USE OF INTEGRATED CIRCUITRY IN A DIGITAL SYSTEM

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ABSTRACT

This paper discusses integrated circuit application in a missile checkout and ground control system. Integrated circuitry refers to any technique that presents in some miniaturized form a basic building-block circuit. This application has evolved from unique circuits using standard components to preferred circuit building blocks also using standard components, and finally, to the use of solid-state integrated circuitry. This paper contains a brief analysis of the sequence. The advantages and disadvantages, as viewed by the author, of the change to integrated circuits for a given use are considered.

The system used to compare the two approaches is a solid-state computer used in ground checkout of an ICBM, and more specifically, in a time interval, phase, and period measurement system requiring digital logic. The system has been under development at Martin Company, Denver, Colorado. The particular type of integrated circuitry now being used and the possible choices for future use are compared.

I. INTRODUCTION

The Denver Division of the Martin Company has initiated a standardization program to reduce the cost and lengthen the MTBF (mean time between failures) of the OGE (operating ground equipment) for the Titan ICBM. The resultant reduction in man-hours and overall costs brought about a state-of-the-art investigation of integrated circuitry techniques. The gratifying results of the study induced the Company to use integrated circuits in a large digital system, thus decreasing the cost and increasing the reliability over existing systems.

II. RESEARCH AND DEVELOPMENT

A solid-state circuit usually will have fewer parts and will consume less power in a given use if it is designed specifically for that job. In the early design and engineering of the OGE for the Titan ICBM, the Martin Company designed each circuit as it was needed in the system to minimize parts and power consumption. However, in a large system, several circuits became repetitive, with only minor variations. Each circuit had been designed independently unless the same engineer worked on both systems. This was expensive and time consuming (see Appendix A).

A Standard Circuits Group was organized, with responsibility for designing a set of logic and switching circuits that would be completely compatible in any combination desired, within predetermined limits. These limits are restricted to fan-in/fan-out capabilities and a common power supply. Few ac circuits are included in the set of preferred circuits, since their use is small in the overall system. These circuits have been in use for about two years, and the results have been satisfactory. Many man-months are being saved in design, drafting, and manufacturing. In addition, quantity purchasing and smaller stock problems have reduced component costs by thousands of dollars (see Appendix A).

It is obvious that savings in other fields allowed more money for the purchase of higher quality parts, thereby increasing the reliability factor in these circuits with no design changes. Not only is it possible to use parts having longer MTBF, but the design margin is increased as compared to previously used components.

In April 1958, the US Army Signal Corps awarded RCA a contract for the design and development of micromodular electronic equipment (Ref. 1). The Air Force has supported large projects at Westinghouse, Texas Instruments, and Motorola in the field of modular electronics (Ref. 2). These are just a few examples of the government support that has been given to the electronics industry in the field of integrated circuitry. RCA began micromodular research in 1956, but received impetus from the Signal Corps support (Ref. 3). Many other companies were already conducting integrated circuitry research, or have since entered the field.

Industry and government support of integrated circuit development has resulted in a great variety of new products from which the electronics user may choose. Several companies produce semiconductor networks of the type from which the circuits used in the Martin system were developed. Other companies are rapidly expanding the market. The growing importance of semiconductors is described in Business Week (Ref. 4).

In an attempt to enter the new market, many firms are offering custom-built integrated circuits for any user who agrees to pay the tooling expense in addition to the price of the custom circuits (Ref. 5).

Miniaturization of integrated circuits in operating ground equipment has only minor value unless it provides other major advantages. However, when OGE becomes spaceborne or moon-based, miniaturization is a major requirement. Certain types of integrated circuits seem to have sufficient value in other applications to merit further investigation. Some of the requirements of ground support equipment are described below, not necessarily in the order of their importance.

Reliability - Although the reliability requirements for ground equipment are lower than those for airborne circuitry, they must be sufficiently high to assure a successful checkout and launch of the missile. Even with redundancy to assure a successful launch, downtime for repairs cannot be afforded.

Reasonable Initial Cost - When applied to initial cost, the word "reasonable" is a vague term and must consider all production processes. It cannot be a simple dollar-for-dollar comparison of the purchase price of standard components, all designed to do the same job. Assembly, maintenance, and life of the component must also be considered. The value received per dollar expended is the basic criterion.

Off-The-Shelf Availability - This might be a debatable requirement, especially to those companies who claim that they can do a better job for the customer by custom building the circuits. In a crash development program, however, the design, tooling, and manufacturing time required for the custom circuits might be unacceptable to the user.

Ease of Manufacturing Assembly - Manufacturing costs represent a large portion of the total cost of most large systems.

Lower Power Dissipation - The cost of electric power alone for the operation of ground equipment would probably be a relatively unimportant consideration. The main problem is the elimination of heat given off by the components. This heat elimination requires special equipment such as blowers, heat sinks, air conditioners, chassis, and racks. Integrated circuitry reduces the amount of heat, thus reducing the need for heat elimination equipment.

Intercircuit Compatibility - A minimum number of interface circuits, which are required to change from one voltage or power level to another, will reduce the cost and complexity of the system.

Standard Circuits for Minimum Stock - Stock problems increase much faster with variety than with quantity.

Reduced Space Requirements - Space becomes important when the system becomes a permanent installation, and the floor area is expensive. Minimum space requirements will allow maximum freedom and convenience for the personnel involved.

