TECHNICAL MEMORANDUM

RECENT DEVELOPMENTS IN SEMICONDUCTOR CIRCUITS

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INTRODUCTION

The work reviewed herein consists of a number of developments in the field of electronics that may have application for general industrial use. Most of this work was undertaken primarily to fulfill a need for very low power logic circuits for space-vehicle applications. This part of the program has involved the study of basic circuits and limitations imposed on their operation by the semiconductor devices used and the construction and testing of the more promising circuits. The other circuits to be discussed come from a number of sources and were made available through the NASA Lewis Patent and Technology Utilization Offices. Most of the circuits to be discussed are new developments, but a few are derived from older concepts that have not been widely applied.

First, a general class of digital logic circuits that has been designed for the lowest possible power consumption at a relatively low operating speed is discussed. Their performance is remarkably well suited to these operating conditions but is in no way limited to them. Operation at high power levels and high speed is equally feasible, and the circuits to be discussed possess many desirable features, such as nearly ideal waveforms, and efficiency independent of the power level for which they are designed. An attempt will therefore be made to describe not only the Lewis work in low power circuitry but also the basic operation of these circuits and the features that recommend them for industrial and computer-type applications.

BASIC CIRCUIT OPERATION

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

If the input is now connected to ground, no current flows into the transistor base and it turns off, just as the equivalent circuit relay opens when no voltage is applied to its coil. In this state, the voltage at the output is determined by the ratio of the resistors R_C and R_L. For a large output voltage R_C must be small. This is in direct opposition to the criterion for minimum power in the on state. If one assumes a 50-percent duty cycle, this circuit can be optimized for power transfer by making R_C equal to 0.707 R_L. Using these values results in a maximum theoretical power transfer efficiency of 17.6 percent.

From the preceding discussion it is obvious that the difficulty in this situation is the collector load resistor R_C and that any successful means of increasing efficiency is dependent on meeting two contradictory requirements simultaneously. These requirements have been met by replacing R_C with a second transistor that acts like an open circuit when the first transistor is turned on and like a very low resistance when it is turned off. The simplest embodiment of this circuit is shown in figure 2.

The upper transistor is a PNP transistor, which is turned on by a negative signal, as opposed to the lower NPN transistor, which is turned on by a positive signal. When a positive signal is applied to the input, the lower transistor is saturated and pulls the output to ground, while the same input cuts off the upper transistor. Since the upper transistor now looks like an open circuit, no power is drawn from the power supply. For a negative or zero input the states are reversed, that is, the upper transistor is saturated and delivers nearly full supply voltage to the load. No power is lost in the lower one. Computing the theoretical power transfer efficiency of this circuit by the same methods used for the conventional inverter results in a figure of 100 percent. In practice, values above 90 percent are not difficult to obtain.

The basic concept illustrated can be extended to provide a wide variety of logic circuits with both the complementary (PNP and NPN) transistor circuit and circuits with 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. Figure 4 is a similar flip-flop except that steering diodes have been incorporated in such a manner that it becomes 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 elements are plotted in figure 5. Note that in the low kilocycle region where they were designed to operate, they consume considerably less than 100 microwatts each. Some idea of the output capabilities of these circuits is shown in table I. At 2000 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 percent efficiencies at 200 kilocycles and an input power of 3 milliwatts. These elements are thus ideal as power drivers and matching elements between low- and high-power systems.

A second important group of circuits has been developed around the basic circuit shown in figure 6. It uses two transistors of the same type to provide many of the same advantages as the complementary circuits. When the lower transistor is turned on, its collector voltage drops to near ground potential. This drop is coupled through diode D_1 to the upper transistor base, which turns it off. Simultaneously, a conduction path is provided to ground through backward diode D_2 and the lower transistor to clamp the output to ground. When no input is applied and the lower transistor turns off, current flows through R_1 into the upper transistor base. This current turns the transistor on, and it supplies 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.

Yet another modification of this circuit produces the monostable multivibrator shown in figure 8. This multivibrator is, basically, a timing circuit that provides a pulse of fixed width after being triggered. 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 have been built at Lewis that operate at power levels from a quarter of a microwatt to many milliwatts and cover the frequency range of a few kilocycles to a megacycle or more.

It is interesting to speculate on what can be accomplished with such elements. If the very realistic figure of 100 microwatts per element is assumed, it would be possible to build a computer containing 15,000 such elements that would consume no more power than an ordinary three-cell flashlight. 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 elements can be built with low-cost components that retain essentially all the advantages of this type of circuitry.

