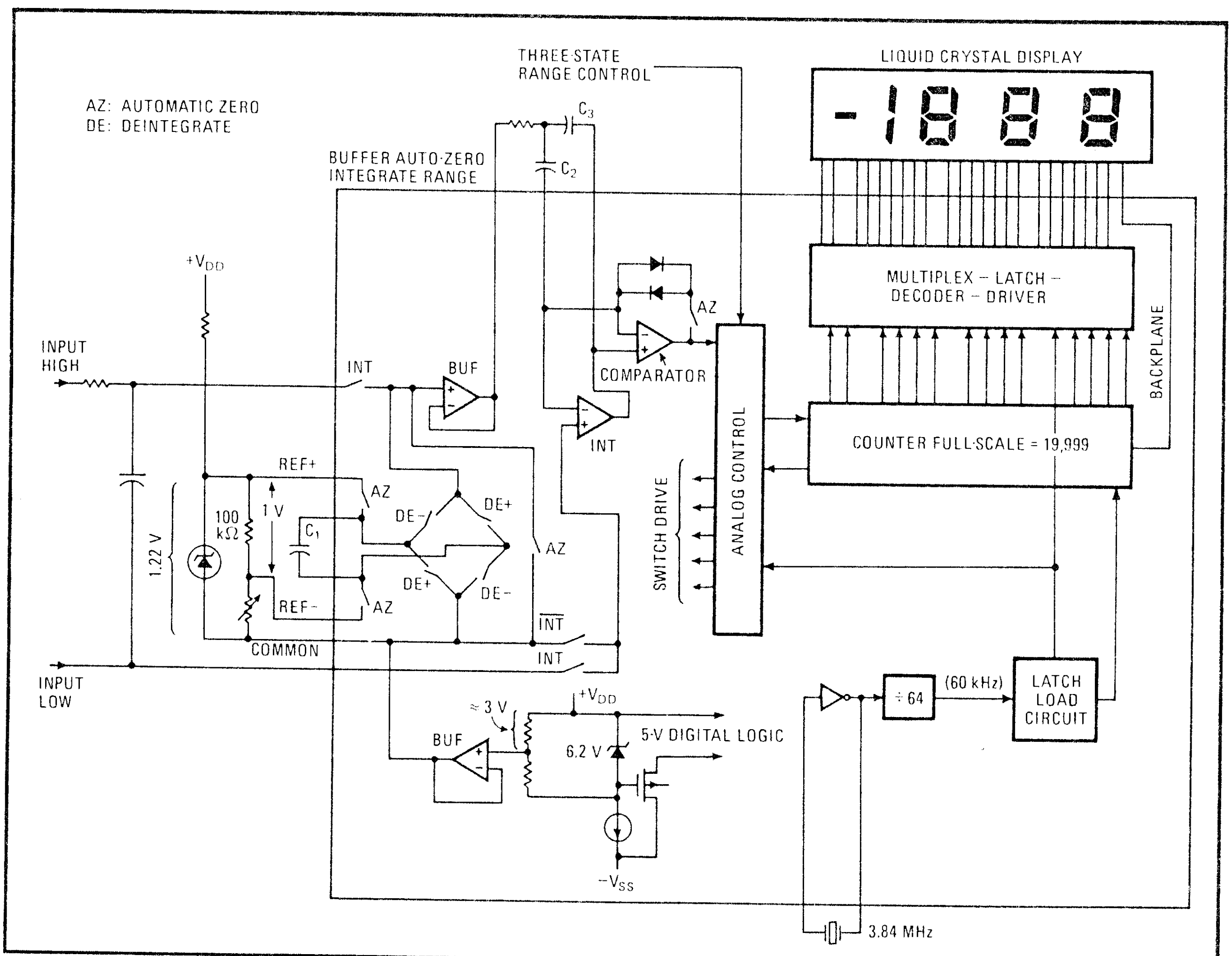
One of the basic requirements is accuracy. For dc voltages, the $169 8020A has an accuracy to within 0.25% of reading ±1 digit. This beats all lower-cost instruments and even some higher-priced ones, such as the $195 Weston 6000, which has 0.35% ±2 digit accuracy. (But Weston's unit also has automatic ranging, which the Fluke unit and others do not). There are at least five higher-priced units that come in with 0.1% ±1 digit accuracies on dc volts—the $279 Ballantine 3028A, the $249.50 Danameter II 2100A, the $234 Data Tech model 22, the $189 Data Precision model 175, and the $235 Simpson model 464D. (Prices differ because different features are offered.) Their manufacturers say the accuracy specs will hold for a time span of one year.

