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THE DESIGN AND PERFORMANCE OF A HIGH EFFICIENCY POWER CONVERSION SYSTEM FOR USE WITH THE WJ-274 TRAVELING-WAVE TUBE

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WATKINS-JOHNSON COMPANY
Palo Alto, California

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

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By Gary S. Oleari
The Watkins-Johnson Company
Palo Alto, California

SUMMARY

One of the prime requirements for spaceborne vehicles, both manned and unmanned is that of a reliable telemetry and communications system. The nature of its application dictates that this system be highly efficient, miniature and capable of surviving severe environmental conditions with no degradation of performance. This report outlines the approach implemented to realize a power conversion system compatible with extraterrestial environments. This system was designed, developed and manufactured specifically to supply the voltages and currents required to operate the WJ-274 traveling-wave tube, which provides the necessary radio frequency amplification to fulfill the requirement of a spaceborne telemetry and communications system.

The design is analytically and empirically described and the performance characteristics discussed. These characteristics are complemented with discussion where necessary and were obtained from one of the power conversion systems in its deliverable configuration.

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INTRODUCTION

This program was undertaken by Watkins-Johnson Company for the NASA Langley Research Center with the prime goal being the design and development of a small and lightweight traveling-wave tube amplifier (TWTA) with a high DC to RF efficiency. This TWTA is intended for use in spaceborne applications which predicates the conformance with many special environmental requirements. The TWTA is required to perform over a wide temperature range as well as survive conditions of high-level shock, random vibration and sustained static acceleration. Pressure environments from mean sea level to hard, outer space, vacuum must also be endured. The TWTA consists of two main component parts; the traveling-wave tube and the power conversion system to power the traveling-wave tube.

Since the design and development of the traveling-wave tube is beyond the province of this paper, only the power conversion system will be discussed in detail.

The prime purpose of the power conversion system is the translation of unregulated low DC voltage into voltages that are compatible with the traveling-wave tube, enabling it to function in the desired manner. This system was designed to be powered from an unregulated source of 24 to 30 volts DC. It converts this unregulated input into high DC voltages of 1170 for the collectors, 1630 for the helix and 1730 for the anode. These voltages must be highly regulated due to the high sensitivity the traveling-wave tube demonstrates to voltage fluctuations. Because of this requirement, the power conversion system is designed to have an output regulation of 1 percent or better over the specified temperature and input voltage ranges (Appendix 1). However, at any given temperature it is possible to optimize the power conversion system to yield an output regulation of .5 percent over the input voltage range. The output regulation can also be enhanced if the system is required to operate over a lower temperature and/or input voltage range.

Another requirement of the power conversion system is that it demonstrate a high input to output efficiency. This design yields an efficiency of 83 percent at worst case line and temperature conditions, which are an input voltage of 30 Vdc and temperature of -40° C (Appendix 1). This efficiency is obtained with an output power of 55 watts, the traveling-wave tube requirement, or greater. The efficiency of the power conversion system is dependent on the output demand since the total loss in the circuitry becomes a smaller percent of the total power at high output levels and a larger percent of the total power at low output levels. A detailed list of these and other requirements, as well as performance achieved, appear in Appendix I.

DESIGN APPROACH

The environmental requirements of the specification controlling the power conversion system (Appendix I) made it clear that considerable effort would have to be put forth on the mechanical as well as the electrical design. This divided the design task into two areas, electrical and mechanical/thermal.

To satisfactorily meet the electrical requirements of the specification it was determined that the power conversion system would be comprised of three functional circuit blocks. These are the regulator, the DC to DC converter and timer/telemetry circuitry (Fig. 1).

The regulator is of the switching type, since it would be impossible with any other type to attain the efficiency required over the wide input voltage range. Magnetic frequency control is used since it is affected very little by wide temperature ranges as opposed to capacitive/resistive timing. Special care is given to those parameters that affect performance in the design configuration. Representative of the type parameters specified for transistors are high gain bandwidth product, high beta, low leakage currents and low junction voltage drops. Capacitors are chosen for low leakage and small capacity/temperature drift. Resistive elements all possess very low resistance/temperature drift characteristics.

The DC to DC converter also reflects the attention given component selection in the regulator. Since there are a large number of magnetic elements in the converter, the selection of cores is very important. All cores used are toroidal because of the large cross-sectional area possible in a small volume. Core selection is determined keeping in mind the high efficiency requirements of the system. For this reason, all cores used are of the high permeability type. This family of cores exhibits a very low core loss characteristic as well as a very linear hysteresis curve. The electrical design of the transformers is such that advantage is taken of these characteristics in order to yield highly efficient circuitry. Special care is taken in the mechanical design of the high voltage transformers to keep interwinding capacity and adjacent-turns voltage to a minimum since they detract from efficiency. The diodes used in the high voltage rectifying circuitry are ultra-fast recovery types, adding to the efficiency of the converter. The transistors, capacitors and resistors used in the converter are chosen in the same manner as those for the regulator.

The timer/telemetry circuitry utilizes the same type components as do the regulator and DC to DC converter. The components used for the timer/telemetry circuitry, as well as the regulator and DC to DC converter are all operated at stress levels of 60 percent or less. This is very important when designing a system with long life

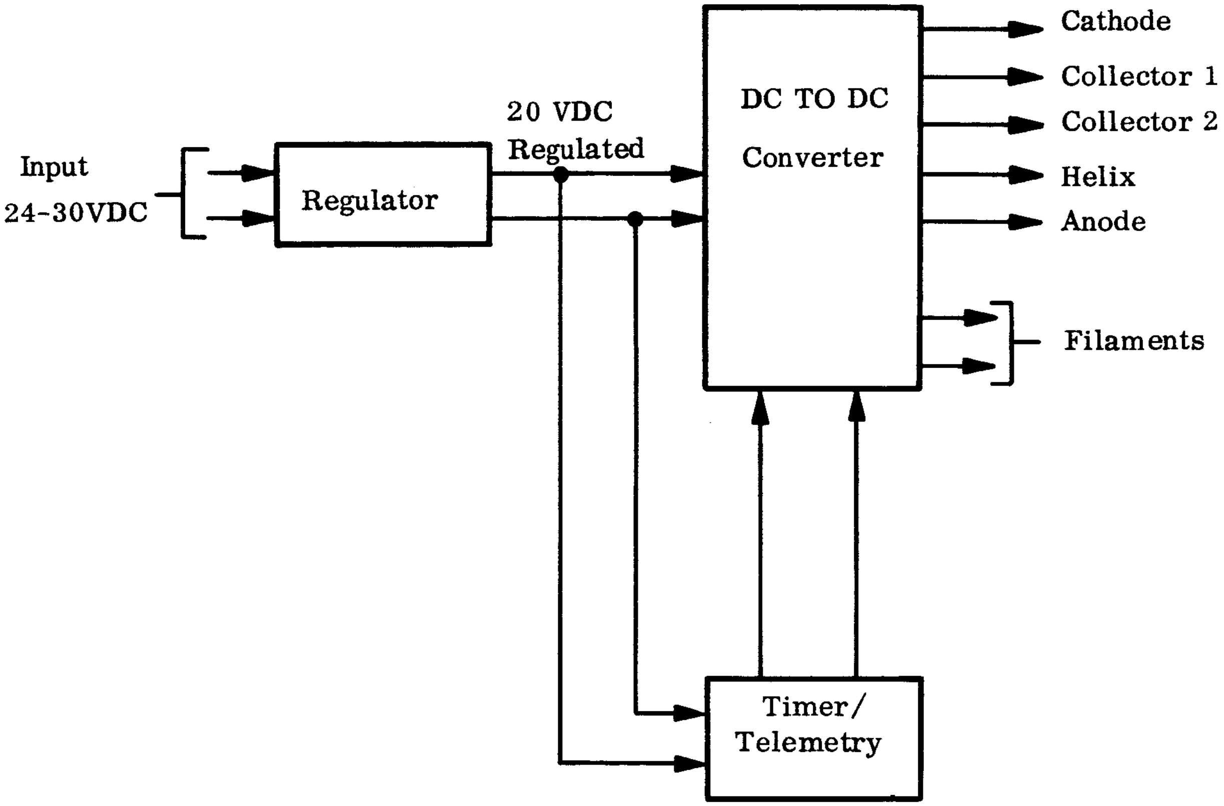

Fig. 1 - Block Diagram of Power Conversion System

and a high degree of reliability. Special care is taken to assure that all components will be well below rated power levels and gain parameters at specified end of life.