Comparing these circuits intelligently with those more commonly used in digital applications necessitates a review of all their various advantages and disadvantages.

The most prominent of these advantages is, of course, the large reduction in power consumption achieved. It is this reduction in power that is either directly or indirectly responsible for a number of the other advantages of this type of circuitry.

This saving of power is attributable 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 case of no output voltage because the lower transistor now 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. This saving is possible since the output is now clamped to the supply by the added transistor, which eliminates the voltage drop formerly appearing across the 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 to drive many more outputs than conventional circuits.

Another direct result of the low internal power dissipation and high efficiency is a negligible rise in temperature. Increased packing density is thus allowed and the need for any auxiliary cooling means is eliminated. Since it is generally accepted that a decrease in operating temperature of 10 Centigrade degrees will halve the failure rate of components, the large reduction in temperature rise should increase reliability and lengthen operating life. Low power requirements also simplify the requirements for standby power in systems that must be protected from primary power line failure.

The reliability of this class of circuit is further enhanced by the excellent tolerance to relatively large variations in supply voltage and component parameters. Thus, greater tolerance and therefore lower-cost components can be used without fear of early failure due to parameter degradation. As an example, the two flip-flop circuits discussed previously were constructed with ordinary 10 percent carbon resistors. They operate perfectly over a temperature range of -20° to 80° 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 supply voltage or ground leads to a number of other advantages. The first 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. It also allows the output to drive loads returned to either supply voltage or ground and thereby doubles the potential number of output loads that the circuit can drive.

Finally, the fact that the output is actively driven by a transistor for both positive- and negative-going outputs eliminates the limits normally imposed by RC (resistance-capacitance) time constants to give nearly ideal waveforms with fast rise and fall times. As an example, the reset-set flip-flop produces 50 nanosecond rise and fall times when operated at a power drain of 50 microwatts.

Of the disadvantages, the most obvious is the larger number of components necessary in this type circuit. In the limiting case nearly doubling the parts count for a given logic circuit is possible. The larger number of parts immediately suggests higher cost and increased size. No factual study has been made to determine whether the advantages will economically justify these circuits for industrial or computer use; however, it is believed that in many instances they will prove advantageous.

PACKAGING OF ELEMENTS

All the elements discussed so far have been intended for space applications. High packaging density and design flexibility were desired. The solution was to use welded cordwood modules as shown in figure 9. The largest module is an eight-stage ring counter and the one below it is a gate module. At the upper right is the reset-set flip-flop, which has already been discussed in some detail. 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 percent as large. It represents the highest component density that Lewis has achieved to date, namely, 130 components per cubic inch. Figure 10 is a side view of two of these modules, and figure 11 is a side view of the toggle flip-flop. The comparatively large metal cans at the top and the bottom are two of the four transistors, the cylindrical components are resistors and ceramic capacitors, and the small disks are microdiodes.

With this method of construction, the 15,000-element computer previously mentioned could be built into a suitcase with sufficient room left for its power supply. Soon, when it becomes practical to build such circuits in integrated form, this computer might be contained in a woman's bandbag - a large one.

APPLICATIONS TO INDUSTRIAL SYSTEMS

Two circuits with the active load concept were built with low-cost components to determine whether the predicted performance could actually be achieved. One was a toggle flip-flop nearly identical in circuitry to the one shown in figure 4. It was built with germanium diodes and transistors. Its performance is tabulated in table II. Note that the overall performance is very similar to the low-power circuit with the exception that all power levels have been increased by approximately an order of magnitude. This standby power level of 1/2 milliwatt is still far lower than any of the commercially available logic circuits.

A more striking comparison of the various flip-flop designs is shown in figure 12. The lower two curves repeat the data of figure 5, the middle curve is for the "industrialized" version of our low-power complementary circuit, and the upper curve is for a conventional flip-flop, which has collector load resistors, designed to operate at minimum power and speed comparable with the other circuits. Note that although it is impossible to achieve operating powers below several hundred microwatts with the low-cost industrialized circuit, the power consumption is still improved by a factor of 10 over the conventional circuit.

The conventional circuit provided a maximum power output to its load of 0.8 milliwatts with 13- to 15-percent efficiency compared with more than 8 milliwatts for the industrialized circuit at 90- to 96-percent efficiency.

