This document describes the warm-up process of the SNAP-27 Generator Assembly after the isotope capsule is inserted. Several inquiries have recently been received regarding this process, and deployment sequence studies are impacted. Because of the several variables associated with the turn-on of ALSEP on the lunar surface, there is no simple plot of available power as a function of time. However, some reasonable estimates can be made of available power for specific turn-on cases.

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Summary

This ATM describes the generator (with emphasis on the warm-up characteristics), estimates short-circuit current as a function of time, and estimates the available power for two turn-on sequences. Data are available for estimating power available for other turn-on sequences.

This analysis shows that for the one-man deployment there will be about 42.5 watts available at the time the station is turned on. This is more than adequate to provide regulation for the initial loading of 34.1 to 37.5 watts, depending on Array.

On the other hand, the two-man deployment sequences do not allow enough warm-up time to provide adequate power at the time the station is turned on. As a result, the output voltages of the Power Conditioning Unit will be approximately 75% of their normal values when transmitter turn-on is attempted.

Generator Description

Figure 1 shows a simple thermal schematic of the generator. Heat from the fuel capsule radiates to the hot frame, flows through the thermopile to the cold frame by conduction, thence to the finned radiator. During steady-state operation, some 5% of this thermal energy is converted to electrical energy and is dissipated in ALSEP. There are other losses, such as end effects, which are not significant for this description.

A voltage is produced at the generator terminals as a result of the thermoelectric conversion (Seebeck Effect). A current determined by internal and external resistance will flow if the terminals are connected to a load, and as a result of the current flow there is an inverse conversion effect (Peltier Effect). The voltage produced by the Seebeck effect is proportional to the temperature drop across the thermopile; however, the Peltier effect tends to decrease this temperature drop. A further effect, which is not considered here, is the efficiency variations of the thermoelectric material as a function of temperature.

