SPACE TRIPS SUMMER SCHOOL

SEVENTH FRAMEWORK PROGRAMME

Theme 9: SPACE

Riga **Latvia**
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COLD SOURCE IN SPACE

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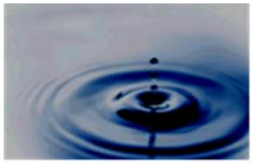
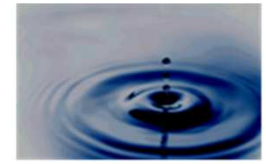
THALES ALENIA SPACE



1. Introduction
2. Space Thermal Environment and Heat Transfer
3. Thermal Architecture (Heat Transfer to a S/C Cold Sink)
   - Passive (heat pipes, LHP)
   - Active (ATCS)
4. Cold Sink (Radiator)
5. Future development (High Temperature Heat Pipes, LHP, lightweight radiators, droplet)
6. Conclusions



1. INTRODUCTION

- Basic thermal concepts in Space: what is the meaning of
  - *Thermal Environment*
  - *Energy Balance*
  - *Heat Collection, Transfer and Rejection*
  - *Heat Sink*
- Thermal design solutions and performance

2. SPACE THERMAL ENVIRONMENT AND HEAT TRANSFER

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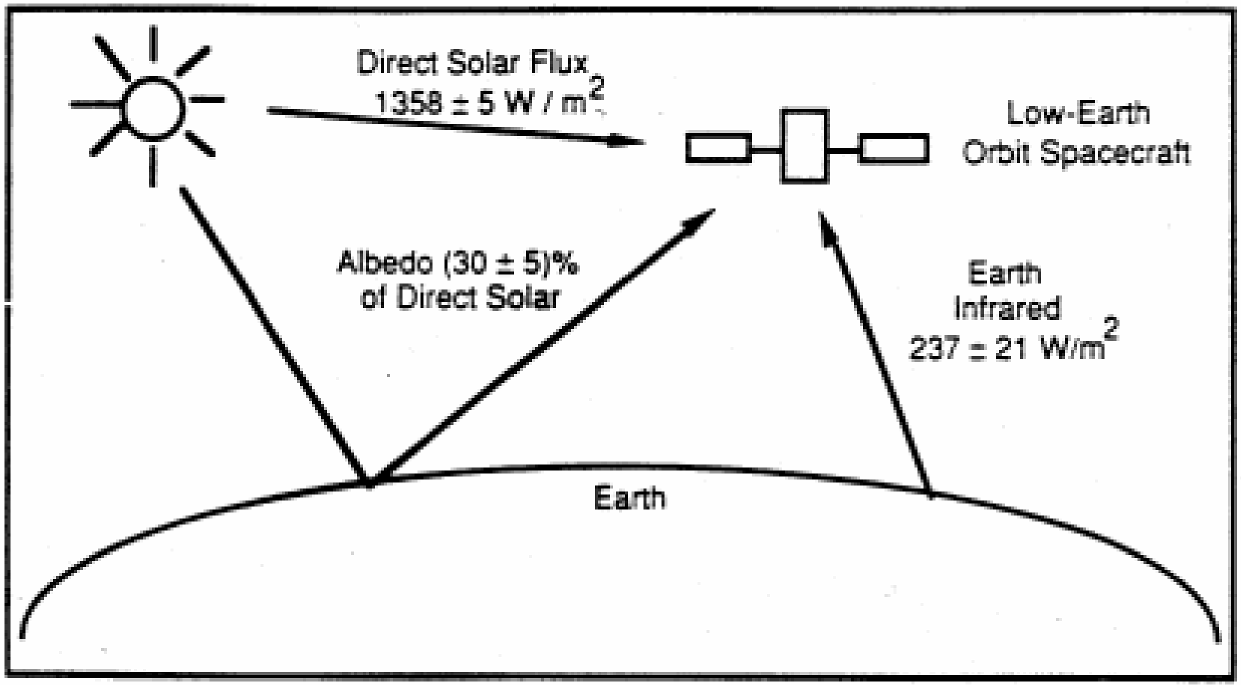
Energy sources:

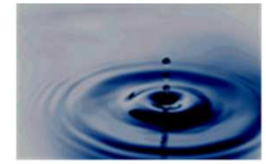
the Sun

- diameter 1.39 Mkm
- mass $1.99*10^{30}$ kg
- Surface T 5780 K
- radiation arriving from the Sun not constant. (average value of ~1358 W/m^2)



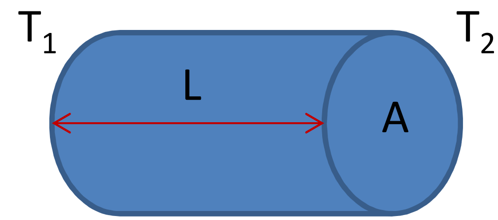
the Albedo (solar): fraction of the incident solar energy reflected by the planet surface back to space

the Planet Emitted Radiation: Infrared Energy re-emitted by a planet mainly in the wavelength field λ> 0.8 micron



2. SPACE THERMAL ENVIRONMENT AND HEAT TRANSFER

- Heat Transfer by **Conduction** (materials): $Q = (KA/L)(T_1 - T_2) \rightarrow$ LINEAR
  - **A** = area [m^2], **L**=length [m]
  - K= material Thermal Conductivity [W/m C],
  - High Thermal conductivity materials:
    - Diamond k=1000 [W/m C]
    - CFRP (hi K) k= up to 400 [W/m C]
    - Copper k= up to 380 [W/m C]
    - Aluminum k= 150/200 [W/m C]
  - Low Thermal conductivity materials:
    - Ti alloy /Stainless steel k= 7 to 16,3 [W/m C]
    - Glass fiber k=0,04 [W/m C]
    - Air (still) k=0,024 [W/m C]



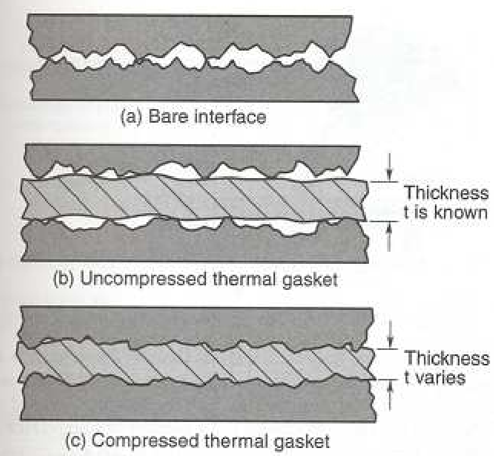


Fig. 8.27. Use of thermal gaskets as an interface filler.

