

Potential Uses of Deep Space Cooling for Exploration Missions

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Nearly all exploration missions envisioned by NASA provide the capability to view deep space and thus to reject heat to a very low temperature environment. Environmental sink temperatures approach as low as 4 Kelvin providing a natural capability to support separation and heat rejection processes that would otherwise be power and hardware intensive in terrestrial applications. For example, radiative heat transfer can be harnessed to cryogenically remove atmospheric contaminants such as carbon dioxide (CO₂). Long duration differential temperatures on sunlit versus shadowed sides of the vehicle could be used to drive thermoelectric power generation. Rejection of heat from cryogenic propellant could counter temperature increases thus avoiding the need to vent propellants. These potential uses of deep space cooling will be addressed in this paper with the benefits and practical considerations of such approaches.

Nomenclature

ACFM	=	Actual Cubic Feet per Minute
ARDSC	=	Air Revitalization via Deep Space Cooling
ATCS	=	Active Thermal Control System
CAMRAS	=	CO ₂ and Moisture Removal Amine System
CHX	=	Condensing Heat Exchanger
COO	=	Concept of Operations
CO ₂	=	carbon dioxide
DRM	=	Design Reference Mission
DSH	=	Deep Space Habitat
ECLSS	=	Environmental Control and Life Support System
EVA	=	extravehicular activity
LH ₂	=	Liquid hydrogen
LiOH	=	Lithium Hydroxide
HX	=	heat exchanger
LEO	=	low-Earth orbit
LOX	=	Liquid oxygen
LM	=	Liquid Methane
LN ₂	=	Liquid Nitrogen
NIAC	=	NASA Innovative Advanced Concepts
RHR	=	Residual Humidity Removal (HX)
TCS	=	Thermal Control System
TSGC	=	Texas Space Grant Consortium
UT	=	The University of Texas at Austin

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I. Introduction

Deep space missions can take advantage of the extremely low sink temperature to reject heat. Active Thermal Control System (ATCS) processes will be more efficient when heat is radiated to an extremely cold and predictably nearly constant deep space heat sink. The heat rejection efficiency can be used to reduce radiator area (and thus weight) to reject vehicle heat (versus LEO heat rejection) or to provide extremely low temperature cooling. Table 1 shows the capability that is possible for deep space heat transfer with the heat that can be rejected per unit area for systems radiating a variety of temperatures.

Heat rejection per unit area to deep space for relevant temperature ranges

Radiator temperature					
	Degrees F	-225	50	70	572
	Degrees K	130	283	294	573
Relevance of temperature Range					
		Cryogenics	Vehicle ATCS		Rocket Cooling
			Low end	Medium	
<u>Heat rejection per area</u>	<u>W/m²</u>	<u>14</u>	<u>311</u>	<u>362</u>	<u>5226</u>

Assumptions - Emissivity = 0.9; Fin efficiency = 0.95; Sink Temperature = 4 degrees K

Table 1 – Heat Rejection per Area at selected relevant heat rejection temperatures (from Gene Ungar)

The predictable low temperature heat rejection can be used to provide cooling at temperatures low enough to be used for processes that have not been practical in LEO environments. Such very low temperatures that can support processes such as chilling cabin air to below 188 degrees K (-122 Degrees F) at which CO₂ will condense from an air stream. Using the energy on a sun facing surface and rejection of heat to deep space could drive thermoelectric power generation. Heat rejection from a cryogenic propellant tank could effectively counter the heat absorbed from the average environment thus eliminating the need to vent propellants (without the use of power consuming cryopumps).

Some of the potential uses for deep space cooling were presented in an overview in Reference 1. Moreover, deep space cooling was also documented in a proposal for new technology for air revitalization via deep space cooling (ARDSC) development via the NIAC program in Reference 2 along with a basic study of the concept Reference 3. The possible power generation via thermoelectric use of the sun-to-shadow temperature differences that can be realized during a deep space mission will be summarized evaluating the efficacy of this concept. In addition, the potential for using heat rejection at very low temperatures to address long duration propellant storage was addressed in a Texas Space Grant Consortium (TSGC) project in 2010⁴. This paper focuses on the applicability of deep space cooling for recent system engineering concepts. An assessment of the engineering considerations associated with vehicle and mission uses of deep space cooling is also offered.

II. Radiative heat transfer to deep space to cryogenically remove atmospheric contaminants such as carbon dioxide (CO₂) (Atmosphere Revitalization by Deep Space Cooling)

What if just by taking advantage of the environment around the vehicle while on a deep space mission we could revitalize the air and cool some or all the equipment with one system? Nearly all exploration mission destinations provide an environment that enables using deep-space radiation to provide cooling. Using such cooling can provide thermal conditioning by efficiently radiating to the deep-space heat sink. In addition, the low temperatures that can be realized via radiating to deep space can be used to cool cabin air to temperatures that are low enough that cabin atmospheric contaminants (water vapor and carbon dioxide and trace contaminants) condense from cabin air and deposit on cold surfaces. These condensed contaminants can then be isolated and recovered to be used in regeneration processes. Such a process can achieve atmosphere revitalization without the use of chemical beds or consumables.

Air revitalization by deep-space cooling (ARDSC) can provide an alternative to air revitalization processes and Thermal Control System (TCS) concepts that are currently being considered for exploration habitats. ARDSC may

provide a significantly simpler and much less massive and power-intensive way of maintaining both air quality and thermal conditions within exploration habitats.

The problem of removing contaminants from the atmosphere of a spacecraft has been addressed using a variety of methods in past programs. Sorbent beds comprised of consumable materials such as lithium hydroxide (LiOH) have been used during early projects and programs (Mercury, Gemini, and Apollo) and, more recently, on the U.S. space shuttle and for contingencies on the International Space Station (ISS) for removal of carbon dioxide (CO₂). Regenerable CO₂ removal systems have been developed employing zeolites and metal oxides. While these materials eliminate consumables, regeneration typically involves power-intensive thermal cycling. Charcoal beds have been included in LiOH canisters to remove trace contaminants and odors. Humidity has been removed via condensing heat exchangers (HXs) in many past programs and via regenerable desiccant beds on ISS. TCSs have used internal coolant loops to acquire and transport heat from the crew and equipment before rejecting that heat to external loops that acquire additional heat and transporting the heat to radiators for rejection.

ARDSC is an alternative to the combined air revitalization and TCSs that take advantage of the availability that exploration missions provide to view deep space. The concept of removing CO₂ from cabin atmosphere by deep-space cooling was addressed in an analytical effort in 2007 (ESCG-4470-07-TEAN-DOC-0103). Preliminary analytical efforts indicate deep space cooling for air revitalization is viable. The results of the investigation suggest only 2 m² of radiating area required to provide the cooling needed to remove CO₂ generated by four crew members.

