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IMPROVED TRAVELING WAVE TUBES

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SUMMARY

After a brief description of how a typical TWT works, there is a discussion of multistage depressed collectors (MDC). A quick method for computing the expected efficiency of a well-engineered TWT is outlined, "to keep the tube salesman honest" and to aid in estimating power supply needs. There are suggestions concerning the applications of improved TWTs and a new power supply.

INTRODUCTION

The electronic countermeasures (ECM) systems currently being preoduced use traveling wave tube (TWT) amplifiers which, typically, operate at 20-25 percent efficiency. This paper is intended for system designers and those who specify ECM amplifiers, so that they may become more aware of techniques, pioneered by NASA, which will allow substantial improvements in amplifier efficiency. Using design techniques developed at the Lewis Research Center (ref. 1), it is possible to approximately double the efficiency of the critical amplifier TWT. A quick method of computing the expected improvement to an ECM TWT is explained. Some of the benefits of such improvements are obvious: less input power, a smaller and lighter power supply, easier cooling. Other benefits are less obvious, but are significant. For example, it is now possible to build efficient TWT's which, rather than operating at saturation, can be very linear amplifiers. A new approach to power supplies is also suggested.

A TYPICAL TWT

A typical TWT, as used for electronic warfare, is depicted schematically in figure 1. On the left, the cathode emits electrons which are focused into to beam. The beam is kept confined by a periodic permanent magnet (PPM) stack. The beam interacts with the rf circuit; in broadband tubes the circuit is usually a helix. By the interaction of the electron beam and the rf wave traveling down the helix, the rf wave is amplified at the expense of the kinetic energy of the electrons in the beam. Hence, the name, traveling wave amplifier tube.

The energy of the electron beam is, of course, the cathode voltage, V_0, times the beam current I_0. For the traveling rf wave to be amplified, the phase velocity must be more or less synchronous with the electron

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bunch velocity in the beam. Hence, the average electron velocity must remain high, and, as the beam exits the helix at the rf output, it still contains, perhaps, 85 percent of the kinetic energy with which the beam left the electron gun, $V_0 I_0$. If the collector, the structure on the right, is at ground potential, the spent beam energy is totally wasted as heat. If, however, the collector electrodes are "depressed," that is, if they are negative with respect to the grounded tube body, the electrons will do work against the potential gradient and impact with less energy. Thus less energy is wasted; the tube is more efficient.

There is a simple hydraulic analogy. Consider a fire hose squirting a "beam" of water 10 stories into the air, whence it falls into a pond and is sucked up to be recirculated through the pumper, or power supply. All of the kinetic energy of the water is wasted as heat in the collecting pond. If, however, the "beam" of water is collected on the roof of a nine story building, whence it is returned by a drain pipe to the pumper, then only 10 percent of the "beam" energy is wasted. The gravitational potential between the collector (roof) and ground level is used, via the hydrostatic pressure in the drain pipe, to recover 90 percent of the otherwise wasted energy. The pumper, or power supply, works less hard to produce the same height of fountain.

The collector depicted in the diagram is a two-stage depressed collector, typical of the more efficient TWT's on the market today. It might be 50 to 60 percent efficient in recovering the energy of th spent beam. If it is further depressed, a space charge builds up, and electrons are accelerated back down the tube in the wrong direction. Of many bad effects, the most obvious is often a burnt-out circuit.

Reverting to the hydraulic analogy, one might imagine the water splashing off the roof and falling down on the fireman.

IMPROVED MDCs

Figure 2 illustrates a NASA Lewis-type multistage depressed collector (MDC), with computer generated electron trajectories (ref. 2). Half of a longitudinal section is depicted, with the axis of symmetry on the right. This type of collector was developed and patented at Lewis Research Center, with some support from the Air Force. The highly negative spike, at cathode potential, disperses the beam and prevents a space charge buildup. Note that most electrons impact the side of the collector plates away from the tube body. Most secondary electrons, which are kicked out by the primary impact, are not accelerated back down the tube. It helps, also, to coat the collector with a material which has a low secondary yield. Properly textured pyrolytic carbon yields only about one fifth as many secondaries as copper.

Figure 3 is another collector, which is not bigger nor notably more complex than the old style collector it was designed to replace, but it is very much more efficient. It should be noted that these collectors work best when there is a refocusing section between the tube output and the collector. The refocusing section, another Lewis patent, collimates the spent beam and reduces the variance of the electron velocities.

