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Simplified Power Supplies for Ion Thrusters

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SIMPLIFIED POWER SUPPLIES FOR ION THRUSTERS

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ABSTRACT

A program addressing less complex and potentially lower cost ion thruster systems has been started at the NASA Lewis Research Center. This paper discusses the initial development and demonstration of power supplies with an order of magnitude reduction in parts count, leading to increased reliability at lower weight, while still maintaining thrust system performance. Two new self-regulating keeper power supply circuits were developed and tested. One supply comprises 14 parts and uses an input voltage range of 18 to 36 volts, the other operates from 200 to 400 volts and requires 22 components. A new technique for controlling heater power is also demonstrated.

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INTRODUCTION

Power processors for both 8 and 30 cm diameter mercury (Hg) ion thruster systems[1,2,3] were designed to thruster requirements specified in the early 1970's.[1,3] The 30 cm Hg ion thruster requirements were specified to accommodate a broad spectrum of electric propulsion missions which had significantly different thruster operating requirements. The resultant power processor allowed great flexibility in thruster operation but at a cost of power processor complexity. For example, 3 percent regulation specifications for the screen supply required closed-loop regulation techniques. Specified load characteristics of both the 8 and 30-cm diameter Hg ion thrusters were based on the assumption that conventional closed-loop control techniques would be used for current and voltage regulation. The effect of other specifications on power processors is discussed in Ref. 4.

A program addressing less complex and potentially lower cost ion thruster systems has been started at the NASA Lewis Research Center. The initial effort which reduced the number of power supplies necessary to operate a 30-cm diameter Hg ion thruster was reported in Ref. 5. Continuation of this effort is discussed in a companion paper.[6]

Relaxing regulation tolerances and redefining required thruster load profiles expands the range of circuit techniques that can be evaluated for the purpose of using simpler circuits.

The beam supply could be simplified by solar array direct drive techniques.[7] Simple solar array maximum power tracking could be incorporated to further enhance system performance.[8] However, mission planners would need to accommodate variable thrust and specific impulse during the time that maximum power tracking would be used. No assessment has been made of the mission performance resulting from relaxed thrust system requirements, however, it is believed that the benefits of greatly simplified hardware warrant an examination of mission performance versus system complexity.

The work reported in this paper is the initial development of new power supplies with an order of magnitude reduction in parts count leading to lower weight while maintining thrust system performance.

The low power supplies required for thruster keepers and heaters provide the best opportunities for simplification. In the 30-cm diameter Hg ion thruster system the low power supplies account for approximately half of the power processor components while handling less than 4 percent of the thruster power (run condition at full power). There are about 1650 parts for the nine low power supplies. This parts count includes redundant control circuits and the multiple inverter power stage and excludes telemetry, set point and compensation circuits and input filter.(9)

Of the low power supplies, the keepers have the most unique requirements and were therefore chosen as the first supplies to be developed and demonstrated.

A development approach was taken that exploits modified thruster requirements, especially relaxed regulation, to achieve low parts count. This approach uses a variable frequency versus input voltage for self regulation. Design equations are developed and detailed designs are discussed for the main and neutralizer keeper supplies of a 30-cm diameter Hg ion thruster. Test results are compared to the design equations. Testing of both supplies with a 30-cm diameter Hg ion thruster is also described. In addition a new single-stage power supply technique for supply and control of heater power is demonstrated.

KEEPER SUPPLY REQUIREMENTS

Neutralizer and cathode keeper supplies are required for both the 8- and 30-cm diameter Hg ion thrusters as well as some inert gas thrusters. Ion thruster keeper loads have a unique requirement for an ignition potential greater than operating potential.(10) A typical keeper discharge characteristic is shown in Fig. 1. Points a, c, and e are stable operating points for the discharge. Points b and d are unstable. For the 30-cm diameter Hg ion thruster point e is the desired operating point. It is desirable to avoid operation at stable points a and c.(11) This can be accomplished either by using a very high voltage together with a high series resistance or a voltage greater than 50 volts(6,11) and a variable low impedance load line as shown in Fig. 1.

A summary of the 30-cm diameter Hg ion thruster relaxed requirements for the cathode keeper supply is given in table 1. The input voltage was assumed to vary over a 2:1 range. Input power could be supplied from the standard unregulated 28-volt spacecraft bus which is bracketed by the 18- to 36-volt range chosen. Alternatively it may be desirable to power the thruster power supplies from a dedicated unregulated high-voltage bus. Based on earlier work, a voltage range of 200 to 400 volts was chosen to represent that option.(9) The cathode keeper has requirements similar to that required for the neutralizer keeper supply which was developed for an input voltage range of from 200 to 400 volts. For the purpose of this effort it was unnecessary to also develop a cathode keeper supply for the 200 to 400 volt range.

A summary of the 30-cm diameter Hg ion thruster requirements for the neutralizer keeper supply is given in table 2. Since the neutralizer keeper load is the same type as the cathode keeper, the requirements are almost the same. However, the neutralizer keeper requires higher current and voltage.

DEVELOPMENT APPROACH

A development approach was taken that exploited modified thruster requirements, especially relaxed regulation to achieve low parts count. A key to low parts count is the elimination of active voltage limiting as well as the closed loop current control used in conventional thruster keeper power supplies. In addition, exclusion of multiple series stages of regulation and power conversion between the input power and output power to the thruster leads to reduced complexity. A single power stage is used for either input voltage range.

Further simplification is achieved through the use of dual-role components. A combined transformer-inductor and power MOSFET transistors with their intrinsic anti-parallel diodes are used. Transformer leakage inductance has been used in the past for current limiting.[12]

Two new self-regulating circuits were developed to meet the keeper supply requirements. Both circuits use a modified Jensen[13] power oscillator. The ocillator frequency is directly proportional to the input voltage. The power oscillator transformer for both circuits is designed with a pre-determined leakage inductance. Since leakage inductance current is reduced as frequency increases, output current going through the leakage inductance is automatically reduced as the oscillator frequency is increased. This interaction results in a first-order correction of the increase in output current due to increased input voltage. Short circuit current is virtually constant over the 2:1 input voltage range. The cathode keeper circuit uses a parallel converter power oscillator for 18 to 36 volts input and the neutralizer keeper supply incorporates a full bridge power oscillator to accommodate a 200 to 400 volt input. Closed-loop regulation techniques using variable frequency are discussed in Refs. 14 and 15. The author could find no relationships describing the interaction of a variable frequency, variable voltage square wave with a series inductor and rectifier, so new relationships were developed.

An expression was derived for the power supply load characteristic. This expression results from the following fundamental relationships:

(1) The voltage-current relationships for the linear leakage inductance:

$$e = L \frac{di}{dt} \tag{1}$$

where e is the instantaneous inductor voltage, L is the leakage inductance in henrys reflected to the transformer secondary, and di/dt is the rate of change of inductor current in amperes per second.

(2) The voltage across the leakage inductance when the transformer primary voltage is positive with respect to the transformer secondary voltage;

$$e = nV_{in} - V_L \tag{2}$$

where n is the transformer secondary to primary turns ratio, V_{in} is the input voltage, and V_L is the load voltage including rectifier diode volt age drop. When the transformer primary voltage is negative with respect to the transformer secondary voltage;

$$-e = nV_{in} + V_L \tag{3}$$

(3) For steady-state operation, the leakage inductance volt second integral equals zero.