Accuracy on ac voltage ranges gets a little more complicated, since it can vary with frequency. Most meters are specified with at least three different ac voltage accuracies, each over a certain frequency range. Here, the 8020A's basic ac voltage accuracy of 0.75% +2 digits from 45 hertz to 1 kilohertz appears to be about right for its price. Again, it is possible to do better with higher-priced instruments, as is true with accuracies for ac and dc currents and for resistance readings.

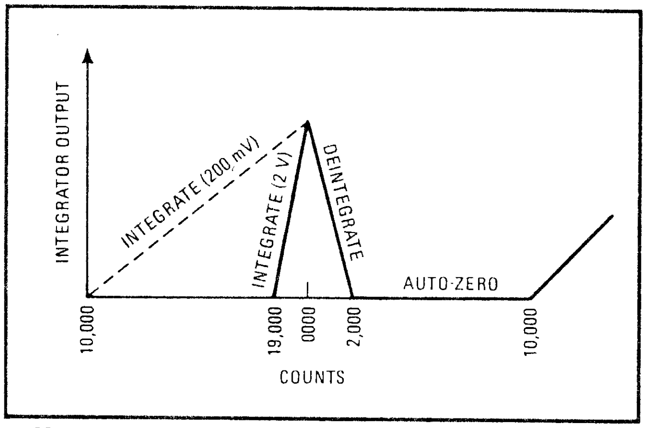
One basic choice facing buyers will be between those instruments that use light-emitting-diode readouts and thus require rechargeable batteries (such as the Simpson and Data Precision meters) and those that use the lower-power liquid-crystal displays and thus can use disposable batteries (such as the Fluke, Data Tech, and Dana meters). The rechargeable units give about six to eight hours of operation and then require overnight recharging. Alkaline batteries, however, generally can give more than 200 hours of operation before they must be replaced.

The Fluke unit has an exclusive feature—it can read conductance, thereby allowing resistance measurements up to 10,000 megohms, which would be useful in measuring leakage in capacitors, diodes, cables, and printed-circuit boards.

Stephen E. Scrupski



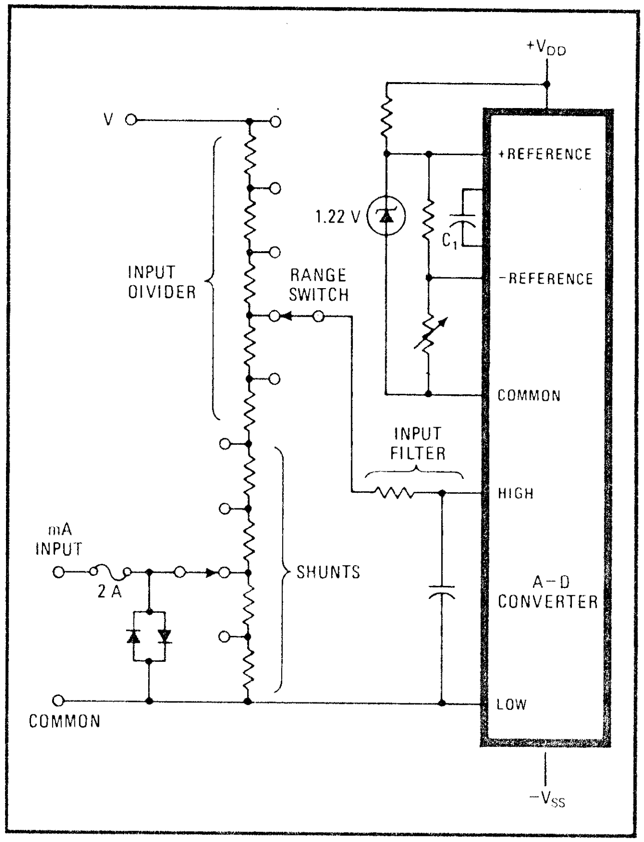
1. Converter chip. The C-MOS analog-to-digital converter chips, within the inner box, basically comprises the counter, display drivers, integrator, buffer amplifiers, and FET switches set by the analog control block during the automatic-zero, integrate, and deintegrate periods.



