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POWER SUPPLIES AND A REMOTE-CONTROL SYSTEM SUITABLE FOR AEROBEE ROCKET INSTRUMENTATION

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ABSTRACT

A general discussion of the operating characteristics and experience with the Airpax 400-cycle, d-c to a-c power inverter is presented. Performance curves for the inverter and circuit diagrams of an electronically regulated power supply and a flexible remote-control system suitable for rocket-borne use are included.

The important problem of power-supply reliability has also received attention. A simple, yet effective, method of enhancing reliability by automatically switching to auxiliary or standby power is diagrammed.

PROJECT OBJECTIVE

The objective of this project is research in temperature, wind, and related properties of the atmosphere and ionization in the upper atmosphere.

INTRODUCTION

In the design of missile-borne instrumentation systems the problem of d-c to d-c and d-c to a-c power conversion is often a troublesome one, particularly when space and weight restrictions are severe. This technical note presents in summary form the details of two missile-borne power supplies which achieve the power conversions mentioned above. In addition, a simple yet dependable remote-control system is outlined which has also proven satisfactory for use aboard the Aerobee Sounding Rocket.

D-C TO A-C POWER CONVERSION

The adoption by this project of an aircraft-type attitude gyroscope for missile aspect instrumentation in 1949 posed the problem of a suitable 400-cycle, 110-volt, 3-phase, a-c power supply for the gyro. A preliminary investigation of available rotary inverters indicated that although there were many varieties available, almost without exception the rated power output was far in excess of what was needed to power the gyro. In addition, the size, weight, and low power-conversion efficiency of rotary inverters made them generally unsatisfactory for rocket-borne service. In spite of these unfavorable characteristics, however, it was necessary to use a rotary inverter for the first Aerobee since there was no other power supply immediately available. The unit weighed 5-1/2 pounds, occupied 67-1/2 cubic inches, and had a power-conversion efficiency of 46 percent at a rated output power of 25 watts.

Shortly thereafter the Airpax Products Company commercially introduced a small, lightweight, 400-cycle, single-phase vibrator-type inverter which appeared to be suitable as a power source for the gyroscope and other applications where a-c power was required. The inverter proved satisfactory and has been used for various purposes on all succeeding Aerobee firings by this project.

DESCRIPTION OF AIRPAX INVERTER POWER SUPPLY

Basically, the inverter consists of a reed-type vibrator operating at 400 cycles, a 400-cycle step-up transformer to provide the 110-volt, single-phase output power, and appropriate buffer capacitors. These components are mounted together in a hermetically sealed container and are presently available in two basic models as follows:

	Model A702	Model A512
Input Volts	6, 12, or 24	6, 12, or 24
Output Volts	110 v, 400 cycle, single phase	110 v, 400 cycle, single phase
Output Power	30 watts continuous	15 watts continuous
Efficiency	70-80%	70-80%
Size	3-5/16 x 3-1/16 x 2-1/8 in.	2-13/16 x 2-3/4 x 1-1/2 in.
Volume	15.1 cu in.	11.6 cu in.
Weight	20 oz	14 oz

In addition, the manufacturer has recently made available a plug-in 400-cycle power vibrator which can be used with a suitable step-up transformer to provide any desired 400-cycle output voltage.

The new vibrator has the following characteristics:

	Model A-500-6	Model A-500-12	Model A-500-24
Input Voltage Nominal	6.3	12.6	26.5
Input Voltage Range*	5.5-8	11-16	22-30
Continuous Volt-Amp Output	15	20	30
Intermittent Volt-Amp Output	100	130	200

*Other input voltages can be supplied.

Size: Cylindrical can, hermetically sealed with octal base; height 2-3/4 in., diameter 1-1/2 in.

Life: On continuous operation in a correctly designed power supply at rated load, the life expectancy exceeds 500 hours and is correspondingly more on lighter loads. The vibrator will furnish the indicated intermittent load with a duty cycle not exceeding 10 percent and a maximum "on" period of one minute for over 50 operations.

Regarding ruggedness of the inverters, the manufacturer states that the units will operate unaffected when subjected to acceleration due to vibration consisting of simple harmonic motion up to 10G, from 10 to 55 cycles per second. In shock, the inverters are designed to withstand 50G acceleration in the plane of the mounting studs and 15G in other planes. Much higher forces can be accommodated if specified on special order.

Optimum performance can be obtained from the Airpax inverter by properly considering the following electrical characteristics:

1. Polarization—The vibrator in the inverter uses a permanent magnet system of drive which means that polarity must be observed in connecting the input supply leads. If polarity is not observed, contact sticking will occur and cause permanent damage to the unit.

