Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR TP 97502

The European Two-Phase eXperiments TPX I & II

A.A.M. Delil, M. Dubois and W. Supper

DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF. NLR TP 97502 U		SECURITY CLASS. Unclassified

ORIGINATOR
National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE
The European Two-Phase eXperiments TPX I & II

PUBLISHED IN
the Xth International Heat Pipe Conference proceedings. Presented in the Two-Phase Heat Transport Session of the IHPC, Stuttgart, Germany, 21-25 September 1997

AUTHORS	DATE	pp	ref
A.A.M. Delil, M. Dubois and W. Supper	971009	12	12

DESCRIPTORS
Capillary flow
Control valves
Evaporators
Heat exchangers
Heat pipes
Heat pumps
Heat transfer
Performance tests
Pressure sensors
Spacecraft radiotors
Temperature control
Temperature sensors
Two phase flow

ABSTRACT
The ESA Two-Phase eXperiment TPX was successfully flown aboard STS60, February 1994, to demonstrate two-phase heat transport technology in-orbit. Based on TPX conclusions and lessons learned, a TPX II is being developed to usefully fill the time between TPX and future full-scale Capillary Pumped Loop flights. TPX II, planned to fly early 1998, is discussed: changes of configuration/components, updates of objectives/scenario, current status, results of components testing and outlook.

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THE EUROPEAN TWO-PHASE EXPERIMENTS TPX I & II

A.A.M. Delil
National Aerospace Laboratory NLR, Space Division
P.O. Box 153, 8300 AD Emmeloord, Netherlands
phone: +31 527 24 82 29, fax: +31 527 24 82 10, e-mail: adelil@nlr.nl
&
M. Dubois
SABCA, ADT-RDS Haachtse steenweg 1470, B.1130 Brussels, Belgium
phone: +32 2 729 55 99, fax: +32 2 729 58 94, e-mail: marc.dubois@sabca.be
&
W. Supper
ESA/ESTEC, Thermal Control and Heat Rejection Section
P.O. Box 299, 2200 AG Noordwijk, Netherlands
phone: +31 71 565 47 35, fax: +31 71 565 61 42, e-mail: wolfgang@yc.estec.esa.nl

SUMMARY

The ESA Two-Phase eXperiment TPX was successfully flown aboard STS60, February 1994, to demonstrate two-phase heat transport technology in-orbit.
Based on TPX conclusions and lessons learned, a TPX II is being developed to usefully fill the time between TPX and future full-scale Capillary Pumped Loop flights.
TPX II, planned to fly early 1998, is discussed: changes of configuration/components, updates of objectives/scenario, current status, results of components testing and outlook.

BACKGROUND

Mechanically pumped two-phase heat transport systems are currently developed to meet the high power and long transport distance requirements of thermal management systems for future large spacecraft. Capillary Pumped Loops (CPL) are developed for applications with special requirements on microgravity disturbance level, temperature stability and controllability.

As two-phase flow and heat transfer in low-g and 1-g is expected to considerably differ, two-phase heat transport technology must be demonstrated in orbit.

The Dutch-Belgian Two-Phase eXperiment (TPX), a Capillary Pumped ammonia Loop downscaled to meet Get Away Special restrictions, incorporated components for mechanically pumped two-phase loops. TPX has flown successfully as Get Away Special G557, aboard STS60, Febr. 1994 (Ref. 1). TPX schematics is shown in figure 1.
TPX has shown to be a good balance between the limited amount of flight opportunities and the aim to realise as many objectives as possible.

Other two phase in-orbit demonstration experiments, already carried out and currently envisaged, are the US Capillary Pumped Loop experiments CAPL 1 to 3 (Refs. 2 to 5), IN-STEP Two-Phase Flow Experiment (Ref. 6), Two-Phase Extended Evaluation (TEEM) (Ref. 7), the Loop Heat Pipe Flight eXperiment LHPFX (Ref. 8).

To usefully and economically fill the time gap between TPX and future full-scale Capillary Pumped Loop and Loop Heat Pipe flights, TPX II - an updated TPX - is foreseen to be launched as Get Away Special G467 on STS, early 1998 (Ref. 9). TPX II will use many TPX(I) parts, replacing or refurbishing components that functioned improperly or non-optimally, replacing components by advanced ones developed since the start of TPX I (evaporators, three-way valve), doubling the number of temperature sensors, and accounting for the lessons learned in TPX I.
The updated scenario will include the completion of experiments not completed in TPX I and will allow testing of earth observation spacecraft (ATLID type) applications (Ref. 10), with thermally imbalanced parallel condensers, simulating spacecraft radiators that are exposed to differently phased radiation environments.

OBJECTIVES

The general objective of TPX II is in-orbit demonstration of the working principle and assessment of the performance of a Capillary Pumped Loop (CPL) with:
- Advanced evaporators, a cylindrical (CE), a flat (FE).
- A Vapour Quality Sensor (VQS).
- Two balanced or imbalanced condensers in parallel.
- A control reservoir.

Another objective is to compare experimental data of low-g CPL behaviour with 1-g performance data and predictions resulting from thermal modelling/scaling excercises (Refs. 11, 12).

Specific objectives for the in-orbit experiment are to demonstrate that the loop is capable:
- To operate under different heat loads imposed on two evaporators in parallel.
- To share heat load between these evaporators.
- To prime evaporators by a controlled management of the reservoir fluid content.
- To start from low temperature conditions.
- To adjust and maintain a temperature setpoint while operating under different heat load and sink conditions, also for two condensers simulated to be exposed to different

thermal environments.
• To use the control system at different accuracy levels.
Additional objectives are:
• Low-g calibration of the vapour quality sensor.
• To carry out quality control exercises to demonstrate the usefulness of a VQS for system control.
• To assess of performance limits of CPL & evaporators.