- Heat Transfer through a joint Contact (interface):
  - $Q = G_c A_c (T_1 - T_2) \rightarrow$ LINEAR
    - $\mathbf{A_c}$= contact area [m^2]
    - G_c=Contact Conductivity [W/m2 C] (bare contact, thermal interfiller)

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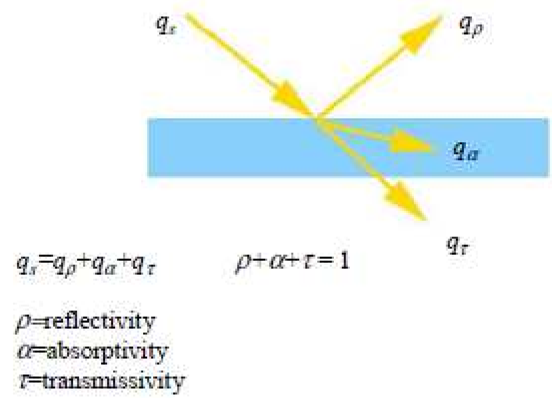
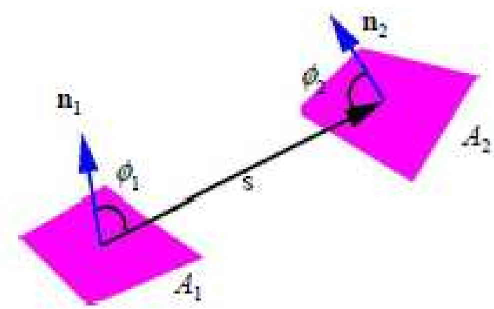
2. SPACE THERMAL ENVIRONMENT AND HEAT TRANSFER

- Heat Transfer by **Radiation** (main mode in vacuum /space)
  - propagation of electro-magnetic energy in straight line, between surfaces
  - reflected, absorbed or transmitted on sorrounding bodies
  - proportional to T^4 (Stefan-Boltzmann law: $\mathbf{q = \varepsilon \sigma T^4}$)
    - σ = Stefan-Boltzmann (5.6705×10^{-8}) [W/m^2K^4]
    - ε = I/R emissivity (dimensionless number between 0 and 1which relates emission to that of a black body)



- when view factors (Vf) apply to radiation exchange between surfaces, the radiative heat transfer equation is:
  - $Q = (A \times Vf) \times \varepsilon_{eq} \times \sigma \times (T_1^4 - T_2^4)$ [W] (T =temp (K))
  - Vf= View Factor between two facing surfaces
  - ε_{eq}= Equivalent Infrared Emissivity



- Absorbed Solar Flux: $Q = S \times A \cos(ß) \times \alpha$
  - S=solar constant (1330 / 1420 W/m^2, at 1 AU)
  - α = Solar Absorptivity; ß = Sun Aspect Angle

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2. SPACE THERMAL ENVIRONMENT AND HEAT TRANSFER

- Energy Balance: **dQint+dQext=dQrej** [W]
  - dQint = thermal power generated inside the s/c (electronics, chemical reactions, thermal control, ...)
  - dQrej = heat flux rejected to external environment (toward a Sink Temp), is the sum of all radiative contribution from the S/C external surfaces to a Sink Temperature (Space), the most important contribution comes from radiators
  - dQext = heat flux absorbed, generated by external sources (dQ (Sun) + dQ (Albedo) + dQ (Planet I/R) + dQ (radiative exchange with other external surfaces as in the case of complex space systems)
- In non equilibrium conditions:

dQint+dQext=dQrej+Mcp dT/dt

  - where cp is the thermal capacity of the system.
- Equilibrium temperatures are those values resulting from the solution of the energy balance equation system.

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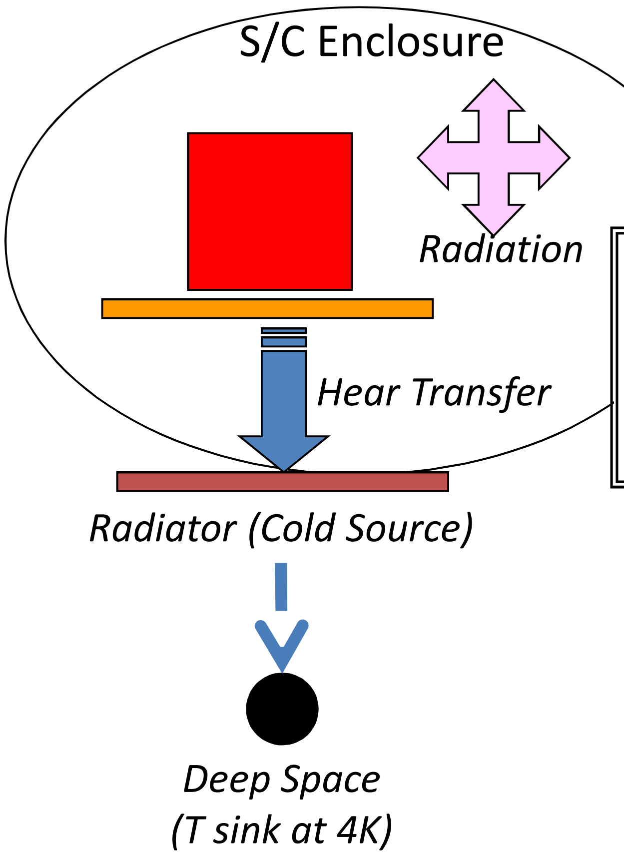
3. THERMAL ARCHITECTURE SCHEME (HEAT TRANSFER TO A SINK)



1- Heat Source (power dissipation)

2- Spacecraft module

- Radiation (within the enclosure and to the radiator)
- Conduction (& joint contacts)

3- Three functions

- Heat *collection*
- Heat *transfer* to the S/C heat sink (thermal radiator)
- Heat *rejection* to Space

4- Major thermal elements

- Heat Pipes-Loop Heat Pipes
- Active pumped loops
- Thermal Radiators
- Paints, finishes and coatings (lo α; hi ε)

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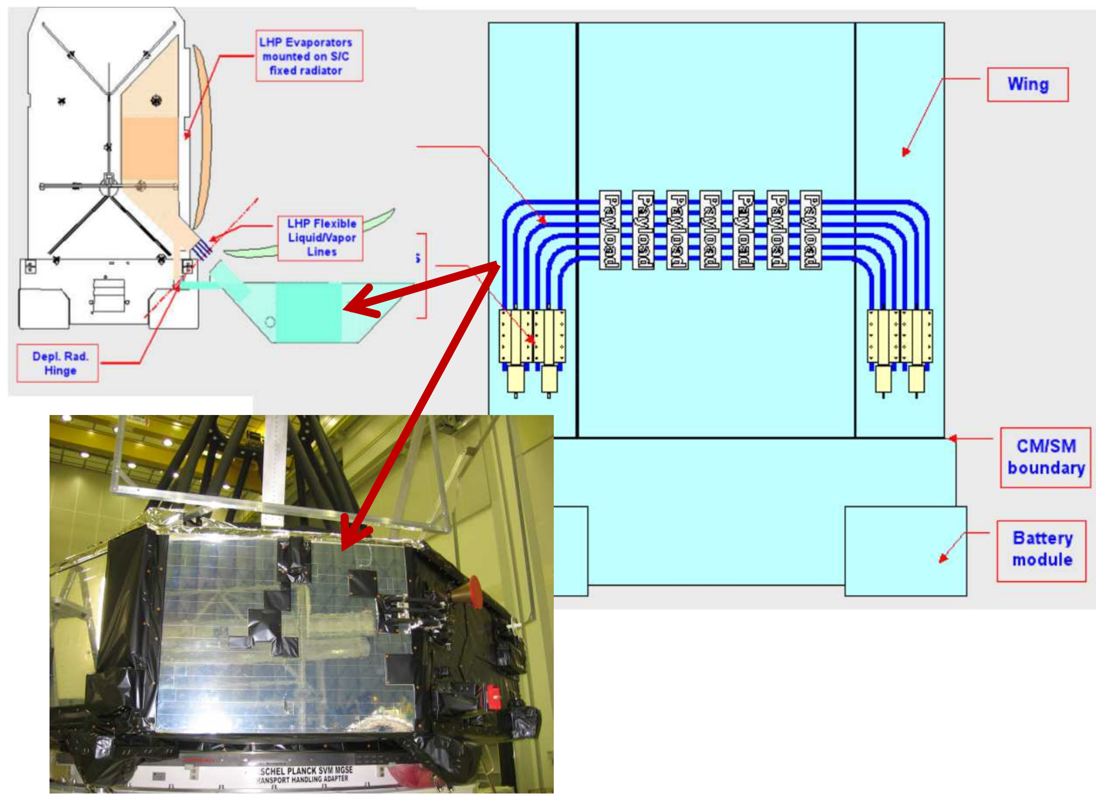
3. THERMAL ARCHITECTURE SCHEME (HEAT TRANSFER TO A SINK)

