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Final Report – PHASE I

ANALYTICAL AND DEVELOPMENTAL INVESTIGATION OF ELECTRON STRIP MULTIPLIERS

CONTRACT NO. NAS5-9262

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GODDARD SPACE FLIGHT CENTER
GLEN DALE ROAD
GREENBELT, MARYLAND

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SRI Project 5747

November 1966

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ABSTRACT

The object of this study was to evaluate the operational characteristics of the SRI distributed dynode strip multipliers as they related to potential NASA space applications. It included evaluation of the long-term gain fatigue effects, operation in a degraded vacuum to ascertain susceptibility to back-ion bombardment, and evaluation of pulse response.

Two strip multipliers, with vastly different resistivities, were operated for periods of 2500 and 600 hours, respectively. They demonstrated similar gain fatigue effects, not only with respect to each other, but also to commercial channel or tubular multipliers fabricated with substantially different materials and geometry. There were also reversible and nonreversible gain changes in the strip multipliers, attributable to prior operational history and to the temperature and pressure environment. When the pressure was increased to 10^{-3} to 10^{-4} torr, under otherwise normal pulsed operation, there was no evidence of significant back-ion effects on the output pulses, but there was a substantial increase in output current, which may be attributable to ionization-enhanced input and/or increased multiplier gain.

This kind of strip multiplier yielded output pulses shorter than 10^{-8} seconds and gains on the order of 10^6 for single electron inputs arriving randomly at a mean rate of 10^4 to 10^5 particles per second.

It is concluded that distributed dynode multipliers have much to offer in terms of physical, electrical, and operational characteristics, and that the parallel strip configuration offers special advantages where evaluation of causes of gain change or other operational characteristics is desirable.

It is recommended that a basic study of the causes of the long-term gain fatigue effect be undertaken, as well as further study of the environmental (especially thermal) effects. If multiplier operation at pressures above 10^{-4} torr is anticipated, the study of the relationship of pressure to the relevant operational characteristics should be extended.

CONTENTS

ILLUSTRATIONS

I INTRODUCTION

A. PURPOSE

The purpose of this first phase of study was to determine and evaluate operational characteristics of existing SRI strip multipliers, in particular, their response to pulsed operation, their tendency towards ion feedback in a degraded vacuum invironment, and their gain characteristics as a function of operating time.

B. SCOPE

This project encompassed the study of the pulse, ion feedback, and gain characteristics of existing SRI continuous-dynode electron multipliers. The pulse studies covered evaluation of output characteristics--particularly pulse height and duration--for 10 microseconds and shorter duration pulses, at repetition rates of 300 or more per second. The ion-feedback studies covered observation of pulsed-multiplier operation as a function of residual gas pressures, up to approximately 10^{-3} torr, in order to ascertain whether ion feedback occurs in this strip multiplier configuration.

In the gain-characteristics studies, two SRI strip multipliers with significantly different (more than two orders of magnitude) distributed dynode resistivities were used. These were operated for more than 2500 and 600 hours, respectively, in a Vac-Ion system, at less than 10^{-8} torr. The gain change was measured and evaluated as a function of operating time and other parameters over these prolonged periods. In addition to the normal high dc voltage operation, a period of ac operation was utilized to briefly study insulator charging, ion mobility, and other related phenomena.

C. BACKGROUND

The fairly recent emergence of "practical" continuous-dynode electron multipliers offers potential solutions to some of the problems encountered in attempts to measure charged-particle parameters in the upper atmosphere and outer space, where weight and power limitations are severe and lifetimes of several years are desired. Experiments with tubular continuous-dynode multipliers from commercial manufacturers have pointed up several effects that reduce their utility for the intended applications. The most important of these effects is a decrease in gain, continuing over periods of hundreds of hours of operation. Another significant effect is the variation in output pulse height for presumed constant inputs and constant gain, attributable (at least in part) to input particle angle and energy variations and statistical variations in secondary-emission phenomena. A third effect is ion feedback, initiating undesired secondary cascades of electrons which propagate through the multiplier to yield spurious output signals. The latter effect can apparently be minimized or eliminated by maintaining an adequate vacuum environment (10^{-5} torr or better) or by altering the physical configuration of the multiplier to limit the ion trajectory.

SRI's microelectronics program had required the development of an electron multiplier that could withstand 900° C vacuum bakeout and could provide gain of the order of 10^6. The resultant strip electron-multiplier, in its current state of development, consists of two identical parallel plane, optically polished fused silica strips, mounted to form a channel, as shown in Figs. 1, 2, and 3. The inner or dynode surfaces are films formed by co-depositing aluminum oxide and molybdenum in proportions adjusted to yield the desired resistivity. The contact electrodes at either end of the dynodes are molybdenum films deposited on the substrates. A molybdenum tab covering the exit end of the channel serves as the collector. The multipliers used in this investigation were existing specimens produced prior to the inception of the NASA program. In their preparation, all depositions were performed in a liquid-air trapped oil-diffusion-pumped system at a pressure of approximately 10^{-5} torr. Subsequent to dynode deposition, the silica strips were baked at about 1050° C for stabilization purposes.

Because of the exclusive use of refractory materials and the high-temperature processing, it appeared reasonable to expect that these strip multipliers would not suffer the substantial gain decrease with life experienced with the tubular multipliers. Additionally, there was reason to believe that the relatively open-channel geometry might be less susceptible to ion-feedback effects than the tubular design. The study reported herein was initiated to obtain operational data on the SRI strip electron-multipliers in order to permit evaluation of their susceptibility to these detrimental effects and their potential usefulness for the proposed applications.

D. WORK SUMMARY

Experiments were conducted using three different SRI strip multipliers, two for the gain fatigue experiments and the third for the thermionic-source pulse experiments. A calibrated thermionic-diode electron source was modified to provide a control grid for the pulse studies. Input pulses of less than one microsecond in duration at repetition rates in excess of 1000 per second were introduced into the input end of one strip multiplier, which was mounted in a liquid-air trapped oil-diffusion-pumped vacuum system operating at room temperature and pressures of about 10^{-5} torr. The multiplier, was operated at gains in the range of 10^5 to 10^6 and developed uniform amplitude output pulses similar in shape to the input. With this same experimental setup, no change in the leading edge or the duration of the output pulse indicative of back-ion bombardment was noted when the pressure was allowed to rise to about 2×10^{-3} torr.

