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SUMMARY

Performance characteristics from on-orbit tests of the Transmitter Experiment Package (TEP) for the Communications Technology Satellite (CTS) are presented. The tests were conducted from February 8 through June 13, 1976.

The TEP consists of a Power Processing System (PPS), an Output Stage Tube (OST) and a Variable Conductance Heat Pipe System (VCHPS), all of which are described. The OST is a coupled-cavity Traveling Wave Tube (TWT) with a Multistage Depressed Collector (MDC) and a stepped velocity-tapered slow wave structure for efficiency enhancement. It has an rf output power of 240 watts and overall efficiency of 51.5 percent at a center band frequency of 12.080 GHz. The PPS provides the required operating voltages, regulation, control and protection for the OST. It has a measured dc-dc conversion efficiency of 86.5 to 88.5 percent. The VCHPS consists of a fin radiator and three dual-artery stainless steel heat pipes using methanol and a mixture of inert gases. Test results presented include efficiencies, rf output power, frequency response, and performance with single and multiple (two) carriers, frequency-modulated by video signals.

INTRODUCTION

The Communications Technology Satellite (CTS) (in Canada, CTS was renamed "Hermes" on May 20, 1976) was developed in a joint U. S.-Canadian program by NASA and the Canadian Department of Communications. It was launched on a Delta 2914 launch vehicle on January 17, 1976 from NASA Kennedy Space Center, and put into a geosynchronous orbit 35,786 kilometers above the equator at 116° west longitude. The purpose of the CTS is to demonstrate advanced high power technology for communications in the 11.7 - 12.2 GHz frequency band and to investigate the use of this technology for communications services such as health, education, and similar user applications[1]. CTS is distinguished from earlier communications satellites by its high rf output power (nominally 200 watts) within the 11.7 - 12.2 GHz frequency band.

The key to increased rf power for communication satellite applications is the development of high power microwave amplifiers with high efficiency. As rf power output increases, the importance of high efficiency is increased. For high power satellites, the efficiency of the transmitter, because of its large power consumption, is a major factor in determining the size of the solar array, the thermal radiator, and the weight of the power processing system for the transmitter output amplifier. One of the major responsibilities of the United States in the CTS program was to provide the high power Transmitter Experiment Package (TEP) for the spacecraft transponder (fig. 1). The spacecraft transponder receives signals in two 85 MHz bands, RB1 and RB2, centered at 14.247 GHz and 14.052 GHz respectively. These bands are translated to bands TB1 and TB2, centered at 12.080 GHz and 11.885 GHz respectively. The TEP is used as the high power, 200 watt, output amplifier for the RB1/TB1 signals. Two simultaneous transmitter outputs of 20 watts and 200 watts are provided by a low power TWT and the TEP, respectively.

The TEP (fig. 2) consists of a nominal 200 watt Output Stage Tube (OST), a supporting Power Processing System (PPS) and a Variable Conductance Heat Pipe System (VCHPS). The location of the TEP on the CTS spacecraft is shown in figure 3. The principal technological objectives of the TEP development are:

1. To demonstrate in space an amplifier operating with an efficiency $\gtrsim 40$ percent and a saturated rf output power $\geqslant 180$ watts at a frequency of 12 GHz.
2. To demonstrate reliable high-efficiency performance for a transmitter experiment package for two years in a space environment.
3. To obtain fundamental data for further advancement in the state-of-the-art of high power microwave amplifier operations in space.

This paper presents a summary of results from tests conducted to determine the on-orbit performance of the TEP for CTS during the period from February 8 through June 13, 1976.

TRANSMITTER EXPERIMENT PACKAGE

Output Stage Tube

The OST[2] is a coupled-cavity Traveling Wave Tube (TWT) augmented with a Multistage Depressed Collector (MDC) as shown schematically in figure 4. This class of linear beam microwave amplifiers convert the kinetic energy of an electron beam into rf energy.

An electron beam is formed by convergent optics in the electron gun. Electrons, emitted by a thermionic cathode, are accelerated to approximately 1/5 the speed of light by the potential difference between the cathode and the anode. The cathode and anode voltages with respect to the TWT body are -11,200 volts and 250 volts respectively. The electrons pass through an interaction region of the TWT, located between the input and output waveguides. This region of the TWT is composed of cylindrical cavities, coupled to form a lumped element transmission line or slow wave structure. It contains three line sections separated by terminations (or severs). Beam focusing is accomplished by magnets placed outside of the cavity structure along the transmission line. The rf wave, in the transmission line, interacts with the electron beam as it passes through each cavity. The kinetic energy of the electron beam is converted to rf energy by fringing rf fields in each cavity which interact with the electron beam.

