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Disruptive Technology Search for Space Applications

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List of Abbreviations

AHP	Analytic Hierarchy Process
BEE	Best Engineering Estimate
CAD	Computer-Aided Design
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DST	Disruptive Space Technology
DT	Disruptive Technology
ESA	European Space Agency
HVI	Hypervelocity Impact
IFAM	Institute for Manufacturing Technology and Applied Materials Research (Institut für Fertigungstechnik und Angewandte Materialforschung)
IICh	Institute of Inorganic Chemistry
MF	Metal Foaming
MMOD	Micrometeoroid and Orbital Debris
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NRC	National Research Council
RD	Reference Document
RS	Real Structure
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TN	Technical Note
TPS	Thermal Protection System
TRL	Technology Readiness Level
TRM	Technology Roadmap
WP	Work Package
R&D	Research and Development
PCM	Phase-Change Memory
DRAM	Dynamic Random-Access Memory
UPA	University of Pardubice
C&DH	Command and Data Handling
CVD	Chemical Vapor Deposition
IPC	Institute of Polymers and Composites
FNS	Functional Nanomaterials and Synthesis

Executive Summary

This Technical Note (TN) documents on Work Package (WP) 5300, which is the Technology Roadmapping part. Its main purpose is to roadmap the technologies with its different development steps (up to TRL 6) that resulted from the Disruptive Space Technology (DST) evaluation of TN04. It fits within the overall research as the DST Roadmapping part, highlighted in the overall structure of the research, depicted in Figure E-1. In this figure, the second chapter of this TN focuses on the theory of technology roadmapping and the creation of a DST roadmap design, followed by 3 chapters (3-5), each displaying one dedicated technology roadmap.

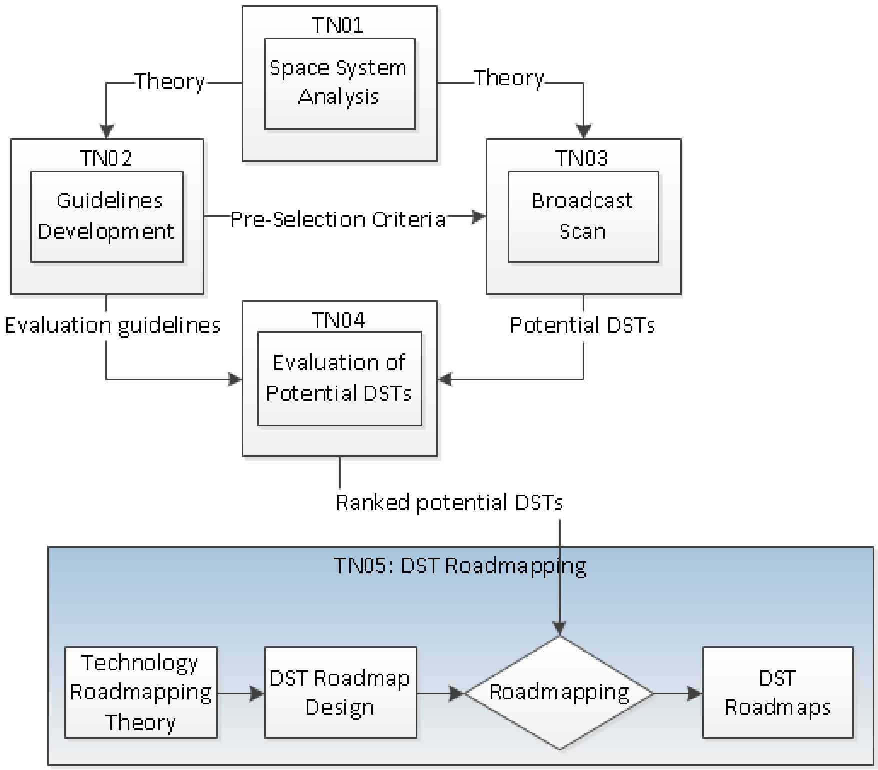


Figure E-1: Overall structure of the DST research.

The aim was to roadmap technologies, which are not supported already by an investment scheme from ESA and have fundable research groups within Europe. Because of this, from the ranked technologies in TN04, the following technologies were initially selected for the roadmapping phase after a teleconference with ESA:

- Metallic microlattice/ Metal foam
- Chalcogenide-based reconfigurable memory electronics
- Silicon nanowire for lithium ion-battery
- Micro-electric space propulsion
- Additional wildcard technology: Aerographite

After researching these technologies in more detail and discussing with the different potential research groups and ESA's technical officer, it was concluded that some of the technologies are different than anticipated, some did not have active research groups after all and some are already invested in by ESA. Because of this, the decision was made in agreement with ESA's technical officer to make the following alterations with respect to the candidates:

- *Metallic microlattice* is a *Porous Metal* with amazing properties, however, its disruptive potential lies in its production process. As no research groups could be found within Europe for the micro lattice material, the decision was made to focus on two production processes for Porous Metals namely Metal Foaming and Additive Manufacturing (as a main production process). These applications are therefore roadmapped instead of *metallic microlattice*.

- Chalcogenide-based reconfigurable memory electronics are actually a subfield of the field of Phase-Change Memory (PCM). Because of this, the focus of the roadmap was set broader, focusing on PCM as a whole rather than focusing chalcogenide-based reconfigurable memory electronics.

- Silicon nanowire for lithium ion-batteries was found to be less disruptive than anticipated. After a discussion with Prof. Ruffo of the University of Milano-Bicocca-Italy, the decision was made to discard this technology, even though silicon nanowires provide an improvement for the anode of a lithium ion-battery, using them will not lead to major improvements in the performance of the battery itself, due to the fact that the cathode is the bottleneck within lithium ion-batteries development. Because of this and because the lack of research groups within Europe, it was decided to drop the roadmap of this technology.

- Micro-electric space propulsion was dropped because after getting into contact with Prof. Herbert Shea of the École Polytechnique Fédérale de Lausanne-Switserland (only group in Europe investigating this specific technology), it was found out that this technology was already recently supported by the ITI funding scheme.

Furthermore, it was decided (at the MTR, compare MoM) to concentrate more on identifying European research groups for the selected technology candidates, rather than deeply elaborate 'virtual' roadmaps for the DST candidates, not specifically targeted to one organization. Therefore, first exploratory talks were performed with these groups in order to prepare them for potential ITI proposal submissions. With this action shift the documented roadmaps in this technical note are more hands-on. The roadmaps were several times iterated with the respective research group. In conclusion, the following DST roadmaps are presented:

- Porous Metals: Metal Foam in combination with Additive Manufacturing (AM)
- Phase-Change Memory (PCM)
- Aerographite

Chapter 2: Technology Roadmapping Theory

In this chapter the fundamentals of technology roadmapping are discussed and the technology roadmapping process is explained. Several different phases of the roadmapping process and their accompanying steps are described in detail.

A proper roadmap design is generated that is used to describe the development steps of the DST candidates. The category of roadmaps 'Program Planning` was chosen and as most suitable roadmap format the so called "single layered bar format" (compare Table E-1) was chosen for displaying the different process steps. This format was chosen because it is the most suitable when it comes to displaying the development of technologies over a longer period of time. The single layered bar format enables the clear representation of the various processes and sub-processes that need to be completed in order to develop a technology further. In addition to that, this chapter contains an elaborate discussion regarding the DST roadmaps' contents as well as a detailed description of the final roadmap design.

Table E-1: Overview of selected roadmap category and format

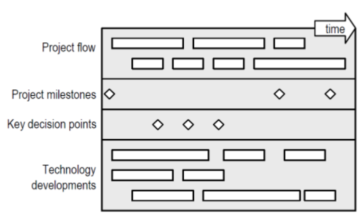
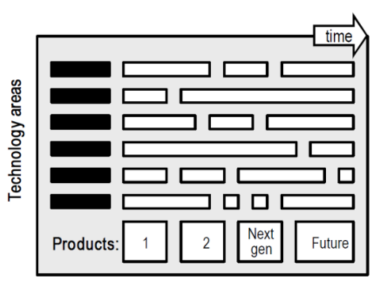
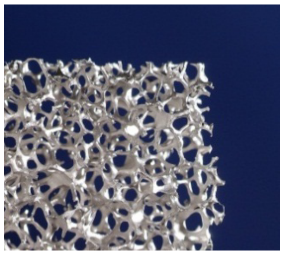
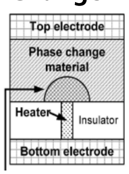
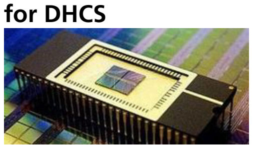
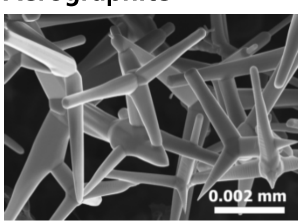
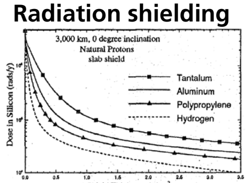
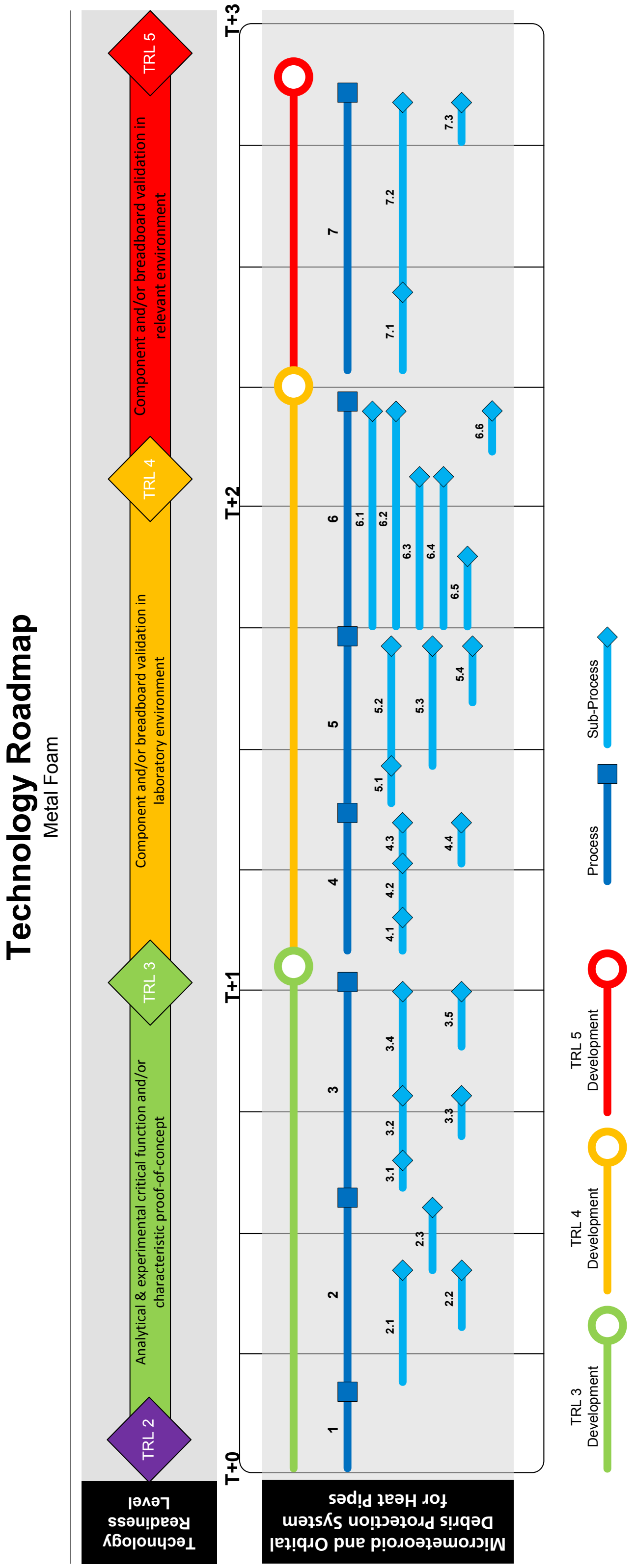
	**Program planning:** This type of TRM includes the implementation of strategy, and more directly relates to project planning such as Research and Development (R&D) programs. The example shown on the left is a NASA roadmap (one of many) for the Origins program, used to explore how the universe and life within it has developed. This particular roadmap focuses on the management of the development program for the Next Generation Space Telescope (NGST), showing the relationships between technology development and program phases and milestones [RD 11].
	**Single Layered (Bar):** This TRM format is closely related to the multilayered format. In particular, the single layered TRM format focuses on one layer of the multilayered roadmap. While less complex, the disadvantage of this format is that the linkages between the layers are generally not shown. The example shown in is the 'classic' Motorola roadmap, showing the evolution of car radio product features and technologies [RD 1]. Motorola has subsequently developed roadmapping to new levels, with roadmaps now forming part of corporate knowledge and business management systems, supported by software and integrated decision support systems [RD 12]. The most commonly applied visual format is the 'bar' format. Applying the bar visual format has the advantage of simplifying and unifying the required outputs,

Table E-2 displays the different key parameters for the selected DST candidate roadmaps, including the research group and contact persons.

Table E-2: Overview of selected technology candidates, potential applications and research groups

Technology Candidate	Example Application	Advantages/Disadvantages	Selected Research Group	Contact Information	Development time
Porous Metals 	**Metal foams MMOD protection for Heat Pipes** 	• Great capability to absorb kinetic energy (impacts) & good mechanical damping properties • Good electromagnetic shielding properties & Low magnetic permeability • Good mechanical damping properties (acoustic and vibration) • High thermal conductivity compared to Whipple shields Drawbacks: • Lower MMOD protection compared to the Whipple shields	Fraunhofer IFAM	**Dipl.-Phys. Joachim Baumeister** Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) Wiener Straße 12 28359 Bremen Tel.: + 49 421 2246 -181 Email:joachim.baumeister@ifam.fraunhofer.de Web: www.ifam.fraunhofer.de	3 years
	Complex lettuce structures using Additive Manufacturing 	• Wide range of selectable materials (e.g. metallic/ ceramic) • Customized small volume production • Dimensional accuracy and quality of the surface finish of the produced objects • Material properties of the produced parts • Production costs Drawbacks: • Slow manufacturing speed • Size limitations	Fraunhofer IFAM	**Dipl.-Ing. Claus Aumund-Kopp** Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) Wiener Straße 12 28359 Bremen Tel.: + 49 421 2246-226 Email: claus.aumund-kopp@ifam.fraunhofer.de Web: www.ifam.fraunhofer.de	6 years
Phase Change Memory  	**PCRAM Electronics for DHCS** 	• Data retention • Low power consumption • Good down-scalability • High radiation resistance Drawbacks: • Low speed • Limited endurance	Univerzita Pardubice	**Prof. Miloslav Frumar**, PhD, DSc, Fac. Chem. Tech. University of Pardubice, 53210 Pardubice, Czech Rep. Tel.: +420 466037161 Email: Miloslav.Frumar@upce.cz Web: http://vzc.upce.cz/home.php	6 years
Aerographite  	**Radiation shielding**  	• Low atomic weight • Good electrical conductivity • High surface area • Very low Poisson ratio • Good compressive and tensile strength • Multiple structural configurations possible • High radiation shielding in combination with H2 Drawbacks: • High amount of uncertainty on the predicted properties	TUHH Polymer Composites	**Prof. Dr.-Ing. Karl Schulte** Technische Universität Hamburg-Harburg Institute of Polymers and Composites M-11 Denickestr. 15 D-21073 Hamburg Tel.: +49 40 42878 3138 Email: schulte@tuhh.de Web: http://cgi.tu-harburg.de	9 years

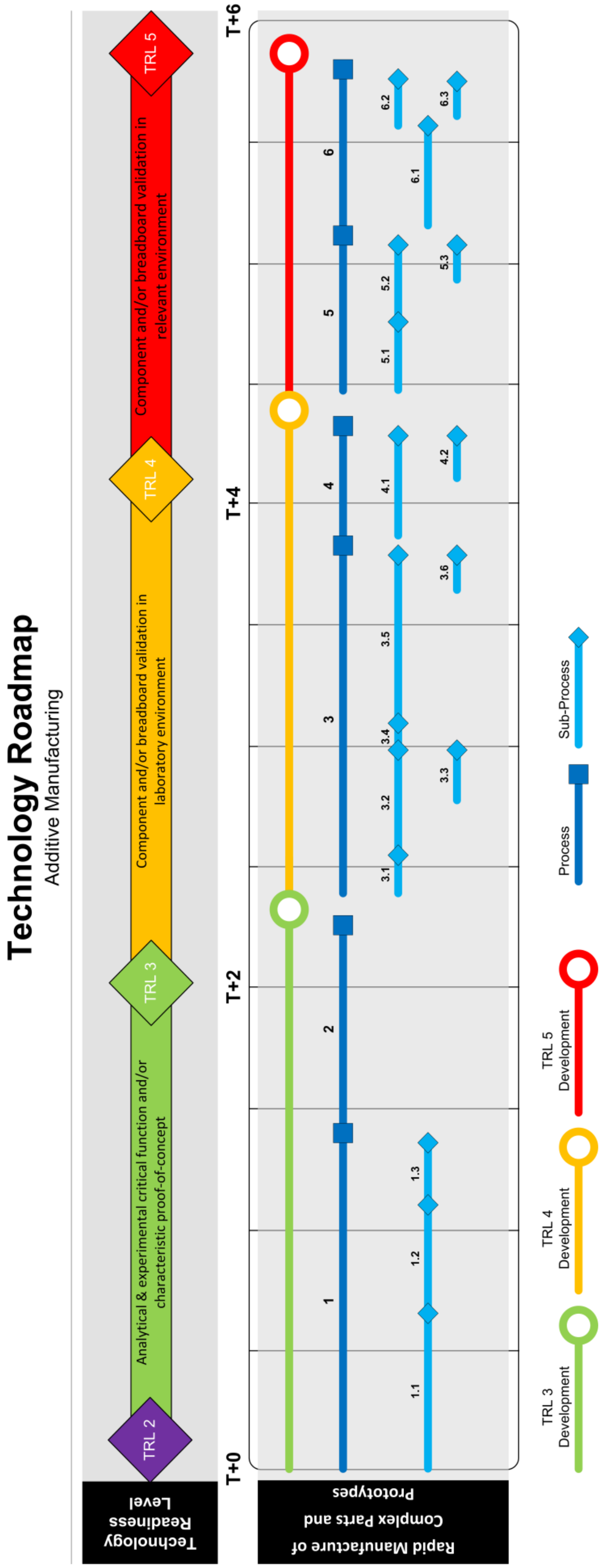
Chapter 3-A: Porous Metals - MMOD Roadmap



Legend - Metal Foam					
Step	Description	Step	Description	Step	Description
1	**Fundamental Research**	**4**	**Metal Foam Production**	**6**	**Intensive Testing**
2	**Modeling & Simulation**	4.1	Metal Foam Selection	6.1	Impact Tests
2.1	Impact Modeling	4.2	Production Process Design	6.2	Thermal Tests
2.2	Thermal Modeling	4.3	Metal Foam Production	6.3	Stress Tests
2.3	Simulation	4.4	Metal Foam Attribute Testing	6.4	Fatigue Tests
3	**System Design**	**5**	**Basic Testing**	6.5	Corrosion Tests
3.1	Define Expected/Potential Mission Parameters	5.1	Preparation of Preliminary Performance Testing Facilities	6.6	Model and Design Update
3.2	Preliminary System Design	5.2	Preliminary Performance Testing	**7**	**Mission Cycle Testing**
3.3	Model Adjustment & Simulation	5.3	Preparation of Intensive Testing Facilities	7.1	Test Preparation
3.4	Detailed System Design	5.4	Model Adjustment & Simulation	7.2	Mission Cycle Tests
3.5	Model Expansion & Simulation			7.3	Model and Design Update

Figure E-2: DST roadmap for metal foam.

Chapter 3-B: Porous Metals – Additive Manufacturing (AM) Roadmap

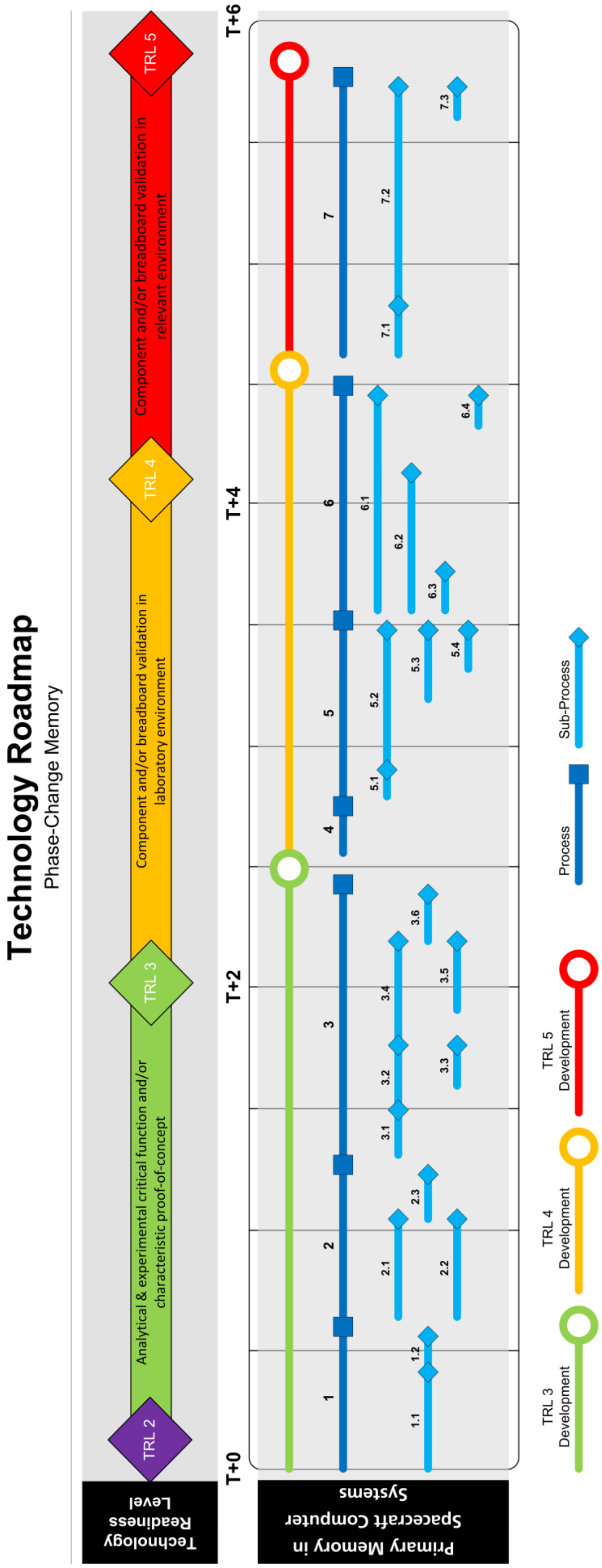


Legend - AM

Step	Description	Step	Description	Step	Description
1	**Research**	3.2	AM Technique Proposal Generation	**5**	**Preliminary Testing**
1.1	Fundamental Research	3.3	Simulation	5.1	Preliminary Performance Testing
1.2	Guidelines & Industry Standards	3.4	Trade-Off	5.2	Reproducibility Testing
1.3	Database Generation	3.5	System Design	5.3	Model Update
2	**Modeling**	3.6	Model Update	**6**	**Dedicated Testing**
3	**Technique Design**	**4**	**Technique Preparation**	6.1	Representative Production Run
3.1	Identification of Growth Potential	4.1	AM Machine Calibration and Adjustment	6.2	Property Testing of Produced Parts
		4.2	Operating Routines	6.3	Model Update

Figure E-3: DST roadmap for Additive Manufacturing.

Chapter 4: Phase-Change Memory Roadmap

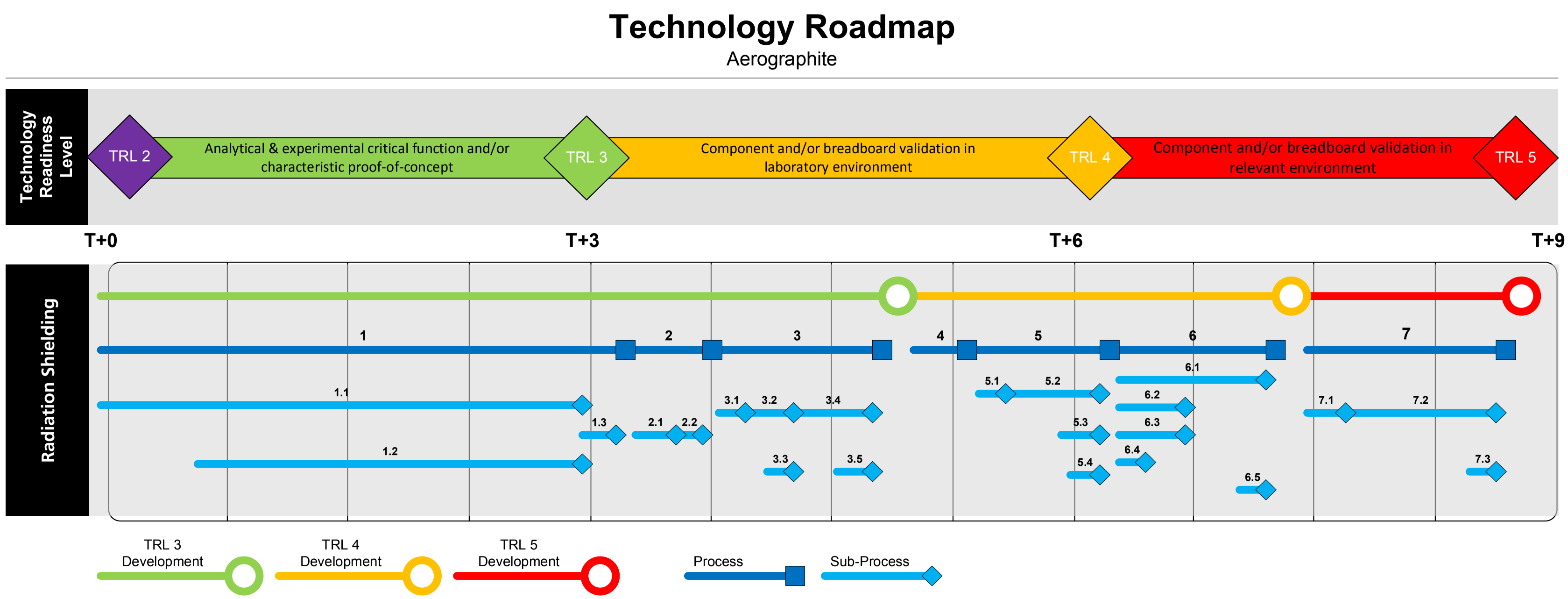


Legend - PCM

Step	Description	Step	Description	Step	Description
1	**Research**	3.3	Model Adjustment & Simulation	**6**	**Intensive Testing**
1.1	Information Gathering	3.4	Detailed Architecture Design	6.1	Thermal Tests
1.2	Database Generation	3.5	Model Expansion & Simulation	6.2	Radiation Tests
2	**Modeling**	3.6	Software Design	6.3	Corrosion Tests
2.1	Memory Modeling	**4**	**Prototype Memory Module Fabrication**	6.4	Model and Design Update
2.2	Thermal Modeling	**5**	**Basic Testing**	**7**	**Mission Cycle Testing**
2.3	Simulation	5.1	Preparation of Preliminary Performance Testing Facilities	7.1	Test Preparation
3	**System Design**	5.2	Preliminary Performance Testing	7.2	Mission Cycle Tests
3.1	Define Expected/Potential Mission Parameters	5.3	Model Adjustment & Simulation	7.3	Model and Design Update
3.2	Preliminary Architecture Design	5.4	Preparation of Intensive Testing Facilities	7.4	Mission Cycle Tests
				7.5	Model and Design Update

Figure E-4: DST Roadmap for Phase-Change Memory.

