

# Characterization of Potassium Superoxide and a Novel Packed Bed Configuration for Closed Environment Air Revitalization

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Potassium superoxide ( $\text{KO}_2$ ) has been used in environmental control and life support systems (ECLSS) ranging from early Soviet spacecraft to self-contained self-rescuer devices for mine safety. By reacting with moisture carried in an air flow,  $\text{KO}_2$  releases oxygen and absorbs carbon dioxide. Because  $\text{KO}_2$  performs multiple functions required in closed environments (humidity removal, oxygen provision, carbon dioxide removal), and its reactions are triggered by a metabolic waste product (respired moisture),  $\text{KO}_2$  can be used as a basis for a simple, passive, and compact air revitalization system. The performance of  $\text{KO}_2$ , lithium hydroxide, and silica gel with respect to carbon dioxide adsorption, oxygen release, and humidity control is reviewed. The operation of these granular chemicals was characterized in sequentially layered, plug-flow, packed beds with both steady state and transient (feedback controlled) inlet conditions for durations of up to 10 days. Because the output of these chemical beds in a symmetric layering configuration either exceeded or fell short of metabolic requirements at different times, an alternative packing configuration was desired. As a result of this research, a proposed system concept of an asymmetrically packed granular bed was developed to provide constant output environmental control utilizing  $\text{KO}_2$ , lithium hydroxide, and silica gel. Such a system can be initially designed to meet an expected metabolic loading profile for a given duration. In this way, a reliable and volumetrically efficient air revitalization system can be provided for applications including mine rescue shelters, military vehicles, and human space transportation vehicles for durations of up to 10 days.

## Nomenclature

$AR$	=	Air Revitalization
$\text{CO}_2$	=	carbon dioxide
$ECLSS$	=	Environmental Control and Life Support System
$\text{H}_2\text{O}$	=	water or water vapor
$ISS$	=	International Space Station
$\text{KO}_2$	=	potassium superoxide
$\text{KOH}$	=	potassium hydroxide
$\text{LiOH}$	=	lithium hydroxide
$LPM$	=	liters per minutes
$\text{O}_2$	=	molecular oxygen
$pp\text{O}_2$	=	partial pressure of oxygen
$RH$	=	Relative Humidity
$RQ$	=	Respiratory Quotient
Efficiency	=	Chemical utilization efficiency, (actual / theoretical) reacted chemical with respect to primary reaction

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## I. Introduction

Air revitalization (AR) is required in any closed environment in order to maintain a breathable atmosphere for living organisms. It includes the primary functions of oxygen (O<sub>2</sub>) provision and carbon dioxide (CO<sub>2</sub>) removal, but can also include secondary functions of humidity regulation, trace contaminant control, and filtration.<sup>1</sup> The selection of AR technologies and the design of AR systems are dependent on the expected operational environment and mission requirements with mass, volume, duration, and loading being the main drivers for applicable technologies.

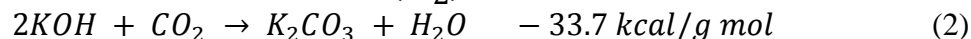
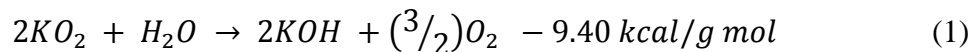
The present research was initiated to investigate the performance, safety, reliability, and controllability of potassium superoxide (KO<sub>2</sub>) as an AR agent for use in an environmental control and life support system (ECLSS) supporting rodent transport to and from the International Space Station (ISS). For this application, an AR system is required to fit within a mid-deck locker (approximate size 20 in. x 17 in. x 10 in., or 55 L) and support the metabolic load of 40 mice for up to 10 days, the specifics of which can be seen in Table 1 and compared with human equivalents for reference. From this, it can be seen that a system designed to support 40 mice for 10 days would be comparable in size to one designed to support one human for 2-3 days, based on O<sub>2</sub> requirements.

**Table 1. Atmospheric metabolic loads of mice compared with humans<sup>2,3,4</sup>**

Subject	O <sub>2</sub> (mole/d-subject)	CO <sub>2</sub> (mole/d-subject)	H <sub>2</sub> O (mole/d-subject)
40 mice (1.2 kg)	6.0	5.2	11.3
1 human (70.0 kg)	26.1	22.7	88

\*values include both respired and perspired moisture

KO<sub>2</sub> is a solid chemical that can release O<sub>2</sub> and absorb CO<sub>2</sub> upon reacting with water. It is particularly attractive for AR purposes because of this multi-functional capability, but also because of its long term storability, proportional output performance to loading, and ambient pressure operation. The theoretical performance of KO<sub>2</sub> yields 0.388 kg O<sub>2</sub> per kg KO<sub>2</sub> and absorbs 0.308 kg CO<sub>2</sub> per kg KO<sub>2</sub>.<sup>5</sup> The primary chemical reactions associated with KO<sub>2</sub> can be seen below in Equations 1-3.<sup>5</sup>



O<sub>2</sub> and potassium hydroxide (KOH) are produced from the reaction of KO<sub>2</sub> and water (H<sub>2</sub>O), typically in the form of water vapor carried in the air. CO<sub>2</sub> is then absorbed mostly in carbonate and bicarbonate forming reactions with KOH. A number of competing hydrating reactions can occur in addition to the reactions listed above, and a complete list can be found in Ref 6 and 7. The primary safety concern associated with KO<sub>2</sub> is the fact that it reacts vigorously with liquid water, causing high temperatures and rapid release of O<sub>2</sub>, raising flammability concerns if non-compatible materials are nearby. This can be avoided by ensuring appropriate material selection, engineering design, and safe operating and handling procedures.

Trade studies have shown that KO<sub>2</sub>-based systems offer a competitive and potentially safer alternative to traditional ECLSS designs that employ high pressure O<sub>2</sub> provision,<sup>8,9,10</sup> but there is currently little experience with KO<sub>2</sub> in spaceflight applications.<sup>8</sup> This is despite the fact that KO<sub>2</sub> has a history of being used as an AR agent for miner safety, firefighting, high-altitude mountaineering, submarines, and even early manned Soviet spacecraft, as seen in an extensive annotated bibliography by Foregger (1996).<sup>11</sup> Therefore, this study serves to provide a basis for understanding the operation of KO<sub>2</sub> under a variety of environmental conditions and in systems that use KO<sub>2</sub> with supplemental chemicals (lithium hydroxide (LiOH) and silica gel desiccant). Based on analysis of the preliminary data from this research, it is speculated that the AR system concept developed in this paper could provide constant output environmental control with respect to O<sub>2</sub>, CO<sub>2</sub>, and relative humidity (RH) with a simple, asymmetrically packed granular bed.

## II. Background – Current and Historical Use

KO<sub>2</sub> has been studied extensively as an AR agent in research supported by agencies including NASA<sup>5,12-17</sup>, the Soviet space program<sup>18-20</sup>, the U.S. military (Navy and Air Force)<sup>6,7,21-23</sup>, and the National Institute for Occupational Safety and Health (NIOSH)<sup>24,25</sup>, and the National Institute of Justice (NIJ)<sup>26</sup>. Alternative metal superoxides (e.g. calcium superoxide and lithium superoxide) have received attention for having higher O<sub>2</sub> and CO<sub>2</sub> capacity per mass

of superoxide than  $\text{KO}_2$ , but they have lost out to  $\text{KO}_2$  due to issues with reactivity, stability, and preparation<sup>1,13–15</sup>. The instances in which  $\text{KO}_2$  has been employed can generally be divided into two categories: 1) AR is needed to manage high loading over short durations, on the order of hours, and 2) AR is needed to manage high loading over long durations, on the order of greater than 3 days.

