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Atmosphere Trace Contaminant Removal for Human Exploration

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As the commercial space industry grows, Environmental Control and Life Support Systems (ECLSS) are required to perform with more efficiency, using less power, holding less mass, and enveloping less volume. This is accomplished by implementing innovative designs and solutions while maintaining or increasing each system's effectivity. A system to remove atmospheric trace contaminants will be required for many human spaceflight programs in the future including space stations in Low Earth Orbit (LEO), Lunar surface habitats, Mars transit vehicles, and Martian surface habitats. This paper will explore design and operational choices which, when implemented, will produce a system to control gaseous trace contaminants that fulfills the needs of future human spaceflight programs.

Nomenclature

AC = Activated Charcoal
AR = Air Revitalization
CAD = Computer Aided Design
CCAA = Common Cabin Air Assembly
CDRA = Carbon Dioxide Removal Assembly
cfm = cubic feet per minute
CHARPA = Charcoal HEPA
ECLSS = Environmental Control and Life Support Systems
HTCO = High Temperature Catalytic Oxidizer
ISS = International Space Station
kg = kilogram
LEL = Lower Explosive Limit
LEO = Low Earth Orbit
LiOH = lithium hydroxide
LOC = Loss of Crew
LOM = Loss of Mission
m = meter
RSOS = Russian Orbital Segment
SMAC = Spacecraft Maximum Allowable Concentrations
TCCS = Trace Contaminant Control Subsystem
USOS = United States Orbital Segment
°C = degrees Celsius

I. Introduction

THROUGHOUT the build and expansion of the International Space Station (ISS), hardware to remove atmospheric trace contaminants has been present and operating. This hardware has primarily been suited to remove

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contaminants released into the atmosphere by off gassing and leaks from space station hardware. However, the same hardware can also be used to remove contaminants present through biological introduction into the spacecraft.

Early gaseous trace contaminant removal hardware on ISS was simple. Initially, Node 1 used “four activated charcoal beds that are direct retrofits of the cabin air particulate filters.”[4] The air was moved through these filters using the Node 1 cabin fan which is the primary ventilation fan for the module. Because mission durations were limited with times of dormancy (no human presence on ISS), the use of activated charcoal (AC) filters along with atmospheric dilution with visiting vehicles was deemed acceptable for removing sufficient trace contaminants to maintain a habitable atmosphere. Major downsides to using only AC filters include the time interval to saturation and the relatively small number of contaminants which AC alone is capable of removing.

Prior to the installation of the Trace Contaminant Control Subsystem (TCCS) on the United States Orbital Segment (USOS), a Russian Orbital Segment (RSOS) micro-impurity adsorption device known as БМП (or [BMP]) was available for more complete gaseous trace contaminant removal on ISS. Subsequently, the USOS TCCS was installed as a dissimilar gaseous trace contaminant removal system. Further reading on the performance of the RSOS and USOS trace contaminant removal devices can be found in several technical papers authored by Jay L. Perry. [1,2,4]

II. Background

The ISS TCCS has been discussed at length in many forums. Analysis of performance, failures, and some potential hardware upgrades have been discussed in detail. However, a brief summary of the USOS TCCS will provide a basic understanding of the hardware and operational modifications which could significantly improve its applicability to future human spaceflight missions.

As seen in Figure 1 below, the USOS TCCS is shown to contain an AC bed, a blower, a high temperature catalytic oxidizer (HTCO), a lithium hydroxide (LiOH) bed, and various sensors. Each of these components perform specific and necessary functions to remove gaseous trace contaminants at a very high single pass efficiency. The AC bed removes higher molecular weight contaminants, the blower provides air flow through the entire system, the HTCO uses high temperatures to oxidize the remaining gaseous trace contaminants, the LiOH bed removes low molecular weight contaminants which either pass through or are created by the HTCO (primarily the acid gases), and the various sensors provide data for system operation.

