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MICROPOWER LOGIC CIRCUITS

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Utilization
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MICROPOWER LOGIC CIRCUITS

By John C. Sturman
Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. May 1965

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FOREWORD

The Administrator of the National Aeronautics and Space Administration has established a Technology Utilization Program for "the rapid dissemination of information. . . on technological developments. . . which appear to be useful for general industrial application." From a variety of sources, such as NASA Research Centers and NASA contractors, space-related technology is screened, and that which has potential industrial use is made generally available. Thus American industry will receive information from the nation's space program about the latest developments in operating techniques, management systems, materials, processes, structures, and analytical and design procedures in numerous technical fields.

This publication is part of a series designed to provide this technical information. It is based on data developed during a continuing series of in-house research studies of ultra-low-power circuits by the Lewis Research Center, Instrument and Computing Division, Jesse H. Hall, Chief.

The report was prepared by J. C. Sturman of the Instrument Systems Research Branch, in coordination with the Lewis Technology Utilization Office.

The Director, Technology Utilization Division
National Aeronautics and Space Administration

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INTRODUCTION

A number of digital logic circuits that were developed primarily to fill a need for very low power logic systems in space-vehicles can be advantageously adapted for specific applications in nonspace computer systems. The more promising circuits were built and tested at the NASA Lewis Research Center. Although certain features of the circuits are considered to be new developments, they are essentially based on older concepts that have not been widely applied.

With relatively simple engineering modifications, applications of these circuits, as well as of three ancillary circuits described in this report, will be apparent for a variety of capital equipment and consumer products. These include automated production systems, numerically controlled machine tools, measuring instrumentation, remote controls and alarm systems, high-fidelity radio and recording systems, and television receivers.

MICROPOWER LOGIC CIRCUITS

Several modifications of a digital logic circuit were designed for the lowest possible power consumption at relatively low operating speeds. Although the basic circuits are particularly suited to these operating conditions, they can be adapted to perform equally as well at high power levels and speeds. These circuits exhibit many desirable features, including nearly ideal waveforms and power transfer efficiencies that are virtually independent of operating conditions within their design range.

Description of Basic Circuits

Most conventional transistor logic circuits can be derived from the standard inverter circuit shown in figure 1. When a positive voltage is applied to the input terminal, current flows through resistor R_B and turns the transistor on. In the "on" or saturated state, the transistor acts much as a closed switch or relay contact. In this state, the output is clamped to ground, no voltage is supplied to the load, and the power output is zero. Power is dissipated, however, in the collector load resistor R_C. In order to minimize this waste of power, it would be necessary to make R_C large.

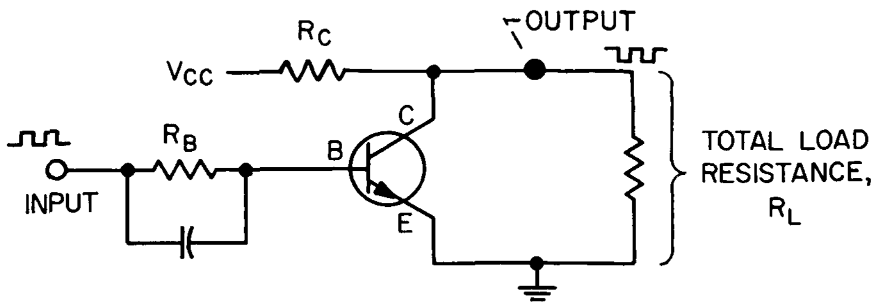

Figure 1. - Conventional transistor inverter circuit.

If the input were then connected to ground, no current would flow into the transistor base and the transistor would turn off. In this state, the voltage at the output is determined by the ratio of R_C to R_L. For a large output voltage, R_C must be relatively small. This requirement is in direct opposition to the condition for minimum power loss in the "on" state. For a 50% duty cycle, a maximum theoretical power transfer efficiency of 17.2% is obtained when R_C is made equal to 0.707 R_L.

It is clear from the above that the difficulty in obtaining maximum power transfer efficiency over a cycle comprising the two states of the circuit is because of the contradictory requirements for the values of the collector load resistor R_C. This difficulty can be eliminated by replacing R_C with a second transistor that acts as an open circuit when the first transistor is turned on and as a very low resistance when it is turned off. The simplest circuit of this type is shown in figure 2. The added transistor Q_2 is of the PNP type which is turned on by a negative signal, as opposed to the NPN transistor Q_1 which is turned on by a positive signal. When a positive signal is applied to the input, transistor Q_1 is saturated and pulls the output to ground while the same input cuts off the transistor Q_2. Since the transistor Q_2 now acts as an open circuit, no power is drawn from the power supply. For a negative or zero input, the states are reversed; that is, transistor Q_2 is saturated and delivers nearly full supply voltage to the load. No power is lost in transistor Q_1. The theoretical power transfer efficiency of this circuit (computed in the same way as for the conventional inverter) is 100%. In practice, values above 90% are not difficult to obtain.

