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In-orbit demonstration of two-phase heat transport technology status of TPX II: reflight of the European two-phase experiment.

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DESCRIPTORS

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ABSTRACT
In order to demonstrate two-phase heat transport system technology in orbit, the Dutch-Belgian two-Phase eXperiment TPX was successfully flown as Get Away Special G557, aboard STS60, February 1994.
Based on TPX conclusions and lessons learned, a reflight experiment TPX II is being developed in order to usefully fill the gap between TPX and possible future full-scale Capillary Pumped Loop flights.
The characteristicss of TPX II, intended to fly early 1998, are discussed in detail: configuration and component changes, updates of objectives/scenario, current status, results of pre-launch (components) testing and outlook.
Keywords: Thermal Control, Two-Phase Flow, Heat Transfer, Capillary Pumped Loops, In-Orbit Experiments, Get Away Special.

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ABSTRACT

In order to demonstrate two-phase heat transport system technology in orbit, the Dutch-Belgian Two-Phase experiment TPX was successfully flown as Get Away Special G557, aboard STS60, February 1994.
Based on TPX conclusions and lessons learned, a reflight experiment TPX II is being developed in order to usefully fill the time gap between TPX and possible future full-scale Capillary Pumped Loop flights.
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1. 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 (Ref. 1).
Capillary pumped systems are being developed for applications with special requirements concerning microgravity disturbance level, temperature stability and controllability .

As two-phase flow and heat transfer in low-gravity and terrestrial environments are expected to considerably differ, two-phase heat transport system technology has to be demonstrated in orbit.

The Dutch-Belgian Two-Phase experiment TPX, a Capillary Pumped ammonia Loop downscaled. to meet Get Away Special restrictions, also incorporated components for mechanically pumped two-phase loops. TPX has been developed within the ESA In-Orbit Technology Demonstration Programme TDPl and has successfully flown as Get Away Special G557, aboard STS60, early February 1994 (Ref. 2).
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. 3 to 5), IN-STEP Two-Phase Flow Experiment (Ref. 6) and Loop Heat Pipe Flight experiment LHPFX (Ref. 7).

To usefully and economically fill the time gap between TPX and future full-scale Capillary Pumped Loop and Loop Heat Pipe flights, TPX II - a reflight of an updated TPX - is foreseen to be launched as Get Away Special G467 on STS, early 1998 (Ref. 8).
TPX II makes use of as much as possible TPX(1) 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. 9), with thermally imbalanced parallel condensers, simulating spacecraft radiators that are exposed to differently phased radiation environments.

2. OBJECTIVES

The general objective of TPX II is to give an in-orbit demonstration of the working principle and to assess the performance of a two-phase Capillary Pumped Loop (CPL) with:
- Two advanced evaporators, a cylindrical (CE) and a flat one (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-gravity CPL behaviour with terrestrial performance data and predictions resulting from thermal modelling and scaling excercises (Ref. 10).

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 control exercises to demonstrate the usefulness of a VQS for system control.
- Determination of the performance limits of the loop and of its evaporators.

3. EXPERIMENT DESIGN

The TPX II baseline is schematically shown in figure 1.

As already mentioned, TPX II is an improved version of TPX I, that has to meet the earlier mentioned Get Away Special requirements, being limited mass (< 90 kg in total), volume (5 cubic feet) and limited heat rejection capability due to an uncontrollable heat sink (Fig. 2).
The main changes are:
- A new evaporator design (Ref. 11), with a sintered metal 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 of in series, in order to simulate imbalanced condenser sink temperatures, being typical for earth observation spacecraft applications (Ref. 11).

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

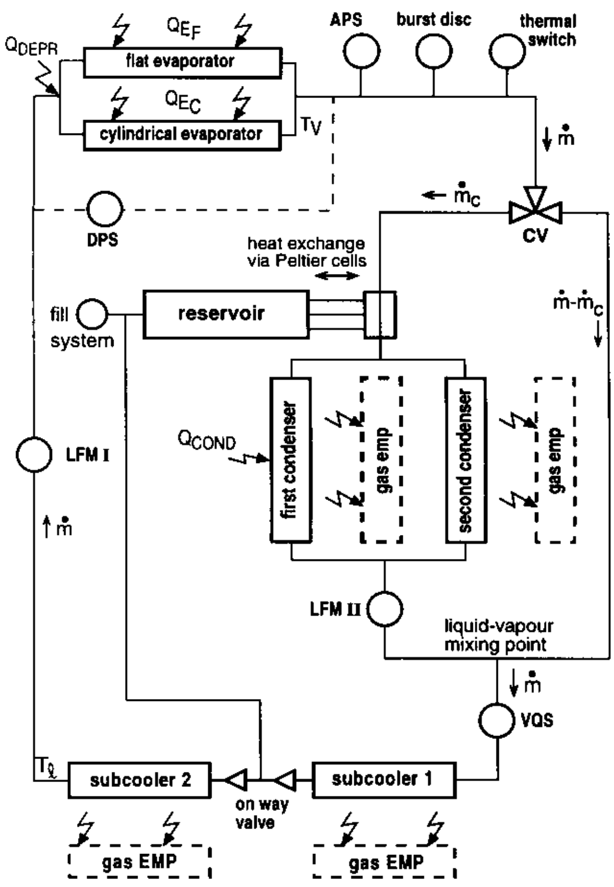

Fig. 1 TPX II Experiment schematics

- 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.