Applications that fall within the first category are mine and fire emergencies where  $\text{KO}_2$  is used in self-contained self-rescuers (SCSR) to support one person for long enough to escape to safety. In this application,  $\text{KO}_2$  is packaged in a sealed package with a respiration mask that, when pulled from the package, opens the seal between the mask and the  $\text{KO}_2$  cartridge. After donning the mask, the user breathes directly into the  $\text{KO}_2$  bed with air flow direction regulated by one-way valves. Respired vapor initiates the  $\text{O}_2$  release and subsequently the  $\text{CO}_2$  scrubbing reactions at high rates due to the high concentration of water vapor in exhaled breath. The user then inhales air with a high concentration of  $\text{O}_2$  and low concentrations of water vapor and  $\text{CO}_2$ . A common complaint about the use of these SCSRs is that the inhaled air is extremely hot and dry, causing breathing to become uncomfortable for the user<sup>23</sup>. These rescue breathers have a usable duration of a few hours due to the intense moisture and  $\text{CO}_2$  loading decreasing  $\text{KO}_2$ 's useful life. Generally, there is unreacted  $\text{KO}_2$  at the end of the operation due to a crust on the outside prevents complete chemical conversion<sup>20</sup>. This is an example of a scenario where a small, lightweight, and simple AR system is the most effective means of accomplishing the design goals, but where chemical utilization efficiency is sacrificed to meet these requirements.

In turn, systems that use  $\text{KO}_2$  for durations on the order of days involve increased complexity. This is required to more efficiently use consumable resources maintaining a breathable atmosphere due to the nature of the performance of  $\text{KO}_2$ . Compared to the respiratory quotient (RQ) of humans, defined as the volume of  $\text{CO}_2$  produced over the volume  $\text{O}_2$  consumed,  $\text{KO}_2$  will operate to overproduce  $\text{O}_2$  for the amount of  $\text{CO}_2$  scrubbed (RQ of humans = 0.8 to 1.0, RQ of  $\text{KO}_2$  = 0.67)<sup>15</sup>. Also, as noted in the previous paragraph,  $\text{KO}_2$ 's utilization efficiency will drop as it is loaded with high concentrations of water vapor. These two utilization issues can be prevented or compensated for by design with the addition of excess  $\text{KO}_2$ , supplemental  $\text{CO}_2$  and moisture scrubbing materials, and process controls.

In one example, a submarine's life support system utilizing  $\text{KO}_2$  was capable of sustaining four crew members for 72 hours or more<sup>10</sup>. This longer operational duration was achieved by having parallel paths in the airflow system. One path contained  $\text{KO}_2$  canisters, sized for  $\text{O}_2$  generation needs, and the other contained lithium hydroxide (LiOH) for supplemental  $\text{CO}_2$  removal. When the partial pressure of  $\text{O}_2$  was low, an air was allowed to flow through the  $\text{KO}_2$  canister and when the partial pressure of  $\text{O}_2$  was high, air was only allowed through the LiOH bed, maintaining low environmental  $\text{CO}_2$  concentrations. Of particular note with this submarine life support system is that the  $\text{KO}_2$ -based system replaced a high pressure  $\text{O}_2$  system of similar size, but increased the nominal mission life support capability from 12 hours to 72 hours<sup>10</sup>.

As for spaceflight applications,  $\text{KO}_2$  was used in the Soviet space vehicles of Vostok, Voskhod, and Soyuz in conjunction with other air revitalization technologies<sup>5,11,17–20</sup>. The life support system concept of operations provided only as much flow and moisture to the superoxide bed as necessary for  $\text{O}_2$  production, otherwise diverting flow to a second, independent flow loop with drying agents, activated carbon,  $\text{CO}_2$  scrubbing chemicals, and a condenser. Independent systems can maintain humidity,  $\text{CO}_2$ , and  $\text{O}_2$  within acceptable ranges more precisely, but they contribute to an increase in the mass, size, and complexity of the total system. Overall system operation characteristics presented by Veronin et al. (1967) on the life support systems of the Soviet vehicles show that a system using  $\text{KO}_2$  can reliably provide the necessary ECLSS functions in a space vehicle. It also shows that with the added complexity of a two stream system,  $\text{KO}_2$ -based systems can operate effectively for up to 13 days<sup>18</sup>.

The systems that use or have used  $\text{KO}_2$  can be summarized as being either simple and inefficient, or efficient at the cost of greater complexity. While the examples of long duration submarine and spacecraft  $\text{KO}_2$  AR systems are a few decades old, more recent system designs have been proposed, specifically for mice payloads. As noted by Wood and Wydeven (1985), system designers intending to improve upon the performance of  $\text{KO}_2$  have historically tried to engineer canister and flow path design or mix  $\text{KO}_2$  with supplemental chemicals for better utilization efficiency<sup>15</sup>. Analysis of more recent designs using these methods show evidence of some mass savings over alternative AR systems<sup>8,9</sup>.

### III. Chemical Characteristics

In this study, three substances in particular were investigated with respect to their operation in packed beds and varied environmental conditions:  $\text{KO}_2$ , lithium hydroxide (LiOH), and silica gel desiccant ( $\text{SiO}_2$ ). Because  $\text{KO}_2$  produces  $\text{O}_2$  and adsorbs  $\text{CO}_2$  disproportionately to meeting the physiological needs of mice, if a  $\text{KO}_2$  is sized to meet  $\text{O}_2$  physiological requirements, then it will be undersized for  $\text{CO}_2$  adsorption requirements. The desirability of

including a desiccant in the system becomes clear in the following discussion of the adverse effects that high moisture loads can have on a  $\text{KO}_2$  bed. Therefore,  $\text{LiOH}$  and  $\text{SiO}_2$  were included in this study in order to provide supplemental  $\text{CO}_2$  and  $\text{H}_2\text{O}$  adsorption capacity. These three chemicals were selected to both supplement and complement each other in an integrated packed bed, as described below, thus the concept of their operation together is also discussed.



**Figure 1. Unreacted bed of  $\text{KO}_2$  pellets.**

#### **A. Potassium Superoxide**

While the basic operation and chemical equations for  $\text{KO}_2$  are described in the introduction of this paper, it is necessary to discuss the characteristics of the chemical and its operational drivers and limitations in greater detail. The design and environmental conditions that have first order effects on the performance of  $\text{KO}_2$  include the ambient pressure, residence time,  $\text{CO}_2$  concentration, and RH of the incoming gas flow. A fresh bed of  $\text{KO}_2$  pellets of approximately 0.25in diameter by 0.1in thickness can be seen in Figure 1. Similar  $\text{KO}_2$  pellets, used throughout this study, were procured from the company Drägerwerk AG & Co. KGaA from the unit Oxy K Plus Oxygen Self-Rescuers. Pellets were removed from the self-rescuer cartridges with minimal exposure to ambient, less than 10% RH air.

Reduced ambient pressure proportionally restricts the rate of the reactions by limiting the amount of gas (and water vapor) in contact with the  $\text{KO}_2$  compared with operation at sea level ambient pressure. Residence time (controlled by the flow rate and packed bed volume), or the time it takes for one bed volume of gas to pass through the chemical bed, dictates the amount of time that a given molecule of gas has to find a suitable reaction site. As residence time decreases, there is a lower probability of the flowing gas molecules reacting with the packed bed chemicals. This influences both the reaction rate and the time until breakthrough of the chemical bed.

In addition to Equations 2 and 3, there are several competing hydrating reactions that utilize potassium hydroxide, potassium carbonate, and potassium bicarbonate as reactants<sup>6,7,14</sup>. These hydrating reactions are thought to be the cause of swelling and deliquescence of a  $\text{KO}_2$  bed, deleterious effects that either restrict gas flow or allow a bypass flow channel through the bed to occur, respectively<sup>8,9,14,15</sup>. These effects can be seen in Figure 2, in contrast to the fresh  $\text{KO}_2$  bed in Figure 1.



