CRYOGENIC HEAT PIPE EXPERIMENT
CRYOHP

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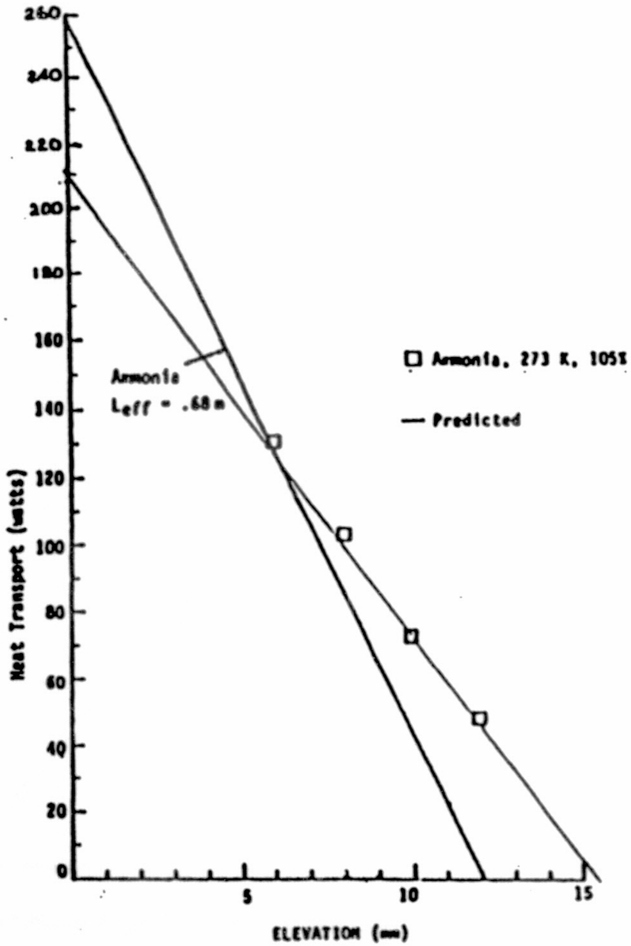
OCTOBER 5, 1992

JUSTIFICATION – HEAT PIPE TECHNOLOGY



PERFORMANCE COMPARISON BETWEEN
PREDICTIONS AND DATA (REF.: AIAA 77-747)

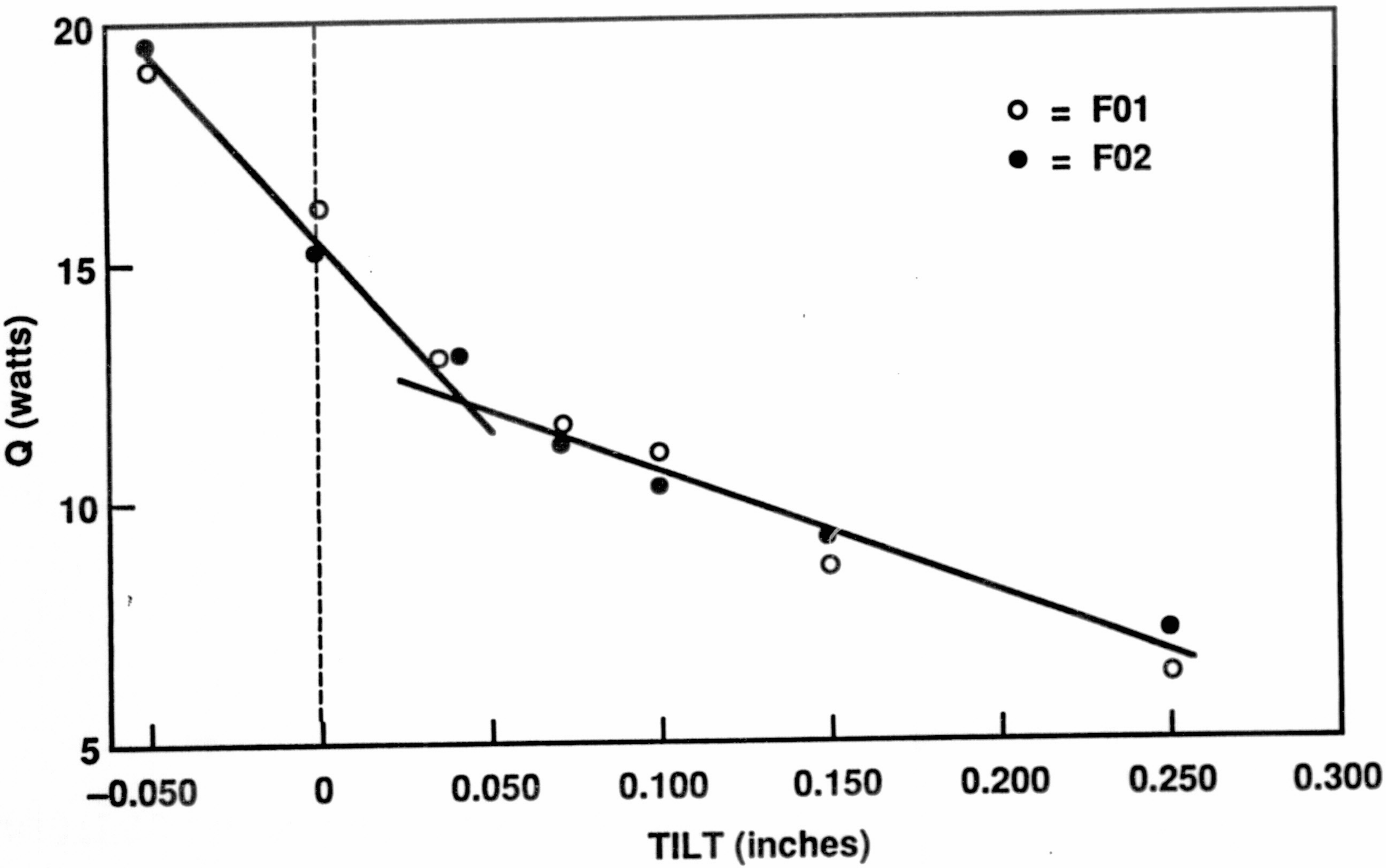
HUGHES

INVESTIGATION OF MICRO-GRAVITY EFFECTS ON HEAT PIPE THERMAL PERFORMANCE AND WORKING FLUID BEHAVIOR (IMEHP)

NASA IN-STEP HEAT PIPE PERFORMANCE (HPP)

40°C FREON HEAT PIPE GROUND TEST DATA

HUGHES



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IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

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OBJECTIVES – SYSTEM LEVEL

- HOW DOES EXCESS LIQUID IN HEAT PIPES AFFECT SPACECRAFT THERMAL PERFORMANCE
- HOW DO SPACECRAFT ACCELERATIONS BETWEEN 0 AND 1-g AFFECT HEAT PIPE PERFORMANCE
- OBTAIN DATA FOR DESIGN IMPROVEMENTS IN SPACE HEAT PIPES:
  - LIGHTER WEIGHT, RELIABLE, AND MORE EFFICIENT SYSTEMS
  - HANDLING EXCESS LIQUID
  - START-UP AND REWICKING IN SPACE

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IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HUGHES

TYPICAL SPACECRAFT ACCELERATIONS BETWEEN 0 AND 1-G:

- RENDEZVOUS AND DOCKING
- ASCENT/DESCENT
- ORBITAL MANEUVERING
- LUNAR BASE OR MARS MISSION
- SPINNING/DE-SPINNING
  - SPINNING S/C (e.g., INTERNATIONAL SOLAR TERRESTRIAL PLATFORM, ISTP–8 FT DIA. x 10 RPM)
  - STABILIZATION (TRANSFER ORBIT, GEO-SYNCHRONOUS)
  - SURVEILLANCE
  - HARDENING
- THREAT AVOIDANCE
  - SPACE DEBRIS
  - MILITARY

V02425

IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HUGHES

APPROACH

- TWO (2) HEAT PIPE CONFIGURATIONS
  - FIXED CONDUCTANCE HEAT PIPES (FCHPs):

    AXIAL GROOVE DESIGN; MOST COMMON DESIGN SPECIFIED FOR COMMUNICATIONS, SURVEILLANCE, SCIENTIFIC, AND OTHER SPACECRAFT

  - VARIABLE CONDUCTANCE HEAT PIPES (VCHPs):

    POROUS WICK DESIGN; CURRENTLY BEING USED ON HUGHES HS-111 SPACECRAFT, AND PROPOSED FOR FUTURE MISSIONS

- HEAT PIPE WORKING FLUIDS/MATERIALS:
  - WATER/COPPER (16 EACH)
  - FREON – 113/ALUMINUM (2 EACH)
  - VARIOUS FILL FRACTIONS (90 TO 120 %)

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IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HUGHES

APPROACH (CONTINUED)

