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Working Fluid and Material Selection for Heat Pipes and Vapor Chambers for use in Air-Cooled Temperature Swing Adsorption Compression Systems

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An Air-Cooled Temperature Swing Adsorption Compressor (AC-TSAC) has been identified as the preferred CO_2 removal system for use in future missions due to its ability to be effectively integrated with other carbon dioxide (CO2) removal technologies. The AC-TSAC compresses CO_2 by thermally cycling an adsorbent material from 20 °C to 200 °C. In this process, temperature uniformity is an important parameter in governing the system efficiency. As a result, because of their low mass and a high effective thermal conductivity, heat pipes and vapor chambers (HP/VC) have been projected for use in the new AC-TSAC design. This will require that the HP/VC's be designed to operate in the 20 °C to 200 °C temperature range. An important first step in this design process is the identification of working fluids and envelope materials that can be used for the HP/VC across this temperature range. In this paper, a detailed selection process was developed in order to identify potential working fluids and envelope materials for HP/VC. Comparison criteria are established, and identified and several potential design solutions are then presented and compared.

Nomenclature

AC-TSAC = Air-Cooled Temperature Swing Adsorbent Compression System
ARC = Ames Research Center
ARS = Atmosphere Revitalization Subsystem
CDRA = Carbon Dioxide Removal Assembly
CMS = Carbon Management Subassembly
CO_2 = carbon dioxide
CTE = Coefficient of thermal expansion
ECLSS = Environmental Closed-Loop Life Support Systems
ESM = Equivalent System Mass
HC = Vapor chambers
HMIS = Hazardous Materials Identification System
HP = Heat pipes
HP/VC = Heat pipes and vapor chambers
ISS = International Space Station
MultiSORB = Multifunctional Sorbent Devices
NASA = National Aeronautics and Space Administration
NCG = Non-condensable Gas
NFPA = National Fire Protection Association
SOA = State of the Art
TC-TSAC = Air-Cooled Temperature Swing Adsorbent Compression System
TSAC = Temperature Swing Adsorbent Compression System

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I. Introduction

Temperature Swing Adsorption Compressor systems (TSAC) are in development at the National Aeronautics and Space Administration (NASA) Ames Research Center (ARC) for both oxygen and carbon dioxide (CO_2) compression. These systems are projected for use in both short and long duration space missions. The TSAC operates on the physics of adsorption, where an adsorbent material is thermally cycled to capture and compress CO_2. The TSAC is projected for use aboard the International Space Station (ISS) in the Atmosphere Revitalization Subsystem (ARS). The TSAC will serve as the Carbon Management Subassembly (CMS), which is responsible for compressing, storing, and then delivering CO_2 to the Sabatier System[1]. The application of the TSAC is not limited to the ISS, as it can have other space or terrestrial applications. A mechanical compressor and accumulator, along with different TSACs, have been compared through various trade studies[2,3,4]. These studies have concluded that the Air-Cooled TSAC (AC-TSAC) has the lowest Equivalent System Mass (ESM) and is the preferred system for long duration space exploration missions. The AC-TSAC (Figure 1) has been shown to meet the CO_2 compression needs of the ARS through integrated testing at Marshall Space Flight Center[5].

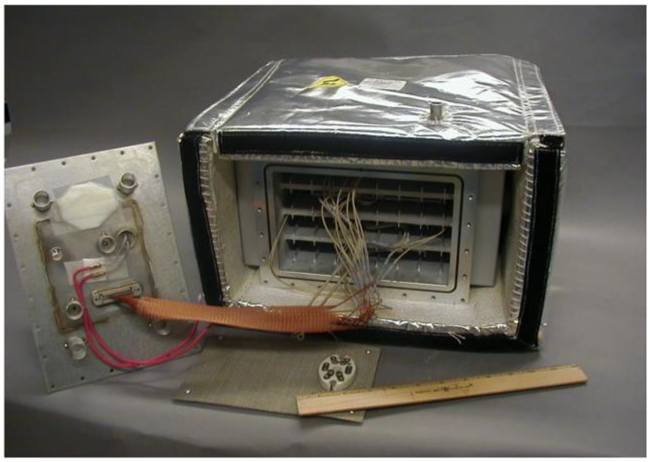

Figure 1. The AC-TSAC 2000 (photo credits Mini Varghese)

The operating cycle for an AC-TSAC is illustrated in Figure 2. Mulloth et. al.[6] outline the four stages of AC-TSAC operation: adsorption, compression, production, and decompression. During adsorption, the AC-TSAC adsorbs CO_2 at low pressure from an upstream system. During compression, the CO_2 is pressurized by isolating the AC-TSAC and heating the adsorbent material, which desorbs the CO_2. As the temperature and pressure are increased, the AC-TSAC outlet is opened, and CO_2 desorbs into the downstream system during the production stage. After the delivery of the high-pressure CO_2, the decompression stage begins. The AC-TSAC is air-cooled to ambient conditions, allowing the adsorbent to adsorb the incoming CO_2 feed. When operating downstream of the Carbon Dioxide Removal Assembly (CDRA), the AC-TSAC absorbs CO_2 at low pressure (approximately 100-200 torr) and delivers it to the Sabatier at higher pressure (approximately 1000-1500 torr). The driving force for CO_2 desorption is the temperature and therefore relies on the ability of the AC-TSAC to transfer heat quickly and uniformly. Temperature uniformity during the heat addition and rejection processes is important for obtaining a higher working capacity[7], which in turn decreases the needed amount of sorbent material. It is also important to ensure the adsorbent bed remains leak proof and free from contaminants and other substances, such as water, which can compete with CO_2 on the adsorbent material surfaces. In the current AC-TSAC, the adsorbent is thermally cycled from 20˚C to 200˚C. To be competitive with state of the art (SOA) systems, the peak power must not exceed 300 Watts (the SOA AC-TSAC peak power[9]).