The output section utilizes cavities with physical dimensions designed to reduce the velocity of the rf wave in the transmission line. The velocity reduction is done in two steps to maintain synchronism between the rf wave and the electron beam, as the electron velocities are reduced. This velocity tapering of the output section produces an interaction efficiency of

26 percent. As the beam exits from the coupled-cavity region of the TWT, it enters the MDC. Magnetic refocusing[3] of the electron beam (see fig. 4) establishes the desired electron entry conditions into the MDC.

The MDC[4] is used to convert kinetic energy remaining in the electron beam to potential energy and thereby reduce the power required to operate the TWT. The MDC is composed of ten collector electrodes or plates. Each, with the exception of the tenth collector has a centrally-located hole which allows the electron beam to penetrate the collector region. The depth of penetration of an electron is determined by its entry velocity or remaining kinetic energy. Electrons are collected by the plates based on their kinetic energies. High energy electrons are collected by the tenth and its neighboring plates, while low energy electrons are collected by the first and its neighboring plates. The shapes of the collector electrodes are designed to produce equipotential surfaces and an electric field configuration necessary to sort and collect electrons in accordance with their entry velocities. The electrons, therefore, are collected near the apex of their trajectories where they have near-zero velocity. In this manner, the electron kinetic energy is converted to potential energy and returned to the PPS. This reduces the power required to operate the OST. The tenth collector is connected to cathode potential; the collector electrodes from the tenth through the second are connected at descending voltages, each differing from its neighboring electrode by 1/10 of the cathode voltage. The use of the MDC results in reduced input power, and therefore, increased efficiency for all rf output powers up to and including saturation.

The unique design approaches used to achieve high efficiency, velocity tapering of the output section of the interaction region, and use of the MDC produce an overall efficiency of 51.5 percent and an average saturated rf output power of 240 watts at center band frequency.

Heat produced in the MDC due to residual velocities of the collected electrons is radiated to the collector enclosure and in turn radiated to space. A combination of internal heat shields and a bellows-type external heat choke is used to reduce the heat flow back to the interaction section of the TWT.

Power Processing System

Electrical power for operation of the TEP is delivered to the PPS at nominal supply voltages of 76 VDC and 27.5 VDC, respectively. The PPS[5] performs the following functions for TEP operations:

1. Develops proper operating voltages for the TWT and MDC.
2. Regulates supply voltages.
3. Provides fault sensing and protection.
4. Provides command control and sequencing for remote operation.

Separate inverters are provided for the cathode heater, cathode and collector supplies, anode, and two ion pumps. Regulation is achieved by pulse width modulation of the switched primary voltage. A high degree of regulation, 0.1 percent, and low ripple, 0.01 percent, is required for the -11.2KV cathode supply. This is required to achieve proper gain and preclude modulation of the rf output.

Variable Conductance Heat Pipe System

The VCHPS is used to remove heat from the PPS and TWT body and maintain controlled operating temperatures for these components. It is composed of three heat pipes and a 52 X 124 cm fin radiator (fig. 2). The heat pipes are dual-artery stainless steel pipes using methanol as the medium fluid and a mixture of nitrogen (90 percent) and helium (10 percent) as the inert regulating gas. The system is designed so that the individual heat pipes become active at different levels of heat rejection. Thus, the active area of the fin radiator increases as the heat rejection rate increases.

MEASURED PERFORMANCE

The results presented in this paper include test results from the periods of February 8 through March 3, and from April 24 through June 13, 1976. Communications operations were discontinued during the eclipse period from March 4 through April 23 due to a failure in the spacecraft power subsystem. The results represent 90 TEP operating days (out of 154 days in orbit) with a total of 1233 hours of actual TEP operation in orbit. It should be noted that the TEP was operated for 1800 hours in pre-launch testing. Operation of the TEP was begun at 9:12 am, EST on February 8, 1976. A series of tests were conducted to determine on-orbit communications, electrical, and thermal performance characteristics of the TEP. The list of tests conducted is given in Table I. Results of some of these tests are described in the following sections of this paper. The key questions to be answered were:

1. What are the TEP operating characteristics in its space environment?
2. Is there observable degradation due to launch, pre-injection, or operating environments?
3. Have there been observable changes with time?

