EPSRC
Engineering and Physical Sciences
Research Council

HyHP
Novel Hybrid Heat Pipe
for Space and Ground Applications

Novel Hybrid Heat Pipes for Space and Ground Applications (**HyHP**)

Kick-off meeting, 4th April 2017

HyHP

EPSRC
Engineering and Physical Sciences Research Council

KAYSER SPACE

LIBERTINE
LINEAR POWER SYSTEMS

SUSTAINABLE ENGINE SYSTEMS

University of Brighton
Advanced Engineering Centre

Agenda

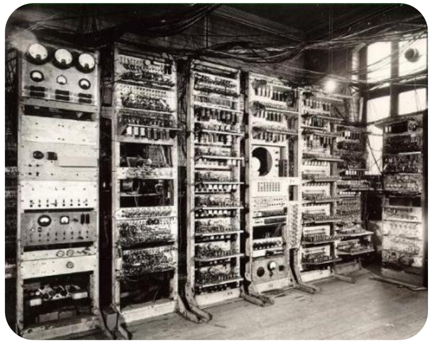
13:00	*Welcoming of the Participants - Lunch*	
	Part I: Presentations	
13:20	**EPSRC HyHP Project: Objectives, Working Plan and Deliverables**	Prof. Marco Marengo
13:40	**Hybrid Thermosyphon/Pulsating Heat Pipe: Ground and Microgravity Experiments**	Dr. Daniele Mangini
14:00	**Upgraded Pulsating Heat Pipe only for Space (U-PHOS): Results of the 22nd REXUS Sounding Rocket. Campaign and Development of the ISS Prototype**	Dr. Mauro Mameli
14:20	**Enhanced VOF-Simulations of Phase-changing Interfaces**	Dr. Anastasios Georgoulas
14:40	**LP Modeling of a Pulsating Heat Pipe**	Prof. Marco Marengo
15:00	*Coffee Break*	
	Part II: Discussions	
15:20	**HyHP Project's Timetable**	
15:40	**Applications and Industrial Involvement**	
16:00	**Dissemination of the Project to the Public**	
16:20	**General Discussion**	
19:00	*Dinner*	

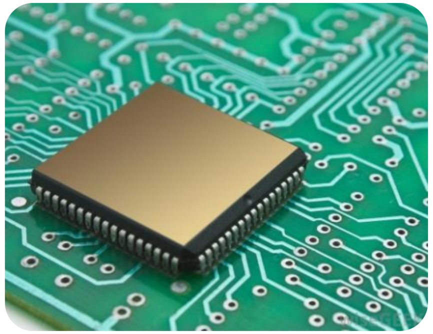
In the last 20 years, industry has become more and more strict with regards to **heat management**.

FLEXIBILITY

LONG LIFE

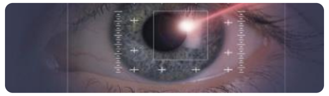
SMALL SIZE





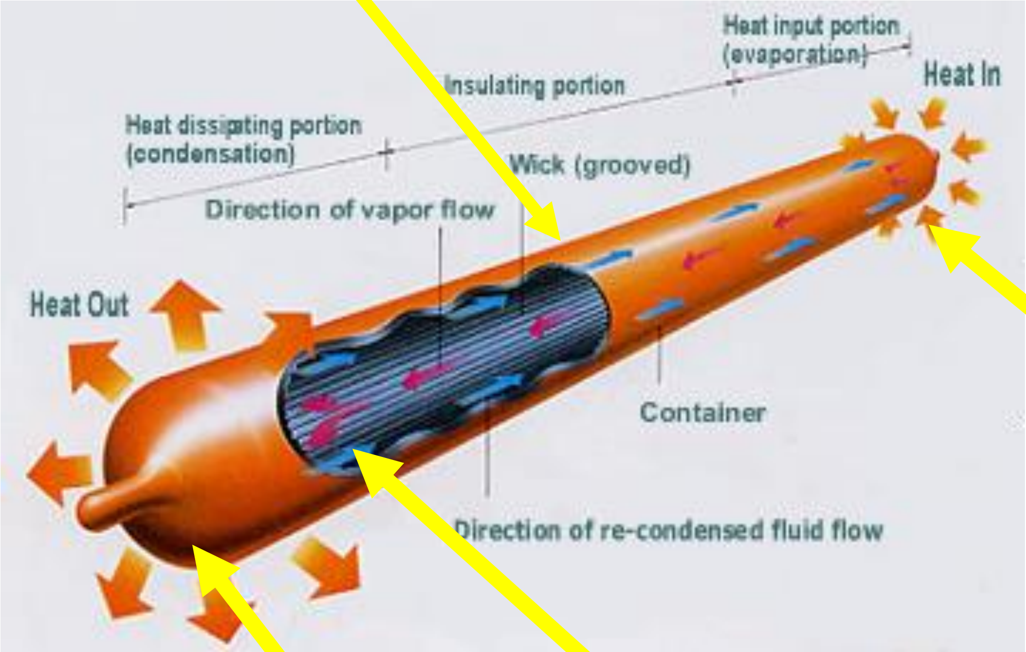
RELIABILITY

LOW COST



HIGH HEAT TRANSFER CAPABILITY

BASIC COMPONENTS



Adiabatic section

Evaporator

Condenser

Wick

http://www.lightstreamphotonics.com/images/tech_orangecontainer_small.png

ADVANTAGES OF HEAT PIPES

- *Very high thermal conductivity*. Less temperature difference needed to transport heat than traditional materials (thermal conductivity up to 90 times greater than copper for the same size) (Faghiri, 1995) resulting in low thermal resistance (Peterson,1994) and very long fin length.

- *Power flattening.* A constant condenser heat flux can be maintained while the evaporator experiences variable heat fluxes. (Faghiri, 1995)

- *Efficient transport of concentrated heat*. (Faghiri, 1995)

- *Temperature Control.* The evaporator and condenser temperature can remain nearly constant (at T_{sat}) while heat flux into the evaporator may vary (Faghiri, 1995) .

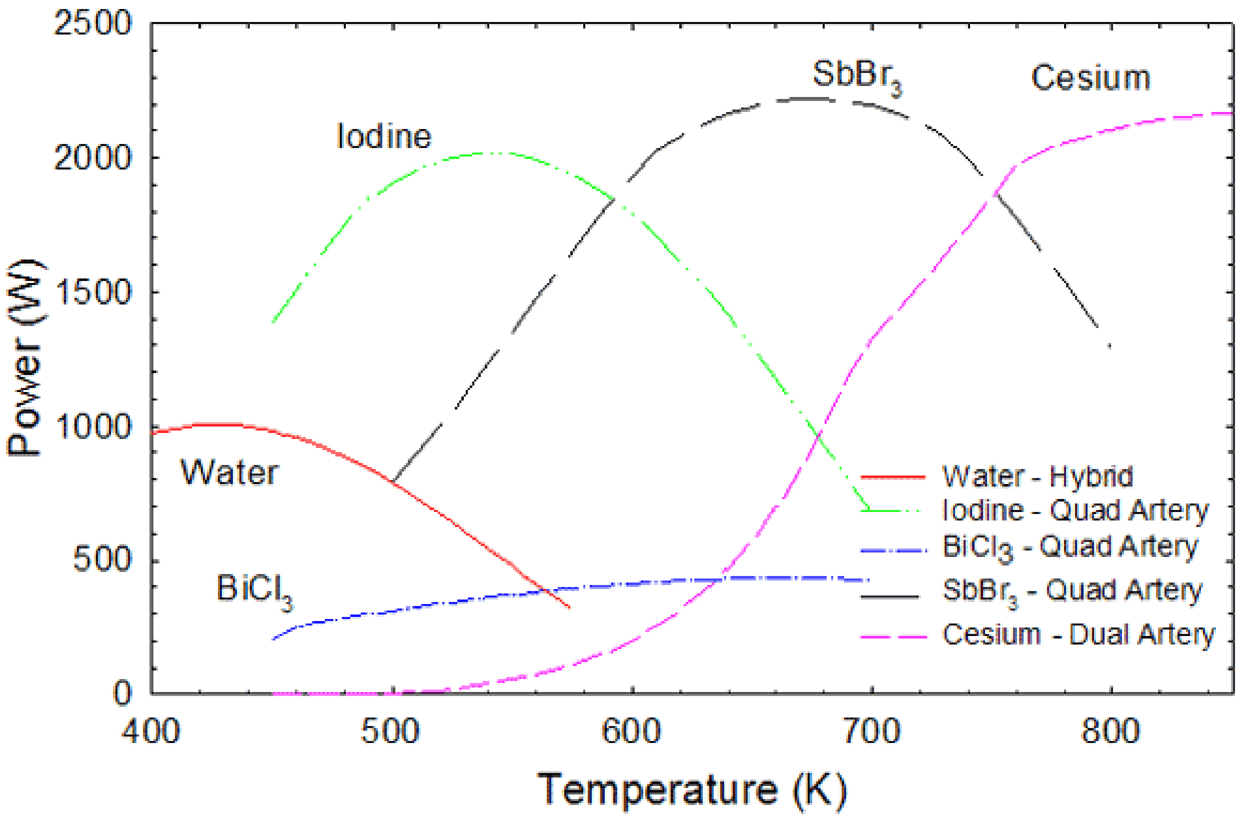
- *Geometry control.* The condenser and evaporator can have different areas to fit variable area spaces (Faghiri, 1995) . High heat flux inputs can be dissipated with low heat flux outputs only using natural or forced convection (Peterson,1994)