It is envisioned that ARDSC would be the primary approach for exploration habitats to control CO₂ and humidity. During those rare periods in which deep-space viewing is unavailable (perhaps assembly in low-Earth orbit [LEO] or lunar noon operations), dissimilar redundancy via a system such as a CO₂ and Moisture Removal Amine System (CAMRAS) could be employed.

The ARDSC concept should take advantage of the very low temperature purified air leaving the CO₂ condensing HX to operate HXs to remove residual water before air enters the CO₂ HX and to operate a Condensing HX (CHX) to remove most water vapor from cabin air. Efficiency will be realized by the following flow stream processes:

- 1) Cabin air enters a CHX where most water vapor is removed by lowering the dewpoint to around 5 °C (40 °F). The CHX would recover condensed water via a slurping process.
- 2) Residual water is removed from the flow stream via another HX (residual humidity removal (RHR) HX)) that freezes water. Water is to accumulate in this HX in the form of ice until a regeneration process is implemented.
- 3) Air enters the CO₂ removal HX and the temperature is reduced to below 188 K (-116 °F or -85 °C). CO₂ will condense from the airstream at that temperature and will accumulate in the HX as dry ice.
- 4) Air leaving the CO₂ HX is ducted to the coolant side of the RHR HX as the coolant. The purified O₂ and N₂ at very low temperature accepts heat from the RHR HX but is still very cold as it exits.
- 5) The airstream from the RHR HX is used to provide the cooling for the CHX.
- 6) Air leaving the cooling side of the CHX may have additional cooling capability that could be used to cool other equipment or it could just reenter the cabin completing the revitalization process

The ARDSC system concept is shown in the simplified schematic in Figure 1.

Air Revitalization via Deep Space Cooling Schematic (Simplified)

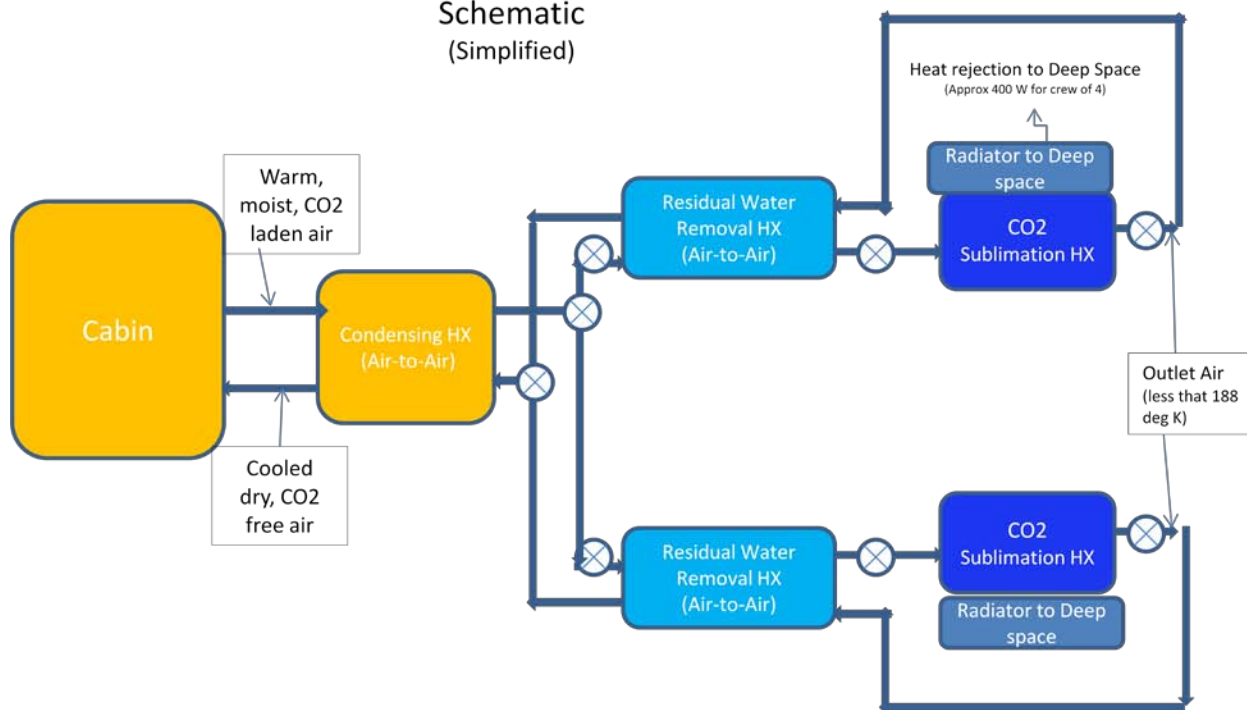


Figure 1. Simplified air revitalization by deep space cooling concept

Before deep space cooling could be used to condense and concentrate carbon dioxide, the cabin air entering the atmosphere revitalization system (ARS) would need to have humidity removed to provide the high purity CO₂ stream desired for O₂ recovery. A condensing heat exchanger (CHX) could be used to reduce the water vapor pressure to just above its triple point, where the vapor pressure is 4.59 mmHg. If no additional water removal mechanism is employed, the remaining water would freeze in the hardware designed to condense CO₂, reducing the purity of the frozen CO₂ and also risking damage to process plumbing.

For example, if the process stream contains 7.6 mmHg of carbon dioxide, if the molecular sieve could dry the process air to a dew point of -19.3°C, the water vapor pressure would be 0.844 mmHg, which would result in a 90% CO₂ / bal H₂O mixture. If a 99% purity is required, the process air dew point would need to be -41.9°C, resulting in a water vapor pressure of 0.077 mmHg. If the process stream contains 3 mmHg of carbon dioxide, and a 90% or 99% purity is required, the molecular sieve would need to dry the air to a dew point of -28.7°C or -49.7°C, respectively. All dew points are very attainable with a molecular sieve sorbent approach.

Two approaches could be employed to remove the residual water vapor from the flow stream. A sorbent technology could be employed or an additional HX could be added specifically to remove the residual water.

Efficiency can be achieved if the cold air stream coming from the CO₂ HX is used to chill air entering the CO₂ HX and such a heat exchange could also remove residual water before it enters the CO₂ HX. Such an approach would result in very high purity CO₂ in the CO₂ HX and the potential to capture and use the ice in the RHR HX.

If a sorbent technology, such as a molecular sieve, is employed it would be able to dry the process air by significantly reducing the vapor pressure of water, and thereby reducing the amount of water that would freeze with the carbon dioxide.

Operation of the ARDSC is planned to involve alternately operating the sections that contain the RHR HX and the CO₂ HX by valving off those HXs and channeling airflow to the other set for residual water and CO₂ removal. Pressure drop across the combined RHR and CO₂ HX sections would be monitored to determine when water ice or solid CO₂ buildup warrants transition from air revitalization to water/carbon dioxide recovery. Control valves for each passage would allow the RHR HX and the CO₂ HX to be isolated. Heaters would raise the temperature in the RHR HX to evaporate the water in the RHX and allow it to be collected or released back into the cabin. Heating the isolated CO₂ HX will evaporate the CO₂ and allow it to be collected into a CO₂ collection vessel. The heating of

the CO₂ ice will elevate the pressure of the CO₂ and assist in CO₂ recovery processes such as Sabatier reactors. The regeneration process will result in the drying RHR HX for reuse with the CO₂ HX only having trace amounts of residual CO₂ gas.

