The atmosphere of Mars has many resources that can be processed to produce things such as oxygen, fuel, buffer gas, and water for support of human exploration missions. Successful manipulation of these resources is crucial for safe, cost-effective, and self-sufficient long-term human exploration of Mars. In our research, we are developing enabling technologies that require fundamental knowledge of adsorptive gas storage and separation processes. In particular, we are designing and constructing an innovative, low mass, low power separation device to recover carbon dioxide and carbon monoxide for Mars ISRU (in-situ resource utilization). The technology has broad implications for gas storage and separations for gas-solid systems that are ideally suited for reduced gravitational environments. This paper describes our separation process design and experimental procedures and reports results for the separation of CO$_2$ and CO by a four-step adsorption cycle.

![Flow diagram of a system for conversion of the Martian atmosphere to O$_2$ and CO at moderate pressures.](image)

**Figure 1:** Flow diagram of a system for conversion of the Martian atmosphere to O$_2$ and CO at moderate pressures.
As illustrated in Figure 1, this work comprises one-third of an overall process for producing O\textsubscript{2} and CO at moderate pressures from the Martian atmosphere. An adsorption compressor, developed by Dr. John E. Finn at NASA Ames Research Center, adsorbs CO\textsubscript{2} from the atmosphere and compresses it to a pressure of 1 bar. The CO\textsubscript{2} is then passed to a solid oxide electrolysis cell developed by K. R. Sridhar at the University of Arizona. This electrolysis cell makes use of yttria-stabilized zirconia to produce oxygen from the compressed planetary CO\textsubscript{2} and will then reject CO and unreacted CO\textsubscript{2} in a separate stream. The efficiency of the oxygen-production process is greatly improved if the unreacted CO\textsubscript{2} is separated and recycled back into the feed stream. The separation will also have a positive impact on the mass of the adsorption compressor because less CO\textsubscript{2} will needed from the atmosphere. Additionally, the CO by-product is a valuable fuel for space exploration and habitation, with applications from fuel cells to production of hydrocarbons and plastics.

Our separation device contains a CO\textsubscript{2}-selective sorbent such that when the mixture is fed from the electrolyzer, CO\textsubscript{2} adsorbs and CO passes through the bed with minimal adsorption. The cycle is illustrated by Figure 2. The mixture is fed at a temperature of 273K. When the bed reaches capacity, it is isolated and heated with no flow at 398K to desorb the CO\textsubscript{2}. CO\textsubscript{2} at high pressure is then allowed to pass to a storage tank at sufficient pressure to feed the electrolyzer. The bed is then cooled back to 273K prior to returning to the feed step. We envision a two-bed system in which one bed is onstream for the feed step while the other is undergoing regeneration and blowdown of CO\textsubscript{2}.

![Figure 2: Depiction of four-step adsorption cycle between CO\textsubscript{2} adsorption isotherms on NaY zeolite.](image)

We have a working prototype and have performed the proposed cycle. We have developed process models and are continuing to optimize the separation. All of these results will be discussed.
Separation of Carbon Monoxide and Carbon Dioxide for Mars ISRU
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ABSTRACT
The atmosphere of Mars has many resources that can be processed to produce useful materials like oxygen, fuel, buffer gas, and water for support of human exploration missions. In this research, we are designing and constructing an innovative, low mass, low power separation device to recover carbon dioxide and carbon monoxide for Mars ISRU (in-situ resource utilization). The separation is accomplished by a four-step adsorption process. The technology has broad implications for gas storage and separations for gas-solid systems that are ideally suited for reduced gravitational environments.

Overall Process Description
- **Yttria-Stabilized Zirconia (YSZ) Electrolyzer**
  - CO2 diffuses through the electrode and liberates an oxygen atom through thermal dissociation and electrocatalysis. The oxygen atom acquires two electrons from the cathode to form an oxygen ion. The electric field drives the ion through the electrolyte. The ion transfers its charge to the anode as it reaches the anode-electrolyte interface and combines with another oxygen atom to form O2.
- **Electrolyzer**
  - Dr. K. R. Sridhar
  - University of Arizona
D.C. voltage source

**Adsorption Compressor**
- The adsorption compressor adsorbs CO2 from the atmosphere and vents N2 and Ar. It reaches capacity and is heated to desorb the CO2, raising the internal pressure. CO2 is then vented to the electrolysis cell at 1 bar until the pressure of the compressor cannot be maintained. The compressor is then cooled until the system pressure is the same as the environment, and a new cycle begins.

**Adsorptive Separation**
- CO2-selective sorbent
- CO2/CO mixture is fed to the electrolyzer. CO2 adsorbs and CO passes through the bed with minimal adsorption. When the bed reaches capacity, it is isolated and heated to desorb the CO2. CO2 at high pressure is then allowed to pass to a storage tank at sufficient pressure to feed the electrolyzer. The bed is then cooled back to at 273 K prior to returning to the feed step.

4-step Adsorption Cycle
- **Adsorption Compressor**
- **Adsorptive Separation**
- **CO2 Breakthrough Curve**

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Experimental Apparatus
- Environmental Chamber
- GC
- Helium/CO
- CO2 Feed

**Adsorption Equilibria: Measurements and Modeling**
We have measured both pure-component and binary adsorption equilibria data for CO and CO2 on NaY zeolite molecular sieve. These data and their description are critical for designing an adsorptive separation process. A temperature-dependent multistate Langmuir equation has been used to model successfully all adsorption equilibria data, both pure component and binary, using only one set of parameters. This model can be used easily in non-isothermal feed-bed simulations.

Our separation device contains a CO2-selective sorbent such that when the mixture is fed to the electrolyzer, CO2 adsorbs and CO passes through the bed with minimal adsorption. The mixture is fed at a temperature of 273 K. When the bed reaches capacity, it is isolated and heated with no flow at 398 K to desorb the CO2. CO2 at a high pressure is then allowed to pass to a storage tank at sufficient pressure to feed the electrolyzer. The bed is then cooled back to 273 K prior to returning to the feed step. We envision a two-bed system in which one bed is onstream for the feed step while the other is undergoing regeneration and blowdown of CO2.