- The heat generated in a Spacecraft by electronic devices, chemical reactions, payloads, thermal control devices must be collected and forwarded to specific heat sinks (internal S/C, fluidic interfaces and eventually thermal radiators).

- The heat flux is naturally transferred in a "***passive***" way by conduction and/or radiation; exchanged heat flows from hotter to colder elements down to the heat sink.
- Use of fluidic devices can facilitate the control of the heat transfer toward specific radiator elements (HP, LHP, ATCS)



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3. HEAT TRANSFER TO A S/C COLD SINK

- ***Heat Pipes*** and ***Loop Heat Pipes*** are fluidic components working at nearly isothermal conditions (two-phase capillary loops),linking dissipating sources to the radiator
- ***Radiators*** are equipped with high emissivity external finishes (tapes, mirrors, paints)
- Heat Rejection capability of Thermal radiators at different Temperature levels are (Vf=0,94; ε=0.8; A=1 m^2)

Q Rejected to space	T= 20℃	T= 30℃	T= 40℃	T= 50℃
η (efficiency)	314*η - Qext [W/m^2]	359*η- Qext [W/m^2]	410*η- Qext [W/m^2]	464*η - Qext [W/m^2]
Typical η	From 0,85 to 0,96			

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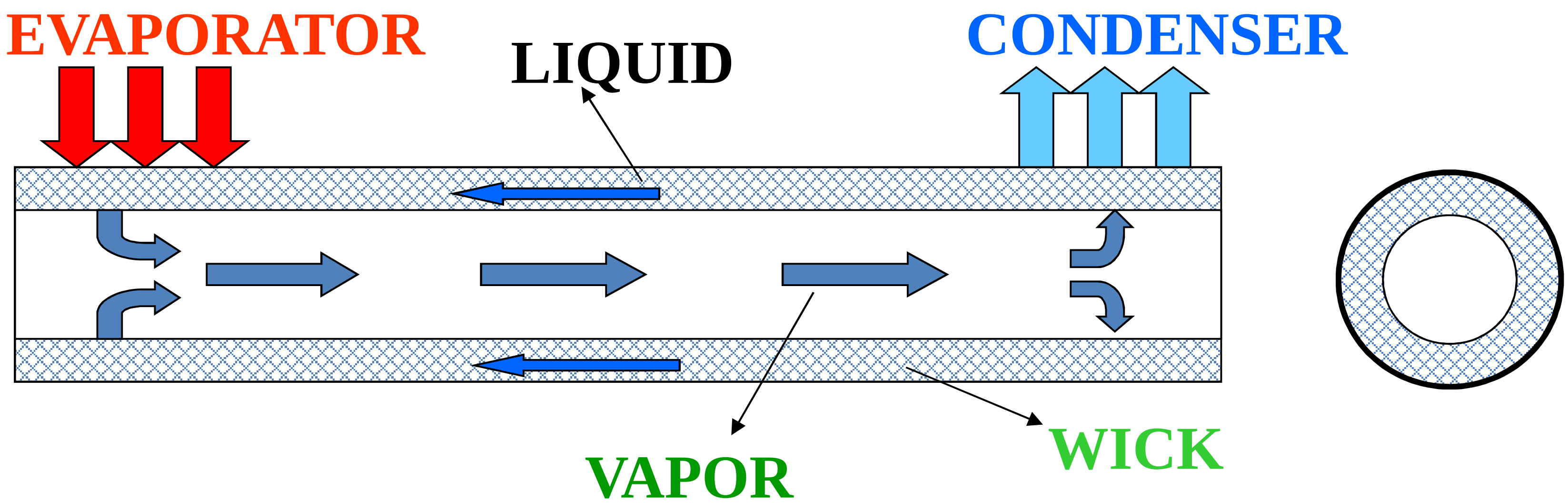
3. HEAT TRANSFER TO A S/C COLD SINK



- ***Heat Pipes*** transfer heat from a source to a sink with minimum temp. gradient
- Passive heat transfer device with high effective thermal conductivity
- Isothermal boiling-condensing cycle
- No moving parts: high reliability and long life
- proper choice of coolant vs pipe material according to the operating temperature range

