NASA'S CRYOGENIC FLUID MANAGEMENT TECHNOLOGY DEVELOPMENT ROADMAPS

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ABSTRACT

The maturation of Cryogenic Fluid Management (CFM) Technologies is essential for achieving NASA's future long duration missions. Propulsion systems utilizing cryogens are necessary to achieve NASA's exploration missions to the moon, Mars, and beyond. Current State Of the Art (SOA) space flight CFM technologies enable cryogenic propellants to be stored for several hours prior to their use. However, some envisioned mission architectures require that cryogens to be stored for two years or longer.

The fundamental roles of CFM technologies are long term storage of cryogens, propellant tank pressure control and propellant delivery. In the presence of heat, the cryogens will "boil-off" over time resulting in excessive pressure buildup, off-nominal propellant conditions for engine consumption, and propellant loss. To achieve long term storage and tank pressure control, the CFM elements will intercept and/or remove any heat from the propulsion system. All functions are required to be performed both with and without the presence of a gravitational field. Which CFM technologies are required is a function of the cryogens used, mission architecture, vehicle design and propellant tank size.

To enable NASA's crewed missions beyond Low Earth Orbit, a total of twenty-five CFM technologies have been identified to support various In-Space Stages and Lander/Ascent Vehicles. A set of CFM Technology Development Roadmaps have been created identifying the current Technology Readiness Level (TRL) of each element, current technology "gaps", and existing technology development efforts. The roadmaps include a methodical approach and schedule to achieve a flight demonstration, hence maturing CFM technologies to TRL 6/7 for infusion into the NASA's exploration elements. Additionally, a survey of the aerospace industry was completed to understand their views on the various technologies and how they would be infused. This does not cover all possible CFM technologies, but rather those that are of interest to NASA specifically.

INTRODUCTION

As NASA began preparation for the development of its most recent architectural mission analysis, assessments were done on the different types of technologies that needed to be developed to enable or even enhance the architectures chosen to implement this campaign. Multiple studies on different transportation elements, such as methane in-space stages[1], lander ascent and descent stages[2-4], and nuclear propulsion stages[5,6], all call for the development of Cryogenic Fluid Management (CFM). These studies make it clear that CFM is an enabling technology suite for exploration, but each element assumed different technologies within the CFM suite for implementation.

Typically, NASA requires that technologies be at TRL 6 prior to the Preliminary Design Review (PDR) of a mission element[7]. As such, identifying what technologies fit into planned architectures is required. Then, these technologies are evaluated for existing Technology Readiness Level (TRL), gravitational sensitivity, and fluid dependency. Based on these results, paths and priorities for maturation can be developed.

Cryogenic Fluid Management technologies are often sub-divided into multiple functional areas. These areas, as shown in Ref 8, often include Thermal Control (sometimes divided between passive and active), Pressure Control and Mixing, Low-Gravity Fluid Behavior and Management, Mass Gauging, and Fluid Transfer. From these functional areas, twenty five technologies were identified to be relevant to the mission elements discussed. Each of the technologies was also given a number (sorted alphabetically) to allow for ease of manipulation in some visual formats. The technologies and associated numerical identifiers are listed in Table 1, the technologies are all defined in Appendix A. These technologies do not cover all possible technologies, merely the ones that NASA has current interest in. Industry does have interest in other technologies for their specific plans.

Table 1: List of Technologies Identified

Technology	*No*	*Technology*	*No*
Advanced External Insulation	1	Propellant Densification	14
Autogenous Pressurization	2	Propellant Tank Chilldown	15
Automated Cryo-Couplers	3	Pump Based Mixing	16
Cryogenic Thermal Coating	4	Soft Vacuum Insulation	17
Helium Pressurization	5	Structural Heat Load Reduction (Active)	18
High Capacity, High Efficiency Cryocoolers 20K	6	Thermodynamic Vent System	19
High Capacity, High Efficiency Cryocoolers 90K	7	Transfer Operations	20
High Vacuum Multilayer Insulation	8	Tube-On-Shield Broad Area Cooling	21
Liquefaction Operations	9	Tube-On-Tank Broad Area Cooling	22
Liquid Acquisition Devices	10	Unsettled Liquid Mass Gauging	23
Low Conductivity Structures (Materials)	11	Valves, Actuators & Components	24
Line Chilldown	12	Vapor Cooling	25
Para to Ortho Cooling	13		

ARCHITECTURES EVALUATED

Multiple architecture elements were evaluated, first from understanding the assumptions were carried by the concept development teams, then from discussion with technical experts who could help identify technologies that should be traded or sensitivities that should be evaluated. NASA is currently evaluating multiple in-space transportation and surface landing/ascent vehicles for various architectures (see Figure 1).