2. Measurement cycle. The basic measurement cycle has three periods. During auto-zero, offset is removed and the reference capacitor is charged. During integration, the unknown input is integrated for either 1,000 counts or 10,000 counts. During deintegration, the reference capacitor voltage is integrated until it causes the integrator to return to its threshold, and the count is displayed.

cause false readings because of the generally slow response time of the LCD. Rapid alternation between 6 and 7 might appear as an 8, for example.

Although clock frequency for the counter circuitry is 60 kilohertz, it is obtained from a 3.84-megahertz oscillator divided by 64 in an on-chip six-state counter. This high oscillator frequency allows use of the highly stable, low-cost AT-cut crystal, which is not available below 2 MHz. Also, crystals close to the television color-burst frequency (3.58 MHz) benefit from the very low production costs of this high-volume equipment.



3. Voltage and current inputs. Unknown input voltages are applied across the divider string of resistors, while unknown currents are applied through a separate input jack, preventing damage to the shunts. For current measurements, the meter input may be connected to any switch position to pick up the voltage across the shunt, since unknown input currents do not flow through the divider.

C-MOS benefits

When Intersil was first asked to design the a-d chip, there was some question about the practicality of meeting some of the very stringent performance requirements. Three, in particular, stood out:

- Low power dissipation (less than 20 milliwatts).
- Input currents in the low-picoampere region.
- Very low noise (less than 30 microvolts peak-to-peak).

Intersil slightly modified its low-voltage C-MOS process to meet these requirements in a chip measuring 124 by 149 mils. The device is packaged in a 40-pin dual in-line package and operates at voltages down to 6 V from the single 9-V alkaline battery. Current drain is less than 1.5 milliamperes.

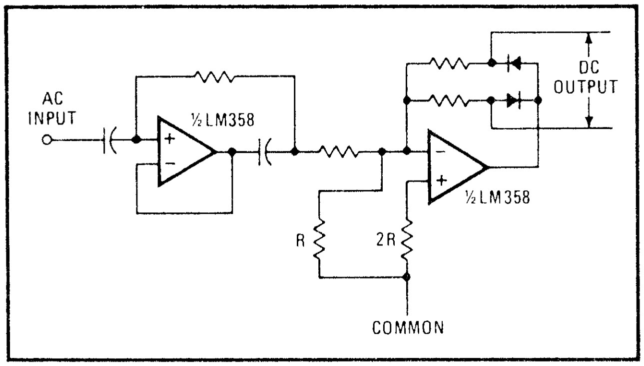
Low power dissipation is an inherent characteristic of C-MOS devices—unless the frequency of digital switching rises into the megahertz region. However, lowering the supply voltage will reduce the current. Since Fluke wanted to operate from a battery whose voltage might be anywhere from 6 to 10 V, the digital logic section was internally regulated to 5 V, while the analog circuits continue to operate at the full battery voltage. This low voltage for the digital section limited the current drain to 300 microamperes.

A zener diode buffered by a large p-channel MOS source follower supplies the digital logic with the 5 V. It also supplies the internal common voltage, which is divided down to 3 V from the positive supply. A buffer amplifier presents a low impedance at the common terminal so that current may be drawn from the supply by circuits external to the chip.