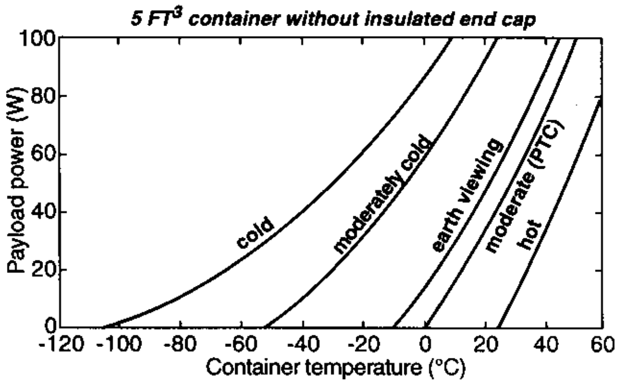

Fig. 2 GAS Thermal Sink Conditions

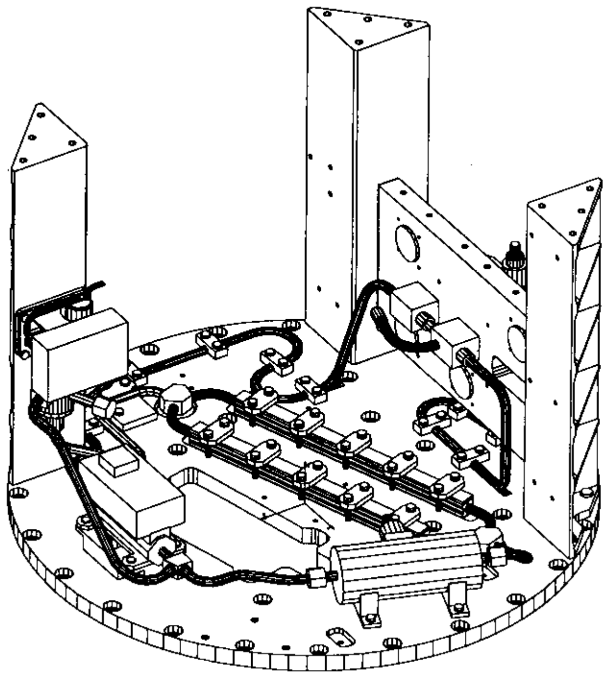

Fig. 4 Loop Plate Layout

3.1. Structure & Loop

The TPX II configuration (Figs. 3 to 5), consists of a structure of four columns with four parallel main plates:

- One, at the end of the columns, called Electronics or DAC Plate, accommodating the battery and electronics hardware at either side.