- THERMAL PERFORMANCE
  - STATIC
  - SPIN
  - REWICKING

IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

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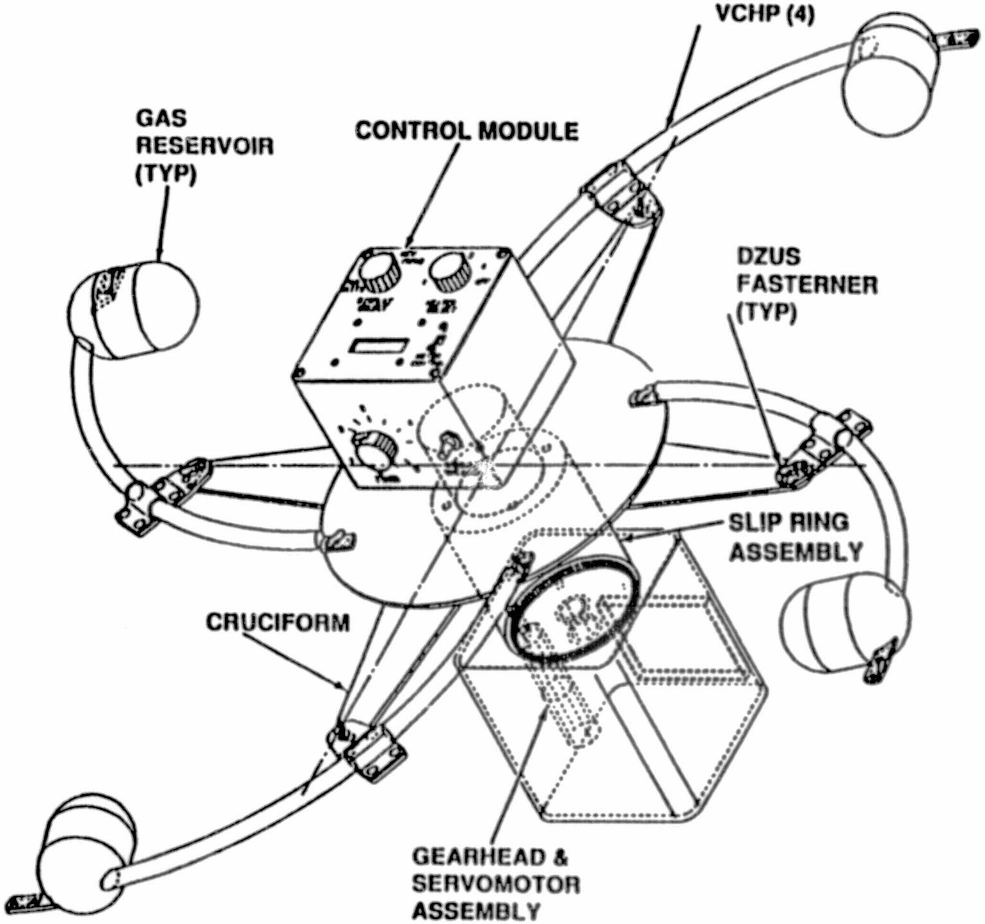

THERMAL PERFORMANCE MODEL

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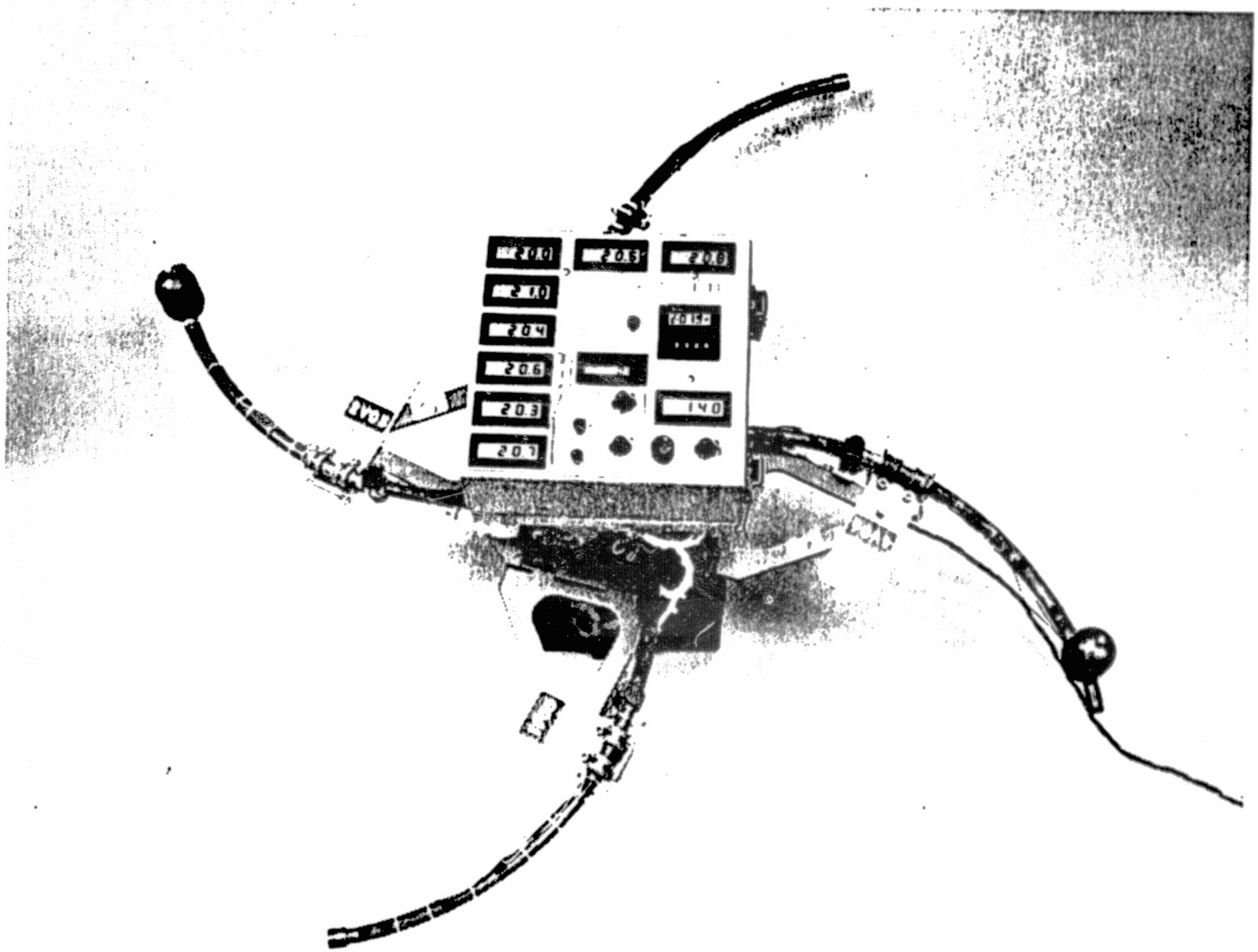
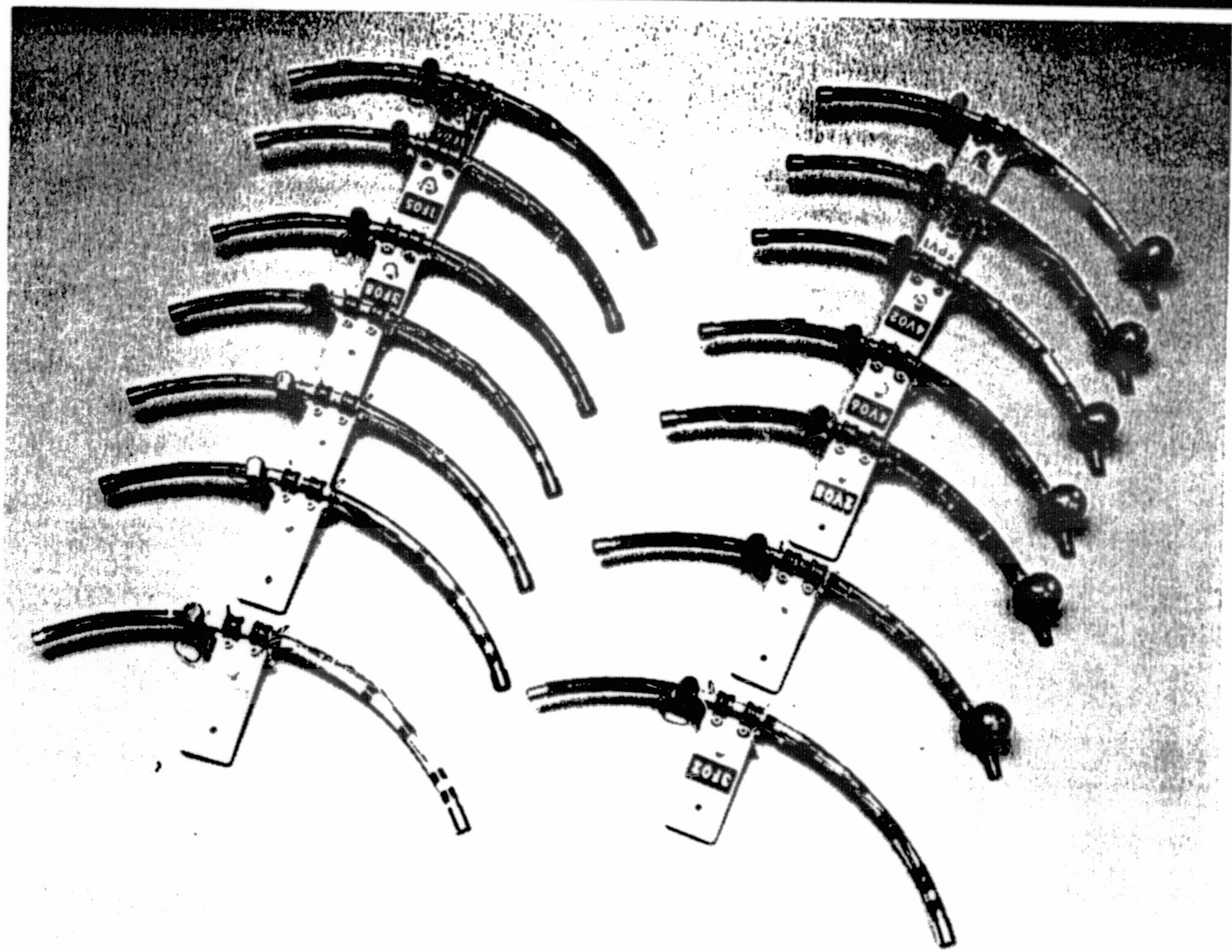
NASA IN-STEP HEAT PIPE PERFORMANCE (HPP) FLIGHT EXPERIMENT APPARATUS (WITHOUT SHROUD)