Furthermore, the conventional flip-flop exhibited a very poor waveform, as shown in the figure, compared with its industrialized counterpart, which maintained a practically ideal output waveform.

Approximately the same comments apply to the performance of the three-input similar transistor NOR gate shown in table II. The main difference is that all devices except the backward diode were silicon to provide increased reliability and high-temperature operation. The backward diode was replaced with a conventional germanium diode for a considerable cost saving. Efficiency of this circuit is somewhat poorer than the complementary circuit as is to be expected, although it is still well above that of conventional circuits of comparable performance.

These two circuits were not optimized for cost or performance and are included merely as an indication of some of the advantages to be gained from the use of these circuit concepts. Other circuits can easily be imagined. The availability of high-quality, low-price silicon NPN transistors, for example, suggests that they might be used in conjunction with germanium PNP transistors in complementary circuits. A hybrid logic system with complementary multivibrators and similar transistor gates would probably approach the ideal for high fan-out industrial systems and would probably be competitive with conventional circuits if all factors were considered.

OTHER NEW OR INTERESTING CIRCUITS

The material presented to this point is representative of new developments made within our own group at Lewis. In addition, there are a number of novel circuits that might be of interest, which have been conceived to solve specific problems. They are typical of the type of development being made in the normal course of work by both NASA and industry. It is hoped that the exchange of such information will be promoted through the recently created Lewis Technology Utilization Office. Several examples of novel circuits follow.

SINGLE-PULSE GENERATOR

Digital systems of most types require some means of entering information from operators or other input devices. A pushbutton or contact closure in conjunction with some type of network is commonly used to provide a single pulse to perform the required function. Unfortunately, the fact that mechanical contacts tend to bounce makes it almost impossible to obtain a fast-rise single pulse directly. 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 pulse width.

Both these problems can be solved by the rather simple circuit shown in figure 13. The circuit employs either a Thyristor or a silicon controlled rectifier as the active element. It makes use of the characteristic that once the device is in the conducting state, the supply voltage must be removed in order for the device to return to the nonconducting state.

With the input switch or relay in the position shown, the controlled rectifier 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.

When the switch is closed to the gate input, sufficient current flows through R_1 to cause conduction. Capacitor C_1 discharges through R_2 and produces the output pulse with a peak amplitude equal to E and a width equal to R_2C_1. Once the capacitor is discharged, the controlled rectifier 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 time constant must be selected to be within the range of pulse widths required and the transformer must be terminated to preserve waveshape.

MULTIPLE INPUT TRIGGER CIRCUIT

Whenever it becomes necessary to detect when a direct-current 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 them has exceeded its particular set point. The circuit of figure 14 eliminates duplication of trigger circuits and associated logic by providing a means of coupling a number of inputs to one trigger while control of each individual set point is maintained.

The trigger circuit used is commonly known as a "Schmitt trigger." Each of the three inputs (A, B, and C) is electrically positive and 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 such that when the input level reaches the desired trip point, the voltage appearing at its variable contact will just start to become positive. This positive voltage will cause current to flow through the diode and will trip the trigger circuit, which will cause it to change its output voltage.

The voltage at which each input will cause the circuit to be triggered is adjustable by the setting of its input potentiometer. Furthermore, there is no coupling between inputs; each 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 circuits in which a number of parameters, such as pressure, temperature, neutron flux, etc., need to be monitored simultaneously.

DUAL VOLTAGE POWER SUPPLY

It is quite common to use several different supply voltages in any given piece of electronic equipment. These voltages may be obtained from separate power supplies or by the use of voltage-regulating devices off one main supply. If these devices are not required for purpose of regulation, their use is expensive, both on the basis of power wasted and circuit complexity and, therefore, cost.

A simple remedy is provided by the circuit of figure 15. The lower portion of it, comprising diodes D_1 and D_2, choke L, and capacitor C_1 comprise a conventional choke input power supply. Choke input supplies have the basic characteristic of providing an output voltage somewhat lower than the root mean square voltage of one-half the transformer secondary voltage V_{rms}.

Consider now the voltage at point A. It is a full wave rectified voltage with a peak amplitude of 1.4 V_{rms} less the diode forward drop. Addition of diode D_3 allows passage of this voltage to capacitor C_2, which will charge to the peak input voltage less the drop across two diodes. For semiconductor diodes, the drop is quite small and the high voltage is very nearly 1.4 V_{rms}. The output is full wave rectified even though only one additional diode and 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 applications.