The operational sequence to implement ARDSC is:

- 1) Cabin air flows thru the CHX then one of the two channels of the RHR HX and CO₂ HX and humidity is removed primarily in the CHX but also in the RHR HX and CO₂ is removed in the CO₂ HX.
- 2) The pressure drop (DP) across the operating channel of the RHR and CO₂ HXs is monitored and used to control cycling of the two channels.
- 3) When the DP exceeds a predetermined level control valves are opened to other RHR and CO₂ HX channel to divert air in to that set of equipment.
- 4) The RHR and CO₂ HXs are isolated from the flow stream and from each other to enable regeneration of those HXs
- 5) Heaters are activated in the RHR HX to evaporate ice that has collected. The RHR HX could be opened to the cabin to recover that water into the cabin or it could be sent to have the water recovered for reuse.
- 6) The CO₂ HX is isolated from the deep space radiator (via Louvers isolating the radiator from deep space or via channeling coolant flow around the CO₂ HX (depending on which cooling option is employed)
- 7) Valving connecting the CO₂ HX interior to a CO₂ storage tanks is opened.
- 8) Heaters are activated to heat the CO₂ HX evaporating the accumulated CO₂ forcing CO₂ into the storage tank.
- 9) Heaters are deactivated and the valve to the CO₂ tank is closed to complete the regeneration process and make the RHR and CO₂ HXs ready to operate again.

The following section addresses details of the CO₂ HX operation and the chemico-physics involved in the process.

III. Cryogenic Carbon Dioxide Freeze Model

In order to evaluate the feasibility of cryogenically freezing carbon dioxide from a dry CO₂-laden cabin air stream, a first principles model has been established. The model presumes characteristic length scales for heat transfer are, by design, small to enhance heat rejection to space. Consequently, cross-sectional variations in concentration and temperature are considered negligible and a plug-flow model becomes an adequate approximation for the material balance of species i .

$$\frac{\partial C_i}{\partial t} + \frac{\partial q_i}{\partial t} = \nabla \cdot (\vec{v} C_i) \quad (1)$$

In Eq. (1), \vec{v} is the superficial gas velocity, C_i and q_i are the interstitial gas and solid loading concentrations of species i , respectively. As carbon dioxide transfers from vapor to solid phase, the overall material balance is enforced through the equation of continuity.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (2)$$

Eq. (1) provides the divergence in gas concentrations across the radiator used for CO₂ freezing while Eq. (2) determines the velocity profile within the radiator as CO₂ vapor condenses to the radiator walls.

It should be noted assumptions of gas ideality are not valid at temperatures close to the freezing point of CO₂. Consequently, overall gas density, ρ , must be calculated while accounting for compressibility, Z .

$$Z = \frac{P\bar{V}}{RT} \quad (3)$$

In Eq. (3), R is the universal gas constant (0.08206 atm-m³/kmole-K), and \bar{V} is the molar volume of the gas (*i.e.* inverse of density such that $\bar{V} = 1/\rho$). Compressibility was calculated employing the Soave Redlich and Kwong equation of state.

For the freezing process, a linear driving force potential was applied. This type of a relationship is exact in the cases where a linear isotherm is employed or when mass transfer is rate limiting⁵. Otherwise, the linear driving force typically tends to be a suitable approximation for non-linear isotherms.

$$\frac{\partial q_i}{\partial t} = k_i(C_i - C_i^e) \quad (4)$$

In the linear driving force potential, k_i is a mass transfer coefficient (m/s). For carbon dioxide, Tunier et al.⁶, found that this parameter was on the order of 105 m/s for cryogenic carbon dioxide freezing. For the non-condensing components, k_i is set to zero. Moreover, C_i^e is the equilibrium vapor concentration of component i . For carbon dioxide, this is associated with the temperature-dependent vapor pressure which was calculated from an empirical fit to data (units of kmole/m³).

$$C_i^e = \frac{1.3158 \times 10^{-3}}{RT} \exp\left(10.257 - \frac{3082.7}{T} + 4.08 \ln T - 2.2658 \times 10^{-2} T\right) \quad (5)$$

In this analysis, the hydraulic diameter, D , for the flat radiator panels was used as the characteristic length scale. Hydraulic diameter is defined as $D = 4A/P$ (four times cross-sectional area divide by the wetted perimeter). For the cryogenic freezers capable of throughput on the order of 30 ACFM, D was on the order of several centimeters. Consequently, the Reynolds number is on the order of 10,000 and above indicating flow is turbulent. As a result, the pressure-flow relationship follows a form derived from a mechanical energy balance on the radiator.

$$\nabla P = \frac{\rho \vec{v}^2}{2D} f \quad (6)$$

In Eq. (5), L is the length-scale of the transverse distance along the radiator and f is the friction factor. In particular, the friction factor was calculated from the Swamee-Jain correlation.

$$f = \frac{0.25}{\left[\log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{\text{Re}^{0.9}}\right)\right]^2} \quad (7)$$

In Eq. (7), ϵ is the pipe roughness (0.0015 mm for aluminum). Re is the Reynolds number of the system characterizing the ratio of inertial to viscous forces ($\text{Re} = \rho v D / \mu$ where μ represents the dynamic viscosity of the gas).

The energy balance for the system as function of cryogenic freezer gas temperature, T , followed the form represented below.

$$\rho c_p \frac{\partial T}{\partial t} + \rho \vec{v}(\nabla T) + \frac{\partial q_i}{\partial t} \Delta H_i = h(T_w - T) \quad (8)$$

In Eq. (8), c_p is the specific heat of the gas mixture (kJ/kmole-K) and ΔH_i is the latent heat of vaporization (for carbon dioxide, $\Delta H_i = 56.82$ kJ/kmole). Moreover, T_w represents the wall temperature of the freezer which is exposed to space for the purpose of radiative heat rejection. The calculation of T_w necessitates an additional energy balance to account for radiative heat transfer.

$$Q_{\text{Rad}} = -\epsilon \sigma A(T_w^4 - T_s^4) = h(T_w - T) \quad (9)$$

In Eq. (9), ϵ represents the emissivity of the radiator (0.85 assumed), A is the area of the radiator, T_s is the sink temperature of deep space (5 K assumed), and σ is the Stefan-Boltzmann constant (5.6704×10^{-8} W/m²-K). The convection coefficient, h , is calculated with the Dittus-Boelter correlation.

$$\text{Nu} = \frac{hD}{K} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.3} \quad (10)$$

The parameters Nu , Re , and Pr represent the Nusselt, Reynolds, and Prandtl numbers, respectively. The thermal conductivity of the material, K , was presumed to be 250 W/m-K (*i.e.* similar in magnitude to aluminum).