HUGHES



NASA IN-STEP HEAT PIPE PERFORMANCE (HPP) FLIGHT HEAT PIPES

HUGHES



NASA IN-STEP HEAT PIPE PERFORMANCE (HPP)
FLIGHT EXPERIMENT APPARATUS

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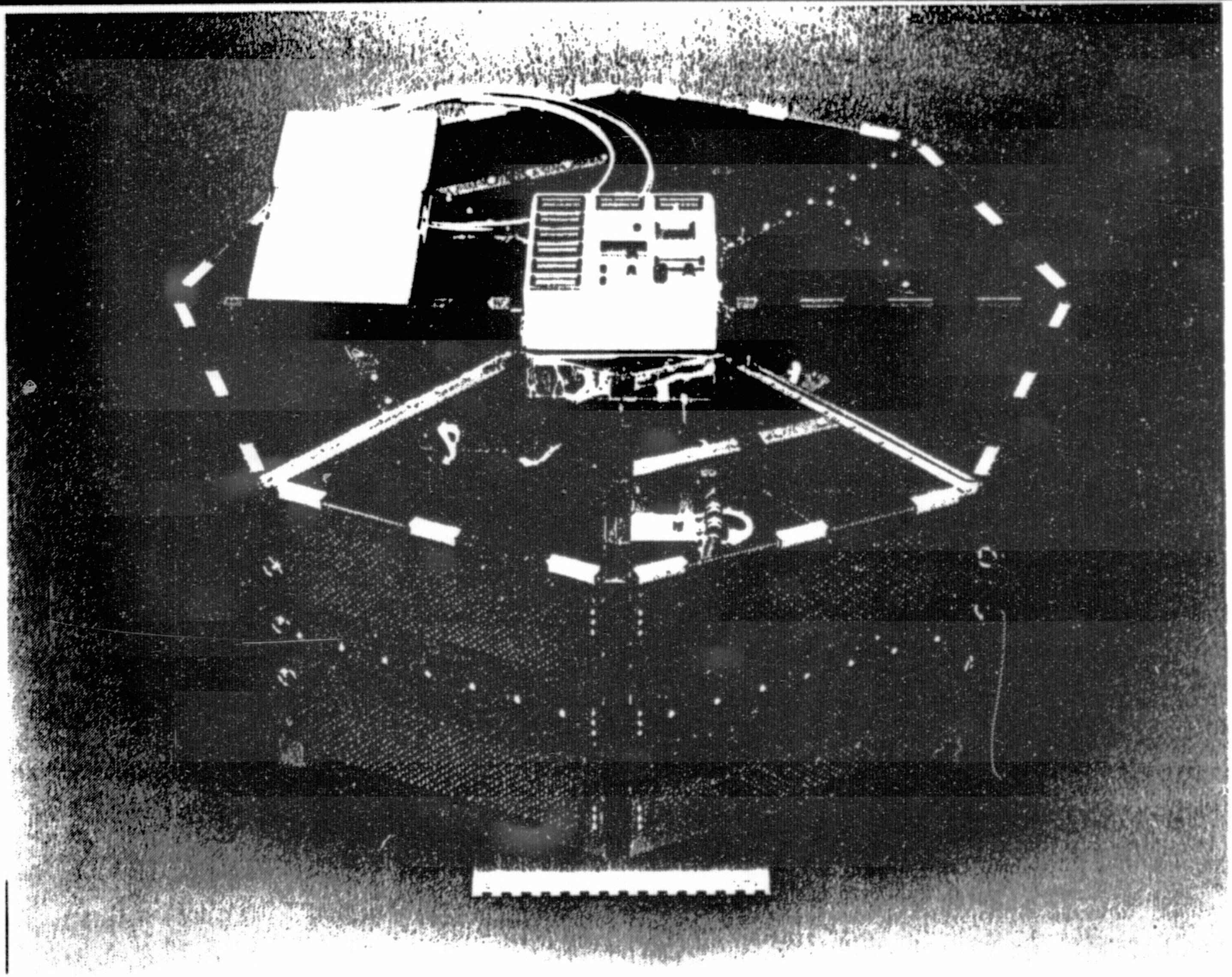

IN-STEP HEAT PIPE PERFORMANCE (HPP)

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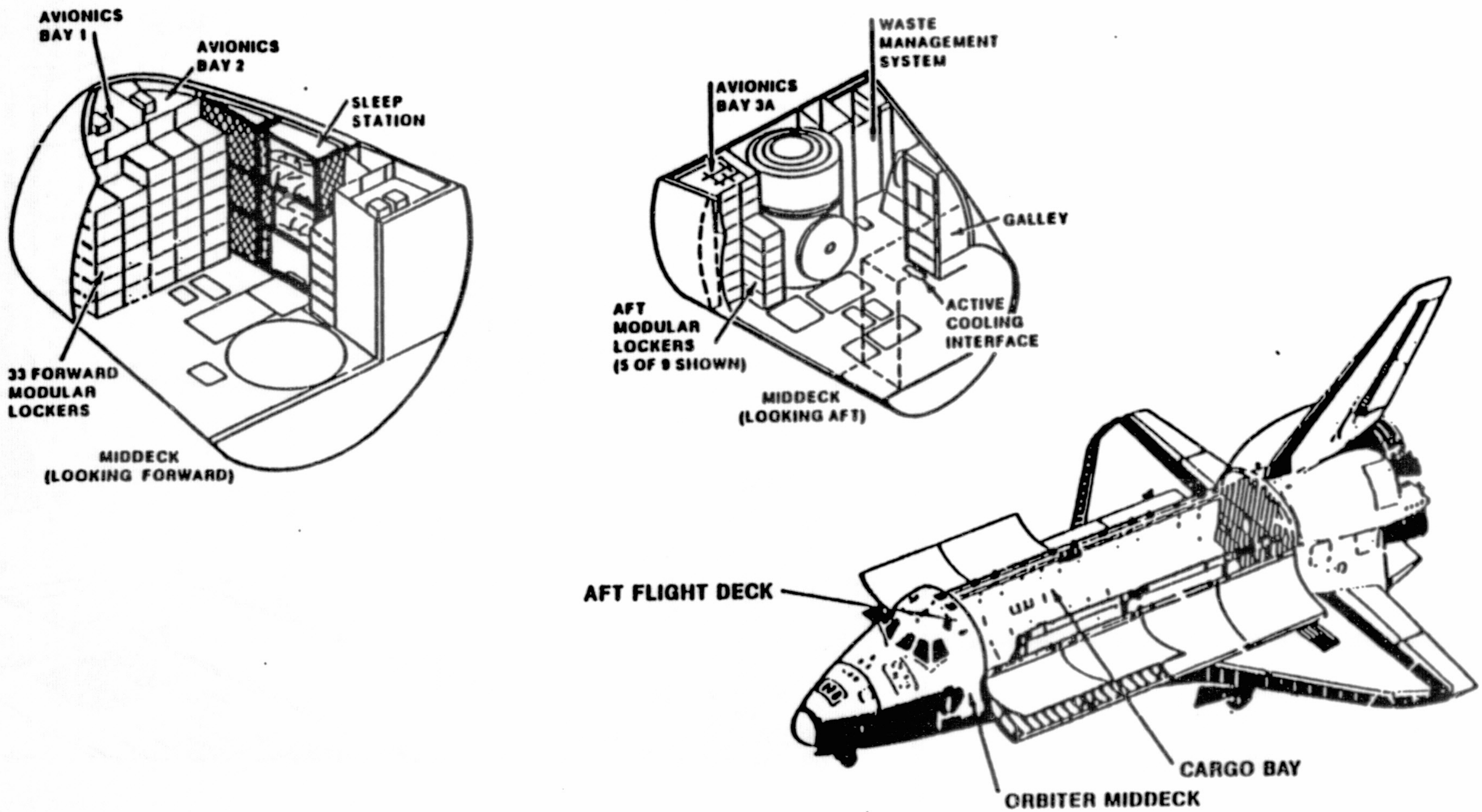
NSTS Shuttle Orbiter Middeck Configuration



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IN-STEP HEAT PIPE PERFORMANCE (HPP)

