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MINIATURE PACKAGING OF ELECTRONICS IN THREE-DIMENSIONAL FORM

by

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MINIATURE PACKAGING OF ELECTRONICS
IN THREE-DIMENSIONAL FORM

Research and development in the field of air- and space-vehicle guidance systems places an ever increasing premium on lightweight, small-size, rugged and reliable avionic equipment. The electronic devices used, though becoming more complex, are also necessarily becoming more compact to allow the maximum possible equipment per cubic foot and the least possible weight to be taken with the vehicle on its mission. They must also be able to operate satisfactorily under an extremely wide range of environmental conditions, particularly those of temperature, humidity, vibration, and acceleration or shock.

A considerable reduction in electronic package size and weight has been achieved through the use of tight designs with existing printed-circuit techniques and miniature components. Manufacturers have been showing new lines of components that are radically smaller than their equivalent of five years ago and this, combined with printed circuitry, has resulted in extremely compact and small electronic systems.

But the requirements for avionic equipment are so exacting that every possible method of achieving minimum space and weight consistent with maximum ruggedness, reliability and long life must be considered. By using miniature components now available from manufacturers and a newly applied method of joining wire leads, the M.I.T. Instrumentation Laboratory has developed an electronic-packaging technique based on the mounting and wiring of circuit components in a miniature three-dimensional unit mass. This new technique, referred to as 3-D or High-Density Electronic Packaging, has achieved a maximum component density without sacrificing production feasibility. Derived from a concept originated by Samuel Francis, of Francis Associates in Marion, Mass., it consists of placing circuit elements in physical contact (side by side) and forming the circuit connections on a three-dimensional basis, as opposed to the two-dimensional printed-circuit board. The wires are joined by electrical-resistance spot welding, which is similar to the vacuum-tube technique. After assembly and electrical checkout, the unit is encapsulated in epoxy potting compounds to form a module. The resulting miniature package

(see Fig. 1, for example) is a maximum-density assembly utilizing all practical space within the package.

The M.I.T. Instrumentation Laboratory commenced its 3-D effort in an exploratory manner with certain portions of an over-all inertial guidance system that was under development. After successful designs were accomplished, the technique was found to be of such value that it mushroomed to several other areas of the inertial-system electronics.

Distinct differences in approach have been found necessary for digital computing circuits and analog servo circuits. In digital wiring, the large number of interconnecting logic wires complicates the design of the 3-D wiring setup and special layout techniques are necessary. In analog packaging, on the other hand, the two chief problems encountered are heat dissipation from the module and electrical inter-element coupling effects of components in close proximity.

ADVANTAGES

Some marked advantages over other methods have emerged from experiments in producing and testing these 3-D units. A significant feature is the fact that present welding facilities for vacuum-tube manufacturing are ideally suited, and the manufacturers are therefore presently equipped, for the production of 3-D modules. It has also been shown, on a developmental basis, that this welding technique greatly reduces the assembly time as compared with the manual assembly of printed-circuit boards. For example, it is estimated that two technicians can assemble a 3-D package in the same amount of time it takes six technicians to assemble the same circuit when using two-dimensional printed-circuit boards. Highly reproducible results can also be achieved.

Design flexibility is another important feature of the three-dimensional module, because of the variety of components that can be handled and the manner in which they can be used. Transistor circuitry from signal level to power level when packaged by this method lends itself to easier solution of problems of heat transfer, mounting accessibility, and package design. This is because the shape of the module can be molded to suit particular needs, and module groups can be arranged to fit unique package configurations. As for reliability, a vacuum-tube manufacturer has estimated, on the basis of vacuum-tube production experience, that for an assembly containing several hundred welds, only one in 10,000 assemblies will be rejected because of bad welds.

When applied to proportional-amplifier circuits (analog circuits), the 3-D technique has achieved component densities up to 65 components per cubic inch (more than 110,000 components per cubic foot). Although these figures do not
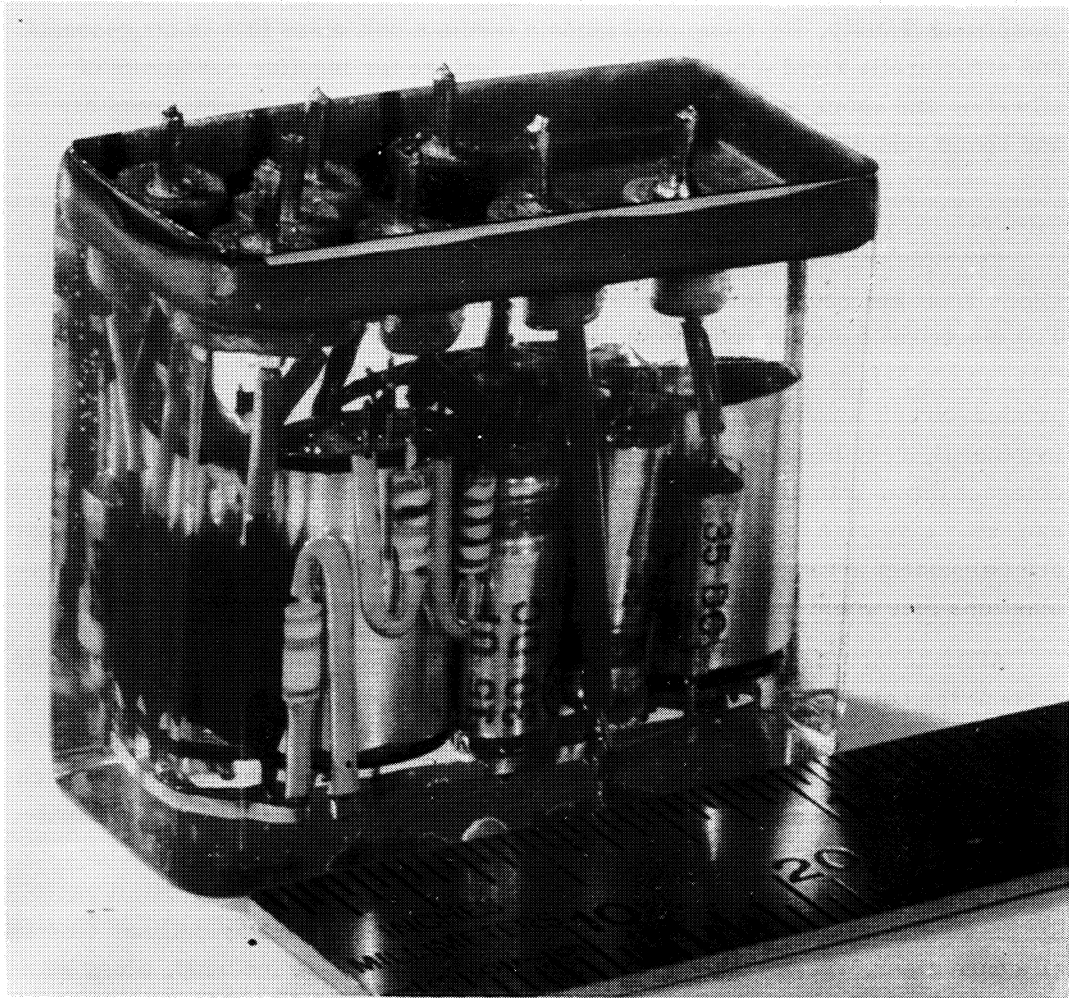
Fig. 1. Three-dimensional packaging technique applied to a resolver drive amplifier.

