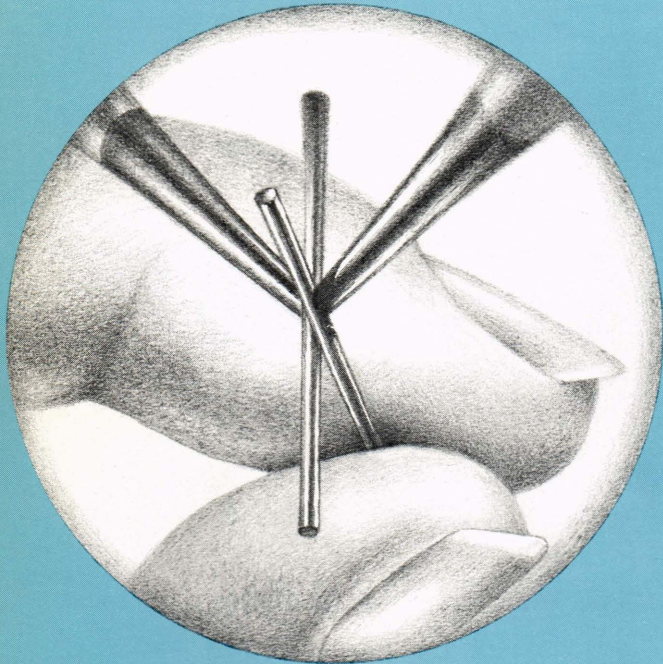


THE APL and



The requirements of reliability prompted a study of the relationship between the metallurgy of a weld and the characteristics of the electrical pulse that produced it. This resulted in three achievements: the development of a welder of superior reproducibility; the determination of an optimum pulse shape (current versus time) for each pair of materials welded; and the discovery of characteristic resistance-versus-time patterns that can be used to verify that each weld made is of high quality. These are discussed briefly in the present paper.

The art of electric welding probably originated when some early experimenter inadvertently short-circuited his Leyden jar and found his wires stuck together. If a switch and step-down transformer should be interposed between this capacitor and a pair of copper welding electrodes, a rudimentary resistance welder would be constructed—one which is improved upon by the modern commercial instruments in appearance, size, and ease of operation but not in the basic principles upon which it relies. Similarly, the art of welding has been developed and polished to the extent that it is presently the favored method of connection in electrical assemblies where high quality rather than low cost is the chief requirement; yet, it is still an art, still requiring operators having intuition as well as skill. The adjustments of the welders are still determined by trial and error; and, as will become clear, each machine must be considered as unique, with its own schedules of settings and its own capabilities.

This situation is amusing to onlookers who secretly rejoice at occasional failures of the forces of progress but is intolerable to those who must produce electrical devices of high reliability, where the failure of one weld in 40,000 can render a satellite silent and useless.

To overcome this difficulty, it seemed reasonable to search for a relationship between the shape of the electrical pulse and the metallurgy of the resulting weld, perhaps to find for each pair of materials a particular current and dura-

RESISTANCE WELDER Its ROLE in SATELLITE RELIABILITY

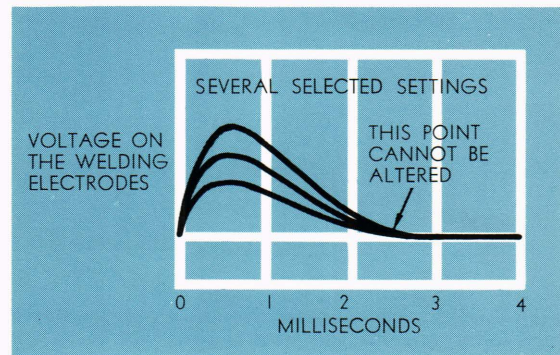
R. C. Evans

tion that would produce stronger welds than any other. Before such a study could be made, a welder had to be devised that would produce electrical pulses that could be varied systematically. The easiest approach was to introduce a series of capacitors into the conventional machine in the expectation that a series of pulse shapes would result; however, this was not successful. The transformer, being saturated, proved to be the determining factor. Attempts to use a series of transformers were no more fruitful, because they changed more characteristics than just current and time and therefore produced no orderly progression of pulses.

