Cryogenic Fluid Management Technology Development for Nuclear Thermal Propulsion

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Cryogenic fluid management technology is critical to the success of future nuclear thermal propulsion powered vehicles and long duration missions. This paper discusses current capabilities in key technologies and their development path. The thermal environment, complicated from the radiation escaping a reactor of a nuclear thermal propulsion system, is examined and analysis presented. The technology development path required for maintaining cryogenic propellants in this environment is reviewed. This paper is intended to encourage and bring attention to the cryogenic fluid management technologies needed to enable nuclear thermal propulsion powered deep space missions.

Nomenclature

SOFI	=	Spray On Foam Insulation
MLI	=	Multi-Layer Insulation
VD-MLI	=	Variable Density Multi-Layer Insulation
DAM	=	Double Aluminized Mylar
CFM	=	Cryogenic Fluid Management
LAD	=	Liquid Acquisition Device
TRL	=	Technology Readiness Level
MLI	=	Multi-Layer Insulation
LEO	=	Low Earth Orbit
K	=	Kelvin
SCIM	=	Standard Cubic Inches per Minute

I. Introduction

Management of cryogenic propellants is a key technology area required to enable many long duration exploration missions. This is an even greater challenge for vehicles powered through a nuclear propulsion system. Nuclear thermal propulsion systems induce a radiation flux on the vehicle. This presents challenges such as material selection for system components, electronics that can survive the radiation environment, crew dose, and thermal energy deposit into cryogenic fluid propellants.[2] Hydrogen, a common propellant for a nuclear thermal propulsion systems, readily absorbs energy from the radiation flux due to its small mass. Unless mitigated, this

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leads to increased boil off of the propellant. This is in addition to boil off caused by the ambient thermal environment.

Various passive and active systems or system concepts exist to counter the deposition of energy into cryogenic propellants. Existing passive technologies such as Spray on Foam Insulation (SOFI) and Multi-Layer Insulation (MLI) have been used extensively in launch vehicles and satellites. Advances in MLI are developing to deliver an insulation system that is more durable and capable of greatly decreased heat leak. Active systems remove heat from cryogens in order to maintain the target cryogenic temperature. Cryocoolers are an example of an active system. Historically, cryocoolers first began to fly in the 1990's. Flight cryocoolers have been small systems required by instruments and sensors. These past systems have been designed to remove small quantities of heat. Cryocooler systems designed to maintain large propellant quantities face challenges in meeting power and flight weight requirements. Cryocooler research is also moving forward to develop large systems.

In addition to managing heat transfer to cryogens, there are other technology development items required for successful long duration mission cryogenic fluid management (CFM). Valve leakage is an important development item. Current state of the art for vent valves, fill and drain valves, disconnects, and other fluid control elements can have leakage rates on the order of 100 Standard Cubic Inches per Minutes (SCIM) or more. These loss rates add up quickly over long duration missions.

Two additional CFM technologies that are important, but not discussed further in the paper are propellant mass gauging and liquid acquisition devices (LAD) in microgravity. Gauging propellant quantities inside of a tank in zero g may be required to properly assess cryogen quantities. Traditionally settling motors are used to bring the propellant to the rear of a tank after which the liquid level is detected. Propellant Gauging research is at a low Technology Readiness Level (TRL) and needs development. LAD's operating in microgravity is also a technology area that needs development to reach reliable flight qualified systems. These microgravity technologies would eliminate the need for settling motors and improve the reliability of propellant mass gauging and acquisition functions.

II. Environment

The thermal environment experienced by a deep space exploration vehicle can have a significant impact upon cryogenic fluids in vehicle systems. Heat transfer from radiation sources in space and conduction from vehicle components should be considered. For a vehicle that operates in the atmosphere of Earth or a destination planet; conduction, convection, and reflected radiation from the planetary environment can lead to significant heat input. CFM systems must maintain very low heat input in order to prevent propellant loss to boil off and the resulting need to carry large quantities of excess fuel. The mass of excess fuel can add significant cost and complexity to the vehicle and mission architecture.