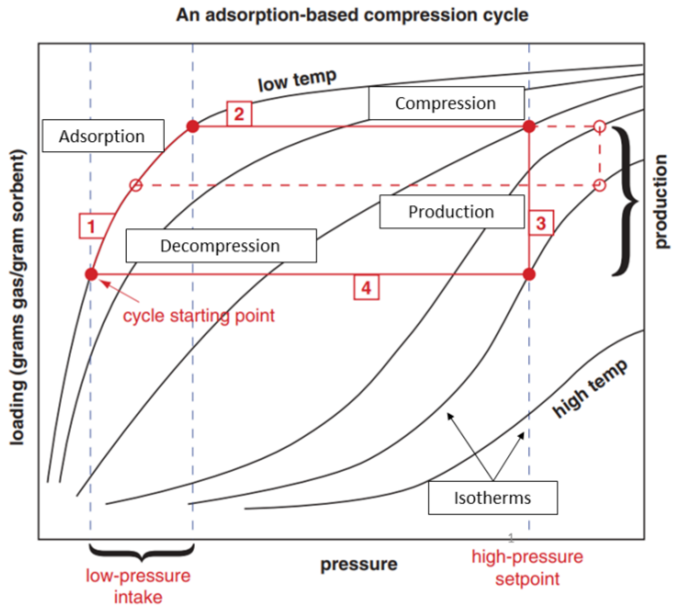

Figure 2. Operating cycle for an Air-Cooled Temperature Swing Adsorption Compressor[6]

The AC-TSAC design has undergone several developmental stages[4,8] at NASA ARC. To reduce ESM, efforts have focused on decreasing the power consumption and improving temperature uniformity in the adsorbent material during thermal cycling of the AC-TSAC[9]. The design of the Thermally-Coupled TSAC (TC-TSAC) uses concentric cylinders so the TSAC can leverage the otherwise lost heat from the CO_2 adsorbent bed. Preliminary testing of the TC-TSAC using this approach demonstrated improved (i.e., reduced) power consumption[3]. However, the TC-TSAC adds complexity to the CO2 removal bed as hardware designs must account for an additional TSAC bed "wrapped around" the CO2 removal bed. The AC-TSAC bed has the advantage of being a stand-alone system and can therefore be integrated with any CO_2 removal system. Additional challenges faced in pellet-based adsorbent beds include inherent disadvantages such as dusting, attrition, channeling, and difficulty encountered during bed loading. An alternative approach to packed beds that could alleviate some of the current difficulties is the use of Multifunctional Sorbent (MultiSORB) Devices. MultiSORB uses zeolite paste formulation to develop sorbent materials that are fabricated into sorbent lattices either via additive manufacturing or slip/freeze casting to produce custom adsorbent lattices[10]. Custom lattice designs characteristics include custom air flow paths with minimal pressure drops, minimized channeling, and decreased contact resistance between the heaters and sorbent materials. Printed MultiSORB adsorbent lattices are shown in Figure 3. The MultiSORB devices will include embedded heaters and sensors to improve contact between the sorbent materials and the sensors and heaters, further optimizing adsorbent bed performance.

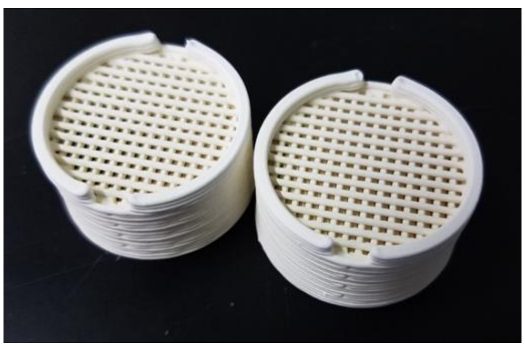

Figure 3: Printed MultiSORB 13X zeolite adsorbent lattices (1" diameter and ½" height)

For long term missions where resources are limited, increasing reliability while minimizing the ESM, power, mass, and volume will support mission success. Based on the design goals for the ARS and the Environmental Control and Life Support System (ECLSS)[11], any new AC-TSAC design must be simple, reliable, and robust. Considering these design objectives, the use of heat pipes and vapor chambers presents a viable alternative for distributing and rejecting heat throughout the adsorbent material.

Heat pipes and vapor chambers (HP/VCs) consist of a saturated fluid enclosed in an envelope material. Through the latent heat of evaporation and capillary action, these devices can transfer heat with an effective thermal conductivity significantly higher than any known solid conductors[12]. HP/VCs (Figure 4) are lightweight, passive, and reliable, when properly designed for the intended application. Heat pipes are typically cylindrical devices that transport heat axially (1-D) and can be flattened and bent for better integration into different assemblies. Vapor chambers can transport heat planarly (2-D) and can be made to be thin and flexible. Other types of heat pipes exist as well[13]. These include loop heat pipes, variable conductance heat pipes, and pulsating heat pipes, each having their own more specialized application. Only capillary driven heat pipes and vapor chambers are considered in this paper.