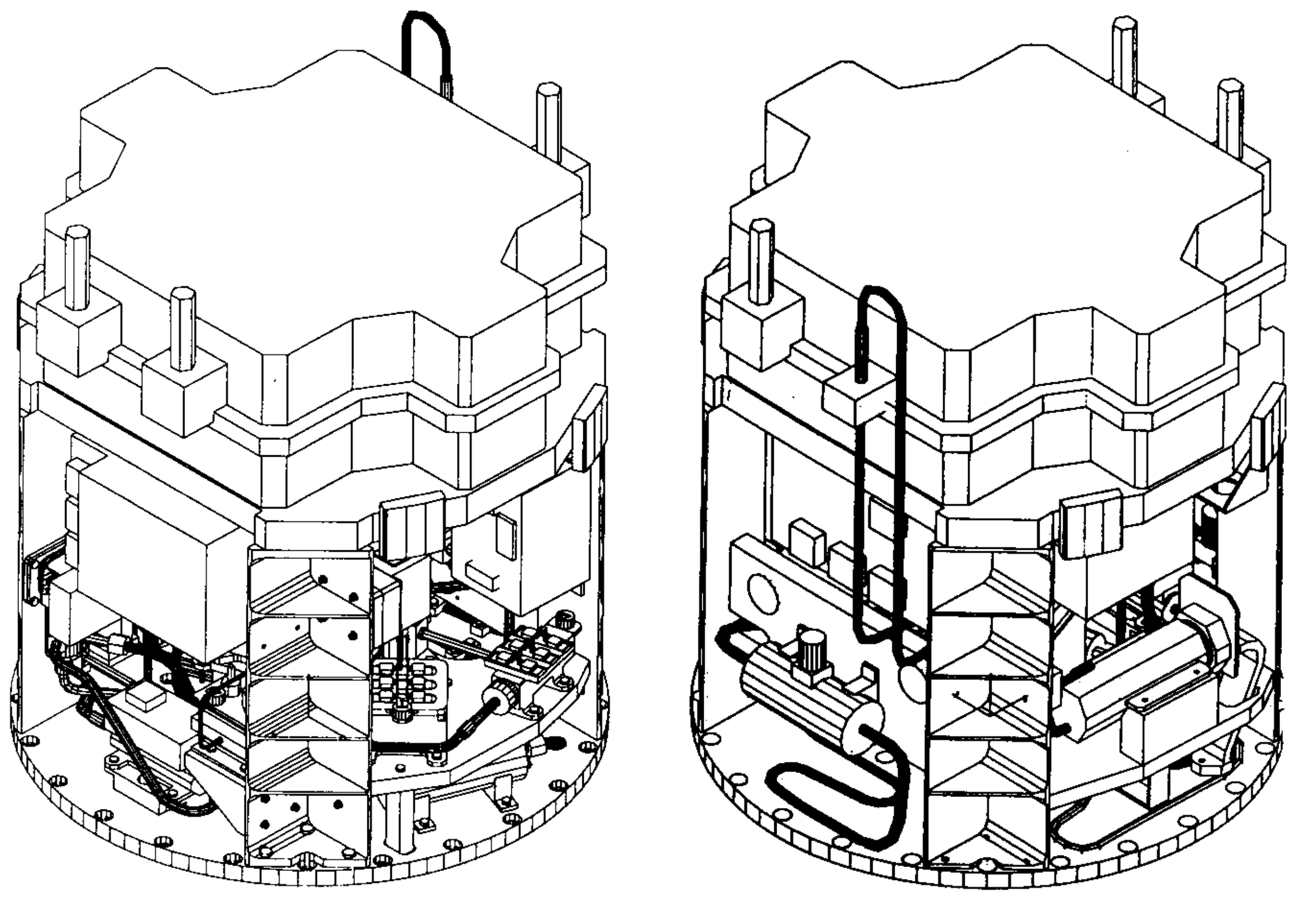

Fig. 3 Experiment Overall Layout

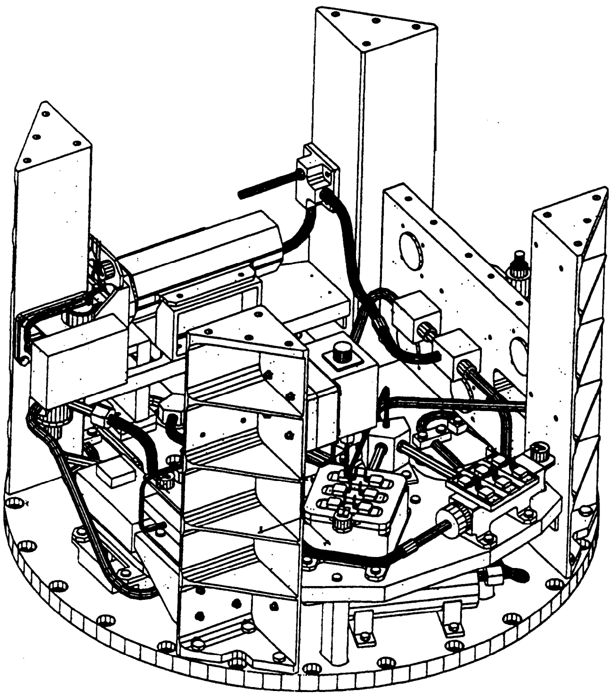

Fig. 5 Evaporators and Reservoir Layout

- One, the TPX Loop Plate, ‘at the other end of the columns, attached in a well-conductive manner to the GAS Experiment Mounting Plate and accommodating the heat dissipating loop components.
- One, between the two others, called Evaporator Plate, 40 mm from the Loop Plate, thermally decoupled from the others, and accommodating the evaporators.
- The fourth one, called Reservoir Plate, also at 40 mm from the Loop Plate, accommodating the reservoir.

The main materials used are aluminium 7075 for the structural components (except the Reservoir and the Evaporator plates which are made of reinforced plastic) and the aluminium 6061 loop components. The pressure sensors and flow meters are made of stainless steel.

3.2 Power & Data Handling

The Data Acquisition and 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 the power for the experiment during flight, is a AgZn battery pack offering at least 1800 Wh @ 28.5 V DC.

The PMCU is the on-board control box for experiment execution and 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.

In order 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, evaporator heater currents (2), depriming heater currents (2), condenser imbalance heater current and peltier current.

3.3. Safety

Because of containment of some ammonia coexisting as vapour and liquid (and due to the exponential temperature dependence of the 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 a maximum pressure of 45 bar (which corresponds to the ammonia saturation pressure at 80 °C). Each component has been proof pressure tested with a factor of 2 against that value (burst test factor 4). The completely 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 the maximum temperature of 80 °C 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 details of experiment parameters are test sequence dependent (based on actual in-orbit conditions), the embedded software is split into a fixed program and a set of experimenter defined tables, without compromising the reliability of the software. Major functions of the embedded software pertain to experiment planning, data acquisition from all sensors, execution of specified control algorithms, actuators control, data recording and safe guarding.

3.4. 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.

Evaporators: 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 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 functional characteristics of the FE are similar to the TPX I FE: the main difference being a nickel sintered wick in TPX II instead of a 30 μm porous polyethylene. The nominal heat load is 200 W under 250 mm tilt, while the capillary pumping pressure can become 38000 Pa. The overall mass is around 0.7 kg.