The ohmmeter ranges of the 8020A require exceptionally low leakage currents at the input and reference terminals. The availability of field-effect transistors with negligible gate currents is another inherent advantage of C-MOS processing, but such circuits are susceptible to damage from static charges. Therefore, when the gate of a FET is brought out to an input pin, a small diode is added for static-charge protection—an important consideration in an instrument for field environments. Even with the diode, the leakage is typically less than 1 pA at operating voltage and room temperature. Low leakage is especially important in this system because any charge that the external capacitors lose through leakage will show up as an error in the instrument reading.

Reducing charge injection

Another way the capacitors can lose (or gain) charge is by charge injection from the switches. As the gate of a FET switch is driven off, its gate-to-drain capacitance injects a charge on any capacitor tied to it. This changes the voltage across the capacitor. However, in the C-MOS chip, each switch comprises an n-channel FET and a p-channel FET in parallel. If the gate-to-drain capacitances of the transistors are equal, the net charge injection will be zero, since the positive-going signal turning off the p-



4. Ac/dc converter. To measure ac input signals, the meter converts them to dc with a full-wave rectifier. Since both sides of the output are connected to one side of the amplifier, offset voltage is canceled, and, with the choice of resistors R and 2R to supply bias current, offset current is traded for offset voltage.

channel FET will exactly cancel the negative-going signal turning off the n-channel FET. Cancellation is not perfect, but capacitor voltage changes less than 2 μV.

If regular low-threshold (0.6-V) n- and p-channel transistors were used, the ones in the analog switches would have turned out to have too much leakage. This comes about because MOS transistors have exponential characteristics at low currents such that:

$$\text{Drain current} = a\,(e^{qV_{GS}/kTn} - 1)$$

where a = a constant, V_{GS} = the gate-to-source voltage (threshold—a negative quantity), q = the charge on an electron, k = Boltzmann's constant, T = device temperature on the absolute scale, n = 2 (a constant for Intersil's low-voltage process).

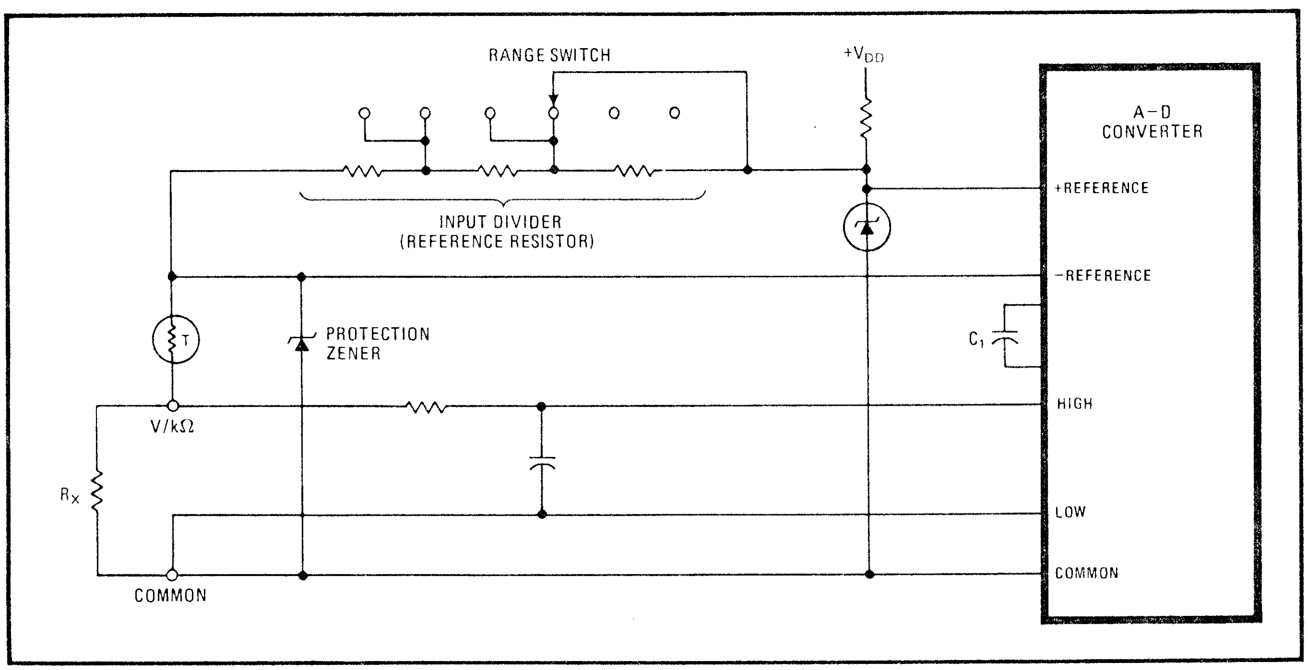
This equation shows that to reduce the drain current by a factor of 10 requires a 0.12-V change in threshold voltage. Thus raising the threshold voltage of the transistors in the analog switches to greater than 1 V means that under no signal conditions will leakage currents be significant. (The increase in threshold from the 0.6 V of the low-threshold transistors to 1 V reduces drain current about 1,000 times.) To achieve this drastically reduced threshold, an extra step of ion implantation is needed during fabrication of the transistors.