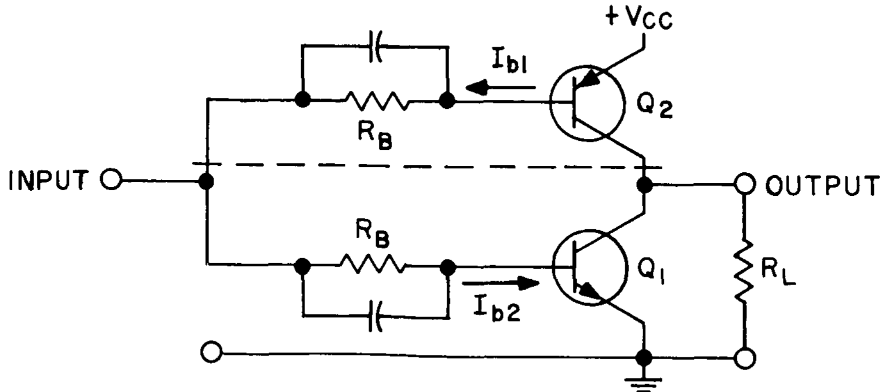

Figure 2. - Basic complementary transistor inverter circuit.

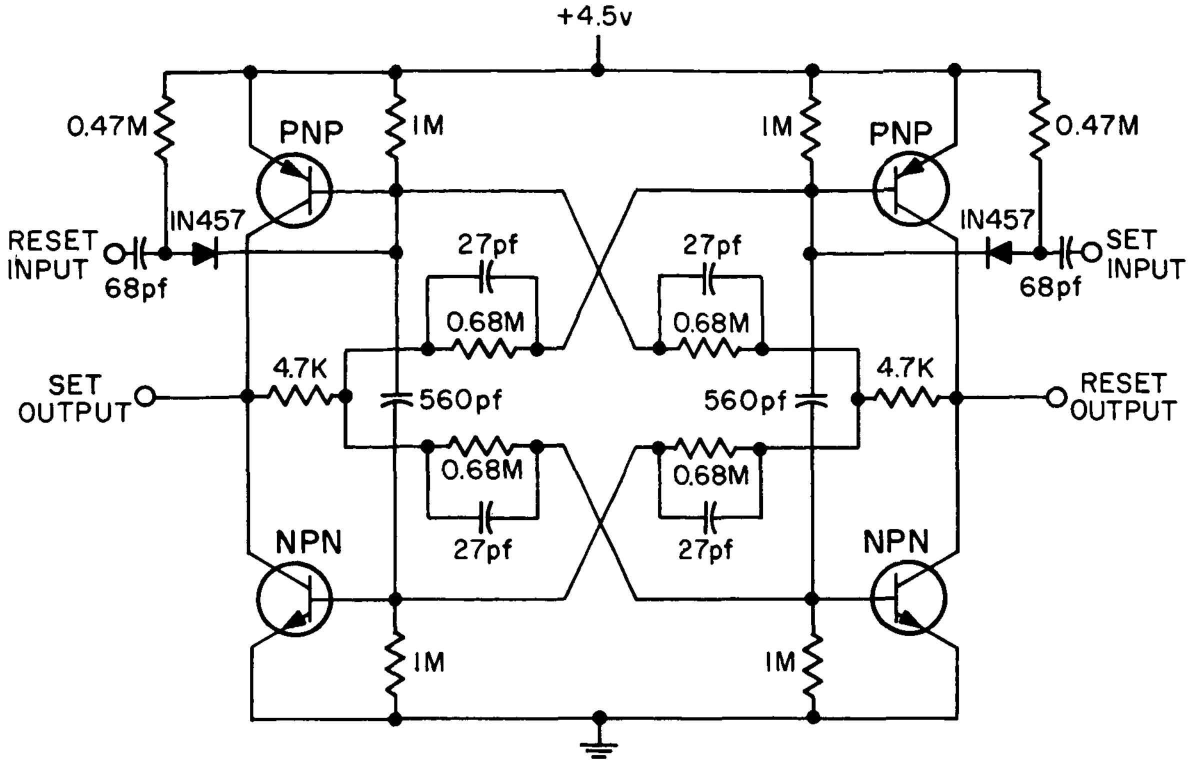

Figure 3. - Reset-set flip-flop.

The basic concept illustrated can be extended to provide a wide variety of logic circuits using either complementary (PNP and NPN) transistors or only one type of transistor. The reset-set flip-flop shown in figure 3 is an example of one of the more complex circuits built by combining two of the basic complementary inverters. Its operation can be compared with that of a latching relay, since either the left or the right half can be turned on by application of a pulse to the corresponding input terminal. Figure 4 shows a similar flip-flop using steering diodes to make it a toggle or "divide-by-two" circuit. This circuit changes its conducting side each time a pulse is applied to the single input. Performance characteristics of these circuits are plotted in figure 5. Note that in the low kilocycle region for which they are designed to operate, each circuit consumes considerably less than 100 microwatts. An indication of the output capabilities of these circuits is given in table I. At 2,000 pulses per second, these circuits are capable of delivering approximately 30 times their unloaded power drain to a useful load. At higher frequencies this value falls somewhat, but the toggle flip-flop is still 83% efficient at 200 kilocycles and an input power of 3 milliwatts. These circuits are thus ideal as power drivers and as matching elements between low- and high-power systems.

