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CRITICAL ELECTRICAL ASPECTS OF ALTERNATING-CURRENT POWER SOURCE FOR CENTAUR SPACE VEHICLE

By Maurice F. Baddour and John P. Quitter

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A solid-state inverter is used on Centaur to supply high-quality three-phase electric power to the guidance, autopilot, and propellant utilization systems. (Centaur is a high-energy, cryogenic-fueled second-stage vehicle.) The results of a test program to evaluate the design and performance of this inverter are described herein. The scope of the program is concerned primarily with measurements on internal parts of the inverter while it was subjected to extreme service conditions.

Detailed data are presented on electrical and thermal design margins. Special attention is directed toward transient susceptibility and the effect of source impedance variations. Significant wave shapes are shown, and their implications are examined. Test failures and critical weaknesses in the system are analyzed, and design improvements are proposed.

These improvements were incorporated into the inverter and verified by test. Subsequent flight performance has been excellent, and the inverter has provided three-phase electric power of high quality at 400 hertz to the Atlas-Centaur launch vehicle on 14 flights.

INTRODUCTION

Rectifiers are commonly used to convert alternating current to direct current because of their unidirectional conductance properties. If the period of conductance is controlled, rectifiers may be used in appropriate circuitry for the inverse function of converting direct current to alternating current. This function is called "inversion," and the equipment which performs it is called an "inverter."

Rotating machines were originally used for this purpose on aircraft and aerospace vehicles. They are heavy and inefficient (typically 50 percent) and often are rated for intermittent duty. Today, solid-state inverters using silicon semiconductors have been developed to overcome the disadvantages of the older equipment. The inverter described in this report uses silicon controlled rectifiers (SCR's), is 70 percent efficient, and is rated for continuous duty.

This report is concerned with the understanding and improvement of circuit design details essential to reliable performance. Specifically, this study and testing program investigated certain critical aspects and phenomena associated with SCR's, in particular those factors contributing to marginal performance of the Centaur inverter. Chief among these is the timing and amplitude of the pulses controlling SCR conductance.

In pairs, SCR's serve as fast-acting synchronous switches to commutate or release stored energy alternately to each half of a transformer winding. Both halves of an alternating current wave are thus generated. Polyphase operation requires two SCR's for each phase. The triggering or "firing" circuits for SCR's must supply voltages and currents that fall within prescribed limits. SCR firing characteristics are temperature dependent, as are associated circuit element characteristics; yet they all must remain compatible over the temperature range. In addition, spurious firing signals or transients must be eliminated to avoid false or asynchronous triggering which leads to electrical short circuits.

Another area of concern was excessive localized temperatures of critical components such as commutating capacitors and SCR junctions. These temperatures were examined. Finally, it was observed that the inverter performed differently when supplied with external power (ground mode of operation) than it did on internal battery power (airborne mode of operation). The cause of this behavior was determined, and certain operating criteria were established.

These inverter tests were part of a comprehensive Centaur ground test program initiated by the Lewis Research Center and General Dynamics, the Centaur contractor. Several inverter failures at the factory and at the launch site led directly to this investigation, because the knowledge then available was not sufficient to explain the problems nor afford solutions. With the cooperation of the inverter manufacturer and vehicle contractor, this investigation and test program was begun. It included a critical review of the entire circuit design and component parts, the verification of performance and environmental limitations, and the making of recommendations for necessary improvements.

The Centaur inverter is rated at 650 volt-amperes, 115 volts, 3 phases, and 0.8 lagging power factor. Performance specifications and the inverter circuit diagram are given in the appendix. This inverter consists of the following stages:

(1) A crystal oscillator for generating a stable signal of precise frequency

(2) Countdown circuits to obtain pulses of the correct frequency and amplitude

(3) A ring counter to store and sequentially release control pulses to trigger the silicon controlled rectifiers for three-phase operation
(4) Three SCR power stages, including transformers and filters
(5) Magnetic amplifier regulators for each phase
(6) A low voltage direct-current power supply
(7) An overload protection circuit

TEST PROCEDURE AND EQUIPMENT

ELECTRICAL TESTS

Functional Tests

Functional tests of the inverter were made to verify compliance with the design specification. The following variables were measured with both resistive and reactive loads on the inverter:

(1) Input and output voltages and currents - no load
(2) Input and output voltages and currents - full load
(3) Frequency, waveform distortion, and phase angle

The electrical connections and instrument list are given in figure 1. Resistive load tests were conducted for direct-current input voltages of 25, 27.5, and 30 volts. Reactive load tests were conducted with an input of 27.5 volts, and power factors of 0.9, 0.75, and 0.5, lagging and leading.

Phase measurements were made with a digital frequency meter, indicating time in microseconds between zero axis crossings of two phases.

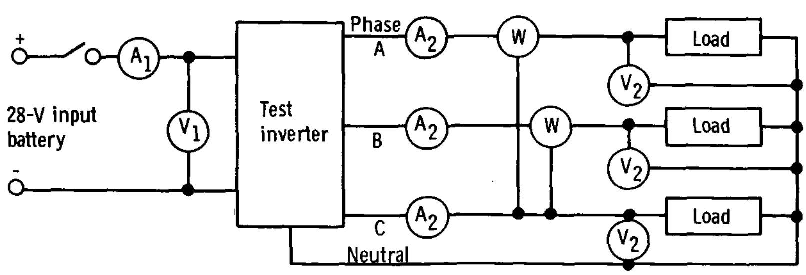


Figure 1. - Inverter test setup. A_1, direct-current ammeter, ±1 percent accuracy; V_1, digital voltmeter, ±1 percent accuracy; A_2, alternating-current ammeter, 1 percent accuracy; V_2, digital voltmeter, ±1 percent accuracy; W, alternating-current wattmeter, ±1 percent accuracy; oscilloscope, dual channel; digital frequency meter, 1×10^{-6} accuracy; digital frequency meter, 1×10^{-7} accuracy; distortion analyzer, ±3 percent accuracy.

Special Circuit Tests

The following special circuit tests were made to check the system performance.

Low voltage operation. - Incipient circuit failure can often be detected by lowering the input voltage. Oscillator and countdown circuits were evaluated for marginal performance by decreasing the direct-current input voltage until signal failure occurred. Similar tests on the ring counter or shift register were run to establish design margins for adequate drive and freedom from spurious pulses.

Overload tests. - Output voltage was measured at 100 percent overload to check reserve margins. Specified maximum capability was determined by applying an additional 70 percent overload for 4 minutes. Short-circuit protection was checked by momentarily connecting each phase to neutral. Three randomly selected SCR's were substituted individually in the protection circuit to ascertain that protection was independent of semiconductor variations.

Transient investigation. - Transient effects are of considerable interest in the operation of the inverter. For example, noise on the input line, caused by the rapid switching action of the SCR's, may adversely affect other systems. Photographs of oscilloscope traces were taken to check the effectiveness of the input filter in reducing the noise.

Recovery time on application of load is important, so that user systems are not subject to low voltage for a significant time. These data were obtained with the oscillograph by direct examination of wavefronts.

Many important SCR switching phenomena occur in microsecond time intervals. Waveshape control for these short durations is essential to avoid possible damaging transients. Testing consisted of switching reactive loads on and off, while observing SCR cathode currents by a current probe and oscillograph. Voltage transients were also observed simultaneously.

Effects of input impedance on inverter operation. - The effect on startup conditions of long lines between the ground power supply and the inverter was investigated. Long lines exhibit not only resistance, but also inductance and capacitance. In this case, capacitance is negligible. A battery of negligibly low impedance was used as a source. Gradually increasing values of resistance and inductance were switched into the circuit to simulate various line lengths. The effect of the ratio of inductive reactance to resistance, known as Q, was also determined. These startup conditions are transient phenomena of short duration and must be examined oscillographically. A 10-megahertz response of the test equipment is considered adequate.

Line impulse tests. - The effect on steady-state operation of momentary voltage dips on the input line was observed. Such input transients may occur when solenoid valves or pyrotechnic devices are actuated. Again, the oscilloscope and photographic techniques were employed.

Thermal Tests

The maximum allowable junction hot spot temperature of the SCR's sets the maximum operating temperature of the inverter. Because the case temperature is the operating criterion, its relation to the SCR must be known. Because it was not possible to place a thermocouple directly at the junction, it was located on the heat sink near the center of the SCR cluster. The temperature increment from there to the junction is small and accurately known.

Finally, an evaluation of all the component parts was made in light of the test results, and in comparison with the highest quality parts available. Specific recommendations are included in this report for upgrading the next generation of Centaur inverters.

RESULTS AND DISCUSSION

ELECTRICAL TESTS

Functional Tests

Data for voltage, current, power, frequency, efficiency, distortion, and phase-angle tests are given in tables I to III. The efficiency is greatest at full load and at high power factors and falls off rapidly as either load or power factor decreases. During all tests, the frequency remained within specifications.

These tests verified that the inverter was functioning properly. All measurements were taken externally and gave no clue as to internal critical design aspects. The remaining sections of this report are concerned with these internal features.

Special Circuit Tests

Low voltage operation. - Starting at 30 volts dc, the input voltage was gradually lowered. In the region from 27.0 to 26.5 volts, a slight change in oscillator waveform was observed, but this did not affect the inverter output. The waveform was normal between 26.5 and 24.0 volts. Below this value, the oscillator output amplitude decreased and the waveform became irregular. This condition may arise when the inverter is operated at the end of a long line from a ground power supply, as at the launch site. When the input voltage falls below the Zener value of the regulator diode CR1, the regulator function is lost. Some of the ground failures of the inverter are now attributed to this

TABLE I. - RESISTIVE LOAD TESTS

Load	Input				Output				
	Voltage, V	Current, A	Power, W	Efficiency, percent	Phase	Voltage, V	Current, A	Power, W	Frequency, Hz
25-V input									
None	26.53	9.3	247	0	A B C	112.9 113.9 113.2	0 0 0	0	400.0 400.0 400.0
One-fourth	26.16	15.75	412	38.7	A B C	112.5 113.5 112.6	0.49 .465 .452	159	400.0 400.0 400.0
Full	25.51	38.5	985	66.6	A B C	112.1 112.3 111.9	1.90 1.91 1.90	656	400.0 400.0 400.0
27.5-V input									
None	28.5	9.0	256	0	A B C	113.7 113.7 113.8	0 0 0	0	400.0 400.0 400.0
One-fourth	28.4	14.75	419	38.2	A B C	113.4 113.5 113.5	0.49 .463 .455	160	400.0 400.0 400.0
Full	27.75	36.0	1000	66.2	A B C	113.4 112.8 112.9	1.89 1.89 1.89	662	400.0 400.0 400.0
30-V input									
None	30.61	8.8	269	0	A B C	114.3 113.9 114.3	0 0 0	0	400.0 400.0 400.0
One-fourth	30.54	14.25	436	36.8	A B C	113.7 113.4 113.7	0.49 .463 .453	160	400.0 400.0 400.0
Full	29.65	33.0	979	66.7	A B C	113.4 112.7 113.0	1.91 1.90 1.91	653	400.0 400.0 400.0