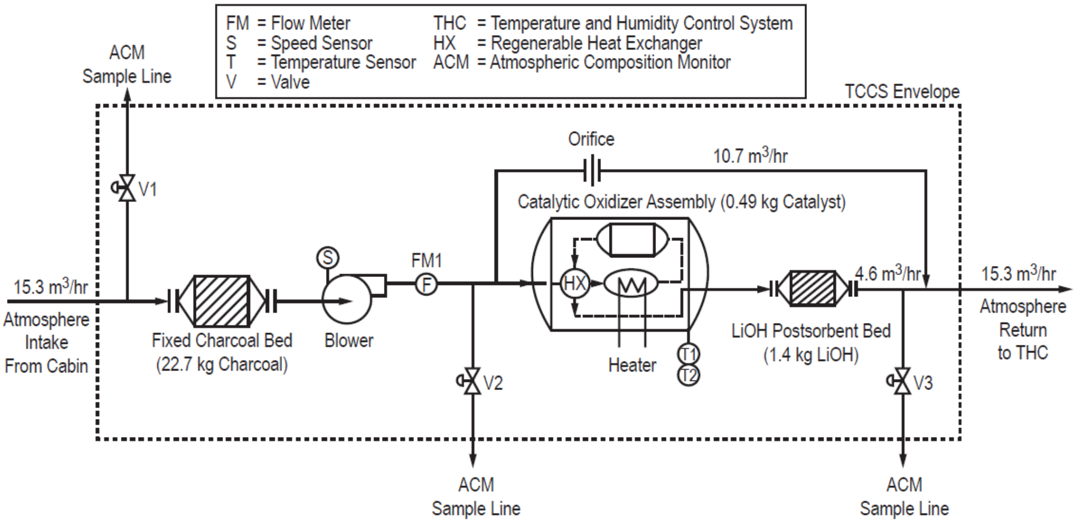

Figure 1. Simple functional schematic of the USOS Trace Contaminant Control Subsystem[1]

The USOS TCCS exhaust combines with the USOS Carbon Dioxide Removal Assembly (CDRA) within the Air Revitalization (AR) rack. This combined exhaust is then directed to the USOS Common Cabin Air Assembly (CCAA) for heat and humidity removal and distribution throughout the ISS.

III. Considerations

There are several aspects of the USOS TCCS which should be reevaluated in order to align the expectations of future human spaceflight opportunities. Human transport spacecraft have limited resources which forces all hardware to consider options to limit specifications such as volume, mass, power, and maintenance requirements. The specifications under review in this paper include catalytic oxidizer operational temperature, volumetric flow rate, catalytic oxidizer bypass, bed capacity, and component packaging.

A. Catalytic Oxidizer Operational Temperature

The USOS TCCS uses a HTCO downstream of the AC bed to oxidize gaseous trace contaminants that are not removed via the AC bed. In nominal operation of the USOS TCCS, the HTCO operates at a consistent temperature of 450 °C to oxidize methane at a greater than 90% single pass efficiency. The design driver of oxidizing methane is typically used because methane is one of the most difficult gaseous compounds to oxidize. Therefore, if a system can oxidize methane with greater than 90% single pass efficiency, it can be assumed all other compounds of interest are oxidized at the same or better single pass efficiency.

Gaseous methane can be introduced into an atmosphere in two primary ways: biologic introduction or a leak from hardware. Biological introduction of methane is primarily via flatulence or eructation from the crew or other living organisms. Based on previous research, the average combined emissions from breath, intestinal gases, and skin account for 27.96 mg/h or 671 mg/d for a single person for the 95% confidence interval upper bound.[2]

Air samples returned for analysis from ISS show the USOS TCCS capabilities far exceed the introduction rate to maintain methane levels well below SMAC. Therefore, an updated design could take advantage this by allowing the HTCO to operate at a much lower temperature during nominal operations and only intermittently operate at 450 °C. A discussion of the fundamental steps to determine the time to the spacecraft maximum allowable concentration (SMAC) for methane can be reviewed in a previously published paper.[3] Using the steps provided, each spacecraft and mission can be assessed independently to determine the time interval required for HTCO operation at 450 °C.

Analysis should also be completed to determine the lower operational temperature such that all gaseous trace contaminants are oxidized sufficiently to keep them below their respective SMAC. Special consideration should be given to identify potential byproducts created from the lower temperature HTCO operation.