Chapter 5: Aerographite Roadmap



Legend - Aerographite					
Step	Description	Step	Description	Step	Description
1	**Fundamental Research**	3.3	Model Adjustment & Simulation	6.1	Radiation Tests
1.1	Research	3.4	Detailed System Design	6.2	Impact Tests
1.2	Experimentation	3.5	Model Expansion & Simulation	6.3	Thermal Tests
1.3	Database Creation	**4**	**Aerographite Production**	6.4	Corrosion Tests
2	**Modeling & Simulation**	**5**	**Basic Testing**	6.5	Model and Design Update
2.1	Radiation model	5.1	Preparation of Preliminary Performance Testing Facilities	**7**	**Mission Cycle Testing**
2.2	Simulation	5.2	Preliminary Performance Testing	7.1	Test Preparation
3	**System Design**	5.3	Preparation of Intensive Testing Facilities	7.2	Mission Cycle Tests
3.1	Define Expected/Potential Mission Parameters	5.4	Model Adjustment & Simulation	7.3	Model and Design Update
3.2	Preliminary System Design	**6**	**Intensive Testing**	7.4	Mission Cycle Tests
3.3	Model Adjustment & Simulation			7.5	Model and Design Update

Figure E-5: DST roadmap for Aerographite

1 Introduction

The main purpose of Work Package 5300 of the Technology Evaluation of Project 4000101818/10/NL/GLC is the roadmapping of the potential DSTs, identified in TN04. It fits within the overall research as the evaluation of potential DSTs part, highlighted in the overall structure of the research, depicted in Figure 1-1.

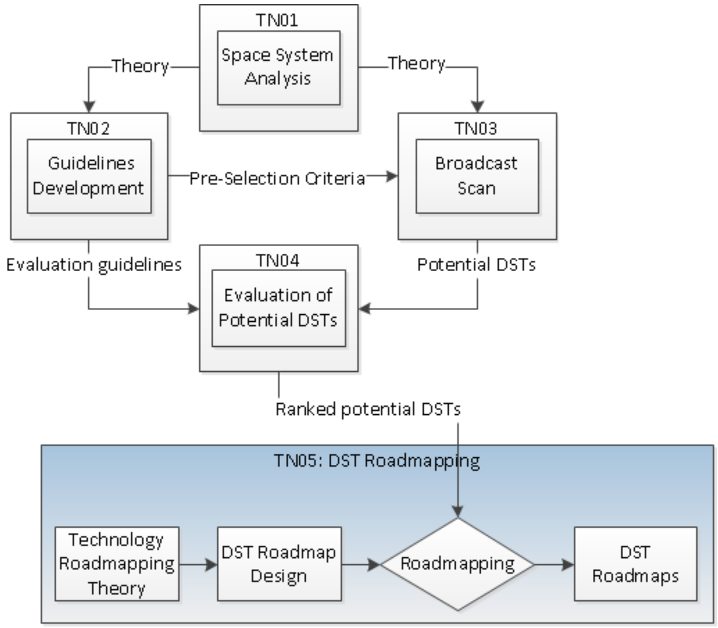


Figure 1-1: Overall structure of the DST research.

Over the last several decades technological progress has been tremendous. New technologies emerged in quick succession and the companies providing these new technologies were barely able to keep up [RD 1]. Partially because of this, the competition between rivaling companies became fierce. As a result, companies had to find new ways to subvert their rivals. The telecommunications company Motorola, for example, developed a new approach in the 1970s that allowed them to support integrated product-technology planning. This marked the birth of the phenomenon "technology roadmapping" [RD 1]. Since then, the technology roadmapping method has been used by different companies and governments for all kinds of technology planning purposes.

A technology roadmap (TRM) identifies the critical system requirements, the product and process performance targets, and the technology alternatives and milestones for meeting those targets. In effect, a technology roadmap identifies alternate technology "roads" for meeting certain performance objectives [RD 2].

The aim was to roadmap technologies, which are not supported already by an investment scheme from ESA and have fundable research groups within Europe. Because of this, from the ranked technologies in TN04, the following technologies were initially selected for the roadmapping phase after a teleconference with ESA:

- Metallic microlattice/ Metal foam
- Chalcogenide-based reconfigurable memory electronics
- Silicon nanowire for lithium ion-battery

- Micro-electric space propulsion
- Additional wildcard technology: Aerographite

After researching these technologies in more detail and discussing with the different potential research groups and ESA's technical officer, it was concluded that some of the technologies are different than anticipated, some did not have active research groups after all and some are already invested in by ESA. Because of this, the decision was made in agreement with ESA's technical officer to make the following alterations with respect to the candidates:

- *Metallic microlattice* is a *Porous Metal* with amazing properties, however, its disruptive potential lies in its production process. As no research groups could be found within Europe for the micro lattice material, the decision was made to focus on two production processes for Porous Metals namely Metal Foaming and Additive Manufacturing (as a main production process). These applications are therefore roadmapped instead of *metallic microlattice*.

- Chalcogenide-based reconfigurable memory electronics are actually a subfield of the field of Phase-Change Memory (PCM). Because of this, the focus of the roadmap was set broader, focusing on PCM as a whole rather than focusing chalcogenide-based reconfigurable memory electronics.

- Silicon nanowire for lithium ion-batteries was found to be less disruptive than anticipated. After a discussion with Prof. Ruffo of the University of Milano-Bicocca-Italy, the decision was made to discard this technology, even though silicon nanowires provide an improvement for the anode of a lithium ion-battery, using them will not lead to major improvements in the performance of the battery itself, due to the fact that the cathode is the bottleneck within lithium ion-batteries development. Because of this and because the lack of research groups within Europe, it was decided to drop the roadmap of this technology.

- Micro-electric space propulsion was dropped because after getting into contact with Prof. Herbert Shea of the École Polytechnique Fédérale de Lausanne-Switserland (only group in Europe investigating this specific technology), it was found out that this technology was already recently supported by the ITI funding scheme.

Furthermore, it was decided (at the MTR, compare MoM) to concentrate more on identifying European research groups for the selected technology candidates, rather than deeply elaborate 'virtual' roadmaps for the DST candidates, not specifically targeted to one organization. Therefore, first exploratory talks were performed with these groups in order to prepare them for potential ITI proposal submissions. With this action shift the documented roadmaps in this technical note are more hands-on. The roadmaps were several times iterated with the respective research group. In conclusion, the following DST roadmaps are presented:

- Porous Metals: Metal Foam in combination with Additive Manufacturing (AM)

- Phase-Change Memory (PCM)
- Aerographite

The structure of this TN is as follows: in Chapter 2 a literature study concerning technology roadmapping is documented. To accomplish this goal, the fundamentals as well as the different uses of technology roadmapping are discussed. In addition, the roadmap architecture that is to be used for disruptive space technologies (DSTs) is selected and the exact content of each roadmap is determined. The chapter ends with presenting the final roadmap design.

Chapter 3 documents the porous metals roadmap incl. the two separate applications: Micrometeoroid and Orbital Debris (MMOD) protection system from made from open pore metal foams and Complex lattice structures using Additive Manufacturing (AM). Chapter 4 displays the Phase-Change Memory roadmap and Chapter 5 displays the Aerographite roadmap. All roadmaps (except the Aerographite because of time constrains) were worked out in close cooperation with selected research groups.

2 Technology Roadmapping Theory

In this chapter the theory behind Technology Roadmapping (TRM) is discussed. First, the fundamentals of technology roadmapping are discussed. Second, the technology roadmapping process is explained in detail. Third, the different purposes and formats of technology roadmaps are discussed. Fourth and final, the design of the TRMs for the DSTs is determined. This includes the selection of a suitable TRM format, the determination of the contents of the roadmaps and the description of the final roadmap design.

2.1 Fundamentals of Technology Roadmaps

In this section the basics of technology roadmapping are discussed. The definition of technology roadmapping used in this report is the following [RD 2]:

"The technology roadmapping process is a widely-used technology planning process that enables users to effectively identify, select and develop technology alternatives to satisfy a set of product needs. Given a set of needs, the technology roadmapping process provides a way to develop, organize, and present information about the critical system requirements and performance targets that must be satisfied by certain time frames. It also identifies technologies that need to be developed to meet those targets. Finally, it provides the information needed to make the trade-offs among different technology alternatives."

The technology roadmapping process is not limited to the product development process since it can be applied for different purposes as well (e.g. service/capability planning, strategic planning, knowledge asset planning). The different purposes of technology roadmapping along with the various ways (formats) in which TRMs can be presented are explored in more detail in Section 2.2. TRMs come in various shapes and sizes and are generally quite flexible. The most common roadmap format is the multilayered roadmap. A generic example of a multilayered TRM is displayed in Figure 2-1.

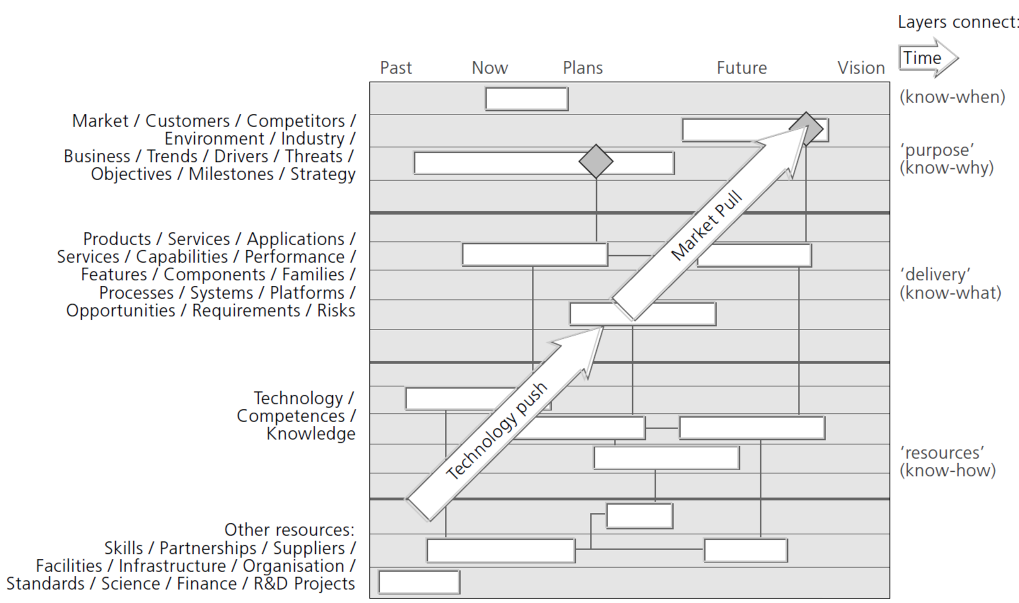


Figure 2-1: Generalized technology roadmap architecture [RD 5].

As can be seen in Figure 2-1, TRMs can be adapted to encompass both technology push and market pull "development paths". A market pull development path is when a technology development process is convergent or, in other words, when a technology development process is aimed towards a customer defined end-product. Oppositely, a technology push development path is not aimed towards an end-product but rather towards new and innovative outcomes (research and development that ultimately should lead to new inventions). The technology push and market pull architectures are illustrated in Figure 2-2. These push and pull development factors with respect to the space sector are discussed in more detail in TN01.

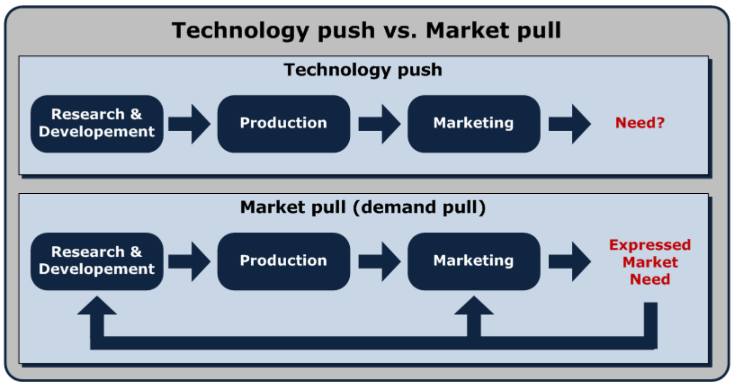


Figure 2-2: Market pull and technology push architectures [RD 6].

According to Phaal, Farrukh and Probert there are several aspects (dimensions) of TRMs that are of particular importance [RD 5]. These dimensions and their descriptions are displayed in Table 2-1.

Table 2-1: Technical roadmap dimensions with descriptions [RD 3].

Dimension	Description
Time scale	This dimension can be adapted to suit the particular situation, for example, the time horizon is typically short in sectors such as e-commerce and software, and much longer for aerospace and infrastructure. The time scale is usually a logarithmic scale, with more space allocated to the short term rather than the long term. Obviously this is also a direct result of the uncertainties that are associated with the long term. Furthermore, the time scale can either be continuous or it can be segregated in intervals (e.g., six month, annual or short, medium and long term). The roadmap can also be constructed such that there is space for vision and very long-range considerations along with the current situation and possibly the history with respect to the competition.
Layers	The vertical axis of the roadmap is critical as it needs to be designed to fit the particular organization and the problem being addressed. Often a considerable part of the initial roadmapping effort will be directed at defining the layers and sub-layers that will form the roadmap. In Figure 2-1 the different types of layers that can be found in roadmaps in general are listed. The sheer number of possible layers highlights the inherent flexibility of the roadmapping approach, when it comes to providing a framework for supporting strategic planning: • The top layers relate to the organizational purpose that is driving the roadmap (know-why). • The bottom layers relate to the resources (particularly technological knowledge) that will be utilized to address the demand from the top layers of the roadmap (know-how). • The middle layers of the roadmap are crucial, providing a bridging or delivery mechanism between the purpose and resources (know-what). Frequently the middle layer focuses on product development, as this is the route through which technology is often deployed to meet market and customer needs. For other situations, however, services, capabilities, systems, risks or opportunities may be more

	appropriate for the middle layer in order to understand how technology can be delivered to provide benefits to the organization and its stakeholders.
Annotation	In addition to the information contained within the layers, on a time-basis, other information can be stored on the roadmap, including: • Linkages between objects in layers and sub-layers (of various possible kinds). • Supplementary information, such as a key, a statement of business strategy or market drivers, people involved in developing the roadmap and assumptions. • Other graphic devices, including objects, notes and color coding. These are typically used to indicate key decision points, gaps, critical paths, opportunities and threats (including DTs and markets).
Process	The steps that will be required to complete the first roadmap and take the process forward thereafter, will typically be different for each organization (and often within the organization as well). The process that is most suitable depends on many factors, including the level of available resources (people, time, budget, etc.), the nature of the issue being addressed (purpose and scope), the available information (market and technology), and other processes and management methods that are relevant (strategy, budgeting, new product development, project management and market research). Strategic planning usually involves balancing an external view of the firm (market and business environment) with an internal view (tangible and intangible assets). Combining these external and internal perspectives (opportunities, threats, strengths and weaknesses) enables a set of product-technology options to be identified and evaluated. For this reason most roadmaps include aspects of both market pull and technology push (see Figure 2-1). Here, the direction and rate of technology, and product and market development reflect a balance between these two drivers. However, it should be recognized that a technology push approach is generally more divergent and complex compared to market pull. This is because a particular technology may have many applications in domains where the firm has limited experience. Most customized roadmapping approaches have included a combination of market pull and technology push considerations, although firms generally have wished to express the strategic plan in a market-oriented fashion.

One of the most common technology roadmapping categorization and process schemes is provided by Sandia National Laboratories [RD 2].

Table 2-2: Technology roadmapping phases with accompanying steps [RD 2].

Phase I: Preliminary activity
1. Satisfy essential conditions
2. Provide leadership/sponsorship
3. Define the scope and the boundaries for the technology roadmap
Phase II: Development of the technology roadmap
1. Identify the “product” that will be the focus of the roadmap
2. Identify the critical system requirements and their targets
3. Specify the major technology areas
4. Specify the technology drivers and their targets
5. Identify technology alternatives and their timelines
6. Recommend the technology alternatives that should be pursued
7. Create the technology roadmap report
Phase III: Follow-up activity
1. Critique and validate the roadmap
2. Develop an implementation plan
3. Review and update

According to this scheme, roadmapping can be performed at two levels: industry or corporate. The commitment in terms of time, cost, level of effort, and complexity is different for each level. In order to come up with a good roadmap for any level, the roadmapping process is divided into several phases and steps. Table 2-2 illustrates the three phases associated with the technology roadmapping process along with their accompanying steps. A detailed description of the three technology roadmapping phases and their accompanying steps can be found in Annex A.

2.2 Technology Roadmapping Approaches

In this section, the various uses of TRMs are discussed. Furthermore, the different formats that have been used in the past for TRMs are explored. Figure 2-3 provides an overview of the different purposes and formats (including their relations) of TRMs.

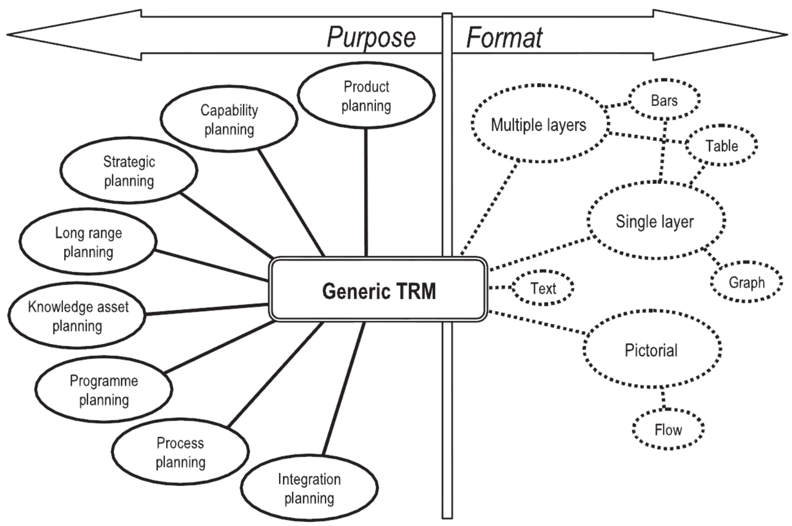
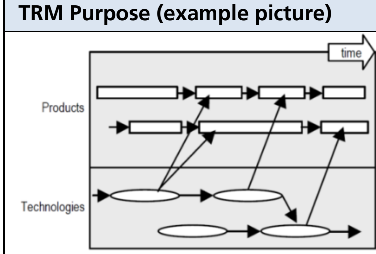
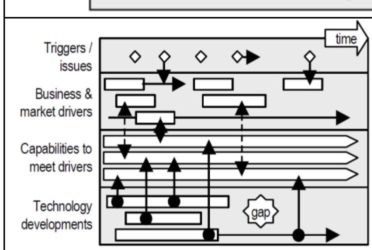


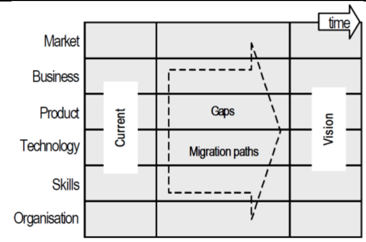
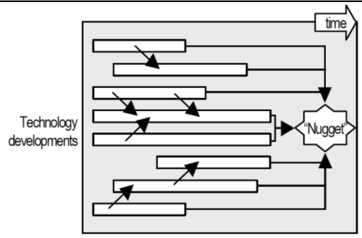
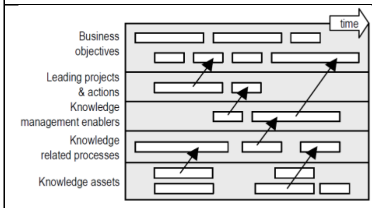
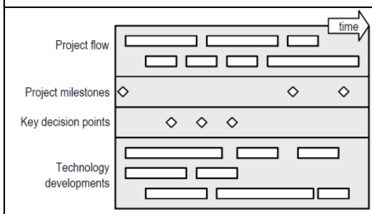
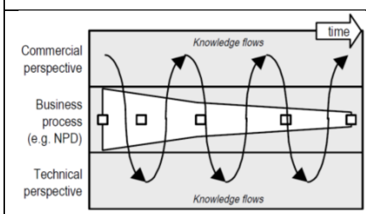
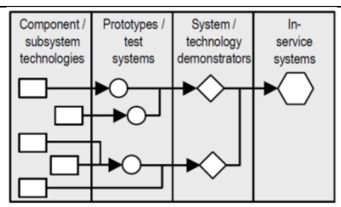
Figure 2-3: Purposes and Formats of Technology Roadmaps [RD 4].

2.2.1 TRM Purposes

Since their conception, TRMs have been utilized in a wide variety of applications. The various TRM purposes are discussed in more detail in Table 2-3. This table also includes an example of each purpose for which a TRM can be utilized.

Table 2-3: TRMs with different purposes [RD 5].

TRM Purpose (example picture)	Description
	**Product Planning:** This is by far the most common type of TRM, relating to the insertion of technology into manufactured products, often including more than one product generation. The example shown on the left is a roadmap from Philips, which has widely adopted the product planning approach. The example shows how roadmaps are used to link planned technology and product developments [RD 6].
	**Service/Capability Planning:** This type of TRM is similar to the product planning type, but more suited to service-based enterprises, focusing on how technology supports organizational capabilities. The example shown on the left is a Post Office roadmap/T-Plan application, used to investigate the impact of technology developments on the business. This roadmap focuses on organizational capabilities as the bridge between technology and the business, rather than products [RD 8].

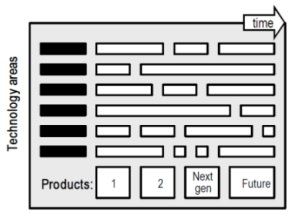
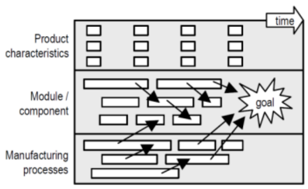
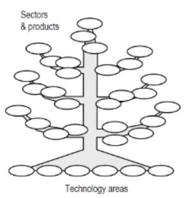
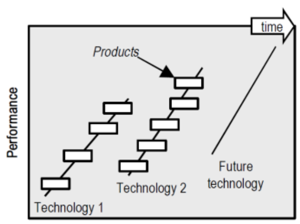
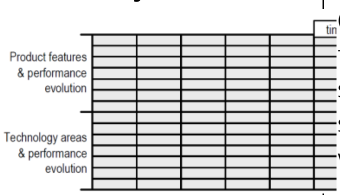
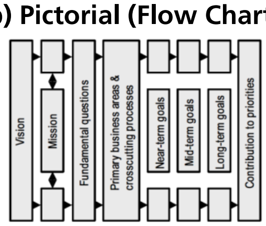
TRM Purpose (example picture)	Description
	**Strategic planning:** This TRM includes a strategic dimension, in terms of supporting the evaluation of different opportunities or threats, typically at the business level. The example shown on the left is a roadmap format developed using the T-Plan approach to support strategic business planning. The roadmap focuses on the development of a vision of the future business, in terms of markets, business, products, technologies, skills, culture, etc. Gaps are identified, by comparing the future vision with the current position, and strategic options are explored to bridge the gaps [RD 5].
	**Long-range planning:** This TRM type extends the planning time horizon, and is often performed at the sector or national level ('foresight'). The example shown in on the left is a roadmap developed within the US Integrated Manufacturing Technology Roadmapping (IMTR) Initiative (one of a series). This example focuses on information systems, showing how technology developments are likely to converge towards the 'information driven seamless enterprise' (a 'nugget') [RD 9].
	**Knowledge asset planning:** This TRM type is used to align knowledge assets and knowledge management initiatives with business objectives. The example shown on the left is a roadmap that has been developed by the Artificial Intelligence Applications Unit at the University of Edinburgh, enabling organizations to visualize their critical knowledge assets, and the linkages to the skills, technologies and competences required to meet future market demands [RD 10].
	**Program planning:** This type of TRM includes the implementation of strategy, and more directly relates to project planning such as Research and Development (R&D) programs. The example shown on the left is a NASA roadmap (one of many) for the Origins program, used to explore how the universe and life within it has developed. This particular roadmap focuses on the management of the development program for the Next Generation Space Telescope (NGST), showing the relationships between technology development and program phases and milestones [RD 11].
	**Process planning:** This TRM type supports the management of knowledge, focusing on a particular process area (for example, new product development). The example shown on the left is a TRM developed using the T-Plan approach to support product planning, focusing on the knowledge flows that are needed to facilitate effective new product development and introduction, incorporating both technical and commercial perspectives [RD 5].
	**Integration planning:** This type of TRM includes the integration and/or evolution of technology, in terms of how different technologies combine within products and systems, or to form new technologies (often without showing the time dimension explicitly). The example shown on the left is a NASA roadmap (Origins program), relating to the management of the development program for the NGST, focusing on 'technology flow', showing how technology feeds into test and demonstration systems, to support scientific missions [RD 11].

For this project, the purpose 'Program planning' was chosen for the most appropriate TRM purpose.

2.2.2 Formats of Technology Roadmaps

As in the aforementioned subsection, TRMs have a significant amount of uses. Besides that, there are also quite a few different formats in which TRMs can be presented. Table 2-4 displays several TRMs, each with a different graphical format.

Table 2-4: Description of the visual TRM formats [RD 5].

Visual TRM Format	Description
Single Layered (Bar)  	The single layered TRM format focuses on one layer of the multilayered roadmap. While less complex, the disadvantage of this format is that the linkages between the layers are generally not shown. The example shown in is the 'classic' Motorola roadmap, showing the evolution of car radio product features and technologies [RD 1]. Motorola has subsequently developed roadmapping to new levels, with roadmaps now forming part of corporate knowledge and business management systems, supported by software and integrated decision support systems [RD 12]. The most commonly applied visual format is the 'bar' format. Applying the bar visual format has the advantage of simplifying and unifying the required outputs,
Multilayered (Bar)  	This format is the most common TRM format. It comprises a number of layers, such as technology, product and market. The roadmap allows the evolution within each layer to be explored, together with the inter-layer dependencies, facilitating the integration of technology into products, services and business systems. The company Philips used this type of roadmaps, showing how product and process technologies integrate to support the development of functionality in future products [RD 6].
Pictorial  	Some roadmaps use more creative pictorial representations to communicate technology integration and plans. Sometimes metaphors are used to support the objective (e.g. a 'tree'). The company Sharp uses this type of roadmaps, relating to the development of products and product families, based on a set of liquid crystal display technologies [RD 13].
Single Layered (Graph)  	Where product or technology performance can be quantified, a roadmap can be expressed as a simple graph or plot, typically one for each sub-layer. This type of graph is sometimes called an 'experience curve', and is closely related to the technology 'S-curves' explained in TN01. Typically, the 'graph' visual format is only applied to single layered roadmaps. The example shown in is a single layered roadmap applying the graph visual format showing how a set products and technologies co-evolve [RD 15].
a) Multilayered (Table)  	In some cases, entire roadmaps, or layers within the roadmap, are expressed as tables (i.e. time vs. performance). The 'table' visual format can be applied to the single layered format as well as the multilayered format. This type of approach is particularly suited to situations where performance can be readily quantified or when activities are clustered in specific time periods. The example shown in is a multilayered roadmap applying the table visual format, including both product and technology performance dimensions [RD 15].
b) Pictorial (Flow Chart)  	The final visual format that can be applied to TRMs is the flow chart, which is a special type of pictorial representation. The flow chart visual format is typically used to relate objectives, actions and outcomes in a pictorial manner. The example shown in is a NASA roadmap, showing how the organization's vision can be related to its mission, fundamental scientific questions, primary business areas, near-, mid- and long-term goals, and contribution to US national priorities [RD 16].
'TEXT'	Other roadmaps are entirely or mostly text-based, describing the same issues that are included in more conventional graphical roadmaps (which often have text-based reports associated with them). An example of a text-based roadmap is the Agfa 'white papers', which support understanding of the technological and market trends that will influence the sector [RD 14].