The three in-space propulsion cryogenic stages include a nuclear thermal propulsion stage, a hybrid solar electric propulsion and liquid oxygen/liquid methane stage, and a liquid oxygen/liquid methane stage[1]. The nuclear thermal propulsion concepts is hydrogen fueled and consists of a series of tanks including a core tank and additional inline tanks (see Figure 2)[5,6]. The hybrid stage has both a solar electrical propulsion component as well as a liquid oxygen/liquid methane chemical propulsion component. This concept tries to pair the two propulsion types in the same vehicle, using the SEP system for transfer between gravity wells and the chemical system for leaving and entering gravity wells. The “split” chemical propulsion option is the Methane Cryogenic Propulsion

Stage, a liquid oxygen/liquid methane stage that would transport crew to various destinations (a cargo SEP stage is also a part of this architecture).

Three lander elements were also assessed, both descent and ascent stages of a liquid oxygen/liquid methane human Mars lander as well as a near term medium class (~2000 kg payload) lunar lander. While other lunar landers have been discussed within NASA, they are not yet at the level of maturity for inclusion in this study.

Finally, the mission element for liquefaction of oxygen on the surface of either the moon or Mars was also evaluated. The one difference between the two surfaces is the need for soft vacuum insulation on Mars and not on the moon. At the present, the CFM team has only been requested to investigate oxygen liquefaction, the liquefaction of methane would not be significantly different than oxygen, hydrogen is much more energy intensive.

Figure 3 is an attempt to lay these applications on a single diagram to show the generically common needs across all of the mission elements. This includes technologies that are both required and those that technologists think would enhance the missions. It is quite useful to see how the different elements may need similar technologies and which technologies are useful over a wider breadth of applications.

Table 2 shows what technologies are currently baselined (green flags), possibly enhancing (yellow flags), and gravitationally dependent in these specific architectures (orange background). As these vehicles mature, the yellow flags will either become green flags or be removed based on the results of engineering trades.

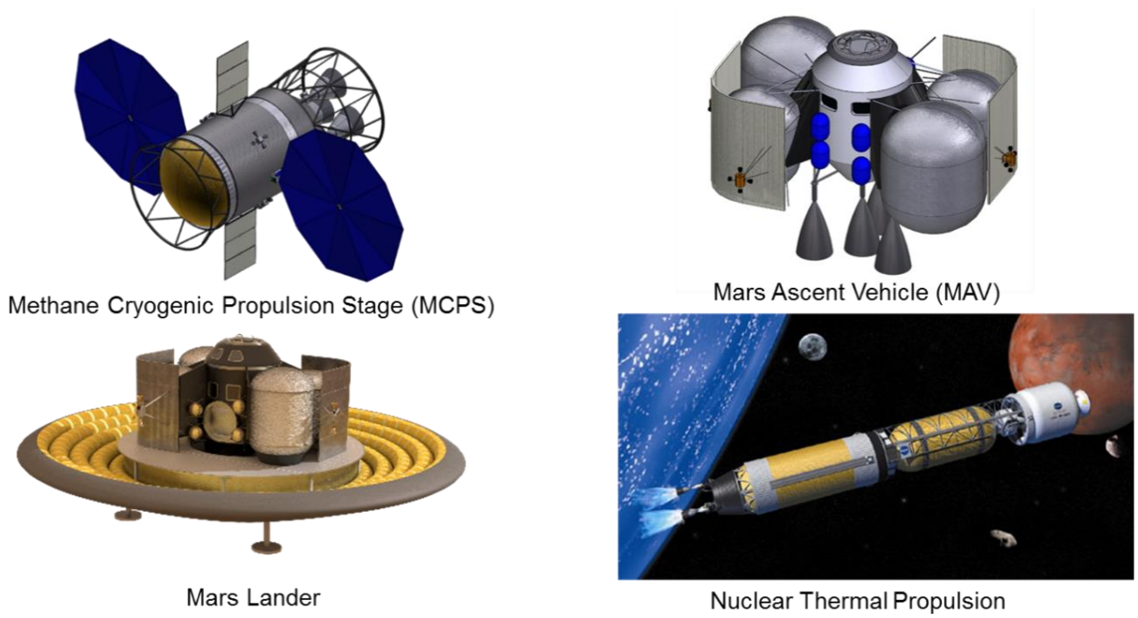


Figure 1: Artist renderings of various cryogenic propulsion elements.