Operation at a lower nominal temperature has the potential to reduce the overall power draw of a TCCS-like system significantly and would provide flexibility when to operate at the higher temperature. Variable temperature operation also allows for targeting removal of specific compounds such as aldehydes and ammonia and any other byproducts created from lower HTCO set points. Notional power draw for various operations plans can be seen in Figure 2, Figure 3, and Figure 4. These graphs demonstrate alternating between high and low temperature has the potential to provide significant power savings over time. Each of the graphs shows operational concepts spanning 90 days.

Operational Concept 1 shows a temperature plan which repeats every 15 days and consists of 14 days of lower temperature operations followed by one day at high temperature. The estimated power savings using this plan is approximately 20% over operating at high temperature for the entire 90 days.

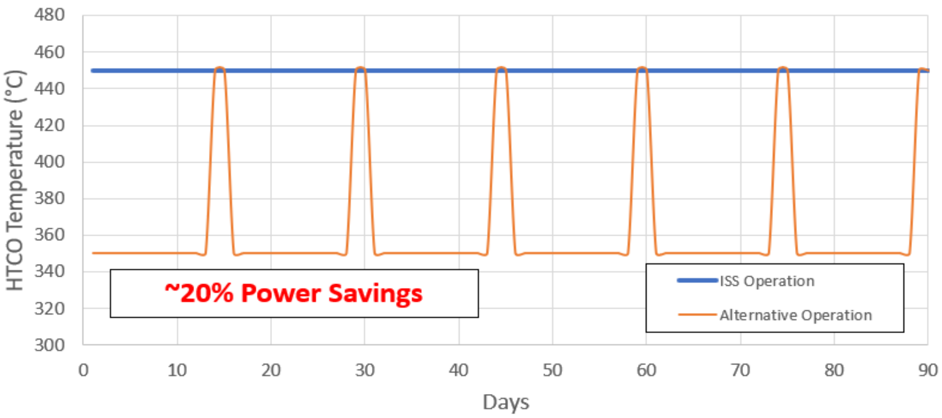

Figure 2. Operational Concept 1

Operational Concept 2 shows a temperature plan which repeats 30 days and consists of 29 days of lower temperature operations followed by one day at high temperature. The estimated power savings using this plan is approximately 21% over operating at high temperature for the entire 90 days.

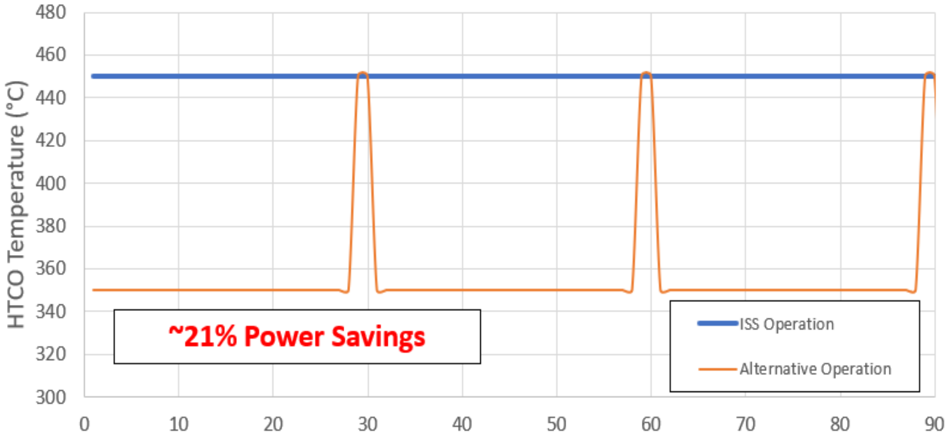

Figure 3. Operational Concept 2

Operational Concept 3 shows an operational plan which repeats 6 days and consists of 3 days of lower temperature operations followed by 3 days of high temperature. The estimated power savings using this plan is approximately 12% over operating at high temperature for the entire 90 days.