Variety - If 80 to 90% of the total system can be supplied as internally compatible integrated circuitry, the interface problems will be further reduced. This characteristic, coupled with previously mentioned requirements, gives a compact, highly reliable system.

III. INTEGRATED CIRCUITRY FOR MARTAC

In the spring of 1959, Martin-Denver thought that it would be more economical and useful to design a single computer-oriented system to replace existing and future subsystems of the operating ground equipment. Since the computer is initially less expensive than the required subsystems, it would, after repeated applications to new programs, save much time and money. Under the existing conditions, a new set of subsystems must be designed and built for each basic change in the missile. For minor changes, the ground equipment must be partially redesigned and rebuilt. The proposal for this multipurpose checkout and launch set specified that the unit be capable of adapting to any changes in the missile or payload.

The new digital checkout system has been named MARTAC (Martin Automatic Rapid Test and Control). Several approaches were considered during the early design phase. In August 1961, Martin decided to use the integrated circuit approach throughout the MARTAC system. At the same time, Fairchild Semiconductor Corporation proposed that Martin could recognize a considerable savings by purchasing the Micrologic elements already being manufactured by Fairchild. Furthermore, costs could be reduced by using units with narrower temperature specification.

Martin accepted the Fairchild offer and began designing the system, using the types of Micrologic that were then available. At the beginning of the design effort, a three-input "nor" gate, a flip-flop, and a half-shift register were available. A counter adapter, a full-shift register, a buffer element, and a half adder have been added. It has been calculated that the number of elements used in the MARTAC system could be reduced by 20 to 50% by using the full range of the presently existing circuits (July 1962).

Since the integrated circuitry used in the Martin system is designed for a 3-volt system that will interface with a 28-volt system, logic must be converted from one level to another. Interface circuitry has been designed to do this job, and at the same time, provide the required power switching. Even these circuits follow the preferred circuit philosophy, and a minimum number of designs are used.

The intended first use for MARTAC is missile-oriented ground checkout, but the system is not limited to that use. Martin intends to produce MARTAC for such uses as:

- Nuclear reactor operations;
- Chemical industry operations and pilot plants;
- Aircraft circuit checkout and verification;
- Electronic manufacturing assembly and subassembly checkout;
- Petroleum industry laboratories.

Martin Company has recently conducted independent research in the thin-film field, but strictly in a research and development category. The decision to use Micrologic in a large control and testing tool was a definite departure from the usual attitude of using nothing radically new in a large system concept. In the past, integrated circuits were most widely used in airborne and mobile units.

MARTAC is composed of two basic sections -- the central unit and the remote unit. The breakdown of functions is shown in Fig. 1, based on Ref. 6.* The purpose of MARTAC is to perform the following functions:

1) Follow a programed input;

2) Permanently record information;

3) Make over 100 decisions concerning system responses;

4) Insert faults to test system response;

5) Conduct self-test to locate internal malfunctions.

MARTAC also has the capacity to make the measurements shown in Table I.

SPECIFIC USE

The circuitry to perform the last three measurements shown in Table I is called the "Time Interval" section of the A-F (analog-to-frequency) converter. These measurements, which may be performed by code programing, are indicated in Fig. 2. Transistors used in the base-driven avalanche mode of operation provide a very accurate, high-input impedance detector.

To eliminate measurement errors caused by differences in propagation time through logic gates, the functional logic was removed from the signal path. The capability to select the required measurements is accomplished by enabling or disabling the eight input detectors at predetermined times. When the start of the period to be measured occurs, a high-power pulse is transferred to the start-stop generator (also an avalanche mode circuit). The same pulse triggers the logic to change its state and prepares it to detect the end of the interval to be measured. The conversion takes place in less than 800 nanosec, allowing a period down to 1 μsec to be satisfactorily measured. The output of the start-stop generator is driven through a coaxial line to a counter system operating at 100 mc. The number of 100-mc pulses counted between start and stop pulses gives the time in tens of nanosec. The proposed design accuracy of the system is ±30 nanosec.

*Figures and Tables are grouped at the end of the paper.

The logic involved in this small portion of MARTAC explains the use of Micrologic. Fig. 3, 4, and 5 show the conversion from standard "and-or" logic to "nor" logic, and finally to Micrologic "nor" logic. A great similarity exists between the "and-or" logic and "nor" logic as to the number of gates concerned. This indicates that "nor" logic can do the same job as "and-or" logic in a large system, and in many cases, can provide a savings in design and types of stocked components. Fig. 5 shows that some of the "nor" gates and flip-flops of Fig. 4 have been integrated into Micrologic elements for an overall reduction of the number of circuits. Fig. 6 and 7 show the assembled MARTAC prototype.

CHOICE OF INTEGRATED CIRCUITS

Choosing the method is sometimes the most difficult task in microminiaturizing a large system. The requirements of the circuitry have been listed. There are few manufacturers who do not claim to meet the majority of these requirements, but very few can meet all of them. Since some manufacturers are sufficiently better on major requirements, we could waive several of the less important requirements to obtain these major benefits.

Using the requirements previously established for the integrated circuitry of ground equipment, we can now analyze the elements used in the Martin system and show the reasons for choosing them.

<u>Reliability</u> - The Fairchild Micrologic devices have an observed MTBF of 1,000,000 hr, and a fraction defective of 0.009 per 1000 hr at 90% confidence and 0.002 per 1000 hr at 60% confidence (Ref. 7). This reliability has been partially verified in-house by Martin. No units have failed when operated within specified ratings.