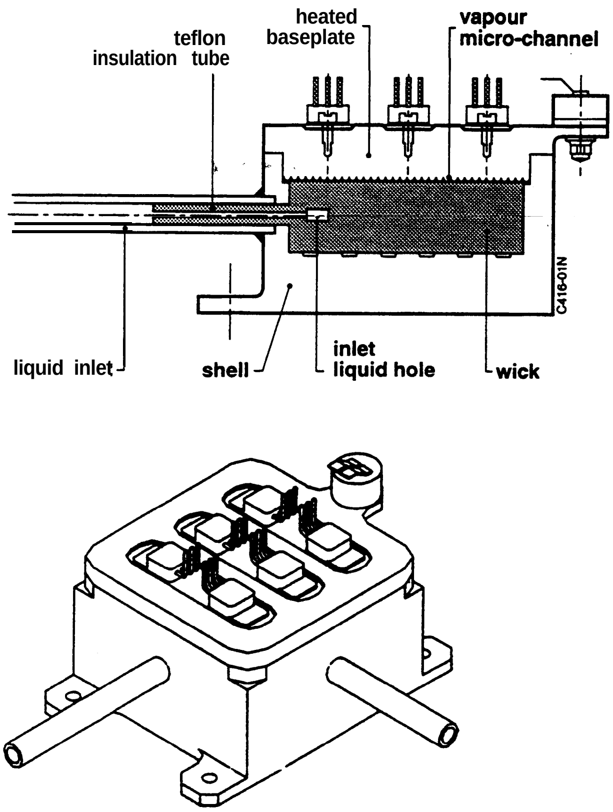

Fig. 6 Flat Evaporator (FE)

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 functional CE characteristics measured are: nominal heat load 250 W for 250 mm tilt and a mass of 0.35 kg.

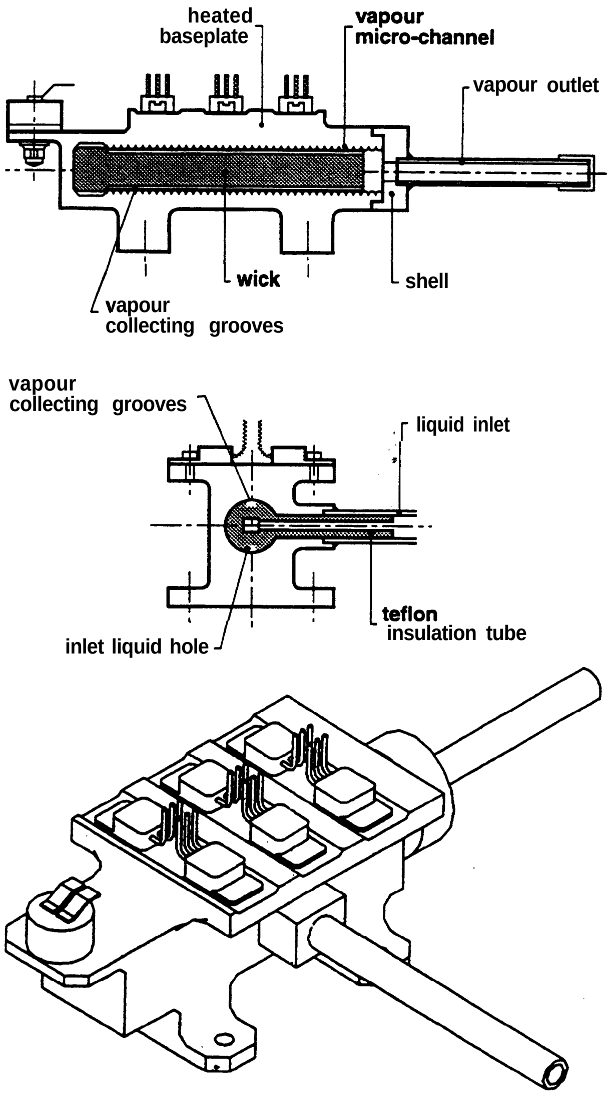

Fig. 7 Cylindrical Evaporator (CE)

Compared to the TPX I design, the TPX II changes are the wick and the implementation of a start-up heater located at the outlet vapour core. This heater has been implemented to generate a vapour bubble during the start-up procedures, thus making the evaporator start-up easier. Some experimental results will be shown below.

Reservoir: 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 l-g and O-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