Cutting noise

The remaining problem was noise. Fluke wanted very low noise to avoid the problem of digit rattle so common on low-priced multimeters. Historically, C-MOS circuits have not been noted for low noise, and anxiety was amplified when preliminary samples of a competitor's C-MOS a-d converter showed 300 μV of noise referred to the input. This was 15 times greater than the 8020A requirement of 20 μV peak-to-peak.

Noise in C-MOS is caused by trapping sites that are filled and emptied at audio and subaudio frequencies. The chip's design attacked noise in two ways. First, a super-clean, gettered, and annealed process minimizes the number of trapping sites per unit area. Second, all FETs that serve noise-sensitive functions were made with very large gate areas. Because their instantaneous drain-to-source noise current is dependent on the percentage of trapping sites under the gate region that are filled at any one time, a large area gives more trapping sites over which to average and thus a smaller drain-to-source current variance (noise). Since the states of the trapping sites are independent of each other, the noise voltage is inversely proportional to the square root of the gate area.

With a big FET area, two other desirable features come free. The source-to-drain dimension (channel length) can be made greater than 2 mils, so that the output impedance is very high. This gives excellent common-mode rejection. Also, the device can be fabricated with a low



5. Ohmmeter circuit. For resistance measurements, the voltage input divider is used as a reference resistor. Its voltage is measured to determine the voltage across, and thus the value of, the unknown resistor. If the roles of the two resistors are reversed, the meter can measure conductance. The thermistor protects the reference resistor by increasing its resistance if the input signal level is too high.

In-step development

The development program for the 8020A portable digital multimeter was closely tied to the development schedule of the custom C-MOS analog-to-digital converter chip. While the chip was being designed, there was a lot of other work for the three-man design team to do: evaluate liquid-crystal displays from several vendors, figure out how to pack all the components into the hand-held enclosure, and design the circuitry that would protect the meter from all the mishandling and misapplications to which a portable DMM is subjected. However, it was not until the first chips from Intersil proved to work that the designers could be assured that they would complete their job on the schedule established about a year before.

The DMM team formed in October 1975 was headed by Stanley W. Jones (left in photo), who had been manager of test and manufacturing engineering. He broke down the design responsibilities in just about the most logical manner possible: analog and digital. Norman Strong (middle), a 13-year veteran with Fluke, handled the design of the analog portions of the meter, while Peter S. Duryee (right), nine years with Fluke, handled the digital design and the selection of the liquid-crystal display.