IV. Parametric Investigation of Cryogenic Freezer Dimensions

The cryogenic freezer analyzed in this investigation is a new concept proposed for spacecraft air revitalization. Consequently, the freezer must be sized to handle flow rates on the order of 30 ACFM². Cabin atmosphere was assumed to be 1.01325 bar (14.7 PSIA). If a lower cabin pressure were to be used, the density of the gas is decreased leading to more favorable pressure-flow characteristics (see Eq. (6)) rendering this a conservative assumption.

In actual implementation, the cryogenic freezer system will have upstream components to remove moisture such that the inlet gas is a relatively dry CO₂ laden air. Consequently, the model assumes water vapor is present in negligible amounts in this analysis. A carbon dioxide partial pressure of 3.0 mm Hg was assumed. The consequence of these assumptions is that a rough approximation can be achieved for the area required to achieve the sensible and latent heat necessary for CO₂ condensation. Sensible heat rejection requirements were calculated from the specific heat of carbon dioxide multiplied by the flow rate of CO₂ into the reactor. Latent heat requirements were calculated based on the heat of vaporization of carbon dioxide (25.455 kJ/mole) multiplied by CO₂ flow rate. Based on the heat rejection requirements, an approximate radiator area was calculated in previous studies³. The optimal cryogenic freezer area was determined to be around 1-2 m². To achieve this area, a duct with a hydraulic diameter of 5 cm and 10 m in length was chosen in initial calculations.

Based on the preliminary dimensions, the gas rapidly cools after entering the radiator and the carbon dioxide begins to condense at about 4.6 meters into the chamber. The greatest amount of accumulation occurs where the difference between partial pressure and vapor pressure is the greatest as Eq. (4) would suggest. The amount of accumulation is dictated by the magnitude of the mass transfer coefficient which was assumed to be 10⁵ m/s based on the results of ⁶. This value will need verified experimentally before the preliminary results described herein can be fully accepted. With this caveat, Figure demonstrates the change in cross-sectional area with ice accumulation at the location of 4.6 m downstream into the cryogenic radiator. The thickness of the ice increases fairly linearly when a constant concentration of CO₂ enters the chamber. Condensation leads to a slightly non-linear decrease in cross-sectional area until around 8.8 hours when the system pressure drop precipitously increases to a prohibitive level at which the fan for the system would likely stall and cease to achieve the desired flow rate. As previously described, this is when the cryogenic freezers would likely be cycled from active revitalization to regeneration. For this manuscript, that time will be referred to as the cycle time.

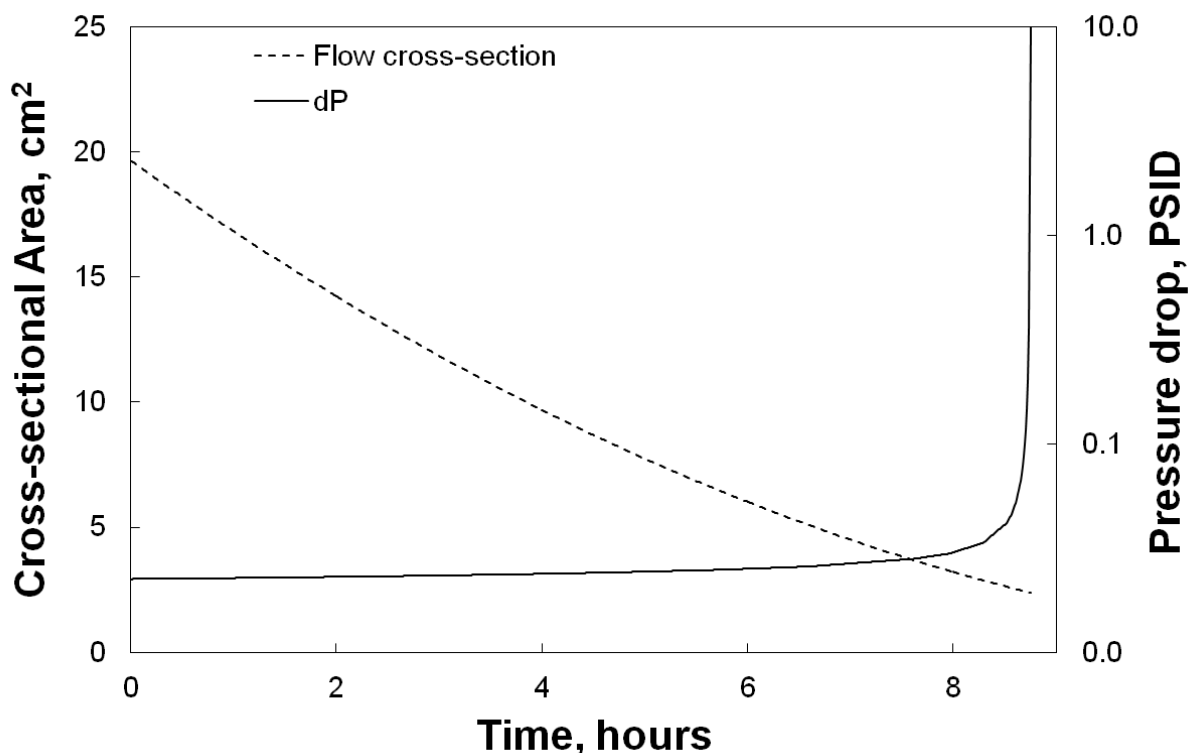


Figure 2: Cross-sectional area and pressure drop as a function of time for a radiator with 5 cm ID and 10 m in length. Incoming gas enters the radiator at 1 ATM (14.7 PSIA), 21.1 °C (70.0 °F), with a CO₂ partial pressure of 3.0 mm Hg and flow rate of 30 ACFM.

A parametric analysis was to evaluate the expected performance as a function of hydraulic diameter and partial pressure of CO₂ in the feed stream. These results are demonstrated in Figure . As would be expected, increasing the diameter increases the cycle time due to the increased cross-sectional area where carbon dioxide can form without closing the duct. What is also evident is that an increase in partial pressure of carbon dioxide reduces the cycle time. While that trend was expected, it was not expected to see that an increase in partial pressure produced a non-linear decrease in cycle time. To explore this relationship, the hydraulic diameter was monitored as a function of position for a few different concentrations of carbon dioxide. These results are depicted in Figure . The model suggests that higher concentrations produce a sharper condensation profiles. Alternatively, the model indicates that higher concentrations of carbon dioxide will condense more rapidly once cooled to cryogenic temperatures which is the result of the assumed linear driving force potential. While this result should be verified experimentally, it seems to suggest high concentration materials will condense in narrow regions within the cryogenic radiator. Consequently, the cryogenic radiator could potentially be used as a separator relying on relative differences in vapor pressure of components to selectively condense at specific axial locations.