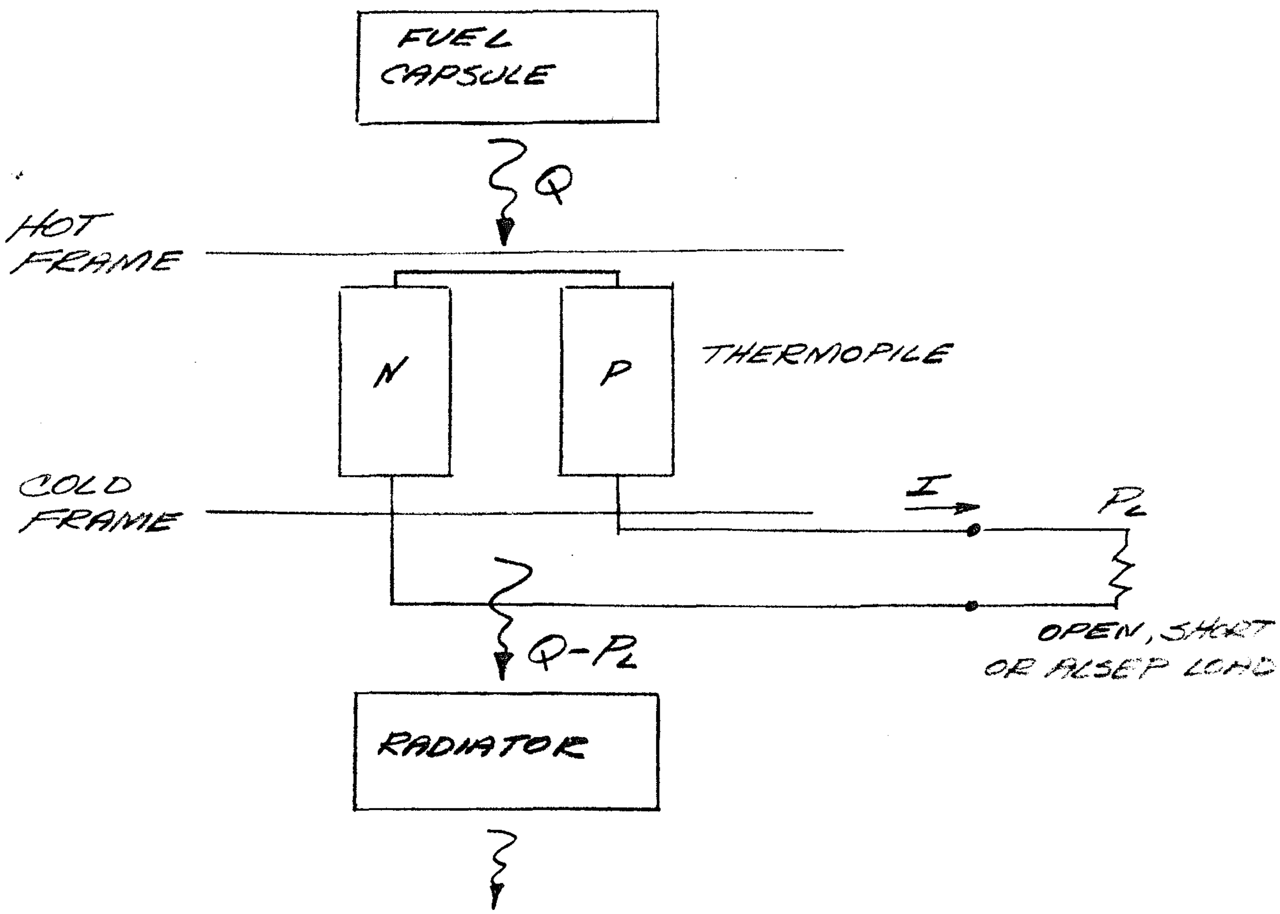

Figure 1 Generator Schematic

The generator performance can be further described by a plot such as shown in Figure 2. Here, steady-state performance is illustrated by curves of voltage, power, hot frame temperature, and cold frame temperature as functions of the current flowing. It is emphasized that these curves, except for the line marked "Dynamic Resistance," are steady-state curves. The points on the curve were obtained by adjusting the load and then waiting several hours for the thermal transient to decay. The dynamic resistance on this figure illustrates the generator internal resistance for an instantaneous load change. In the figure the dynamic resistance is illustrated for the ALSEP operating point of 16 volts. The instantaneous internal resistance is also approximately the same for other points on the steady-state curve. This means that when the operating point is changed, the new point will be on a line through the old point with a slope of the dynamic resistance. As the thermal transient decays, the operating point will move to the steady-state line along a path determined by the variable which is held constant.

The generator design was optimized to give maximum power out while keeping weight and volume to a minimum. Other variables which were considered were thermal input, temperature limits of structural materials, radiator size, radiator operating temperature, and the efficiency and temperature limits of the thermoelectric material, lead telluride. As a result, the thermopile hot junction temperature was set near the upper material limit. As shown in Figure 2, the hot junction temperature goes up when the load current is decreased and would be very high for steady-state, open-circuit operation, exceeding the lead telluride limits. Operation at temperatures in the region of 1200°F would degrade the thermopile.

At the other extreme, operation shorted is conservative. The hot junction temperature is low, and the slight rise in cold junction temperature accounts for the additional electrical power being dissipated within the thermopile due to the Peltier Effect.

Warm-Up

After the capsule is inserted into the generator on the lunar surface, the shorting plug will keep the generator shorted until the button is pushed by the astronaut. There are two reasons for this provision: (1) to keep the generator hot junction temperature down in case the deployment sequence is interrupted before the Central Station is connected, and (2) to minimize the voltages present on the connector when the Central Station is connected.