Figure 4 is a family of curves which show the relationship between overall TWT efficiency and collector efficiency for different values of electronic efficiency. The electronic efficiency is simply the portion of the beam power which is converted to rf. These curves ignore other losses but clearly show why a typical TWT, with a collector efficiency of about 50 percent, is only about 20 percent efficient, overall.

Aside from the collector, there are two other large sources of losses, interception of the beam by the circuit and low circuit efficiency, considering the circuit as a transmission line. Figure 5 shows the effect of circuit efficiency. These losses are usually difficult to measure, but one will want to know them if he is concerned about buying an efficient tube. It is advisable not to be too credulous. The tube salesman may honestly think his circuit is 95 percent efficient, but NASA has measured losses as low as 68 percent.

Figure 6 shows the results of efforts to improve a standard production line tube by putting a refocusing section and a multistage depressed collector on it (ref. 3). The new MDC roughly doubles the efficiency of the tube, which is similar to those currently flying in Air Force pods.

Figure 7 shows that the improved tube can be operated in the linear region, far below saturation, and still exhibit acceptable efficiency. Because the collector efficiency increases as the electronic efficiency decreases, that is, with decreasing power levels, the tube was useful over a 10-dB range. Optimized for low power, it was even more efficient, while the dc beam recovery was better than 97 percent. A tube for satellite communications is being built along these lines, designed to operate in a range of 4 to 14 dB below saturation (ref. 4). It will be so efficient in the no-rf or dc mode that it will not need to be shut off. That should contribute greatly to reliability.

COMPUTING TWT EFFICIENCY

With elaborate computer models, as used at Lewis, it is possible to predict the performance of a TWT to within the precision with which the performance can be measured. However, anyone can, with a pocket calculator, get a fairly good estimate of what the efficiency of a TWT should be. The system designer will find this useful, for sizing power supplies and so forth. Knowing what a good tube can do will help to keep the salesman honest.

The tube salesman can describe what the rf output of a tube is, and what the prime power required is. The ratio of these, rf out/dc in, is the overall efficiency. To compute what the efficiency might be with an improved multistage collector, one will need the following data:

1. V_0, the cathode voltage
2. I_0, the cathode current
3. The electronic efficiency, η_e
4. The circuit efficiency, η_{crt}
5. The interception efficiency, η_{int}

One can compute the collector efficiency, η_c, and then the overall efficiency:

$$\eta_{ov} = \frac{\text{rf out}}{\text{dc in}} = \frac{\eta_e \eta_{crt}}{1 - \eta_c + \eta_c(\eta_e + \eta_{int})} \tag{1}$$

The cathode heater power, relatively small, is neglected.

The vendor will know V_0 and I_0 very well, but he may not know much about the circuit efficiency or the interception. The product $\eta_e\eta_{crt}$ is approximately the rf output divided by V_0I_0, the beam power. Try for a good estimate of η_{crt}, and compute η_e. η_{int} should be small, 1 or 2 percent for a well focused low frequency tube, but perhaps as high as 10 percent at K-band. If the tube has a depressed collector, electrically isolated from the tube body, and the tube can be run with the collector undepressed, to avoid backstreaming, then η_{int} is approximately the measured helix or body current, to ground, divided by the beam current, I_0.

That leaves η_c, the collector efficiency, to be computed. The collector efficiency depends on the number of stages and the energy spread of the spent beam which is to be collected. As figure 8 shows, the energy distribution is a function of microperveance

$$\mu \text{ perveance} = \frac{I_0}{V_0^{3/2}} \times 10^6 \tag{2}$$

For example, a TWT with a beam current of 1 ampere and a cathode voltage of 10 000 volts has a microperveance of 1. (Tubes with a microperveance of much more than 1 will be hard to focus with permanent magnets.)

Go to figure 9 for a value of $f_{(perv)}$. This is an as yet nameless function, derived at NASA Lewis.

Next choose a number of collector stages, N. Note that N should be at least 2, with one of the stages at cathode potential, because at least two stages are needed to form the electrostatic lens which disperses the beam.