If only a CO₂ HX is used without a RHR HX upstream, judiciously selecting diameter and flow rate combinations, water could potentially be condensed at the front of the cryogenic radiator while using the remaining section of the radiator for carbon dioxide condensation. For thermal regeneration of the radiator, heaters could be selected based on the latent heat requirements for the specific materials condensed along the bed in order to minimize heat loads.

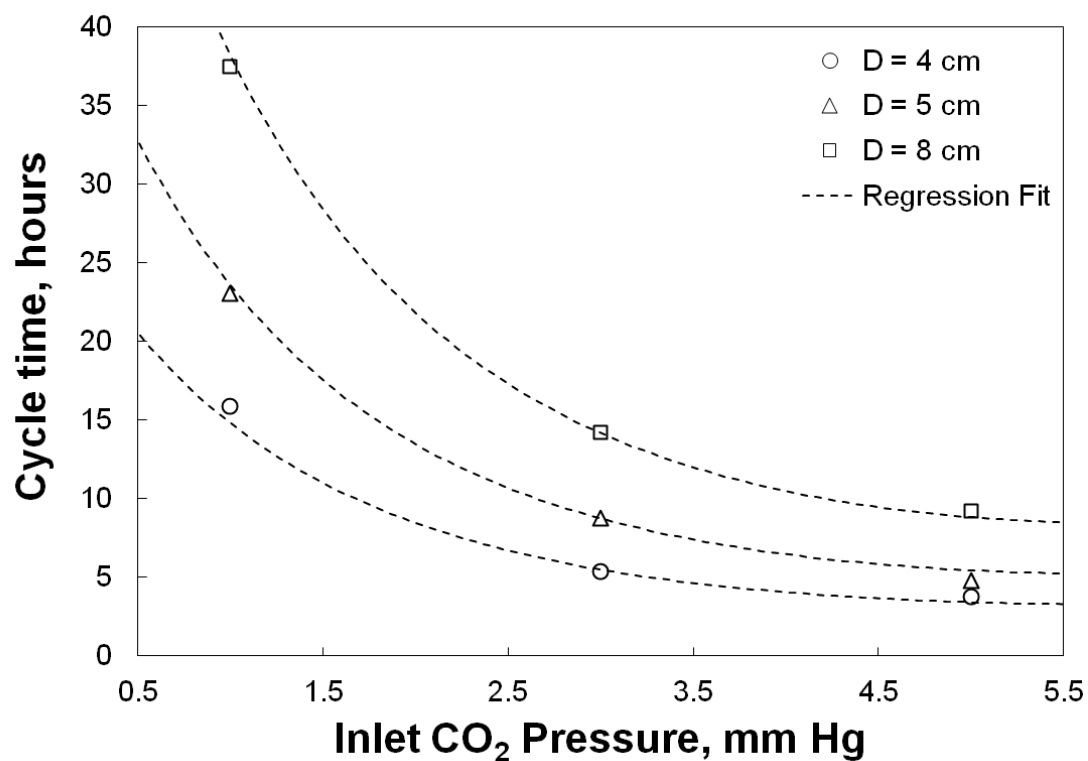


Figure 3: Parametric investigation of cycle time as a function of hydraulic diameter and partial pressure of CO₂ in the feed stream.

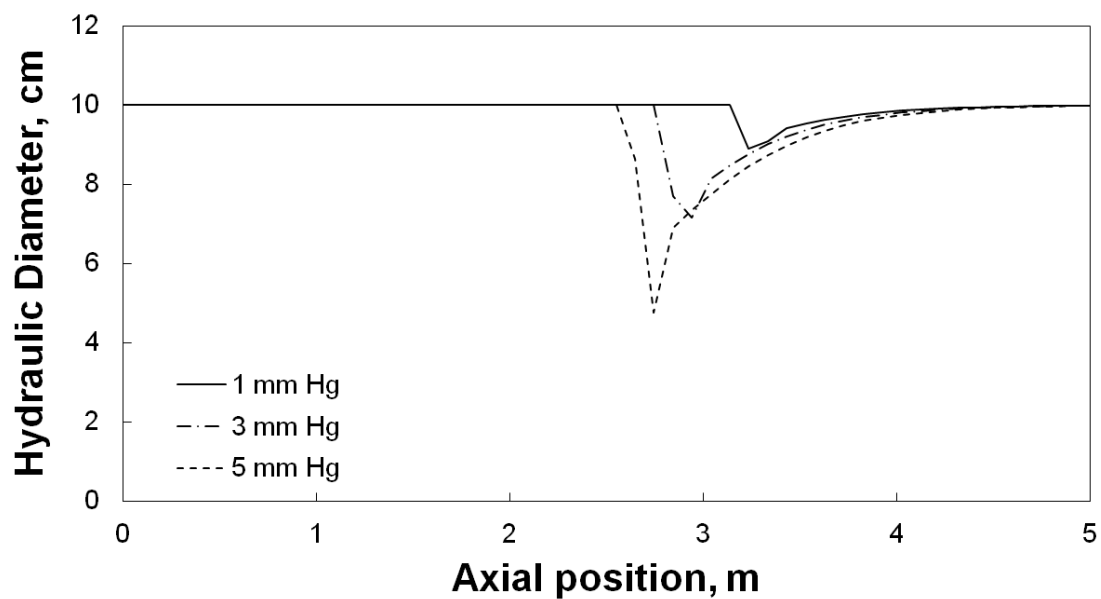


Figure 4: Profile of the inner hydraulic diameter of the cryogenic radiator during condensation versus inlet partial pressure CO₂. Results are for an incoming gas at 1 ATM (14.7 PSIA) and 21.1 °C (70.0 °F), with a flow rate of 30 ACFM.

V. Model Conclusions

A first principles model has been developed to evaluate the feasibility of utilizing deep-space cooling for air revitalization. The model seems to predict that the concept is indeed feasible and cycle times for condensation tend to be on the order of several hours. Moreover, a fair amount of the length of ducting within the cryogenic radiator is used to sensibly cool the incoming gas until partial pressure of carbon dioxide is in excess of vapor pressure. Thereafter, condensation occurs generating a profile that is dependent upon the partial pressure of the incoming stream. While the modeling effort strictly focuses on the feasibility of carbon dioxide removal, this result suggests that materials with drastically different vapor pressures will condense at different locations within the radiator meaning geometry and flow rate can be used to tune the radiator for selective separation. Future efforts will be to verify the former concluding by incorporating water within the model. In addition, experimental data will be needed to verify these results.

• Perceived Impact to the State of Knowledge in the Field

Air revitalization by deep-space cooling can provide an alternative to adsorption approaches to CO₂ removal that should be much more efficient in mass and power use than current approaches. The simplicity of the approach should significantly improve reliability of air revitalization processes. Air resistance will be much less (than that achieved through adsorbent beds) using this approach to CO₂ removal, thus reducing air-circulation system pressure drop and improving the efficiency of the air ventilation system. It is feasible that the entire thermal control for the habitat could be addressed via the ARDSC air-to-deep-space heat transfer, which could eliminate the need for a separate external thermal cooling system.