2.3 DST Roadmap design

In this sub chapter, the design of the TRMs for the DSTs is determined. This includes the selection of a suitable TRM format, the determination of the contents of the roadmaps and the description of the final roadmap design. Part of the DST roadmap design has come from an analysis of roadmap usage in the space sector, documented in Annex B.

2.3.1 Roadmap Architecture Selection

As can be seen in Section 2.2, technology roadmaps come in various shapes and sizes. Of particular importance is the format of the roadmap, which has to serve the overall purpose of the roadmapping process. Therefore, it is of paramount importance to know what the essence of the technology to be roadmapped is and what needs to be included in the roadmap.

The ultimate purpose of the roadmaps presented in this report is to be used as a reference for the future development of technologies with disruptive potential within the space sector. Due to the fact that the roadmaps in this report are meant to reflect the development process of potential DSTs, the roadmap format needs to be such that it can effectively display:

- a timeline,
- the various processes (incl. sub-processes), involved in the development of the tech. and
- the development milestones.

Therefore, of the architectural formats presented in Table 2-4, the "pictorial" and "text" formats (and any accompanying visual formats) are not suited for the roadmaps presented in this report. Although, in principle, the text format can be used to create a roadmap for any purpose, it is unable to provide the user with a clear overview of the roadmap in the form of a diagram or a chart like the other formats. At this point, the only architectural TRM formats that remain are the "single layered" and the "multilayered" formats. With the purpose of the roadmaps in mind, it can be stated that the focus of the roadmaps should be primarily, if not entirely, on product/technology development. Therefore, when it comes to the creation of a roadmap with such a focus, market, business and organizational aspects can be omitted, because they are less important (at least for the purpose of this project). This means that using a multilayered format for the roadmaps in this report is not practical. Therefore, the most suitable architectural roadmap format is the single layered roadmap format.

When it comes to the visual roadmap format, the "bar" format would be best suited for the roadmaps presented in this report. This is because this visual format has been applied successfully to similar technology roadmaps in the past. When compared to the other visual roadmap formats that can be used to customize a single layered TRM, the "table" format and the "graph" format, the bar format is also the clearest and most robust. Therefore, the format that is to be used for the DST roadmaps is the "single layered bar" format.

2.3.2 Roadmap Contents

In order to present a clear and coherent picture of the future development of a DST candidate in a roadmap, the roadmap should have certain characteristics. These characteristics follow directly from the requirements of the user. In the case of the DST roadmaps, the layout should be such that the level of development of a DST at a certain point in time can be immediately recognized. The level of development of a DST is indicated by its Technology Readiness Level (TRL). Around the world, agencies use different definitions of the TRL of a technology. However, due to the European context of this project, the definition as used by ESA is utilized in this report (according to the "ESA Science Technology Development Route"). For the DST roadmaps, it can be said that the TRLs make up the backbone of the various development paths. The purpose of every process described in the roadmaps is to increase the TRL of the DST.

Since the content of a roadmap for a certain technology depends to some extent on the potential applications of that technology, the development path outlined by the roadmap should incorporate and express those applications (even if those tech. are only example technologies e.g. metallic foam => MMOD for heat pipes). This is done by displaying several development paths per roadmap, each focusing on a different potential application of a DST. The differences between the development paths in each roadmap serve to point out the effect that different applications have on the overall development of a DST. Naturally, when a DST candidate only has one potential application, such a comparison is not possible. The information that is used to build the roadmaps has been obtained in two ways: by performing a literature study and by contacting experts of the selected research groups. The literature study is performed in order to explore the characteristics of the technologies further. Experts are contacted and interviewed regarding the DSTs in order to get a more experience-based insight into the technologies and to transform them into TRM process steps (with their adjoining time allocations). Perhaps the most important aspect of this research is the identification of the weak points of the DSTs. After all, it is primarily because of these weaknesses that the DSTs are not yet dominant within their respective areas of application. Therefore, the development paths of the DSTs as displayed in the roadmaps should be focused in such a way that these weaknesses are addressed.

2.3.3 Final Roadmap Design

As can be seen in Figure 2-4, the generic DST roadmap design can consist of several layers, each layer displaying the development path of the same DST, but focused on a different potential application of that DST. Therefore, depending on the DST and particularly the differences between the chosen potential applications, the development paths depicted in the layers can be either very similar, very different or anywhere in between. At this point, it must be noted that the roadmap design presented here is still categorized as a single layered roadmap even though it technically it can have multiple layers. This is because the layers in the roadmap contain the same type of information and are independent. In the DST roadmaps, each development path is subdivided into several TRL development steps. These are the major steps that need to be taken in order to increase the TRL of a DST. The TRL development steps are subdivided into processes, which, in turn, are subdivided into sub-processes. The sub-processes in a development path reflect all the actions required to increase the TRL of a DST with a certain application. In order to keep the roadmaps organized, every process and sub-process is numbered and described. This description includes an explanation of the various steps, processes and sub-processes as well as their purpose.

The timeline of the DST roadmap is in years and does not have a predefined start date (T + years). This is because the start date of the various development programs is not known as of yet.

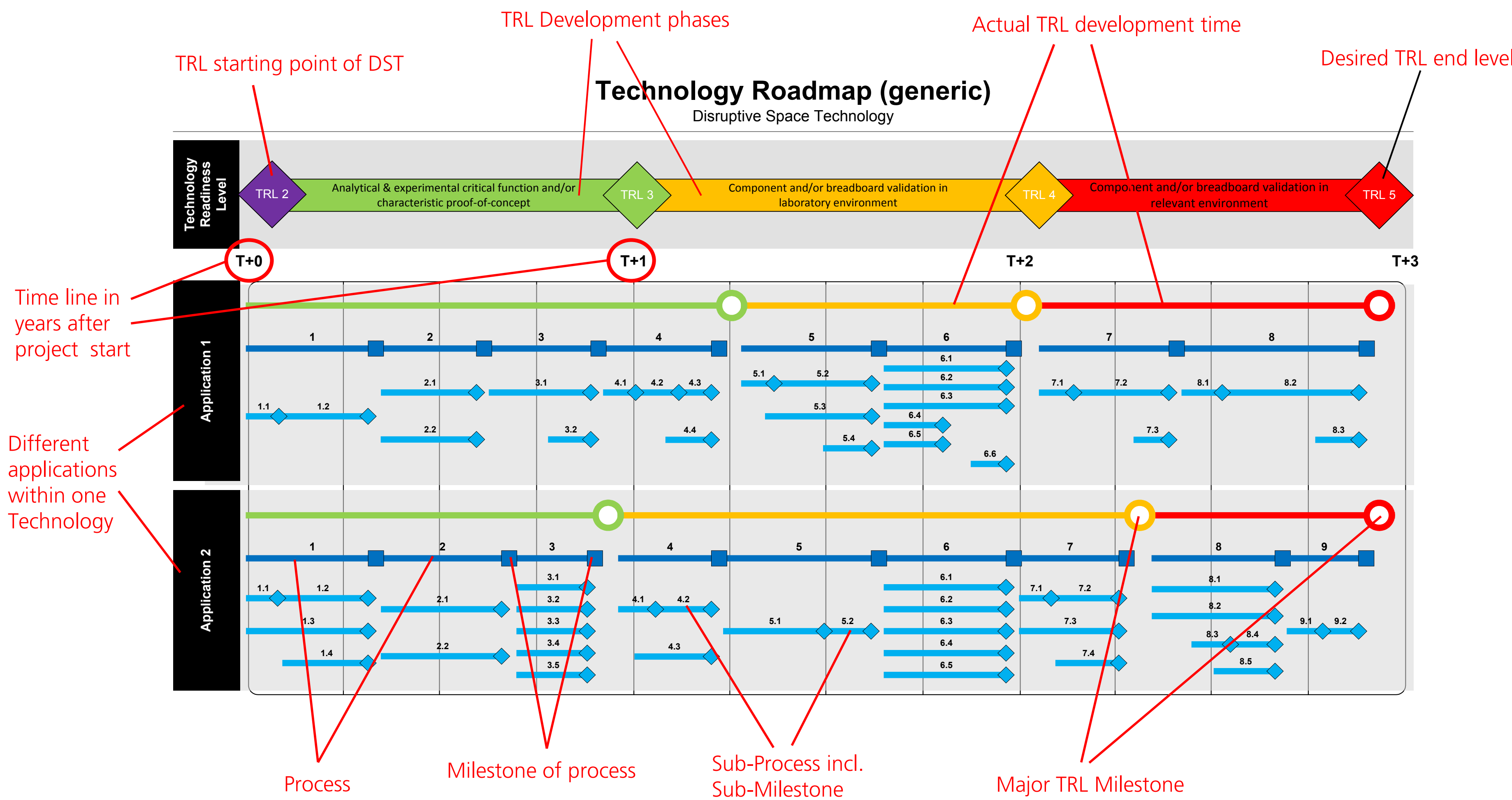


Figure 2-4: Generic DST roadmap design.

3 Porous Metals– Technical Roadmap

Within this chapter the several applications of porous metals, which is the overall categorization of the DST candidate micro lattice is roadmapped. Since a concrete application is needed for the development of a technology to TRL 6, an example application needs to be selected. Particularly for the domain *advanced materials*, which stands at the foundation of many other technology developments, many possible applications can be chosen. The applications are ordered according to two manufacturing process able to make porous metals, Metal Foaming and Additive Manufacturing.

Additive Manufacturing **(AM)**

AM is a technique that is used to create three-dimensional metallic objects directly from a Computer-Aided Design (CAD) model by applying a layer-by-layer approach. Although, porous metallic foams are produced with another production process (e.g. mold principle with active gas injection), the AM production process frames the fundament for similar producible products/ applications than porous metallic foams in future spacecraft.

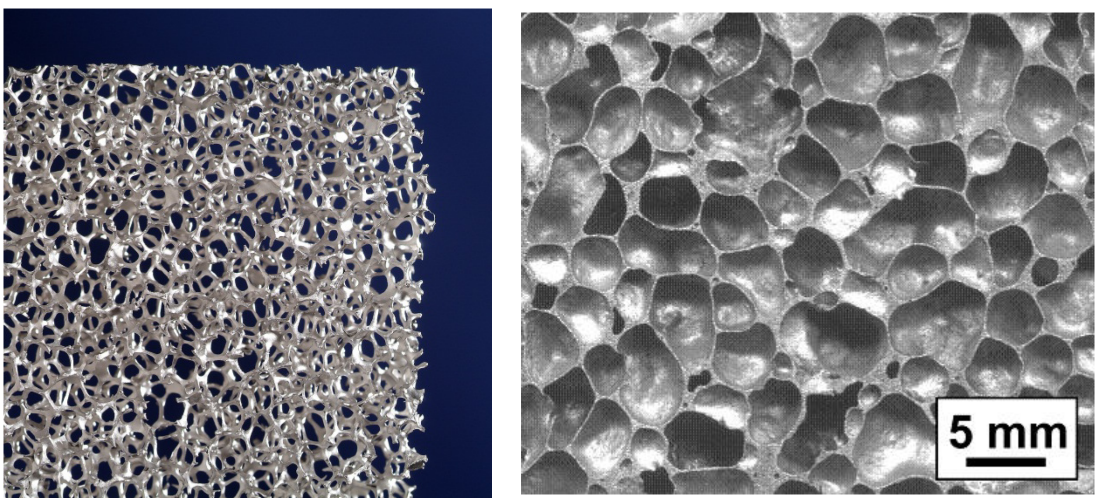


Figure 3-1: Metal foam with an open-cell structure on the left [RD 22]. Metal foam with a closed-cell structure on the right. [RD 23]

Metal Foaming (MF)

A report written by OHB System in cooperation with Fraunhofer – IFAM, identified several promising applications [RD 25] for metal foams. The most promising applications identified were:

(1) Micrometeoroid and Orbital Debris (MMOD) protection system
(2) Crushable mechanism with Thermal Protection System (TPS) functionality
(3) High efficiency heat exchanger system

For this roadmap, the *Micrometeoroid and Orbital Debris (MMOD)* protection system (especially for heat pipes) were selected as example application for metal foams. Nevertheless, for the sake of completeness, the other two applications for metal foams (2 & 3) were also translated into proper roadmaps and listed in Annex C & D.

Metal foam is a highly porous cellular material. The pores in metal foam generally represent 60 to 95 percent of the total volume of the material. Two types of metal foams exist: open-cell foams and closed-cell foams. In open-cell foams the pores form an interconnected network whereas in closed-cell foams the pores are sealed and therefore not connected to each other. An example of both cell structures can be found in Figure 3-1. In general, the most important characteristics of metal foam are the following [RD 24]:

- Great capability to absorb kinetic energy (impacts)
- Good electromagnetic shielding properties
- Good mechanical damping properties (acoustic and vibration)
- Low magnetic permeability
- Low thermal conductivity (compared to a solid structure of identical material)

In sub chapter 3.1 & 3.2, the roadmaps for metal foams in application of the Micrometeoroid and Orbital Debris (MMOD) protection system and the complex porous structures by using are presented.

3.1 Porous Metals – MMOD Protection System for Heat Pipes (example application)

The example application of metal foam that is incorporated into the DST roadmap is using open-cell metal foams in MMOD protection systems for heat pipes. Although tests have shown that a panel with a multiple wall configuration provides better protection against MMOD impacts (for impact velocities higher than 5 km/s) than a panel of identical mass per unit area with a metal foam core, metal foam used in a MMOD protection system still shows promise [RD 27]. This seems somewhat counterintuitive, but it is the versatility of metal foam that makes it a suitable candidate for multiple purpose applications. For example, when considering the satellite's structure, it would be ideal if the panels have certain attributes such as high stiffness, sufficient strength, low mass, the capability to withstand Hypervelocity Impacts (HVIs), and good vibrational and acoustic damping properties. Although metal foam does not excel in any of these attributes compared to other candidate materials, it does not have any weaknesses either. It can therefore be stated that metal foam is a suitable overall candidate for the panel material. That being said, it is not necessarily the case that using metal foam for this application would constitute a major improvement in mission capability, since other candidates are just as suitable (if not more so in some cases). Therefore, using metal foam as the primary material in the MMOD protection system in the wall panels of a spacecraft does not have disruptive potential.

Using metal foam in the MMOD protection system for heat pipes, however, does show disruptive potential (illustrated in Figure 3-2). Nowadays, heat pipes in radiators are usually protected by the commonly used multiple wall configuration (Whipple shield). Although such a configuration is quite effective in protecting the heat pipes from HVIs, its functionality ends there. This is not the case for metal foam because, aside from providing more than adequate protection against HVIs, it also increases the effectiveness of the radiator. Radiators with a multiple wall MMOD protection system usually contain empty spaces between the heat pipes and the radiating surface, because this is necessary for such a protection system. Such empty spaces, however, are detrimental to the effectiveness of the radiator. One can avoid this problem by using metal foam for the MMOD protection system because in such a system there are no empty spaces between the heat pipes and the radiating surface. If the heat pipes are embedded and covered in metal foam, there are no such empty spaces.

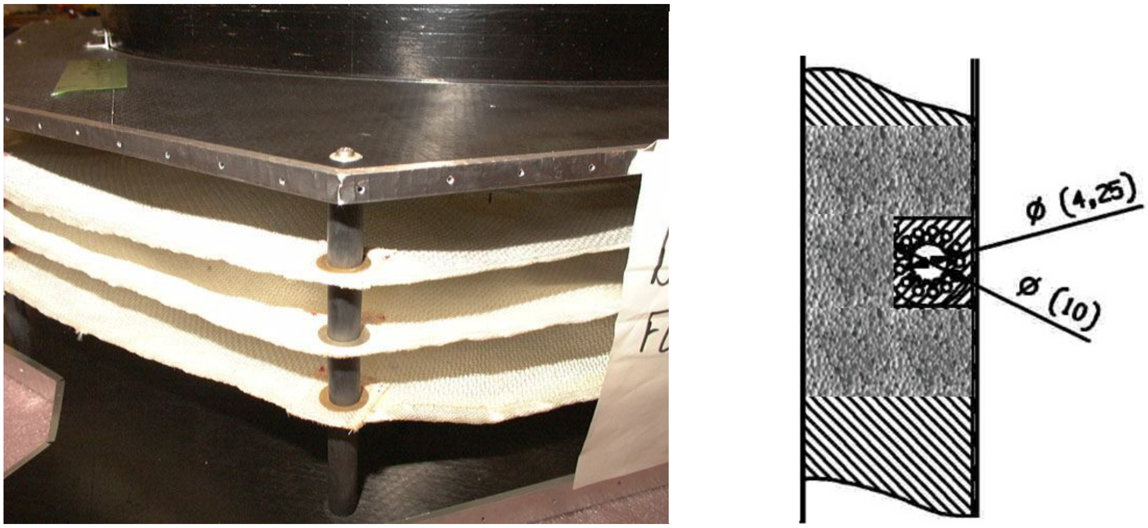


Figure 3-2: Left: Conventional Whipple shield; Right: MMOD Protection system for embedded heat pipes with metal foam. [RD 27]

A MMOD protection system with such a configuration is capable of protecting the heat pipes as well as increasing the heat transfer from the heat pipes to the radiating surface. Furthermore, the eradication of the empty spaces in the MMOD protection system would constitute a reduction in volume and consequently mass for the radiator as a whole. Additionally, such a system is capable of providing omnidirectional protection, whereas a traditional multiple wall system needs to be oriented in a certain manner to function optimally, which leads to design constraints and increased mass due to the presence of additional joining elements (welds, fastener, etc.).

The difference in relative performance between Whipple shields and Metal foam in the application of MMOD shielding for heat pipes is illustrated in Figure 3-3. As can be seen here, the drawback of decreased MMOD protection is counteracted by the increase in thermal conductivity, omnidirectional protection, and total mass of the system. This method of illustrating differences in performance has been elaborated in section 2.1 of TN01. If there is a group of customers who perceive this performance mix of attributes as more valuable than the dominant technology, than is will become disruptive.

When it comes to the development of a MMOD protection system based on metal foam, the focus is on Hypervelocity Impact (HVI) analysis. Although several HVI tests have been performed in the past involving metal foam, a comprehensive study aimed to thoroughly characterize the performance of metal foam has not been performed as of yet. This means that the effects of design variables such as pore size, relative foam density, foam layer thickness and facesheet thickness on the foam's capability to protect against HVIs have not been conclusively determined [RD 27]. Therefore, a significant part of the development path of metal foam for use in a MMOD protection system is devoted to determine what the effects of these design variables are. This mostly involves building models and running simulations, as well as performing a significant amount of tests. Part of the future development of metal foam for this application should also be aimed towards maximizing the effectiveness of the system's heat transfer capabilities without sacrificing its MMOD protection capability. The DST roadmap for metal foams as a MMOD protection system is illustrated in chapter 3.4.

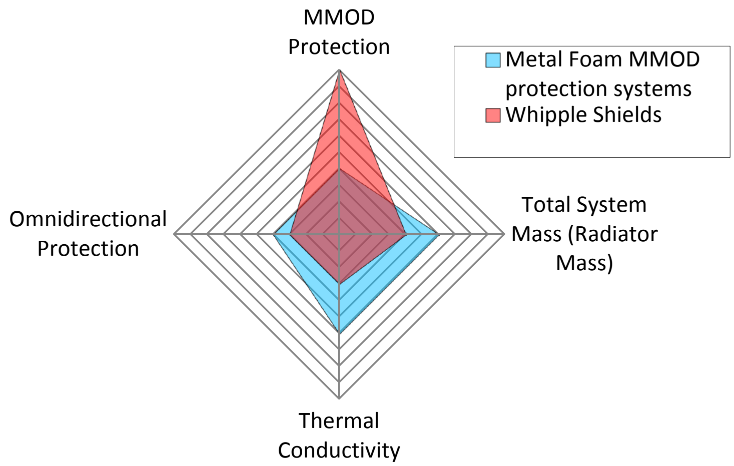


Figure 3-3: Performance mix for MMOD in comparison to Whipple shields. Rating was performed with BEE methods.

3.2 *Additive Manufacturing (AM) as additional roadmap string*

AM is a technique that is used to create three-dimensional (3D) objects directly from a Computer-Aided Design (CAD) model by applying a layer-by-layer approach. Established machining techniques have the common characteristic that they are subtractive processes. This means that these techniques all involve cutting away material from a larger workpiece.

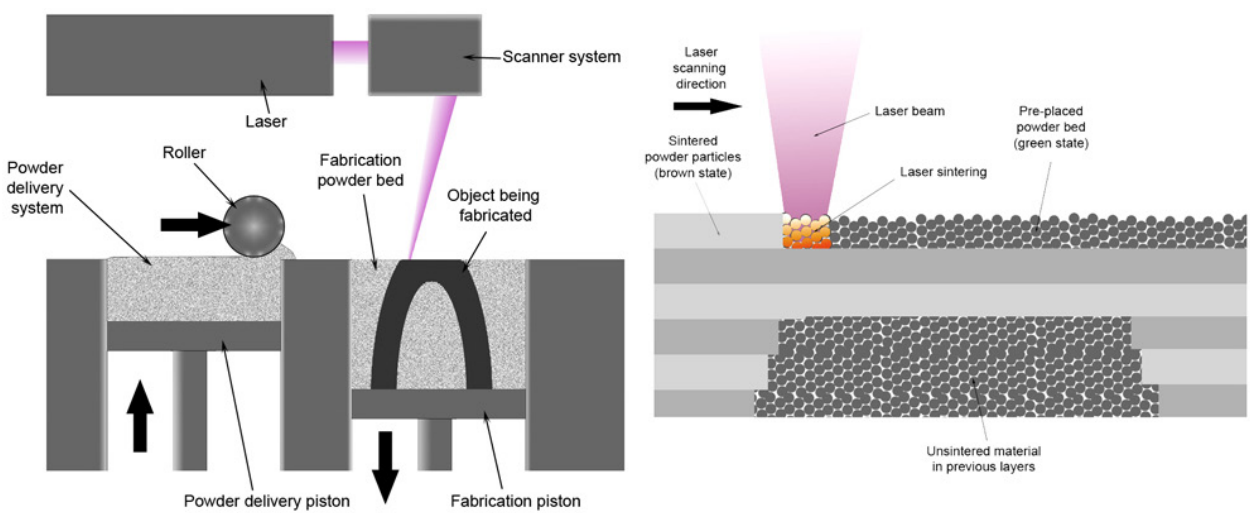


Figure 3-4: Schematic representation of the SLS process [RD 30].

Other manufacturing techniques such as casting and forging require the use of heavy duty tools and/or molds, which put boundaries on design and have high set-up costs. The field of AM encompasses a variety of techniques that are fundamentally different from these conventional

manufacturing techniques because they involve building an object from the ground up one layer at a time with each layer adhering to the previous one [RD 28]. In order to clarify AM process further, a commonly used AM technique, known as Selective Laser Sintering (SLS), is explained. SLS is a 3D printing process where a powder is sintered by means of a laser [RD 29]. A typical SLS machine has a chamber filled with an inert gas, in which the process takes place. A laser sinters the powder at specific areas for each layer according to the design (the 3D CAD model). By means of pistons and a roller, a new powder layer is formed after the sintering process for the previous layer has been completed. This process repeats itself until the part is completed. A schematic representation of the SLS technique can be found in Figure 3-4.
The various AM techniques have different characteristics meaning that each technique has its own advantages and disadvantages. Some of the characteristics that differentiate the AM techniques are the following [RD 31][RD 32]:

- Choice of materials (some techniques are more suited for polymers whereas others are more suited for metals)
- Manufacturing speed
- Dimensional accuracy and quality of the surface finish of the produced objects
- Material properties of the produced parts
- Production costs

The choice of AM process that is to be used to create a certain part depends largely on the intended purpose the part or, in other words, its requirements. Examples of objects manufactured through AM processes are displayed in Figure 3-5.

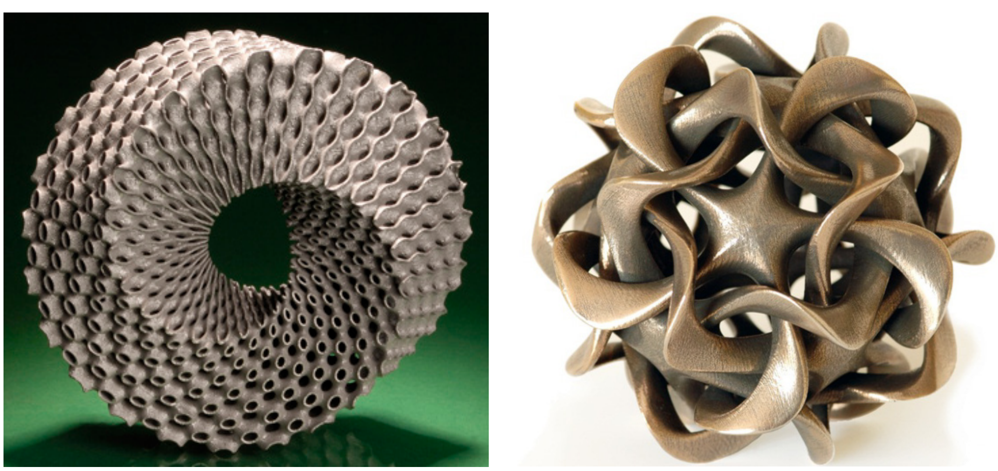


Figure 3-5: Object created using SLM on the left [RD 33]. Object created using SLS on the right [RD 34].

Although the objects illustrated in this figure are abstract shapes, they serve to illustrate the level of complexity that can be achieved using AM techniques.
The range AM parts that can be produced with AM techniques is virtually limitless, the purpose of the AM process itself is singular: the creation of complex parts in a fast and efficient manner. Since

the AM DST roadmap focuses on the development of the AM processes rather than the development of the produced parts, the potential purpose of these parts is irrelevant for this roadmap. Therefore, the application that is selected for AM is using AM techniques for the rapid manufacture of complex parts and prototypes for the space sector. The capability of AM techniques to quickly manufacture parts from a 3D CAD model can be exploited during the testing phases of these parts. Being able to adjust the design of a part and quickly manufacture a new prototype of said part can be very advantageous because, when using AM techniques, applying an iterative design process is more viable as compared to when conventional manufacturing techniques are used. Besides enabling the rapid production of prototypes, AM also allows the user to manufacture highly complex parts without the need for assembly, which is usually a necessary step when using conventional manufacturing techniques. In order to illustrate the capabilities of AM, the advantages of using AM techniques compared to conventional manufacturing techniques are listed below:

- **Manufacture of parts without the need for customized tools and/or machines**
  In the space sector it is often the case that for conventional manufacturing processes tools, molds and/or machines need to be designed and constructed before an actual part can be produced. For AM this is not the case because, aside from the actual AM machine, only a 3D CAD model of the to be produced object is required to actually build it.

- **High Manufacturing Speed**
  The time it takes to go from a completed design of a part (a 3D CAD model) to a prototype of said part using conventional manufacturing techniques is much higher than it is using AM techniques. This is largely due to the fact that for AM techniques only a 3D CAD model is required to create a part and no customized tools and/or machines are needed. The time gained by using AM techniques can be used for iterations in the development process, which would increase the quality of the final product. It has to be noted though that if the preparation time required for manufacturing is omitted, the manufacturing speed of AM techniques is actually lower (on average) than that of conventional manufacturing techniques. In other words, the advantage that AM techniques have over conventional manufacturing techniques regarding manufacturing speed originates from the fact that little (if any) preparation time is needed for AM techniques.

- **Manufacture of complex parts and geometries without the need for assembly**
  Highly complex parts can be created using AM techniques because parts are constructed from the ground up layer-by layer. The level of complexity that can be achieved using conventional manufacturing techniques is limited by several factors. For example, the level of complexity of parts produced by means of casting is limited by the intricacy of the mold. For machining, the level of complexity is limited by the fact that only external features of the part can be manipulated. In order to achieve a certain level of complexity using conventional manufacturing techniques it is often the case that parts need to be assembled from several smaller components. In some cases even this measure is not enough to achieve a certain

level of complexity, in which case design concessions need to be made. Complex geometries are found in several space systems such as heat exchanger systems (heat pipes) and hydraulic systems. By using AM techniques to create such systems, the total mass is decreased or the performance is increased because designs are allowed to be more complex (since the limitations of conventional manufacturing techniques have been eliminated).