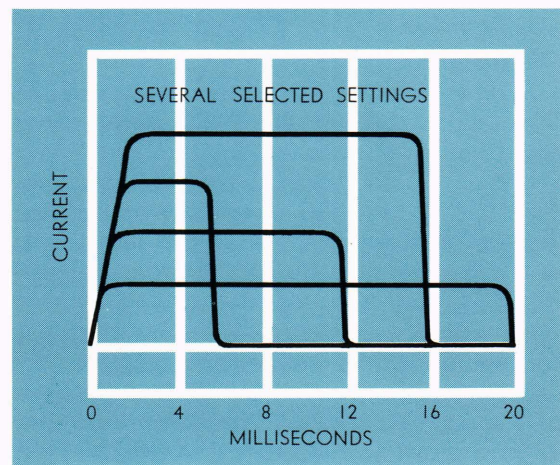
The solution was ultimately found in the use of storage batteries to produce the current and a bank of parallel transistor switches to control it. The details of this device will be discussed briefly later on, but at present we shall only compare, in Fig. 1, its capabilities with those of the conventional capacitor welder.

The current is determined by the number of transistor switches placed in parallel, and its duration by an independently set control circuit. Because the internal resistance is high compared with weld resistance, the current is constant and unaffected by changes in resistance of the weld as it is being formed.

In early experiments with the new instrument it was found that oscilloscope patterns of weld resistance versus time are characteristic for each kind of weld; they can be correlated with weld



CAPACITOR WELDER



APL WELDER

Fig. 1—Typical pulse shapes for the capacitor welder and the APL-designed welder.