(4) The average output current, I_L, is equal to one half the value of the peak current.

The resulting expression for load voltage versus load current is:

$$V_L = nV_{in}\left(1 - \frac{I_L}{I_{SC}}\right)^{1/2} \tag{4}$$

where the short circuit current is:

$$I_{SC} = \frac{nV_{in}}{8fL} \tag{5}$$

and f is the oscillator frequency in Hz corresponding to the particular V_{in} used since

$$\frac{V_{in}}{f} = \text{a constant} \tag{6}$$

Another design equation is the transformer equation resulting from Faraday's induction law.[16]

$$N_S = \frac{nV_{in} \quad 10^8}{4fA_cB_{max}} \tag{7}$$

where N_S is the number of turns in the transformer secondary, A_C is the cross-sectional area of the core secondary leg in cm^2 and B_{max} is the maximum flux density in gauss.

To achieve a high value of leakage inductance a core with a magnetic shunt was used. The magnetic shunt diverts some of the magnetic flux from linking both the primary and secondary windings. This markedly increases leakage inductance compared to a standard transformer. For convenience a pair of Ferroxcube EC series gapped cores (Fig. 2) were chosen for the transformer.[17] These E-shaped cores are designed so that the winding normally fits on the cylindrical center leg. The outer leg cross section is undercut to accommodate the outer radius of the cylindrical center winding. For this transformer, windings were placed on each outer leg instead of the center leg. The center leg was used as a magnetic shunt. The primary was wound on one outer leg, the secondary was wound on the other outer leg. The core undercut, rectangular outer leg cross section results in a longer winding mean length of turn than a core designed for winding on these outer legs.

The transformer equivalent circuit used is an ideal transformer with an inductor in series with the secondary. The inductor represents the secondary leakage inductance plus the reflected primary leakage inductance.[16] Developing an accurate analytical expression for leakage inductance based on the core and winding geometry was not practical here. For this structure leakage inductance calculations must take into account flux paths in addition to the center shunt since the center shunt gap is large.[18] The field problem of fringing flux around the center leg also complicates the calculation. An involved calculation would be required each time the center gap is changed.[16]

An approximate expression for the leakage inductance was developed that incorporates an empirically determined dimensionless constant, a:

$$L = aA_L N_S^2 \quad 10^{-9} \text{ henrys} \tag{8}$$

where A_L is the inductance index in mH per 1000 turns for a given core configuration, material, and air gap.

The values for A_L given in the core catalog[17] are minimum values. Measured values of A_L for the particular cores used were 10 to 20 percent higher than the minimum values listed. Measurements of the constant, a, for EC41 cores ranged from about 1.8 for a 60-mil gap to 2.5 for a 120-mil gap.

Combining Eq. (5) for short-circuit current, Eq. (7), Faraday's induction law and the leakage inductance relationship, Eq. (8), an expression for secondary turns was developed:

$$N_S \simeq \frac{5A_C B_{max}}{aA_L I_{sc}} \tag{9}$$

Secondary turns are a function of short-circuit current and magnetic core characteristics. Equation (9) was used to select a transformer core for a given short-circuit current.

CATHODE KEEPER POWER SUPPLY

Design

The cathode keeper power supply schematic is shown in Fig. 3. The breadboard of the circuit is shown in Fig. 4. The circuit is a modified Jensen power oscillator designed so that the oscillator frequency is directly proportinal to the input voltage. The frequency is about 9 kHz at an input of voltage of 18 volts and 18 kHz at 36 volts. The transformer turns ratio, n was 2.5 and the leakage inductance referred to the secondary was 0.60 mH. The leakage inductance current and therefore the load current is reduced as frequency increases. This automatically corrects the tendency of the leakage inductance current to increase as input voltage increases. Load current which is the average value of the rectified leakage inductance current is given by Eq. (4).

The power MOSFET transistors Q_1 and Q_2, have unique properties that make them well suited to this application. One property is the anti-parallel diodes contained in these devices.[19] Since the current in the circuit is out of phase with the voltage, anti-parallel diodes provide a conduction path for the inductive current. Another very important property for simplification is the field effect transistor transfer characteristics. The device turns full on with about 6 volts gate to source voltage and can withstand ±20 volts gate to source. This transfer characteristic easily allows a two to one variation in gate drive voltage. This in turn permits direct gate drive from the transformer where the voltage change is two to one for this circuit.

Starting this oscillator, even into a short circuit is easy because the switch load is inductive, i.e., the initial load condition appears as an open circuit.

The start circuit comprises R_3, CR_1, and C_3. Q_1 and Q_2 have a gate to source threshold voltage of about 3 volts. Voltage is applied to Q_1 and Q_2 gates through R_3. The switch with the lowest threshold voltage turns on first. Input voltage is then reflected through transformers T_1 and T_2. This causes the opposite switch to be held off and an increase in drive to the transistor turning on. The on transistor remains on until T_2 saturates, removing drive to the on transistor. Inductive energy causes the transformer voltage to reverse and the opposite transistor is turned on. The cycle repeats and the circuit has started. The zener diode (IN5338B chosen for convenience) limits the total gate to source voltage during normal operation. A resistor could have been used instead of the zener diode but the zener allows a higher voltage to be applied to the gate to source terminals of the switches at high input voltage. This becomes important for large input voltage ranges since the upper limit on gate to source voltage is specified at +20 volts. About 6 volts is required to turn on fully at the lowest input voltage. This limits the range of input voltages that can be used with this particular circuit. However, the range of input voltages could be extended by adding gate to source zener diodes. The capacitor, C_3 provides a low impedance path for gate to source currents during the switching interval and reduces switching losses.

This basic keeper circuit requires 14 components. However, it is desirable to include a high-voltage zener diode across the output both to limit the voltage rating required for C_2 and to provide a safe path for high pulse currents. High transient currents could occur if the keeper positive output is shorted to the screen power supply return.

The output winding of T_1 as well as the rectifying diodes and filter capacitor is referenced to screen potential (1100 V) so the transformer secondary winding must be insulated for high voltages. Ocasionally during normal thruster operation the screen shorts and arcs so the cathode keeper must also be protected from these transients. The physical configuration of the transformer, with the secondary located far away from the primary effectively reduces electrostatic coupling of quickly changing screen potentials during arcs. In addition, the high leakage inductance isolates the primary from rapid current changes in the keeper supply output.

Transistor switch and transformer waveforms are shown in Fig. 5 for both maximum and minimum input voltage. Q_1 voltage and current waveforms illustrate the large phase shift between voltage and current caused by the leakage inductance. The figure also shows that the average rectified transformer secondary current increases only slightly when the input voltage is doubled and the frequency also doubles. The load current is equal to the average rectified transformer secondary current so it remains virtually constant.

On-off control could be accomplished using a series switch or relay. Another method was developed that does not require a power handling component. The circuit takes advantage of the power MOSFET's high threshold voltage. The simple circuit is shown in Fig. 6. A TIL119 optocoupler is used in conjunction with two diodes to clamp the gates of Q_1 and Q_2 below the threshold voltage. Gate resistors R_1 and R_2 (Fig. 3) were changed from 100 to 180 ohms to accommodate the TIL119 worst case current

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limit. The circuit provides an on-off control that is electrically isolated from the power return. Isolation is a useful feature for most systems.

