THE AMS-2 TRACKERTHERMAL CONTROL SYSTEM: DEVELOPMENT OF THE MECHANICALLY PUMPED TWO-PHASE CARBON DIOXIDE COOLING LOOP

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Abstract

The Alpha Magnetic Spectrometer AMS-2 is an ISS-attached international payload searching for anti-matter, dark matter and lost matter. AMS-2 is an improved version of AMS-1, the demonstration experiment that has successfully flown on STS-91. AMS-2 is manifested on Space Shuttle flight UF-4.1 for a three to five year mission on ISS. The AMS-2 Tracker Thermal Control System (TTCS) is the two-phase heat transport system technology development by NLR and NIKHEF. It concerns a mechanically pumped two-phase cooling loop for the Tracker, the most critical part of AMS-2. The paper discusses the TTCS objectives and requirements, the trade-off based choice and experimental feasibility demonstration of the mechanically pumped two-phase Carbon Dioxide cooling loop, and the development of several test set-ups, including and a full-scale TTCS simulation loop and its components. Results of many experiments and of the thermal modelling and simulation activities are discussed in detail.

KEYWORDS

Alpha Magnetic Spectrometer, Anti-matter, Dark Matter, Lost Matter, Spacecraft Thermal Control, Two-Phase Flow, Two-Phase Heat Transfer, Mechanically Pumped, Two-Phase Heat Transport Systems, Evaporation, Condensation, Cooling Systems, Micro-Gravity, International Space Station.

INTRODUCTION

The Alpha Magnetic Spectrometer AMS-2 [1] is an international experiment, led by Nobel Prize laureate Samuel Ting of MIT, searching for anti-matter, dark matter and lost matter. It is a particle detector for high-energy cosmic rays (Figs. 1, 2) consisting various sub-detectors, being the (Silicon) Tracker, Time of Flight (ToF) system, Veto Counters, Transition Radiation Detector (TRD), Synchrotron Radiation Detector (SRD), Ring Imaging Cherenkov Counter (RICH), Anti-Coincidence Counter (ACC), and the Electromagnetic Calorimeter (EC).

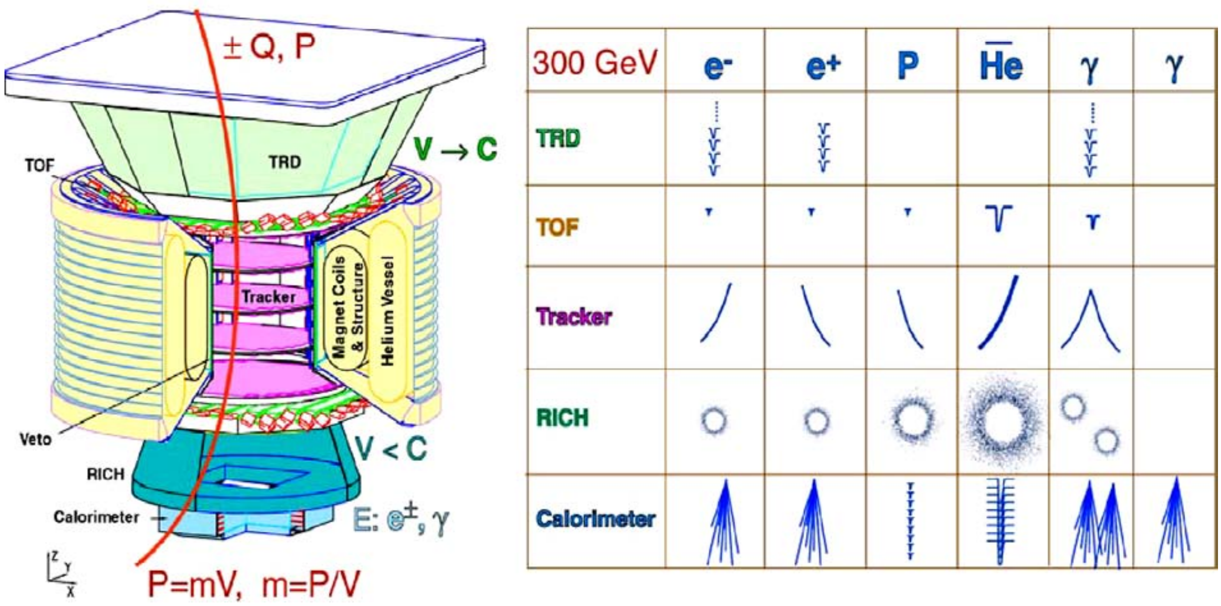


Figure 1. Alpha Magnetic Spectrometer AMS-2 and the particles to be detected by signals of the different detectors (electrons, positrons, protons, Helium nuclei and gamma rays).

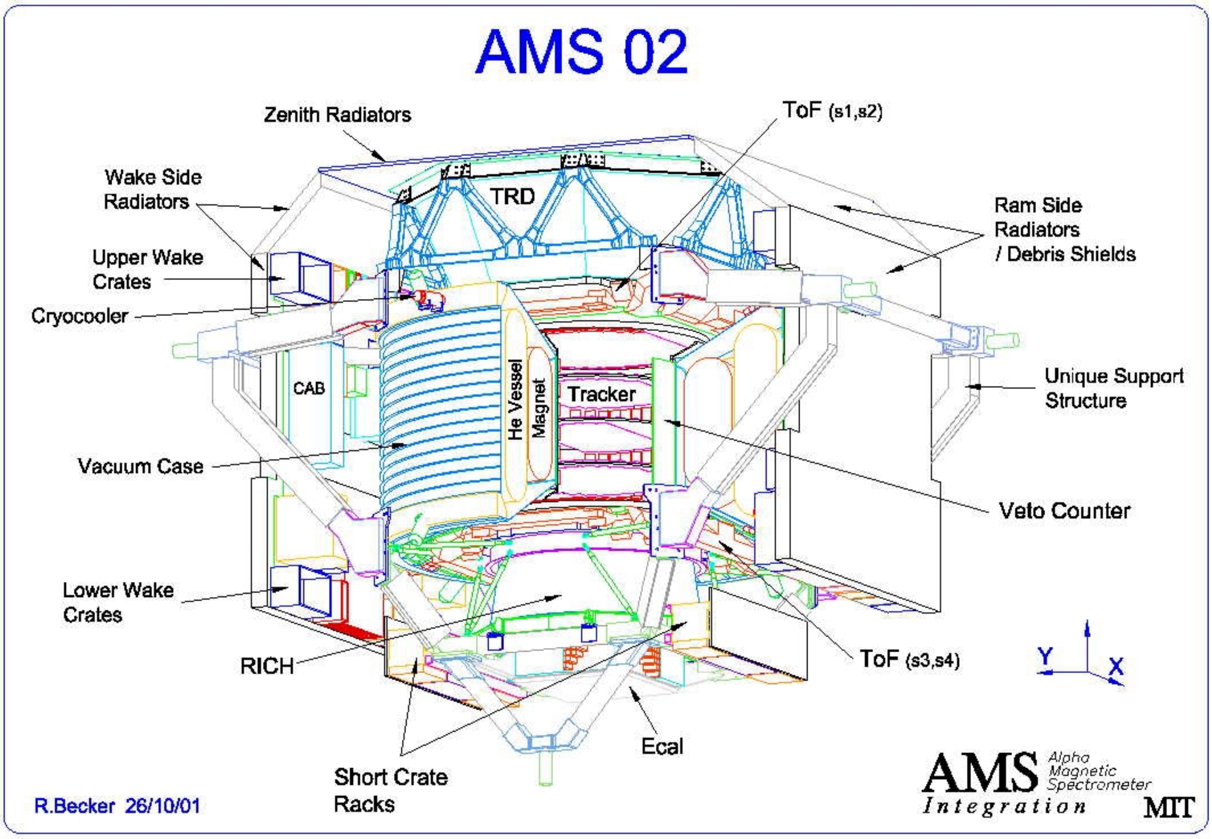


Figure 2. Alpha Magnetic Spectrometer AMS-2.

The AMS demonstration experiment, AMS-1, has successfully flown in June 1998 on the Space Shuttle Discovery STS-91 (Fig. 3a). AMS-2 is an improved (resolution) version of AMS-1. AMS-2 is manifested on Shuttle flight UF-4.1 for a 3 to 5 years mission as attached payload on the truss of the International Space Station ISS (Fig. 3b).

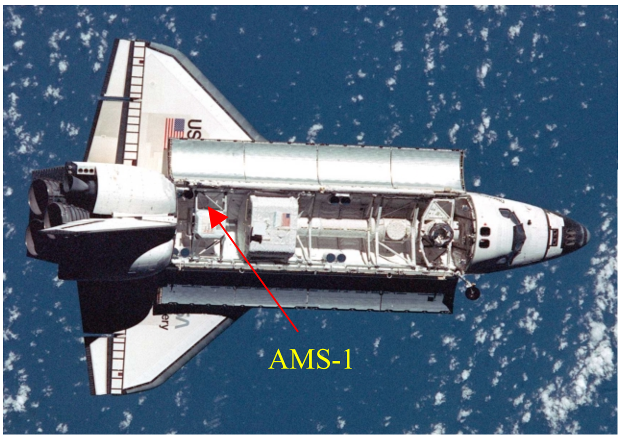


Figure 3a. AMS-1 payload aboard STS-91.