The electrical design will be discussed at this point and will be followed by the mechanical and thermal design.

Regulator Electrical Design

Design of the regulator, of which a schematic diagram is shown in Fig. 2, begins with the selection of a suitable core for use in T1. Selection is empiric and the criteria are small size and high permeability. Use of the smallest possible size is important since the overall package is to be small and light. High permeability is chosen since it is inherently more linear and can support higher voltage for the same cross-sectional area than can lower permeability types.

Once the core has been selected, the number of turns to be wound T1, terminals 3-4 and 4-5, the primary can be computed. The number of turns are determined by the following relationship:

$$N = \frac{.5E}{2Bm \times Ac \times f \times 10^{-8}} \qquad (1)$$

Where E is the voltage applied

Bm is the magnetic strength in gauss

Ac is the cross-sectional area of the core

f is the frequency of operation

The voltage applied is 20 Vdc, since T1 is to be operated from the output of the regulator (Fig. 1). The magnetic strength level, in gauss, is selected to be in the most linear portion of the hysteresis loop. The cross-sectional area is a function of the physical size of the core. The frequency of operation, which is determined by T2, is selected to be 10 kilocycles. This frequency is selected since the switching losses in the transistors as well as the core losses throughout the system are relatively small at 10 kilocycles. At frequencies much higher than 10 kilocycles, the rise and fall times of the transistors become a large portion of the frequency period, therefore increasing their effective loss. At lower frequencies it is necessary to have larger reactive components in the circuitry, detracting from small size.

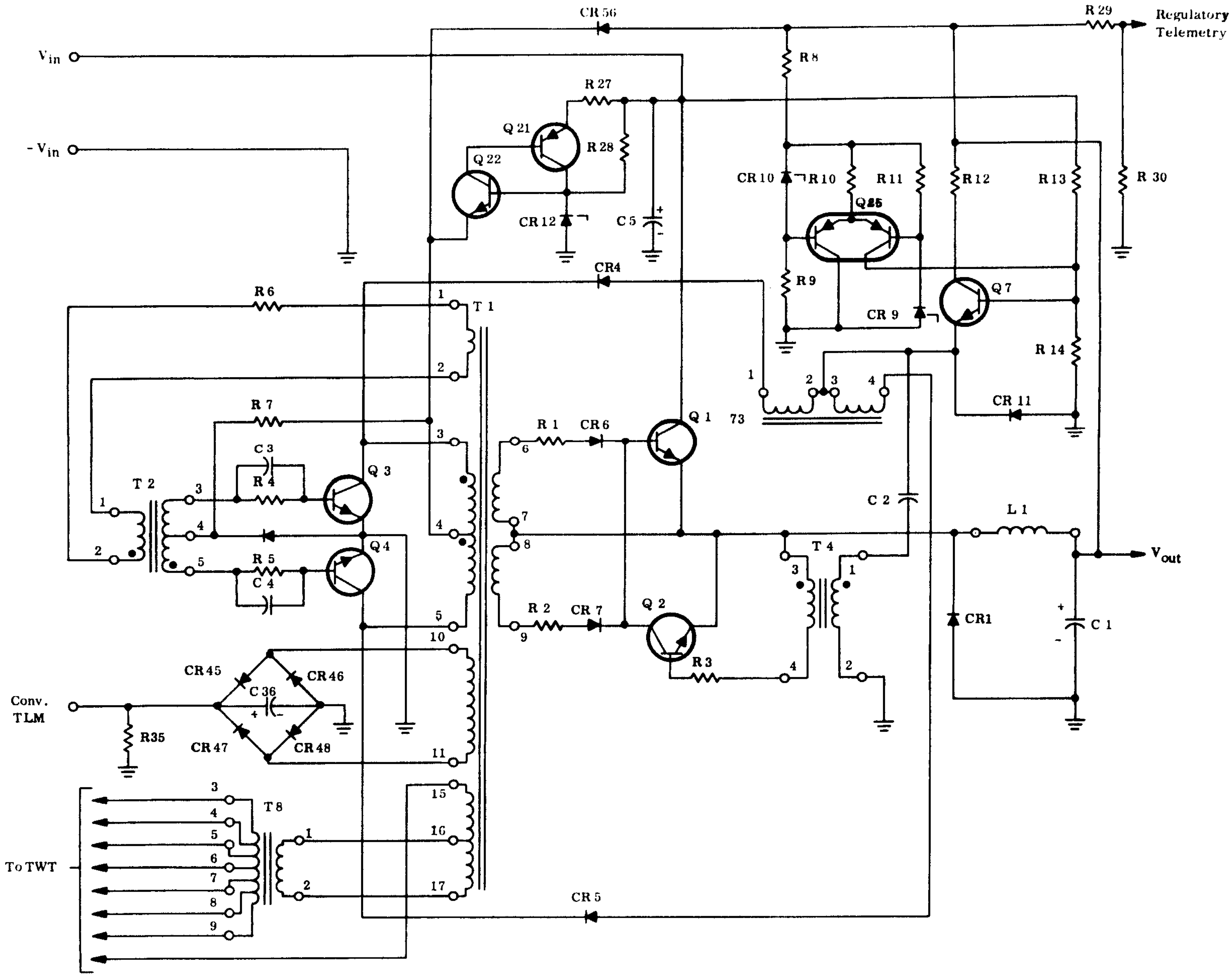

Fig. 2- Regulator schematic

Once the primary turns are determined, a voltage feedback winding, terminals 1-2, is wound on T1. The number of turns for secondary terminals 1-2 are calculated using the following:

$$N_1 = N_2 \left(\frac{V1}{V2}\right) \tag{2}$$

Where N_1 is the number of turns on T1 terminals 1-2

N_2 is the number of turns on T1 terminals 3-4

V1 is the voltage required on T1 terminals 1-2

V2 is the voltage available on T1 terminals 3-4

The number of turns on terminals 3-4 of T1 have been determined from (1) and the voltage available on terminals 3-4 is known since it is the output of the regulator (Fig. 1). It is now necessary to select the feedback voltage required on terminals 1-2. The feedback voltage is selected to be 4 Vdc. This allows the number of turns required for terminals 1-2 to be relatively low, enhancing miniature size of the transformer. Another benefit of using 4 V dc will be borne out in the discussion of T2 design.