Several options are possible for connecting the CO₂ HX thermally to deep space radiative cooling:

- 1) The original conceptual study⁴ assumed a direct connection of the air stream to a surface radiating to deep space. That option is probably the most efficient with direct connection to the deep space environment. Louvers could provide isolation of that surface during the regeneration heating process. Directly interfacing radiators would need to consider the potential for MM damage or penetration of such a radiator. Such a concept would probably necessitate that two separate radiators be employed since the regeneration process would require one be insulated while the other continues to reject to deep space.
- 2) A separate cooling loop connecting the CO₂ HX to a deep space radiator could be employed using a low temperature coolant such as LN₂ or He. The efficiency and complexity of such a system would be affected since heat transfer efficiencies would be a factor and a pumped loop components would be required. Such a system would be more robust for protecting against MM damage and would eliminate the need for separate radiators by allowing valving to channel flow to the active CO₂ HX. This option could also provide orientation capabilities to make vehicle operation less dependent on keeping sun from the radiator.

If the earlier system concept using a Residual Humidity Removal HX is employed it would have the following benefits:

- 1) The entire loop operates without a connection to vacuum
- 2) Pressure drop will be less than a packed bed design thus reducing fan power required
- 3) Less moving parts are required in ARDSC than in standard approaches (like CDRA for ISS)
- 4) The entire process does not require a coolant loop
 - a. Only the connection of the CO₂ HX to deep space is required for all the cooling.
- 5) The RHR HX is a simple air-to-air HX
 - a. Heat transfer should be pretty straightforward
 - b. Collection of ice is expected to be on fins and will be at such a low temperature that water to ice shouldn't be a significant part of the process – thus expansion shouldn't be a concern
 - c. Regeneration of the RHR HX should be really simple by just adding heat to raise the HX (and thus contents) above water melting temp
 - d. With a sweep of cabin atmosphere thru the RHR HX the humidity could be reintroduced into the cabin to avoid cabin low dewpoint problems (maybe)
- 6) The CO₂ HX is pretty simple (except for the temperature swings it will undergo)
- 7) The regeneration of the HX after CO₂ has accumulated should result in a dry HX core at the combined pressure of the CO₂ storage tank and the core.

- a. The residual CO₂ in gaseous form in the HX core after regeneration heating should not be enough (volume wise) to cause concern about it reentering the cabin.
- 8) The CHX is standard ISS level technology that we know well

- **Relevance**

Air revitalization by deep-space cooling is a new approach to removing CO₂ from habitat airstreams and thermal control of a habitat. It uses the natural resource of deep-space viewing to accomplish CO₂ removal that otherwise would be done via packed beds of zeolites, amines, or other sorbents. The same heat rejection to deep space could also provide enough cooling to address some of the rest of the thermal control needs of the habitat.

Given the success of projects to develop this technology, ARDSC will become an alternative that could be better suited for exploration habitats envisioned for all deep space missions. It could provide the robust and reliable solution needed for long-duration exploration missions.

- **Recommended future actions**

System engineering, modeling, and analysis need to be continued to develop details of the implementation of the ARDSC concept. To anchor models and system concepts buildup and testing via a one flow pass of system in a laboratory environment should be conducted to demonstrate and quantify the capabilities of the ARDSC concept should be pursued. The laboratory demonstration could be a relatively simple use major components such as a fan, condensing HX, a normal air-to-air HX for the RHR HX, and primary HX for CO₂ condensation. Inventories of parts that are currently available from past testing or from the shuttle or ISS inventory of parts may be sufficient for such a test. One side of the CO₂ HX would be connected to a flowing source of cryogenic liquid such as LN₂ to simulate predicted radiation of heat to deep space.

VI. Rejection of heat from cryogenic propellant could avoid temperature increase thus avoiding the need to vent propellants.

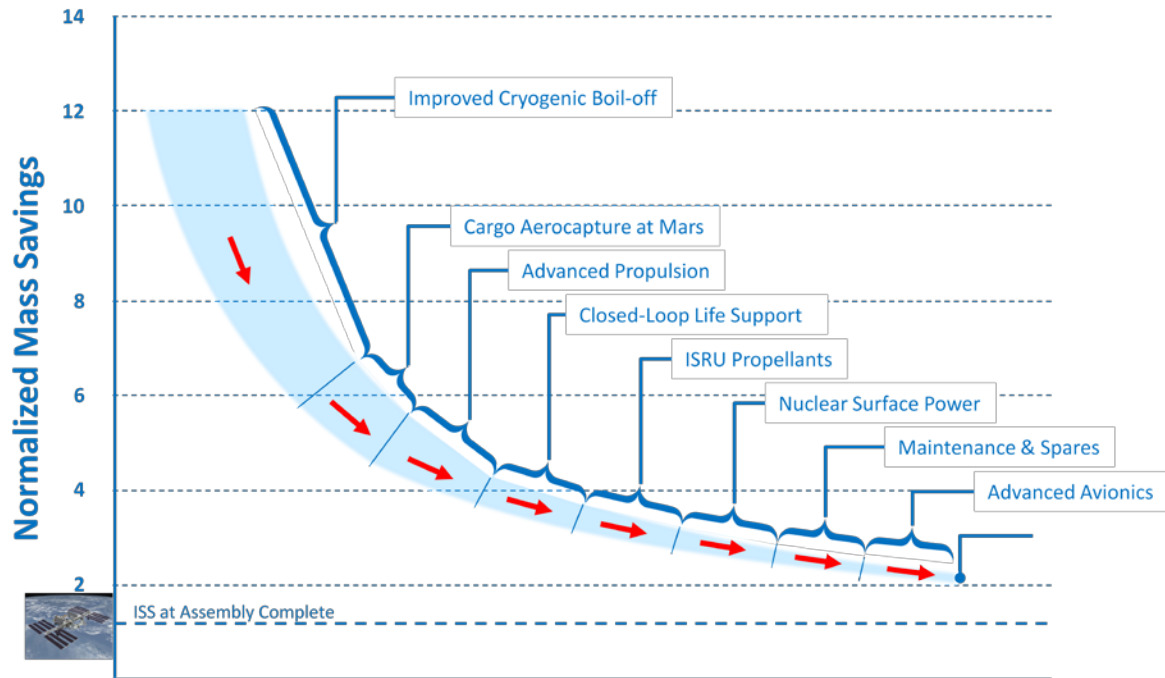
A major concern for deep space missions is the need to store propellant at cryogenic temperatures for long periods. Cryogenic storage of propellants has to address the needs to isolate the propellant from the ambient environment because the temperatures that are required to keep propellants in liquid cryogenic state are very low. Propellant tanks are very well insulated to avoid heat leak into the propellant. However, some heat is predicted to leak into the propellant due to the average environment temperature (versus the very low cryogenic fluid temperatures) and due to localized heat shorts. Cryogenic propellant tanks circulate liquid propellant to prevent the possibility of localized heating that could result in vaporization. (confirm with Studak)

Table 2 provides some insights into the temperatures that are required to store likely propellants of Liquid Oxygen (LOX), Liquid Hydrogen (LH2) and Liquid Methane (LM).