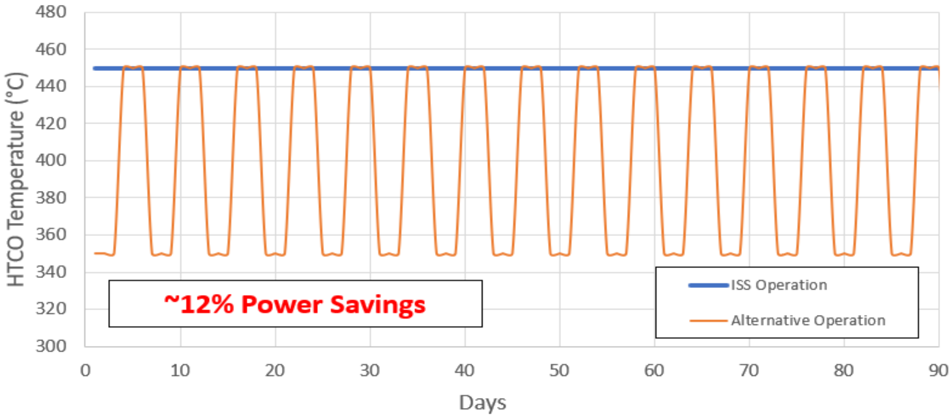

Figure 4. Operational Concept 3

These examples are only intended to show potential power savings and do not serve as a prescription for operations. Each individual mission or spacecraft should assess its operational needs while regularly analyzing atmosphere samples to ensure contaminants are well controlled. Adjustments to the operational plan should be incorporated as the environment changes.

B. Volumetric Flow Rate

In the current configuration of the USOS TCCS, the blower provides a total flow rate of 9 cubic feet per minute (cfm) – approximately 2.7 cfm through the HTCO and approximately 6.3 cfm through the HTCO bypass. The flowrate has been sufficient to maintain nominal gaseous trace contaminant levels below SMAC. However, evaluation of the flow rate through a TCCS-like system is imperative for optimizing its performance, mass, and power.

Evaluating flowrate should look at efficacy and blower requirements. Upon initial review, a slower flowrate may allow for a less robust blower (lower power required due to slower speed and lower delta pressure to overcome within the system), but will require more time to fully scrub gaseous trace contaminants from the atmosphere. A faster flowrate will likely require a more robust blower (higher power due to increased speed and higher delta pressure), but should require less time to fully scrub gaseous trace contaminants from the atmosphere. In general, a more robust blower has higher mass, higher volume, and requires more power to operate.

Considering this assumption, it is important to strike a balance between achieving a faster flowrate and respecting residence time of the system (AC bed and LiOH bed) to allow for sufficient single pass scrubbing of gaseous trace contaminants. Insufficient residence time is likely to allow trace contaminant breakthrough prior to utilizing the desired hardware capacity. This could lead to larger components or a more frequent maintenance interval than at a slower flow rate.

Additional impacts from flowrate changes should also be considered. As discussed previously, the HTCO oxidizes contaminants by heating the air flowing through it to a high temperature. Therefore, when the flowrate through the HTCO is changed, the effectiveness of the HTCO to heat the air flowing through it must be considered. Faster air flow through the HTCO will likely require a higher setpoint temperature to achieve and maintain the air temperature required to achieve the expected oxidation. Select mitigations are discussed below in section C.

Therefore, any adjustment to the flow rate must be carefully considered. This balance between flowrates and gaseous trace contaminant scrubbing efficacy underscores the intricate nature of optimizing TCCS performance in future spaceflight applications.

C. Catalytic Oxidizer Bypass

Alternative flow paths for a TCCS-like system should also be considered during the design process. The USOS TCCS configuration contains a flow bypass downstream of the AC bed that routes a large fraction (approximately 6.3 cfm of the total 9 cfm) of the air around the HTCO and LiOH bed. This bypass air is then combined with the air which flowed through the HTCO and LiOH bed to form a single exhaust flow. This configuration allows for a faster flowrate through the AC bed than the HTCO and LiOH bed while remaining in a single system using a single blower. Additional high molecular weight contaminant removal capability was later supplemented on the USOS by the addition of the Charcoal HEPA filters (known as CHARPAs). These filters experience the higher flow rates found in the CCAAs and help combat the presence of di-methyl-silanediol (DMSD).