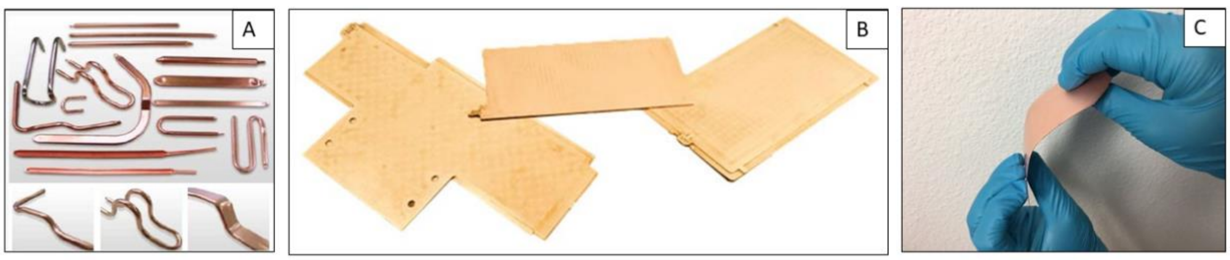

Figure 4. (a) Heat Pipes of different shapes, sizes and configurations[14] (b) Typical vapor chambers[15] (c) Ultra-thin and flexible vapor chambers[16]

AC-TSAC design criteria requires that the HP/VC be capable of operating from 20˚C to 200˚C and be consistent with the design goals for the ARS. It is particularly important for the HP/VC to be lightweight to trade well with the SOA. Few common lightweight HP/VC solutions exist for this temperature range; therefore, one goal here is to identify and compare different working fluids and envelope material combinations that can be used through a detailed selection process. This paper will discuss the material selection for HP/VCs for use in ECLSS applications.

II. Operating Principles for Heat Pipes and Vapor Chambers

Heat pipes and vapor chambers operate on the same working principles. A diagram of the key components for HP/VCs is shown in Figure 5. This includes the envelope, wick structure, vapor space, and working fluid, which can be divided into the evaporator, adiabatic, and condenser regions. When heat is added to the evaporator region, it travels through the envelope and into a liquid-saturated wick. The increase in temperature results in vaporization of the liquid and a concomitant increase in pressure. The resulting high pressure, high temperature vapor travels to the low pressure, low temperature, condenser regions. When the vapor reaches the cooler, condenser region, it condenses, releasing the latent heat. A capillary pressure, created by the difference in the curvature of the meniscus in the evaporator and condenser wick structure, drives the liquid back to the evaporator region where the process continues. The adiabatic region is the insulated space between the evaporator and condenser regions where no heat transfer occurs between the working fluid and the envelope.

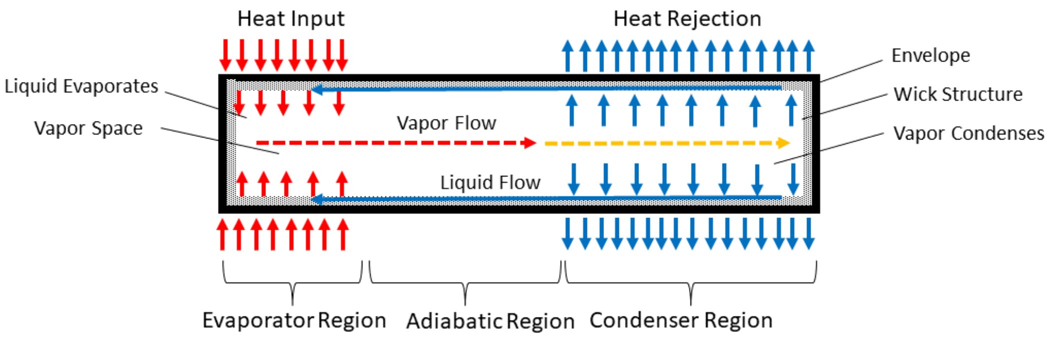

Figure 5. Heat pipe and vapor chamber working principles diagram

Because of the phase change process, HP/VCs can transport heat with an extremely high effective thermal conductivity. However, this is only true within the bounds of defined operating limits. These bounds include the capillary, sonic, viscous, boiling and entrainment limits, as outlined in Table 1. These limits define the maximum power that can be transported at a given operating temperature, and are dependent on the working fluid, envelope/wick material, wick structure, and size of the HP/VC. A more detailed description and modeling approaches for calculating these operating limits can be found in heat pipe textbooks such as those by Peterson[12], Kew and Reay[17], Zohuri[18], and Chi[19]. An example of HP/VC operating limits from Zohuri[18] is presented in Figure 6. General scenarios where each limit can occur are described by Nemec and Malcho[20], as well as a summary of modeling approaches. Avoiding these limits is an important part of the HP/VC design.

Table 1. Heat pipe and vapor chamber operating limits

Capillary Limit	The capillary pressure head provided by the wick structure cannot overcome the pressure drops from gravity, liquid flow through the wick, and vapor flow through the vapor space. This causes liquid in the evaporator region of the wick to dry-out, as it can no longer be replenished.
Sonic Limit	The vapor velocity approaches the speed of sound, and the flow becomes choked. This causes a large temperature to drop across the normally isothermal vapor region. The Sonic Limit usually occurs at low vapor pressures and high-power inputs.
Viscous Limit	This occurs at low vapor pressure, when the viscous forces cannot be overcome, and the vapor remains or becomes stagnant.
Boiling Limit	Liquid in the wick starts to boil, which can cause dry-out. This occurs at high heat fluxes.
Entrainment Limit	High shear forces from the vapor at the liquid-vapor interface causes entrainment. During entrainment, liquid in the wick is sheared into the vapor space and prevented from returning to the evaporator region.

