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MICROELECTRONIC POWER SUPPLIES

CONTRACT NO. NAS8-24817

FINAL REPORT

MAY 1971

PREPARED FOR:

ASTRIONICS DIVISION-NATIONAL AERONAUTICS & SPACE ADMINISTRATION
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LIST OF SCHEMATICS (CONTD)

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1.0 SYNOPISIS

This report describes a series of miniature power supplies developed by Electronic Communications, Inc.(ECI), for NASA/MSFC under contract number NAS8-24817. These units are designed for operation in an aerospace application where small size and weight and high efficiency are of primary concern. Two basic types of circuits have been developed; main supplies and remote regulators. The main power supply interfaces with the spacecraft 28 volt power source and provides output voltages which are transformer isolated via a DC-DC converter from the primary 28-volt lines. Reverse-polarity protection and EMI filtering are included. Each main supply delivers up to three (3) watts to a group of remote regulators. The remote regulators are thick film hybrid circuits suitable for providing "on-card" regulation for integrated circuits. Four types of remote regulators have been developed which provide output voltages of +5, +15, -15, -5.2 and -27 volts. Each remote regulator incorporates overload protection and has an output power rating of 0.5 watts.

Prototype units of all the power supply circuits have been fabricated, tested and delivered. Nominal efficiency at full load for both the main supplies and the remote regulators are in the 80 to 85 percent range. All circuits are designed for and have been tested over the temperature range of -40°C to +100 degrees centigrade.

2.0 MAIN POWER SUPPLIES

The primary function of the main power supply is to provide DC isolation from the nominal 28 volt power source and to establish an output voltage which is near the optimum level to power the associated remote regulators. In addition, the main supply must be protected from reverse polarity input voltage and must include EMI filtering to prevent the generation of conducted interference on the 28 volt supply line. In the initial phase of this program, a design was investigated which provided output overload protection and which also provided a degree of voltage regulation. Although this design did function properly, it became apparent that the additional components necessary to provide protection and regulation increased the circuit complexity by a factor of two. This would of course increase the physical size of the main supply and decrease the reliability of the unit. After weighing the relative merits of the simple versus the complex design, a decision was made to proceed with the simple design approach without the regulation and overload protection features.

A total of three main supplies have been developed which are very similar in construction and in operation. The only differences among the three are in the transformer and rectifiers necessary to provide the appropriate output voltages.

2.1 TTL Main Power Supply

A schematic diagram of the TTL main power supply is shown in Figure 1. This circuit is comprised of an EMI filter with a reverse-polarity diode and a saturating-core inverter with the

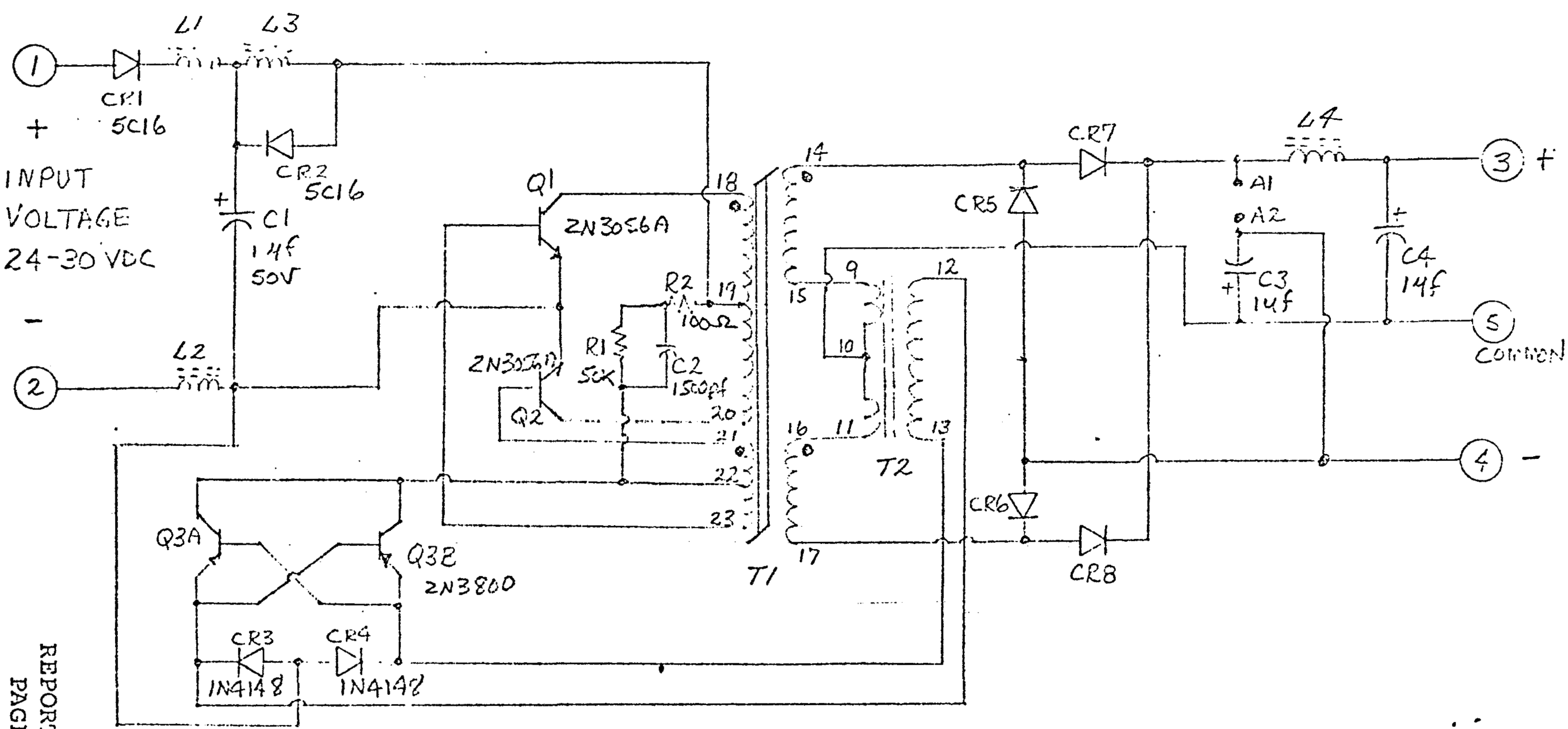


FIGURE 1. MAIN POWER SUPPLY SCHEMATIC DIAGRAM.

Note 1. Configuration shown is valid for MOS/Linear and TTL/ECL Main Supplies

Note 2. For TTL Main Supply, omit CR5, CR6. Reverse polarity of C3. Jumper A1, A2.

associated rectifiers and filters. This circuit provides DC isolation between the 28-volt main power source and the output voltage.

In order to maximize the efficiency over a large load current range, the base current drive for the inverter transistors is derived primarily from current transformer T2. In this manner the base drive is proportional, to the load current thereby minimizing the power loss in the base drive circuitry. A small fixed base current is provided via R1 to assure starting of the inverter. The output of the current transformer T2 is fullwave rectified by Q1-Q2 and CR3-CR4 in such a manner that the voltage developed across the secondary of T2 is the base-emitter voltage of Q1 or Q2 which is approximately 600 millivolts. This voltage is substantially independent of the load current level and thereby approximates a low impedance load which is necessary for proper operation of a current transformer.

The secondary voltage of inverter transformer T1 is fullwave rectified and filtered by a pi-section filter to minimize the output ripple voltage. The rectifier diodes used are ion-implanted units which have a very low forward voltage drop and extremely fast switching speed. Both of these characteristics maximize the overall efficiency.

The shunt diode across L3 in the EMI filter prevents a large voltage spike from being developed when the inverter core saturates and the inverter commutates. The operating frequency of the inverter varies from 25 to 31 kHz for input voltages of 24 to 30 volts.

Test data measured on the breadboard and prototype unit is shown graphically in Figures 2 through 6. The output ripple voltage is less than 0.1 volt peak-to-peak for less than 3 watts load.

Since the circuit is comprised primarily of discrete components and since several of the components are relatively large magnetic devices, a potted cordwood module was chosed as the packaging technique. A thick film hybrid construction was also evaluated but, because of the bulky magnetics, offered an insignificant reduction in overall size. The encapsulated main power supply module has a total volume of 1.6 cubic inches and weighs 0.106 pounds.

2.1.1 Thermal Characteristics

The internal temperature rise in the final potted module assembly was measured under worst case conditions to determine the actual hot spot temperature. This was done by mounting a small bead thermistor on the flange of one of the 2N3056A inverter transistors and bringing out test leads from the thermistor. The thermistor resistance was then measured as a function of temperature to obtain a calibration curve as shown in Figure 7. Using this curve, the case temperature of the inverter transistor was measured while the power supply was delivering approximately 3.5 watts with 24 volts input voltage. These load and input conditions result in maximum internal dissipation in the module.

The thermal response of the main power supply module is shown in Figure 8. As may be seen, the maximum temperature rise is

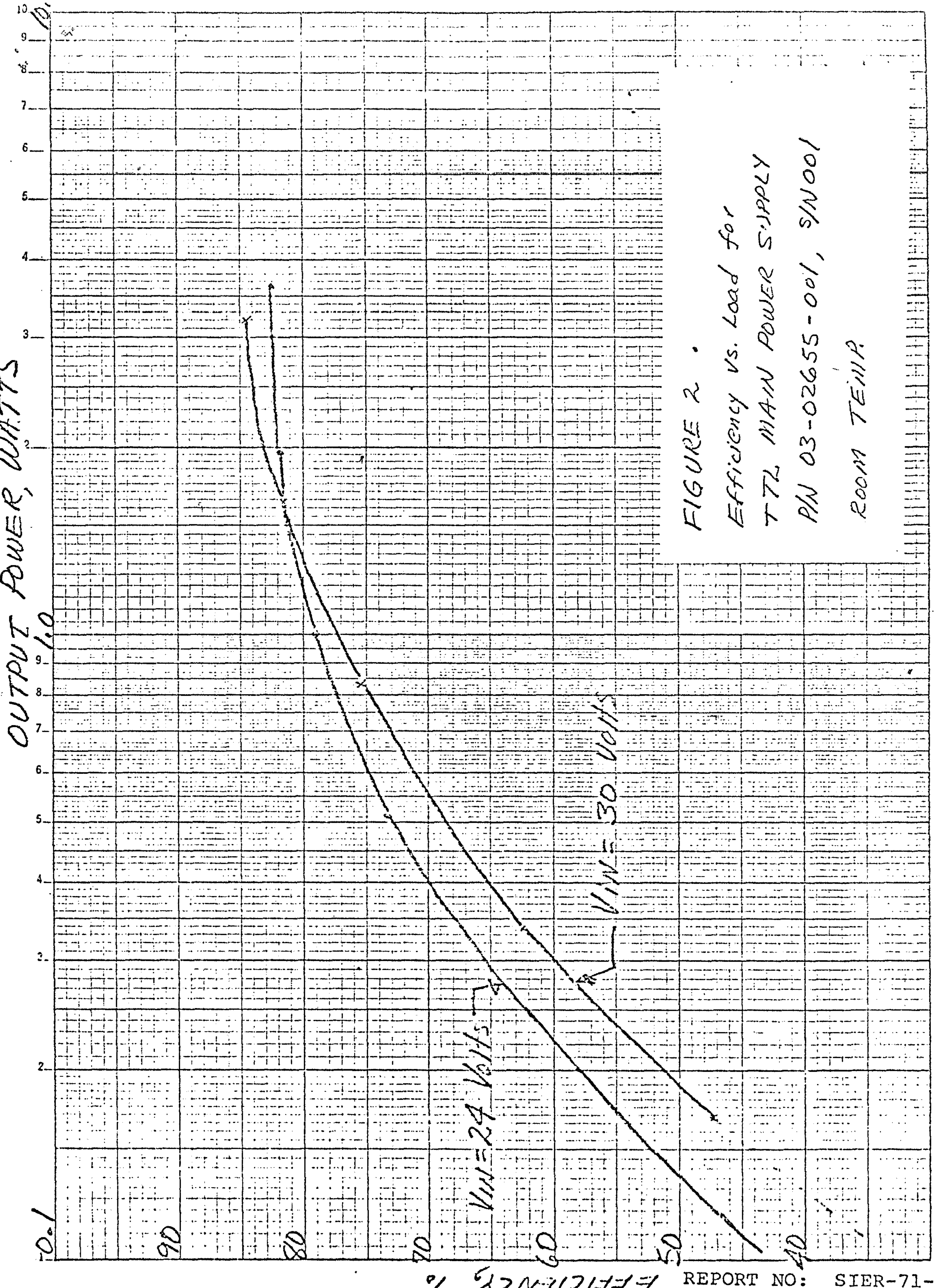
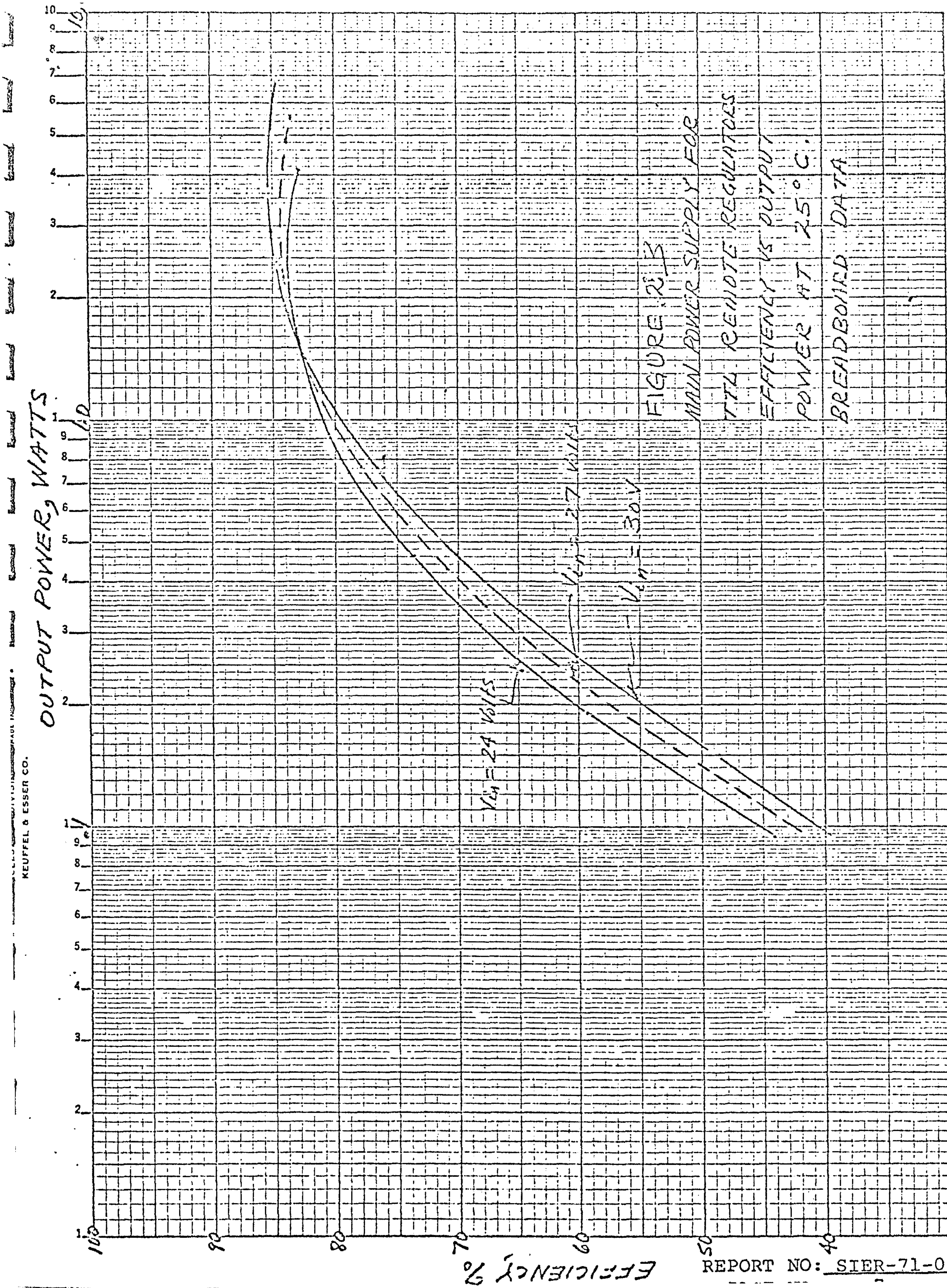


FIGURE 2.
Efficiency vs. Load for
TTL MAIN POWER SUPPLY
P/N 03-02655-001, S/N001
ROOM TEMP