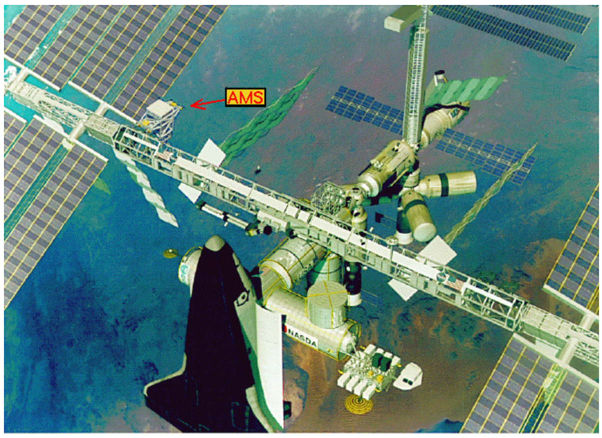


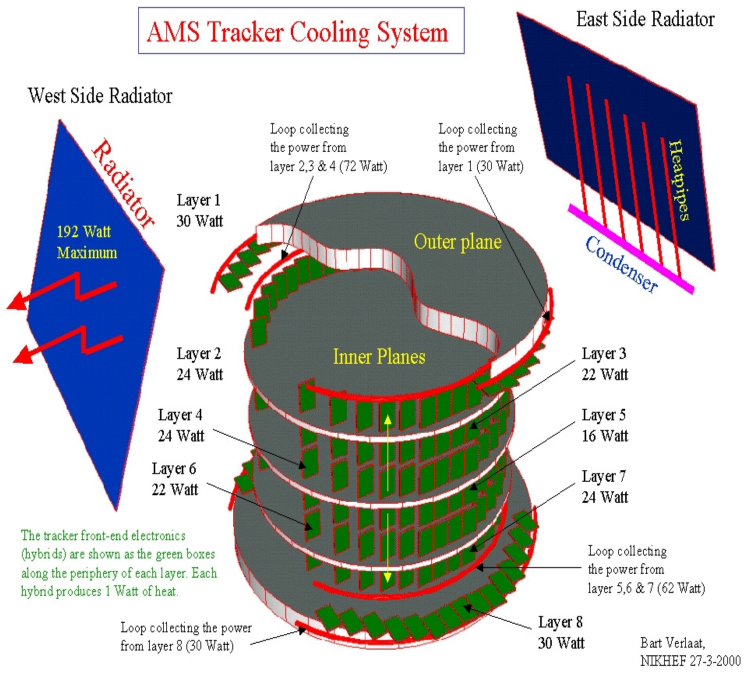
Figure 3b. AMS-2 location on ISS.

The AMS-2 thermal issues are far more demanding and critical than in AMS-1, because of the replacement of the original (heavy, high thermal capacitance) magnet by a liquid Helium II cooled super-conductive magnet, and by the long mission duration. Therefore a team consisting of NLR, NIKHEF, Geneva University and IFN Perugia is developing a cooling system for the most critical part, the so-called Tracker Thermal Control System TTCS.

The TTCS involvement offers NLR the possibility to use two-phase thermal control expertise obtained in the past for the challenging task to develop and operate an advanced, demanding system like the TTCS, probably being the first full- size mechanically pumped two-phase thermal control system in space. NLR joined the AMS collaboration because it offers, in addition, the possibility to do scientific research with the two-phase cooling loop during the various dormant periods in the AMS experimentation. The to be gathered information is expected to yield a far better understanding of the physics of two-phase flow and heat transfer in a low-gravity environment, The latter is essential for the development of reliable two-phase thermal control systems for future spacecraft applications.

TRADE-OFF RESULT: A CARBON DIOXIDE MPL IS THE TTCS BASELINE

The Tracker, located inside the vacuum case, is surrounded by the cryogenic magnet, which is not allowed to receive any heat from inside. Moreover the Tracker has severe requirements with respect to spatial and temporal temperature gradients. This and the existing complicated three-dimensional configuration, requires that the power dissipated inside the Tracker has to be removed to two thermally out of phase radiators (one in the RAM, one in the Wake direction) to be dumped into space. This task could be done by a mechanically pumped two-phase loop system, by a mechanically pumped liquid loop and by a capillary pumped loop system. The latter system requires heat collecting heat pipes to transport the dissipations from the silicon front-end electronics to the capillary system, as a capillary system can’t properly handle evaporators (heat sources) in series. In addition, a parallel, capillary system [2, 3] leads to an unacceptable tubing length and mass, which can not be accommodated by the already existing 3-D Tracker configuration. To meet the isothermality requirements, the liquid loop needs large diameter, thick-walled tubing. Apart from its unacceptable mass, the existing AMS configuration does not offer enough spacing to accommodate large diameter liquid loop lines, because the chosen system has to be installed in two-fold to guarantee the full redundancy requirement. A schematic of the Tracker configuration and the requirements are depicted in figure 4.



Silicon wafer requirements:

- **Operating temperature:** **-10 ºC / +25 ºC**
- **Survival temperature:** **-20 ºC / +40 ºC**
- **Temperature stability:** **3 ºC per orbit**
- **Maximum accepted gradient between any silicon:** **10.0 ºC**
- **Dissipated heat:** **2.0 W EOL**

Hybrid circuit requirements:

- **Operating temperature:** **-10 ºC / +40 ºC**
- **Survival temperature:** **-20 ºC / +60 ºC**
- **Dissipated heat:** **192 W, 1 W per hybrid pair**

Figure 4. Silicon Tracker thermal issues.

All hybrid circuit power values in this figure have to be multiplied with 0.75, as the dissipation figure for the 192 hybrid pairs, 1 W per pair, was very recently reduced to 0.75 W per pair. In addition two Star Trackers were coupled opposite each other to the top loop, each one dissipating 3.4 W. The currently valid requirements are: For the silicon wafer:, operating temperature 263-298 K, survival temperature 253-313 K, temperature stability 3 K per orbit, maximum gradient between any silicon: 10 K, and dissipated heat 1.5 W End of Life; for the hybrid circuit, operating temperature 263-313 K, survival temperature 253-333 K, dissipation 144 W total (± 10%), 0.75 W nominal per hybrid pair; for the two Star Trackers , operating temperature 263-313 K, survival temperature 253-333 K, dissipation 3.4 W each.

Keeping the above in mind and following the contents of earlier publications on the TTCS [3, 4], it can be said that:

- A series or hybrid two-phase Mechanically Pumped Loop (MPL) is well compatible with existing Tracker hardware. It is characterised by minimal material inside or near the tracker field of view. It is directly connected to the thermal bars, hence no additional heat collector needed. Multiple source heat input is possible, with minimum T-gradients (order of magnitude 1 K). It has also the possibility to implement a fully redundant system. Costs and mass are relatively low. The only drawback is the mechanical pump.
- A Single-Phase (liquid) Mechanically Pumped Loop (SPL) has more or less the same layout as the MPL option, so it is relatively easy to fall back on the SPL solution, in case of unforeseen (serious) problems with the MPL development. It has the possibility of parallel and counter-current flow system set-up. It is a low-risk design, as there is sufficient experience in space with SPL's. Main drawbacks are the far larger temperature gradients (order of magnitude 10 K), as compared to the nearly isothermal MPL, and larger dimensions, mass, and the serious conflict with the full redundancy requirement.
- Any parallel two-phase system (MPL, LHP, CPL) can not to accommodate the existing Tracker hardware multiple location heat input, by it self in one stage, as of the huge mass and (not available) space needed, induced by redundancy. A two-stage approach needs an additional heat collector, heat pipe or TPG-flange, leading to significant mass increase and serious integration problems.