CONCLUSION

A

The intent of this presentation is to convey some idea of the type of electronics development being actively pursued by the Lewis Research Center. The specific circuits chosen for inclusion were selected as representative of the general work at Lewis as well as potentially useful to industry.

Of more importance than the specific ideas presented is the fact that NASA, as well as other government agencies, has similar developments available on request. These advances, brought about by the space effort, could have great value for industry. Those discussed herein should find application in the computer industry as well as for consumer products such as radio, television, high-fidelity systems, and remote controls. One of the largest fields of potential application is equipment for automated manufacturing lines, including measuring and process control instrumentation.

All these fields and others can benefit from the advanced technology being developed by the space program. These developments are not usually in a form directly applicable to industrial needs, as has been shown. Obviously, further engineering will be necessary to adapt these new developments to specific requirements.

The Technology Utilization Office was organized to provide ready access to these developments and will provide information and discuss potential applications with anyone requesting its services.

TABLE I. - FLIP-FLOP PERFORMANCE CHARACTERISTICS

(a) Reset-set

[Supply voltage, 4.5 v.]

Input power, mw	Pulse rate, pps	Load resistor, ohms	Power efficiency, percent
0.058	0	0	--
.06	2,000	0	--
1.8	2,000	10K + 10K	96
1.9	20,000	10K + 10K	94
.1	25,000	0	--

(b) Toggle

[Supply voltage, 4.0 v.]

Input power, mw	Pulse rate, pps	Load resistor, ohms	Power efficiency, percent
0.015	0	0	--
.022	2,000	0	--
.96	2,000	15K + 15K	98
.5	200,000	0	--
3	200,000	3.3 K	83

TABLE II. - "INDUSTRIALIZED" CIRCUITS PERFORMANCE CHARACTERISTICS

(a) Toggle

[Total component cost per unit in quantities of 1000, $2.25; supply voltage, 6.0 v.]

Input power, mw	Pulse rate, pps	Load resistor, ohms	Power efficiency, percent
0.5	100	0	--
12.5	100	1.5 K + 1.5 K	96
.87	67,000	0	--
11.7	67,000	1.5 K + 1.5 K	91
10.9	200,000	1.5 K + 1.5 K	89

(b) Similar transistor NOR gate

[Total component cost per unit in quantities of 1000, $3.00; supply voltage, 6.0 v.]

Input power, mw	Pulse rate, pps (a)	Load resistor, ohms	Power efficiency, percent
0.755	500	0	----
4.63	500	3.3 K	82.5
.766	10,000	0	----
8.48	10,000	1.5 K	87.2
1.27	200,000	0	----
6.65	200,000	3.3 K	71.5

[a]With 50 percent duty cycle.

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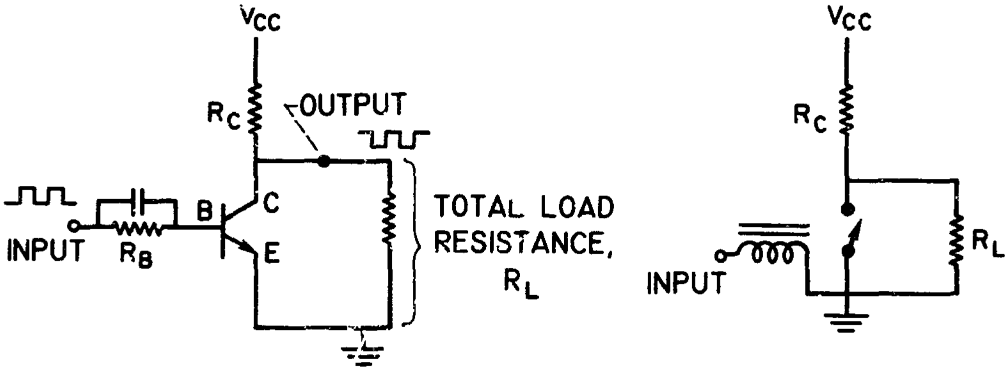
LOGICAL INVERTER CIRCUIT



CONVENTIONAL TRANSISTOR INVERTER CIRCUIT (OPTIMIZED FOR MAXIMUM POWER EFFICIENCY)