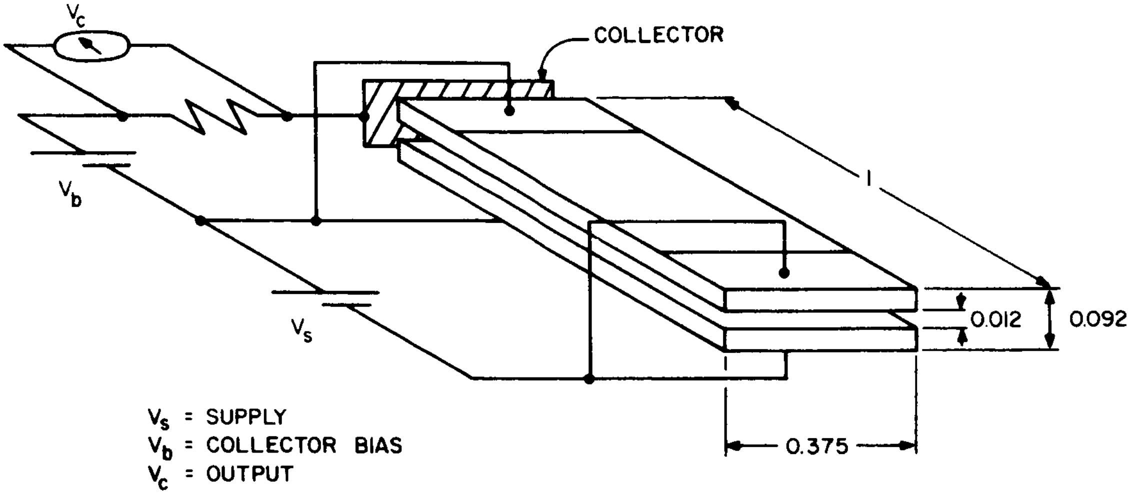

FIG. 1 ELECTRON MULTIPLIER

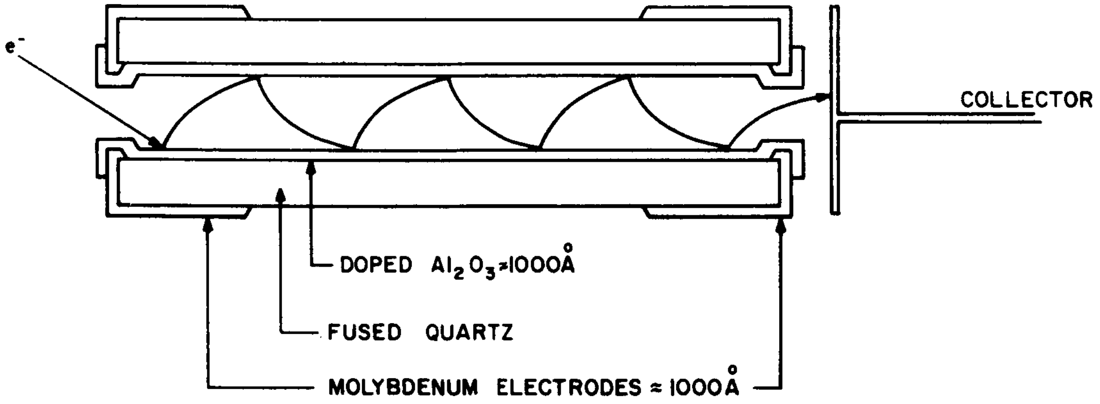

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FIG. 2 FILM PATTERNS AND ELECTRON TRAJECTORY

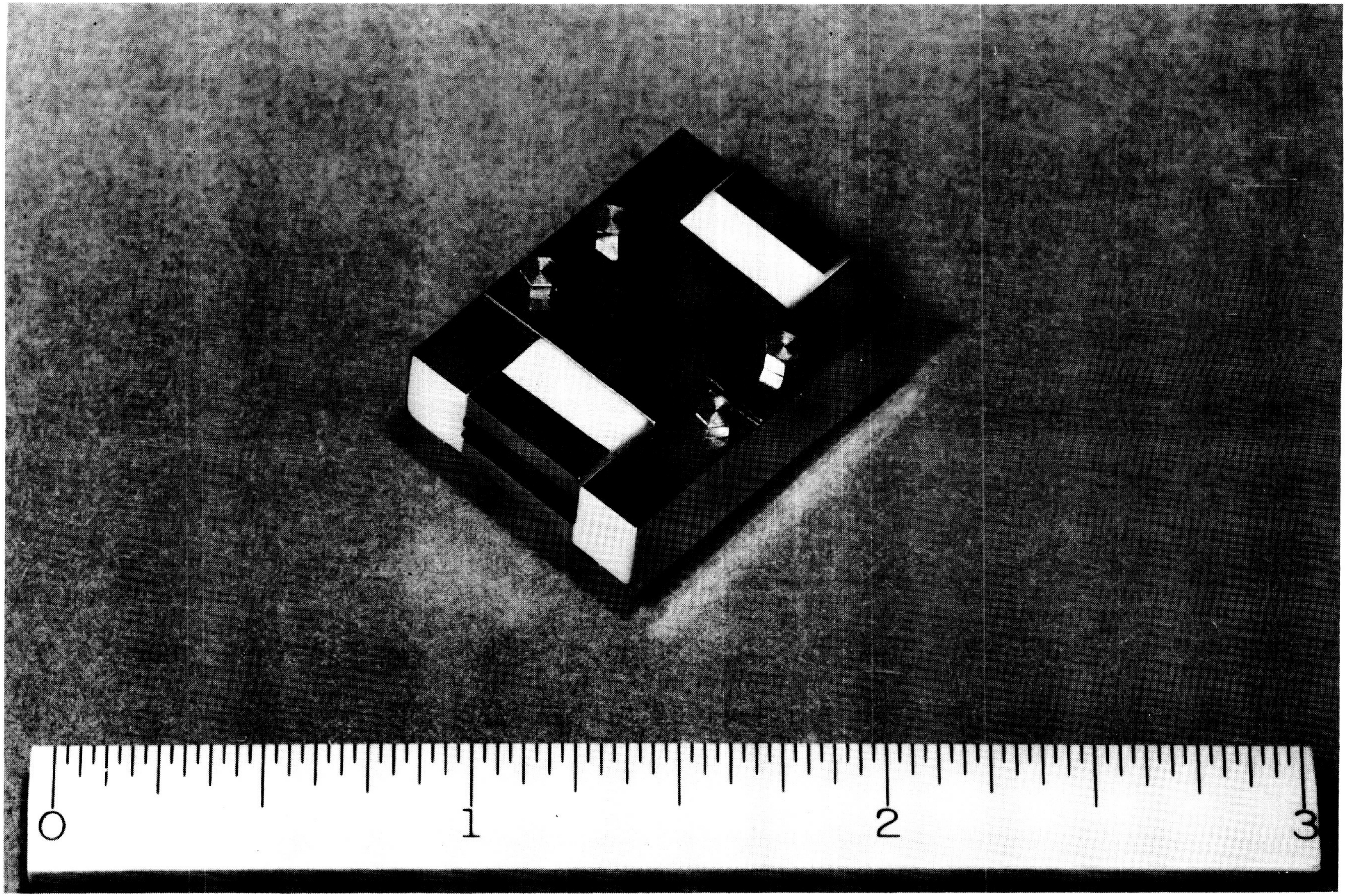

FIG. 3 ASSEMBLED ELECTRON MULTIPLIER

A relatively high-resistance strip multiplier was set up in a Vac-Ion pumped system with a Ni^{63} radioactive beta source input. Following a system bakeout to approximately 200° C maximum, this multiplier was operated for a period in excess of 2500 hours in a 10^{-8} to 10^{-9} torr vacuum under a variety of test conditions, including different accelerating voltage levels, ac as well as dc; low-temperature bakes; and variations in vacuum level, including one exposure to atmosphereic air pressure. Throughout this operational period, the output current was measured under these varied conditions. In one portion of the operational period, the output pulses resulting from individual input beta particles were examined with a wide-band amplifier and fast oscilloscope. The Vac-Ion vacuum level was purposely degraded to about 10^{-4} torr to facilitate detection of back-ion effects. No such effects were found.

Following the 2500 hours of operation on the high-resistance device, a "low-resistance" strip multiplier was installed in an identical manner in the Vac-Ion system and operated for a period of approximately 600 hours. This device exhibited some surprising gain-thermal effects, attributable to the I^2R heating by the current establishing the accelerating field for the multiplier. Once this phenomenon was resolved, it was apparent that the gain changes in the two multipliers were similar, not only to each other but also to similarly operated commercial tubular or channel multipliers.

II DISCUSSION

A. GAIN FATIGUE STUDIES

1. Experimental Facility

The UHV system used for this experiment was a 6 inch diameter by 12 inch long cylindrical stainless steel chamber with two 8 inch and five 2-3/4 inch copper gasketed ports; the ports provided adequate viewing windows and electrical feedthrough capability. The chamber was roughed in succession by a liquid-air trapped mechanical pump and a liquid air cooled Vac-Sorb pump. A 40-liter/sec Vac-Ion pump and its related vacuum gauge were used for attaining and measuring high vacuum. Provision for heating the system to 200° C or higher was made by winding heating tapes around the main cylinder and the pumping port. The multiplier quiescent and output currents were measured with separate HP 425A DC micro-volt ammeters. The multiplier accelerating voltage was provided by a North East Scientific Corp. RE 5002 regulated power supply. Figure 4 illustrates the experimental setup. The 45-volt battery at the output end of the multiplier provided the appropriate electric field for the collector electrode.

2. Beta Source Excitation

The NASA-provided source was an 0.26 millicurie Ni^{63} beta emitter (92-year half life; 67 KeV max) of electrolytically deposited nickel on a stainless steel stud. The emitting area of the source was a 1/8 inch diameter circle. This provided about 10^7 total disintegrations per second, or a maximum current of 1.5×10^{-12} amps if all beta particles were emitted. A large electrode in close proximity and biased positive with respect to the beta source collected a fairly uniform current of 5×10^{-13} amps for collection voltages between 15 and 100 volts.

The input aperture of the channel multiplier was a 0.012 inch x 3/8 inch slit. Experiments were performed with the following configurations: (1) the source in close proximity to the multiplier input slit; (2) the source in a cylindrical housing with a collimating slit; (3) a pair of funnel electrodes at the input of the multiplier; and (4) the configuration illustrated in Fig. 4. The last configuration was selected because it provided the most efficient input geometry. Electron accelerating voltages between the source and intermediate electrode (V_S) and between the intermediate electrode and multiplier input (V_E) were provided. The input current to the multiplier was larger when these voltages were about equal and increased as both voltages were increased to a maximum in the range from 125 to 150 volts. Figure 5 illustrates these characteristics and the general gain-voltage

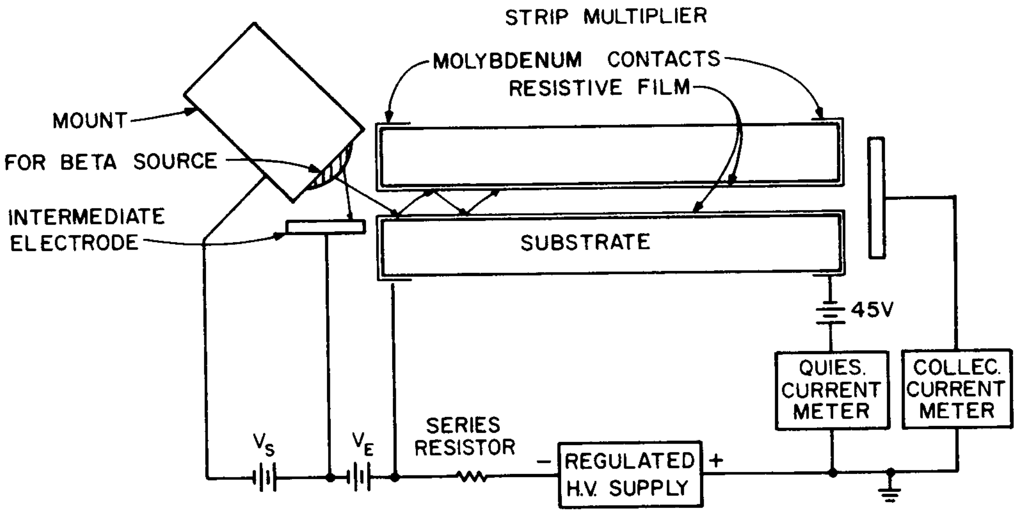

FIG. 4 GAIN FATIGUE EXPERIMENTAL SET-UP

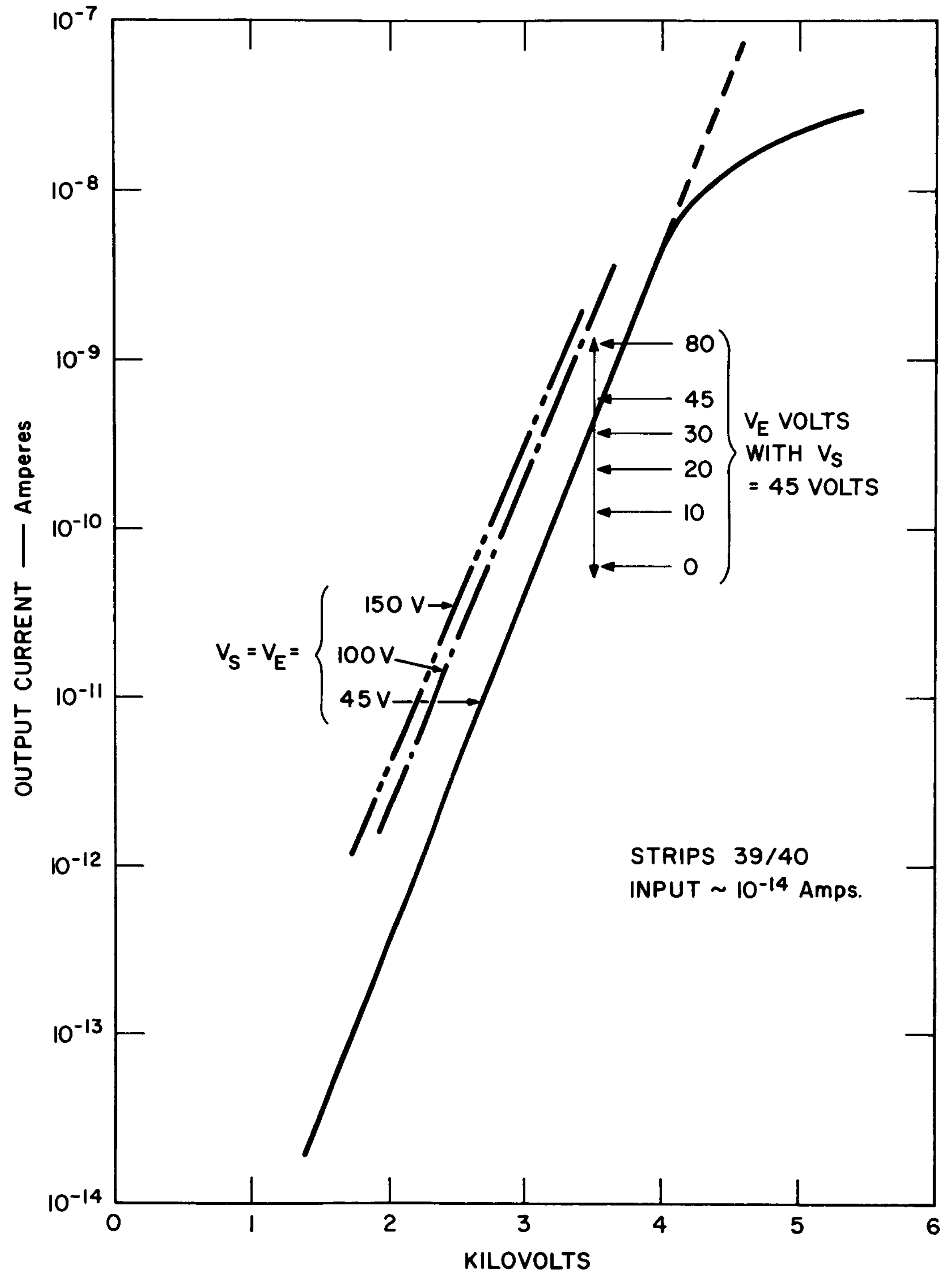

FIG. 5 MULTIPLIER GAIN AND INPUT VOLTAGE RELATIONSHIPS

relationship of the high-resistance multiplier used for the first gain-fatigue study described in the next section. The effective multiplier input current was approximately 10^{-14} amps, which obviously included some secondary electrons emitted from the intermediate electrode and accelerated to the multiplier input.