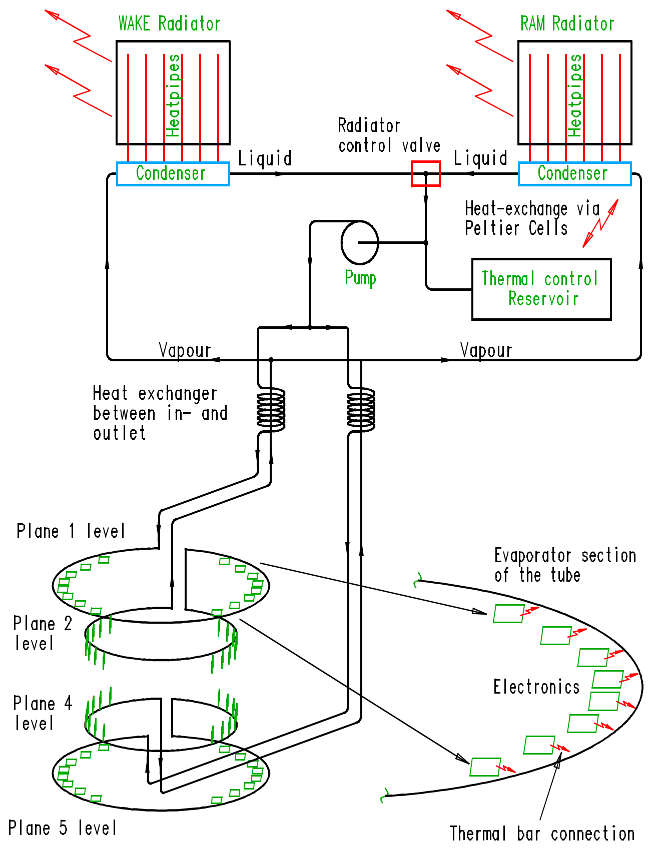
The above makes obvious that by far the best solution is the series or hybrid two-phase MPL. A parallel or hybrid SPL is a possible back-up solution, but at the cost of more massy and lengthy lines and larger pumps. Parallel concepts are non-recommendable or impossible solutions. CO_2 has to be the working fluid because:

- It is considered to replace Freon-like refrigerants, as it is environment friendly and non-toxic. It is used for nuclear power plant cooling, as it is inert for radioactive radiation. For AMS-2 this means no ISS safety-related problems.
- It has a very low liquid/vapour density ratio, Order (1-10), being profitable for a series 2-phase system; its alternative, ammonia: Order (10^2-10^3).
- CO_2 experience was gained at NIKHEF, where tests have proven the concept feasibility of CO_2 cooling for the LHCb Vertex detector [5]. For the Tracker this means small tube dimensions (3 mm OD) in case of 2 loops, low temperature drops (< 1 K) and low pumping power (< 10 W).

In addition it is remarked [4] that:

- The basic difference between mechanically pumped single-phase (caloric heat transport by the liquid) and two-phase systems (transport by latent heat of evaporation/ condensation). This implies for dissipating stations in series in a single-phase system a temperature increase in the downstream direction of the loop. For two-phase systems, with evaporators in series, it means an increase of the vapour quality in the downstream direction, accompanied by a (usually small) decrease of the saturation temperature.
- In mechanically pumped two-phase loops, the flow pattern dependent heat transfer coefficient for convective flow boiling is reported [6] to be between say 4 and 5 $kW/m^2 \cdot K$. This is not true for refrigerants (to be used in the TTCS) at qualities below 0.15 for which the value can increase to say 20 $kW/m^2.K$ at qualities of less than 0.03 [6, 7]. Data from experiments with CO_2 in small diameter tubes confirm this [8]. The above implies that a mechanically pumped system has to be designed such that any evaporator exit quality is below 0.15 (preferably even much lower) for efficiency reasons.
- In the case of very lengthy mechanically pumped two-phase loop lines, the pressure (saturated temperature) gradient has to be kept small to guarantee a small end-to-end pressure (saturated temperature) difference. This is to meet the requested isothermality, and to keep the evaporator exit vapour quality below 0.15, as in flowing refrigerants the vapour quality usually increases with pressure decay (if one assumes isentropic flow [9]). Ethane is an exception: Quality increases below say 0.7, decreases above. In real flow is isenthalpic [10], meaning that the quality always increases, also for ethane.

The general conclusion is that a dedicated hybrid two-phase TTCS loop configuration, as it is schematically depicted in figure 5, will guarantee both the "isothermal" specifications and the preferred quality range.



- **Maximum expected operating pressure: TBD (depends on maximum TTCS temperature):**
  125 bar @60°C, 140 bar @70°C, 160 bar @80°C, 175 bar @90°C
- **Pressurized volume ca. 3 liter CO_2 per loop:**
  600 cc tubes, 2.5 liter accumulator
- **2 (almost) identical fully separated loops (1 for redundancy)**
- **2 serial evaporators in parallel per loop**
- **2 parallel condensers controlled per loop controlled by a 3-way valve**
- **Pressure control by thermal control reservoir**
- **Thermal control using the USCM**
- **Critical parts are redundant (pump, valves)**
- **Most fluid components in 2 dedicated TTCS boxes on the USS at wake side**
- **RAM and WAKE heat pipe radiator**
- **All hardware in debris safe areas, debris shields added if needed**

Figure 5. Hybrid MPL concept for the TTCS.

CURRENT STATUS OF TTCS DESIGN

The proposed TTCS primary loop is depicted in figure 6. It is a closed two-phase system: Heat is absorbed in the evaporators and withdrawn at the condensers, and rejected to space by the radiators. As the mechanical pump provides the liquid flow rate needed, it has to be located after the condensers, as it needs pure liquid to operate properly. Hence the condensers/radiators need not only to condense all vapour, but also to provide a certain amount of sub-cooling.

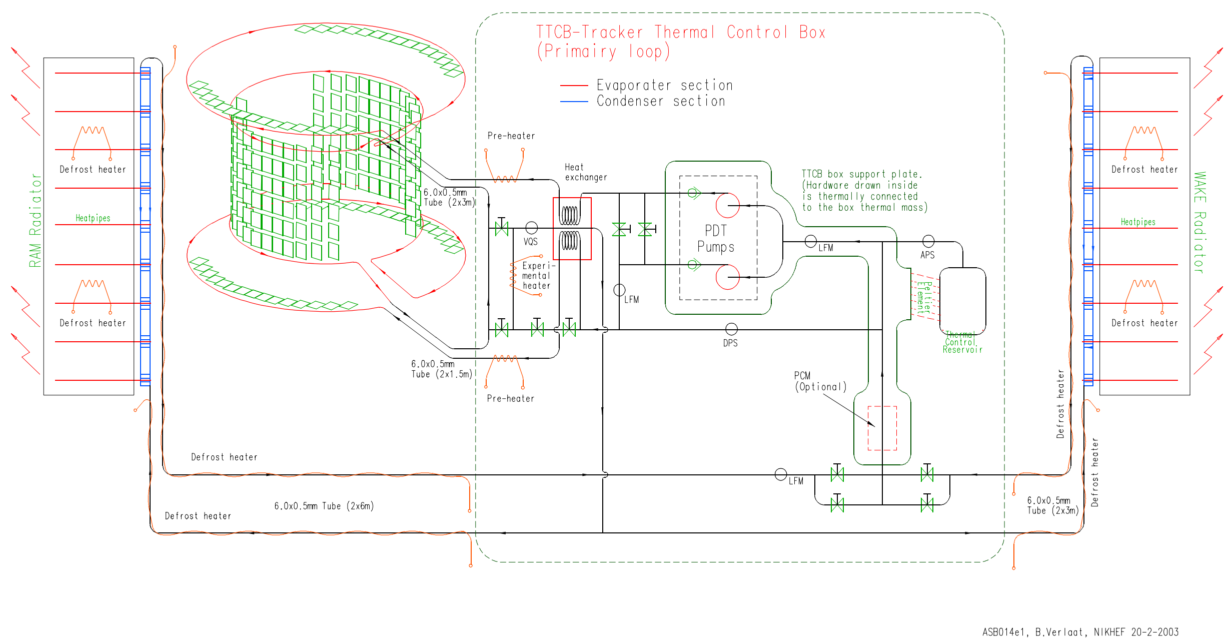


Figure 6. TTCS Primary loop (Secondary loop is almost identical, it only has less instrumentation).

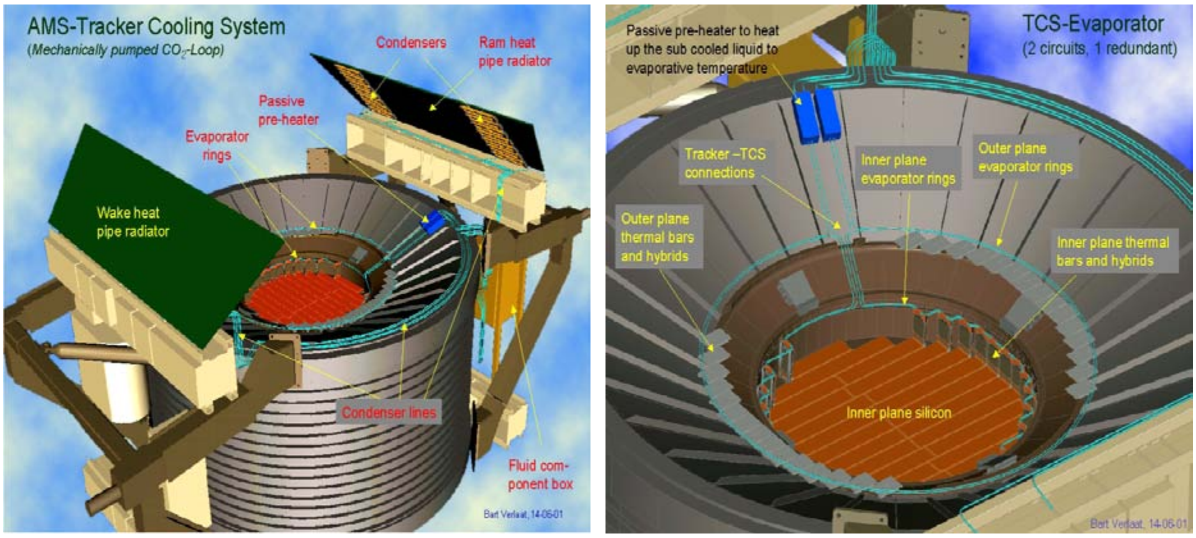


Figure 7. Impression of integrated TTCS (left)and TTCS evaporator (right).