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compare with densities achieved in binary-circuit techniques now under development (such as DOFOL, RCA, and Varo), the important thing is that they have been obtained while using such components as JETEC-cased transistors, transformers, microfarad capacitors, and others not found in binary circuitry. In digital circuits, densities of 3-D modules up to 160 components per cubic inch (more than 250,000 components per cubic foot) have been produced. With a high component density, the completed module forms a unit mass that is nonresonant and structurally rigid – a desirable design feature for meeting conditions of vibration and shock that may be encountered under operating conditions of air and space vehicles.

ANALOG CIRCUITS

Examples of wiring configurations and component arrangements of an analog-type circuit are shown in Fig. 1, which illustrates a resolver drive amplifier. The electrical designer must deal with the problem of inter-element coupling in this type of 3-D module, a problem usually not found on the breadboard or printed-circuit assembly. The types of circuits used in analog electronics are, in general, very broad-band, high-gain amplifiers with generous feedback. A compact three-transistor amplifier, for example, if potted in a Mu-metal shielding can, may give rise to stray coupling through the can to the input. Circuit design and component arrangement, therefore, must be carefully planned to avoid combinations that would lead to any oscillatory instabilities.

After accomplishment of the circuit design and component layout, taking into account the coupling problem and also the most efficient packing arrangement, a production drawing is prepared in plan and elevation showing all views of the unit and the location and orientation of each component as well as the location of each weld. As shown in Fig. 2, components are numbered on the drawing in accordance with a parts list, with R1, R2, R3, etc. for resistors, C1, C2, C3 for capacitors, TR1, TR2, TR3 for transistors, and likewise for other detail parts for production identification. The wiring configuration is clearly outlined showing all connections. Terminal-connection instructions are also included, along with color coding of the terminals.

The welding, as mentioned earlier, utilizes techniques for vacuum-tube construction. One problem that constituted a major road block in the assembly of analog-type circuits was the variety of weld types to be handled, since component lead-wires span quite a range of sizes and several materials. It was found that by using a flat, nickel ribbon as the common lead-joining medium, welding became more uniform and one weld setting could handle a number of weld-types. A by-product of the use of this type wiring was an increase in

GREEN
to leads
of R1,
R18, R19

GRAY to
lead of R5

BROWN to
lead from point (A)

RED to lead
from point (C)

ORANGE to
lead from point (B)