Use this equation to compute the expected collector efficiency, η_c.

$$\eta_c = 0.97\left[1 - \frac{1}{N-1}\cdot\frac{f(\eta_e \mu\text{perv})^{1/3}}{2 - f(\eta_e\ \mu\text{perv})^{1/3}}\right] - \Delta \tag{3}$$

The 0.97 is a "fudge" factor to account for our observation that it is tough to exceed 97 or 98 percent of the theoretical ideal collector efficiency. The Δ is a correction for that portion of the beam which is wasted because the energy of some electrons is greater than the cathode potential. For a microperveance of less than 1, Δ is about 0.01; for a higher μperv, use 0.02.

Then go back to equation (1) to compute the overall efficiency.

$$\eta_{ov} = \frac{\eta_e \eta_{crt}}{1 - \eta_c + \eta_c(\eta_e + \eta_{int})} \tag{1}$$

The result should be within a few percent of reality. It is adequate, for example, for estimating how much prime power one will save if one adds another stage to the collector. (Generally, there is little to be gained with $N > 5$.)

Table 1 shows that this method of quickly predicting efficiency does, in fact, work. The measured and predicted efficiencies are within 2 or 3 percent.

APPLICATIONS OF MDC'S

Since it is possible to double the efficiency of the power amplifier tube, it becomes possible to halve the required prime power and reduce the cooling to one third. Further, since collector efficiency increases to compensate as electronic efficiency decreases, it is now practical to build tubes which operate in the linear portion of the gain curve, "high-fidelity" TWT's.

NEW POWER SUPPLIES

One additional opportunity concerns the integration of the tube and the power supply. Historically, whenever a new, high efficiency TWT was demonstrated, it required a new power supply to provide the proper collector voltages. The power supply, with a custom-built transformer, is a long lead-time item, which inhibits change.

There may be several advantages to using a Capacitor Diode Voltage Multiplier (CDVM) power supply, instead of the conventional transformer supplies now in use (ref. 6). As the schematic in figure 10 shows, it can be assembled from parts in the parts bins; there are no custom-built components. Further, it is easy to imagine mass-produced modules of diodes and capacitors which could be simply stacked together with a standard chopper(s) to deliver any desired voltage-current combination. Multiple taps, for multiple collector stages, are "free" by simply tapping between modules. Such a stack of modules is easy to package. It has no large, hot lumps in it. The CDVM could, for instance, be packaged within the TWT outer covering, eliminating high voltage connectors by combining both power supply and tube in one line-replaceable unit (LRU), not greatly larger than the tube itself.

NASA laboratory work has already found expression in contractor-built devices with rather respectable performance, shown in figure 11 (ref. 7).

While the CDVM is already performing at least as well as the typical conventional power supply, there is a great deal of potential for improvement. When energy is stored in capacitors, rather than inductors, it is logical to operate at higher frequencies than is done now. That means even less weight and less ripple in the output. While transformers have almost a century of development behind them, and seem to have reached a plateau of performance, we are, with the CDVM, still low on the learning curve. That is where we will stay unless someone shows the initiative to develop the CDVM further.

CONCLUSION

The technology to build more efficient, lighter, cooler, and more linear amplifiers exists today as laboratory demonstrations. NASA Lewis Research Center can provide reports, computer design programs, and personal advice. With the equations given above, it is easy to evaluate the performance improvements which can be expected from adoption of the NASA Lewis developments.

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TABLE 1. - COMPARISON OF MEASURED AND PREDICTED VALUES

FOR COLLECTOR AND OVERALL TWT EFFICIENCIES FOR

TWO MICROPERVEANCES

TWT NO. 1: μ perv = 0.41; η_e = 0.1535; η_{ckt} = 0.86; η_{int} = 0.012

	MEASURED		PREDICTED	
	η_c	η_{ov}	η_c	η_{ov}
N = 5	0.86	0.47	0.89	0.51
N = 4	.84	.44	.865	.475
N = 3	.81	.41	.82	.42

TWT NO. 2: μ perv = 0.535; η_e = 0.146; η_{ckt} = 0.835; η_{int} = 0.019

	MEASURED		PREDICTED	
N = 5	0.86	0.51	0.88	0.525
N = 4	.82	.475	.85	.49
N = 3	.795	.44	.795	.435

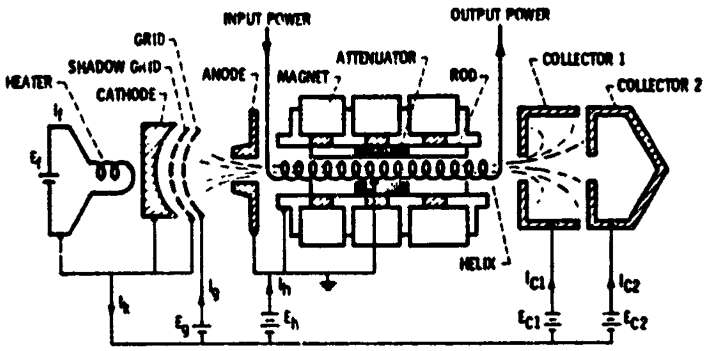

Figure 1. - Schematic of TWT and power supplies.