MIDDECK MODULAR LOCKERS

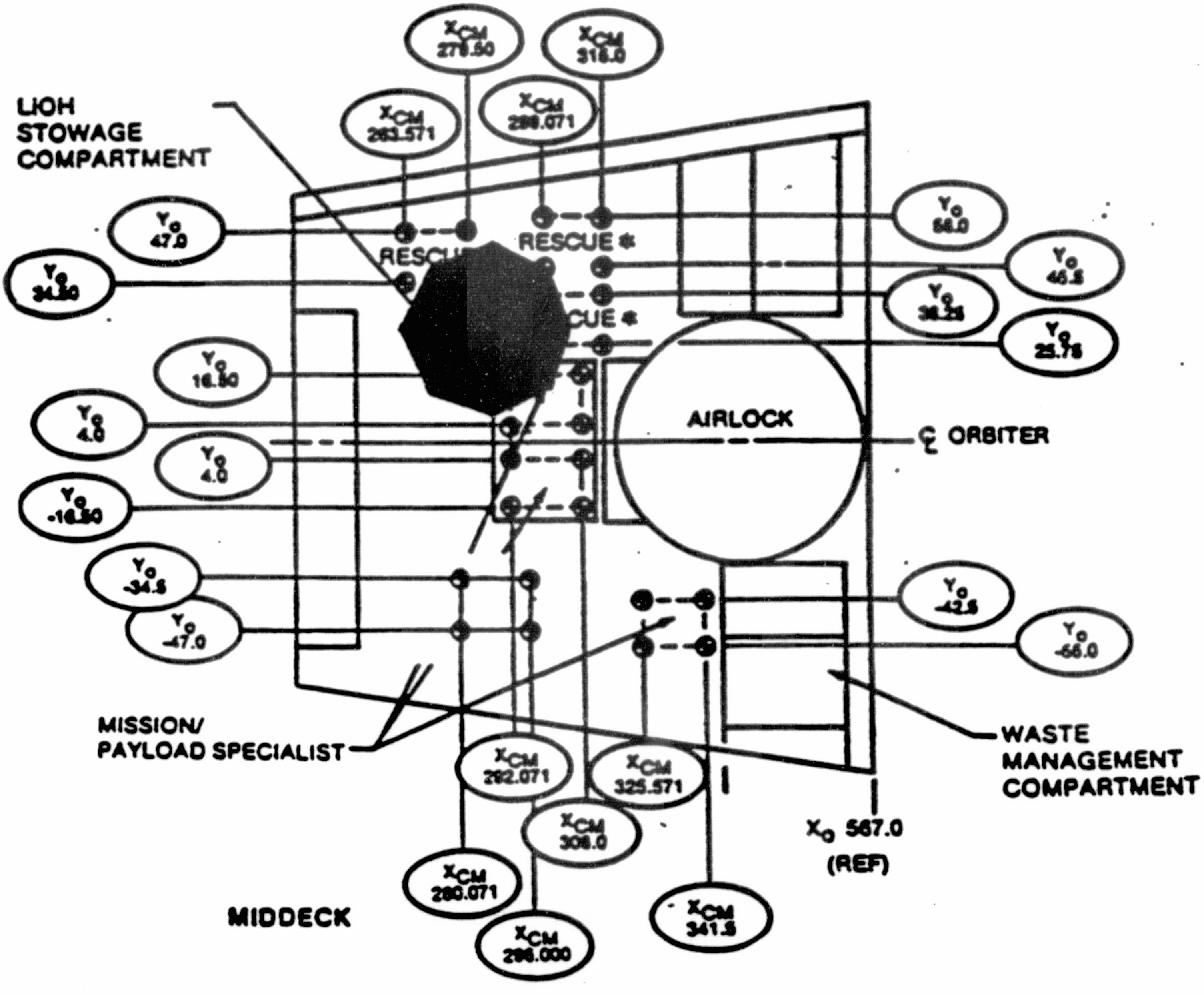
Heat Pipe Performance Experiment
Weight and Power Summary

Item	Quantity	Weight (lbs)	Orbital Power (watts)
Heat Pipe, Warmers,* and Thermostats**	14	10.9	<60.0
Control/Motor Module	1	27.7	<32.0
Safety Shroud, Quarter Pieces with Brownline Fittings	1	27.8	
Data Loggers and Cables	2 ea	9.4	
Batteries, Data Logger (Spares)	4	4.0	
HPP Tool Kit***	1	~5.0	
Crowmember Deerskin Gloves	1 pr	0.25	
DC Power Cables	1	~1.0	
35mm Film, Kodak 5017	2	0.41	
VIU with Cables	1	2.71	
Video Camcorder Assembly	1	3.3	9.6
Camcorder Videocassettes	12	2.0	
Camcorder Batteries (Spares)	8	5.0	
Total Weight		99.2	
Total Power			<103.6

*One (1) per heat pipe.
**Two (2) per heat pipe warmer.
***Includes spare circuit board interface assembly and motor amplifier board assembly.

Table 2. NASA Supplied Equipment Flown in HPP Lockers

Item	JSC Part No.	Qty	Usage
1. Video Camera	SED33103370-301	1	Video Recording
2. Video Interface Unit	SED39121272-301	1	Camera Adapter
3. Video Cable	SED39122102-301	1	Camera Power/Signal
4. Deerskin Gloves	TBS	1 pr	Hand Protection



HPP Apparatus Mounted to Middeck Floor

STS-52 MISSION SPECIALIST
DR. T. JERNIGAN

HUGHES

HUGHES

STS-52 COMMANDER

J. WETHERBEE

IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HEAT PIPE THERMAL PERFORMANCE ANALYSIS

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- **Simple Closed Form Heat Pipe Models (Cotter's Equations):**

$$\Delta P_{cap} - \Delta P_c \geq \Delta P \;\; + \Delta P_v$$

Where:

ΔP_{cap} = Capillary Pressure Head

ΔP_c = Centrifrugal Pressure Head Due to Rotation

ΔP = Liquid Pressure Drop

ΔP_v = Vapor Pressure Drop

- **Wick Capillary Pumping Based on Eninger's Approach for Fibrous Wicks:**

$$\Delta P_{cap} = 6.36 \, \frac{(1-\varepsilon)}{\varepsilon} \, \frac{\sigma}{d_w} \, {}^{*}$$

Where:

d_w = Wire Diameter

ε = Wick Porosity

σ = Surface Tension

*AIAA Paper No. 75-661

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IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HEAT PIPE THERMAL PERFORMANCE ANALYSIS (CONTINUED)

HUGHES

- **Wick Pressure Drop Based on Darcy's Equation:**

$$\Delta P_\ell = \frac{\mu_\ell Q L_{eff}}{K_w A_w h_{fg} \rho_\ell}$$

Where: $K_w = \frac{d_w^2}{122} \frac{\varepsilon^3}{(1-\varepsilon)^2}$

K_w = Wick Permeability

μ_ℓ = Liquid Viscosity

h_{fg} = Latent Heat of Working Fluid

Q = Heat Transport

L_{eff} = Effective Heat Pipe Length

- **Groove and Vapor Pressure Drops Based on Channel Flow:**

$$\Delta P_{cap} = \frac{2\sigma}{w_g}$$

w_g = Groove Width

$$\Delta P_{\ell,v} = \frac{2\,(fRe)_{\ell,v}\,\mu_{\ell,v}\,Q L_{eff}}{(d_h^2)_{\ell,v} A_{\ell,v} \rho_{\ell,v} h_{fg}}$$

fRe = Constant (Laminar Flow)

$d_h = \frac{4A}{P_w}$

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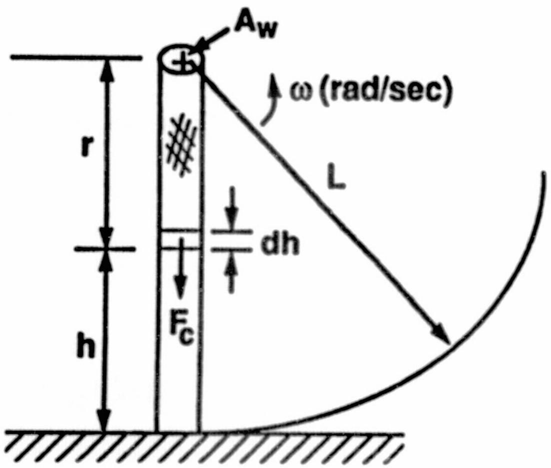
Centrifugal Force Due to Spinning:



- r = Radius About Axis of Rotation
- L = Heat Pipe Length
- A_w = Wick Cross-Sectional Area
- ρ = Liquid Density
- ω = Angular Velocity

Centrifugal Force (F_c) on Element at Radius, r:

$$dF_c = r\,\omega^2 dm$$
$$dF_c = \rho\,\omega^2 r\,A_w\,dh$$

Pressure Drop at Radius, r, Due to Centrifugal Force on Element:

$$\frac{dF}{A_w} = dp = \rho\,\omega^2 r\,dh$$
$$r = L - h$$
$$dp = \rho\,\omega^2 (L-h)\,dh$$

Pressure Drop at Radius, r, Due to Centrifugal Force on Liquid column of Length, h:

$$\Delta P_c = \rho\,\omega^2 \int_o^h (L-h)\,dh$$
$$\Delta P_c = \rho\,\omega^2 h\left(L - \frac{h}{2}\right)$$

IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT
HEAT PIPE THERMAL PERFORMANCE ANALYSIS

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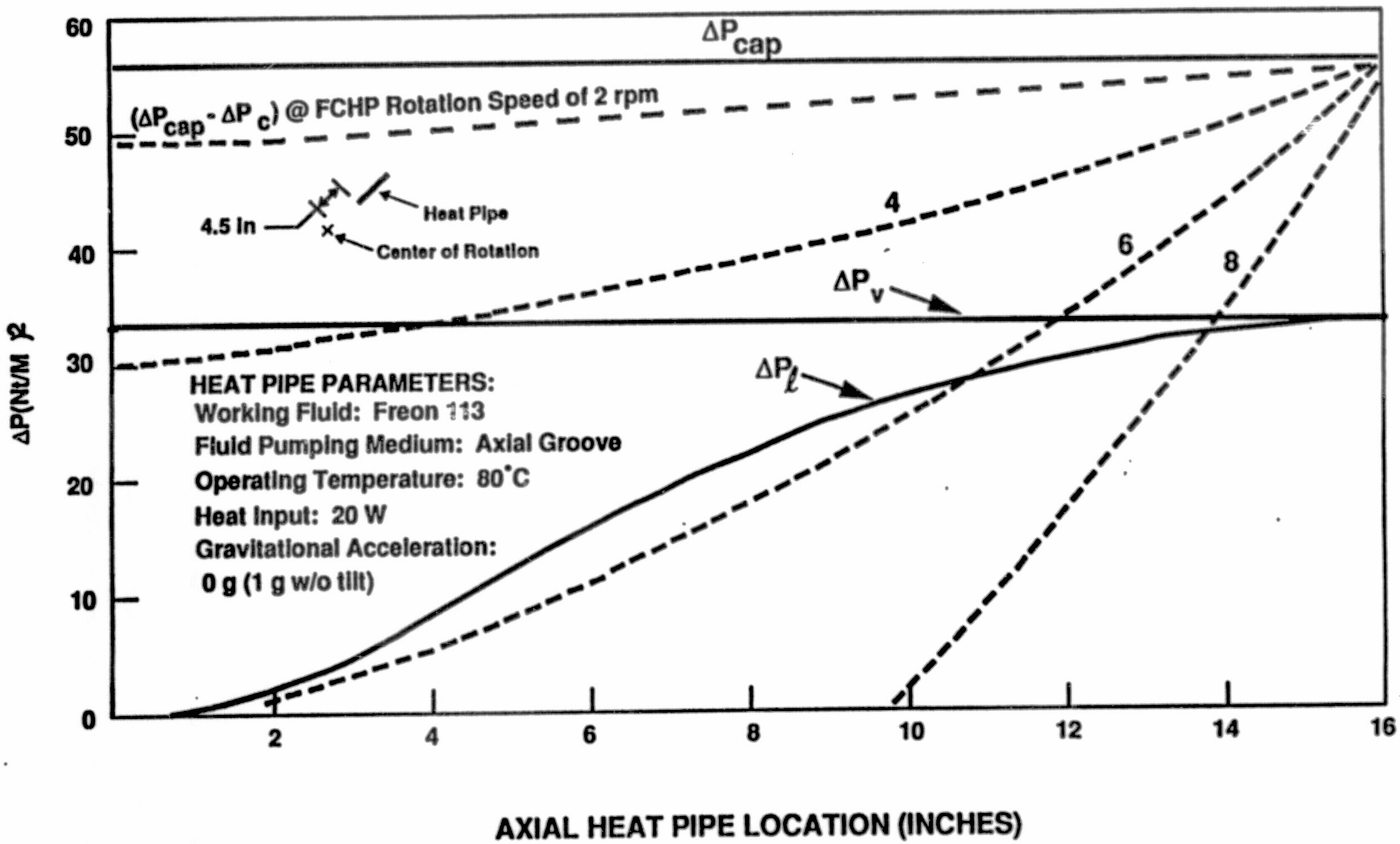
PRESSURE HEAD DIFFERENTIAL ARISING FROM FCHP ROTATION



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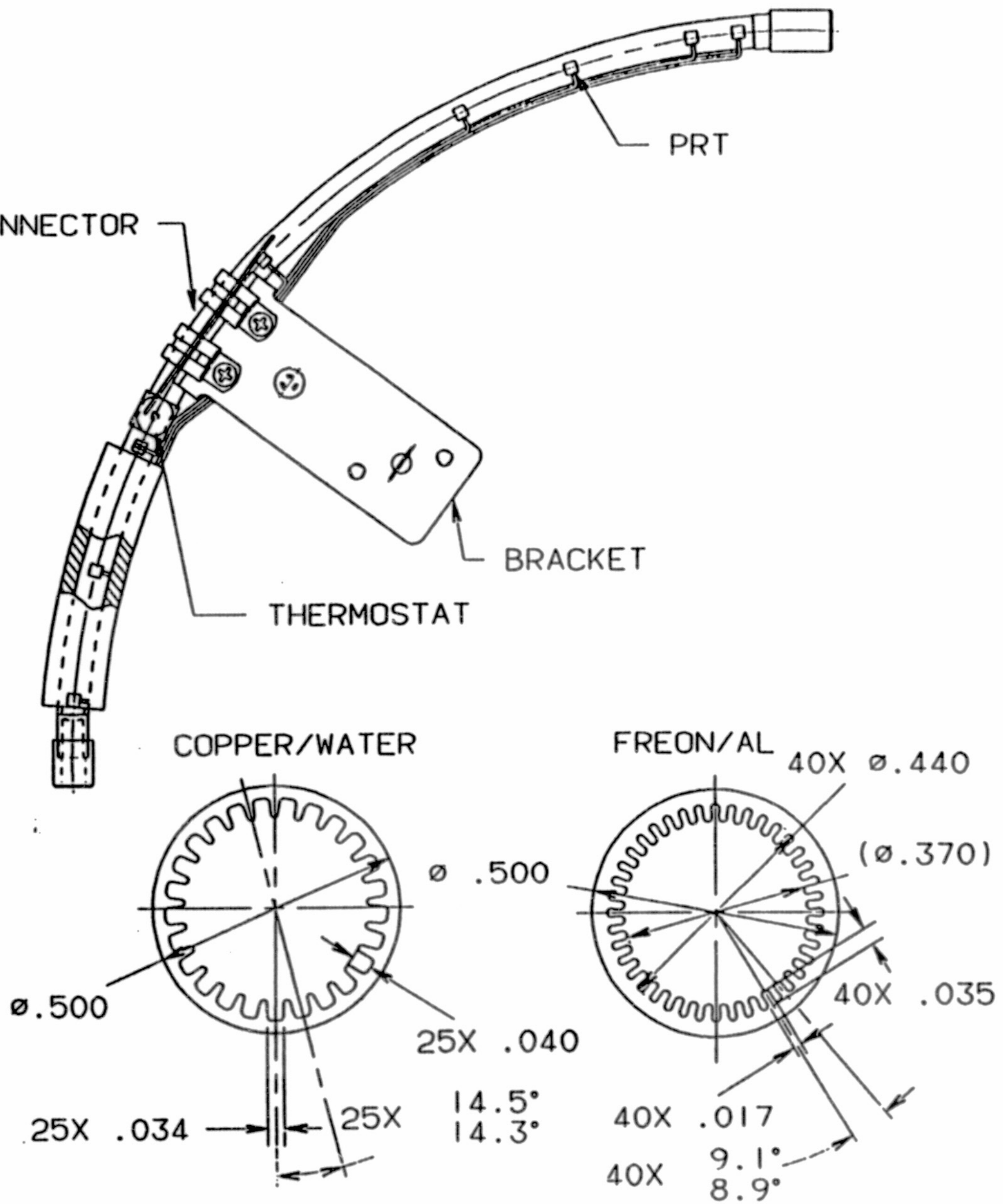
Description of Experimental Pipes

Item	Fixed Conductance Heat Pipes (FCHPs)		Variable Conductance Heat Pipes (VCHPs)
	Copper - Water	Aluminum - Freon	
Envelope:			
Outside Diameter (in.)	0.50	0.50	0.50
Wall Thickness (in.)	0.020	0.030	0.020
Active Length (in.)	17.0	17.0	17.0
Gas Reservoir	None	None	1.5 OD x 2.5*
Material	OFE Copper	6063-T6 Aluminum	OFE Copper
Wick:			
Description	25 axial grooves electro-discharge machined in envelop wall	40 axial grooves extruded in envelop wall.	80% porosity knitted mesh center core wick with three 70% porosity spacer wicks; 1-layer #100 mesh evaporator wall wick.
Dimension (in.)	0.040 depth 0.034 width	0.035 depth x 0.017 width	0.34 dia. center core; 0.090 square spacers
Material	N/A	N/A	Copper
Working Fluid	Triply Distilled Water	Freon-113	Triply Distilled Water
Nominal Fluid (gm)	7.7	8.8	23.2
Liquid Fill Fractions (%)	90,100,105	100	90,100,120
Weight per pipe, dry (lbm)	0.32	0.15	0.56
Quantity (Flight)	6	2	6

* Two (2) VCHPs will have non-condensible gas and four (4) will not. Reservoir has hemispherical end caps.