A. Radiation Flux from a Reactor

Absorption of nuclear radiation produced by fission can result in degradation or damage to structural components, and each interaction ultimately produces heat in the surrounding material. Such nuclear heating is a special concern for spacecraft that rely upon cryogenic propellant, and the system must be designed to minimize the thermal burden that can result in cavitation at the pump or increased boil-off of stored propellant. Those effects and possible mitigating strategies are discussed within this section.

1. Nuclear Heating Mechanisms

Primary concerns for nuclear heating in spacecraft are from the gamma ray photons and fast neutrons exiting the core region. In both cases, particles of higher energy have a longer mean-free-path than those of lower energy. The majority of neutrons produced in the reactor are born at high energy, and thus travel at high velocity, hence the term "fast neutrons". That energy can be shed by elastic collisions with lighter nuclei, especially that of hydrogen, thereafter the probability of further interaction increases. After their first collision, fast neutrons are quickly slowed to the point that their kinetic energy is equal to that maintained by thermal equilibrium in the surrounding medium, hence the term "thermal neutrons". Heavy nuclei do little to absorb the kinetic energy of neutrons (consider the analogy of ping pong balls bouncing between bowling balls), so fast neutrons tend to travel through metallic structure relatively unhindered, while stopping quite abruptly in hydrogenous materials such as water, polymers, and of course liquid hydrogen. Neutrons traveling at low speed are more readily absorbed by the atomic nuclei, and the resulting change of structure to the absorbing atom tends to produce secondary radiation. A major source of gamma rays in nuclear-propelled spacecraft indeed comes from the absorption of thermal neutrons by hydrogen. By contrast, gamma ray interact more readily with heavy material, such as metallic structure, and pass through low-density material, such as liquid hydrogen, far more easily than neutrons.

The result of this dichotomy is that direct heating of propellant occurs in two manners concurrently. First, neutrons slowing and stopping in the aft portion of the propellant tank closest to the engine produce a great deal of localized heating (and secondary gamma radiation) at the tank wall that diminishes quickly with increased depth. Second, gammas absorbed throughout the tank volume produce a bulk heating effect that is more pronounced at the aft portion of the tank, but not to the extent caused by neutron heating. Indirect heating of propellant is also caused by nuclear heated structural components and tank walls. Monte Carlo simulations of a reference design indicate that fast neutrons typically deposit around one fifth of the total energy deposited by gamma rays. The maximum energy density deposited by neutrons at the engine-facing surface is several times that deposited by gamma rays, but is almost entirely absorbed within the first 50 cm of liquid hydrogen, as shown in Figure 1.

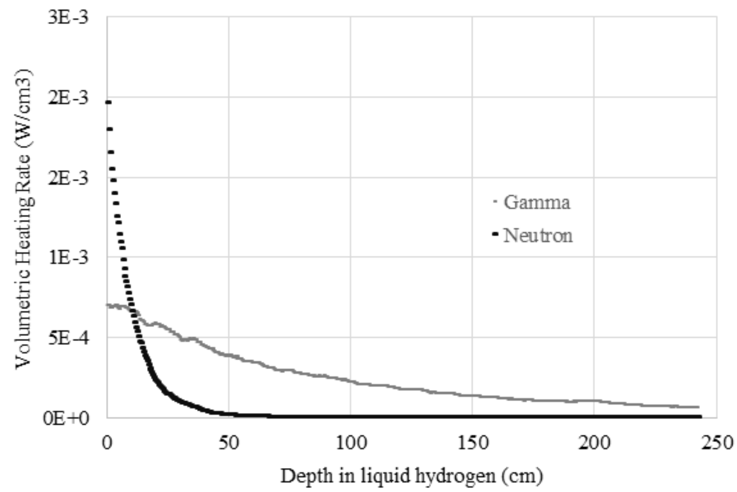

Figure 1. Example nuclear heating profile comparing neutron and gamma contributions for a 3-engine cluster with cylindrical LiH-S.S. and tungsten shield.