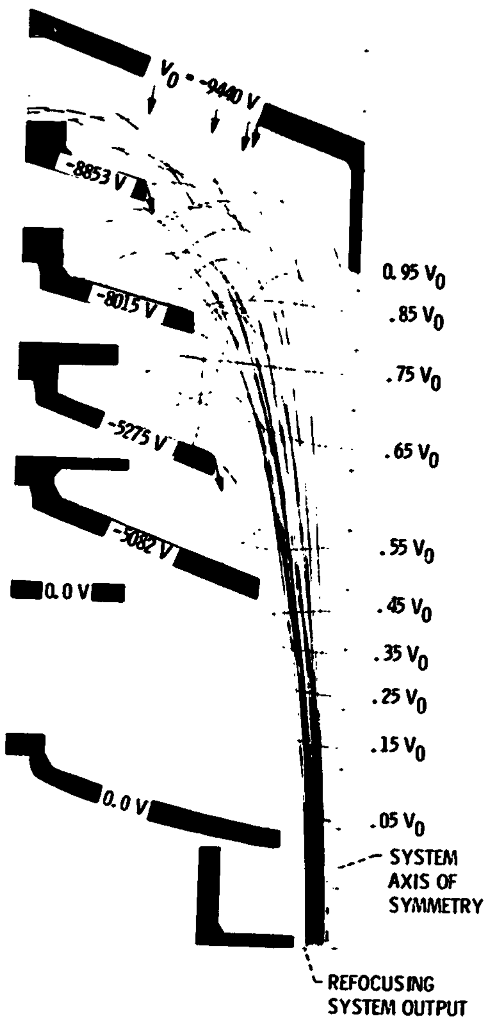

Figure 2. - Electron trajectories in experimental collector with five depressed stages; TWT operating at 3 decibels below saturation. Secondary electron emission yield, δ, 1/2.

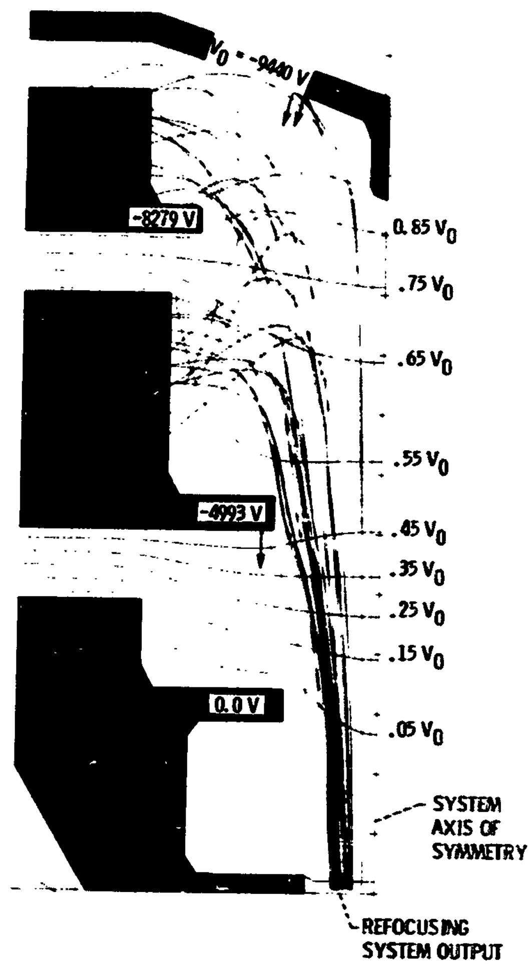

Figure 3. - Electron trajectories in scaled-down collector with three depressed stages; TWT operating at saturation. Secondary electron emission yield, δ, 1/2.