TABLE II. - POWER FACTOR LOAD TESTS

(a) Inductive load tests

Power factor[a]	Output						Input			Efficiency,[a] percent
	Phase			Current, A	Power, W	Power,[a] VA	Voltage, V	Current, A	Power,[a] W	
	A	B	C							
	Voltage, V									
0.891	112.7	112.5	112.1	1.9	570	641	26.4	33.0	871	65.5
.748	112.8	112.3	112.2	1.9	480	642	26.5	28.0	742	64.8
.518	113.2	112.7	112.4	1.88	330	636	26.6	21.5	571	57.8

(b) Capacitive load tests

Power factor[a]	Output						Input			Efficiency,[a] percent
	Phase			Current, A	Power, W	Power,[a] VA	Voltage, V	Current, A	Power,[a] W	
	A	B	C							
	Voltage, V									
0.912	112.6	112.5	112.0	1.9	586	642	26.35	36.0	949	61.9
.757	112.9	112.5	112.3	1.9	486	643	26.45	33.0	869	55.9
.511	113.4	112.5	112.7	1.9	330	646	26.40	26.5	700	42.9

(c) Values calculated for reactive power factors per phase (full load)

Power factor[a]	Power, W	Resistance, ohms	Volt-amperes reactive, VARS	Inductance, mH	Inductive reactance, X_L, ohms	Capacitance, C, μF	Capacitive reactance, X_c, ohms
0.9	195	67.5	94	55.5	141	2.8	141
.75	162	81.5	143	36.7	92.5	4.3	92.5
.50	109	121.0	188	28.0	70.5	5.6	70.5

(d) Harmonic distortion tests at power factor of 1; direct-current input, 27.5 volts; balanced load on all phases

Load	Phase		
	A	B	C
	Distortion, percent		
None	1.82	1.75	1.79
One-half	2.26	2.18	2.23
Full	3.22	3.15	3.30

[a]Values computed from the other columns (measured). The output current was adjusted to full load value with the load resistor.

TABLE III. - PHASE DISPLACEMENT TESTS

Line-to-line	Load					
	None		One-fourth		Full	
	Displacement,[a] μsec	Phase angle,[b] φ, deg	Displacement,[a] μsec	Phase angle,[b] φ, deg	Displacement,[a] μsec	Phase angle,[b] φ, deg
A-B	831.7	119.5	832.7	119.9	825.5	118.8
B-C	842.0	121.3	840.4	121.1	841.5	121.25
C-A	828.0	119.3	828.6	119.35	834.5	120.2

[a]Measured period, 2499.8 μsec.
[b]φ (deg) = $[\varphi(\mu sec)\ (360^\circ)]/2499.8$; (maximum limit, $120^\circ \pm 2^\circ$).

cause. This low voltage characteristic also accounts for susceptibility of the inverter to negative input transients.

Changing the Zener diode CR1 from 1 watt at 22 volts to 10 watts at 18 volts corrected this problem. This change not only improved operation of the oscillator and countdown circuits at low voltages, but also improved the regulation characteristics because of the lower dynamic impedance of the 10-watt Zener diode.

The low-voltage tests also showed that the drive to the ring counter or shift register was adequate. Approximately 100 percent margin was available to trigger the SCR core driver. A tendency to generate double pulses was discovered, however. This tendency may cause improper firing of the main SCR's, and could lead to inverter dropout, depending on the particular pulse combination randomly generated. This condition was corrected by the addition of a resistor in the anode circuit of the core driver SCR.

The elimination of double pulsing in the shift register along with the improved regulation of the oscillator-countdown circuits has improved the reliability of operation. Inverters incorporating these changes recover from input transients quickly, and unexplained dropouts due to misfire of the main SCR's no longer occur.

Overload tests. - On application of a 100-percent overload to all phases, output voltage dropped from the normal 115 to 100 volts. This voltage drop is within specification, and the inverter will operate indefinitely under this condition. Application of an additional 70-percent load (totaling 5.35 A/phase) caused the output voltage to drop to 89 volts. This drop is normal, and it demonstrates that excess heating or catastrophic failure does not occur during the specified 4 minutes of additional overload operation.

Phase-to-neutral short circuits caused normal actuation of the self-protection or circuit breaker feature of the inverter. Since operation of this circuit is highly dependent on characteristics of the control SCR, three SCR substitutions were made at random, without circuit adjustment. Self-protection was retained, and the inverter resumed normal operation after removal of each short circuit.

Transient investigation. - Oscilloscope measurements were made on the input direct-current line on both sides of the input filter FL-1. Figures 2(a), 2(b), and 2(c) show recurrent 2400-hertz peaks accompanied by "ringing." This ringing frequency is approximately 35 kilohertz, which agrees with the self-resonant frequency calculated from the circuit constants of the filter. As the inverter load is increased, the amplitude of the transient decreases.

The following data and calculations show the magnitude of the transients:

Load			Input current, I_{dc}, A	Input resistance,[a] R, ohms	Peak voltage,[b,c] E_p, V	Peak current,[b,c] I_p, A	Input impedance,[d] Z, ohms	Peak power,[e] P_p, W
None	One-half	Full load						
Input voltage, E_{dc}, V								
29.0	----	27.7	35.5	0.037	2.0	50	0.04	100
28.9	28.0	----	21.5	.042	2.2	50	.044	110

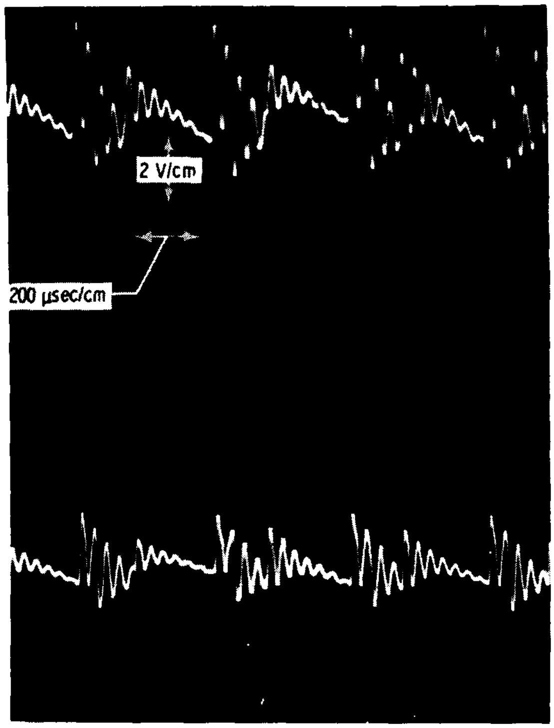
[a]Calculated from $(\Delta E_{dc})/I_{dc}$, where ΔE_{dc}, the line voltage loss, is $E_{no\ load} - E_{load}$.
[b]Peak values of voltage and current are in phase.
[c]Scaled from figs. 2(a) to (c).
[d]Impedance, $Z = E_p/I_p$.
[e]Peak power, $P_p = I_pE_p$.

When the load was switched on and off, the inverter recovered from the transient condition in about 10 periods of the 400-hertz wave, or 25 milliseconds. This time constant is acceptable to the guidance system.

Although this inverter normally is loaded inductively, it is of interest to study operation with capacitive loads, especially when these loads are switched on and off. This condition causes transient currents which may degrade the SCR's, especially for rapid cycling.

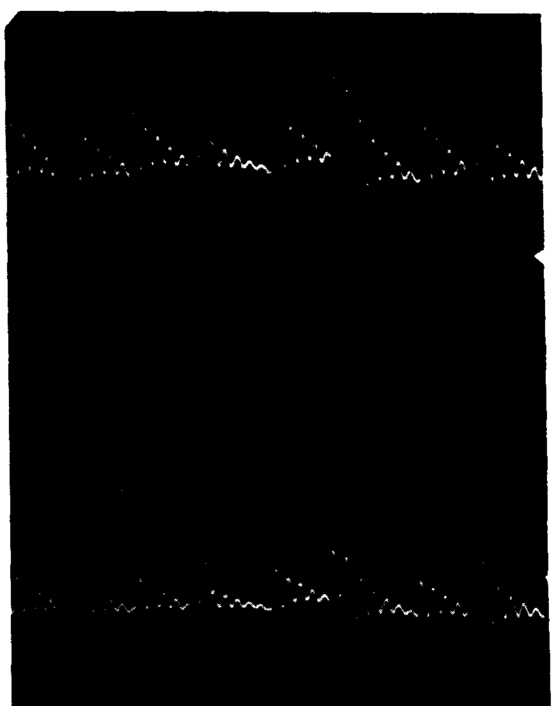
The inductive load tests were conducted slowly enough so that momentary heat generated at SCR junctions could have time to dissipate. In the capacitive tests, 0.5-microfarad loads per phase were switched in and out of the circuit every 7 or 8 seconds for 6 minutes. Then the inverter itself was cycled off and on for similar duty cycles and time. One SCR failed completely as a result. Two SCR's indicated rounding of the sharp knee of the Zener characteristic, a condition indicating junction degradation.

The magnitude of these deleterious effects was assessed by repeating the switching



(a) Inverter side of filter; one-half output load, 325 watts; input voltage, 28 volts dc at 21.5 amperes.

(b) Battery side of filter; one-half output load, 325 watts; input voltage, 28 volts dc at 21.5 amperes.



(c) Inverter side of filter; full output load, 650 watts; input voltage, 27.5 volts dc at 35.5 amperes.

(d) Battery side of filter; full output load, 650 watts; input voltage, 27.5 volts dc at 35.5 amperes.

Figure 2. - Input direct-current line steady-state transients. Filter, FL-1.

operations slowly with new SCR's, so that heating effects would not accumulate. A current probe and an oscilloscope were used to measure the transient currents.

When the load was switched, 30-ampere peak-load currents occurred with corresponding peak SCR currents of 15 amperes. When the inverter itself was switched on and off, these values were reduced to 5.3 amperes peak for load current and 8 amperes peak for the SCR's.

These values compare favorably with the 50-ampere peak recurrent rating of the SCR (type 2N685A). Subsequent marginal operation of the SCR's due to the altered characteristic is attributed to a combination of the effects of previous heat tests and later localized heating in the transient tests.

In addition to the SCR current transients just described, SCR voltage transients are also important. These transients occur as a result of switching commutating capacitors (C18, C23, and C28) alternately across each half of the output transformer primary. The combination of inductance and capacitance presents results in the voltage transients shown in figure 3. All the commutating SCR's throughout the inverter show similar waveshapes. Figure 3 shows typical anode-to-cathode voltages for various input conditions.