"We started out defining the performance requirements for the particular spot in the marketplace we wanted to hit with the 8020A," says Jones, "and then we started looking at Intersil and other semiconductor companies to determine the best LSI approach. We knew right from the beginning that we would have to develop our own chip, since there was nothing available at that time (nor is there now) that would meet all our requirements.'

The early part of the project thus was dominated by the selection of the semiconductor process and the manufacturer. "Once that was tied down and we had a quote from Intersil as to how much it would cost and how long it would take, the rest of the project sort of revolved around that schedule," Jones says.

While the chip was in development, Duryee worked with Intersil's David Bingham while also checking on the LCD makers, and Strong worked with Intersil's Lee L. Evans. "We built quite a few breadboards using C-MOS op amps and even built some op amps out of discrete C-MOS transistors in an effort to determine the safest approach from a standpoint of noise and accuracy," Jones says.

"This was by far the smoothest chip development project that Fluke has ever been involved with," he says. That set the tone for the whole project. One of the high points, according to Jones, was when the first run of chips at Intersil actually worked. "The first die they put the probes on worked," he says. "We had some people in Europe at a sales meeting and we sent them a telegram—all we said was: 'The chip works.' That was all they needed to know, because it meant the schedule was realistic."

One of the major problems was maintaining adequate frequency response without many compensation adjustments. The small size and a requirement for no hand-soldered parts eliminated many alternatives. After many iterations of printed-circuit-board layout, a design was created with a compensation adjustment on only the 2-volt range. The solution was to move the first pole of the divider network beyond 35 kilohertz, which required less than 0.5 picofarad of capacitance across the input divider.

SES

bias current, and thus only a 0.3-v turn-on voltage is required. This increases the common-mode voltage range of the amplifiers, which also makes operation from a single 6-v supply possible.

LCD readout

The LCD also is essential to the meter's design, since it is the only type of display that would satisfy the power-drain requirements. However, examples from several vendors did have several problems for DMM applications:

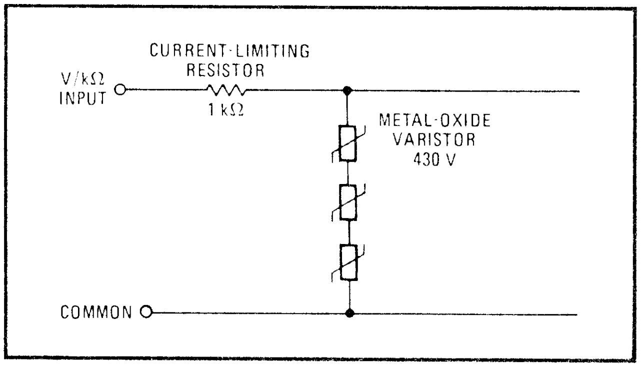
- Poor viewing angle.
- Slow operation at low temperatures.
- Serious degradation with humidity.
- Fragility of the thin glass plates.

The cooperation of engineers from Fluke and from several LCD vendors produced a display satisfying all the requirements originally set for the new multimeter.

By reducing the liquid-crystal thickness, both the speed at low temperatures and the viewing angle improved dramatically. An extra, protective laminate atop the polarizer material helped the display resist degradation for thousands of hours at high humidity.

The final problem was to protect the LCD from rough handling. Since the front is covered by a polarizing film, it seemed logical to protect it with a plastic lens with a mar-resistant surface. Unfortunately, the most mar-resistant plastic tends to shift the polarization of light, once again reducing the viewing angle (and making the display unreadable through Polaroid sunglasses). The solution to this was a special thermosetting plastic-rigid allyl diglycol carbonite inherently hard enough to provide mar resistance without special processing.

The signal conditioners, switches, and the all-important input-protection components extend the basic



6. Input protection. Three metal-oxide varistors are connected in series across the input. If the voltage applied is too high, the varistors will short-circuit to protect the internal circuitry of the meter.

circuitry to the outside world and make the device a multimeter. Figure 3 is a simplified representation of the input circuits, showing how the shunts and input divider are connected to the a-d chip to measure voltage and current. No switching is necessary to get from voltage to current; the user transfers a probe to the appropriate input jack. This helps protect the meter's shunts.