The blue boxes on top (Fig. 7) are heat exchangers, thermally connect inlet and outlet of the evaporator together. In this way the absorbed heat can be used to heat the entering sub-cooled liquid from the pump so it gets close to the evaporative temperature needed in the Tracker. The evaporators consist of two parallel tubes each having an ID of 2.6 mm and a length of 10 metres. These two tubes are serially cooling the hybrid circuits, located on the outer periphery of the Tracker. The parallel evaporator branches (Fig. 5). are routed as two rings following the widely distributed Tracker hybrids. The second branch is located similarly at the bottom of the Tracker. The evaporator tube is mounted with a copper connection bridge to the hybrid thermal support structure named thermal bars. The figures 8 to 11 show the thermal connection from the inner thermal bars to evaporator. Clearly visible is the bent configuration of the evaporator tube; which is needed to follow the stepped orientation of the tracker hybrid boxes. This stepped orientation is one of the reasons that a small diameter evaporator tube was selected as the baseline, because it seemed to be the only design that was compatible with the already existing tracker hardware. There are two tubes, one acts as the redundant line in the case of a failure.

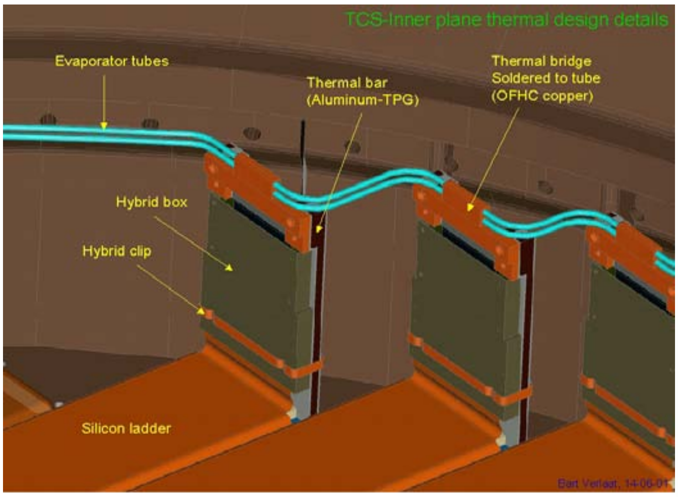


Figure 8. Evaporators connected to inner bars.

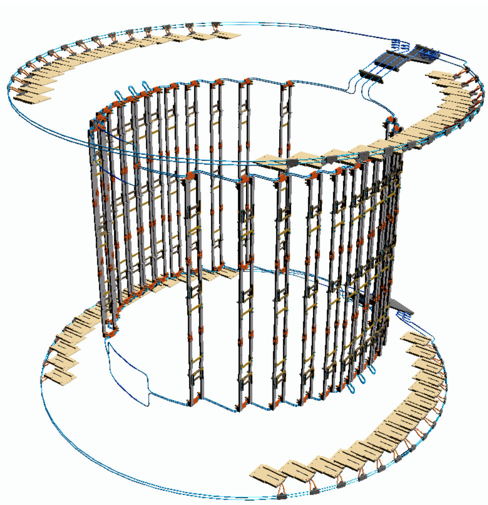


Figure 9. Complete system inside the Tracker.

The AMS-2 radiator panels are outside the experiment (Fig. 7). They are covered with high emissivity and low solar absorptivity coatings/paints. The two opposite radiator panels are thermally speaking out of phase, meaning that there is always one radiator shaded from the sun, hence able to radiate waste heat to space. The evaporation temperature is adjusted by the system pressure. This pressure is controlled via the accumulator, a small reservoir with a mixture of vapour and liquid. A Peltier element controls the reservoir temperature, hence the system pressure by condenser flooding.

The majority of the TTCS hardware is in a box outside on the support structure. The evaporators, heat exchangers and condensers (Fig. 12) are outside this box.

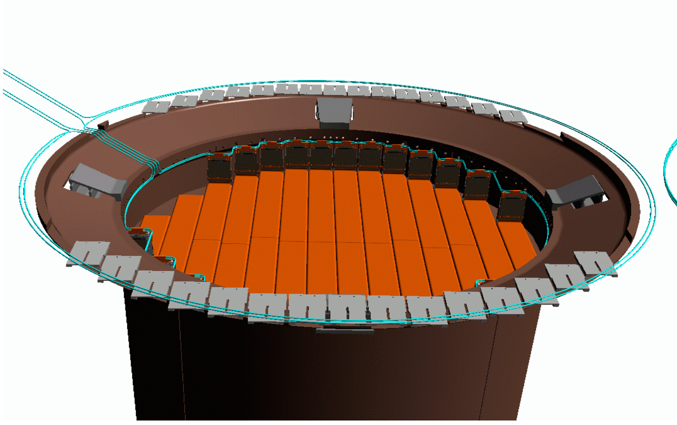


Figure 10. Overview of one TTCS evaporator.

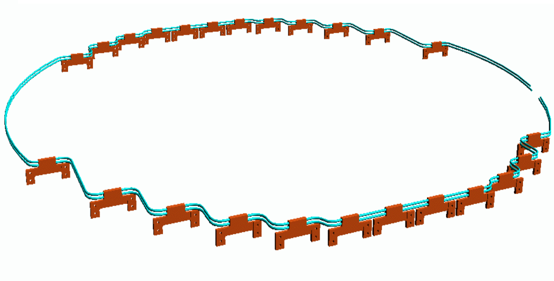


Figure 11. Inner planes evaporator.

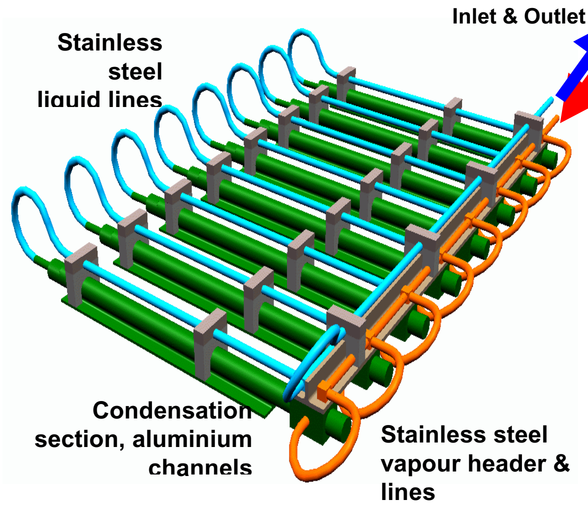
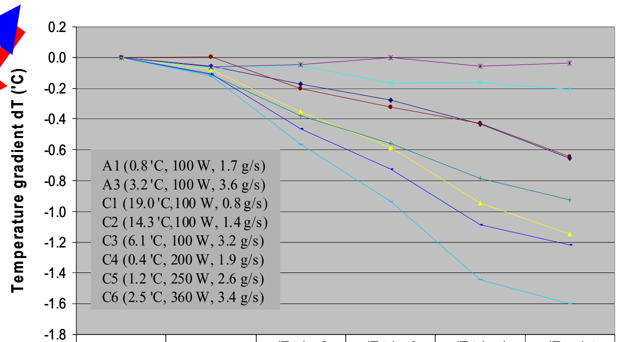


Figure 12. TTCS condenser



	dT inlet (0m)	dT tube 1 (1m)	dT tube 2 (3.4m)	dT tube 3 (5.8m)	dT tube 4 (8.3m)	dT outlet (9.3m)
A1	0.0	-0.1	-0.2	-0.3	-0.4	-0.7
A3	0.0	-0.1	-0.4	-0.6	-0.9	-1.1
C1	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
C2	0.0	-0.1	0.0	0.0	-0.1	0.0
C3	0.0	0.0	-0.2	-0.3	-0.4	-0.6
C4	0.0	-0.1	-0.4	-0.6	-0.8	-0.9
C5	0.0	-0.1	-0.5	-0.7	-1.1	-1.2
C6	0.0	-0.1	-0.6	-0.9	-1.4	-1.6

Figure 13. Temperature gradient along evaporator.