With this feedback voltage value known, the next step is to design T2, which is a saturable transformer and generates the fundamental frequency of the multivibrator consisting of R4, R5, C3, C4, Q3 and Q4. The design of T2 proceeds in a manner analogous to that used for T1 (1), except that the gauss level selected for T2 is that at which the core will saturate. The voltage applied, E, is 4 volts since it is derived from T1 terminals 1-2. With these values known it is then possible to compute the correct number of turns to saturate T2 at a 10 kilocycle rate (1).

The operation of the multivibrator commences when DC voltage is applied between T1 terminal 4 and ground. Current leaks through R7 and finds a path to ground through Q3 or Q4. Since the beta parameters are not identical for the transistors, one of them will amplify the current through R7 more than the other. This causes more current flow in the respective collector, in turn developing voltage across one half of the primary of T1. A portion of this voltage is fed back to T2 through R6. The phasing of T1 with respect to T2 is such that this fed-back signal is additive to the drive of the transistor which is on. The transistor that is on remains on until such time that T2 can saturate. When T2 saturates, the voltage across it decreases through zero, thereby turning on the alternate transistor. The feedback action again takes place and this transistor remains on until such time as T2 again saturates. In this manner a square wave signal source is provided. Since on alternate half cycles the transistor that is in the off state has its base-emitter junction back biased by T2, it is important to assure that this level does not exceed the BV_{ebo} of the transistor. Because the primary voltage on T2 is 4 volts and the BV_{ebo} on the transistors is 6 volts, it is possible to wind T2 with a 1:1 turns ratio facilitating its manufacture.

The square wave signal is transformer coupled into windings 6-7 and 8-9 of T1. This is full wave rectified through R1/CR6 and R2/CR7 and applied to the base of Q1. Since Q1 has its emitter tied directly to the junction of T1 7 and 8, the signal applied to the base of Q1 is always positive with respect to the emitter due to CR6 and CR7 and therefore would essentially hold Q1 on at all times were it not for a controlling action of some type.

Control of the conduction of Q1 is achieved by periodically turning on Q2. This will immediately cut off Q1 since the value of V_{ce} (sat) of Q2 is of a lower value than V_{be} (sat) of Q1. The drive for Q2 is obtained from T4 terminals 3-4 through R3. The primary of T4, winding 1-2 is driven from the center tap of T3 and the emitter of Q7.

It will be noted that terminals 1 and 4 of T3 are tied through CR4 and CR5 to the collectors Q3 and Q4. It follows that any time Q3 is on, terminal 1 of T3 is near ground potential. The same holds true for T3 terminal 4 any time that Q4 is on. The only potential holding these points above absolute ground is the V_{ce} (sat) of the transistors, which is on the order of .25 volts. Since Q3 and Q4 are on alternately it follows that the ends of T3 are alternately tied to ground. The center tap of T3, terminals 2 and 3, are tied to the emitter of Q7, which is approximately .6 volts (the forward drop of the base-emitter diode) below its base. The base voltage, disregarding for the time being any contribution from Q25, is at a potential determined by the following:

$$V_b = V_{in} \frac{R14}{R13 + R14} \qquad (3)$$

Where V_b is the voltage on the base of Q7

V_{in} is the input voltage to the regulator

Now by examining one half of T3 it is possible to describe the sequence that generates the drive for T4 and subsequently Q2.

Since it has been previously stated that the ends of T3 are alternately tied to ground, it will be assumed for this portion of the discussion that the circuit has the configuration shown in Fig. 3.

Before going into the discussion of the actual circuit operation, a brief comment on the behavior of magnetic components will be interjected. For any given core the following will hold:

$$V = N \frac{d\phi}{dt} \tag{4}$$

And

$$Vdt = Nd\phi \tag{4a}$$

And

$$V\int dt = N\int d\phi \tag{4b}$$

From which

$$V_t = N\phi \tag{4c}$$

Where V is voltage applied to a coil

N is the number of turns on the coil

t is time

$\phi = 2\ Bm \times Ac$

Bm is magnetic strength in gauss

Ac is the cross sectional area of the core

When simplified, the equations state that the gauss level attained by a magnetic component is a function of the voltage applied, the number of turns on the core and the length of time the voltage is applied. Assuming that it is desirable to saturate a core after some length of time, it is necessary to obtain the gauss level at which the core will saturate, the voltage available to saturate the core and wind the proper number of turns onto the core. With this in mind, the operation of the circuitry controlling Q2 can now be readily described.

With reference to Fig. 3, the operation commences when Q3 is turned on by the signal from T2. This in turn pulls terminal 1 of T3 down to ground. Since the emitter of Q7 is at some potential determined by the divider of R13 and R14, the gauss level in T3 begins to increase. Meanwhile, C2 has charged to the voltage potential on the emitter Q7. It will be noted that the phasing on T4 is such that the current charging C2 will