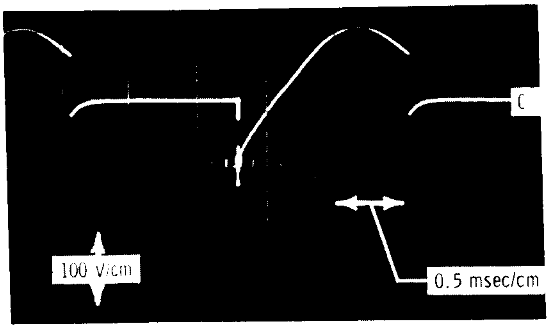
The horizontal trace is taken as zero potential because it represents a negligible voltage drop across the SCR during firing. The transients were observed for both no-load and full-load conditions, while input impedance was varied. Figures 3(b) and 3(d) show that the full-load transient is about twice as large as the no-load transient of figures 3(a) and 3(c), when the SCR is switched off. The magnitude of this transient is -130 volts at no load and -230 volts at full load.

The mechanism by which this transient is generated is of interest. It is caused not by the actual turnoff of a given SCR, but rather by firing the opposite member of a pair. This SCR attempts to drive part of its firing current through the high reverse impedance of the quiescent SCR. Close examination of this sharp transient shows that the pulse width is 0.1 microsecond at the 10-percent level.

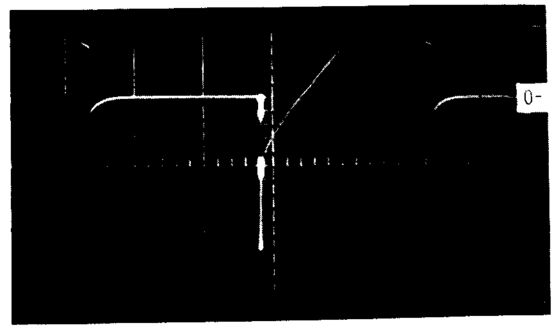
The peak inverse voltage rating of the 2N685A SCR is 200 volts. This rating is exceeded under full-load conditions. The rating is not absolute however, but is time dependent and provides a safety margin.

Figure 3 also shows that the amplitude of the transient is independent of the input line impedance, that is, the same for the various ground sites where the inverter is used. For example, figures 3(c) and 3(d) show operation under direct-current line conditions simulating those at the launch site, namely, 0.038 ohm resistance and 0.6 ohm inductive reactance.

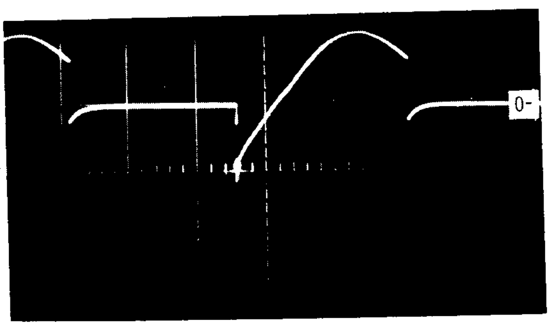
These figures further show that after an SCR is turned off, voltage across it increases sinusoidally for one-half cycle, after which it is again triggered on. At this time, the slope of the wave is steep. However, in this case the low forward resistance



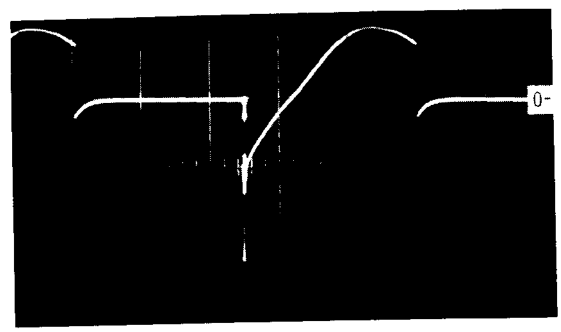
(a) No-load voltage; direct-current line impedance, 0 + j0 ohm.



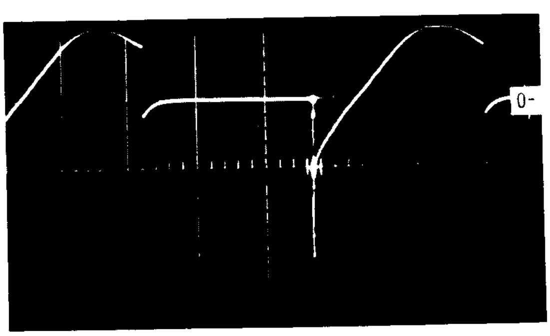
(b) Full-load voltage; direct-current line impedance, = 0 + j0 ohm.



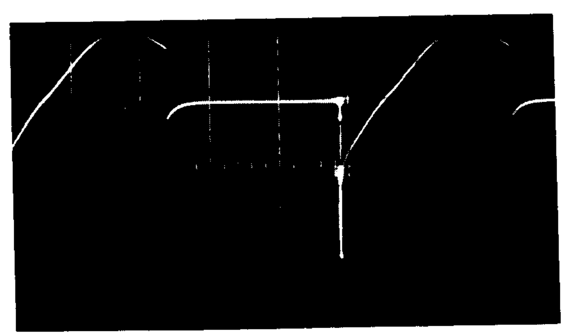
(c) No-load voltage; direct-current line impedance, 0.038 + j 0.6 ohm.



(d) Full-load voltage; direct-current line impedance, 0.038 + j 0.6 ohm.



(e) Full-load voltage; direct-current line impedance, 0 + j 1 ohm.



(f) Full-load voltage; direct-current line impedance, 0 + j 3 ohms.

Figure 3. - Silicon controlled rectifier, CR-28 (typical), voltage transients. Battery voltage, 27.5 volts dc.

of the SCR and the dampening effect of the load prevents the development of large transients.

Since the rise of forward voltages is sinusoidal, its derivative dv/dt is not large and falls well within the SCR specifications, which permits a rise of 25 volts per microsecond. The figures show that approximately 900 microseconds are actually required for an increase of about 200 volts.

Effects of input impedance on inverter operation. - After several unexplained inverter failures occurred during ground operation, it was concluded that insufficient information and knowledge were available about this mode of operation. Because of the 1000-foot (300-m) lengths (or more) of wire at the launch site, it was necessary to learn how these lengths affected inverter performance. Because of the large current peaks drawn by the inverter, resistance and inductance values of the direct-current line are critical. A brief discussion of the phenomena involved should prove useful in understanding them.

In the Centaur inverter, series resonance of the commutating capacitor and associated inductances develops maximum voltage on the primary of the output transformer. The inductances consist of the element in series with the input line and half the transformer primary. To minimize voltage drops due to winding resistance, the input inductance value is limited to 100 millihenries. Therefore, small values of inductive reactance on the input line will alter the resonant frequency of the combination and affect starting conditions.

Voltage drops across resistance and reactance elements in the input circuit lower the voltage to the inverter, both statically and dynamically. This condition is further aggravated by the load regulator of the inverter. The regulator is designed to maintain constant inverter output voltage. In so doing, the input current is increased to maintain a constant product of voltage and current. The increased current increases circuit losses, reduces efficiency, and increases internal heating.

If the input impedance is sufficiently high, input current will be large enough to activate the self-protection circuit, which cannot distinguish between this condition and a true overload. Activation of the self-protection circuit occurs whenever the inverter is turned on in these circumstances, and the inverter will fail to start through no internal fault. Instead, so called "multiple start" attempts occur, in which the time constant of the self-protection circuit will cause this circuit to cycle on and off at 0.2-second intervals. Such malfunction has been observed, especially when line resistance increases because of heating and the ground supply voltage is low.

There are three events which must occur in proper sequence to start the inverter:

(1) At turn-on, 28 volts dc are applied to a trigger power supply which develops alternating-current voltage. This voltage is transformed, rectified, and applied to the trigger circuit.

(2) The trigger circuit fires the overload SCR which applies the 28 volts dc to the rest of the inverter.

(3) The oscillator is then energized and applies pulses to the main SCR's through the countdown circuit at a rate of 2400 hertz. Since the output is three phase and each phase consists of two SCR's in push pull, the resultant output is 400 hertz.

The pulses at the trigger electrodes or gates of the main SCR's must be phase-correlated to the oscillations of the resonant charging circuit. If not, misfires occur. If two or more SCR's attempt to fire simultaneously, the resultant short circuits draw excess current which actuates the self-protective circuit.

If the resistance of the input circuit is large, the selectivity or Q of the resonant charging circuit is lowered, resulting in lowered voltage across the elements. If this voltage is not sufficient to switch off an SCR, both members of a pair may remain on, resulting in a virtual short circuit. In this case, the over-load circuit is actuated and turns the inverter off.

If the inductance of the input circuit is large, the resonant frequency of the series circuit will be lowered. If this effect is great enough, the resonant rise in voltage at the commutating capacitors will not coincide with the firing pulse at the SCR gate. A misfire results.

The magnitudes of excess resistance and inductance for the input circuit were investigated using lumped parameters and a battery source of negligibly low impedance. Both steady-state and startup conditions were investigated.

Steady State

In order to define starting limitations, the input resistance was increased from a value of 0.02 to 0.15 ohm (see curve 1, fig. 4). Above this value, consistent starts or sustained operation would occur only if the inverter was not loaded. During this adverse condition, the input voltage to the inverter dropped to 20.35 volts, and the current rose from the normal value of 36.5 to approximately 46 amperes. It should be recalled that heating effects are proportional to the square of the current.

An input resistance of 0.15 ohm dissipates 317 watts of power, or approximately half the rated output of the inverter. Overall system efficiency under this condition is 50.6 percent compared with the normal value of 66.4 percent (see table IV(a)).

The input and output power of the inverter, as well as efficiency, remain fairly constant over the range of test conditions. This demonstrates good regulation qualities of the inverter. Figure 4 shows that input line dissipation rises rapidly with small changes in line resistance. Although heating of the long conductors is small, the resultant current increase to the inverter causes significant internal I^2R losses.

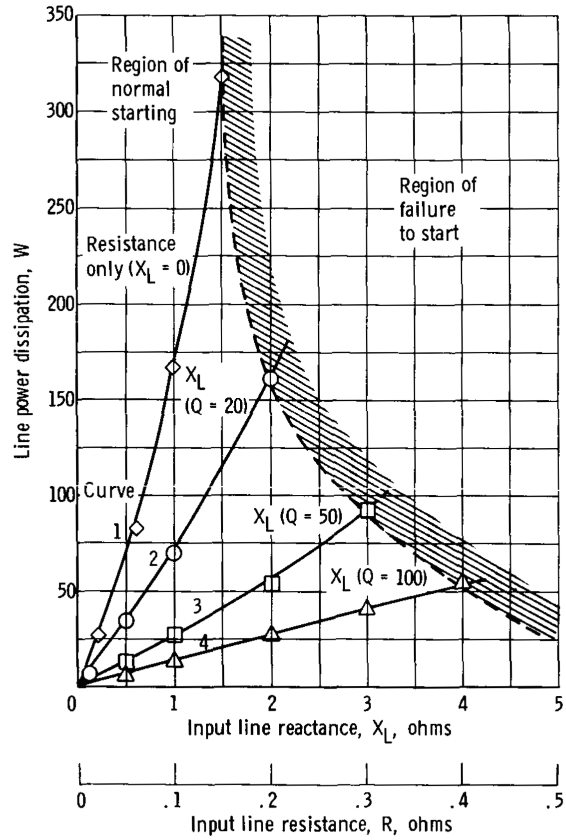


Figure 4. - Input line loss as function of resistance and inductive reactance. Battery input voltage, 28 volts; output, full load.