BLUE to
lead of C7

COVER ASSEMBLY OF
RESOLVER DRIVE AMPLIFIER

0.006 IN. THICK
ALUMINUM FOIL
FORM

NOTES

1. LEADS FROM POINTS (A), (B) AND (C) TO
   COVER TERMINALS SHALL BE NO. 24 SOLID
   DUMET WIRE INSULATED.
2. BUSSES SHALL BE 0.010 × 1/32 A NICKEL RIBBON.
3. RIBBON-TO-RIBBON BUS CONNECTIONS AND
   RIBBON-TO-COMPONENT CONNECTIONS SHALL
   BE RESISTANCE WELDED.
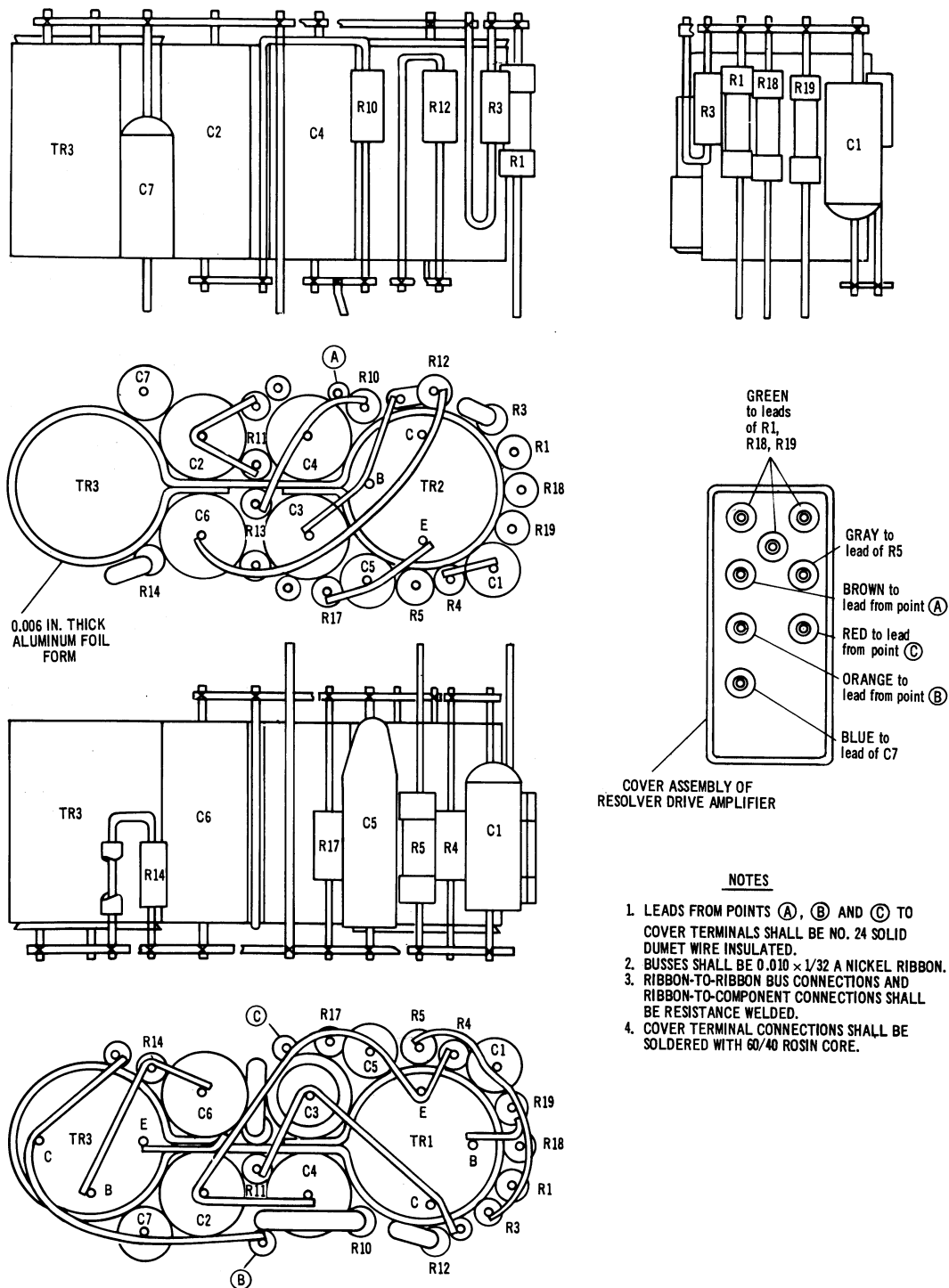4. COVER TERMINAL CONNECTIONS SHALL BE
   SOLDERED WITH 60/40 ROSIN CORE.

Fig. 2. Production drawing showing layout of components and wiring configurations of the three-dimensional module in Fig. 1.

structural rigidity of the unit before encapsulation. This is an important consideration since the unpotted assembly is held together only by leads, welds and small amounts of Mylar tape. Handling must be kept to a minimum since damaging strains can result from excessively rough treatment. After potting, of course, the modules are quite rugged and are fully capable of meeting missile environmental specifications. Figure 3 shows a weld being made on a 3-D component, using a miniature welding head and a special jig to hold the components during welding.

As an illustration of the densities to be achieved, plans are in effect at the Instrumentation Laboratory to provide for a package containing analog electronics with dimensions of 0.15 to 0.19 cubic feet, weighing 15 to 20 pounds, in one unit mass structure. In contrast, for this same system, using printed-circuit boards, a tightly designed electronics package has previously been assembled with a volume of 0.6 cubic foot and a weight of slightly less than 40 pounds.

THERMAL PROBLEMS

Thermal conditions within modules must be seriously studied. If power levels are reasonably low, as in the case of digital-computer circuitry, the modules can be stacked into one block and tied together, with the thermal problem handled rather loosely. For example, aluminum foil can be placed between layers to conduct the dissipated heat to an appropriate heat sink. However, analog circuitry contains circuit elements that require more heat-sinking than corresponding elements of digital circuitry. To accomplish the necessary heat transfer, in the case of individual signal-level transistors, the transistor can be wrapped in aluminum foil, which in turn is attached to an aluminum plate on one face of the module. A layer of such modules can be clamped to each side of a cold plate, which will remove the heat from each module.

In addition to signal-level modules, power transistors potted into modules with the copper heat-transfer face exposed (without studs) can also be effectively handled by this clamping-to-a-cold-plate method. Pictures of a 100-watt servo output stage, illustrating the heat-transfer surfaces, are shown in Fig. 4. The result is a greatly simplified (and cheaper) cold-plate design; and there are no mounting studs to interrupt the heat-transfer fluid passages. This design feature alone effects a considerable reduction in the volume required for heat-exchanger equipment. An example of an operational heat exchanger and the module mounting arrangement is illustrated in Fig. 5.

