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THE CAPILLARY PUMPED LOOP (CPL) GAS EXPERIMENT G-471

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INTRODUCTION

The Capillary Pumped Loop (CPL) experiment, G-471 is a thermal control system with high density heat acquisition and transport capability. The CPL consists of two capillary pumped evaporators with integral heaters, a fluid loop charged with ammonia (NH3), a condenser plate (heat sink), and various control electronics. The purpose of the experiment is to demonstrate the cpability of a capillary pumped system under zero gravity conditions for use in the thermal control of large scientific instruments, advanced orbiting spacecraft, and space station components.

A unique feature of the CPL is the capillary pumps, which contain no moving parts. Each pump contains a wick of porous material which is saturated with the working fluid (anhydrous ammonia). As heat is added to the fluid, it evaporates and travels to the condenser, thus transporting the heat (via the latent heat of vaporization) from the heat source to its sink at nearly a constant temperature.

The evaporation process produces the pressure gradient or pumping action that circulates the fluid. This is the same principal that plants and trees use to transport water and nutrients from their roots to their leaves against gravity. The difference is that the CPL employs a closed system to return the fluid directly to the pumps, whereas "Mother Nature" has an open system where the fluid is indirectly returned to the roots by condensation of water from the clouds in the form of rain. It should be noted that the CPL experiment was the first flight of a thermal control system of this type. It was also the first shuttle experiment from the Space Station Advanced Development Program.

The principal investigator of the CPL is Roy McIntosh of NASA's Goddard Space Flight Center, Greenbelt, Maryland.

BACKGROUND

The concept of a capillary pumped loop (CPL) was pioneered by F.J. Stenger of NASA/Lewis in the mid 1960's (ref.1). The design of the CPL is shown in Figure 1. The evaporator contains a porous wick material which produces the pumping action in the closed loop system via capillary forces. The liquid is drawn through the wick to the metallic shell of the evaporator where it vapoizes and then travels to the condenser. The heat is removed at the condenser and the vapor is thus condensed back to a liquid. The liquid is then returned to the evaporator to repeat the cycle. A cross section of the evaporator pump is shown in Figure 2 (from reference 2).

The CPL system has been undergoing development and ground testing at GSFC for the past several years. An engineering model was built for GSFC by the OAO Corporation. It uses ammonia as the working fluid and has demonstrated heat carrying capabilities of up to 6.4 Kilowatts. The CPL ground test engineering model is depicted in Figure 3. This system features eight capillary pumps mounted in parallel (left side of figure). The multiple evaporator pump feature demonstrates the ability to accommodate multiple users on a single thermal control loop. It also provides for heat sharing, whereby heat can be removed from the the system as well as added. Another important part of this system is the two-phase reservoir. By controlling the reservoir temperature, the loop temperature is controlled as well, since the saturation temperature of the working fluid is controlled at the reservoir. This means that the pumps (evaporators) stay at a relatively constant temperature regardless of the heat load or heat sink temperature variation, thus establishing temperature control in the loop. The loop temperature can be varied simply by raising or lowering the reservoir temperature to the desired level. Another salient feature of the reservoir is fluid inventory control. The reservoir can also be used for pressure priming of the pumps during startup operations.

The CPL system also includes a condenser zone (right side of Figure 3). The vapor travels from the evaporator pumps to the condenser where the heat is removed and the vapor is returned to the liquid state. A chiller (refrigerator) is used on the ground system for the heat removal, while a heat rejection radiator is used for space applications. After the vapor is condensed, the fluid is returned to the pumps through an isolator to complete the cycle. The isolator allows the pumps to operate individually within the loop. It also prevents vapor from travelling the "wrong way" or backing up, thus providing direction to the flow within the loop.

CPL-GAS

The next step in CPL development is zero-g verification of its performance. Since the capillary pumps are sensitive to the effects of gravity, space flight experiments are required. The GAS system was chosen for the initial experiment due to its low cost, ease of integration, and frequent flight opportunities.

The CPL-GAS experiment was developed utilizing existing hardware where possible (see Figure 4). The support structure and battery are identical to those used for the STS-3 GAS Flight Verification Payload. The electronics and tape recorder were flown previously on the Atomic Oxygen Monitor GAS experiment flown on STS-8 and STS-11. Unfortunately, the space available for the CPL experiment is constrained due to the volume requirements of the battery and electronics. Nonetheless, a working mini-CPL has been developed that mounts directly to the GAS top plate between the structural support struts. It measures approximately 14" by 14" by 4" high and maintains most of the operating features of the large ground system. Figure 5 shows the mini-CPL experiment both before and after installation of the heaters, wiring, instrumentation, and electronics.

The mini-CPL has two evaporator pumps mounted in parallel, with heaters attached directly to their outer surfaces. A temperature controlled, two-phase reservoir and an isolator are also included in this system. The boxes seen in Figure 5 contain additional electronics for reservoir temperature control and over-temperature limitstats to prevent overheating of the experiment (via heater cutoff). The entire system is mounted on the condenser plate with fiberglass thermal isolators. The condenser plate is then mounted directly to a CPL unique GAS top plate (supplied by the CPL project). The majority of the mini-CPL is constructed of aluminum, with the exception of the reservoir and isolators, which are stainless steel.

The CPL-GAS experiment is shown fully assembled in Figure 6. The mini-CPL is covered with a multi-layered insulation blanket (MLI) in order to thermally isolate it from the battery and electronics. A thermostatically controlled heater is used on the battery to maintain its temperature above its lower limit of 0°C during potential cold case operations. The electronics box is covered with high emittance Kapton tape to radiatively dissipate its internally generated heat, which is approximately 12 watts. The container was flown without the insulating end cap since the GAS top plate is used as the heat rejection radiator for the experiment. The top plate exterior surface was coated with silver teflon tape.

Since the mini-CPL is a closed system containing ammonia, it is a pressure vessel and therefore subject to special design requirements as required by the NASA safety office. These include design to a 2400 psi pressure for all of the pressure system components. The design pressure level is unique for each system. depending on the pressurant and the predicted maximum system pressure. Also, a second identical mini-CPL was fabricated and then burst tested in order to prove the design. This unit, which burst at 3700 psi, now serves as a display model of the CPL. It should be pointed out that there is more than one possible method to flight qualify pressure vessels. We chose the ASME Boiler Code as the least expensive of the options available. Reference 3 describes the other alternatives as well as the generic safety requirements for shuttle payloads.