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NASA IN-STEP HEAT PIPE PERFORMANCE (HPP)

FIXED CONDUCTANCE HEAT PIPE

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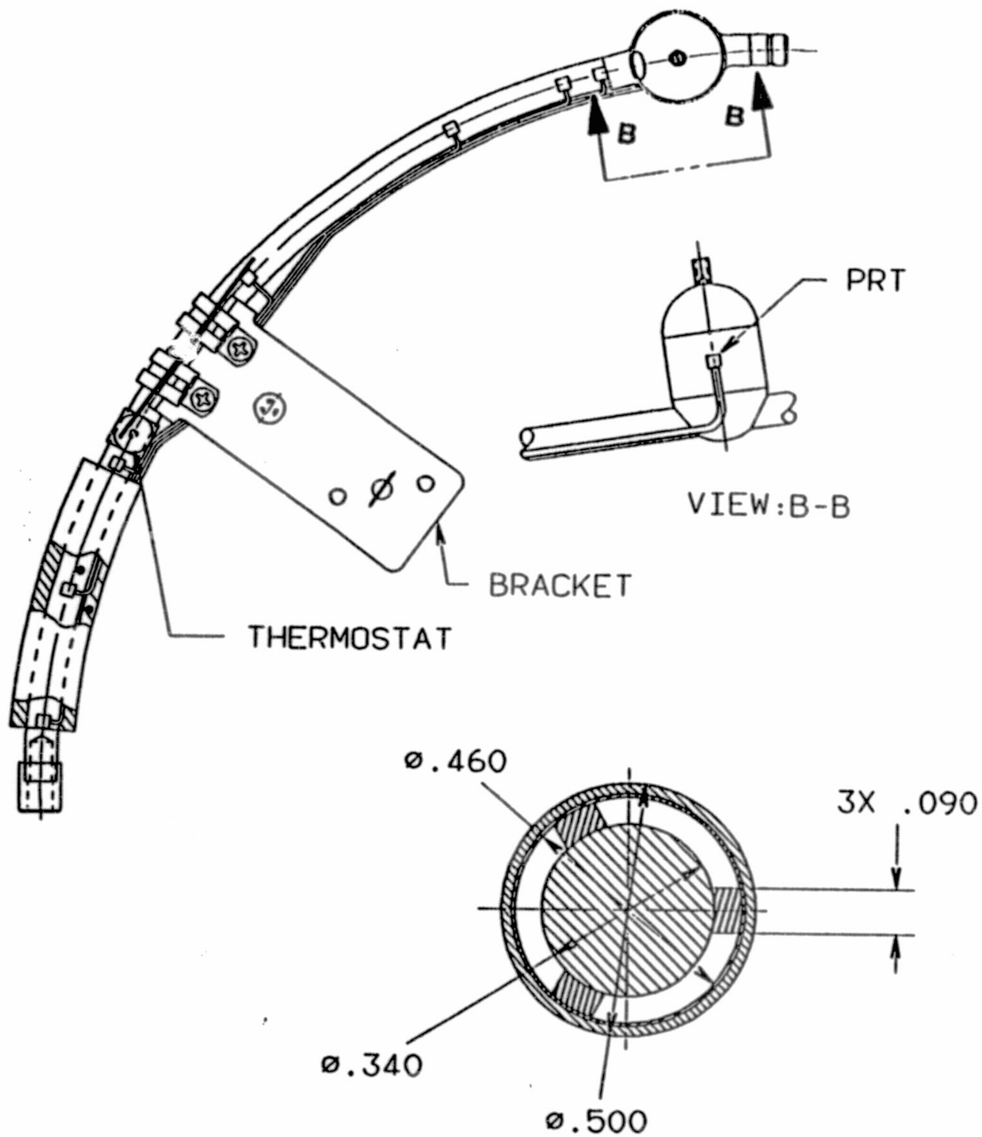

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NASA IN-STEP HEAT PIPE PERFORMANCE (HPP)

VARIABLE CONDUCTANCE HEAT PIPE

Heat Pipe Pressure Characteristics

	Nominal Operating Pressure (PSIA) at 65°C	Maximum Design Pressure (PSIA) at 85°C*	Minimum Required Burst Pressure (PSIA)**	Calculated Burst Pressure (PSIA)	Safety Factor ***	Proof Pressure (PSIG)	Qty.
FCHP Freon 113/ Al 6063-T6	24.7	44.7	111.8	1149	26.	223.5	2
FCHP Water/ Copper	3.6	8.4	21.0	1667	198	42.0	6
VCHP Water/ Copper	3.6	8.4	21.0	1129	134	42.0	6

* *This pressure results from the temperature corresponding to the worst-case two-failure condition.*

** *This pressure corresponds to the MDP with a safety factor of 2.5*

*** *Based on the temperature corresponding to MDP (i.e. SF = calculated burst pressure/MDP)*

NASA IN-STEP HEAT PIPE PERFORMANCE (HPP) COMPONENT STRESS ANALYSIS SUMMARY

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Component	Material	Max. Stress (kPa)	Ult. Stress (kPa)	Factor of Safety
Motor Mount				
Screw A	Steel	30.3	517	17.1
Screw B Mount	Aluminum	3.69	75.8	20.6
Screw C	Steel	120	517	4.3
Heat Pipe Bracket DZUS Fastener	Steel	4.44	317	71.6
Cruciform Arm Hinge Pin (2)	Steel	6.25	317	50.7
Fan Blade	Steel	21.7	193	8.9
Safety Shroud	Lexan	43.1	65.5	1.5

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HPP EXPERIMENT FEATURES
PAYLOAD INTEGRATION

HUGHES

- **Mechanical Integration**
  - Modular Design Facilitates Assembly and Stowage (Nominal and Emergency)
  - Hardware Stows in Three Middeck Locker Drawers
  - HPP Complies with NSTS 21000-IDD-MDK Weight and c.g. Requirements
  - Total HPP Weight: 99.2 lbs (36 lbs Maximum in Single Locker)

- **Electrical Integration**
  - Total Orbiter DC Electrical Power Used by HPP: 104 Watts (Maximum)
  - Fuse (5 amp) at Payload/Orbiter Interface Protects Against HPP Failure
  - SSP-Provided Power Cord (15 ft Length) Connects HPP to Orbiter
  - Relay Prevents Inadvertant Activation Upon Power Cord Connection

HPP EXPERIMENT FEATURES
THERMAL, MECHANICAL DESIGN

HUGHES

- **Thermal Design Features**
  - Redundant Thermostats (Elmwood 3200) Mounted on Each Heat Pipe Preclude Overheating
  - Active Cooling Uses 35 CFM Fan (Pabst 8124 G) on Each Pipe
  - Aluminum and Lexan 9600 Safety Shround Prevents Contact with Surfaces at Elevated Temperatures (up to 85°C)

- **Mechanical Design Features**
  - Heat Pipes Incorporate Large Safety Factors ($P_{BURST}/P_{MAX} > 25$)
  - Rotating Structure Safety Factors Exceed 1.4 Ultimate
  - Collision Hazard Prevented by Safety Shroud, Internal Clutch, and Low Angular Momentum; Safety Factor Exceed 1.4 Ultimate
  - Design Contains no Fracture Critical Components as Defined by NHB8071.1 (19,307 Joules Criterion)

IN-STEP HEAT PIPE PERFORMANCE (HPP)