2. Thermal mixing and stratification

The localized nature of nuclear heating results in a complex heat distribution that changes through the duration of an engine burn. Vehicle acceleration, coupled with the density gradient due to heating, also induces convective flows that drive the aft-heated fluids counter to the pump-driven outflow. This phenomenon is also seen in studies of more traditional externally heated tank walls in spacecraft[13,14]. These phenomenon then serve to counter one another, with preferential accumulation of heated propellant in the fore section and preferential nuclear heating of propellant in the aft section. The resulting dynamics are then highly dependent upon multiple factors, including the

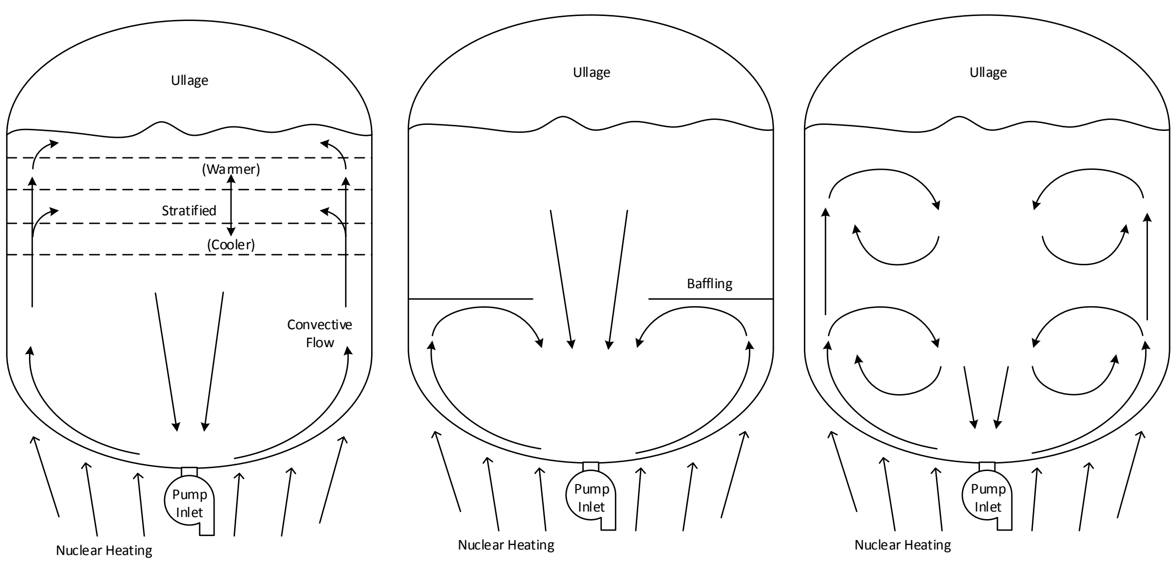

Figure 2. (Left) Thermal stratification of heated propellant near the ullage interface or fore-end (top) of tank. Propellant temperature is critical near end of burn. (Center) Local mixing forces immediate consumption of heated propellant and prevents buildup of heated fluid near end of burn. (Right) Complete mixing homogenizes thermal distribution in the tank.

flow rate of propellant exiting the tank into the engine, the radiation flux entering the aft face of the tank, and the presence of any mitigating devices to direct the flow of propellant inside of the tank. Accumulation of stratified layers of heated propellant can likely be avoided with careful design of baffling and mixing devices inside of the propellant tank[12]. A set of possible scenarios are sketched in Figure 2.

3. Mitigation Strategies

Several strategies may be employed to reduce the impact of radiation upon stage performance and to optimize the system for mass savings. Most obvious among these is the use of a radiation shield between the reactor core and the thermally sensitive staging systems. Even in the absence of any crew, or with the assumption that the crew are otherwise adequately shielded, some amount of shielding will be required to reduce the neutron and gamma radiation flux to the propellant storage and transfer systems. Determining the maximum permissible flux to these components will in fact drive the constraints for design of radiation shielding. Shielding brings a costly penalty in terms of mass, however, and should be minimized by designing the staging systems with consideration for radiation transport.

Table 1 – Calculated total heating rates in core stage tank for varying tank diameter and standoff distance. Identical shielding in all cases.