2. Power source—Since the vibrator receives energy only during the period of time in which the vibrator contacts are closed, it is necessary to provide a low-impedance source of power for the inverter. This generally precludes the use of such sources of power as battery eliminators or others relying on rectified alternating current unless they are shunted by large capacitances—the order of 1000 microfarads. In addition, it is necessary that the wire size from the power supply to the inverter be sufficient to allow the large peak currents drawn by the inverter during the vibrator "on" periods.

3. Power-factor correction—Motors such as Gyro wheels and Selsyns present a lagging power-factor load to the power source. For proper operation of the inverter, the total load must be corrected to unity power factor. This can be accomplished by connecting appropriate capacitors either in series or in parallel with the load. The manufacturer comments that where possible, the parallel-connected correction is to be avoided as this often results in high currents through the vibrator contacts, with a consequent reduction in vibrator life. It is important to note here that motors usually exhibit different characteristics between starting and running, which sometimes makes the application of series-connected power-factor correction rather difficult. This is particularly true when the ratio of motor starting to running current is large. Each application of this type must be carefully checked to obtain optimum operation.

Figures 1, 2, and 3 present the waveforms at the output of the inverter and illustrate the waveforms seen for proper and improper correction.

4. Rectifier loads—When the inverter is to be used to supply a rectifier load, it is necessary that either the rectifier be a full-wave circuit or, if half-wave rectification is used, the output load must not exceed 5 percent of the rated inverter load. This restriction is necessary to avoid the serious vibrator unbalance presented by half-wave rectifiers.

WAVEFORM: AS SEEN ACROSS
TRANSFORMER PRIMARY

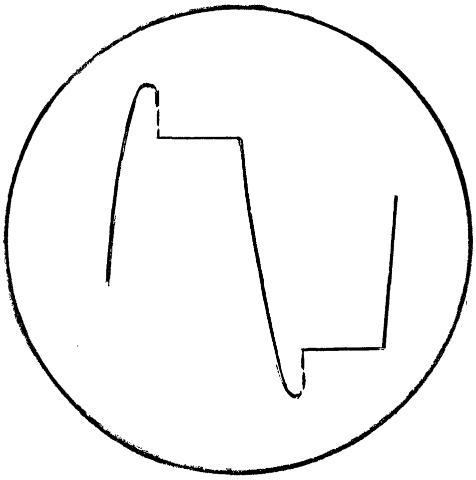


Fig. 1. Supply has insufficient buffer, resulting in sparking at the contacts and poor vibrator life.

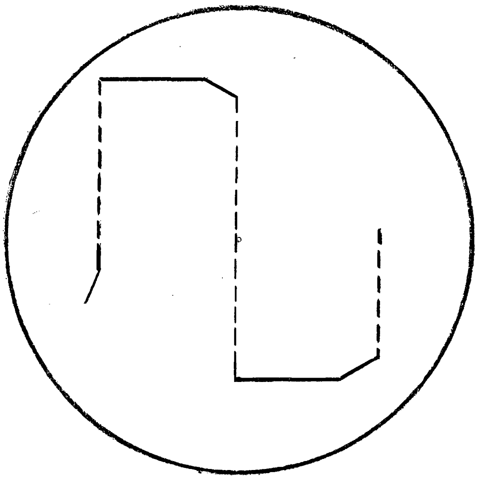


Fig. 2. Overbuffering resulting in excessive wear on the contacts.

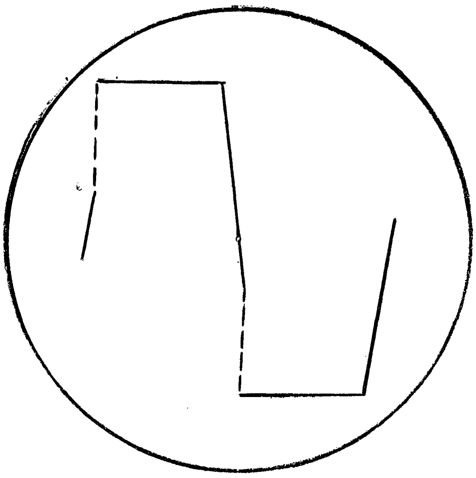


Fig. 3. Normal buffering, showing about 60% "swingback." Adjust between 50 and 70%. Allow for safe operation at the highest input voltage likely to be encountered.

5. Filtering of the inverter—Because this is a vibrator-type (i.e., a current interrupter) device, a certain amount of interference is inevitable, on both the input and output lines. Since each application presents different problems regarding the amount of filtering necessary, it is difficult to generalize regarding filtering. Experience has shown, however, that adequate filtering usually can be achieved. A later section will discuss a filter that has been found acceptable for use with Aérobee instrumentations utilized by this project.