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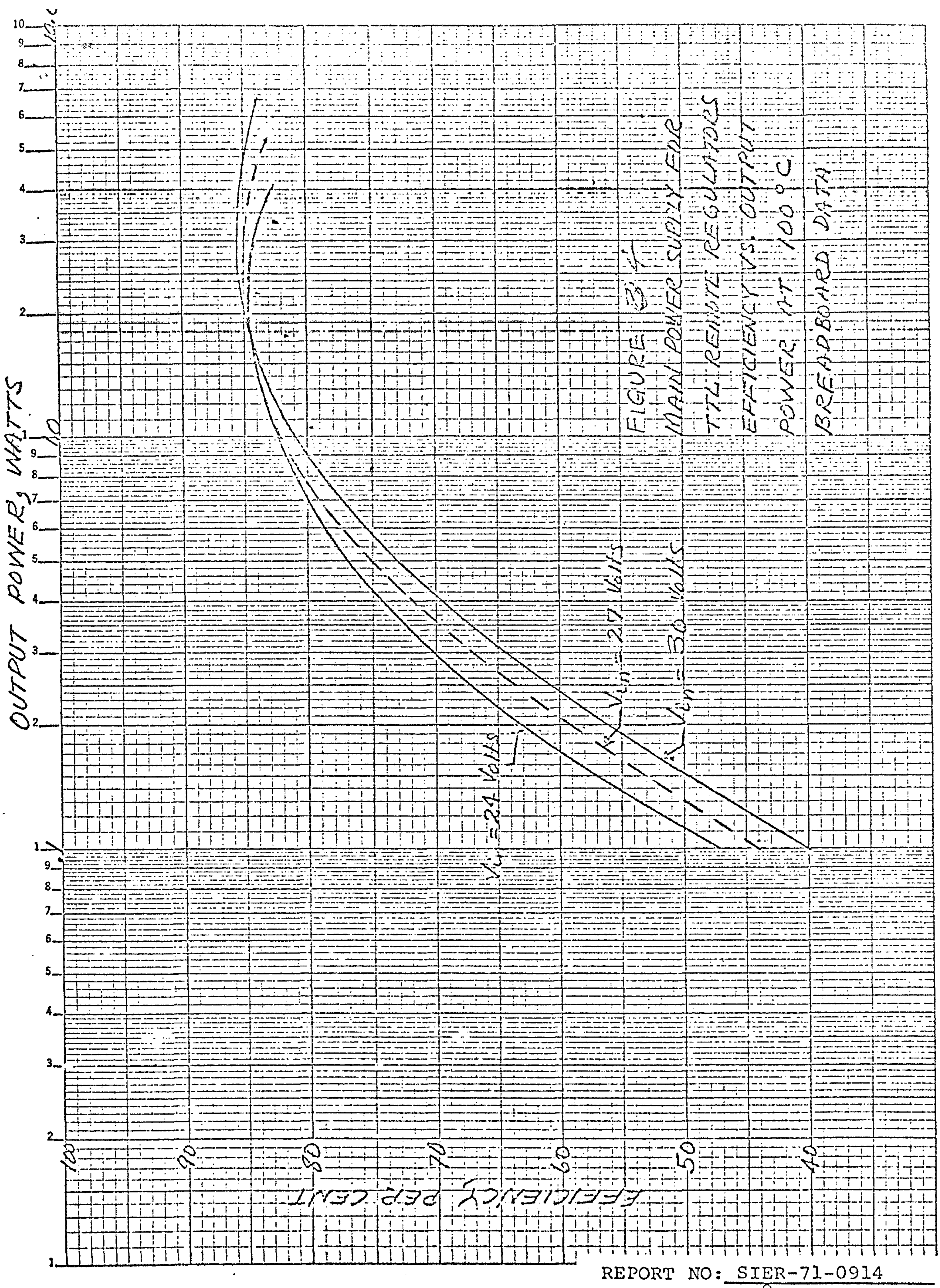


FIGURE
MAIN POWER SUPPLY
TTL REMOTE REGULATORS
EFFICIENCY VS. OUTPUT
POWER AT 100°C
BREADBOARD DATA
OUTPUT POWER, WATTS
EFFICIENCY PER CENT
100
90
80
70
60
50
40
Vin=21 Volts
Vin=27 Volts
Vin=30 Volts

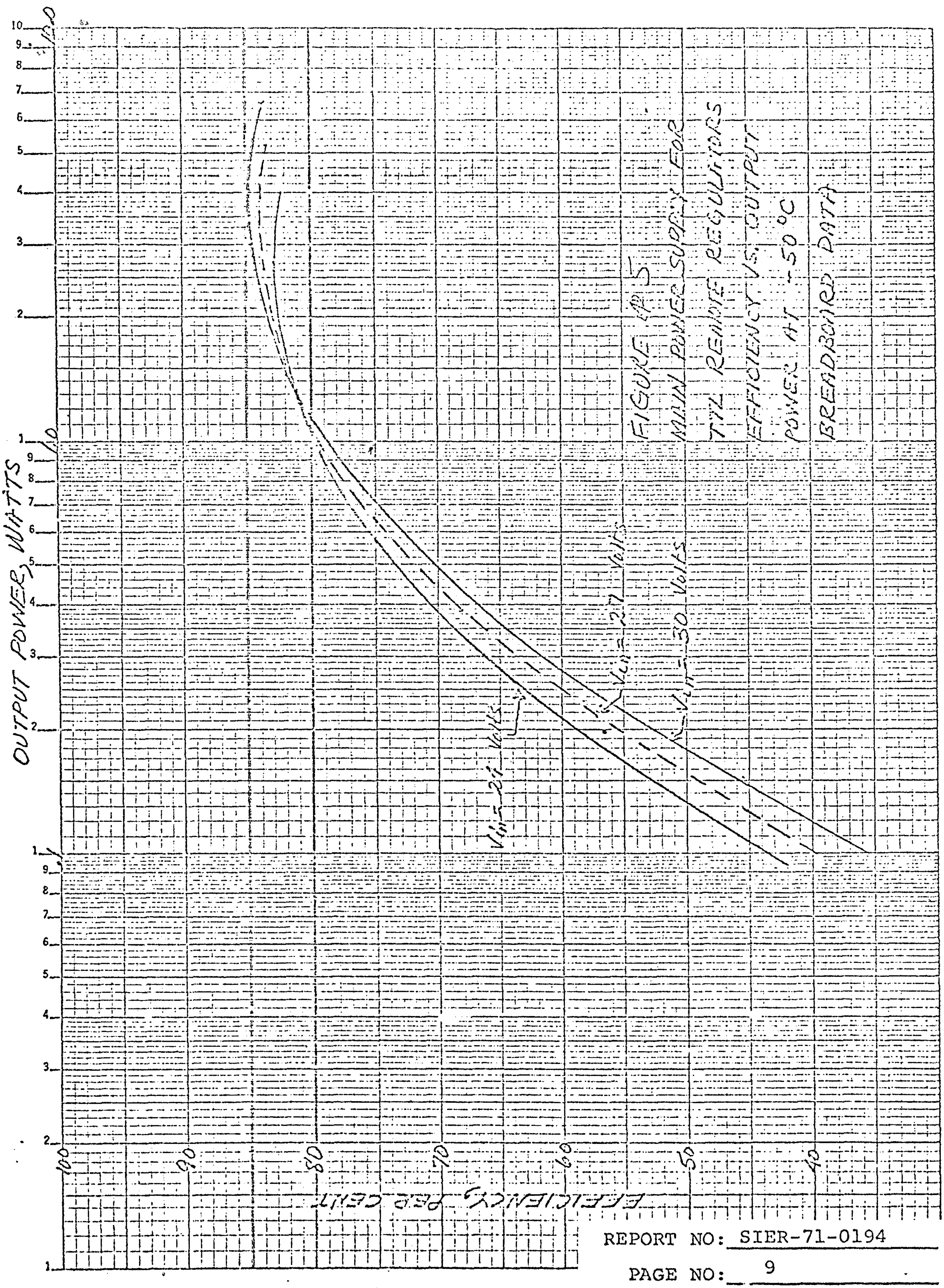


FIGURE NO 5
MAIN POWER SUPPLY FOR
TTL REMOTE REGULATORS
EFFICIENCY VS. OUTPUT
POWER AT -50 °C
BREADBOARD DATA
OUTPUT POWER, WATTS
EFFICIENCY, PER CENT
Vin = 24 Volts
Vin = 27 Volts
Vin = 30 Volts
100
90
80
70
60
50
40
10.0
1.0

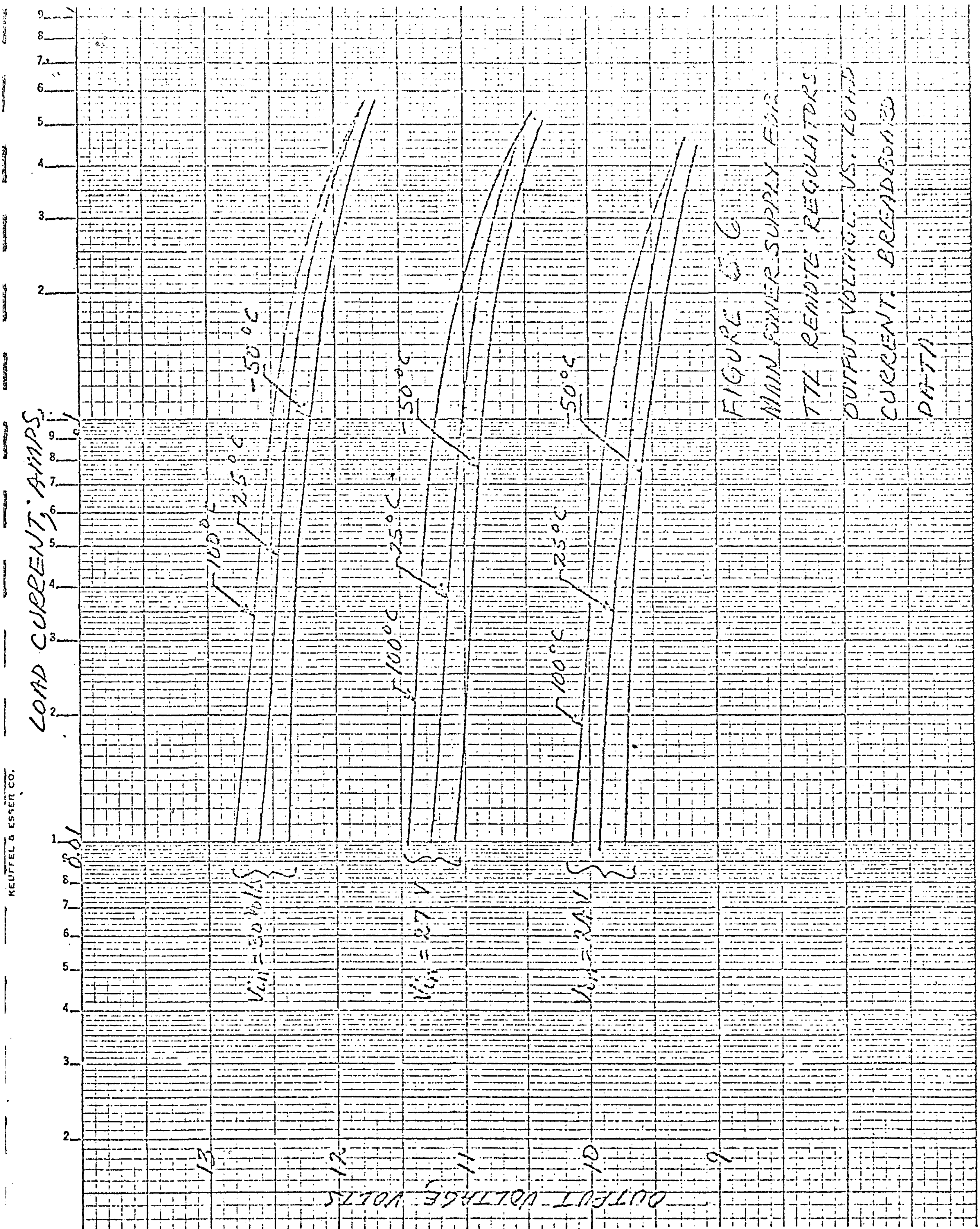


FIGURE 6
MAIN POWER SUPPLY FOR TTL REMOTE REGULATORS
OUTPUT VOLTAGE VS. LOAD CURRENT. BREADBOARD DATA
LOAD CURRENT, AMPS
OUTPUT VOLTAGE VOLTS
Vin = 30 volts
Vin = 27 V
Vin = 24 V
-50°C
25°C
100°C
13
12
11
10
9

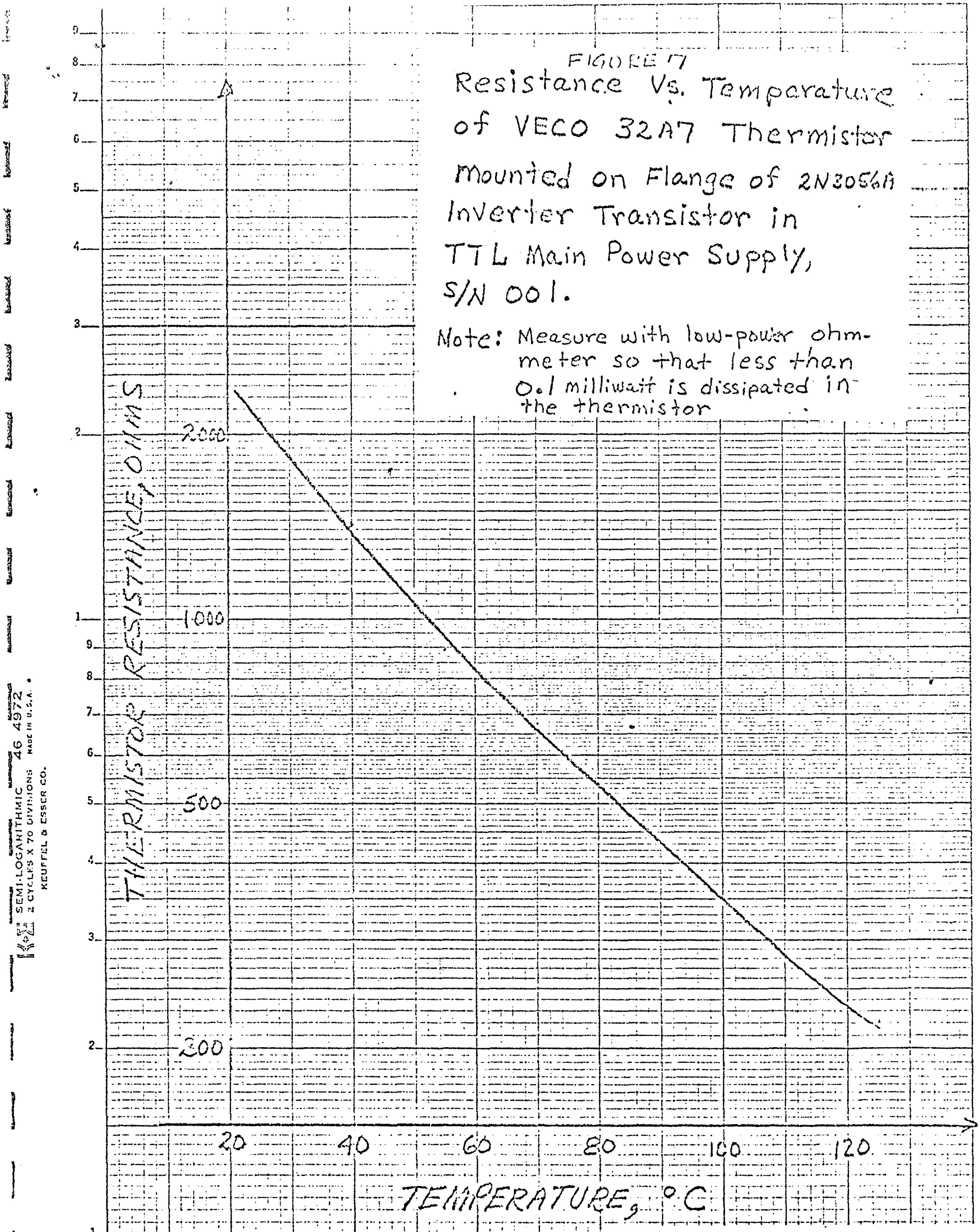


FIGURE 7
Resistance Vs. Temperature of VECO 32A7 Thermistor Mounted on Flange of 2N3056A Inverter Transistor in TTL Main Power Supply, S/N 001.
Note: Measure with low-power ohm-meter so that less than 0.1 milliwatt is dissipated in the thermistor
THERMISTOR RESISTANCE, OHMS
2000
1000
500
200
20
40
60
80
100
120
TEMPERATURE, °C
SEMI-LOGARITHMIC 46 4972
2 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