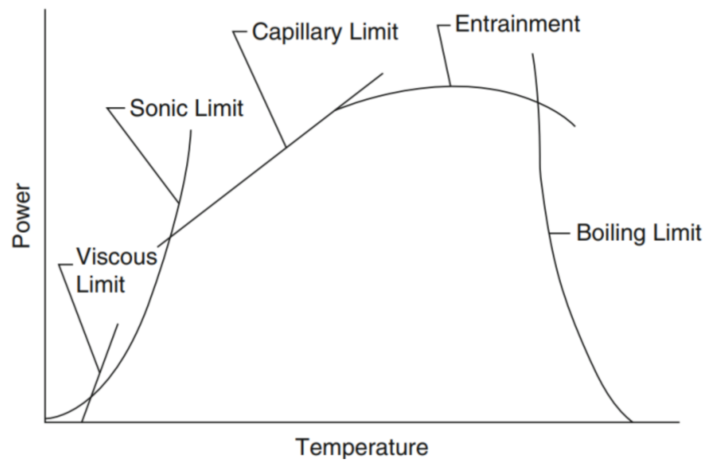

Figure 6. HP/VC operating limits[18]

III. HP/VC Working Fluid and Envelope Material Selection Requirements and Comparison Criteria

The focus of this paper is to identify and compare candidate working fluid and envelope combinations for HP/VCs applied to a new AC-TSAC design. The selection of the working fluid and envelope material is an important first step in the HP/VC design process, as outlined by Peterson[12]. Consideration must be given to the fluid's thermophysical properties, such as the triple and critical points, in addition to wettability with the wick material, and compatibility with the solid material used for the wick and envelope. The triple point and critical point define the absolute temperature limits over which a working fluid can be used, however, the actual operating temperature range is often well within these limiting conditions[12]. Factors such as poor surface tension or low vapor pressure constrain the working fluid into an approximate useful temperature range[12].

Using working fluids and solid materials that are not compatible often leads to corrosion and/or non-condensable gas (NCG) generation inside the HP/VC. Often generated by chemical reactions or fluid-solid decomposition, NCGs get swept into the condenser region of the HP/VC. This effectively blocks the vapor from the cooler, condensing region, resulting in a larger temperature drop and eventual failure. Corrosion of the solid material can be caused by fluid-solid reactions and can lead to structural failure, while corrosion of the wick structure can block pores and restrict the return of liquid to the evaporator. To establish compatibility between a working fluid and solid material, extensive life testing is required. During life tests, heat pipes are tested with different solid-fluid combinations at fixed temperatures for long durations of time. Fluid-solid compatibility is temperature-dependent and difficult to fully establish.

For a heat pipe or vapor chamber to be considered for AC-TSAC applications, the effective operating temperature range must fully include the AC-TSAC temperature cycle of 20 ˚C to 200 ˚C. The working fluid must also be compatible with the solid materials used in the interior for the wick and envelope up to at least 200 ˚C. Constraints for the AC-TSAC design must also be considered when selecting a working fluid and envelope material. For operation in spacecraft, the working fluid must be non-hazardous, and provides no serious concern for health, flammability, or physical hazard. To assess the safety of different working fluids, either the Hazardous Materials Identification System (HMIS) or the National Fire Protection Association (NFPA) system are used. In case the working fluid leaks into the bed, no serious reaction concerns should be present between the working fluid and air, water, oxygen, CO_2, aluminum, or stainless steel. The material used for the envelope must also be capable of withstanding a humid environment, as water is sometimes present in the process stream. The selection requirements are summarized below in Table 2, and dictate which working fluid and solid material combinations merit further consideration for HP/VCs applied to the AC-TSAC.

Table 2. Selection requirements for heat pipes and vapor chambers applied to a new AC-TSAC design

	Selection Requirements	Pass Condition
1	The useful temperature range of the identified working fluid must be compatible with the AC-TSAC temperature cycle	Capable of operating from 20 ˚C to 200 ˚C
2	The working fluid must be compatible with all present solid materials up to the maximum expected temperature for the AC-TSAC	Working fluid and solid materials are compatible to at least 200 ˚C
3	The working fluid must be appropriate to use in the AC-TSAC	Low HMIS or NFPA rankings and meets the reactions concerns
4	The solid material used for the envelope must be capable of withstanding a humid environment	Solid material must have a high corrosion resistance

Working fluids that meet or exceed the selection criteria can be compared using a "Merit number"[12]. The Merit number is calculated as $N_l(T) = \frac{\sigma\lambda\rho_l}{\mu_l}$, where $\sigma, \lambda, \rho_l, \mu_l$, are the surface tension, liquid viscosity, liquid density, and enthalpy of vaporization evaluated at temperature T, respectively. The Merit number is a temperature-dependent fluid property index and is derived from the capillary limit. It is used to compare the expected heat transport capabilities for different working fluids across a variety of temperature ranges. Having a higher Merit number indicates that for any given wick structure, the fluid can transport more heat before reaching the capillary limit.

Comparison criteria for various envelope materials includes the strength ratio and conductance parameter. The strength ratio is calculated as the yield strength divided by the density; and the conductance parameter is calculated as the thermal conductivity multiplied by the yield strength[19]. An envelope material having a higher strength ratio indicates that the HP/VC will be lighter. A higher conductance parameter indicates a smaller temperature drop across the envelope and wick structures, which will result in a higher effective thermal conductivity for the HP/VC. For application to the AC-TSAC, it is also of interest to have an envelope material with a smaller coefficient of thermal expansion (CTE), as this will help prevent damage to the adsorbent lattices (e.g. producing cracks). It is important to minimize power consumption for the AC-TSAC, therefore a HP/VC with a low thermal mass is preferred. The energy parameter is used to estimate this and is calculated as the specific heat multiplied by density over yield strength. Criteria for comparing envelope materials is summarized in Table 3 below.