To determine the values, and the distribution of values, of the thermal resistance between encapsulated power transistors and the surface of a cold plate, tests were made with representative modules mounted on a heat exchanger. An average value of the mounting thermal resistance for H-10 transistors, based on 64 test points, was determined to be 0.38° C/watt with
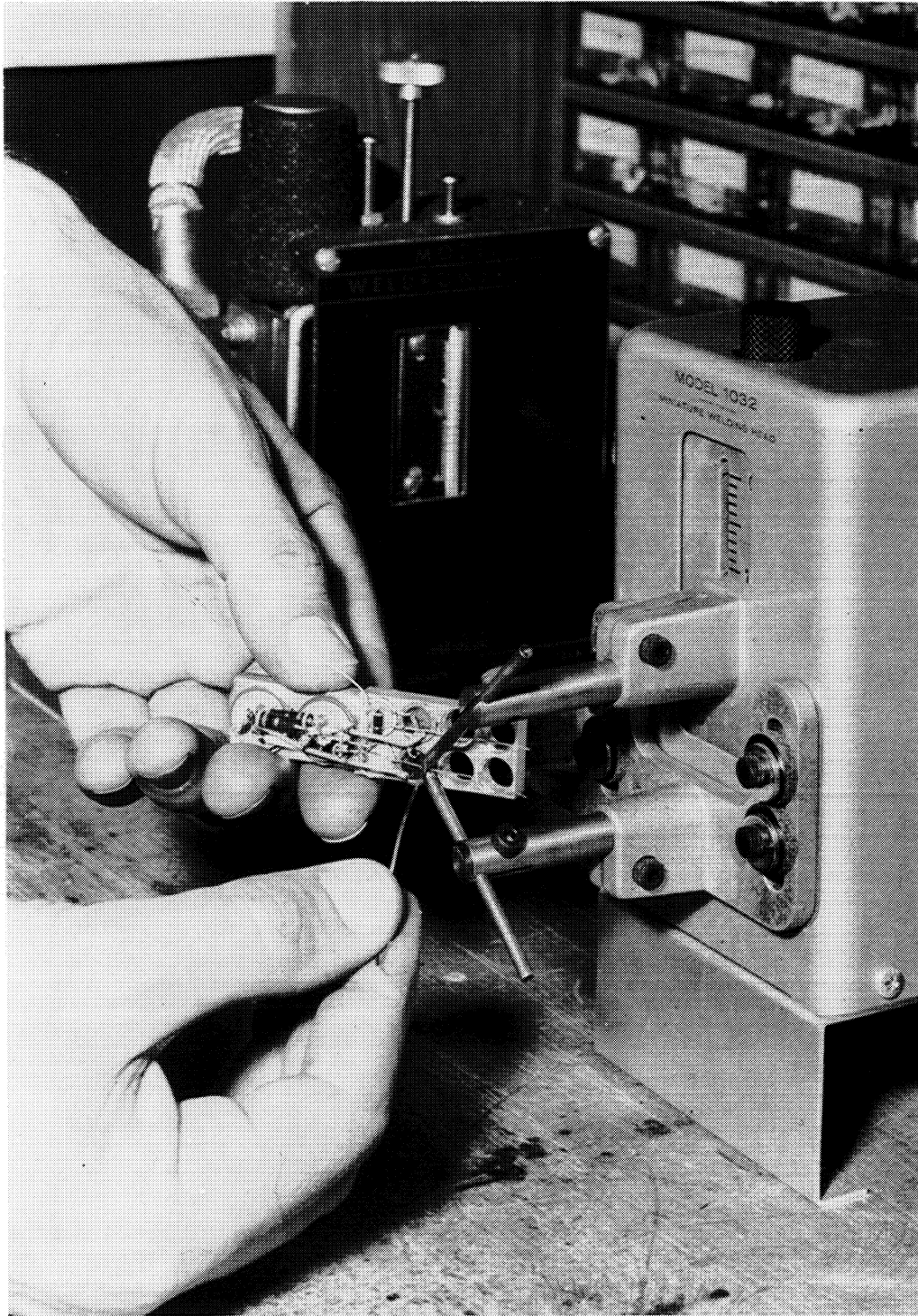
Fig. 3. Welding of three-dimensional component lead-wires using welding equipment of the type used for vacuum tubes.