Since inductance is always associated with resistance and it is not practical to separate the parameters, three different inductors were chosen for the reactive tests: one had a Q of 20, another 50, and the third 100. The Q value, or figure of merit, is the ratio of inductive reactance to resistance, or X_L/R. The inductive reactance $X_L = 2\pi fL$.

For the inductor with a Q of 20, X_L was 2 ohms and R was 0.1 ohm. The inverter failed to start (see curve 2, fig. 4). Although inverter input voltage was 23.85 volts, transient peaks pulled this value below reliable starting levels. Line dissipation was 160 watts under this condition.

The tests involving inductors with Q values of 50 (curve 3, fig. 4) and 100 (curve 4, fig. 4) showed that the resistance is more critical than the reactance. A Q value of 100 permitted inductive reactance as large as 4 ohms before multiple starting occurred. Figure 4 shows critical values of R and X_L above which the inverter will not start.

TABLE IV. - LINE LOSS AS FUNCTION OF RESISTANCE AND INDUCTANCE

(a) Resistance measurements; full-load output; battery voltage, 28 volts dc

Resistance, R, ohms	Inverter input voltage, E_{inv}, V dc	Input current, I_{in}, A	Input power, P_{in}, W	Output power, P_{out}, W	Inverter efficiency, percent	Line power dissipation, P_{diss}, W	Total efficiency, percent
0.02	26.4	36.5	960	655	68.3	26.7	66.4
.06	25.1	38.0	952	650	68.2	87.0	62.6
.10	23.3	40.7	949	645	68.1	166	57.8
.15	20.35	46.0	935	635	68.0	317	50.6
[a].20	-----	-----	----	---	----	-----	----

(b) Inductive reactance measurements; full-load output; battery voltage, 28 volts dc

Inductive reactance, X_L, ohms	Inverter input voltage, E_{inv}, V dc	Input current, I_{in}, A	Input power, P_{in}, W	Output power, P_{out}, W	Inverter efficiency, percent	Line power dissipation, P_{diss}, W	Total efficiency, percent
Ratio of reactance to resistance, Q, 20							
0.02	27.24	36.0	980	655	67.0	1.3	66.8
.06	26.95	35.75	986	655	66.5	4	66.2
.10	26.70	36.25	967	655	67.8	7	67.3
.50	26.45	36.75	970	655	68.3	34	63.0
1.00	25.80	37.25	960	650	67.7	70	63.0
2.00	23.85	40.00	956	648	67.8	160	58.2
[a]3.00	-----	-----	----	---	----	-----	----
Ratio of reactance to resistance, Q, 50							
0.5	26.32	36.75	970	652	67.5	13	66.4
1.0	25.60	37.00	950	650	68.5	27	66.5
2.0	25.10	38.00	955	650	68.2	58	64.1
3.0	24.40	39.00	970	650	67.2	91	61.2
[a]4.0	-----	-----	----	---	----	-----	----
Ratio of reactance to resistance, Q, 100							
0.5	28.10	35.2	980	658	66.2	6	66.0
1.0	28.05	35.5	985	655	66.3	13	65.6
2.0	28.05	36.1	1005	651	64.8	26	63.1
3.0	28.04	36.5	1007	650	64.3	40	62.0
4.0	28.00	38.0	1010	630	62.5	58	59.0
[a]5.0	-----	-----	----	---	----	-----	----

[a]Unit did not fire.

Starting Transients

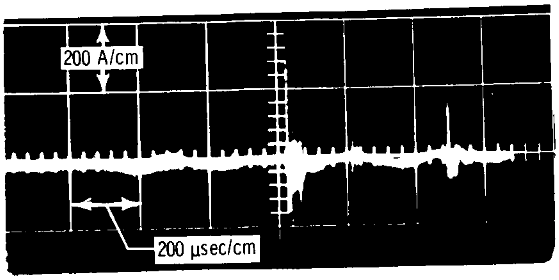
The effect of line impedance on starting transients, both voltage and current, was investigated. Figures 5 to 7 are a series of photographs taken for various values of resistance and inductance in the direct-current input line. Various time scales were employed, according to the length of the transient being observed.

Figure 5 shows the effect of line resistance on the waveshape at starting. Figure 5(a) is the condition for line resistance close to zero. A short, sharp pulse approaching 200 amperes peak is observed. Duration of the transient is considered to be too short to disturb the inverter and is reduced in magnitude for the cases of finite input impedance. Since the zero resistance case is not realized in practice, it is of academic interest only.

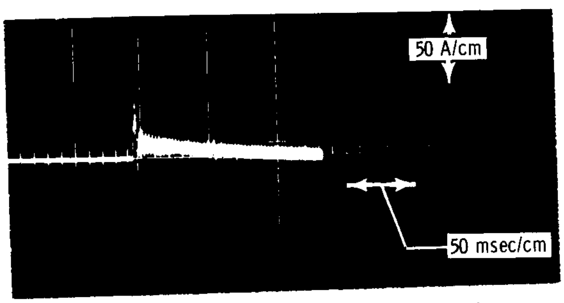
Figures 5(b) to (h) show an initial pulse of about 4 milliseconds. Its peak value is 40 amperes at no load and 55 amperes at full load. These values do not indicate excessive current stress on parts. Figure 5(i) is interesting because it shows that the inverter stops functioning after several SCR's have fired in normal sequence. This is indicated by the individual current peaks. The protective circuit has turned the inverter off as a result of a sustained overload apparently caused by misfire of one or more SCR's. No evidence of restart attempts is present. Figure 5(j) shows complete shutoff by the overload protection circuit, and a second start attempt approximately 0.2 second later. Voltage transients in all cases are the same as those of figure 2.

Figure 6 shows the effect of inductance in the input line on the inverter starting current and voltage. Figure 6(a) is the case corresponding to that of 5(a) for negligible line impedance. The starting current durations of 4 milliseconds in figure 6(b) and (c) are similar to those of figure 5. The recurrent firing peaks are approximately twice as large, however, or 15 to 25 amperes instead of 10 to 15 amperes. Figures 6(d) and (e) show corresponding voltage waveforms, in which the starting events are clear. If the left edge of the photograph is considered as T = O, a spike at 1.7 milliseconds corresponds to the application of power. At 4 milliseconds, the overload SCR conducts and current flows to the rest of the inverter. (The positive current axis is downward.) A misfire occurs at 7.4 milliseconds (fig. 6(d)) followed by restoration to normal operation.

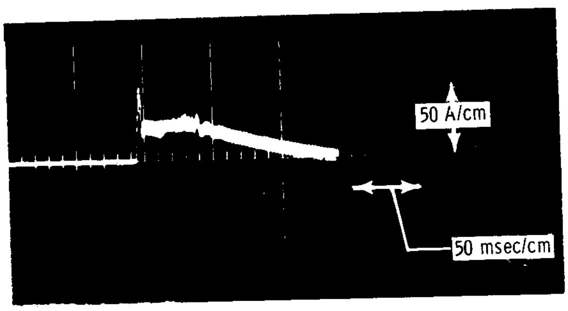
The series of photographs in figures 6(f) to (m) show operation for various input impedance and load conditions. Figure 6(h) shows a misfire after normal starting with 0.1-ohm line reactance. The misfires become more pronounced (as shown by irregularity of the waveshape) and occur more often as line reactance is increased (figs. 6(l) and (m)). Finally, in figure 6(o) a delayed start due to commutation failure is observed, and the current rises rapidly from 50 to over 100 amperes. This rise is followed by a damped oscillation due to the ringing of leakage inductance and stray capacity as the overloaded SCR opens the circuit. The second start is not shown in this figure. The inverter did operate, however, after a delayed start. Figures 6(p) to (s) also exhibit the ringing described in figure 6(o).



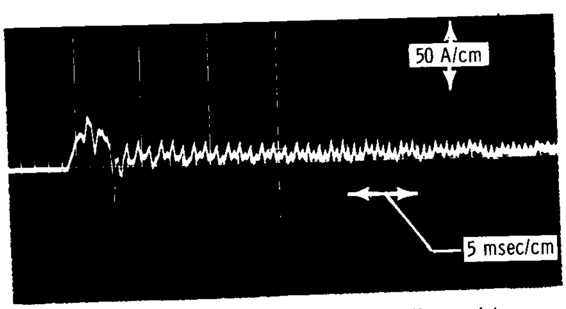
(a) Starting current, full load; direct-current line resistance, 0 ohm.



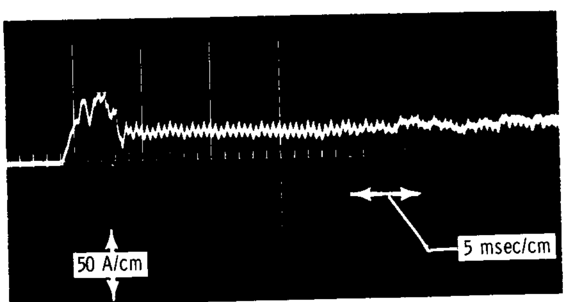
(b) Starting current, no load; direct-current line resistance, 0.02 ohm.



(c) Starting current, full load; direct-current line resistance, 0.02 ohm.

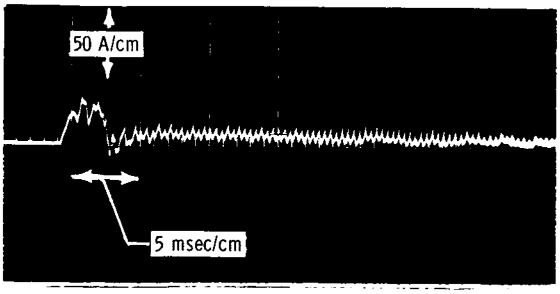


(d) Starting current, no load; direct-current line resistance, 0.06 ohm.

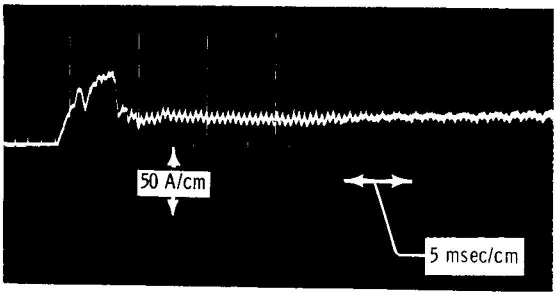


(e) Starting current, full load; direct-current line resistance, 0.06 ohm.

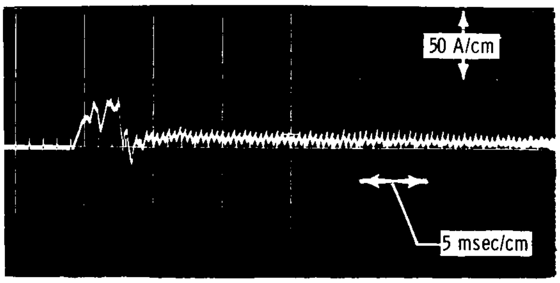
Figure 5. - Effect of resistance in direct-current input line on inverter starting. Battery input voltage, 28 volts dc.