Performance

The cathode keeper power supply regulation, power efficiency, high and low temperature regulation and efficiency were measured. In addition the power supply was run with a laboratory 30 cm diameter Hg ion thruster. Tests for input audio susceptibility and reflected ripple were not performed.

Although low component weight and adequate power efficiency were achieved, no effort was spent to maximize power efficiency or to reduce weight. The main purpose of this effort was to demonstrate the circuit concept and to obtain benchmark data.

The total component weight of the supply, substituting a flight type capacitor for the output filter capacitor, C_2 was approximately 150 grams. The short-circuit current of the breadboard turned out to be 1.1 amperes instead of 1.0. No effort was made to readjust the current by increasing the frequency or increasing the leakage inductance by reducing the length of the magnetic shunt air gap.

The cathode keeper load characteristics for inputs of 18.0 and 36.0 volts are shown in Fig. 7. The experimental data agree well with the values of load voltage predicted from Eqs. (4) and (5). Power efficiency versus load current appears in Fig. 8. Power efficiency is about 88 percent for optimal loading and 35 to 50 percent at the keeper operating point chosen for the 30-cm diameter Hg ion thruster. This compares with the 30-cm diameter Hg ion thruster thermal vacuum breadboard low power supplies total full load efficiency of about 75 percent, and 50 percent efficiency at the run condition.[20] Power efficiency would be much higher for a higher voltage load such as the neutralizer keeper.

Worst case output ripple is about 0.5 volt peak-to-peak at room temperature when the output filter capacitor, C_2 is the aluminum electrolytic capacitor used for convenience.

Temperature tests. - A temperature chamber was used to test the cathode keeper supply in an ambient temperature environment from -20° to +71° C. The automatically controlled chamber used liquid nitrogen for cooling and electric heaters for high temperatures. Test article temperature was maintained or changed quickly by convection from internal fans. Before electrical tests, the circuit was soaked for 1 hour or longer after the desired chamber temperature was reached.

The upper temperature of +71° C was arbitrarily chosen since it is commonly used in military specifications. The lower temperture was limited by the output capacitor, C_2 that was chosen for convenience. At -20° C the equivalent series resistance of the aluminum electrolytic capacitor increased so much that the output ripple increased to about 4 volts peak-to-peak with a 5.4-ohm load.

Short-circuit current changed slightly with temperature as shown in table 3. This was due mainly to changes in frequency with temperature since short-circuit current is inversely proportional to frequency (see Eq. (5)). Frequency is determined by the input voltage and the characteristics of transformer T_2. As the flux capacity of the T_2 core is decreased with rising temperature the frequency increases and the short-circuit current is reduced. Short-circuit current is directly proportional to the flux capacity of the timing core. Table 3 shows the observed correspondence between short-circuit current and the change in flux capacity of square permalloy 80.[21]

Cathode keeper supply approximate power loss versus temperature for a 5.4-ohm load is shown in Fig. 9. Power loss changes slightly for temperatures between 25° and 71° C. The power measurement accuracy at -20° C is adversely effected by a 4-volt peak-to-peak ripple voltage caused by the equivalent series resistance increase in C_2, the aluminum electrolytic capacitor used for convenience. The increased equivalent series resistance of C_2 also results in about a 0.7-watt increase in power loss.

Ion thruster test. - The cathode keeper supply was operated with the 30-cm diameter Hg ion thruster and test facility described in Ref. 5. As a precaution against excessive supply currents caused by thruster arcs, an anti-parallel diode (TRW SVD400-12) was connected across the power supply output terminals. For one test the input voltage to the cathode keeper supply was set at 18.0 volts. Initially the keeper output voltage measured 58 volts before the thruster was started. Full open circuit voltage was not reached due to high resistance loading in the thruster or in the test setup. After keeper ignition the cathode keeper voltage remained at 5.5 volts. The corresponding cathode keeper current was 1.09 amperes. The thruster was run at the baseline conditions listed in Ref. 5. During startup the thruster screen arced demonstrating keeper supply transient isolation capability as well as high voltage isolation.

The thruster was shut down, allowed to cool, and another test was started. The input voltage to the cathode keeper supply was set at 36.0 volts and the output no load voltage was about 170 volts. After startup the keeper voltage varied between 5.6 and 5.8 volts corresponding to a keeper current of 1.12 amperes. Again screen arcs were observed. The thruster tests demonstrated power supply and ion thruster compatibility since the cathode keeper operated in a stable mode and no component overstresses occurred during thruster arcing.

NEUTRALIZER KEEPER SUPPLY

Design

The neutralizer keeper supply was developed to demonstrate the high voltage input capability of the new self regulating single power stage approach for keeper supplies. A full bridge oscillator version of the Jensen oscillator was developed. The circuit schematic is shown in Fig. 10. The breadboard is shown in Fig. 11. Transistors Q_1 and Q_2 were driven from windings on the power transformer T_1 instead of from the timing transformer T_2. This was done for convenience since electrostatic shields and 400-volt insulation would have been required in a tiny transformer wound by hand. The electrostatic shields were added to T_1 as a precaution because 400 volts is switched in only about 300 nanoseconds. The resulting high dV/dt could couple charge through stray circuit capacitances and possibly cause difficulties.

The start circuit was not fully developed for the neutralizer keeper supply. The start circuit shown in the schematic requires closing a momentary switch to pulse T_1. This turns on Q_2 and Q_3 simultaneously and oscillation begins. If all four transistors were driven from T_2 then the start circuit would have different requirements. However, better performance might be obtained by driving all transistors from T_2, so a different start circuit would then be needed. When the circuit was first tested it was found that the lower transistors, Q_3 and Q_4 turned on slightly before transistors Q_1 and Q_2 turned off resulting in the undesirable condition that Q_1 and Q_3 as well as Q_2 and Q_4 being on simultaneously for a short time. It was desirable to fix the condition quickly without a major redesign of the circuit. This was done by adjusting the time constants formed by the gate source capacitance and drive resistors. Q_1 and Q_2 were driven by 27 ohm resistors whereas Q_3 and Q_4 have gate resistors of 270 ohms. This allowed operation over the full input voltage range from 200 to 400 volts without simultaneous turn on of Q_1 and Q_3 or Q_2 and Q_4. At 200 volts input the frequency of oscillation was 20.6 kHz and at 400 volts input the circuit oscillated at 38.5 kHz. The frequency of oscillation was not quite proportional to the input voltage, resulting in an 8-percent higher short-circuit current at 400 volts input than at the 200-volt input condition. The slight non-proportionality of frequency versus input voltage was due to approximately 3 μsec fixed frequency independent delay that occurred during each cycle. The transformer turns ratio, n was 0.25 and the leakage inductance referred to the secondary was 0.10 mH. The value of short-circuit current predicted by Eq. (5) was about 20 pecent high for this circuit. But Eq. (5) does not account for power loss or voltage drops in the circuit.

Circuit waveforms are shown in Fig. 12. Drain to source voltage, V_{DS}, and drain current, I_D, of Q_3 and transformer T_1 primary current, I_p, are shown for input voltages of 200 and 400 volts. Circuit operation is very similar to the cathode keeper supply. Output current for heavy loads is maintained nearly constant for changes in input voltage. The figure shows the change in frequency and voltage while the current remains nearly constant.