<u>Reasonable Initial Cost</u> - Table II shows that there is less than a 2:1 ratio between the initial cost for standard components versus Micrologic, but this is offset by reduced manufacturing costs. When ordered in quantities of ¼-million, the price per unit is $10. This is the quantity required for about 100 MARTAC units. The projected price for 1963 is less than $10 in 1000-lot quantities.

<u>Off-the-Shelf Availability</u> - All of the units now in production are available off the line at a rate of 2000 per day, with enough stock on distributors' shelves for total orders of 1000 pieces. Up to 250,000 units of one type can be delivered in a 4-mo period.

<u>Ease of Manufacturing Assembly</u> - Microminiature components usually introduce new problems to the assembly line. Their manufacture and assembly require special equipment and specially trained operators. However, Micrologic uses only standard-size transistor leads coupled to standard TO-5 or TO-47 cans. Any assembler of standard components can handle them; no special tools are needed.

Low Power Dissipation - Typical power dissipation ranges from 15 to 75 mw. This is not exceptionally good when compared to other techniques. Many are much better, and some are worse in this characteristic. The heat dissipated is still low enough that heat sinks are not required, and only a minimum ventilation system is needed. In most ground equipment, this is sufficient.

Intercircuit Compatibility - Any Micrologic circuit will drive any other Micrologic circuit without an interface. The fan-in and fan-out capabilities vary from one type to another. Some other methods allow more fan-out and fan-in, especially the diode-resistor coupled technique.

Standard Circuits for Minimum Stock - Most binary functions can be performed by using only two of the units -- the three-input "nor" gate and the buffer element. By using the seven basic circuits available, a greatly simplified and less-expensive system can be built.

Reduced Space Requirements - The cordwood techniques results in a space reduction of about 5:1 over standard packaging of standard components (Ref. 8). Micrologic increases this density factor by 10, or a space reduction of 50:1 with respect to standard components. Molecular electronic circuits seem to have a projected density many decades greater, but at present, these circuits are only in research and development. Micrologic ranks among the more compact in the currently available circuitry.

Variety - This has been covered under Minimum Stock Requirements. When comparing off-hhe-shelf with custom-built circuitry, there is little hope for the off-the-shelf item. However, as mentioned before, custom-built circuitry is unacceptable in the basic logic of the MARTAC system.

With the above consideration and past experience with planar, surface-passivated transistors, an exceptional confidence level has developed in this Company for the Micrologic approach to digital systems.

A report concerning the present and future use of microminiaturization was published by P. R. Mallory Company in 1961 (Ref. 10). This industry survey showed very little anticipated use of Micrologic in the very near future, but it ranks fourth among all the approaches anticipated for use by 1965, and remains fourth in 1975. Molecular electronics heads the list by 1970, followed in second place by Texas Instruments' solid-state circuits -- essentially the same technique used by Fairchild Micrologic.

Future changes in the choice of technique will be governed by the state of the art and availability in production quantities at the time needed. Martin feels it has taken a big step into the future with the MARTAC system.

IV. CONCLUSIONS

The highly successful use of standard, off-the-shelf components designed into unique circuits in large systems caused the Martin Company to use that technique in their first step into missile age production. It later became obvious that the savings in power and in parts did not justify the additional engineering time required to produce these unique circuits.

The limited use of preferred circuits in the first system is obvious, since many of the so-called unique circuits had the same specifications as other circuits in both the same and other subsystems. If the same engineer were involved in the design of more than one subsystem, the same circuit might appear in both, but this proved to be the exception rather than the rule.

To overcome this problem, a Standard Circuits Group was organized to develop a set of preferred circuits to be used where possible throughout the system. The savings were even more than expected; not only was there a saving in design time, but repeated use of a given component reduced the price of these parts through quantity buying. This allowed the use of better parts in a given circuit to increase reliability.

At the same time as this evolution in circuit design, government support of microminiaturized integrated circuitry permitted increased study and analysis in that area. Several companies not subsidized by government agencies were aided in their own development programs by the results obtained by those companies who had government support. The result has been a great variety of integrated circuitry, each having advantages and disadvantages. Most of this circuitry is still very expensive. Many companies attempting to enter the new market are offering to custom-build integrated circuits for any company that will pay the tooling expense in addition to the price asked for the circuits.

The microminiaturization obtained through the development of integrated circuitry was really not too much of an advantage in ground equipment. However, some of the other results of integrated circuitry seemed to have sufficient merit to require more investigation. The following requirements were assumed to be necessary to justify the use of integrated circuitry in ground support systems:

1) Reliability;
2) Reasonable initial cost;
3) Off-the-shelf availability;
4) Ease of manufacturing assembly;
5) Low power dissipation;
6) Intercircuit compatibility;
7) Standard circuits for minimum stock;
8) Reduced space requirements;
9) Sufficient variety of circuits to provide 80 to 90% of each subsystem with the minimum-required interface circuitry.

With these requirements in mind, the most reasonable first attempt at using the integrated circuits was in a digital logic system. The use of integrated circuitry in this system seemed to provide all the nine required advantages. Martin designed a computer-controlled ground equipment checkout system called MARTAC that uses the integrated circuit technique, with only three standard integrated logic circuits throughout the system. The three circuits used were a "nor" gate, a half-shift register, and a flip-flop. Interface circuits were designed to handle power switching. Unique circuits were also designed for an A-F converter section. Even in this section, however, the integrated circuits were used for logic functions where possible.