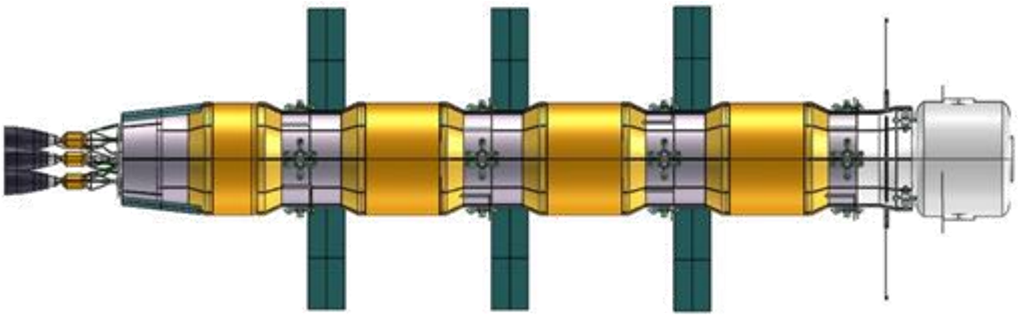


Figure 2: Nuclear Thermal Propulsion concept with from left to right: the core stage, three inline stages, and a Deep Space Habitat.

Table 2: Applicability of selected technologies to mission elements.

Technology	Nuclear (LH2)	In-space Hybrid (LCH4/LO2)	In-space Split/MCPS (LCH4/LO2)	Medium Lunar Lander	Mars Ascent Stage (LCH4/LO2)	Mars Descent Stage (LCH4/LO2)	ISRU based System (production) (LO2)
Advanced External Insulation	Potential						
Autogenous Pressurization	Baseline ■	Baseline ■		Potential ■			
Automated Cryo-Couplers	Baseline				Baseline		Potential
Cryogenic Thermal Coating	Potential		Potential		Potential	Potential	
Helium Pressurization	Potential ■		Baseline ■	Potential ■	Baseline ■	Baseline ■	
High Capacity, High Efficiency Cryocoolers 20K	Baseline						
High Capacity, High Efficiency Cryocoolers 90K	Potential	Baseline	Baseline		Baseline	Baseline	Baseline
High Vacuum Multilayer Insulation	Baseline	Baseline	Baseline	Baseline		Baseline	Potential
Liquefaction Operations							Baseline
Liquid Acquisition Devices	Potential ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	
Low Conductivity Structures (Materials)	Potential	Baseline	Baseline	Baseline	Baseline	Baseline	
Line Chilldown	Potential ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	
Para to Ortho Cooling							
Propellant Densification	Potential						
Propellant Tank Chilldown		Baseline ■	Potential ■				
Pump Based Mixing	Potential ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	Baseline ■	
Soft Vacuum Insulation					Baseline	Baseline	Baseline
Structural Heat Load Reduction (Active)	Potential		Potential				
Thermodynamic Vent System	Potential ■	Potential ■	Potential ■	Baseline ■			
Transfer Operations	Potential ■	Baseline ■	Potential ■				Potential
Tube-On-Shield BAC	Potential						
Tube-On-Tank BAC	Baseline ■	Baseline ■	Baseline ■		Baseline ■	Baseline ■	Baseline
Unsettled Liquid Mass Gauging	Potential ■	Potential ■		Potential			Potential
Valves, Actuators & Components	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Vapor Cooling				Potential			

Colored boxes need to fly to get to TRL 6 ■
Potential for Architecture Enhancement (yellow flag: Potential)
Currently Listed in Architecture Baseline (green flag: Baseline)