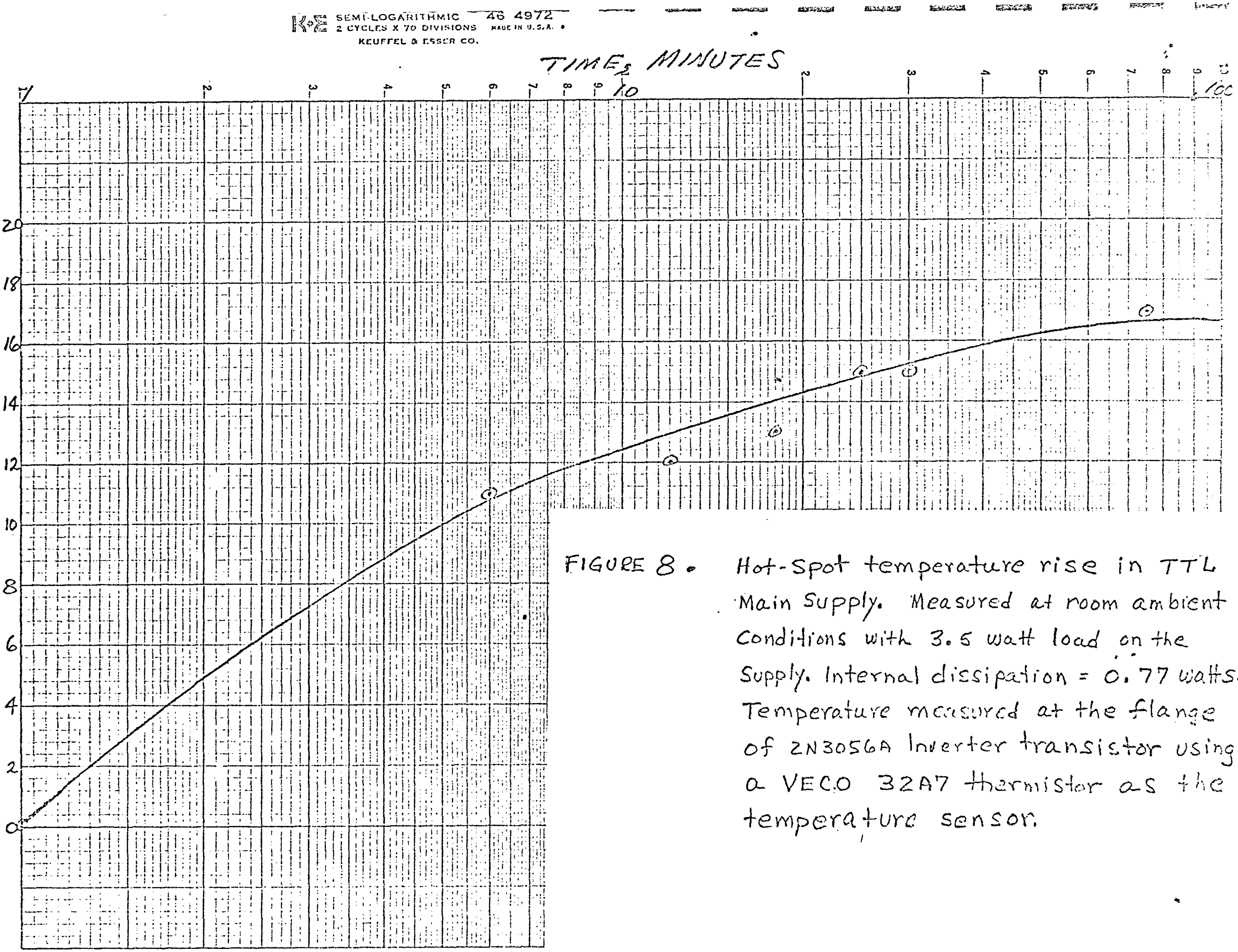


FIGURE 8. Hot-Spot temperature rise in TTL Main Supply. Measured at room ambient conditions with 3.5 watt load on the Supply. Internal dissipation = 0.77 watts. Temperature measured at the flange of 2N3056A Inverter transistor using a VECO 32A7 thermistor as the temperature sensor.

approximately 17°C for a module dissipation of 0.77 watts. This data should apply for all the main power supply modules since the construction and internal dissipation is similar.

2.2 MOS/Linear Main Supply

This circuit is used to operate remote regulators which in turn supply regulated power for MOS logic circuitry, and linear integrated circuits. The basic circuit configuration is also shown in schematic form in Figure 1. Operation is identical to that described above for the TTL main supply. In fact, the same printed circuit layout and assembly drawings are used for both main supply modules. Different transformer windings are used to provide the required voltage levels.

Measured performance data for the MOS/Linear main supply are shown in Figures 9 through 11.

2.3 TTL/ECL Main Supply

This circuit fills the need for a negative supply voltage to power high speed emitter-coupled logic circuitry. The resultant circuit is identical in configuration to the MOS/Linear main supply shown in Figure 1. The inverter transformer and the current feedback transformer used for the TTL main supply are used in this circuit. In fact, this circuit fills the requirements of the TTL main supply and can be used as a replacement. Operation is again identical to that described for the TTL main supply.

Measured test data for the TTL/ECL main supply are shown in Figures 12 and 13.

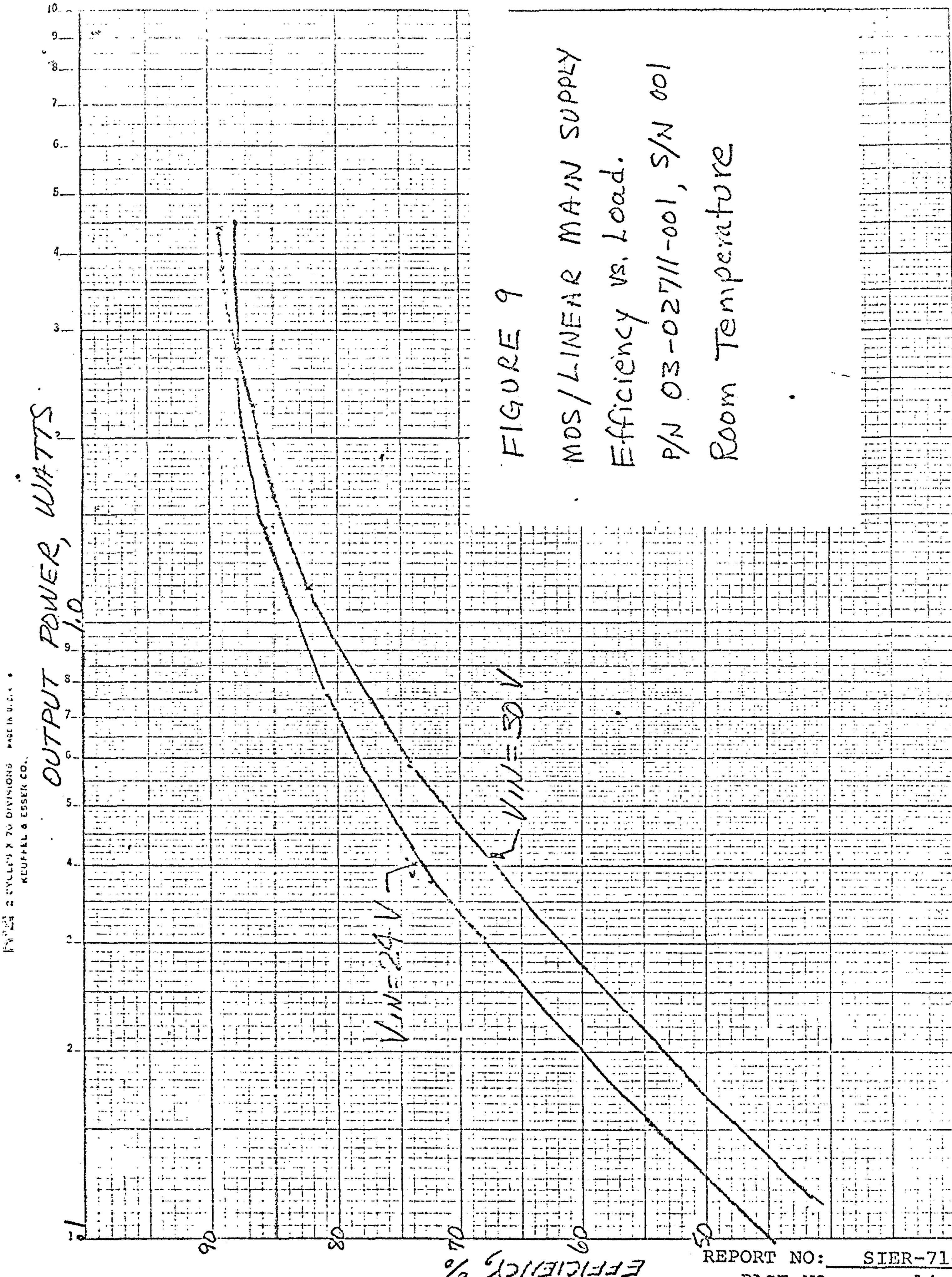


FIGURE 9
MOS/LINEAR MAIN SUPPLY
Efficiency vs. Load.
P/N 03-02711-001, S/N 001
Room Temperature
OUTPUT POWER, WATTS
1.0
VIN=24 V
VIN=30 V
90
80
70
60
50
EFFICIENCY %
KEUFFEL & ESSER CO.

