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COMPENSATED CONTROL LOOPS FOR A 30-CM ION THRUSTER

by R. R. Robson
Lewis Research Center
Cleveland, Ohio 44135

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COMPENSATED CONTROL LOOPS FOR A 30-CM ION THRUSTER

R. R. Robson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Abstract

The vaporizer dynamic control characteristics of a 30-cm diametric mercury ion thruster were determined by operating the thruster in an open loop mode and then introducing a small sinusoidal signal on the main, cathode, or neutralizer vaporizer current and observing the response of the beam current, discharge voltage, and neutralizer keeper voltage, respectively. This was done over a range of frequencies and operating conditions. From these data, Bode plots for gain and phase were made and mathematical models were obtained. The Bode plots and mathematical models were analyzed for stability and appropriate compensation networks determined. The compensated control loops were incorporated into a power processor and operated with a thruster. The time responses of the compensated loops to changes in set points and recovery from arc conditions are presented.

Introduction

The long term stable operation of 30-cm diameter mercury ion thrusters requires that the beam current, discharge voltage, and neutralizer keeper voltage be maintained within less than one percent of their setpoints to achieve proposed mission goals. These parameters are controlled by the mercury vapor flow through the main vaporizer, the cathode vaporizer, and the neutralizer vaporizer, respectively. The mercury vapor flow rate through a porous tungsten vaporizer is a function of the temperature of the porous plug which is controlled by the current through its heater. Therefore, to automatically control the beam current, the discharge voltage, and the neutralizer keeper voltage at their setpoint values, the respective vaporizer heaters must be closed loop controlled.

In the past, this control has been implemented with uncompensated proportional control loops. This approach does not allow sufficient open loop gain to maintain the controlled parameters within ±1% while maintaining stability. It also results in a nonlinear relationship between the reference signal and the controlled parameter due to the nonlinear relationship between the vaporizer heater current and the controlled parameter. This nonlinearity is undesirable for computer control of the thruster. Therefore, a control philosophy is required that will provide an open loop gain of greater than 100 to maintain the controlled parameters within ±1% and will linearize the relationships between the reference signals and the controlled parameters.

The approach adopted was to use an integrator in the control loop. This results in infinite d.c. open loop gain and linearizes the relationship between the reference signal and the controlled parameter. The control loop is then compensated to provide a stable system over a 4 to 1 thrust range and a simulated thruster thermal environment of 0 to 2 suns.

The time response of the control loops is equally important. The thruster should respond to changes in setpoints in less than 60 seconds and return to a steady state operating point from an arc condition in less than 15 seconds. An additional requirement is that the beam current must not overshoot its setpoint by more than 15% to prevent possible collapse of the solar array voltage on a spacecraft.

Compensated control loops also eliminate the need for fine tuning the control loops in a power processor to a given thruster. The compensation is achieved for the range of thruster characteristics that normally exists from one thruster to another.

The assistance of Mr. James Budinger in obtaining this data is greatly appreciated.

Apparatus

The thruster tests were performed in the 3.05 m bell jar of the 7.6 m diameter vacuum facility at Lewis Research Center. The power supply system used to operate the thruster for these tests was an inverter type laboratory system. The thruster tested was Engineering Model Thruster (EMT) serial number 802. The 0 and 2 solar constant (sun) thermal environment was provided by a heated cylindrical shield placed around the thruster. This shield was used to heat the ground screen and back plate of the thruster to temperature representative of two suns. These temperatures were determined in thermal tests using an arc lamp solar simulator source.

Procedure

The thruster was operated at selected points in an open loop mode and allowed to reach thermal equilibrium. The cathode and neutralizer vaporizer currents were held constant, and a small sinusoidal signal was introduced on the main vaporizer current. The subsequent response of the beam current and discharge voltage were recorded on a strip chart recorder, along with the main vaporizer current. The responses were recorded for a number of frequencies between 0.001 and 0.1 Hz. The main and neutralizer vaporizer currents were then held constant, and the sinusoidal signal introduced on the cathode vaporizer current. The response of the beam current, and discharge voltage were recorded along with the cathode vaporizer current. Finally the main and cathode vaporizers were operated at a fixed current and the sinusoidal signal introduced on the neutralizer vaporizer current. The response of the neutralizer keeper voltage was recorded along with the neutralizer vaporizer current.