One section of this A-F converter that uses a logic section has been analyzed using both the preferred circuit approach and the integrated circuitry approach. Comparing both approaches with the above-listed requirements will show that each has its advantages. The final decision as to which is the better approach depends on the relative importance assigned to each requirement. Considering these requirements, the integrated circuitry seems to be better than preferred circuitry.

The choice of the integrated circuit technique used in MARTAC was limited by the availability of those techniques that met the preassumed requirements, especially the noncustom or off-the-shelf requirement. The choice of a particular approach for use in any redesign of the existing breadboard will again depend mostly on the state of the art at the time of the redesign and the ease of conversion from the existing logic to the new approach.

V. REFERENCES

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2. "The New Shape of Electronics", Business Week, No. 1702, April 14, 1962, p. 172.

3. Micromodule--New Concept of Electronic Parts Packaging, Sales Brochure, RCA Seminconductor and Materials Division, Somerville, New Jersey, 1962.

4. Business Week, loc. cit.

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6. Barry Miller, "Integrated Circuits Cut Computer Cost," Aviation Week and Space Technology, Vol 76, No. 21, May 21, 1962, p. 83.

7. Micrologic Reliability, Brochure, Fairchild Semiconductor Corporation, Palo Alto, California, June 1962.

8. Micrologic Familiarization, Application and Sales Group, Fairchild Semiconductor Corporation, Palo Alto, California, 1962, p. 34. (In-house publication, not for release).

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10. S. M. Stuhlbarg, How Industry Sees Microminiaturization, P. R. Mallory & Company, Inc., Indianapolis, Indiana, April 1961.

Appendix A
COMPONENT COST REDUCTION

In the two years that Martin Company has used the preferred circuit approach in ground equipment, a substantial cost reduction has been realized in the component field. Table III is a sampling of cost reduction for some of these components. Not all this cost reduction has resulted from quantity buying. The general cost trend has been downward as semiconductors grow more important in industry. The component type numbers shown are not standard in the industry, but are special Martin specifications.

Other advantages are reflected directly or indirectly in cost reduction. Basic engineering time is reduced. Preferred circuits reduce the scrap that normally would result from subsystem changes required by changes in checkout criteria. The subsystem design time required to incorporate a change is reduced. The logistics problems are also reduced, as only 40 circuit modules need be stocked to service approximately 170 different plug-in printed circuit boards.

Manufacturing cost reduction has resulted primarily from volume purchasing of fewer component types and greater reliability in the initial design. The following tabulation gives the various cost reduction categories and the percentage saved by using preferred circuits.

Circuit design and test	50%
Packaging	30%
Components	50%
Assembly	None
Testing and Troubleshooting (Measure of Reliability)	75%
Logistics	75%
TOTAL OVERALL COST REDUCTION	Over 50%

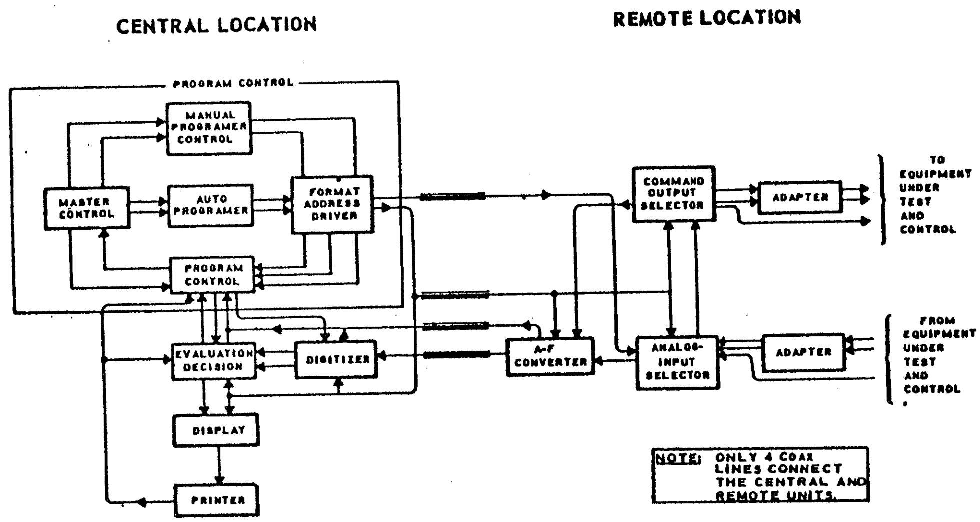

FIG. 1 MARTAC FLOW DIAGRAM. The functional relationship between the central control unit, the remote unit, and the equipment being tested is indicated.