EXPERIMENT DESIGN

The TPX II baseline is schematically shown in figure 2.
As already mentioned, TPX II is an improved version of TPX I, that has to meet Get Away Special restrictions: limited mass, volume (5 cubic feet) and limited heat rejection capability due to an uncontrollable heat sink.
The main changes are:
• A new evaporators design, with a sintered nickel wick yielding high pumping power.
• A more accurately controllable bypass valve and tuned vapour bypass line flow resistance.
• An updated position of the reservoir-loop connection.
• Condensers in parallel, instead in series, to simulate imbalanced condenser sink temperatures, being typical for earth observation spacecraft applications (Ref. 9).
• Enhanced and/or refurbished Liquid Flow Meters and Differential Pressure Sensor.
• A larger number of temperature sensors.
• An updated flight scenario.
To reduce costs and to meet time constraints, the TPX II design, manufacture and assembly is entirely based on the TPX I approach, described in the references 2 and 3.

Structure & Loop

The TPX II configuration (Figs. 3 to 5), consists of a structure of four columns with four parallel main plates:
• At the end of the columns the DAC Plate, with the battery and electronics hardware at either side.
• The Loop Plate, at the other end of the columns, attached in a well-conductive manner to the Experiment Mounting Plate, accommodating heat dissipating loop components.
• Between the two others the Evaporator Plate, 40 mm from the Loop Plate, thermally decoupled from the others, and accommodating the evaporators.
• Reservoir Plate, also at 40 mm from the Loop Plate, accommodating the reservoir.
Materials used are Al 7075 for the structural components (except reservoir and evaporator plates: made of reinforced plastic) and the Al 6061 loop components. Pressure sensors/flow meters are made of stainless steel.

Power & Data Handling

The Data Acquisition & Control (DAC) system includes all electric/electronic hardware and the software for testing and operating TPX II, storing measured data, including retrieval of the experimental data. The DAC flight-hardware includes of Battery Pack, Cable Harness, and Payload Measurements and Control Unit (PMCU).

The battery, providing experiment power during flight, is a AgZn battery pack: at least 1800 Wh @ 28.5 V DC.

The PMCU is the on-board control box for experiment execution, safe-guarding, sensor measurements, actuator control, data storage and communication with Electrical Ground Support Equipment (EGSE). The PMCU housing contains the System Processor Unit, Sensor Data Acquisition Board and Actuator Control Board, being interconnected by a standard VME bus. DC-DC converters provide internally required supply voltages for analogue and digital circuitry, as well as for the sensors and actuators. Fuses are present at appropriate locations to ensure the safety of the electrical subsystem.

To receive all relevant information about the performance of the loop and its components, e.g. location of condensation front, degree of subcooling, loop set point, evaporator temperature distribution and pressure drop, reservoir temperature and sink (baseplate) temperature distribution, the following quantities will be measured: temperatures (76), flow rates (2), vapour quality, absolute vapour pressure, pressure drop across the evaporators, valve position and the evaporator heaters (2), start-up heaters (2), condenser imbalance heater and peltier currents.

Safety

Because of containment of some ammonia coexisting as vapour and liquid (and due to the exponential temperature dependence of ammonia vapour pressure), the two-phase loop has to be protected against an overheating leading to an unacceptable loop pressure. All pressurised components have been designed for Maximum Designed Pressure (MDP) 45 bar, corresponding to the ammonia saturation pressure at 80 °C. Each component will be proof pressure tested with a factor of 2 against MDP (burst test factor 4). The assembled loop will be proof pressure tested also.

During the whole operation of the experiment the PMCU will measure the temperature sensors, switching off a heat dissipating unit, when the predefined maximum allowable temperature of this unit is reached. In addition, there are thermal switches on the vapour line and on heating devices that wil interrupt the power to the evaporator heater assemblies, depriming heaters and Peltier element, when MDP is reached. Also housekeeping data (6 voltages, PMCU current and more than 10 temperatures) will be measured. The measuring/control interval is set to 8 s, as most parameters follow slowly changing temperatures.

The DAC software consists of on-board (embedded) and EGSE software. As operational behaviour and experiment parameter details depend on test sequence (based on actual in-orbit conditions), the embedded software is split into a fixed program and a set experiment defined tables, without compromising the software reliability. Major functions of this software are experiment planning, data acquisition of all sensors, execution of specified control algorithms, actuators control, data recording and safeguarding.

Loop Components

The different TPX II loop components will be reviewed in detail focusing mainly on their differences with respect to the corresponding TPX I components.

The **Flat Evaporator**, FE (Fig. 6), consists of a heated baseplate with micro-channels for the vapour, a 2 µm sintered nickel wick (void fraction 0.71 and permeability $5*10^{-14}$ m^2) with an inlet hole for liquid and a box shell, electron-beam welded to the baseplate, with a liquid inlet tube, teflon insulator and outlet vapour tube. The characteristics of the FE are similar to the TPX I FE: the difference is the sintered nickel wick in TPX II (instead of 30 µm porous polyethylene) and a start-up heater, discussed later. Nominal power 200 W at 250 mm tilt, while capillary pumping pressure up to 38000 Pa. Overall mass: 0.7 kg.

The **Cylindrical Evaporator**, CE (Fig. 7), consists of a aluminium I-shaped body (20 mm width), a liquid inlet tube with teflon insulation, an outlet vapour tube and a cylindrical sintered nickel wick having vapour collection grooves and an inlet hole for the liquid. The CE characteristics measured are: nominal heat load 250 W for 250 mm tilt, mass 0.35 kg. Compared to the TPX I design, the TPX II changes are the wick and a start-up heater.

The **Control Reservoir** (Fig. 8) consists of a cylindrical vessel with an inlet/outlet (liquid) tube, a vapour/liquid separator made of 2 µm sintered nickel, an inner acquisition (folded) wick to get similar fluid distribution in 1-g and 0-g and a cover welded on the vessel, equipped with two Peltier elements and a copper braid connected to the vapour line via an aluminium block. Due to the presence of this block in the TPX II configuration, the electrical power needed for the Peltier control is considerably increased. TPX II control power is estimated 8 W at maximum (TPX I: 4.7 W). The other reservoir characteristics stay similar to TPX I: liquid content 0.2 liter, mass 0.95 kg and temperature control accuracy ± 0.1 °C within the range 263 K to 323 K.