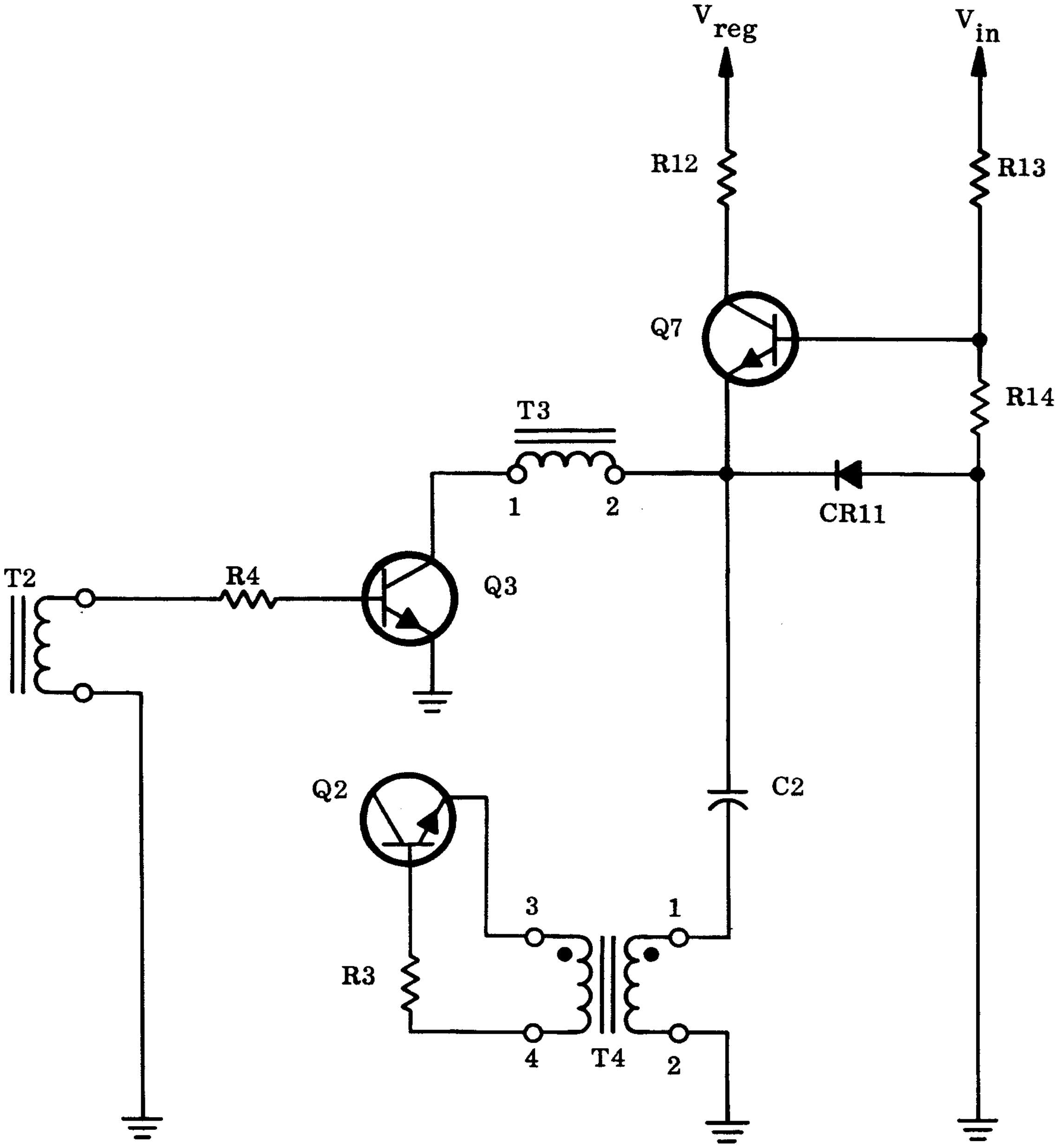

Fig. 3- Output switching transistor control

back bias the base-emitter of Q2. When the gauss level in T3 reaches the point where the core saturates, its impedance lowers and the voltage across it drops to a value near zero. When this occurs, C2 begins to discharge through T3, CR4 and Q3. The voltage on C2 now appears across T4 in the direction that forward biases Q2. Q2 then turns on and cuts off the conduction of Q1. Since alternate ends of T3 are tied to ground, when Q3 ceases to conduct and Q4 turns on, T3 is pulled out of saturation and the timing sequence takes place again.

It follows that the value of V_{in} will control the time it takes T3 to saturate, since the voltage available at Q7 emitter is directly proportional to V_{in}. This relationship is true and the following holds:

$$V_{out} = V_{in} \frac{t_1}{t_2} \tag{5}$$

Where V_{out} is the voltage out of the regulator

V_{in} is the input voltage

t_1 is the time required to saturate T3

t_2 is the time Q3 or Q4 are on

The voltage divider comprised of R13 and R14, while providing a good input voltage regulation, does nothing to account for changes that may occur in the loop. For this reason, now consider the differential amplifier, Q25, and its function (Fig. 2). The amount of current being injected into the node of R13 and R14 is the sum of the currents provided through R13 and Q25. This in turn sets the potential at the base of Q7 by means of resistor summing. The purpose of the differential amplfier, Q25, is to adjust for small changes that may be present in the regulated output (V_{out}). This is accomplished by varying the current contribution of Q25 to the summing node of R13 and R14. It V_{out} tends to increase, the base of Q25 connected to CR10 will follow, pulling the emitter with it. Since the two emitters are tied together, they both tend to rise together. The other base, however, is fixed with relation to ground by CR9. This condition increases the conduction of the CR9 side of the differential amplifier thereby pushing more current into the summing node. The increased current into R14 causes the voltage on Q7 base to rise. This increase is directly reflected to the saturating transformer, T3. Since T3 will now saturate faster, thereby shortening t1, it can be seen (5) that V_{out} will decrease. The converse of the above is true for the case where V_{out} tends to decrease.

The output of the power switch, Q1, is fed directly to the commutating circuit, comprised of CR1, L1 and C1. When Q1 is on, current flows from V_{in} through Q1 and L1 into the load. CR1 is off and C1 is charged to V_{out}. At the time Q1 is opened by the action of Q2, the polarity across L1 reverses since the current flowing through it cannot be stopped instantaneously. This polarity reversal forward biases CR1 and affords a path for current to flow out of L1 and C1 through the load. These two components support the load until such time that Q1 is again turned on.

Another section of the regulator that bears discussion is the start circuit, comprised of Q22, Q21, R27, R28, CR12, C5 and CR56. The purpose of this circuit is to provide a voltage source for the multivibrator circuit, upon applying V_{in}, until such time that V_{out} can attain a value near nominal. When DC is applied to the V_{in} terminals, CR12 zeners through R28 with a value of 19 volts. This positive voltage turns on Q22. The collector of Q22, being tied to the base of Q21, turns it on. This then completes a current path from terminal 4 of T1 to V_{in}. The multivibrator commences to run and V_{out} begins to climb toward its nominal value. When V_{out} reaches a value that is within a .6 volts of the zener voltage of CR 12, Q22 becomes back biased and is extinguished. This opens the current path through the start circuit since it also eliminates the drive for Q21. The multivibrator is then fed through CR56 back to V_{out}. V_{out} at this time has a level high enough to fall within the dynamic range of the differential amplifier. The differential amplifier immediately sees the low voltage condition and provides a current correction to R14, thereby bringing V_{out} up to its proper level.

Filament voltage for the TWT is supplied from T1 by the addition of an additional winding; this winding consists of the number of turns required to produce the nominal voltage required for the filaments. Because it is sometimes necessary to make fine-grain adjustments on the filament voltage, T8 is added. As shown in Fig. 2, a small portion of the voltage provided for the filaments is tapped off and used to drive the primary of T8. This is on the order of .5 volts. T8 is wound as a 1:1 transformer. By placing the desired number of turns of T8 secondary it is possible to break the .5 volts into any desired increments. In the case of the WJ-274, the adjustment increments are set at 0.1 volts. If required, the output of the filament section can be swung from 0.75 volt below to 0.75 volts above the nominal through the selection of both primary and secondary connections of T8.

DC to DC Converter

The dc to dc converter, a schematic of which appears in Fig. 4, converts the regulator output into high voltages for the TWT. It receives both its drive and dc power from the regulator. The dc provided by the regulator has low ripple content and low source impedance. The square wave drive is taken from T1 terminals 12 and 14, which both reference terminal 13. Disregarding for the present Q18 and assuming that T1 terminal 13 is tied to ground, a discussion of the dc to dc converter follows:

T1 windings 12, 13 and 14 are driven from an alternating source, the multivibrator in the regulator. Since terminal 13 is grounded, it follows that on alternate half cycles terminals 12 and 14 will be positive and negative with respect to ground. It also follows that when terminal 12 is positive with respect to ground that terminal 14 will be negative. Taking the case where terminal 12 is positive, it can be seen from Fig.4 that Q8 and Q10 will be biased on. Their drive is through R15/C6 and R17/C8 respectively. R15 and R17 are used for current limiting. C6 and C8 are used to enable fast turn on of the transistors, since they appear as shorts at the instant positive voltage is placed on terminal 12 of T1 and allow a large surge of current to flow in the base circuits. The drive to the power transistors assumes a worst case beta of 10. The value of the resistors in the base leads are low enough to assure that there will be ample drive under all temperature and load conditions. Care is exercised in the selection of the transistors such that BV_{cbo} is not exceeded during the half cycle when they are not conducting. As mentioned above, terminal 14 will be negative at this time and will hold Q9 and Q11 off. Because Q8 and Q10 are on, the full output voltage of the regulator, minus the V_{ce} (sat) of the transistors will appear across one half of the primary windings of T5 and T6. This condition will hold until such time as the signal on T1 terminals 12, 13 and 14 reverses due to the multivibrator switching. At this time Q8 and Q10 will turn off and Q9 and Q11 will turn on. This will in turn apply the output of the regulator across the other half of the primary windings of T5 and T6. The net result is a square wave signal appearing on the primaries of the two high voltage transformers.