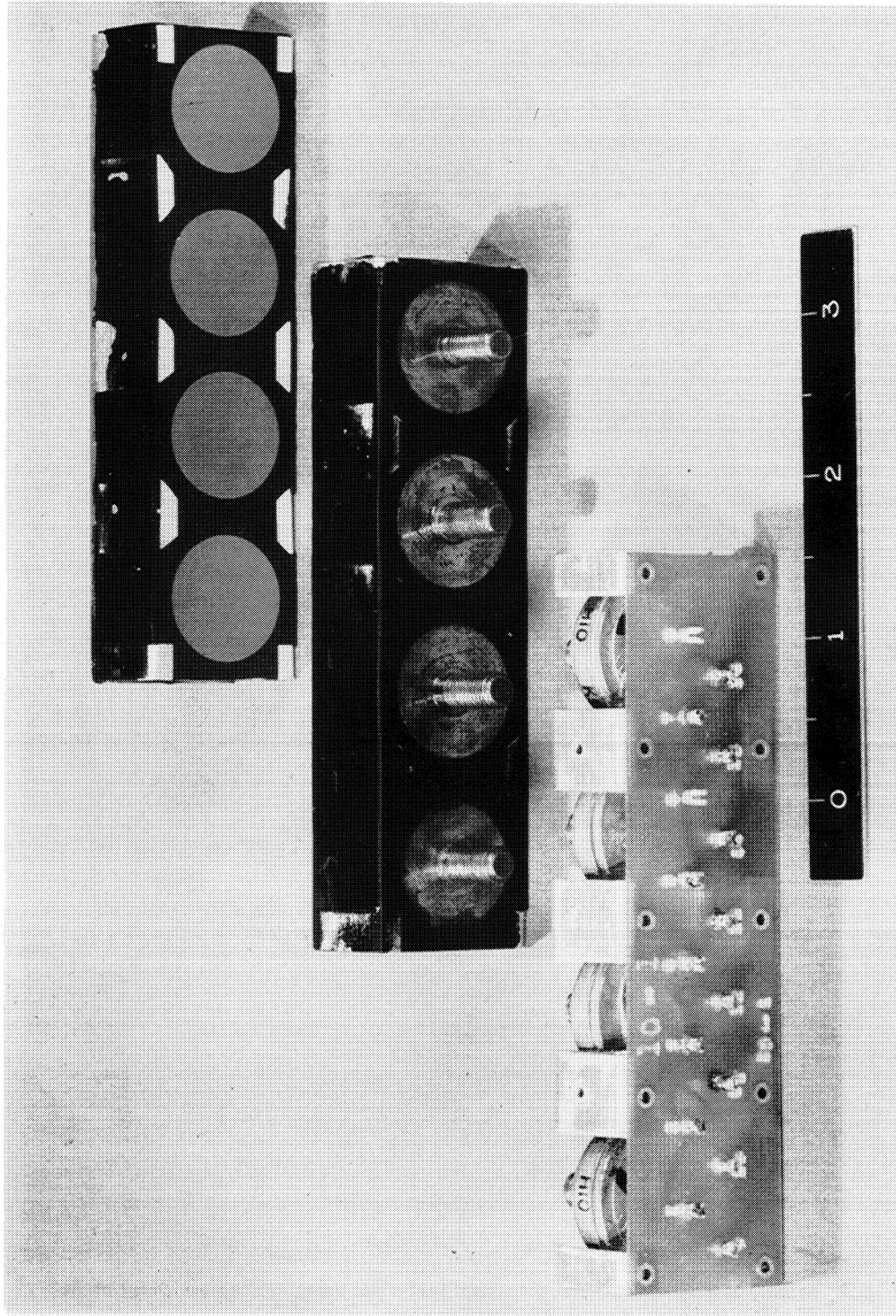
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Fig. 4. Example of a power-transistor module.
A 100-watt servo output stage with unpotted assembly shown in lower view, encapsulated assembly in middle view, and finished module with studs removed and heat-transfer faces exposed in top view.
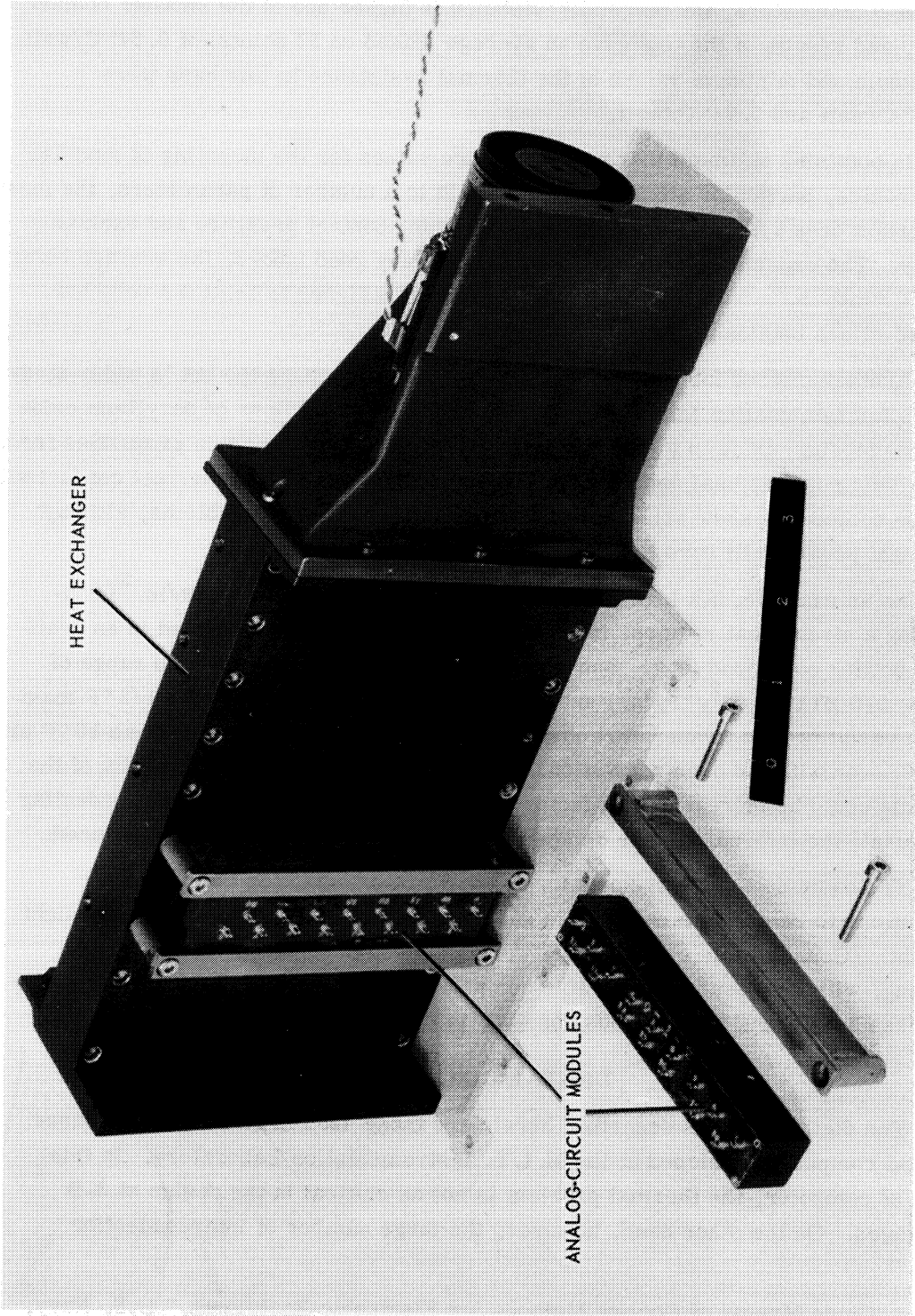
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HEAT EXCHANGER