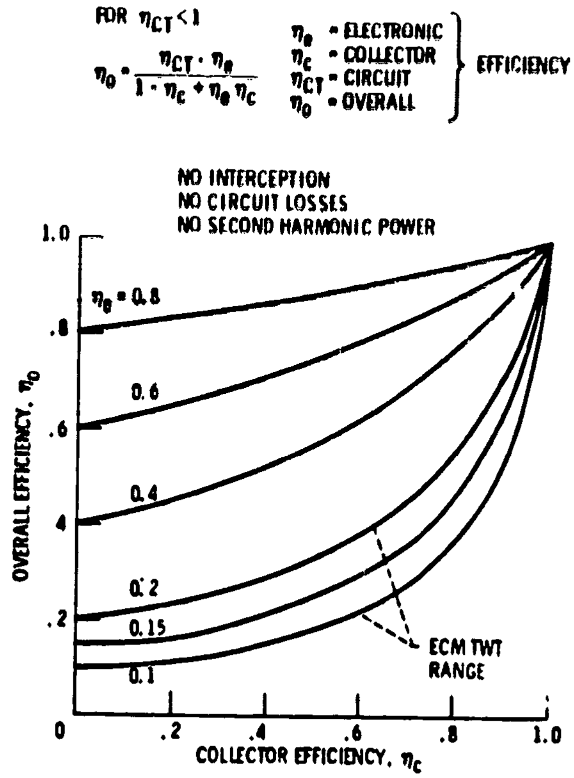

Figure 4. - Overall efficiency vs. collector efficiency.

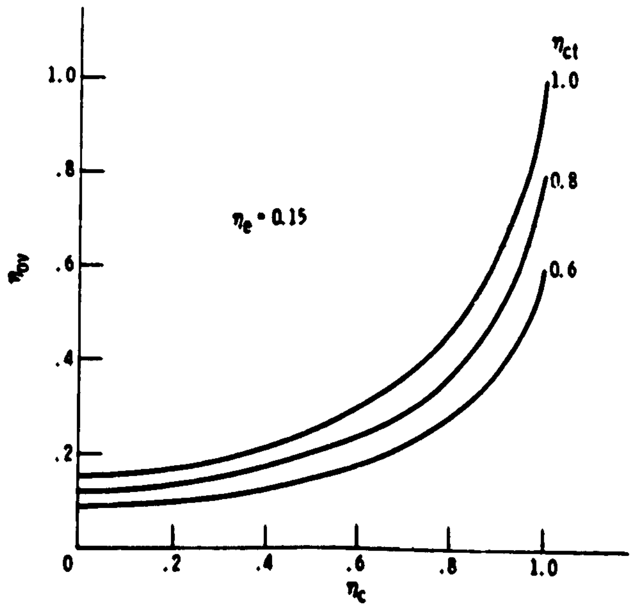

Figure 5. - Effect of circuit losses on the overall tube efficiency for electronic efficiency η_e = 0.15.

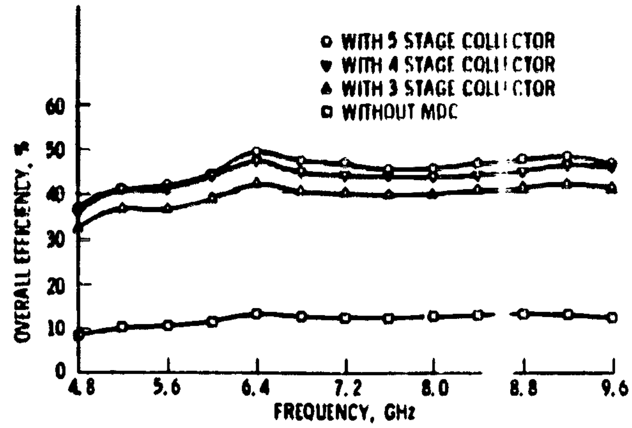

Figure 6. - Overall efficiency vs. frequency at saturation low mode.

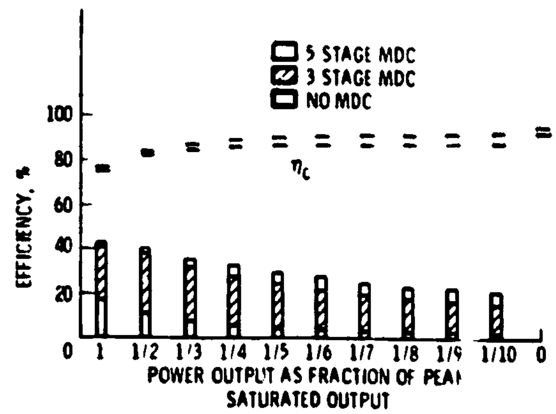

Figure 7. - TWT performance vs. power output.