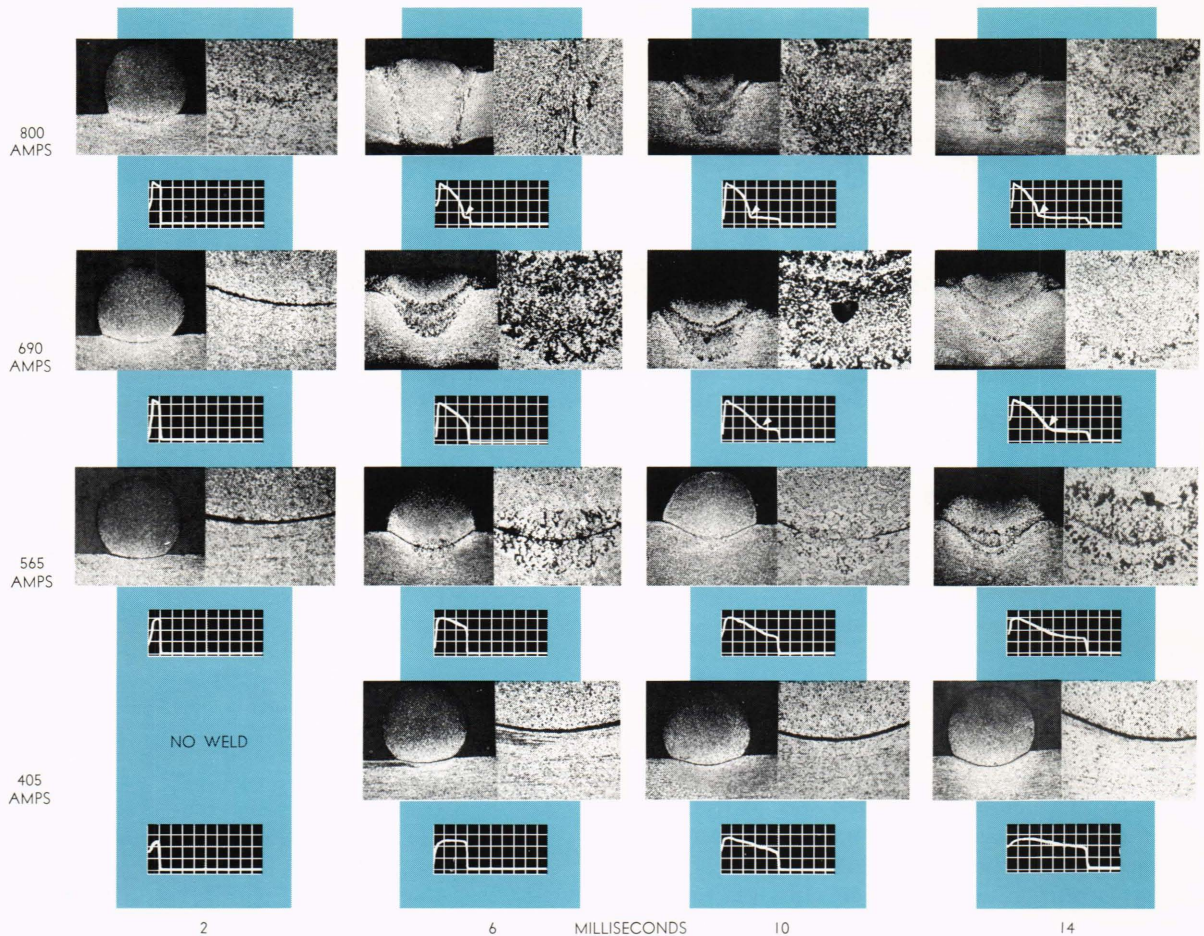


Fig. 2—Metallograms and resistance patterns for the APL welder, for nickel wire-to-nickel wire welds, with increasing currents and weld times.

strength and metallographic pictures and therefore can be used as a rapid means of weld analysis.

Such an analysis for the nickel wire-to-nickel wire weld is given in Fig. 2, where the patterns are arranged by increasing time from left to right and by increasing current from bottom to top. Attention is called to the breaks in the curves designated by arrowheads. When metallograms of the same set of welds are similarly arranged in Fig. 2, it is apparent that the welds in which the boundary between the two wires has disappeared correspond to the oscilloscope patterns which show a break in the curve. This, and the fact that the break occurs at the same time (for a given current) without regard to length of pulse, leads to the conclusion that the break signifies the completion of the weld. Because the resistance reaches a low value upon weld completion, continued flow of current generates little heat

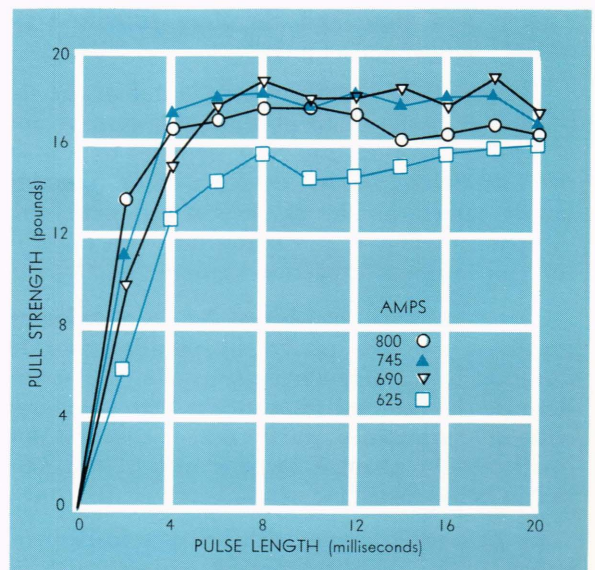


Fig. 3—Pull strength versus pulse length at various currents for nickel wire-to-nickel wire welds.

and consequently has little further effect. The force that is required to pull the welds apart is plotted as a function of pulse-length for a series of pulse-currents in Fig. 3. Here, as with the oscilloscope pictures and metallograms, it is clear that a certain minimum pulse is required to form a strong weld and that further input of

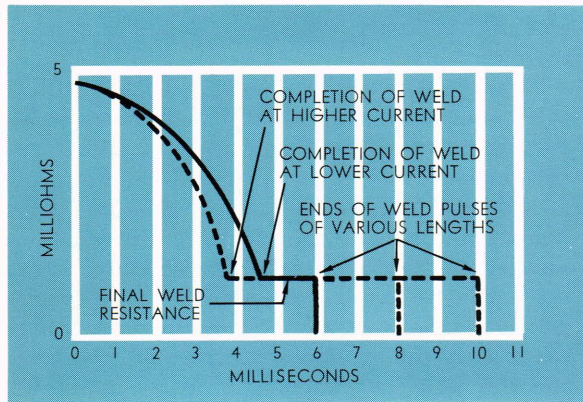


Fig. 4—With the requirement satisfied for a minimum pulse to produce a strong weld, further weld time is shown to be unnecessary.

energy is unnecessary though not harmful. We see this illustrated in Fig. 4.

Each of the combinations of metal can be identified by its resistance pattern, so different are they. While the pattern for nickel-to-nickel just described has a satisfying orderliness about it, that for dumet-to-dumet* at first glance appears to be utterly chaotic. Fortunately, as we assemble these patterns for all combinations of current and time of which the welder is capable, as illustrated in Fig. 5, regularities appear. Momentary peaks of resistance appear at almost all settings where pull strength tests (Fig. 6) show the weld to be strong and where metallographic pictures (Fig. 5) show the copper sheath to be pierced and a core-to-core weld formed. Where the relatively weak copper sheath-to-copper sheath weld is made or where there is no weld at all, the transient peaks, as seen in Fig. 7, are missing.