ANALOG-CIRCUIT MODULES

Fig. 5. Heat exchanger and mounting arrangement for removing heat from analog-circuit modules.

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maximum and minimum values of 0.49° C/watt and 0.26° C/watt, respectively. For H-7 transistors, the thermal resistance is higher due to the smaller contact area, and results of the test gave an average (based on 56 points) of 0.84° C/watt. Maximum and minimum values of the thermal resistance in this case were 1.00° C/watt and 0.74° C/watt.

In obtaining optimum thermal-resistance values for the mounting of modular electronics, particular attention must be paid to a number of parameters, the most important ones being surface finish and flatness, contact pressure and exclusion of air. The experimental figures derived are very good indeed, the average being 0.2° C/watt/in.^{2} Reference sources * show this figure to be at the very low end of values obtainable.

Another method for preventing components from getting too hot is under study at the Instrumentation Laboratory. It is based on using fillers of beryllium oxide and magnesium oxide in the potting compounds, to adjust the resin properties from relatively poor thermal conductivity to a noticeable increase in thermal conductivity. These compounds show some promise of alleviating thermal problems, although a weight penalty will have to be paid if they are used.

As an example, if a high-power-density module (e.g., 0.7 watt/in.^{3}) containing a circuit that requires temperature regulation is encapsulated in an available potting compound (e.g., one whose thermal conductivity is in the range of 1.0 - 2.0 BTU/hr/ft^2/°F/in.) and is placed in a regulated oven of ± 1/2 °F maximum variation, the temperature rise within the module may be as high as 10°F or 15°F, even with the oven regulation. However, if the thermal conductivity of the module could be increased by a factor of 3 to 7 by filling it with a heat-conducting material, the internal module-temperature variation would be greatly reduced.

The basic potting compounds themselves are selected for the particular conditions to be encountered and, in general, should be of high strength and light weight. Considerable experimental work has been undertaken with regard to potting, with the result that suitable compounds and methods for the High-Density process are in use, with various possibilities of improvement under study.

DIGITAL CIRCUITS

The digital circuits described herein are those used in an inertial-guidance digital computer developed at the M.I.T. Instrumentation Laboratory. In this type of computer, the thermal problem is not as critical in the design of 3-D packages. On the other hand, however, the large number of interconnecting

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*"Guide Manual of Cooling Methods for Electronic Equipment," U.S. Navy, Bureau of Ships, NAVSHIPS 900, 192.

wires and the importance of correct logic wiring has made it necessary to develop special techniques in applying the design to the 3-D package.

It may be seen, from a brief explanation of the type of data-handling circuits used in the computer, that the logic wiring has been made the controlling member in the computer design.

The computer is made up of three basic elements: "nor" gates, a shift-register memory, and a crystal-controlled clock. The interconnecting wiring between these three elements provides the logical function of the computer.

The nor gate is the only type of circuit "building-block" used in the logic, the memory read-in and the memory read-out circuits. Each memory read-out consists of two nor gates connected to provide a set-reset flip-flop, resistor-coupled to the memory. The memory read-in circuit consists of an "or" block, which is the same standard nor-gate circuit with the collector load-resistor removed. The installation of the resistor between the flip-flop and the memory and the removal of the collector load-resistor in establishing the "or" block are both part of the production process when the logic wiring is applied. The circuit diagram shown in Fig. 6 is an example of the data-handling arrangement. An explanation of the "nor" and "or" symbols is also shown. Because of the exclusive use of identical nor gates, a series of identical circuits can be used in 3-D packages and interconnected as needed in the design throughout the computer.

The computer is designed around the shift-register memory (denoted also by the term "memory stick"), which also contains repetitive circuit features whereby a standardized form of component layout can be employed in the 3-D module. The clock is the only element containing nonrepetitive circuits. Therefore, the design of the computer is established by controlling the pattern of the logic wiring.

The resulting High-Density or 3-D package can be constructed in the form of a "stick." This form of module can easily be assembled into a cube or other shape to provide for a multiple-stick assembly. Figure 7 shows the various stages of assembly of a logic stick and also a complete package of sticks, with all wiring between sticks interconnected by means of an end-connector assembly.