**Figure 2. Left:  $\text{KO}_2$  with swelling; Right:  $\text{KO}_2$  deliquescence and channeling<sup>8</sup>.**

By observations made during this study, the competing hydrating reactions occur more readily when the ratio of water vapor to  $\text{CO}_2$  supplied to the  $\text{KO}_2$  bed high. Alternatively, carbonate and bicarbonate forming reactions will occur more readily than the hydrating reactions if the ratio of water vapor to  $\text{CO}_2$  is low.

While there are obvious reasons to ensure the ratio of  $\text{H}_2\text{O}:\text{CO}_2$  is low (pressure drop, utilization efficiency), having too low of a ratio can be detrimental to performance as well. If  $\text{CO}_2$  is supplied at a much higher rate than water vapor,  $\text{KOH}$  will not be created as a product of Equation 1 at a rate high enough to keep up with the supply of  $\text{CO}_2$  and the chemical bed will get hot. These effects will result in all of the produced potassium hydroxide immediately reacting with  $\text{CO}_2$ , creating a risk that carbonate and bicarbonate layers will form on the outer layers of the  $\text{KO}_2$  pellets. These layers would restrict the ability of water vapor to reach the inner layers of unreacted  $\text{KO}_2$ , thereby limiting the ability of  $\text{KO}_2$  to continue performing as an AR agent.

The ratio of supplied water vapor to  $\text{CO}_2$  that provides the lowest risk of reduced  $\text{KO}_2$  performance is unity. If  $\text{KO}_2$  is exposed to the proper ratio of water to  $\text{CO}_2$ , stable performance of the chemical has been observed. It should be noted that in the event that  $\text{KO}_2$  is shielded from both  $\text{CO}_2$  and moisture, no reactions occur.

The release of  $\text{O}_2$  by  $\text{KO}_2$  is driven by either water vapor supplied in an incoming gas flow or moisture created as a product of the carbonate forming reaction in Equation 2. A previous NASA study found that water can be “recycled” in a  $\text{KO}_2$  bed via the carbonate forming reaction, allowing a water molecule to react within the bed

multiple times<sup>14,15</sup>. It was observed by Wood et al. (1982) that, on average, a molecule of water can react with  $\text{KO}_2$  in the bed 2.36 times. This finding supports the concept that even a low amount of supplied water vapor can sustain  $\text{KO}_2$  reaction rates longer than otherwise possible if only incoming (and not recycled) water vapor were utilized. It also allows the supplied  $\text{H}_2\text{O}:\text{CO}_2$  molar ratio to be some amount below unity and still have efficient reactions.

Parametric experiments of  $\text{KO}_2$  performance with respect to RH (5% to 30%) and at constant  $\text{CO}_2$  (0.3%) loading were performed at the University of Colorado Boulder, as seen represented in the three panels of Figure 3. These were conducted to gain preliminary information the  $\text{O}_2$  generation efficiency of  $\text{KO}_2$  at low RH in particular, but also to gain performance data on  $\text{CO}_2$  absorption and  $\text{H}_2\text{O}$  usage. The test tubes for these experiments, seen in Figure 1, had an inner diameter of 1.6in and a length of 3in. The cross-sectional flow area of this tube size represents approximately 0.6% of the largest area dimension on a mid-deck locker. Volumetric flow rates averaged at 2 LPM, a fast flow rate for the size of this bed, set at this point in order to accelerate testing from a 10-day duration scale to a 1-day duration. The plots are displayed as 60 point (1 minute of data) moving averages.

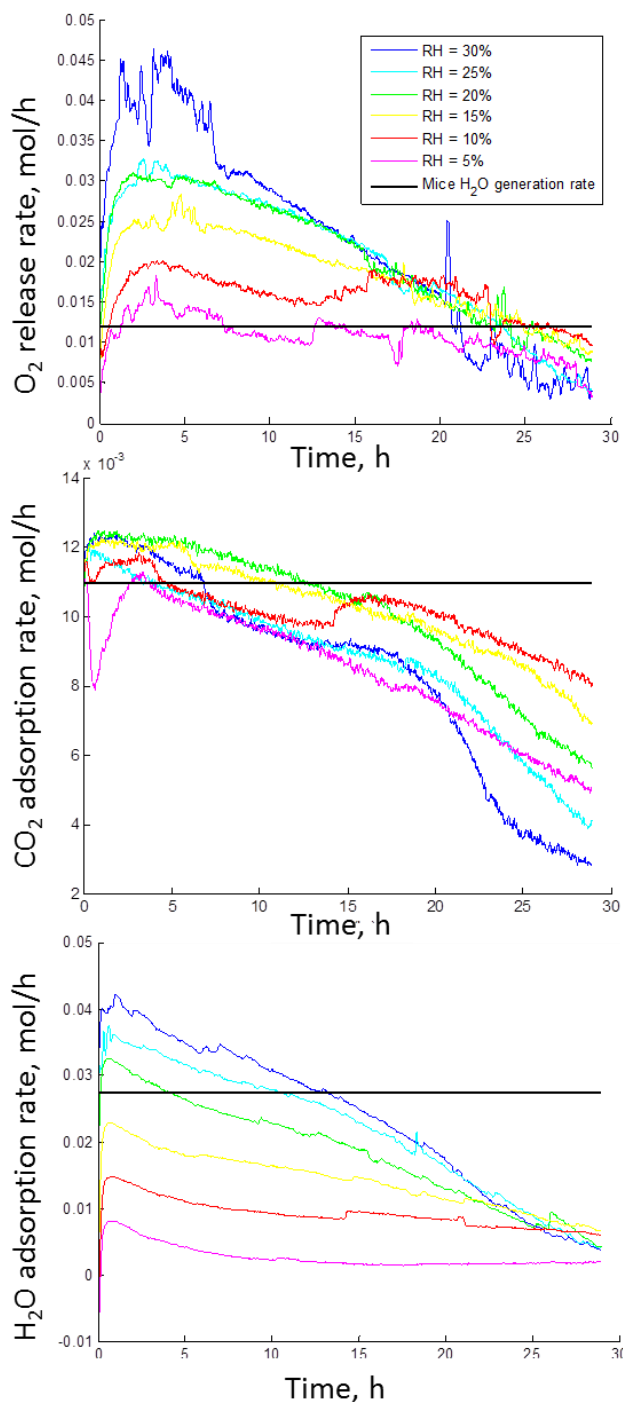
A black line in each of the charts represents the respiratory rate of 40 mice, similarly scaled with respect to flow area and duration, for  $\text{O}_2$  usage,  $\text{CO}_2$  production, and  $\text{H}_2\text{O}$  respiration, in order to compare actual  $\text{KO}_2$  performance with required performance. The closer the plots of the data match the black lines, the more closely the  $\text{KO}_2$  bed's performance meets the metabolic requirements of the mice.

The results of the preliminary parametric tests indicate  $\text{O}_2$  overproduction with increasing RH, as expected from the literature. With lower RH,  $\text{O}_2$  rates more closely match the required rates (improving efficiency), but the  $\text{CO}_2$  and  $\text{H}_2\text{O}$  curves show that rate requirements for those substances are not being met. This empirically shows evidence that supplemental chemicals are needed for a  $\text{KO}_2$  bed to match the  $\text{O}_2$  requirements.