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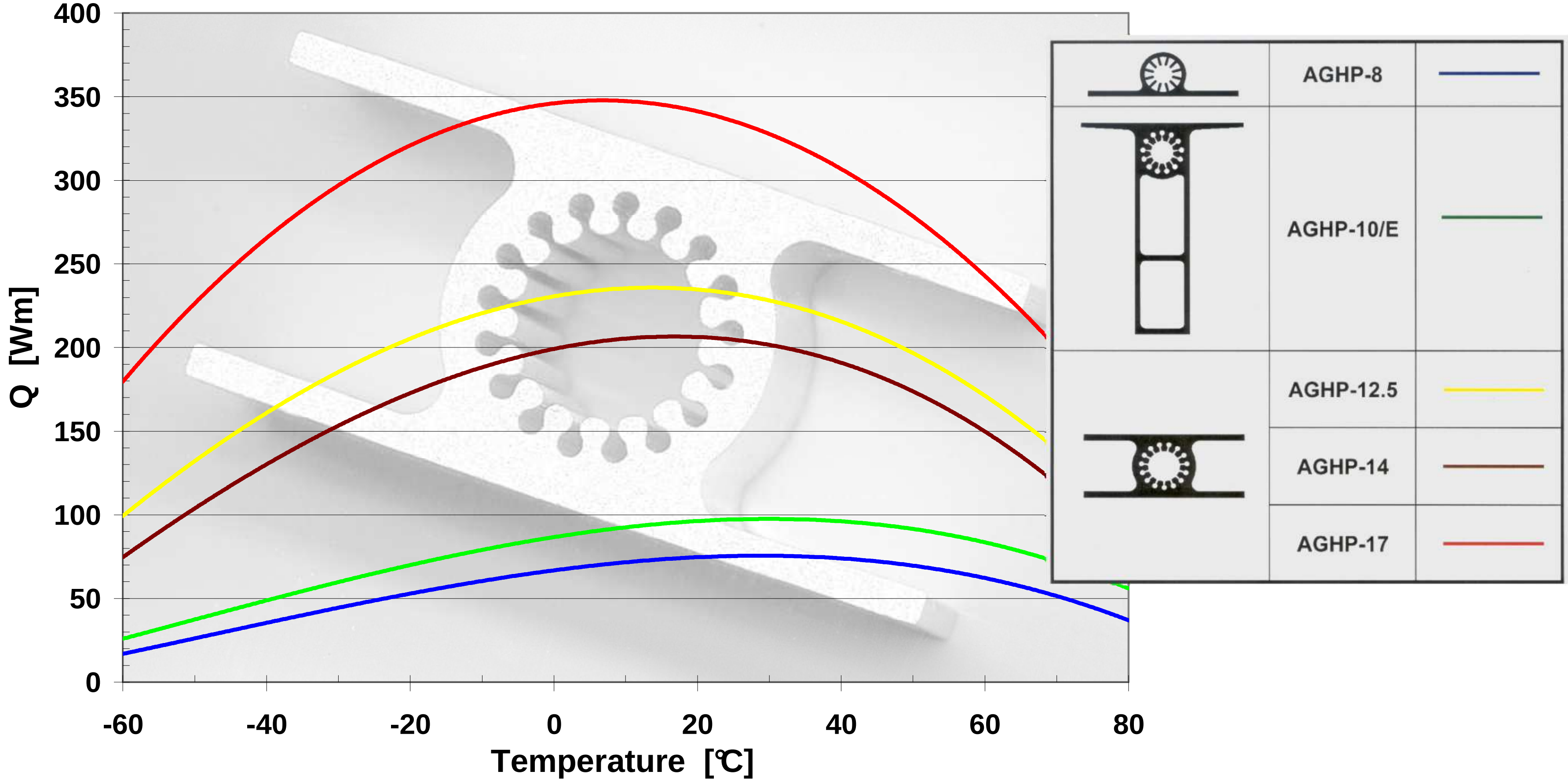
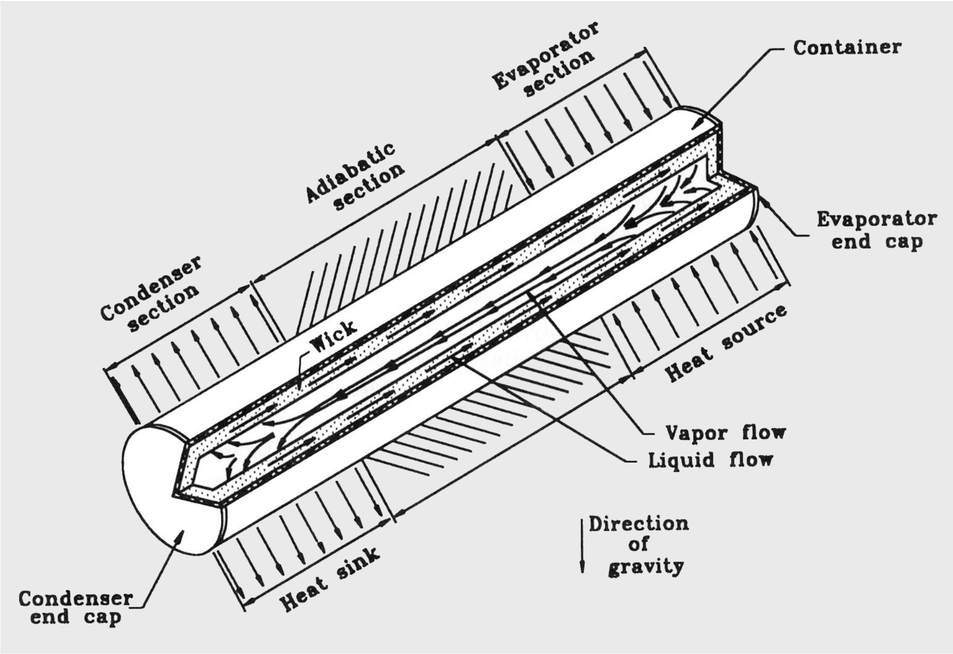
3. HEAT TRANSFER TO A S/C COLD SINK

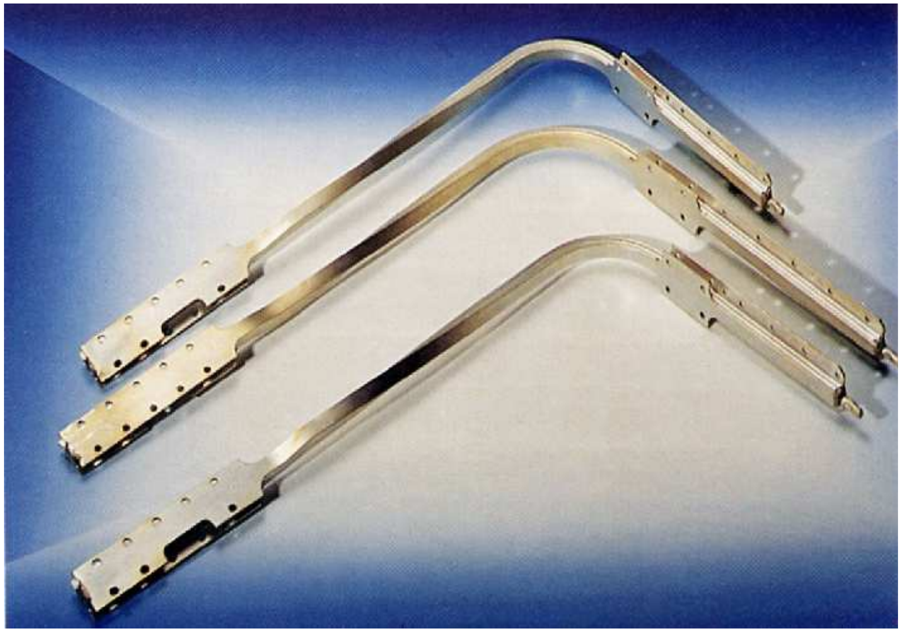


Axially Grooved Heat Pipe Performance (example)

3. HEAT TRANSFER TO A S/C COLD SINK

- The most obvious application of a heat pipe is the one where heat source and sink are physically separated.