3. Multiplier Operational Results

a. Gain Fatigue vs Time

The multiplier (strips 39/40), source, and related electrodes were installed in the UHV system and the system was evacuated. Following a 200° C bakeout, the vacuum was about 6×10^{-9} torr, decreasing during subsequent operation to between 1 and 2×10^{-9} torr. Using the Ni^{63} source, with 3.95 KV applied to the multiplier, the initial output current was 2.8×10^{-9} amps. This decreased rapidly, but at a decreasing rate, reaching 0.6×10^{-9} amps after 110 hours. Figure 6 illustrates this gain fatigue effect during the entire operational period.

At the 110-hour point, the voltages were turned off for the weekend. When the voltages were reapplied, the output current was found to have partially "recovered" to 1.5×10^{-9} amps; however, this current decreased very rapidly initially, and then resumed the earlier decay slope. After a second week's run, to 270 hours elapsed time, the multiplier was again shut off. When turned on following the weekend, it again exhibited the "recovery" and rapid decay, followed by the resumption of the prior declining decay rate.

After 385 hours of operation, the output current was at 0.5×10^{-9} amps, down a factor of 6 from the original output. The multiplier voltage was then reduced by 500 volts to 3.45 KV, which produced an order-of-magnitude decrease in output current to 0.4×10^{-10} amps, arriving at and remaining at 0.29×10^{-10} amps during the 450- to 500-hour operational period. The voltage was then restored to 3.95 KV and the output current increased to the level represented by an extension of the decay curve from the preceeding 3.95 KV operation, with the decay rate still decreasing.

At the 550-hour point, the multiplier voltage was increased by another 500 volts to 4.45 KV, yielding an output current of 2.8×10^{-9} amps. This fell off less rapidly than during the initial hours of operation, but at a more rapid rate than at the prior 3.95 KV level, again with the decay rate decreasing. At about 650 hours there was a modest unexplained drop, presumably abrupt, in output current. Except for brief test periods, operation was continued at 4.45 KV to a total of over 2500 hours of elapsed time. The gain continued to drop at a slow and decreasing rate, possibly representing an exponential decay to a constant value. Additional experiments affecting the multiplier voltage, temperature, and environmental exposure were conducted during this period and are reported in subsequent sections.

The general test procedure was to read and record the multiplier voltage, quiescent current, output current, and vacuum several times during each working day, and at other times during the night and weekends when measurements of significance were anticipated.

In a May 14, 1965 letter from Don Lind of the NASA GSFC staff, data had been provided on the initial gain decay of a commercial channeltron during its first 100 hours of operation. These data have been added to Fig. 6 to permit ready comparison with the results for the SRI strip multiplier during its corresponding operational period. The results are strikingly similar.

b. Recovery Effects

The partial and temporary gain recovery following non-operational periods, reported in the preceding section, was given further study. The collector voltage, the input beta source, and intermediate electrode voltages were left on, and the multiplier high-voltage turned off. The high voltage was reapplied for brief (10- to 20 second) periods at intervals of a few minutes to determine the recovery rate. Figure 7 illustrates the output current vs time characteristic, showing that recovery to a stable level is exponential. The ratio of this stable level to the operating level prior to turn-off of the high voltage varied between 1.5 and 3. The time required to attain 1/e of the total "recovered" current level was approximately 1 minute.

When the multiplier high voltage was reapplied, the output current dropped exponentially at an initial rate only slightly slower than the recovery rate. In 45 minutes the output current decreased to within about 15% of the preturnoff level and resumed the prior decay rate.

To explore the possibility that this recovery effect might be caused by dc charging of the multiplier strip spacers or support structure, or to ion mobility in the resistive film, the multiplier was operated for a period with a high ac voltage rather than dc. This is described in more detail in a subsequent section. There was no noticeable recovery effect during ac operation.

Following the system bakeout described in the subsequent section, the multiplier no longer exhibited this recovery effect. In fact, after the bake, there was a slight loss in output current (10-15%) when the multiplier high voltage was temporarily turned off and then reapplied. The multiplier would quickly regain its prior operating level when the voltage was left on continuously.

c. Thermal Effects

During the 200° C preoperational bakeout of the 39/40 strip multiplier, a significant decrease in output current with increasing temperature was noted. As the gain fatigue study progressed, the

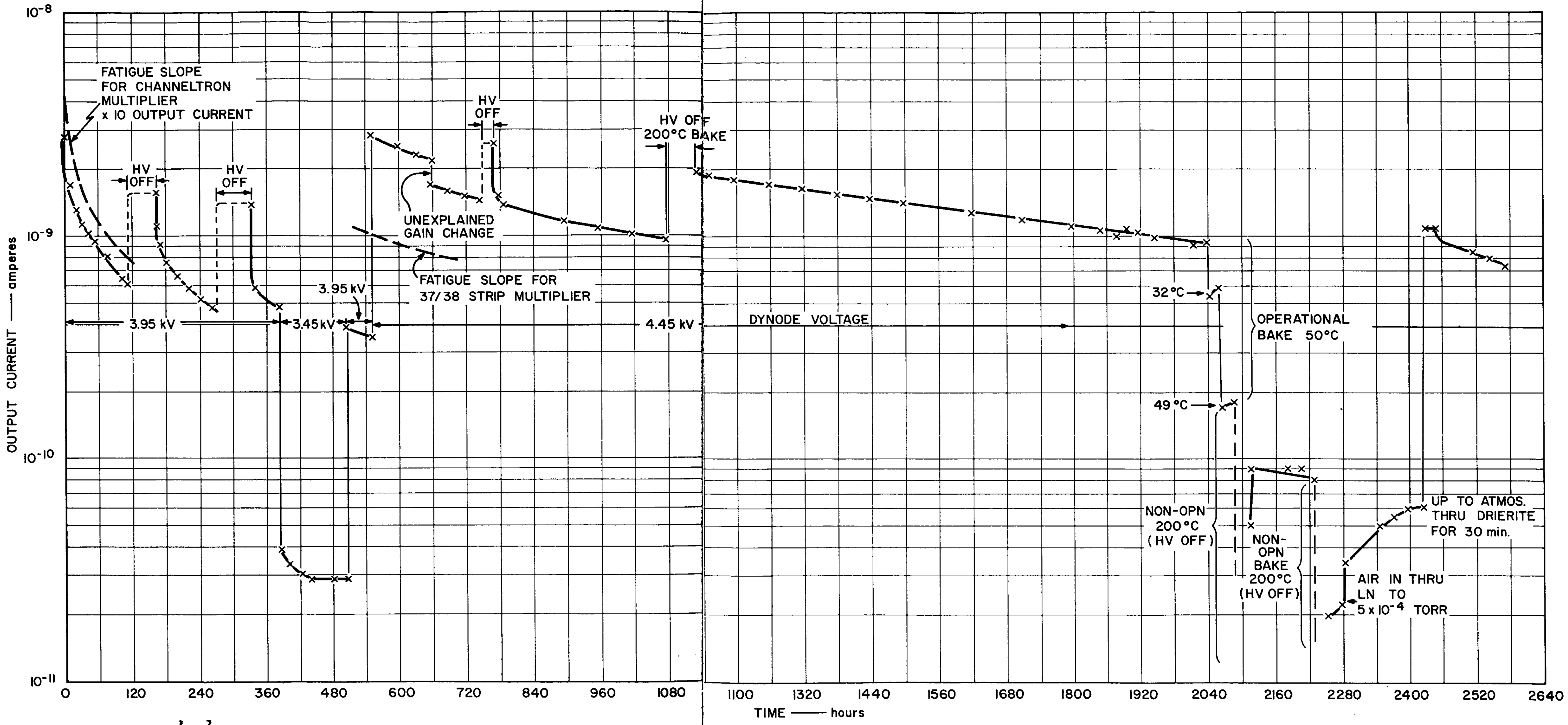

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FIG. 6 GAIN FATIGUE RUN

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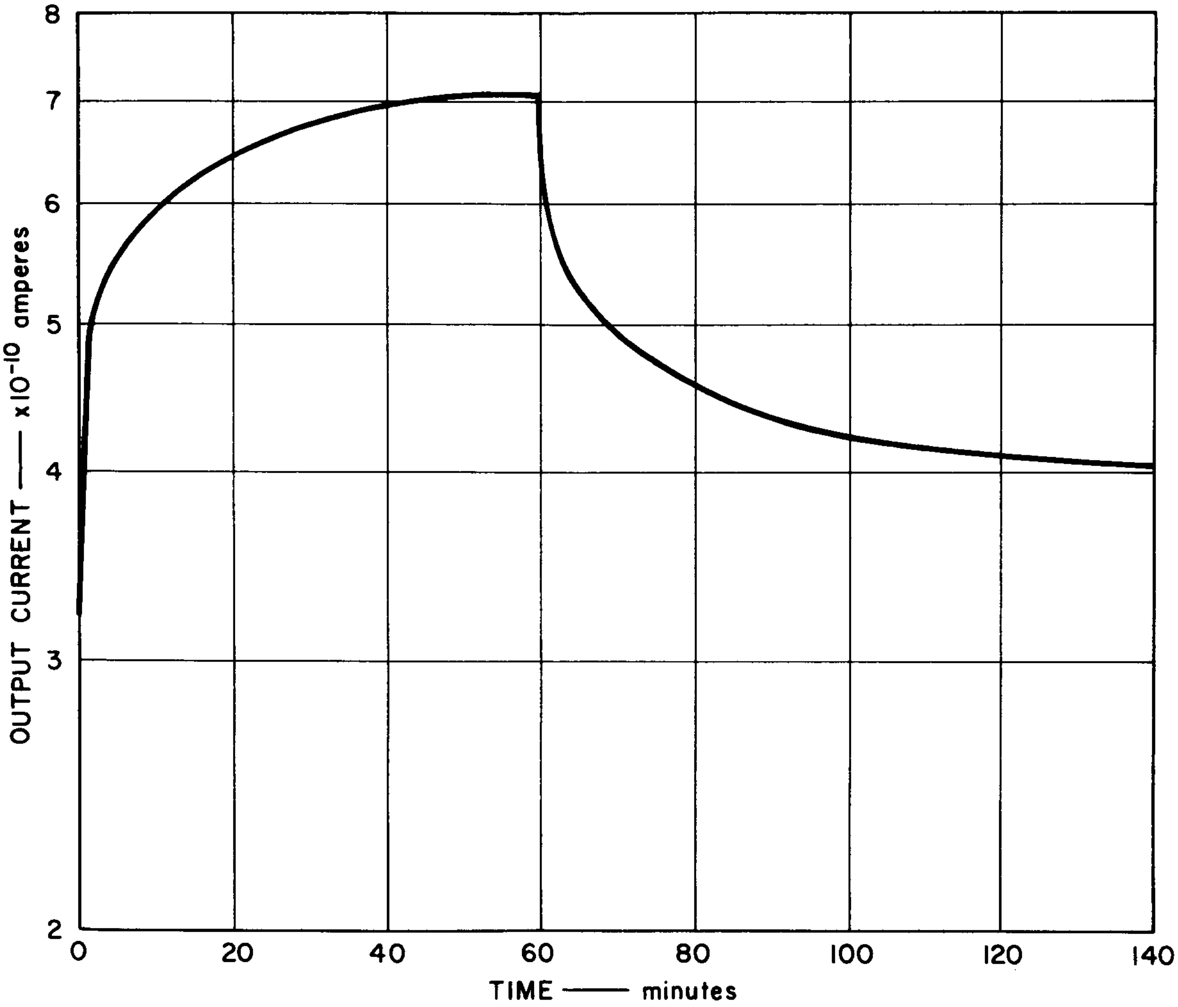