Another innovative aspect of TPX II is the two **Parallel Condensers Configuration** (Fig. 9). One condenser is equipped with an electrical heater (power up to 30 W) to create imbalanced controllable heat sink conditions. The condensers are aluminium rectangular grooved heat pipe profiles (15 mm * 15 mm * 235 mm), with welded end caps. The end cap at the outlet of a condenser has been designed to restrict the vapour flow exiting the condenser.

The condensers are designed to dissipate at least 100 W (under nominal conditions) for an overall thermal resistance of 0.29 W/K. In order to achieve a constant conductance of 7500 W/m^2K, a PTFE gap filler (thickness 0.03 mm) is between the condensers and the heat sink.

The **Vapour Quality Sensor** (VQS) consists of a glass tube with glass covered capacitor electrodes on the internal wall, surrounded by a stainless steel envelope for strength reasons, with on top of it the sensor electronics (Fig. 10). The TPX II VQS is a refurbished/re-calibrated TPX I VQS. To perform vapour control exercises with the VQS, a Three-Way **Control Valve** (Bradford Engineering) is in the TPX II loop, allowing to by-pass (partially or fully) the condensers and therefore to adjust and control the vapour quality of the flow entering the VQS. The control valve design is based on a spindle actuation (allowable stroke 4 mm) made via a DC-motor (Fig. 11). Compared to TPX I, the TPX II valve has better functional properties, smaller dimensions (100 mm * 40 mm * 70 mm), smaller mass (0.5 kg), tuned electronics, increased leak tightness (10^{-8} std cc/s He) and reduced pressure drop (< 250 Pa).

Like in TPX I, a **Differential Pressure Sensor** (DPS) is arranged in parallel to the evaporators. The TPX II DPS (NE Technology) allows differential pressure measurements from 0 up to 10000 PA with an accuracy of ± 1 % FS for a temperature range from 253 to 353 K. Allowed delta pressure across the membrane: 0.35 bar.

The loop pressure is measured by the ENTRAN **Absolute Pressure Sensor** (APS):70 bar max., accuracy ± 0.25% FS.

78 PT1000 **Temperature Sensors** are used in TPX II.

As in TPX I, two **Liquid Flow Meters** (LFM) are in the loop to measure the overall loop mass flow rate (redundant during experiments with closed by-pass line) and to determine the flow rate through the by-pass line (by subtracting the LFM flow rates), necessary to obtain the vapour quality at the mixing point for VQS calibrations and control exercises. The LFM used are the LFM of TPX I (Rheoterm, INTEK Inc.), able to measure from 0.002 g/s to 0.2 g/s ammonia with an accuracy of ± 1.5 % FS.

PRE-LAUNCH TESTING

The pre-launch testing consists of the different tests to be performed on the loop or on the loop components prior to delivery to NASA. These tests, performed at different stages of assembly, include:

- Functional Tests on components: evaporators, VQS, reservoir, condensers, control valve, etc. These tests demonstrate the reliable behaviour of the TPX II components with respects to their specifications.
- Acceptance Tests at loop level (prior to loop closure, after the environmental testing), which will give full confidence on the TPX II loop to fulfil the test objectives.
- Performance Tests on the fully assembled experiment, consisting of the Mission Scenario test sequences and finalising the Mission Scenario test parameters/figures.

Loop components are currently undergoing functional tests. Due to NASA major safety requirements updates, the second step of the pre-launch testing has not been done yet.

Figure 12 presents the VQS results obtained in TPX I. The left hand side of the figure pertains to slug flow, the right hand side to annular flow. A control exercise could not be realised in TPX I, as the chosen quality setpoint (0.5) turned out to be in the non-uniquely defined (unstable) churn flow regime. The TPX II VQS electronics has been tuned such that calibrations can be done in the slug and annular regimes. Two quality control exercises will be done, one around a setpoint in the annular regime (0.9), the other around a setpoint in the slug regime (0.1).

Functional tests are the mission scenario tests, plus extra

tests to prove the reliable behaviour of components.
For the evaporators, these tests consist of:

- Start-up at 40 W (reservoir 35 °C, condensers 15 °C).
- Heat load changes at 20, 40 and 60 °C (100 W→25→100 →10→100 W).
- Reservoir temperature variation for a constant heat load of 50 W (40 °C→42→46→40→38→35→34→40 °C), condenser at 20 °C.
- Decrease of the subcooling level by varying the vapour temperature with a constant heat load of 50 W (40→35→ 30→25→24→23→22→21→20 °C), condenser at 20 °C.
- Increase of the heat load in steps of 10 W from 50 W (reservoir at 40 °C, condenser at 20 °C).
- Heat load decrease from 50→15→10→5→2 W.
- Increase of the loop pressure drops by means of a valve (reservoir at 40 °C, condenser at 20 °C).
- Variation of start-up heater power for various conditions:
  - A subcooling level of 2, 5 and 10 °C.
  - A heat load of 20, 50 and 100 W.
  - A start-up heater power of 0, 1, 2, 3, 5, 8 and 10 W.

The functional tests are performed using a simplified two-phase breadboard loop, consisting of one evaporator, one reservoir and one condenser. The loop is equipped with 12 thermocouples, fixed on the loop components, and with a DPS, similar to the TPX II one, placed in parallel to the evaporator. Heating is done on the evaporator and on the reservoir by manually switching on electrical heaters bolted on the components. Cooling is by a water heat exchanger. To test a specific flight component, the breadboard loop component will be replaced by the TPX II flight model.