http://www.1-act.com/hpphot.html

TEMPERATURE RANGE OF HEAT PIPES

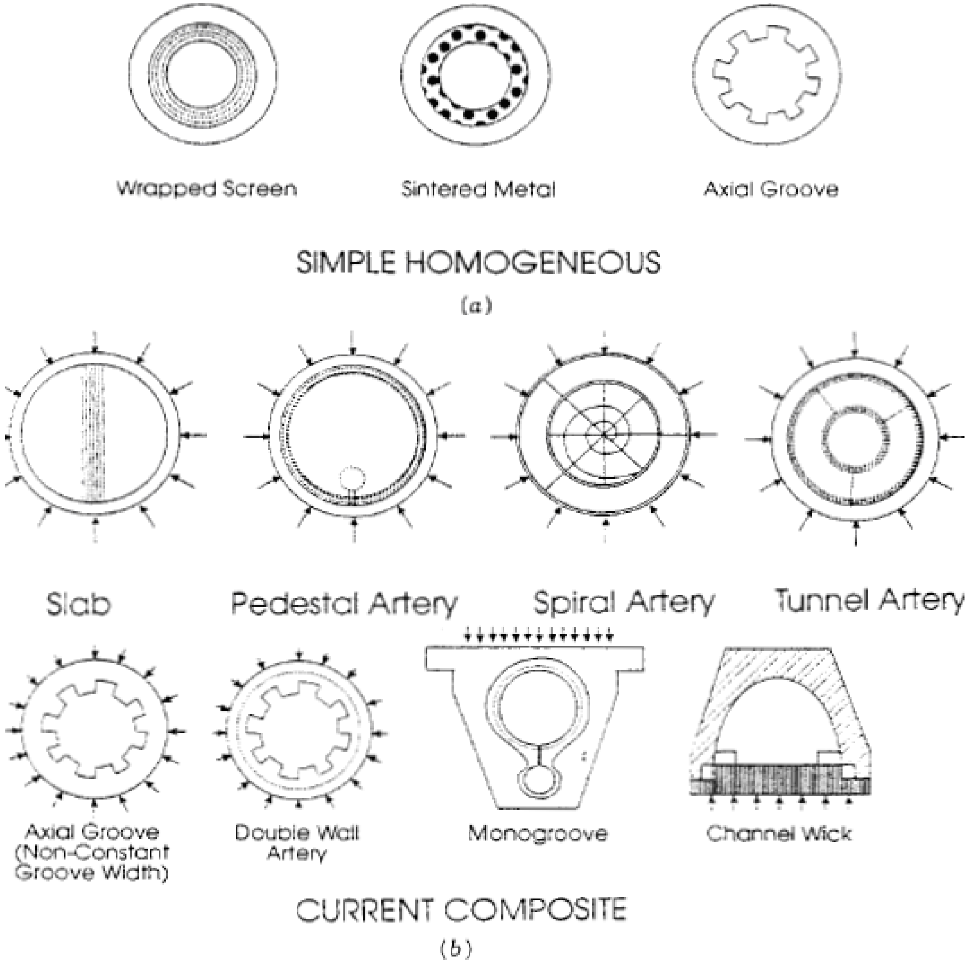
Table 1. Typical Operating Characteristics of Heat Pipes

Temperature	Working Fluid	Vessel	Measured axial[a] heat flux	Measured surface[a] heat
		Tungsten		



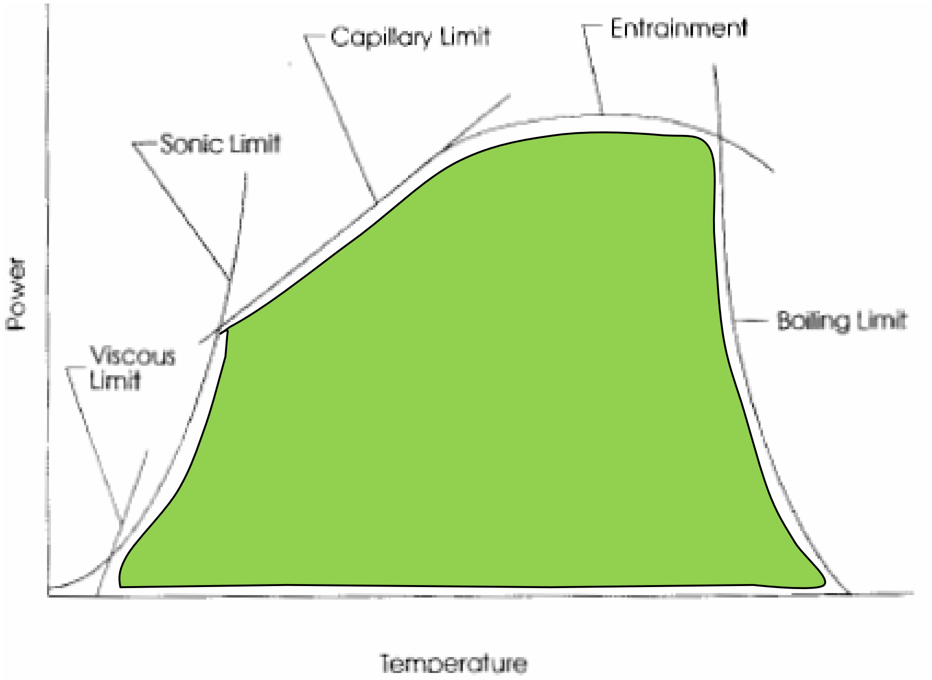
[a] Varies with temperature
[x] Using threaded artery wick
[•] Tested at Los Alamos Scientific Laboratory
[*] Measured value based on reaching the sonic limit of mercury in the heat pipe
Reference of "Heat Transfer", 5th Edition, JP Holman, McGraw-Hill