Care is used in the design of the two high voltage transformers to assure that their cores do not saturate at a higher frequency than the multivibrator core. If high the voltage transformers are allowed to saturate at a frequency higher than that of the multivibrator, the power transistors will be conducting into a short. This is due to the behavior of the transformers under saturated conditions. This condition creates large current surges into the converter for which no output is realized, detracting from efficiency.

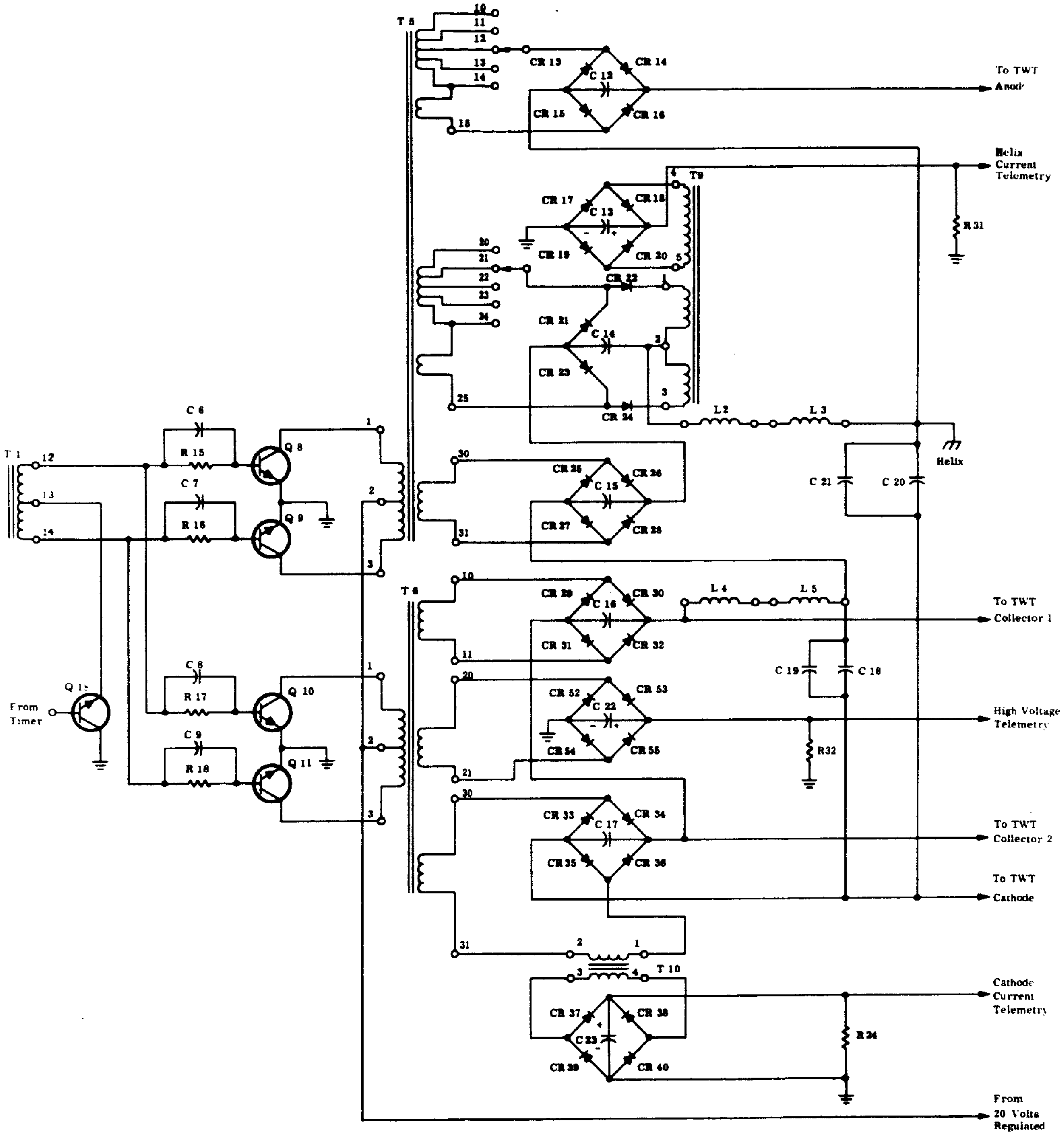

Fig. 4- DC to DC converter schematic

The voltage across the primary of T6 is stepped up to the value required for Collector 2. The secondary voltage is full wave rectified across a bridge circuit and converted to dc. There is a capacitor directly across the bridge circuit which reduces ripple to a low level.

The voltage required for collector 1 is obtained in a similar manner. The main difference being that the windings needed to obtain collector 1 voltage are only those required to generate the difference between the two collectors, since the collector 1 bridge circuit is added atop the collector 2 bridge. This approach reduces the number of turns required to attain the correct voltages and also allows the filter capacitors to be smaller physically, since their voltage rating can be reduced.

The helix and anode voltages are obtained in a similar manner and are summed atop the collector 1 bridge circuit. The main difference between the collector transformer, T6, and the helix/anode, T5, lies in the fact that the T5 is wound in a manner that allows for the adjustment of the anodes and helix. This is accomplished through the use of taps that are wound onto the secondary of T5. These are shown in the schematic Fig. 4., as terminals 20 through 24 and 10 through 14.

The use of two transformers to generate the high voltages offers several advantages over single transformer application. Due to the high current required by the collectors, approximately 90 percent of total load, the primary of the collector transformer, T6, cannot be kept as free of switching transients and current spikes as can that of the lower current transformer, T5. Since the helix and anode of the traveling-wave tube are the two electrodes most susceptible to voltage fluctuations and ripples, it is logical to keep their source as free from noise as possible. This would be very difficult to do if they were driven from a source, such as the collector transformer, that was electrically noisy. Another advantage to load splitting with the transformers is the reduction of interwinding capacity that is present on cores that are heavily burdened. This capacity is a function of the number of turns on the core. It has to be charged and discharged as if it were actual capacitors across the secondary and thereby detracts from efficiency.

In addition to the filter capacitors placed directly across each of the bridge circuits, there are low pass filters across the collector 1 and helix potentials. The filter across the collector 1 potential serves two purposes. It reduces the ripple on collector 1 but more important, it effectively reduces the ripple on the helix. The filter across the helix potential further reduces the ripple to a value that is compatible with the traveling-wave tube.

Both of the output filters are of the same type and obey the transfer function described by:

$$\frac{E_1}{E_2} = \frac{1}{1 - \omega^2 LC}$$

E_1	is the voltage out of the filter
E_2	is the voltage into the filter
ω	is angular frequency $(2 \pi f)$
L	is the value of the choke in henries
C	is the value of the capacitor in farads

The values of L and C are chosen such that the attenuation is 40 dB per decade with a break point that is slightly above the operating frequency of the converter.

Timer/Telemetry

The function of the timer circuitry is to disable the high voltage converter until such time that the filaments of the traveling-wave tube can attain the proper operating temperature.

The telemetry circuitry serves the purpose of monitoring critical parameters of the traveling-wave tube and power conversion system and presenting an output signal analogous to these points.

