Multi-Constituent Airborne Contaminants Capture with Low Cost Oxide Getters and Mitigation of Cathode Poisoning in SOFCs

Prabhakar Singh

Department of Materials Science and Engineering
University of Connecticut, CT

WORK PERFORMED UNDER AGREEMENT DE-FE 0023385, 0027894 and 0031182

FE SOFC program at the 2020 AMR meeting, Crystal City
May 20, 2020
## Technical Contributors

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prabhakar Singh</td>
<td>Professor</td>
</tr>
<tr>
<td>Steven Suib</td>
<td>Professor</td>
</tr>
<tr>
<td>Avinash Dongare</td>
<td>Associate Professor</td>
</tr>
<tr>
<td>Boxun Hu</td>
<td>Assistant Research Professor</td>
</tr>
<tr>
<td>Ashish Aphale</td>
<td>Post-doctoral research associate</td>
</tr>
<tr>
<td>Pawan Kumar Dubey</td>
<td>Post-doctoral fellow</td>
</tr>
<tr>
<td>Junsung Hong</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Michael Reisert</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Su Jeong Heo</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Junkai He</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Yanliu Dang</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Seraphim Belko</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Scott Misture</td>
<td>Professor</td>
</tr>
</tbody>
</table>

### UConn

- Alfred University
- UAlabama

**Program Manager:** Dr. Patcharin N. Burke, NETL
Outline

• Accomplishments
• Program objectives
• Technical Approach
• Experimental
  • Getter materials synthesis and stability evaluation
  • Long-term validation of getter performance for multi-contaminant capture
  • In-situ validation using electrochemical tests and transpiration tests.
  • Posttest characterizations
• Results
• Discussion
• Acknowledgements
• Publications
Benefits of Technology to the Programs

**Potential benefits of this project:**

- The programs remain significant to the commercialization of SOFC systems by improving the TRL.
- Mitigation of cathode poisoning and highly durable anode enables increased performance stability and long-term reliability of SOFC systems thus accelerating demonstration and deployment of the technology.

**Impact**

- Mechanistic understanding of the degradation processes in pure electronic and mixed electronic and ionic conducting (MEIC) cathodes.
- Development of mitigation process utilizing low cost getters to capture trace levels of airborne contaminants.
- Reduction in oxide evaporation by developing surface pretreatment conditions.
- Mitigation of carbon deposits in the cell anode.
- Improved cell and stack temperature distribution.
- Eliminated external reformer by using DIR solid oxide fuel cells.
- Improved cell and stack electrochemical performance and durability.
- Reduced materials cost.
Program Objectives

- The overall objective of the proposed research programs is to develop and validate reliable, cost-effective getter approaches for mitigation of SOFC cathode degradation through incorporation of reliable materials and architectures to inhibit detrimental solid-solid and solid-gas interactions.
- It is also the objective of the program to development of low-cost alloy anodes for distributed internal reforming of fuels to potentially increase the flue-flexibility, reliability and long-term endurance of SOFCs.

Approaches:
- Develop mechanistic understanding of cathode degradation in “real world” air atmosphere.
- Develop materials and architectures of cost-effective getters for application in stacks and BOP.
- Develop alloy surface pretreatment conditions to minimize chromium evaporation.
- Validate and demonstrate getter performance to capture trace levels of airborne multi-components impurities.
- Independent validation of getter performance has been performed by industrial partners and national laboratories under their systems operating conditions.
- Fundamental thermodynamic calculations complemented the experimental observations.

Outcome
- Proposed approaches successfully developed, validated and implemented.
- Proposed program milestones have been met.
- Conducted materials and technology transfer.
Program Accomplishments

- Developed getter for the capture of trace levels of multi-components impurities present in ambient and process air.
- Develop mechanistic understanding of cathode degradation under ambient air atmosphere.
- Group II Alkaline earth and transition metal oxide based low cost getter offers excellent capture of trace airborne contaminants.
- Getter performance has been validated for the capture of single (Cr or S) and multiple (Cr and S) contaminants in their trace concentrations in ppm-ppb range.
- Electrochemical tests indicates stable cathode performance under SOFC systems conditions.
- Getter posttest characterization indicates high concentration of both Cr and S at the inlet, while no/negligible concentrations at the outlet indicating complete capture of contaminants.
Background: Sources of Contaminants

- Air in fuel cell stack and system may also contain component derived impurities such as Cr (from metals and alloys) and Si, B, and alkali (from glass and insulation).
- Air electrodes remain prone to degradation due to acid-base interactions with contaminants.
- Dopant exolution, Compound formation, Surface/Interface morphology changes and Interdiffusion.