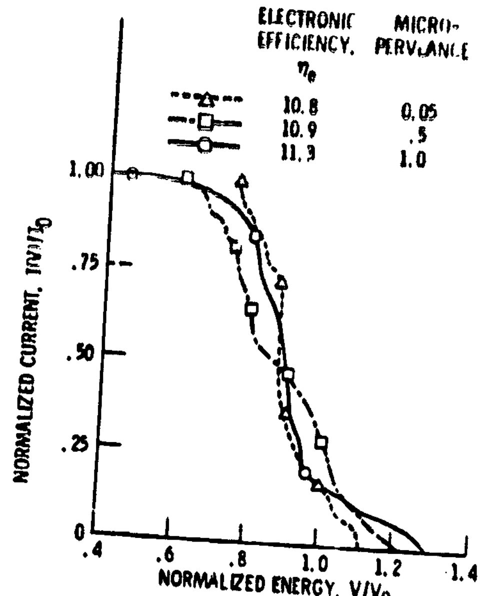

Figure 8. - Computed energy distributions for tubes of same efficiency as function of perveance.

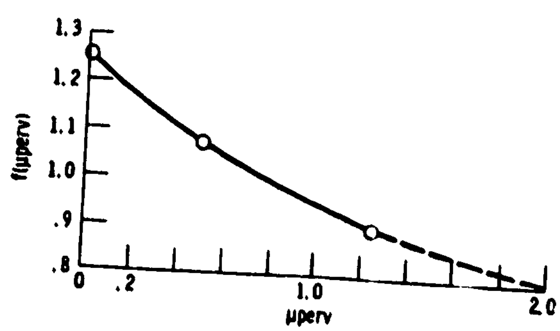

Figure 9. - f(μperv) as function of the microperveance.

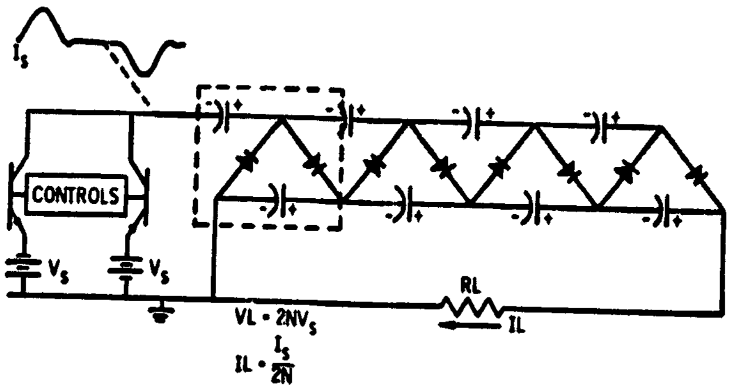

Figure 10. - Transformerless capacitor diode voltage multiplier dc-dc power converter.

- 100-W CONVERTER
  - SHORT CIRCUIT PROTECTION
  - CLOSED LOOP REGULATION
  - TWO-PHASE OPERATION
  - EFFICIENCY, 9.1%
  - COMPONENT WEIGHT, 1 kg/kW
- 1.2-kW CONVERTER
  - SHORT CIRCUIT PROTECTION
  - UNREGULATED
  - FIVE-PHASE OPERATION
  - EFFICIENCY, 96.5%
  - COMPONENT WEIGHT, 0.55 kg/kW

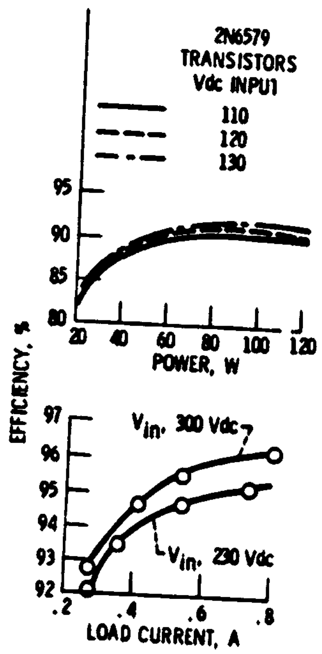

Figure 11. - Contract activities/Hughes Aircraft.