6. Performance—The output-voltage shape as shown in Fig. 1 is essentially square, with a form factor of 1.055. Consequently, output voltages when read with a rectifier-type meter should be corrected as follows:

$$E_{rms} = \frac{E(\text{rect. meter})}{1.055} .$$

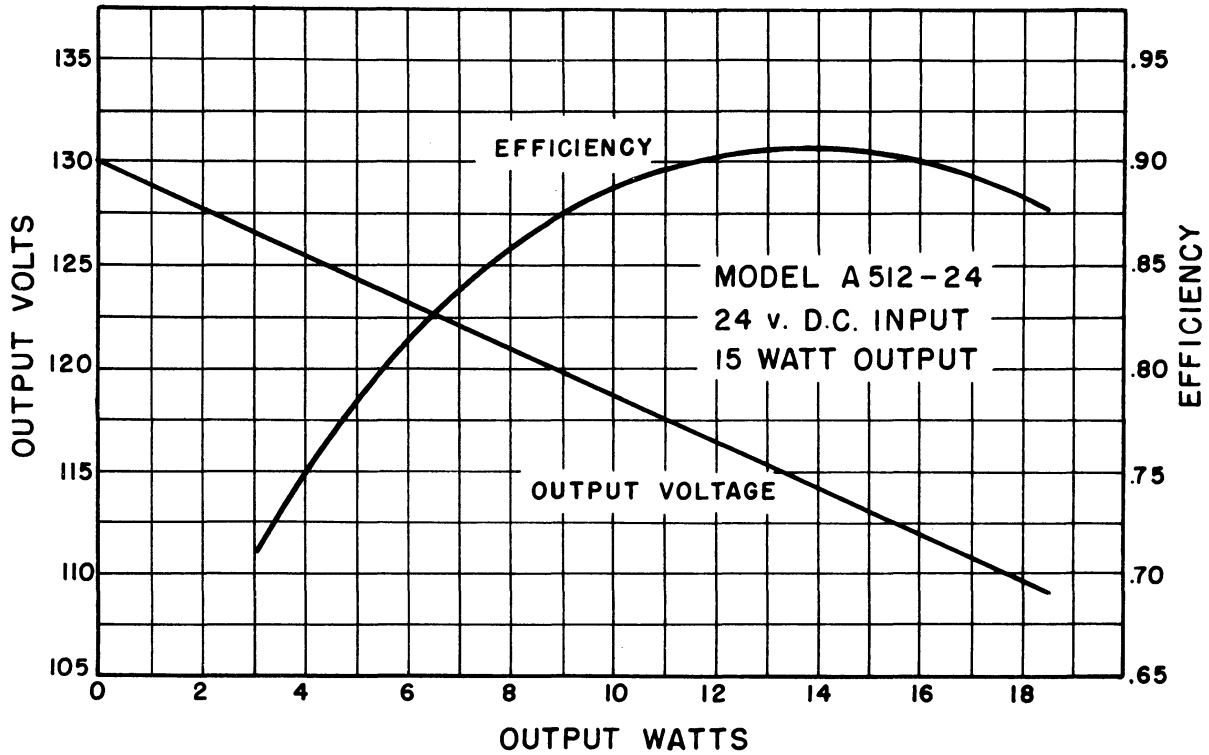
As an example, an inverter power supply with an output of 115 volts ac rms will appear as 121 volts ac as measured on a rectifier-type meter. A similar procedure with appropriate correction factors should be used with meters responding to the peak (or other) value of the a-c wave shape.

It has been observed in practice that a 10-percent decrease or increase in the input voltage to the inverter will produce a corresponding 10-percent increase or decrease in the output voltage. In addition, it is to be expected that the output regulation of this inverter will not be too good. For a typical 24-volt-input, 115-volt-output inverter with a rated capacity of 15 watts (see Fig. 4), the no-load—full-load regulation with a resistive load is of the order of 15 percent.

7. General—The foregoing data have been extracted in part from literature provided by the manufacturer of the inverter. In some cases, operating comments also are included, but it is to be expected that these data will change as time goes on since the manufacturer has shown considerable interest in improving the product. Specific comments concerning actual experience with the inverter appear in a later section.

APPLICATIONS OF THE INVERTER

Since 1950 the Airpax inverter has been used to power eight gyroscopes as well as other equipment on six Aerobee firings. No evidence of in-flight failure of any of the inverters has been observed. Figure 5 presents a complete wiring diagram of the missile instrumentation for a Bendix J-8 Gyroscope and the associated remote-control blockhouse equipment.