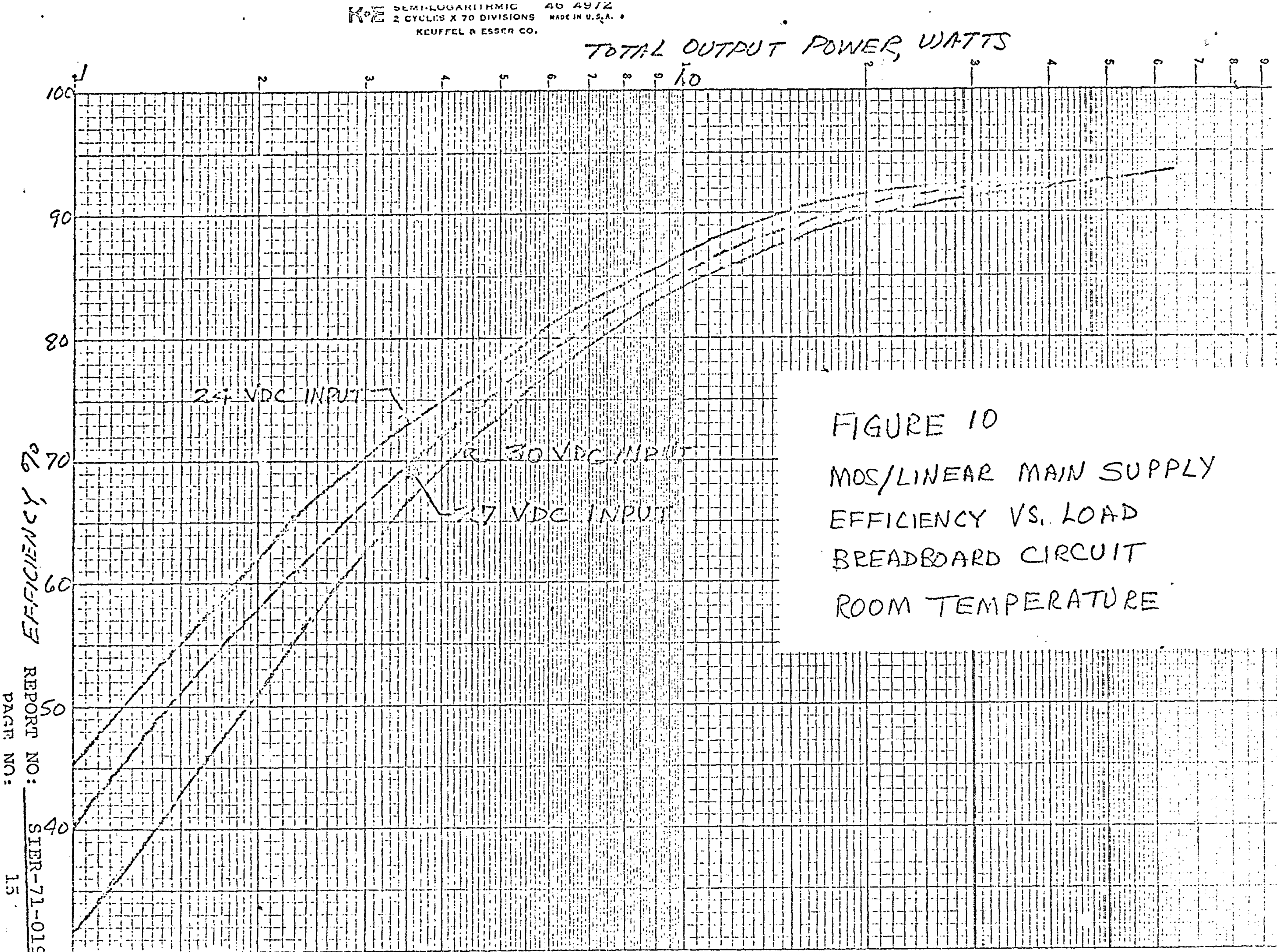


FIGURE 10
MOS/LINEAR MAIN SUPPLY
EFFICIENCY VS. LOAD
BREADBOARD CIRCUIT
ROOM TEMPERATURE

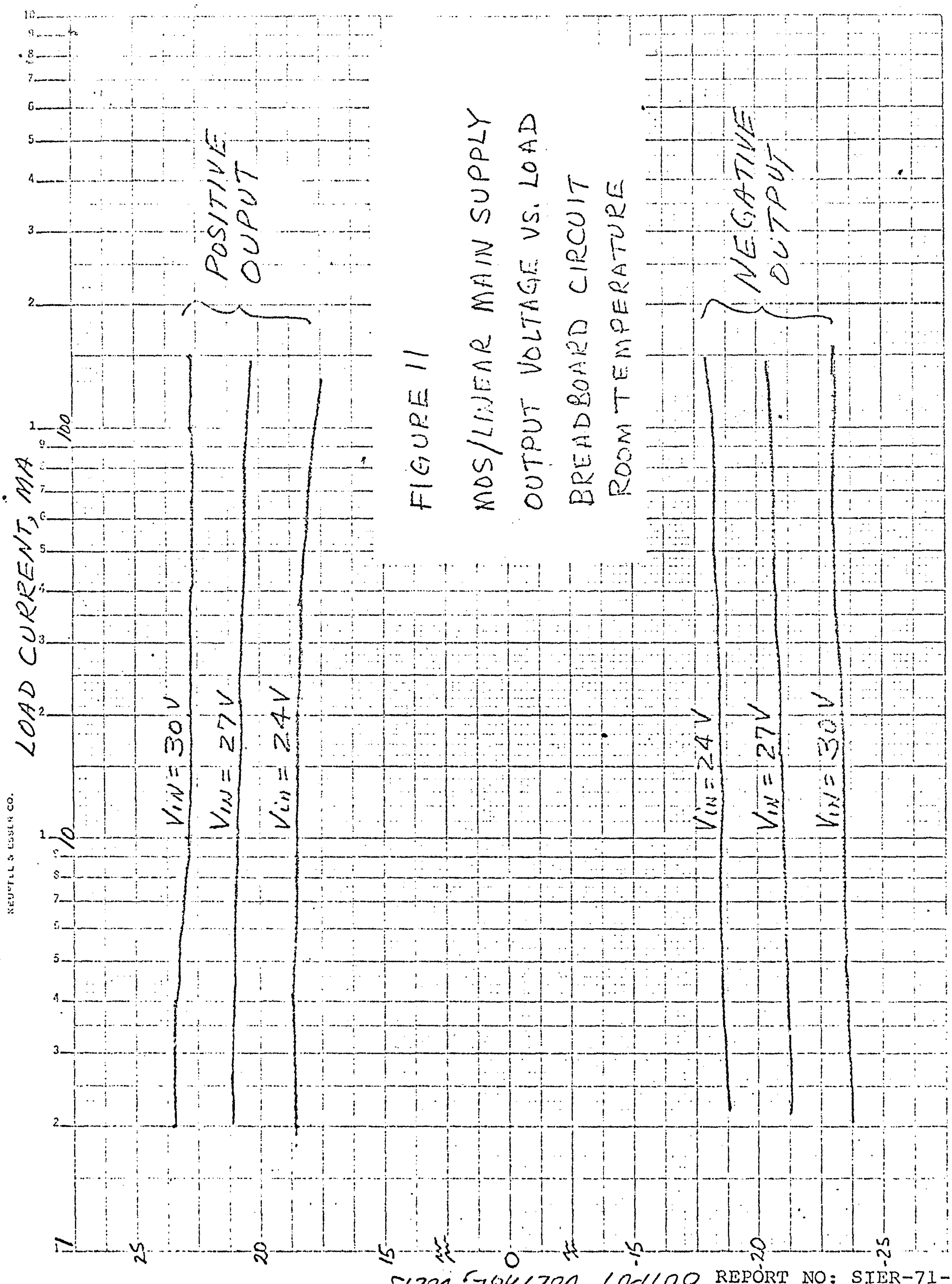


FIGURE 11
MOS/LINEAR MAIN SUPPLY
OUTPUT VOLTAGE VS. LOAD
BREADBOARD CIRCUIT
ROOM TEMPERATURE

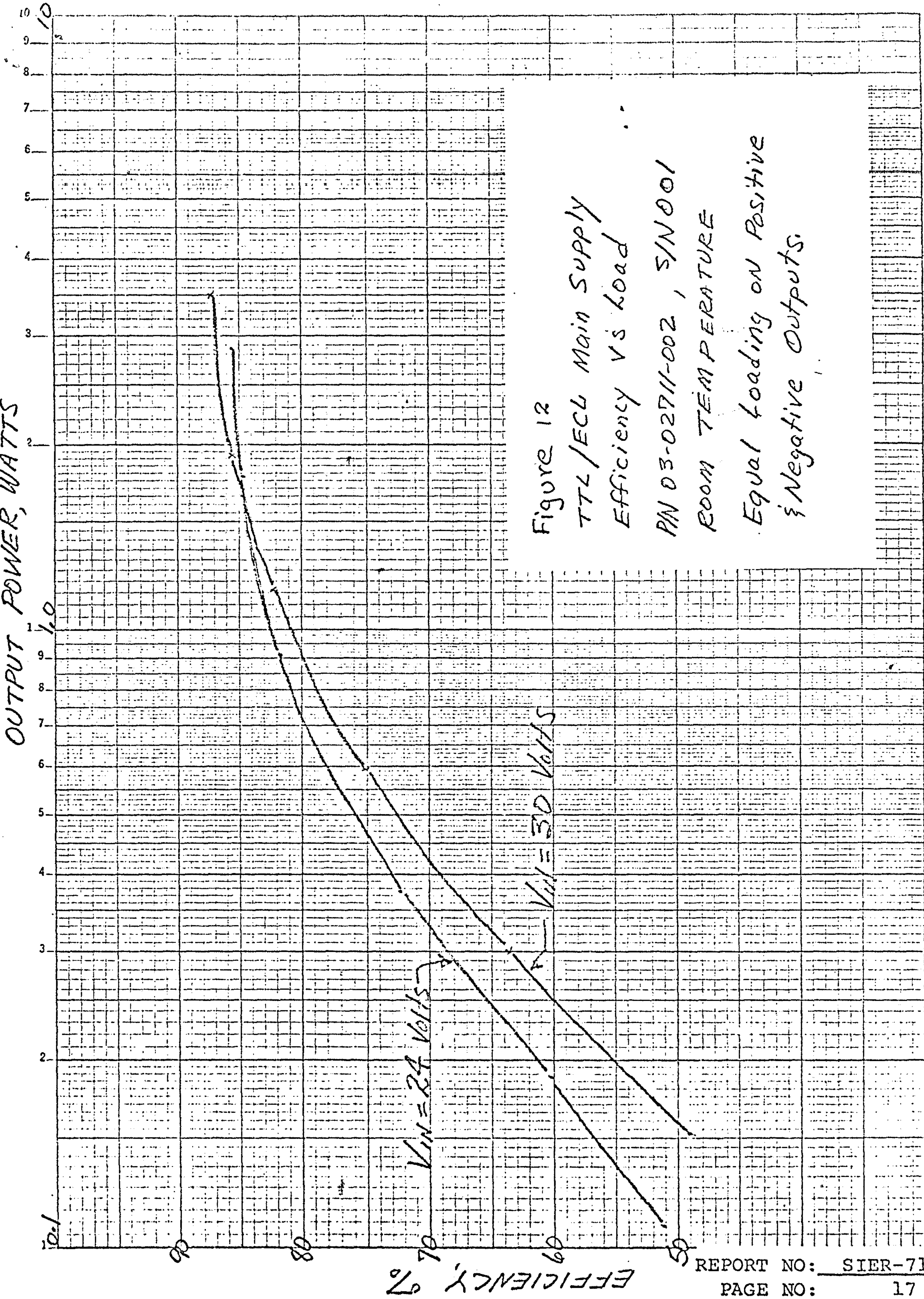
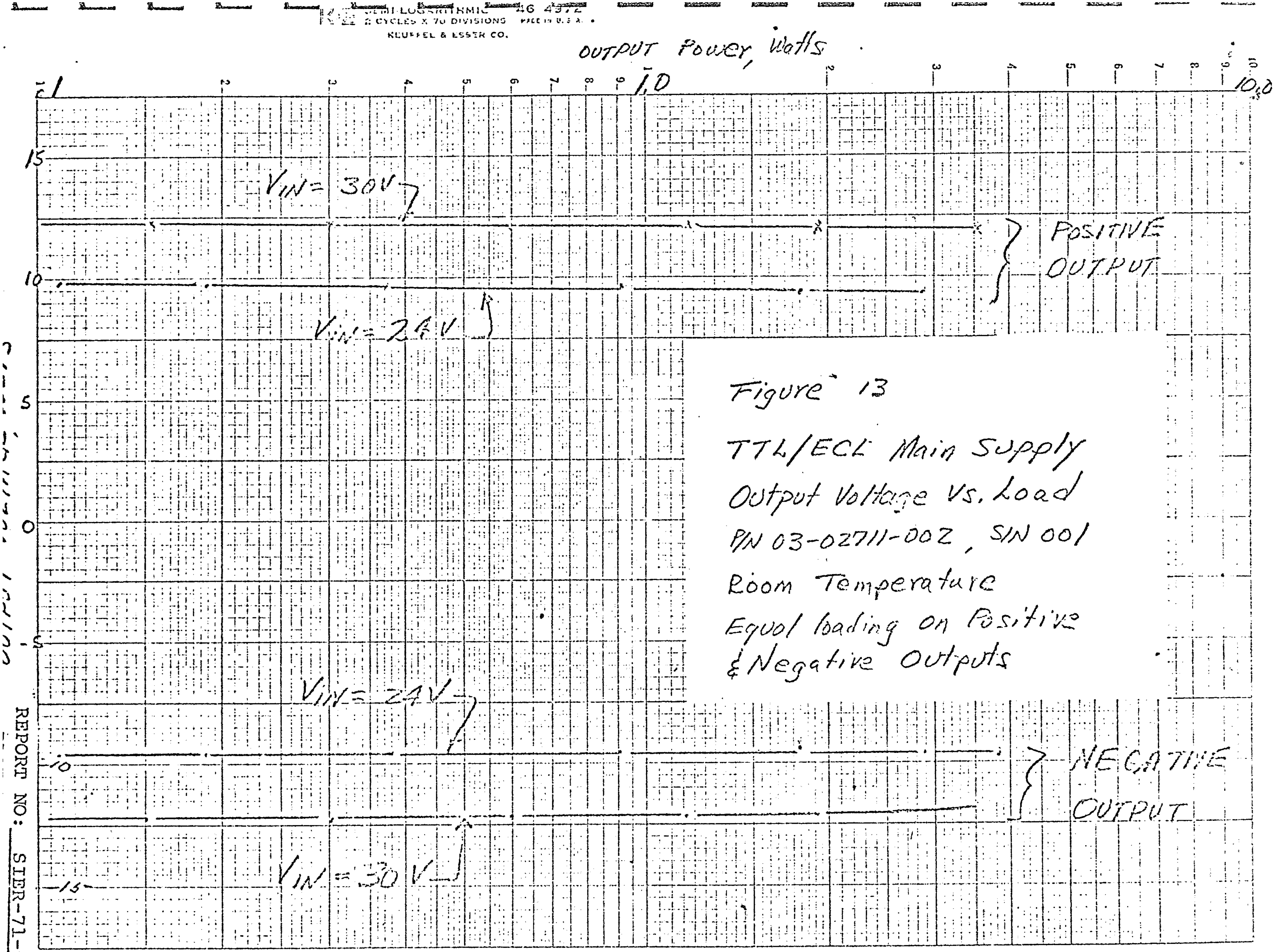


Figure 12
TTL/ECL Main Supply
Efficiency Vs Load
P/N 03-02711-002, S/N001
Room Temperature
Equal Loading on Positive
& Negative Outputs.
OUTPUT POWER, WATTS
EFFICIENCY, %
Vin=24 Volts
Vin=30 Volts
90
80
70
60
50
.1
1.0
10
2 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
MADE IN U.S.A.


SEMI-LOGARITHMIC 46 4972
2 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
OUTPUT POWER, Watts
1
1.0
10.0
15
10
5
0
-5
-10
-15
VIN = 30V
VIN = 24V
POSITIVE OUTPUT
VIN = 24V
VIN = 30V
NEGATIVE OUTPUT
Figure 13
TTL/ECL Main Supply
Output Voltage Vs. Load
P/N 03-02711-002, S/N 001
Room Temperature
Equal loading on Positive
& Negative Outputs

2.4 Main Power Supply Magnetic Components

Descriptions of all the magnetic components used in each of the main power supplies are given in Figure 14.

3.0 REMOTE REGULATORS

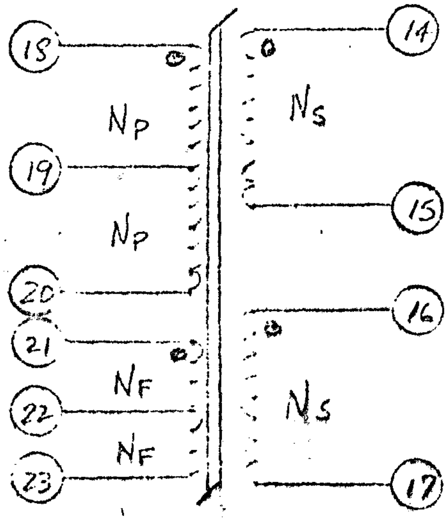
The family of remote regulators developed during this contract and which are described in the following pages have several features in common. All are switching-mode series regulators for maximum efficiency and all are short-circuit proof. Each circuit is constructed on a ceramic substrate using thick film resistors and interconnects. The assembled circuit is enclosed in a solder-sealed flatpack. Prototype units were tested for a leak rate of less than 10^{-6} SCC/SEC however, any future flight hardware circuits will be tested to 10^{-8} SCC/SEC if this leak rate is required.

3.1 TTL Remote Regulator No. 1

The initial circuit developed to supply regulated 5-volt power for TTL logic circuitry did not include overload protection. This circuit was designated as TTL Remote Regulator No. 1. With the exception of the overload protection circuitry, it was similar to the circuit described below.

3.2 TTL Remote Regulator No. 2

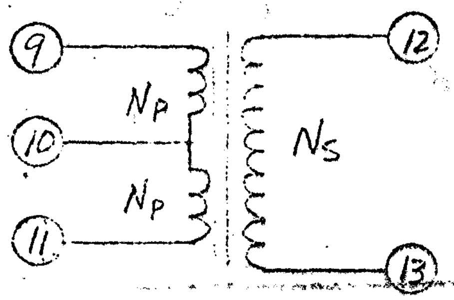
A schematic diagram of the TTL Remote Regulator No. 2 is shown in Figure 15. This circuit provides a regulated output of 5 volts at a load current of up to 100 milliamperes. The input voltage is obtained from the TTL main power supply and varies between 9.0 and 13.0 volts according to the primary input



MAGNETICS, INC. CORE
PART NO. 80517-½D
ALL WINDINGS BIFILAR

	TTL, TTL/ECL	MOS/LINEAR
N_P	100T, #30 AWG	100T, #30 AWG
N_F	10T, #36 AWG	10T, #36 AWG
N_S	43T, #28 AWG	80T, #30 AWG

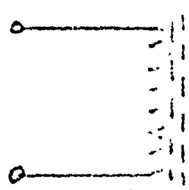
(a) Inverter Transformer, T1



MAGNETICS, INC. CORE
PART NO. D40600

	TTL, TTL/ECL	MOS/LINEAR
N_P	4T, # 28 AWG	8T, #30 AWG
N_S	90T, # 39 AWG	90T, #39 AWG

(b) Current Transformer, T2



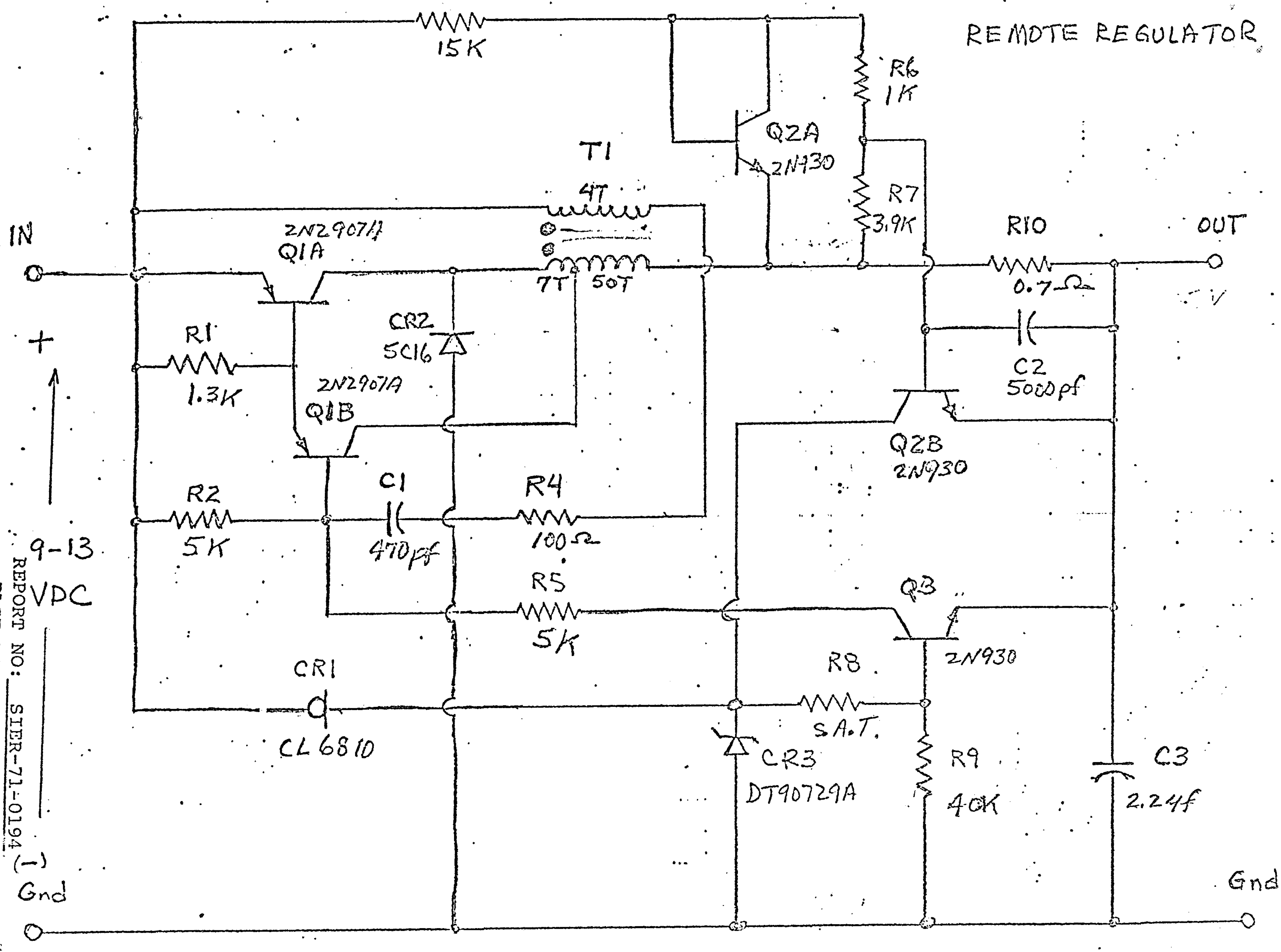
L1, L2, L3 - 43T, #30 AWG, 55016-A2 Core

L4 - 20T, #28 AWG, 55016-A2 CORE

(c) Filter Chokes.

FIGURE 14. MAIN POWER SUPPLY MAGNETICS.

FIGURE 15. TTL. REMOTE REGULATOR



voltage to the main supply. This regulator is protected against overloads on the output and will withstand a short circuit indefinitely without damage.