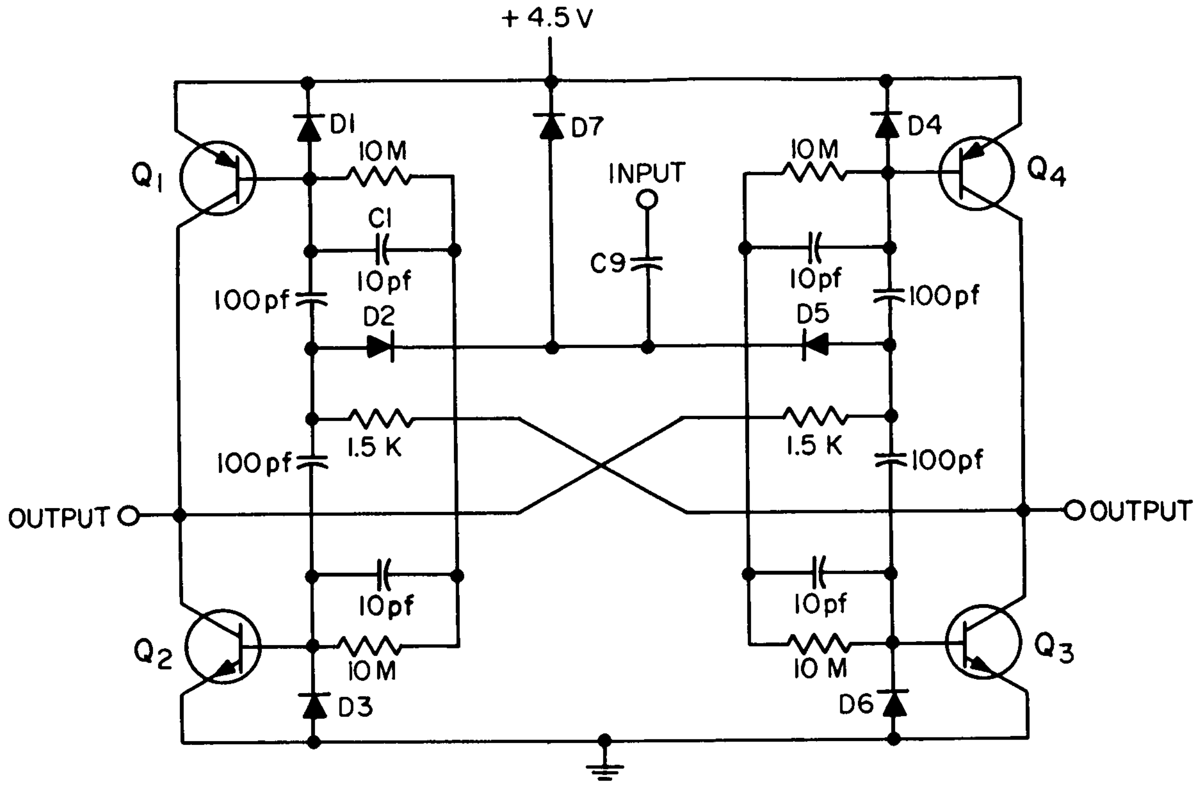

Figure 4. - Complementary toggle flip-flop.

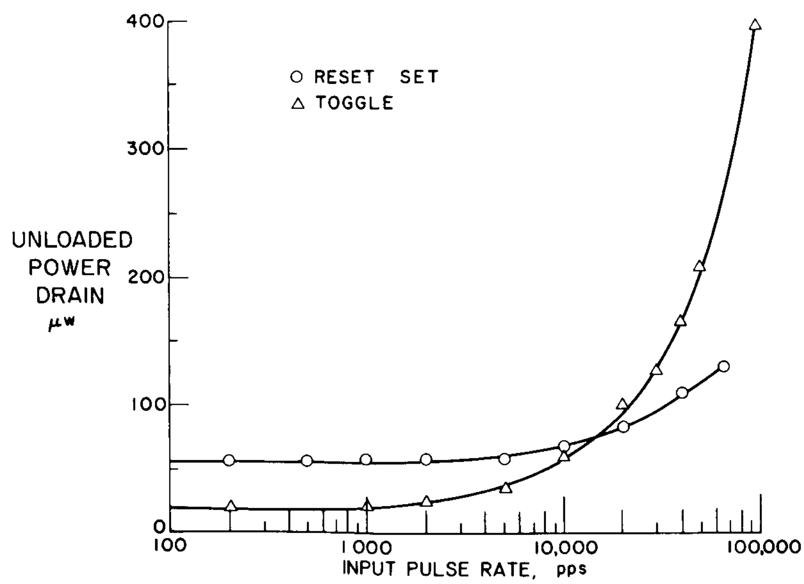

Figure 5. - Power drain for reset-set and toggle flip-flops.

TABLE I.-FLIP-FLOP PERFORMANCE CHARACTERISTICS

Input power, mW	Pulse rate pps	Load resistor, kΩ	Power efficiency, %
(a) Reset-set - supply voltage, 4.5 V			
0.058	0	---	--
.06	2,000	---	--
1.8	2,000	10 and 10	96
1.9	20,000	10 and 10	94
0.1	25,000	---	--
(b) Toggle - supply voltage, 4.0 V			
0.015	0	---	--
.022	2,000	---	--
.96	2,000	15 and 15	98
0.5	200,000	---	--
3	200,000	3.3	83

The design of a second important group of circuits is based on the similar-transistor inverter circuit shown in figure 6. This circuit uses two transistors of the same type to provide many of the advantages of the complementary circuits. When transistor Q_1 is turned on, its collector voltage drops to near ground potential. This drop is coupled through diode D_1 to the base of transistor Q_2, which is thus turned off. Simultaneously, a conduction path is provided to ground through backward diode D_2 and transistor Q_1 to clamp the output to ground. When no input is applied and transistor Q_1 turns off, current flows through R_1 into the base of transistor Q_2. This current turns the transistor on to supply power to the load. A two-input NOR gate based on this concept is shown in figure 7. A signal present at either of the two inputs will cause the output to drop to zero.