- **Wide range of selectable materials**
  When compared to conventional manufacturing techniques, most AM techniques are capable of using a relatively wide range of materials. For example, SLS can be used for metal, polymers and ceramics [RD 29]. This is in sharp contrast with conventional manufacturing techniques. Casting, for example, is limited to metals and the same holds for forging. Furthermore, injection molding can only be used for polymers. This makes the average AM technique much more versatile than the average conventional manufacturing technique.

- **Customized small volume production**
  The use of AM techniques for customized small volume production purposes is very advantageous from a cost perspective. Although in general the variable cost for using AM techniques is higher than it is for conventional manufacturing techniques, the total cost is lower for small production volumes. This is due to the fact that for AM techniques the initial investment (or fixed cost) is minimal, whereas for conventional manufacturing techniques the initial investment is substantial because of the cost of the required customized tools and machines. Seeing as the manufacture of parts in the space sector usually occurs in small production volumes (most parts are unique), AM techniques are indeed very well suited for use in the space sector when considered from a cost perspective.

AM techniques also have some drawbacks when compared to conventional manufacturing techniques. These drawbacks are listed below:

- **No advantages of scale**
  As a result of the fact that the variable cost for using AM techniques is higher than it is for using conventional manufacturing techniques, the total cost is higher for large production volumes. Therefore, if parts are to be produced in bulk it is more cost-effective to apply conventional manufacturing techniques since the cost due to investments in machines, tools and molds (or fixed cost) makes up a smaller percentage of the total cost. In other words, AM techniques have no advantages of scale.

- **Reproducibility of parts**
  Currently it has proven to be quite difficult to reproduce a part using AM techniques. More specifically, when an attempt is made to create two identical parts using the same technique or even the same machine, the result is often less than satisfactory. This is in no small part

due to the fact that the underlying science of the various AM techniques is not well understood [RD 36]. For example, the influence of energy input and distribution on the resultant microstructure and part properties has not been conclusively determined as of yet.

- **Limited size of produced parts**
  Another drawback of AM is that the size of the parts that can be produced with AM techniques is relatively small. The maximum dimensions of the so called build chamber found in most AM machines are 0.5 by 0.5 by 0.5 meters [RD 35]. This means that the size of parts constructed using AM techniques can never exceed these dimensions. Therefore, if a larger part needs to be constructed using AM techniques assembly is still required, which often makes conventional manufacturing techniques more attractive.

The future development of AM should focus on mitigating or overcoming today's shortcomings of the technology. As can be seen in the performance mix in Figure 3-6, the main shortcomings of AM are its inability to reproduce parts and the maximum size of the produced parts. Therefore, in the initial stages of the development process, an extensive study needs to be performed on the current capabilities of AM techniques and their future potential. There are two main ways in which the disruptive potential of AM can be increased: either by finding ways to exploit its advantages further or to mitigate its disadvantages. During the development process a new AM technique is developed that is ideally suited for the manufacture of parts in the space sector. Figure 3-6 summarizes the above by the illustrating the relative performance differences between conventional manufacturing & AM.

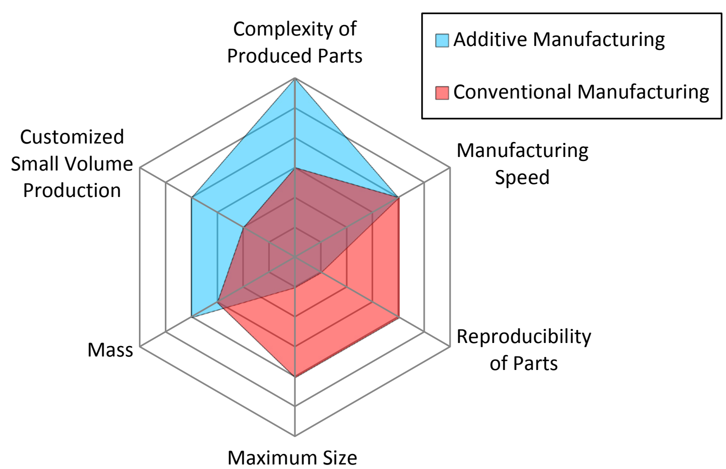


Figure 3-6: Radar chart of performance mix of AM with respect to conventional manufacturing. Analysis was performed with BEE methods

The here visualized performance values are based on best engineering estimates and further investigation still need to be performed.

3.3 *Selected Research Groups*

Table 3-1 displays the selected research group for porous metals in combination with Additive Manufacturing (AM). For both roadmap strings two separated research groups were selected, both located within the Fraunhofer *Institute for Manufacturing Technology and Advanced Materials* (Germany).

Table 3-1: Roadmapping partner Metal Foam & AM

Institute Fraunhofer IFAM	Fraunhofer IFAM is one of about 60 Institutes of the Fraunhofer-Gesellschaft. The majority of the 17,000 staff is qualified scientists and engineers, who work with an annual research budget of approximately 1.5 billion. Of this sum, more than 1.3 billion is generated through contracted research. Two thirds of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects.
Porous Metals – MODD Protection System for Heat Pipes	
Experience	Fraunhofer IFAM in Bremen has been working in the field of lightweight materials and highly porous cellular materials for more than 20 years. It has worked on numerous national and international R&D projects (e.g. the EC funded projects LISA and METEOR) in the field of porous metals and metallic foams. IFAM holds more than 20 patents and more than 120 scientific publications in this field.
Contact Person	Dipl.-Phys. Joachim Baumeister is an expert in the field of metal foams [RD 26]. Mr. Baumeister has a Diploma in Physics from the University of Bonn. He has worked at Fraunhofer IFAM since 1985 initially as a research scientist focusing on monolithic steels, steel sandwiches and superplasticity. As of 1991 Mr. Baumeister is the project manager for metal foams. His work on metal foams includes process developments as well as research into the creation of open- and closed-cell metal foams by means of powder metallurgical and casting methods. Furthermore, Mr. Baumeister has performed research into the application of metal foams in the form of crash absorbing materials and composite materials.
Contact Information	Dipl.-Phys. Joachim Baumeister Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) Wiener Straße 12 28359 Bremen Tel.: + 49 421 2246 -181 Email: joachim.baumeister@ifam.fraunhofer.de Internet: www.ifam.fraunhofer.de
Porous Metals – Additive Manufacturing (AM)	
Experience	Fraunhofer IFAM has been working in the development of metallic AM materials and processes for more than 15 years and has adapted several processes for use with new materials as well as improved the processes and materials themselves. Especially combinations of powder materials and alternative processing strategies have been developed. Examples are the integration RFID into metallic parts using SLM and the manufacture of complex and thin structures by combining SLM and electropolishing.
Contact Person	Mr. Claus Aumund-Kopp received his diploma of Production Engineering from the University of Bremen in 1995 and has more than 15 years of experience in product development and material processes, especially in the field of AM. He has worked for Fraunhofer IFAM since 2005 as a senior scientist. Presently, his responsibilities include the development of new processes and materials for AM systems in the institute.

	Current special interests include metal powder-based AM processes.
Contact Information	Dipl.-Ing. Claus Aumund-Kopp Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) Wiener Straße 12 28359 Bremen Tel.: + 49 421 2246-226 Email: claus.aumund-kopp@ifam.fraunhofer.de Internet: www.ifam.fraunhofer.de

3.4 Porous Metals TRM (incl. MMOD & AM)

Figure 3-6 displays the two major roadmaps for the *porous metals,* displaying an example application (MMOD) as well as the frame process *Additive Manufacturing (AM).* Highlighted shall be the two different time frames set for each string, where the MMOD application has a total time frame of 3 years while the AM has a total time frame of 6 years. In the following two sub chapters, the two roadmap strings are explained in detail.

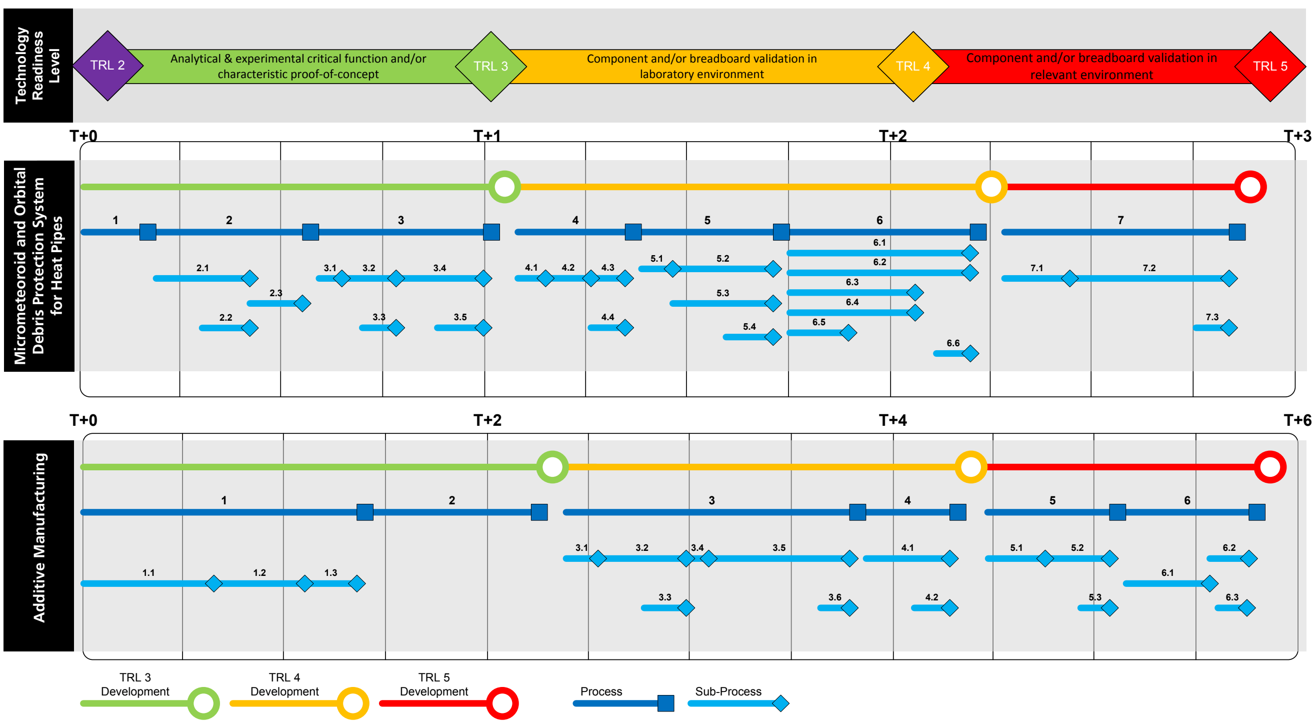


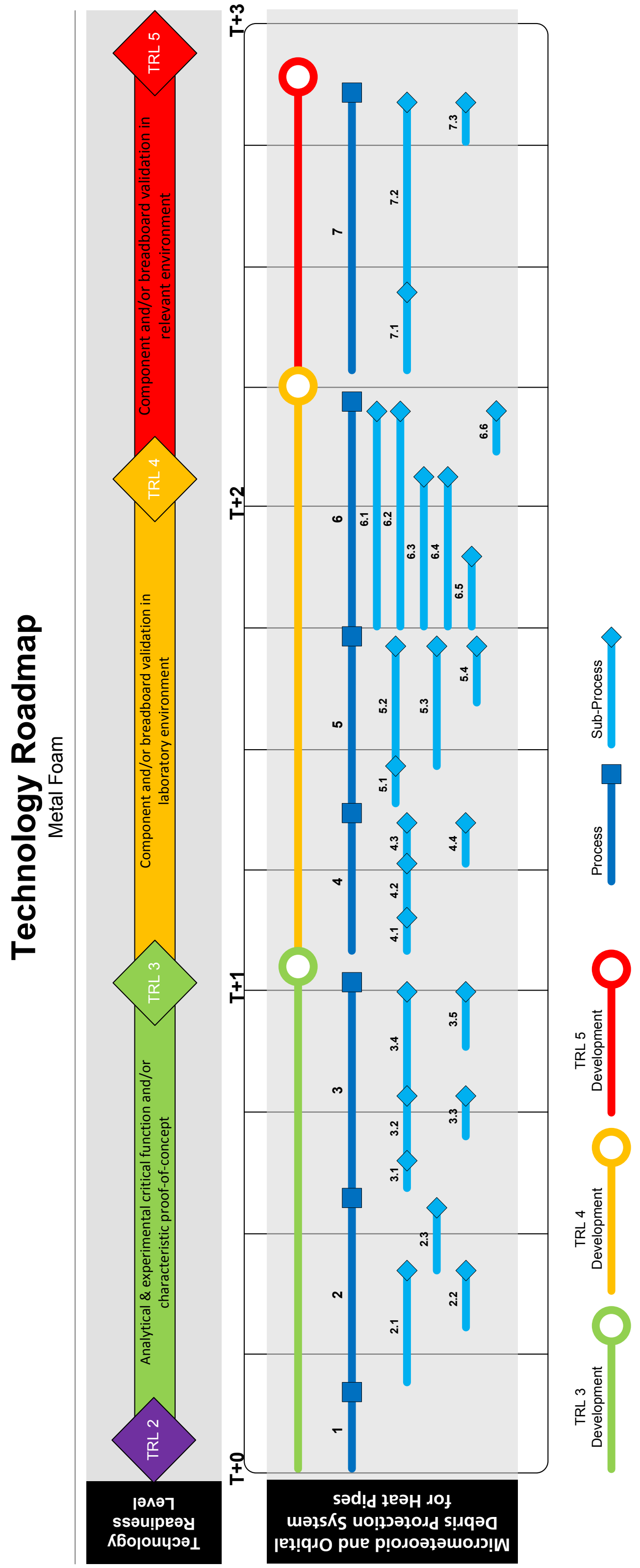
Figure 3-7: Overall Technology Roadmap (TRM) for *Porous Metals* incl. example application MMOD and frame process Additive Manufacturing (AM)

Since there are many possible applications for the category *'materials'*, only example applications shall be highlighted here (e.g. MMOD). The possibility exists that future research will make another application within 'porous metals' more suitable for space sector. There were also two additional roadmaps developed for the DST category *Porous Metals:*

- Crushable Mechanism with Thermal Protection System Functionality (Metal Foam)
- High Efficiency Heat Exchanger System (Metal Foam)

Please refer to Annex C & D for a detailed roadmap description.

3.4.1 Detailed Roadmap Steps (MMOD Protection System for Heat Pipes)



Legend - Metal Foam

Step	Description
1	**Fundamental Research**
2	**Modeling & Simulation**
2.1	Impact Modeling
2.2	Thermal Modeling
2.3	Simulation
3	**System Design**
3.1	Define Expected/Potential Mission Parameters
3.2	Preliminary System Design
3.3	Model Adjustment & Simulation
3.4	Detailed System Design
3.5	Model Expansion & Simulation
4	**Metal Foam Production**
4.1	Metal Foam Selection
4.2	Production Process Design
4.3	Metal Foam Production
4.4	Metal Foam Attribute Testing
5	**Basic Testing**
5.1	Preparation of Preliminary Performance Testing Facilities
5.2	Preliminary Performance Testing
5.3	Preparation of Intensive Testing Facilities
5.4	Model Adjustment & Simulation
6	**Intensive Testing**
6.1	Impact Tests
6.2	Thermal Tests
6.3	Stress Tests
6.4	Fatigue Tests
6.5	Corrosion Tests
6.6	Model and Design Update
7	**Mission Cycle Testing**
7.1	Test Preparation
7.2	Mission Cycle Tests
7.3	Model and Design Update

Figure 3-8: DST roadmap for metal foam.

The following process steps and their sub process steps were worked out in cooperation with the selected research group.

1. Fundamental Research [~2 months]

During this process a general research study is conducted concerning metal foam. This research includes a literature study as well as consultations with experts. A research study is necessary in order to identify the pitfalls of the technology in more detail so they can be avoided. For example, there exists a wide range of techniques that can be applied to create metal foam, however, most of these techniques have an empirical basis instead of a scientific one. In the past, trial and error has been applied extensively to come up with the most suitable foaming process. This was caused by the fact that the underlying mechanisms of metal foaming are not well understood. This is something that needs to be remedied if the technology is to be developed further. At the end of this process, a database is created containing all relevant information on the metal foaming process. The information contained in this database then serves as a basis for the subsequent development of the DST.

2. Modeling & Simulation [~4 months]

Due to a general lack of knowledge regarding HVIs and metal foam, more information needs to be obtained regarding the behavior of metal foam when subjected to HVIs before a system design can be generated. At this stage of the development process, the easiest way (and coincidentally the most cost effective way) to obtain this information is by building a model and running simulations. Therefore, in this sub-process, an impact model needs to be built that is able to simulate the effects of a HVI on a metal foam structure as accurately as possible. For now, the only available pieces of information that can be used to build the impact model are the known properties of metal foam and the results of impact tests that have been performed in the past.

As explained in Subsection 3.1, the secondary function of metal foam in this case is to facilitate the heat transfer from the heat pipes to the radiating surface of the radiator. This means that the thermal aspect of metal foam is also very important for this application. Therefore, during this process, a thermal model needs to be created as well.

Based on the results of the simulations performed using the models created in this process, the design of the system is generated in the next process. Furthermore, these models need to be adaptive such that they can be expanded at a later stage of the development process to incorporate newly obtained information gathered during the design and testing phases. Therefore, the models are evolving as the development of the system progresses.

2.1. Impact Modeling [~3 months]

During this sub-process, a model is created that can be used to simulate the effects of a HVI on a metal foam MMOD protection system. The model should be capable of incorporating all mechanical and thermal effects that are associated with HVIs. Also, the mechanical behavior (structure) of metal foam needs to be incorporated into the model.

2.2. Thermal Modeling [~2 months]

Although the thermal effects of HVIs are already incorporated in the impact model, the heat transfer from the heat pipes to the radiating surface needs to be modeled separately. This model should incorporate the thermal behavior of the heat pipes as well as the structure and thermal behavior of the metal foam.

2.3. Simulation [~2 months]

In this sub-process, the behavior of a generic MMOD protection system is tested in a virtual environment. The information gathered during this sub-process is subsequently used to create the system design.

3. System Design [~5 months]

During this process the system is designed based on the performed study and the results of the simulations performed during the previous process. In this process the preliminary and detailed design stages are combined into one large design process.

3.1. Define Expected/Potential Mission Parameters [~1 month]

The mission parameters define largely the necessary functionality of the system (what the system needs to do). Therefore, knowing the mission parameters and thereby the mission requirements before coming up with a system design is paramount.

3.2. Preliminary System Design [~2 months]

Here the system architecture is generated that is capable of fulfilling the mission requirements that have been determined in sub-process 3.1.

3.3. Model Adjustment & Simulation [~1 month]

During this sub-process the models (built in the previous process) need to be adjusted so that they incorporate the specifics of the system, which are determined during the preliminary design phase. This sub-process also involves using the updated models to perform new simulations and subsequently improve the system design.

3.4. Detailed System Design [~3 months]

In this sub-process the actual detailed design of the system is generated. This design incorporates all information gathered in previous processes (i.e. Literature study, preliminary design and the simulations)

3.5. Model Expansion & Simulation [~2 months]

During this sub-process, the models are expanded by incorporating the information obtained during the detailed system design phase. Additionally, new simulations are performed that are used to improve the design further. These latest simulations should also serve as a definitive theoretical proof of concept.

4. Metal Foam Production [~3 months]

The manufacturing process for metal foams is crucial in achieving the required properties of the material. Several types of metal foams exist as well as different ways to produce them. Therefore, selecting the most appropriate metal foam and production process is a time consuming, yet imperative process. During this process, the type of metal foam is selected and its production process is determined. Subsequently, the metal foam is produced and undergoes preliminary testing.

4.1. Metal Foam Selection [~1 month]

Selecting the most appropriate metal foam for the area of application is arguably the most important decision that needs to be made in the entire development process. This mainly involves a trade-off analysis between the different combinations of production techniques and materials.

4.2. Production Process Design [~1 month]

Due to the fact that there are many methods available to create metal foams (all of which have their own advantages and disadvantages), selecting the most suitable production process is paramount. This sub-process is closely linked to sub-process 4.1 due to the fact that the most suitable production techniques for the purpose of creating metal foams follow from the properties of the selected metal foam. This sub-process also includes initial production steps such as the construction (if no existing facilities are available or suitable) and preparation of the production facilities.

4.3. Metal Foam Production [~1 month]

This step involves the actual production of the material. The production of metal foams is a very sensitive process and it will most likely involve some trial and error to get everything right.

4.4. Metal Foam Attribute Testing [~1 month]

As the selected metal foam is being produced, it needs to be tested as well. This is done to determine whether the produced metal foam actually performs according to specifications. Some of the tests that need to be performed here are basic material tests (e.g. tensile and compression tests) to determine the attributes of the produced material. If these tests indicate that the material is unable to perform according to specifications, a different metal foam and/or production technique should be selected (back to sub-process 5.1). Other, non-destructive tests (e.g. ultrasonic and radiographic tests) need to be performed as well to identify any deficiencies (internal flaws) within the produced material. If any such deficiencies within the material are found, the production process needs to be repeated, adjusted or, if necessary, altered.

5. Basic Testing [~3 months]

This is where the practical proof of concept occurs. Does the system perform the way it was intended to? If there are unforeseen problems, iterations have to be performed (back to the drawing board).

5.1. Preparation of Preliminary Performance Testing Facilities [~1 month]

During this sub-process the preliminary performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

5.2. Preliminary Performance Testing [~3 months]

The most important question that needs to be answered during this sub-process is whether the performance of the system is as expected (or at least reasonably close). Are there discrepancies that have to be dealt with? Is the model used to come up with the detailed design accurate enough? During this sub-process the functionality of the system is tested by means of general performance tests. These tests are different from the tests that are performed during the next process in that they are not yet dedicated to this specific design. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the system can move on to the intensive testing phase (see next process). For this development path, the preliminary tests should focus on the thermal behavior of the system and, if at all possible at this stage, on the impact behavior of the system.

5.3. Preparation of Intensive Testing Facilities [~3 months]

During this sub-process the intensive performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

5.4. Model Adjustment & Simulation [~2 months]

Adjust the models (built in process 2 and updated in process 3) so that they better simulate the behavior of the actual system. This is done by incorporating the observed behavior of the selected metal foam (as tested during sub-process 4.4) as well as the behavior of the various components and the system as a whole during the preliminary performance tests. During this sub-process, new simulations are performed as well.

6. Intensive Testing [~6 months]

To get a basic feel of the behavior of the system as well as the individual components under different (loading) conditions, various tests have to be conducted. These tests also serve for the purpose of exploring the limits of the system. The tests are therefore by nature destructive.

6.1. Impact Tests [~6 months]

The impact tests are the most important tests that need to be performed during the entire development path. The question whether the system is able to protect the heat pipes in the radiator sufficiently from HVIs by micrometeoroids and orbital debris needs to be answered here. In order to do this, the system is subjected to a large amount of HVIs. The influence of impact parameters such as particle size, impact velocity and impact direction need to be determined conclusively. During this process, the impact tests are performed and the effects of HVIs on the system are analyzed extensively.

6.2. Thermal Tests [~6 months]

Although facilitating the transfer of heat from the heat pipes to the radiating surface is only a secondary function of the system, it is important that the thermal characteristics of the system are analyzed extensively. During these tests, the system is subjected to heat and its heat transfer capability is determined. One of the questions that need to be answered during this sub-process is what effect damage to the MMOD system caused by HVIs has on its heat transfer capability.

6.3. Stress Tests [~5 months]

During these tests, the question whether the forces generated during the mission (primarily forces due to acceleration and deceleration) compromise the functionality of the system is answered.

6.4. Fatigue Tests [~5 months]

Launch loads, electrical vibrations and acoustic vibrations need to be taken into account. Due to the fact that the system needs to function for the entire mission duration, it has to be verified that every periodic load that acts on the system will not compromise its functionality sometime during the mission. Particularly the effects of periodic loads combined with damage induced by HVIs needs to be investigated during this sub-process.

6.5. Corrosion Tests [~2 months]

Is the corrosion resistance of the system sufficient? Such tests are necessary because materials that are corrosion resistant on Earth are not necessarily so in space (atomic oxygen). The effects of prolonged exposure of the system to the space environment need to be established during these tests.

6.6. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

7. Mission Cycle Testing [~7 months]

In a mission cycle test, the system is subjected to the loads that are encountered in a full mission cycle. This means that the system is to be subjected to all loads that are encountered from launch until touchdown in chronological sequence in a controlled environment. This includes exposing the system to a near-vacuum environment. All this can be done on the ground providing there are adequate testing facilities available. This test also provides an indication as to the reliability of the system.

7.1. Test Preparation [~2 months]

During this sub-process the mission cycle test is prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap). For this development path, the test preparation time is somewhat longer compared to the other development paths due to the fact that extensive HVI tests need to be incorporated in the mission cycle test for this application.

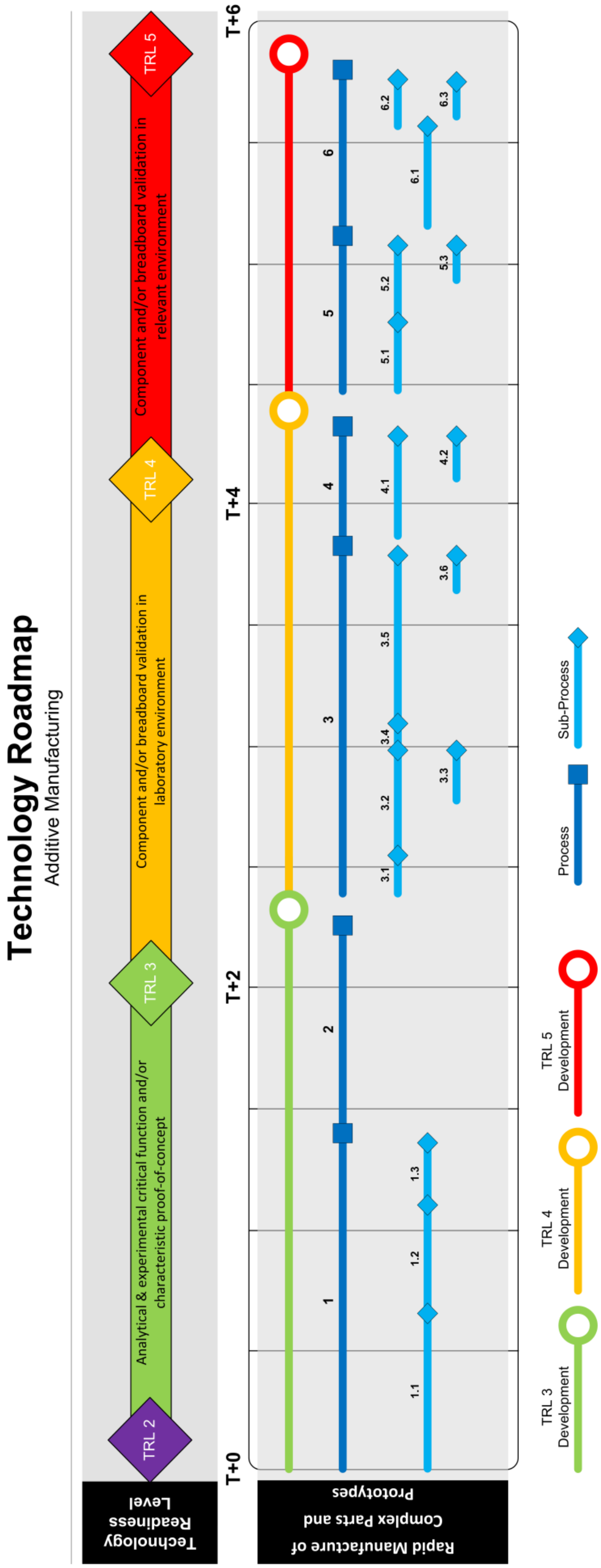
7.2. Mission Cycle Tests [~5 months]

During this sub-process the mission cycle tests are performed. The main goal of these tests is to determine the performance of the system over the course of a full mission as well as to determine its reliability. A large part of this sub-process comprises the analysis of the obtained test results.