These transient peaks probably have their origin in the peculiar dependence of resistivity

* Dumet is a registered trademark of the Sylvania Corp. It is a highly useful wire made up of a core of 54 nickel-46 iron alloy surrounded by a conductive copper sheath.

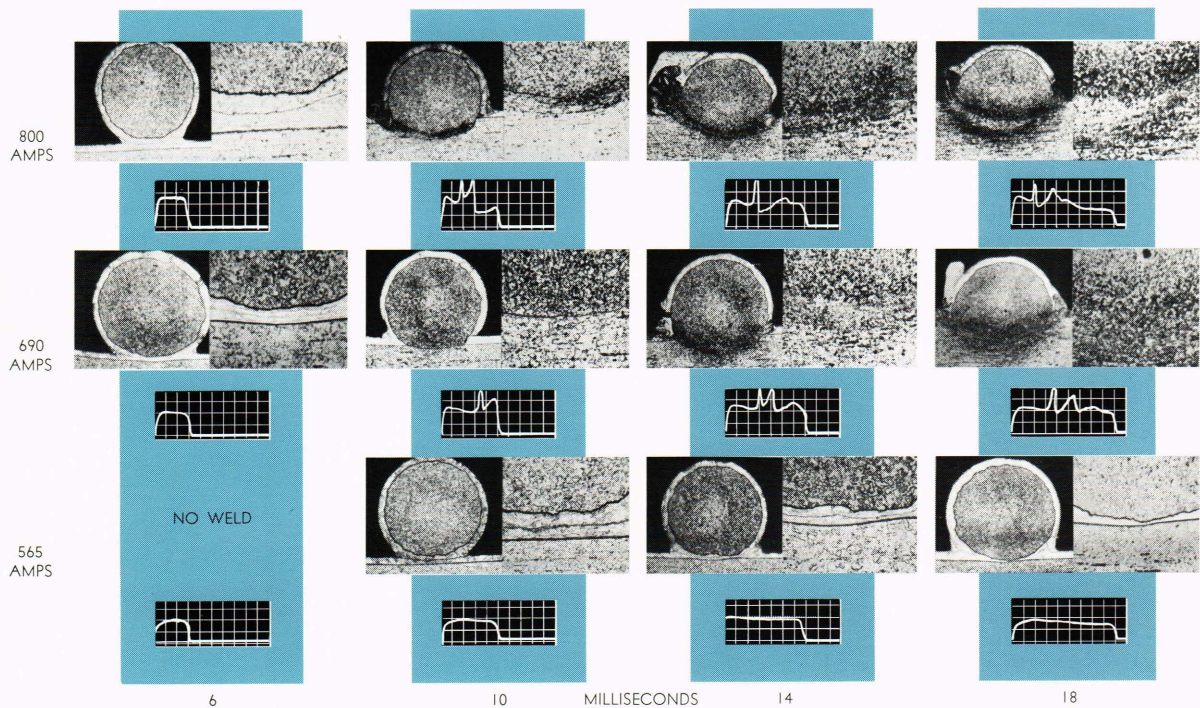


Fig. 5—Metallograms and resistance patterns for the APL welder, for dumet-to-dumet welds, with increasing currents and weld times.

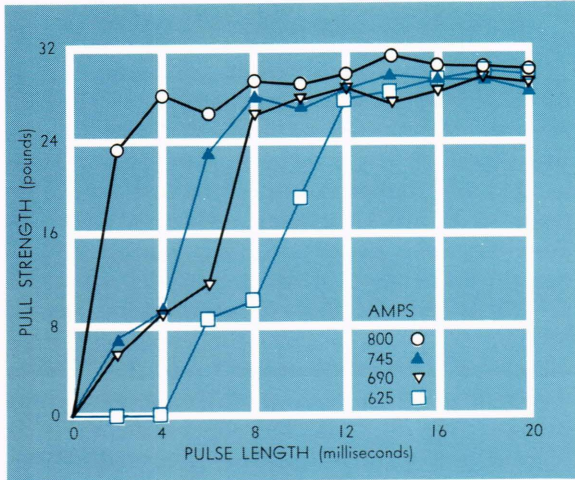


Fig. 6—Pull strength versus pulse length at various currents for dumet-to-dumet welds.