RELAY EQUIVALENT INVERTER CIRCUIT

Figure 1

BASIC COMPLEMENTARY INVERTER CIRCUIT

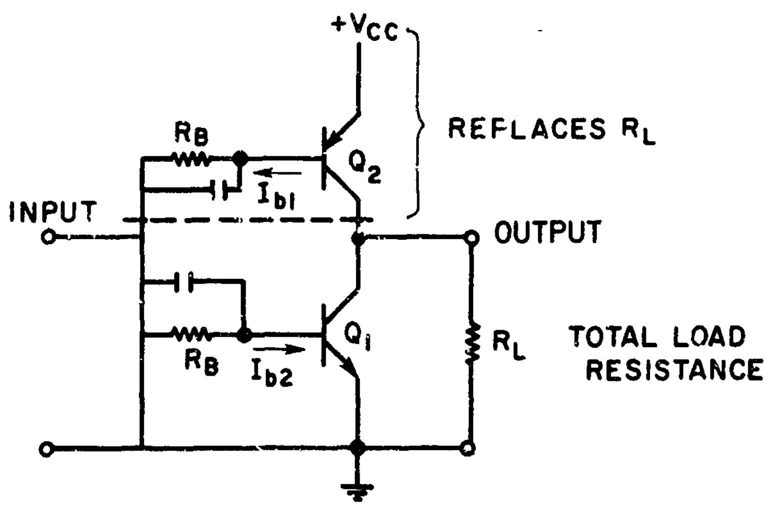


Figure 2

RESET-SET FLIP-FLOP

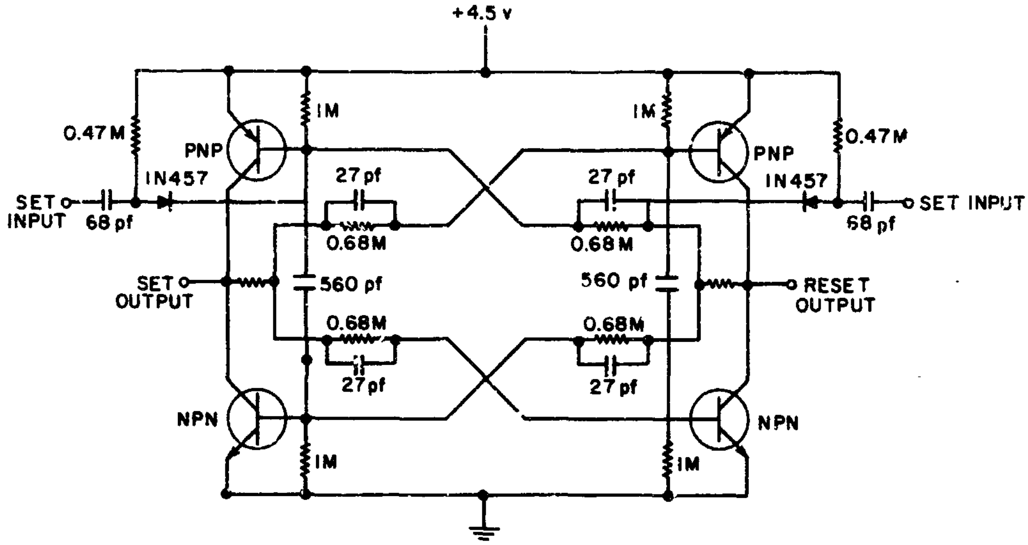


Figure 3

COMPLEMENTARY TOGGLE FLIP-FLOP