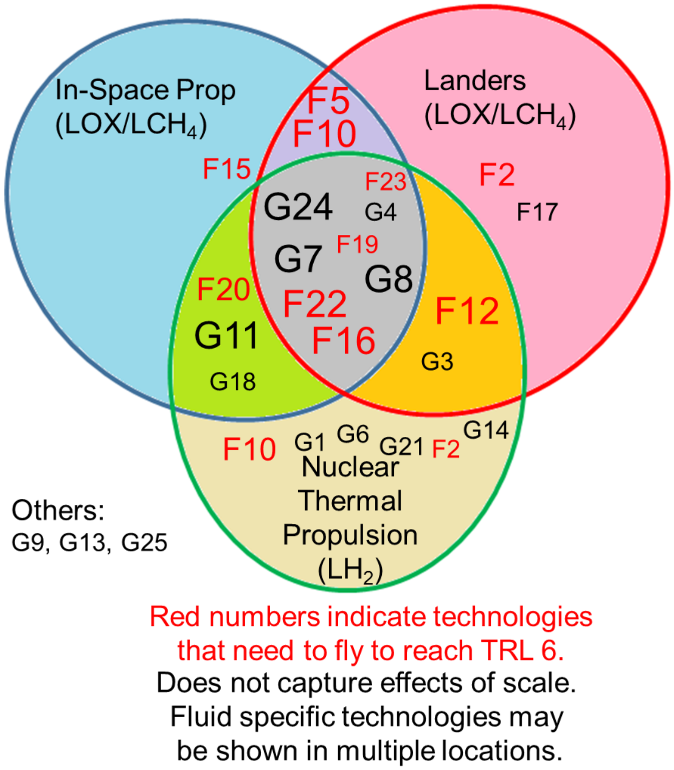


Figure 3: The Venn diagram showing how development needs overlap between multiple elements. F and G imply flight or ground development required.

TECHNOLOGY EVALUATIONS

With the technologies selected for possible inclusion in the mission elements, the team then proceeded to define the path forward on each of the technologies. The evaluation represent a consensus from the team but does not imply unanimity from all of those who supported the development of the roadmap.

TECHNOLOGY STATUS

The twenty five technologies were first evaluated on their current status. This included the current TRL of the technologies, whether or not the technology required microgravity testing as a part of its development to TRL 6, and if the technology was fairly similar across fluid options (oxygen, methane, hydrogen) or had features that had to be tailored to a specific fluid. The results of this is shown in Figure 4. In addition, much detail was gathered as to steps required for the technologies to reach TRL 6, this information is too detailed for a single paper. However, in general, Figure 4 identifies what technologies are imminently ready for a flight demonstration or mission infusion and what technologies need further development.

CFM Elements				
Technologies	**Current TRL**	**Gravity Dependant (Y/N)**	**Path to TRL 6**	**"Cross Cutting" or "Fluid Specific"**
Low Conductivity Structures	6	No	Ground Test	Cross Cutting
High Vacuum Multilayer Insulation	5	No	Ground Test	Cross Cutting
Tube-On-Shield BAC	5	No	Ground Test	Cross Cutting
Valves, Actuators & Components	5	No	Ground Test	Cross Cutting
Vapor Cooling	5	No	Ground Test	Fluid Specific
Helium Pressurization	5	Yes	Flight Demo	Cross Cutting
MPS Line Chilldown	5	Yes	Flight Demo	Cross Cutting
Pump Based Mixing	5	Yes	Flight Demo	Cross Cutting
Thermodynamic Vent System	5	Yes	Flight Demo	Cross Cutting
Tube-On-Tank BAC	5	Yes	Flight Demo	Cross Cutting
Unsettled Liquid Mass Gauging	5	Yes	Flight Demo	Cross Cutting
Liquid Acquisition Devices	5	Yes	Flight Demo	Fluid Specific
Advanced External Insulation	3	No	Ground Test	Can Be Both
Automated Cryo-Couplers	4	No	Ground Test	Cross Cutting
Cryogenic Thermal Coating	3	No	Ground Test	Cross Cutting
High Capacity, High Efficiency Cryocoolers 90K	3	No	Ground Test	Cross Cutting
Soft Vacuum Insulation	3	No	Ground Test	Cross Cutting
Structural Heat Load Reduction	3	No	Ground Test	Cross Cutting
Propellant Tank Chilldown	3	Yes	Flight Demo	Cross Cutting
Transfer Operations	4	Yes	Flight Demo	Cross Cutting
High Capacity, High Efficiency Cryocoolers 20K	3	No	Ground Test	Fluid Specific
Liquefaction Operations (MAV & ISRU)	3	No	Ground Test	Fluid Specific
Para to Ortho Cooling	4	No	Ground Test	Fluid Specific
Propellant Densification	4	No	Ground Test	Fluid Specific
Autogenous Pressurization	4	Yes	Flight Demo	Fluid Specific