### NAAQS (US EPA)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>20.9 v%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>78 v%</td>
</tr>
<tr>
<td>Water</td>
<td>&lt;1 to 3 v%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>350 ppm</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Noble gases</td>
<td>&lt;1 v%</td>
</tr>
<tr>
<td>Particulate matter (PM)</td>
<td>&lt;50 µg/m³</td>
</tr>
</tbody>
</table>

### Long-term Degradation

- **Acidic gaseous species**
  - Electrocatalytic Deactivation
  - Compound Formation
  - Surface adsorption

- **Basic AE Surface**

- **Short term**
  - SrO
  - SrCrO₄
  - SrSO₄

- **Intermediate**
  - Cr₂O₃

- **Long term**
  - SrO
  - SrCrO₄
  - SrSO₄
  - H₂O, CO₂, SO₄, Cr
Background: Technical Approach

• Cathode poisoning leading to the long-term degradation in SOFC systems
• Permanent performance degradation leading high polarization losses
• Interfacial deposition limits the oxygen access at the triple phase boundary (TPB) sites
Prior work: Cathode Poisoning in “Real World” Air

Cathode degradation mechanism

H₂O-Air

CO₂-Air

Cr-Air

Thermodynamic calculations

Cathode undergoes significant morphological and chemical changes in ambient air atmosphere

- Ashish Aphale, Aman Uddin, Boxun Hu, Su Jeong Heo, Junsung Hong and Prabhakar Singh, ECS, 2018
Getter Synthesis and Stability

Thermo-calculations

\[
\Delta G (kJ) = \text{SrO} + \text{CrO}_2(\text{OH})_2 (g) = \text{SrCrO}_4 + \text{H}_2\text{O} (g)
\]

\[
2\text{SrO} + 2\text{CrO}_2(\text{OH})_2(g) + \text{O}_2(g) = 2\text{SrCrO}_4 + 2\text{H}_2\text{O} (g)
\]

Getter powder phase and morphology

Phase stability diagram

High temperature in-situ XRD performed on SrNiOx powder for 40h

XRD analysis after sintering

Getter powder remains stable under SOFC operating conditions

Ashish Aphale, Aman Uddin, Boxun Hu, Su Jeong Heo, Junsung Hong and Prabhakar Singh, Synthesis and Stability of SrxNiOz Chromium Getter for Solid Oxide Fuel Cells”, ECS, 2018
Chromium Capture Validation

Transpiration Tests

Without getter

With getter

Electrochemical Tests

Successful capture of gas phase Cr vapors and mitigation of cathode poisoning is demonstrated

Air Flow Rate (SCCM) : 50, 100, 200, 500 completed

Chromium Capture Validation

- Half-cell fabrication procedure was maintained for all the half-cell fabrication
- LSM was screen printed and sintered at 1200 °C for 1h
- SNO or LSCF/SNO getter was brush coated and sintered at 850 °C for 20h
- Config-1: Getter paste is 5 mm apart from LSM and Config-2: Getter paste is in direct contact with LSM

I-t data

Cr Poisoning of TBP Sites

Cross sectional FIB-STEM micrograph and mapping of LSM/YSZ interface after Cr poisoning at 650°C

- FIB-STEM and mapping reveals deposition of chromium at LSM/YSZ interface
- HRTEM results show it is rhombohedral Cr$_2$O$_3$ (space group R-3c, no. 167)

(a) TEM image of region of the chromium deposition taken along [110], (b) The corresponding FFT pattern (c) HRTEM image of the crystalline and (d) the atomic model illustrated.

SJ Heo, J Hong, A Aphale, B Hu, P Singh, Journal of The Electrochemical Society 166 (13), F990-F995
Surface Morphology: Pretreatment V/s of Conventional Alloy

- Oxidation of alumina forming alloy leads to formation of mixed oxide scales and alumina subscale.
- Surface pretreatment leads to the formation of exclusive alumina scale only.