With the above knowledge of  $\text{KO}_2$  operation, it is apparent that low levels of RH and sufficient levels of  $\text{CO}_2$  should increase the utilization efficiency and the effective operating life of  $\text{KO}_2$ . If humidity and  $\text{CO}_2$  supplied to the  $\text{KO}_2$  can be regulated,  $\text{O}_2$  can be produced at rates on the order of various constant metabolic loads without deleterious effects occurring. And if control of the  $\text{O}_2$  is provided, a supplemental means of  $\text{CO}_2$  scrubbing is required. It is therefore justified and necessary to investigate desiccant and  $\text{CO}_2$  scrubbing materials for potential use in conjunction with  $\text{KO}_2$ .

## B. Silica Gel Desiccant

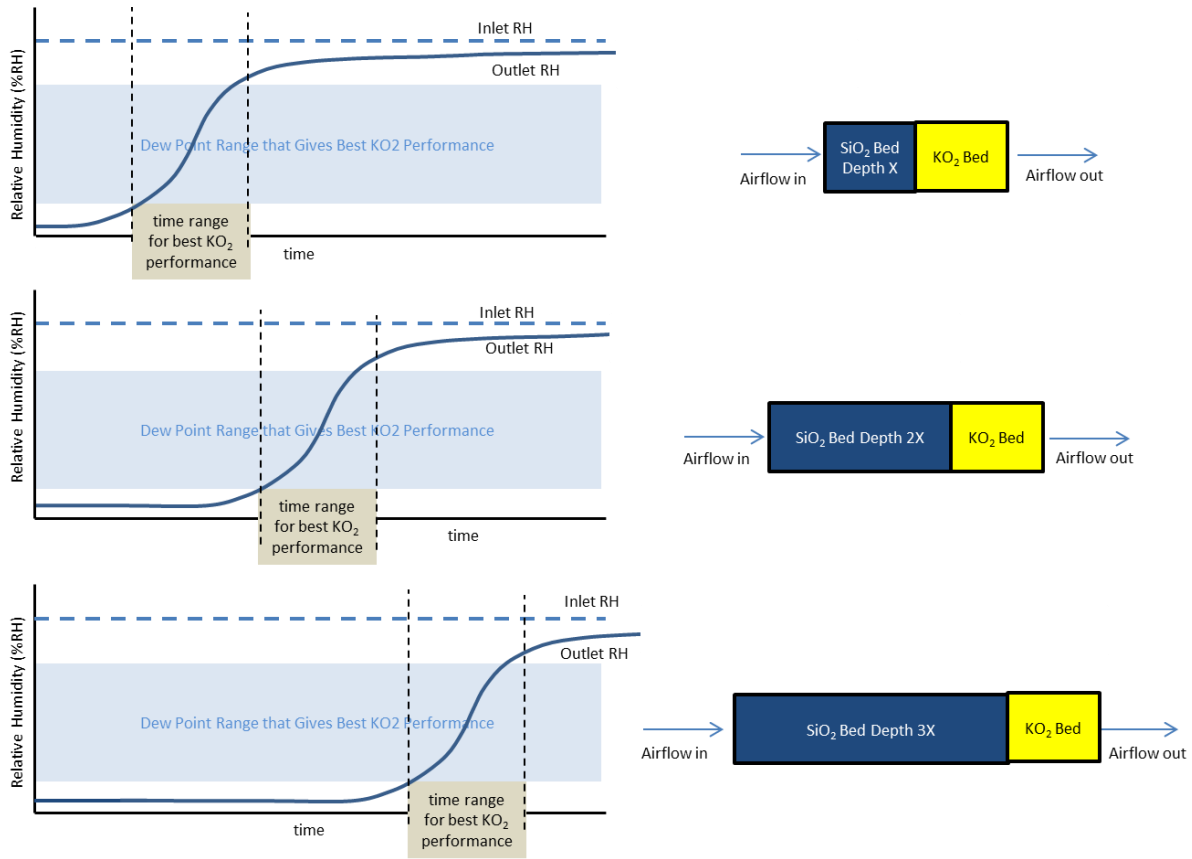
Silica gel ( $\text{SiO}_2$ ) desiccant is widely used in commercial industries and has very predictable performance of water adsorption with respect to temperature and RH of the process gas flow. If the desiccant is initially cool and



**Figure 3. Top:  $\text{O}_2$  generation rate (g/s), Middle:  $\text{CO}_2$  absorption rate (g/s), Bottom:  $\text{H}_2\text{O}$  usage rate.**

dry, it has a low surface vapor pressure, allowing it to attract water from a humid gas flow with a higher vapor pressure until equilibrium is reached. If the desiccant is wet and hot, represented by a high surface vapor pressure, the desiccant will desorb moisture to an atmosphere with a lower vapor pressure. The equilibrium moisture content of silica gel is thus controlled by the humidity and temperature of the atmosphere that it is in contact with. The silica gel used for this study was color indicating, grade 44, 3-8 mesh.

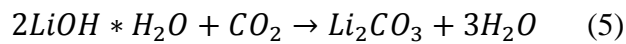
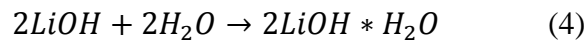
The purpose of using silica gel in conjunction with  $\text{KO}_2$  is to both provide a  $\text{KO}_2$  bed with favorable humidity conditions and to supplement  $\text{KO}_2$ 's water scrubbing capacity.  $\text{SiO}_2$  upstream of a  $\text{KO}_2$  bed can act as a humidity buffer, protecting  $\text{KO}_2$  from excess moisture. By increasing the bed depth of a silica gel bed, the capacity for moisture at a given RH increases. A longer bed (and more silica gel) increases the time delay for when moisture breakthrough occurs. This effect of bed depth on humidity buffering performance is shown in Figure 4, assuming a flow with constant RH and temperature. A notional idea of where potassium superoxide achieves its best performance with respect to RH and time is also included in Figure 4.



**Figure 4.  $\text{SiO}_2$  as a humidity buffer upstream of  $\text{KO}_2$  as a function of  $\text{SiO}_2$  bed depth.**