Standoff b/w Tank and Engines		3 m	6 m	9 m
Tank Diameter	6 m	**10.9 kW**	**3.7 kW**	**1.5 kW**
	7.6 m	**24.1 kW**	**7.5 kW**	**3.2 kW**
	8.4 m	**32.3 kW**	**10.0 kW**	**4.2 kW**

A number of key parameters influence the amount of radiation imparted on the cryogenic storage system. Chief among these are standoff distance from engine to storage tank as well as tank diameter (particularly at the aft face). Shadow-shielding for engines close to a broad tank surface requires a very large diameter slab to effectively intercept the radiation cast from the peripheral surfaces of the core and reflector. This problem is exacerbated for clustered engines where the emitting surfaces are off of the central axis. The diameter (and mass) of the shield can be reduced drastically by either moving the engines further from the core stage tank or by reducing the apparent diameter of the tank at the aft side. This is especially important for shield designs restricted approximately to the diameter of the containment vessel and radial reflector, as is demonstrated by the Monte Carlo calculation described in Table 1 and Figure 3. For that calculation a reference cylindrical shield design was used with 1 meter diameter to match that of the radial reflector, composed of lithium hydride with stainless steel for neutron absorption, lead for gamma attenuation, and weighing approximately 1 metric ton. The design is not considered optimized in terms of geometry, mass, or materials, but serves as a reference for comparison of certain geometric effects of the stage. Actual shielding designs must be optimized specifically for a given staging design, mission profile, and permissible radiation flux.

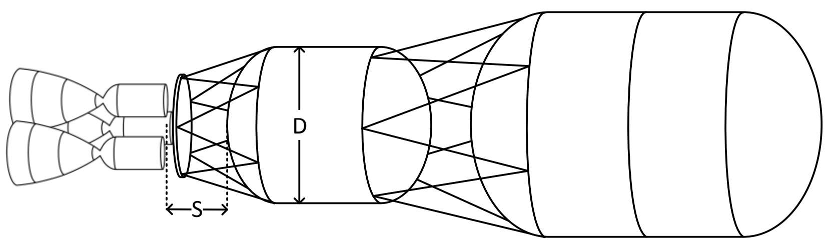

Figure 3. Sketch describing variable parameters of Monte Carlo calculation in Table 1. S = Standoff distance between nuclear engines and bottom of tank. D = Diameter of cryogenic storage tank, including 20 cm insulation thickness.

In addition to the optimization of stage design to mitigate radiation heating of cryogens, a small heat leak may be permitted in order to power a small combustion type system with the excess boil off for auxiliary power. This would ease shielding and thermal protection requirements for the stage.

The results of this survey study; however, indicate the dramatic effect that stage design may have upon thermal performance of a nuclear rocket in terms of nuclear heating. Consideration should be made for the use of distance trusses and/or a narrowed/tapered core stage to optimize against the mass penalty for shielding.

B. External Thermal Environment

1. Earth Atmosphere and Low Earth Orbit

A deep space vehicle will be put into orbit, possibly in multiple modules for on orbit assembly, by a launch vehicle. While the exploration vehicle will likely be protected by a payload shroud, some thermal heat soak may reach the on board cryogens. After ascent, vehicle components will be placed into a low earth orbit (LEO). Deep space exploration vehicles will likely need to be assembled in orbit due to the large size needed propellant and payload mass requirements. Assembly time will be driven by the rate at which launch vehicles can be fielded and exploration vehicle components prepared. Many weeks or months will pass before a vehicle is assembled in orbit. This long loiter time results in the LEO thermal environment having significant impact on cryogenic fluid storage. Factors to account for are heating from rarefied gas molecules, radiation reflected off the Earth, Earth's magnetic field and charged particle interaction, and solar radiation (average of 1370 W/m^2).[10]

2. Deep Space

The primary source of thermal energy in deep space (deep space being outside the sphere of influence of a planet) is radiation. Background radiation will deposit energy into the spacecraft and cryogenic fluids. Cosmic microwave background radiation fills the universe nearly uniformly. It is nearly isotropic radiation in the microwave spectrum that is a relic of the big bang. Cosmic radiation is an isotropic particle radiation generated outside the solar system by super nova explosions. It is made up of high energy particles (~109 eV) that include protons, alpha particles, beta particles, and some heavier nuclei.[10]