The operation of the timer circuit (See Fig. 5)commences with the application of dc voltage to the system and the regulator reaching its output voltage. CR51 is a zener diode that avalanches at 20 volts. Across it are C26 and R21. As soon as voltage is applied and CR51 zeners, the node of C26, R21 and Q20 base are placed at the 20volt potential. C26 then begins to charge and the node voltage begins to decrease toward ground according to:

$$E_o = E_1 \left(1 - e^{-t/RC}\right)$$

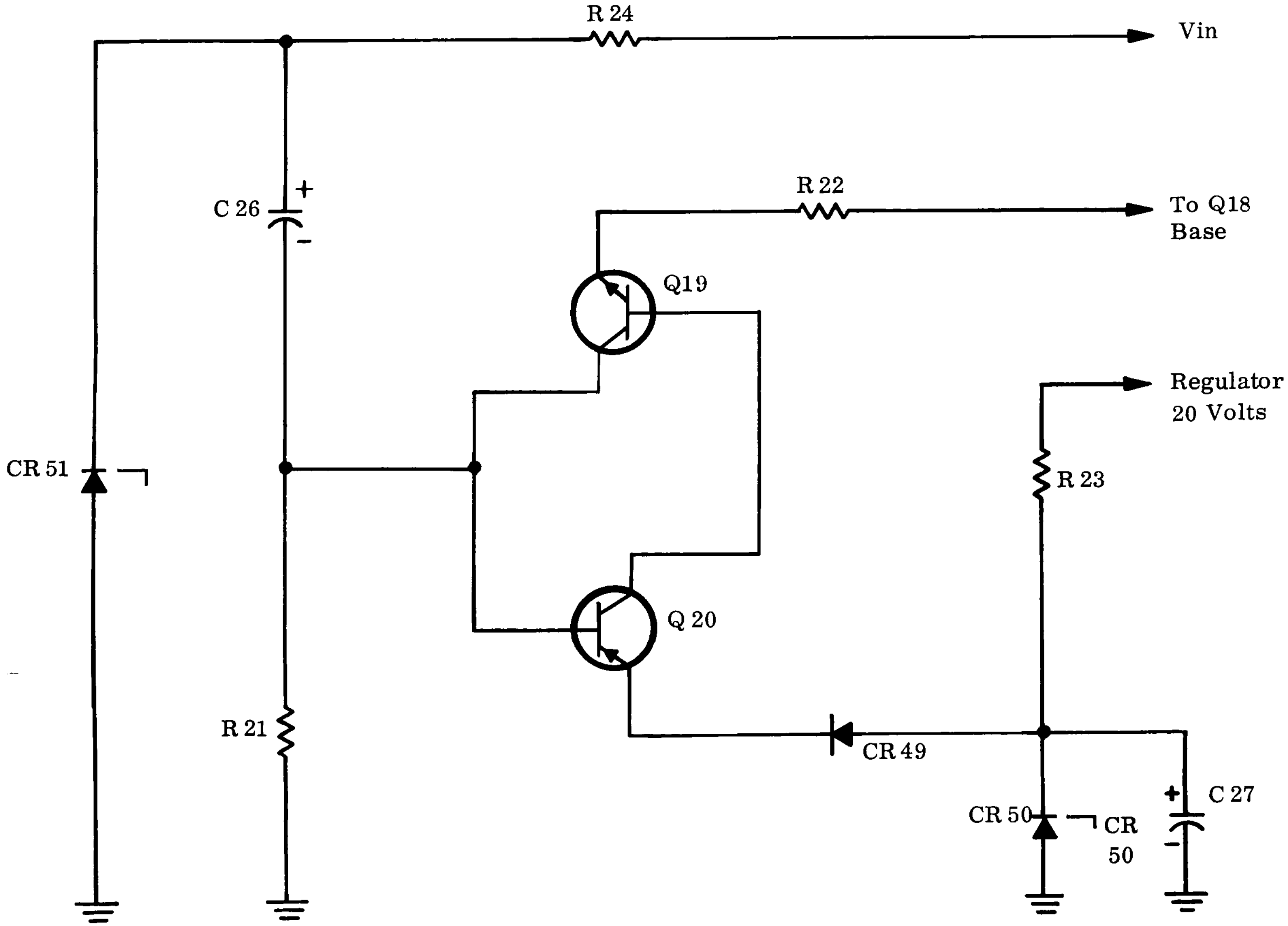

Fig. 5- Timer schematic diagram

Where	E_o	is the voltage at the node of R_{21} & C_{26}
	E_i	is the voltage applied (V_Z of CR51)
	e	is the base of natural logarithms (2.718)
	t	is the time the voltage is applied
	R	is the value of R21
	C	is the value of C26

Zener diode CR50 is avalanched through R23 and zeners at 6.7 volts. The node of CR50 and R23 is tied to the emitter of Q20. Since the base of Q20 is at some point near 20 volts and decreasing, it follows that Q20 will be held off until such time that the voltage at the C26, R21 and Q20 base node reaches a point below 6.7 volts. The values of R21 and C26 are selected such that the time required for this to occur is the warm-up period required for the traveling-wave tube. At the time Q20 begins to conduct, it turns on Q19. Once the turn-on sequence starts, it is very rapid due to the positive feedback between Q19 and Q20. This snap action causes Q18, which had been off since it had no base drive, to turn on sharply. This sharp turn-on is necessary because of the damage that would occur in the power transistors if the drive were brought up slowly, causing a long transistion through class "A" operation before becoming fully saturated (See Fig. 4). With Q18 turned on the dc to dc converter can commence operation since its base drive loop is closed.

There are five telemetry points monitored. These are converter telemetry, high-voltage telemetry, regulator telemetry, helix current telemetry and cathode current telemetry.

The converter and high voltage telemetry are the same type of circuits. Auxiliary windings are placed on the multivibrator and collector transformers and afford a simple binary output when converted to dc through full-wave bridges. They are not intended for accurate analog measurements, but provide only an indication that the multivibrator and power amplifiers are operational.

The regulator telemetry consists of a simple resistor voltage divider placed across the output of the regulator. The output voltage is divided down across two precision resistors to a range that is compatible with the requirements of the specification. By monitoring this divided output it is possible to attain highly accurate analog information relating the output voltage of the regulator.

The helix current and cathode current telemetry circuits are similar to one another. Since their function is to relate a current condition, different approaches can be used. One is to place a series resistor in the lead to be measured and develop a voltage across it. A drawback to this type of scheme is its inefficiency, since the voltage could not be read directly out due to the potentials of the leads being monitored, and would require further translation. The technique used is the implement current transformers, since secondary current is a function of primary current and the turns ratio. The secondary current is rectified through a full-wave bridge circuit and fed through a precision resistor, developing a voltage output that is the analog of the current in the primary.

Mechanical Design

The environmental requirements of the specification, although not extremely stringent, require the mechanical and thermal design to be approached judiciously. Experience gained on projects having environmental requirements of a similar nature proved very useful in the design and development of a mechanical and thermal configuration for the power conversion system.

To facilitate the manufacture of the final package as well as establish an economical program of component replacement, if necessary, the power conversion system is packaged in two cordwood-type modules (see Fig. 6). The complexity and difficulty of manufacture of a cordwood-type module is directly proportional to the component population therein, therefore the use of two modules reflects a substantial savings in the event it becomes necessary to discard one because of a failure of catastrophic nature.

The volume and weight requirements are not restrictive enough to predicate the use of welded module construction, therefore the more economical and easier to assemble printed circuit board technique is used. The components are mounted both between and on the boards. Between module interconnections are accomplished through the use of terminal pins appearing on the top of the modules. These pins are interwired making the connections between modules.