Performance

The neutralizer keeper power supply regulation and power efficiency were measured over the full range of load currents and voltages for both 200 and 400 volts input. The data are plotted in Figs. 13 and 14. Output ripple measured 0.6 volt peak-to-peak worst case. Temperature tests and tests for input audio susceptibility and reflected ripple were not performed. As with the cathode keeper supply no effort was spent to maximize power efficiency or to minimize weight. Weight of the components is estimated to be about 200 grams compared to about 150 grams measured for the cathode keeper. The power efficiency of the neutralizer keeper supply at the nominal operating voltages of 15 volts is about 60 percent at 400 volts input and 76 percent at 200 volts input. The efficiency at the operating point is much higher than the cathode keeper because the output voltage is 15 volts instead of 5 volts. The neutralizer keeper supply is operated nearer its maximum power capability.

Ion thruster tests. - The neutralizer keeper power supply was run with the 30-cm diameter Hg ion thruster and test facility described in Ref. 5. Only the neutralizer was operated for this test since the screen supply was inoperable when the test was run.

In the first test the power supply input was set below the specified 200 volts, to 150 volts to check lowest voltage ignition. The neutralizer Hg vaporizer was run open loop. The neutralizer ignited and started running at 12.1 volts and 2.1 amperes then the voltage drifted to 9.7 volts at 2.17 amperes. The voltage was lower than 15 volts because the neutralizer was running Hg rich. The power supply input voltage was then increased to 200, 300, and 400 volts. The corresponding measured neutralizer keeper operating points were 9.6 volts at 2.31 amperes, 9.7 volts at 2.49 amperes, and 9.8 volts at 2.63 amperes. The input voltage to the supply was set at 200 volts and the Hg flow and tip heat were turned off. As the Hg flow decreased, the keeper voltage increased and current decreased until 46 volts was reached. Two data points taken near the nominal operating voltage were 14.3 volts at 2.18 amperes and 18.2 volts at 2.05 amperes. After this test the input of the neutralizer keeper supply was increased to 400 volts. The voltage prior to ignition was 101.7 volts. After ignition the operating point was 13.5 volts at 2.6 amperes. Then fuel flow and tip heat were shut off. The test was stopped when the operating point reached 25.6 volts at 2.53 amperes.

Short-Circuit Current Adjustment

For production, a method of adjusting power supply short-circuit current is necessary. Tolerances in the flux capacity of the timing core as well as winding tolerances in the transformer inductor determine short-circuit current. One way to adjust short-circuit current is to change the gap length in the magnetic shunt of T_1. This requires stocking a variety of core halves. However, this is an easy adjustment since gap length is not critical. Doubling the gap length of T_1 in the neutralizer keeper supply reduced the leakage inductance by only about 20 percent.

HEATER POWER SUPPLIES

Several resitance element heaters are used in ion thrusters. The heaters all have a high thermal mass so the heaters can time average odd-shaped voltage and current waveforms to provide an even temperature. This property can be used to develop simplified heater supplies. For example the vaporizer heater time constant is on the order of 10 seconds.[22] So if the vaporizer power supply can be cycled on and off rapidly with an adjustable duty ratio then variable power can be supplied to the vaporizer heater.

The cathode keeper power supply (Fig. 3) together with the ON-OFF control circuit (Fig. 6) can be turned ON and OFF very rapidly because the circuit starts easily. A supply similar to the cathode keeper supply, but designed with a lower open-circuit voltage, can be turned on and off rapidly enough to supply a continuously varying RMS current to the heater. For controlling vaporizer heaters the duty ratio could be varied using one of several integrated circuits used for pulse width modulation in power supplies.

Pulse Width Modulation Test

To demonstrate feasibility of the concept, the cathode keeper circuit with the ON-OFF control circuit was pulse width modulated using a variable duty ratio pulse generator. A fixed period of 58 msec was arbitrarily chosen. Very rapid ON-OFF control of this circuit is possible because the switching transistor load is inductive and starting drain currents are virtually zero. The input voltage to the supply was set at 28 volts and the load was approximately 6 ohms. The duty ratio was varied continuously from full off to full on. Figure 15 shows load current, I_L and Q_1 drain to source voltage, V_{DS} for a duty ratio of about 50 percent. Note that the output filter capacitor rounds off the output waveform and reduces electromagnetic interference.

The test shows that it is possible to control heater power by ON-OFF duty ratio control of a circuit similar to the cathode keeper power supply.

CONCLUSIONS

Relaxing ion thruster power supply regulation tolerances and redefining load profile requirements expands the range of circuit techniques that can be evaluated for the purpose of using simpler circuits.

A key to achieving low parts count is the elimination of active voltage limiting as well as closed-loop current control used in conventional ion thruster power supplies. In addition, a single self regulating power stage between the power source and thruster eliminates the need for a pre-regulator circuit. The incorporation of dual-role components such as a transformer-inductor and power MOSFET transistors with their intrinsic antiparallel diodes results in further simplification.

Two new, single power stage, self regulating power supplies were developed and demonstrated for the main and neutralizer keepers of a 30-cm diameter Hg ion thruster. These keeper supplies have an order of magnitude reduction in parts count from contemporary supplies leading to increased reliability at lower weight, while still maintaining thrust system performance.

The keeper power supplies provide:

1. An ignition potential greater than 50 volts at low source resistance
2. Input-output isolation
3. Operation into short circuits and overloads
4. Output current regulation

The cathode keeper power supply demonstrated operation from a low voltage voltage bus, 18 to 36 volts, and thruster compatibility as well as high- and low-temperature operation.

The neutralizer keeper power supply demonstrates operation from a high-voltage bus, 200 to 400 volts. Thruster compatibility was also demonstrated.

A new, single-stage technique, for supplying and controlling heater power was demonstrated. The self-regulating cathode keeper supply has the capability of being turned on and off very rapidly. This property was used to pulse width modulate heater power. The high thermal mass of the heater averages the pulsed energy to provide a nearly constant temperature. Further work is needed to fully impliment this circuit technique for ion thruster use.

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4. Biess, J. J., and Schoenfeld, A. D., "Effect of Requirement Specification on Implementation of a Power Processor," 24th Power Sources Symposium, 1970, pp. 123-128.
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TABLE 1. - 30-CM DIAMETER HG ION THRUSTER CATHODE KEEPER SUPPLY

REQUIREMENTS

Item	Requirement
Nominal operating point	5 Volts at 1 ampere
Ignition	≥50 Volts at low source impedance
Current regulation	Nominally ±10 percent near operating current
Input voltage	2:1 Range, 18 to 36 volts or 200 to 400 volts
Input-output isolation	≥10 Megohms D.C. Resistance, output return is tied to screen potential of 1.1 kV
Noise imunity	Imunity from transients induced by screen arcs
Operation into open circuit	Required
Operation into short circuit or overload	Required
Output ripple	Approximately 0.5 volt peak-to-peak maximum

TABLE 2. - 30-CM DIAMETER ION THRUSTER NEUTRALIZER KEEPER

SUPPLY REQUIREMENTS

Item	Requirement
Nominal operating point	15 Volts at 2.1 amperes
Ignition	≥50 Volts at low source impedance
Current regulation	Nominally ±10 percent near operating current
Input voltage	2:1 Range, 18 to 36 volts or 200 to 400 volts
Input-output isolation	≥10 Megohms D.C. Resistance
Operation into open circuit	Required
Operation into short circuit	Required
Output ripple	Approximately 0.5 volt peak-to-peak maximum