The sun is an additional source of heating. Energy is transferred through solar radiation interaction with a vehicle and its systems. Energy is deposited via sunlight or photons. The quantity of which is dependent upon the distance from the sun. Solar wind must also be accounted for in thermal energy management. Solar wind is a fluctuating stream of plasma released from the sun through regions of concentrated magnetic field. It is composed of high energy particles which may interact with spacecraft systems. [10]

3. Other Celestial Body

When in the vicinity of the destination celestial bodies (for example: Mars) the same types of environmental factors are present as in LEO, but in different magnitudes which vary based on Celestial Body characteristics. Factors affecting the thermal environment (e.g. distance from the sun, diameter, reference temperature, emissivity) must be well understood in order to properly design cryogenic fluid management systems. [10]

III. Cryogenic Fluid Management Technology

Technology that conditions cryogenic fluids has been around for decades. There are various systems for non-aerospace related applications. Launch vehicles have long been flying with cryogenic propellants for decades. Application of cryogenic propellants has been over short periods of time on the order of several hours. Long duration missions in the past have relied on other forms of propulsion such as hypergolic or electric propulsion. These have been smaller robotic missions. For human and larger scale exploration missions, cryogenic propellants will be needed for high thrust propulsion systems.

[††]Current capabilities in storing cryogenic propellants are inadequate for long duration missions. Current state of the art is Centaur's 9-17 hours with boil off rates of approximately 30% per day. Mars missions are expected to take roughly 18 to 24 months to complete. This mission time is vastly larger than current cryogenic storage capabilities. Cryogenic fluid management technologies must be developed in the present to enable future exploration missions beyond Earth.

A. Passive Systems

Passive systems act as thermal barriers. They reduce the heat flux into the cryogenic fluid by decreasing thermal conductivity and radiation. Support structures are a source of heat conduction in which heat flows from the vehicle structure into the cryogen storage tank. Support structures are designed to be low conductivity to reduce this heat flux. Insulation systems are applied to tanks, pipes, and any cryogen carrying components.[11] Spray on Foam Insulation (SOFI) is applied to outer surfaces. It is most effective in atmospheric environments. Multi-Layer Insulation (MLI) is made up of thin layers of high reflectance metal that act as radiation shields wrapped around cryogenic systems in many layers.[3] Historical systems have been ineffective in the atmosphere but have performed well in vacuum.

[††] Information obtained through interviews with engineers at Marshall Space Flight Center

MLI for cryogenic storage is designed for high vacuum conditions and typically consists of many radiation shields, separated by low conductivity spacer material, between the hot and cold boundaries. The radiation shielding normally consists of a thin plastic film coated on one or both sides with a thin layer of high reflectance metal, usually aluminum or gold. MLI systems are often comprised of multiple double aluminized Mylar (DAM) radiation shields with Dacron net spacer material between shields. While radiation generally dominates heat transfer, solid conduction through the spacer material becomes an issue at low temperatures such as those experienced by the inner MLI layers on a cryogenic fluid tank[3].

Recent research into MLI has shown that, with some design changes, significant performance improvements can be made. Advanced forms of MLI are being developed in industry. Some companies are working on several significant improvements. These companies are developing low conductivity spacers to replace conventional netting that control layer spacing.[4] Their design has shown 40 – 60 % lower heat flux than conventional MLI.[4] Spacers have been designed to be load responsive and provide support for a light weight vacuum shell for launch vehicle applications. The new design offers two orders of magnitude decrease in heat leak and one order of magnitude decrease in mass.[4]

NASA has also investigated the use of variable density MLI. To optimize the MLI for a cryogenic application, the colder inner layers can be spaced further apart than the warm outer layers where radiation dominates heat transfer. This type of MLI is referred to as variable density MLI (VD-MLI) because the layer spacing varies across the MLI cross section, reducing both insulation mass and thermal heat leak. The spacing geometry in a VD-MLI system can be controlled by the addition of bumper strips constructed with folded Dacron netting. The bumper strip thickness can be easily adjusted by varying the number of folds. In addition, larger but fewer perforations for venting during ascent to orbit can be used to reduce radiation heat transfer through the MLI. Tests have shown that variable density MLI decreased heat leak by 41% compared to standard MLI performance for a warm boundary condition of 305K and 25 fewer layers than the standard.[3]