TESTING

The CPL-GAS was subjected to testing which included a vibration test, thermal vacuum tests, and extensive functional tests. A workmanship level vibration test was conducted in order to verify that we didn't have any loose screws and that everything would hang together during the flight. Structural qualification testing was not required since the support structure was previously qualified on earlier GAS flights. Pressure testing was performed on the mini-CPL as already described.

A thermal vacuum test was performed to insure proper operation of the CPL under extreme temperature conditions and the vacuum environment of space. Figure 7 shows the test setup in the vacuum chamber. The CPL-GAS container was situated upside-down in the chamber to allow for proper operation of the CPL in the gravity environment. A thermally controlled cold plate served as a direct radiative heat sink for the GAS container top plate, which is also the heat sink for the mini-CPL experiment. The GAS container also had to be levelled so that gravity effects on the CPL would be minimized. Cabling from the experiment to a data and control system was routed through the GAS container bottom end plate and insulating end cap.

The chamber temperature profile for the thermal vacuum test is shown in Figure 8. The first part of the test (A) was a cooldown and cold case startup. The electronics were allowed to cool to -2 C and the mini-CPL cooled to -20 C for a cold start check. These levels correspond to the predicted cold case startup conditions. The next portion of the test (B) was a flight mission simulation with the thermal environment (chamber and cold plate temperature) set at -10 C, corresponding to the expected shuttle payload bay temperatures for the earth viewing case. The mission profile included experiment heater cycles of up to 220 watts total (110 watts on each pump) for operating times of up to one hour, followed by a cooldown period lasting approximately 10 hours. These operation times were based on the thermal analysis of the CPL-GAS. The experiment condenser was intitially allowed to cool to approximately 5°C, then the experiment heaters were activated. Since the power input exceeds the instantaneous heat rejection capability of the GAS top plate, the condenser temperature increases. When the condenser temperature approaches the CPL operating temperature of 29°C, it can no longer absorb any more heat and the system is shut down and again allowed to cool down. The heater cycle is then repeated after the condenser cools back down to about 5°C. During flight, the cycles are repeated for the total mission time, approximately 120 hours. This portion of the test verified the heatup and cooldown times predicted by the thermal analysis. The last part of the thermal vacuum test was a hot case operational check (C), with the environment set at 30°C. This test was conducted to verify the electronics system performance under the predicted hot case conditions.

As in many tests, things don't always go as planned. Problems were encountered when one of the experiment heaters wouldn't turn off. Difficulty also occured during the cold start attempts of the electronics. The test had to be stopped to correct these problems and then restarted. However, further difficulties arose with the operation of the mini-CPL experiment itself, and with the understanding of its capabilities and limitations. The planned operational profile as proposed by the OAO Corporation (reference 4) started out with low power on the pumps (25 watts each), with 25 watt step increses to 100 watts each at the end of 45 minutes. When this power profile was tried, the evaporator pumps deprimed soon after startup and would no longer carry the applied heat load, as evidenced by a sudden rise in their temperature. Several other startup or priming techniques were tried, but none were entirely successful. After two weeks in the thermal vacuum chamber, testing was abandoned due to the high costs of the thermal vacuum facility and schedule conflicts with other experiments.

A low cost functional test setup was then pursued so that the mini-CPL could be further evaluated "at leisure". Reference to Figure 6 reveals the functional test setup. The GAS container was again oriented upside-down, but now the GAS top plate rested on a continuously cooled cold plate that removed the heat from the experiment via conduction. This provided more test time since the top plate cooled down in a couple of hours with this setup as compared to 6-10 hours for the thermal vacuum test setup. Although this setup was not a realistic simulation of the Shuttle environment, it did allow for low cost functional testing in our own laboratory.

The functional testing started with little more success than the thermal vacuum testing. The reservoir did not have enough heater power to maintain the system temperature during cold startup, thus leading to flow instability in the loop. Additional heaters were added to reduce the transient thermal effects on the reservoir temperature. Although the reservoir was indeed a problem, unfortunately it wasn't the only problem. The mini-CPL still encountered evaporator pump deprime during startup in many instances. Comparison with the larger ground system showed that the lower power levels used on the mini-CPL had not been tried on the larger unit. Furthermore, miniaturization of the system had increased thermal "crosstalk" between the various components of the mini-CPL. Mr. John Ripple of NASA/GSFC finally pinpointed the solution to the startup problem. He suggested that the fluid flow rate was very low at low power since the pumps were designed to operate at power levels of up to 700 watts each. The thermal and power limitations of the GAS system forced the 110 watt per pump limit on the mini-CPL. Since the flow rate was so low, heat was leaking down the inlet tubes and pre-heating the fluid prior to entry to the evaporator pumps. This resulted in vapor flow into the pumps instead of liquid, thus causing the pumps to deprime.

Mr. Ripple's solution was to increase the amount of heater power to the evaporator pumps at startup rather than decrease it, as conventional wisdom might suggest. The increase in power resulted in an increase in flow rate, thus reducing the amount of liquid pre-heating. In other words, it worked! This new power profile was called the "100 watt zapp" (figure 9). Rather than proceedeng through a gradual warm-up period, the evaporator pumps are given their maximum power level immediately. Additional functional testing showed that this higher power level can be maintained indefinitely, provided that adequate cooling of the condenser can be maintained. Lower power operation of the mini-CPL would require redesign and isolation of the fluid inlet tubes on the evaporator pumps.

The functional testing continued for a total run time of approximately 8 weeks. Additional power profiles were developed and flight simulations were conducted. The value of testing cannot be overstated, especially in experiments dealing with new systems and technology development.

CPL-GAS FLIGHT

The mission profile for the CPL was established based on the shuttle bay-Earth thermal environment, since this is the primary orientation for most shuttle missions. Each power cycle consists of an experiment heater on period followed by a cooldown period, as previously described in the testing section. The first power cycle (figure 9) was initiated four hours after payload activation. The delay was built in to allow the battery to heat up, if its temperature was below 0°C, since its capacity significantly degrades below 0°C. Nine hour cooldown times were alloted between the cycles, which provided ample thermal margin above the predicted nominal requirement. The majority of the power cycles were the 100 watt zapp, with other types of cycles interspersed, for a total of 13 cycles in a 120 hour period. The other power cycles included heat sharing (power in one evaporator pump only), power stepdown profiles, low power steady-state, and induced deprime (intentional deprime of one of the pumps with inlet heaters).