TABLE 3. - CHANGE IN CATHODE KEEPER SUPPLY SHORT-CIRCUIT CURRENT AND

MAXIMUM FLUX CAPACITY OF THE TIMING CORE WITH TEMPERATURE

Temperature, °C	$\frac{I_{SC} - I_{SC} \text{ at } 25^\circ C}{I_{SC} \text{ at } 25^\circ C} \times 100$ percent		Percent change in maximum flux capacity from capacity at 25° C for square Permaloy 80
	18.0 V_{in}, percent	36.0 V_{in}, percent	
-20	+2.6	+2.9	+3.1
+25	0	0	0
+51	-2.0	-2.0	-2.0
+71	-3.8	-3.8	-3.8

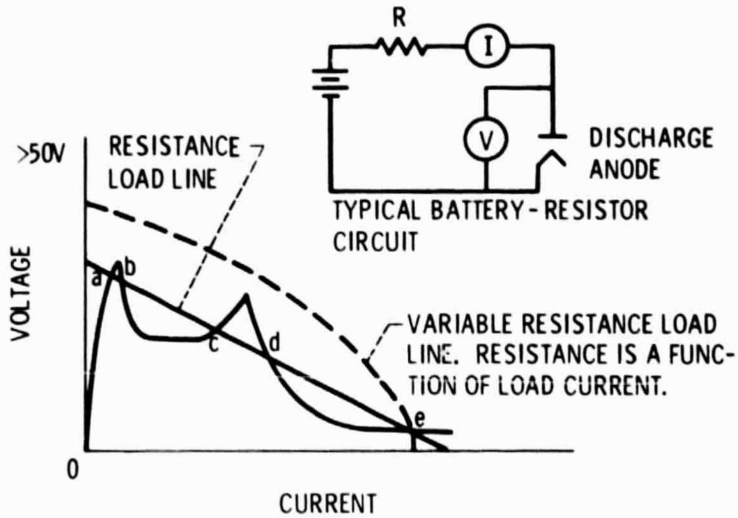

Figure 1. - Static discharge characteristics for typical glow-arc discharge. Letters denote load line intersects.


Figure 2. - Ferroxcube EC series transformer core.

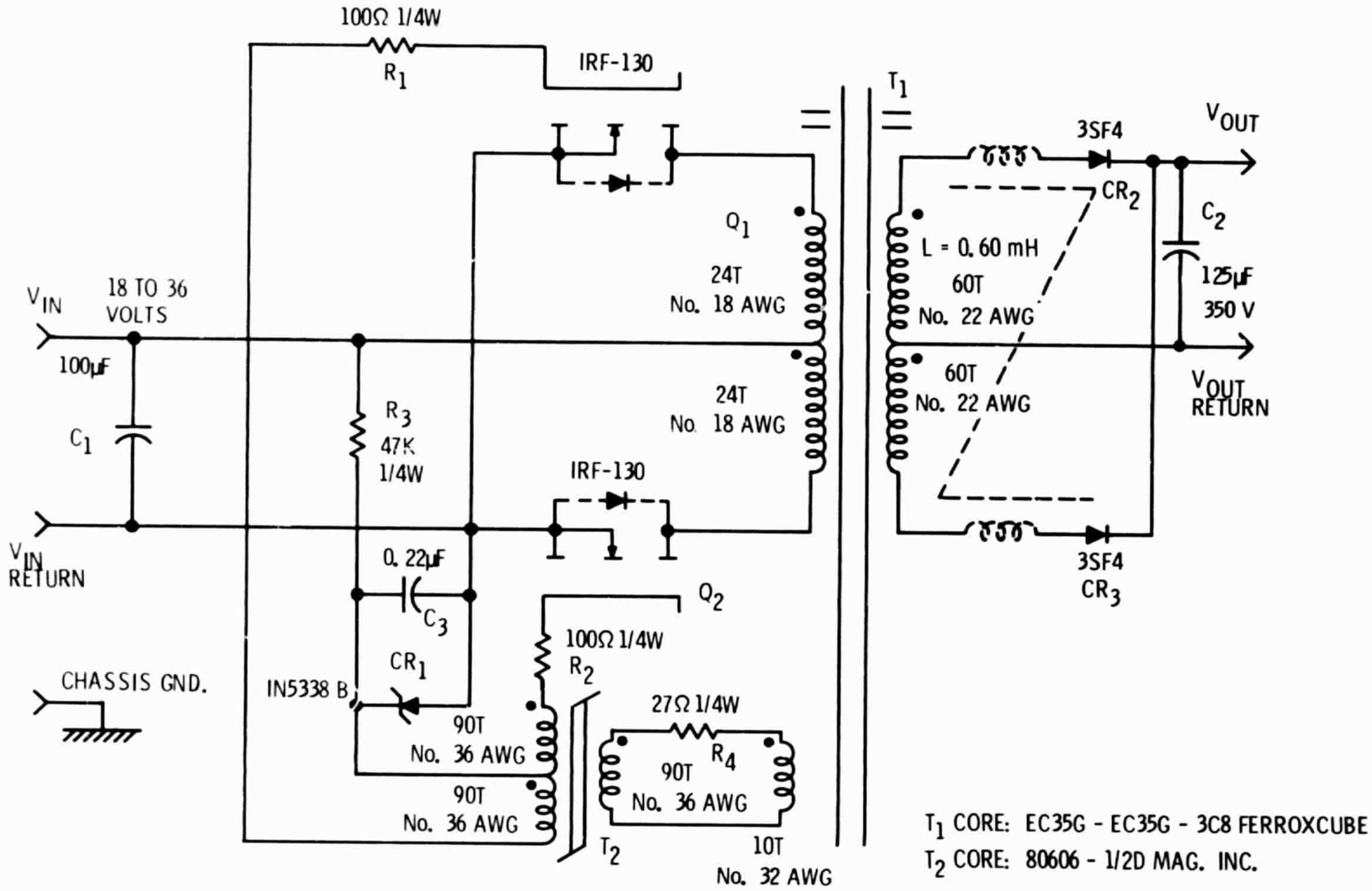

Figure 3. - Schematic diagram 30 cm Hg ion thruster cathode keeper power supply.

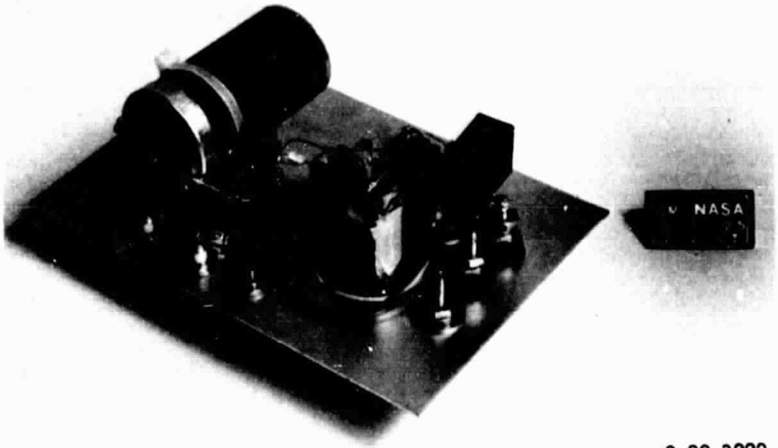

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Figure 4. - Breadboard of 30 cm ion thruster cathode keeper supply.