B. Active Systems

Active thermal control systems remove heat from the target reservoir. Cryocoolers are a maturing active cooling technology. They began flying in the early 1990's. The primary use of flight cryocoolers has been for instrumentation. Many of NASA's space instruments require cryogenic refrigeration to improve dynamic range, increase wavelength coverage, or enable the use of advanced detectors. Typical cooling temperature range has been 55 to 150 K.[5] Many cryocoolers that function to cool instrumentation have flown and been successful. These small cryocooler systems have operated for extended periods of time with high reliability. Examples of successful cryocooler systems include the Jet Propulsion Laboratory Sorption cryocooler for the PLANCK space telescope and the 50-80K Astrium for Helios 2A and 2B.[6]

[‡‡]Initially, the cryocooler development effort was focused on reliability and lifespan of systems to make them suitable for supporting instrumentation that would operate for long periods of time on orbit. More recently efforts have turned to developing systems for lower temperature applications 10 to 20 K range with larger heat removal capabilities. Improving efficiency, watt removed per watt used, has also been an area of focus. An ongoing cryocooler developmental project is underway as a joint effort between Creare Inc. and Glenn Research Center. The goal of the project is to develop and demonstrate a cryocooler using a turbo-brayton cycle to provide 20 Watts of cooling at 20 K.[8,15] This category of cryocooler is what will be needed for future long duration missions since hydrogen will need to be maintained in the 20 K range to remain in a liquid state. It is important that this technology continues to be supported as it will be required to keep the propellant mass requirements of an exploration vehicle within achievable limits.

C. Low Leakage Valves

Often it is assumed for long duration missions that propellants are sealed in vessels (tanks) and the mass of the propellants is not lost if boil off is stopped. However, the state of the art for valves, fill and drain valves, disconnects, and other fluid control elements of a size relative to a launch vehicle or NTR mars exploration vehicle have leakages on the order of 100 Standard Cubic Inches per Minute (SCIM). As many as ten of these components in the main propulsion system, for a mission of up to three years, could lose on the order of 100,000 lbs. of propellant. Losing propellant mass of this quantity would mean the vehicle must have significantly larger tanks or risk running short on propellant.[1]

[‡‡] Information gathered through interviews with engineers from the Jet Propulsion Laboratory, Glenn Research Center, and Creare Inc.

Clearly there is a need to develop valves with leakages many orders of magnitude lower than the current state of the art. The propulsion department at Marshall Space Flight Center has begun work in this area to develop leakages as low as 10^{-3} SCIM. Several concept seat designs are being explored to achieve low leakage rates. Seats, which break and remate as the valve opens and closes, are the primary source of leakage. Consistent sealing is difficult and contamination can prevent a proper seal. Most main propulsion system state of the art valves use a flat seat design and a large load to achieve leakage acceptable for a short mission. These designs have contact stresses and controlling contact angle, concentricity, and achieving flatness is difficult for lower leakages. Smaller valves use a tooth seat design, but previous work has shown this is difficult to scale up. Currently, an effort is underway to design a large spherical seat design and a differential angle seat design that will be tested and scaled up to a size more relevant to a nuclear Mars exploration vehicle.[1]

Low leakage valves require increased support and attention to reach maturity and leakage performance required for long duration missions. Low leakage rates must be achieved to make a long duration mission possible. Even small leaks will add up to large quantities of propellant.

IV. Conclusion

There are many challenges to storing cryogenic fluid and propellants on a long duration deep space mission. These challenges are complicated by the presence of radiation emanating from a reactor of a nuclear thermal propulsion system. Fluid temperature must be controlled and heat leak minimized through the use of passive insulation systems such as multi-layer insulation and active heat removal systems such as cryocoolers. Leakage through valves and other fluid control devices must be decreased and brought as close as possible to zero. While current technologies are quite inadequate, research and development efforts are ongoing through multiple organizations to meet these technology goals. It is important that cryogenic fluid management be recognized for its significance and the technologies enabling cryogen storage for long periods of time be fully supported. These technologies will be required to accomplish large scale and manned exploration missions to the asteroids and Mars.

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