### C. Lithium Hydroxide

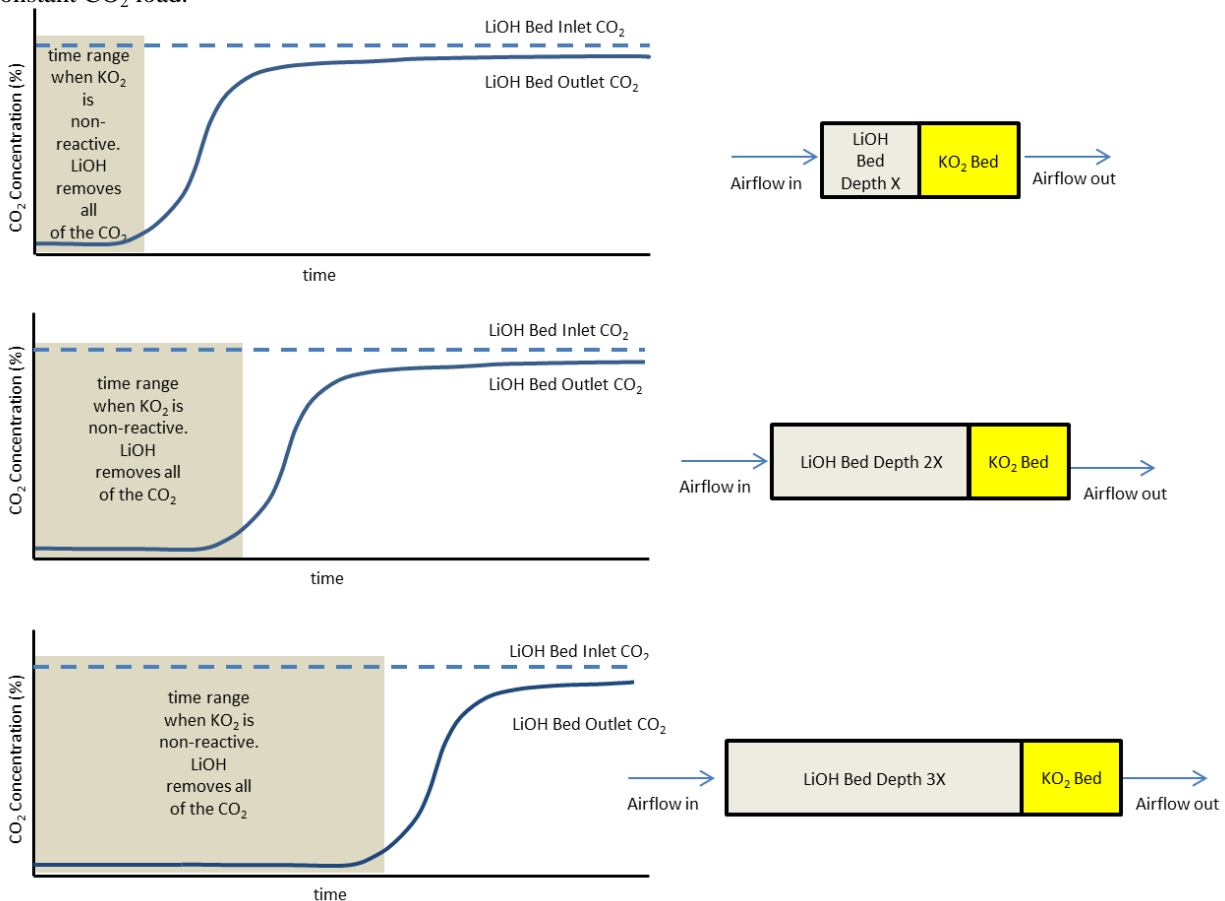
$\text{LiOH}$  has been used extensively in both spaceflight and underwater diving applications as a  $\text{CO}_2$  absorbing material. The primary chemical equations governing the reaction of  $\text{LiOH}$  with  $\text{H}_2\text{O}$  and  $\text{CO}_2$  can be seen below in Equations 4 and 5.



There are two things of importance to note from these equations: 1)  $\text{LiOH}$  requires water vapor as a reactant to initiate  $\text{CO}_2$  absorption, and 2) one mole of water is produced per mole of  $\text{CO}_2$  scrubbed. While some of the water vapor released as a product of Equation 5 can be exhausted from a bed of  $\text{LiOH}$  by the process flow, some water

may also remain in the bed to continue  $\text{CO}_2$  absorption. When the environmental conditions for LiOH are maintained within an envelope of not being too wet, dry, or hot, the performance of LiOH as a  $\text{CO}_2$  scrubber is relatively well characterized: A constant supply flow of  $\text{CO}_2$  to a LiOH bed is scrubbed with near complete efficiency until a relatively sharp breakthrough occurs near the end of the LiOH bed's lifetime.

In operation, if a bed of LiOH is located behind a bed of  $\text{KO}_2$ , then it simply supplements the total bed capacity for carbon dioxide. If, however, a bed of LiOH is located in front of a bed of  $\text{KO}_2$ , then the LiOH additionally acts as an upstream  $\text{CO}_2$  scrubber to the  $\text{KO}_2$ , delaying the time until a  $\text{KO}_2$  bed sees  $\text{CO}_2$  at its inlet. This second operating concept is shown below in Figure 5 as a function of LiOH bed depth, assuming a supply flow with a constant  $\text{CO}_2$  load.



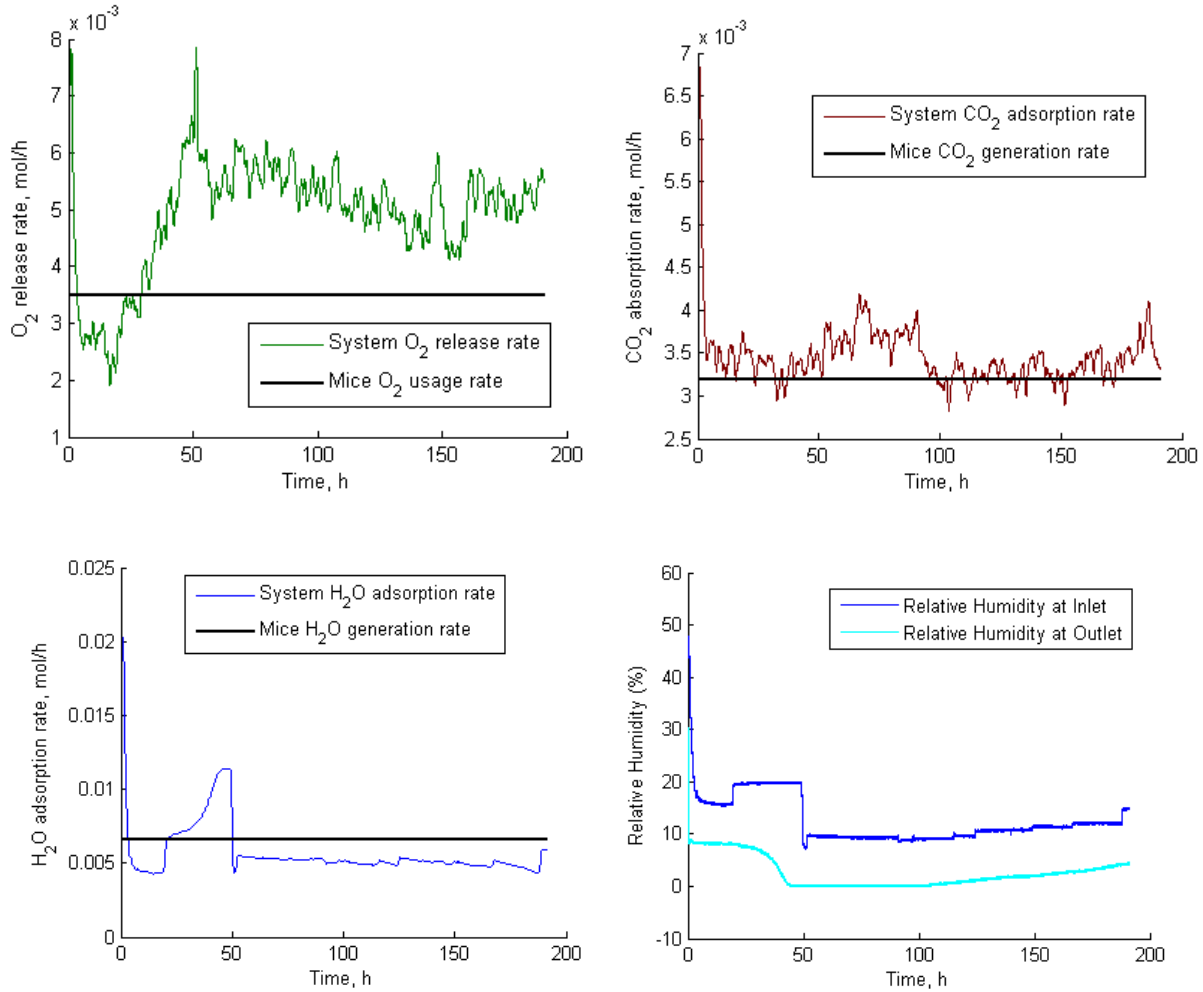
**Figure 5. LiOH as a  $\text{CO}_2$  scrubber upstream of  $\text{KO}_2$  as a function of LiOH bed depth.**

#### IV. Description of the Problem

Packed bed systems with granular reactive chemicals, such as one with  $\text{KO}_2$ , LiOH, and  $\text{SiO}_2$ , change their chemical nature and their chemical performance over time. The result is a dynamic system that depends on both transient environmental conditions and the transient conditions produced by each chemical. Because of these system dynamics, granular reactive chemical beds have difficulty in meeting constant performance requirements with respect to time without some level of upstream or parallel stream environmental control.