TESTING ISSUES

An open loop test set-up [4], built at NIKHEF to prove the feasibility of the TTCS evaporator concept for CO_2, consisted of an evaporator section connected to a liquid CO_2 filled bottle. The CO_2 flow was adjusted by a needle valve, the pressure in the test tube by a spring-relieve valve (at the exit). In the real TTCS all thermal bridges are individually connected to the to evaporator tubes. In the feasibility test set-up heat is applied over the test section tube wall using the electric resistance of the tube as heater. Flow, pressure drop and temperatures along the tube were measured. Figure 13 shows some test results, which confirm that CO_2 is an adequate refrigerant for the TTCS.

More experiments were done next at NIKHEF [4] to confirm this in a closed-loop test set-up, which more realistically simulates the TTCS. The goals of the experiments were:

- To measure the pressure drop characteristics and heat transfer coefficients at different flow rates, heat input and evaporation temperatures, using a 10 m long, 2.5 mm ID test evaporator, with helical sections between the long sections to simulate the multiple bends in the real Tracker.
- To compare the test outcomes to theoretical predictions and experimental data produced in a NIKHEF/SINTEF CO_2 test set-up.
- To prove the merits inserting a heat exchanger (as pre-heater) between evaporator in- and outlet.
- To yield recommendations for further TTCS development, on pumping rates and evaporators.

Though many experiments were executed [11], the results given here pertain only to the 10 m long, 2.5 mm ID evaporator performance, i.e.:

- Figure 14, showing the pressure and temperature drops, as a function of the mass flow, at 273 K.

- Figure 15, showing the heat transfer coefficients and observed flow patterns versus vapour quality and heat flux, at 278 K and nominal flow 2.7 g/s.

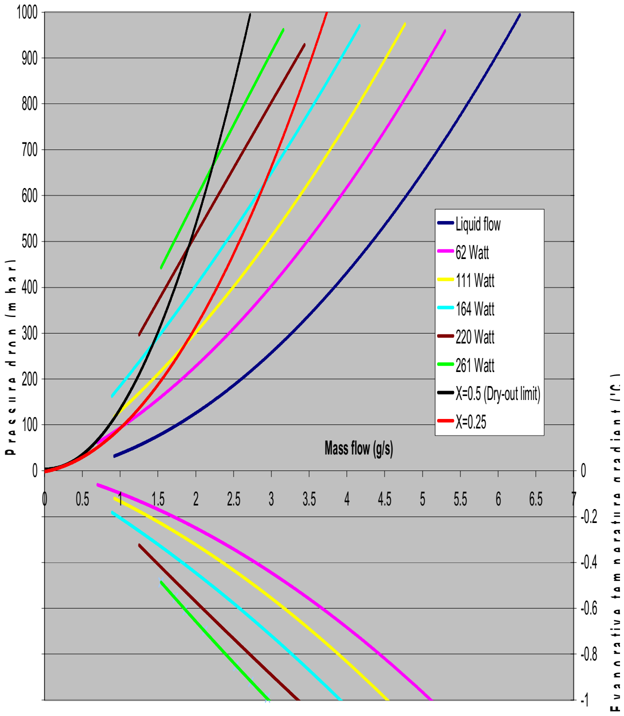


Figure 14. Power dependence of pressure and temperature drops at 273 K.

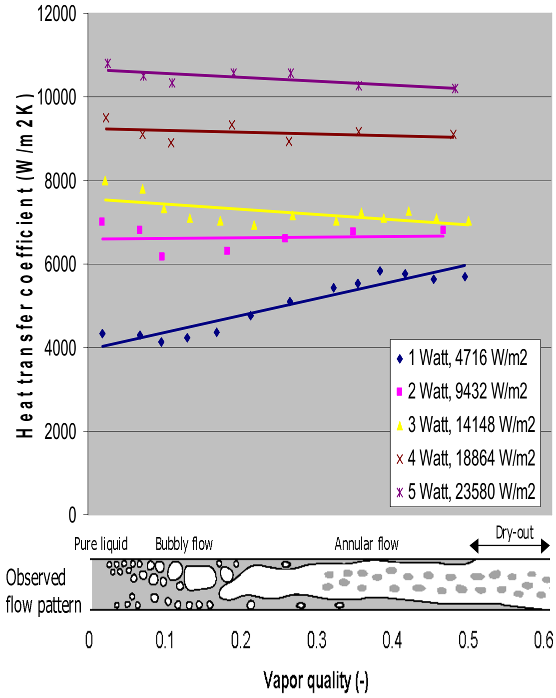


Figure 15. HTC and power (density) versus flow patterns and vapour quality at 2.7 g/s & 278 K.

Finally it is remarked that preliminary test results confirm the usefulness of the presence of a heat exchanger as pre-heater between the in- and outlet of the evaporator. It was observed that up to say 90% of the heat collected in the evaporator could be reused for pre-heating the sub-cooled liquid coming from cold radiators. This amount of heat replaces part of the power to be added to the electric pre-heater that has to condition the liquid such that the fluid entering the evaporator is a pure liquid, close to saturation temperature as desired. It is obvious that the above yields a substantial power saving. Apart from this power saving impact, it can be said that the presence of the heat exchanger has also a stabilising effect on the temperature excursions of the evaporator during orbital radiator temperature variations.

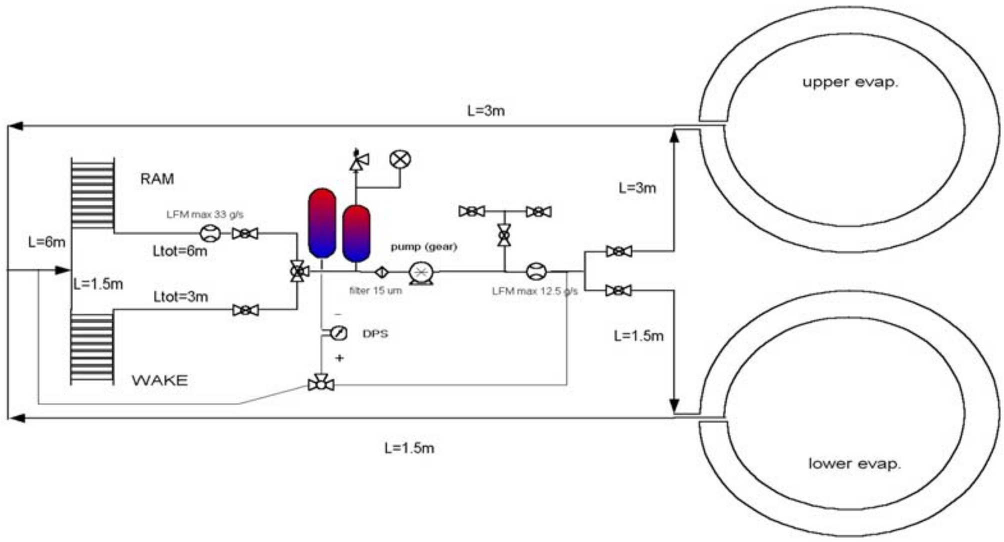


Figure 16. Schematic of NLR's full-size simulation test rig.

The next step in the development was the creation of a full-scale test set-up at NLR for a more realistic simulation of the TTCS. A preliminary rig was designed and built. Based on experimental results obtained with this rig, the full-scale test set-up was designed and manufactured. Figure 16 depicts the schematic of the set-up. Figure 17 shows a photograph of the current test set-up in the NLR climate chamber. Details are shown in figure 18 (evaporator) and in figure 19, a specimen of the baseline for the TTCS condensers, consisting of elements, which will interface the Ram and Wake heat pipe radiators.

The first experiments with this full-size test set-up yielded very encouraging results: The pressure drops across the system turned out to be even smaller than predicted: Almost ideal isothermality is approached.