The circuit shown in Figure 15 is a switching mode series regulator. Operation in the switching mode is mandatory to achieve high efficiency. In this type of circuit, regulation is achieved by modulating the duty cycle of an internally generated pulse waveform so that the average value of the waveform is constant and equal to the desired output voltage. In the circuit of Figure 15, Q3 functions as a comparator which compares the output voltage to a reference voltage established by CR3 and the resistor divider R8 and R9. The output of Q3 controls the driver transistor Q1B which in turn drives the main pass element, Q1A. Switching mode operation is assured due to the phase shift through the loop which results in regenerative operation at the switching frequency. The pulse waveform which exists at the collector of Q1A is averaged by the LC filter comprised of T1 and C3. CR2 is a "free-wheeling" diode which provides a conduction path for the stored energy in T1 while Q1A is non-conducting.

Several features of this circuit result in more efficient operation than would otherwise be practical. Note that the darlington connection of Q1A and Q1B is modified by connecting the collector of Q1B to a tap on the switching choke, T1. This permits Q1A to be driven into saturation thereby decreasing the voltage drop across it and lowering the power dissipation in the pass elements. If the collectors of Q1A and Q1B were common, the voltage drop across the pass element would be considerably greater - approximately 1 volt compared to 0.3 volts. The free-wheeling diode, CR2, is a unit in which the junction is formed by ion-implantation. This results in a diode having a low forward threshold voltage and very fast switching speed. Both these factors contribute toward high efficiency.

The switching speed of the pass transistors has a significant effect on the efficiency of the circuit. In Figure 15, the four-turn secondary winding on the switching choke provides regenerative base drive to Q1B to increase the switching speed and thereby enhance the overall efficiency.

Overload protection is accomplished by sensing the load current via the voltage drop across R10. When the current exceeds a pre-determined level as indicated by the voltage across R10, a "cross-over" point is reached and the circuit functions as a switching mode current regulator instead of a voltage regulator.

The operation of the circuit may be described by referring to Figure 15. A voltage of approximately 0.6 volts (V_{BEA}) developed across the base-emitter junction of Q2A which is biased via the current supplied by R3. A fraction, K, of this voltage is developed across R7. This voltage, KV_{BEA}, plus the voltage across R10, which is proportional to the load current, is applied to the base-emitter junction of Q2B. In equation form we have:

$$V_{BEB} = KV_{BEA} + R10\ I_{LOAD}$$

When the load current is below the maximum level, V_{BEB} is less than the conduction threshold of Q2B and the circuit functions normally as a voltage regulator. As the load current increases, V_{BEB} increases to approximately 0.6 volts at which point Q2B conducts and diverts the current supplied by CR1 from the reference zener diode CR3. This action reduces the reference voltage at the base of Q3 and thus reduces the output voltage. If the load current tends to increase further, Q2B conducts more heavily and the voltage at the base of Q3 is further reduced thereby limiting the load current to a safe level. The limiting current level is given by:

$$I_{LOAD\ MAX} = \frac{V_{BEB} - KV_{BEA}}{R10}$$

where: $K = \frac{R7}{R_6+R_7}$ and V_{BEA}, V_{BEB} are the base-emitter voltages of Q2A and Q2B at the operating current level.

Figures 16, 17 and 18 show the efficiency and load regulation characteristics measured for the breadboard and prototype circuits. Overall circuit performance over the temperature range was very satisfactory.

3.3 MOS Remote Regulator

A schematic diagram of the circuit developed for the MOS remote regulator is shown in Figure 19. This circuit is also a switching mode series regulator. The circuit configuration is slightly different from the TTL remote regulator because of the higher output voltage and the lower current level. Overload protection is incorporated so that a short circuit can be sustained indefinitely without damage.

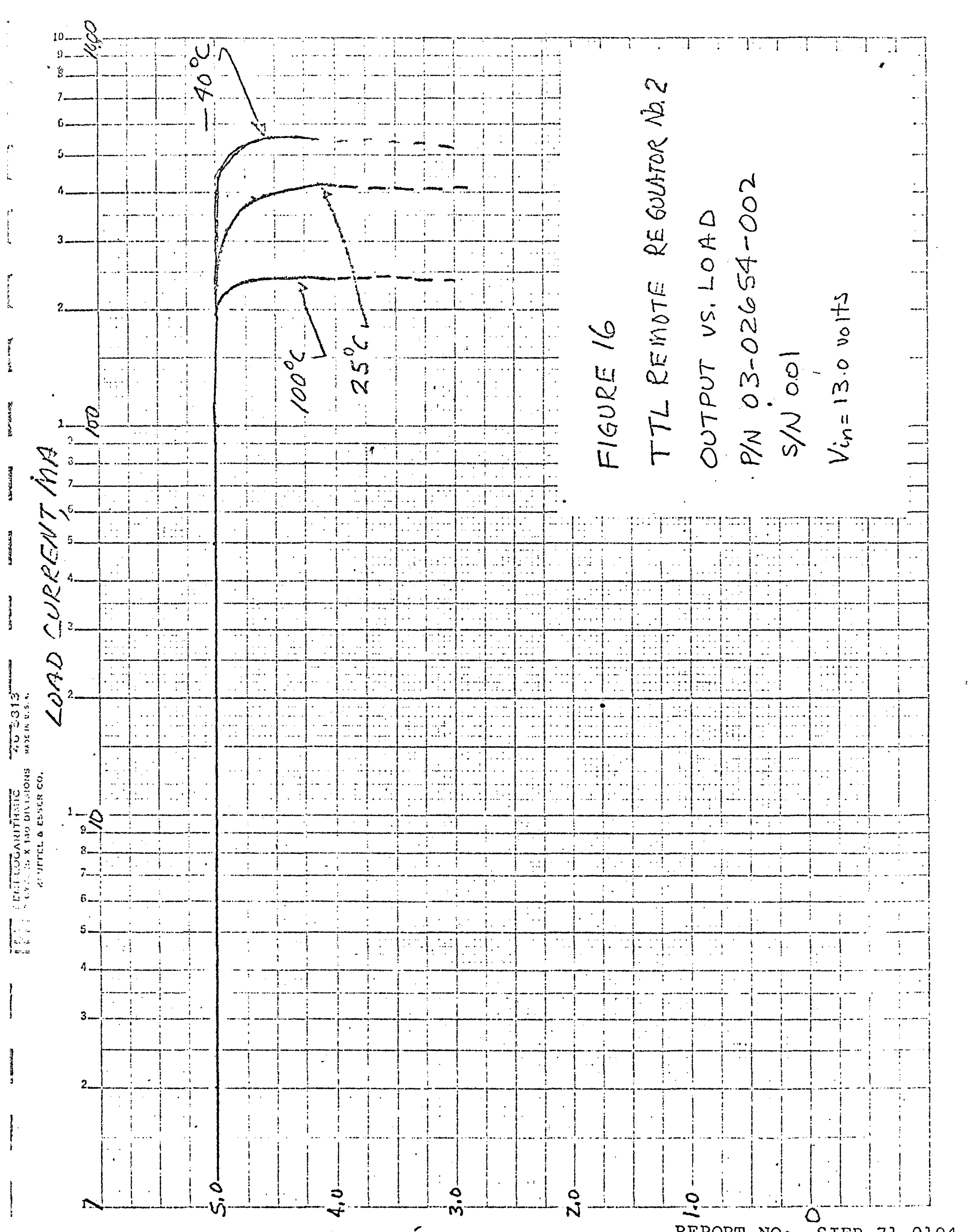


FIGURE 16
TTL REMOTE REGULATOR No. 2
OUTPUT VS. LOAD
P/N 03-02654-002
S/N 001
V_{in} = 13.0 volts
-40°C
25°C
100°C
LOAD CURRENT, MA
OUTPUT VOLTAGE, VOLTS
5.0
4.0
3.0
2.0
1.0
0
1000
100
10

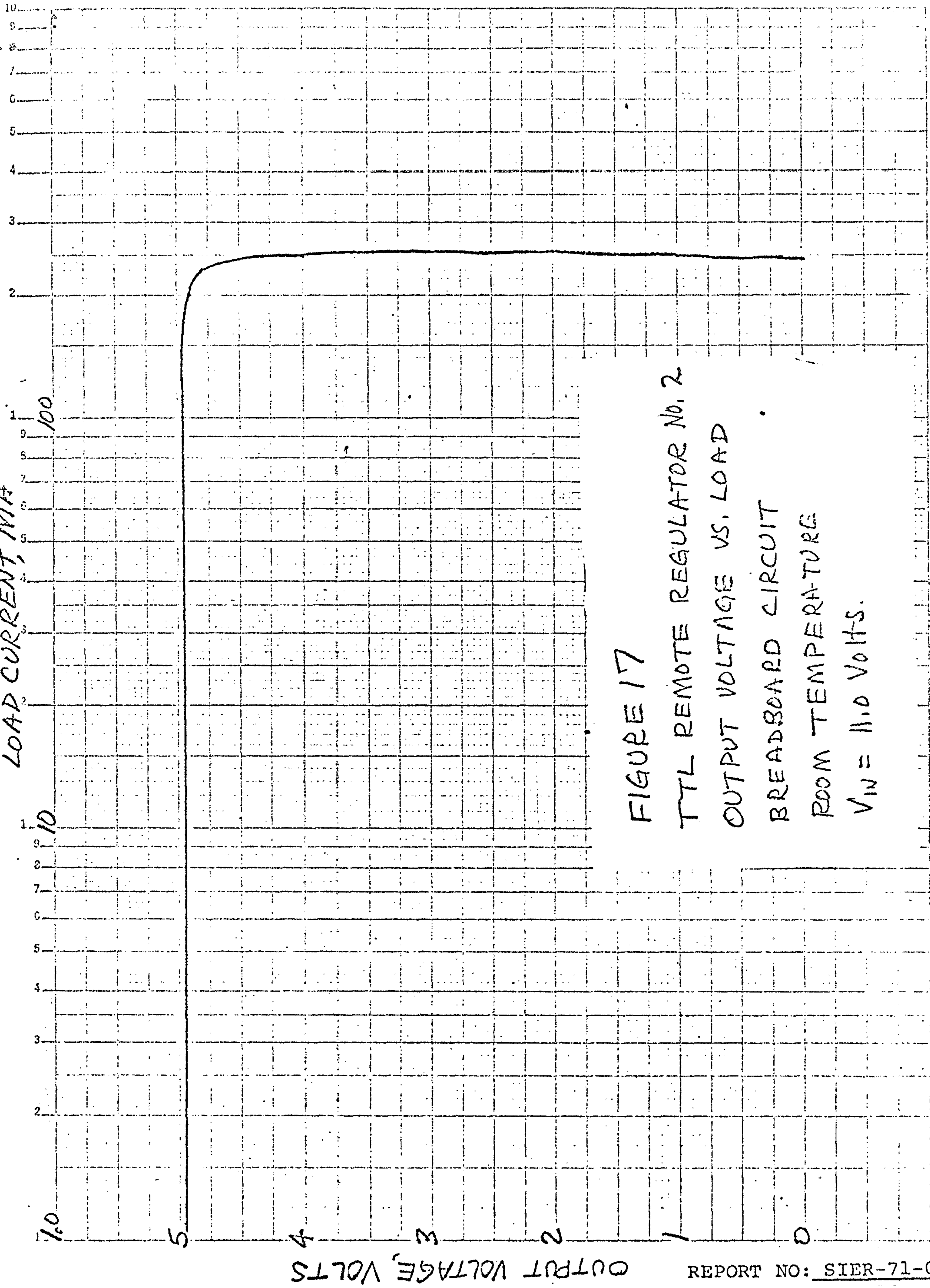


FIGURE 17
TTL REMOTE REGULATOR No. 2
OUTPUT VOLTAGE VS. LOAD
BREADBOARD CIRCUIT
ROOM TEMPERATURE
V_{IN} = 11.0 Volts.