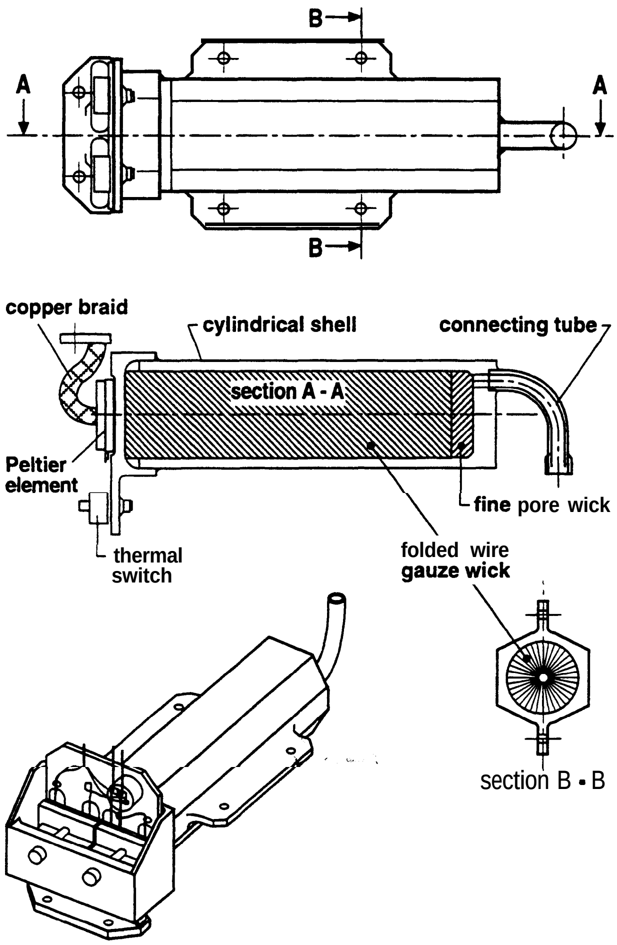

Fig. 8 Control Reservoir

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.

Condensers: Another innovative aspect of TPX II is the two parallel condensers configuration. One condenser is equipped with an electrical heater (power up to 30 W) to create imbalanced controllable heat sink conditions.
The TPX II condensers consist of aluminium rectangular grooved heat pipe profiles (15 mm * 15 mm * 235 mm), with welded end caps. At the outlet of each condenser, the end cap has been designed in order 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^{2}K, a PTFE gap filler (thickness about 0.03 mm) is between the condensers and the heat sink. The condensers are depicted in figure 9.

Three-Way Control Valve: In order to perform useful vapour control exercises with the VQS, a three-way valve (of Bradford) is implemented 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 coming into the VQS.
The control valve design is based on a spindle actuation (allowable stroke 4 mm) made via a DC-motor (Fig. 10).
With respect to the TPX I three-ways valve, the TPX II valve has better functional characteristics, more compact 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 drops (< 250 Pa).