Experiment sequencing was accomplished with the use of an electronic clock and a pre-programmed hardwired memory. The memory was a bi-polar fusible link 8K ROM built by the Harris Corporation to military specifications. Experiment data was written onto a lockhead tape recorder that is contained in the larger electronics box. The data includes thermistor readings, experiment heater power levels, battery and calibration voltages, and command status. The data was taken at approximately one minute intervals. The data collection system was built by TS Infosystems Incorporated, and the command sequencing and data storage system was built by ITE Incorporated.

The first flight of the CPL-GAS experiment occurred in April 1985 on STS-51D. Unfortunately, the GAS batteries that actuate the relay to activate the experiment failed, so the CPL could not be turned on during flight. The failure was apparently due to a bad batch of batteries that failed under a combination of vacuum and cold temperatures, even though they had passed qualification testing. The GAS project has solved the problem by enclosing the batteries in a hermetically sealed box; a fix that will be incorporated in future GAS and SPARTAN flights. Fortunately, a reflight opportunity was available on STS-51G in June, 1985. On this flight the GAS relays operated satisfactorily, and we had a very successful experiment. The mini-CPL operated for the planned 120 hours and 13 power cycles were run. The experiment worked even better than expected; all of the power profiles worked, even the low power cycle that wouldn't work on the ground. As of this writing, the data is being reduced and will be made available in later reports.

CONCLUSIONS

One of the important aspects of any project deals with how it is presented--public relations. It was suggested by Mr. John Krehbiel of GSFC that a logo should be designed for our two-phase technology development program. A logo design contest was sponsored within the Thermal Engineering branch at GSFC, and the winning entry is shown in Figure 10. This entry was submitted by Mathew Jarrell, a high school student whose father, Bill Jarrell, works for the NASA/GSFC thermal branch. Decals of the logo will be made and distributed to all interested parties.

Future plans for the two-phase flow heat transfer project include four more shuttle flight experiments over the next three years. The next flight in December, 1985 will be a reflight of the mini-CPL on the Hitchhiker-G carrier system. It will again be located in a GAS container, but power and real time data and command capability will be available from the STS. This will allow for higher experiment power levels (up to 800 watts) and control of the experiment during the flight. A specially designed 140 pound GAS container top plate will be used to absorb the large power dissipations from the CPL. The new top plate as well as the GAS container will not be insulated in order to enhance the heat rejection capability of the GAS system. The GAS container will be painted white, while the top plate will be coated with silver teflon tape.

The mission profile will resemble that used for the CPL-GAS, with short 30 minute power cycles followed by longer cooldown times. A larger, full-scale version of the CPL will be flown in December, 1986. It will have a large 100 square foot radiator that will allow for continuous operation of the experiment at a 1000 watt power level.

A Pumped Two-Phase system (PTP) is also being developed that uses a small mechanical pump instead of capillary pumps to transport the two-phase working fluid. A Hitchhiker flight is planned for July, 1986 for the first flight demonstration of a PTP system. It will be followed by a larger full-scale flight experiment utilizing the 100 square foot radiator in December, 1987.

What is the purpose of all this development work on two-phase systems? Figure 11 depicts a proposed design of the Space Station. The Space Station requires high capacity heat transport systems that can carry tens of kilowatts of heat over distances of tens of meters of more. Present single phase loops cannot do the job unless large, massive, and costly systems are built. Two-phase systems offer the potential of doing the job much more efficiently at a fraction of the cost. This technology will undoubtedly be applied in other areas as well, after it's development matures and more people become aware of it's potential.

REFERENCES

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2. E.J. Kroliczek, J.Ku, S. Ollendorf, "Design, Development, and Test of a Capillary Pump Loop Heat Pipe", AIAA-84-1720, AIAA 19th Thermophysics Conference, June 25-28, 1984.

3. "Safety Policy and Requirements, For Payloads Using the Space Transportation System (STS)", NASA NHB 1700.7 Rev.A