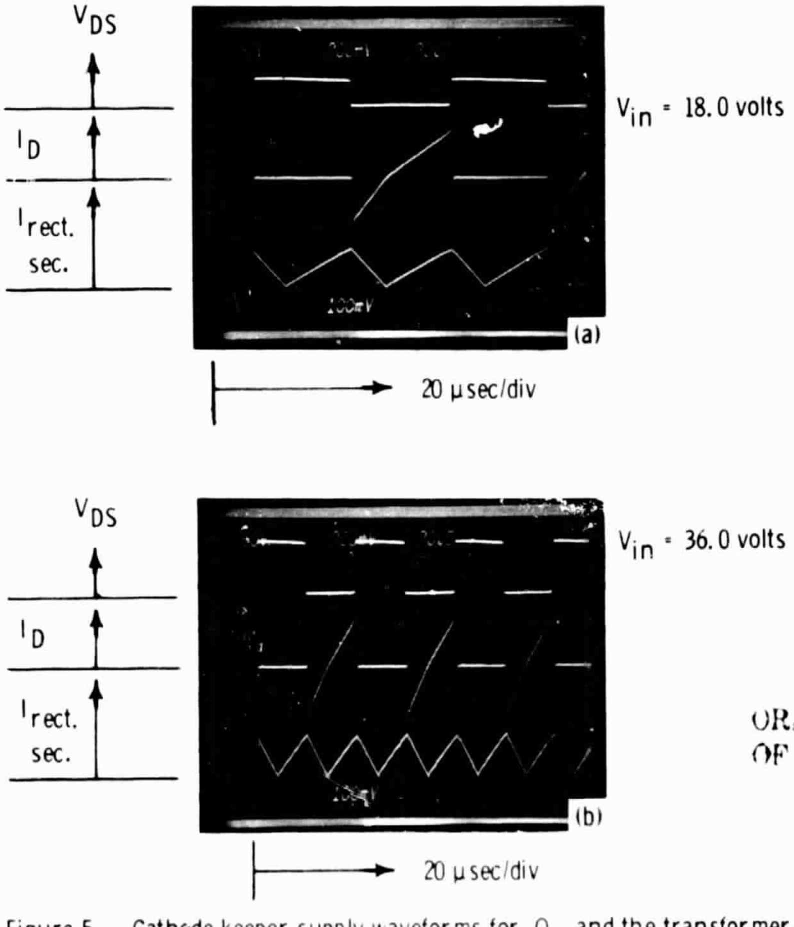

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Figure 5. - Cathode keeper supply waveforms for Q_1 and the transformer rectified secondary current under condition of input voltages of 18 volts and 36 volts with a 10 ohm load. Vertical scale factors; V_{DS}, 50 volts/div; I_D, 4 amperes/div; $I_{rect.\ sec}$ 2 amperes/div.

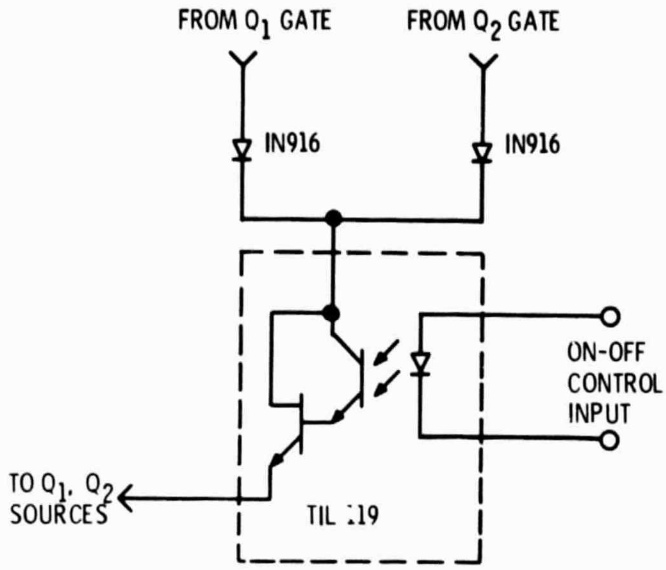


Figure 6. - Schematic diagram, cathode keeper supply isolated on - off control circuit.

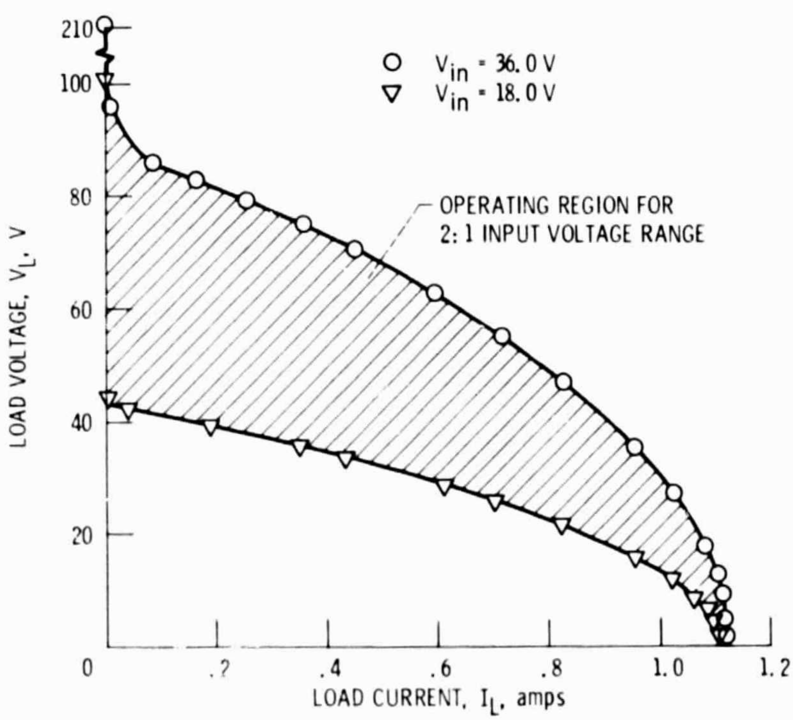


Figure 7. - Cathode keeper supply load characteristics.

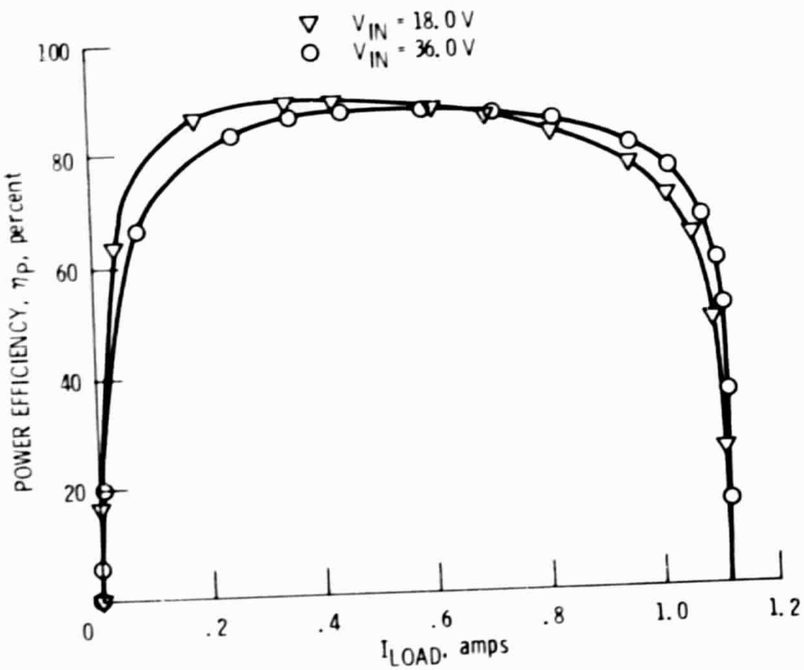


Figure 8. - Cathode keeper power supply. Power efficiency versus load current.