Properties of potential Deep Space Mission Propellants					
(at 14.7 PSIA pressure)					
Propellant	Boiling Point Temperature			Liquid Density	
	°K	°F	°C	kg/m3	
Liquid Hydrogen (LH2)	20	-423	-252	68	
Liquid Oxygen (LOX)	90	-297	-183	1141	
Liquid Methane (LM)	111	-259	-162	422	
For comparison					
Liquid Nitrogen (LN2)	77	-321	-196	808	

Table 2 – Properties of Selected Potential Deep Space Mission Propellants

NASA studies of exploration architectures have shown that the total vehicle mass needed to conduct exploration missions is prohibitive given current technologies for conducting such missions. A large portion of the total mission mass is the propellant needed to reach a destination then safely return to Earth, all of which must be onboard the vehicle at Earth departure. A significant portion of the propellant needed at Earth departure is required because predictions of the thermal environment of the propellant storage tanks show that much of the propellant needed for later mission activities will boil-off and must be vented to maintain tank pressures.



- Without technology investments, the mass required to initiate a human Mars mission in LEO is approximately twelve times the mass of the International Space Station
- Technology investments of the type proposed in the FY 2011 budget are required to put such a mission within reach

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Figure 5 - The importance of addressing the boil-off of propellant for long duration missions such as a mission to Mars is illustrated via the estimated mass savings that eliminating boil-off would provide – 6 times the mass of ISS.

Current approaches to avoid the need for venting propellants use cryo-coolers to cool propellant via a refrigeration cycle. Cryo-coolers use energy to pump a two-phase coolant to remove heat from the propellant via evaporation of the coolant in a heat exchanger. Cryo-coolers are heavy and use a significant amount of energy to keep propellant within temperature limits.

University of Texas at Austin senior design team study of deep space cooling to avoid venting

In the fall of 2010, a University of Texas at Austin senior design team studied the possibility of rejecting heat to deep space to address the boil-off problem⁴. They designed a system that assumed a radiator was mounted external to propulsion tanks to reject heat to the deep space environment. They connected the radiator to a coolant loop that cooled a heat exchanger mounted in the prop tank. The HX cooled the prop to maintain temperatures below that that would require boil-off.

The heat leak for NASA's preliminary design for a lunar sortie mission for the phases of the mission and the design of propellant storage tanks was used to calculate the heat rejection required from the radiator system and thus to size the radiators. The radiator size and the calculations of other system needed resulted in an estimate of the weight of the system.

The team evaluated the potential for long term storage for the 3 propellants identified above and concluded that it was possible to address cooling of liquid propellant via deep space cooling for LOX and LM but that the efficiency of such a system would be too low if rejection is required to address the very low temperatures required for LH2 storage. Thus this approach is feasible for propellant systems using LM and LOX (referred to as Methane/LO2 or MOX) systems. Another approach would be required for long term storage of LH2 if that propellant is employed.

The UT study evaluated the heat leak of propellant tanks for a lunar sortie mission and calculated the resulting propellant venting required to maintain required internal conditions. The team sized the radiator and HX and

developed a trade of how long the storage period would be when this system is more cost effective than a cryo-pump cooled system. They concluded that, if the mission requires more than 9 months, it is cost effective to employ deep space cooling.

The study established the potential of the concept for employing the deep space environment to address temperature control of stored propellant.

NASA Evolution of the Concept

NASA review of the UT study identified several facets of the assumptions and the approach where changes could result in a better performing connection to the deep space heat sink. The most promising alternative to the UT design concept uses a circulation pump in the propellant tank to flow propellant across a wall of the tank that is designed to radiate to deep space. This concept should simplify the connection to deep space and make the heat exchange more efficient since no dedicated HX or coolant loop and no penetrations of the propellant tank are required.

The evolved concept uses a direct connection of a section of the pressure vessel itself to reject heat to deep space. That section of the tank would have a flap that covers that area that would provide insulation during launch and other phases when deep space viewing is not available. When deep space viewing is available, the flap would be mechanically deployed to expose the section of the tank. The internal tank pump would operate completely within the tank and would address:

- 1) Cooling to deep space via convectively exchanging heat between the circulating propellant and the wall
- 2) Circulating propellant within the tank to address the potential that localized heat leaks could produce pockets of heated propellant.

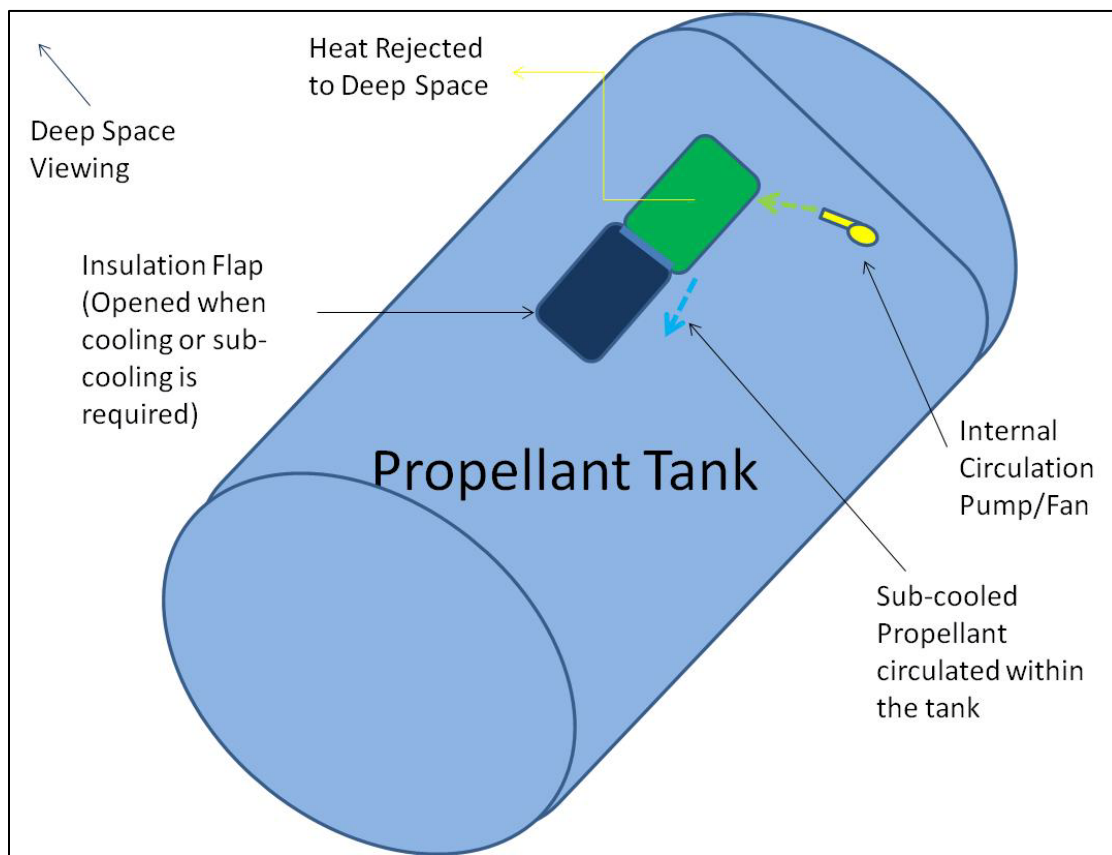


Figure 6 - The concept for cooling cryogenic propellant for long duration storage during deep space missions (or at storage facilities) for LOX or LM prop storage tanks.