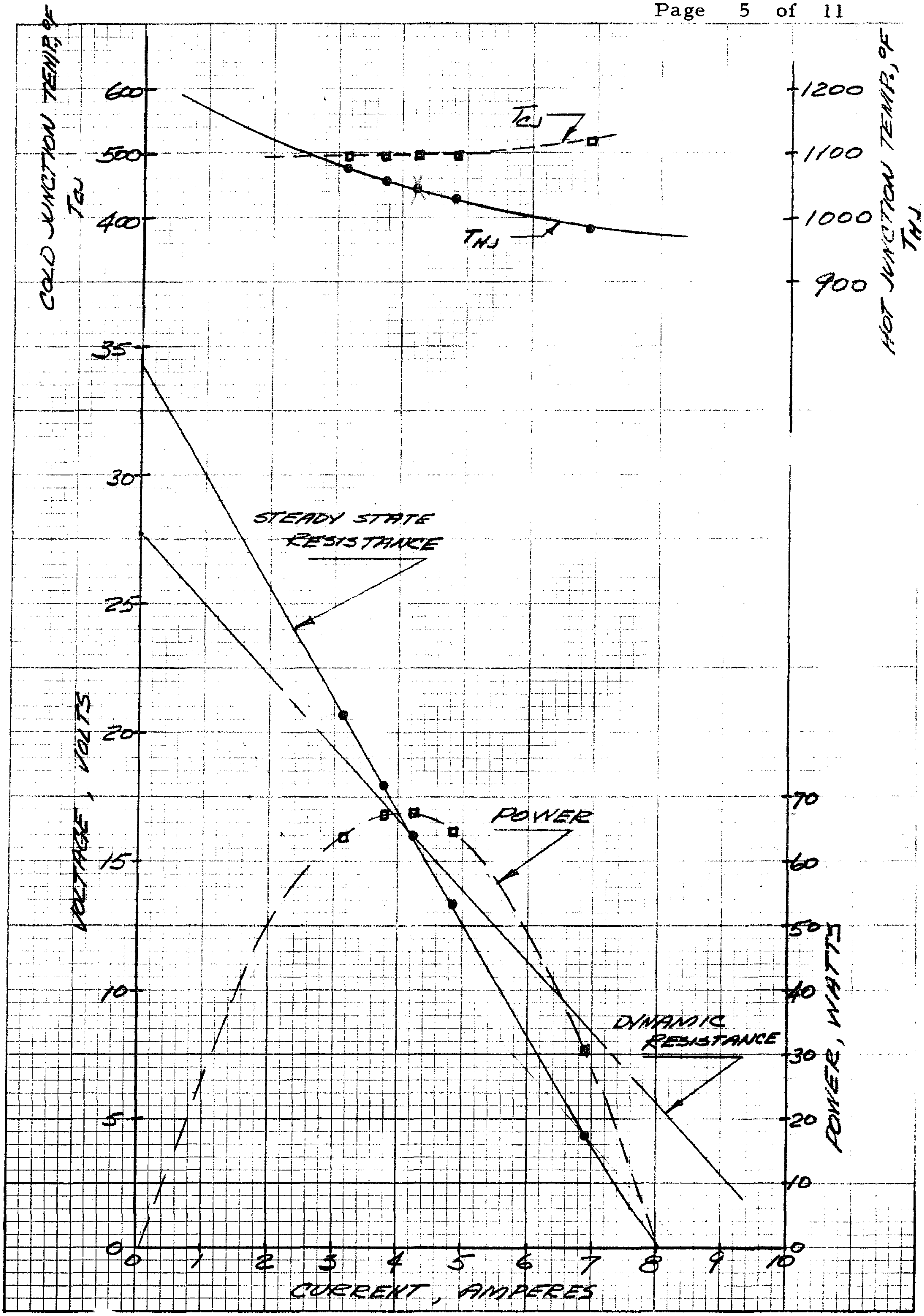

Figure 2 Generator Characteristics

Operation during a shorted warm-up will be along a load line of 0.05 ohm which is the shorting plug resistance as shown on Figure 3. This short-circuit current, which can be directly read on the ammeter in the shorting plug, gives an indication that the generator is operating properly. Figure 4 shows the expected short-circuit current as a function of time for a continuous warm-up in the shorted condition.