FIG. 7 RECOVERY CURVE

measured output current showed a modest 24-hour cyclical variation superimposed on the long-term fatigue effect. This corresponded closely to the daily room temperature variations, but delayed by several hours due to the thermal isolation of the multiplier device in its mounting within the UHV system. An excursion of approximately ±10% around the average output current level was representative during the 9- to 10-hour daily observation period. Typical room temperature variations were ±4° to 5° C from a nomimal 21° C point.

The resistive film of the multiplier has a high inverse resistance coefficient with temperature; hence the quiescent dynode current also varied with temperature. Figure 8 shows a representative dynode temperature-resistance relationship. Since the high-voltage supply was well regulated, there was no measurable change in the multiplier accelerating voltage. Measurement of the quiescent current permitted calculation of the strip resistance and estimation of the temperature.

It is generally recognized in the literature that there would be no measureable change in secondary emission ratio with temperature for the range of experimental temperatures involved here. It would appear that the gain change was due to mechanical displacement of the strip multiplier surfaces because of differential thermal expansion coefficients of the mounting structure, and/or to slight changes in the resistive film uniformity, and hence in the distribution of the multiplier accelerating field. A Control Science Corporation report[1] notes a factor of three to four increase in output current from a Bendix channeltron multiplier for a change in temperature from 23° to 50° C.

In addition to these reversible gain-temperature effects, bakeout of the experimental setup produced some nonreversible changes. At 1080 hours, all voltages were removed from the multiplier, and the system baked to 200° C for 10 hours. Because of the thermal isolation, the multiplier strips were cooler than the surrounding vacuum system walls, reaching an estimated 130° C (a figure derived from the change in multiplier film resistance). After cooling, and with the former voltages reapplied, the output current was double its prebake operational level (1.9×10^{-9} vs 0.95×10^{-9} a), and resumed its prior decay rate from this higher level.

At 2040 hours, the output current had again declined to the 0.95×10^{-9} amp level. With all voltages on, the vacuum chamber temperature was raised to 32° C, producing an output current drop to 0.55×10^{-9} amps. The temperature was then raised to 49° C, yielding a corresponding output current of 0.17×10^{9} amps. The temperature was next raised to 200° C on the vacuum chamber wall, with the high voltage reduced to 2 KV to avoid the possibility of thermal runaway.

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[1] "Channeltron Experiment" Final Report, Control Science Corp. Contract NAS 5-3749, 5 October, 1964.

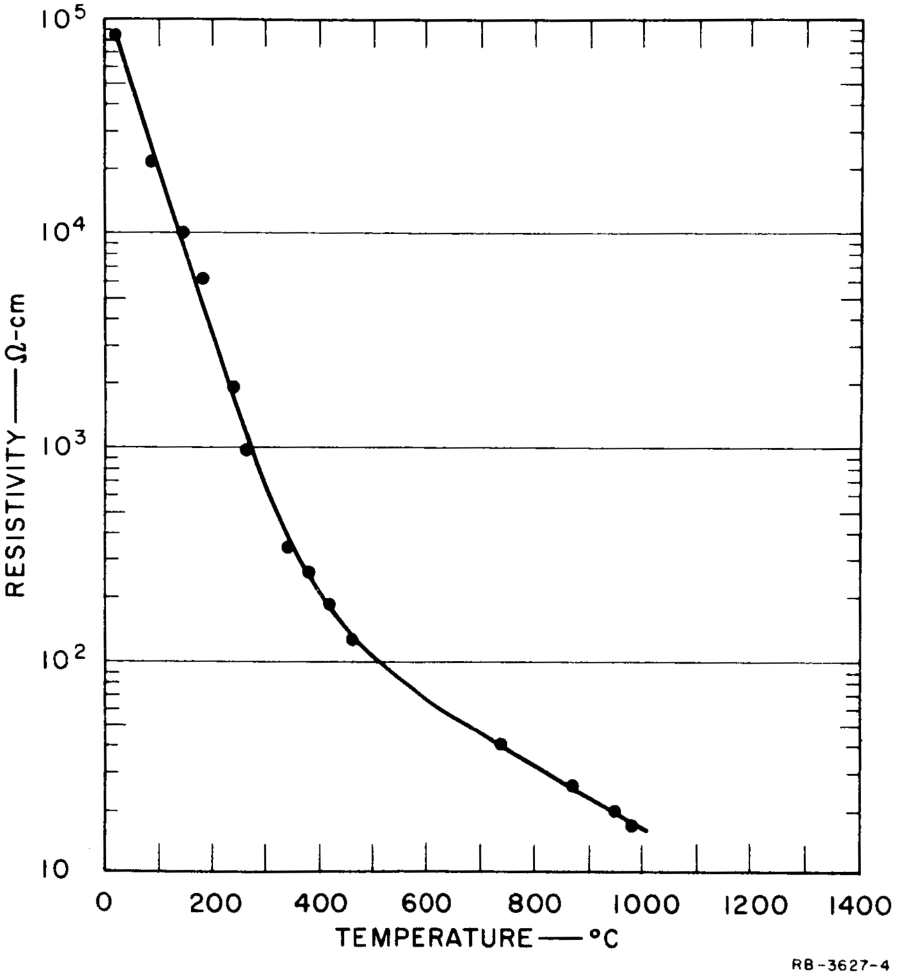


FIG. 8 DYNODE RESISTIVITY vs. TEMPERATURE

The multiplier strip resistance dropped more than a factor of 10, to 1.7 x 10^9 Ω. After cooling overnight, operation was reestablished with the previously applied voltages, producing an initial output current of 0.05 x 10^{-9} amps, which rose to 0.09 x 10^{-9} amps and stabilized. Next followed a 200° C bake with the high voltage turned off. After cooling, the output current had fallen to 0.02 x 10^{-9} amps. Thus, where previously a 200° C bake with the high voltage off had doubled the gain, a similar bake with the high voltage left on (only 2 KV during the higher temperature portion) reduced the gain by more than an order of magnitude. A subsequent high-voltage-off bake reduced the output still further.

The preceding results were obtained using the high-resistance multiplier. In the study of the low-resistance strip multiplier, where the I^2R heating of the resistive film is significant, a very substantial gain-temperature relationship was noted. This is illustrated in Fig. 10.

d. AC Operation

In an attempt to shed light on the previously noted recovery effect, the multiplier was operated for a period of over an hour with 2.2 KV ac rms in place of the 4.45 KC dc accelerating voltage. It was determined experimentally that 2 KV dc was a sufficient voltage to prevent any recovery. The recovery effect was checked prior to, during (with brief restoration of the dc voltage), and immediately following the application of the high-voltage ac. During the checks before and after the ac operation, the gain recovery effect was as noted previously. There was no significant recovery (i.e., gain change) when the multiplier was checked with the normal dc voltages for brief intervals during the period of ac operation. In other words, the ac high voltage sustained the level of gain in a manner similar to that developed under dc high-voltage operation. This would seem to indicate that the recovery effect was not due to dc charging of the multiplier strip spacers or mounting structure, or to a slow ion mobility or drift in the resistive film.

e. Atmospheric Exposure

Just prior to the conclusion of the first gain fatigue run, the effect of exposure of the multiplier surfaces to partial and full atmospheric pressure was explored. At 2280 hours, air drawn through a liquid nitrogen trapped tube was admitted to the vacuum system through a needle valve, briefly raising the system pressure from its nominal 2 x 10^{-9} torr to 5 x 10^{-4} torr. This followed the final operational and nonoperational (i.e., with and without dc high-voltage applied) system bakes. The needle valve was then closed and the normal vacuum level quickly restored. The output current jumped from its prior 0.02 x 10^{-9} amp level to 0.04 x 10^{-9} amps, and over a period of several days rose to 0.06 x 10^{-9} amps.

At 2420 hours, the system was let up to air through a DRIERITE cylinder, held at atmospheric pressure for 30 minutes, and then re-pumped to the 10^{-7} to 10^{-8} torr level. The output current (with the previous voltages applied) rose to 1.15×10^{-9} amps, dropping slowly over a period of days to 0.75×10^{-9} amps. It appeared to be approaching an output level and decay rate corresponding to an extension of the decay slope preceeding the final bakes and air exposures.

f. High vs Low Strip Resistance

Following the 2500-hour run with the first strip multiplier (strips 39/40; 1.8×10^{11} ohms resistance at 1 KV), a multiplier with substantially lower resistance (strips 37/38; 1.6×10^{8} ohms resistance at 1 KV) was mounted in the UHV system in the same manner as the prior device. Because of the long prior operation of the UHV system at low pressure and the very modest amount of handling and new material inserted into the system, a pressure of 5×10^{-8} torr was readily achieved without a preoperational bake. The pressure dropped to 7×10^{-9} torr during the operational period. The operational setup was the same as for the earlier run (Fig. 4). Because of the substantial inverse temperature coefficient of resistance of the dynode strip film, the series resistor functioned as a current-limiting resistor, preventing thermal run-away in the relatively low-resistance multiplier. Since the quiescent current flowing in the lower-resistance multiplier was in the range of 10's to 100's of microamps, substantial voltage drops were developed across the series-limiting resistor. An electrostatic voltmeter was installed across the multiplier to measure the actual accelerating voltage. A two-step (0-5.5 and 5.5-10 KV) North East Scientific Corp. high-voltage supply was used to provide the requisite total operational voltage.