One example of a simple, so-called “fan and a can,” solution is to have a layering order of desiccant,  $\text{KO}_2$ , and LiOH in a packed bed. The concept of operation is that a blower provides airflow to a layer of desiccant that would scrub the incoming air to have low moisture content. The relatively dry air would then enter a layer of  $\text{KO}_2$  and trigger  $\text{O}_2$  generation at a relatively low rate, providing good utilization efficiency and preventing the performance degrading modes of swelling and deliquescence. Next, the layer of LiOH would scrub  $\text{CO}_2$  down to acceptable levels and would continue to provide supplemental  $\text{CO}_2$  scrubbing throughout the lifetime of the chemical bed. An 8-day duration test was performed at NASA Johnson Space Center with this layering configuration at approximately 1.4% of the cross-sectional flow area of a mid-deck locker in the 20 in. x 17 in. plane. The operation of this layering

configuration with respect  $O_2$  generation,  $CO_2$  absorption,  $H_2O$  usage rates can be seen in Figure 6 with the inlet and outlet RH. The test was roughly “feedback controlled” by a test attendant: inlet conditions were set based on initial cabin environmental conditions, then updated at variable intervals based on the dynamics of the chemical bed performance and the modeled metabolic rates of 40 mice, scaled to 1.4% of the total loading. Test conditions that remained approximately constant throughout the experiment were the volumetric flow rate (0.98 LPM), ambient pressure (1 atm), and temperature (22°C). A high water vapor load was artificially imposed within the first 50 hours to simulate off-nominal metabolic loading (e.g. mice during launch and adjustment to microgravity periods).

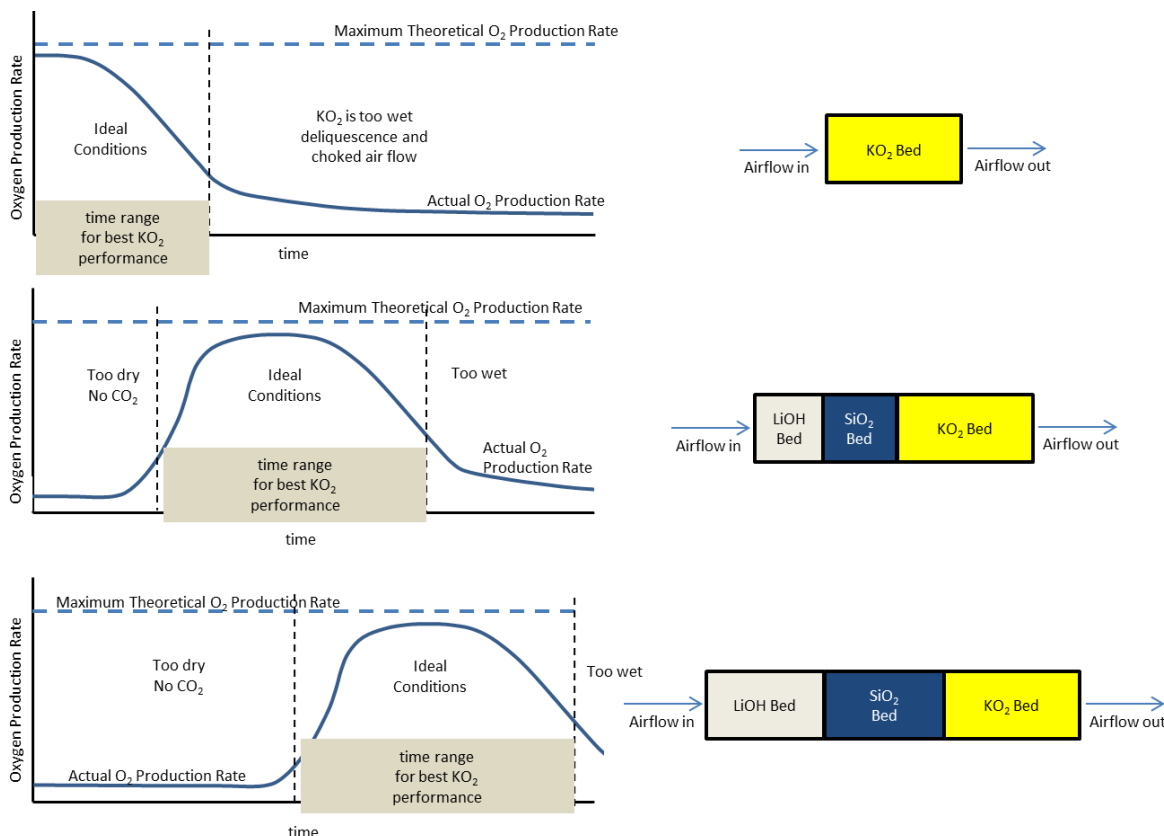


**Figure 6.  $O_2$  generation (top left),  $CO_2$  absorption (top right),  $H_2O$  usage (bottom left) rates of a  $SiO_2/KO_2/LiOH$  ordered packed chemical bed. Relative humidity at inlet and outlet to the bed (bottom right) shows how inlet parameters were controlled, including a short duration artificial high load. Layering order: inlet sensors, silica gel,  $KO_2$ ,  $LiOH$ , outlet sensors.**

Another example is derived from a layering order with silica gel and  $LiOH$  upstream of the layer of  $KO_2$ . By providing a greater capacity and buffering for moisture and scrubbing upstream  $CO_2$ , the initiation of the active period of  $KO_2$  can be delayed and the duration of time where  $KO_2$  sees an ideal operating conditions can be expanded. A qualitative concept of the operation of such a chemical bed and its dependency on bed depth of the upstream chemicals can be seen in Figure 7.

As can be seen from these examples, the release of  $O_2$  by  $KO_2$  is the most sensitive to system dynamics. When conditions are too dry for the  $KO_2$ , insufficient  $O_2$  is produced. When  $KO_2$  is producing  $O_2$  most efficiently, too much  $O_2$  can be produced- this is especially true if a chemical bed is simply layered and the whole layer of  $KO_2$  is releasing  $O_2$ . Even with upstream humidity buffering and  $CO_2$  scrubbing, the output of a simple layered bed is a first

order infeasible solution to meeting constant metabolic loads. An alternative design solution is required in order to provide a relatively constant output of such a chemical bed. As discussed in the background of this paper, these challenges are usually solved by adding system complexity. However, if these added complexities can be avoided, more mass and volume can be allotted to chemical storage, increasing the lifetime, usefulness, and versatility of a small, packed bed life support system.