7.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

3.4.2 Detailed Roadmap Steps (Additive Manufacturing)



Legend - AM

Step	Description	Step	Description	Step	Description
1	**Research**	3.2	AM Technique Proposal Generation	**5**	**Preliminary Testing**
1.1	Fundamental Research	3.3	Simulation	5.1	Preliminary Performance Testing
1.2	Guidelines & Industry Standards	3.4	Trade-Off	5.2	Reproducibility Testing
1.3	Database Generation	3.5	System Design	5.3	Model Update
2	**Modeling**	3.6	Model Update	**6**	**Dedicated Testing**
3	**Technique Design**	**4**	**Technique Preparation**	6.1	Representative Production Run
3.1	Identification of Growth Potential	4.1	AM Machine Calibration and Adjustment	6.2	Property Testing of Produced Parts
		4.2	Operating Routines	6.3	Model Update

Figure 3-9: DST roadmap for Additive Manufacturing.

The following process steps and their sub process steps were worked out in cooperation with the selected research group.

1. Fundamental Research [~8 months]

At present AM techniques are not used very often in high-tech industries such as the space industry. This is mainly due to the fact that AM is not viewed as a viable manufacturing method by most industries. However, when the actual capabilities of current AM techniques are examined it can be concluded that AM is a viable manufacturing technology particularly for applications with low quantity, high performance requirements. Therefore, the fact that AM is not used more currently (particularly in niche markets such as that of the space sector) can be largely attributed to the negative image that is associated with AM (Bourell, Leu, & Rosen, 2009). This negative image is the result of the fact that at present no clear guidelines and industry standards exist for AM. Potential users therefore tend to stick to proven conventional manufacturing methods. This process is aimed towards remedying this problem by performing extensive and dedicated research.

1.1. Fundamental Research [~4 months]

During this sub-process the science behind the various AM techniques is investigated further. Currently, most AM techniques are based on simplified physics models. This leads to the fact that two different parts with the same design created with the same technique are not always identical. In other words, the consistency of most AM techniques leaves something to be desired. The goal of this sub-process is to determine the underlying fundamental science of the various AM techniques in order to be able to create more accurate models in process 2. This is achieved primarily by means of consultations with experts and literature studies.

1.2. Guidelines & Industry Standards [~3 months]

Currently, AM techniques are not considered to be viable alternatives for conventional manufacturing techniques by most high-tech industries. For this reason guidelines and standards need to be generated in order to make AM a more attractive option. In particular, the existence of product, process and material certification that conform to internationally recognized industry standards would drive the adoption of AM techniques significantly (Bourell, Leu, & Rosen, 2009). In this sub-process, a handbook needs to be created detailing the standards for parts created using AM techniques. This handbook needs to be created by a workgroup of which the appointed members possess all relevant knowledge and represent all interested parties.

1.3. Database Generation [~1 month]

In this sub-process a database is created that contains all relevant information on AM. This includes specifics on every AM technique currently in existence as well as information on the characteristics of parts produced using AM techniques in the past. The findings of sub-process 1.2 are also included in this database. The main goal of this database is to serve as a source of information for designers and to aid them in selecting the most appropriate AM technique for their purpose.

2. Modeling [~4 months]

During this sub-process a comprehensive model needs to be created that can be used to simulate the performance of all AM techniques with accuracy. The main source of information for the creation of the models is the database created in sub-process 1.3. In the future, the model is to be used by designers as a tool capable of predicting the characteristics of specific parts produced using certain AM techniques with sufficient accuracy. The model should therefore incorporate all factors that can influence the quality of the final product. The proposals for new AM techniques (that are to be generated in process 3) are based on the model created here. Furthermore, the model needs to be adaptive in the sense that it can be expanded and/or adjusted at a later stage of the development process to incorporate newly obtained information gathered in the design and testing phases. Therefore, in a sense, the model is evolving as the development of the technology progresses.

3. Technique Design [~9 months]

During this process the design is generated for an AM technique capable of meeting the future demands of the space industry. The first sub-process involves determining in what direction the technology should be developed. During the second sub-process several proposals for new AM techniques are generated that could increase the disruptive potential of AM. During the third sub-process the various proposed techniques are analyzed and one of them is selected for further development. In the fourth sub-process the selected AM technique is worked into a final system design. The system design generated during this process is to be used in process 4 as a blueprint for the new AM technique. The fifth and final sub-process involves updating the model created in process 2.

3.1. Identification of Growth Potential [~1 month]

During this sub-process, the direction of the development path needs to be determined. At this point there are two ways in which AM techniques can be developed further: either by increasing their performance or by mitigating their disadvantages. An increase in performance could be achieved by for example finding ways to produce individual layers all at once rather than the point processing techniques that are currently used; this would increase the manufacturing speed significantly. Also, the versatility of AM could be enhanced by developing techniques capable of using an even wider range of materials. A disadvantage that could be mitigated is the cost of AM machines. The reduction of cost could be achieved if the design of new AM techniques is performed with cost as a primary design criterion. For example, if portions of AM processes are modularized and/or standardized, the costs can be reduced (Bourell, Leu, & Rosen, 2009). During this sub-process the most effective way of increasing the disruptive potential of AM is identified.

3.2. AM Technique Proposal Generation [~3 months]

This sub-process involves the generation of several proposals of new AM techniques (which are either cost-saving or performance-increasing as mentioned in sub-process 3.1) that could increase the disruptive potential of AM. These proposals should include details concerning the envisioned process (i.e. details concerning the applied process) as well as performance estimates (based on simulations performed using the model built in process 2). The proposals are based in no small part on the results of simulations run using the model created in process 2 (see sub-process 3.3).

3.3. Simulation [~1 month]

During this sub-process, simulations are run for each of the proposed AM techniques. The simulation results are used as input for the refinement of the AM techniques. The entire proposal generation process is therefore iterative in nature.

3.4. Trade-Off [~1 month]

After the proposals have been successfully generated, the most promising one needs to be selected. The results of the simulations (performed in the previous sub-process) are the determining factor in the trade-off. During this sub-process, the proposals are compared to one another and their future potential as a manufacturing technique in the space sector is assessed.

3.5. System Design [~4 months]

After one of the proposals is selected, the design is worked out during this sub-process. The result of the design phase is a report detailing the exact process that is to be applied for the new AM technique. In addition to that, the report contains information regarding the hardware that is required to be able to apply the newly developed AM technique. Based on the information contained in this report, the new AM technique is prepared in process 4.

3.6. Model Update [~1 month]

When the system design phase (sub-process 3.4) draws to an end, the model (built in process 2) is updated with the information obtained during this phase.

4. Technique Preparation [~4 months]

During this process the newly developed AM technique is prepared. This involves the calibration and adjustment of existing AM machines as well as the formation of operating routines for the new AM technique.

4.1. AM Machine Calibration and Adjustment [~4 months]

This sub-process involves the calibration and adjustment of an existing AM machine. The activities that are to be performed during this sub-process depend on the characteristics of the newly developed AM technique. If the AM technique is sufficiently different from existing AM techniques, this sub-process also involves the construction of an entirely new AM machine. However, this would significantly increase the duration and cost of the entire development process.

4.2. Operating Routines [~1 month]

During this sub-process operational guidelines need to be written to facilitate the efficient use of the AM technique. In addition to that, these guidelines should ensure that the AM technique can be applied in a safe and responsible manner.

5. Preliminary Testing [~4 months]

This is where the practical proof of concept occurs. Does the technique perform the way it was intended to? If there are unforeseen problems or large discrepancies, iterations have to be performed (back to the drawing board). If this is indeed the case, the duration of the development process will be significantly longer than indicated in the roadmap.

5.1. Preliminary Performance Testing [~2 months]

Is the performance of the technique as expected (or at least reasonably close)? Are there discrepancies that have to be dealt with? Is the model used to come up with the AM technique accurate enough? During this sub-process the AM technique is tested by means of general performance tests. Specifically, the AM technique is used to create generic shapes and parts in order to determine whether its performance is as expected. These tests are different from the tests that are performed during the next process in that they do not yet involve creating parts for the space sector. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the technology can move on to the intensive testing phase (see next process).

5.2. Reproducibility Testing [~2 months]

During this sub-process the reproducibility of the AM technique is put to the test. In order to do this several generic part designs are created (or reused from the previous sub-process). The AM technique is subsequently used to create batches of identical parts based on these designs (one batch per design). The parts of each batch are analyzed and then compared to one another in order to determine the reproducibility of the technique. This analysis involves careful measurement of the dimensions of the produced parts as well as extensive property testing.

5.3. Model Update [~1 month]

The model (built in process 2 and updated in process 3) is updated so that it better simulates the behavior of actual systems. This is done by incorporating the behavior and performance of the AM technique as observed during the preliminary performance tests and reproducibility tests (sub-process 5.1).

6. Dedicated Testing [~4 months]

During this process the performance of the newly developed AM technique is conclusively determined. In order to do this a representative production run is performed in a simulated space sector production environment. In addition to that, the parts produced during this run are tested and their quality/performance is compared to other, similar parts that have been produced in the past by other means (other AM techniques or conventional manufacturing techniques).

6.1. Representative Production Run [~3 months]

During this sub-process, a representative production run is performed. This means that the AM technique is used to create actual parts and geometries (i.e. no generic shapes) that have been created in the past for the space sector by means of other manufacturing techniques. Examples of such parts and geometries are intricate heat exchanger systems and honeycomb wall structures. The circumstances that surround average production runs are simulated as well. The performance of the technique under these conditions needs to be observed and documented. If it is necessary or otherwise beneficial changes need to be made to the operating routines (written in sub-process 4.2).

6.2. Property Testing of Produced Parts [~1 month]

During this sub-process the parts that have been produced during the representative production run are subjected to extensive tests. These tests are necessary to get an idea regarding the characteristics of parts produced using the newly developed AM technique. The properties of the produced parts are also compared to those of the parts produced using conventional manufacturing techniques or other AM techniques.

6.3. Model Update [~1 month]

During this sub-process, the model is updated by incorporating the results of the tests performed during this process.

4 Phase-Change Memory - Technical Roadmap

Phase-Change Memory (PCM) is a type of non-volatile random-access memory. Non-volatile memory is computer memory capable of retaining information even when not powered (much like computer hard disks and optical discs). When it comes to the physical principle that is applied, the most significant difference between PCM and the widely-used volatile Dynamic Random-Access Memory (DRAM) is that the former is based on a thermally-driven process and the latter is not. PCM exploits the large difference in resistivity between the crystalline and amorphous phases of phase-change material (chalcogenides). When a phase-change material is in a crystalline state its resistivity is low (corresponding to bit value "1") and when the material is in an amorphous state its resistivity is high (corresponding to bit value "0"). Figure 4-1 (middle) shows a schematic representation of a cross-section of a conventional PCM cell.'

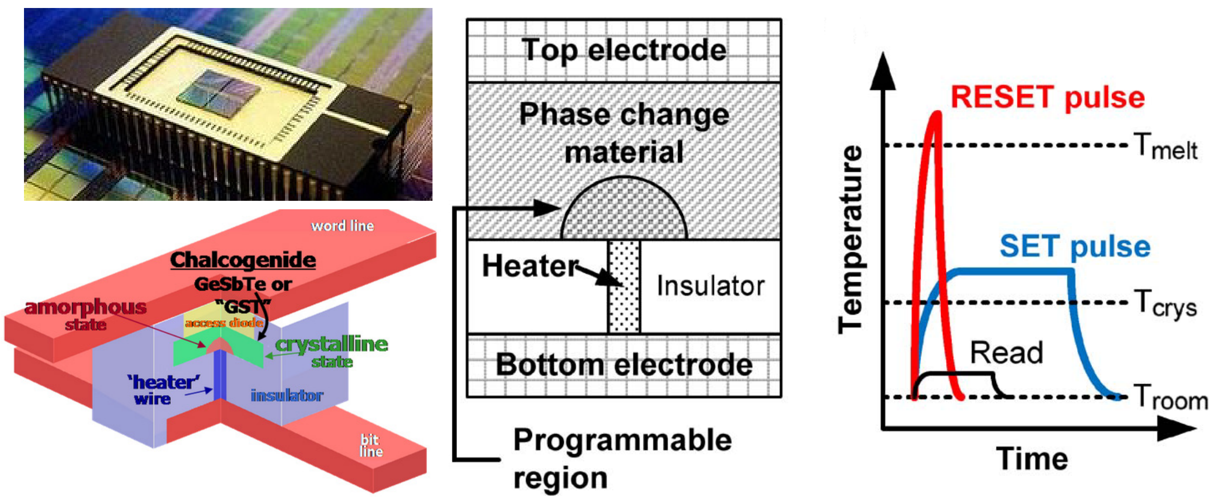


Figure 4-1: Schematic representation of a conventional PCM cell on the left and electrical pulses used to change and read the resistivity of a PCM cell on the right [RD 37].

In order to change the bit value of a cell or, in other words, to change the phase of the chalcogenide material, electrical pulses are applied. These electrical pulses heat up the heating element in the cell, which in turn heats up the phase change material allowing it to change from an amorphous state to a crystalline state or vice versa. If the PCM cell has a bit value of "0" (the chalcogenide material is in an amorphous state), a moderate electrical current pulse is applied to anneal the chalcogenide material at a temperature somewhere between the crystallization temperature and the melting temperature of the material. This pulse, often referred to as the "SET pulse", is maintained long enough for the amorphous material to crystallize. Conversely, if the PCM cell has a bit value of "1" (the chalcogenide material is in a crystalline state), a large electrical current pulse, often referred to as the "RESET pulse", is applied for a short time period to melt the chalcogenide material and subsequently cool it down quickly (or quench it) to "freeze" it in its amorphous state. The resistivity and thereby the bit value of the PCM cell is read by means of a small electrical current pulse. This pulse heats up the chalcogenide material only slightly (the attained temperature is well below the crystallization temperature) and therefore it does not change the structure of the chalcogenide material.

Due to the nature of PCM, its range of applications is rather limited. PCM can only be realistically applied in spacecraft computer systems. Therefore, the application that is selected for PCM is using Phase-Change Random-Access Memory (PCRAM) as the primary memory in spacecraft computer systems. This application shows a lot of promise largely due to the non-volatile nature of PCM as well as its performance. The type of memory that is currently used in spacecraft is usually volatile, which means that all data is lost if a (momentary) loss of power occurs. In addition to that, memory that is currently used in spacecraft is sensitive to radiation and high-energy particles. Therefore, a significant amount of shielding is required to protect the memory and prevent data corruption from occurring, which increases the mass of the spacecraft. By using PCRAM as the primary memory in spacecraft, these problems disappear. In order to illustrate the capabilities of PCRAM, the advantages of PCRAM over DRAM are listed below:

- **High data retention**
  When compared to DRAM, PCRAM has an immense advantage when it comes to data retention. This is a direct result of the fact that PCRAM is non-volatile and DRAM is volatile. If power is cut, DRAM will retain the stored information for no longer than 64 ms, whereas PCRAM will retain the information indefinitely. Therefore, when it comes to the reliable storage of data in spacecraft, the use of PCRAM is preferred over DRAM.
- **Low power consumption**
  Writing data to a PCRAM module generally requires more power than writing the same amount of data to a DRAM module. This is due to the fact that a high current is required to heat up the phase-change material to temperatures between 400 and 700 degrees Celsius. However, due to the fact that PCRAM is non-volatile, only the active of the memory parts (parts where data is either written or read) need to be powered. The result of this is that the total power consumption of PCRAM is considerably lower than it is for DRAM despite the high current that is necessary for PCRAM write cycles. In the future, the power consumption of PCRAM can be decreased even further if the technology is scaled down.
- **High scalability**
  Due to fundamental technology limits, it is not possible to scale down DRAM much further in the future [RD 39]. For PCRAM, a significant increase in performance (in all aspects) can still be achieved. Therefore, PCRAM is expected to be a viable successor to DRAM [RD 40].
- **High radiation resistance**
  Due to the fact that space is a high-energy radiation environment, using DRAM in space is troublesome. DRAM is prone to radiation-induced data corruption and therefore extensive radiation shielding is required. Since PCRAM uses heat as a programming device rather than electricity (as opposed to DRAM), PCRAM is inherently radiation resistant (electromagnetic radiation does not effect it). This means that if PCRAM is used only minimal (if any) radiation shielding is required on account of the spacecraft’s memory, which saves mass.

Compared to DRAM, PCRAM also has some drawbacks which are mentioned below:

- **Low speed**
  The write speeds of PCRAM are generally lower than those of DRAM. This is due to the fact that PCRAM relies on the phase transformation of chalcogenide material by the application of heat to write data. This is a relatively time-consuming process when compared to the writing mechanism applied by DRAM (the (dis)charge of capacitors). That being said, the read speed of PCRAM is on par with that of DRAM. In the future, the write speed of PCRAM will increase when the technology is scaled down. This is because it takes less time to heat up a smaller amount of material and also less time to transform this smaller amount of material to a different phase.
- **Limited endurance**
  At present, the maximum number of write cycles before failure for PCRAM is significantly lower than that of DRAM. DRAM can achieve more than 10^{16} cycles before failure (which is practically forever), whereas the maximum amount of write cycles that can be achieved using PCRAM is around 10^{9} [RD 37]. Although the endurance of PCRAM is sufficient for most present-day applications, this is not necessarily true for future applications. Also, when it comes to space missions, reliability is of paramount importance and the endurance margin should be as high as possible.

The strengths and weaknesses of PCM as compared to DRAM are illustrated in the performance mix in Figure 4-2.

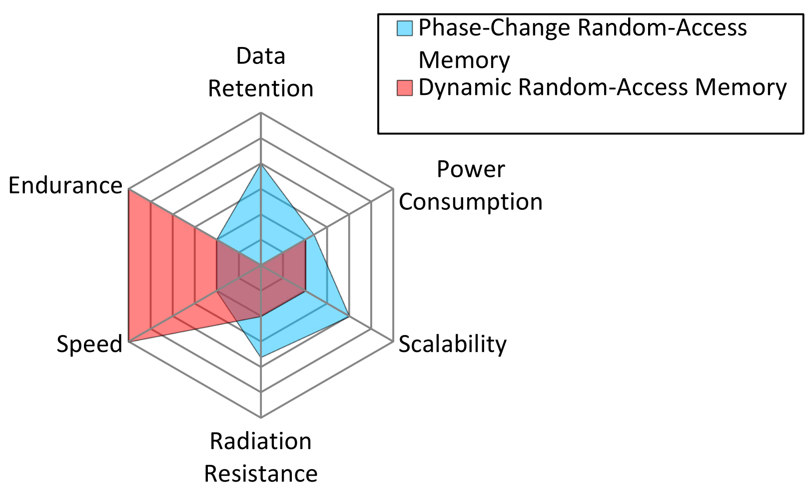


Figure 4-2: Performance mix of Phase-Change Random-Access Memory and Dynamic Random-Access Memory (Analysis was performed with BEE methods).

In the early stages of the development process, a research study is to be performed aimed at the creation of a database containing all relevant (theoretical, experimental and practical) information on PCM. Using this database a model is created capable of simulating the behavior of PCM over time. At a later stage of the development process, a suitable PCRAM architecture is generated and prototypes are fabricated, which subsequently are subjected to extensive tests. Due to the fact that PCRAM has not been used in any environment remotely similar to the space environment, the memory's capability to cope with such an environment should be focus of these tests. These tests involve extensive radiation tests (even though the technology is considered to be inherently radiation resistant) as well as thermal tests. In short, the space qualification of the technology is paramount. Since PCRAM uses heat as a programming mechanism, thermal control of the system is very important. Therefore, during the development process special attention should be given to this aspect. In addition to that, the reliability of PCRAM should be conclusively determined during the development process by means of tests performed in a relevant (simulated) environment.

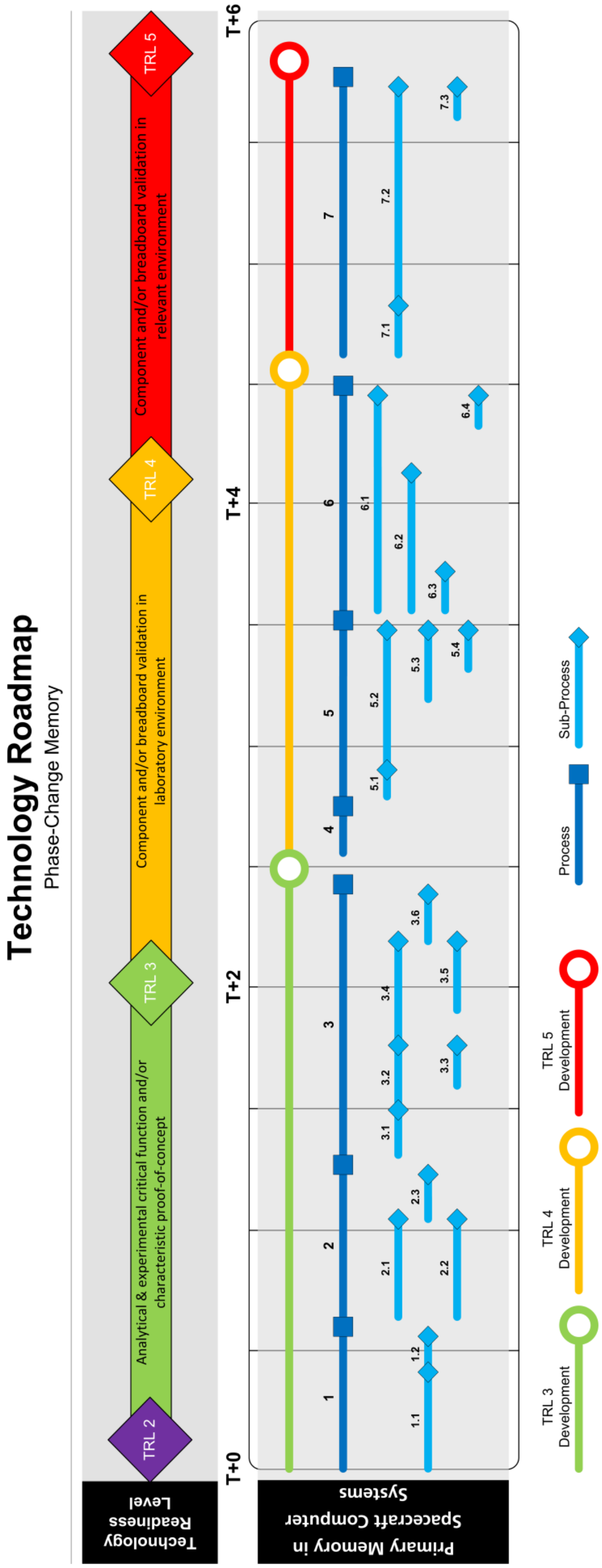
4.1 Selected Research Group

Table 4-1 displays the selected research group for Phase-Change Memory (PCM). The selected research group is at the University of Pardubice (UPA) in the Czech Republic.

Table 4-1: Selected Roadmapping partner PCM

University Univerzita Pardubice	The University of Pardubice (UPA) is one of 26 public higher education institutions in the Czech Republic, and the only higher university-type educational institution in the Pardubice Region. It has 7 faculties and 1 institute with over 10 thousand students in 60 undergraduate or postgraduate study programmes with more than 130 study specializations.
Research Center	Research Center LC 523 (RC), is a cooperation between the UPA and the Institute of Inorganic Chemistry (IICh). This main focus of research is on inorganic and inorganic-organic compounds. The RC was established in July 2005 and its main goal is to combine the experience of both institutions to further the research in materials science. As a result, young researchers have contributed to applications in (opto)electronics, medicine and catalysis and have furthered the quality of research in the Czech Republic in general.
Contact Person	Prof. Ing. Miloslav Frumar, Dr.Sc. of the University of Pardubice, Czech Republic (UPA) at the department of General and Inorganic Chemistry, is an expert in the field of PCM and chalcogenides [RD 38]. Next to his work for the UPA, Prof. Frumar is the head of Research Center LC 523.
Contact Information	Prof. Miloslav Frumar, PhD, DSc, Fac. Chem. Tech. University of Pardubice, 53210 Pardubice, Czech Rep. Tel.: +420 466037161 Email: Miloslav.Frumar@upce.cz Internet: http://vzc.upce.cz/home.php

4.2 Detailed Roadmap Steps (Phase-Change Memory)



Legend - PCM					
Step	Description	Step	Description	Step	Description
1	**Research**	3.3	Model Adjustment & Simulation	**6**	**Intensive Testing**
1.1	Information Gathering	3.4	Detailed Architecture Design	6.1	Thermal Tests
1.2	Database Generation	3.5	Model Expansion & Simulation	6.2	Radiation Tests
2	**Modeling**	3.6	Software Design	6.3	Corrosion Tests
2.1	Memory Modeling	**4**	**Prototype Memory Module Fabrication**	6.4	Model and Design Update
2.2	Thermal Modeling	**5**	**Basic Testing**	**7**	**Mission Cycle Testing**
2.3	Simulation	5.1	Preparation of Preliminary Performance Testing Facilities	7.1	Test Preparation
3	**System Design**	5.2	Preliminary Performance Testing	7.2	Mission Cycle Tests
3.1	Define Expected/Potential Mission Parameters	5.3	Model Adjustment & Simulation	7.3	Model and Design Update
3.2	Preliminary Architecture Design	5.4	Preparation of Intensive Testing Facilities	7.4	Mission Cycle Tests
				7.5	Model and Design Update

Figure 4-3: DST Roadmap for Phase-Change Memory.

The following process steps and their sub process steps were worked out in cooperation with the selected research group.

1. Research [~4 months]

Currently a significant amount of research is being done on the subject of PCM. In order to create an overview of this research, this process 0 is aimed towards the creation of an extensive database containing all relevant information on the subject of PCM. In order to create this database all relevant information needs to be gathered. This is done by means of a literature study and expert consultations. After all information has been collected it is to be categorized in the form of a database. This database is to be used as the primary source of information by designers for the creation of the models (process 2) and the design of the memory modules themselves (process 3). For this reason, the database should be easily accessible and clear.

1.1. Information Gathering [~3 months]

During this sub-process all relevant information pertaining PCM is collected. Firstly, this involves performing a literature study. Secondly, the gathering of information involves the identification of the mayor players in the PCM research field. Through collaboration with these players more information is acquired.

1.2. Database Generation [~1 month]

In this sub-process a database is created that contains all relevant information on PCM. This includes specifics on the physics behind PCM (or rather the fundamentals of PCM) as well as information on ongoing research in the field of PCM. The information contained in the database is gathered during sub-process 1.1. The main goal of this database is to serve as a source of information for designers and to aid them in creating the most suitable memory architecture for space applications.

2. Modeling [~4 months]

During this sub-process comprehensive models are created that can be used to simulate the behavior of PCRAM memory modules with significant accuracy. The main source of information for the creation of the models is the database created in sub-process 1.2. In the future, the model is to be used by designers as a tool capable of simulating the behavior of PCRAM under different conditions over an extended period of time. The model should therefore incorporate all factors that can influence the quality of the final product. For the use of PCRAM in space the most important aspect to be modeled is the thermal aspect. In addition to that, a functional model is created during this process that can be used to simulate the general functionality of PCRAM modules over an extended period of time. In process 3, these models are used to come up with a suitable memory module architecture. These models need to be adaptive in the sense that they can be expanded at a later stage of the development process to incorporate newly obtained information gathered in subsequent design and testing phases. Therefore, in a sense, the models are evolving as the development of the system progresses.