4. OAO Corporation, "Development of a Capillary Pump Loop Experiment (CPL), Critical Design Review", April 10, 1984

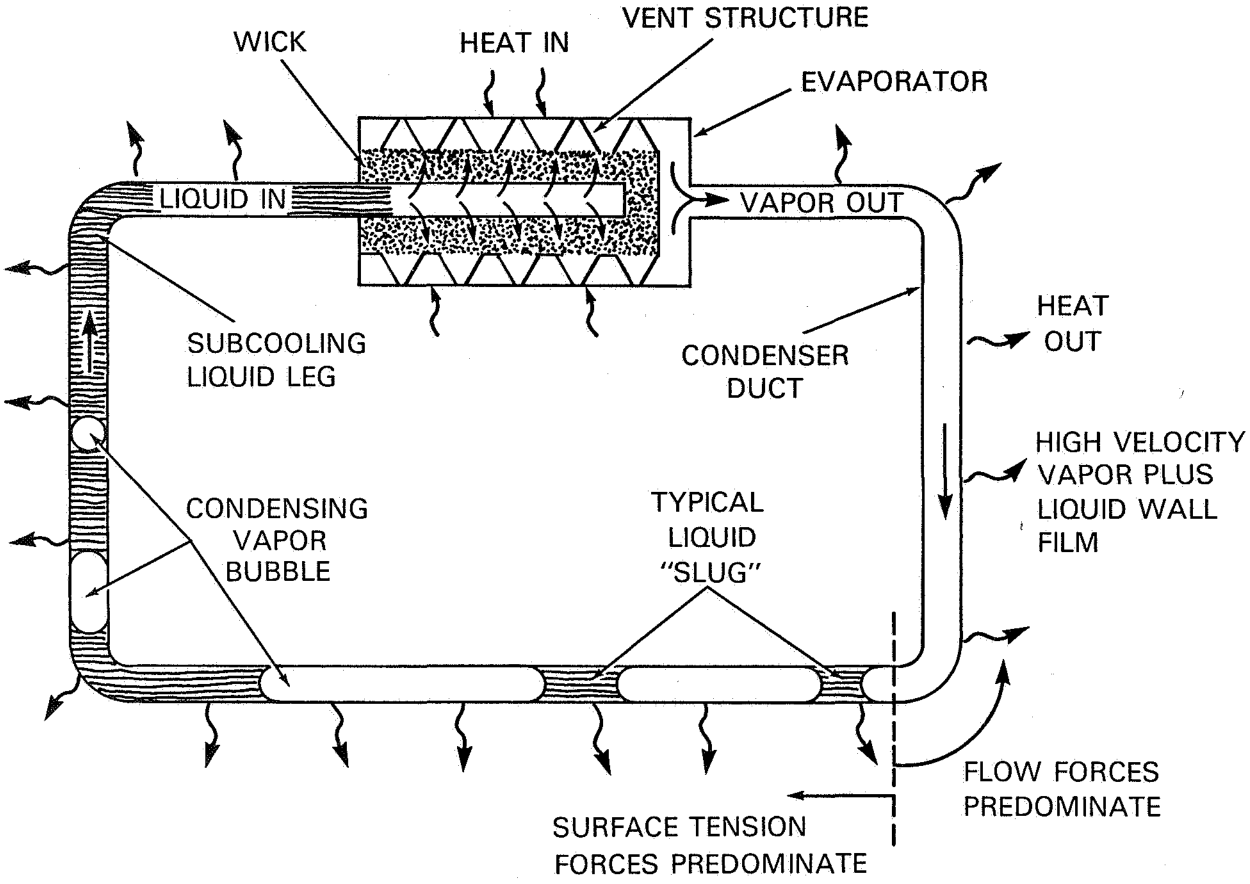

Figure 1. Model of a Capillary Pumped Heat Transfer Loop

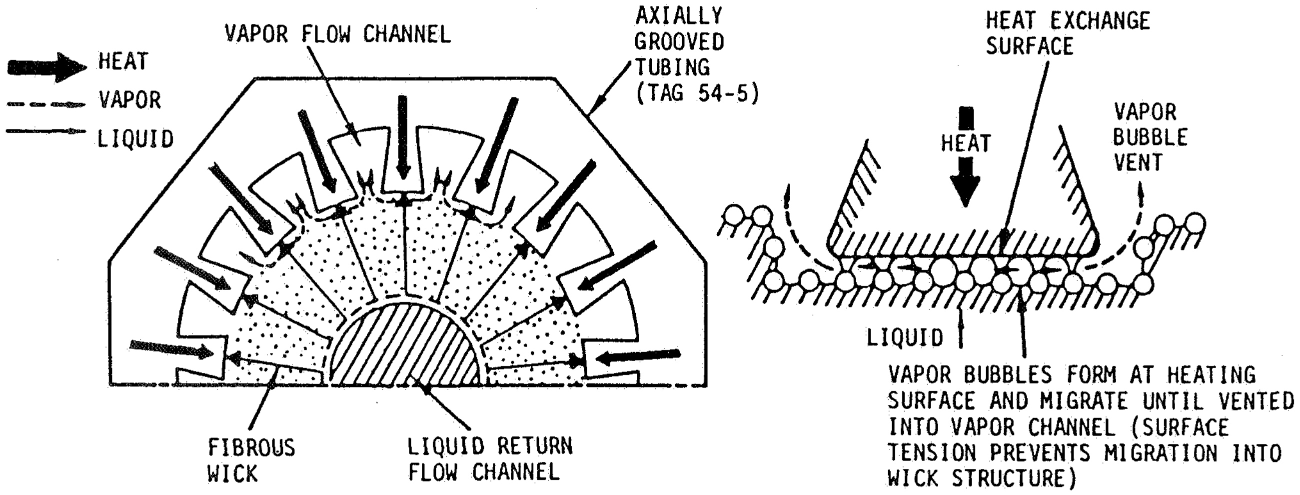