NASA is proposing further study of this concept with the intent to show that such a system concept would be cost effective versus cryo-coolers and other approaches for long duration storage of LOX and LM.

VII. The potential use of deep space-to-sun side temperature differences to produce power thermoelectrically

Power generation via use of the sun-to-shadow temperature differences can be realized by employing thermoelectric technology during a deep space missions. A top level study considered achievable temperature differences on sunlit and shadowed sides, the size and probable radiator surface characteristics of a deep space exploration vehicle was conducted. Calculations of the heat rejection capability of a representative vehicle radiator were addressed in a spreadsheet with results shown in Table 3. In talks with the JSC experts in thermoelectric power generation, it was established that an efficiency of conversion of around 6% can be achieved. Based on that conversion efficiency and the heat rejection capability the power that could be provided is also shown in Table 2.

Heat Rejection for Radiators to Support Power Generation					
Trad		Q	Power at 6% efficiency		
(K)	(F)	(kW)	(kW)		
100	-280	0.1518	0.0091		
150	-190	0.7685	0.0461		
200	-100	2.429	0.1457		
250	-10	5.9302	0.3558		
300	80	12.297	0.7378		
350	170	22.782	1.3669		
400	260	38.864	2.3319		
(Heat Sink Temperatue assumed to be 13 Deg K (-436 F))					
(Epsilon = 0.9; Area = 35 m2; Fin efficiency - .85)					

Table 3 – Heat rejection for a deep space vehicle that could be used to support thermoelectric power generation

Based on this set of calculations and a photovoltaic power generation efficiencies of nearly 30% currently; it is unlikely that generation of power via thermoelectric power generation will trade well even for deep space vehicles.

Other ways to use the potential difference in sun side versus deep space thermal conditions such as described in a Batelle Study for Lunar surface Systems⁷ is probably a better way to address energy storage

VIII. Practical Considerations on Use of Deep Space Cooling

To employ deep space cooling to perform the functions described requires that the whole deep space mission be considered. Launch and operations that are conducted near earth need to be considered in addition to the mission phases where deep space viewing is available. Deep Space Habitat (DSH) attitude must also be considered as will the vehicle architecture.

During launch and operations near earth the environment for a deep space habitat will be affected by the proximity to Earth. This phase of mission operations has not been defined in detail on Concept of Operations (COO) to date. It could be a transient phase only with the vehicle in a passive transportation mode or there could be a period of checkout near Earth to verify readiness of the vehicle prior to departing Earth vicinity. The functionality of the DSH and thus the requirement for operation of a deep space cooling system would depend on the COO implemented for a particular mission. It is possible that vehicle attitude constraints could be implemented during this period to address the need to function using the deep space cooling systems. Alternatively, CO constraints could be imposed that don't require full operation of deep space viewing dependent systems. Alternatively the short duration transient thru the Earth vicinity could make the period of time in that environment inconsequential to vehicle operational. Some of those same concerns would pertain to operations near destinations such as the moon, an asteroid or Mars.

Vehicle attitude is expected to be dominated by solar power orientation requirements. Solar arrays could be articulated to allow the vehicle attitude flexibility; however it is unlikely that vehicle attitude will not be constrained by the need to orient solar arrays toward the sun. Vehicle angles to the sun will probably vary during transit due to the change in flight path to and from a destination. Angles will be different as the vehicle leaves the vicinity of earth

than they will be during the return to Earth transit. The side of the vehicle that faces deep space will need to be considered to take advantage of deep space cooling processes. Details of the mission scenario will have to be considered during mission planning for the impact attitude and proximity has on vehicle systems.

An alternate system might be employed during Earth proximity operations whereas more efficient deep space systems might be operated during the dominant part of missions wherein deep space cooling is available. Such redundancy might serve as dissimilar redundancy. A flow path leading to a CAMRAS CO₂ removal technology might provide such a function for the ARDSC concept.

Vehicle architecture would need to consider the need to view deep space when arranging module clusters since blockage of the view to deep space or influence by a module surface would affect heat transfer and the ability to achieve the thermal conditions intended.

The option of an articulated radiator to accomplish deep space viewing offers a potential solution to most of the concerns identified above. Such a system might also offer the possibility to reject heat from two sides of a radiator thus decreasing the size of radiators required. A trade of the complexity of an articulating radiator versus the flexibility provided is merited.

Lunar missions could benefit from deep space viewing available in the up direction continuously for polar locations. Indeed Lunar outpost at polar locations was the first time the ARDSC concept was considered for. For lunar equatorial locations, thermal control will be a challenge (as discussed in reference 1).

For environments wherein deep space viewing is a challenge; a possible solution might be to use a cryo-cooler technology to temporarily address the environment transient.

IX. Summary and Conclusions

Use of deep space cooling to address vehicle thermal control will provide an efficient way to control vehicle conditions. Several concepts for using the unique quality of long duration low temperature cooling have been described with some engineering approaches. Engineering facets that will need to be considered when employing deep space cooling approaches were addressed but are viewed as challenges that can be addressed.

The Air Revitalization via Deep Space Cooling concept was presented with some technical detail. The approach is feasible and offers many potential benefits (versus more historical air revitalization approaches). The ARDSC approach will provide a very high purity of CO₂ for recovery of the O₂. The approach is very robust and would result in a very simple and regenerable system. Further study of the ARDSC concept is advocated to experimentally validate the concept that could become a viable alternative to current humidity and CO₂ removal technologies.

Deep space cooling to address propellant long duration storage required for exploration missions could provide a solution that would eliminate the need to vent propellant with a low power and weight system that is robust and simple. Assessment of the characteristics of potential propellants leads to the conclusion that Liquid Methane would be much easier to store for long duration missions than Liquid Oxygen.

Top level evaluation of the potential use of sun side to shadow side thermal gradients established that the use of thermoelectric power generation is feasible. However, the efficiency of such a system would make that approach to vehicle power generation inferior to photovoltaic power generation.

Use of the ambient environment during deep space missions can provide important alternatives to traditional approaches to air revitalization and propellant thermal maintenance.

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