2.1. Memory Modeling [~3 months]

During this sub-process, the workings of PCRAM modules are modeled. The main goal of this model is to simulate the behavior of PCRAM modules over extended periods of time. In other words, designers should be able to use this model to predict the reliability and endurance of any PCM architecture. Particularly the drift in resistance of the amorphous and crystalline states over time needs to be modeled as accurately as possible since this drift is the determining factor when it comes to the endurance of PCM (Burr, et al., 2010). In addition to that, the drift in crystallization and melting temperatures needs to be modeled as well.

2.2. Thermal Modeling [~3 months]

During this sub-process a model is created with which the influence of external thermal influences on PCRAM modules can be simulated. Designers should be able to use this model to predict the effects of the space environment on PCRAM modules. This model is also used to determine the extent of thermal control required for a PCRAM module to function in space without problems.

2.3. Simulation [~1 month]

In this sub-process, the behavior of a generic PCRAM module is simulated in a virtual space environment. The information gathered during this sub-process is subsequently used during the design of the actual memory architecture.

3. System Design [~6 months]

During this process space-worthy PCRAM modules are designed based on information gathered during the performed study and the results of the simulations run during sub-process 2.3. In this process the preliminary and detailed design stages are combined into one large design process.

3.1. Define Expected/Potential Mission Parameters [~1 month]

The mission parameters define largely the necessary functionality of a system (what a system needs to do). Since the goal of each space mission is usually unique, the requirements of the subsystems for each mission are unique as well. This also goes for the Command and Data Handling (C&DH) subsystem. Therefore, knowing the mission potential parameters and thereby the mission requirements before coming up with a memory architecture is paramount. In short, the required capabilities of the PCRAM modules need to be determined during this sub-process.

3.2. Preliminary Architecture Design [~1 month]

Within this sub-process, the preliminary memory architecture is generated that is capable of fulfilling the mission requirements that have been determined in the previous sub-process.

3.3. Model Adjustment & Simulation [~1 month]

During this sub-process, the models (built in the previous process) need to be adjusted so that they incorporate the specifics of the system, which are determined during the preliminary design phase. This sub-process also involves using the updated models to perform new simulations and subsequently improve the system design in an iterative manner.

3.4. Detailed Architecture Design [~2 months]

In this sub-process the actual detailed memory architecture is generated. This design incorporates all information gathered in previous processes (i.e. information gathering, preliminary design and the simulations).

3.5. Model Expansion & Simulation [~2 months]

During this sub-process, the models are expanded by incorporating the information obtained during the detailed architecture design phase. Additionally, new simulations are performed that are used to improve the design further. These latest simulations also serve as a definitive theoretical proof of concept.

3.6. Software Design [~1 month]

The last sub-process in the system design process involves the design of the software that ensures the correct operation of the memory modules. The preferred way of doing this is by adapting existing software as this would save time and money. The software needs to be specially designed for the memory architecture generated during this process. It should be able to compensate for the resistance drift of the amorphous and crystalline phases of the chalcogenide material that occurs over time. Also, the software should be able to adapt to a drift in crystallization and melting temperatures of the chalcogenide. The software becomes even more important if the memory architecture involves multiple-level designs and/or multiple bits per cell configurations. By designing adequate software for this purpose, the endurance and reliability of the modules are increased significantly.

4. Prototype Memory Module Fabrication [~1 month]

During this process, several prototype memory modules are fabricated based on the design generated in the previous process. This process also involves the selection of suitable production facilities and, if none are available, the design and construction of these facilities, however, this would increase the duration and cost of the development process considerably.

5. Basic Testing [~4 months]

This is where the practical proof of concept occurs. Does the PCRAM module perform the way it was intended to? If there are unforeseen problems, iterations have to be performed (back to the drawing board).

5.1. Preparation of Preliminary Performance Testing Facilities [~1 month]

During this sub-process the preliminary performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed.

5.2. Preliminary Performance Testing [~3 months]

Is the performance of the designed memory modules as expected (or at least reasonably close)? Are there discrepancies that have to be dealt with? Is the model used to come up with the system design accurate enough? During this sub-process the functionality of the system is tested by means of general performance tests. These tests are different from the tests that are performed during the next process in that they are not yet dedicated to this specific design. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the system can move on to the intensive testing phase (see next process). For this development path, the preliminary tests should focus on the thermal behavior of modules as well as on their general functionality.

5.3. Model Adjustment & Simulation [~2 months]

Adjust the models (built in process 2 and updated in process 3) so that they better simulate the behavior of the actual memory modules. This is done by incorporating the observed behavior of the various components and the modules as a whole during the preliminary performance tests. During this sub-process, new simulations are performed as well.

5.4. Preparation of Intensive Testing Facilities [~1 month]

During this sub-process the intensive performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

6. Intensive Testing [~6 months]

To determine the behavior of the PCRAM modules under different (loading) conditions, various tests have to be conducted. During these tests, the modules are integrated into a representative spacecraft computer system to test their behavior in such an environment. These tests also serve for the purpose of exploring the limits of the system. The tests are therefore by nature destructive.

6.1. Thermal Tests [~6 months]

Since PCRAM uses heat as a programming mechanism, the thermal aspect of the space environment is paramount. How do sharp temperature gradients affect the system? The day-night cycle is very important in this. Do the temperature gradients diminish the functionality of the system over time? The most important question that needs to be answered during this sub-process is what type of thermal control is required to enable the PCRAM modules to function optimally in a space environment.

6.2. Radiation Tests [~4 months]

Although PCRAM is inherently radiation resistant, radiation tests still have to be performed. This is mainly because PCRAM has never been used in a high-radiation environment before and the effects of such an environment on the functionality of PCRAM are therefore unknown. The tests performed during this sub-process are meant to gather experimental data on the effects of radiation on PCRAM modules. Although radiation has no effect on the writing mechanism employed by PCRAM, the electrical support architecture of PCRAM modules might still be sensitive to radiation. Therefore, during this sub-process, the radiation sensitivity of complete PCRAM systems needs to be determined.

6.3. Corrosion Tests [~1 month]

In all likelihood, PCRAM memory modules will never be directly exposed to the space environment when installed in spacecraft. However, be that as it may, the modules could still be exposed to the space environment accidentally (for example due to the failure of hermetic seals). If this were to be the case, one needs to know the effects this will have on the memory's functionality. For this reason, the effects of prolonged exposure of PCRAM modules to the space environment need to be investigated during this sub-process.

6.4. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

7. Mission Cycle Testing [~7 months]

In a mission cycle test, the PCRAM modules are subjected to the loads that are encountered during a full mission cycle. This means that the system is to be subjected to all loads that are encountered from launch until end-of-mission in chronological sequence in a controlled environment. This includes exposing the system to a near-vacuum environment which resembles the space environment as closely as possible. All this can be done on the ground, providing there are adequate testing facilities available. This test also provides an indication as to the reliability of the system.

7.1. Test Preparation [~2 months]

During this sub-process the mission cycle test is prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

7.2. Mission Cycle Tests [~5 months]

During this sub-process the mission cycle tests are performed. The main goal of these tests is to determine the performance of the PCRAM modules over the course of a full mission as well as to determine their reliability. Another important question that needs to be answered during this sub-process is whether the software designed in sub-process 3.6 functions as expected. When the tests have completed a representative mission cycle, the modules are analyzed. Afterwards, the tests are continued until failure of the memory modules occurs. This is done to ascertain the endurance of these modules in a relevant environment. If the endurance of the modules is lacking, the amount of required redundancy for a space mission needs to be determined or a different memory architecture needs to be generated (back to process 3). A significant part of this sub-process comprises the analysis of the obtained test results.

7.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

5 Aerographite Technical Roadmap

Aerographite is an extremely lightweight sponge like material that is constructed by coating a Zink-Oxide (ZnO) template with a thin layer of graphite. After removal of the ZnO template the resulting material has remarkable mechanical properties. These properties can be tailored by adjusting both the template structure and the coating process, which makes the material highly flexible. Its properties make it a suitable material for a range of different applications and can possibly combine different functions leading to simpler, more efficient and/or cheaper systems.

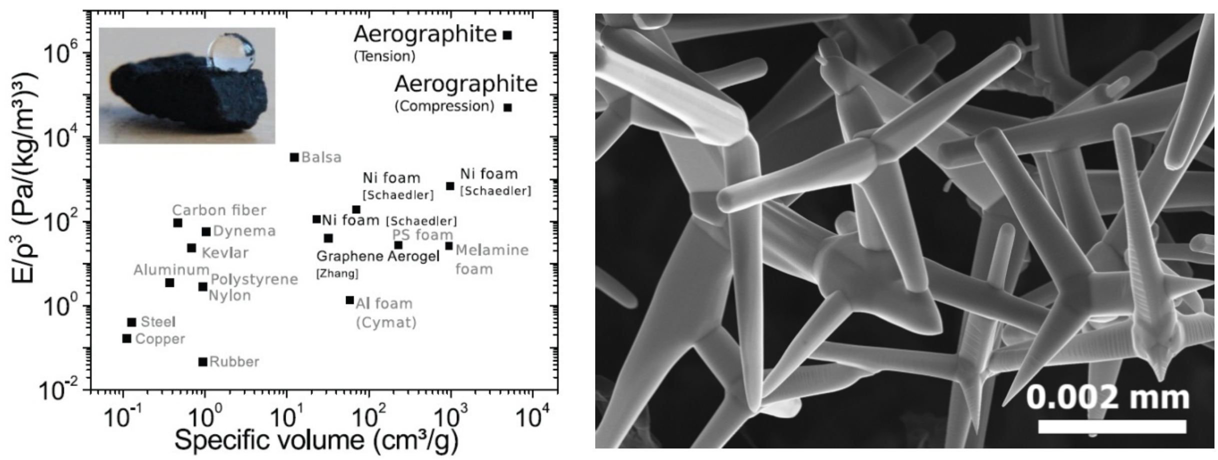


Figure 5-1: Aerographite compared to other lightweight materials on the left (Mecklenburg, et al., 2012). Aerographite's zinc-oxide tetrapod structure (TUHH, 2012).

The main properties of Aerographite are the following (Mecklenburg, et al., 2012):

- Good electrical conductivity
- High surface area
- Very low Poisson ratio
- Good compressive and tensile strength
- Multiple structural configurations possible

Part of the information required to build the DST roadmap for Aerographite has been obtained by means of correspondence with Prof. Dr. Ing. Karl Schulte and Dipl. Ing. Matthias Mecklenburg from the Hamburg University of Technology (TUHH). Unfortunately because of time constraints, they could not validate the steps of the roadmap in time. Nonetheless they are available for any further information concerning the development of this material.

Aerographite has properties that are very valuable for space applications. Low atomic weight elements such as carbon (atomic weight 12) are suitable for shielding purposes since they represent a relative high number of atoms per unit area. This higher atomic density increases the ability of a material to absorb ionizing radiation. This effect can be enhanced by bonding the Aerographite with hydrogen atoms (atomic weight 1), which have an even lower atomic weight and hence more atoms per unit area to reduce ionizing radiation further (see Figure 5-1). An added benefit is that low atomic weight elements create reduced amounts of secondary radiation (Loomis & Arnold, 2005) (Fan et.al, 1996). Currently the amount of hydrogen that can be stored on graphite remains limited to around 7 wt% (Schlapbach & Züttel, 2001), but this requires a special process. Improvements in this area can also benefit the space sector by improving radiation protection. Aerographite can however also be used in combination with a currently common radiation shielding material, polyethylene. By bonding the two materials, the shielding effect might be increased.

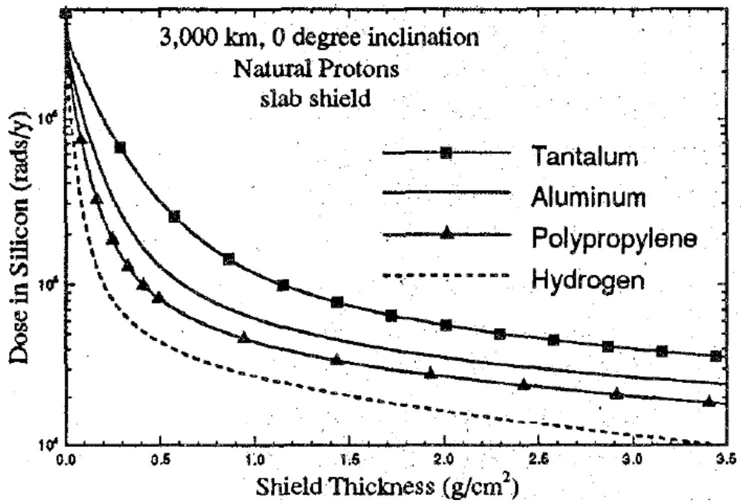


Figure 5-2 Graph representing possible increase in radiation shielding by using hydrogen. (Fan et.al, 1996)

It should be noted that research is still progressing, through mapping the properties of different variants of Aerographite in different conditions. Therefore the area of possible (space)applications might increase further. The strengths and weaknesses of Aerographite shielding as compared to conventional aluminum shielding are illustrated in the performance mix in Figure 5-3.

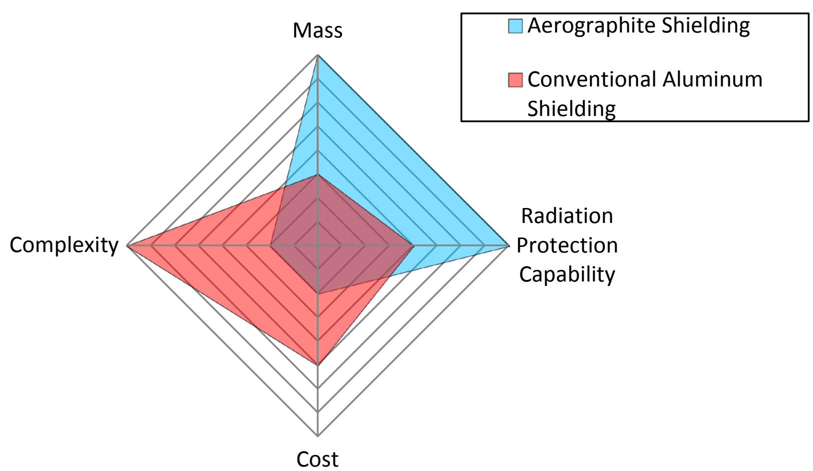


Figure 5-3: Performance mix of Aerographite filters and conventional carbon filters.

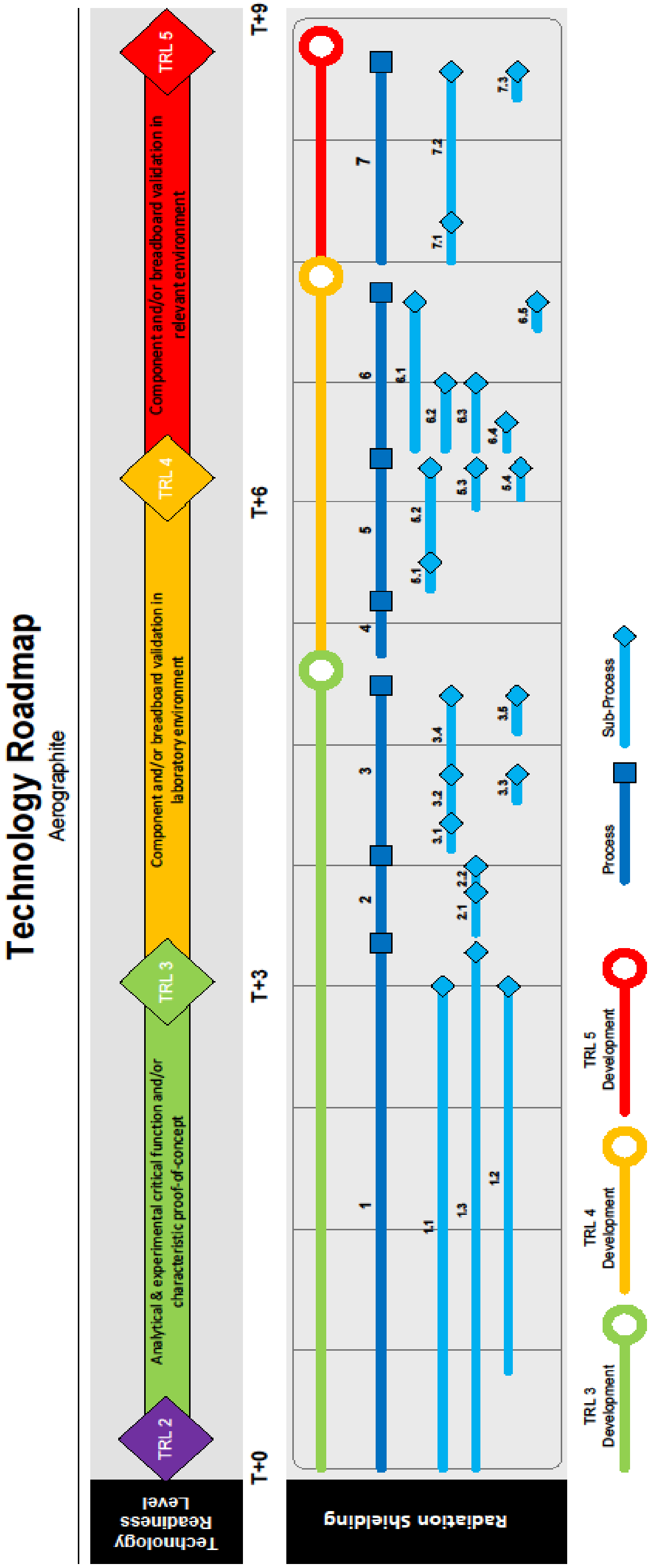
5.1 Selected Research Group

Table 4-1 displays the selected research group for Aerographite. The research group is at the University of Hamburg-Harburg (Division for Polymer Composites). The research group shall only be listed here for future contacts. There hasn't been compliance by this research group for this roadmap yet. Future work will need to be invested to team up with this research group.

Table 5-1: Selected research group for Aerographite applications (no compliance has yet been reached with this research group)

Institute TUHH POLYMER COMPOSITES	The Institute of Polymers and Composites' (IPC) main research activities are in the fields of advanced fiber reinforced polymer composites, such as CFRP, GFRP and Nano composites based on both carbon nanotubes (CNT) and various ceramic nanofillers. Structure/property relationships are investigated by means of processing, determination of morphology, mechanical and physical properties and modeling.
Experience	IPC's goal is to develop a deep insight into the behavior of polymers and fibre enforced composites over dimensions, beginning at the morphology and nano level towards to the dimensions of coupons and smaller structural components. Recent research involves: • Nanocomposites with a polymeric matrix • Investigations on the electrical conductivity of nanocomposites – percolation, sensing, dielectrical properties • Fatigue properties and degradation of CFRP and GFRP. Effect of Defects • Processing and characterization of fiber reinforced composites with a CNT modified matrix • Investigation and development of NDT methods for the detection of damage • Multiaxial structural testing
Contact Persons	Matthias Mecklenburg completed his studies of mechanical engineering with major studies in materials science at the TUHH closed with a diploma thesis on „the influence of alternating electrical fields on the fracture resistance of a ferroelectrical lead-zirconate-titanate ceramic under combined electromechanical loads". Within the scope of the fabrication and characterization of polymer-nano-composites (PNCs) he is dealing with CVD synthesis of aligned carbon nanotubes, whose densification - / matrix embedding processing and characterization. Prof. Schulte has been head of the IPC since 1992. Graduating as a mechanical engineer from Ruhr University Bochum, he followed with a period as scientific collaborator at DLR Cologne from 1975 until 1991. He attained hiss doctoral degree in 1979 on the research on crack propagation in aluminum alloys.
Contact Information	Prof. Dr.-Ing. Karl Schulte Technische Universität Hamburg-Harburg Institute of Polymers and Composites M-11 Denickestr. 15 D-21073 Hamburg Tel.: +49 40 42878 3138 Email: schulte@tuhh.de Internet: http://cgi.tu-harburg.de/

5.2 Detailed Roadmap Steps (Aerographite)



Step	Description
Legend - Aerographite	
1	**Fundamental Research**
1.1	Research
1.2	Experimentation
1.3	Database Creation
2	**Modeling & Simulation**
2.1	Radiation model
2.2	Simulation
3	**System Design**
3.1	Define Expected/Potential Mission Parameters
3.2	Preliminary System Design
3.3	Model Adjustment & Simulation
3.4	Detailed System Design
3.5	Model Expansion & Simulation
4	**Aerographite Production**
5	**Basic Testing**
5.1	Preparation of Preliminary Performance Testing Facilities
5.2	Preliminary Performance Testing
5.3	Preparation of Intensive Testing Facilities
5.4	Model Adjustment & Simulation
6	**Intensive Testing**
6.1	Radiation Tests
6.2	Impact Tests
6.3	Thermal Tests
6.4	Corrosion Tests
6.5	Model and Design Update
7	**Mission Cycle Testing**
7.1	Test Preparation
7.2	Mission Cycle Tests
7.3	Model and Design Update
7.4	Mission Cycle Tests
7.5	Model and Design Update

Figure 5-4: DST roadmap for Aerographite

The following process steps and their sub process steps were mainly worked out by the project team. The selected research group has to confirm and iterate the different steps.

1. Fundamental Research [~13 months]

During this process a general research study is conducted concerning Aerographite. Since the material was only recently discovered, more research needs to be performed on the subject before the material can be used. In addition to that, a significant amount of experiments need to be conducted before the overall quality of the material is on par with existing applications. There are significant gains to be made if more avenues are explored regarding the structure of the material as well as its fabrication methods. The research performed during this process includes a literature study as well as consultations with experts. A research study is necessary in order to identify the pitfalls of the technology in more detail so they can be avoided. At the end of this process, a database is created containing all relevant information on the Aerographite process. The information contained in this database then serves as a basis for the subsequent development of the material. The duration of this process is significantly longer than the duration of the other technology developments due to the fact that Aerographite has a low maturity level.

1.1. Research [~12 months]

During this sub-process, research is conducted aimed at conclusively determining the future potential of Aerographite. Part of the research performed here should focus on finding ways to effectively store hydrogen in the Aerographite structure, particularly under the influence of radiation, as this would increase Aerographite's radiation protection capabilities further. The research performed involves performing a literature study as well as consulting experts in the field of Aerographite.

1.2. Experimentation [~10 months]

During this sub-process, experiments are conducted with new designs and configurations in order to conclusively determine the theoretical capabilities of Aerographite beyond the initial findings of sub-process 1.1.

1.3. Database Creation [~1 month]

In this sub-process a database is created that contains all relevant information on Aerographite. The information contained in the database is gathered during sub-processes 1.1 and 1.2. The main goal of this database is to serve as a source of information for designers and to aid them in creating the most suitable type of Aerographite for space applications.

2. Modeling & Simulation [~2 months]

Due to a general lack of knowledge regarding the interaction of radiation with Aerographite, more information needs to be obtained regarding the behavior of Aerographite when subjected to radiation before a system design can be generated. At this stage of the development process, the easiest way (and coincidentally the most cost-effective way) to obtain this information is by building

a model and running simulations. Therefore, in this sub-process, a radiation model needs to be built that is able to simulate the effects of a radiation on an Aerographite structure as accurately as possible. For now, the only available pieces of information that can be used to build the radiation model are the known properties of Aerographite (as determined in process 1) and the known characteristics of the space radiation environment.
Based on the results of the simulations performed using the model created in this process, the design of the system is generated in the next process. Furthermore, the model needs to be adaptive such that it can be expanded at a later stage of the development process to incorporate newly obtained information gathered during the design and testing phases. Therefore, the model is evolving as the development of the system progresses.

2.1. Radiation model [~1 month]

During this sub-process, the radiation model is created. This includes modeling radiation in space as well as modeling the interaction with Aerographite. The applied Aerographite structure should also be reflected accurately in the model.

2.2. Simulation [~1 month]

In this sub-process, the behavior of a generic radiation protection system is tested in a virtual environment. The information gathered during this sub-process is subsequently used to create the system design.

3. System Design [~3 months]

During this process the system is designed based on the performed study and the results of the simulations performed during the previous process. In this process the preliminary and detailed design stages are combined into one large design process.

3.1. Define Expected/Potential Mission Parameters [~1 month]

The mission parameters define largely the necessary functionality of the system (what the system needs to do). When it comes to radiation protection, the requirements are significantly different for a manned mission than for an unmanned mission. Also, spacecraft that venture beyond the protection envelope of the Earth's electromagnetic field require additional protection. Therefore, knowing the mission parameters and thereby the mission requirements before coming up with a system design is paramount.

3.2. Preliminary System Design [~1 month]

Here the system architecture is generated that is capable of fulfilling the mission requirements that have been determined in sub-process 3.1.

3.3. Model Adjustment & Simulation [~1 month]

During this sub-process the models (built in the previous process) need to be adjusted so that they incorporate the specifics of the system, which are determined during the preliminary design phase.

This sub-process also involves using the updated models to perform new simulations and subsequently improve the system design.

3.4. Detailed System Design [~2 months]

In this sub-process the actual detailed design of the system is generated. This design incorporates all information gathered in previous processes (i.e. research, preliminary design and the simulations).

3.5. Model Expansion & Simulation [~1 month]

During this sub-process, the models are expanded by incorporating the information obtained during the detailed system design phase. Additionally, new simulations are performed that are used to improve the design further. These latest simulations should also serve as a definitive theoretical proof of concept.

4. Aerographite Production [~2 months]

During this process, several prototype Aerographite radiation protection systems are fabricated based on the design generated in the previous process. This process also involves the selection of suitable production facilities and, if none are available, the design and construction of these facilities. During this process the produced Aerographite is also tested. This involves property testing and the scanning for deficiencies in the produced material.

5. Basic Testing [~3 months]

This is where the practical proof of concept occurs. If there are unforeseen problems, iterations have to be performed (back to the drawing board).

5.1. Preparation of Preliminary Performance Testing Facilities [~1 month]

During this sub-process the preliminary performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered

5.2. Preliminary Performance Testing [~2 months]

The most important question that needs to be answered during this sub-process is whether the performance of the system is as expected (or at least reasonably close). Questions will need to be asked such as: Are there discrepancies that have to be dealt with? Is the model used to come up with the detailed design accurate enough? During this sub-process the functionality of the system is tested by means of general performance tests. These tests are different from the tests that are performed during the next process in that they are not yet dedicated to this specific design. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the system can move on to the intensive testing phase (see next process). For this development path, the preliminary tests should focus on the thermal behavior of the system and, if at all possible at this stage, on the radiation behavior of the system.

5.3. Preparation of Intensive Testing Facilities [~1 month]

During this sub-process the intensive performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

5.4. Model Adjustment & Simulation [~1 month]

Adjust the models (built in process 2 and updated in process 3) so that they better simulate the behavior of the actual system. This is done by incorporating the observed behavior of the selected Aerographite components and the system as a whole during the preliminary performance tests. During this sub-process, new simulations are performed as well.

6. Intensive Testing [~3 months]

To get a basic feel of the behavior of the system as well as the individual components under different (loading) conditions, various tests have to be conducted. These tests also serve for the purpose of exploring the limits of the system. The tests are therefore by nature destructive.

6.1. Radiation Tests [~3 months]

During these tests, the actual capability of the Aerographite protection system to protect against radiation is determined. This involves exposing the Aerographite to different levels of ionizing radiation.

6.2. Impact Tests [~2 months]

Although it is likely that the Aerographite radiation shield is protected by a dedicated MMOD protection system, impact tests still need to be performed. This is done to determine the effects of damage on Aerographite's capability to protect against radiation. The tests involve subjecting the Aerographite system to a large amount of HVIs. The influence of impact parameters such as particle size, impact velocity and impact direction need to be determined conclusively. During this sub-process, the results of the impact tests are analyzed extensively.

6.3. Thermal Tests [~2 months]

Even though Aerographite should be stable at elevated temperatures, the thermal effects on the system as a whole need to be determined during this sub-process (Also included extreme cold temperatures). This is done to make sure the system can cope with the thermal space environment.