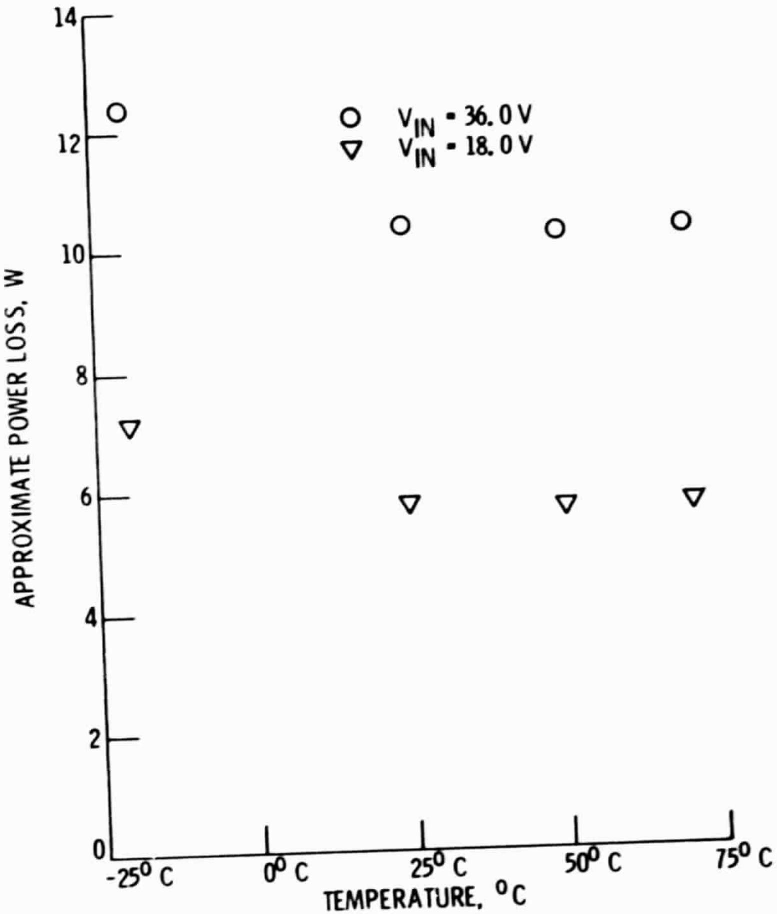


Figure 9. - Cathode keeper supply approximate power loss versus temperature for a 5.4 ohm load.

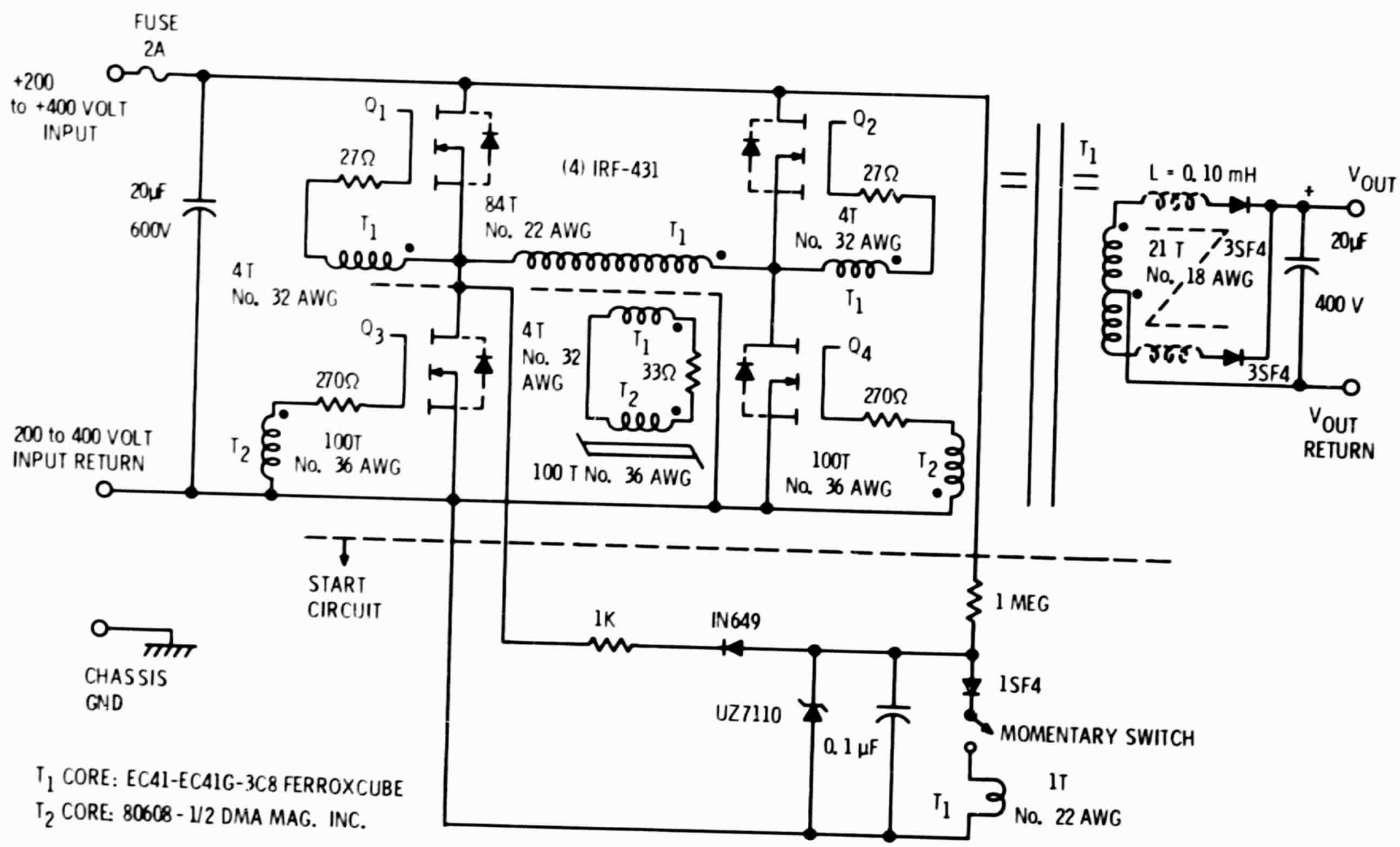


Figure 10. - Schematic diagram, 30 cm Hg Ion thruster neutralizer keeper supply.