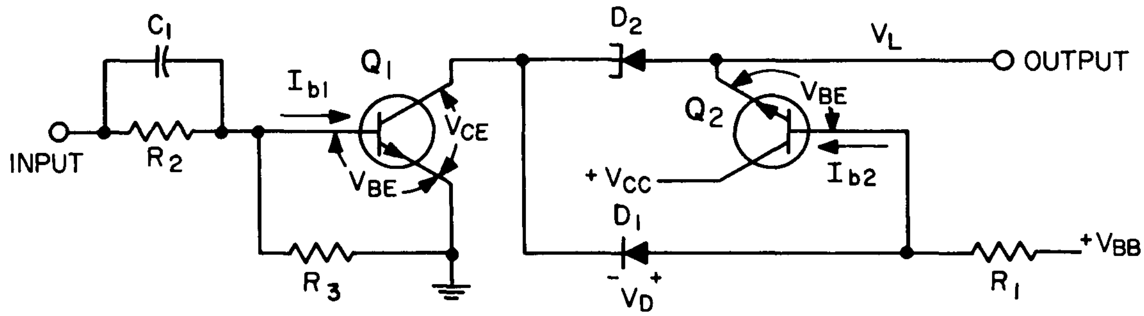

Figure 6. - Basic similar-transistor inverter.

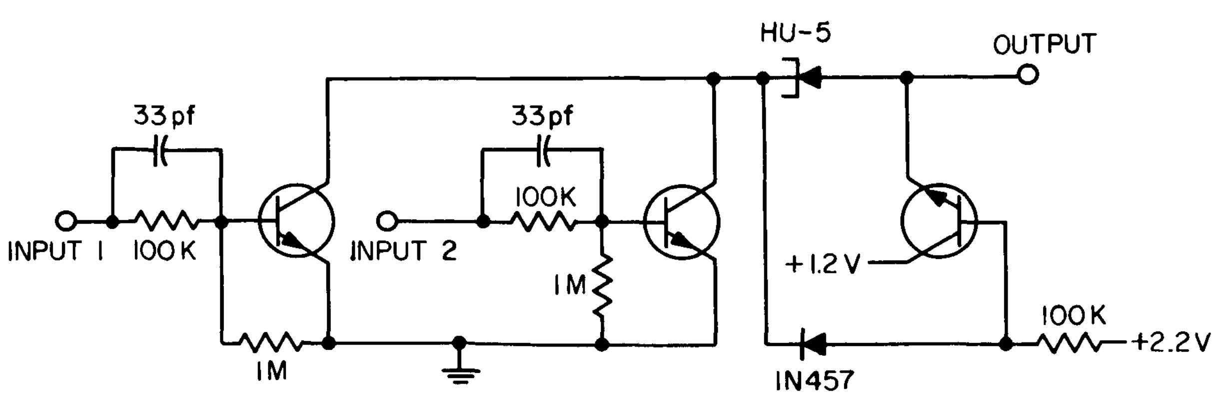

Figure 7. - Transistor input NOR.

Another modification of the basic circuit (shown in figure 6) is the monostable multivibrator shown in figure 8. This multivibrator is basically a timing circuit which on being triggered provides a pulse of fixed width. The width of this pulse can be varied from a few microseconds to many milliseconds by proper choice of the timing capacitor C_T. Circuits of these two types built at the NASA Lewis Research Center operate at power levels from a quarter of a microwatt to many milliwatts over the frequency range of a few kilocycles to more than a megacycle.