The above procedure was followed for operating points of full, one-half, and one-fourth thrust and for solar thermal environments of zero and two suns. Bode plots were made from these data and the control loops analyzed for stability. Integrators and lead networks were then added to the control loops of the power processor and the gains of the loops adjusted.
Results and Discussion

Frequency Responses

The Bode plots for beam current ($J_B$) versus main vaporizer current ($J_V$), and discharge voltage ($AV_1$) versus main vaporizer current ($J_V$) at beam currents of 2, 1, and 0.5 amperes are shown in Figure 1 for the zero sun condition. These beam currents represent thrust levels of full, one-half, and one-fourth thrust, respectively.

The thruster operating conditions for all data taken are shown in Table 1.

The Laplace transfer functions, in the s domain, derived from these Bode plots are:

$$JB = \frac{K}{(s^{0.01} + 1)(s^{0.2} + 1)}$$

where $K = 2.4$ for 2 amperes, 1.9 for 1 ampere, and 0.7 for 0.5 ampere and

$$AV_1 = \frac{K}{(s^{0.01} + 1)(s^{0.2} + 1)}$$

where $K = 50$ for 2 amperes, 11 for 1 ampere, and 18 for 0.5 ampere (Table 2).

Except for the gain term $K$, both transfer functions are identical for all three beam currents with break frequencies at $\omega = 0.01$ radians/second and $\omega = 2$ radians/second.

The Bode plots for $J_B$ versus $J_V$ and $AV_1$ versus $J_V$ at 2 suns are shown in Figure 2.

The transfer functions derived from these Bode plots are:

$$JB = \frac{K}{(s^{0.01} + 1)(s^{0.2} + 1)}$$

where $K = 2.8$ for 2 amperes and 1.6 for 1 ampere, and 0.7 for 0.5 ampere and

$$AV_1 = \frac{K}{(s^{0.01} + 1)(s^{0.2} + 1)}$$

where $K = 28$ for 2 amperes and 18 for 1 ampere.

Again, except for the gain term $K$, both transfer functions are identical for both beam currents and are identical with the zero sun transfer functions. Therefore, gain is the only parameter that changes as operating-conditions change with the break frequencies remaining constant. Therefore, in compensating the control loop, gain change is the only parameter that needs to be taken into account.

The Bode plots for discharge voltage ($AV_1$) versus cathode vaporizer current ($J_{CV}$) and beam current ($J_B$) versus cathode vaporizer current ($J_{CV}$) for 2, 1, and 0.5 amperes beam currents at zero sun are shown in Figure 3.

The transfer functions derived from these Bode plots are:

$$AV_1 = \frac{K}{J_{CV}} \left(\frac{s^{0.01}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 32$ for 2 amperes, 40 for 1 ampere, and 14 for 0.5 ampere and

$$JB = \frac{K}{J_{CV}} \left(\frac{s^{0.01}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 1.3$ for 2 amperes, 0.35 for 1 ampere, and 0.18 for 0.5 ampere.

The Bode plots for $AV_1$ versus $J_{CV}$ and $J_B$ versus $J_{CV}$ at 2 suns are shown in Figure 4.

The transfer functions derived from these Bode plots are:

$$AV_1 = \frac{K}{J_{CV}} \left(\frac{s^{0.01}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 56$ for 2 amperes and 22 for 1 ampere and

$$JB = \frac{K}{J_{CV}} \left(\frac{s^{0.01}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 0.89$ for 2 amperes and 0.45 for 1 ampere.

As in the case of the main vaporizer, the break frequencies for the cathode vaporizer remain fixed and gain is the only parameter that changes. The break frequencies for the cathode vaporizer occur at $\omega = 0.03$ radians/second and $\omega = 0.5$ radians/second.