In the normal deployment sequence, after the short-circuit current is read and the button is depressed, the generator will "see" a load of about 32 ohms consisting of the fixed or "ON" loads on the 29-volt PCU output line through the autowinding of the PCU output transformer. This is a near-open-circuit load for the generator. A thermal transient will be initiated inside the generator (mostly at the hot frame) due to the decrease in Peltier cooling, which is superposed on the warmup transient occurring. The generator voltage will move along the dynamic resistance line to the intersection with the 32-ohm load line. The open-circuit voltage will then increase along the 32-ohm line until the #1 Astronaut Switch is closed or the automatic turn-on point of 24 volts is reached.

At the time either of these events occurs, the generator voltage will again move along the dynamic line to 16 volts or a power balance condition at reduced voltage. If the intersection of the dynamic line and 16 volts results in more than the initial load of 34.1 watts (Array A), the PCU regulator will keep the generator output at 16 volts; otherwise, the PCU output voltages will be lower than normal, approximately on a 7.5 ohm load line. The PCU turn-on then introduces another thermal transient into the generator as the current flow is significantly increased.

Figure 3 illustrates the expected turn-on sequence for a one-man Array A deployment.[1] At 13 minutes and 28 seconds after the capsule is inserted in the generator, the astronaut reads the short-circuit current. The expected value is 6 amperes or point A on Figure 3. At 14:54 after insertion, he pushes the button causing the generator voltage to move instantly from point B to C. As warm-up continues, the generator voltage moves from C to D. After 20 minutes and 46 seconds, the Astronaut Switch #1 is closed, moving the generator voltage instantly from point D to E at 16 volts. It has been assumed in estimating the point

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[1] Deployment sequence based on ATM-739, dated 27 May 1968.