LOGIC-STICK CONSTRUCTION

In order to position the multitude of parts in the stick and to hold them together during welding, a technique of film jigging was developed. This technique utilizes two punched insulating films of Mylar tape to accurately position all component leads. The film becomes a permanent part of the assembly, also acting as a physical insulating barrier between the stick components
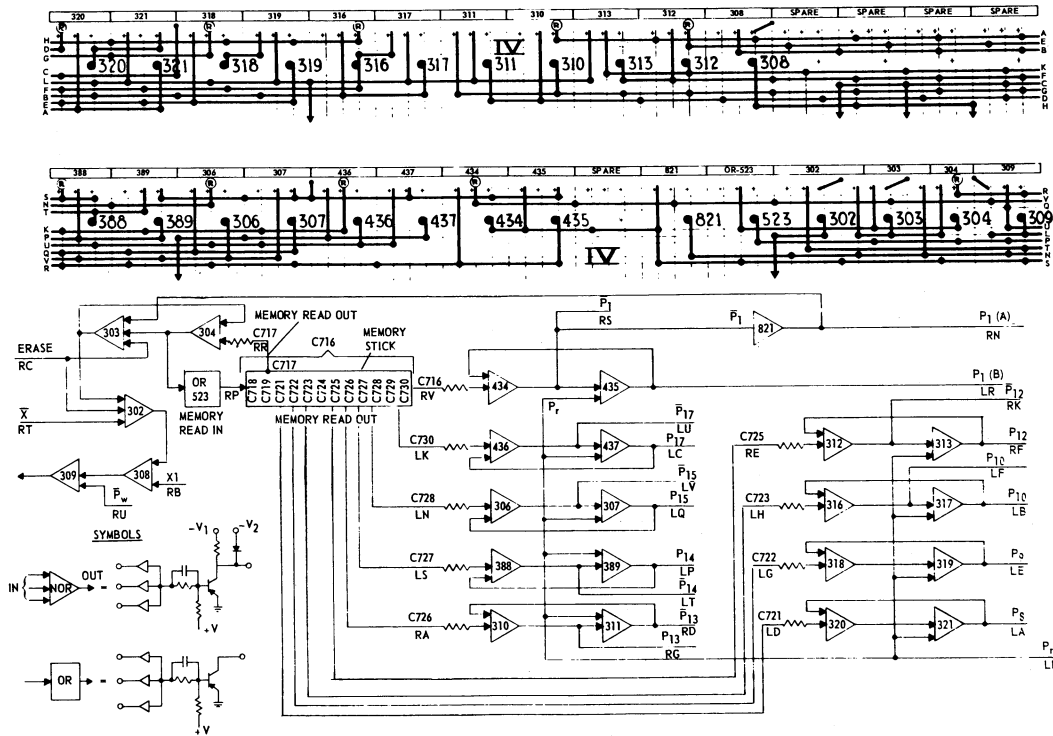
Fig. 6. Example of circuit diagram and corresponding logic wiring layout used in construction of logic stick.

and the power busses and/or logic wiring incorporated on them. The original layout of the stick, made by hand, as with analog 3-D packages, is reflected in the instructions on the film, thus providing the information for proper positioning of the components. The film-jig information is based on the original component-layout drawings, which indicate all component positions, lead locations, and power-bus interconnections in plan and section. From these drawings, 5×-scale overlay drawings are made showing the location of each lead, in the plane of the film jig, and this layout is photographically reduced to the jig size and produced on the Mylar tape. The lead locations are punched on a power punch to provide the properly oriented holes through which the lead wires are to protrude when the components are inserted. In the design and layout of sticks, the film-jigging procedure eases the design process and ultimately results in the transfer of information to the fabricator in an expeditious manner.

The logic-wiring matrix that is applied to each side of the stick is manufactured separately, from a wire-mesh structure mounted in a frame. Mylar tape, with instructions for the welder, is also used in this operation to separate and
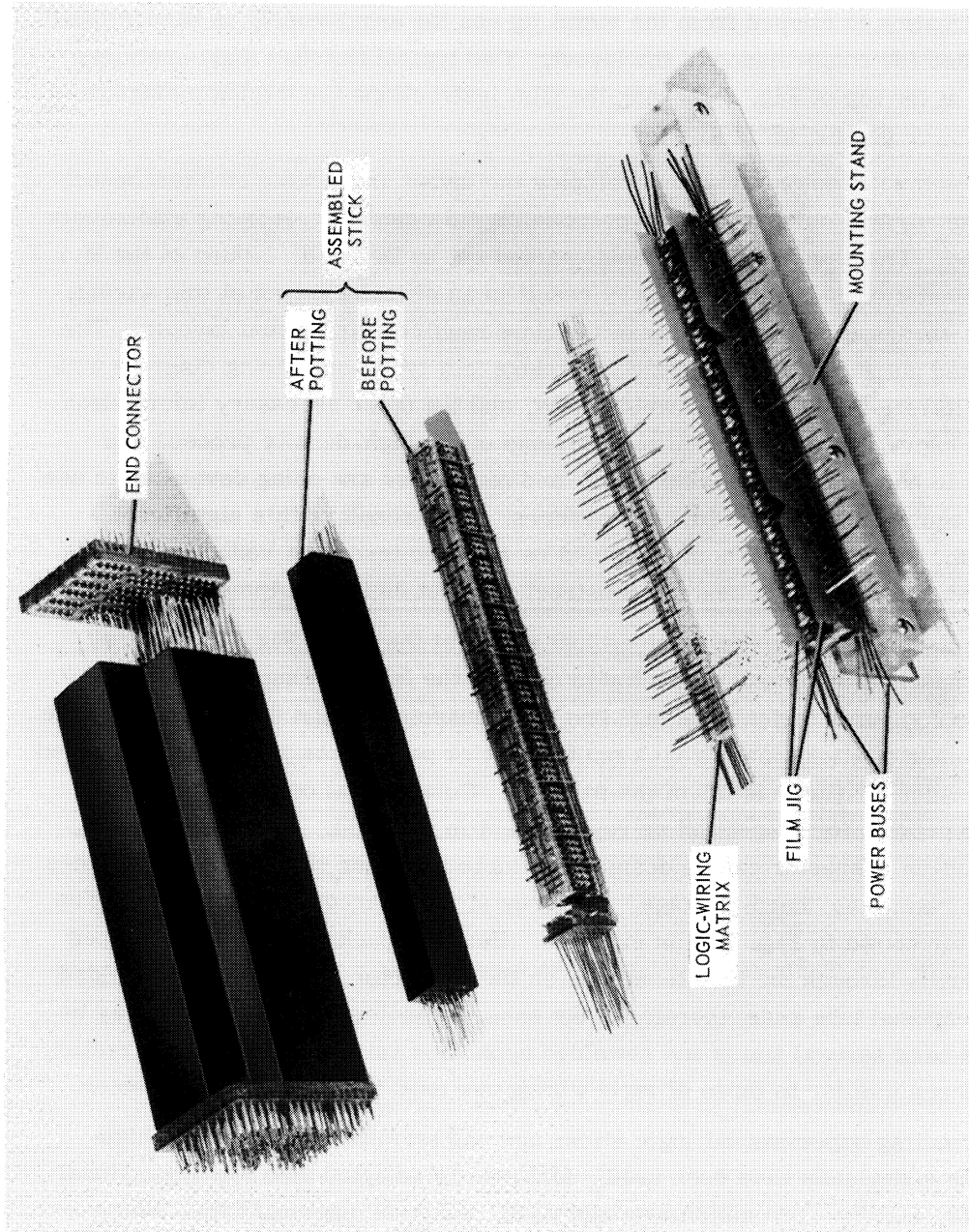
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END CONNECTOR