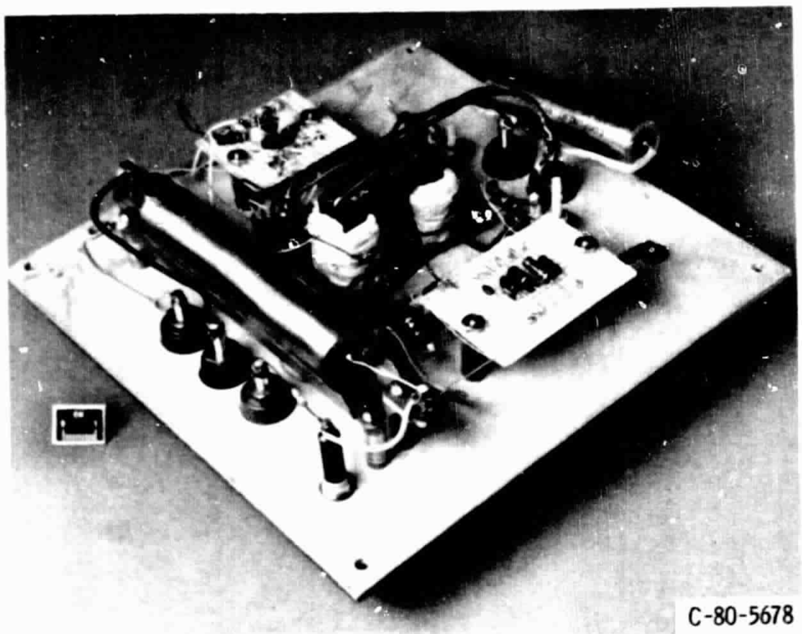
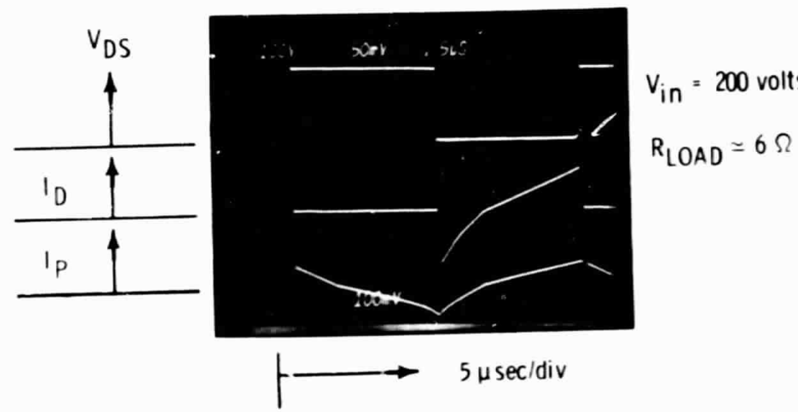
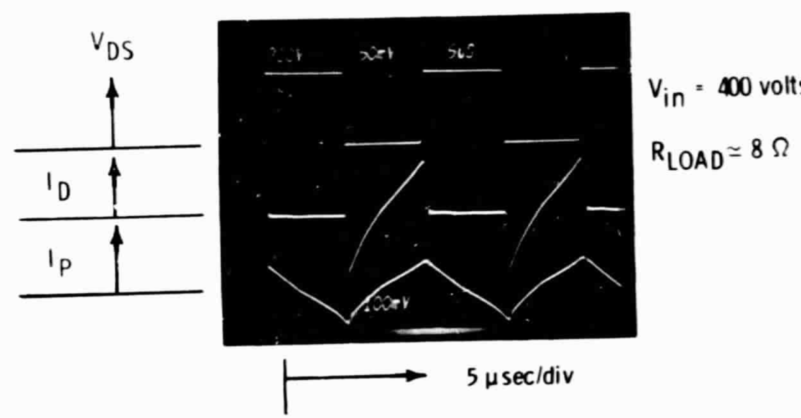


Figure 11. - Breadboard of 30 cm ion thruster neutralizer keeper supply.



(a) V_{DS}, 100 volts/div; I_D, 1 ampere/div; I_P, 2 ampere/div.



(b) V_{DS}, 200 volts/div; I_D, 1 ampere/div; I_P, 2 ampere/div.

Figure 12. - Neutralizer keeper supply waveforms for Q_3 and transformer T_1 primary current under conditions shown.

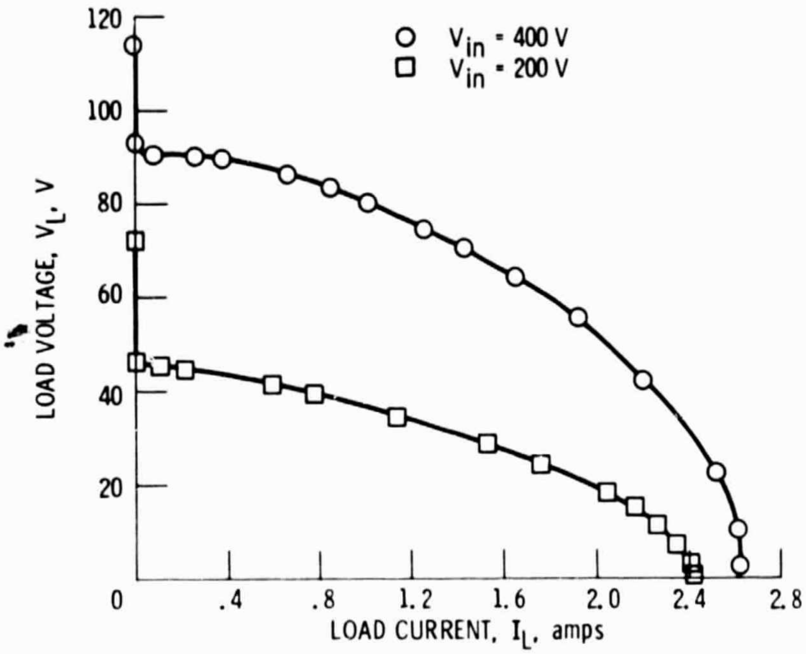


Figure 13. - Neutralizer keeper supply load characteristics.

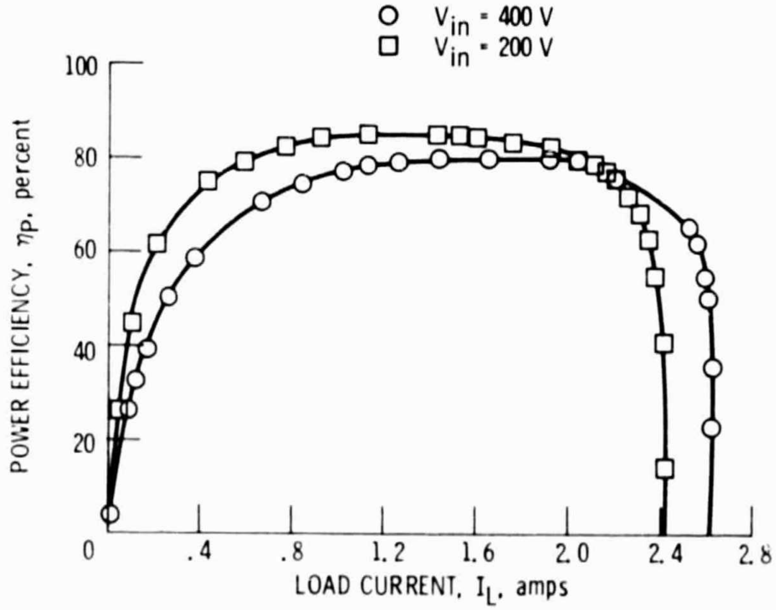


Figure 14. - Neutralizer keeper supply power efficiency versus load current.