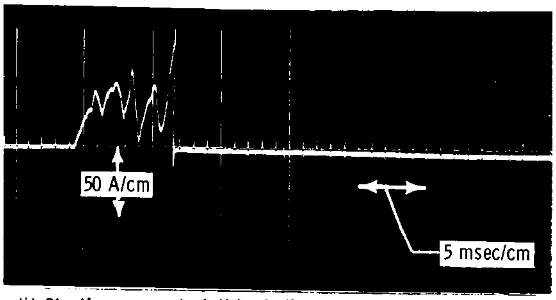
(f) Starting current, no load; direct-current line resistance, 0.15 ohm.



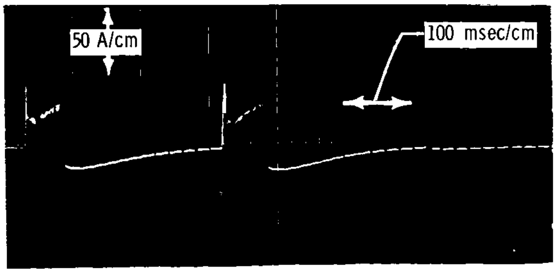
(g) Starting current, full load; direct-current line resistance, 0.15 ohm.



(h) Starting current, no load; direct-current line resistance, 0.2 ohm.

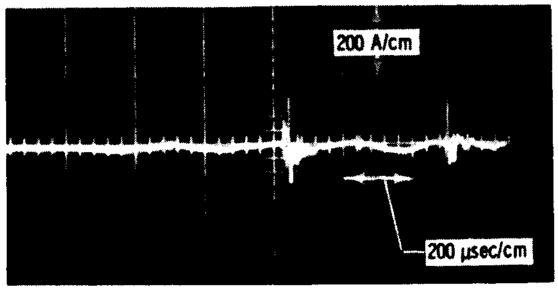


(i) Starting current, full load; direct-current line resistance, 0.2 ohm; FAILED TO START.

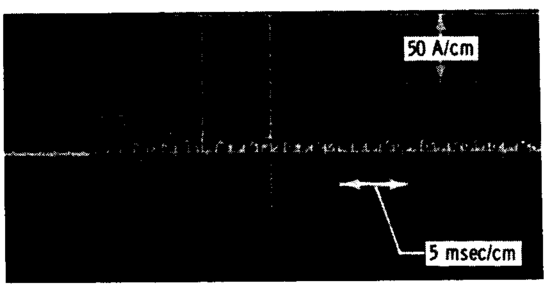


(j) Starting current, full load; direct-current line resistance, 0.2 ohm; FAILED TO START.

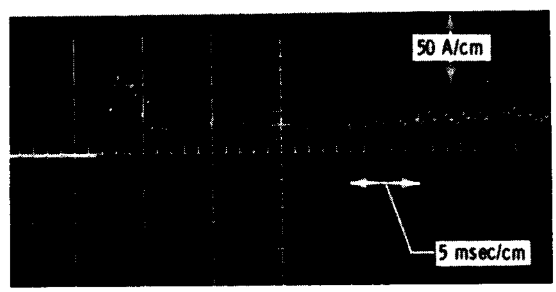
Figure 5. - Concluded.



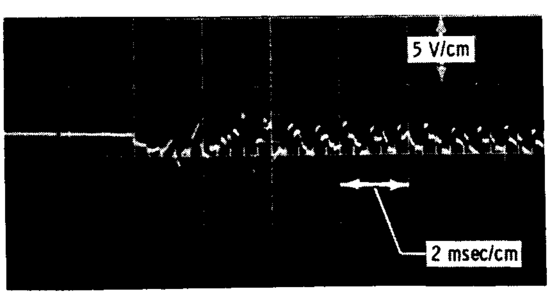
(a) Starting current, full load; direct-current line reactance, 0 ohm.



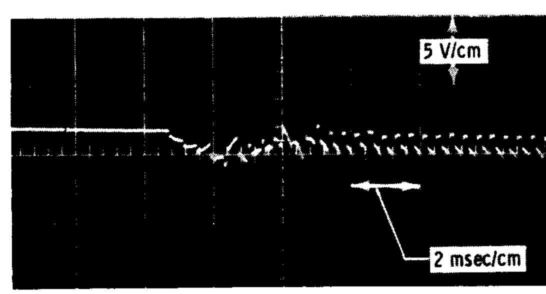
(b) Starting current, no load; direct-current line reactance, 0.02 ohm.



(c) Starting current, full load; direct-current line reactance, 0.02 ohm.

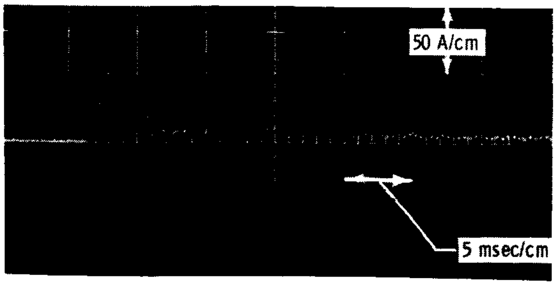


(d) Starting voltage, no load; direct-current line reactance, 0.02 ohm.

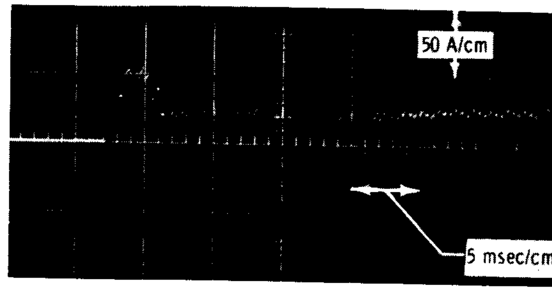


(e) Starting voltage, full load; direct-current line reactance, 0.02 ohm.

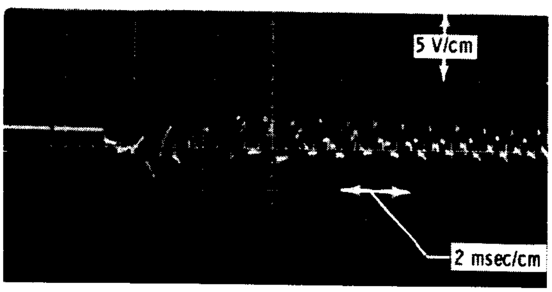
Figure 6. - Effect of inductive reactance in direct-current input line on inverter starting. Input battery voltage, 28 volts dc.



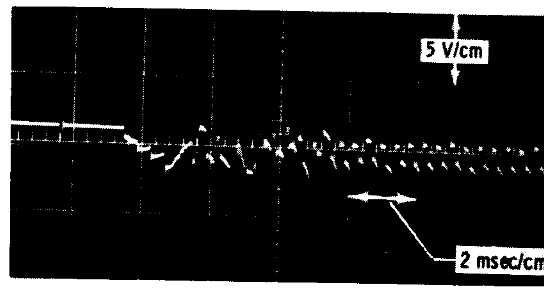
(f) Starting current, no load; direct-current line reactance, 0.1 ohm.



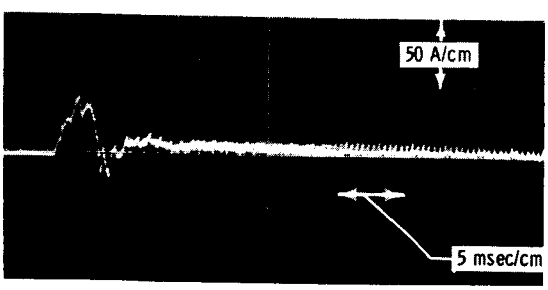
(g) Starting current, full load; direct-current line reactance, 0.1 ohm.



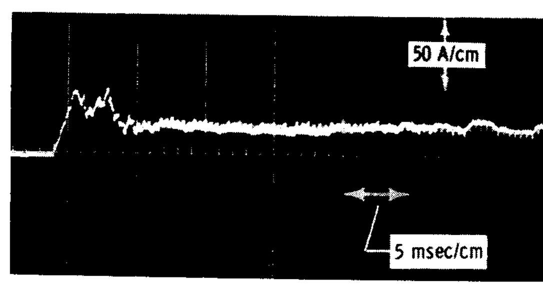
(h) Starting voltage, no load; direct-current line impedance, 0.1 ohm.



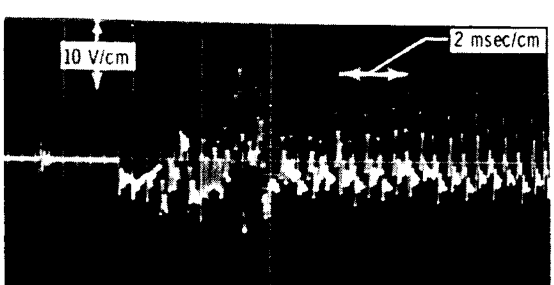
(i) Starting voltage, full load; direct-current line impedance, 0.1 ohm.



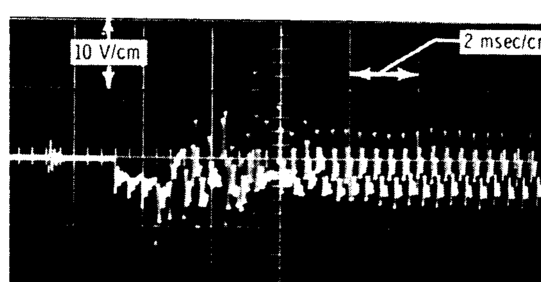
(j) Starting current, no load; direct-current line impedance, 1.0 ohm.



(k) Starting current, full load; direct-current line impedance, 1.0 ohm.

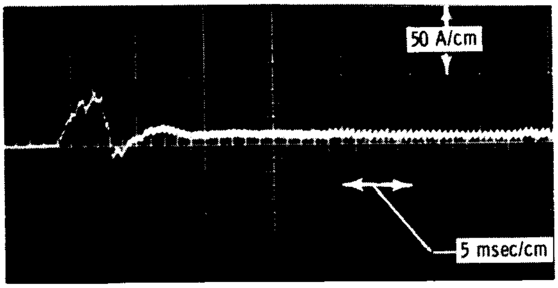


(l) Starting voltage, no load; direct-current line impedance, 1.0 ohm.

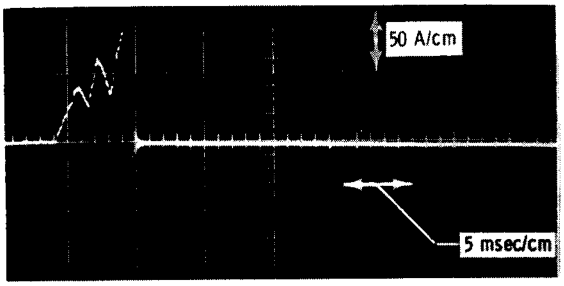


(m) Starting voltage, full load; direct-current line impedance, 1.0 ohm.