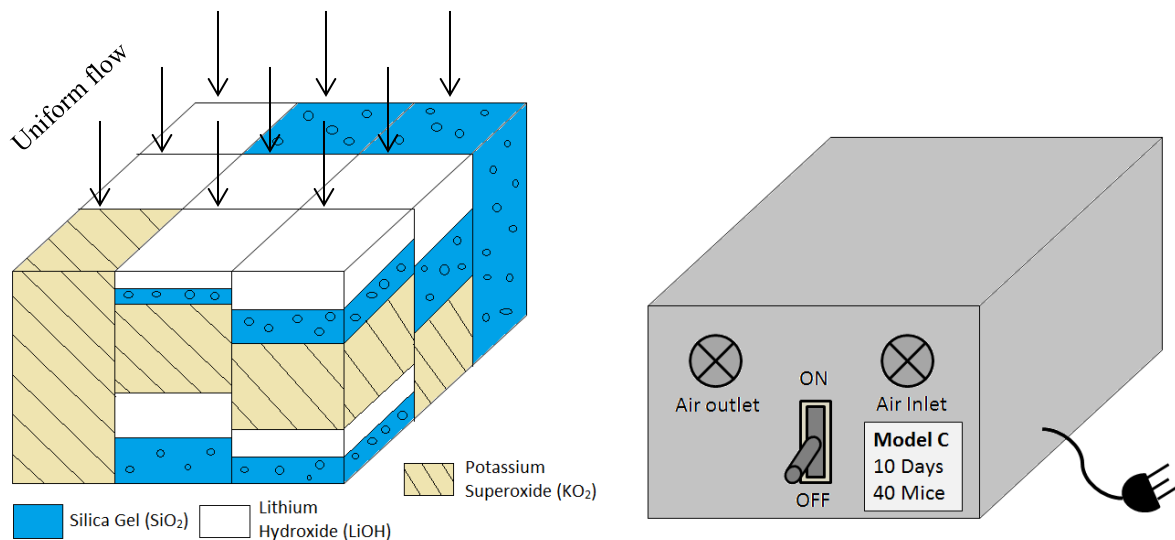
**Figure 7. Oxygen release of  $\text{KO}_2$  with variable bed depth of upstream chemicals.**

While discussing this issue, we came up with a novel solution that does not appear to have been considered in the literature for this particular application. Instead of using a simple, 2-D symmetric layering configuration, we vary the layering of the chemicals in three dimensions. The result, presented below, is that the output of each separate section of the chemical bed will remain transient, but the integrated performance of each section should result in relatively constant rates of  $\text{O}_2$  generation,  $\text{CO}_2$  absorption, and  $\text{H}_2\text{O}$  regulation. This concept is based on preliminary data collected to-date and remains as a speculative solution until more rigorous design analysis and performance characterization can be conducted.

## V. Proposed Solution

An asymmetric chemical bed for constant output environmental control is proposed. There are two main components to this system: 1) a blower that provides constant and continuous airflow through a packed bed of granular reactive chemicals, and 2) a packed bed of granular reactive chemicals composed of a series of isolated and uniquely layered columns in a parallel flow configuration. For the particular application of providing air revitalization to mice in transit to the International Space Station, a chemical bed segmented into nine of the uniquely layered columns and layered with various amounts of silica gel desiccant,  $\text{LiOH}$ , and  $\text{KO}_2$  is proposed. This asymmetric chemical bed can be sized and packed into an EXPRESS rack locker, henceforth referenced as an ECLSS locker, and connected to a separate payload locker inhabited by mice in a commercial crew vehicle. The concept of operations would be to connect the mice locker to the ECLSS locker, power on a blower, and then close the hatch before launch. The asymmetric chemical bed could be sized such that the mice would be kept alive for any

transit duration of up to 10 days. If a shorter one-way transit is executed, there is a potential for the ECLSS locker to be restarted or reused for a return transit if it is either properly stowed or repacked with fresh granular reactive chemicals. A conceptual drawing of the overall design of the asymmetric chemical bed and the operational ECLSS locker unit and can be seen in Figure 8. For the initial design, 9 columns were chosen to represent the concept, but this could be increased or reduced to suit the needs of the application, e.g. if fine tuning is necessary to maintain the cabin environment within narrow bands of conditions.

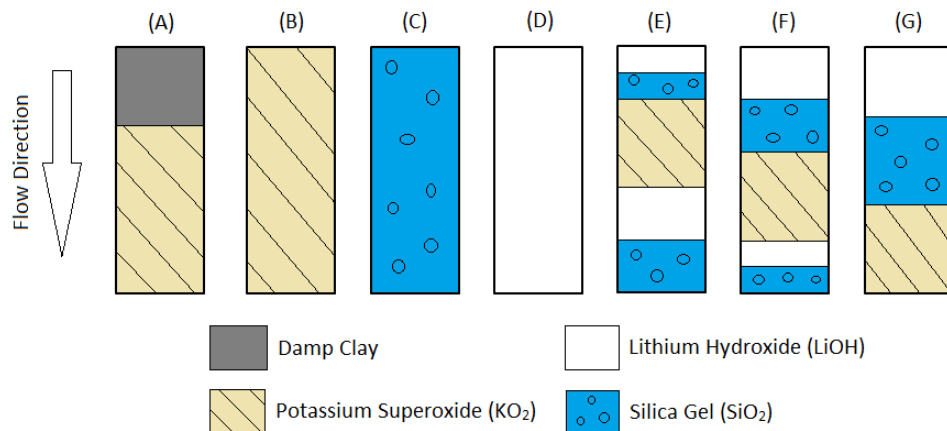


**Figure 8. Asymmetric chemical bed design (left) and ECLSS locker unit (right).**

Rather than actively controlling the flow and conditions within the ECLSS locker, there are numerous design and sizing parameters that can be manipulated in the initial design of an asymmetric chemical bed to control how it performs in a variety of mission scenarios and their expected environments. These parameters are as follows:

- Sizing for total required capacity based on mass of each chemical in the bed
- Sizing the airflow through each particular chemical constituent to provide target environmental condition ranges and meet per pass efficiency requirements
- Controlled scheduling of the activity of particular chemical layers based bed depths providing upstream buffering capacities and the desired durations until breakthrough
- Sizing the airflow rate through the total bed to meet environmental condition ranges

From these design and sizing parameters, a number of unique column layering combinations can be derived to provide various overall effects or to meet specific needs. An example of some of the types of layered columns that could be mixed and matched to configure an asymmetric bed for ECLSS can be seen in Figure 9, and reasons why each particular column might be included in a complete bed are provided in Table 2.



**Figure 9. Unique column layering combinations for an asymmetric chemical bed.**

**Table 2. Purpose for using a particular column layering type in an asymmetric chemical bed.**

Column	Purpose
<b>A</b>	Damp clay provides a short duration supply of humid air to $\text{KO}_2$ for $\text{O}_2$ release to sustain $\text{O}_2$ rate requirements if initial conditions are extremely dry.
<b>B</b>	Full column of $\text{KO}_2$ provides initial $\text{O}_2$ release if initial conditions are relatively dry and largely supplements $\text{O}_2$ release of the first few days of operation. Reduces the flow through $\text{LiOH}$ and $\text{SiO}_2$ .
<b>C</b>	Full column of $\text{SiO}_2$ provides a large humidity buffering capacity. Reduces the flow through $\text{KO}_2$ and $\text{LiOH}$ and should be used if high water vapor production is expected.
<b>D</b>	Full column of $\text{LiOH}$ provides a large $\text{CO}_2$ scrubbing capacity. Reduces the flow through $\text{KO}_2$ and $\text{SiO}_2$ and should be used if high $\text{CO}_2$ concentrations are expected.
<b>E</b>	Humidity and $\text{CO}_2$ are denied to $\text{KO}_2$ for a <b>1-2</b> day duration by $\text{LiOH}$ and $\text{SiO}_2$ . $\text{KO}_2$ is activated for $\text{O}_2$ release after as breakthrough is achieved. Downstream layers of $\text{LiOH}$ and $\text{SiO}_2$ provide supplemental humidity and $\text{CO}_2$ removal as $\text{KO}_2$ performance degrades.
<b>F</b>	Similar to Column E, buffering occurs for <b>3-5</b> days before $\text{KO}_2$ is activated in preferred environmental conditions.
<b>G</b>	Similar to Column E, buffering occurs for <b>6-8</b> days before $\text{KO}_2$ is activated in preferred environmental conditions.