6.4. Corrosion Tests [~1 month]

Is the corrosion resistance of the system sufficient? Such tests are necessary because materials that are corrosion resistant on Earth are not necessarily so in space (atomic oxygen). The effects of prolonged exposure of the system, particularly the Aerographite itself, to the space environment need to be established during these tests.

6.5. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

7. Mission Cycle Testing [~5 months]

In a mission cycle test, the system is subjected to the loads that are encountered in a full mission cycle. This means that the system is to be subjected to all loads that are encountered from launch until end-of-mission in chronological sequence in a controlled environment. This includes exposing the system to a near-vacuum environment. All this can be done on the ground providing there are adequate testing facilities available. This test also provides an indication as to the reliability of the system.

7.1. Test Preparation [~1 month]

During this sub-process the mission cycle test is prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

7.2. Mission Cycle Tests [~4 months]

During this sub-process the mission cycle tests are performed. The main goal of these tests is to determine the performance of the system over the course of a full mission as well as to determine its reliability. A large part of this sub-process comprises the analysis of the obtained test results.

7.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

Annex A
Phases of the Technology Roadmapping Process

In this annex, the three phases of the technology roadmapping process along with their accompanying steps are described in detail.

Phase I: Preliminary Activity

The first phase of the technology roadmapping process contains the preliminary work that is required to create a roadmap. It is in this phase that the decision makers need to decide on what the scope of the roadmap will be and for what reason. Furthermore, the decision makers need to decide on how the TRM will help them make investment decisions. The sufficient allocation of resources to the roadmapping process as well as the willingness to use the roadmap in strategic planning largely depend on the acceptance and support (buy-in) of the decision makers. The successful completion of the first phase of the technology roadmapping process requires several steps to be taken. These steps are described in Table A-1.

Table A-1: Steps of phase I of the technology roadmapping process [RD 2].

Step	Description
1. Satisfy essential conditions	For a technology roadmapping effort to succeed, a number of conditions must be satisfied. This step involves checking to ensure that those conditions are already met or that someone is taking the necessary actions to meet them. These required conditions are similar, but not identical, for corporate- and industry-level technology roadmapping: • There must be a perceived need for a technology roadmap and collaborative development, although a much broader group must perceive this need for an industry roadmap. • The technology roadmapping effort needs input and participation from several different groups, which bring different perspectives and planning horizons to the process. • The corporate technology roadmapping process needs participation from various parts of the organization (e.g., marketing, manufacturing, R&D, planning, etc.) as well as from key customers and suppliers. • The industry technology roadmapping process needs participation from members of the industry, its customers and suppliers, as well as the government and universities. The focus should be on areas of common need and adversarial conditions must be avoided. • The technology roadmapping process should be needs-driven rather than solution-driven. There must be a clear specification of the boundaries of the effort. In other words, it needs to be known what is and what is not within the scope of the technology roadmap. Furthermore, it needs to be identified how the roadmap will be used.
2. Provide leadership and sponsorship	Because of the time and effort involved in roadmapping, there must be committed leadership and sponsorship. Furthermore, this leadership and sponsorship must come from the group that is going to do the actual implementation and benefit from it. For a corporate-level technology roadmap, this means that the line organization must drive the roadmapping process and use the roadmap to make resource allocation decisions. For an industry level technology roadmap, this means that industry must lead the effort, although

Step	Description
	its customers and suppliers, along with government and universities, should also be participants in developing, validating, and implementing the technology roadmap.
3. Define the scope and boundaries for the technology roadmap	This step ensures that the context for the roadmap has been specified. It ensures that a vision exists (for either the industry or corporation) and that a roadmap can support that vision. It identifies why the technology roadmap is needed and how it will be used. Finally, it clearly specifies the scope and boundaries of the roadmap. A roadmap starts with a set of needs. The intended use of the roadmap determines the planning horizon and the level of detail. The time horizon for roadmaps varies, but for industry roadmaps it is typically at least 10 to 15 years, although there are intermediate points every three to five years. Corporate roadmaps may have a shorter time horizon. This step is important for roadmapping at both the corporate and industry level. However, it is more difficult, complex and time-consuming at the industry level for two reasons: • First, there are many levels of needs, which must be decomposed, and different levels of product, subsystems, and/or components that can be roadmapped. The level selected must have a commonality for the various participants. • Second, since many companies do not know how to effectively collaborate, this step (and the previous two) involves a major learning effort. This means that this phase of industry roadmapping can easily take at least six months. The involvement of an industry umbrella organization, such as a consortium or a trade association, can improve the speed and efficiency of the process and can often provide some of the support resources.

Phase II: Development of the Technology Roadmap

In the second phase, the actual roadmap is created. The steps needed to successfully complete this phase are similar for both the corporate and industrial level. In this phase it is imperative that working groups or teams are employed to develop the content of the roadmap. In order to complete the second phase of the technology roadmapping process, several steps need to be taken. These steps are described in Table A-2.

Table A-2: Steps of phase II of the technology roadmapping process [RD 2]

Step	Description
1. Identify the "product" that will be the focus of the roadmap	The critical step in roadmapping is to get the participants to identify and agree on common product needs (e.g., for an energy-efficient vehicle) that must be satisfied. This agreement is important to get their buy-in and acceptance of the roadmapping process. Depending on the complexity of the product, there may be many components and levels on which the roadmap may focus. Selecting the appropriate focus is critical. If there is major uncertainty about the product needs, the use of scenario-based planning can help. For example, for an energy-efficient vehicle there could be a scenario based on a major oil find or a breakthrough in a renewable energy technology that would drastically lower the price of gas or of another fuel. Another scenario could be based on another oil shock that would drastically reduce the supply and drive up the cost. Each scenario must be reasonable, internally consistent, and comparable with the other scenarios in that it affects one or more of the needs postulated for the roadmap. The scenario analysis could include

Step	Description
	extreme cases, but they should not overemphasize them or let them be the driving factor for the roadmap. The important point is that the scenarios are not ends in themselves. They are only a means for addressing uncertainty in the environment and thereby improve the quality of the roadmap. The scenarios are used to better identify the needs, services or products. In many cases, there will be common needs that apply across all of the scenarios, although the demand may be different for different scenarios. In other cases, a need may be critical for a particular scenario that has too high a probability of occurrence to be ignored. Some of the work on this type of need could be considered insurance. Over time, as the degree of uncertainty about needs changes, the emphasis on technologies addressing this need could be increased or decreased. This is one of the reasons for periodic reviews and updates of the roadmap and its implementation plan.
2. Identify the critical system requirements and their targets	The critical system requirements provide the overall framework for the roadmap and are the high-level dimensions to which the technologies relate. Once the participants have decided what needs to be roadmapped, which is not a trivial process, they must identify the critical system requirements. Examples of critical system requirements for an energy-efficient vehicle include the fuel consumption, reliability, safety, and cost. For example, the target for the fuel consumption of a particular vehicle could be 20 km/L by 2015 and 30 km/L by 2025.
3. Specify the major technology areas	The major technology areas are areas that can be explored such that the critical system requirements for the product can be satisfied. When it comes to the fuel consumption requirement of a vehicle (30 km/L by 2025), there are several technology areas that can be explored in order to satisfy the requirement. Examples of these technology areas include materials, engine controls, sensors, and modeling and simulation.
4. Specify the technology drivers and their targets	At this point, the critical system requirements are transformed into technology-oriented drivers for the specific technology areas. These technology drivers are the critical variables that will determine which technology alternatives are selected. For the materials technology area, examples of technology drivers could include vehicle weight and acceptable engine temperature, whereas a technology driver for the engine controls technology area could be the cycle time for the computer controlling the engine. Technology drivers are dependent on the technology areas being considered, but in any case they relate to how the technology addresses the critical system requirements. At this point, technology driver targets are also set based on the critical system requirement targets. The technology driver targets specify how well a viable technology alternative must be able to perform by a certain date. For example, to get 30 km/L by 2025 (a system requirement), engine control technology may need to be able to deal with x number of variables and adjust engine parameters every y milliseconds, which in turn requires a processor cycle time of z (i.e., technology driver targets).
5. Identify technology alternatives and their time lines	Once the technology drivers and their targets are specified, the technology alternatives that can satisfy those targets must be identified. A difficult target may require breakthroughs in several technologies or a technology may impact multiple targets. For each of the identified technology alternatives, the roadmap must also estimate a time line for how it will mature with respect to the technology driver targets. When multiple technologies are being pursued in parallel, decision points need to be identified for when a technology will be

Step	Description
	considered the winner or when it will be dropped from further consideration.
6. Recommend the technology alternatives that should be pursued	This step selects the subset of technology alternatives to be pursued. These technology alternatives vary in terms of cost, schedule and/or performance. One path may get you there faster, another path may be cheaper, while yet another path may result in a 20 percent performance improvement over the target. Considering the trade-offs, a faster path may not matter if the technology is not on the critical path for the end product/service. However, if it is on the critical path, then a faster path can result in faster time to market, which would be an important competitive advantage. In some cases, a 20 percent improvement over the minimum performance target may be worth the extra time or cost, whereas in other cases doubling the performance may not significantly affect the value of the end product, especially when other product aspects are more dominant. Therefore, the choice of a technology alternative largely depends on the circumstances of the product/service to be roadmapped. To further complicate the problem, it could be the case that a certain technology satisfies one or two technology driver targets, but cannot satisfy later targets. On the other hand, another technology may not satisfy the immediate targets but can meet the subsequent targets. The latter is called a disruptive technology (DT). For clarification, a DT is a technology that cannot satisfy current needs and therefore it is often ignored in favor of the current technology. However, its potential performance and rate of improvement (if it is developed) is much greater than the current technology. Therefore, if the development of a DT is facilitated it will eventually replace the current dominant technology. Without the broader perspective provided by a technology roadmap (or other tools), a potentially disruptive technology is often underfunded (when it comes to development) or even completely ignored. In some cases, there may be analytical and modeling tools to help determine which technology alternative to pursue and when to shift to a different technology (i.e., jump to a new technology curve with a disruptive technology). In other cases, the tradeoffs and decisions are determined by the best judgment of the experts. In either case, the road-mapping process has consolidated the best information and developed a consensus from many experts. Furthermore, the roadmapping process (at either the corporate or the industry level) has begun a collaborative effort that, when carried into the implementation, will result in more effective and efficient use of limited technology investment resources.
7. Create the technology roadmap report	By this point you have developed your roadmap(s). It becomes one of the documents within the roadmap report. This report should also include: • The identification and description of each technology area and its current status. • Critical factors (show-stoppers) which if not met will cause the roadmap to fail. • Areas not addressed in the roadmap. • Technical recommendations. • Implementation recommendations. The report may also include additional information, such as information on competencies that cut across multiple technologies as well as political/economic issues that impact the entire R&D establishment.

Phase III: Follow-up Activity

As mentioned earlier, the third phase involves the actual use of the roadmap. It is in this phase that the (draft) roadmap created in phase II is critiqued, validated and eventually accepted by those that are involved with its implementation. Also, due to evolving needs and technologies, the roadmap needs to be periodically reviewed and updated: roadmapping is an iterative process. The exact procedure to be followed in phase III is described in Table A-3.

Table A-3: Steps of phase III of the technology roadmapping process [RD 2].

Step	Description
1. Critique and validate the technology roadmap	In Phase II, a relatively small group or groups of experts and technologists developed a draft technology roadmap or roadmaps if multiple technology areas are involved. This work must be exposed to a much larger group for validation and buy-in for two reasons: • First, the draft needs to be reviewed, critiqued, and validated. If the recommended technology alternatives are developed, will the targets be met? Are the technology alternatives reasonable? Are any important technologies missed? Is the roadmap clear and understandable to people who were not involved in the drafting process? • Second, there must be buy-in from the broader corporate or industry group that will be involved in implementing the plan. With an industry roadmap, a large, highly structured workshop is often used to provide this feedback. Implicit in this step is the possible revision of the roadmap.
2. Develop an implementation plan	At this point, there is enough information to make better technology selection and investment decisions. Based on the recommended technology alternatives, a plan is then developed. At the corporate level, the implementation plan may be one or more project plans, which would be developed based on the selected technology alternatives. At the industry level, the same type of project plan may be developed by the participants, but there is also a need for explicit coordination, which is often done through an industry association. In other cases, there may not be an industry plan — only corporate project plans by the participants.
3. Review and update	Technology roadmaps and plans should be routinely reviewed and updated. A formal iterative process occurs during this review and update. With the initial roadmap, uncertainty increases with the time frame. Over time, as certain technologies are explored and better understood, some of this uncertainty is reduced, although other areas of uncertainty may develop. Also if scenarios were used up front to address uncertainty about the needs, there may be refinement, or even elimination, of some of the scenarios, which could affect the roadmap or its implementation plan. The review and update cycle allows both the roadmap and the implementation plan to be adjusted for these changes. The review cycle may be based on a company's normal planning cycle or based more appropriately on the rate at which the technology is changing.

Annex B: Roadmap Examples of the Space Sector

In this annex several examples of technology roadmaps are presented that could serve as a foundation for the roadmaps for potential DSTs built in Chapter 3. The first examples to be presented here are the NASA Space Technology Area Roadmaps, developed for review by the National Research Council (NRC). These roadmaps were made in an effort to foster the development of advanced technologies and concepts that address NASA's needs [RD 17]. Of the fourteen roadmaps that NASA made, several are shown in this section.

Roadmap Example 1

The first roadmap as shown in Figure B-1 is a multilayered roadmap centered on the development of launch propulsion systems over the timespan of 2010-2035. It details key missions and milestones in the first layer, planned launch vehicle flights in the second layer and expected development milestones of several technologies in the remaining layers.

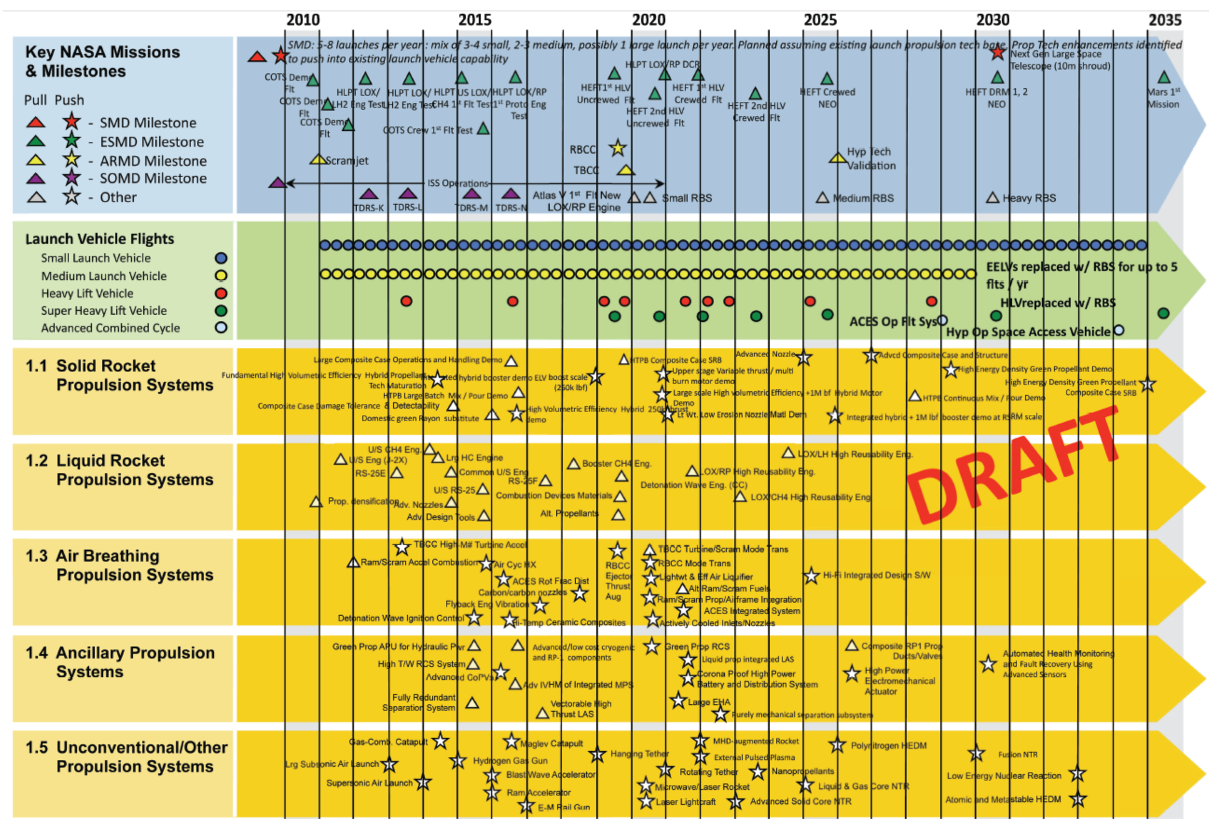


Figure B-1: NASA DRAFT launch propulsion systems roadmap [RD 18].

Since it can be very difficult to display all relevant information effectively in one roadmap, it is not uncommon that additional roadmaps are built to supplement the main roadmap. For example, due to the scope of the launch propulsion systems domain, NASA built five supplementary roadmaps detailing the development path of each individual type of launch propulsion system. One of those supplementary roadmaps, detailing the development path of unconventional/other launch propulsion systems is displayed in Figure B-2. This roadmap applies a multilayered bar format. By comparing the roadmaps in Figure B-1 and Figure B-2, it can be concluded that the supplementary roadmap corresponds nicely with the bottom layer of the main roadmap shown.

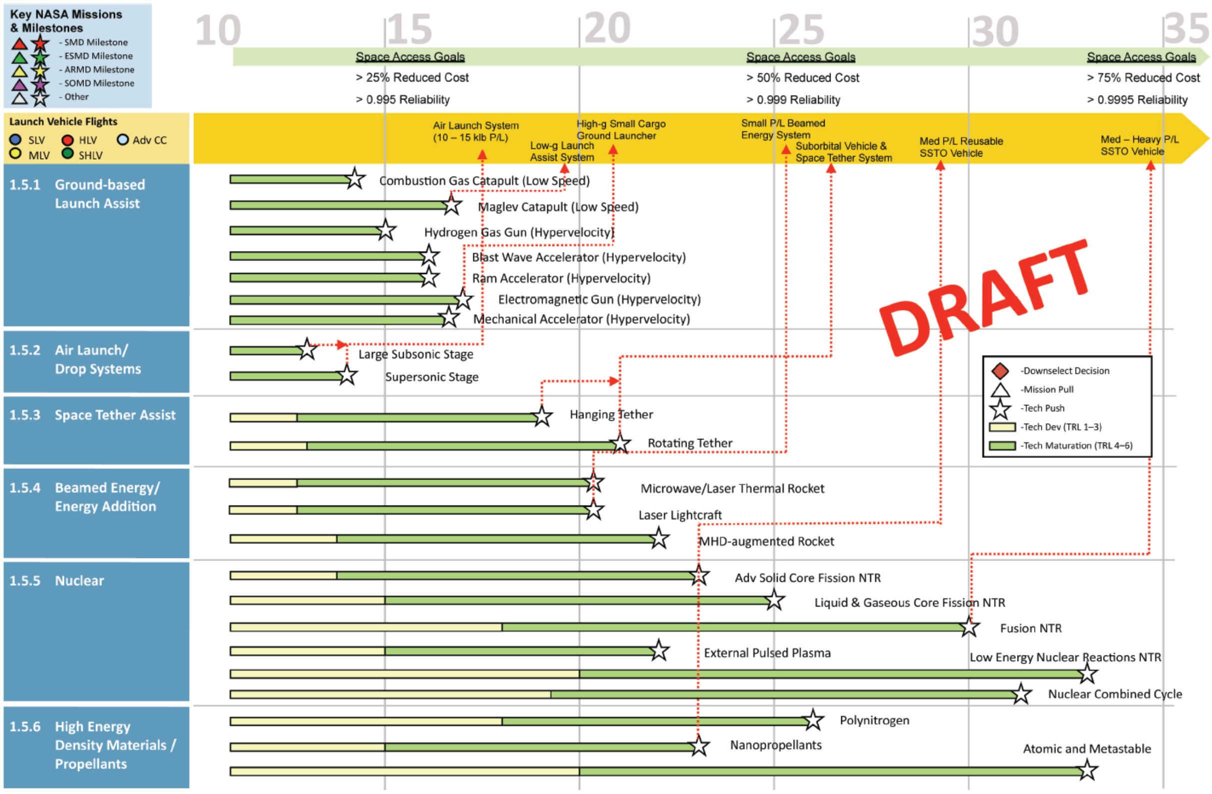


Figure B-2: NASA DRAFT unconventional/other launch propulsion systems roadmap [RD 18].

Roadmap Example 2

The next example roadmap, shown in Figure B-3, is a multilayered roadmap as well. This roadmap, which is also part of the NASA Space Technology Area Roadmaps, focuses on the development of space power and energy storage technologies. The general structure of the roadmap is similar to the one shown in Figure B-1, with the exception that in this case there are linkages between the different layers. The technology development milestones are linked to capability milestones and, in turn, some of the capability milestones are linked to envisioned missions. Using this approach provides an overview of the potential use and application of newly developed technologies.

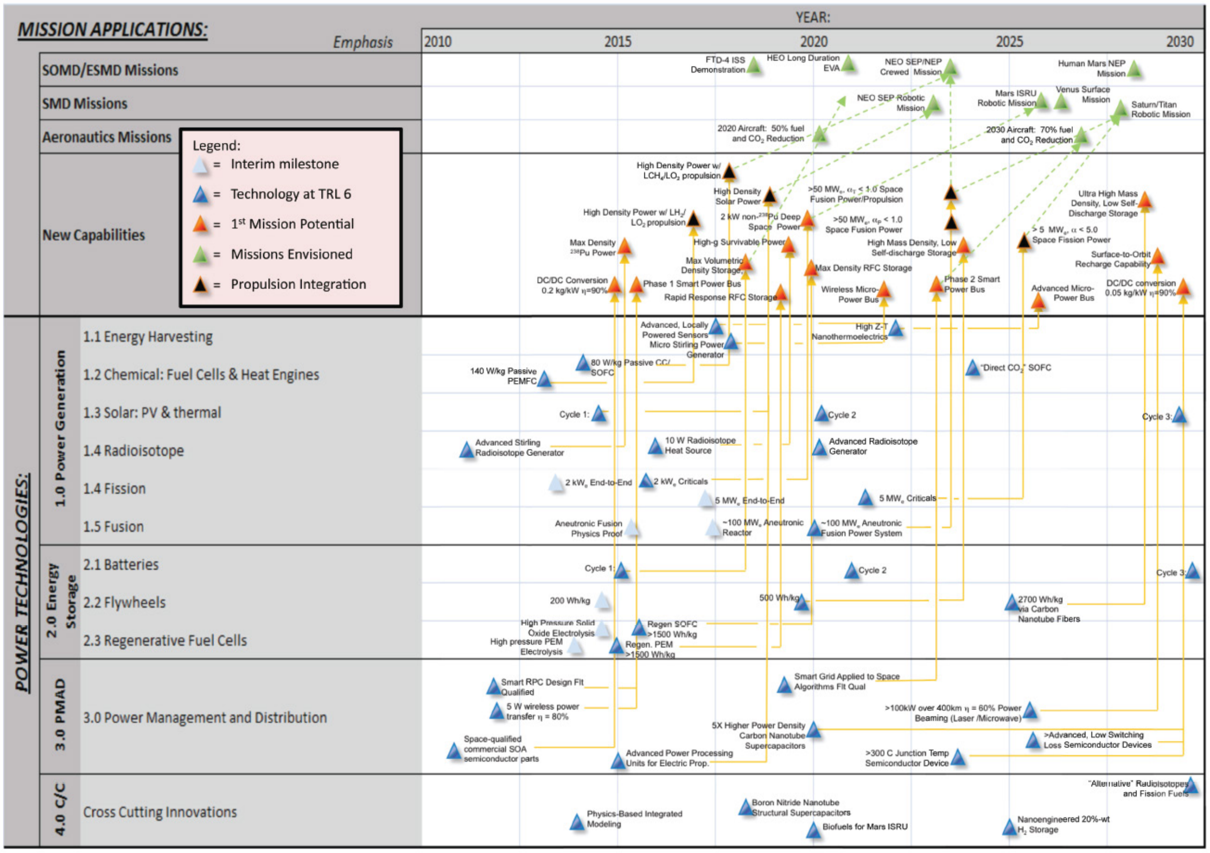


Figure B-3: NASA DRAFT space power and energy storage roadmap [RD 19].

Roadmap Example 3

In Figure B-4 the next technical roadmap example can be found. This roadmap, made by the European Space Agency (ESA), is a single layered bar roadmap detailing the development of electric propulsion technologies. The roadmap shown in Figure B-4 is actually only a part of a considerably larger total roadmap for electric propulsion technologies, however, for the purpose of illustration this part suffices. Due to the fact that all layers represent technology development paths (i.e. all layers contain the same type of information), this roadmap is categorized as a single layered roadmap and not as a multil0ayered roadmap. Every layer in this roadmap is therefore called a sub-layer, with each sub-layer specifying the development path of a technology or process within the electric propulsion domain. The timespan of this ESA roadmap is significantly shorter than it is for the other roadmaps presented in this chapter. Furthermore, the colors used for the bars represent the funding allotted to each development path, with red indicating that no funding has been allotted, green indicating that the development path is fully funded and yellow indicating that only partial funding has been allotted so far. Using such a color scheme can therefore effectively link a TRM with a funding scheme, providing decision makers a clearer picture of where funding is necessary the most and where it is not.