The 37/38 multiplier was initially operated at about 3 KV. This required a total voltage of 5.75 KV. The resistance of the multiplier dropped rapidly from 170 to about 60 megohms, and continued dropping slowly. This, of course, changed the quiescent current flowing through the series resistor and multiplier, and hence the accelerating voltage across it. To determine the constant-voltage output current, a gain/voltage curve was run on the multiplier to determine the magnitude of output current change as a function of accelerating voltage. Using this data, a "3-KV normalized" output current was computed. This is shown in Fig. 9 and compared with the initial portion of the earlier gain fatigue run.

The normalized output current initially decreased rapidly from a 2.3×10^{-9} amp level. This decay abruptly changed after a few hours; the output current increased from 1.0×10^{-9} to 1.4×10^{-9} amps and leveled off.

After 45 hours of operation, the high voltage was turned off to see if the recovery effect noted in the prior run was present. Instead, the output current decreased, but resumed the former level following

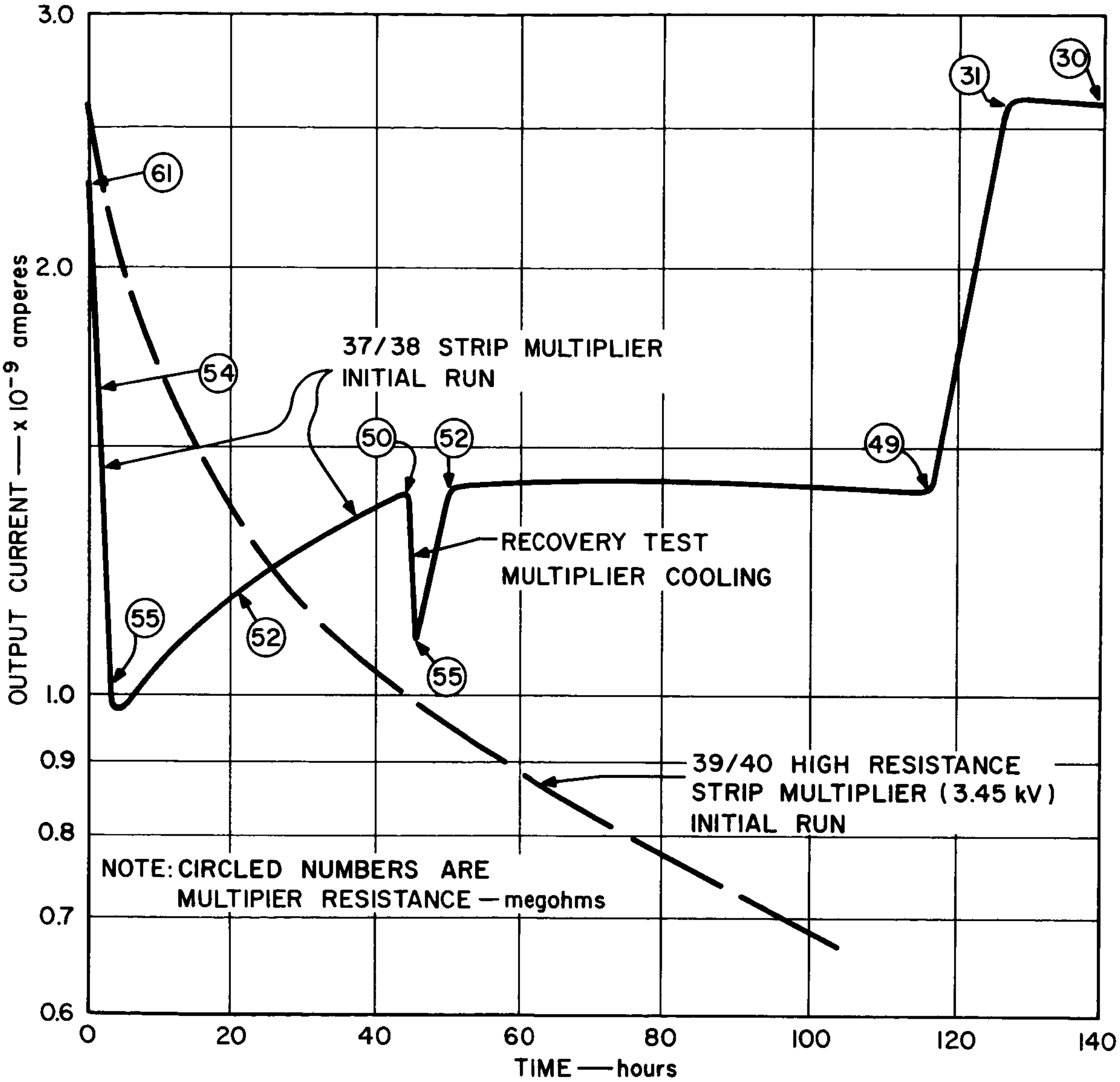


FIG. 9 INITIAL LOW-RESISTANCE MULTIPLIER RUN

reapplication of the high voltage. The multiplier resistance was calculated and is indicated in Fig. 9 for pertinent points on the gain/time curve. It seemed evident that some multiplier thermal effect associated with the resistance change could be the cause of these unexpected results. With an increase in the applied high voltage to 8.25 KV, the multiplier resistance decreased to about 30 megohms, producing a significant increase in the 3-KV normalized output current. The series resistance was next reduced to 8 megohms to reduce the variation in multiplier voltage with resistance. The multiplier resistance continued to decrease to 22.4 megohms, and the output current increased to 5.1×10^{-9} amps (normalized).

From a stable operating point (8-megohms series resistance; 2.6-KV multiplier voltage; 9.9-megohms multiplier resistance; 0.25×10^{-9} amps actual output current) a series of gain-voltage measurements were run. The series resistor was removed and the high-voltage stepwise varied quickly from 1.0 to 4.0 KV while the corresponding quiescent and output currents were recorded at convenient voltage intervals. Then the high voltage was turned off, allowing the multiplier to cool down. At time intervals starting with 10 minutes and increasing, additional brief gain-voltage measurements were made. The results presented in Fig. 10 show a marked change in output current with multiplier resistance (and hence with temperature), increasing to a maximum and then falling off with increasing temperature (decreasing resistance). This family of curves represents dynamic, not stable conditions, since the measurements were taken in brief periods of time without allowing the multiplier to come to equilibrium. At the higher voltages (and quiescent currents) the measured values were varying rapidly due to the multiplier heating occasioned by the measurement itself. These data provided an excellent basis for understanding the prior and subsequent multiplier operational results.

The multiplier temperature was not measured directly, but from prior resistance-temperature curves for similar resistive films (Fig. 8), together with three operational temperature check points, approximate temperature values were assigned to the resistance abcissa of Fig. 10.

The multiplier was next operated at 2.5 KV with no series resistor for about 200 hours. The initial warm-up and equilibrium points are shown on Fig. 10, in which the blocked-out area represents the range of parameters encompassed during this gain fatigue run. The gain vs. time graph is plotted on Fig. 6, for the equivalent operational period, superimposed on the earlier higher-resistance multiplier curve. The two multipliers demonstrated a fairly comparable decay slope.

B. PULSED OPERATION STUDIES

1. Experimental Facilities

The initial pulse tests were conducted in a MIKROS oil diffusion pump vacuum system, with a liquid air-cooled baffle. An aluminum adapter ring provided for electrical feedthroughs and ion-gauge mounting and supported the bell jar enclosure. The vacuum level was typically 5×10^{-5} torr. Operation was at room temperature.

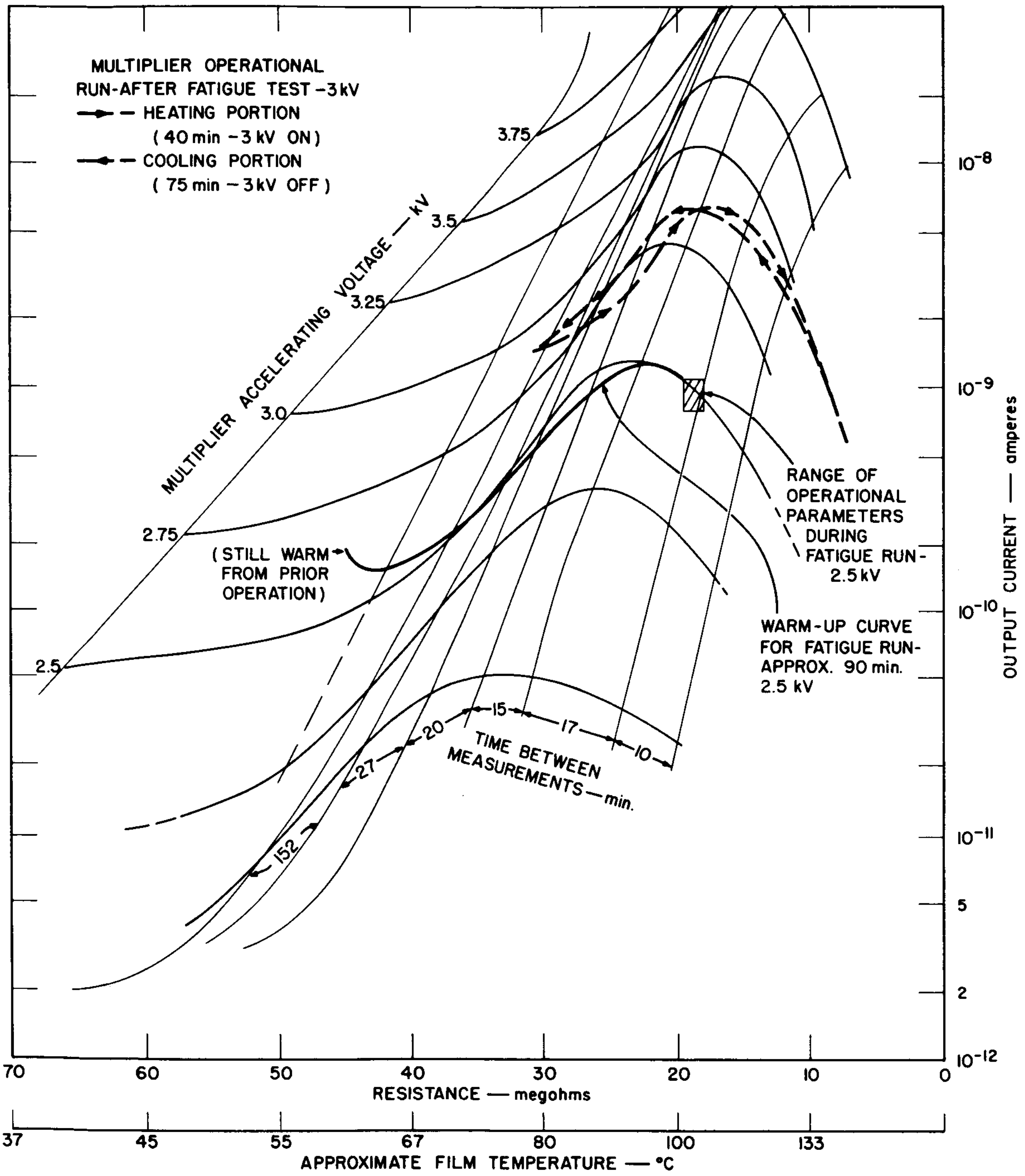


FIG. 10 GAIN vs. RESISTANCE — LOW-RESISTANCE MULTIPLIER

A thermionic diode electron source, illustrated in Fig. 11, was modified for triode operation, to provide a pulsed input to the multiplier. Dynode strips 35/36 were used, with a resistance (at 2.5 KV) of 2.6×10^8 ohms. The experimental setup was similar to that illustrated in Fig. 4, with the pulsed thermionic electron source replacing the radioactive emitter and intermediate electrode. A load resistor and oscilloscope connected to the collector permitted viewing the output waveform.