Ashish Aphale, Michael Reisert, Su Jeong Heo, Boxun Hu, Junsung Hong and Prabhakar Singh, 2020 (Manuscript ready to be submitted)
Capture of Gas phase SO$_2$ and Cr Species

- SrO is better than CaO, and MgO as a getter material for Cr and S capture.
- SrO can form SrCrO$_4$ and SrSO$_4$ compounds at extremely low concentrations of Cr and SO$_2$ vapors.
- Operational feasibility under wide temperature ranges.
Advanced Getter: Materials Section and Fabrication

- Thermodynamic reaction feasibility (\(\Delta G\)) for capture of both S and Cr on select getter
- 5 um thick getter layer coating achieved on cordierite substrate

J Hong, AN Aphale, SJ Heo, B Hu, M Reisert, S Belko, P Singh, ACS applied materials & interfaces 11 (38), 34878-34888 (2019)
Getter Performance Validation

Experimental Matrix

<table>
<thead>
<tr>
<th>Test #</th>
<th>SMO getter (with S &amp; Cr)</th>
<th>With S &amp; Cr</th>
<th>With S only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>LSM/YSZ/Pt</td>
<td>LSM/YSZ/Pt</td>
<td>LSM/YSZ/Pt</td>
</tr>
<tr>
<td>Getter</td>
<td>With SMO getter</td>
<td>No getter</td>
<td>No getter</td>
</tr>
<tr>
<td>Cr Source</td>
<td>Cr₂O₃ pellets</td>
<td>Cr₂O₃ pellets</td>
<td>-</td>
</tr>
<tr>
<td>S Source</td>
<td>Various SO₂ concentration</td>
<td>Various SO₂ concentration</td>
<td>Various SO₂ concentration</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Air + 3% H₂O</td>
<td>Air + 3% H₂O</td>
<td>Air + 3% H₂O</td>
</tr>
<tr>
<td>Flow rate</td>
<td>150 sccm (C) / 50 sccm (A)</td>
<td>150 sccm (C) / 50 sccm (A)</td>
<td>150 sccm (C) / 50 sccm (A)</td>
</tr>
<tr>
<td>Temp.</td>
<td>750 °C</td>
<td>750 °C</td>
<td>750 °C</td>
</tr>
<tr>
<td>Applied bias</td>
<td>- 500 mV</td>
<td>- 500 mV</td>
<td>- 500 mV</td>
</tr>
</tbody>
</table>

Getter performance validated at 150 ppb-4 ppm range of SO₂ concentration
Long-term Electrochemical Validation of SMO Getter

LSM performance when exposed to 4 ppm SO₂ and Cr containing air at 700°C for 230 hrs.

- Stable performance of LSM cathode observed in presence of SMO Getter
- Rapid degradation of cathode in Cr containing air observed.
- Exposure to only SO₂ (4 ppm) also leads to significant degradation of cathode in air. Partial recovery of the cathode is observed after removing SO₂.
Electrochemical Performance and Morphology

- Nyquist plot shows significant increase in polarization resistance for LSM when exposed to Cr and S containing air.
- Significant S concentration is observed at the LSM/YSZ interface.
- Presence getter demonstrates stable cathode performance and clean interface.
Cr and S Capture Profile on Posttest Getter

- Large concentrations of Cr and S appear at the getter inlet with no/negligible concentrations at the outlet.
- Raman spectroscopy reveals presence of SrSO4 formation on SMO getter.
Cr Capture Profile on SMO Getter (Transpiration)

- Capture of Cr vapor demonstrated on SMO getter at 700°C for 500 hrs.
- SEM-EDS spectra indicated significant concentrations of Cr (at.%) at the getter inlet.
- SEM micrographs show Cr capture at the inlet of getter.
- Raman spectroscopy reveals formation of SrCrO4 on SMO getter.
FIB/STEM Analyses and Elemental Mapping of Posttest Getter

- Co-capture of Cr and S is observed from FIB/TEM analyses.
- Elemental mapping confirms presence of S and Cr with in SrMnO\textsubscript{x} getter.
- SMO getter provides continues absorption of contaminants by morphology elongation.
Air in fuel cell stack and system may also contain component derived impurities such as Cr (from metals and alloys) and Si, B, and alkali (from glass and insulation).
Getter selection for multi-contaminant systems

Capture of gas phase impurities by ‘Getters’ based on Gibbs free energy and equilibrium constant k. Unit solid phase activity assumed.