- This configuration is also the one conventionally adopted when the heat pipes are tested (for qualification and acceptance)

3. HEAT TRANSFER TO A S/C COLD SINK

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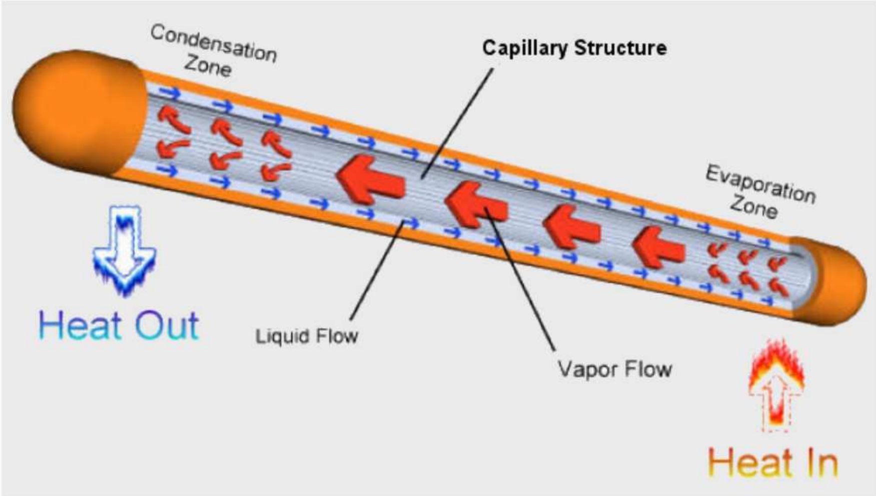
- ***Heat Pipes*** and ***Two-phase Capillary Loops*** are closed two-phase fluid circuits with an evaporator and a condenser to transport relatively large quantities of heat from a source to a sink without electrical power thanks to the capillary head.



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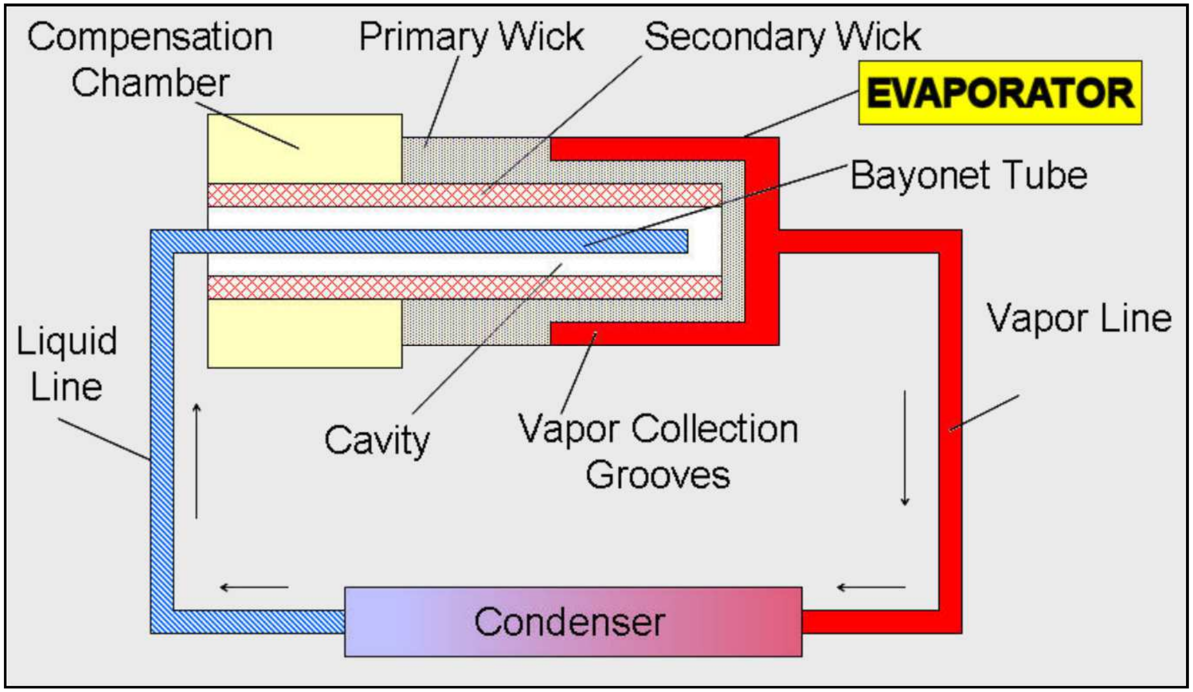
3. HEAT TRANSFER TO A S/C COLD SINK

- A 2-phase Capillary Loop is composed by: Evaporator (heat collection), Condenser (rejection), Liquid Phase/Vapor Phase Lines (transport) and Reservoir (Compensation chamber) → supports heat transport from few [W] to several [kW]
- Capillary head provided by primary and secondary wicks, in the evaporator
- Multi-evaporator and multi-condenser systems are under development
- Robust concept: Low sensitive to bubbles in the evaporator
- Control: by heater on the Compensation Chamber (small fraction of LHP power)



3. HEAT TRANSFER TO A S/C COLD SINK

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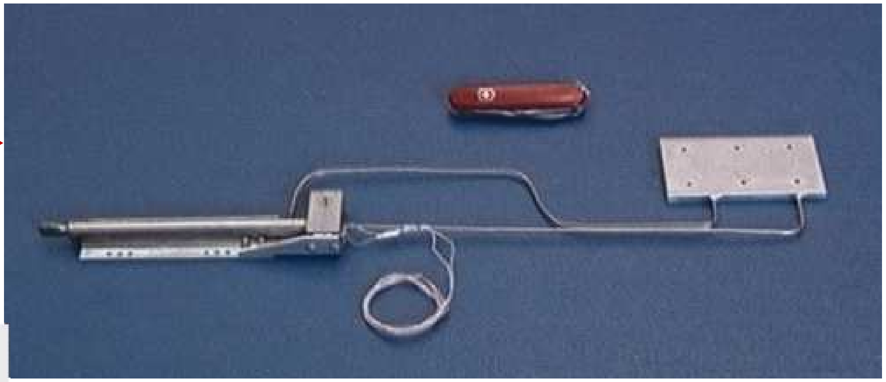
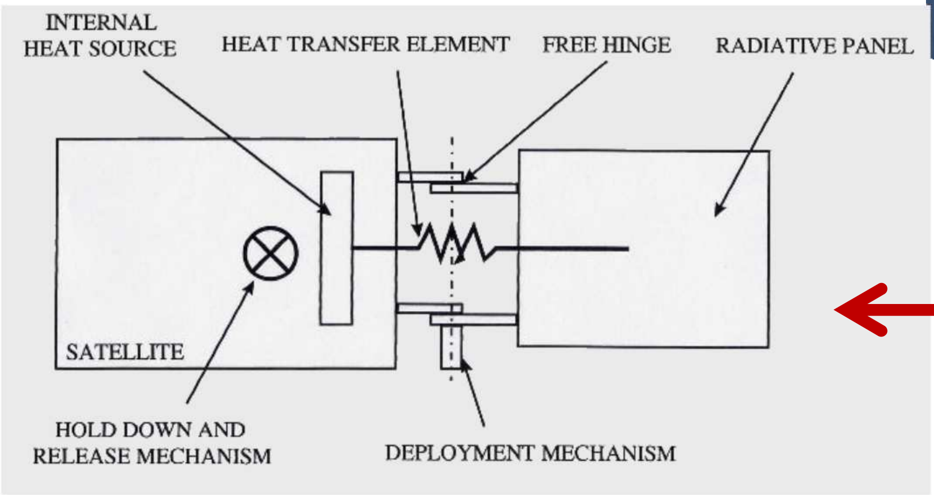
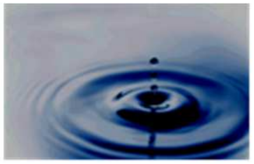
- Individual thermal control of a single equipment box with heat sink located elsewhere