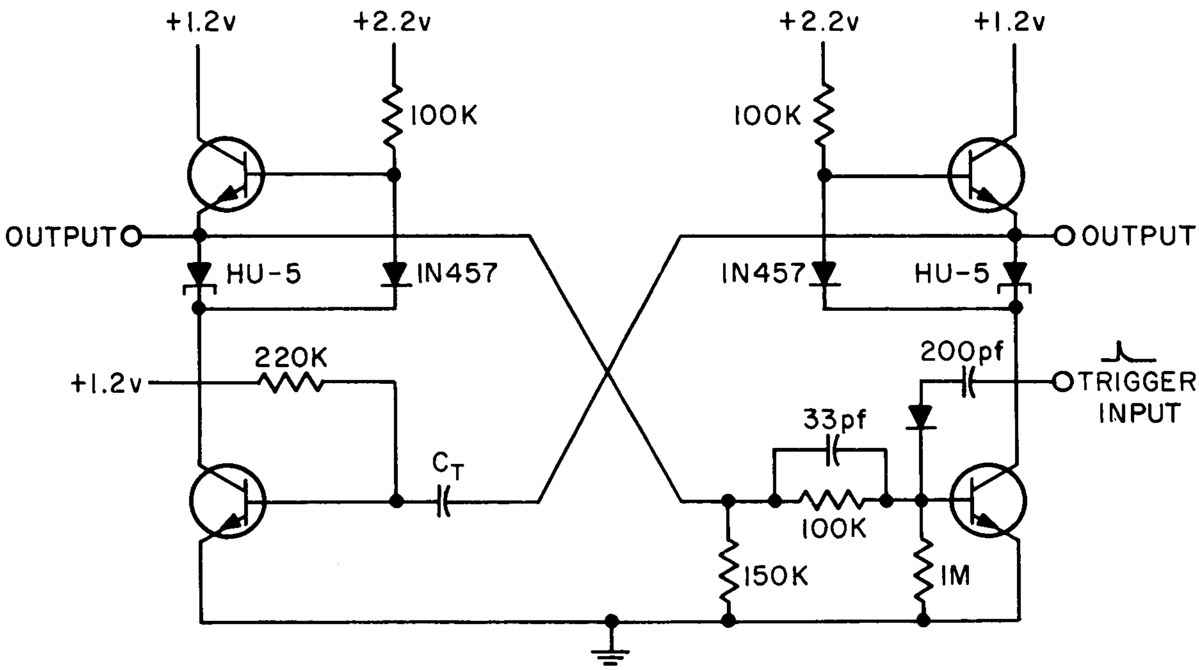

Figure 8. - Similar-transistor monostable multivibrator.

It is interesting to consider what can be accomplished with the use of monostable multivibrators. If the realistic power consumption value of 100 microwatts per unit is assumed, it would be possible to build a computer containing 15,000 such units that would consume no more power than an ordinary three-cell flash light. At present, the cost of such a system would be prohibitive for industrial applications. However, if the power consumption is increased by at least 10, useful units can be built with low-cost components that retain essentially all the advantages of this type of circuitry.

The advantages and disadvantages of these circuits may be compared with those of the circuits more commonly used in digital applications. The most significant advantage of the new circuits is, of course, their relatively very low power consumption. It is this lower power requirement that gives rise to a number of the other advantages of these circuits. The saving of power is due to two separate effects, both the result of driving the load from a transistor instead of a conventional collector load resistor. Elimination of the collector resistor, without making any other changes in the circuit, would save considerable power for the condition of zero output voltage, because the lower transistor (Q_1 in figure 2) sees a high impedance when it is turned on. It therefore draws only a very small current. A further saving in power is realized by lowering the supply voltage. The latter saving results from the fact that the output is clamped to the supply by the added transistor, which eliminates the voltage drop across a collector resistor, and allows the supply voltage to be made equal to the required output voltage. The high power output and efficiency also allow one circuit of this type to drive many more outputs than can be driven by conventional circuits.

Another direct result of the low internal power dissipation and high efficiency is a negligible rise in temperature. The component packing density can therefore be increased without the need for auxiliary cooling means. Since a decrease in operating temperature of 10° C approximately halves the failure rate of components, the very small temperature rise should result in increased circuit reliability and operating life. The low power consumption of these circuits simplifies the requirements for standby power, which must be used in the event of primary power line failure.

The reliability of circuits of this type is also due to their high tolerance to relatively large variations in supply voltage and component characteristics. Therefore, less expensive components can be used without adverse effect on circuit reliability. As an example, the two flip-flop circuits containing ordinary 10-percent carbon resistors operate reliably over a temperature range of -20° to $+80^{\circ}$ C within supply-voltage limits of 3.5 to more than 6 volts.

The fact that the output of these circuits is clamped to either the supply voltage or the ground results in a number of other advantages. A main advantage is that the output levels are very well defined and differ by no more than a few tenths of a volt from the clamping level, even under maximum load. Clamped outputs also provide a low output impedance which, in turn, inhibits unwanted response from line transients and other noise sources, and allows the output to drive loads returned to either the supply voltage or the ground and thereby doubles the number of loads that the circuit can drive.

Finally, since both positive-and negative-going outputs are actively driven by a transistor, the limits normally imposed by RC time constants are eliminated and nearly ideal waveforms, with fast rise and fall times, are obtained. As an example, the reset-set flip-flop produces 50-nanosecond rise and fall times when operated at a power drain of 50 microwatts.

The relatively large number of components required in these circuits may be a major limitation from the standpoint of size and cost. These circuits may offer sufficient advantages for various applications in those instances where their cost can be justified.

Packaging of Units

High packaging density and design flexibility were desired for aerospace applications. Accordingly, the circuits, containing silcon transistors and diodes, were packaged in individual modules, using the welded cordwood construction shown in figure 9. The largest module is an eight-stage ring counter; the smaller module below it is a gate circuit. At the upper right is the reset-set flip-flop, which has already been discussed. The small module below it is the toggle flip-flop. It is of more recent construction, and although it has approximately as many components as the reset-set unit, it is only 56% as large. It represents the highest component density that the NASA Lewis Research Center has achieved to date, namely, 130 components per cubic inch. Figure 10 shows side views of two of these modules.