The input divider and the two shunts with the largest resistance are thick-film networks. Thick film was chosen over thin film because it is capable of withstanding severe transient overloads without damage. Even low-energy transients can cause sharp shifts in the value of a thin-film resistor. The low-value shunts are wirewound.

Ac/dc converter

Figure 4 is a simplified representation of the ac/dc converter used for ac measurements. The differential output to the a-d converter makes possible both full-wave output and direct coupling. Full-wave output doubles the ripple frequency, allowing much less filtering and resulting in a faster settling time. It also cancels the offset voltage of the amplifiers, since both sides of the output are connected to the same amplifier input.

Without proper corrective design, amplifier bias currents would flow through one of the diodes to only one side of the output, causing a voltage drop in that half of the circuit and an apparent offset. Placing a large resistor (2R) in series with one amplifier input and one half that value (R) in series with the other, means that the required two units of bias current are supplied through R. Therefore, offset current can be traded for offset voltage, to which the circuit is insensitive, and the error is cancelled. All resistors in the circuit are contained in a single low-cost network.

The ohmmeter

Figure 5 shows the 8020A connected to measure ohms. The input divider used for volts is also used as a reference resistor. Since the same current flows through it and the unknown resistor, the two voltage drops, which are the basis for the dual-integration measurement, are proportional to the respective resistances.

The voltage across the unknown resistance is integrated first, for 1,000 counts, and then the unknown voltage across the reference resistor is integrated downward until the zero crossing. The resulting accumulated count during the deintegrate period is proportional to the unknown voltage and thus to the unknown resistance. By changing reference resistors and a-d ranges, resistances from 0.1 ohms to 20 megohms can be measured by the new multimeter.

For higher resistances, the inverted range, referred to above, comes in. By integrating the voltage across the reference resistor first and using the unknown voltage as the reference during the deintegrate period, the 8020A will read the reciprocal of an unknown resistance—its conductance. This is the only practical means of measuring hundreds or thousands of megohms on a digital multimeter.

In this way, the 8020A can be used to read up to 10,000 MΩ. The scale is called 200 nanoSiemens (formerly known as the mho, the Siemens is the international unit of conductance). The conductance range extends the usefulness of the multimeter by three orders of magnitude without requiring the addition of a single component.

Electrical protection

A positive-temperature-coefficient thermistor protects the reference resistor, the most delicate component, against inadvertent high voltages across the input. This device maintains a low resistance of about 1 kilohm up to a critical temperature, at which point the resistance rises rapidly to thousands of times its original value. If an external overvoltage is applied to the input terminal, a high current flows through the zener clamp and the thermistor. The current heats the thermistor to its switching point, whereupon its resistance increases to protect the internal component. Although the thermistor is in series with the unknown and reference resistors, its voltage drop is not part of either of the independently measured input or reference voltages.

To protect against high-voltage transients, the 8020A has a string of metal-oxide varistors connected across the input in series with a current-limiting resistor (Fig. 6). The varistors look like an open circuit up to their rated voltage. At that point, their conductance increases exponentially, effectively short-circuiting the input pulses. The action is instantaneous and provides positive input protection.

Long-sustained overvoltages will, of course, destroy the varistors. They are designed to fail as short circuits, however, and the current-limiting resistor is designed to fail as an open circuit, so that protection remains positive. The milliampere input terminal is protected by a 2-ampere fuse and a pair of clamping diodes in the standard fashion.

The complete 8020A is built on a single printed-circuit board with fewer than 50 components, all wave-soldered at one time. The LCD display is mounted above the a-d converter chip, and the single 9-v transistor battery is connected to the pc-board by a flexible connector with snap-on terminals (the fuse holder is mounted on the battery connector). Battery life, using an alkaline battery, is over 200 hours. Calibration is an annual affair involving three adjustments; one for dc, one for ac, and one for ac frequency response. □