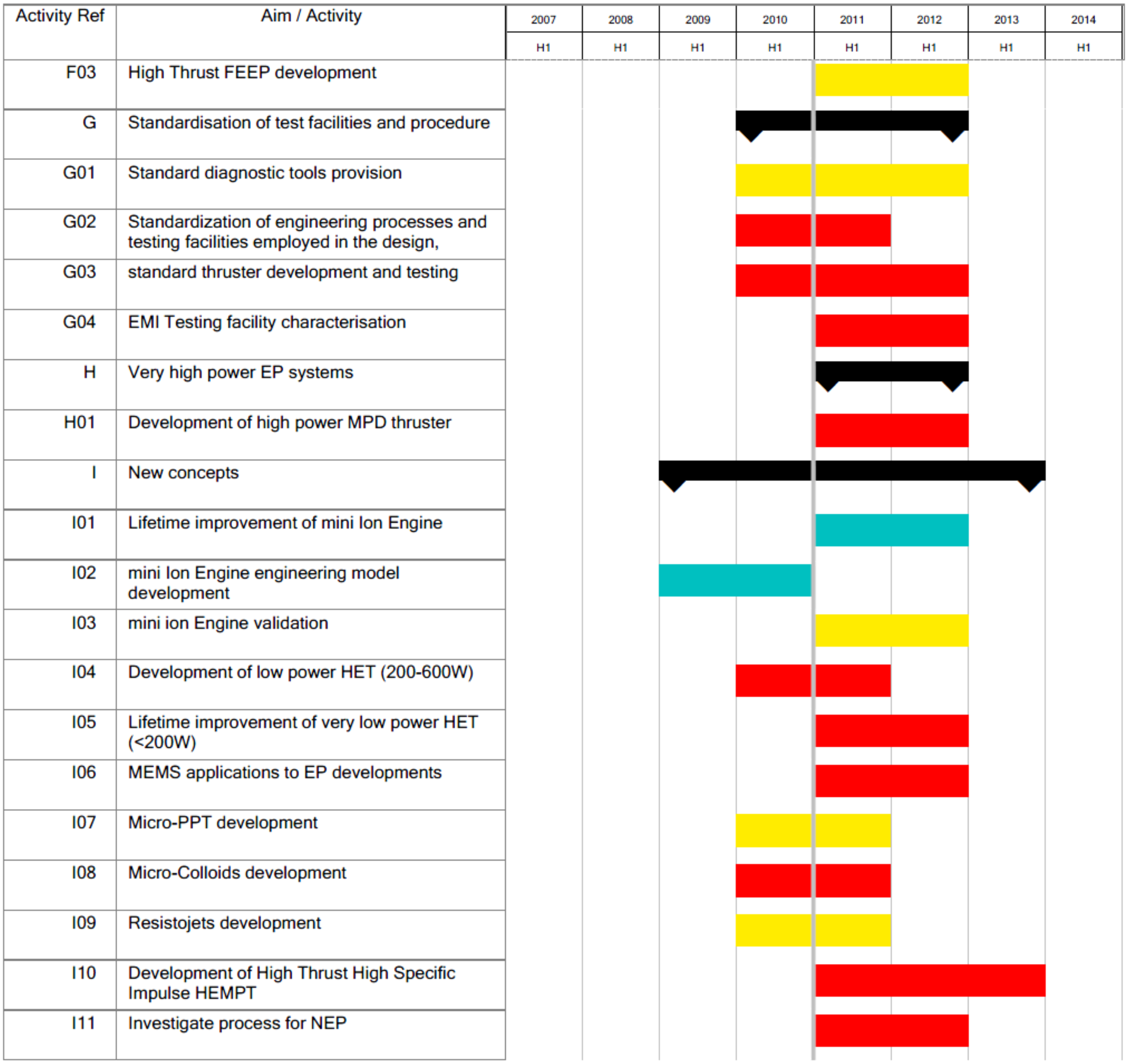
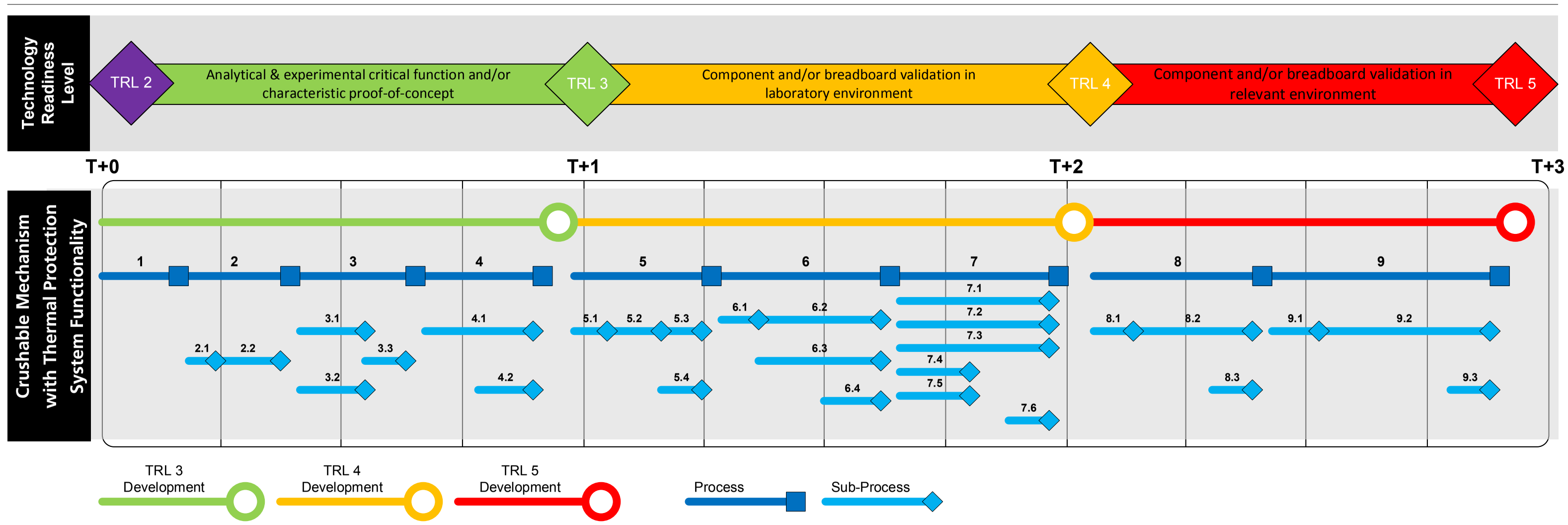


Figure B-4: Part of an ESA roadmap for electric propulsion technologies [RD 20].

Annex C: Crushable Mechanism with Thermal Protection System Functionality

Technology Roadmap

Metal Foam



Legend - Crushable Mechanism with Thermal Protection System Functionality

Step	Description	Step	Description	Step	Description
1	**Fundamental Research**	5.2	Production Process Design	7.4	Impact Tests
2	Preliminary System Design	5.3	Metal Foam Production	7.5	Corrosion Tests
2.1	Define Expected/Potential Mission Parameters	5.4	Metal Foam Attribute Testing	7.6	Model and Design Update
2.2	Preliminary Design	**6**	**Basic Testing**	**8**	**Mission Cycle Testing**
3	**Modeling & Simulation**	6.1	Preparation of Preliminary Performance Testing Facilities	8.1	Test Preparation
3.1	Mechanical Modeling	6.2	Preliminary Performance Testing	8.2	Mission Cycle Tests
3.2	Thermal Modeling	6.3	Preparation of Intensive Testing Facilities	8.3	Model and Design Update
3.3	Simulation	6.4	Model Adjustment & Simulation	**9**	**Landing Testing**
4	**Detailed System Design**	**7**	**Intensive Testing**	9.1	Test Preparation
4.1	Detailed Design	7.1	Stress Tests	9.2	Landing Test
4.2	Model Expansion & Simulation	7.2	Thermal Tests	9.3	Model and Design Update
5	**Metal Foam Production**	7.3	Fatigue Tests	9.4	Model and Design Update
5.1	Metal Foam Selection				

Detailed Roadmap Description

1. Fundamental Research [~2 months]

During this process a general research study is conducted concerning metal foam. This research includes a literature study as well as consultations with experts. A research study is necessary in order to identify the pitfalls of the technology in more detail so they can be avoided. For example, there exists a wide range of techniques that can be applied to create metal foam, however, most of these techniques have an empirical basis instead of a scientific one. In the past, trial and error has been applied extensively to come up with the most suitable foaming process. This was caused by the fact that the underlying mechanisms of metal foaming are not well understood. This is something that needs to be remedied if the technology is to be developed further. At the end of this process, a database is created containing all relevant information on the metal foaming process. The information contained in this database then serves as a basis for the subsequent development of the DST.

2. Preliminary System Design [~3 months]

For this particular development path, a preliminary design needs to be finished before any modeling can be done. This is because the characteristics of the system as a whole have a large influence on its overall functionality. Therefore, during this process the preliminary system design is generated so that in the next process a representative system can be modeled.

2.1. Define Expected/Potential Mission Parameters [~1 month]

The mission parameters define largely the necessary functionality of the system (what the system needs to do). Therefore, knowing the mission parameters and thereby the mission requirements before coming up with a system design is paramount.

2.2. Preliminary Design [~2 months]

Here the system architecture is generated that is capable of fulfilling the mission requirements that have been determined in sub-process 2.1.

3. Modeling & Simulation [~3 months]

The preliminary system design and the known properties of metal foam are used to model the behavior of the system. The models are used later to come up with a more detailed system design. When it comes to metal foam used as a crushable material attached to the TPS, the most important aspects to be modeled are the mechanical behavior and the thermal behavior of the system. Furthermore, these models need to be adaptive in the sense that they can be expanded at a later stage of the development process to incorporate newly obtained information gathered in subsequent design and testing phases. Therefore, in a sense, the models are evolving as the development of the system progresses.

3.1. Mechanical Modeling [~2 months]

The mechanical behavior of the system is modeled. The model should be capable of incorporating all mechanical stresses that are expected to act on the system throughout the mission.

3.2. Thermal Modeling [~2 months]

All thermal loads that are expected to act on the system throughout the mission need to be incorporated in the model.

3.3. Simulation [~1 month]

After both models have been constructed, the first mechanical and thermal simulations are performed. This is done to determine the basic behavior of the system. Based on the results of the performed simulations, the design is adjusted and improved during the next process.

4. Detailed System Design [~3 months]

Based on the models and the performed study, a more detailed system design is generated. Based on this design the initial prototype components will be produced in the next process

4.1. Detailed Design [~3 months]

In this sub-process the actual detailed design of the system is generated. This design incorporates all information gathered in previous processes (i.e. Literature study, preliminary design and the simulations)

4.2. Model Expansion & Simulation [~2 months]

During this sub-process, the models are expanded by incorporating the information obtained during the detailed system design phase. Additionally, new simulations are performed that are used to improve the design further. These latest simulations should also serve as a definitive theoretical proof of concept.

5. Metal Foam Production [~3 months]

The manufacturing process for metal foams is crucial in achieving the required properties of the material. Several types of metal foams exist as well as different ways to produce them. Therefore, selecting the most appropriate metal foam and production process is a time consuming, yet imperative process. During this process, the type of metal foam is selected and its production process is determined. Subsequently, the metal foam is produced and undergoes preliminary testing.

5.1. Metal Foam Selection [~1 month]

Selecting the most appropriate metal foam for the area of application is arguably the most important decision that needs to be made in the entire development process. This mainly involves a trade-off analysis between the different combinations of production techniques and materials.

5.2. Production Process Design [~1 month]

Due to the fact that there are many methods available to create metal foams (all of which have their own advantages and disadvantages), selecting the right production process is paramount. This sub-process is closely linked to sub-process 5.1 due to the fact that the most suitable production techniques for the purpose of creating metal foams follow from the properties of the selected metal foam. This sub-process also includes initial production steps such as the construction (if no existing facilities are available or suitable) and preparation of the production facilities.

5.3. Metal Foam Production [~1 month]

This step involves the actual production of the material. The production of metal foams is a very sensitive process and it will most likely involve some trial and error to find the optimal process parameters.

5.4. Metal Foam Attribute Testing [~1 month]

As the selected metal foam is being produced, it needs to be tested as well. This is done to determine whether the produced metal foam actually performs according to specifications. Some of the tests that need to be performed here are basic material tests (e.g. tensile and compression tests) to determine the attributes of the produced material. If these tests indicate that the material is unable to perform according to specifications, a different metal foam and/or production technique should be selected (back to sub-process 5.1). Other, non-destructive tests (e.g. ultrasonic and radiographic tests) need to be performed as well to identify any deficiencies (internal flaws) within the produced material. If any such deficiencies within the material are found, the production process needs to be repeated, adjusted or, if necessary, altered.

6. Basic Testing [~4 months]

This is where the practical proof of concept occurs. Does the system perform the way it was intended to? If there are unforeseen problems, iterations have to be performed (back to the drawing board).

6.1. Preparation of Preliminary Performance Testing Facilities [~1 month]

During this sub-process the preliminary performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

6.2. Preliminary Performance Testing [~3 months]

Is the performance of the system as expected (or at least reasonably close)? Are there discrepancies that have to be dealt with? Is the model used to come up with the detailed design accurate enough? During this sub-process the functionality of the system is tested by means of general performance tests. These tests are different from the tests that are performed during the next process in that they are not yet dedicated to this specific design. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the system can move on to the intensive testing phase (see next process). For this development path, the preliminary tests should focus on the mechanical and the thermal behavior of the system.

6.3. Preparation of Intensive Testing Facilities [~3 months]

During this sub-process the intensive performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

6.4. Model Adjustment & Simulation [~2 months]

Adjust the models (built in process 3 and updated in process 4) so that they better simulate the behavior of the actual system. This is done by incorporating the observed behavior of the selected metal foam (as tested during sub-process 5.4) as well as the behavior of the various components and the system as a whole during the preliminary performance tests. During this sub-process, new simulations are performed as well.

7. Intensive Testing [~4 months]

To get a basic feel of the behavior of the system as well as the individual components under different (loading) conditions, various tests have to be conducted. These tests also serve for the purpose of exploring the limits of the system. The tests are therefore by nature destructive.

7.1. Stress Tests [~4 months]

During these tests, the question whether the forces generated during the mission (primarily forces due to acceleration and deceleration) compromise the functionality of the system is answered.

7.2. Thermal Tests [~4 months]

How do sharp temperature gradients affect the system? The day-night cycle is very important in this. Do the temperature gradients diminish the functionality of the system over time? How does the system cope with the temperatures generated during reentry? Although the heat shield is supposed to protect the rest of the systems from the bulk of the thermal energy generated during reentry, there is always some heat that is transferred to the rest of the spacecraft including the metal foam structure. The creep behavior should be investigated during these tests as well (possibly in conjunction with the fatigue tests) since prolonged heating of the material might have an effect on the system's functionality.

7.3. Fatigue Tests [~4 months]

Launch loads, electrical vibrations and acoustic vibrations need to be taken into account. Due to the fact that the system needs to function a certain amount of time after mission start, it has to be verified that every periodic load that has acted on the system before this has not compromised the system. When it comes to the TPS it is often the case that the integrity of the system needs to be maintained for the entire mission duration, which could amount to years.

7.4. Impact Tests [~2 months]

Do HVIs (micrometeoroids) compromise the integrity of the system? During these tests the system is impacted by particles of varying size at varying velocities in order to determine the system's capability to cope with such impacts.

7.5. Corrosion Tests [~2 months]

Is the corrosion resistance of the system sufficient? Such tests are necessary because materials that are corrosion resistant on Earth are not necessarily so in space (atomic oxygen). The effects of prolonged exposure of the system to the space environment need to be established during these tests.

7.6. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

8. Mission Cycle Testing [~4 months]

In a mission cycle test, the system is subjected to the loads that are encountered in a full mission cycle. This means that the system is to be subjected to all loads that are encountered from launch until touchdown in chronological sequence in a controlled environment. This includes exposing the system to a near-vacuum environment. All this can be done on the ground providing there are adequate testing facilities available. This test also provides an indication as to the reliability of the system.

8.1. Test Preparation [~1 month]

During this sub-process the mission cycle test is prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

8.2. Mission Cycle Tests [~3 months]

During this sub-process the mission cycle tests are performed. The main goal of these tests is to determine the performance of the system over the course of a full mission as well as to determine its reliability. A large part of this sub-process comprises the analysis of the obtained test results.

8.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

9. Landing Testing [~6 months]

The full system is to be released in the atmosphere to perform the final phase of the potential mission or, in other words, the touchdown phase. Likely this will involve simply dropping the system from a test rig providing this simulates the touchdown phase with enough accuracy. These landing test are therefore the first tests that are not performed in a laboratory setting.

9.1. Test Preparation [~1 month]

This sub-process involves the preparation for the landing tests. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

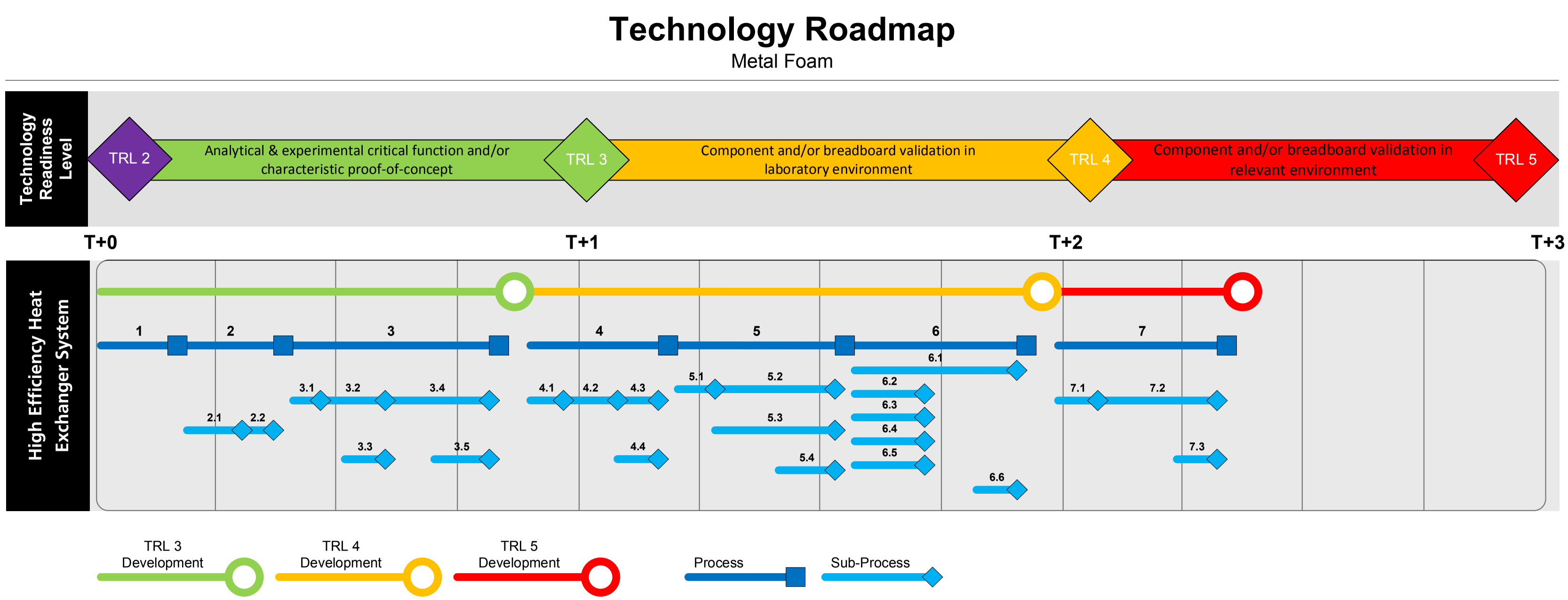
9.2. Landing Test[~5 months]

This sub-process involves the actual landing tests. The main goal of these tests is to get a sense of the behavior of the system under mission conditions. These tests involve the full system and not just the individual components.

9.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

Annex D: High Efficiency Heat Exchanger System



Legend - High Efficiency Heat Exchanger System					
Step	Description	Step	Description	Step	Description
1	**Fundamental Research**	4.1	Metal Foam Selection	6.1	Thermal Tests
2	Modeling & Simulation	4.2	Production Process Design	6.2	Stress Tests
2.1	Thermal Modeling	4.3	Metal Foam Production	6.3	Fatigue Tests
2.2	Simulation	4.4	Metal Foam Attribute Testing	6.4	Impact Tests
3	**System Design**	**5**	**Basic Testing**	6.5	Corrosion Tests
3.1	Define Expected/Potential Mission Parameters	5.1	Preparation of Preliminary Performance Testing Facilities	6.6	Model and Design Update
3.2	Preliminary System Design	5.2	Preliminary Performance Testing	**7**	**Mission Cycle Testing**
3.3	Model Adjustment & Simulation	5.3	Preparation of Intensive Testing Facilities	7.1	Test Preparation
3.4	Detailed System Design	5.4	Model Adjustment & Simulation	7.2	Mission Cycle Tests
3.5	Model Expansion & Simulation	**6**	**Intensive Testing**	7.3	Model and Design Update
4	**Metal Foam Production**				

Detailed Roadmap Description

1. Fundamental Research [~2 months]

During this process a general research study is conducted concerning metal foam. This research includes a literature study as well as consultations with experts. A research study is necessary in order to identify the pitfalls of the technology in more detail so they can be avoided. For example, there exists a wide range of techniques that can be applied to create metal foam, however, most of these techniques have an empirical basis instead of a scientific one. In the past, trial and error has been applied extensively to come up with the most suitable foaming process. This was caused by the fact that the underlying mechanisms of metal foaming are not well understood. This is something that needs to be remedied if the technology is to be developed further. At the end of this process, a database is created containing all relevant information on the metal foaming process. The information contained in this database then serves as a basis for the subsequent development of the DST.

2. Modeling & Simulation [~3 months]

Before a system design can be generated, more information regarding the performance of metal foam heat pipes is required. In order to obtain this information, a thermal model is constructed in this process. The thermal model will initially be based on other thermal models that have been created for other missions. Based on information that needs to be obtained at a later stage of this development path, the model will be expanded such that it is specifically suited to simulate the thermal behavior of a metal foam heat exchanger system. After the initial model has been created, simulations are performed to determine the expected performance of a metal foam heat exchanger system. Furthermore, the model needs to be adaptive in the sense that it can be expanded at a later stage of the development process to incorporate newly obtained information gathered in subsequent design and testing phases. Therefore, in a sense, the model is evolving as the development of the system progresses.

2.1. Thermal Modeling [~2 months]

During this sub-process a model is created with which the thermal behavior of a metal foam heat exchanger system can be simulated. This model will include the known properties of metal foam and all relevant thermodynamic processes. The fluid that is present in the heat pipes needs to be modeled as well. Particularly the interaction between the fluid and irregular metal foam structure is important here.

2.2. Simulation [~1 month]

After the model has been constructed, the first thermal simulations are performed. This is done to determine the basic thermal behavior of a generic metal foam heat exchanger in a virtual environment. The information gathered during this sub-process is subsequently used to create the system design.

3. System Design [~5 months]

During this process the system is designed based on the performed study and the results of the simulations performed during the previous process. In this process the preliminary and detailed design stages are combined into one large design process.

3.1. Define Expected/Potential Mission Parameters [~1 month]

The mission parameters define largely the necessary functionality of the system (what the system needs to do). Therefore, knowing the mission parameters and thereby the mission requirements before coming up with a system design is paramount.

3.2. Preliminary System Design [~2 months]

Here the system architecture is generated that is capable of fulfilling the mission requirements that have been determined in sub-process 3.1.

3.3. Model Adjustment & Simulation [~1 month]

During this sub-process the models (built in the previous process) need to be adjusted so that they incorporate the specifics of the system, which are determined during the preliminary design phase. This sub-process also involves using the updated models to perform new simulations and subsequently improve the system design.

3.4. Detailed System Design [~2 months]

In this sub-process the actual detailed design of the system is generated. This design incorporates all information gathered in previous processes (i.e. Literature study, preliminary design and the simulations)

3.5. Model Expansion & Simulation [~2 months]

During this sub-process, the models are expanded by incorporating the information obtained during the detailed system design phase. Additionally, new simulations are performed that are used to improve the design further. These latest simulations should also serve as a definitive theoretical proof of concept.

4. Metal Foam Production [~3 months]

The manufacturing process for metal foams is crucial in achieving the required properties of the material. Several types of metal foams exist as well as different ways to produce them. Therefore, selecting the most appropriate metal foam and production process is a time consuming, yet imperative process. During this process, the type of metal foam is selected and its production process is determined. Subsequently, the metal foam is produced and undergoes preliminary testing.

4.1. Metal Foam Selection [~1 month]

Selecting the most appropriate metal foam for the area of application is arguably the most important decision that needs to be made in the entire development process. This mainly involves a trade-off analysis between the different combinations of production techniques and materials.

4.2. Production Process Design [~1 month]

Due to the fact that there are many methods available to create metal foams (all of which have their own advantages and disadvantages), selecting the right production process is paramount. This sub-process is closely linked to sub-process 4.1 due to the fact that the most suitable production techniques for the purpose of creating metal foams follow from the properties of the selected metal foam. This sub-process also includes initial production steps such as the construction (if no existing facilities are available or suitable) and preparation of the production facilities. However, this would significantly increase the duration and cost of the entire development process.

4.3. Metal Foam Production [~1 month]

This step involves the actual production of the material. The production of metal foams is a very sensitive process and it will most likely involve some trial and error to get everything right.

4.4. Metal Foam Attribute Testing [~1 month]

As the selected metal foam is being produced, it needs to be tested as well. This is done to determine whether the produced metal foam actually performs according to specifications. Some of the tests that need to be performed here are basic material tests (e.g. tensile and compression tests) to determine the attributes of the produced material. If these tests indicate that the material is unable to perform according to specifications, a different metal foam and/or production technique should be selected (back to sub-process 4.1). Other, non-destructive tests (e.g. ultrasonic and radiographic tests) need to be performed as well to identify any deficiencies (internal flaws) within the produced material. If any such deficiencies within the material are found, the production process needs to be repeated, adjusted or, if necessary, altered.

5. Basic Testing [~4 months]

This is where the practical proof of concept occurs. Does the system perform the way it was intended to? If there are unforeseen problems, iterations have to be performed (back to the drawing board).

5.1. Preparation of Preliminary Performance Testing Facilities [~1 month]

During this sub-process the preliminary performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

5.2. Preliminary Performance Testing [~3 months]

Is the performance of the system as expected (or at least reasonably close)? Are there discrepancies that have to be dealt with? Is the model used to come up with the detailed design accurate enough? During this sub-process the functionality of the system is tested by means of general performance tests. These tests are different from the tests that are performed during the next process in that they are not yet dedicated to this specific design. Instead, these tests serve a practical proof of concept and therefore, if the design passes these tests, the development of the system can move on to the intensive testing phase (see next process). As is to be expected for a metal foam heat exchanger system, the preliminary tests should focus on the thermal behavior of the system.

5.3. Preparation of Intensive Testing Facilities [~3 months]

During this sub-process the intensive performance testing facilities are prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

5.4. Model Adjustment & Simulation [~1 month]

Adjust the models (built in process 2 and updated in process 3) so that they better simulate the behavior of the actual system. This is done by incorporating the observed behavior of the selected metal foam (as tested during sub-process 5.4) as well as the behavior of the various components and the system as a whole during the preliminary performance tests. During this sub-process, new simulations are performed as well.

6. Intensive Testing [~5 months]

To get a basic feel of the behavior of the system as well as the individual components under different (loading) conditions, various tests have to be conducted. These tests also serve for the purpose of exploring the limits of the system. The tests are therefore by nature destructive.

6.1. Thermal Tests [~5 months]

During this sub-process, the thermal aspects of the system are put to the test. The question whether the system is capable of facilitating the necessary heat transfer is answered. Furthermore, the thermal characteristics of the system are analyzed extensively and the factors that are most important if successful operation to be achieved are identified.

6.2. Stress Tests [~2 months]

During these tests, the question whether the forces generated during the mission (primarily forces due to acceleration and deceleration) compromise the functionality of the system is answered.

6.3. Fatigue Tests [~2 months]

Launch loads, electrical vibrations and acoustic vibrations need to be taken into account. Due to the fact that the system needs to function a certain amount of time after mission start, it has to be verified that every periodic load that has acted on the system before this has not compromised the system. When it comes to the TPS it is often the case that the integrity of the system needs to be maintained for the entire mission duration, which could amount to years.

6.4. Impact Tests [~2 months]

Do HVIs (micrometeoroids) compromise the integrity of the system? During these tests the system is impacted by particles of varying size at varying velocities in order to determine the system's capability to cope with such impacts.

6.5. Corrosion Tests [~2 months]

Is the corrosion resistance of the system sufficient? Such tests are necessary because materials that are corrosion resistant on Earth are not necessarily so in space (atomic oxygen). The effects of prolonged exposure of the system to the space environment need to be established during these tests.

6.6. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.

7. Mission Cycle Testing [~4 months]

In a mission cycle test, the system is subjected to the loads that are encountered in a full mission cycle. This means that the system is to be subjected to all loads that are encountered from launch until touchdown in chronological sequence in a controlled environment. This includes exposing the system to a near-vacuum environment. All this can be done on the ground providing there are adequate testing facilities available. This test also provides an indication as to the reliability of the system.

7.1. Test Preparation [~1 month]

During this sub-process the mission cycle test is prepared. If it is the case that there are no suitable in-house testing facilities available, the use of facilities of other partners and/or external facilities should be considered. If there are still no suitable existing test facilities available, they should be designed and constructed, however, this would significantly increase the duration and cost of the entire development process (not taken into account in the roadmap).

7.2. Mission Cycle Tests [~3 months]

During this sub-process the mission cycle tests are performed. The main goal of these tests is to determine the performance of the system over the course of a full mission as well as to determine its reliability.

7.3. Model and Design Update [~1 month]

During this sub-process, the models are updated by incorporating the results of the tests performed during this process. Afterwards, new simulations are run. Subsequently, the design is updated by incorporating the latest test results and the results of the performed simulations.