Figure 2. Heat and Fluid Transport in CPL Evaporator

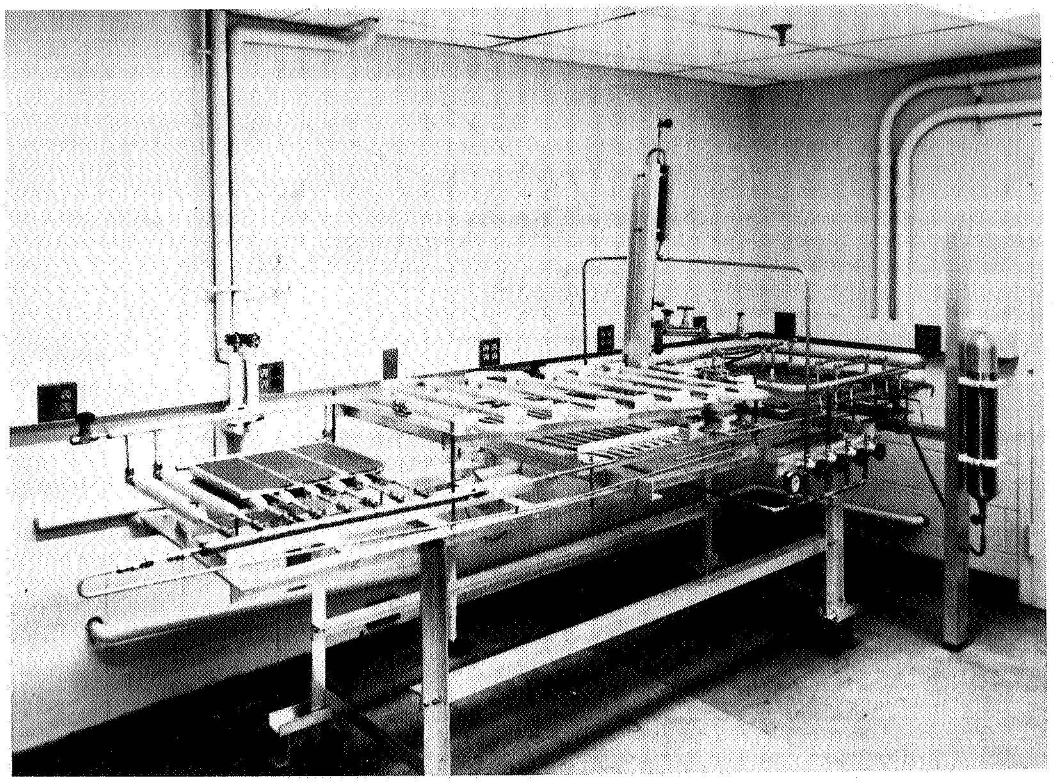

Figure 3

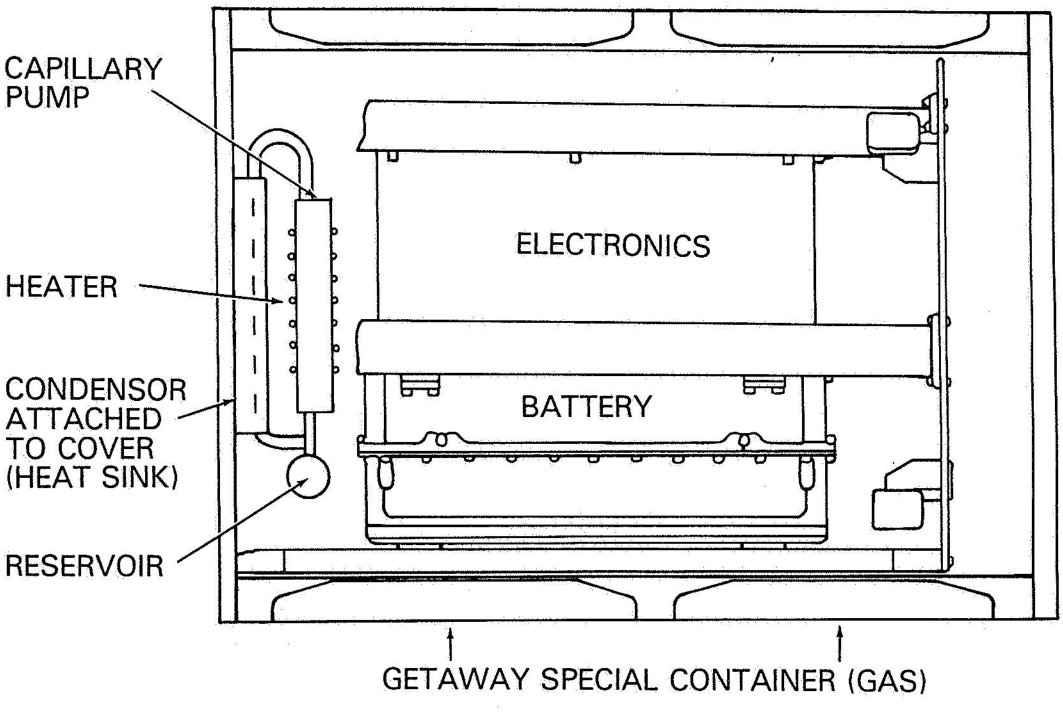

Figure 4. Capillary Pump Priming Experiment in GAS Container

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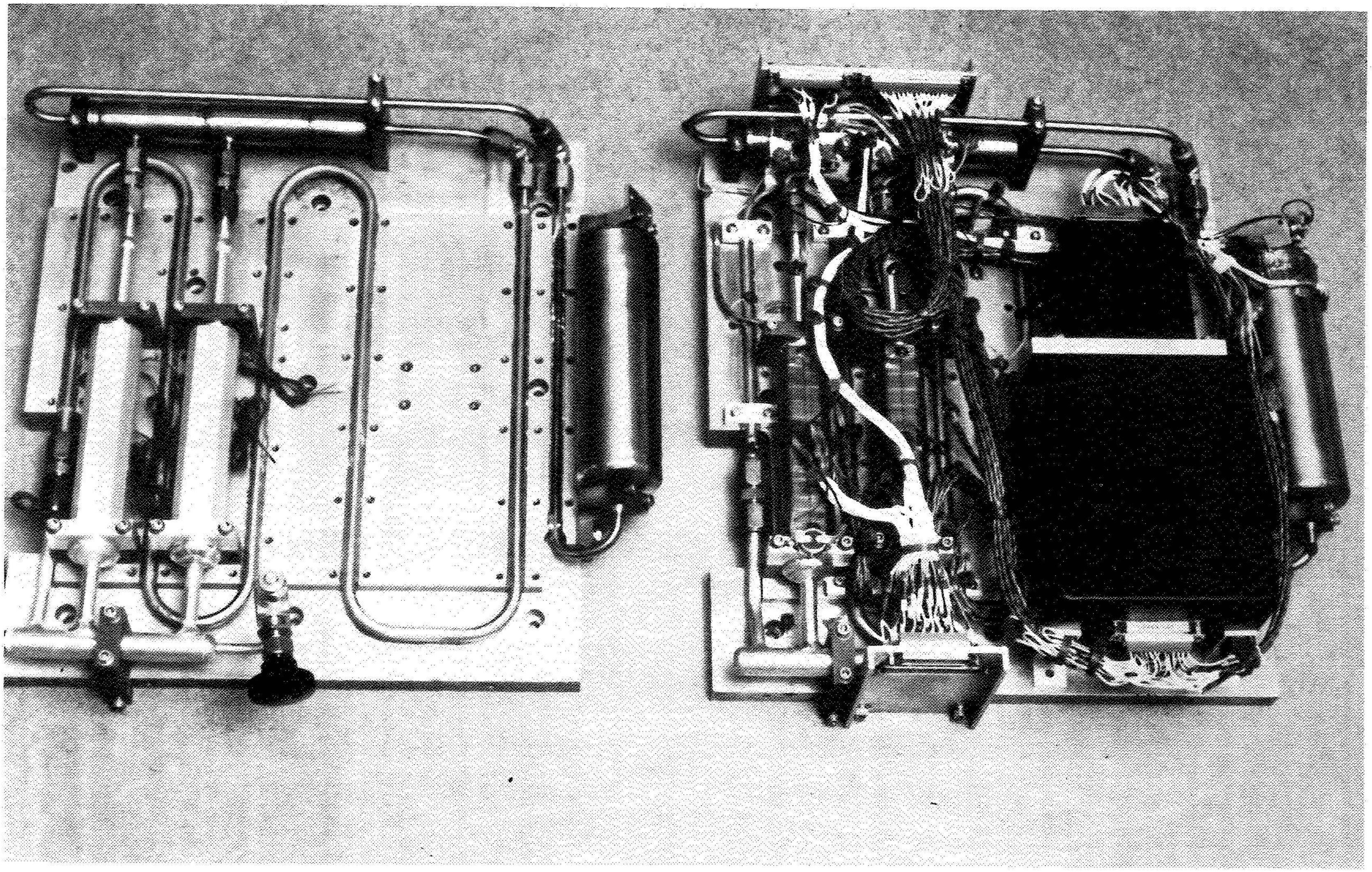