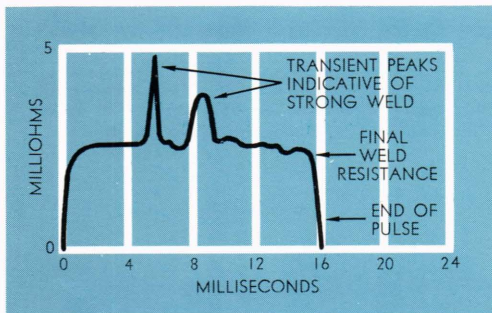


Fig. 7—Resistance pattern transient peaks for a relatively strong core-to-core weld.

upon composition in the copper-nickel alloys. Coles¹ gives a diagram (Fig. 8) that shows a 50-fold increase in resistivity as nickel concentration is increased from zero to 50% and then a gradual decrease to the resistivity of nickel itself.

The initial resistance of the weld is that of copper-to-copper contact. As the copper is melted and dissolves in the nickel-rich core, the resistance abruptly rises, reaching a peak and then diminishing as the copper is still further diluted, finally reaching a nickel-iron-copper weld resistance not far different from the initial value.

It is never possible to tell whether a solder joint or weld is good merely by looking at it. Nor can an inspector, however skilled, be expected to make no mistakes whatever in 40,000 examinations, and yet this level of excellence is

¹ B. R. Coles, "Electronic Structure and Physical Properties in the Alloy Systems Nickel-Copper and Palladium-Silver," *Proc. Phys. Soc.*, 65, Sect. B, Mar. 1, 1952, 221-229.

needed. A non-destructive weld testing procedure has therefore been sought for many years but without success. The resistance pattern provided a solution to the problem. Using a storage-type oscilloscope in which the trace will persist until erased, the resistance pattern of each weld can be scanned as the weld is made. If the pattern reproduces the known standard, the weld may be presumed sound, with a high degree of confidence; if different, it may be repaired then and there.

Usually a new development brings with it about as many new problems as solutions to old ones, and the welder is no exception. Where the two materials being welded are different, the direction of current flow has a profound effect upon the time required to form the weld. In some cases twice as long a pulse is required when the current flows in one direction as when the same current is reversed. Metallograms of the welds show the heat to be distributed differently and the weld resistance patterns are noticeably changed. In Fig. 9 are metallograms of welds which differ only in the direction of current flow. This peculiarity has been noticed with the capacitor welders, but with them it is far less serious. We have no explanation for it.

While the performance of the welder has met with praise, just as often has its cumbersome truck-battery power supply met with scorn; yet it is likely that the steady current of the battery, generally free of high frequency components, is responsible for the effectiveness of the welder.

For the materials with which we are normally concerned, currents well in excess of 1000 amperes are sometimes required. Our inability to switch such large currents directly with precision

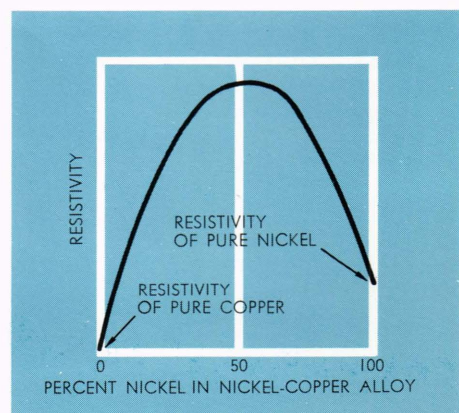


Fig. 8—Increasing resistivity with increasing nickel concentration in copper-nickel alloys (Ref. 1)