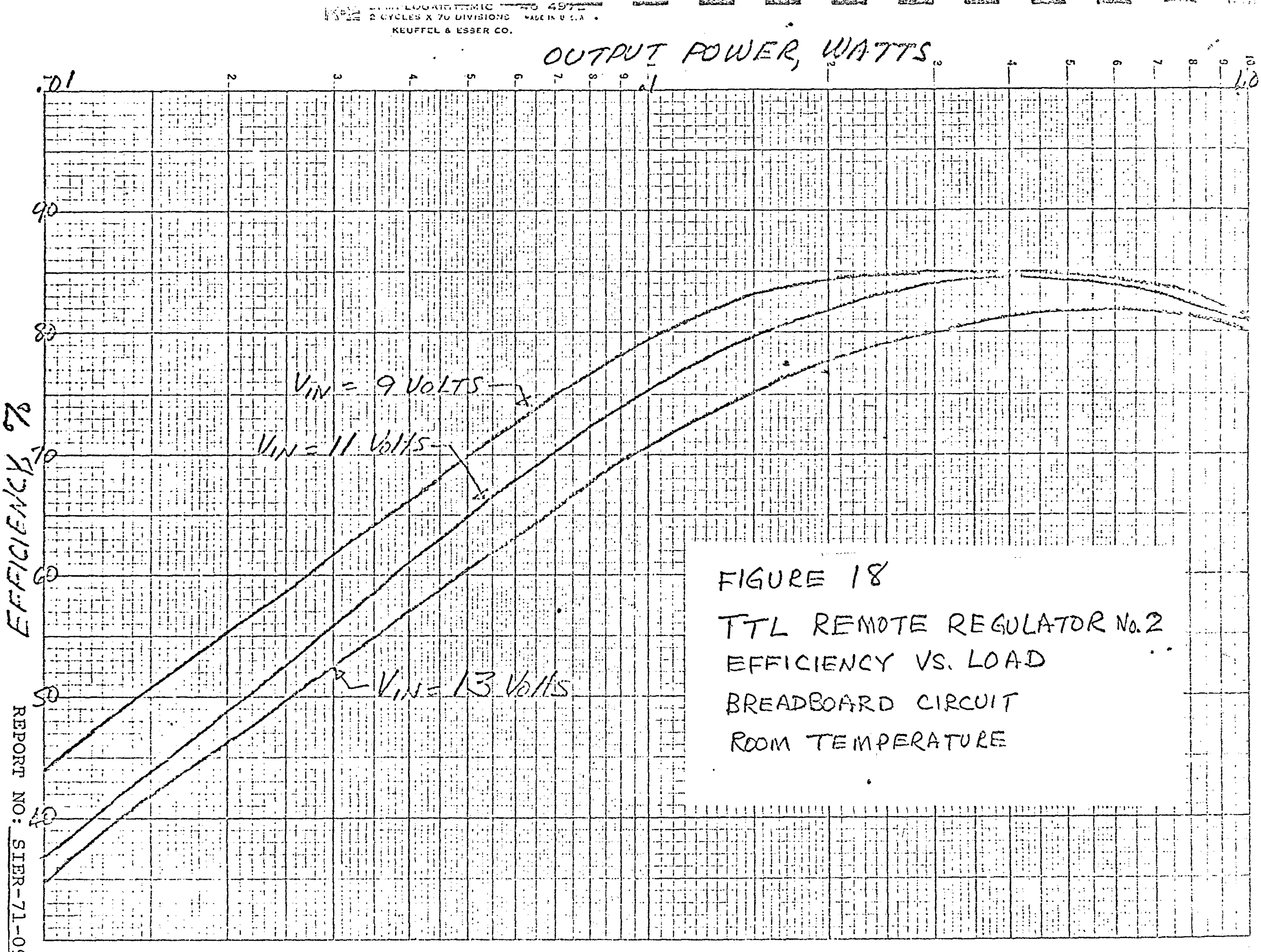


FIGURE 18
TTL REMOTE REGULATOR No. 2
EFFICIENCY VS. LOAD
BREADBOARD CIRCUIT
ROOM TEMPERATURE

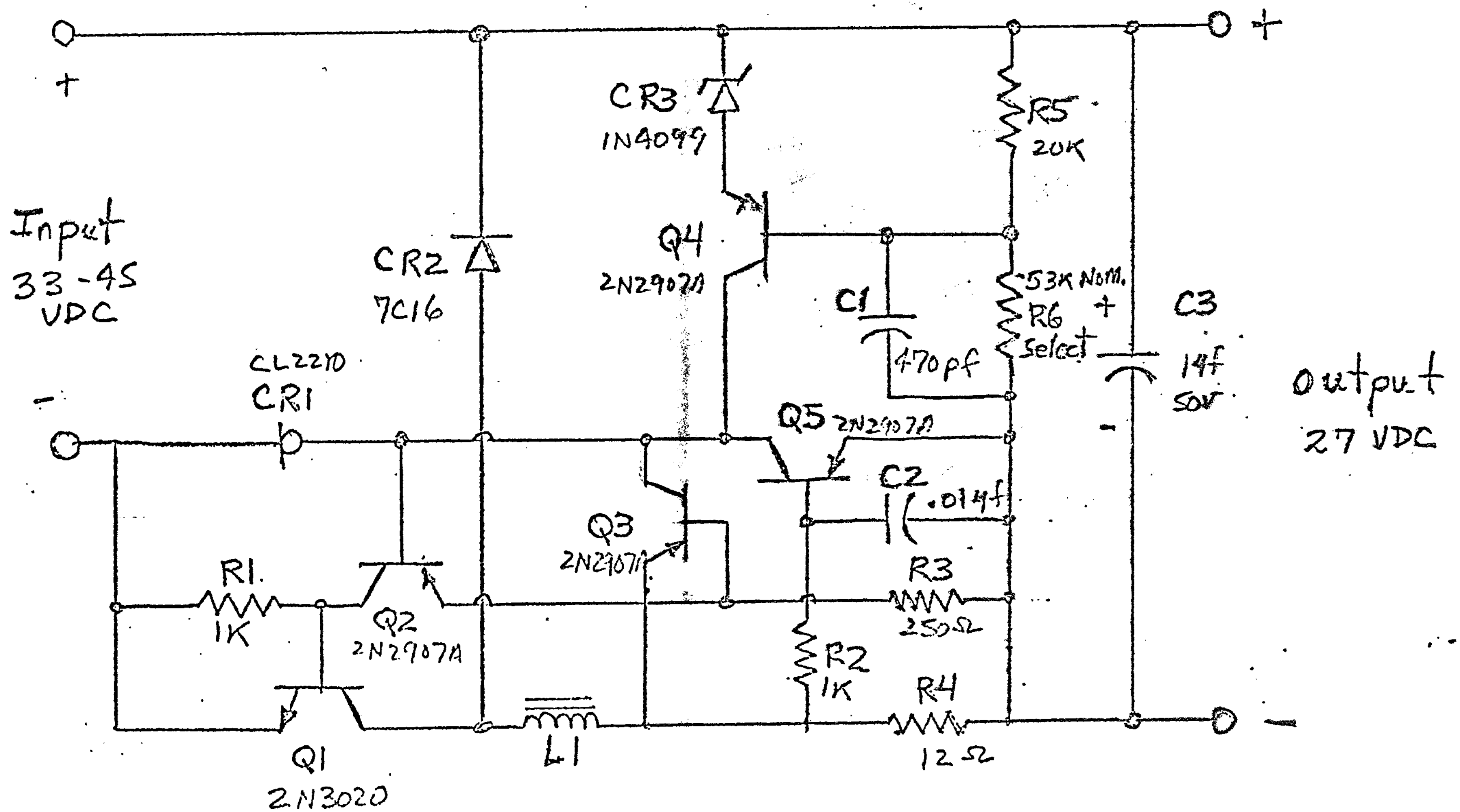


FIGURE 19. MOS Remote Regulator Schematic

In the circuit of Figure 19, the output voltage is compared via the resistor divider formed by R5 and R6 to a reference voltage of approximately 7.4 volts established by CR3 and the base-emitter voltage of Q4. Resistor R6 is selected to compensate for the initial tolerance of zener CR3 and to set the output voltage level at -27 volts. Capacitor C1 provides additional high-frequency feedback which improves the regulation and reduces the output ripple voltage.

Transistor Q4 functions as a comparator amplifier and drives transistor switch Q2 which in turn, drives the main power switch Q1. The emitter current of Q2 and therefore the base current of the main power switch, Q1, is fixed at a level determined by the load current and is virtually independent of the input voltage. This improves the efficiency of the circuit considerably. Referring to Figure 19, it may easily be shown that the emitter current of Q2 is given by the following equation.

$$I_{B1} = I_{E2} = \frac{V_{BE3}}{R3} + \frac{R4}{R3} I_{LOAD} .$$

Short circuit protection is provided by sensing the load current via the voltage developed across R4. When this voltage reaches the conduction threshold of the base-emitter junction of Q5, the circuit functions as a current regulator in much the same manner as described for the TTL remote regulator.

Figures 19 through 22 show, in graphical form, the performance data obtained for both the breadboard and prototype circuits.

3.4 Linear IC Remote Regulator

This circuit must provide two regulated output voltages of ±15 volts to power linear integrated circuits. A schematic

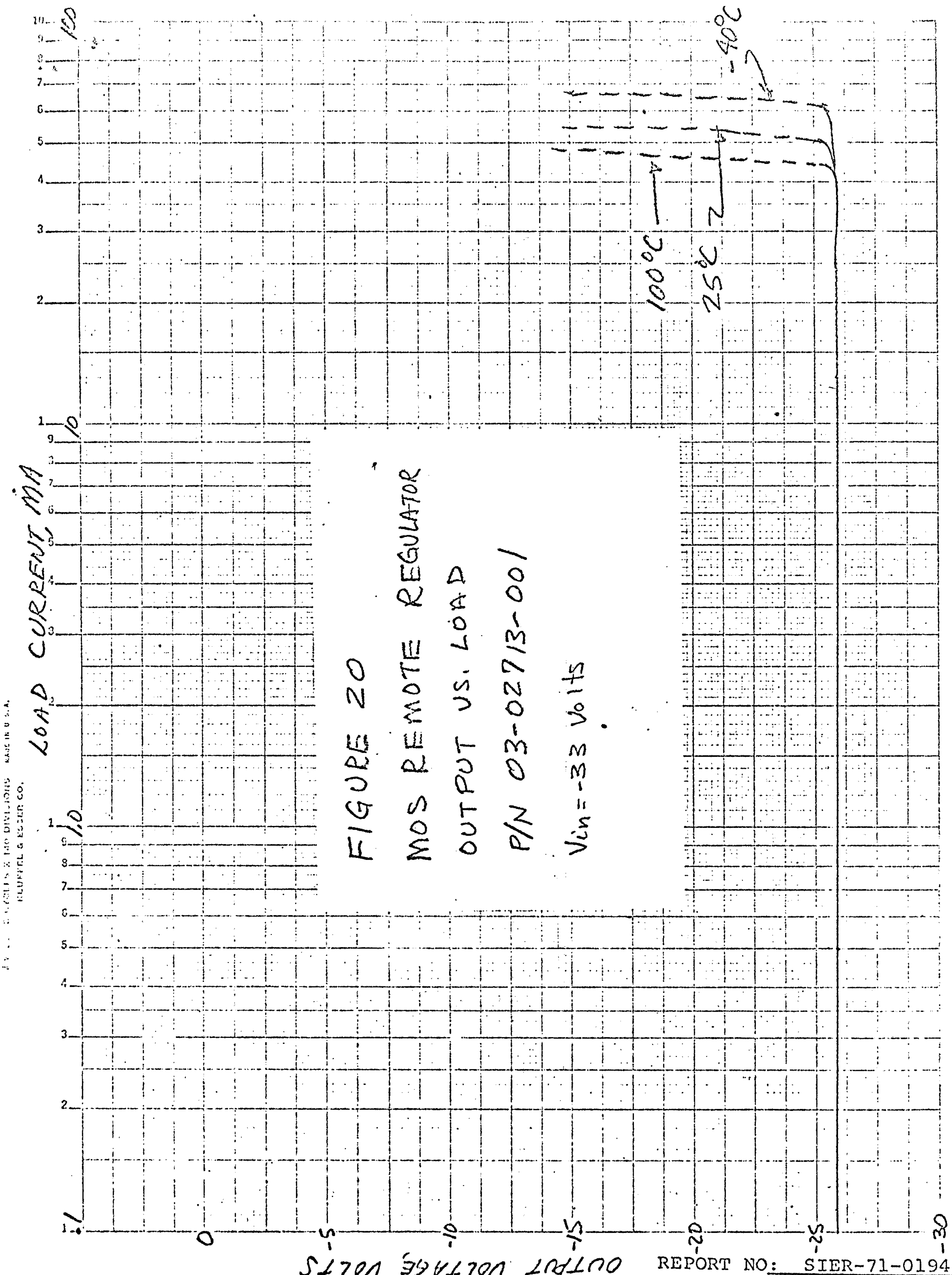


FIGURE 20
MOS REMOTE REGULATOR
OUTPUT VS. LOAD
P/N 03-02713-001
Vin = -33 Volts
LOAD CURRENT, MA
OUTPUT VOLTAGE VOLTS
100°C
25°C
-40°C
0
-5
-10
-15
-20
-25
-30
100
10
1.0
.1

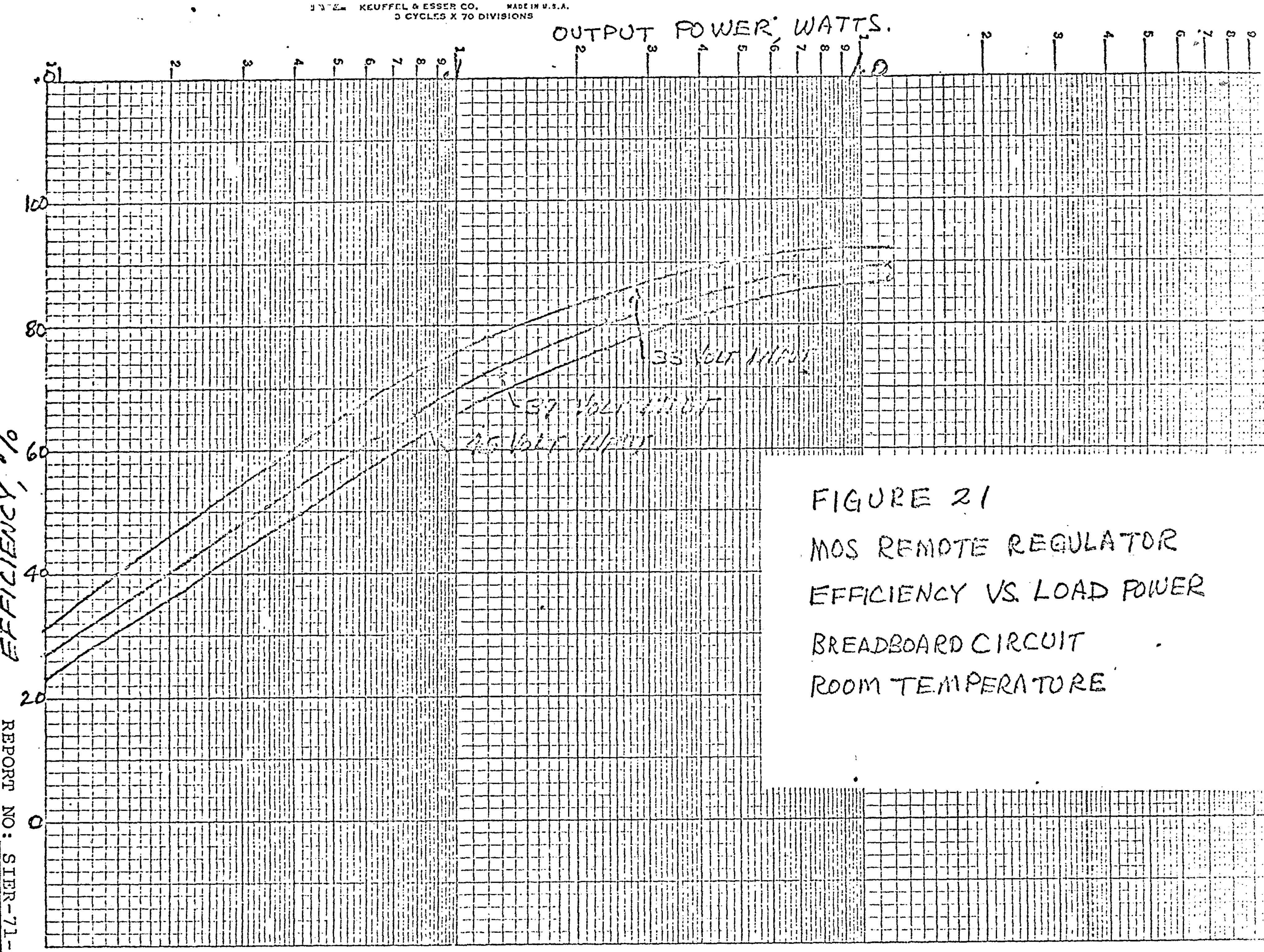


FIGURE 21
MOS REMOTE REGULATOR
EFFICIENCY VS. LOAD POWER
BREADBOARD CIRCUIT
ROOM TEMPERATURE

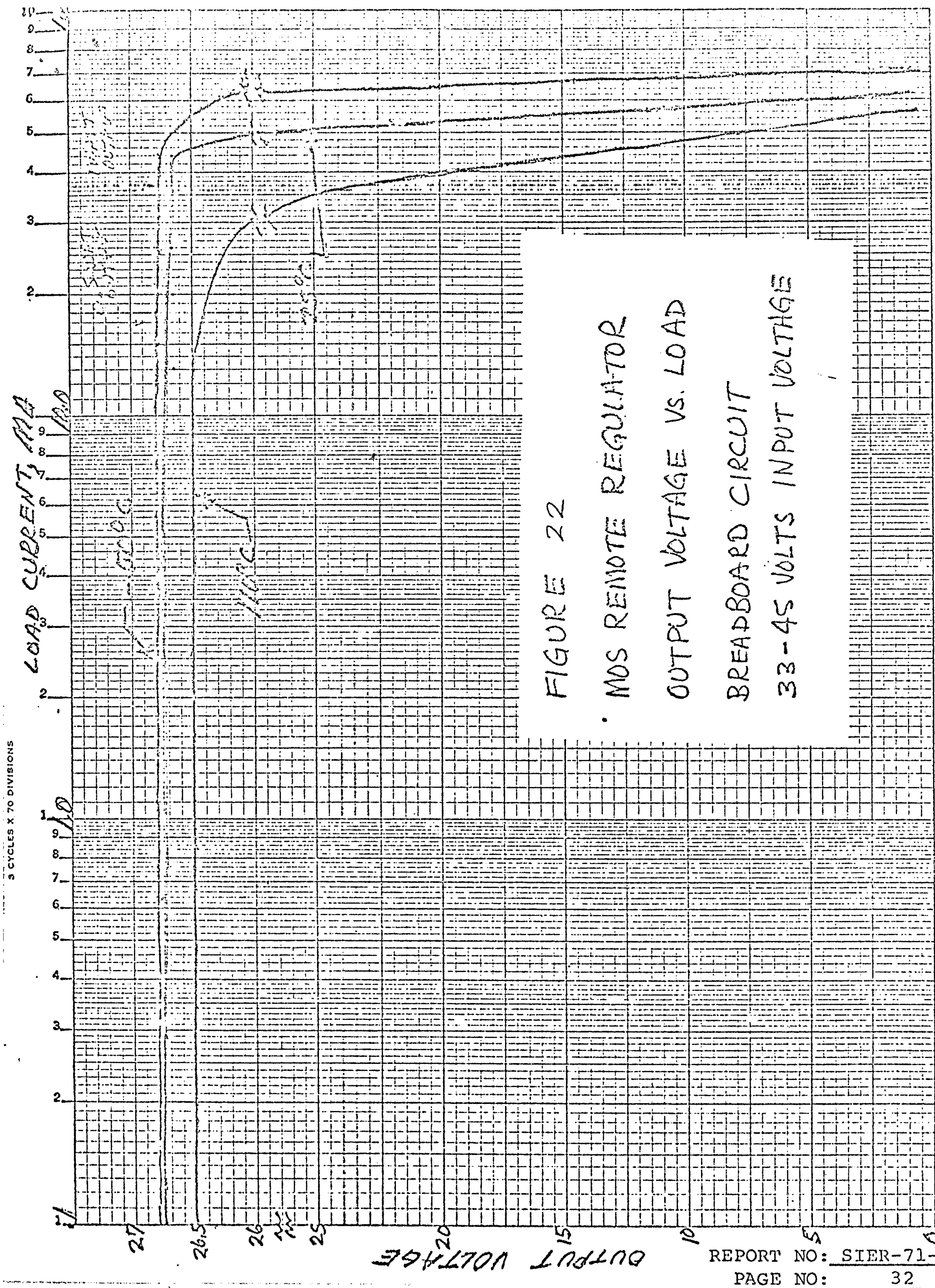


FIGURE 22

MOS REMOTE REGULATOR
OUTPUT VOLTAGE VS. LOAD
BREADBOARD CIRCUIT
33-45 VOLTS INPUT VOLTAGE

of the circuit developed is shown in Figure 23. Since two output voltages are required, two regulators must be used since the supplies may be unequally loaded. Referring to Figure 23, it may be seen that the regulator circuit used to provide -15 volts is identical in configuration to that of the MOS remote regulator. The only difference is the output voltage level. The positive voltage regulator is virtually a mirror image of the negative regulator and functions in the same manner. However, the reference voltage for the positive regulator is derived from the negative output. This feature permits the use of a single zener reference voltage and also permits both output voltages to be adjusted by changing a single resistor, R8. This feature also assures that the output voltage of the positive regulator tracks the output of the negative regulator. For example, if the negative output is shorted, the positive output also approaches zero. However, shorting the positive regulator does not affect the negative regulator.