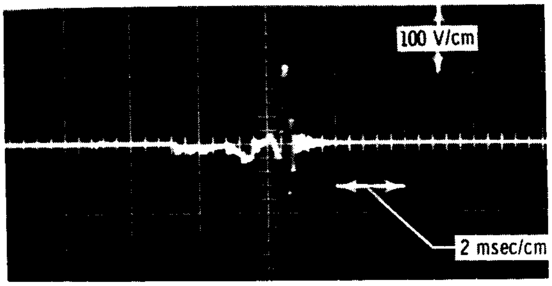
Figure 6. - Continued.



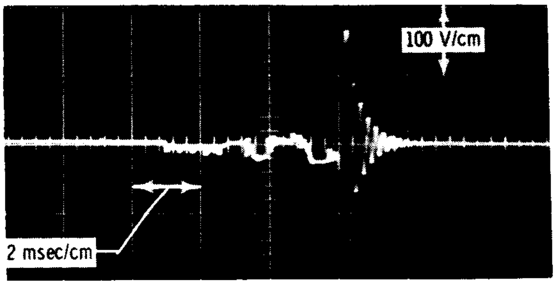
(n) Starting current, no load; direct-current line reactance, 3 ohms.



(o) Starting current, full load; direct-current line reactance, 3 ohms; DELAYED START.

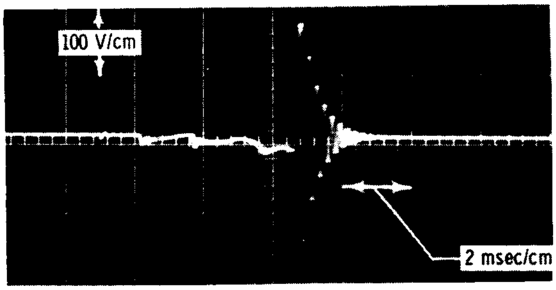


(p) Starting voltage, no load; direct-current line reactance, 3 ohms; DELAYED START.



(q) Starting voltage, full load; direct-current line reactance, 3 ohms; DELAYED START.

(r) Starting voltage, no load; direct-current, line reactance, 4 ohms; DELAYED START.



(s) Starting voltage, full load; direct-current line reactance, 4 ohms; DELAYED START.

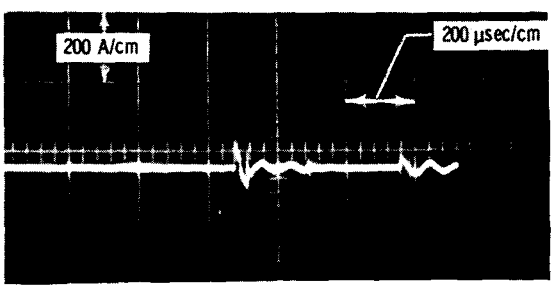
Figure 6. - Concluded.

All the figures show that, though the inverter will operate, even small values of line reactance cause occasional multiple start attempts and misfires. At larger values of line inductance, multiple starts always occur, and the overload circuit is activated before a new commutation cycle begins.

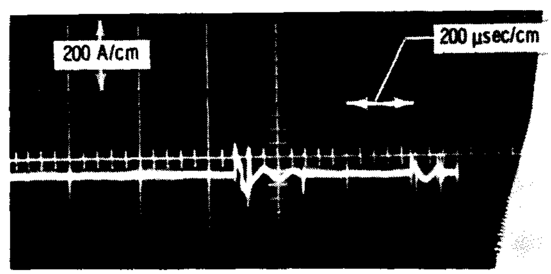
The effects of long ground lines at the launch site can be simulated by using lumped parameters, whose values are approximately 0.04 + j 0.63 ohm to represent the measured line impedance. Current and voltage waveforms for both no-load and full-load conditions are shown in figure 7.

Since the camera was manually synchronized with the starting transient, these photographs represent selections from many attempts. Figures 7(a) and (b) depict normal operation, and figures 7(c) and (d) show two start attempts. This random effect shows that the line impedance at the launch site was large enough to cause occasionally difficult starting. The line impedance was decreased by reducing the resistance, and by canceling the inductive reactance with capacitance.

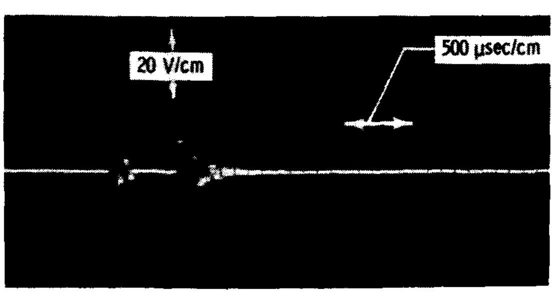
Line impulse tests. - Low input voltage results in excess current which may cause the overloaded circuit to deactivate the inverter. Such momentary dips may be caused by the actuation of valves or pyrotechnic devices. Impulse tests were performed on the



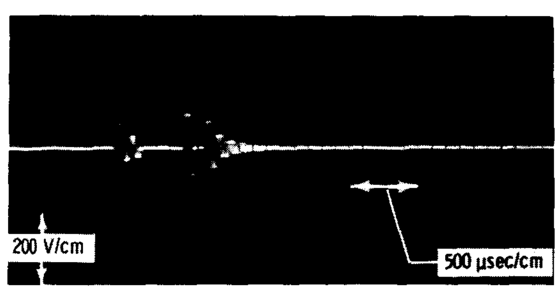
(a) Starting current, no load; direct-current line impedance, 0.04 + j 0.63 ohm.



(b) Starting current, full load; direct-current line impedance, 0.04 + j 0.63 ohm.



(c) Starting voltage, no load; direct-current line impedance, 0.04 + j 0.63 ohm.



(d) Starting voltage, full load; direct-current line impedance, 0.04 j + 0.63 ohm.

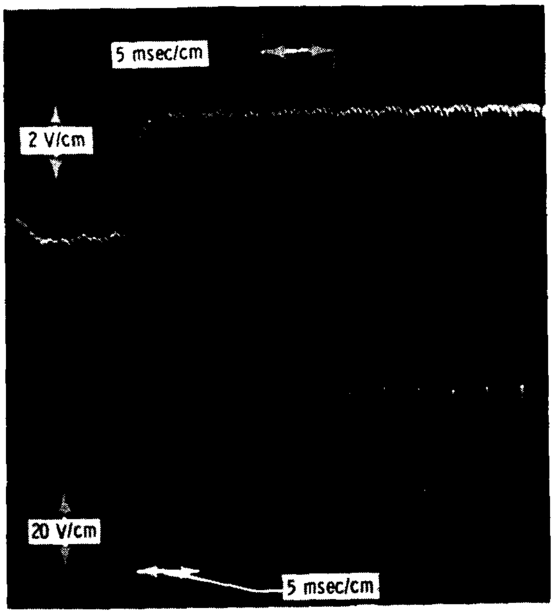
Figure 7. - Effect of simulated launch site line on inverter starting. Input battery voltage, 28 volts dc.

input line to study this effect. Low impedance of the input line was retained by using a large battery and low resistance leads, totaling less than 0.4 ohm. A 100-ampere load was shunted across the battery and disconnected by fuse actuation. Various fuse sizes result in different time durations ranging from 8 to 470 milliseconds, although not accurately controllable. Presence of the shunt load reduces the battery voltage from 27.5 to 22.5 volts, a 5-volt dip.

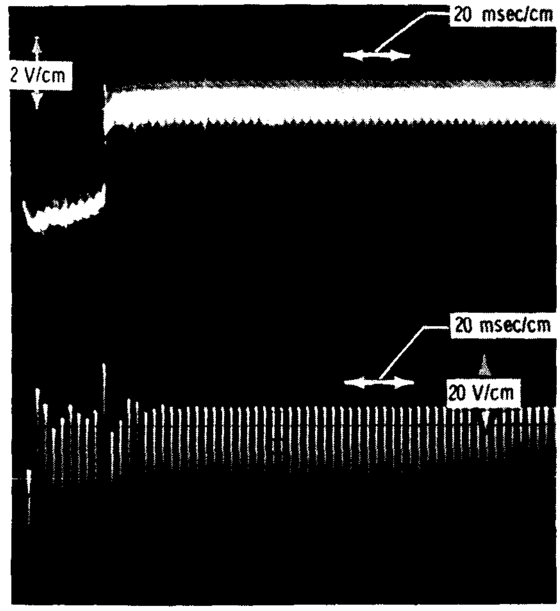
Figure 8 consists of a series of two oscilloscope traces coincident in time. The top trace is the input voltage to the inverter, while the bottom trace is one phase of the output voltage. All the traces have similar characteristics, and it is apparent that the inverter recovers from momentary input reduction in less than 25 milliseconds. During the time of the disturbance, the output voltage falls by an rms value about equal to that of the input voltage dip, as determined by the oscillograph.

It is significant that the overload protection circuit is not actuated during the disturbing intervals, and therefore the inverter does not drop out. The small loss in output voltage is attributed to the relatively slow time constant of the output regulator, which is a magnetic amplifier. It is of further significance to note that short disturbances of this magnitude on the alternating-current line do not adversely affect user systems.

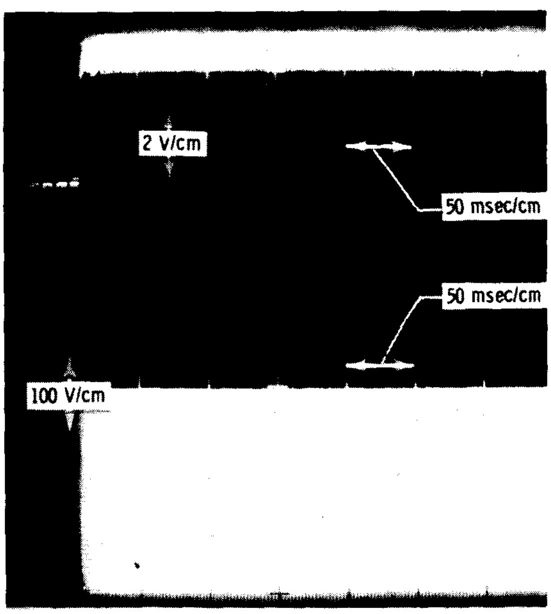
Input transients observed in flight are both smaller in magnitude and shorter in duration than those used for this test. These tests are therefore more severe, and still the results are satisfactory.