Start-up tests have frequently shown evaporator dry-out, induced by the sintered nickel wick, as the small wick pore size, yielding high pumping pressure, has an impact on vapour generation inside the wick. The high flow resistance nickel wick requires higher overheating than the TPX I polyethylene wick, before a vapour bubble is produced. The generation of a vapour bubble in the nickel wick evaporator needs an overheating of more than 5 K. When evaporation takes place, this is accompanied by a high pressure spike (more than 0.5 bar higher than the capillary pumping pressure), leading to the depriming of the evaporator wick (vapour present at the evaporator inlet), yielding evaporator dry-out. The CE proved to be more sensitive than the FE. Dry-out is prevented by creating nucleation points to avoid the need of liquid overheating to generate vapour. Therefore a start-up heater can be used, creating an initial bubble inside the vapour core. The heater has to be activated only shortly. If the start-up heater is activated a vapour bubble is already present at the evaporator outlet, when switching on the evaporator power. A temperature peak does not occur and the pressure spike has been drastically dampened, yielding a correct evaporator start-up.

Two start-up heater locations have been tested: one on the vapour exit line and one inside the evaporator vapour core. The first one gave reliable results for the FE only. For the CE the results were unreliable for non-gravity assist conditions, which suggests improper behaviour in low-g. The second location is the better one, having the advantage that the hot spot generator, creating the initial bubble, is at the best location (under the heat source, just at the liquid/vapour interface). Another advantage is the minimum power needed for start-up: as there is no heat loss, all power is used for vapour generation. A drawback of the second location is the complexity to place a heater inside the evaporator. But it turned out to be possible using a THERMOCOAX heater with qualified inserting device. Tests, with a start-up heater with a diameter of 1 mm, proved proper start-up behaviour for the CE and FE, also in horizontal orientation. This is illustrated by the figures 13 to 16, which confirm that the in-core start-up heaters are essential for TPX II.

CONCLUDING REMARKS

The status of TPX II has been described, including results of components testing. Test results indicate that the start-up heater configuration needs further investigation.

A completely new NASA safety philosophy has led to delays, in particular with respect to the loop assembly, which will start after solving the safety problems. Thereafter loop assembly and loop testing, completed by the acceptance testing, will precede the delivery of TPX II to NASA for STS-90 flight, April 1998.

REFERENCES

1. Delil, A.A.M. et al., *TPX for in-orbit demonstration of two-phase heat transport technology - Evaluation of flight & postflight experiment results*, NLR TP 95192 U, SAE 95150, 25th Int. Conf. on Environmental Systems, San Diego, CA, 1995.
2. Butler, D. & Ottenstein, L. & Ku, J., *Flight testing of the capillary pumped loop flight experiments*, SAE 951566, 25th Int. Conf. on Environmental Systems, San Diego, CA, 1995.
3. Ku, J. & Ottenstein, L. & Butler, D., *Performance of CAPL 2 Flight Experiment*, SAE 961431, 26th Int. Conf. on Environmental Systems, Monterey, CA, 1996.
4. Ku, J. & Hoang, T., *Start-Up Behavior of the CAPL 2 Flight Experiment*, SAE 972328, 27th Int. Conference on Environmental Systems Lake Tahoe, NV, 1997.
5. Kim, J.H., et al., *The Capillary Pumped Loop III Flight Demonstration, Description, and Status*, AIP Conf. Proc. 387, Space Technology & Applications Int. Forum, Albuquerque, NM, 1997, 623-628.
6. Nienberg, J. & Pohner, J., *IN-STEP Two-Phase Flow Thermal Control Experiment*, ESA WPP-112, "CPL 96" Int. Workshop on Capillary Pumped Two-Phase Loops, Noordwijk, NL, 1996.
7. Hurlbert, K., *The Two-phase Extended Evaluation in Microgravity (TEEM) Flight Experiment: Description and Overview*, AIP Conf. Proc. 387, Space Technology & Applications Int. Forum, Albuquerque, CA, 1997, 547-554.

8. Bienert, W. et al., *Loop Heat Pipe Flight eXperiment*, ESA WPP-112, "CPL 96" Int. Workshop on Capillary Pumped Two-Phase Loops, Noordwijk, NL, 1996.
9. Delil, A.A.M. & Dubois, M. & Supper, W., In-Orbit *Demonstration of Two-Phase Heat Transport Technology - Status of TPX II: Reflight of the European Two-Phase eXperiment*, NLR TP 97283 U,
SAE 972479, 27th Int. Conference on Environmental Systems Lake Tahoe, NV, 1997, ESA SP-400, 355-364, 6th European Symp. on Space Environmental Control Systems, Noordwijk, NL, 1997.
10. Dunbar, N.W., *ATLID Laser Head Thermal Control-Design and Development of a Two-Phase Heat Transport System for Practical Application*, SAE 961561, 26th Int. Conf. on Environmental Systems, Monterey, CA, 1996.
11. Delil, A.A.M., *Thermal gravitational modelling and scaling of two-phase heat transport systems: Similarity considerations and useful equations, predictions versus experimental results*, NLR TP 91477 U, European Symp. on Fluids in Space, Ajaccio, F, 1991, ESA SP-353, 579-599.
12. Hamme, T.A. & Best, F.R., *Gravity Dependent Flow Regime Mapping*, AIP Conf. Proc. 387, Space Technology & Applications Int. Forum, Albuquerque, NM, 1997, 635-640.