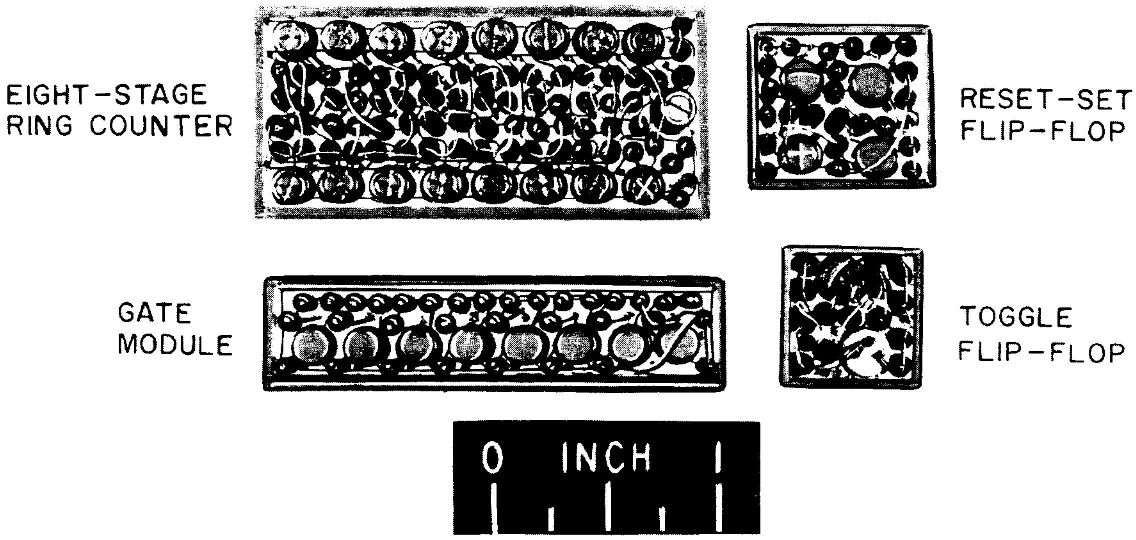

Figure 9. - Welded cordwood logic modules, top view.

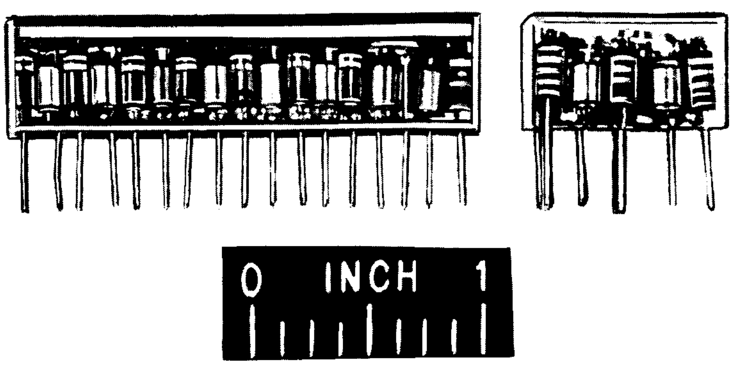

Figure 10. - Gate and reset flip-flop modules, side view.

With this method of construction, the 15,000-element computer, previously mentioned together with its power supply, could be built into a suitcase. It may soon be practical to build such circuits in integrated form; when this is achieved, it will be possible to package the computer in a much smaller volume.

Possible Industrial Applications

Two additional circuits based on the active-load concept were constructed using transistors and diodes of germanium instead of the more costly silicon. One was a toggle flip-flop nearly identical in circuitry to that shown in figure 4. The performance of this "industrialized" circuit is tabulated in table II(a). Note that its overall performance is quite similar to that of the low-power aerospace unit (with silicon transistors and diodes characterized in table I(b)), with the exception that all power levels have been increased by approximately an order of magnitude. However, as shown in table II(a), the standby power level of 0.5 milliwatt is still far lower than that required for any of the commercially available logic circuits.

A more striking comparison of the different flip-flop designs is shown in figure 11. The lower two curves (also graphed in figure 5) are for the aerospace designs (with silicon transistors and diodes); the middle curve is for the "industrialized" complementary toggle flip-flop module with germanium semiconductors; the upper curve is for a conventional flip-flop module, which has collector load resistors and is designed to operate at the minimum power and speed comparable with those of the other circuits. Note that although the low-cost industrialized circuit does not operate with an input power of less than several hundred microwatts, its power consumption is only one-tenth that of the conventional circuit. The conventional circuit provides a maximum power output to its load of 0.8 milliwatt at an efficiency of 13 to 15%, compared with more than 8 milliwatts for the industrialized circuit at 80 to 96% efficiency. Furthermore, the conventional flip-flop circuit exhibits a very poor waveform (shown in figure 11), compared with its industrialized counterpart, which puts out a practically ideal waveform.

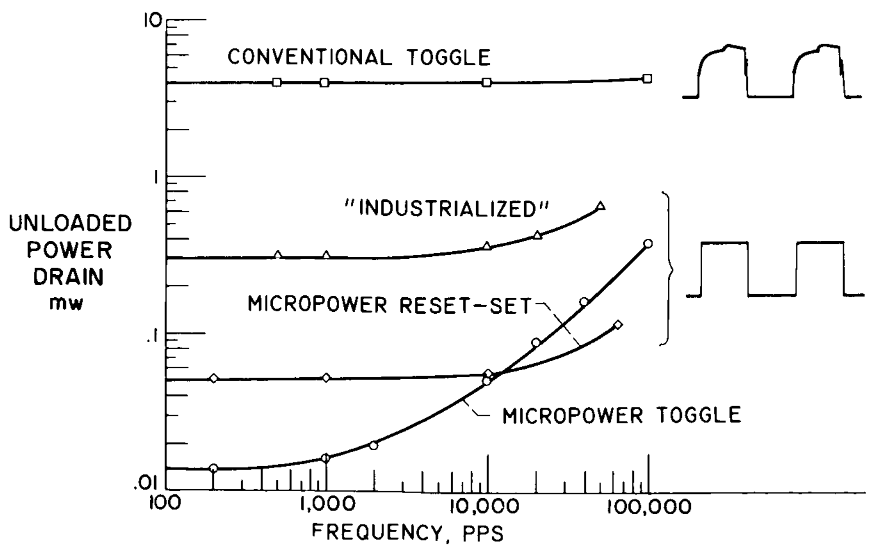

Figure 11. - Input power as a function of frequency for different flip-flops.