- Thermal connection between spacecraft main body and fixed or Deployable Radiators



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3. HEAT TRANSFER TO A S/C COLD SINK

Two-phase Capillary Loop main advantages:

- Tolerance of large adverse tilts (heat source up to 5 m above heat sink) facilitating ground tests and terrestrial applications
- Tolerance of complicated layouts and transport paths
- Easy accommodation of flexible sections (e.g. in deployable radiators)
- Fast and strong “diode” action
- Straightforward application in either constant conductance or variable conductance (active temperature control) mode

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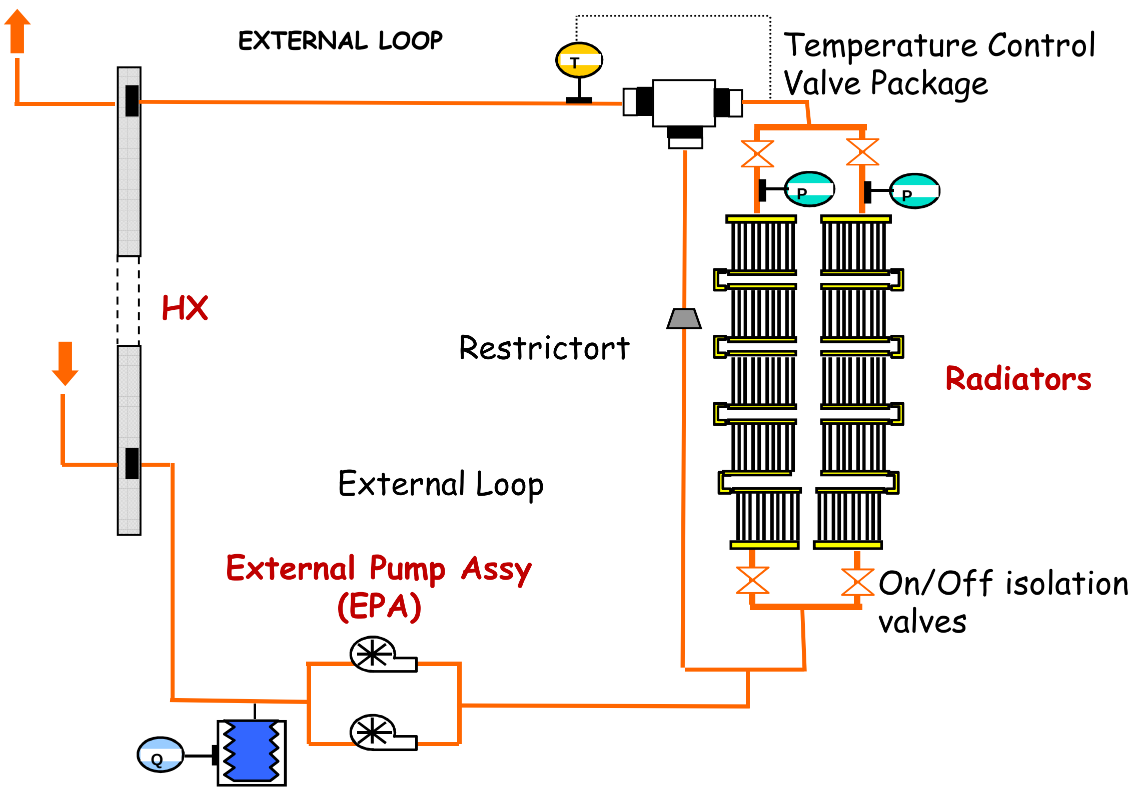
3. HEAT TRANSFER TO A S/C COLD SINK: ATCS architecture

Main Critical elements:

- Choice of coolant
- Single phase / Two phase
- Redundancy
- Cold plates & HX
- Temperature drop
- Pressure drop
- Flow rate
- Radiators concept & architecture (serial, parallel configuration)
- Radiator performance
- Pump working point



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4. SPACECRAFT COLD SOURCE (SINK)

Thermal Radiators

- Radiator provides the cold source to the spacecraft (S/C) thermal control. It is a heat exchanger that transfers the waste heat from the S/C to the radiation temp. environment of space. Waste heat is then ultimately rejected to space by radiator surfaces.
- Optimised radiator area requires:
  - Efficient thermal optical properties (surface coating)
  - Efficient thermal distribution over the whole surface (high thermal conductivity materials and efficient thermal transfer solutions (HP, fluid loop)
  - Radiator average temperature as high as possible (efficiency increases as the radiator temperature increases, according to $q = \varepsilon \sigma T^4$)

4. SPACECRAFT COLD SOURCE (SINK)

Thermal Radiators

- Radiators can use, proper hi thermal conductivity structural materials, heat pipes, fluid loop or a combination of the above solutions
- Radiator configuration:
  - structural panel
  - Body mounted (i.e. fixed to a structure)
  - Deployable
- Designed to environmental conditions (Micro Meteoroid & Debris, Aomic Oxugen, Radiation, other …)

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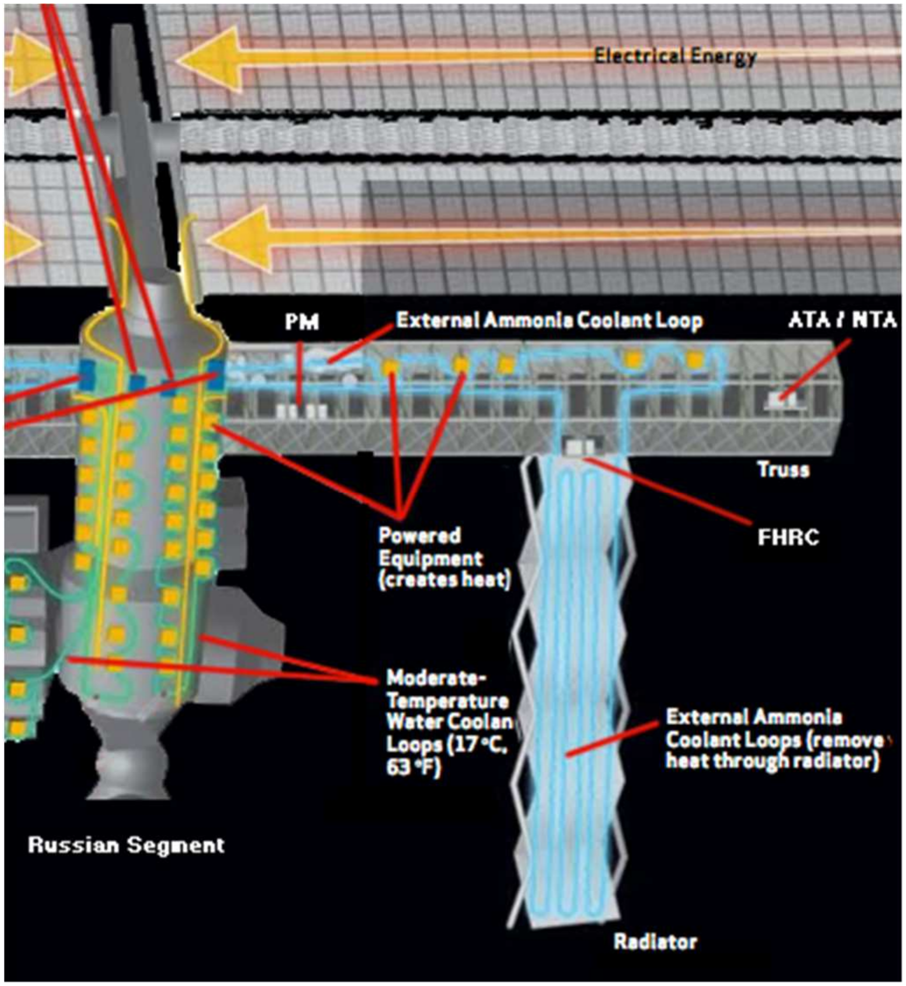
4. SPACECRAFT COLD SOURCE (SINK)