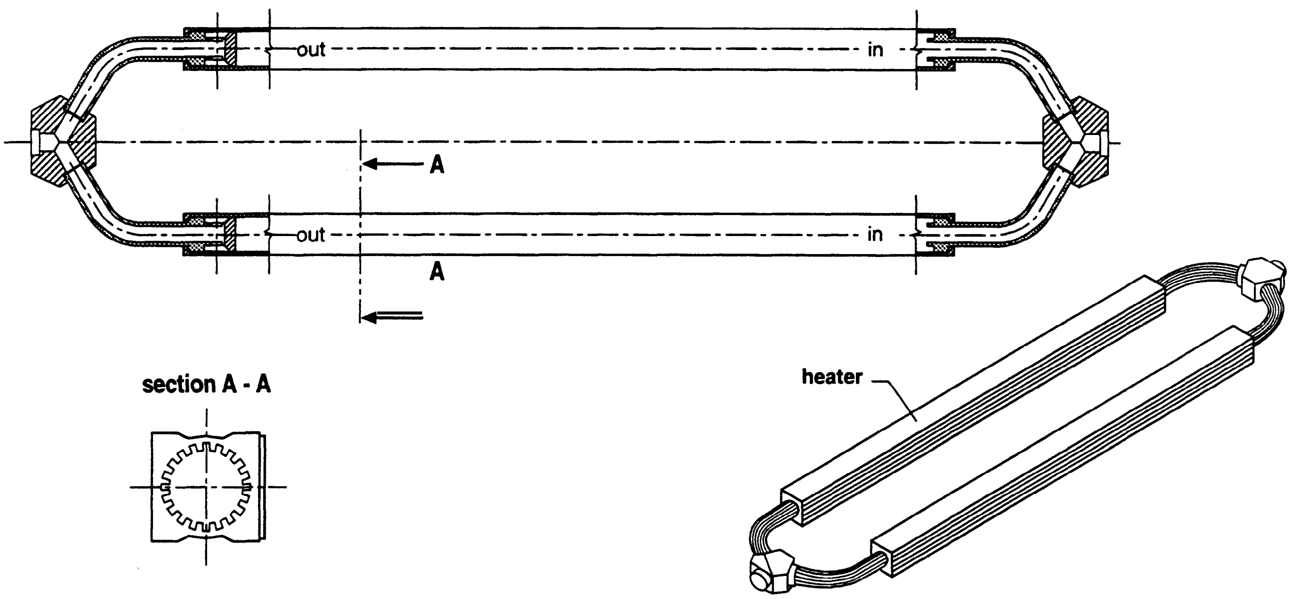

Fig. 9 Condensers

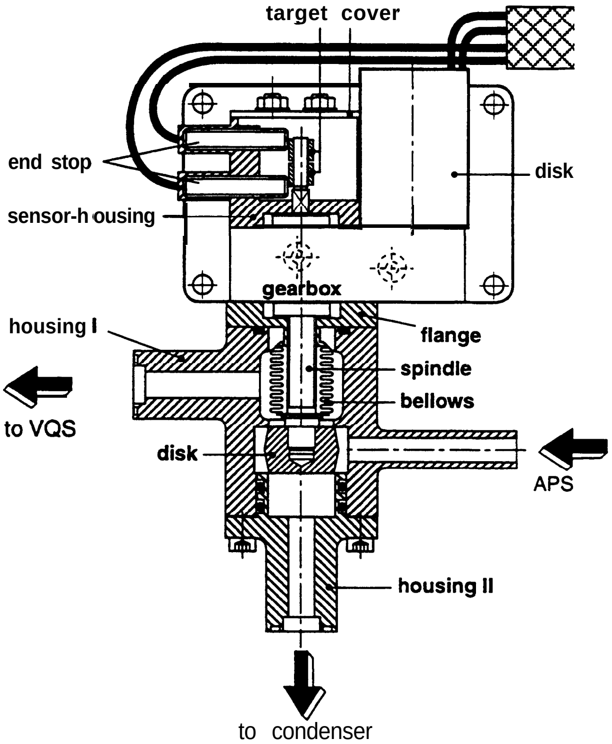

Fig. 10 TPX II Controllable Valve

Vapour Quality Sensor: The VQS (Fig. 11) 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. The TPX II VQS is one of the sensors flown in TPX I, after refurbishment and calibration.

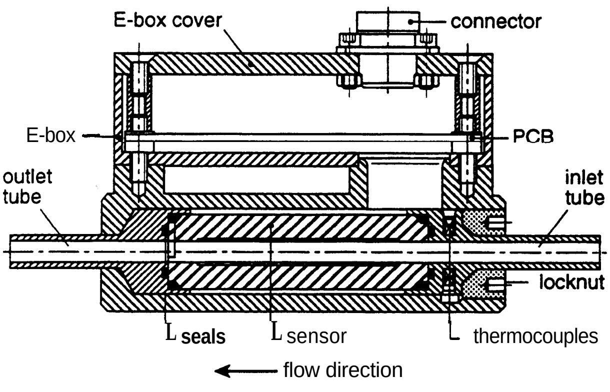

Fig. 11 TPX II Vapour Quality Sensor

Other Sensors: 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 absolute pressure is measured by the ENTRAN Absolute Pressure Sensor: maximum pressure 70 bar, 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. This allows 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.), allowing measurement from 0.002 g/s to 0.2 g/s ammonia with an accuracy of ± 1.5 % FS.

4. 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 Testing at loop level (prior to final loop closure and after the environmental testing), which will give full confidence on the TPX II loop to fulfil the required test objectives.
- Performance Tests on the TPX II experiment fully assembled. These tests consist of the Mission Scenario test sequences and will finalise the' Mission Scenario test parameters and figures.

The loop components are currently undergoing functional testing. Due to NASA constraints and major safety requirements updates, the second step of the pre-launch testing has not been performed yet.

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 °C, 40 °C and 60 °C (100 W - 25 W - 100 W - 10 W - 100 W).
- Depriming test by increasing the load of a depriming heater placed on the inlet liquid line, from 0 to 5 W in steps of 1 W (reservoir at 40 °C, condenser 15 °C).
- Variation of the reservoir temperature with a constant heat load of 50 W (40 °C, 42 °C, 46 °C, 40 °C, 38 °C, 35 °C, 34 °C and 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 °C, 35 °C, 30 °C, 25 °C, 24 °C, 23 °C, 22 °C, 21 °C and 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).

- Decrease of the heat load from 50 W to 15 W, to 10 W, to 5 W and to 2 W.
- Increase of the loop pressure drops by means of a valve (reservoir at 40 °C, condenser at 20 °C).
- Variation of the heat load applied to the start-up heater under various conditions:
  - Subcooling level of 2 °C, 5 °C and 10 °C.
  - Heat load of 20 W, 50 W and 100 W.
  - Start-up heater power of 1 W, 1 W, 2 W and 3 W.

The functional testing is 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.

The figures 12 to 19 give, as an example, some test results for the Cylindrical Evaporator CE. The figures 12 and 13 pertain to the depriming test, during which a heater placed on the evaporator inlet tube is activated. Figure 12 refers to the evaporator power, the depriming heater power and the differential pressure sensor measurements, while figure 13 refers to the temperature measurements. This test, performed at a controlled temperature of 40 °C and a heat sink temperature of 15 °C, shows clearly the correct behaviour of the CE up to a depriming heater power of 6 W.
Similarly figures 14 and 15 present the functional behaviour of the evaporator while decreasing and increasing the evaporator power.

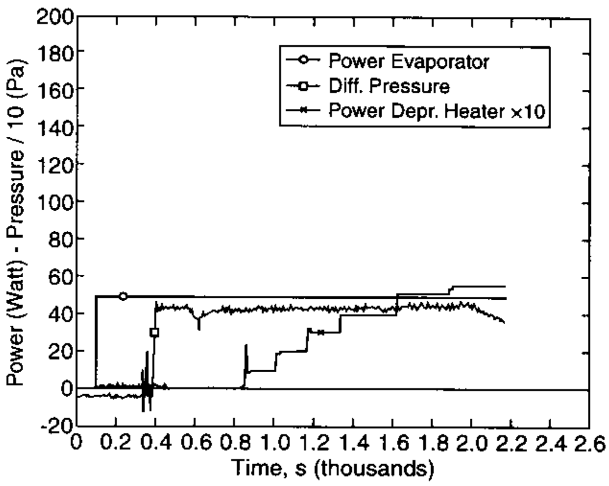

Fig. 12 Cylindrical Evaporator Depriming Test (Power and Pressure Distributions)