APS	Absolute Pressure Sensor	LFM	Liquid Flow Meter
DPS	Differential Pressure Sensor	$\dot{m}$	Mass flow
CV	Controllable 3-way Valve	$\dot{m}_C$	Flow Rate in Condenser Branch
T_V	Vapour Temperature	Q_{E_F}	Flat Evaporator Heater Power
T_ℓ	Liquid Temperature	Q_{E_C}	Cylindrical Evaporator Heater Power
EMP	Experiment Mounting Plate (GAS canister lid)	Q_{COND}	Condenser Imbalancing Power
GAS	Get Away Special	VQS	Vapour Quality Sensor

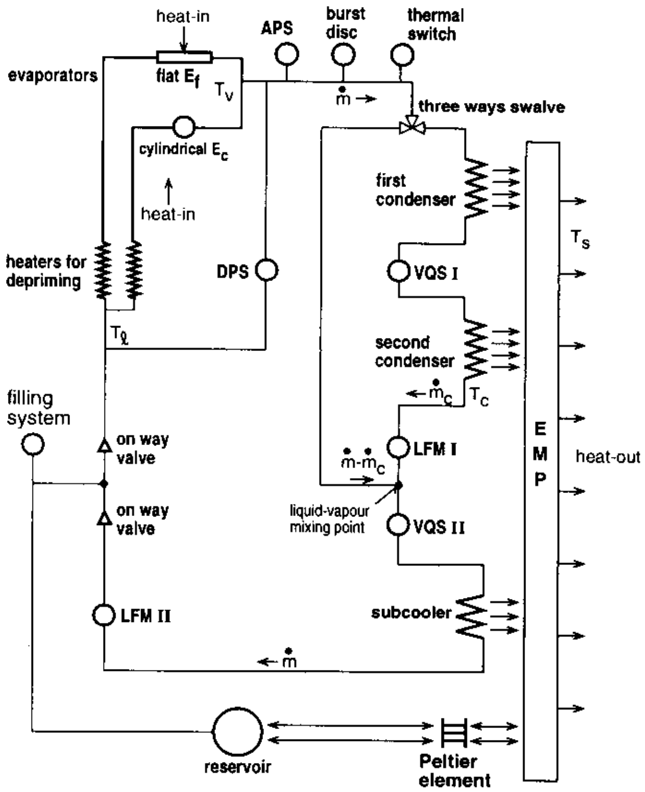

Fig. 1 TPX I Schematic.

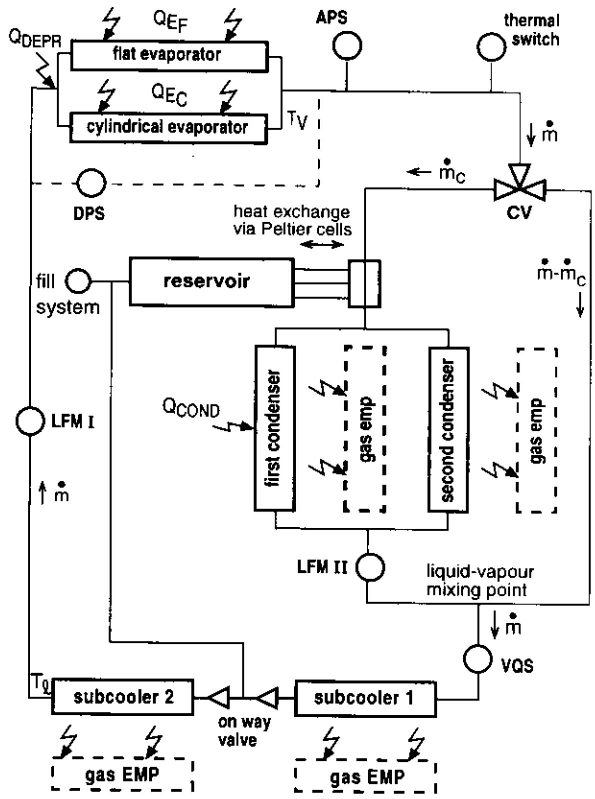

Fig. 2 TPX II Schematic.