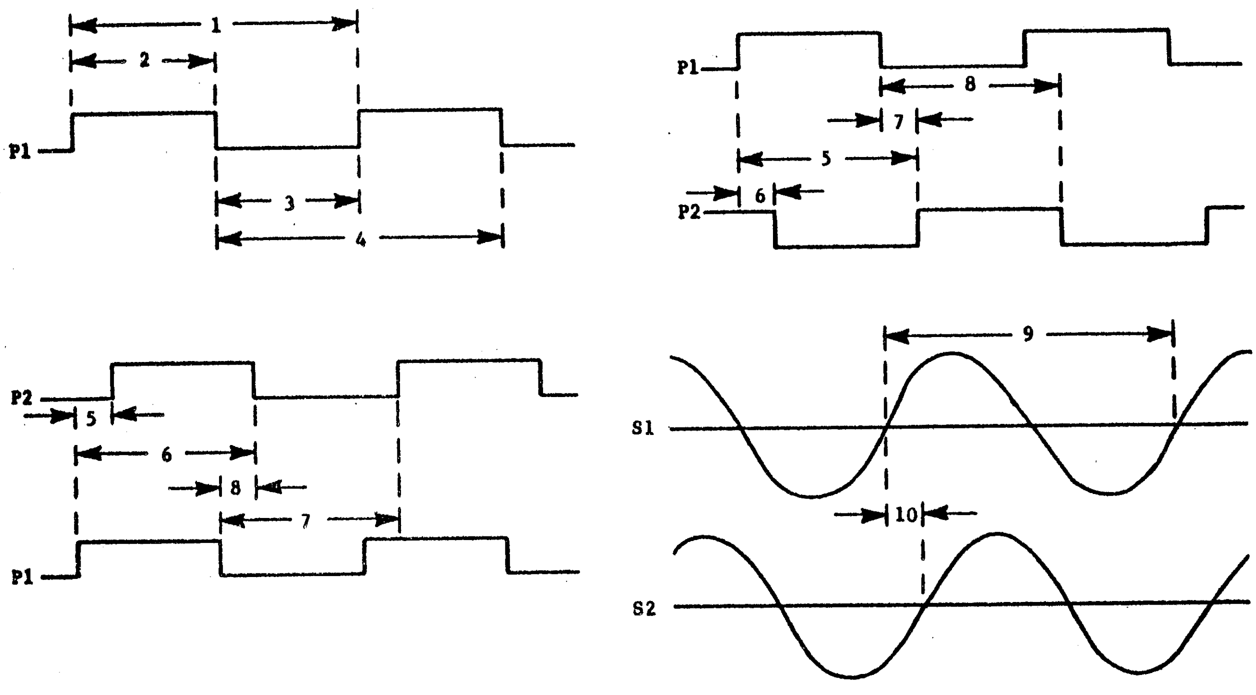

FIG. 2, INTERVAL MEASUREMENTS. MARTAC is capable of making these 10 measurements in the working prototype.

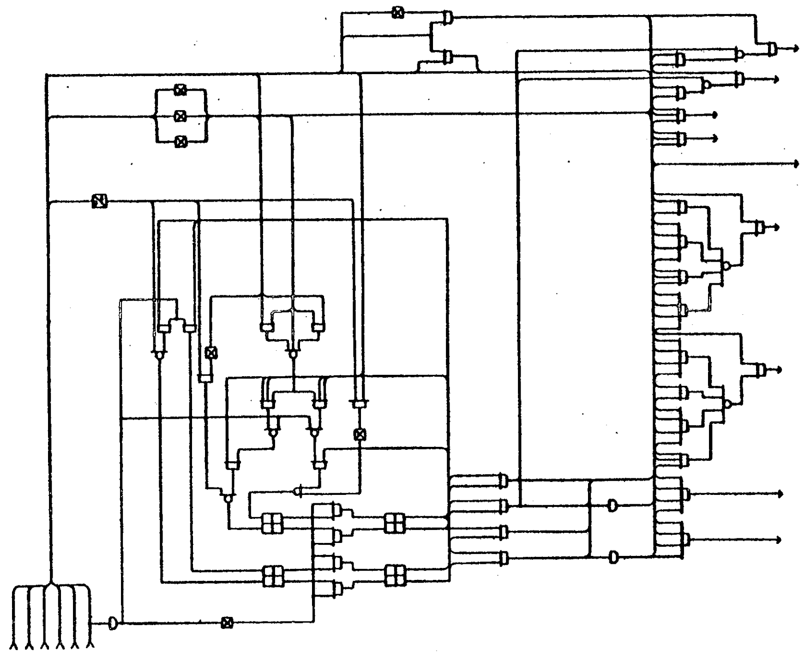

FIG. 3. "AND-OR" LOGIC. The logic of the Time interval Section of the A-F converter in standard "and-or" is indicated.