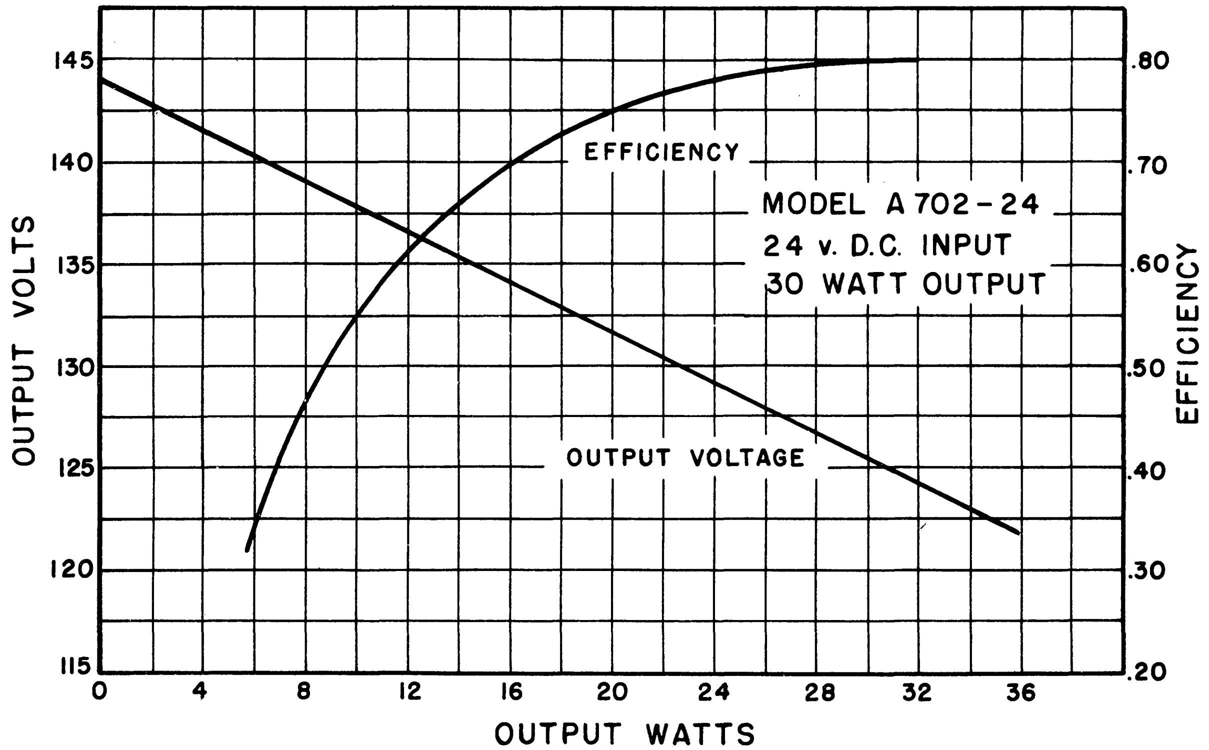


Fig. 4. Airpax 400-cycle vibrator inverter; typical performance characteristics with constant resistance load.