Test data measured for the linear IC remote regulator is shown in Figures 24,25 and 26. The performance of this circuit in terms of regulation and efficiency is comparable to that obtained for the other remote regulators as can easily be seen by a direct comparison.

3.5 ECL Remote Regulator

The remote regulator developed to supply -5.2 volts for emitter-coupled logic circuits is shown schmatically in Figure 27. This circuit is the complement of the TTL remote regulator which provides +5 volts output. In fact, the same circuit layout is used. The only changes in the assembly of

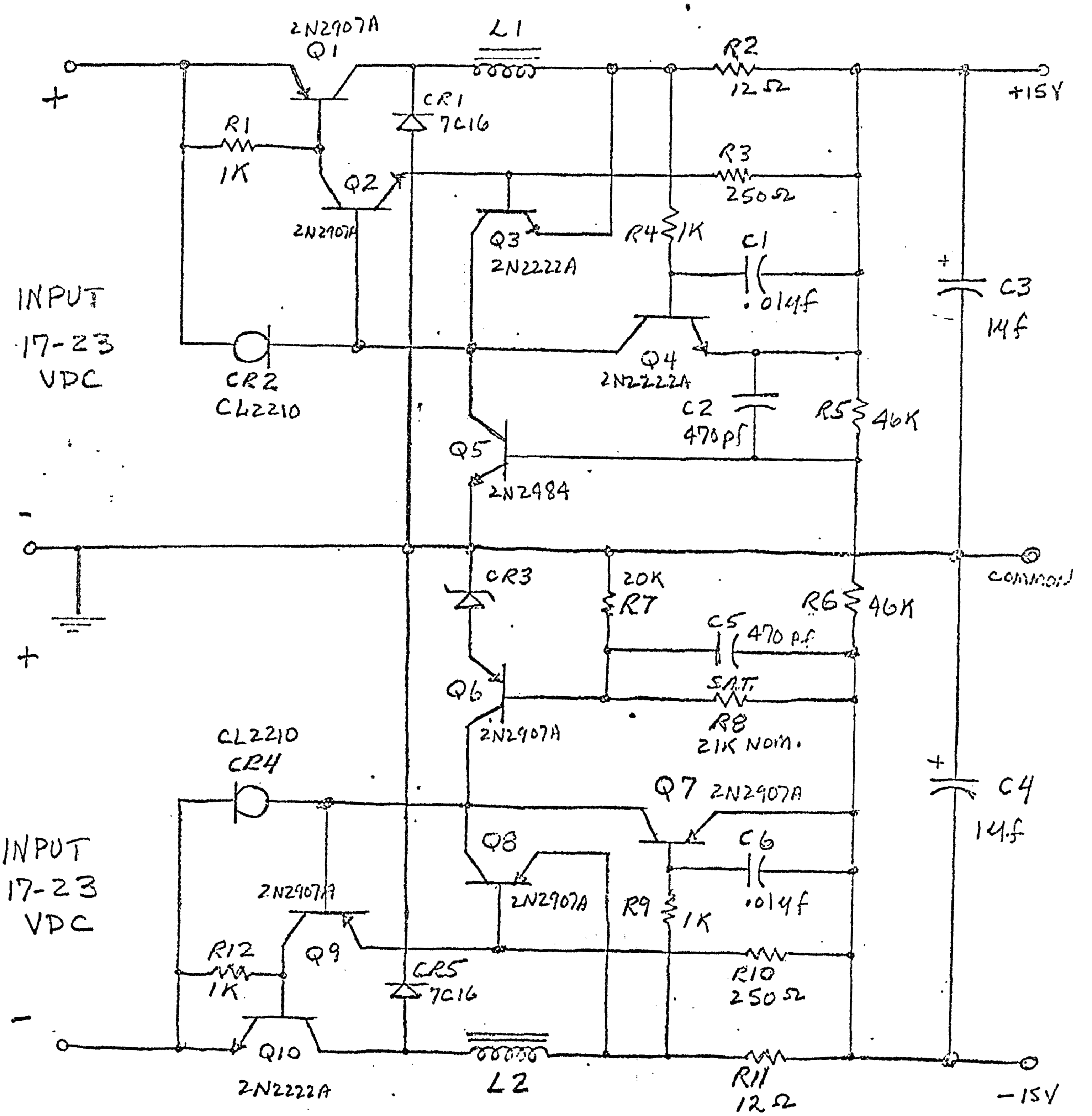


FIGURE 23. LINEAR IC REMOTE REGULATOR

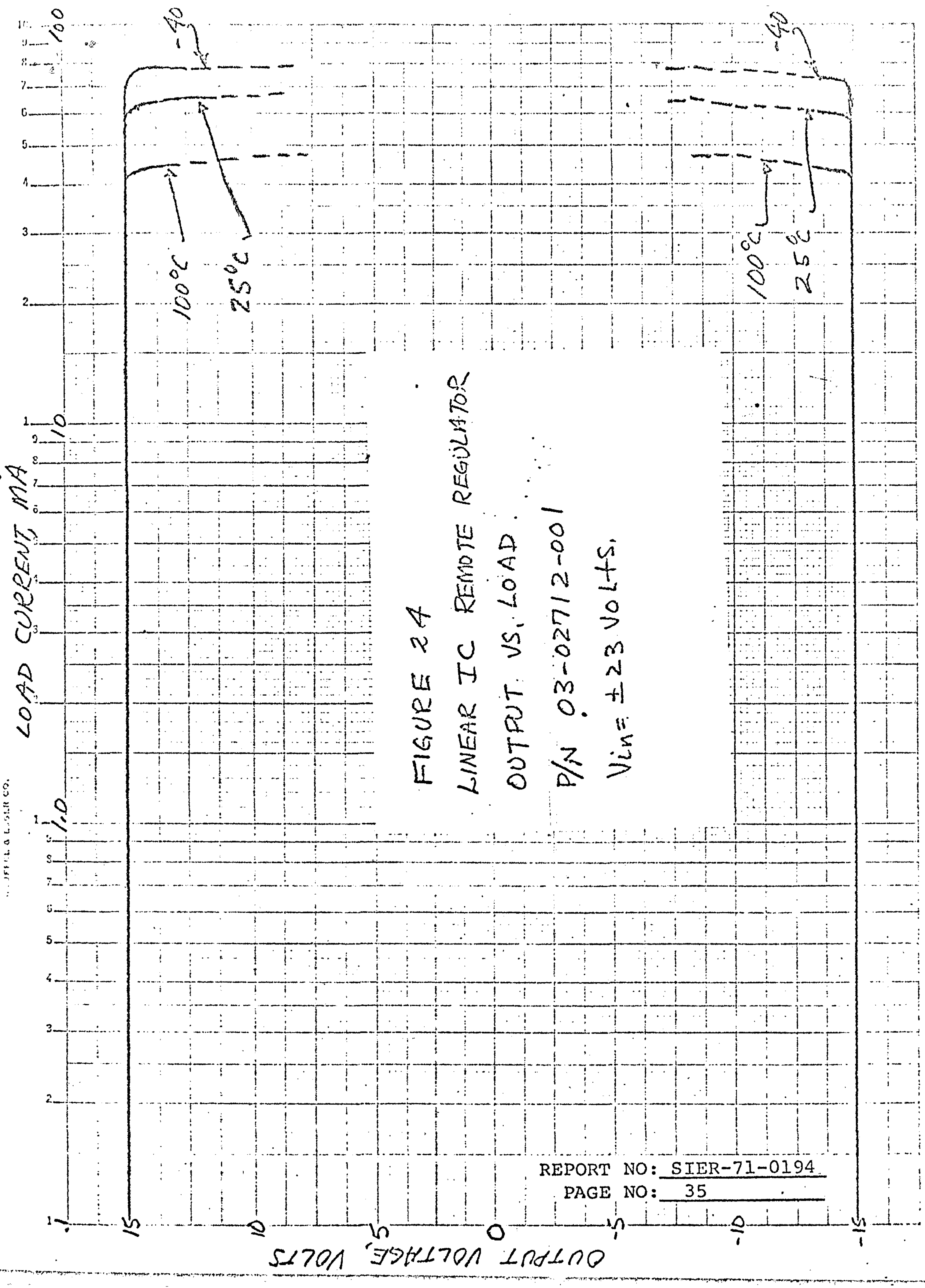


FIGURE 24
LINEAR IC REMOTE REGULATOR
OUTPUT VS. LOAD
P/N 03-02712-001
Vin = ±23 VOLTS.
LOAD CURRENT, MA
OUTPUT VOLTAGE, VOLTS
100
10
1.0
.1
-40
25°C
100°C
15
10
5
0
-5
-10
-15

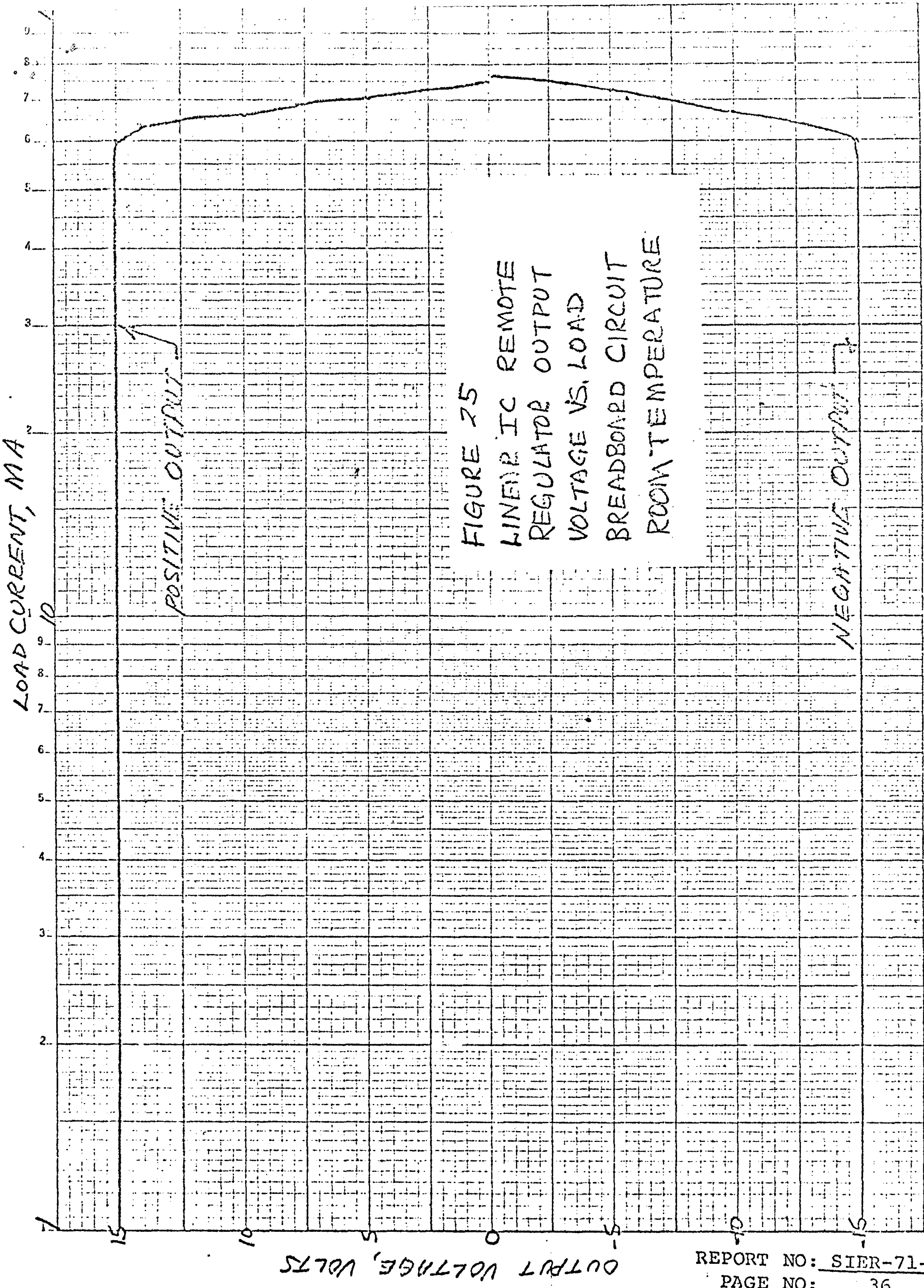


FIGURE 25
LINEAR IC REMOTE REGULATOR OUTPUT VOLTAGE VS. LOAD
BREADBOARD CIRCUIT
ROOM TEMPERATURE

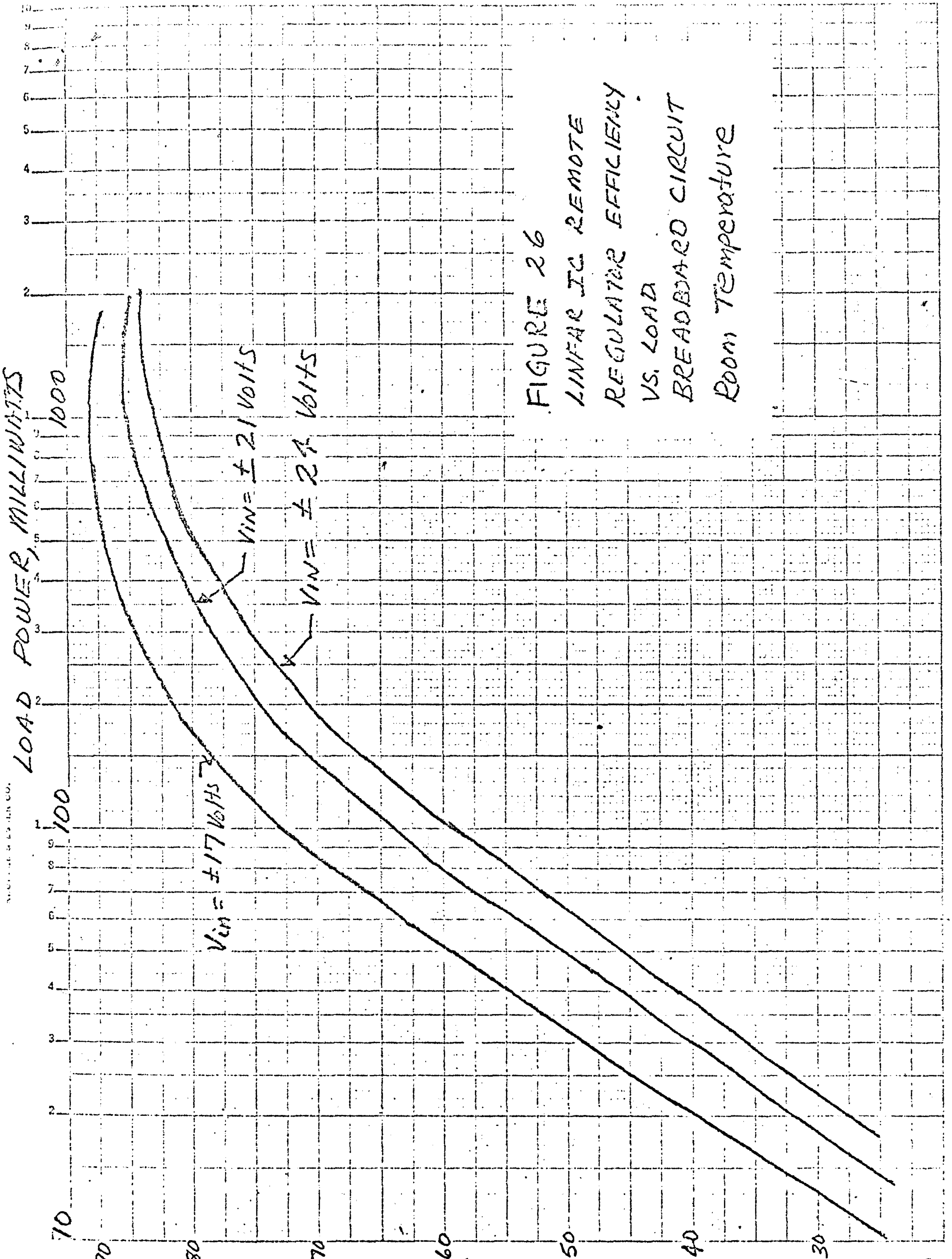


FIGURE 26
LINEAR IC REMOTE REGULATOR EFFICIENCY VS. LOAD
BREADBOARD CIRCUIT
Room Temperature

the circuit are that diode and capacitor polarities are reversed and complementary transistors are used.

The operation of the ECL remote regulator is identical to that described for the TTL remote regulator. Test data measured for this circuit is shown in Figures 28 through 30.

3.6 Remote Regulator Magnetics

A description of the switching chokes used in the remote regulators is given in Figure 31.