Figure 5

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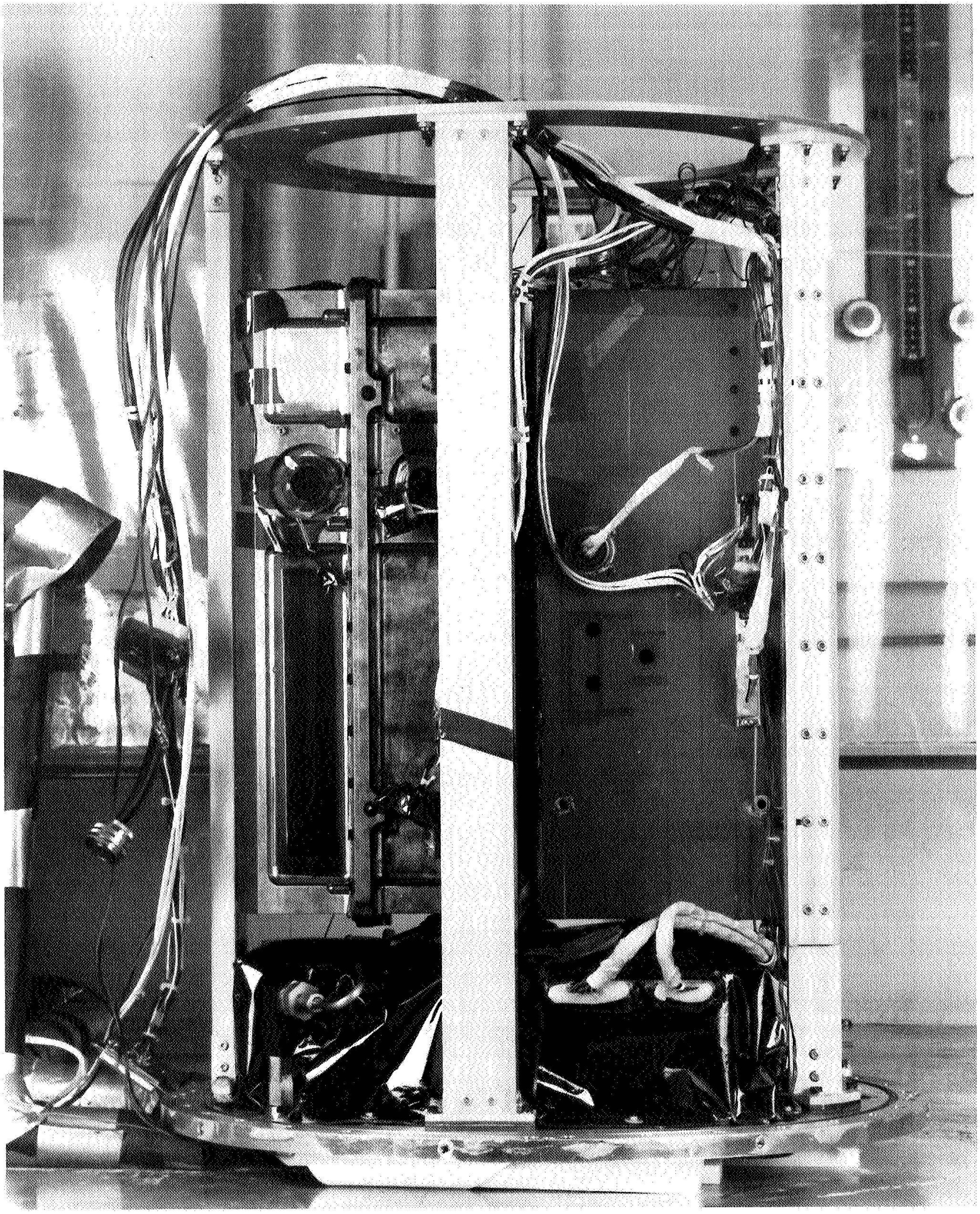

Figure 6

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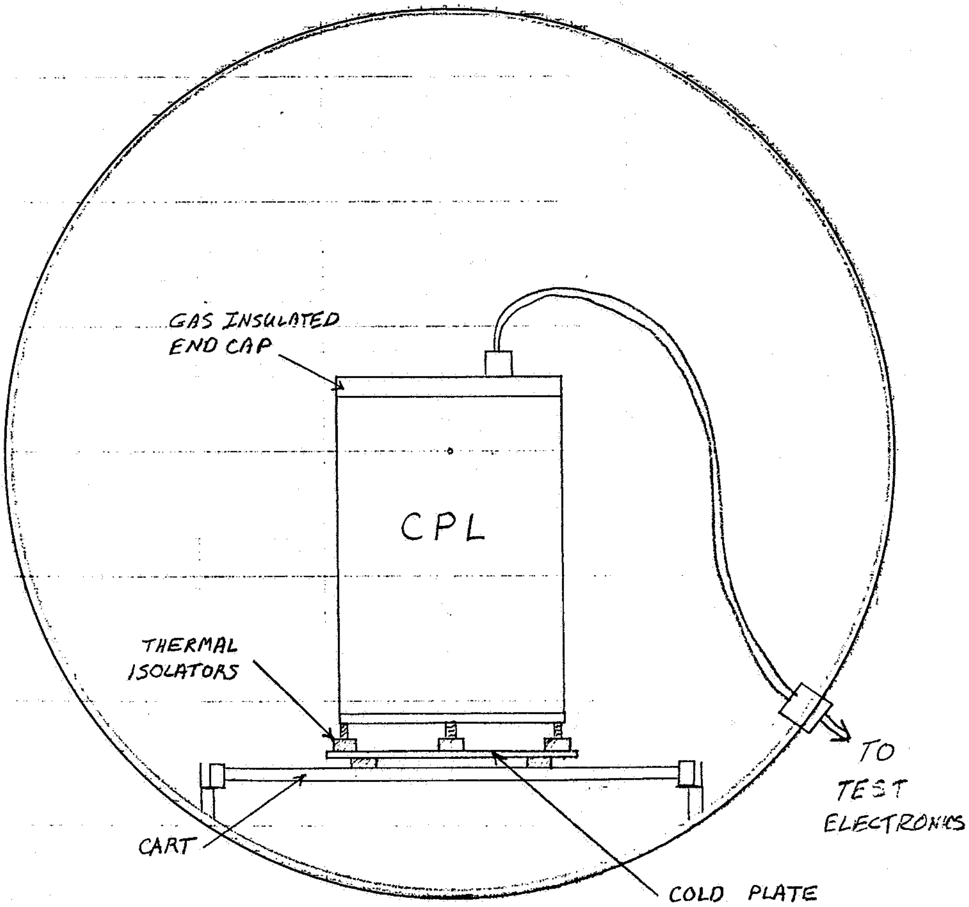