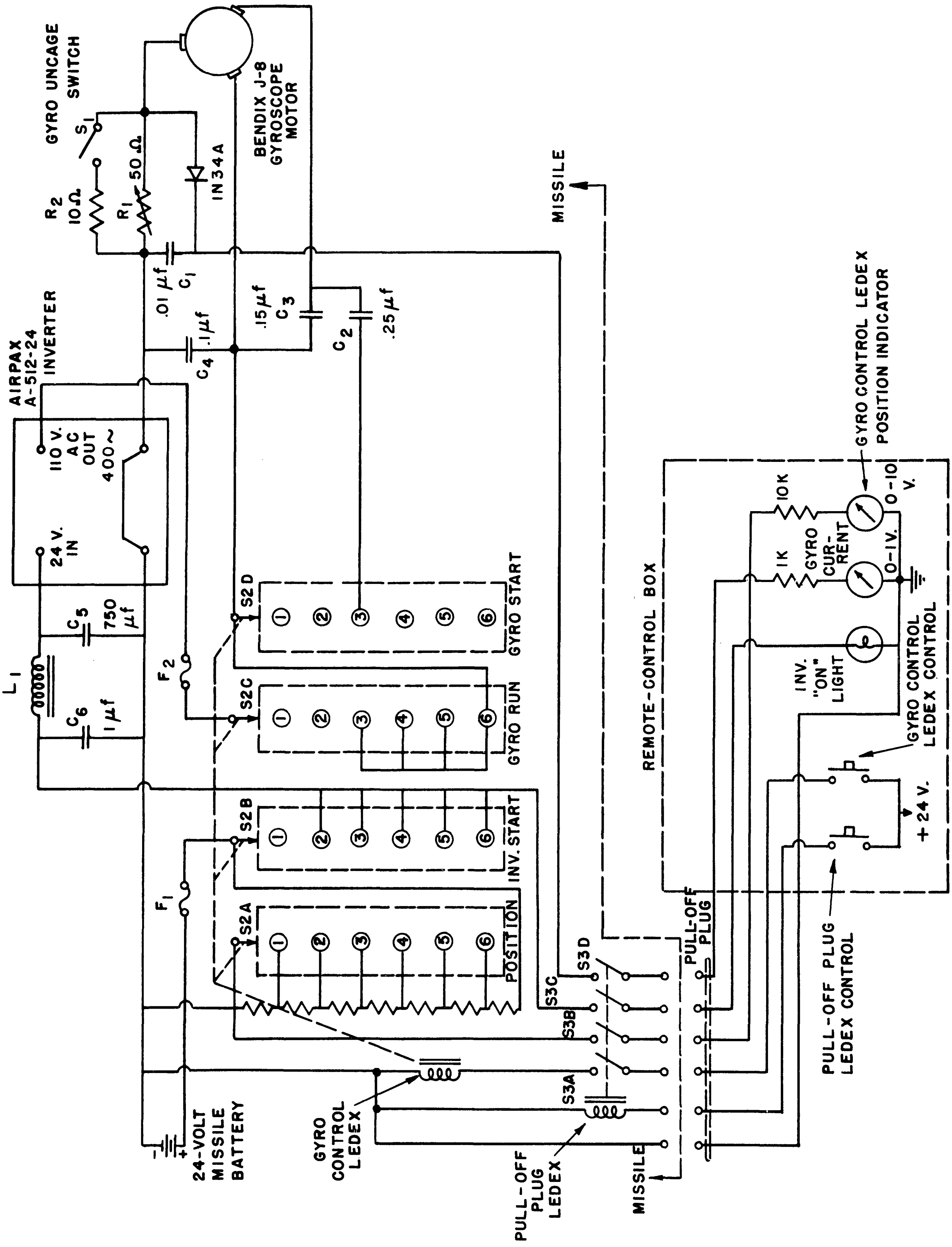


Fig. 5. Gyro power supply and remote-control system.

The Bendix J-8 and Giannini Model-3416 gyro require 110-volt, 400-cycle, 3-phase power for the gyro rotor; to accomplish this, a capacitor is used to shift the phase of the voltage on one line by 90 degrees. This, of course, does not provide the ideal 120-degree phase shift required for a 3-phase motor, but the approximation is good enough to provide reasonable starting and operation of the gyro. It will be noted that a start-run circuit (C_2 and C_3) is included in the 3-phase network. This system is desirable since the amount of starting current demanded by the gyroscope is considerably higher than that necessary when the gyro rotor is up to speed; by providing a start-run position, the gyro can be brought up to speed at a much more rapid rate. Figure 5 also indicates the use of a parallel-connected power-factor-correction capacitor (C_4), which is contrary to the manufacturer's recommendation, as stated earlier. Although series correction is generally desirable, it has been found unsatisfactory for the Bendix J-8 and the Giannini Model-3416 gyroscopes because of the variation in starting vs running volt-amperes required by the gyro motor. In the past no difficulty has been encountered which can be ascribed to this parallel-connection method of correction.

The network composed of the 1N34A crystal diode, R_1, R_2, and C_1, in the ground leg of the inverter output provides a monitor of the a-c current flowing into the gyro motor. This enables the operator to monitor run-up of the motor and also verify the occurrence of gyro uncaging. In normal use the gyro current meter will indicate full-scale value when the gyroscope motor is first energized. As the gyro rotor comes up to speed, less current is demanded by the motor and the current correspondingly decreases in the meter monitoring circuit. Cage-uncage information is introduced into the circuit by switch S_1 which is actuated by the gyro-caging mechanism. When the gyroscope is uncaged, switch S_1 closes, thereby decreasing the amount of current flowing to the meter. Thus, the operator at the blockhouse, after initiating the uncaging command, can observe when the gyro has been completely uncaged.

The gyro run switch S_2C and the inverter start switch S_2B are part of a Ledex rotary-solenoid-operated stepping relay employed extensively in Aerobee instrumentation by this project. The contacts are arranged on a wafer switch in sequence so that during a normal starting procedure S_2B is energized prior to the closure of S_2C. This makes it possible to start the inverter under a no-load condition, thereby, it is felt, improving the contact life of the inverter. The Ledex shown here utilizes a 12-contact wafer switch with two independent 6-position switch sections per wafer. A complete switching sequence of the control Ledex is as follows:

Position 1. Off
Position 2. Inverter on
Position 3. Gyro start
Position 4. Gyro run
Position 5. Gyro uncage
Position 6. Ready for take-off.