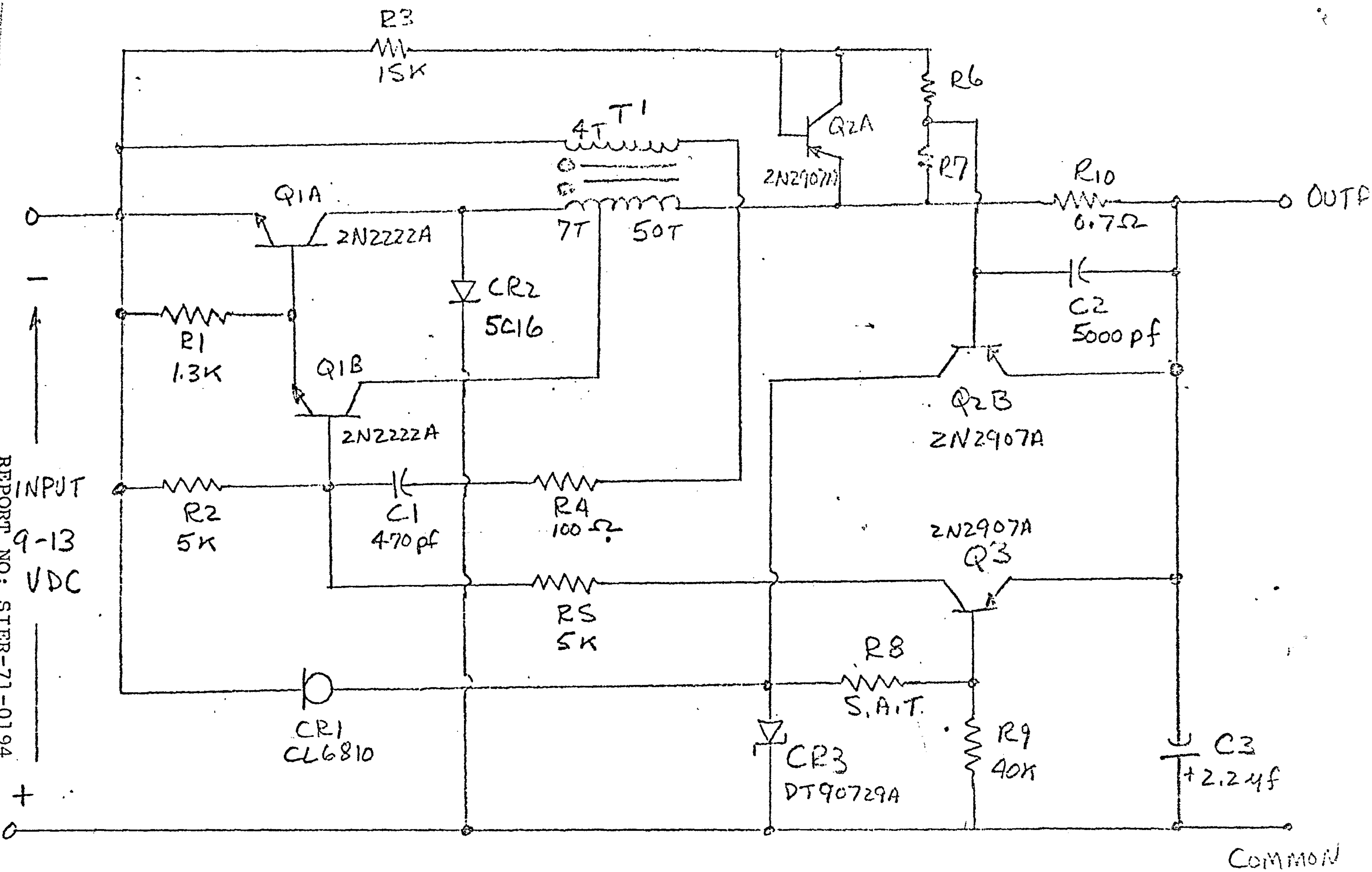


FIGURE 27. ECL REMOTE REGULATOR

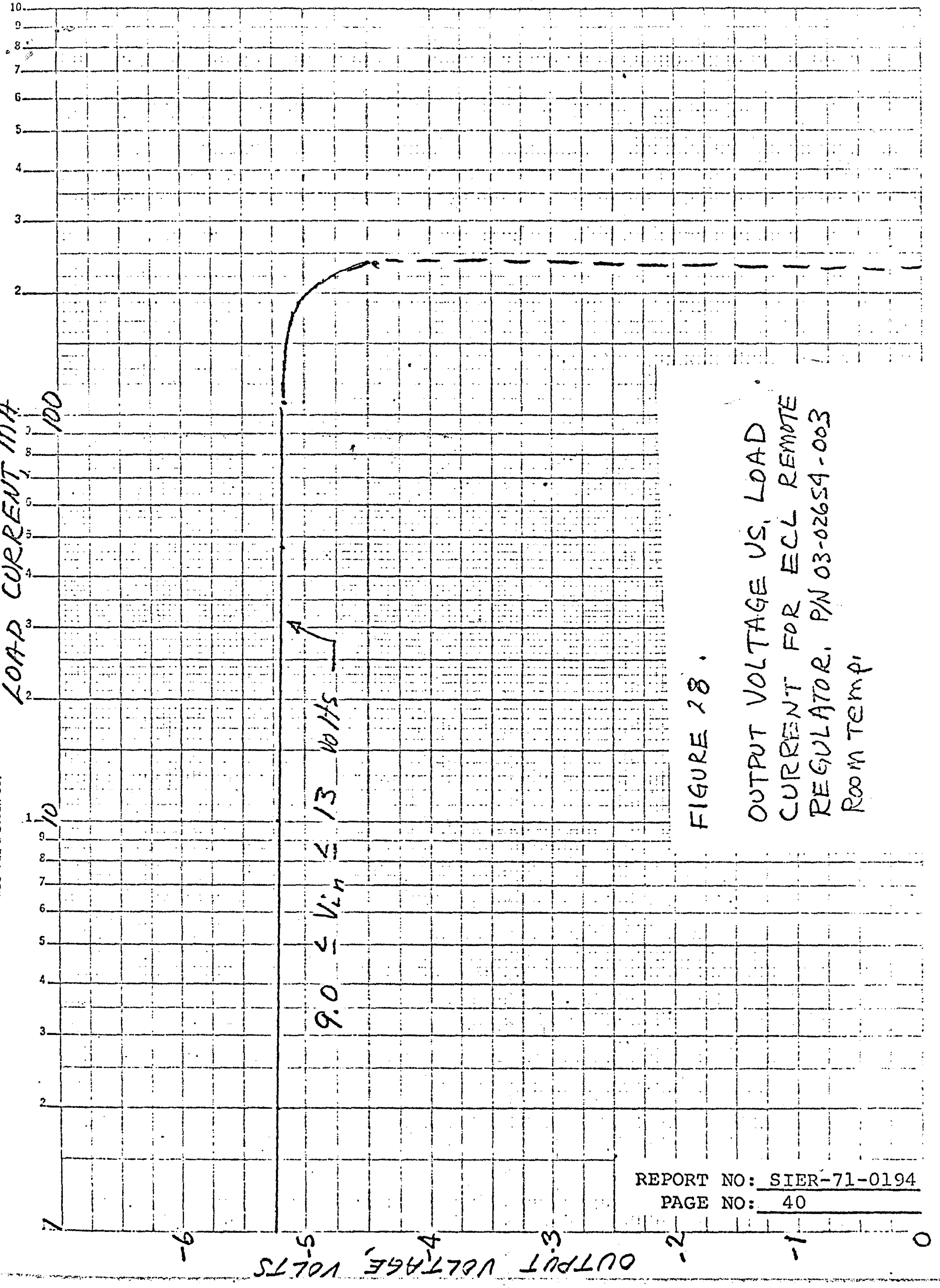


FIGURE 28. OUTPUT VOLTAGE VS. LOAD CURRENT FOR ECL REMOTE REGULATOR. P/N 03-02659-003 Room Temp.

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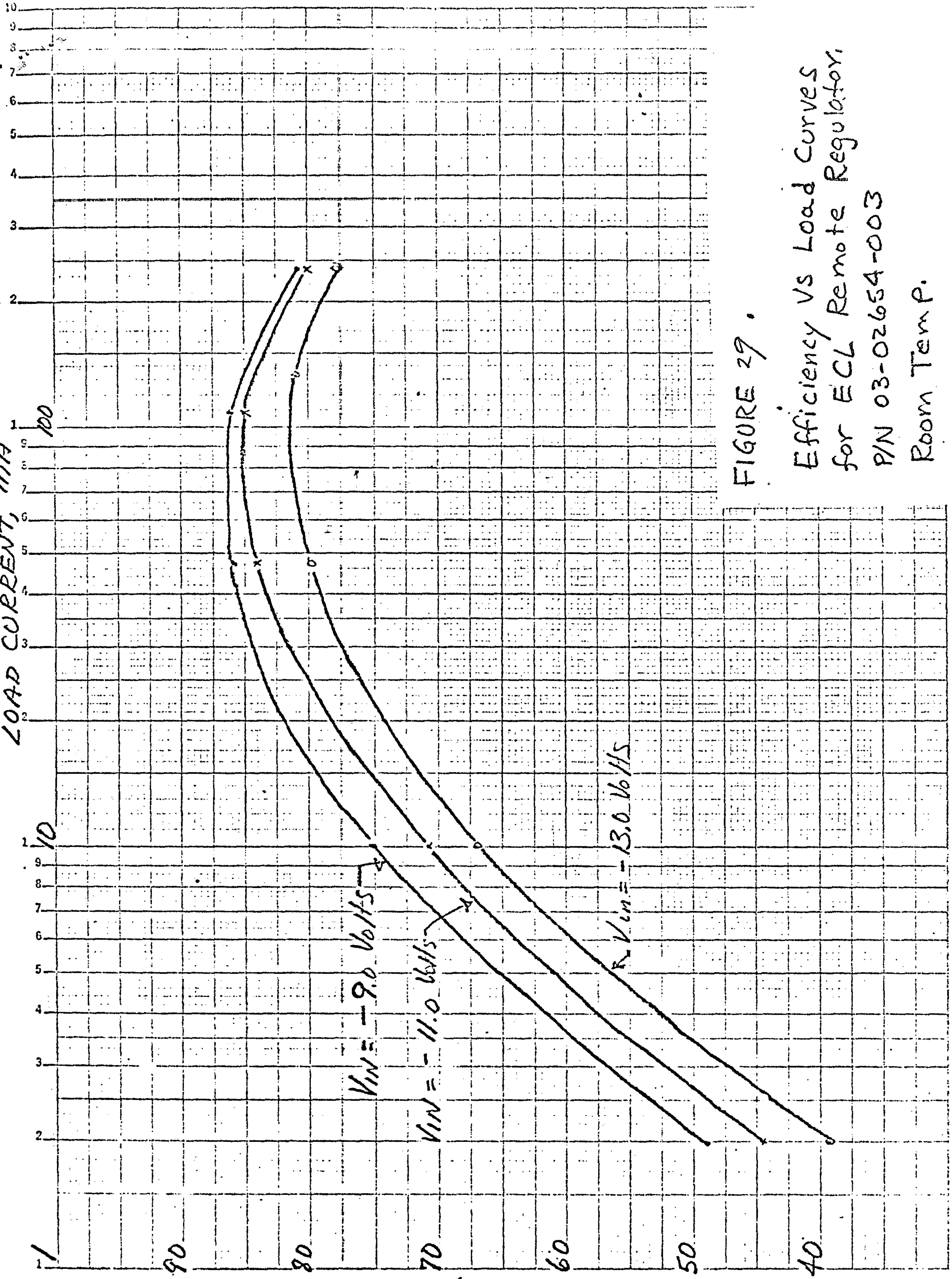


FIGURE 29.
Efficiency Vs Load Curves
for ECL Remote Regulator,
P/N 03-02654-003
Room Temp.

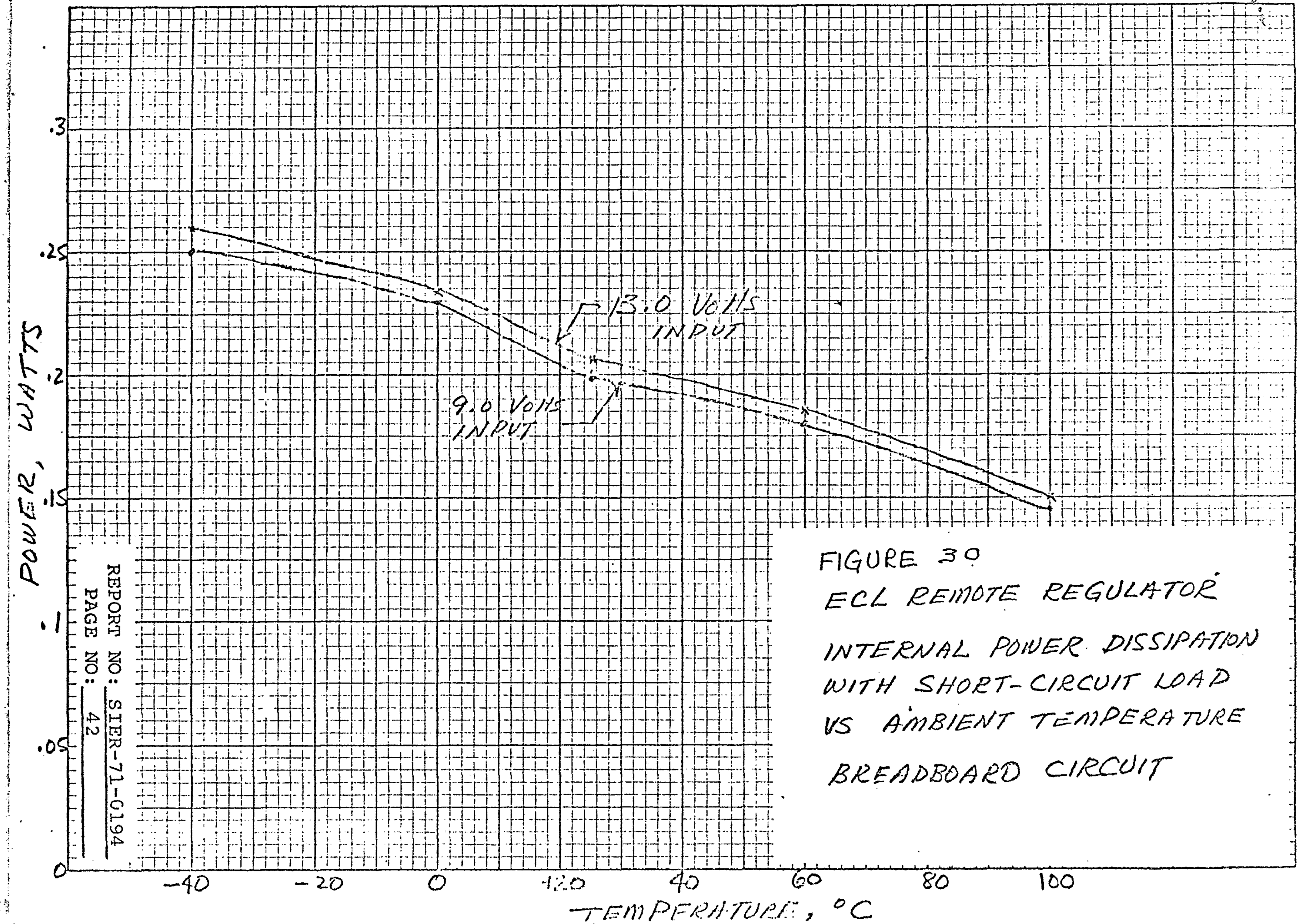
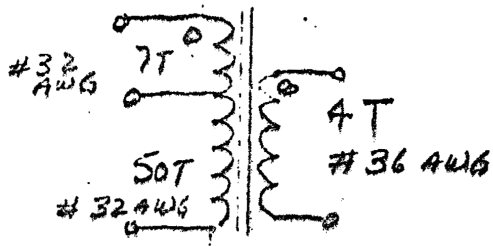
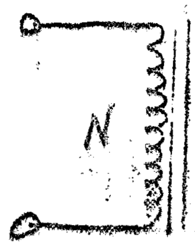


FIGURE 30
ECL REMOTE REGULATOR
INTERNAL POWER DISSIPATION WITH SHORT-CIRCUIT LOAD VS AMBIENT TEMPERATURE
BREADBOARD CIRCUIT



CORE: MAGNETICS INC
PART NO. 550.5-A2

(a) Switching transformer used on TTL REMOTE REGULATOR and on ECL Remote Regulator.



CORE: Magnetics, INC.
Part No. 55015-A2

Linear Remote Regulator	L1, L2	95T, #34 AWG
MOS Remote	L1	95T, #36 AWG

(b) Switching Chokes for MOS, Linear Remote Regulators.

Figure 31. Magnetic Components Used in Remote Regulators.