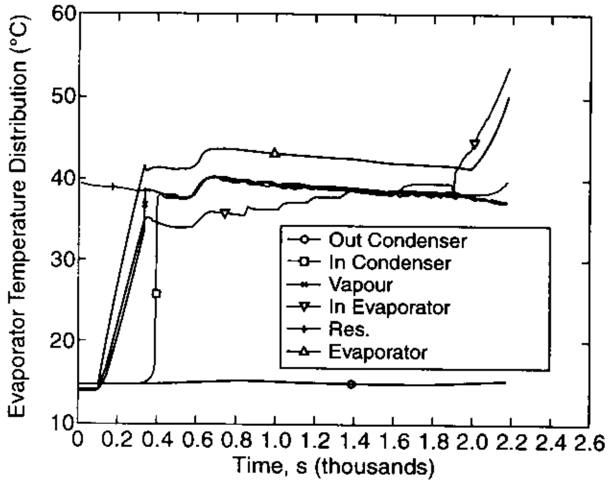

Fig. 13 Cylindrical Evaporator Depriming Test (Temperature Distributions)

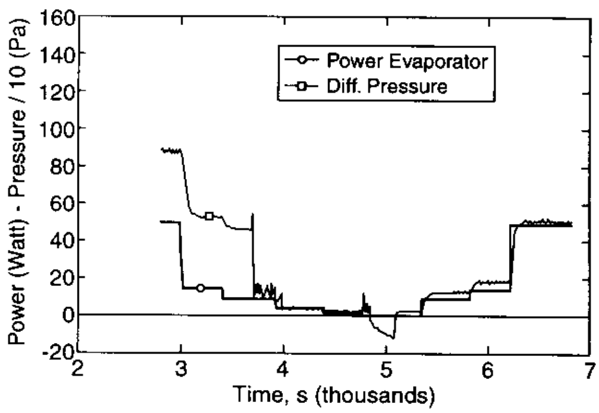

Fig. 14 Cylindrical Evaporator Variable Heat Load Test (Power and Pressure Distributions)

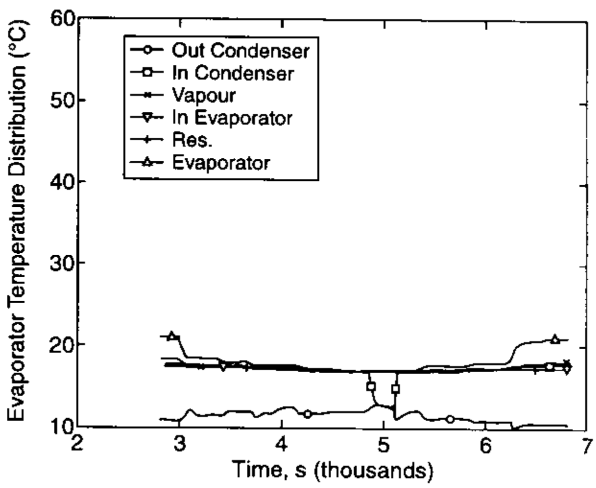

Fig. 15 Cylindrical Evaporator Variable Heat Load Test (Temperature Distributions)

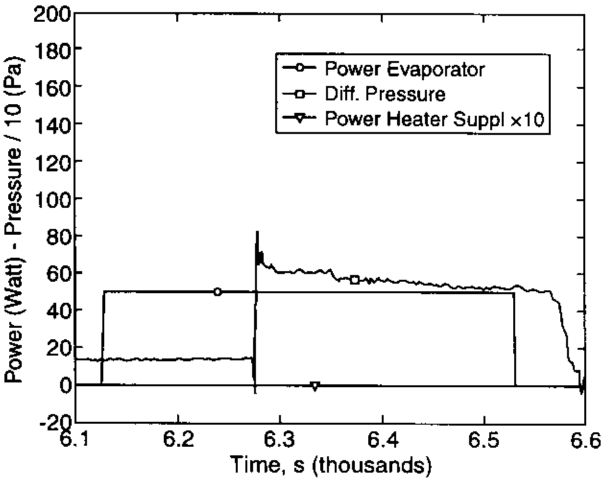

Fig. 16 Cylindrical Evaporator Start-up Test without Activating the Start-up Heater (Power and Pressure Distributions)

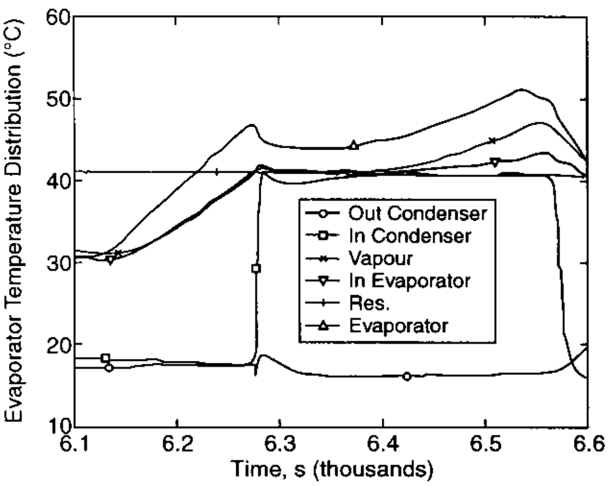

Fig. 17 Cylindrical Evaporator Start-up Test without Activating the Start-up Heater (Temperature Distributions)

The two tests, shown in the figures 12 to 15, were done with a start-up heater power of 3 W. This start-up heater, placed at the vapour outlet of the evaporator, provides a smooth and reliable start-up of the cylindrical evaporator. The figures 16 to 19 present the test results obtained for two start-up conditions.