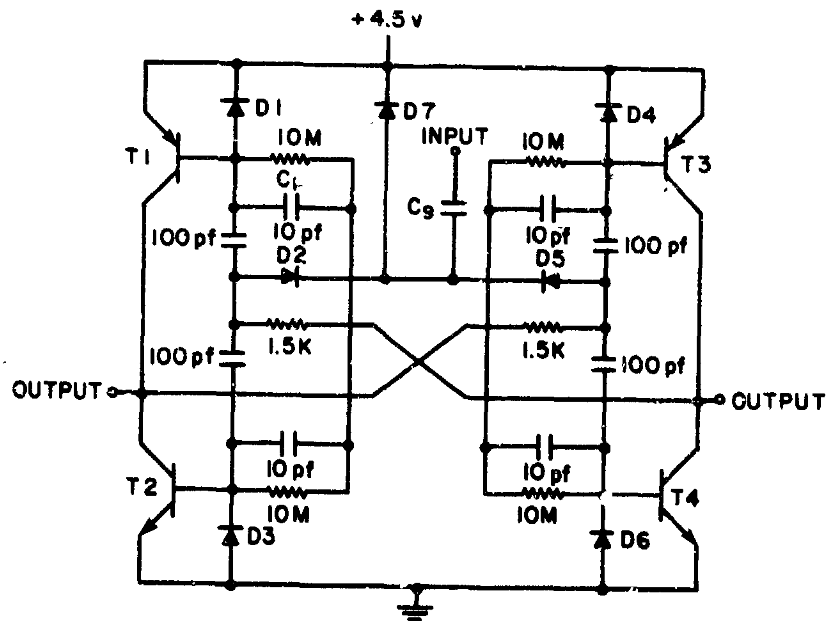


Figure 4

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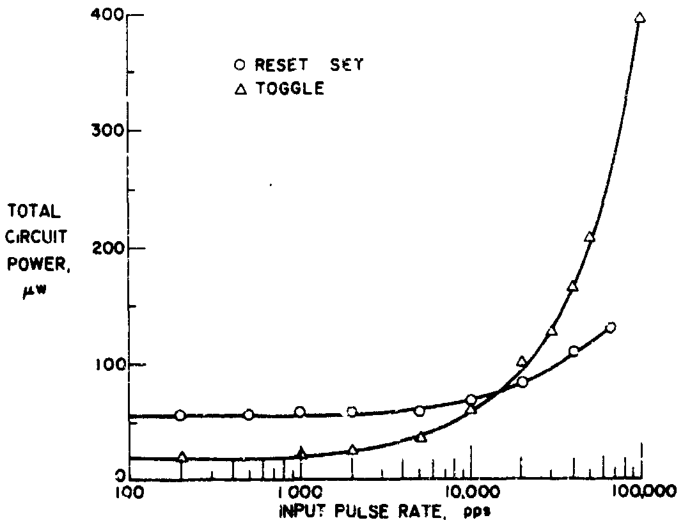
POWER DRAIN FOR RESET-SET AND TOGGLE FLIP-FLOPS
SUPPLY VOLTAGE, 4.5 VOLTS