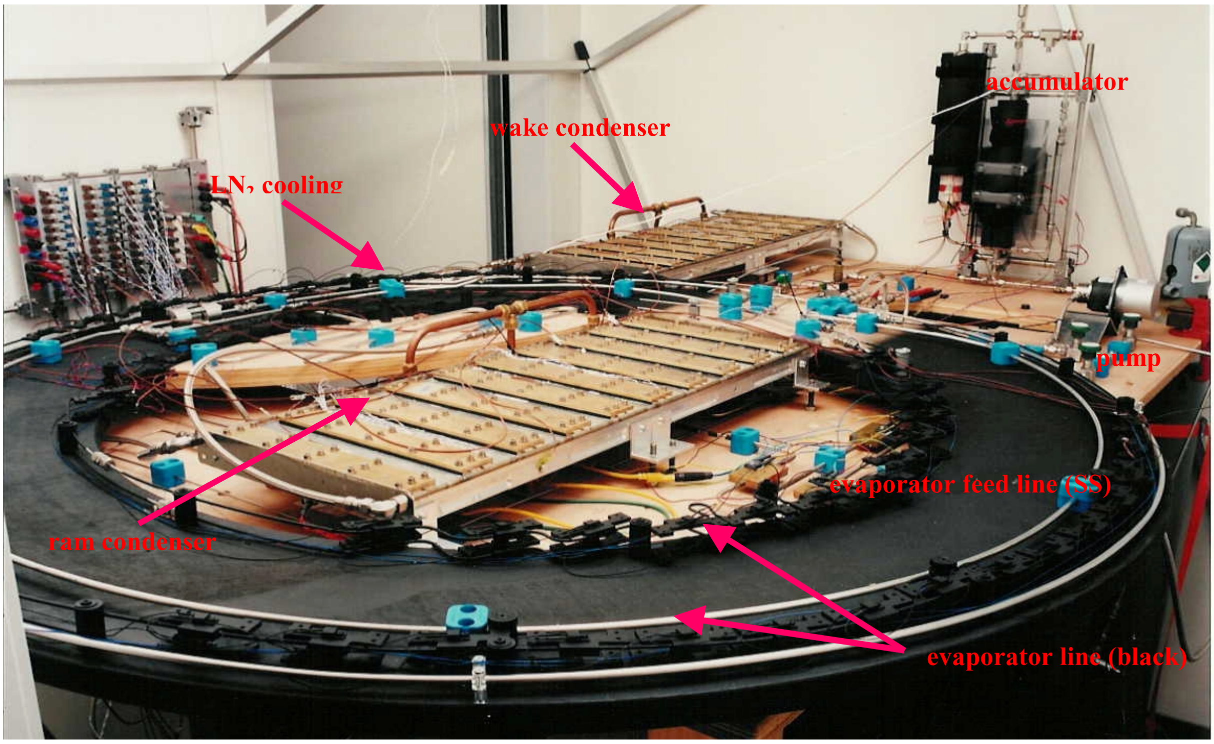


Figure 17. Full-size simulation test rig. at NLR.

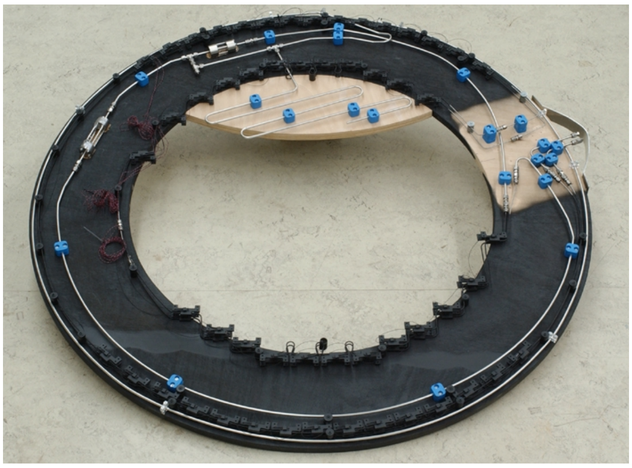


Figure 18. Full size evaporator.

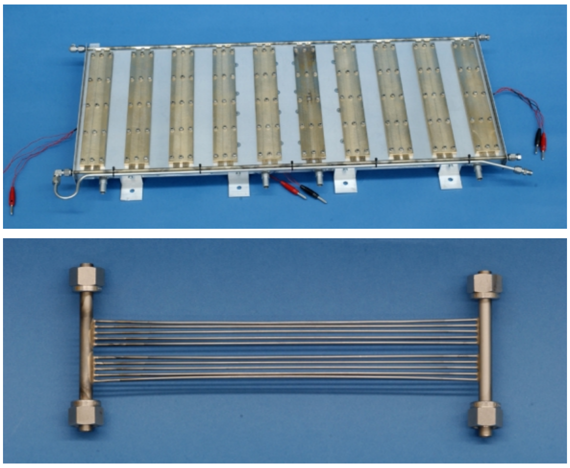


Figure 19. TTCS condenser & element.

In order to study the heat transfer in vacuum, along the thermal bar itself and from the thermal bar to the loop evaporator, a test set-up has been built at NIKHEF (Figs. 20, 21). Some results will be presented in the next chapter, in order to compare these with the outcomes from thermal modelling exercises.

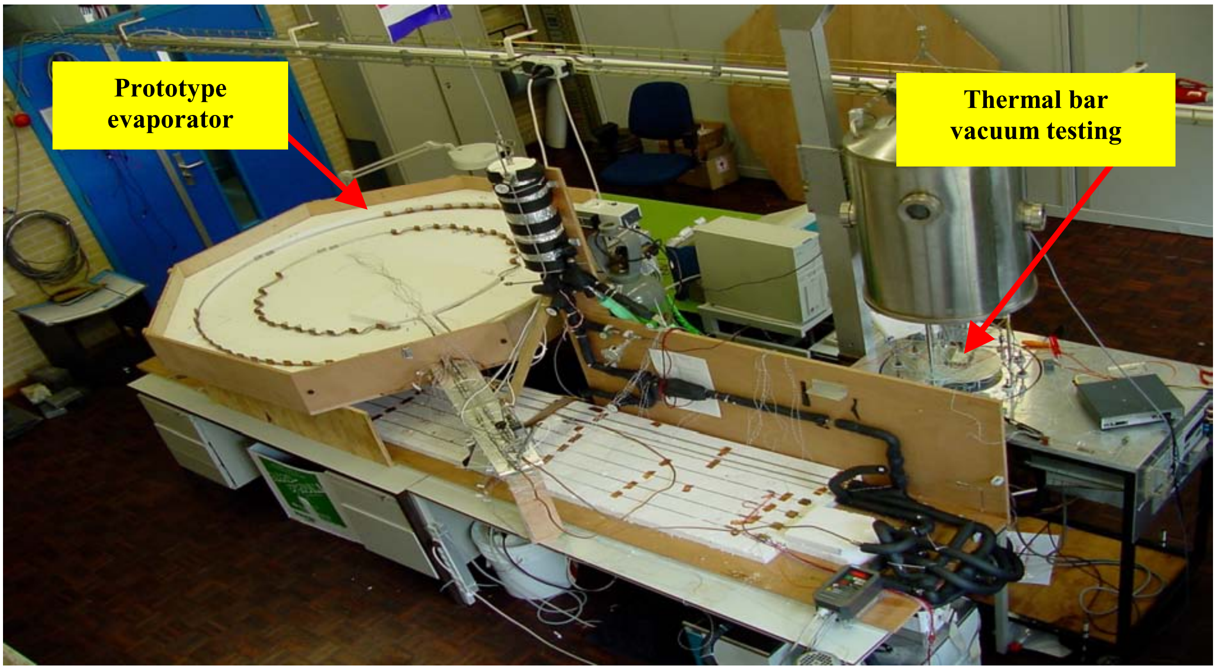


Figure 20. NIKHEF's evaporator & thermal bar (in vacuum) test loop.

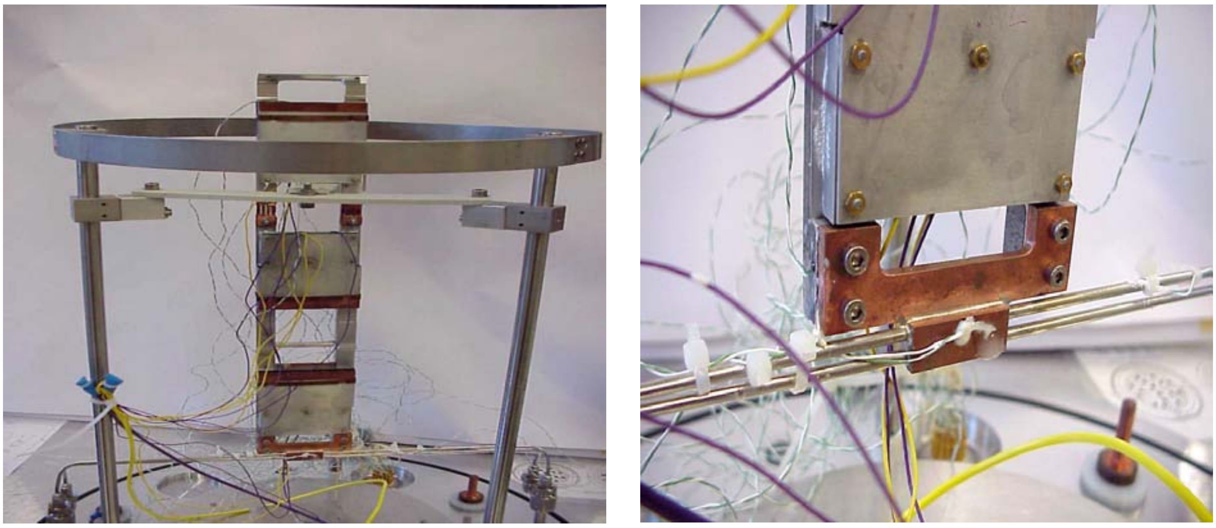


Figure 21. Thermal bar array with evaporator connection for thermal vacuum testing, connection detail.