Figure 7. TV Test Set-up

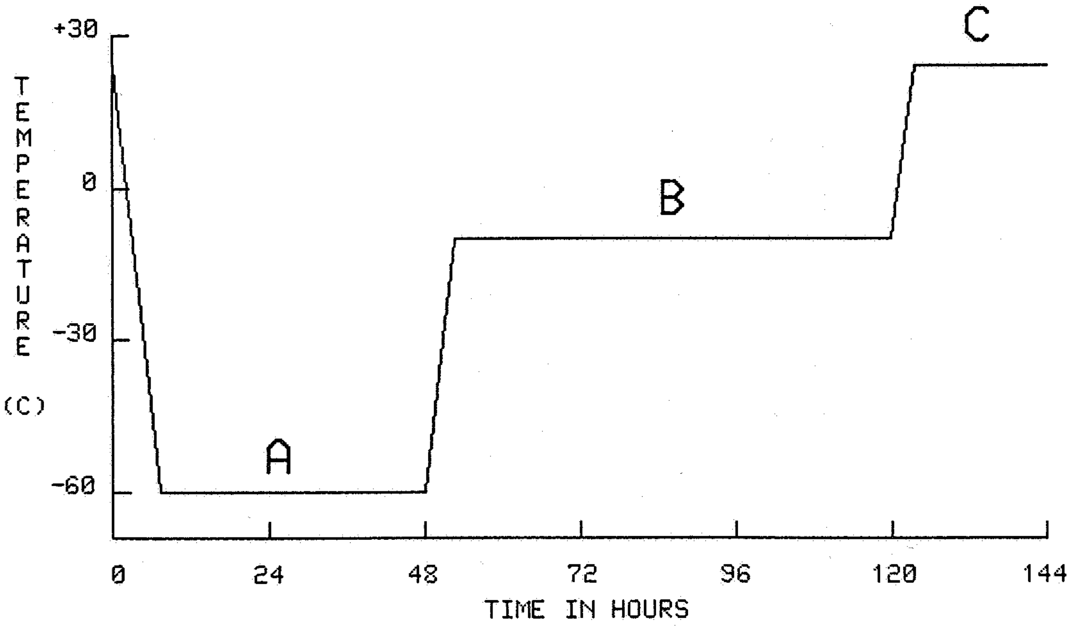

Figure 8. CPL TV and Mission Simulation

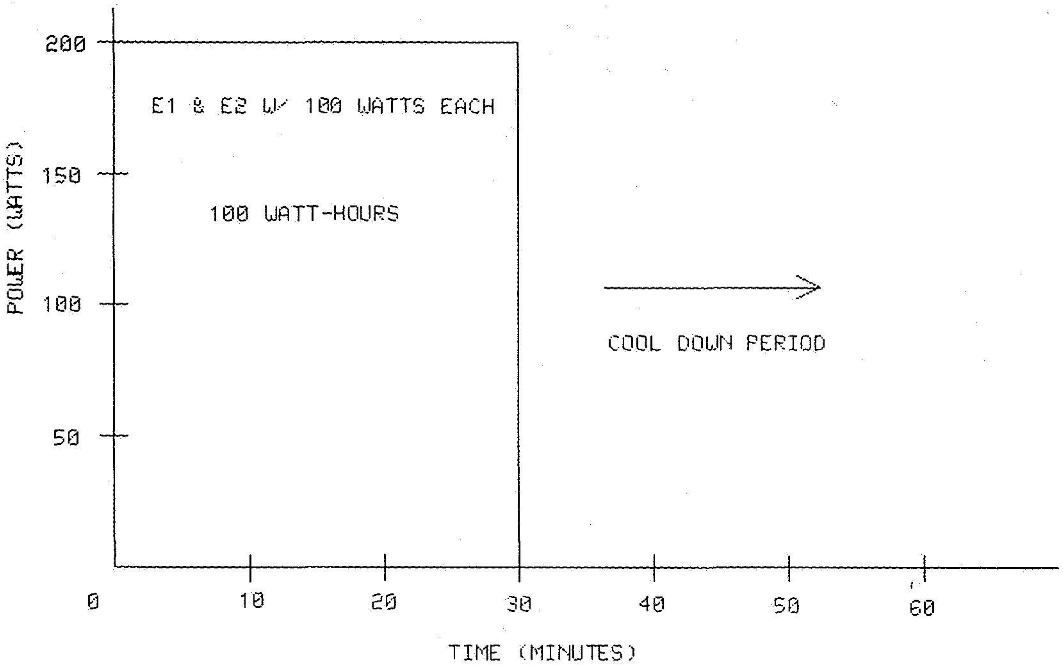

Figure 9. Cycle A (100 watt zapp)