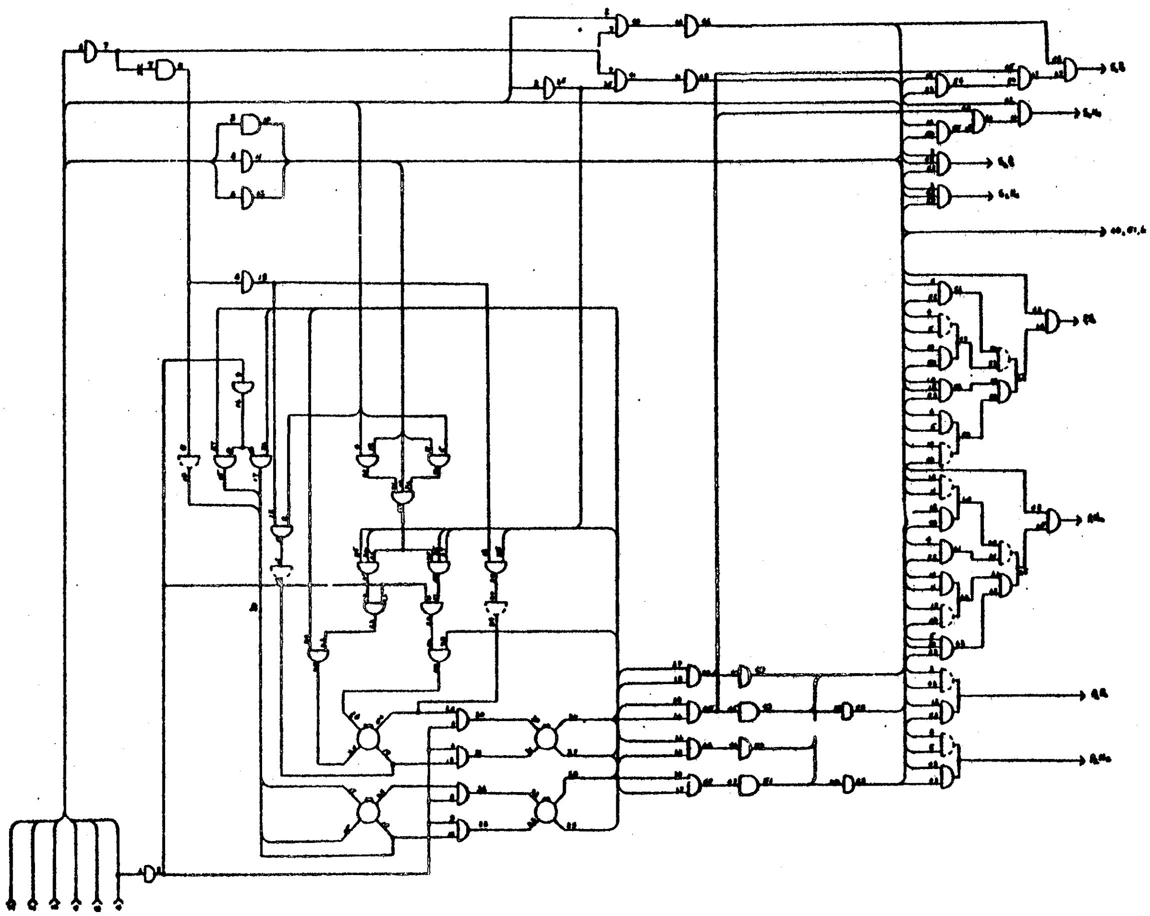

FIG. 4. "NOR" LOGIC. This diagram shows the logic of the Time Interval Section of the A-F converter in standard "nor" logic.

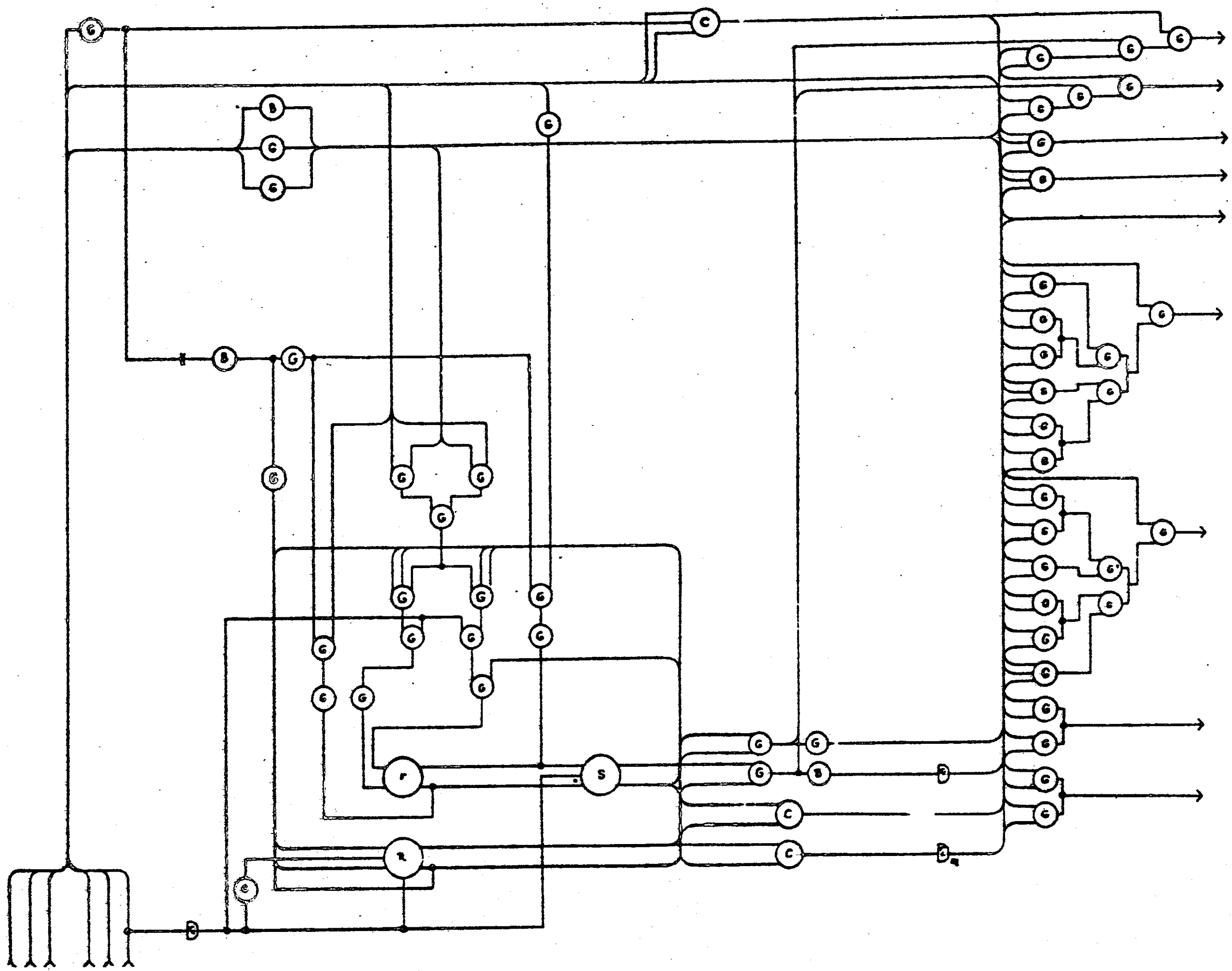

FIG. 5. MICROLOGIC. This diagram shows the logic of the Time Interval Section of the A-F converter in "Micrologic".