THERMAL MODELLING ISSUES

Calculations with a very detailed transient TTCS model (Fig. 22) have been done for many possible orbital (environmental loading) cases. The outcomes [13] clearly indicate that:

- The TTCS will operate without problems at the nominal loop set-point temperature 273 K, for the nominal case and most other thermal loading cases (Fig. 23).
- In some hot orbital cases, the set-point temperature of the loop has to be increased by roughly 10 K (Fig. 24).
- The incorporation of the heat exchanger between evaporator in- and outlet considerably reduces the pre-heater power needed (Fig. 25). This is important, since the power available for pre-heating is very limited.
- Figure 26 proves that the outcomes of the measured thermal bar temperature gradients and the thermal modelling predictions are in reasonably agreement.

The modelling was refined when more accurate environmental loading conditions were provided by CGS, the "AMS Overall Thermal" main contractor. Using these new boundary conditions, new calculation runs were executed for various orbital environments and loop temperature set-points. The results shown in the figure 27 confirm the must of including a heat exchanger: Considerable reduction of pre-heater power, though the pre-heat power needed is still far higher than the power available.

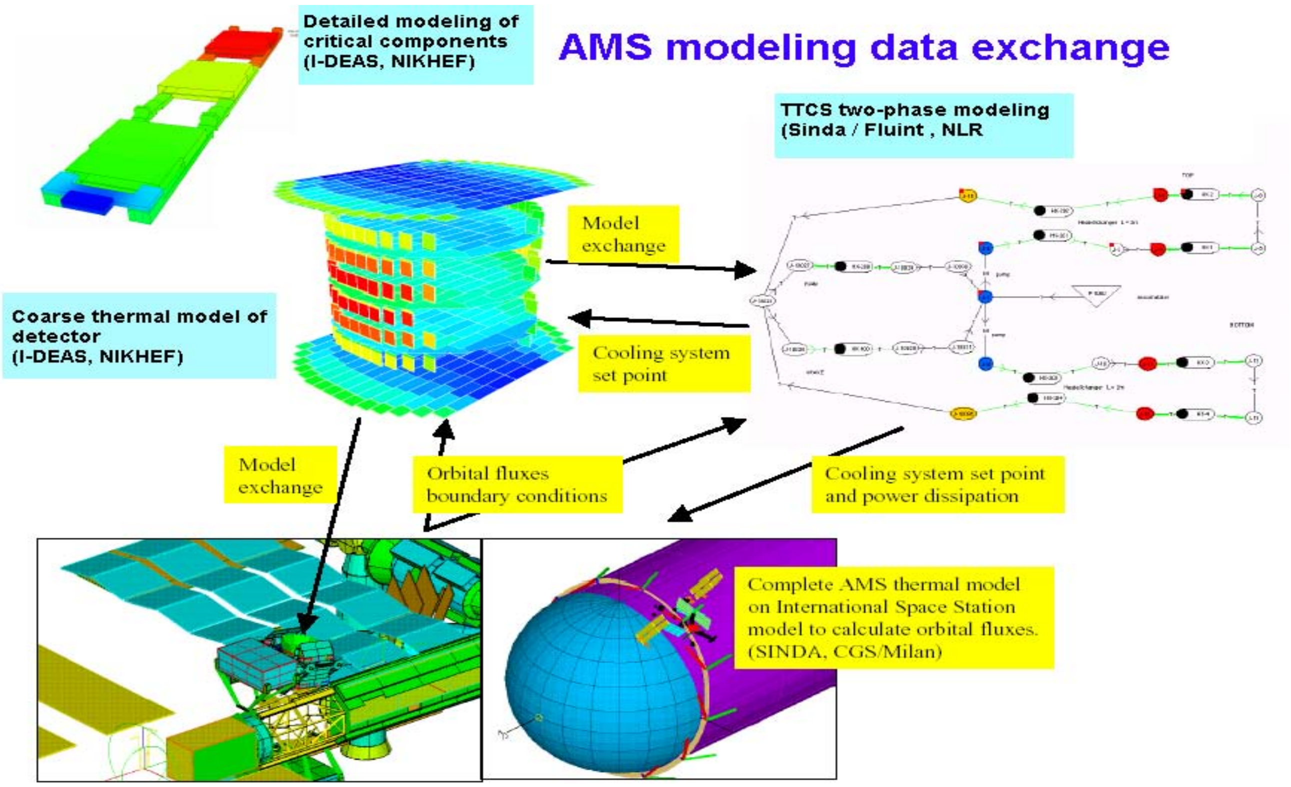


Figure 22. AMS-2 Modelling data exchange diagram.

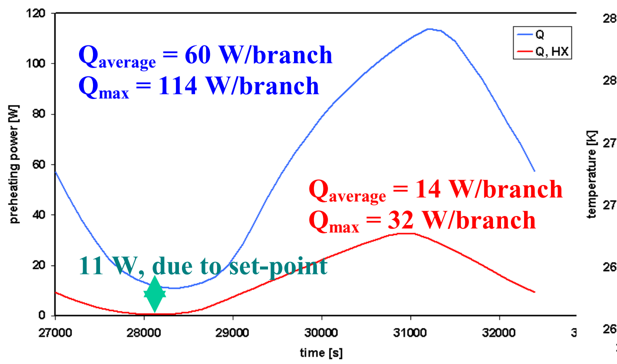


Figure 23. Influence of presence of heat exchanger.

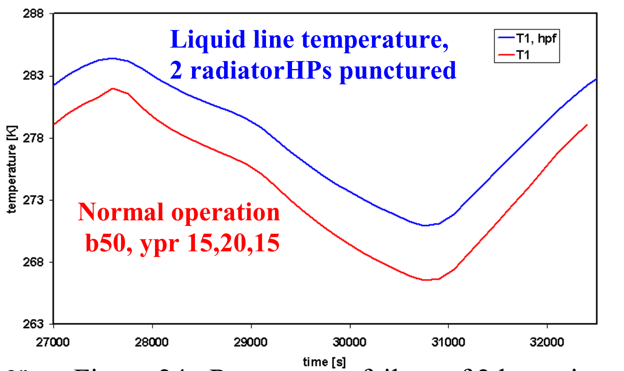


Figure 24. Response to failure of 2 heat pipes.

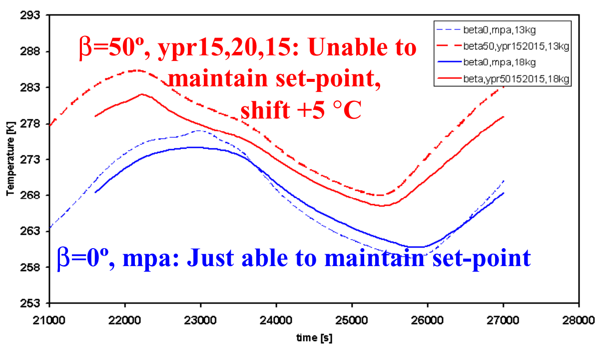


Figure 25. Liquid temperatures entering pump: Effect of total mass of radiators (2x13 kg /2x18 kg & orbit. (β=0°/50°).

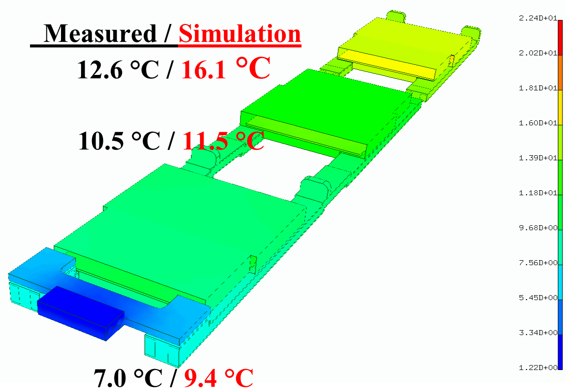


Figure 26. Outcomes of thermal bar modelling versus results of experiments.