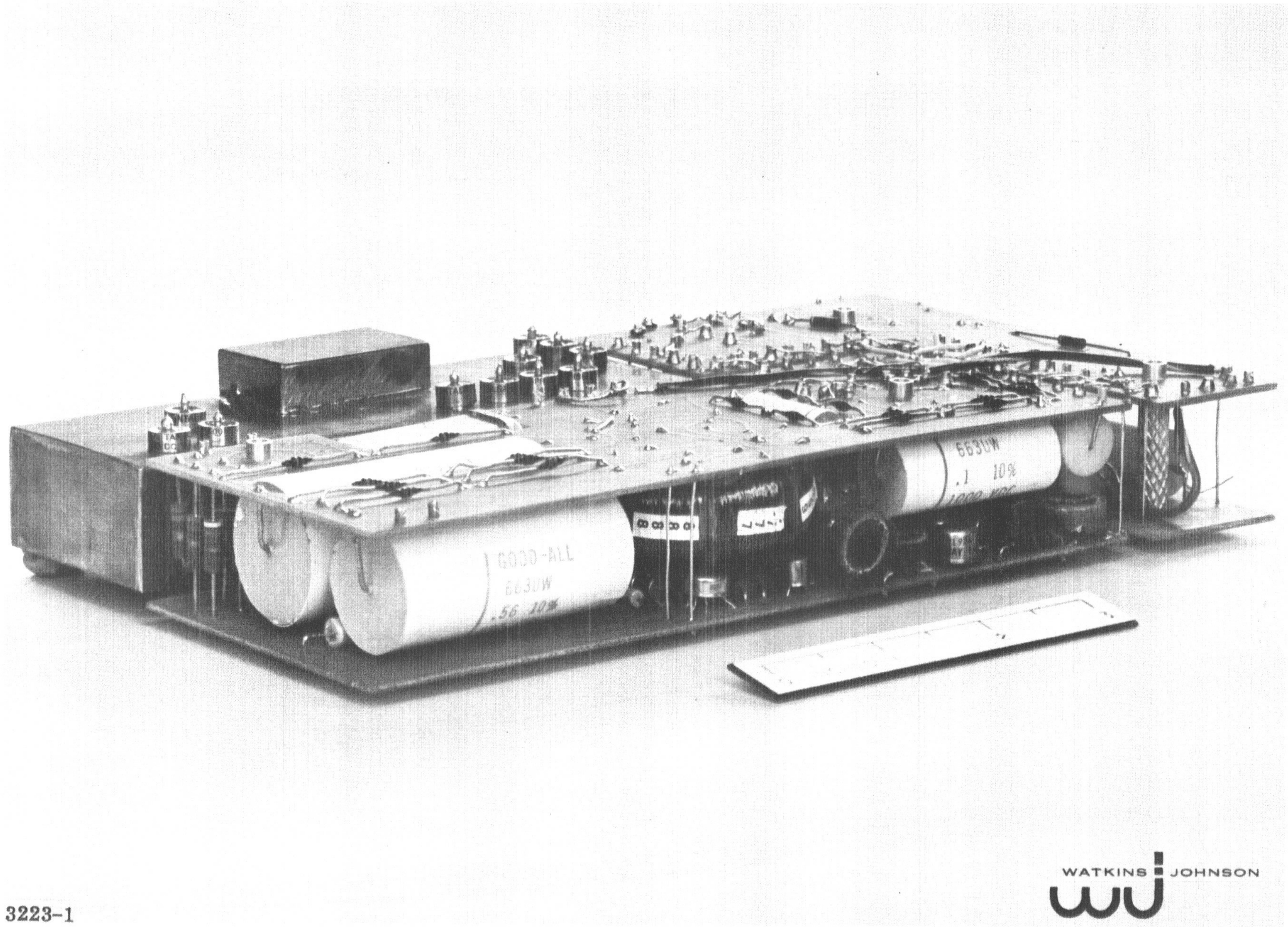

Fig. 6 - Regulator/dc to dc converter and filament/telemetry modules.

Provisions for mounting the modules to the support structure are made through the use of aluminum spacers. These spacers run completely through the modules perpendicular to the mounting surface, (see Fig. 6). They are threaded through to provide a suitable mechanical connection. The spacers have a large diameter on the portion inside the printed circuit boards forming a shoulder that provides an accurate board spacing jig. The high voltage transformer taps mentioned in the discussion of the dc to dc converter also appear on the top of the module so the voltage may be easily adjusted.

The complete module sandwich is hard potted once completed. The material used is Stycast 1090 filled with micro-balloons to decrease its weight. This configuration provides an extremely rugged component part.

After the two modules have been assembled, tested and potted, they are interwired and the system is tested. Once it is verified that the power conversion system is in operation, the interconnnect wiring is also covered with potting compound. This final potting assures operation of the system in any pressure or humidity environment, since the potting renders the wiring impervious to any outside conditions.

Due to the efficiency of the power conversion system, there is very little heat to be extracted from its components. The power switch in the regulator and the power switches in the dc to dc converter are the only elements that require any heat transferral consideration.

These components are mounted on an aluminum heat conductor that runs directly to the surface to which the system mounts. Care is exercised that the bodies of the transistors, which are electrically common with the transistor collectors, are insulated from the heat conductor. This is accomplished through the use of a hard anodize finish on the heat conductors as well as mica washers placed between the transistors and heat conductor. Silicone heat conducting compounds are used on all interfaces between heat generating components and their sinks. Using this technique, an analytic temperature gradient of 3 to 5 degrees centigrade is exhibited between the transistor cases and the mounting surface.