- Significant vapor pressures exist from contaminants in ambient air as well as ones evaporating from alloys and glass-based seals.
- Select oxides have shown potential to capture these contaminants under wide operating temperature range of 500-1000°C in humidified air atmosphere.
- Transpiration and electrochemical validation tests setups have been established to understand multi-capture of contaminants under SOFC operating conditions.
Getter Validation Test: Multi-contaminant Capture

Response parameters:
- Contaminants vapor pressure
- Getter validations
- Posttest getter morphology and chemistry
- Cathode performance: surface and cross section
Getter Validation Test: Boron Transpiration

**Boron transpiration test:**
- Borosilicate crystal structure
- Borosilicate vaporization over temperature
- Evaluation of boron getter ability of SMO

- **XRD**
- **TGA**
- **SEM**
- **SEM-EDS**
- **ICS analysis**
**Getter Validation Test: Boron Vapor Capture**

**Inlet of the getter**

No clear detection of B and Si by EDS as the signals for B, C, and Si are overlapped.

**Boron getter ability of SMO:**
- No significant morphology change
- Not clear signals for B and Si by EDS
- Though, ICP showed the B concentration decrease with the SMO getter
- Further tests will be needed to clarify the result.
Publications (Papers)

- B Hu, S Krishnan, C Liang, SJ Heo, AN Aphale, R Ramprasad, P Singh, “Experimental and thermodynamic evaluation of La1− xSrxCr2O3-xS and La1− xSrxCr1− yFeO3− δ cathodes in Cr-containing humidified air”, International Journal of Hydrogen Energy 42 (15), 10208-10216, 2017
- C Liang, B Hu, A Aphale, M Venkataraman, MK Mahapatra, P Singh, “Mitigation of chromium assisted degradation of LSM cathode in SOFC”, ECS Transactions 75 (28), 57, 2017
- MA Uddin, A Aphale, B Hu, SJ Heo, U Pasaogullari, P Singh, “Electrochemical validation of In-cell chromium getters to mitigate chromium poisoning in SOFC stack” Journal Of The Electrochemical Society 164 (13), F1342-F1347, 2017
Publications (Books and Presentations)


- Prabhakar Singh, Boxun Hu, Ashish Aphale, Junsung Hong, Su Heo, PACRIM 13, 2019, Okinawa, Japan (Invited talk)


- Ashish Aphale, Md Aman Uddin, Boxun Hu, Justin Webster, Su Jeong Heo, Junsung Hong and Prabhakar Singh, “Role of Select Minor Airborne Impurities on SOFC Cathode Degradation: Computational Simulation and Experimental Studies”, 42nd ICACC, Daytona, FL Jan 2018


- Ashish Aphale, Md Aman Uddin, Boxun Hu, Justin Webster, Su Jeong Heo, Junsung Hong and Prabhakar Singh, “Role of Select Minor Airborne Impurities on SOFC Cathode Degradation: Computational Simulation and Experimental Studies”, 42nd ICACC, Daytona, FL Jan 2018 (Talk)


Conclusions

- Gas phase extrinsic and intrinsic impurities originate from incoming air, cell/stack and BOP components.
- Significant degradation of SOFC cathode has been observed in the presence of airborne impurities.
- Cathode degradation mechanisms have been identified and experimentally validated.
- Cr capture using “Getters” has been successfully demonstrated from In-cell and BOP sources.
- Getters have also confirmed combined capture of Cr and SO2 impurities present in air.
- Characterization of experimentally tested getters reveal high concentration of S and Cr near the inlet only.
- Novel getters are being tested for validation of multiple contaminant capture (Cr, S, Si and B) in air.

Application of “Getters” provide a cost-effective method of mitigating electrode poisoning and performance degradation in high-temperature electrochemical systems:

SOFC ← SOEC ← P-SOEC ← OTM
Acknowledgements

- Financial support from the US DOE (Office of Fossil Energy)
- Dr. Rin Burke for guidance
- UConn for providing laboratory support
Thank you
Supporting slides
## Milestones of Project 1