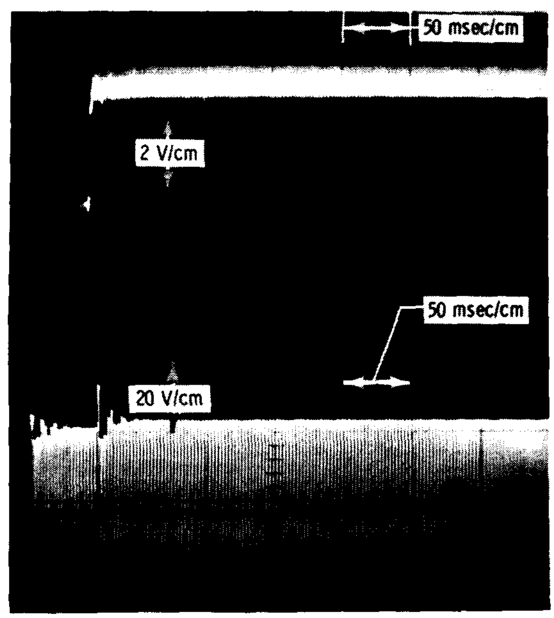
(a) Top: impulse on direct-durrent line, 8 milliseconds.
(b) Bottom: phase A; output frequency, 400 hertz.



(c) Top: impulse on direct-current line, 24 milliseconds.
(d) Bottom: phase A; output frequency, 400 hertz.

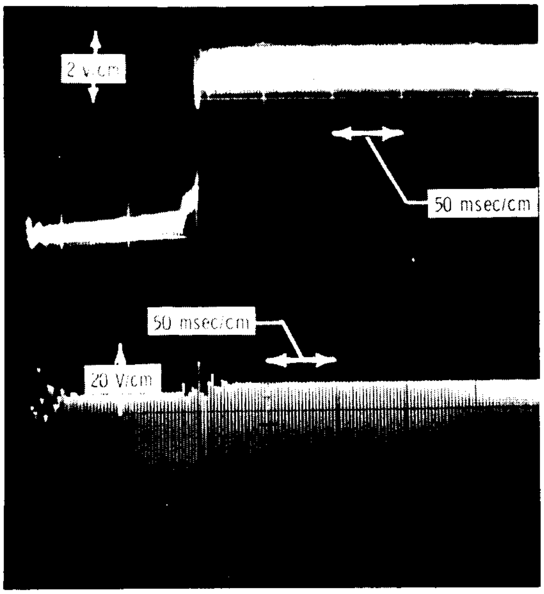


(e) Top: impulse on direct-current line, 40 milliseconds.
(f) Bottom: phase A; output frequency, 400 hertz.

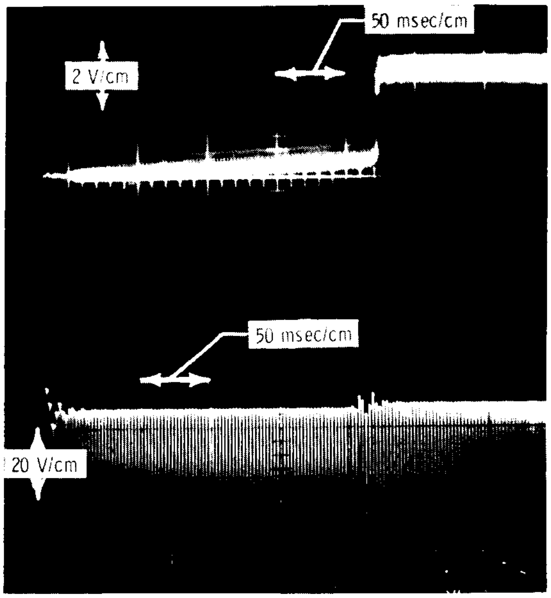


(g) Top: impulse on direct-current line, 48 milliseconds.
(h) Bottom: phase A; output frequency, 400 hertz.

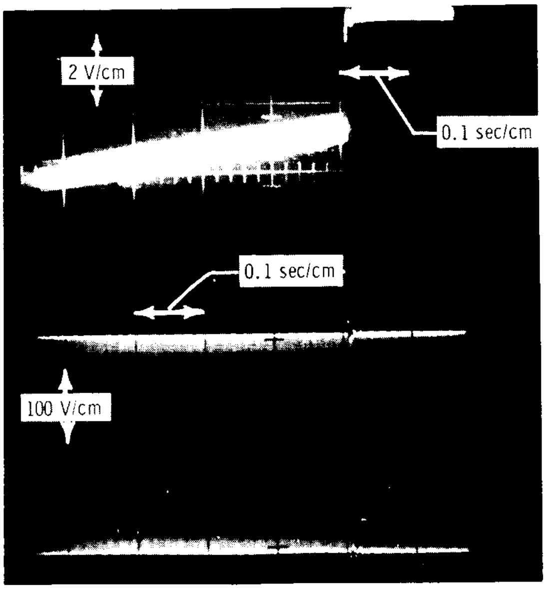
Figure 8. - Alternating-current output as function of impulse transients on direct-current input line. Input battery voltage, 27.5 volts dc; output, full load.



(i) Top: impulse on direct-current line, 120 milliseconds.
(j) Bottom: phase A; output frequency, 400 hertz.



(k) Top: impulse on direct-current line, 240 milliseconds.
(l) Bottom: phase A; output frequency, 400 hertz.



(m) Top: impulse on direct-current line, 470 milliseconds.
(n) Bottom: phase A; output frequency, 400 hertz.

Figure 8. - Concluded.

THERMAL TESTS

After the inverter, cooled with a blower, had been in operation long enough to attain thermal equilibrium, a check of all hot components was made. The SCR's were by far the hottest. Other parts were operating well within their temperature rating, as shown by spot thermal tests performed by others. The SCR temperatures were assessed by thermocouples located near the center of the SCR groups, as shown in figure 9. The

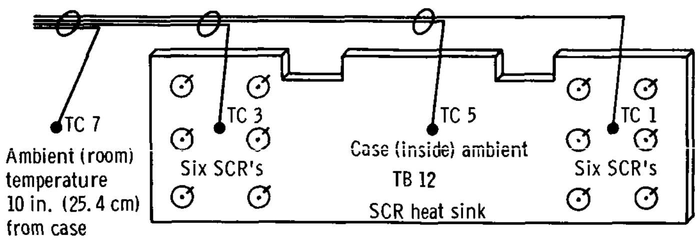


Figure 9. - Location of thermocouples on silicon controlled rectifier mounting plate.

tests were run in a laboratory environment without the benefit of cooling; consequently, the tests were not intended to reproduce the solar heating or radiation cooling of space. Thermocouple 7 indicated ambient temperature, while 5 indicated the air temperature inside the case. Thermocouple 1 is located near the center of six regulating SCR's, while thermocouple 3 is located near the center of the power-switching SCR's. Because the power-switching SCR's dissipate more power at full load, thermocouple 3 indicates higher average temperatures.

Test results are listed in table V and plotted in figure 10. Although thermal equilibrium was being approached, the test was discontinued after 2 hours to avoid overheating the SCR's. Published data give temperature drops between SCR junction and its main mounting stud, and between the stud and its heat sink. The SCR mounting stud is electrically insulated from the heat sink with mica washers to minimize temperature drop. These temperature differentials are about 15° F (8.5° K) each for the heat fluxes encountered. The SCR limiting junction temperature is 257° F (398° K), and the test was stopped at a heat sink temperature of 222° F (378° K).

TABLE V. - THERMAL TEST DATA

Time, min	Input		Output			Thermocouple								Frequency, Hz
	Voltage, V dc	Current, A	Voltage, V ac	Current, I ac	Power, W	1		3		5		7		
						°F	°K	°F	°K	°F	°K	°F	°K	
0 (on)	27.7	35	112.8	1.9	650	80	299.7	90	305.4	80	299.7	75	297.0	400.0
1	27.7	35	112.8	↓	↓	85	303.2	100	311.0	92	306.5	75	297.0	↓
2	27.7	35	112.8			90	305.4	110	316.5	100	311.0	75	297.0	
4	27.6	35.5	112.8			98	309.7	117	320.4	110	316.5	76	297.5	
7	27.6	35.5	112.7			107	314.7	128	326.5	121	322.7	76	297.5	
12	27.8	35.5	112.7			119	321.7	139	332.7	135	330.5	76.5	298.0	
19	27.7	35	112.5			132	328.7	150	338.7	148	337.5	77	298.2	
25	27.6	35	112.5		645	140	333.2	162	345.4	158	343.2	78	298.6	
34	27.5	35	112.6	1.88	↓	150	338.7	172	351.0	169	349.4	77	298.2	
44	27.4	35	112.4	1.88		159	344.0	182	356.5	181	356.0	81	300.4	
54	27.2	35.5	112.2	1.88		167	348.2	191	361.5	190	361.0	80	299.7	
64	27.1	35.5	112.1	1.88		173	351.5	198	365.5	197	366.0	78	298.6	[a]399.97
74	26.8	36.5	112.0	1.9		179	355.0	204	368.6	204	368.6	82	301.0	[a]399.95
84	26.6	36.4	111.8	↓		183	357.0	208	371.0	208	371.0	83	301.7	[a]399.95
94	26.3	37	111.6			188	360.0	212	373.2	213	374.2	81	300.4	[a]399.95
104	25.9	37	111.5			190	361.0	216	375.0	217	376.2	84	302.0	[a]399.96
114	25.3	38	111.2			194	363.2	219	377.2	221	379.2	84	302.0	[a]399.95
124	23.2	41	110.6		640	195	364.0	222	380.2	222	380.2	85	303.2	[a]399.95
Off														

[a]Average of 10 consecutive readings.

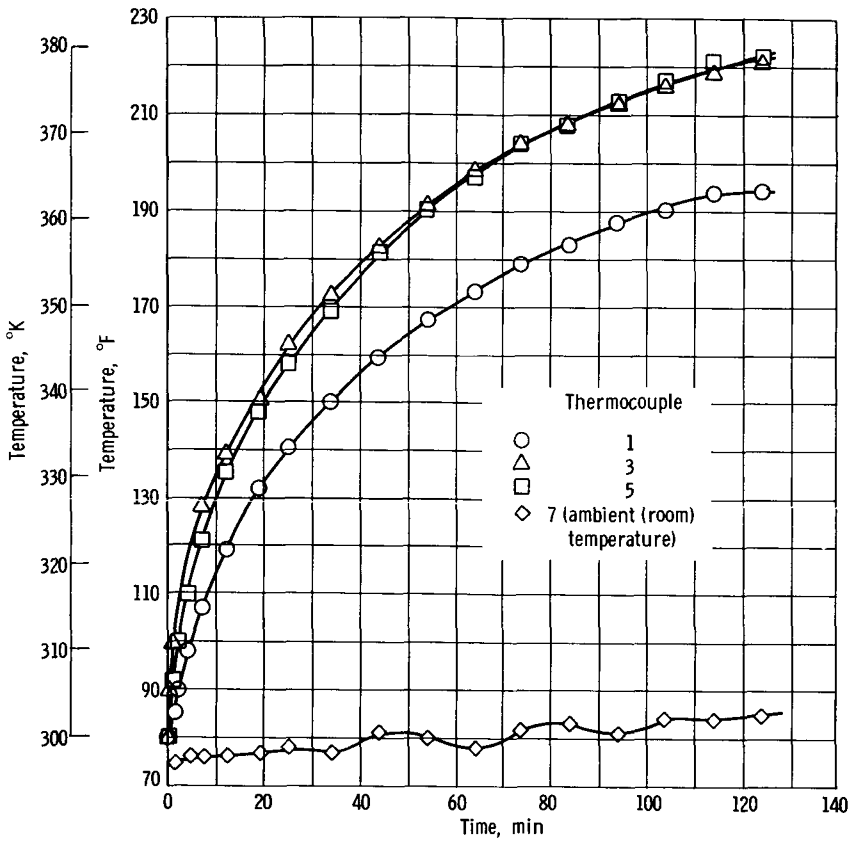


Figure 10. - Plot of thermal tests.