Table 3. Comparison criteria for the envelope material

Maximize	Minimize
Strength ratio (yield strength/density)	Coefficient of thermal expansion (CTE)
Conductance parameter (thermal conductivity multiplied by yield strength)	Energy parameter (specific heat multiplied density over yield strength)

IV. Identification of Potential Working Fluids and Envelope Materials

Based on the useful temperature range of different working fluids, HP/VCs can be applied at high temperatures (> 400 ˚C), medium temperatures (270 ˚C to 400 ˚C), room temperatures (-70 ˚C to 270 ˚C) or cryogenic temperature (-270 ˚C to -70 ˚C)[21]. Room temperature working fluids are of interest for AC-TSAC applications. Other working fluids, such as those for high temperature HP/VCs, do not have an appropriate or useful temperature range for applications in the AC-TSAC. Common working fluids for the room temperature range include ammonia, methanol, acetone, and water[21]. The useful temperature range for each of these working fluids have been reported by Advanced Cooling Technologies (ACT)[22] and are summarized in Table 4. Note that few common solutions exist for the temperature range of 20 ˚C to 200 ˚C. Water is often used with copper from 20 ˚C to 150 ˚C, however at higher temperatures a copper envelope is not capable of containing the high saturation pressures associated with water[23]. The compatibility of water with Monel and titanium was developed through more recent life tests by Anderson et. al.[24] and Rosenfeld J. H. & Gernert N. J.[25] with the intent of expending the useful temperature range of water. Life tests using other working fluids and envelope materials have been done as well, presented by Anderson et. al. [26].

Table 4. The useful temperature range for common room temperature heat pipes or vapor chambers[22]

Working Fluid	Envelope Materials	Useful Temperature Range
Ammonia	Aluminum, Steel, Stainless Steel, Nickel	-65 ˚C to 100 ˚C
Methanol	Copper, Stainless Steel	-60 ˚C to 100 ˚C
Acetone	Aluminum, Stainless Steel	-50 ˚C to 100 ˚C
Water	Copper, Nickel, Monel, titanium	20 ˚C to 280 ˚C *Copper has poor strength beyond 150 ˚C

Considering the life tests for water[24,25], water has been shown to be compatible with commercially pure titanium, titanium alloys (such as 15-3), Monel K500, Monel 400, Nitinol-titanium alloy, and 70/30 cupronickel at temperatures beyond 200 ˚C. Due to high stress creep at elevated temperatures, the use of commercially pure titanium is not recommended beyond 200 ˚C[25]. Titanium alloy 15-3 was suggested as the preferred material due to its high strength to mass ratio[25]. More recent life tests have continued to show compatibility between water and titanium, its alloys, Monel K500, and Monel 400[26]. Water and the previously mentioned envelope materials agree with the selection requirements in Table 2.

An expansive set of other potential working fluids has been presented previously by Anderson et. al.[26]. The fluids considered include pure elements, organic fluids, and halides. The elements considered are sulfur and mercury, however neither fluid is applicable to the AC-TSAC due to their high triple points. Toluene, an organic fluid, has been shown to be compatible with mild and stainless steel up to 250 ˚C, titanium up to 250 ˚C, and copper or nickel up to 280 ˚C. However, toluene poses health hazards and is highly flammable[27]. Other organic fluids, such as naphthalene, do not have a low enough triple point to be applicable. Similarly, the use of Dowtherm A is not recommended below 200 ˚C[22]. N-octane has a suitable triple and critical point and was shown to be compatible with mild and stainless steel up to 230 ˚C and 250 ˚C, respectively. However, n-octane is highly flammable and can form explosive mixtures with air[28], and is therefore not suitable for AC-TSAC applications. For halides, titanium chloride ($TiCl_4$) has agreeable triple and critical points and was shown to be compatible with titanium up to 227 ˚C and with Hastelloy up to 300 ˚C. However, $TiCl_4$ is not applicable to the AC-TSAC, as it can be fatal if inhaled and reacts violently with water[29].

Based on these results, water seems to be the most viable working fluid, with envelope materials shown in Table 5 below. Toluene provides some advantages over water, such as compatibility with stainless and mild steels, and is not as hazardous as other working fluids such as $TiCl_4$ and n-octane. However, toluene is still a hazardous working fluid, and is not ideal for AC-TSAC applications in ECLSS. Toluene may be a possible solution for HP/VC applications in systems with less constrictive safety requirements, and so it is further assessed for comparative purposes.

Table 5. Potential fluids and envelope materials

Working Fluid	Compatible Envelope Materials From Life Tests up to at Least 200˚C
Water	Copper, Copper-Nickel, Monel 400, Monel K500, titanium (CP-2, Grades 5, 6, 7, 9), Beta-titanium alloy 15-3, Nitinol
Toluene	Mild Steel (ST 35, 13CrMo44), Stainless Steel (SS 316), Copper-Nickel, titanium (CP)

V. Comparison of Identified Working Fluids and Envelope Materials

The Merit number of water and different working fluids are highlighted in Figure 7Figure 7. Notice that water has a significantly higher Merit number than other fluids over the temperature range of interest, 20 ˚C to 200 ˚C, which is approximately 290 K to 470 K. This indicates that water will be capable of transporting more heat at a given temperature then the other working fluids. However, a disadvantage of using water at higher temperatures is its high saturation pressure. At 200 ˚C, the saturation pressure of water is 15.3 atm. This poses structural challenges to the HP/VC design, as the envelope needs to contain this high pressure without bursting or pillowing out. By adding structural support columns, ribs, or thicker walls, containing this pressure will result in a heavier VC/HP.