The losses attendant to the large power consumption of the TEP necessitated special care to accommodate widely varying heat rejection rates from both the OST body and the MDC enclosure. Because the TEP thermal condition is influenced greatly by its operating point, it was necessary to operate at constant rf power levels for periods up to two hours to achieve thermal equilibrium. This was done to establish repeatable test conditions. All tests were conducted using the CTS ground station facility[6] at Lewis Research Center for uplink test signal transmission and downlink reception.

DC and RF Performance of TEP

Some of the observed TEP performance characteristics are summarized in Table II. The average OST overall efficiency at saturated rf output power at center band frequency was 51.5 percent for the testing period, as shown in figure 5. For these operating conditions, figure 6 indicates the average rf output power was 23.8 dBW, or 240 watts, while figure 7 shows the average body current was 6.38 mA.

The average OST overall efficiencies measured as a function of operating frequency were 42.5 percent at the lower band edge frequency (12.038 GHz) and 37.5 percent at the upper band edge frequency (12.123 GHz), as shown in figure 8. This figure again indicates that the average overall efficiency at the center band frequency (12.080 GHz) was 51.5 percent. The PPS efficiency measured was 86.5 to 88.5 percent. This small variation in the PPS efficiency was caused primarily by variations in the input supply voltage from the solar arrays. The resultant overall efficiency at saturated rf output power, center band frequency, was 45.6 percent.

Swept frequency measurements at saturated rf output power during thermal-vacuum testing and on-orbit tests show nc changes in output characteristics (fig. 9), except for minor differences due to the differences in the measurement systems.

The variations in efficiency, rf output power, and body current with operating time are attributed to the inability to exactly duplicate operating conditions. Based on these data, there appears to be no change in the dc or rf performance of the TEP.

In addition to the test results described, measurements were also made which are intended to provide early identification of long-term degradations of OST vacuum integrity, cathode emission, or contamination of insulators due to material migration or depositions. Such contamination of the insulators could cause leakage currents. There was no evidence of any changes during the testing period described which would indicate the start of any of these life-limiting effects.

TEP Communications Performance

Communications tests were conducted to evaluate the performance of the TEP as part of a space communications link. Both single and dual channel video tests were conducted.

The single channel video tests were conducted using the TEP to amplify a carrier, frequency-modulated by a video signal. To determine the quality of the channel, differential gain (dG), differential phase (dØ) and unweighted signal-to-noise ratios (S/N) were measured. The tests were conducted using video modulation index 2 (18 MHz peak-to-peak deviation) along with video pre-and de-emphasis in accordance with CCIR recommendation 405-1 for a 525-line system. The worst case dG and dØ were 4 percent and 4.5°, respectively. These effects were imperceptible. The worst case S/N level experienced using the Lewis Research Center CTS ground support facility was 40 dB. For most tests, the S/N was limited by the signal sources.

Dual channel video tests were conducted by using the TEP to simultaneously amplify two frequency-modulated carriers, each modulated with a video signal. To determine the quality of the channels, video crosstalk was subjectively evaluated. The optimum conditions found for dual channel performance were:

Channel 1	12.055 GHz
Channel 2	12.105 GHz
Power out	70 watts per channel

The video crosstalk between channels for these conditions was found to be imperceptible. The crosstalk was found to increase with increasing drive of either of the two signals. The worst case conditions, with 50 MHz spacing, occurred with the drive of one channel increased by 6 dB above the optimum. This was the limit of tests conducted. For these conditions, the crosstalk was barely perceptible. The S/N for both channels during these tests was 46 dB or better.

CONCLUDING REMARKS

On orbit tests were conducted to evaluate the performance of the CTS transmitter experiment package. The TEP efficiency at center band frequency was determined to be 45.6 percent. Corresponding efficiencies for the PPS and OST were 87.5 and 51.5 percent, respectively. There were no observable degradations in TEP performance due to launch, pre-injection, and operating environments, nor were there observable degradations from operating for 1233 hours during 154 days in orbit.