2. Pulsed Operation

a. Thermionic Input

The calibrated triode thermionic electron source and the multiplier mount with dynode strips 35/36 were positioned in the MIKROS station and the system evacuated. The multiplier was operated at 2.5 KV, corresponding to a gain of about 3×10^5. Pulsing the grid of the thermionic source provided electron bursts controllable in amplitude, duration and frequency for input to the multiplier. Several levels of current pulses, ranging from 0.5 to 10 microseconds in duration, at repetition rates of 100 to 2000 per second, were applied to the multiplier. No significant difference was observed between the input and output waveforms. When the unit was operated at 2000 pulses per second of 10-microsecond duration, it was on the threshold of saturation. Increasing either the repetition rate or duration gave a decreased output amplitude. As the pulse duration was decreased below 1 μsec, capacitive coupling caused the leading and trailing edge of the input signal to show up in the output waveform to an increasing degree, making quantitative measurement difficult.

It had been planned to further refine the experimental pulse setup to carry the study further and obtain more quantitative data, but the pulse information obtained from observation and analysis of the output current of the beta-source activated multiplier in the gain fatigue setup made this unnecessary. The beta source provided an input more consistent with the intended applications, with random inputs in the range of tens of thousands per second, and of very short duration, far shorter than could reasonably be achieved by the thermionic triode unit.

b. Beta Source Input

The output current of the 39/40 multiplier on life test was examined using a fast oscilloscope. With careful adjustment of the scope triggering circuit, the output pulses from individual input electrons could be viewed on the scope. As the experimental setup was refined (faster scopes, better amplifiers, and better coupling), the observed output pulse width was decreased from 180 to 40 and finally to about 10 nanoseconds. The final setup consisted of 6 inches of direct lead from the collector to the vacuum feedthrough, then 18 inches of coax terminated with 50 ohms at the input to a Tektronix 581 scope. The resulting wave form is shown in Fig. 12. Estimating 50 pf for the

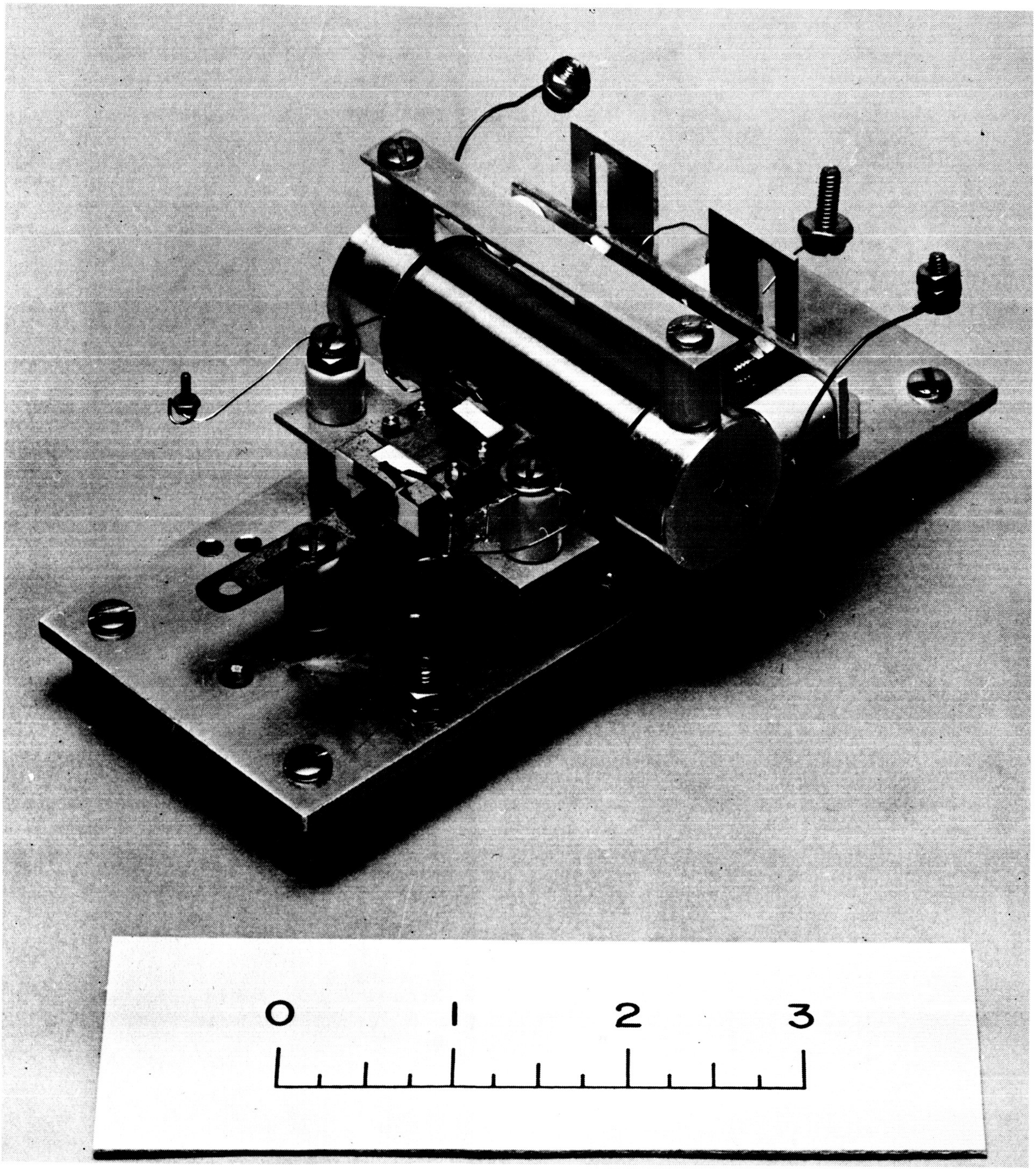


FIG. 11 LOW CURRENT ELECTRON SOURCE

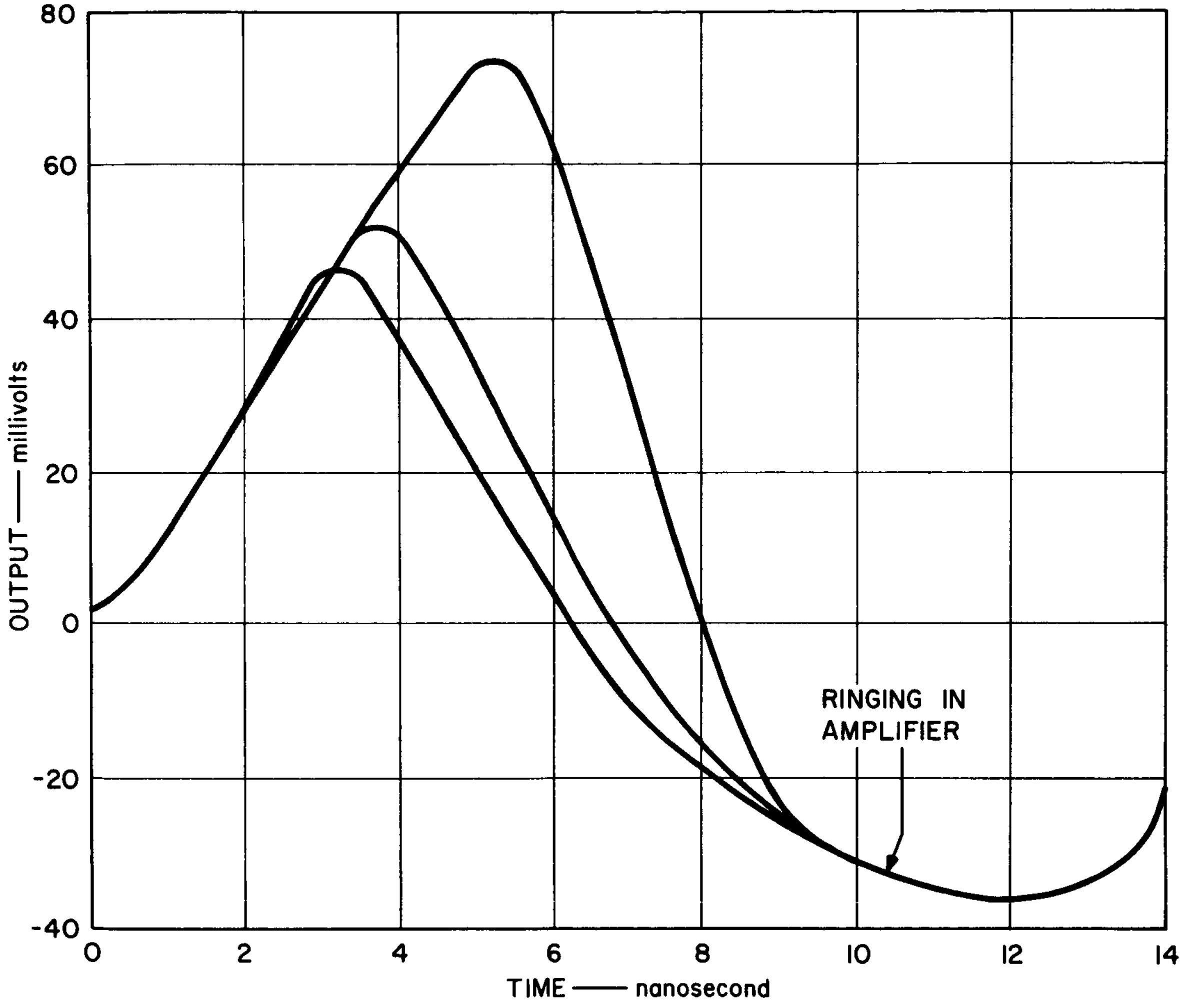


FIG. 12 MULTIPLIER OUTPUT PULSES FOR BETA SOURCE INPUTS

collector, lead, coax, and scope input capacity and a 50-ohm impedance, the circuit time constant was about 2.5 nanoseconds. Scope rise time was 1.5 nanoseconds. Since the calculated electron transit time through the multiplier is about 10 nanoseconds, if a ±10% spread in transit time is assumed for an individual pulse, the circuit and instrument characteristics were approaching compatibility with the anticipated result.