Anderson et. al.[26] pointed out several unique advantages of using toluene over water, even though water has a Merit number about 50 times larger. Toluene is compatible with mild and stainless steel in addition to titanium and copper-nickel, giving more options for wick and envelope materials. At 200 ˚C, toluene has a saturation pressure of 7.4 atm, which is almost half that for water (15.3 atm). A HP/VC using toluene would be lighter than one using water, as less envelope material and support structures would be needed to contain the saturation pressure. This shows that having a higher Merit number does not always imply that a particular working fluid is ideal for the HP/VC, as other design factors need to be considered. As mentioned, toluene is hazardous and not suitable for HP/VC in the AC-TSAC for ECLSS applications. However, based on these advantages, it would be beneficial to consider toluene for other HP/VC applications at 20˚C to 200˚C with less restrictive safety requirements.

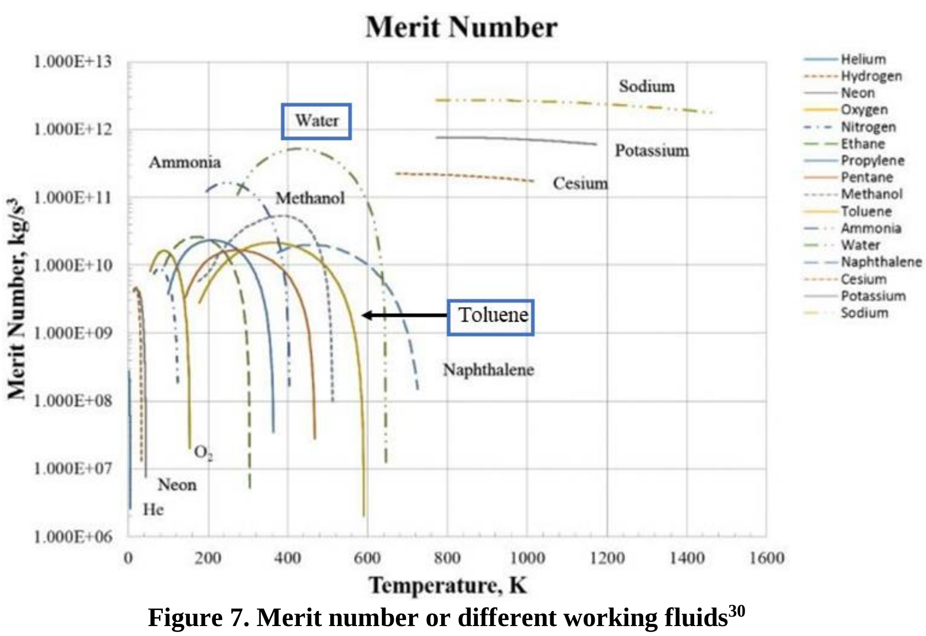

Figure 7. Merit number or different working fluids[30]

Potential envelope materials were compared using the criteria in Table 3 through Ashby charts made using GRANTA EduPack. The strength ratio and conductance parameter for different material groups are compared in Figure 8. As expected, copper has a high conductance parameter but poor strength ratio. Aluminum is the ideal material; however, it is unfortunately not compatible in the desirable temperature range. Titanium alloys have a higher strength ratio than steels or nickel-based superalloys such as Monel 400 and Monel K500, and the conductance parameter of titanium alloys is comparable, due to its lower thermal conductivity. Commercially pure titanium was comparable to steels and nickel-based super alloys. Based on this, from a material properties point of view, titanium alloys would be ideal. Although titanium alloys do have a lower conductance parameter, for AC-TSAC applications having a higher strength ratio is preferred. Figure 8 also indicates that Monel and steel HP/VCs will have similar strength and thermal conductance characteristics. In Figure 9, the thermal mass parameter and CTE of different material groups are compared. Steels and nickel-based superalloys are comparable, while titanium alloys are particularly well suited for low thermal mass and low CTE. This indicates that an AC-TSAC using HP/VCs made from titanium alloys will be less power demanding and less destructive to the sorbent material. Monel and steel HP/VCs will have similar thermal mass and CTE characteristics.