Radiator technology

- Pumped circuit radiator

circulation of a liquid in a fluid circuit

- through pump(s)
- (e.g. ISS radiators, temperature 300K and area, 450m^2 , consolidated technology)



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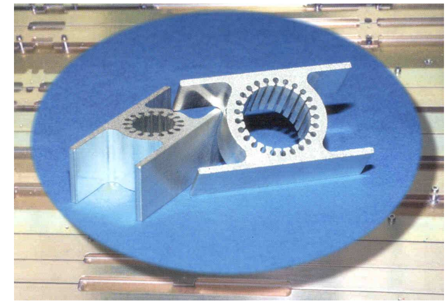
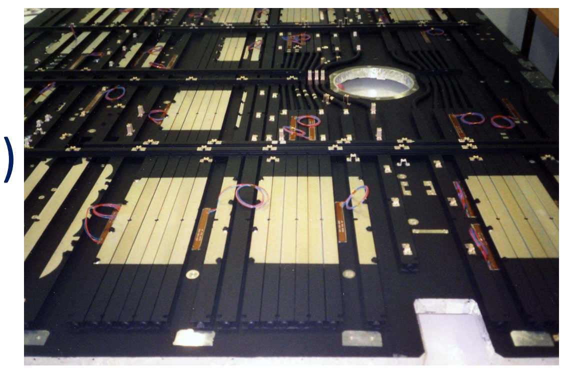
4. SPACECRAFT COLD SOURCE (SINK)

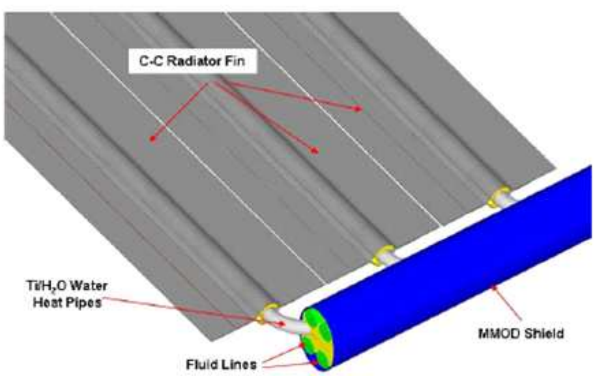
Heat pipes radiators

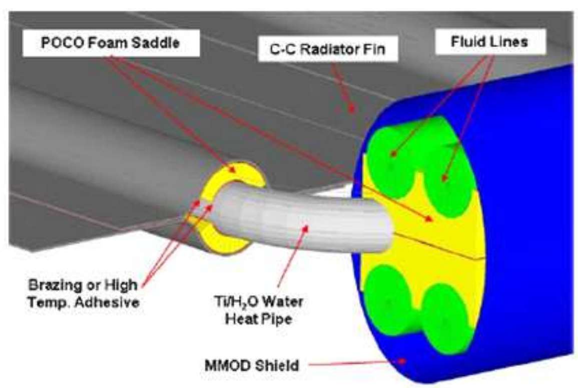
Radiator equipped with a network of heat pipes to spread the heat at an isothermal temperature level.



- meteoroid impact could damage a single item, no impact on the radiator system functionality
- capillary action to return the liquid from condenser to evaporator, no pumps
- radiator of reduced mass (using honeycomb sandwich)
- widely used in space applications







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4. SPACECRAFT COLD SOURCE (SINK)

Heat pipes radiators

Issues:

- Selection of materials and design → working fluid compatibility with piping and radiator manufacturing technologies, heat exchanger concept, operating temperature range

	Melting point, K a 1 atm	Boiling Point, K at 1 atm	Useful range, K	Compatible material	Incompatible Material
Ammonia	195,5	239,9	233-360	Aluminum, stainless steel, Nickel	Copper
Freon	236	320	263-373	Aluminum	
methanol	175,1	337,8	283-403	Stainless steel, iron , nickel	Aluminum
Water	273,1	373,1	303-473	Stainless steel, copper, nickel, titanium	Aluminum, Inconel
sodium	371	1151	873-1473	Stainless steel, nickel, Inconel, niobium	titanium

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4. SPACECRAFT COLD SOURCE (SINK)

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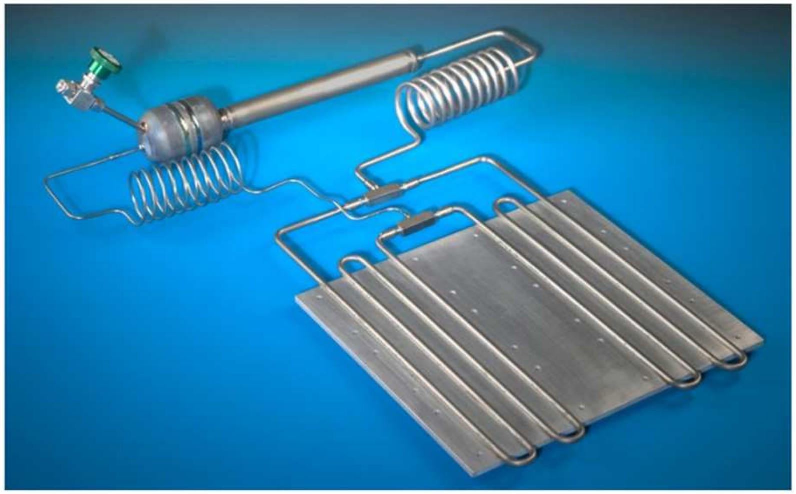
Loop Heat Pipes Radiator

As for the heat pipes issues are still open for high temperature above 500/550K, for the right selection of the working fluid

Development of Multievaporator /multicondenser concept



4. SPACECRAFT COLD SOURCE (SINK)

Droplet Radiator

Liquid is expulsed in form of fine droplets from a generator and then recuperated in a collector

- circulation of a liquid is assured by additional pump(s)
- no need of radiant metallic surface: the droplets provides themselves a high radiant surface
- performance would be very attractive for radiator: 4kg/m
- working fluid could be silicon-based oil or a liquid metal, because their low vapor pressure, minimizing the losses during the droplets transmission from generator to collector
- part of working fluid is sublimated to space: needs of a reservoir
- Mass impact for new components
- Radiator technology free of meteoroids impact and deployment / on-orbit assembly issues