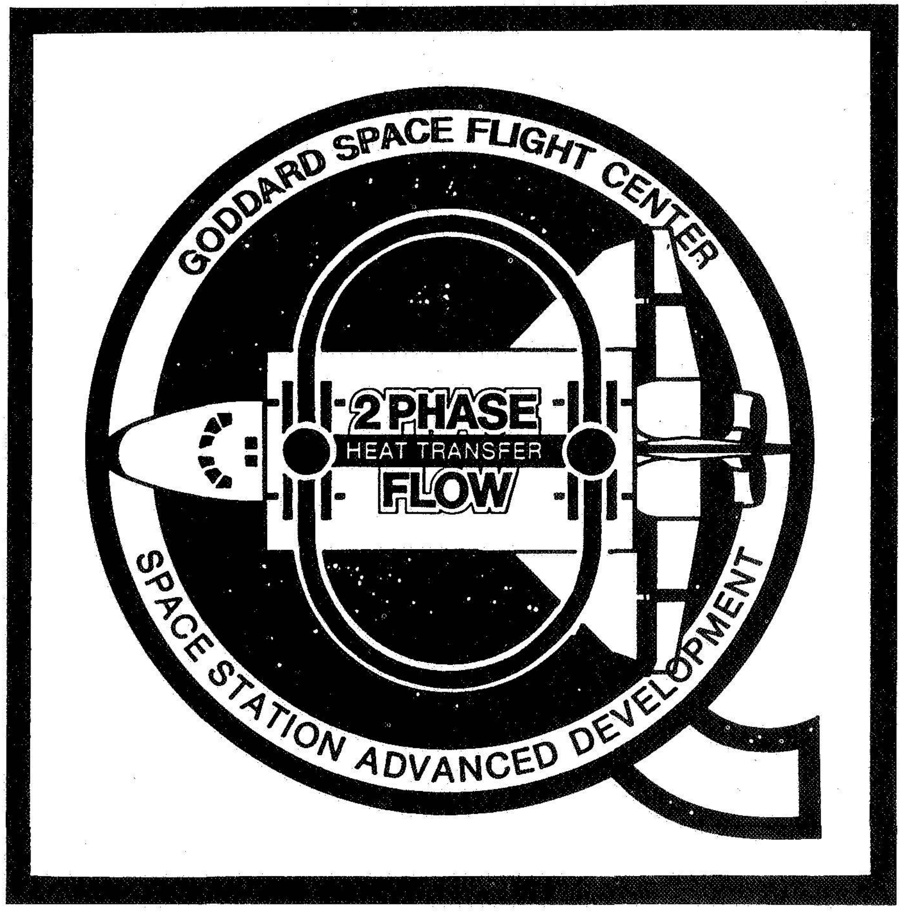

Figure 10

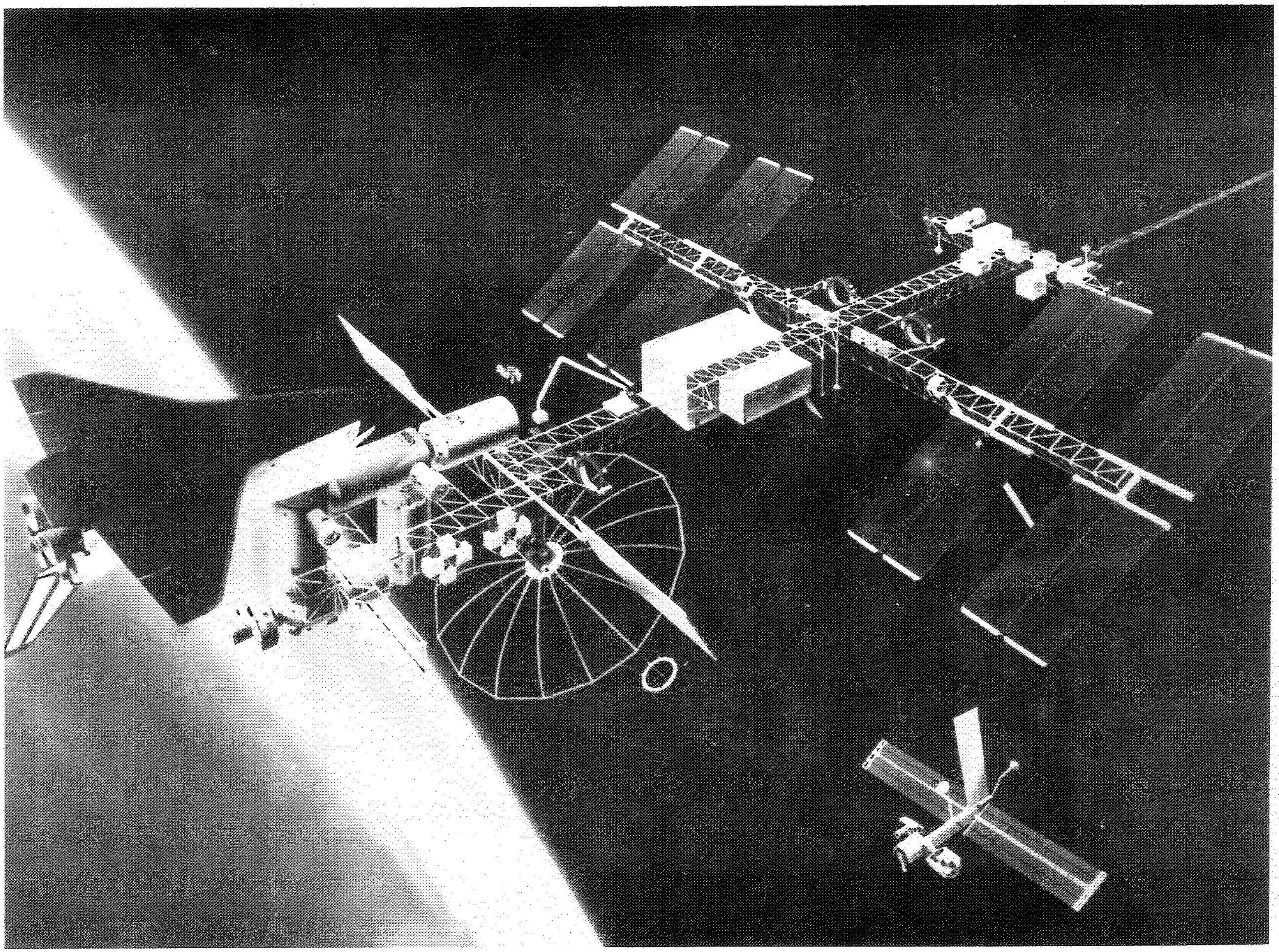

Figure 11