Variable-amplitude, randomly-timed output pulses were noted as expected. A counter driven from the signal-triggered, pulse-forming output of the scope gave counts on the order of 1000 per second, the number being variable with multiplier voltage and extremely sensitive to the scope trigger setting. It appeared that the majority of the lower amplitude output pulses were too close to the noise level to permit reliable separation by the scope trigger circuit and subsequent counting.

Assuming a gain of 6×10^6 from the multiplier for the higher amplitude output pulses, and assuming that half of the output electrons arrive within 1 nanosecond, a current peak of 5×10^{-4} amps would be developed. With a 50-ohm load, this would give a 25-millivolt pulse. The pulses recorded by the scope ranged from 10 to 70 or 80 millivolts.

For 6×10^4 input particles per second and 2×10^5 average gain, an output current of 2×10^{-9} amps should result, which was quite consistent with the measured values.

C. DEGRADED VACUUM OPERATION

Operation of the strip multipliers under deliberately increased pressure was studied while looking for effects attributable to ion-feedback through the multiplier.

The multiplier in the MIKROS system was operated at 2.6 KV with 2 microsecond pulses at a 2000 per second rep rate. The multiplier setup was located intermediate in the system between a needle valve and a vacuum gauge. The needle valve was opened slightly, and the output wave form viewed closely as the vacuum gauge reading rose from its normal 5×10^{-5} torr to as high as 2×10^{-3} torr. There was no change in the rising slope or in the duration of the output pulse. The amplitude of the output pulse increased with pressure and at 10^{-3} torr was double the value in the 10^{-5} torr range. Meanwhile, the input pulse to the multiplier decreased by a factor of 2, presumably due to decreased emission from the filament and/or electron collisions with gas molecules. The increased output may be attributable to the ionization of gas molecules near the multiplier input increasing the effective input current and/or to increased gain in the multiplier caused by the reaction of the air constituents with the dynode surfaces.

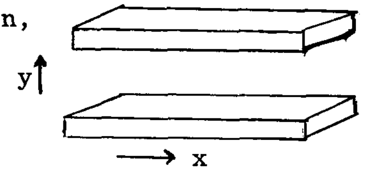
The high-resistance multiplier in the UHV system was also exposed to increased pressure while the output pulses from the beta particle input were being viewed. The vacuum roughing tube (copper) was cooled in liquid air and mechanically pumped. The roughing valve of the vacuum system was cracked open, and the system pressure was allowed to rise. The multiplier was physically offset from the direct line between the air inlet and the vacuum gauge; hence, the operating pressure in the vicinity of the multiplier was probably somewhat lower than the gauge reading.

The integrated multiplier output current remained constant as the pressure rose from the 10^{-8} torr range to 10^{-6} torr. At 10^{-5} torr it had increased by about 40% and at 10^{-4} torr by an order of magnitude. No change in the approximately 10-nanosecond pulse width or the shape of the output pulses was noted, although there was some increase in the frequency of occurrence. The scope sweep speed was decreased so that the 10-microsecond period immediately following each output pulse could be viewed. This encompassed the time period for ions generated near the multiplier output to travel to the input and initiate another cascade of electrons. No significant number of pulses were observed within this period. Again, the increased current may be attributable to an ionization-supplemented input and/or increased multiplier gain resulting from air constituent, dynode interaction.

D. MULTIPLIER CALCULATIONS

1. Gain

With some simplifying assumptions, a series of fairly straightforward calculations provided a surprisingly realistic theoretical gain voltage curve. Using the equations of motion, and disregarding space charge effects,



$$y = V_y t \text{ or } V_y = \frac{y}{t}$$

$$eV = \frac{1}{2} mV_y^2 \text{ or } V_y^2 = \frac{2eV}{m} ,$$

where V_y = secondary-emission velocity normal to substrate.

Hence, $t^2 = \frac{my^2}{2eV}$, where t is time for a secondary electron to traverse the multiplier plate spacing.

$$x = V_{ox} t + \frac{1}{2} a_x t^2 .$$ Assume zero secondary velocity in x direction; i.e., $V_{ox} = 0$

$$F_x = Ma_x = eE_x \text{ or } a_x = \frac{eE_x}{m} ,$$ and

$$t^2 = \frac{2mx}{eE_x} .$$ Equating t's.

$$x = \frac{E_x y^2}{4V} .$$

For the fixed multiplier spacing and length, at any applied voltage, E_x is determined. For assumed secondary-electron velocities normal to the multiplier surface, the x distance travel per hop was computed, as well as the number of hops to transit the X dimension. From a secondary-emission ratio versus voltage curve for the dynode film material (Fig.13), the gain/voltage curve of Fig. 14 was developed. For comparison, the measured gain/voltage relationship for multiplier strips 35/36 is also included. Figure 15 shows an intermediate construction helpful in the calculation. The calculation does not take into account the gain saturation effect which occurs when the secondary current leaving the resistive film near the output end is such a high fraction of the quiescent current in the film establishing the axial field that the uniformity of the field is disturbed.

2. Transit Time Calculation

For the multiplier geometry used, 2.5-KV accelerating voltage, and assuming a nominal 2.5-eV secondary emission normal to the dynode surface, secondary electrons would travel 0.04 inch in the x direction before striking the opposite surface, and arrive with 100-eV energy. This would give 25 hops for complete transit.

Transit time

$$T = \frac{v_o \pm \sqrt{v_o^2 + 2\frac{e}{m}V}}{\frac{e}{m}\frac{V}{d}}$$

where

v_o = axial secondary emission velocity

V = terminal electron velocity

d = electron travel per hop

$T = 3.8 \times 10^{-10}$ seconds per hop, or 9.5 nanoseconds, for a 25-hop transit.

The direct-electron transit time for 1 inch of travel with 2.5 KV acceleration would be about 1.7×10^{-9} sec. A singly charged ion of mass 30 would have an m/e value of about 6×10^4 times that of an electron, for a velocity factor of 1/245; hence ion transit time for the length of the multiplier would be on the order of tenths of microseconds.