Figure 4: Evaluation of Technologies for Development

The technologies were also evaluated for needed tasks to complete to raise the maturity of the technologies such that they are ready for infusion into flight articles. Many technologies require a flight demonstration, but some technologies either require some development prior to flight or can be fully demonstrated via ground testing.

STATUS OF MODELING THE TECHNOLOGIES

For using technologies on a flight system, not only are demonstrations required, but also, the ability to predict their performance across a wide spectrum of conditions. This implies that some sort of modeling capability is needed for each technology, this could be wide ranging from excel calculations to computational fluid dynamics and everything in between. As such the modeling status of each technology was evaluated. In general, the modeling approaches for the technologies fell into four groups, computational fluid dynamics (CFD), fluid nodal models, thermal models, and other models (typically Microsoft excel based models with also some very specific modeling capabilities used for individual technologies). As various model verifications and validations are made with existing test data in methods that are thought to be fundamentally extensible to microgravity, the progress within the technologies is increased until ready for use in the design or evaluation of flight hardware. A good example of recent validations include the Zero-Boil-off Tank experiment on the International Space Station[9] and recent line chilldown nodal modeling results[10,11].

Technology / Model	Fluid/Nodal	CFD	Thermal	Other
Advanced External Insulation			●	●
Autogenous Pressurization	●	●		
Automated Cryo-Couplers				●
Cryogenic Thermal Coating			◑	
Helium Pressurization	●	◑		
High Capacity, High Efficiency 20 K Cryocoolers		●		●
High Capacity, High Efficiency Cryocoolers 90K		●		●
High Vacuum Multilayer Insulation				●
Liquefaction Operations (MAV & ISRU)	◑	◑	●	
Liquid Acquisition Devices		○		○
Low Conductivity Structures			●	
Line Chilldown	●	○		
Para to Ortho Cooling				◑

Technology / Model	Fluid/Nodal	CFD	Thermal	Other
Propellant Densificaton				
Propellant Tank Chilldown	○	◑		
Pump Based Mixing	●	●		●
Soft Vacuum Insulation				●
Structural Heat Load Reduction			●	
Thermodynamic Vent System	●	●		●
Transfer Operations	◑	○		○
Tube-On-Shield BAC	●			
Tube-On-Tank BAC	●	◑		
Unsettled Liquid Mass Gauging				●
Valves, Actuators & Components				●
Vapor Cooling	◑			◑

Microgravity Sensitive (green shading)
● Ready when μg data avialable
◑ Needs Limited Model Development
○ Needs Significant Model Development

Figure 5: Computational Modeling Status of Technologies

INTEGRATION INTO ROADMAP

With the information developed for tasks required to develop technologies and also the technologies required to support the different elements, those can be combined into schedule driven charts like the one shown in Figure 6 for a notional oxygen/methane in-space stage.

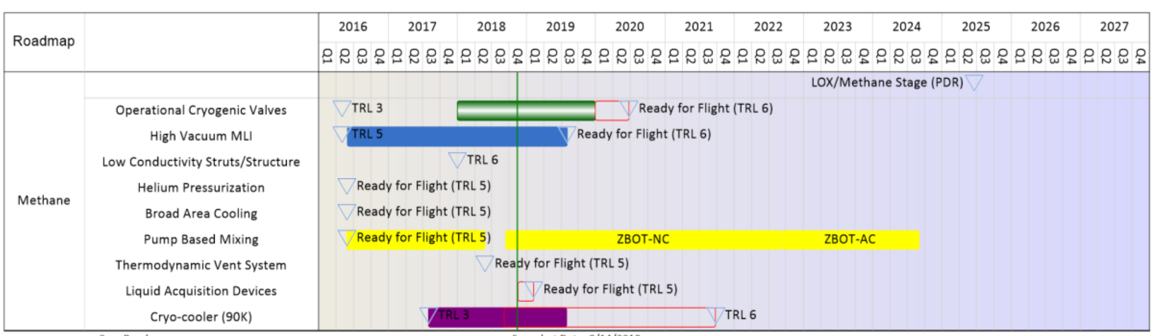
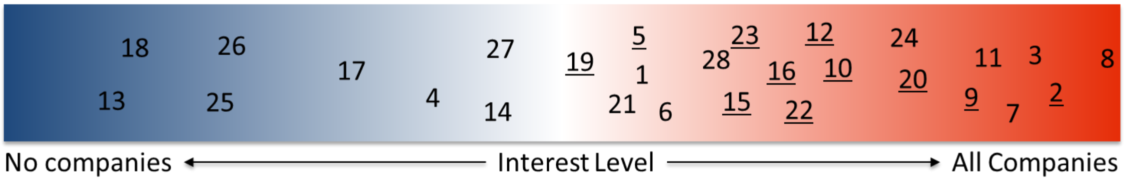