WICK DESIGN



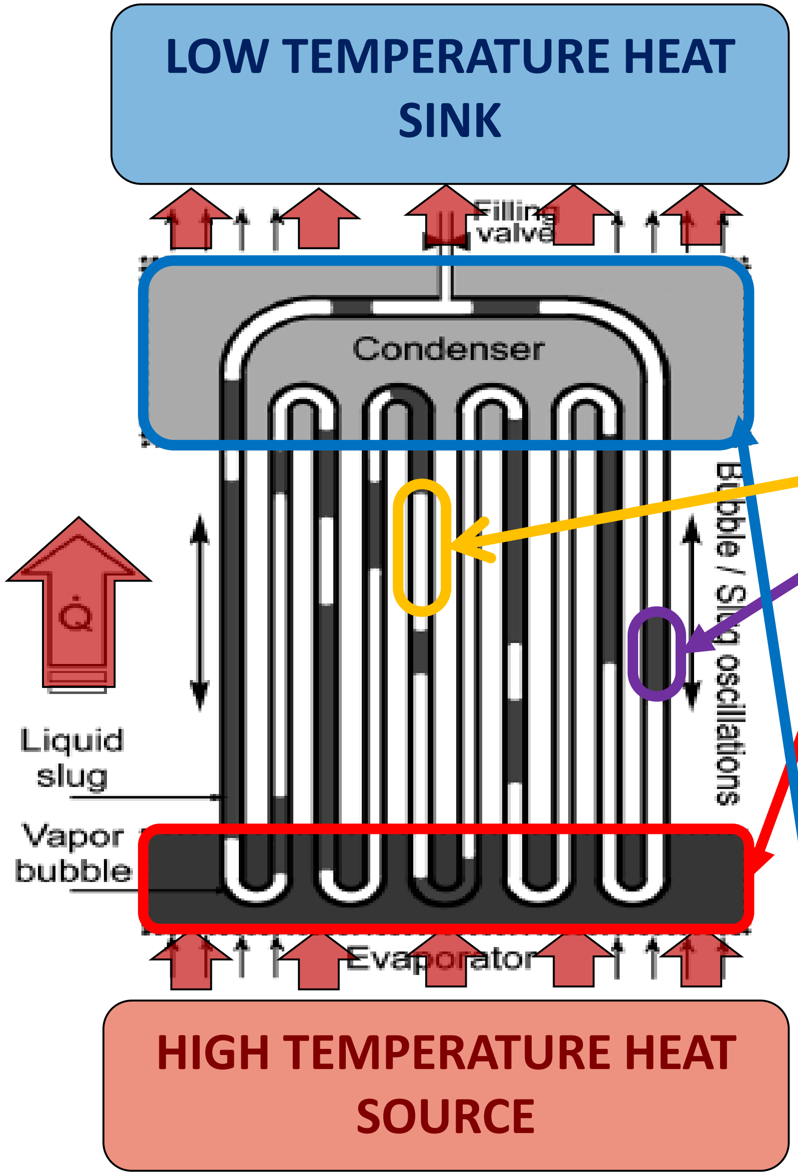
Typical heat pipe wicking configurations and structures.

- Each limit has its own particular range in which it is important. However, in practical operation, the capillary and boiling limits are the most important. The figure below is an example of these ranges.



Heat pipe performance map.

PULSATING HEAT PIPE: basic working principles



THERMALLY DRIVEN HEAT TRANSFER DEVICE

- Capillary tube evacuated and then filled with a working fluid.

$$Bo = \frac{\rho g D^2}{\sigma} \rightarrow D_{crit} \approx 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

- Alternation of VAPOUR PLUGS and
- LIQUID SLUGS.

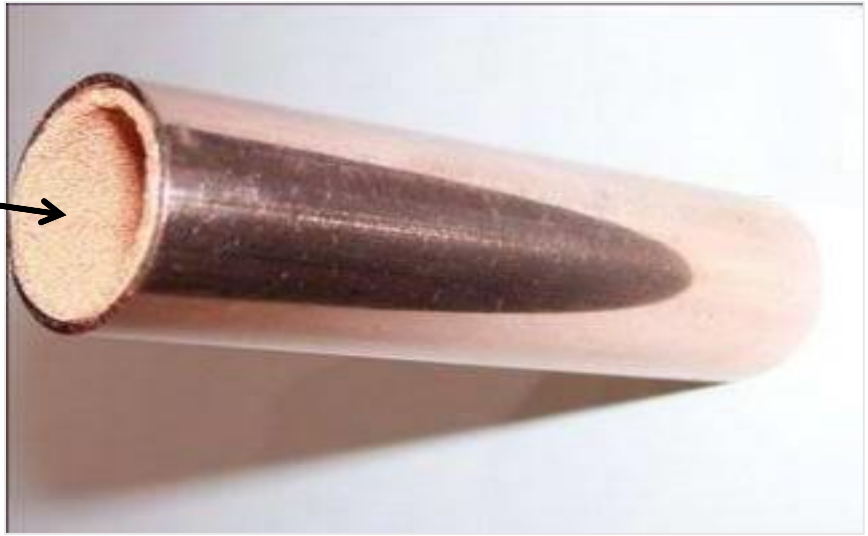
- A zone where heat enters the device: EVAPORATOR.

- A zone where heat goes out the device: CONDENSER.

- An optional adiabatic zone between the evaporator and the condenser.

PULSATING HEAT PIPE: benefits and drawbacks

BENEFITS AND DRAWBACKS WITH RESPECT TO THE STANDARD HP TECHNOLOGY



ADVANTAGES

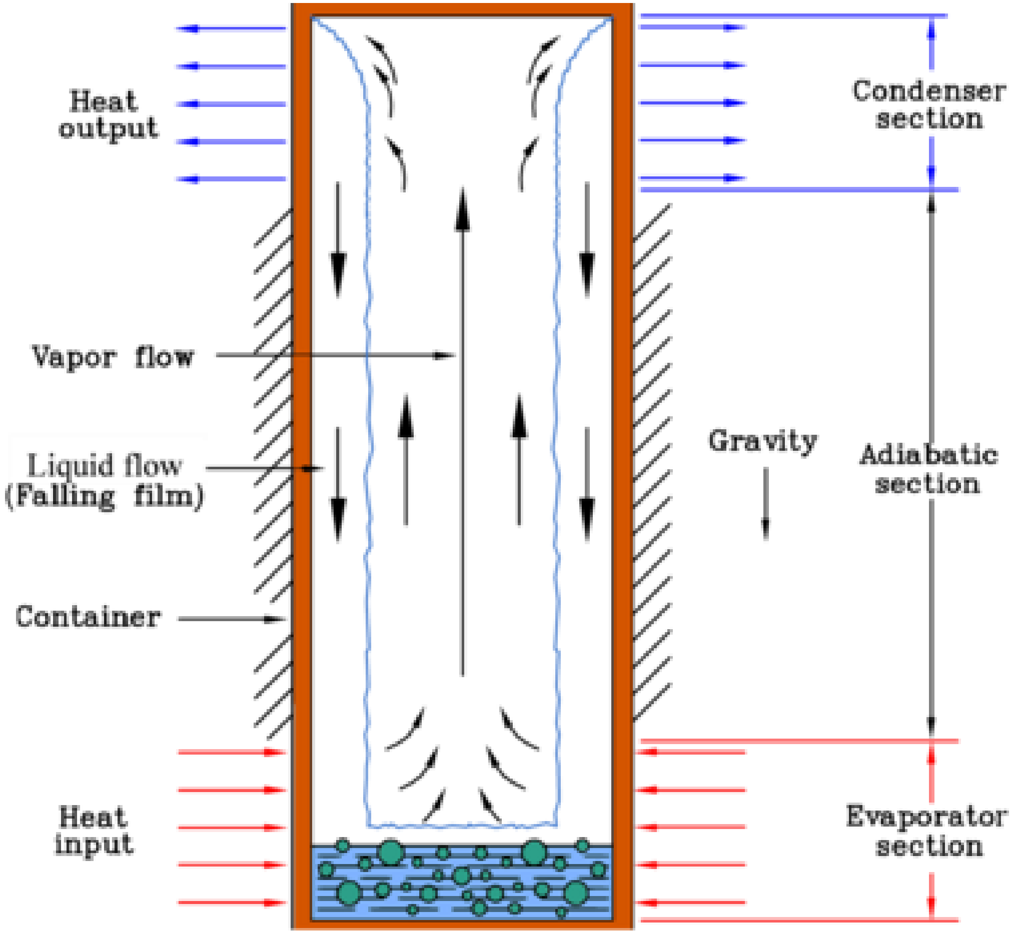
- **No wick structure**
- Lower manufacturing costs
- Higher flexibility
- Ability to cover wider surfaces

DISADVANTAGES

- Lower heat fluxes.
- Performance is affected by geometry and boundary conditions (filling ratio, internal diameter, number of turns, heat input level, inclination angle with respect to gravity…).
- The governing physics is more complex:

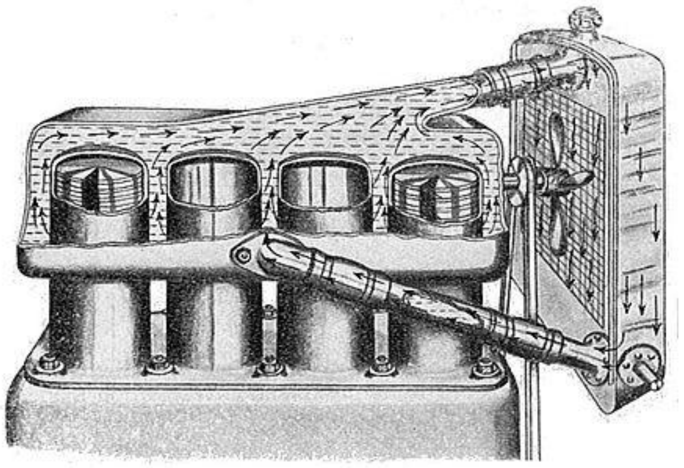
  it is rather difficult to develop a mathematical/numerical model.