The TEP was found to amplify video signals with negligible picture degradation due to dG and dØ distortions. The TEP was found to amplify two video signals simultaneously with 70 watts per channel and with imperceptible crosstalk due to distortions. The worst case condition with 50 MHz spacing produced barely perceptible interference when the drive of one channel was increased by 6 dB.

REFERENCES

1. W. H. Robbins and P. L. Donoughe, "CTS United States Experiments - A Progress Report," NASA TM X-73510, 1976.

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3. H. G. Kosmahl, "Electron Beam Controller," U. S. Patent 3,764,850, 1973.

4. H. G. Kosmahl, "A Novel Axisymmetric Electrostatic Collector for Linear Beam Microwave Tubes," NASA TN D-6093, 1971.

5. Farber, B. F., Schoenfeld, A. D., and Thollot, P. A., "Power Processing System for a 200 W Communication Satellite Transmitter," in IEEE International Conference on Satellite Communications Systems Technology, Inst. Electr. Electron. Eng., 1975.

6 Lewis Research Center, "Early Performance of the 12 GHz, 200-Watt Transmitter Experiment Package in the Communications Technology Satellite," proposed NASA Technical Memorandum.

Table I. Summary of TEP Performance Tests

Quick Turn-on
Power Output versus Power Input
Efficiency
Frequency Response
Single Channel Video
Dual Channel Video
PPS Noise
Multichannel Telephony Simulation
Gain Suppression
Amplitude Modulation to Phase Modulation Conversion
Overdrive
Amplitude Modulation and Phase Modulation Noise
Intermodulation

Table II. - TEP Performance Characteristics Summary at Saturated RF Output Power

OST Overall efficiency (dc-to-rf) (plotted in fig. 5)	51.5 percent
PPS efficiency (dc-to-dc)	86.5 to 88.5 percent
TEP efficiency (dc-to-rf)	45.6 percent
OST input power (dc)	386 to 493 watts
PPS input power (dc)	444 to 561 watts
OST saturated rf output power (plotted in fig. 6)	23.8 dBW
OST body current (plotted in fig. 7)	6.38 mA
OST band width	85 MHz

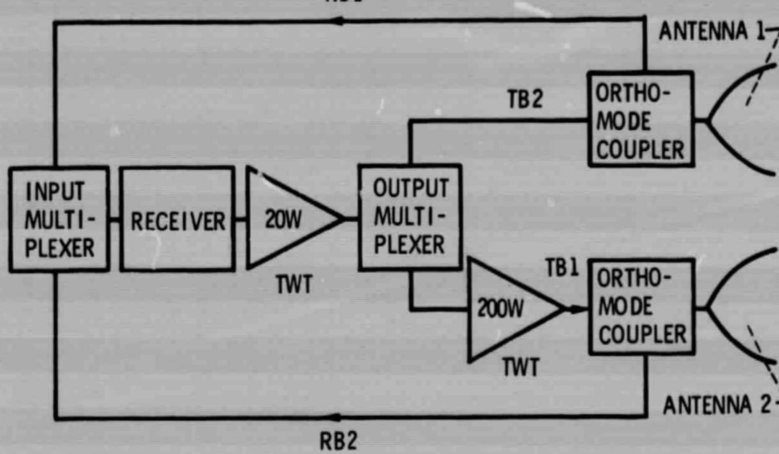

Figure 1. - Simplified diagram of CTS spacecraft transponder.

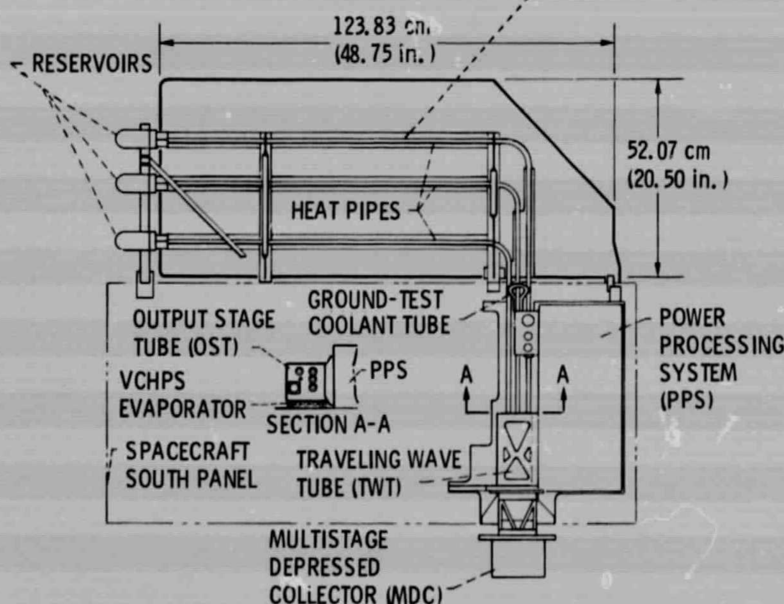

Figure 2. - CTS transmitter experiment package.