The Bode plots for neutralizer keeper voltage ($V_{NK}$) versus neutralizer vaporizer current ($J_{NV}$) for 2, 1, 0.5, and 0.0 ampere beam currents at zero sun are shown in Figure 5. The transfer function derived from these Bode plots is:

$$V_{NK} = \frac{K}{J_{NV}} \left(\frac{s^{0.02}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 10.0$ for 2 amperes, 7.1 for 1 ampere, 4.48 for 0.5 ampere, and 12.5 for 0.0 ampere.

The Bode plots for 2 suns are shown in Figure 6. The transfer function derived from these Bode plots is:

$$V_{NK} = \frac{K}{J_{NV}} \left(\frac{s^{0.02}}{0.02 + 1}\right) \left(\frac{s^{0.2}}{0.5 + 1}\right)$$

where $K = 14$ for 2 amperes and 50 for 1 ampere.
As in the case of the other two vaporizers, the break frequencies for the neutralizer vaporizer remain fixed and gain is the only variable. The break frequencies for the neutralizer vaporizer occur at $\omega = 0.02$ radians/sec and $\omega = 2$ radians/sec.

From the Bode plots for these transfer functions, it can be determined that the maximum open loop gains permissible to maintain a minimum 60° phase margin, using straight proportional control are:

<table>
<thead>
<tr>
<th>Loop Type</th>
<th>Maximum Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main vaporizer loop</td>
<td>39 dB</td>
</tr>
<tr>
<td>Cathode vaporizer loop</td>
<td>17.5 dB</td>
</tr>
<tr>
<td>Neutralizer vaporizer loop</td>
<td>34 dB</td>
</tr>
</tbody>
</table>

However, these gains are not sufficient to maintain $J_B$, $\Delta V_Y$, and $V_{NK}$ within 1% of their set points under all conditions.

The interactions of the main vaporizer and cathode vaporizer on $J_B$ and $\Delta V_Y$ can also be seen from these Bode plots. Although $J_C$ is the primary control for $\Delta V_Y$, the $J_B/\Delta V_Y$ transfer function under some conditions has a higher gain than the $\Delta V_Y/\Delta V_Y$ transfer function (Table 2). The neutralizer vaporizer also has a strong effect on the beam current. This strong interaction between the two loops could lead to instabilities.

**Compensated Loops**

Figure 7 shows the straight line approximation Bode plots for the compensated loop of $J_B/J_Y$. The transfer function for this compensated loop is:

$$J_B = 7.5(0.05 + 1)(\frac{\omega}{0.5} + 1)$$

$$J_Y = \frac{1}{(1 + \frac{\omega}{0.01})(\frac{\omega}{0.5} + 1)}$$

The control loop that was implemented into the power processor is shown in Figure 8. This compensated loop contains an integrator to provide infinite gain and to linearize the relationship between the reference signal and the $J_B$ signal. This integrator passes through 0.0 dB at $\omega = 1.0$ radians/sec. The loop also contains two lead networks to maintain 60° of phase margin out past $\omega = 5$ radians/sec. One lead is at $\omega = 0.05$ radians/sec and the other one is at $\omega = 8.0$ radians/sec. The open loop gain at $\omega = 1.0$ radians/sec is 4 dB.

The output of the integrator is limited in both the positive and negative directions to the minimum values needed to provide a steady state $J_B$ range of 0.0 to 2.0 amperes. This is done to prevent the integrator from running away during off-normal conditions. If the integrator is not limited, large overexcursions occur when recovering from these off-normal conditions.

The straight line approximation Bode plots for the compensated loop of $\Delta V_Y/J_Y$ are shown in Figure 9. The transfer function for this loop is:

$$\Delta V_Y = -1.9(\frac{\omega}{0.15} + 1)(\frac{\omega}{0.5} + 1)$$

$$J_Y = \frac{1}{(0.05 + 1)(\frac{\omega}{0.5} + 1)}$$

**Time Responses**

Figure 10 shows the control loop that was implemented into the power processor. This loop, like the $J_B/J_Y$ loop contains an integrator and two lead networks. The integrator passes through 0.0 dB at $\omega = 1.0$ radians/sec and the two loops are at $\omega = 0.15$ radians/sec and $\omega = 0.3$ radians/sec. This provides 60° of phase margin out past $\omega = 5$ radians/sec. The open loop gain at $\omega = 1.0$ radians/sec is 10 dB.