THERMOSYPHON



Gravity driven

$$Bo = \frac{\rho g D^2}{\sigma} \rightarrow D_{crit} \approx 2\sqrt{\frac{\sigma}{g\left(\rho_l - \rho_v\right)}}$$



Scan from *Manual of Driving and Maintenance for Mechanical Vehicles* (1937). *Engine cooling entirely by thermosiphon circulation*

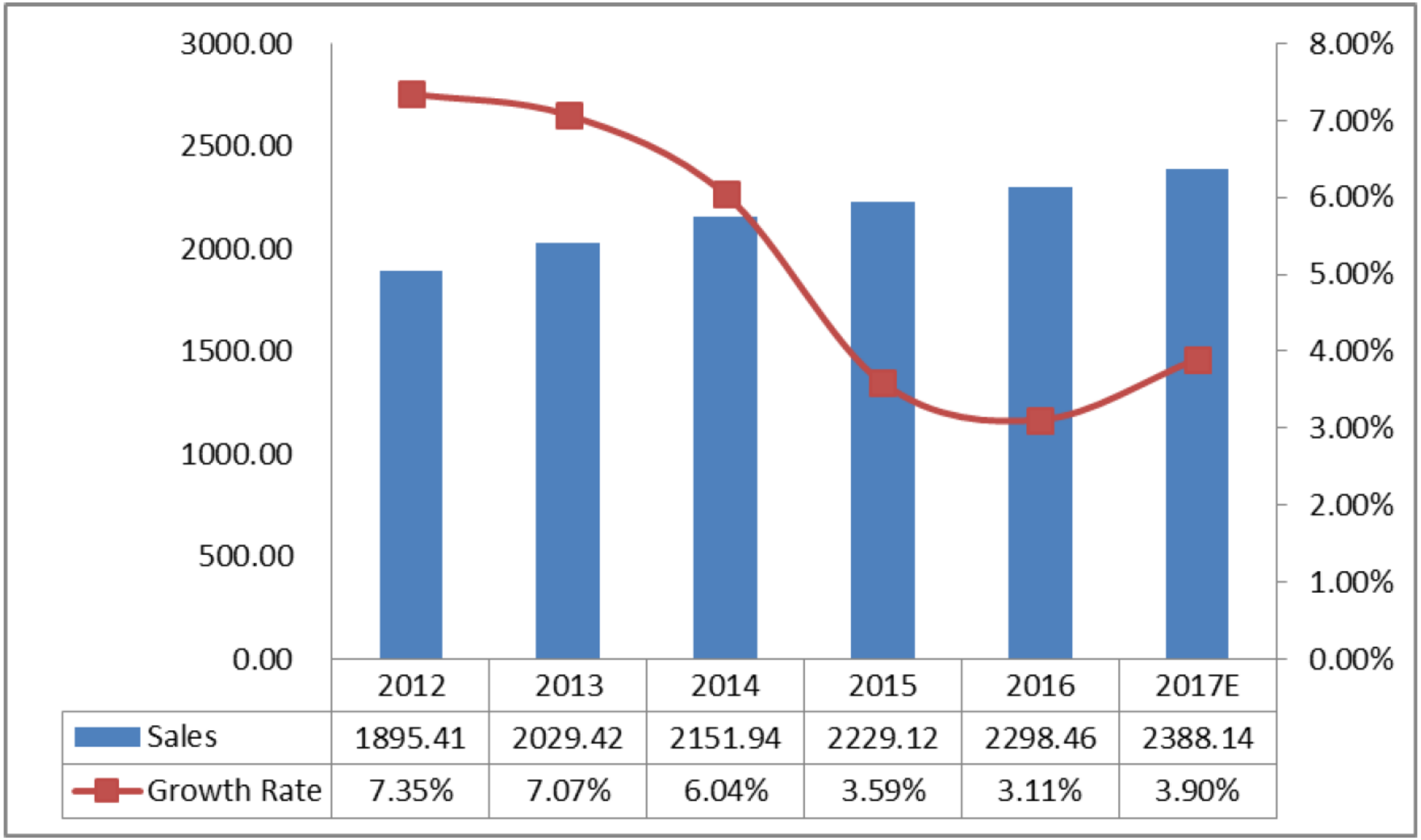
	Sintered HP - wicked	PHP - wickless	TS - wickless
Radial Heat Flux	Very High: up to 250 W/cm^2	Medium: up to 30 W/cm^2	High: up to 100 W/cm^2
Axial Heat Flux [7]	High: up to 600 W/cm^2	High: up to 1200 W/cm^2	-
Total Power	Medium: up to 200W per unit	High: up to 5000W	High: up to 10kW per unit
Thermal Resistance	Very low: < 0.01 K/W	Very Low: < 0.02 K/W	Very low: < 0.01 K/W
Equivalent Conductivity	Very high: up to 40 kW/(m K)	Medium: up to 10 kW/(m K)	Very high: up to 200 kW/(m K)
Start Up Time	Fast: Few seconds	Medium: 2-3 minutes	Medium: 2-3minutes
Effect of Inclination Angle	Medium: sintered HPs suffer in top heating mode. Efficient in bottom heating mode	Critical: a proper design may avoid strong effects, but top heating mode is difficult	Critical: Evaporator above, only for complex systems (e.g. valves or active control)
3D Space Adaptability	Low	High (highly foldable)	Low/Medium (gravity limit)
Controlled Surface	Medium	Large	Medium
TRL	9	3	9
Cost	Medium (wick structure)	Low (capillary tube)	Low/Medium

MISSION

1) Understanding the physics behind the behaviour of a HyHP
2) Increasing the Technological Readiness Level of a HyHP
3) Supporting and complement the ESA activities for an experiment on the SpacePHP (HyHP) on the ISS

CONTEXT

The Heat Exchang
been a major proc
of more than **£0.6**
increasing attenti
The Space Sector
opportunity of 5B
The thermal mana
business. It is ther
systems for space
a value of more th

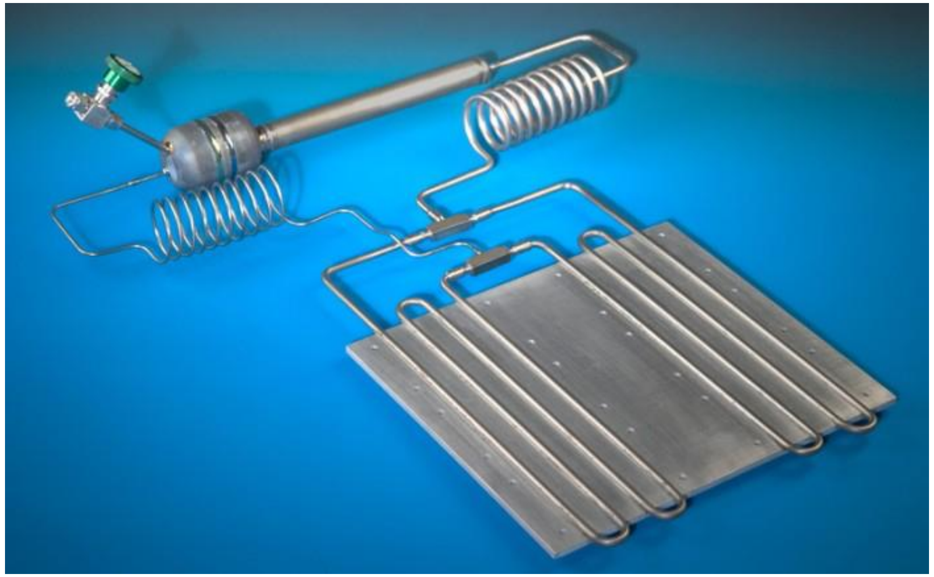


	2012	2013	2014	2015	2016	2017E
Sales	1895.41	2029.42	2151.94	2229.12	2298.46	2388.14
Growth Rate	7.35%	7.07%	6.04%	3.59%	3.11%	3.90%

Source: Expert Interviews, Secondary Sources and GIR Analysis, 2017

Fujikura Ltd.