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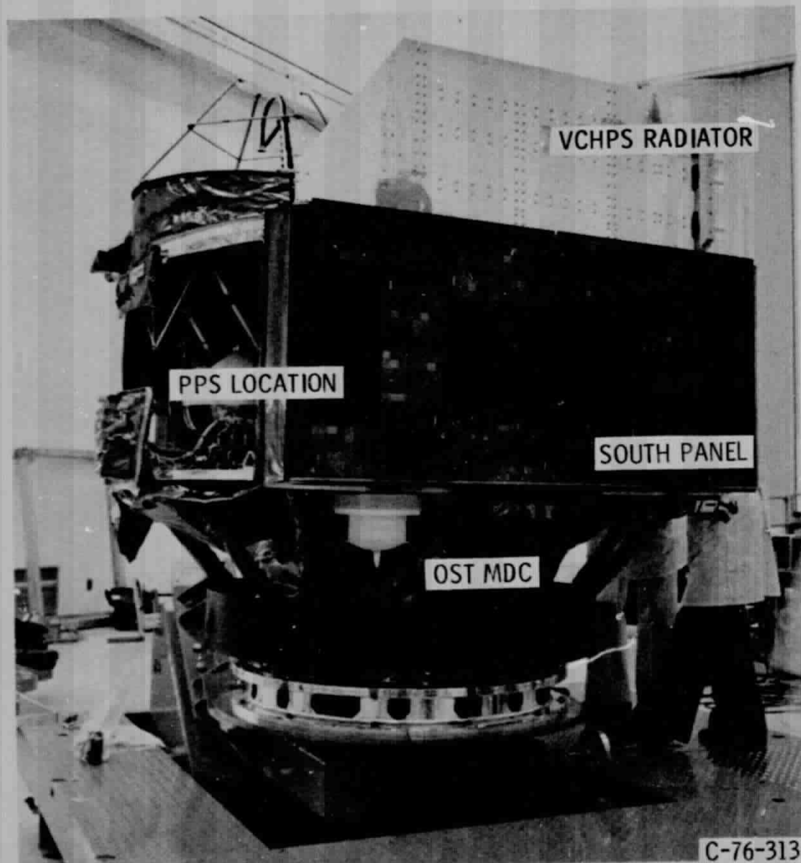

Figure 3. - The CTS spacecraft during pre-launch check-out.