TABLE II.-"INDUSTRIALIZED" CIRCUITS PERFORMANCE CHARACTERISTICS

Input power mW	Pulse rate pps	Load resistor, kΩ	Power efficiency, %
(a) Toggle - Total component cost per unit in quantities of 1000, $2.25; supply voltage, 6.0 V			
0.5	100	-------------	--
12.5	100	1.5 and 1.5	96
.87	67,000	-------------	--
11.7	67,000	1.5 and 1.5	91
10.9	200,000	1.5 and 1.5	89
(b) Similar-transistor NOR gate - Total component cost per unit in quantities of 1000, $3.00; supply voltage, 6.0 V			
0.755	500 [a]	----	----
4.63	500 [a]	3.3	82.5
.766	10,000 [a]	----	----
8.48	10,000 [a]	1.5	87.2
1.27	200,000 [a]	----	----
6.65	200,000 [a]	3.3	71.5

[a]With 50% duty cycle.

Essentially, the same comments apply to the performance of the three-input similar-transistor NOR gate shown in table II(b). A main feature of the circuit is that all semiconductor components, except the backward diode, were of silicon to ensure increased reliability and high-temperature operation. The backward diode was of conventional design using germanium at a considerable cost saving. The efficiency of this circuit is somewhat less than that of the complementary circuit, as is to be expected, although it is appreciably above that of the conventional circuits.

These two circuits (the industrialized complementary flip-flop and the similar-transistor NOR gate), although not optimized for cost or performance, further indicate some of the advantages to be gained from the use of these circuit concepts. Variations of these circuits can easily be designed. For example, the availability of high-quality, inexpensive silicon NPN transistors would recommend their use with germanium PNP transistors in complementary circuits. A hybrid logic system with complementary-transistor multivibrators and similar-transistor gates could very well be economically competitive with conventional circuits.

OTHER INNOVATIONS IN RELATED CIRCUITRY

Several other useful digital logic circuits have been developed by the NASA Lewis Research Center and its contractors. Although these circuits were designed to solve specific problems, their applicability is of much broader scope.

Single-Pulse Generator

Digital systems generally require some means of entering information from input devices. A pushbutton or other mechanical contact closure in conjunction with some type of network is commonly used to provide a single pulse to perform the required function. Fast-rise single pulses cannot be reliably obtained with such contacts, however, because of their tendency to bounce. Long time-constant filters and magnetic trigger circuits reduce contact bounce problems considerably, but have rather limited flexibility for providing pulses of fast-rise time and widely variable width.

These problems can be solved by the rather simple circuit shown in figure 12. The circuit employs either a Thyristor or an SCR (silicon controlled rectifier) as the active element. It makes use of the characteristic that once the element is in the conducting state, the supply voltage must be switched off to return the element to the nonconducting state.

With the input switch or relay in the position shown, the SCR will not conduct, because there is no current source to the gate input. Current will flow through R_1 and the switch contact, charging the capacitor.

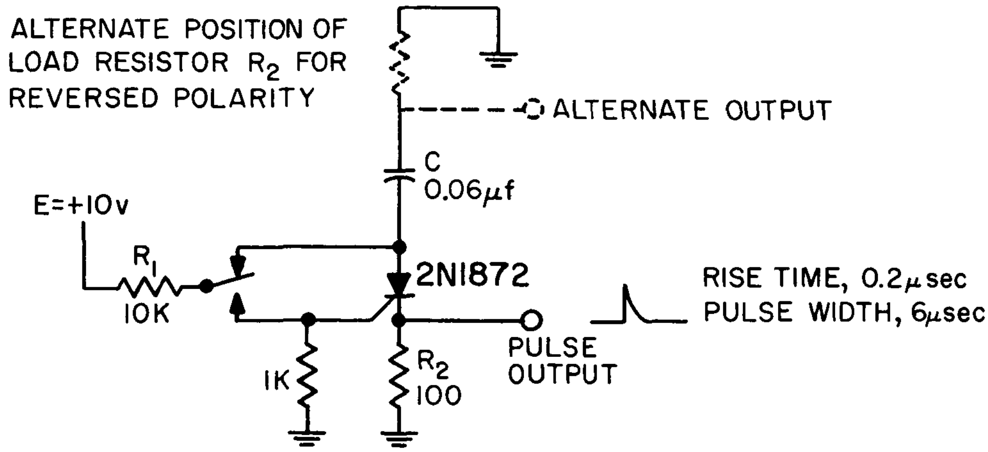

Figure 12. - Single-pulse generator.

When the switch is closed to the gate input, sufficient current flows through R_1 to cause conduction. The capacitor, therefore, quickly discharges through R_2 and produces the output pulse with a peak amplitude equal to E and a width equal to R_2C. Once the capacitor is discharged, the SCR stops conducting. The switch used must be of a nonbridging type, so that when it is returned to its original position, the gate current is removed before return of the anode supply voltage.

If pulses of the opposite polarity are desired, it is necessary only to move the load resistor R_2 to the anode circuit as shown by the dashed resistor in the figure. Alternatively, a pulse transformer can be used in conjunction with the load resistor to provide an output of either polarity as well as a floating or multiple output. The transformer must be terminated to preserve waveshape, and its time constant must be within the range of the required pulse widths.