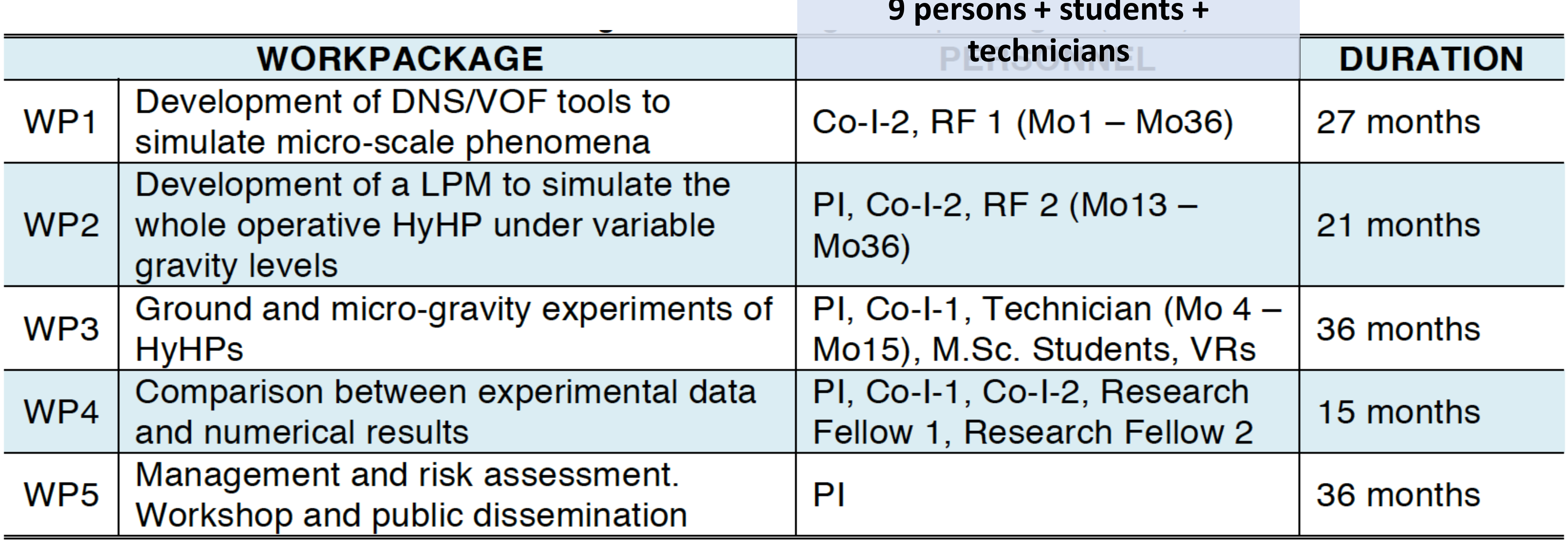
Advanced Cooling Technology



HyHP project could become a **flagship for the integration of Energy Systems and Fluid Dynamics and in particular for heat transfer research in the UK**. The project complements EPSRC national strategies: HyHP builds a scientific leadership in the field of twophase thermal systems and heat pipes, moving knowledge, skills and scientists from other countries to UK.

OBJECTIVES

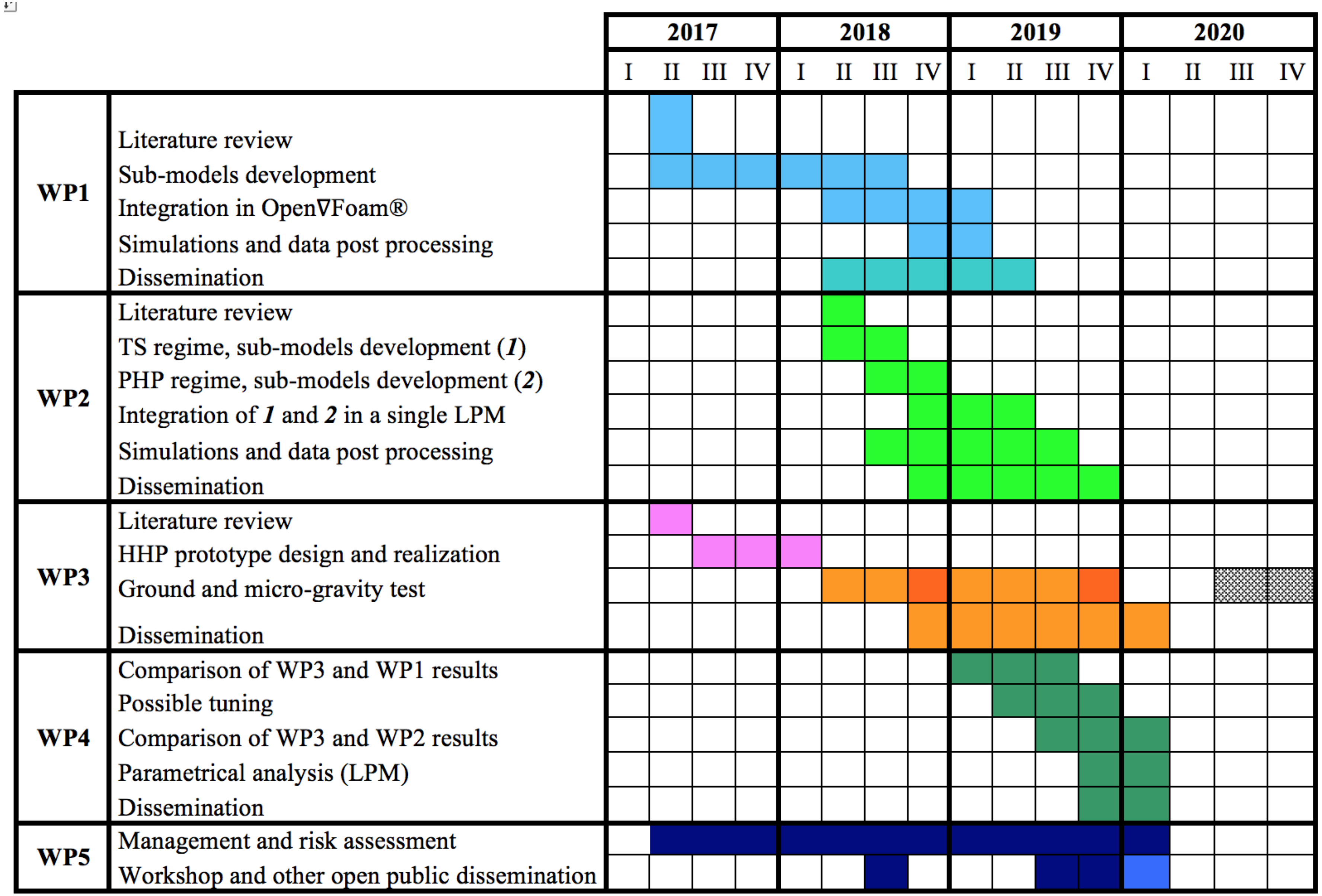
1. An advanced numerical method for the simulation of oscillating bubbles in capillary slug flows and in stratified conditions
2. Implementation of the method in an open source CFD code (OpenFOAM®)
3. Evaluation of heat transfer coefficients in oscillating multiphase flows
4. A novel thermal network code, able to predict the behaviour of Thermosyphon-like and Capillary-like two-phase systems
5. The implementation of a HyHP in microgravity conditions and eventually in the Thermal Platform on the ISS



WORKPACKAGE		9 persons + students + technicians	DURATION
WP1	Development of DNS/VOF tools to simulate micro-scale phenomena	Co-I-2, RF 1 (Mo1 – Mo36)	27 months
WP2	Development of a LPM to simulate the whole operative HyHP under variable gravity levels	PI, Co-I-2, RF 2 (Mo13 – Mo36)	21 months
WP3	Ground and micro-gravity experiments of HyHPs	PI, Co-I-1, Technician (Mo 4 – Mo15), M.Sc. Students, VRs	36 months
WP4	Comparison between experimental data and numerical results	PI, Co-I-1, Co-I-2, Research Fellow 1, Research Fellow 2	15 months
WP5	Management and risk assessment. Workshop and public dissemination	PI	36 months

PI : Marco Marengo
Co-I: Anastasios Geourgoulas (NUM) and Nicolas Miche’ (EXP)
RF1: Manolia Andredaki (1fte), numerical aspects and modeling (36 months)
RF2: NN (0.8fte), experimental aspects and Lumped Parameter Model (24 months)
RO: Marco Bernagozzi (0.8fte), technical support for the microgravity campaign (12 months)
VRs: Lucio Araneo and Mauro Mameli
PhD: Luca Pietrasanta, Evaluation of heat transfer coefficients in oscillating two-phase flows in space and ground environment