ASSEMBLED STICK

AFTER POTTING

BEFORE POTTING

LOGIC-WIRING MATRIX

FILM JIG

POWER BUSES

MOUNTING STAND

Fig. 7. Construction of a logic stick and of a multiple-stick assembly.

From bottom to top, views show (a) film jig holding components in position on the outside of the jig, (b) assembly of logic-wiring film and logic wiring, (c) assembled stick (unpotted), (d) assembled stick (potted), and (e) multiple-stick assembly, showing one end connector welded in place. The single stick shown contains 36 transistors, 144 diodes, 36 capacitors and 108 resistors, and measures 0.5" × 0.75" × 7.5".

hold the wires. Logic-film layouts are prepared, as in the component layout, and tack-weld points, clip areas, switch number, bus identification and subassembly identification are all included on the film. The logic-film is slipped between the longitudinal and cross-bus layers of the wire mesh and all welds are then made. Weld points are indicated by a hole punched in the tape. The welded matrix is clipped from the metal jig and the subassembly is hand clipped and tested for conformance to the layout. Two typical finished logic-matrices appear at the top of Fig. 6 showing the film instructions for the logic diagram in the lower portion of the figure.

A method of automatically developing the layout and testing of interconnecting logic wiring, using a general-purpose digital computer, is being extensively explored. This undertaking is being carried out by Dr. J.H. Laning of the M.I.T. Instrumentation Laboratory and will result in an efficient layout of this wiring, without errors, and in a fraction of the time required for manual layouts. The generated output of this automatic procedure is a typed-out wiring diagram with stick-alteration instructions, weld points, and the other necessary information for the logic-film jig. In addition, portions of the high-density process are subject to human error in fabrication, and techniques are being developed to use digital equipment to check for these errors. As a result of this significant program, substantial economies should be realized through a reduction in the man hours necessary to design, construct and test digital equipment.

An assembly of sticks, such as that shown at the top of Fig. 7, requires interconnection or an end connector to connect the logic wiring in accordance with the computer logical design. The end-connector design depends on the size and number of sticks making up a multiple-stick package as well as the proposed maintenance characteristics of the package. Commercial connectors may be used to provide for inspection or replacement in the field. On the other hand, a welded-on connector can be designed so as to allow for removal several times and yet retain the "hard-packaged" features of the interconnecting wiring. The connector shown in Fig. 7 is an example. Here the package wires are slipped individually through the tube terminals on the connector, as shown, and welded at the exposed tube ends; therefore, the ends, including the weld point, may be clipped back several times and rewelded upon each reinstallation. Construction procedures similar to those of logic wiring are used in this type of connector.

In potting experimental logic sticks and end terminals, lightweight high-strength compounds have been used. Material is selected also for dimensional stability, rigidity, low moisture absorption, and good machinability. These

features result in a very satisfactory finished package with characteristics that are highly desirable in the construction of an airborne computer with minimum support structure. The potting procedure for end terminals is similar and several types have been potted achieving the aforementioned features.

A total of 28 logic sticks, for life tests and environmental tests, have been manufactured for the M.I.T. Instrumentation Laboratory by the Raytheon Manufacturing Company's Subminiature Tube Division. Another 8 logic sticks have been produced by Sippican Corp., Marion, Mass. Of this total, 16 sticks in a completely welded computer are now on life test at the Instrumentation Laboratory. The others have been undergoing various types of environmental tests.

As a further comparison with the printed-circuit-board technique, a 3-D digital-computer electronic package now being designed will have a total volume of 0.1 cubic feet and weigh under 10 pounds, whereas the volume of a tightly designed printed-circuit computer package, assembled for the same system, is 0.4 cubic feet with a weight of approximately 26 pounds.

GENERAL CONSIDERATIONS

It is obvious that three-dimensional module packaging will require rigid quality-control procedures not only for checking the reliability of the packages themselves but for checking the reliability of components before assembly. These components must meet design specifications, and 100% inspection of incoming parts is now required in order to minimize any chance of failure after completion of a module. The correctness of welds is also an item that must be closely controlled. It is quite likely that more than the usual amount of test equipment will have to be employed because the throw-away cost, once the unit is packaged, is higher than in other miniature-packaging techniques. However, the basic technique of welding connections using vacuum-tube methods as opposed to conventional soldered connections has a high degree of reliability.

The several marked advantages of 3-D welded electronic packages and the successful results achieved with them in the earlier period of development have prompted the comprehensive program now underway at the M.I.T. Instrumentation Laboratory, under systems sponsorship by the U.S. Navy and U.S. Air Force. The further addition of automatic design processes should greatly reduce lead-time between the stages of logical design and the availability of finished hardware. making possible much faster development of whole new compact guidance systems.