Multiple-Input Trigger Circuit

In order to detect when a dc voltage exceeds a given level, some form of trigger or comparator circuit is required. The usual procedure is to have a separate trigger for each input, even if it is necessary only to detect when any one of the inputs has exceeded a particular set point. The circuit of figure 13 eliminates duplication of trigger circuits and associated logic circuits by providing a means of coupling a number of inputs to one trigger (a Schmitt trigger circuit) while maintaining control of each set point. Each of the three inputs (A, B, and C) is electrically positive, and the input terminals are connected through a potentiometer to a negative voltage. The variable contact on the potentiometer is connected through a low-leakage diode to the input of the Schmitt trigger. Each potentiometer is set so that the voltage appearing at its variable contact will just become positive when the input level reaches the desired trip point. This positive voltage will cause current to flow through the diode and trip the trigger circuit to change its output voltage.

There is no coupling between inputs; each input will, therefore, trigger the circuit independently at its particular threshold regardless of the signal applied to the other inputs -- provided, of course, that the circuit has not yet been triggered. This circuit should provide considerable savings in alarm systems in which a number of variables such as pressure, temperature, neutron flux, and such need to be monitored simultaneously.

Dual-Voltage Power Supply

It is commonly necessary to supply several different voltages to electronic equipment. These voltages may be obtained from separate power supplies or from voltage-regulating devices connected to one main supply. If voltage regulation is not required, the use of voltage regulators for supplying power adds additional complexity and expense.

A simple solution is provided by the circuit of figure 14. The portion of the circuit comprising diodes D_1 and D_2, choke L, and capacitor C_1 constitutes a conventional choke input power supply. Choke input supplies have the characteristic of providing an output voltage that is somewhat less than the rms voltage appearing across one half of the transformer secondary.

The voltage at point A is full-wave rectified and has a peak amplitude of nearly 1.4 V rms. The voltage drops across semiconductor diodes D_1 and D_3 are relatively negligible, so that the high voltage at the output is very nearly 1.4 V rms. The output is full-wave rectified, even though only two additional circuit elements (a diode and a capacitor) are used.

The advantages of this circuit are its simplicity; the fact that it does not use a special transformer; and the fact that its efficiency is high, since no power is lost in voltage-dropping elements. The high-voltage output can approach 1.5 times the low-voltage output, and the ratio may be modified by proper choice of components. This circuit should find use in many industrial instruments as well as radio and television systems.

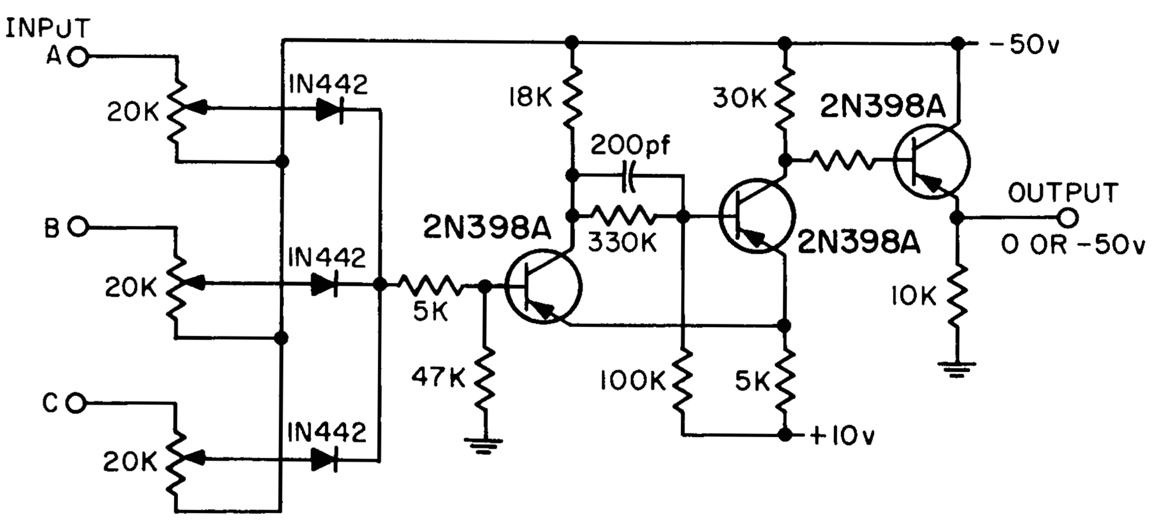

Figure 13. - Multiple-input trigger circuit.

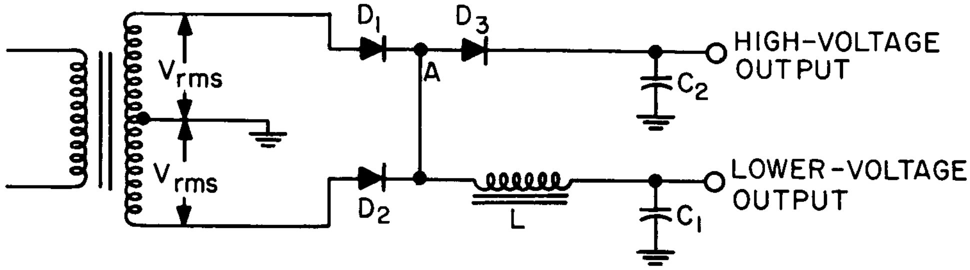

Figure 14. - Dual-voltage power supply.