CONCLUSIONS

Engineering tests and analysis of the critical electrical aspects of a solid-state alternating-current power source for the Centaur space vehicle were made. The following conclusions were drawn:

1. Inverters of the class using switching silicon controlled rectifiers can operate reliably in space booster environment. They are, however, subject to a number of critical performance areas. These areas were identified, their causes found, and the deficiencies were corrected. The inverter described in this report is suitable for Centaur missions requiring orbital coast periods as well as those employing continuous engine firings with no coast in space.

2. Inverters using silicon controlled rectifiers for switching stored energy demand large transient current peaks. As a result, source impedance is critical, particularly in ground operation. This criticality was evaluated, and boundary limits established for proper operation.

3. The oscillator, countdown, and shift register circuits were found to be highly

susceptible to input voltage variations and negative transients on the power line. The cause was found and corrected.

4. Inverters of this type were found to recover satisfactorily from normal negative input transients, with minor output variations. Input transients large enough to disturb the inverter are beyond the specification limits of other systems, such as guidance. Such large transients have not been observed in flight, or in ground test.

5. Information gained in this investigation has led to the development of an improved or "second generation" SCR inverter. In cooperation with the vehicle contractor, such an inverter is now being produced.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 30, 1967,
491-03-00-01-22.

APPENDIX - SPECIFICATIONS FOR CENTAUR INVERTER

Weight, lb; kg	38; 17
Size, in.; cm	10 by 5 by 16; 25 by 13 by 41
Power input at full rated conditions, kW	1
Input voltage, V dc	25 to 30
Output power:	
volt-amperes	650
phases	3
Output voltage:	
V ac	115
phases	3
Output connection	Wye
Output regulation:	
Voltage from no load to full load, V rms (±2. 5 percent)	115
Output frequency, Hz	400
Phase accuracy and stability, deg	120 ± 2
Efficiency at full load, percent	65
Ambient operating temperature range, ^{o}F; ^{o}K	40 to 80; 277 to 299
Power factor	0. 8 lagging to 1

Overload capability is 200 percent of rated full-load current for 30 seconds and 150 percent of rated current for 60 seconds.

Short circuit protection: The output load may be varied from short circuit to open circuit without injury to the inverter.

Output regulation: Output voltage and frequency is regulated within 100 milliseconds of any change in output load.

Environmental: The inverter is capable of normal operation in a free space environment for 6. 5 hours under maximum and minimum solar radiation.

The inverter is capable of normal operation in an atmospheric pressure range of 0. 01 microns to 30 inches (101.4×10^{3} N/cm^{2}) of mercury and in relative humidities up to 100 percent. The case is not pressurized, but vented to the atmosphere.

The circuit diagram of the inverter is shown in figure 11.

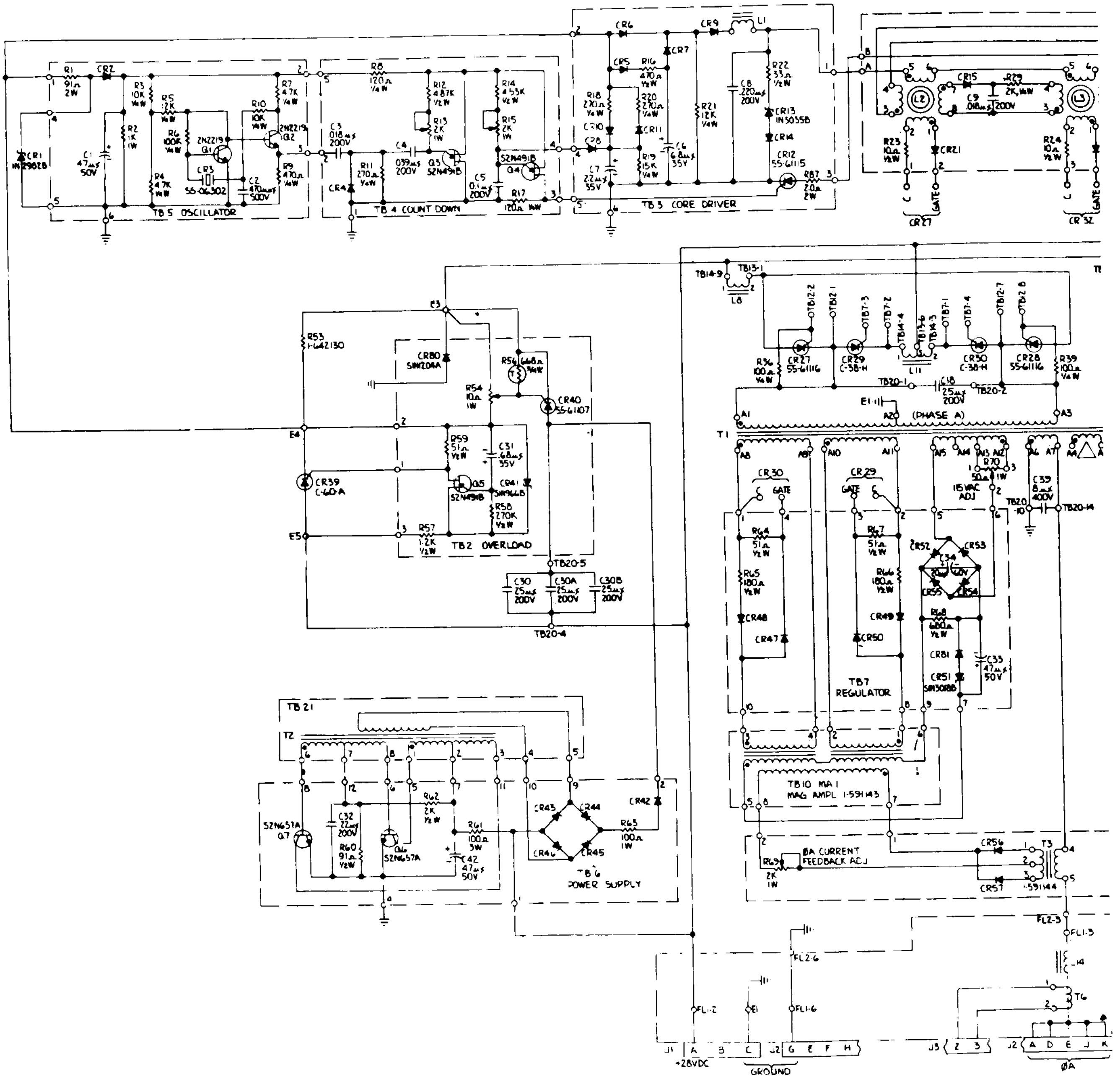
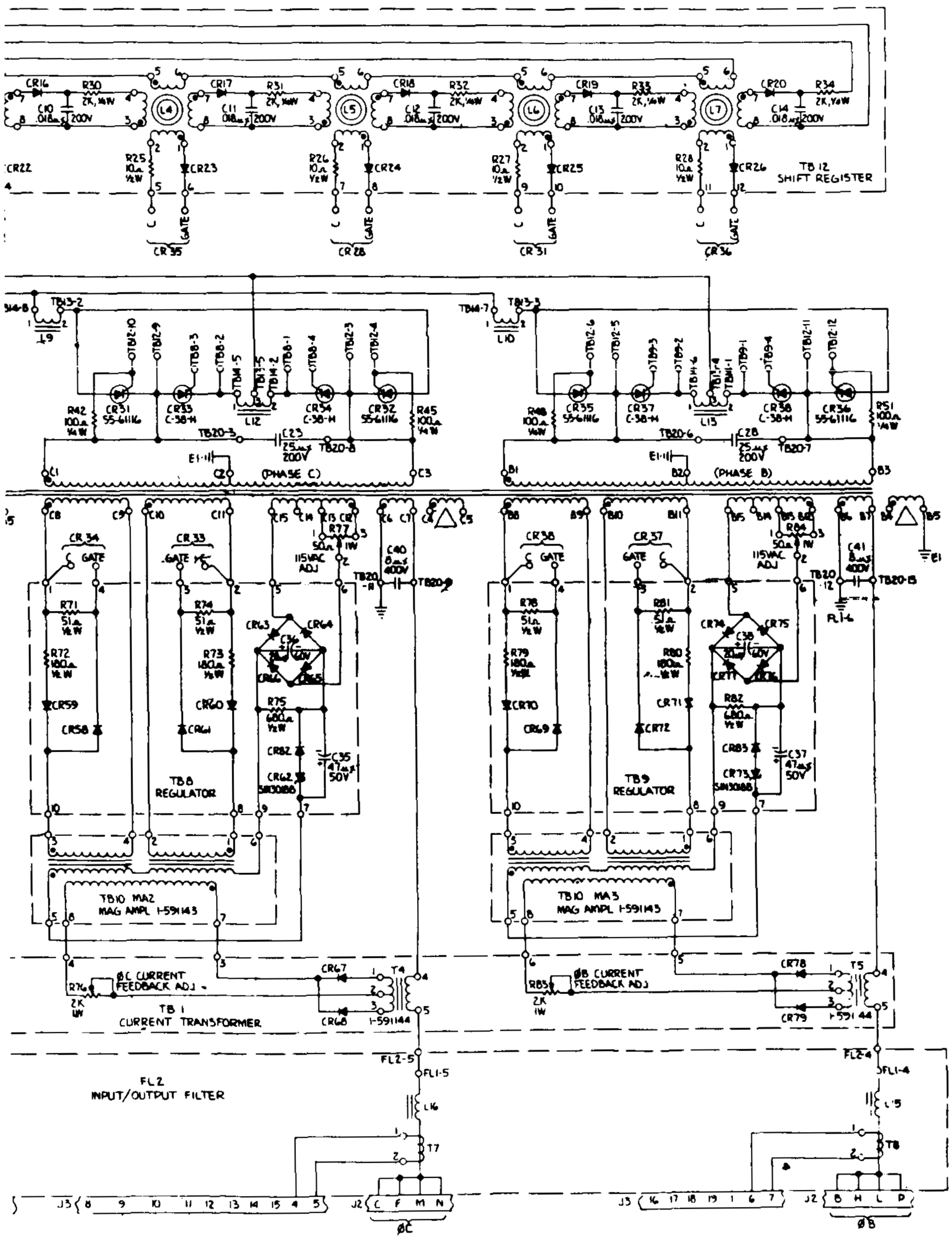


Figure 11. - Circuit diagram



of Centaur inverter.