When the Ledex is stepped to its next position, the wafer switch is arranged to repeat the sequence given above, with the next step again being Position No. 1. It should also be noted that this control Ledex serves other switching functions such as turning on lights, starting photographic equipment, and so forth, but for simplicity these circuit functions are not shown here.

The primary power for the inverters in all missile applications has been one or more lead acid storage cells, Willard Type N-T-6. These batteries are capable of supplying adequate current to the inverter. However, due to their limited capacity, an appreciable ripple voltage does appear on the primary leads. Since the batteries often supply power to other equipment, it is often desirable to eliminate this ripple by an inclusion of the filter shown on the diagram as L_1C_5 and C_6. It is particularly important in the design of such a filter that the d-c resistance of L_1 be as low as possible and the capacitance of C_5 be as large as is practicable. To insure proper operation of the vibrator contacts, the combined IR drop and ripple voltage at the inverter input should not exceed 10 percent of the nominal supply voltage when rated load is being supplied by the inverter. For the case illustrated in Fig. 5, C_5 is a 750-microfarad, 50-working-volt electrolytic capacitor. When 12- or 6-volt inverters are employed, correspondingly larger capacitors and smaller inductors should be utilized for C_5 and C_4.

It has not been necessary in the past to include external filters in the inverter output circuit; however, shielded wire has been used for the 110-volt wiring to reduce the radiation of high-frequency components in the 110-volt output circuits. It will be recognized here that electrical characteristics of other portions of the instrumentation will determine the amount of shielding and filtering required.

Fuses F_1 and F_2 in Fig. 5 are shown in the primary and secondary circuits of the inverter, respectively. These fuses are incorporated primarily as a means of protecting the power supplies, since the batteries and inverters are often used to supply power to other experiments. Thus, a short circuit in the gyro circuitry will blow fuse F_2 and protect the inverter from damage. In a like manner, fuse F_1 protects the N-T-6 batteries from an overcurrent or short-circuit condition caused by malfunction in the inverter primary circuits. This philosophy of protection has proven quite valuable in the past. As a subsidiary benefit, the fuses often provide a convenient means to de-energize circuits during testing or trouble-shooting procedures.

INVERTER DEPENDABILITY

Although earlier remarks have indicated an accumulation of five years' experience with the Airpax inverter, it would be well to point out here that when considered statistically, the data obtained to date cannot be considered too conclusive. This can be attributed principally to the use of a relatively small number of different inverter models for a variety of applications. To be specific, both 15- and 30-watt units are available for use with 6-, 12-, or 24-volt supply systems. Of these six types, all three 15-watt models have been used, while use of the 30-watt inverter has been restricted to the 24-volt model.

The power requirements have varied with each application, ranging from uniform resistive to fluctuating reactive loads, with and without inverter input filters. Thus, it can be seen that an accurate basis for judgment is difficult to establish here. The reliability problem has been further complicated by the recent introduction of the new A-500 vibrator which is claimed to be more dependable than its predecessor. Nonetheless, one failure developed in a 30-watt inverter which incorporated the A-500 vibrator. The malfunction occurred during laboratory prefiring tests of the September, 1955, University of Michigan Aerobee (USAF 58). A replacement was installed and no further difficulty was encountered. The defective inverter has been returned to the manufacturer for determination of the cause of failure.

In spite of the factors mentioned above, one can generalize at least to some extent regarding inverter dependability as follows:

1. A total of 18 Airpax inverters have been obtained by the project in the last five years. Of this number, 11 have been flown in missile instrumentations with no failures observed.

2. Four failures during laboratory testing not ascribable to negligence have been encountered. In each case, the failure occurred with a relatively small number of total operating hours on the inverter.

3. The remaining units either have been utilized in laboratory testing or are presently considered suitable for future flights.

4. When maximum reliability is required, it appears desirable to bench test each inverter for 5 to 10 hours under the anticipated load. A number of starts and stops should be included in the procedure and the output-voltage waveform should be checked for evidence of abnormal behavior.

The foregoing comments summarize the accumulated experience and project opinion to date. They should not be construed as a final judgment, but rather as a guide to provide more satisfactory utilization of the Airpax inverter in the future.

REMOTE-CONTROL SYSTEM

Included in Fig. 5 is a portion of the circuitry which provides the means for remote control of missile instrumentation. In addition to the control and monitoring functions described in the preceding section on inverter applications, the remote-control box includes a push-button switch to energize the gyro-control Ledex and a meter to indicate the position of the gyro-control Ledex wafer switch. This is accomplished by the voltage divider connected to switch S_2A. When it is necessary to conserve pull-off plug leads, the Ledex position indicator is definitely advantageous since only one lead and ground is required to convey all the necessary information. In this regard, the inverter "on" light will be recognized as a somewhat redundant, albeit useful, aid to the operation when sufficient remote-control leads are available.