BASIC SIMILAR TRANSISTOR INVERTER

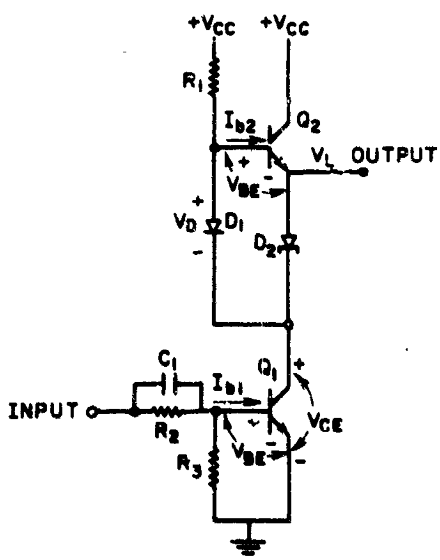


Figure 6

TRANSISTOR INPUT NOR

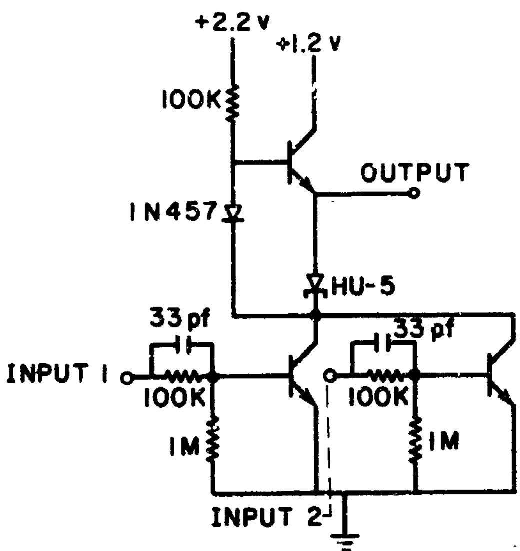


Figure 7

SIMILAR TRANSISTOR MONOSTABLE MULTIVIBRATOR

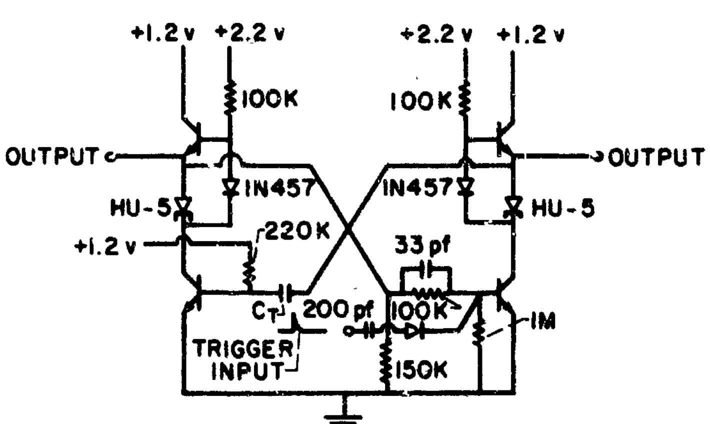


Figure 8

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WELDED CORDWOOD LOGIC MODULES
TOP VIEW

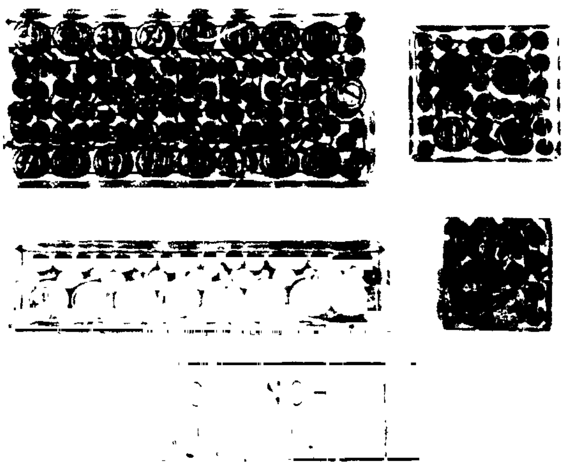

Figure [illegible]

GATE AND FLIP-FLOP MODULES
SIDE VIEW

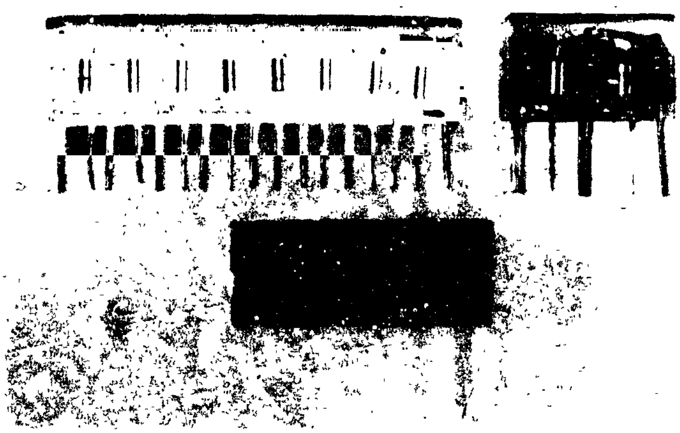

Figure [illegible]