ORIGINAL



		2017				2018				2019				2020			
		I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
WP1	Literature review		🟦														
	Sub-models development		🟦	🟦	🟦	🟦	🟦	🟦									
	Integration in Open∇Foam®						🟦	🟦	🟦	🟦							
	Simulations and data post processing								🟦	🟦							
	Dissemination						🟦	🟦	🟦	🟦	🟦						
WP2	Literature review						🟩										
	TS regime, sub-models development (*1*)						🟩	🟩									
	PHP regime, sub-models development (*2*)							🟩	🟩								
	Integration of *1* and *2* in a single LPM								🟩	🟩	🟩						
	Simulations and data post processing							🟩	🟩	🟩	🟩	🟩					
	Dissemination								🟩	🟩	🟩	🟩	🟩				
WP3	Literature review		🟪														
	HHP prototype design and realization			🟪	🟪	🟪											
	Ground and micro-gravity test						🟧	🟧	🟥	🟧	🟧	🟧	🟥			▨	▨
	Dissemination								🟧	🟧	🟧	🟧	🟧	🟧			
WP4	Comparison of WP3 and WP1 results									🟩	🟩	🟩					
	Possible tuning										🟩	🟩	🟩				
	Comparison of WP3 and WP2 results											🟩	🟩	🟩			
	Parametrical analysis (LPM)												🟩	🟩			
	Dissemination												🟩	🟩			
WP5	Management and risk assessment		⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛			
	Workshop and other open public dissemination							⬛				⬛	⬛	🟦			

HyHP

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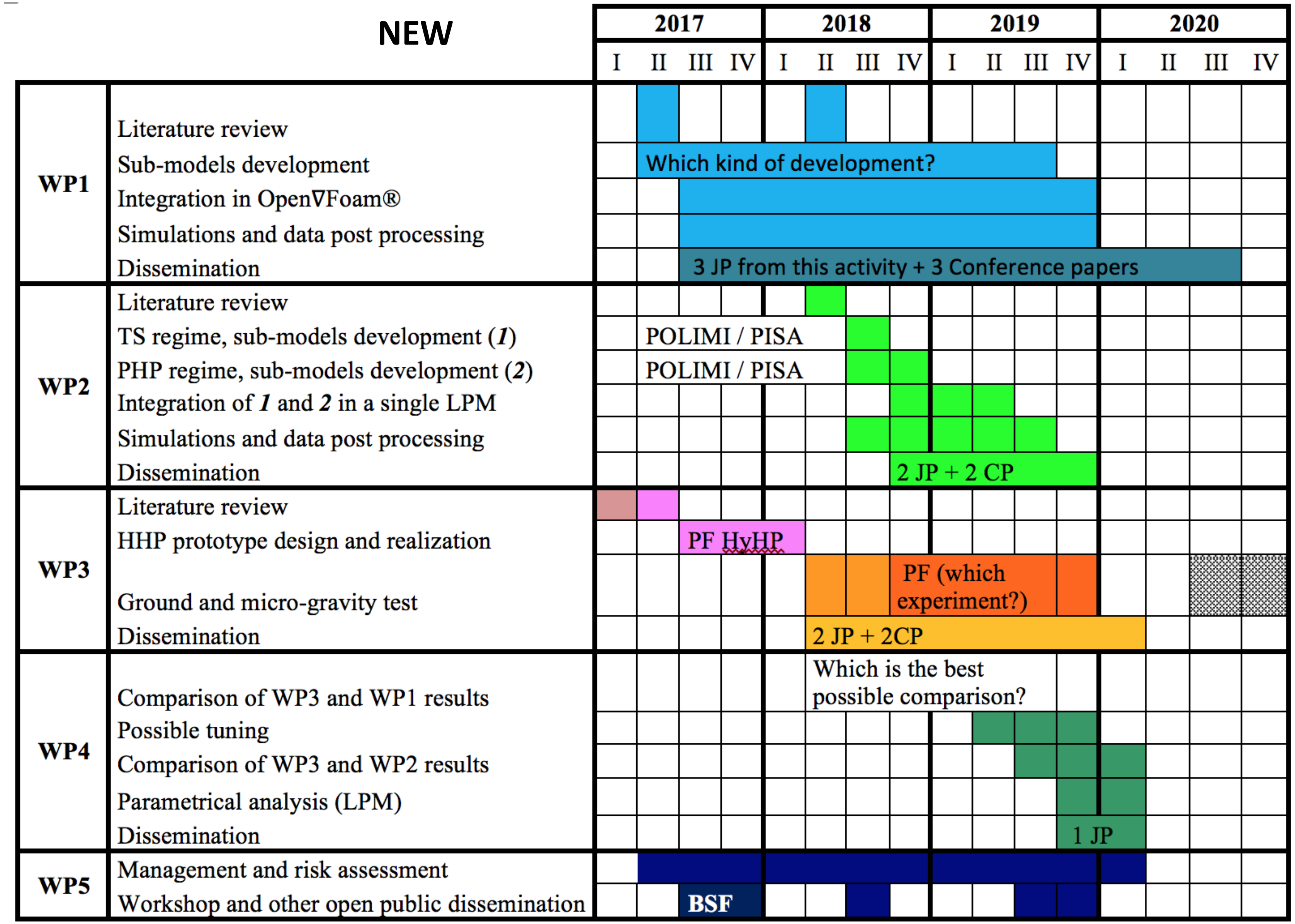
NEW