The circuitry discussed above constitutes one independent and flexible control channel. Experience has shown that a 32-wire remote-control cable can accommodate 6 such control channels and various other features which are common to the complete system. The features which contribute to increased versatility of the system are as follows:

1. Pull-off plug Ledex—This circuit shown in Fig. 5 (S_3A through S_3D) is actuated just prior to missile take-off and serves to disconnect the pins of the pull-off plug. Thus, any damage to the missile-borne section of the plug will not cause malfunction of the instrumentation circuitry.

2. Master "on" light—When several or all of the channels are utilized for control of the missile instrumentation, the master "on" light assists the operator by indicating when all the instrumentation-control Ledexes are in the "take-off" or "fire" position. This is accomplished by a single-series circuit through all the Ledexes, which is arranged to have continuity only when each switch is in its proper position for take-off.

3. Battery charging—Provision is also made for remote battery charging in this control system. Meters are provided to monitor both charging current and battery terminal voltage. To conserve battery power, a charger with sufficient capacity to float the complete battery load and its attendant line drop is desirable. In practice this means that a power supply capable of supplying 5 to 10 amperes at 50 volts will usually be adequate for a 24-volt missile battery. This technique makes the instrumentation performance virtually independent of interruptions in the firing schedule caused by weather or other unforeseen difficulties, at least as far as batteries are concerned.

4. Monitoring-meter return circuit—When large amounts of current are being supplied to the instrumentation, the potential drop in the common (ground)

return line often is as much as 10 volts. To alleviate the consequent problem in the monitoring-meter circuits, all voltmeter grounds are paralleled (but not grounded) in the remote-control box. The meter common point is grounded in the missile via a separate lead from the control box. The total meter return current is only a few milliamperes and line drop in the circuit is negligible; accurate monitoring of instrumentation voltages is therefore possible.

5. Communication—Under some circumstances it has proven helpful to have a communication link from blockhouse control to instrumentation which is not subject to interruption. This can be accomplished during prefiring checks by assigning one pull-off lead for use with sound-powered phones. Prior to pull-off plug connection, the phones can be connected directly to the missile tower section of the plug. After connection of the pull-off plug to the missile, a simple phone jack mounted somewhere on the missile nose cone serves to provide the connection.

INVERTER CHANGEOVER CIRCUIT

When additional 400-cycle power-system dependability is desired, an automatic switching circuit can be utilized to transfer the load from one inverter to another in the event of supply failure. Figure 6 shows a changeover circuit suitable for this purpose. It is necessary to have both inverters operating for the system to be effective and, in addition, during the starting process the "main" inverter must be energized prior to the start of the auxiliary inverter. The system illustrated can be further cascaded if the need arises.

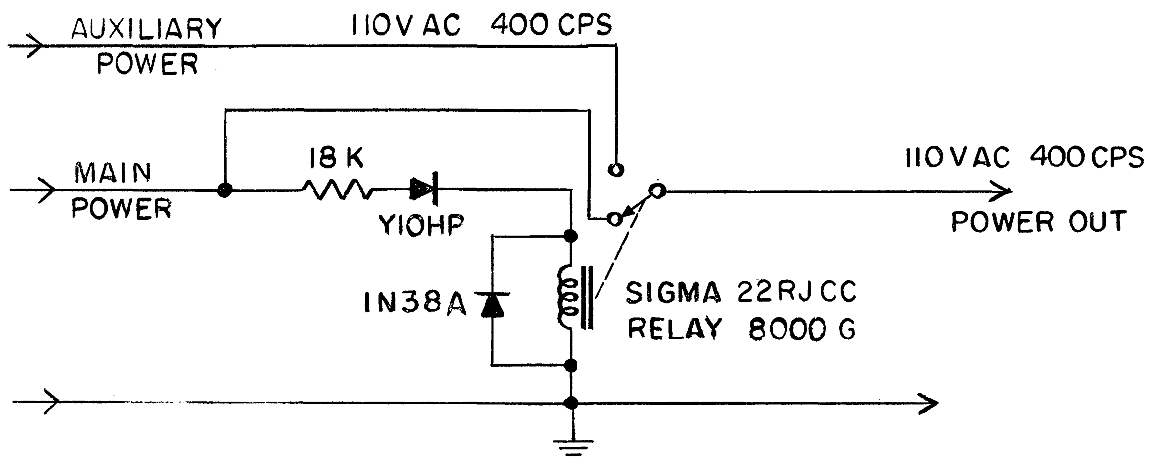


Fig. 6. Inverter changeover circuit.