## VI. Solution Example

As an example of how a particular asymmetric bed might be designed and how it might operate for a certain mission and environment, consider the scenario of 40 mice in a payload locker with an estimated mission duration of up to 10 days. From the average metabolic loading of mice over the 10 days, a total amount of makeup  $\text{O}_2$  must be provided and a total amount of  $\text{CO}_2$  and moisture must be scrubbed to keep the mice alive and environmental conditions nominal. Based on the efficiencies of  $\text{KO}_2$ ,  $\text{LiOH}$ , and desiccant to perform their air revitalization functions within the anticipated range of environmental conditions, a total amount of each chemical is sized to meet and exceed (for conservative margin) the total requirements from the metabolic loading.

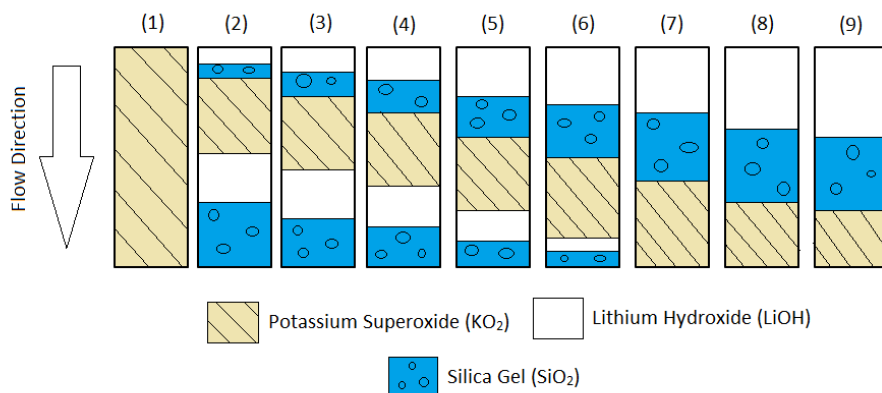
The total flow rate and the flow through each chemical are sized next to ensure that a sufficient flow is provided to achieve environmental conditions in the desired ranges. The total flow rate dictates how much air is available per pass to the bed for reaction throughout the duration of the operation. The minimum supply rate requirement of  $\text{O}_2$  and scrubbing rate of  $\text{CO}_2$  should be considered, especially with some margin included if reduced performance over the lifetime can occur. The flow to each chemical also dictates the per pass efficiency of each air revitalization

function. For example, if a particular chemical is spread across all of the 9 columns, the highest per pass efficiency of that chemical's function is achieved. If instead only 7 or 8 of the columns contain that particular chemical, assuming the total flow is equally spread to each of the 9 columns, the per pass efficiency is thus reduced. Total capacity for that chemical's function can still be maintained as long as the total mass of that chemical is maintained by distributing the mass to the other columns, thereby increasing their bed depths.

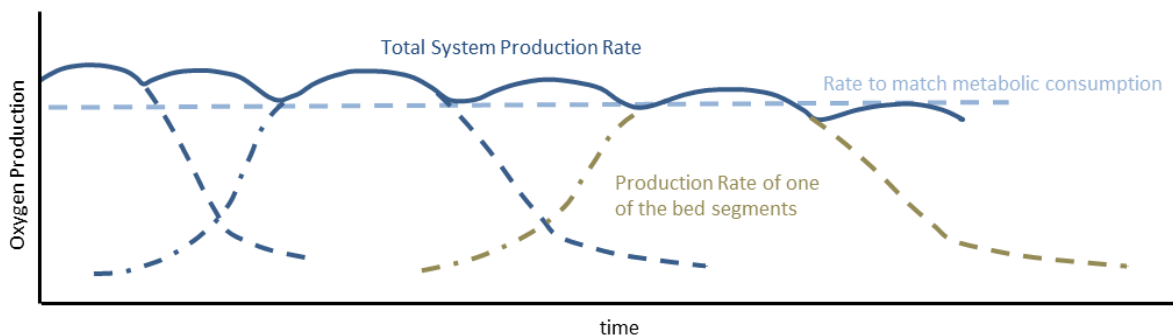
Once the amount of chemicals, the flow rate, and the relative column-wise distribution of the chemicals have been determined, the scheduling of chemical activity should be designed. In this case,  $\text{KO}_2$  must be active and producing  $\text{O}_2$  at sufficient rates through the life support duration. This means that some material must be producing in the beginning of the duration, some during the middle, and some still at the end. To schedule the activity of  $\text{KO}_2$ , buffering with  $\text{SiO}_2$  and  $\text{LiOH}$  is required. The deeper the layers of  $\text{SiO}_2$  and  $\text{LiOH}$  are in front of  $\text{KO}_2$ , the longer they are capable of sufficiently buffering humidity and scrubbing  $\text{CO}_2$  before they reach  $\text{KO}_2$ . After a layer of  $\text{KO}_2$  has been activated, its performance will degrade over time and it will require supplemental moisture and  $\text{CO}_2$  removal. For this reason, a layer of  $\text{SiO}_2$  and  $\text{LiOH}$  may also be placed behind  $\text{KO}_2$ .

An additional consideration for this particular scenario is that mice have relatively low metabolic rates compared with humans. It is possible that when all of the chemicals are fresh in the beginning of ECLSS operation, the conditions in front of buffered  $\text{KO}_2$  beds may be too dry to maintain oxygen production at sufficient rates. Including some amount of  $\text{KO}_2$  in the very front of a column will ensure that even some low (but not dry) humidity air will be able to initiate  $\text{O}_2$  release.

An example of how a configuration of 9 uniquely columns could be layered to provide ECLSS to mice is presented in Figure 10. Figure 11 shows a chart of the conceptual operation of such a configuration with respect to the expected oxygen production rates from each of the 9 beds over time. It can be seen that, while not one column is capable of supplying a sufficient rate of  $\text{O}_2$  for the duration, the integration of these columns enable a relatively constant output of  $\text{O}_2$ .



**Figure 10. An example configuration of 9 uniquely layered columns of reactive chemicals.**



**Figure 11. Oxygen production rates of individual columns and the integrated, total system**

Therefore, in an integrated sense, a bed designed and sized correctly could achieve such a relatively constant O<sub>2</sub> generation rate, matching a desired metabolic loading. A similar effect would be observed as the chemical bed functions to remove CO<sub>2</sub> and water vapor. Based on observations made thus far, however, if O<sub>2</sub> generation rates can be made to match the metabolic requirement, CO<sub>2</sub> and H<sub>2</sub>O scrubbing should also meet performance requirements.

## VII. Conclusion and Future Work

The concept of an asymmetric chemical bed for constant output environmental control is a promising idea for applications requiring a small package, simple life support system. The design of such a system can be scaled to match various lifetime loads, the flow rate and chemical layering combinations can be configured to meet performance requirements, and the upstream chemical bed depths can be varied to impose scheduling on downstream chemical activity. This technology targets applications involving ECLSS in confined spaces for durations of between 6 hours and 10 days. While a combination of potassium superoxide, lithium hydroxide, and silica gel have been proposed with the asymmetric chemical bed concept, potential exists for use of other chemicals with this concept for different applications.

To advance the development of this technology, various chemical layering configurations for each column should be tested and characterized. Consideration should be given to pressure drop and flow rate characteristics throughout the lifetime of the beds. Tests should be carried out in a sealed environment with either a simulated or actual metabolic load, or with feedback control on the supplied mix gas to the test based on downstream sensor readings. Full-scale asymmetric packed beds configurations should be put to test to determine operation during both nominal and off-nominal conditions, as well as to determine the envelope of environmental conditions within which acceptable performance still occurs. These tests should be done simultaneously with efforts to simulate and model the performance of chemical layering configurations and full-scale chemical beds.

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