This uncovers an area of potential system optimization directly impacting the mass, volume, and complexity of the system. Consideration should be given to eliminating the bypass flow in favor of a single path through a TCCS-like system which includes every component: the AC bed, the HTCO, and the LiOH bed. Assuming the flow through the HTCO is not increased (remains at 2.7 cfm), consideration should be given to supplementing the role of the AC bed housed within the system. Similar to the ISS, the addition of AC filters in line with the primary ventilation system should be evaluated to ensure sufficient high molecular weight contaminant control. HEPA or dust filters are already a standard part of the primary ventilation system for human rates spacecraft. AC filters in the ventilation system in addition to the dust or HEPA filters could be a viable approach to supplementing the reduced airflow through the TCCS AC beds. If higher flow rates through the HTCO are deemed desirable, evaluating potential HTCO modifications such as adding a recuperating heat exchanger to the flow could help lessen the potential increased power draw from higher heating demands on the faster air stream.

Further trades are needed to understand the viability of this approach. Evaluations and testing should accompany any change, but eliminating the bypass flow within the TCCS could allow for benefits such as a more compact system design, minimizing volume and mass, potentially allow for a resizing of the blower, and reducing the system complexity.

D. Bed Capacity

The AC bed and LiOH bed were initially estimated to have a very short life. Based on NASA analysis of the expected atmospheric loading, the guidelines regarding the preventative maintenance interval for the USOS TCCS AC beds was determined to be 90 days to prevent contaminant breakthrough.[7] Over the years, both AC beds and LiOH beds used on ISS were returned and evaluated along with atmosphere samples. Using these data points, the preventative maintenance intervals for the bed were extended incrementally. It is worth noting preventative maintenance intervals for the AC bed and LiOH bed each include a 25% margin based on analyzed capacity to scrub a nominal atmosphere.

The dimensions for the cylindrical USOS TCCS AC bed are 0.58 m in length with a diameter of 0.32 m. This gives a total volume of about 0.047 cubic meters.[7] The AC bed is currently specified to contain 22.7 kg of AC per bed with a preventative maintenance interval of 4.7 years. Because a common maintenance interval for future human spaceflight programs is 18 months, this allows for a physically smaller AC bed volume and a reduced mass. Not only will this allow for a smaller volume for the operational system, but a smaller volume required for spares stowed within the spacecraft. While there will be more spares likely required over a long duration, this should be balanced with the mass and volume savings achieved with the smaller beds.

The dimensions for the cylindrical USOS TCCS LiOH bed are 0.234 m in length with a diameter of 0.129 m. This gives a total volume of about 0.0031 cubic meters. The LiOH bed is currently specified to contain 1.4 kg of LiOH per bed with a preventative maintenance interval of 6.3 years. However, LiOH media degrades and sticks together in the presence of water – both atmospheric humidity and created water due to chemical reactions within the LiOH bed. When this degradation occurs, the delta pressure within the LiOH bed increases. As the delta pressure increases, the blower speed must be increased the maintain flow through the system. At a sufficient delta pressure, the blower speed can no longer increased resulting in a system-wide flow reduction. Therefore, the typical maintenance interval is approximately 4 years. For future human spaceflight programs which commonly have maintenance intervals of 18 months, a physically smaller LiOH bed can be used reducing volume and mass. This reduction is likely not to be as substantial as the AC bed due to media degradation issues discussed earlier, but should be considered as potentially significant overall mass and volume savings for the entire program.

Because LiOH is toxic to humans, a preliminary review of alternative media to perform the same function has been examined. Calcium hydroxide or potassium hydroxide could potentially serve the same function as LiOH within a TCCS-like system. Unfortunately, neither provide substantial trace contaminant removal benefits over LiOH. Additionally, both calcium hydroxide and potassium are also considered toxic to humans. Given NASA’s flight heritage with LiOH, moving away from it for these alternative chemicals is not recommended. However, more research into new sorbent medias, gaseous trace contaminant removal chemistry, and LiOH bed packaging should be pursued.