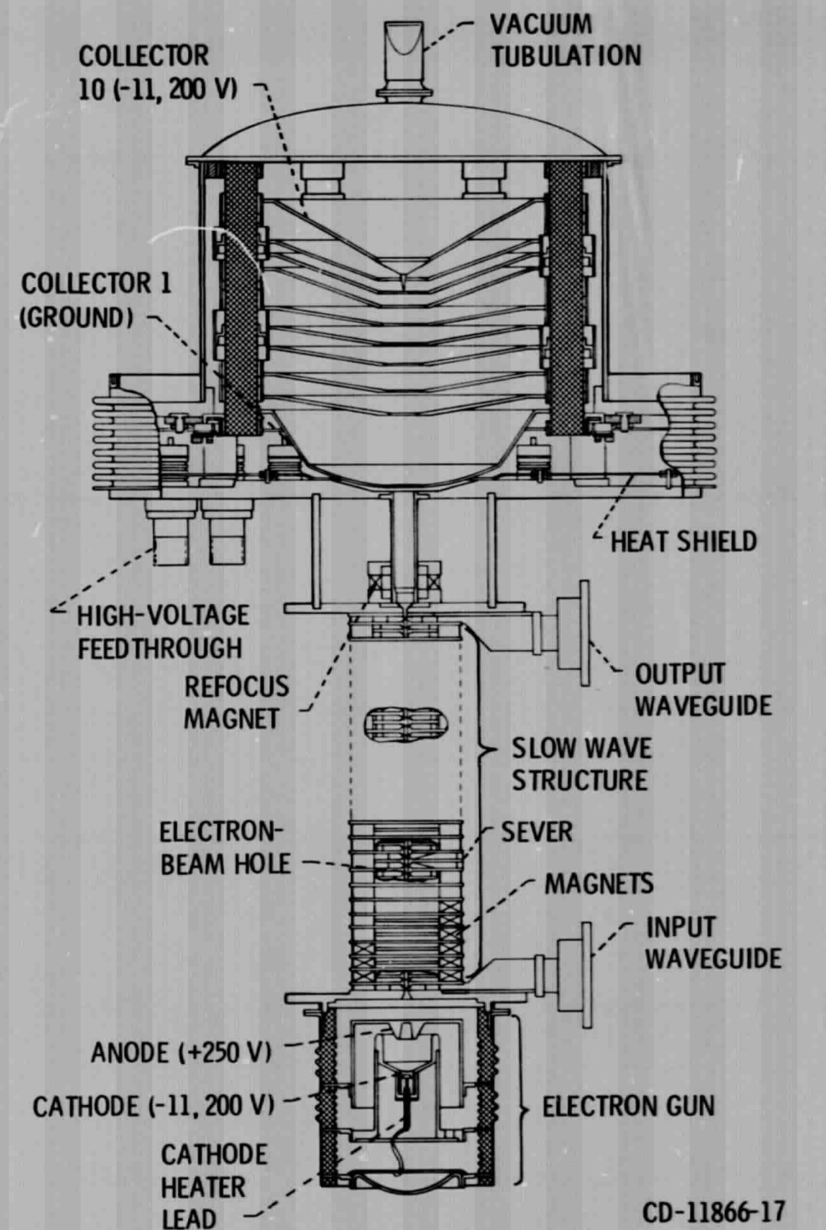

Figure 4. - CTS traveling wave tube with multistage depressed collector.

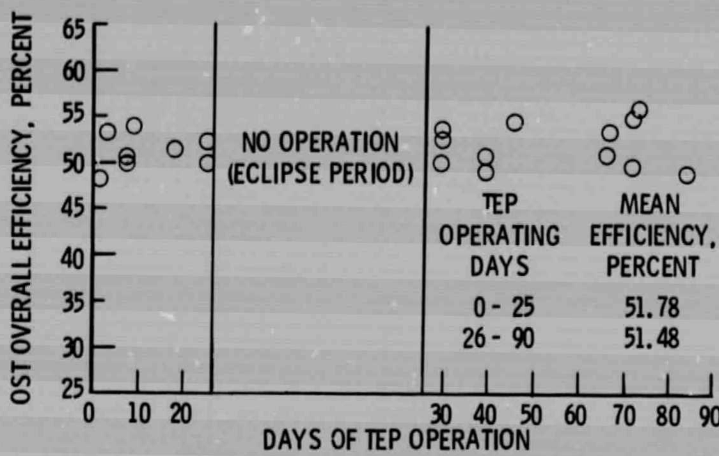

Figure 5. - CTS OST overall efficiency at saturated rf output power at center band frequency as a function of time.

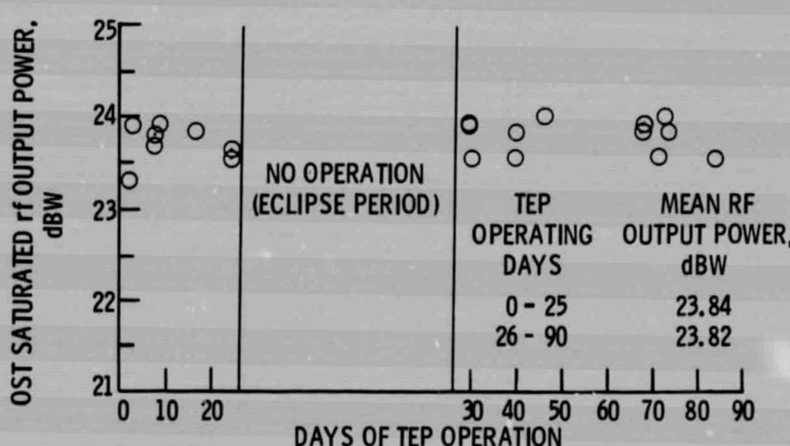

Figure 6. - CTS OST saturated rf output power at center band frequency as a function of time.