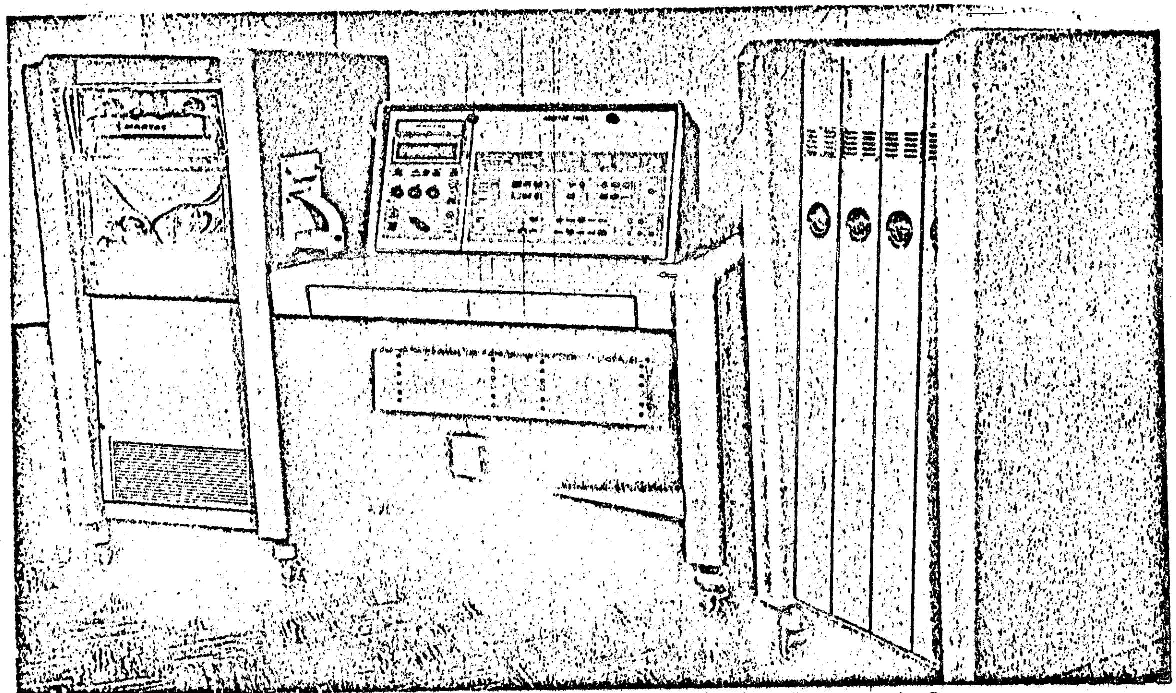

FIG. 6. MARTAC PROTOTYPE. The computer was developed by Martin-Denver for checking out missiles and space boosters. The digital system consists of a central unit, a control panel, and a remote unit.

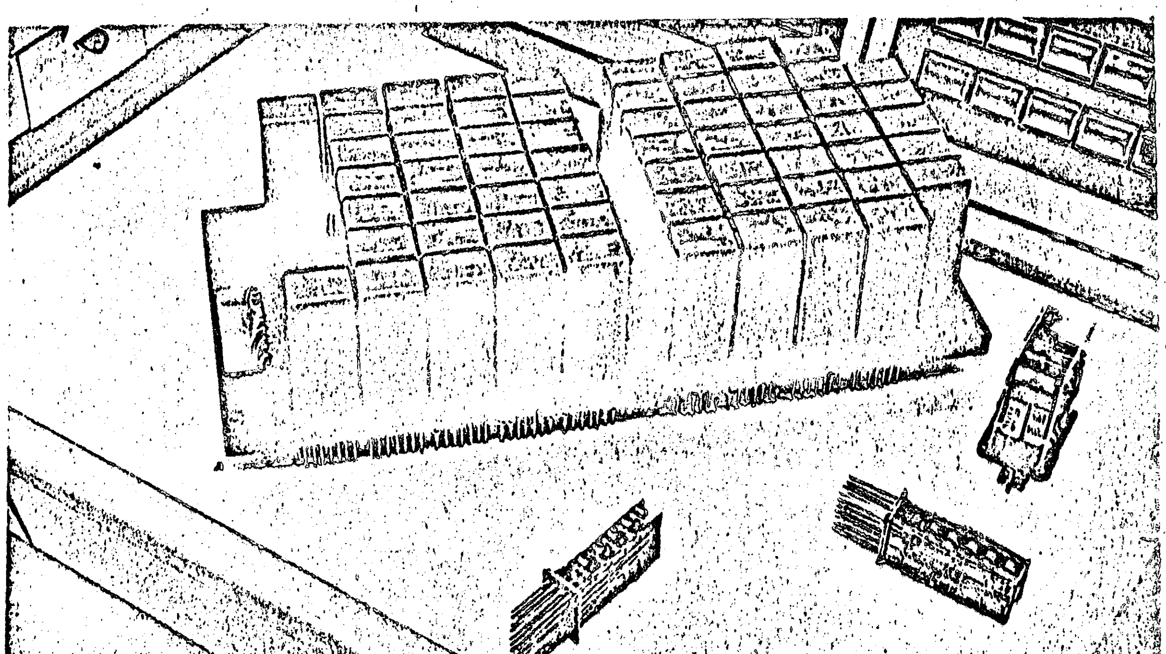

FIG. 7. MARTAC PACKAGING. The integrated circuit concept used in MARTAC reduces component cost and increases reliability.