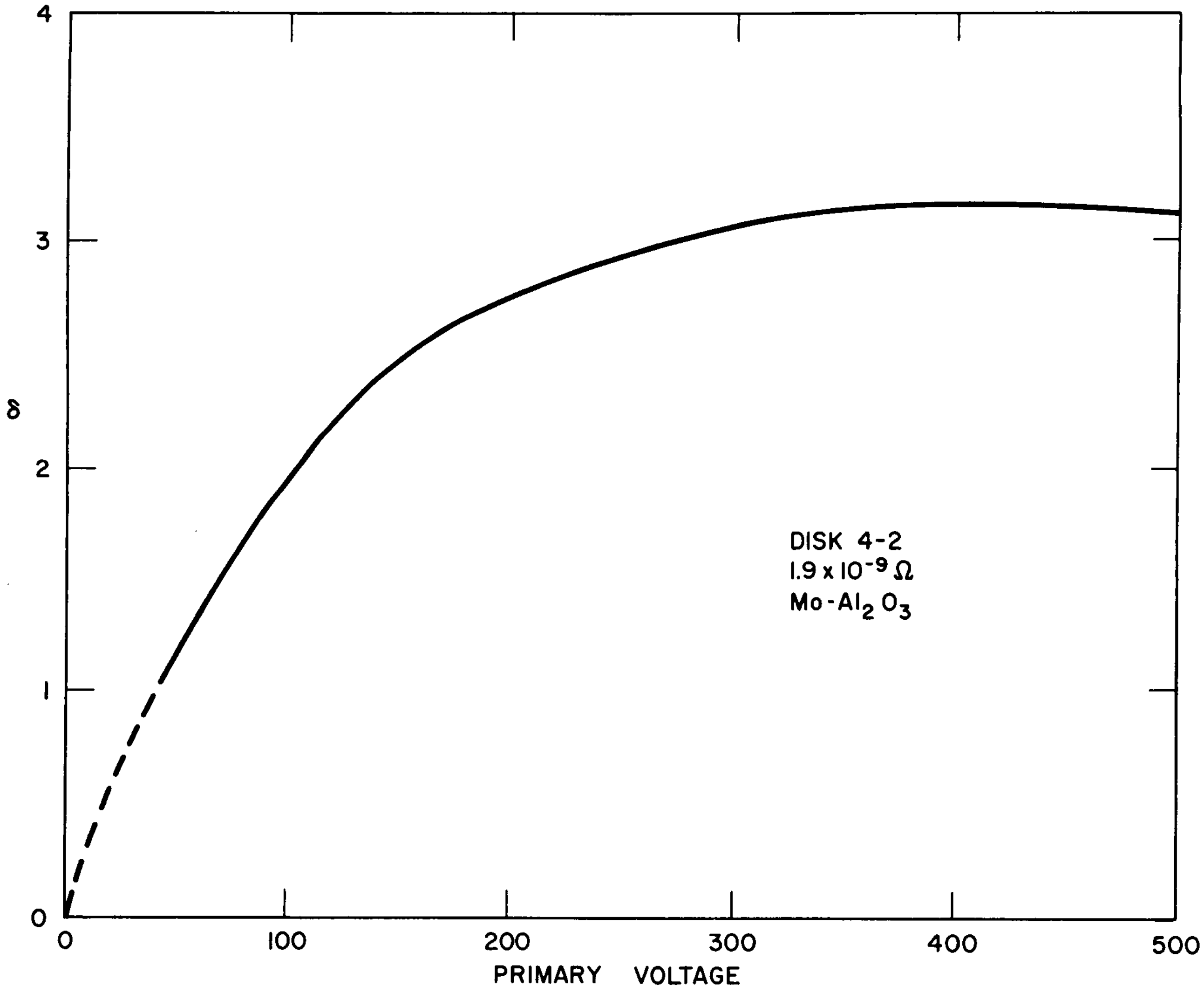


FIG. 13 DYNODE SECONDARY EMISSION CURVE

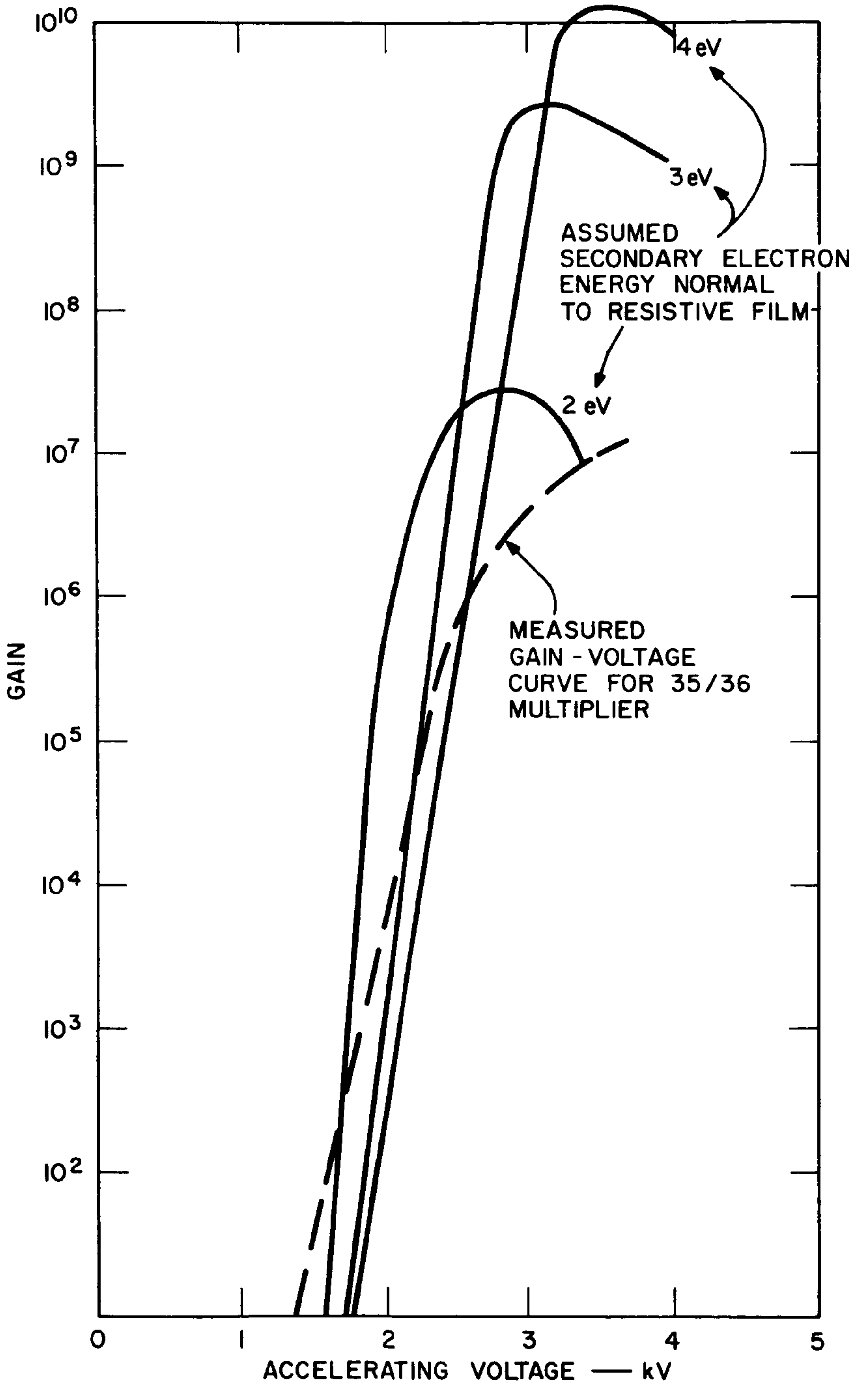


FIG. 14 THEORETICAL GAIN-VOLTAGE RELATIONSHIP

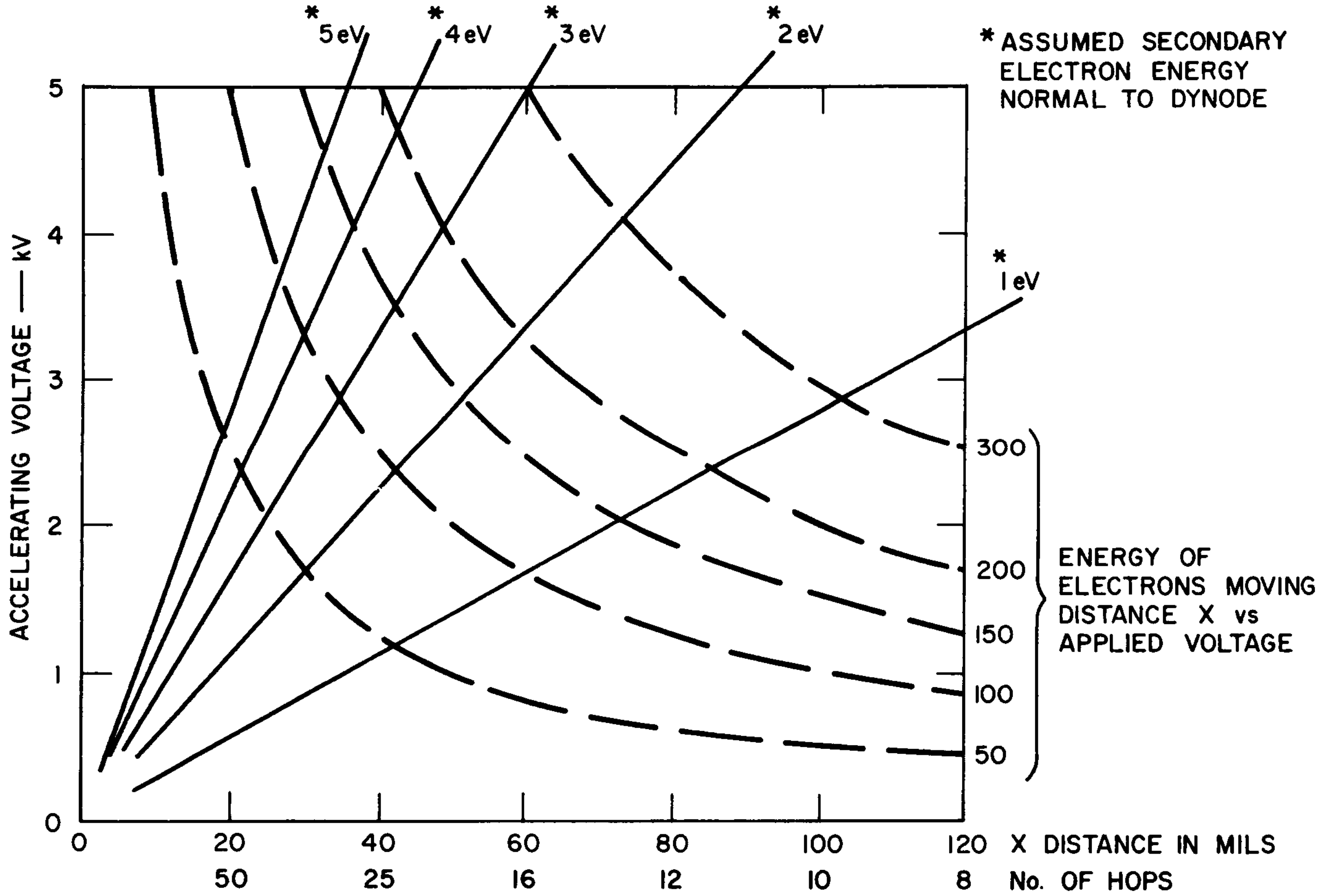


FIG. 15 THEORETICAL VOLTAGE, DISTANCE, ENERGY RELATIONSHIPS

III CONCLUSIONS

A. GAIN FATIGUE

Tubular or channel-type multipliers and SRI parallel-plane or strip-type multipliers undergo strikingly similar gain fatigue effects when operated under similar conditions (i.e., room temperature; 10^{-8} to 10^{-9} torr vac-ion environment; radioactive beta emitter input). These units differed substantially in their substrate material, geometric shape, contact electrode material, resistive film (dynode) material, and fabrication process. Two different pairs of strip multipliers with more than two orders of magnitude different quiescent current also exhibited similar fatigue effects. The bulk of evidence indicates that this gain fatigue phonomena is caused by a decrease in the secondary, emission characteristics of the resistive (dynode) surface, attributable to physio-chemical processes affecting the active surface of the multiplier.

B. GAIN CHANGE

The gain of these distributed dynode mulitpliers is also affected by the temperature (both reversibly and nonreversibly) and the pressure at which they operate, as well as the prior usage (including interrupted usage) to which they have been subjected.

C. PULSE OPERATION

The strip multipliers have capability for output pulses, from single-particle input, of less than 10^{-8} second duration at gains of 10^6 to 10^7, and operate at random time repetition rates of at least 10^4 to 10^5 per second.

D. ION FEEDBACK

Exposure to pressures of 10^{-3} to 10^{-4} torr under otherwise typical operating conditions disclosed no evidence of ion feedback phenomena.

E. CHARACTERISTICS

The distributed dynode multipliers have numerous favorable characteristics, i.e., small size and weight, minimal support structure and number of leads, low power, high gain, and intrinsic potential distribution, which are all important for many potential space applications. In addition, the construction of the parallel-plane strip multipliers permits ready access to the active dynode surfaces, prior to and following operation, to permit study and measurement of changes that may affect the gain or other operational characteristics.

IV RECOMMENDATIONS

Gain Fatigue: A basic study of the gain fatigue effect should be undertaken to determine the cause or causes of this phenomenon. Details of a suggested approach to such a study are contained in SRI proposal No. ESU 66-22, "Analytical and Developmental Investigation of Electron Strip Multipliers - Phase III", 20 June 1966.

Thermal Effects: Further study of the reversible and nonreversible gain changes attributable to the multiplier thermal environment is in order to provide a better understanding of these phenomena and to develop means for either utilizing or minimizing these effects.

Recovery: An awareness of the recovery phenomena noted during some periods of interrupted multiplier operation should be maintained. If a consistent pattern develops it should be studied to provide insight into the cause and means for alleviation of this effect.

Gain-Pressure Effect: Further study of the pressure-output current relationship should be conducted if operation at pressures above 10^{-4} torr is anticipated.

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13. ABSTRACT

The object of this study was to evaluate the operational characteristics of the SRI distributed dynode strip multipliers as they related to potential NASA space applications. It included evaluation of the long-term gain fatigue effects, operation in a degraded vacuum to ascertain susceptibility to back-ion bombardment, and evaluation of pulse response.

Two strip multipliers, with vastly different resistivities, were operated for periods of 2500 and 600 hours, respectively. They demonstrated similar gain fatigue effects, not only with respect to each other, but also to commercial channel or tubular multipliers fabricated with substantially different materials and geometry. There were also reversible and nonreversible gain changes in the strip multipliers, attributable to prior operational history and to the temperature and pressure environment. When the pressure was increased to 10^{-3} to 10^{-4} torr, under otherwise normal pulsed operation, there was no evidence of significant back-ion effects on the output pulses, but there was a substantial increase in output current, which may be attributable to ionization-enhanced input and/or increased multiplier gain.

This kind of strip multiplier yielded output pulses shorter than 10^{-8} seconds and gains on the order of 10^6 for single electron inputs arriving randomly at a mean rate of 10^4 to 10^5 particles per second.

It is concluded that distributed dynode multipliers have much to offer in terms of physical, electrical, and operational characteristics, and that the parallel strip configuration offers special advantages where evaluation of causes of gain change or other operational characteristics is desirable.

It is recommended that a basic study of the causes of the long-term gain fatigue effect be undertaken, as well as further study of the environmental (especially thermal) effects. If multiplier operation at pressures above 10^{-4} torr is anticipated, the study of the relationship of pressure to the relevant operational characteristics should be extended.