Figure 11 shows the Bode plots for the compensated loop of $V_{NK}/J_Y$. The transfer function for this loop is:

$$V_{NK} = -6.2(\frac{\omega}{0.1} + 1)(\frac{\omega}{0.5} + 1)$$

$$J_Y = \frac{1}{(0.02 + 1)(\frac{\omega}{0.5} + 1)}$$

Figure 12 shows the control loop that was implemented into the power processor. This loop, like the other compensated loops contains an integrator and two lead networks. The integrator passes through 0.0 dB at $\omega = 1.0$ radians/sec and the two loops are at $\omega = 0.1$ radians/sec and $\omega = 1.0$ radians/sec. This provides 60° of phase margin out past $\omega = 5.0$ radians/sec. The open loop gain at $\omega = 1.0$ radians/sec is 4 dB.

The time responses of $J_B$ and $\Delta V_Y$ in throttling from a beam current of 1.0 to 1.9 to 2.0 to 1.9 to 1.8 amperes. In throttling to higher $J_B$ (up), $J_B$ reaches steady state within 1.1 seconds with less than 1% overshoot. $\Delta V_Y$ immediately increases to 37.3 volts due to the step change increase in emission current ($J_B$), and returns to 36 volts within 20 seconds. In throttling to lower current (down), $J_B$ reaches steady state within 10 seconds with no noticeable overshoot. $\Delta V_Y$ immediately decreases to 35 volts due to the step change decrease in $J_B$, and returns to 36 volts within 20 seconds.

The time responses of $J_B$ and $\Delta V_Y$ in throttling from 1.0 to 1.1 amperes and back to 1.0 amperes are shown in Figure 14. In throttling up, $J_B$ reaches steady state within 15 seconds with approximately 1% overshoot. $\Delta V_Y$ immediately increases to 36 volts due to the step change increase in $J_B$, and returns to 36 volts within 30 seconds. In throttling down, $J_B$ reaches steady state within 20 seconds with no undershoot. $\Delta V_Y$ immediately decreases to approximately 34.5 volts due to the step change decrease in $J_B$, and returns to 36 volts within 20 seconds.

The time responses of $J_B$ and $\Delta V_Y$ in throttling from 0.5 to 0.6 amperes and back to 0.5 amperes are shown in Figure 15. In throttling up, $J_B$ reaches steady state within 30 seconds and does not overshoot. $\Delta V_Y$ shifted its operating point at 0.5 amperes to approximately 35 volts due to the effects of a very noisy $\Delta V_Y$ signal on the control loop. The thruster operated in a very noisy mode at this beam current level. $\Delta V_Y$ immediately increased to 38 volts due to the step change increase in $J_B$ for throttling up. It then settled out the 35 volt operating point within 50 seconds. In throttling down, $J_B$ reaches steady...
state with a 40 seconds and does not undershoot. AV_1 immediately decreases to 22 5 volts due to the step change decrease in J_b, and returns to 35 volts within 50 seconds. The longer throttle up time at this current level is due to the lower gain in the thruster of the J_b/AV_1 transfer function.

There does not appear to be any instabilities in these two loops caused by the loops themselves or by the strong interaction that exists between them.

Throttling of the thruster had no noticeable effect on VNK.

The responses of J_b and AV_1 to a high voltage recycle of the thruster at a beam current of 2.0 amperes are shown in Figure 16. When the high voltages turn off and J_b goes to zero, J_b is automatically cut back to less than 4 amperes. This causes the immediate drop in voltage of AV_1. When the high voltages are turned back on and J_b increases up to its 11.0 amperes set point, AV_1 overshoots its 36 volt set point and goes to 40 volts. J_b also rises and overshoots its 2 amperes setpoint by 52 due to the overshoot of AV_1. Both loops then settle out to their set points within 25 seconds. There is no way to prevent the overshoot of J_b by control of the main vaporizer if AV_1 overshoots there is no way to prevent the overshoot of AV_1 by control of the cathode vaporizer. The prevention of the overshoot of AV_1 is a function of the recycle sequence. The power processor being used did not have a proper sequence to prevent this overshoot.