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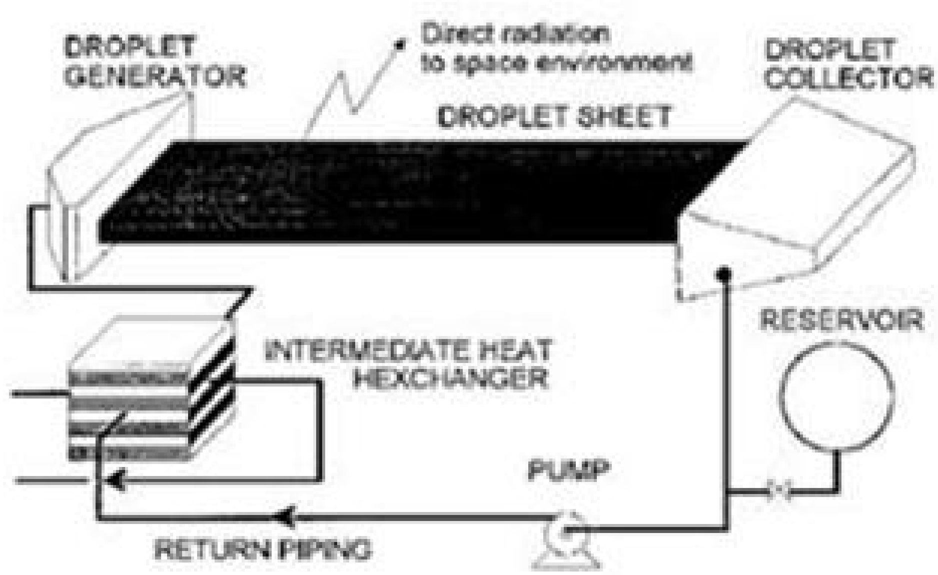
4. SPACECRAFT COLD SOURCE (SINK)

Droplet Radiator (cont.'d)

- Up to 300 K, the silicon oils are suggested or eutectic compound as NaK
- From 600 to 1000 K liquid metals (Lithium, Sodium, Indium and Tin) are available, practically opaque, they have a low emissivity value (epsilon = 0.1). As example, to increase their performance for emissivity, a fine black carbon powder has to be added
- Technology experiments currently planned to demonstrate the Droplet Radiator technology.



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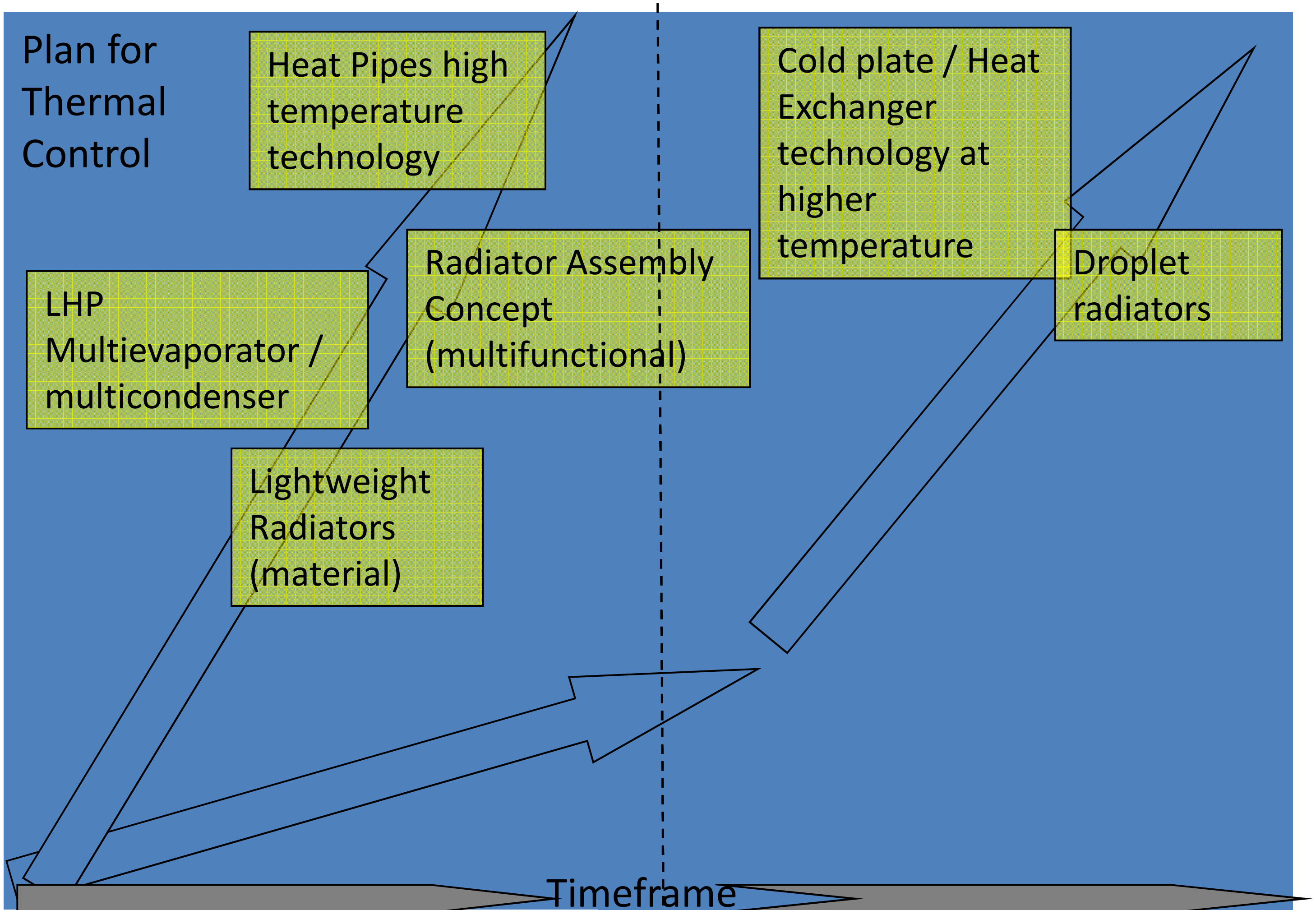
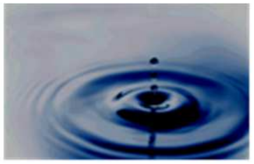
5. COLD SOURCE IN SPACE: FUTURE DEVELOPMENT





5. CONCLUSIONS

a) Cold sources in space are basically constrained by the natural cold sink (deep space) and by the mean of heat exchange with it (i.e. by radiation)

b) The key elements are:
- the thermal radiator
- the means for heat collection and transport

c) Basic technologies for heat collection and transport include (beside pure passive means:
- heat Pipes and LHP
- Fluid loops (single and two phase)

d) Technologies for conventional operating temperature range (250/+370K) are consolidated

e) New development focused on improving radiator performances in terms of weight (lightweight), thermal efficiency, reliability, hi-temperature range (450-600K) for HP and LHP.