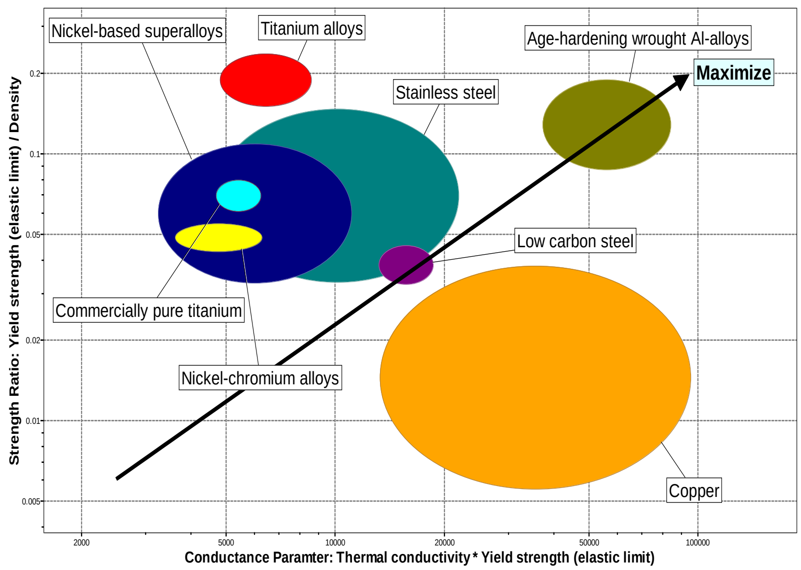

Figure 8. Ashby chart for strength ratio and conductance parameter

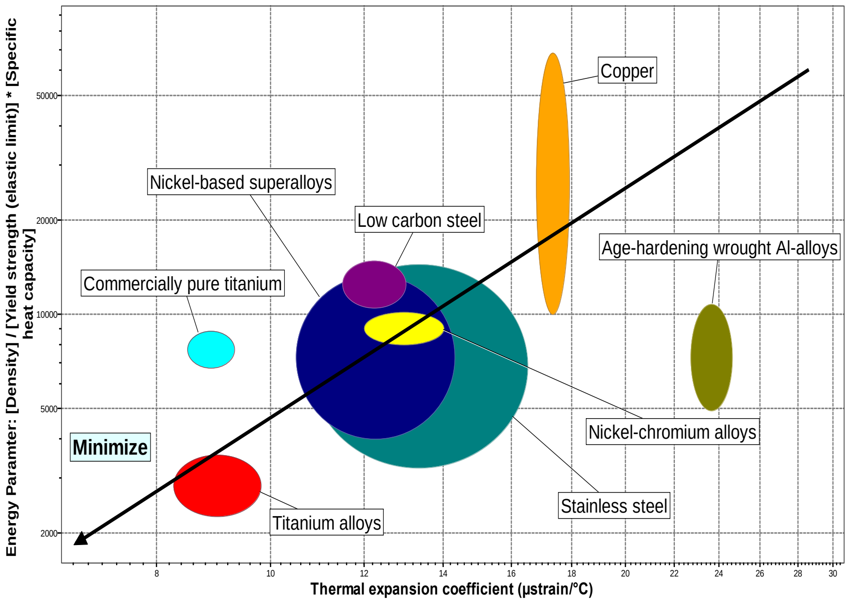

Figure 9. Ashby chart for energy mass parameter and CTE

As presented in Table 6, the yield strength of different alloys of titanium and Monel were compared by Anderson et. al.[24]. This comparison was done for temperatures of 26 ˚C and 256 ˚C, as for this application it is important to consider that materials decrease in strength with increasing temperature. At elevated temperatures, the use of pure titanium and Monel K400 becomes questionable due to their decreased strength. This indicates that a solution using pure titanium or Monel K400 may not be ideal, as more material will be needed compared to Monel K500 or titanium alloys. Both titanium alloys and Monel K500 maintained a high yield strength at 256 ˚C, however titanium alloys are more lightweight. For instance, Ti 15-3 has a higher yield strength at 256 ˚C and almost half the density of Monel K500. It can be concluded that Ti 15-3 or other titanium alloys appear to the preferred envelope material. This agrees with the conclusions made from Figure 8 and Figure 9.

Table 6. Material property comparison for titanium and Monel[24]

Material	Density (g/cm^3)	Condition	2% Yield at 256˚C, MPa	2% Yield at 26˚C, MPa
Monel 400	8.80	Annealed	193	220
Monel K500	8.44	Annealed	290	338
Monel K500	8.44	Annealed, then Aged	655	725
Ti CP-2	4.51	Annealed	150	280
Ti Grade 5			450	830
Ti Grade 6				790
Ti Grade 7				280
Ti Grade 9			360	480
Ti 15-3	4.76	Annealed	830	1140

Some examples of the development of lightweight HP/VCs are given by Yang et. al[21]. Titanium water heat pipes have been applied for the design of space radiators[31] at similar operating temperatures as the AC-TSAC. The development of this application involved a similar comparison of potential working fluids and envelope materials[32]. In this comparison, it was concluded that although other working fluids, such as toluene, offer the advantage of a lower vapor pressure and could be used for a more lightweight design, the use of water with titanium or Monel is a safer and more established solution. For example, titanium water heat pipes are used in gallium nitride power amplifiers at temperatures up to 150 ˚C[33]. These titanium heat pipes were 3D-printed and tested, and it was decided that using titanium would result in a more lightweight heat pipe when compared to Monel.

VI. Conclusions and Future Work

The high effective thermal conductivity of HP/VCs can help establish a more isothermal temperature distribution throughout the adsorbent bed, which would significantly improve the operating characteristics and overall efficiency of the current AS-TSAC design. The previous discussion has focused on identifying and comparing potential working fluid and envelope material combinations for HP/VCs. Working fluids and envelope materials were assessed through selection requirements and comparison criteria to identify the HP/VC solutions most appropriate for the AC-TSAC.

After reviewing the compatibility of different working fluids and envelope materials, water was determined to be the only viable working fluid for using HP/VC in an ECLSS environment. Water was shown to be compatible with copper, Monel, titanium, and titanium alloys across the expected temperature range for the AC-TSAC. Water is an effective working fluid, as indicated by its high Merit number, however it has a high saturation pressure. This can be difficult to contain and will result in a heavier HP/VC. Other working fluids were addressed; however, all were too hazardous for ECLSS applications. One such fluid was toluene, which could be a viable working fluid for HP/VC applications at 20 ˚C to above 200˚C in systems with less restrictive safety requirements than the AC-TSAC. Using toluene can result in a lighter HP/VC due to its lower saturation pressure and it can also be used with stainless and mild steels.

Different candidate envelope materials were compared and indicated that for water HP/VCs, the preferred envelope material will be a titanium alloy, such as 15-3. Titanium alloys are strong, lightweight, and can handle operating up to 200 ˚C without a significant decrease in strength. Monel K500 was also identified as a viable envelope material, however it is significantly heavier than the considered titanium alloys. Only material properties were used to compare different envelope materials, and it would be beneficial to consider manufacturing difficulties or restrictions as well.