Figure 6: Development schedule for notional oxygen/methane stage. Red boxes are unfunded.

INDUSTRY INPUTS

A team from NASA visited multiple companies who are active in the cryogenics and space flight who have interest in the development of cryogenic fluid management technologies. The interest of those companies was gauged on both NASA's technologies and any technologies that they may be interested in that NASA didn't have in their list. The results are shown in Figure 7, items 26 – 28 indicate items that had multiple companies interested in that NASA did not have initially.



Technologies	Number	Relative Interest
Composite Tanks	28	
Advanced External Insulation	1	
Helium Pressurization	5	
High Capacity, High Efficiency Cryocoolers 20K	6	
Propellant Densification	14	
Thermodynamic Vent System	19	
Tube-On-Shield BAC	21	
Cryogenic Thermal Coating	4	
Sun Shields	27	
Soft Vacuum Insulation	17	
Vapor Cooling	25	
2 Phase Flow Meter	26	
Para to Ortho Cooling	13	
Structural Heat Load Reduction	18	

Technologies	Number	Relative Interest
High Vacuum Multilayer Insulation	8	
Autogenous Pressurization	2	
Automated Cryo-Couplers	3	
High Capacity, High Efficiency Cryocoolers 90K	7	
Liquefaction Operations (MAV & ISRU)	9	
Low Conductivity Structures	11	
Transfer Operations	20	
Valves, Actuators & Components	24	
Liquid Acquisition Devices	10	
MPS Line Chilldown	12	
Propellant Tank Chilldown	15	
Pump Based Mixing	16	
Tube-On-Tank BAC	22	
Unsettled Liquid Mass Gauging	23	

Figure 7: Heat map of industry interest/need for technologies. This includes three technologies that are not in NASA's roadmap that are more widely supported throughout industry.

SUMMARY AND CONCLUSIONS

The roadmap described allows prioritization of technology development work within cryogenic fluid management based on technology needs and desires of specific development elements. It also shows the various commonalities between different architectural elements and also those to be tracked as the elements make implementation decisions. The roadmaps developed can show the path forward towards a flight demonstration as needed to meet specific element milestones.

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APPENDIX A – TECHNOLOGY DEFFINITIONS

Advanced External Insulation: On launch vehicles that have in-line tanks, the only insulation system currently available for the barrel sections is spray-on foam insulation (~100 W/m2). In order to use these vehicles for more than a few hours, a reduction in heat load through the side wall by at least an order of magnitude if not more must be achieved. The same technology *may* be applicable to Mars surface applications. These insulation systems must be able to survive acoustic and thermodynamic loads on the outside of a launch vehicle.

Autogenous Pressurization: Traditional autogenous pressurization on a flight vehicle typically relies on helium gas for pre-pressurization and re-pressurization of the tank, then utilizes the energy from the engine burn to vaporize and pressurize liquid propellant for use as a pressurant gas. However, the dependence on helium pressurization can be eliminated if an alternate energy source exists to increase the energy state of the propellant tank ullage. This energy source could come from a variety of technologies, including, but not limited to, ambient self-pressurization, compressors, or heat exchange with energy-generating systems such as proton-exchange membrane (PEM) fuel cells or internal combustion engines. Autogenous pressurization will also be applicable to depot applications for propellant transfer. In situations where the Bond number is much less than one, it will be uncertain if the injection is into a vapor space or liquid space and this will influence the thermodynamics and fluid dynamics of the tank pressurization sequence.