TABLE I. MEASUREMENT SPECIFICATIONS FOR MARTAC

TYPE OF MEASUREMENT	NO. OF RANGE STEPS	FULL-SCALE ON LOWEST RANGE	FULL-SCALE ON HIGHEST RANGE	INPUT IMPEDANCE	FREQUENCY RANGE	MAXIMUM ERROR
Voltage, dc (volts)	15	±10 millivolts	±500 volts	10 megohms	(dc)	±0.1% of reading above 1/3 full scale
Voltage, ac (volts, rms)	12	100 millivolts, rms	500 volts, rms	10 megohms	60 to 10,000 cps 20 to 100,000 cps	±0.2% of reading above 1/3 full scale (sine wave) ±1.0% of reading above 1/3 full scale (sine wave)
Resistance (ohms)	12	1000 ohms	5 megohms	--	--	±0.5% of reading above 1/3 full scale (open-circuit recovery 50 milliseconds)
Ratio, dc/dc Voltage	5	1.0	10,000	10 megohms	(dc)	±0.5% of reading Vref above 10% full scale
Ratio, ac (rms)/ac (rms) Voltage	5	1.0	1000	10 megohms	60 to 10,000 cps	±0.6% of reading Vref above 10% full scale (ac sine wave)
Ratio, dc/ac (rms) Voltage	5	1.0	1000	10 megohms	dc/60 to 10,000 cps	±0.5% of reading Vref above 10% full scale (ac sine wave)
Ratio, ac (rms)/dc Voltage	5	1.0	10,000	10 megohms	60 to 10,000 cps/dc	±0.5% of reading Vref above 10% full scale (ac sine wave)
Interval (seconds)	4	10 milliseconds	10 seconds	50 ohms	Single pulse to 1 mc	±2 Parts in 10^6 (0.0002%) per week ±1 Count, trigger jitter ±5 nanoseconds
Interval, High Resolution (seconds)	2	100 microseconds	1 millisecond	50 ohms	Single pulse to 1 mc	±5 Parts in 10^8 (0.000,005%) per day ±1 Count, trigger jitter ±5 nanoseconds
Phase-Delay or Period (seconds)	4	10 milliseconds	10 seconds	0.25 megohm	0.1 to 5000 cps	±2 Parts in 10^6 (0.0002%) per week ±1 Count, trigger jitter ±10 nanoseconds
Phase-Delay or Period (high resolution) seconds	2	100 microseconds	1 millisecond	0.25 megohm	0.1 to 5000 cps	±5 Parts in 10^8 (0.000,005%) per day ±1 Count, trigger jitter ±10 nanoseconds
Frequency (cps)	3	10 kc per second	1 mc per second	1.0 megohm	100 cps to 1 mc	±2 Parts in 10^6 (0.002%) per week ±1 Count
Discrete Time Series (mark pulse) seconds	1	1000 seconds	1000 seconds	50 ohms	Single pulse to 10 kc	±1 Part in 10^4 (0.01%) per day ±1 Count
Time Delay (seconds)	1	1000 seconds	1000 seconds or up to 100,000 seconds, 100 repeats			±1 Part in 10^4 (0.01%) per day ±1 Count

NOTES: 1. All inputs are floating and provide for electrical isolation of the circuits under test from each other and from the MARTAC.

2. 120 db common mode rejection normally provided by shielding, isolation, and optional guarded input (when required).

3. Voltage and resistance over-scale up to approximately 30% is possible with slight degradation in accuracy. Exceeding the scale will be indicated with the over-scale reading. Excessive over-scale results in amplifier blocking which may require up to several seconds to clear after removing the input signal.

TABLE II. COMPONENT COST COMPARISON FOR TIME INTERVAL LOGIC

	Standard Components		Micrologic
	Resistors	Transistors	
Number of Components	67	155	62
Cost per Component	$0.04	$ 8.50	$ 30.00
Net Component Cost	$2.68	$1317.50	$1860.00
Incoming Inspection Costs	Nil	$ 0.40 ea.	$ 2.00 ea.
Gross Cost, Incoming	$1382.18		$1984.00

TABLE III. COST REDUCTION DATA

Component	Type	July '59	Nov '61	Savings
Diode	1N457	$ 1.58	$0.19	$ 1.39
Diode	1N645	3.20	0.35	2.85
Diode	1N754A	4.15	1.00	3.15
SCR	78E2-1	43.00	7.75	35.25
Transistor	78D1-2	34.00	3.75	30.25
Transistor	78E26-1	55.99	6.60	49.39
Unijunction	2N492	8.00	6.35	1.65
Capacitor	90D2-38	9.95	5.55	4.40
Capacitor	90E26	2.72	1.55	1.17