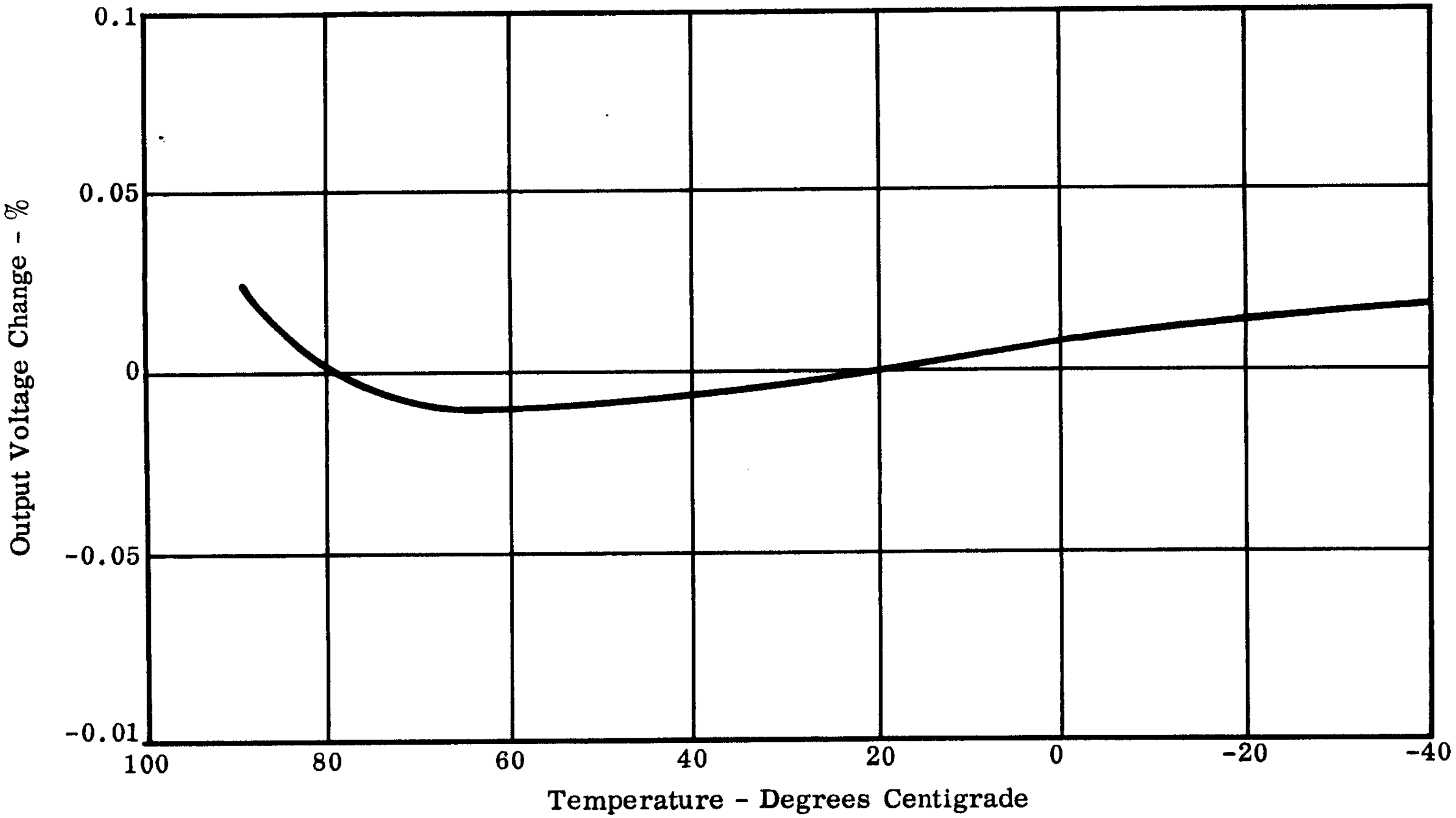

Fig. 7 - Output voltage drift vs. temperature reference point $25^{o}C$.

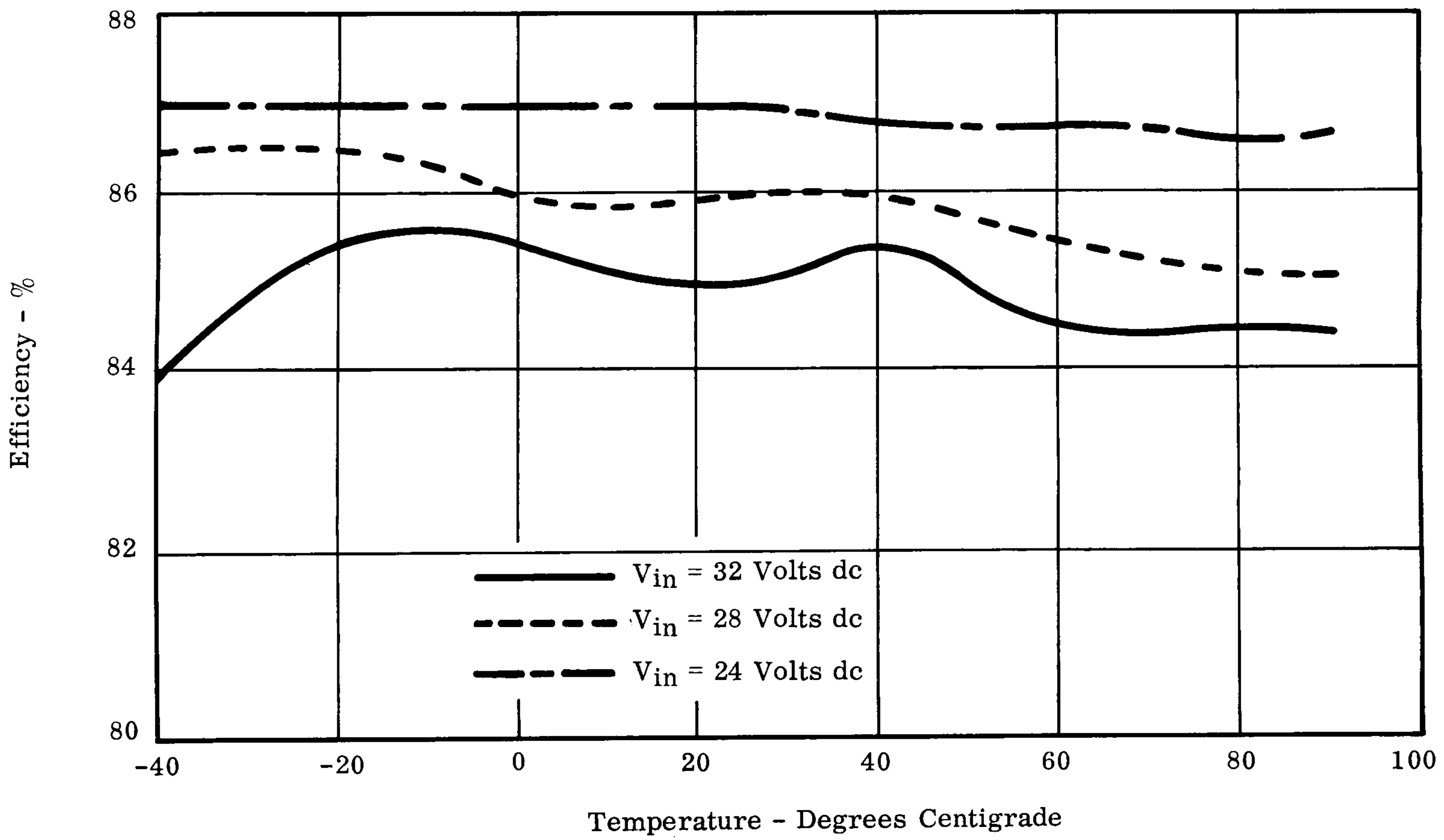

Fig. 8 - Power conversion system efficiency versus temperature.

APPENDIX I

DETAILED SPECIFICATIONS AND ACHIEVED PERFORMANCE

NAS1 - 3766	Achieved Performance
Input Voltage	
24 - 30 volts DC	23 - 32 volts DC
Minimum Efficiency	
85%	83% over all line and temperature ranges.
Weight	
4.0 pounds or less	Meets specification
Volume	
80 cubic inches or less	Meets specification
Static Acceleration	
50 g in each direction, along each of three (3) mutually perpendicular axes.	Meets specification
Vibration	
Sinousoidal sweep at rate of 2 minutes/octave along each of three (3) mutually perpendicular axes: .5" D. A., 5 cps to 18 cps ± 25g (vector) 18 cps to 2,000 cps.	Meets specifications
Random Vibration (Gaussian)	
12 minutes along each of the three mutually perpendicular axes $.10g^2$/cps, 20 to 2,000 cps.	Meets specification
Shock Acceleration	
70g, 11 msec dwell, each axis, each direction	Meets specification

APPENDIX I

(continued)

DETAILED SPECIFICATIONS AND ACHIEVED PERFORMANCE

NAS1 - 3766	Achieved Performance
Pressure	
760 mm to 10^{-8} mm of Hg.	Meets specification
Humidity	
90 percent	Meets specification
Temperature	
Continuous operation at any heat sink temperature within the range -40° C to +85° C.	Meets specification