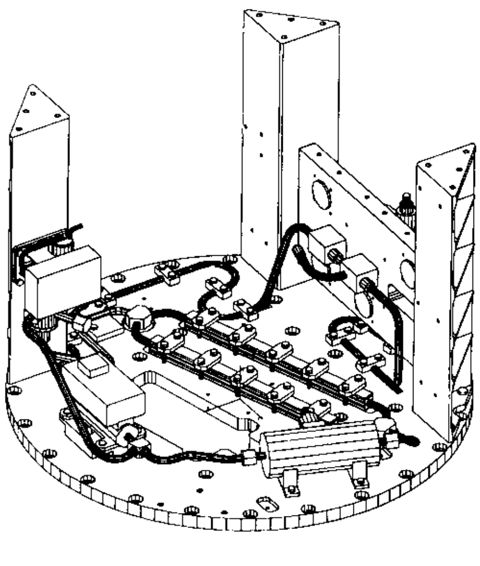

Fig. 3 Loop Plate Layout

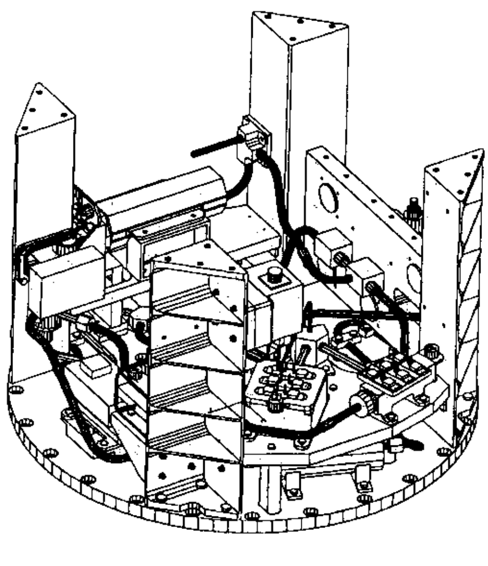

Fig. 4 Evaporators and Reservoir Layout

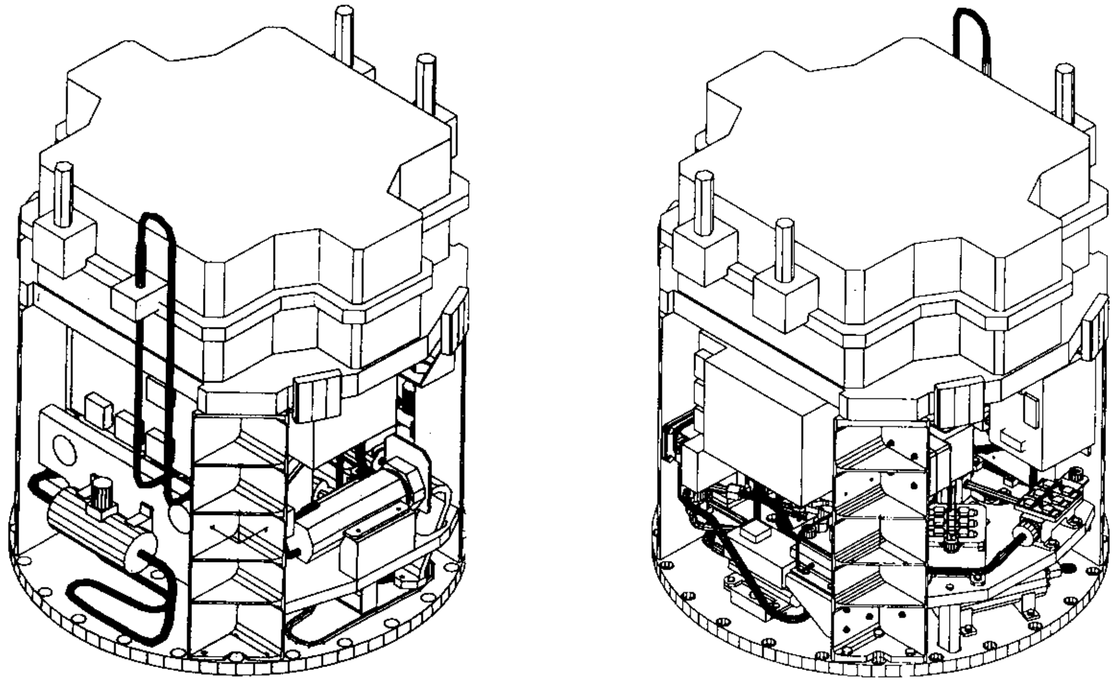

Fig. 5 Experiment Overall Layout

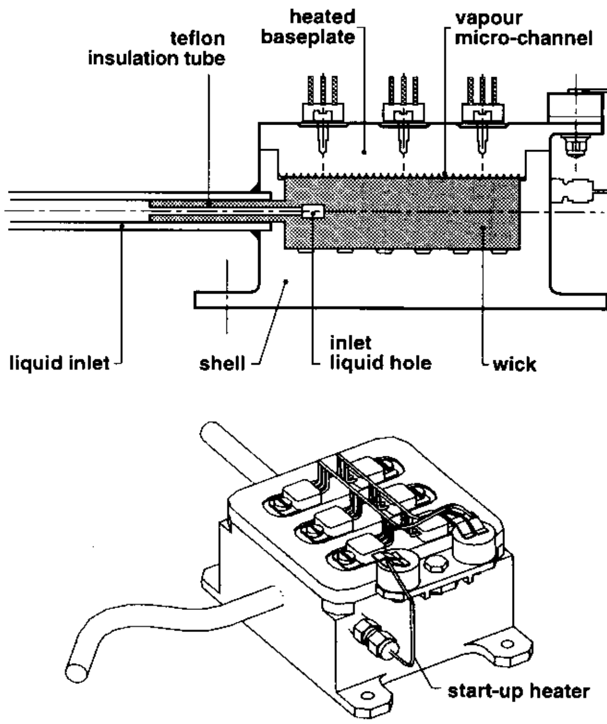

Fig. 6 Flat Evaporator (FE)

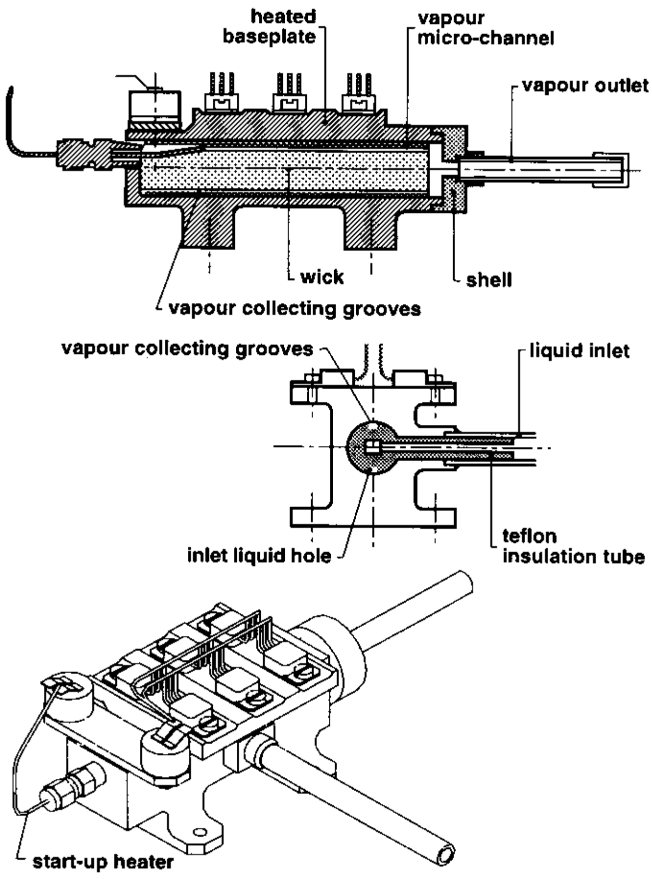

Fig. 7 Cylindrical Evaporator (CE)