ELECTRICAL DESIGN

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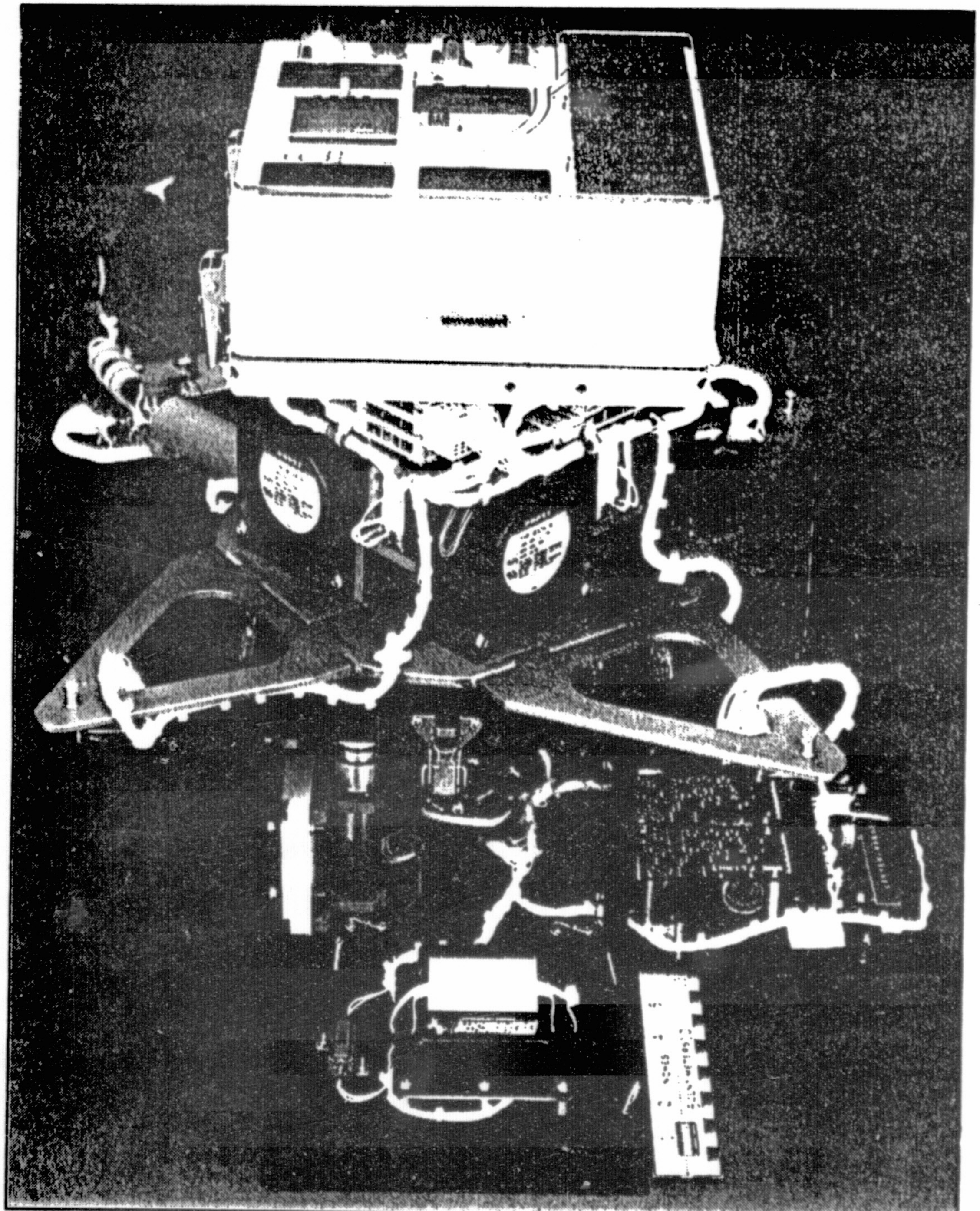
- Design Constraints
  - 115 Watt Power Limit
  - 28±4 VDC Power Supply From Spacecraft Bus
  - Specified Low Conductive and Radiative EMI
- Design Features
  - Switching Voltage Regulators Versus Analog for High Efficiency, Constant Output Regardless of Input Voltage Variation.
  - LCDs for Low Power Consumption
  - Each Controller Designed with Schottky Diode EMI Suppression
  - EMI Block Filter Installed on Input Line
  - Brushless DC Motor Used on Fans and Drive Mechanism
- Safety Features
  - Specified NASA Approved Circuit Breakers
  - Warmer/Fan Interlock
  - Dual Thermostats for Heat Pipe Over-Temperature Protection
  - Fail-Safe Start-up
  - Exclusive Operation of a Single Heat Pipe and Fan at Any Time



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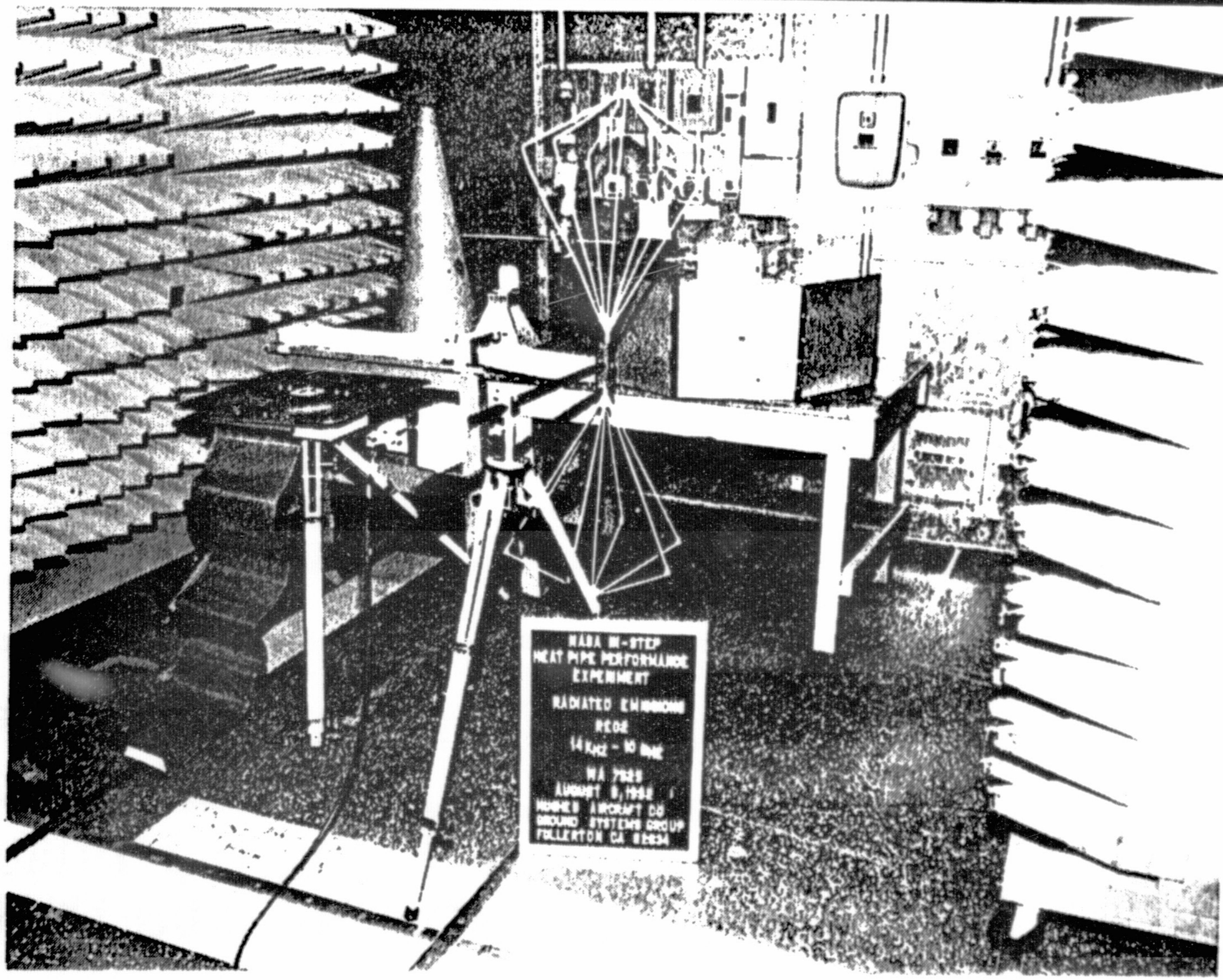
NASA IN-STEP

HEAT PIPE
PERFORMANCE
(HPP)
EXPERIMENT

CONTROL/MOTOR
MODULE

NASA IN-STEP HEAT PIPE PERFORMANCE (HPP) ELECTROMAGNETIC COMPATIBILITY TESTS

HUGHES



HEAT PIPE PERFORMANCE (HPP) THERMAL PERFORMANCE EXPERIMENT

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- Total HPP Duration is 18 Hours not Including Set-up and Restowage Time
- HPP Includes Three Types of Experimental Runs:

  1) Static Testing-at 0 RPM (no Rotation) Heat Pipes are Warmed at Increasing Power Levels Until:

     a) Dryout Occurs;

     b) 40 W Maximum Power Level is Reached; or

     c) Heat Pipe Temperature Exceeds 85° C

  2) Spin Testing-at Warmer Power of 20 to 40 W, Spin Rates are Increased Until:

     a) Dryout Occurs; or

     b) 30 RPM Spin Rate is Reached

  3) Rewicking Testing – See Next Viewgraph

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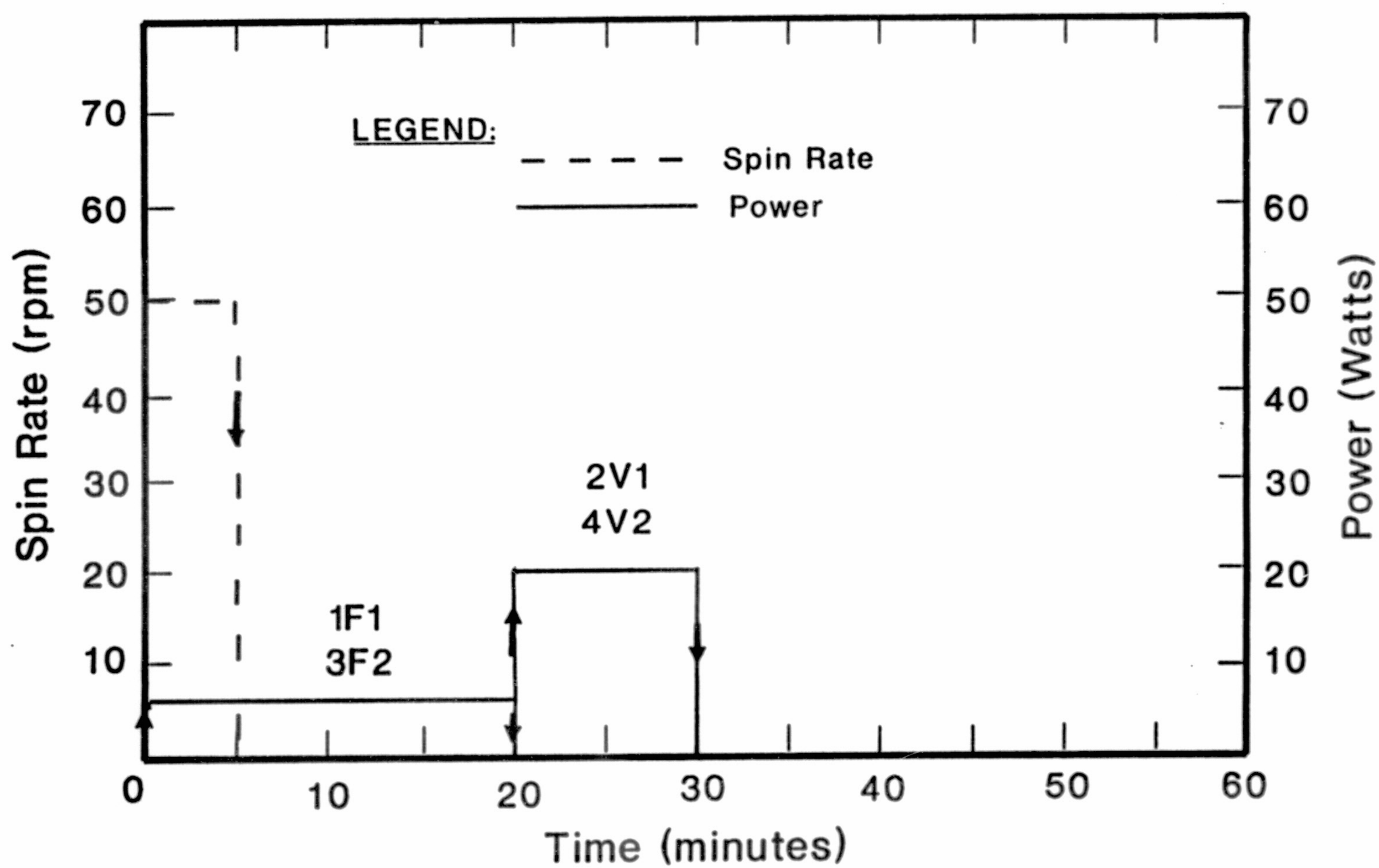
HPP REWICKING TEST TIMELINE



HPP TEST MATRIX

RUN	TEST	HEAT PIPE	FLUID	POWER LEVEL	TEST INCREMENT	SPIN RATE	WARM TIME	RUN TIME
A1	STATIC	1F1	Freon-113	8 → 16 W	2 W	0 RPM	15 min	90 min
A2	STATIC	2V1	Water/NCG	20 → 40 W	20 W	0 RPM	15 min	30 min
A3	STATIC	3F2	Freon-113	8 → 16 W	2 W	0 RPM	15 min	90 min
A4	STATIC	4V2	Water/NCG	20 → 40 W	20 W	0 RPM	15 min	30 min
B1	SPIN	1F1	Freon-113	6 W	2 RPM	2 → 8	10 min	40 min
B2	SPIN	2V1	Water/NCG	40 W	3 RPM	20 → 29	10 min	40 min
B3	SPIN	3F2	Freon-113	6 W	2 RPM	2 → 8	10 min	40 min
B4	SPIN	4V2	Water/NCG	40 W	3 RPM	20 → 29	10 min	40 min
C1	REWICK	1F1	Freon-113	5 W	N/A	50 RPM	20 min	20 min
C2	REWICK	2V1	Water/NCG	20 W	N/A	50 RPM	10 min	10 min
C3	REWICK	3F2	Freon-113	5 W	N/A	50 RPM	20 min	20 min
C4	REWICK	4V2	Water/NCG	20 W	N/A	50 RPM	10 min	10 min
D1	STATIC	1F3	Water	20 → 40 W	20 W	0 RPM	15 min	30 min
D2	STATIC	2V3	Water	20 → 40 W	20 W	0 RPM	15 min	30 min
D3	STATIC	3F4	Water	20 → 40 W	20 W	0 RPM	15 min	30 min
D4	STATIC	4V4	Water	20 → 40 W	20 W	0 RPM	15 min	30 min
E1	SPIN	1F3	Water	40 W	2 RPM	8 → 14	10 min	40 min
E2	SPIN	2V3	Water	40 W	3 RPM	20 → 29	10 min	40 min
E3	SPIN	3F4	Water	40 W	2 RPM	8 → 14	10 min	40 min
E4	SPIN	4V4	Water	40 W	3 RPM	20 → 29	10 min	40 min
F1	REWICK	1F3	Water	20 W	N/A	50 RPM	20 min	20 min
F2	REWICK	2V3	Water	20 W	N/A	50 RPM	10 min	10 min
F3	REWICK	3F4	Water	20 W	N/A	50 RPM	20 min	20 min
F4	REWICK	3V4	Water	20 W	N/A	50 RPM	10 min	10 min

HPP TEST MATRIX (CONT.)

RUN	TEST	HEAT PIPE	FLUID	POWER LEVEL	TEST INCREMENT	SPIN RATE	WARM TIME	RUN TIME
G1	STATIC	1F5	Water	40 W	N/A	0 RPM	15 min	15min
G2	STATIC	2V5	Water	40 W	N/A	0 RPM	15 min	15 min
G3	STATIC	3F6	Water	40 W	N/A	0 RPM	15 min	15 min
G4	STATIC	4V6	Water	40 W	N/A	0 RPM	15 min	15 min
H1	SPIN	1F5	Water	40 W	2 RPM	8 → 14	5 min	20 min
H2	SPIN	2V5	Water	40 W	3 RPM	20 → 29	5 min	20 min
H3	SPIN	3F6	Water	40 W	2 RPM	8 → 14	5 min	20 min
H4	SPIN	4V6	Water	40 W	3 RPM	20 → 29	5 min	20 min
I1	REWICK	1F5	Water	20 W	N/A	50 RPM	20 min	20 min
I2	REWICK	2V5	Water	20 W	N/A	50 RPM	10 min	10 min
I3	REWICK	3F6	Water	20 W	N/A	50 RPM	20 min	20 min
I4	REWICK	4V6	Water	20 W	N/A	50 RPM	10 min	10 min
J1	STATIC	1F7	Water	40 W	N/A	0 RPM	15 min	15 min
J2	STATIC	3F8	Water	40 W	N/A	0 RPM	15 min	15 min
K1	SPIN	1F7	Water	40W	2 RPM	8 → 14	5 min	20 min
K2	SPIN	3F8	Water	40 W	2 RPM	8 → 14	5 min	20 min
L1	REWICK	1F7	Water	20 W	N/A	50 RPM	20 min	20 min
L2	REWICK	3F8	Water	20 W	N/A	50 RPM	10 min	10 min
					TOTAL =			1100

HEAT PIPE PERFORMANCE (HPP)
THERMAL PERFORMANCE EXPERIMENT

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- Four Heat Pipes are Mounted at Once in "Pinwheel"; Only One of the Four is Thermally Active at Any Time During the Flight
- Temperature Control is Maintained by Power Regulation Circuitry and by Fans Mounted on Rotating Platform
- Thermostatic Switches Mounted on Heat Pipes Prohibit Overheating
- Thin Film Warmers are Attacheed to the Evaporator Section of Pipes; Maximum Temperature (Inaccessible Surfaces) is 85°C
- Safety Shroud with Aluminum Sides, Lexan 9600 Top Provides Thermal and Collision Protection for Crew
- HPP Operation is Controlled from Raised Panel of "Control Module"
- Data Recorded Using Solid State Data Loggers and Videotape Recording of Control Module Panel Meters
- Orbiter Power Used for Warmers; Power and Data Transferred Through Slip Rings to HPP Rotating Platform
- HPP Attached to Middeck Floor Using Fittings Mounted to Seat Studs

V03631-05

IN-STEP HEAT PIPE PERFORMANCE (HPP) EXPERIMENT

HUGHES

OBJECTIVES – HEAT PIPE TECHNOLOGY

- HOW DOES HEAT PIPE PERFORMANCE IN SPACE DIFFER FROM PERFORMANCE ON THE GROUND?
  - GRAVITY DOMINATES IN GROUND TESTING
  - SURFACE TENSION DOMINATES IN MICRO-GRAVITY ENVIRONMENT
  - EFFECT OF UNDERFILL AND OVERFILL?
- OBTAIN QUANTITATIVE DATA FOR AXIAL GROOVE AND POROUS WICK HEAT PIPES IN A MICRO-GRAVITY ENVIRONMENT FOR:
  - COMPARISON WITH ANALYTICAL MODELS
  - COMPARISON WITH GROUND TEST DATA
  - COMPARISON WITH EXISTING FLIGHT DATA

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HEAT PIPE PERFORMANCE (HPP) BACKGROUND

HUGHES

- Primary Objectives of HPP Middeck Experiment:

  1) Obtain Quantitative Data on Thermal Performance of Heat Pipes in a Microgravity Environment for Comparison with Ground Testing

  2) Develop an Increased Understanding of Heat Pipes Subjected to Accelerations in Space

  3) Results will be Used to Improve Design of Spacecraft Thermal Control Systems

- HPP Design Heritage Includes Hughes Fluid Dynamics Experiment (FDE), and Several KC-135 Experiments