Figure 17 shows the responses of J_b and AV_1 to a recycle of the thruster at a beam current of 1.0 amperes and Figure 18 shows their responses to a recycle of the thruster at a beam current of 0.5 amperes. The responses are similar to the 2.0 amperes case except the overshoots of AV_1 and J_b are smaller.

Figure 19 shows the responses of VNK to a recycle of the thruster at a beam current of 2.0 amperes. When the high voltages are turned off and the beam current goes to zero, the neutralizer keeper current (J_K) is automatically increased from 1.8 to 2.4 amperes and this causes VNK to increase. After the high voltages have been turned back on and the beam current established, J_K is reduced from 2.4 amperes back to its setpoint of 1.8 amperes. This causes VNK to decrease and settle out at its setpoint within 15 seconds.

The response of VNK to recycles of the thruster at beam currents of 1.0 and 0.5 amperes are shown by Figures 20 and 21, respectively. The 2.0 amperes case is similar to the 2.0 amperes case. At 0.5 amperes, the neutralizer discharge was extinguishing during the recycle and then reigniting after the beam current was established again. This is not normal and is believed to have been caused by the output impedance of the neutralizer keeper power supply being capacitive rather than inductive. Once the neutralizer was reestablished, the control loop returned VNK to its set point.

Conclusion

The dynamic vaporizer control characteristics of a 30-cm diameter mercury ion thruster were obtained. This was accomplished by operating the thruster in an open loop steady state mode and then introducing a small sinusoidal signal on the main cathode, or neutralizer vaporizer current and observing the response of the beam current, discharge voltage, and neutralizer keeper voltage, respectively. Bode plots were made from this data and transfer functions of the thruster determined from the Bode plots.

The relationships between the controlled parameters and their reference signals were linearized by adding integrators to the control loops. The integrators also provide infinite d.c. gain to hold the parameters within 1% of their respective setpoints over a 25 to 100% thrust range and a solar thermal environment of 0 to 2 suns. Two lead networks were added to each of the control loops. These provide stability, and allow for sufficient gain to keep the time responses, to changes in operating conditions, less than 60 seconds. The beam current overshoots its setpoint by less than 1% during throttling, but by 5% in return to steady state after an arc condition. This 5% is a function of the recycle sequence used on this particular power processor and can be eliminated with a proper recycle sequence. If the beam current overshoots its setpoint by more than 1%, the solar array on a spacecraft may collapse.

These compensated control loops provide a stable low drift control for an ion thruster. They also eliminate the need for fine tuning the control loops in a power processor to a particular thruster. This is accomplished by the compensated control loops's ability to cover the narrow range of thruster characteristics that normally exists from one thruster to another.

References

Table 1 Thruster nominal (±3%) operating conditions for all data taken

<table>
<thead>
<tr>
<th>Beam current, $J_B$, A</th>
<th>Thermal input, sun, $V_1$, V</th>
<th>Screen voltage, $V_s$, V</th>
<th>Accelerator voltage, $V_A$, V</th>
<th>Discharge voltage, $V_d$, V</th>
<th>Emission current, $I_E$, A</th>
<th>Neutralizer current, $I_N$, A</th>
<th>Neutralizer voltage, $V_N$, V</th>
<th>Neutralizer keeper current, $J_{NK}$, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>1100</td>
<td>-390</td>
<td>36.2</td>
<td>10.96</td>
<td>2.2</td>
<td>13.3</td>
<td>1.81</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1100</td>
<td>-400</td>
<td>35.9</td>
<td>5.53</td>
<td>2.4</td>
<td>13.5</td>
<td>1.83</td>
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<td>-390</td>
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<td>1.3</td>
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<td>1.92</td>
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<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>36.0</td>
<td>10.4</td>
<td>2.2</td>
<td>16.0</td>
<td>2.4</td>
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<td>1100</td>
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<td>35.9</td>
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<td>2.2</td>
<td>14.0</td>
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<td>36.2</td>
<td>5.50</td>
<td>2.4</td>
<td>15.0</td>
<td>1.83</td>
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</table>