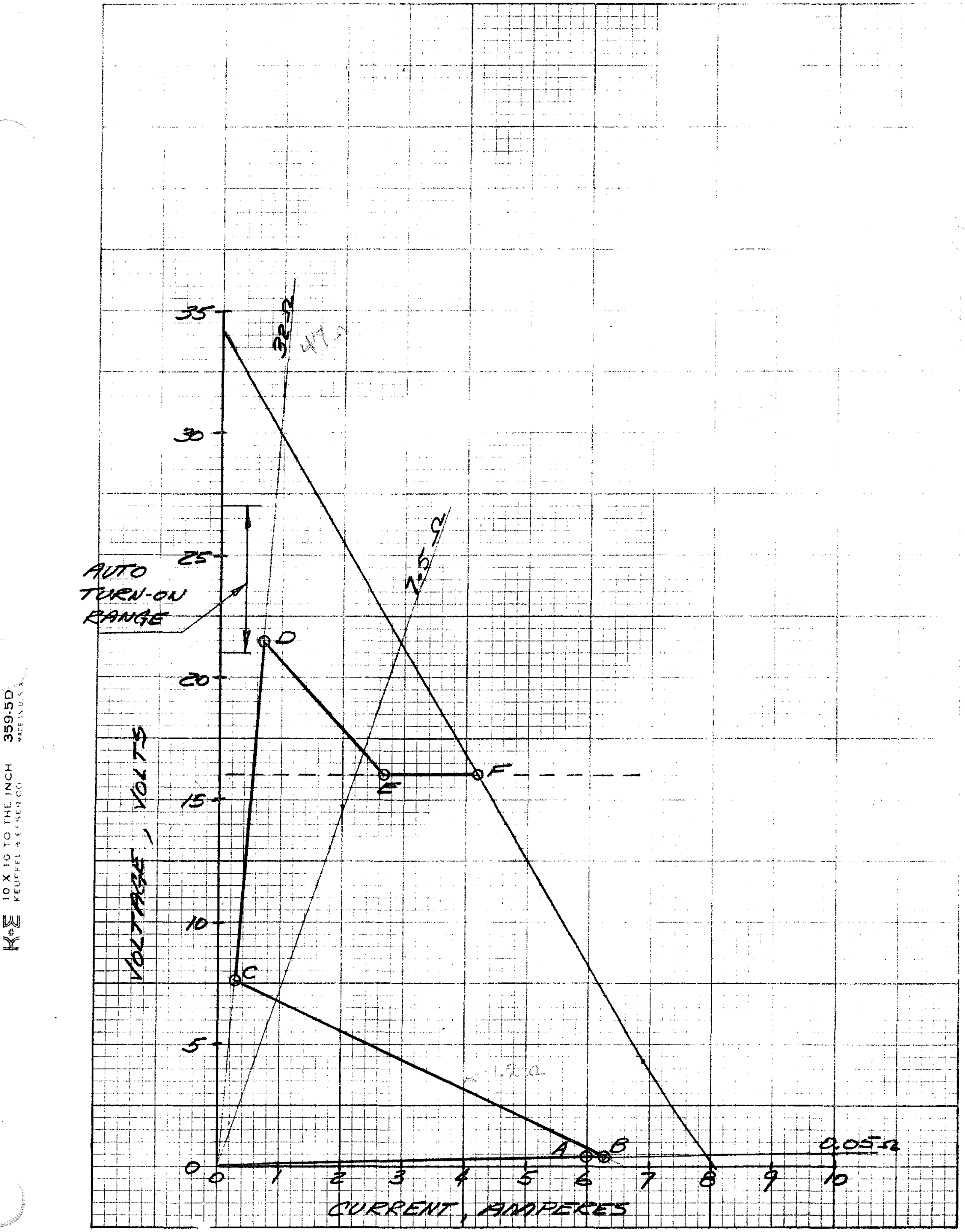

Figure 3 One-Man Deployment Warm-Up

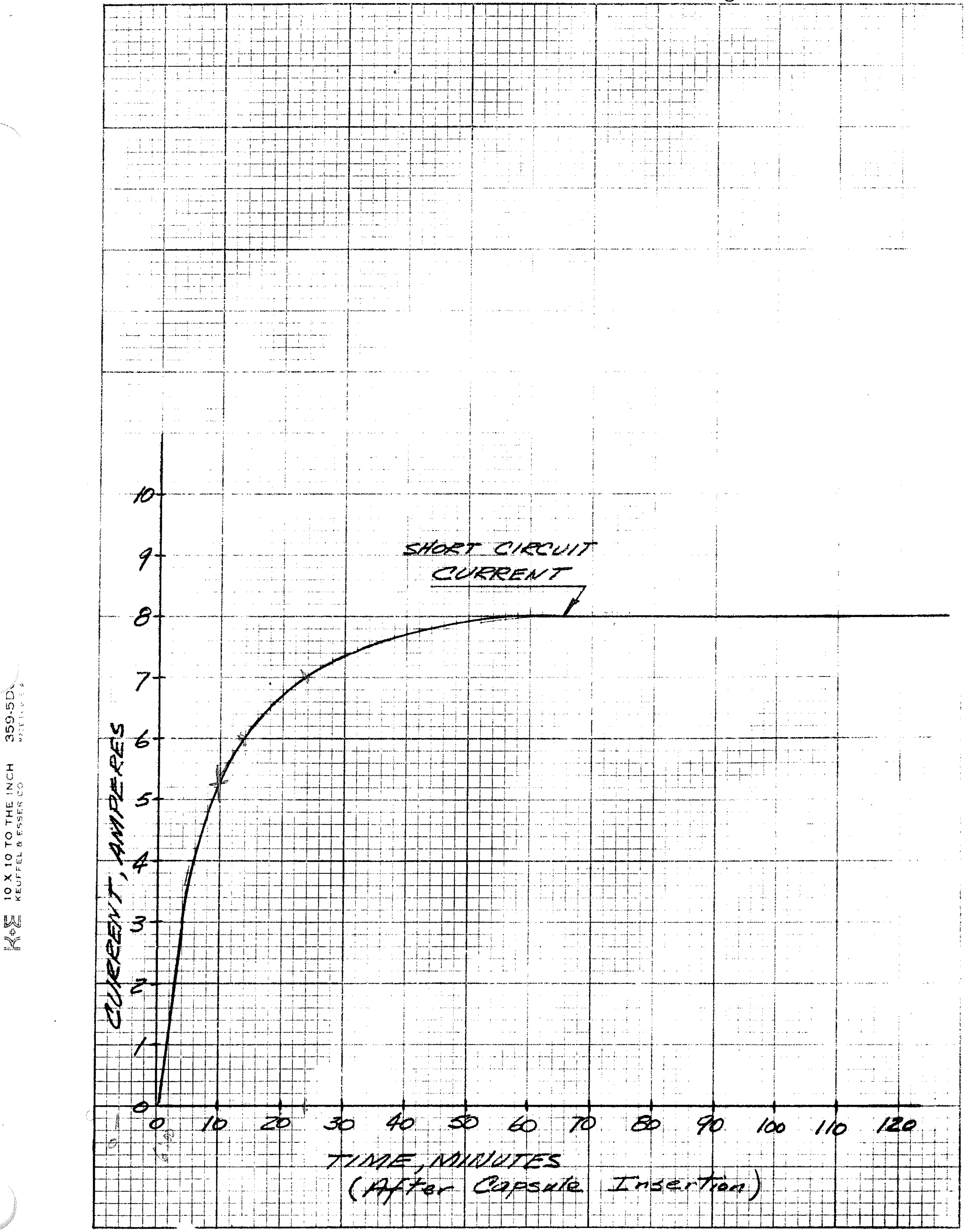

Figure 4 Generator Short Circuit Current During Warm-Up

D voltage that the thermal transient associated in moving from point B to C has a small effect compared to the schedule for a warm-up completely along a 32-ohm load line.

The power at point E of 42.5 watts is adequate for the initial load of 34.1 watts, and all PCU output voltages will be regulated. The operating point will probably remain near point E for several minutes as the Peltier Effect tends to decrease the thermal drop across the thermopile. The operating point will then move to point F as steady-state thermal conditions are reached during the next hour.

In the two-man deployment sequences,[2] the shorting plug button is pushed approximately 12.5 minutes after fueling and then approximately 10 minutes later the station is turned on by closing Astronaut Switch #1. This sequence is shown by points G through M on Figure 5. At station turn-on, at point K determined by a 7.5-ohm equivalent system load, approximately 19 watts will be available, but all the PCU voltages will be reduced to 75% of their regulated values. As the warm-up continues, point K to point L, the voltages will rise to their normal values and then will remain constant for the remaining warm-up.

This analysis is based on a series of three tests performed at General Electric[3] in which a hot electric fuel capsule was inserted remotely into the MOD 8B generator assembly. In these tests, the capsule was allowed to reach steady-state temperatures in vacuum with a 0°F sink. It was then driven into the generator assembly in 35 seconds. Generator thermal and electrical measurements were made until the generator reached equilibrium. In the first two tests, the generator was shorted electrically except that instantaneous open-circuit voltage measurements were made on a periodic basis. In the third test, the generator was open-circuited except for instantaneous short-circuit measurements on a periodic basis. The results of these tests are a warm-up voltage versis current plot for a 0.6-ohm load (test console minimum resistance) and an open-circuit voltage versus time plot. In addition, the generator internal resistance can be estimated by assuming that the instantaneous measurements at a given time can be connected to the steady-state points by a straight line and that other instantaneous load points would lie along this straight line.

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[2] Deployment sequences based on ATM's 803, 804 and 805, all dated 26 September 1968.