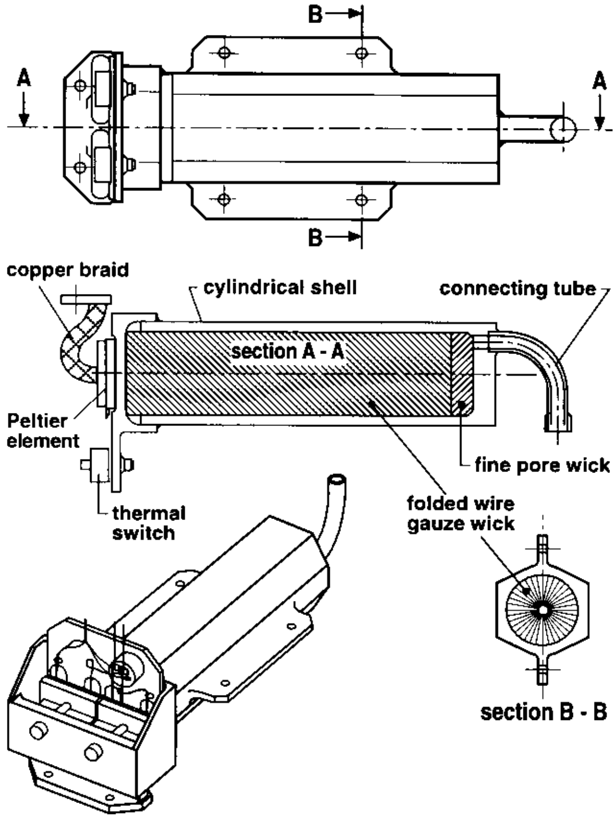

Fig. 8 Control Reservoir

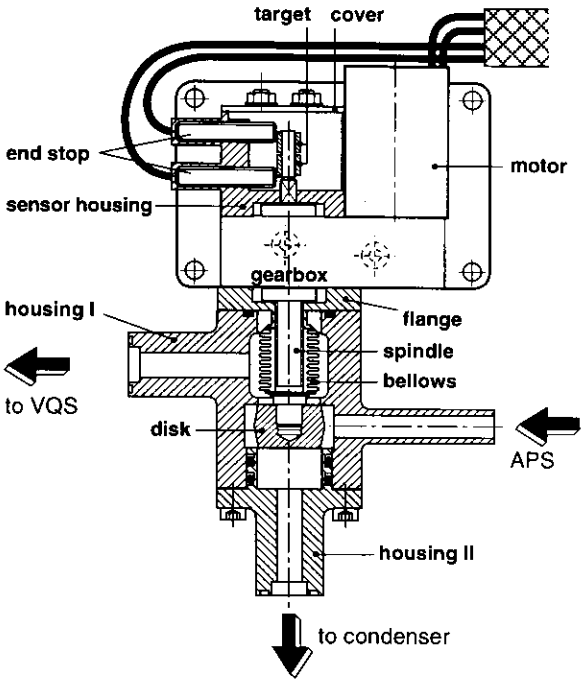

Fig. 11 TPX II Controllable Valve

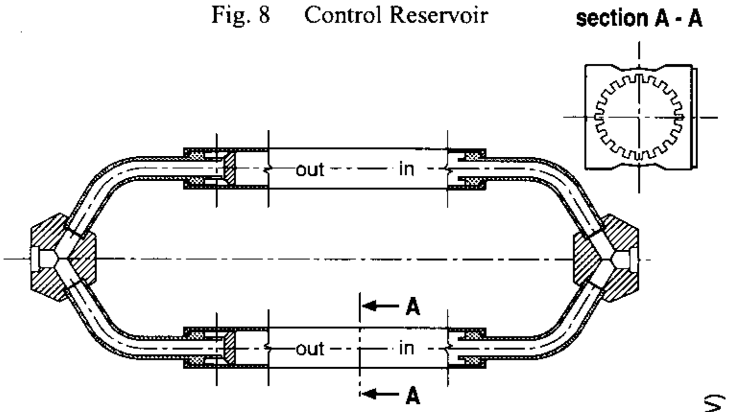

Fig. 9 Condensers

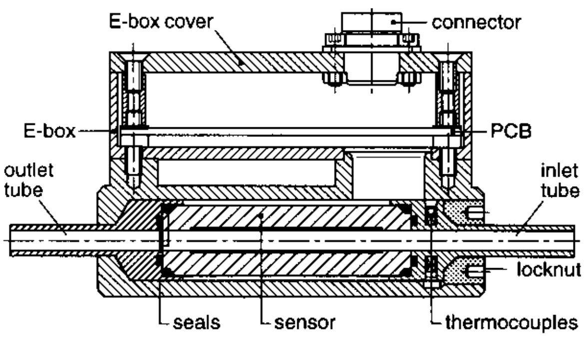

Fig. 10 TPX II Vapour Quality Sensor

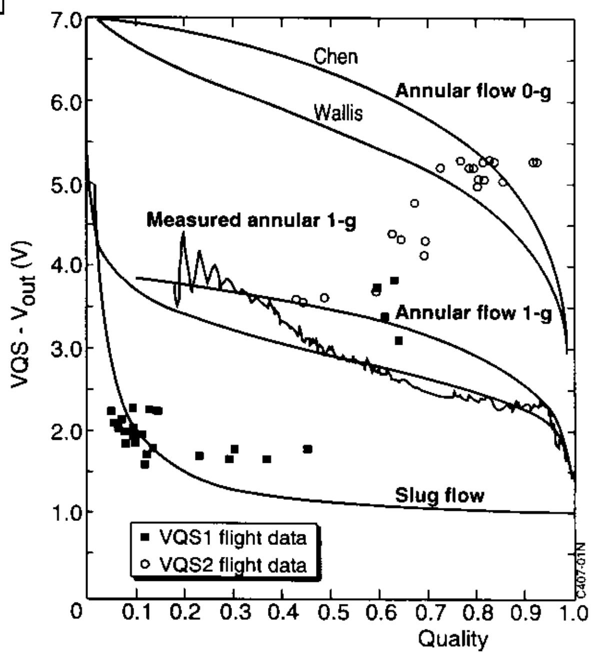

Fig. 12 VQS, plus Theoretical Response and Test Data