Automated Cryo-Couplers: For transferring fluids between vehicles, a connection between the vehicles must be made (and subsequently broken). These "quick disconnects" may need to act like valves, but also must be assembleable by robotic means (and possibly by astronauts in suits on planetary surfaces).

Cryogenic Thermal Coatings: The best available thermal control coatings absorb 6% of the Sun's radiant power (about 80 W/m^2) which is too much to achieve cryogenic temperatures in space. Coatings are needed that will absorb less than 0.3% of the Sun's power, while still allowing far infrared emission so that equilibrium temperatures below 90K can be reached.

Helium Pressurization: There is a lot of data which currently exist for pressurizing a propellant tank filled with a settled liquid. In a micro-g environment, Surface Tension dominates over Gravity and the propellant no longer remains in a settled condition. For a given pressurization system configuration, the diffuser may be exposed to the tank ullage when the propellant is settled, but submerged when the propellant is unsettled. The adverse effects on a pressurization systems performance due the pressurant diffuser being submerged can be evaluated on the ground, however to capture the gravitational effects (bubble dynamics) a flight demonstration is needed.

High Capacity, High Efficiency 20 K Cryocooler: Present state of the art is a <1W at 20K Pulse Tube Cryocooler that does not provide distributed cooling. The development of the high capacity 20K cryocooler moves would increase this up to 20 W and perhaps higher. This technology provides a meaningful path to in-space LH2 zero boil-off storage.

High Capacity, High Efficiency 90 K Cryocoolers: Cryocoolers enable propellant conditioning, tank pressure control, and potentially the liquefaction of ISRU generated propellants on the Martian and Lunar surfaces. Industrial cryocoolers are available in various sizes and refrigeration capacities, however they tend to be extremely heavy and require a considerable amount of power to operate. The cryocooler needs to be "flight like" which implies both low Specific Power and low Specific Mass. A "flight like" 90K unit is applicable to the propellant conditioning, pressure control, and liquefaction of Soft Cryogens like liquid oxygen (LOX), liquid methane (LCH_4), and liquefied natural gas (LNG), but is also applicable to Hard Cryogens liquid liquid hydrogen (LH_2) when integrated with a Broad Area Cooling (BAC, tube-on-shield) shield for interception of environmental heat loads.

High Vacuum Insulation: Multilayer Insulation, i.e. reflective based insulation designed to work in a hard vacuum ($< 10^{-4}$ torr).

Liquefaction Operations: NASA needs to identify and develop technologies needed to liquefy ISRU products. These technologies and their operation should meet end user (propulsion) requirements and integrate with ISRU subsystems to minimize integrated system power and thermal. Day/night/seasonal integrated con-ops (including ISRU) should be considered.

Liquid Acquisition Devices: In milli- or micro-g environments, in the absence of settling, Propellant Management Devices (PMDs) are required to extract vapor-free liquid from a propellant tank to either an engine or receiver tank downstream. For vehicles requiring omni-directional, omni-g level propellant acquisition, the problem of extracting vapor-free liquid is exacerbated. A robustly designed PMD is required to minimize residuals and extend mission duration, particularly in unsettled conditions.

Low Conductivity Struts: Current in-space cryogenic propellant tankage is supported by metallic structures with high heat loads suitable to mission timeframes of hours/days. These structure must handle launch loads which further penalizes in-space low-gravity thermal performance. The use of non-metallic materials has the potential to significantly reduce the heat input while still providing structural margins. These structures are typically in the form of struts or skirts. Additionally, integrated active cooling technologies and methods to "disconnect the thermal connection" of the tankage support structure in low-g have the potential to further enhance cryogenic propellant storage times/mission durations.

Chilldown (Feedline or tank): In the absence of electrically powered cold boundaries (cryocooler controlled), some amount of propellant will be used to chill transfer line hardware (lines, valves, tanks, etc.) down to cryogenic temperature. Chilldown may be optimized for time or mass. Chilldown heat transfer coefficients and pressure drops are needed to reduce safety factor, margin, and cost in design and sizing of tanks and liquid acquisition devices. Also, within **propellant tanks** in microgravity the fluid flow properties and method of ensuring the liquid comes in contact with the wall may be driven by different techniques (such as a spray bar or jet cooling).