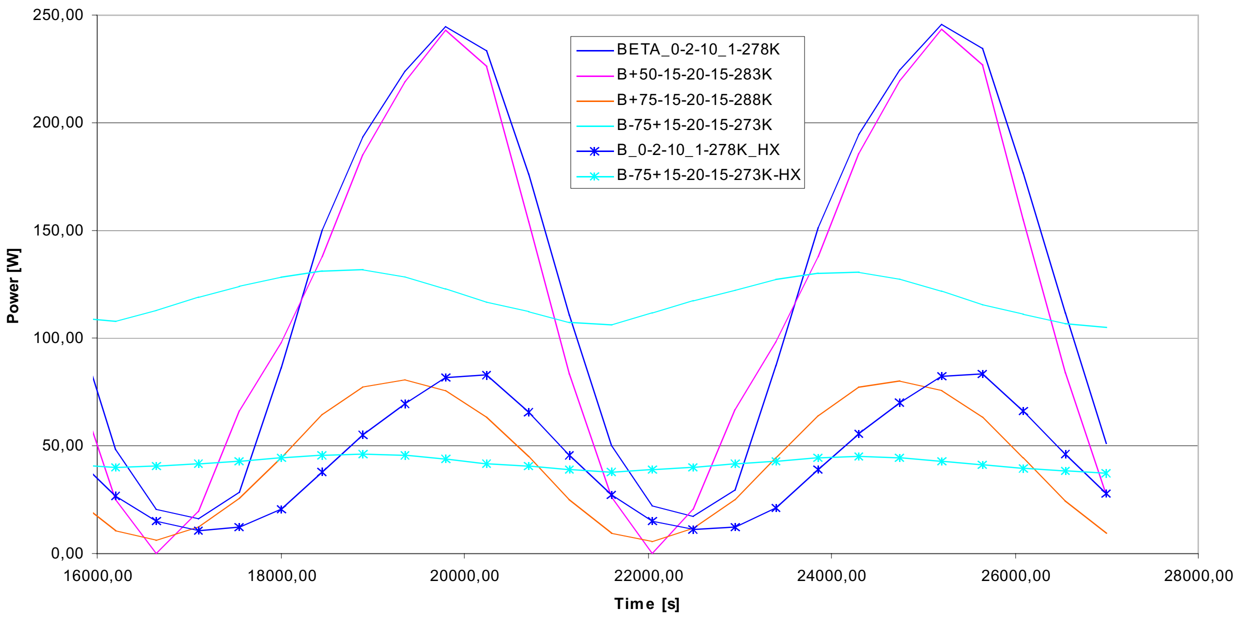


Figure 27. Pre-heater power curves for six different orbits.

The above results are indicative only, because up to this point all calculations were done for a total hybrid dissipation of 192 W (1 W per hybrid pair) for 1.6 m^2 radiators. But the measured dissipation of recently delivered hybrids turned out to be only 0.75 W (±10 %). Consequently all the following design calculations were to be done for a total hybrid dissipation of 144 W (+10 % for the hot orbits, -10 % for the cold orbits). In addition, the door dimensions of the Boeing 747 (the carrier to transport AMS-2 from Europe to NASA-JSC and KSC) limit the radiator size appreciably. Therefore the calculations were to be done for the maximum radiator sizes possible, being 1.25 m^2, 11 kg for a flat radiator option, 1.43 m^2, respectively 12 kg, for a curved radiator option (both radiator options are shown in figure 28).

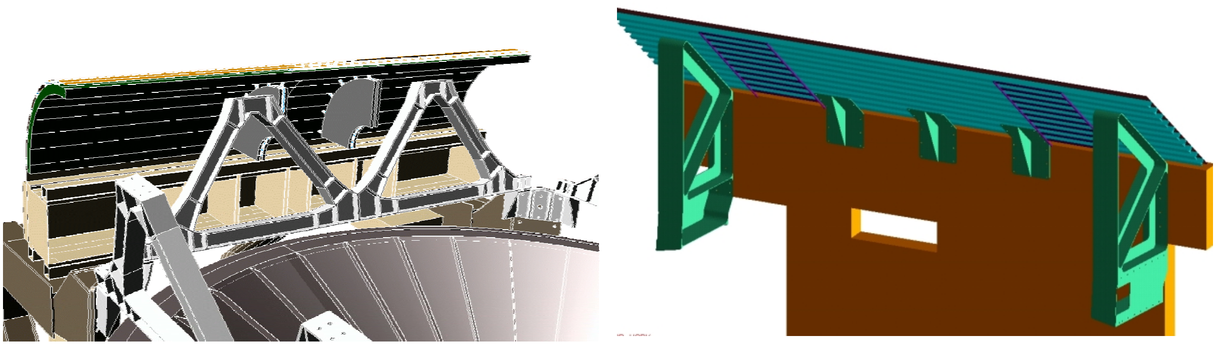


Figure 28. Curved (left) and flat (right) radiators (incl. the condenser configurations).

Results of calculated have shown that:

- For cold orbits, like B-75+15-20-15, both radiators show almost identical performances, for a flow rate of 2 g/s . The need for pre-heater power is less than 12 W maximum, 6 W average, at a set-point of 258 K for the flat radiator, 257 K for the curved one.
- For an average (nominal) orbit, like B_0-2-10_1, the pre-heater power needed is for both options (for a flow rate of 2 g/s and a hybrid pair dissipation of 0.75 W) the same: 33 W maximum, 17 W average. But the set-point in the case of the flat radiator is 278 K, being 6 K higher than for the curved one. Set-points close to or somewhat below 273 K are preferred ones.
- For the hottest case, B+75-15-20-15 and a hybrid dissipation of 0.825 W per pair (and a flow rate of 2 g/s), about 10 W maximum and 6 W average pre-heater power is needed for both options. However, the set-point for the curved radiator is acceptable (285 K), the flat radiator option yields a set-point slightly above the maximum value permitted (290 K).

The above results suggest that the curved radiator option is (thermally seen) the better one. It is also structurally the stronger one and is easier transportable (with respect to the B747 envelope limitations). It also can accommodate easier producible condensers, which can be designed such that the chance of condenser penetration by micro-meteorites etc., hence loss of the loop, is extremely close to zero (probability of non-penetration pnp = 99.999 %) for a 5 years mission. The only drawback of the curved radiators is the price, twice the flat radiator price.

The above mentioned pre-heater power values are encouraging, but still too high. A further reduction will be realised by incorporating a PCM (Phase Change Material) device. This thermal capacitor or energy storage device will dampen the temperature excursions of the loop and thus further reducing the pre-heater power needed, by a melting and solidification cycle of the PCM, a paraffin or mixture of paraffins (to create a melting trajectory instead of a fixed melting point).

The TTCS loop model (Fig. 22) was recently extended by including a PCM device. Because of the loop operating temperature requirements, three different PCM's were chosen for the calculations and for experimenting: n-dodecane (melting point 263.5 K, melting heat 210.5 kJ/kg), n-tetradecane (melting point 279.0 K, melting heat 229.9 kJ/kg), and and n-eicosane (melting point 307.5 K, melting heat 247.3 kJ/kg). Preliminary calculation results confirm that the presence of the PCM device dampens the temperature excursions of the loop and substantially reduces the pre-heater power needed, for various orbital cases. The outcomes suggest that an optimal profit of a PCM device incorporation will be reached by either creating a melting trajectory (if realisable) by a mixture of different PCM's, or by a PCM device consisting of sections, each section containing an optimised amount of a specific PCM.

IN-ORBIT EXPERIMENTS AND FINAL REMARKS

Apart from the challenge to develop a novel two-phase thermal control system for such an advanced experiment as AMS-2, NLR interest also pertains to the acquiring of in-orbit experience with real two-phase thermal control systems. NLR joined the AMS Collaboration, as it was guaranteed that the AMS-2 dormant (non-operation) periods could be used by NLR to execute dedicated experiments to study in-orbit two-phase heat transport system technology issues. Therefore the TTCS will be equipped with extra heaters, sensors, meters. The baseline philosophy will be that:

- There is minimum risk for Tracker and AMS-2.
- Any period AMS is not active can be used for thermal experiments
- There is at least one week of thermal experiments during the first six months
- Minimum power and mass will be added.
- The TTCS loop will, in principle, not be intruded.

The reported TTCS status already reflects the AMS-2 overall mass reduction requirements. It is developing straightforwardly to the status required at its Critical Design Review in October 2003. Critical issues like the development of the pumps, minimising of mass and the required power, etc. are more or less solved. But it should be stressed that the results of experiments, with the full-size test set-up, still may lead to substantial changes.

NOMENCLATURE

ACC	Anti-Coincidence Counter
AMS	Alpha Magnetic Spectrometer
APS	Absolute Pressure Sensor
CPL	Capillary Pumped Loop
DAC	Data Acquisition and Control System
DPS	Differential Pressure Sensor
DP	Pressure Difference (Pa or mBar)
EC	Electromagnetic Calorimeter
HTC	Heat Transfer Coefficient ($W/m^2.K$)
INFN	Italian Institute for Nuclear Physics
ISS	International Space Station
LFM	Liquid Flow Meter
LHP	Loop Heat Pipe
MPL	Mechanically Pumped Loop

NIKHEF Dutch Inst. for Nuclear & Particle Physics
NLR Dutch National Aerospace Laboratory
RICH Ring Imaging Cherenkov Counter
SPL Single-Phase Loop
SINTEF Norwegian Foundation for Scientific and Industrial Research
SRD Synchrotron Radiation Detector
STS Space Transportation System (Space Shuttle)
TC Thermal control
TM Thermal Model(ling)
ToF Time of Flight
TPG Thermal Pyrolytic Graphite
TPHTS Two-Phase Heat Transport System
TRD Transition Radiation Detector
TTCS Tracker Thermal Control System
VQS Vapour Quality (Mass Fraction in %) Sensor

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