[3] PIR No. U-ANSO-SNAP-1112, May 25, 1967, Missile and Space Division, General Electric Company

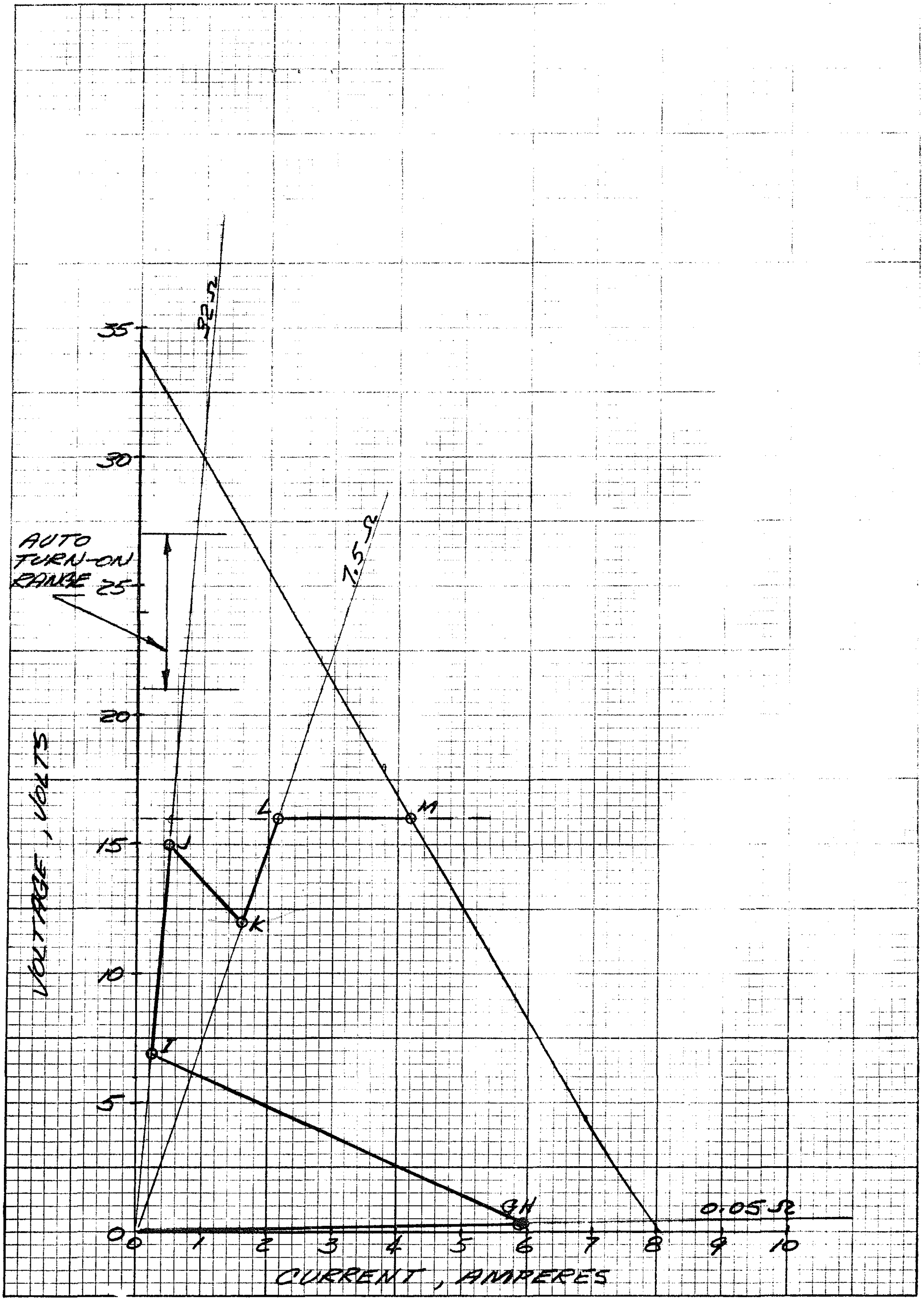

Figure 5 Two-Man Deployment Warm-Up

These tests also show that the dynamic resistance changes somewhat during warm-up. Early in the warm-up sequence, the dynamic resistance is about one ohm, while the final value is about 2.7 ohms. The equation: $R = 1.34 + 0.024\ t$ ohms, where t is in minutes after capsule insertion, can be used to determine the dynamic resistance in this range. The effect of this change was considered in constructing the plots in Figures 3 and 5.