Para to Ortho Cooling: See Vapor cooling.

Propellant Densification: Reducing the temperature (and saturation pressure) of a liquid below the normal boiling point of the liquid will increase the density and heat absorption capacity of the fluid. This can be used in one of two ways: to decrease the size of the tank (or get more propellant in the same size tank) or to allow the liquid to absorb energy and expand, effectively increasing the duration of storage before venting/depressurization is required.

Propellant Tank Chilldown: See Chilldown.

Pump Based Mixing: If a tank is allowed to self-pressurize, it will do so and also stratify the tank where liquid or vapor is separated by temperature gradients. In order to lower the pressurization rate and also keep the tank temperatures closer to uniform, mixing with a pump can be used to physically mix the fluid.

Soft Vacuum Insulation: Soft Vacuum Insulation is needed for cryogen storage in the Mars surface environment. Design concepts have been developed. Thermal performance is good in some cases but mass penalties are very high. Concepts include elements such as conventional multi-layer insulation (MLI) within a metallic vacuum jacket and layered composite or aerogel insulation.

Structural Heat Reduction: Structural heat loads coming down metallic skirts are on the order of kWs for current upper stages. In addition to insulation on the acreage heat loads, something could be actively done to reduce the structural heat loads coming into the tanks. This could manifest itself in multiple different ways, from thermal breaks in a skirt, separation of multiple skirts, and coatings that preferentially reject heat to deep space while not absorbing solar energy.

Thermodynamic Vent System: Thermodynamic Vent System (TVS) is used to control the tank pressure of cryogenic propellant stored in low-gravity. TVS typically includes a Joule-Thompson (J-T) expansion device, a two-phase heat exchanger, and a mixing pump to destratify and extract thermal energy from the tank without significant propellant losses. The TVS also allows for ensuring that only vapor is vented from the tank.

Transfer Operations: There is a lack of experience in transferring cryogens between tanks in an unsettled/micro-gravity condition. There is also a lack of experience in automated transfer with the goal of conserving propellant.

Broad Area Cooling: For long duration cryogenic storage (hard and soft cryo's) broad area cooling shields coupled with cryocoolers are needed to reject heat from entering the tank. Broad area cooling is an integration method between a cryocooler and a heat source where the main method of heat transfer is driven by a circulating gas that goes through an array of tubing that is hard-mounted to the heat source over a wide distribution of area.

Broad area cooling can operate in two different methods: **Tube-On-Tank** is where the cooling network is directly attached to the tank wall and is nominally at the same temperature that the propellant is being stored. **Tube-on-Shield** is where the cooling network is coupled to a metallic shield that is within the multilayer insulation and is at some intermediary temperature that lowers the heat load onto the tank, decreasing the amount of heat required to be rejected via Tube-On-Tank.

Unsettled Mass Gauging: Current state of the art mass gauges typically need a relatively high g-level to gauge the propellant tanks. The gauges perform well during engine burns, but do not work in low-g or under very low settled g conditions. There is a gap in propellant quantity gauging during periods of micro-g or even low-g settled conditions, which can be long times for long duration missions. Propellant sloshing during landing or initial engine thrust can also compromise settled gauging accuracy.

Valves, Actuators, and Components: Numerous technologies have been targeted to minimize heat leak into the cryogenic fluids to reduce boil-off, but commodity loss also occurs through valves. State of Art Flight/Launch Vehicle valves (3" – 8") at required flow capacity have orders of magnitude higher leakage rates. Other (non-flight) cryogenic valves have acceptable leak rates, but may be unacceptable for adaption due to actuation forces, system heat loads, mass of valve/actuator, etc.

Vapor Cooling: A major cause of boil-off is the heat leak into the tank from support structures, including tank skirts and struts. One method to decrease the heat load and resultant boil-off is to utilize cold vented hydrogen vapor for cooling to reduce skirt heat leak using a vapor-cooling system. The addition of vapor-cooling hardware has shown to reduce the heat leak from structure into propellant tanks by 50% - 80% depending on the tank fill level. The effectiveness of this vapor-cooling could be further improved by as much as 50% through **para-to-ortho (PtO)** conversion of the molecular spin state of the gaseous hydrogen via a catalytic endothermic reaction combined with vapor-cooled structure.