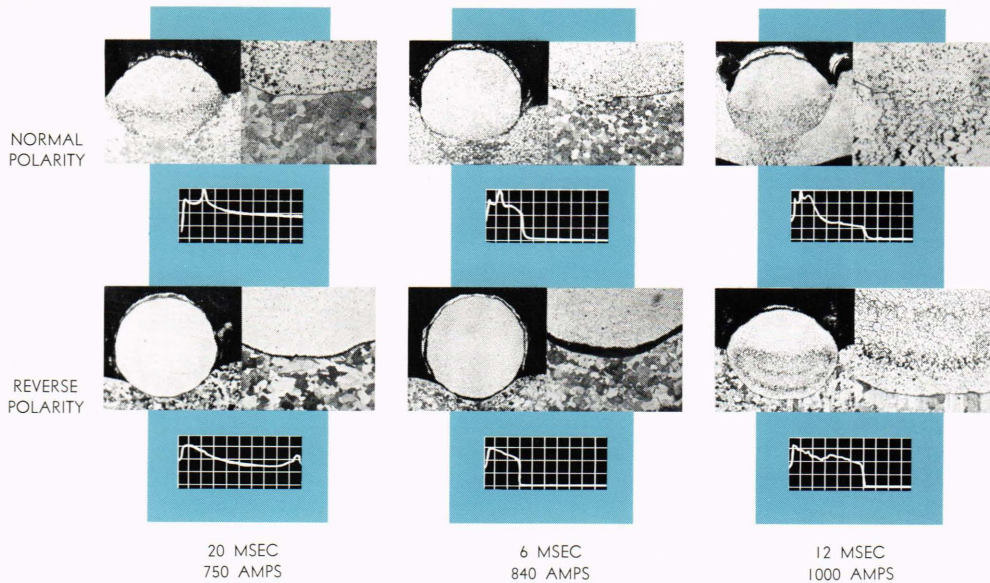


Fig. 9—Metallograms of welds showing variations resulting from normal and reverse polarities.

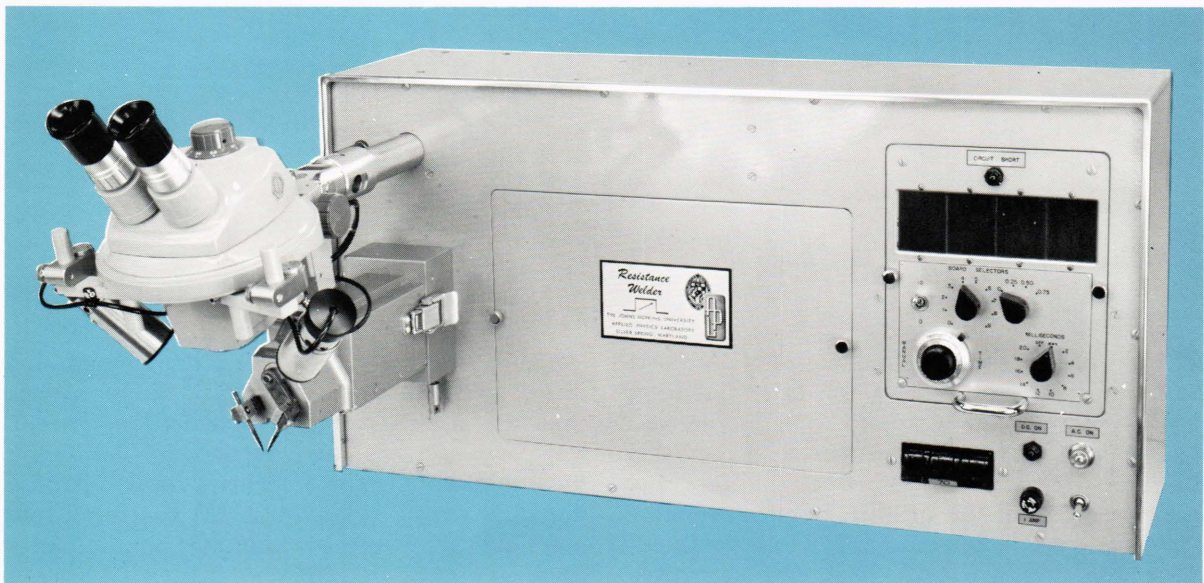


Fig. 10—The APL-designed production resistance welder, with commercial welding head, microscope, and lights.

led to the development of a transistor circuit† that is capable of controlling currents up to 1500 amperes for times up to 20 msec. This circuit is divided into two parts: a bank of 20 parallel transistor switches, each of which is capable of passing 100 amperes; and a time control that activates all of the switches for a preset

interval. The current is determined by selecting manually the appropriate number of parallel transistor switches in the circuit, though of course the increment of current is smaller for each additional switch added. Figure 10 shows the APL-designed welder, equipped with commercial welding head, microscope, and lights. This is typical of the ten that are now in regular operation in the APL Electronic Resistance-Welding Workshop.

† The electrical circuitry is the work of A. A. Dargis, formerly of APL.