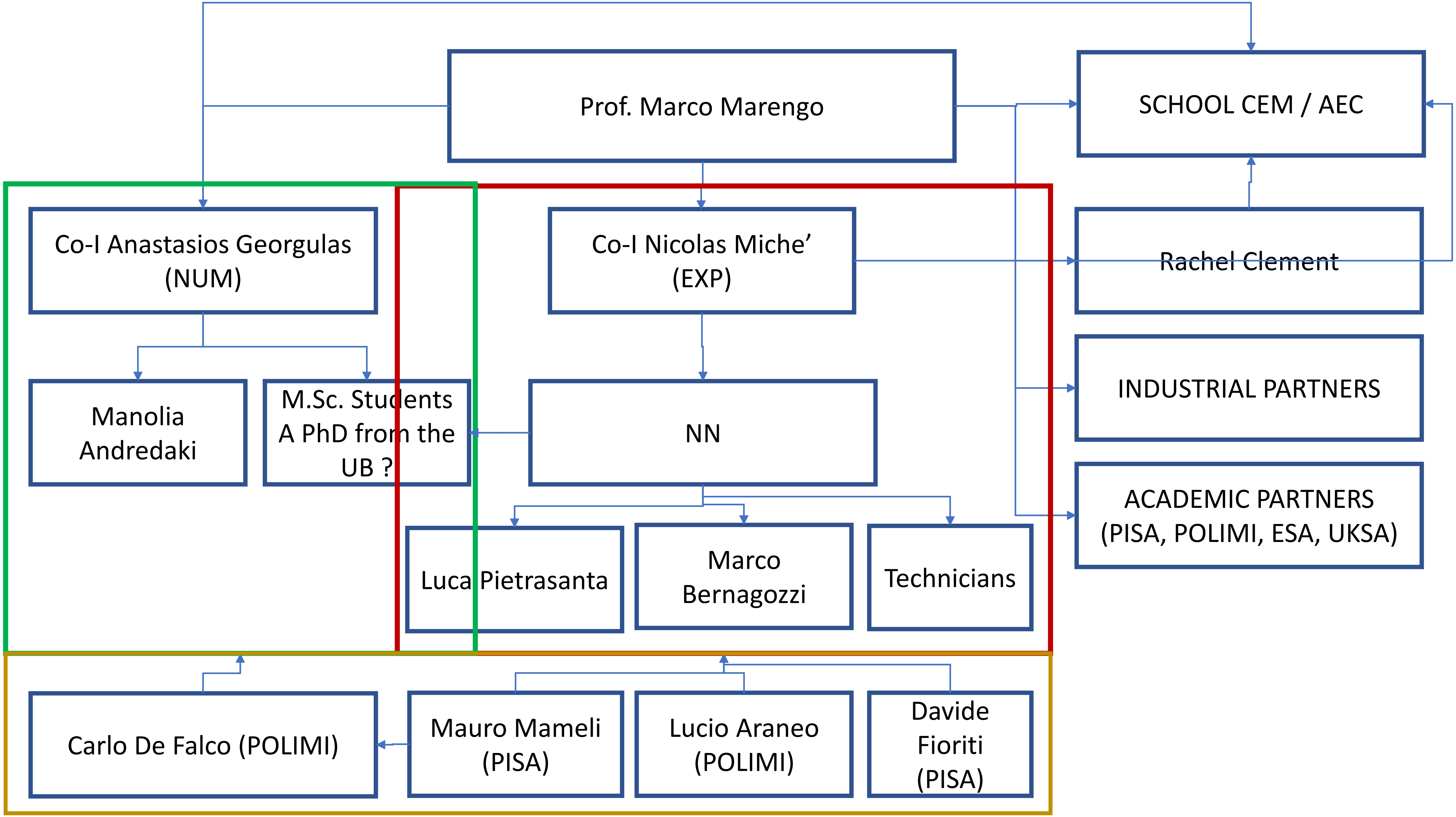


		2017				2018				2019				2020			
		I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
WP1	Literature review		🟦				🟦										
	Sub-models development		🟦 Which kind of development?	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
	Integration in Open∇Foam®			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				
	Simulations and data post processing			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				
	Dissemination			◆ 3 JP from this activity + 3 Conference papers	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	
WP2	Literature review						🟩										
	TS regime, sub-models development (*1*)		POLIMI / PISA					🟩									
	PHP regime, sub-models development (*2*)		POLIMI / PISA					🟩	🟩								
	Integration of *1* and *2* in a single LPM								🟩	🟩	🟩						
	Simulations and data post processing							🟩	🟩	🟩	🟩	🟩					
	Dissemination								🟩 2 JP + 2 CP	🟩	🟩	🟩	🟩				
WP3	Literature review	🟥	🟪														
	HHP prototype design and realization			🟪 PF HyHP	🟪	🟪											
	Ground and micro-gravity test						🟧	🟧	🟧 PF (which experiment?)	🟧	🟧	🟧	🟧			▨	▨
	Dissemination						🟨 2 JP + 2CP	🟨	🟨	🟨	🟨	🟨	🟨	🟨			
WP4	Comparison of WP3 and WP1 results						Which is the best possible comparison?										
	Possible tuning										▩	▩	▩				
	Comparison of WP3 and WP2 results											▩	▩	▩			
	Parametrical analysis (LPM)												▩	▩			
	Dissemination												▩ 1 JP	▩			
WP5	Management and risk assessment		■	■	■	■	■	■	■	■	■	■	■	■			
	Workshop and other open public dissemination			■ BSF	■			■				■	■				

- 🟦 CI-2, RF-1
- 🟩 PI, CI-2, RF-2
- 🟪 CI-1, MSc Students, Visiting Researchers, Technician
- ◆ PI, CI-2, RF-1
- 🟧 PI, CI-1, Visiting Researchers, Technician
- ▩ PI, CI-1, CI-2, RF-1, RF-2
- ■ PI

Every 3 months a report will be prepared on each WP

Two Parabolic flight campaigns are expected: in Nov 2017 and Autumn 2018. The experiment on the ISS should run before the end of 2020.



Prof. Marco Marengo

SCHOOL CEM / AEC

Co-I Anastasios Georgulas (NUM)

Co-I Nicolas Miche’ (EXP)

Rachel Clement

Manolia Andredaki

M.Sc. Students A PhD from the UB ?

NN

INDUSTRIAL PARTNERS

ACADEMIC PARTNERS (PISA, POLIMI, ESA, UKSA)

Luca Pietrasanta

Marco Bernagozzi

Technicians

Carlo De Falco (POLIMI)

Mauro Mameli (PISA)

Lucio Araneo (POLIMI)

Davide Fioriti (PISA)

WP1

The VOF code will simulate the local flow patterns and to study the micro-scale phenomena involved during the operation of a HyHP.

All the main physical processes within a HyHP (bubble growth due to evaporation, bubble detachment, bubble **condensation**, coalescence and break-up) will be directly resolved (temporally and spatially) by the numerical model *without relying on empirical sub-models*.

Further enhancements of the CFD solver will be:

1)

PARTIALLY DONE

2)

3) The addition of compressibility effects in order to account for the **variation of the working fluid properties** with temperature
4) The addition of appropriate **sub-grid scale evaporation and condensation models**
5) Better estimation of the HTC for the different cases

Which are the cases?

WP1

We need to decide which are the cases to simulate, starting from a robust validation against experimental data. There are three main questions to answer:

1) Which is the effect of oscillations (amplitude and frequency) on the HTC? (Schlichting experiment)
2) Which are the dynamic effects when the velocity of the liquid slugs is very fast ? (Garimella number..)
3) Which is the effect of the liquid film thickness? (Nikolayev theory)
4) Other?

Which cases? Which liquids? We need to build a good simulation matrix

From the point of view of the simulation technique we need to answer to the question: Which is the variation of the sim results when we take into account variable properties?

For the future: Can we try to simulate the Single Loop Pulsating Heat Pipe?

WP2

The CFD/VOF approach cannot be applied directly to the simulation of an entire HyHP, since the requested computational costs are excessive: only single branches or even part of them can be reasonably analysed. Therefore, a LUMPED PARAMETER METHOD cannot be avoided to simulate the whole HyHP.

We are going to start with the code developed in Octave by Miriam Manzoni (supported also by Carlo De Falco and his team/students)

Further improvements are:

1) Physics of the liquid film (liquid film dynamics, wetting and dewetting)
2) Nucleation model and bubble growing, coalescence and collapse
3) Dry-out limit
4) Implementing a correlation for the heat transfer coefficient between a wall and a oscillating two-phase flow.

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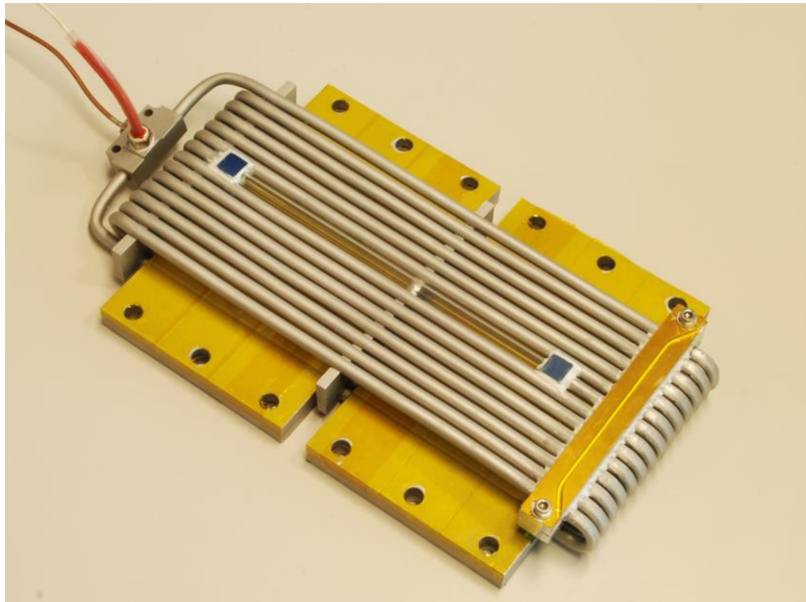
WP3 We have the SpacePHP with the sapphire insert to test in November 2017 on the Parabolic Flight

We still need to validate this idea, especially in terms of requested power, size and location of the evaporator heating.

We need to work in direction of other fluids and materials. For example Titanium and water. We need to check the possibility to bond the glass plate to the metallic plate, and so on.



Also in this case, we need to define a detailed plan for the next two years of experiments, in order to answer to all the issues linked to the Experimental Scientific Requirement (ESR) for the ISS experiment.

Furthermore, it is very important to have experiments to compare with the numerical simulations, especially regarding the measure of the HTC for a single bubble oscillation.

INDUSTRIAL COOPERATION

- Two research fellows/officers are 0.8fte. This implies that we can leverage their work with industrial contracts for 0.2fte.

- One research officer is for one year. There is a potential to offer a later position for a knowledge transfer activity.