Bed capacity margin is another aspect which should be further evaluated. As discussed previously, the USOS TCCS beds have significantly outperformed their initially estimated lifespan. If atmospheric sample analysis shows the gaseous trace contaminants are controlled, the operating capacity of the AC bed and LiOH bed should be reassessed. Reducing the margin from 25% to 10% could extend the life of the beds by several months without redesigning the beds physically. Evaluation of trace contaminants should be completed to ensure breakthrough does not occur during the updated preventative maintenance interval. Analysis of expended AC beds and LiOH beds should be performed to confirm the remaining bed capacity. The planned use of contingency gaseous trace contaminant removal hardware may be required to manage anomalous releases.

As a caution, reducing the bed dimensions and capacity introduces other impacts to consider. A reduced bed capacity will reduce the maintenance intervals. A reduce maintenance interval will increase the frequency of maintenance. More frequent maintenance activities may require more overall crew time as the same period as larger beds with a longer maintenance interval. These aspects should play key roles in determining if changing bed capacity is viable for each program.

E. Component Packaging

The design and packaging of the USOS TCCS has room for improvement. The USOS TCCS design was completed before modern computer aided design (CAD) and analysis tools were available. Although every aspect of the design was required to survive the launch loads of the transport vehicles operating at the time, much of the packaging (component layouts and support structure) was not optimized by current standards.

Many advances in transport packaging tools (such as vibration attenuating foam) were less available at the time the USOS TCCS was in its design phase. This lead to a system with a very robust structural design with a large mass and volume. Using currently available and modern design tools commonly found in multiple industries, a reduction in unnecessarily robust structure is possible without compromising system viability during launch or landing.

Along with potentially reducing the robustness of the support structure, careful attention should be given to the environment where the TCCS-like system will be operating. If the nominal operational location has little to no significant vibrations (such as in space orbit or stationery on a planet/lunar surface), consideration should be given to removal of unnecessary support structure once the system is permanently installed. This could further aid in reducing the system mass and volume while also potentially reducing the time required to perform future maintenance.

Finally, the arrangement of system components should be considered. Using solid modeling, CAD analysis tools, and fluid flow modeling software will allow components to be arranged such that they are volumetrically optimized. Special attention should be given to air flow through the system as some arrangements could impede flow, such as near hairpin turns (air flow paths which are forced to sharply change direction) or other pinch points.

Beyond system performance and volumetric concerns, consideration should be given to the human interfaces and interactions with the system. Component accessibility during maintenance should be a significant consideration of the updated design. A system which has a high volumetric optimization could limit maintenance because fasteners or connectors are nearly impossible to reach or remove by crew.

In addition, advances in manufacturing practices can have big payoffs in end product mass efficiency. With the gain in popularity of additive manufacturing, component manufacturing can now utilize additive manufacturing processes to produce a large array of components with complex geometries using a variety of materials. This allows engineering and manufacturing to align more closely as they relate to intended design and manufacturability. General manufacturing processes have also come a long way since the USOS TCCS was first built. More intricate and complex shapes can be made with greater ease. Utilizing these modern capabilities may allow for a reduction in the number of components while maintaining the same functionality.

Other factors which may have played a role in the USOS TCCS design lacking optimization were likely schedule and funding challenges. Designing, testing, and iterating a newly designed system will likely have challenges and setbacks. These cannot be fully accounted for in the initial project schedule as they are highly variable. Not only do these challenges and setbacks impact the project schedule, but they also impact the project budget. Therefore, margin is placed in every schedule and budget to account for some percentage of challenges. The amount of margin placed in the schedule and budget is generally determined by the company developing the system. It is expected some portion of this margin will be consumed, but schedule and financial constraints can limit the optimization of any design regardless of the tools and experts available.

IV. Conclusion

The future of human spaceflight will require atmospheric trace contaminant control. Understanding ways to improve upon the heritage systems can propel future missions to success while maintaining the robustness required to sustain humans in space. Reducing the mass, volume, and power of a trace contaminant control system through optimizations to HTCO operation, system flowrate, system flow path, component packaging, and bed capacity are a few ways to reach the goals of returning to the Lunar surface and reaching the surface of Mars. Any modifications discussed in this paper should be analyzed against specific mission profiles prior to implementation to ensure changes to the current working ISS USOS TCCS design are appropriate and compatible to support the individual mission.

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