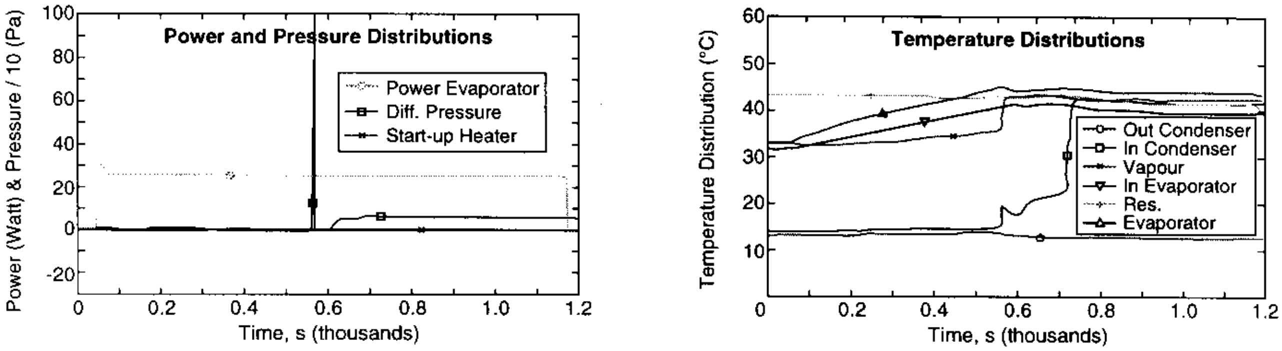

Fig. 13 Flat Evaporator Start-up Test with Heater Off

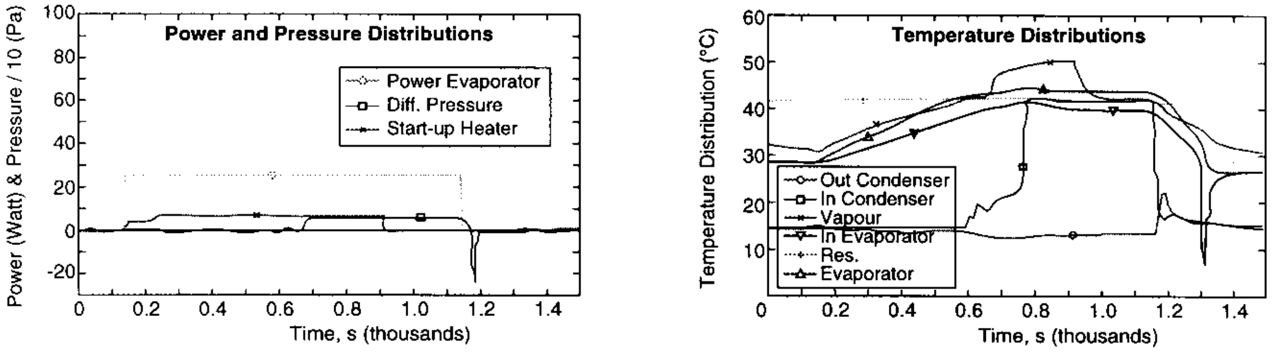

Fig. 14 Flat Evaporator Start-up Test with Heater On

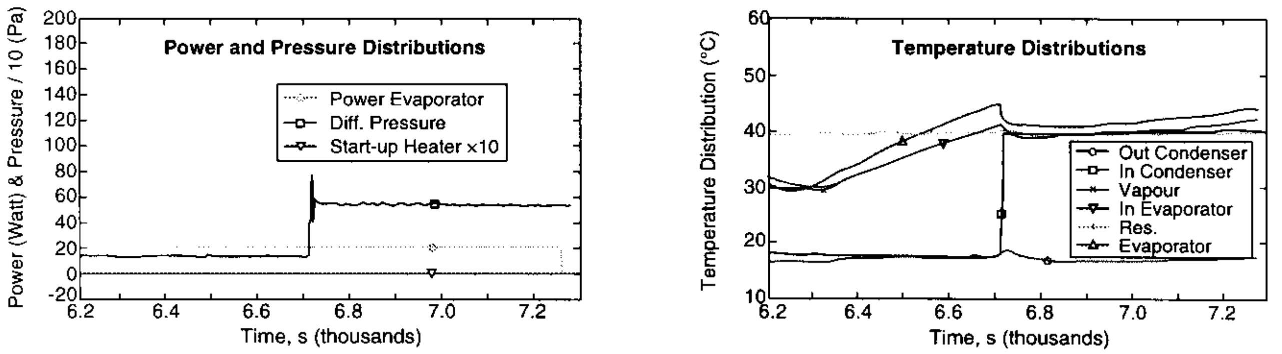

Fig. 15 Cylindrical Evaporator Start-up Test with Heater Off

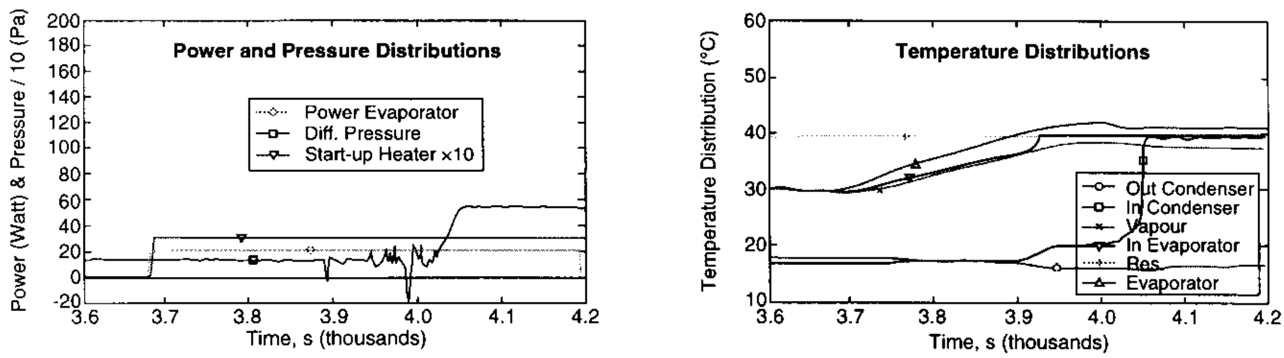

Fig. 16 Cylindrical Evaporator Start-up Test with Heater On