REGULATED POWER SUPPLY

A small electronically regulated power supply has been developed for missile use in conjunction with the inverter power source. Figure 7 is a circuit diagram of the supply, which utilizes standard parts throughout.

The circuit will supply 50 milliamperes at 125 volts with less than 10 millivolts ripple when operating from a 15-watt inverter. A 1-volt variation in the 24-volt inverter supply produces less than a 100-millivolt change in the regulated output voltage. A balanced load for the inverter is provided by the two selenium rectifiers arranged in a full-wave voltage-doubler circuit. With this circuit, ground can be established at either the a-c input to the supply or the d-c output, but not both. Subminiature tubes are employed for V_1, V_2, and V_3. V_4 is a ruggedized version of the standard 5651 voltage reference tube.

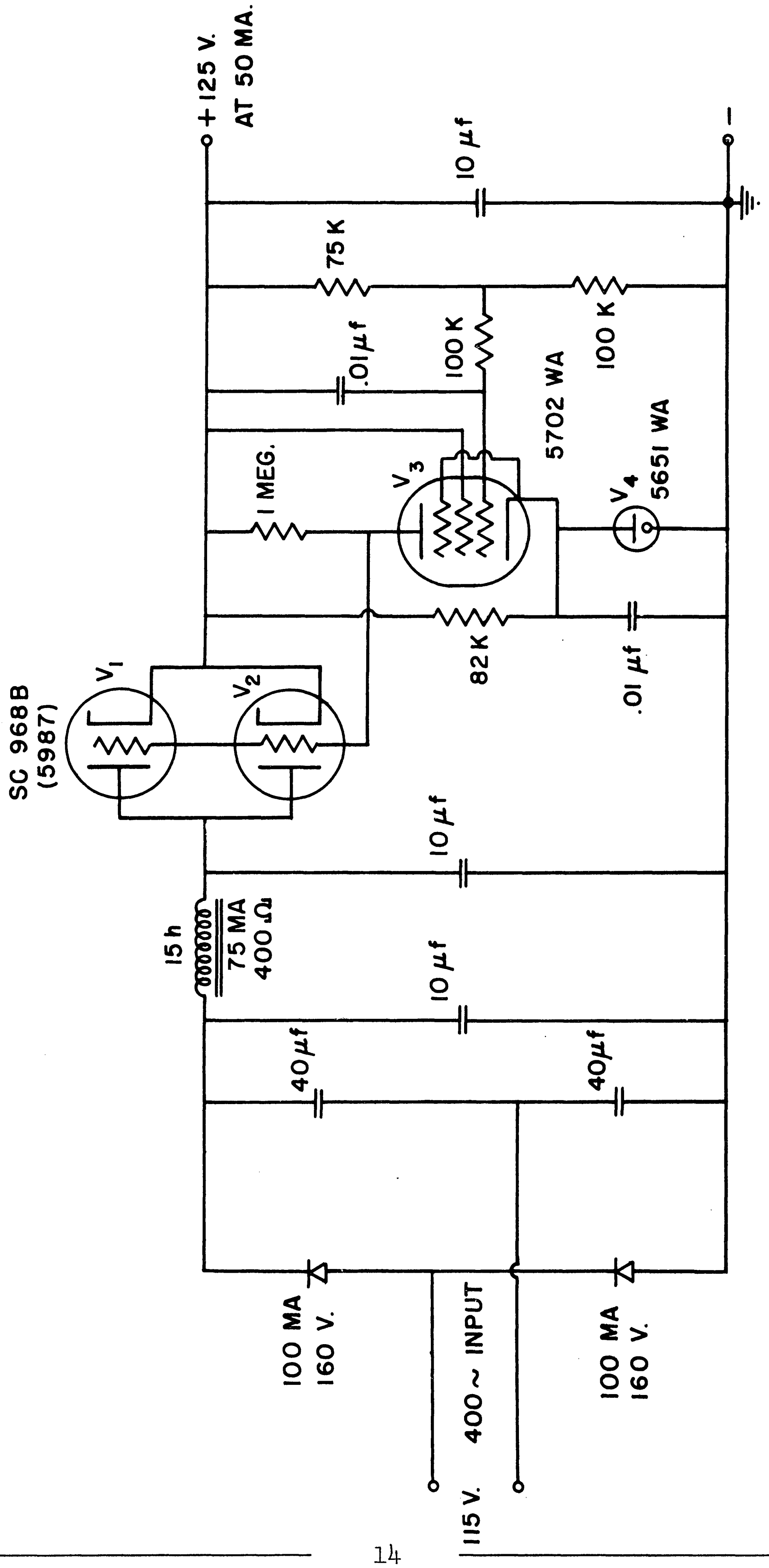


Fig. 7. Regulated power supply.