- Since HyHP intends to improve the TRL of the Pulsating Heat Pipe, it could be very important to have the chance to implement the PHP on a real breadboard

- We are keen of building up partnerships:
  - ☐ INNOVATE UK
  - ☐ EngD
  - ☐ KTP
  - ☐ Patents

We are looking to support the design of novel two-phase systems for your ground and space application

① 9 papers in International Journals with high impact factor

② >3 papers in International Conference Proceedings

③ Enhanced/Improved VOF-based numerical models for OpenFOAM

④ Submission of an "Innovate UK" project

⑤ European Workshop on "Wickless Heat Pipe Technology"

⑥ 3 internal seminars at UoB

⑦ 1 public lecture at UoB

⑧ A dedicated website under the UoB website

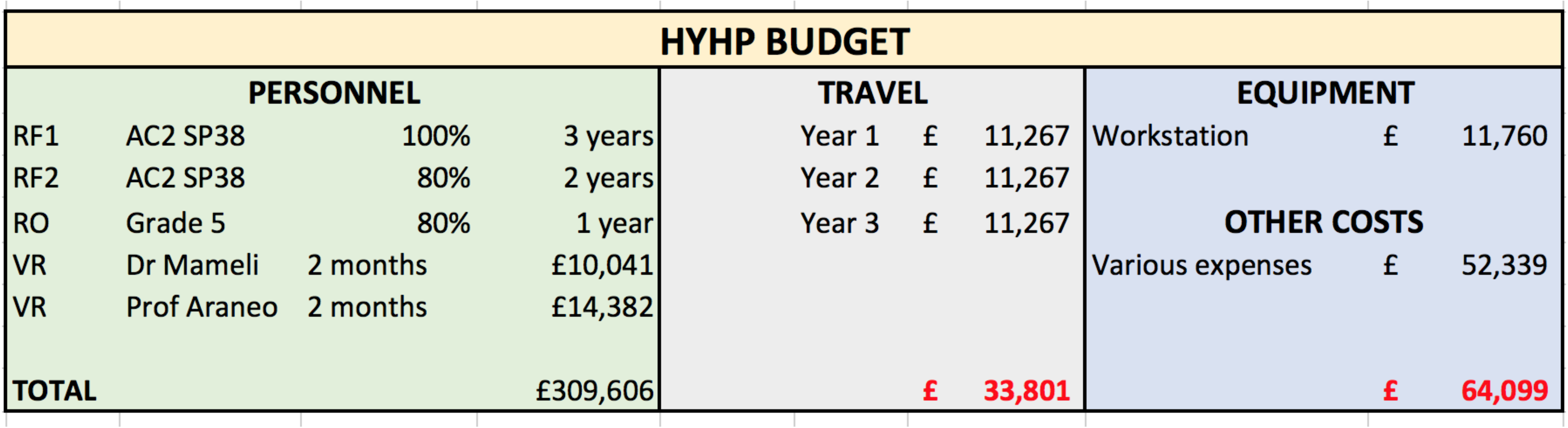
⑨ Participation in science festivals, such as the Brighton Science Festival

⑩ A potential final implementation of the system inside the International Space Station

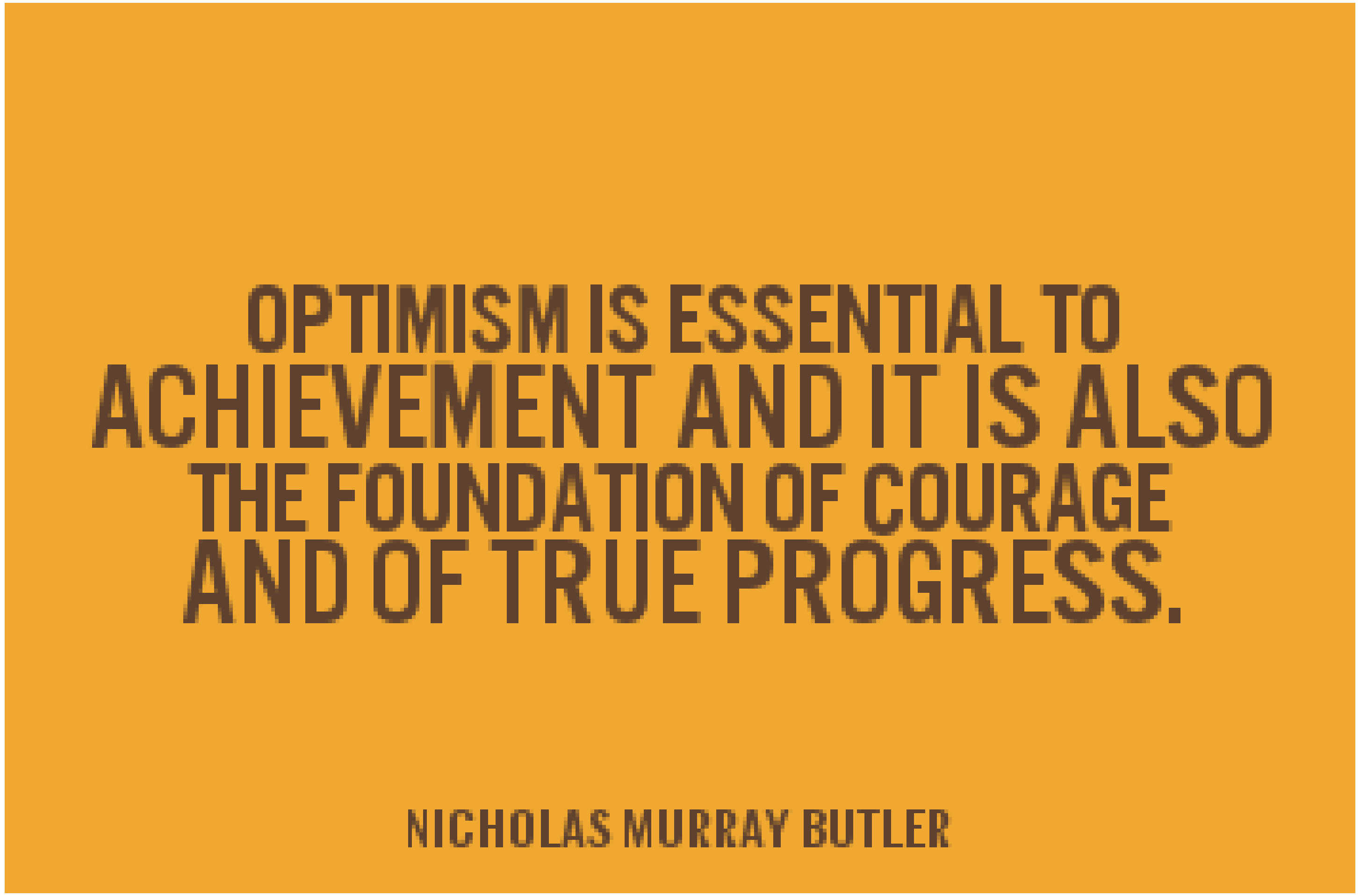
Heat and Mass Transfer

①	9 papers in International Journals with high impact factor	3 JP per years 3 Conference papers per year
②	>3 papers in International Conference Proceedings	
③	Enhanced/Improved VOF-based numerical models for OpenFOAM	December 2018
④	Submission of an "Innovate UK" project	
⑤	European Workshop on "Wickless Heat Pipe Technology"	October 2019
⑥	3 internal seminars at UoB	March 2018 – March 2019 – October 2019
⑦	1 public lecture at UoB	February 2020 – ISS?
⑧	A dedicated website under the UoB website	
⑨	Participation in science festivals, such as the Brighton Science Festival	September 2017 – May 2019
⑩	A potential final implementation of the system inside the International Space Station	

BUDGET



HYHP BUDGET									
PERSONNEL				**TRAVEL**			**EQUIPMENT**		
RF1	AC2 SP38	100%	3 years	Year 1	£	11,267	Workstation	£	11,760
RF2	AC2 SP38	80%	2 years	Year 2	£	11,267			
RO	Grade 5	80%	1 year	Year 3	£	11,267	**OTHER COSTS**		
VR	Dr Mameli	2 months	£10,041				Various expenses	£	52,339
VR	Prof Araneo	2 months	£14,382						
TOTAL			£309,606		£	33,801		£	64,099



OPTIMISM IS ESSENTIAL TO ACHIEVEMENT AND IT IS ALSO THE FOUNDATION OF COURAGE AND OF TRUE PROGRESS.

NICHOLAS MURRAY BUTLER