For the figures 16 and 17 the start-up heater power (called Pow. Heater Suppl in the figures) is not activated, while in figures 18 and 19 this heater has been set to 3 W (under the same operating conditions).

Figure 17 shows that the generation of a vapour bubble in the evaporator needs an overheating of more than 5 K (taking into account the evaporator body thermal resistance). When the vaporisation takes place, this occurs with a high pressure spike (more than 0.5 bar, higher than the capillary pumping pressure), leading to the depriming of the evaporator wick material (vapor present at the evaporator inlet).

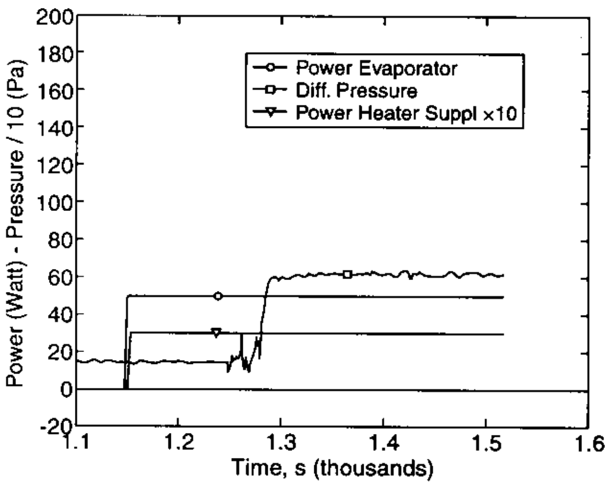

Fig. 18 Cylindrical Evaporator Start-up Test with the Start-up Heater Activated (Power and Pressure Distributions)

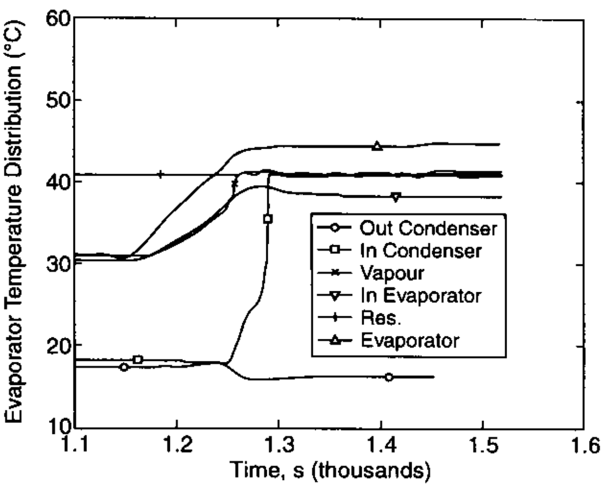

Fig. 19 Cylindrical Evaporator Start-up Test with the Start-up Heater Activated (Temperature Distributions)

In the case of figure 19, the start-up heater is activated. A vapour bubble is therefore already present at the evaporator vapour outlet when switching on the evaporator power. It is clear that no temperature peak does occur, which means that the pressure spike has been drastically dampened, leading to a correct start-up of the evaporator.

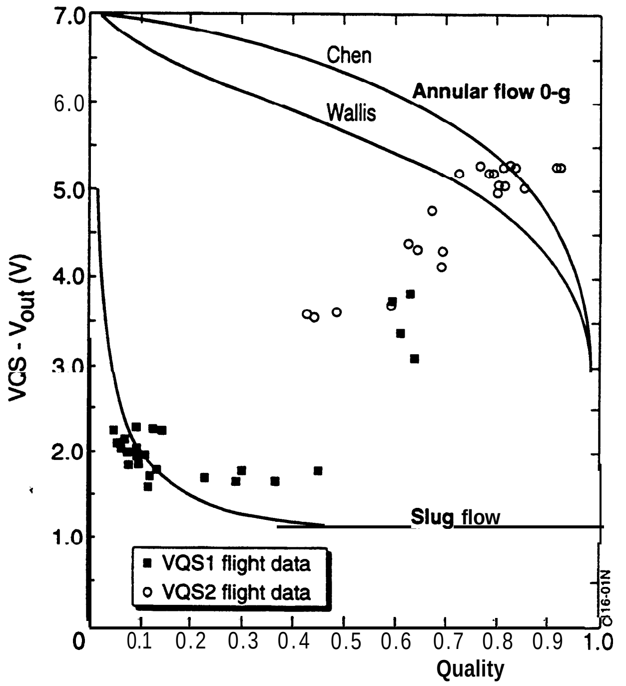

Fig. 20 VQS O-g Theoretical Responses and Flight Data

Figure 20 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) chum flow regime.
The TPX II VQS electronics has been tuned such that proper 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).

5. CONCLUDING REMARKS

The status of TPX II has been described in detail, including results of components testing.

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 an STS flight early 1998.

6. ACKNOWLEDGEMENT

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