**Table 1 Continued**

<table>
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<tr>
<th>Coupling voltage, $V_C$, V</th>
<th>Main vaporizer temp., $T_V$, °C</th>
<th>Cathode vaporizer temp., $T_C$, °C</th>
<th>Neutalizer vaporizer temp., $T_N$, °C</th>
<th>Ground screen temp., °C</th>
<th>Back plate temp., °C</th>
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<tr>
<td>-11.3</td>
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<td>322</td>
<td>289</td>
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<tr>
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<td>326</td>
<td>260</td>
<td>(a)</td>
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<td>-11.7</td>
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<td>330</td>
<td>217</td>
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<tr>
<td>-11.5</td>
<td>265</td>
<td>340</td>
<td>300</td>
<td>197</td>
<td>185</td>
</tr>
</tbody>
</table>

\(^a\) Data not available.
\(^b\) Data does not apply.

Table 2 Transfer function gains

<table>
<thead>
<tr>
<th>Beam current, A</th>
<th>Zero sun</th>
<th>2 suns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J_B/J_{01}$, dB</td>
<td>$J_B/J_{02}$, dB</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>5.5</td>
<td>-9</td>
</tr>
<tr>
<td>0.5</td>
<td>-3</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>$V_{NV}/J_{NV}$, dB</td>
<td>$V_{NV}/J_{NV}$, dB</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>0.5</td>
<td>25</td>
<td>23</td>
</tr>
</tbody>
</table>

\(^a\) Data not taken.
Figure 1. - Response of thruster to changes in main vaporizer current at zero sun.
(a) MAGNITUDE PLOT OF $J_{B}/J_{V}$.

(b) PHASE PLOT OF $J_{B}/J_{V}$ (ADD -180° FOR PHASE PLOT OF $\Delta V_{T}/J_{V}$).

(c) MAGNITUDE PLOT OF $\Delta V_{T}/J_{V}$.

Figure 2. - Response of thruster to changes in main vaporizer current at 2 suns.
Figure 3. - Response of thruster to changes in cathode vaporizer current at zero sun.
Figure 4. - Response of thruster to changes in cathode vaporizer current at 2 suns.
Figure 5. - Response of thruster to changes in neutralizer vaporizer current at zero sun.

Figure 6. - Response of thruster to changes in neutralizer vaporizer current at 2 suns.
Figure 7. - Compensated loop for $J_B/J_V$.
Thruster gain = 10 dB.

Figure 8. - Compensated control loop for $J_B/J_V$.
Figure 9. - Compensated loop for $\Delta V_I / J_{CV}$.
Thruster gain = 35 dB.

Figure 10. - Compensated control loop for $\Delta V_I / J_{CV}$.
Figure 11. - Compensated loop for $V_{NK}/J_{NV}$.
Thruster gain = 35 dB.

Figure 12. - Compensated control loop for $V_{NK}/J_{NV}$. 
$\frac{56}{(s/(0.02+1))(s/2+1)}$
Figure 13. - Time response of beam current and discharge voltage to throttling at the 2 amp level.

Figure 14. - Time response of beam current and discharge voltage to throttling at the 1.0 amp level.
Figure 15. - Time response of beam current and discharge voltage to throttling at the 0.5 amp level.

Figure 16. - Time response of beam current and discharge voltage to a recycle at the 2 amp level.
Figure 17. - Time response of beam current and discharge voltage to a recycle at the 1 amp level.

Figure 18. - Time response of beam current and discharge voltage to a recycle at the 0.5 amp level.
Figure 19. - Time response of neutralizer keeper voltage to a recycle at the 2 amp level.

Figure 20. - Time response of neutralizer keeper voltage to a recycle at the 1 amp level.

Figure 21. - Time response of neutralizer keeper voltage to a recycle at the 0.5 amp level.