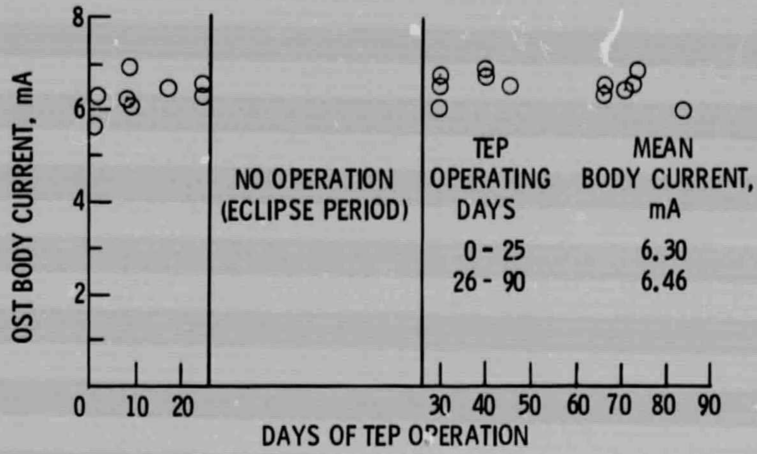

Figure 7. - CTS OST body current at saturated rf output power at center band frequency as a function of time.

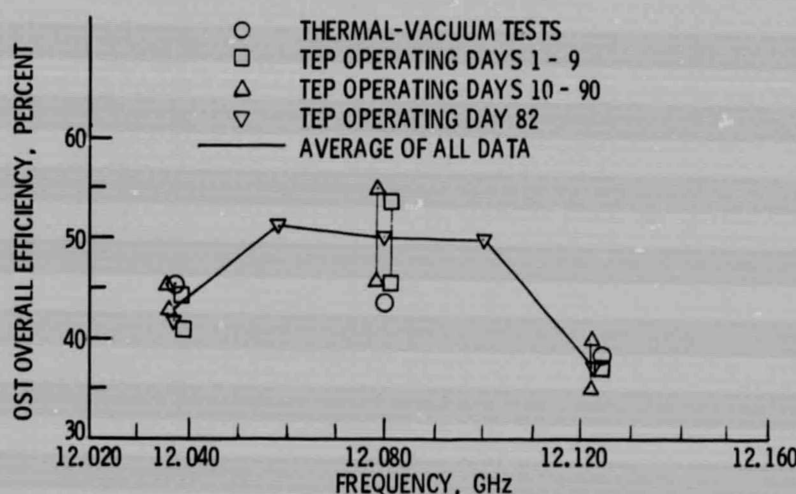

Figure 8. - CTS OST overall efficiency at saturated rf output power as a function of frequency.

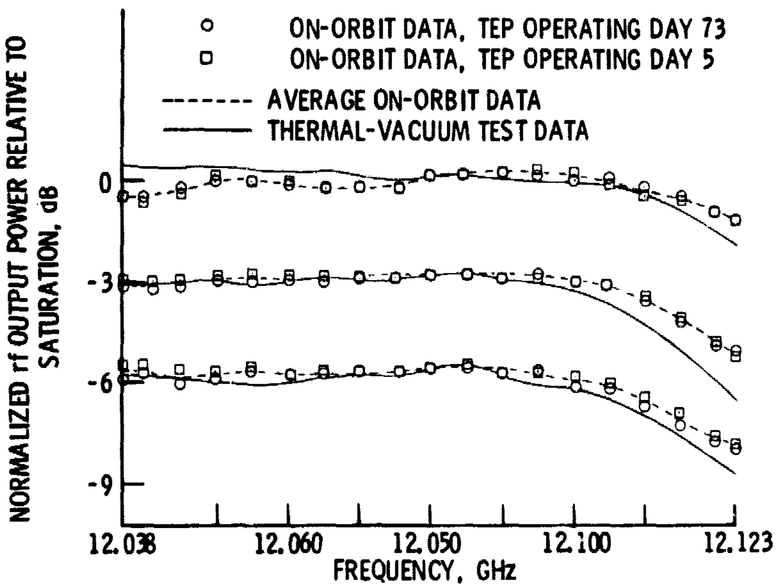

Figure 9. - CTS OST normalized rf output power as a function of frequency.

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