The next steps for HP/VC application to the AC-TSAC involve the development of conceptual designs. This will be focused on how HP/VCs can be effectively used for an improved AC-TSAC. Following this, more specifics on the HP/VC design can be determined.

VII. References

[1] Mulloth, L. M., & Finn, J. E. (2000). A Solid-State Compressor for Integration of CO 2 Removal and Reduction Assemblies (No. 2000-01-2352). SAE Technical Paper.
[2] Richardson, T. M. J. Carbon Dioxide Compression, Storage, and Delivery Trade Assessment. 2015. In 45th International Conference on Environmental Systems
[3] Richardson, T. M. J., & Jan, D. (2018, July). A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process. 48th International Conference on Environmental Systems.
[4] Richardson, T. M. J., & Jan, D. (2019, July). Current Development Status of the Temperature Swing Adsorption Systems and Updated Trade Study Results. 49th International Conference on Environmental Systems.
[5] Murdock, K. (2010). Integrated Evaluation of Closed Loop Air Revitalization System Components (No. M-1300).
[6] Mulloth, L. M., Affleck, D. L., Rosen, M., LeVan, M. D., Wang, Y., & Cavalcante, C. L. (2004). Air-cooled design of a temperature-swing adsorption compressor for closed-loop air revitalization systems. SAE transactions, 685-691.
[7] Moate, J. R., & LeVan, M. D. (2010). Temperature swing adsorption compression: effects of nonuniform heating on bed efficiency. Applied thermal engineering, 30(6-7), 658-663.
[8] Alcid, M., Jan, D., Kan, K., Richardson, T.J..(2021, July).Air-Cooled Temperature Swing Compression System Rebuild 2021. 51th International Conference on Environmental Systems.
[9] Mulloth, Lila M., Mini Varghese, and B. J. A. Luna. "Power Optimization Options for a Temperature-Swing Adsorption Compressor Design." AIAA 6037 (2010): 2010.
[10] Richardson, T.J., Peterson, K., Boghozian, T., Klar, G., Lesh, A., (2022, July). Multifunctional Sorbent Devices Paste Formulation and Fabrication Techniques. 51st International Conference on Environmental System.
[11] Jernigan, M., Gatens, R., Perry, J., & Joshi, J. (2018, July). The next steps for environmental control and life support systems development for deep space exploration. 48th International Conference on Environmental Systems.
[12] Peterson, G. P. (1994). An introduction to heat pipes. Modeling, testing, and applications. Wiley Series in Thermal Management of Microelectronic and Electronic Systems.

[13] Faghri, A. (2012). Review and advances in heat pipe science and technology. *Journal of heat transfer*, *134*(12).
[14] Image taken from Flat Sintered Copper Heat Pipe With Diameter 8mm - Buy Heat Pipe,Copper Heat Pipe,Computer Heat Pipe Product on Alibaba.com
[15] Image taken from Ultra Thin Vapor Chambers (boydcorp.com)
[16] Image taken from Kelvin Thermal - Thinnest and Most Flexible Cooling Solution
[17] Kew, P. & Reay, D. (2006). *Heat pipes*. Elsevier.
[18] Zohuri, B. (2011). Heat pipe design and technology. *FL: Taylor and Francis Group, LLC*.
[19] Chi, S. W. (1976). Heat pipe theory and practice: a sourcebook.
[20] Nemec, P., Čaja, A., & Malcho, M. (2013). Mathematical model for heat transfer limitations of heat javascript:void(0);pipe. *Mathematical and Computer Modelling*, *57*(1-2), 126-136.
[21] Yang, X., Yan, Y. Y., & Mullen, D. (2012). Recent developments of lightweight, high performance heat pipes. *Applied Thermal Engineering*, *33*, 1-14.
[22] Heat Pipe Material Compatibility for Fluid-Envelope-Wick| Heat Pipe Technology (1-act.com)
[23] High Temperature Water Heat Pipes | Heat Pipe Technology (1-act.com)
[24] Anderson, W. G., Dussinger, P. M., & Sarraf, D. (2006, January). High temperature water heat pipe life tests. In *AIP Conference Proceedings* (Vol. 813, No. 1, pp. 100-107). American Institute of Physics.
[25] Rosenfeld, J. H., & Gernert, N. J. (2008, January). Life test results for water heat pipes operating at 200 C to 300 C. In *AIP Conference Proceedings* (Vol. 969, No. 1, pp. 123-130). American Institute of Physics.
[26] Anderson, W. G., Tamanna, S., Tarau, C., Hartenstine, J., & Ellis, D. (2013). Intermediate temperature heat pipe life tests and analyses. In *43rd International Conference on Environmental Systems* (p. 3304).
[27] C364-20190529195156 (osha.gov) (Toluene safety sheet)
[28] msds (fishersci.com) n-octane safety sheet
[29] msds (fishersci.com) TiCl4 safety sheet
[30] Figure taken from Heat Pipe Working Fluids | Heat Pipe Technology (1-act.com)
[31] Lee, K. L., Tarau, C., Anderson, W. G., & Beard, D. (2020). Titanium-water heat pipe radiators for space fission power system thermal management. *Microgravity Science and Technology*, *32*(3), 453-464.

[32] Sarraf, D. B., & Anderson, W. G. (2006). High-temperature water heat pipes. In *IMAPS International Conference on High Temperature Electronics.–Santa Fe, NM:–may* (pp. 15-18).
[33] Ababneh, M., Tarau, C., & Anderson, W. (2019, July). 3D Printed Thermal Management System for the Next Generation of Gallium Nitride-based Solid State Power Amplifiers. 49th International Conference on Environmental Systems.