TOGGLE FLIP-FLOP
SIDE VIEW

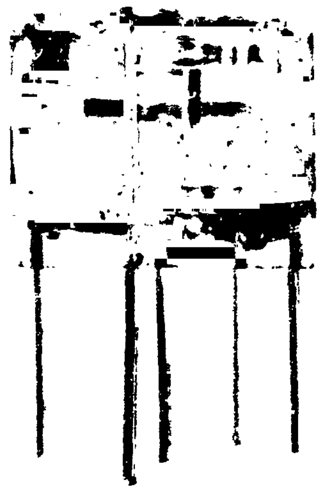

Figure 11

INPUT POWER AGAINST FREQUENCY FOR VARIOUS FLIP-FLOPS

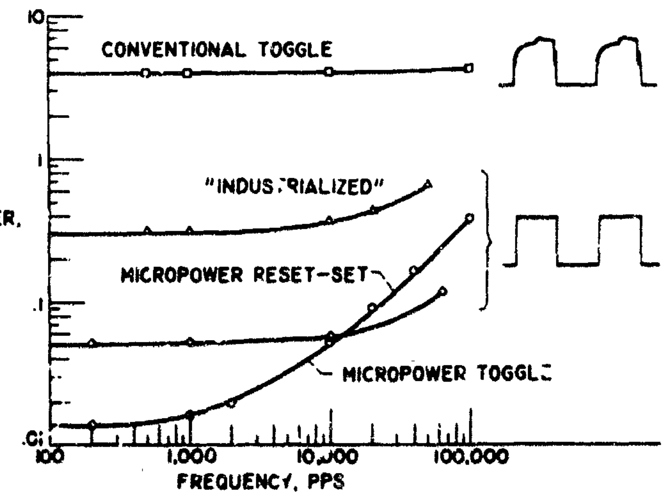

Figure 12

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SINGLE-PULSE GENERATOR

INVENTOR, ROBERT L. MILLER

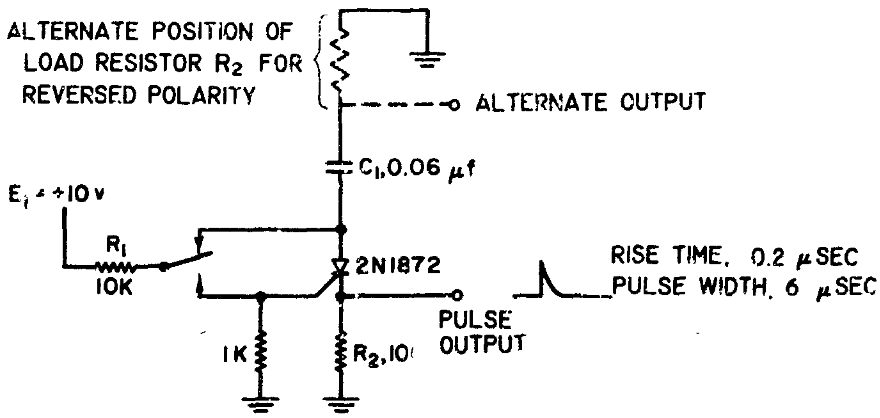

Figure 13

MULTIPLE-INPUT TRIGGER CIRCUT

INVENTORS, R. W. WELSH AND D. P. ORANGE

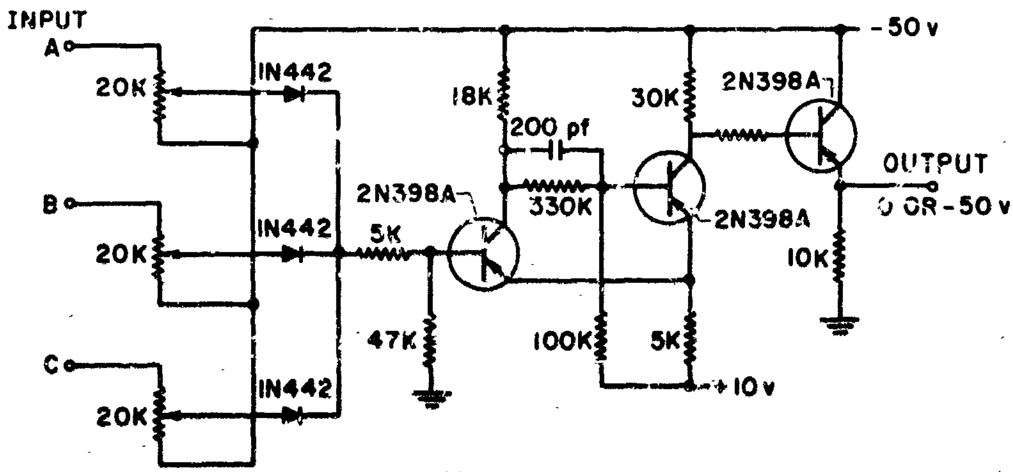

Figure 14

DUAL-VOLTAGE POWER SUPPLY

PATENT NUMBER 3,053,991

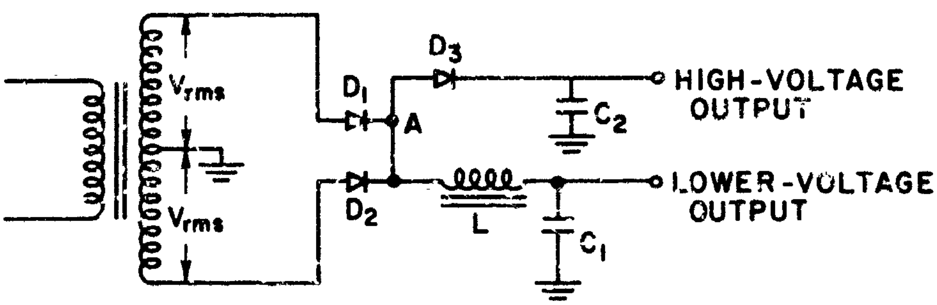

Figure 15