<table>
<thead>
<tr>
<th>Task / Subtask Number</th>
<th>Deliverable Title</th>
<th>Anticipated Delivery Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Project Management Plan</td>
<td>Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the Project Officer.</td>
</tr>
<tr>
<td>2.0</td>
<td>Getter materials identification, selection and synthesis</td>
<td>30 days after completion of task 2</td>
</tr>
<tr>
<td>2.1</td>
<td>Rational section of candidate getter materials</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Getter materials synthesis</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Thermodynamic modeling to screen potential getter materials</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Synthesis of HSA nano-porous coating and optimized getter architecture</td>
<td>30 days after completion of task 3</td>
</tr>
<tr>
<td>3.1</td>
<td>High surface area (HSA) getter powder synthesis</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>Characterization of synthesized getter materials</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Identification of materials properties and development of coating technique</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>Getter validation for combined capture of gas phase impurities</td>
<td>30 days after completion of task 4 and three months after task 3</td>
</tr>
<tr>
<td>4.1</td>
<td>Electrochemical validation of getters</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Posttest getter parametric study</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>Getter design optimization using computational flow analysis</td>
<td>30 days after completion of task 5</td>
</tr>
<tr>
<td>5.1</td>
<td>Getter optimization using computational modeling</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Development of optimal coating and getter design</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>Scale-up and long-term testing under SOFC systems conditions</td>
<td>30 days after completion of task 6 and three months after task 5</td>
</tr>
<tr>
<td>6.1</td>
<td>Materials scale-up to meet large systems requirements</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Identification and development of quality control procedures</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Independent validation of getters by SOFC industrial partners</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>Post-test characterization and mechanistic understanding</td>
<td>30 days after completion of task 7 and three months after task 6</td>
</tr>
</tbody>
</table>
## Milestones of Project 2

<table>
<thead>
<tr>
<th>Task/Subtask #</th>
<th>Milestone Title/Description</th>
<th>Planned Completion Date</th>
<th>Actual date &amp; Current Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Establishment of program priorities with program manager</td>
<td>12/31/2017</td>
<td>12/31/2017 Milestone meet</td>
</tr>
<tr>
<td>2.1-2.3</td>
<td>Select target HEA anode materials</td>
<td>3/30/2019</td>
<td>In process, Close to target</td>
</tr>
<tr>
<td>3.1-3.2</td>
<td>Identification of carbon formation conditions</td>
<td>03/30/2019</td>
<td>In process</td>
</tr>
<tr>
<td>4.1-4.2</td>
<td>Obtain optimal activation energy.</td>
<td>2/28/2019</td>
<td>In process</td>
</tr>
<tr>
<td>5.1-5.3</td>
<td>Stable CH₄ reforming is achieved.</td>
<td>6/30/2019</td>
<td>In process</td>
</tr>
<tr>
<td>6.1-6.3</td>
<td>Achievement of large-scale synthesis.</td>
<td>09/30/2019</td>
<td>25 gram batch is achieved.</td>
</tr>
<tr>
<td>7.1-7.2</td>
<td>Characterization of posttest materials and long-term degradation mechanisms</td>
<td>09/30/2019</td>
<td>In process</td>
</tr>
<tr>
<td>8.1-8.2</td>
<td>Documentation, Reporting, and Publication</td>
<td>9/30/2019</td>
<td>In process</td>
</tr>
<tr>
<td>9.1</td>
<td>Intellectual property and technology transfer</td>
<td>9/30/2019</td>
<td>In process</td>
</tr>
</tbody>
</table>
Project schedule (which format you want to use?)

<table>
<thead>
<tr>
<th>Milestone</th>
<th>10/18</th>
<th>11/18</th>
<th>12/18</th>
<th>11/19</th>
<th>12/19</th>
<th>01/20</th>
<th>02/20</th>
<th>03/20</th>
<th>04/20</th>
<th>05/20</th>
<th>06/20</th>
<th>07/20</th>
<th>08/20</th>
<th>09/20</th>
<th>10/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milestone I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone II</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 2</td>
<td></td>
<td></td>
<td>12/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 3</td>
<td></td>
<td></td>
<td></td>
<td>11/19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone III</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 2</td>
<td></td>
<td></td>
<td>12/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 3</td>
<td></td>
<td></td>
<td></td>
<td>11/19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone IV</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 2</td>
<td></td>
<td></td>
<td>12/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone V</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 2</td>
<td></td>
<td></td>
<td>12/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone VI</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 2</td>
<td></td>
<td></td>
<td>12/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 3</td>
<td></td>
<td></td>
<td></td>
<td>11/19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone VII</td>
<td>10/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-task 1</td>
<td></td>
<td>11/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The diagram shows the timeline for each milestone and sub-task with the corresponding dates. The black triangles indicate milestones that have been completed.
Long-term stability of SrNiOx Getter in Ambient Air

SNO phase has tendency for being hygroscopic accompanied by volume expansion

\[ \text{Sr}_9\text{Ni}_7\text{O}_{21} + x\text{H}_2\text{O} \rightarrow 2\text{Sr(OH)}_2\cdot8\text{H}_2\text{O} + 7\text{SrNiO}_3 \]

J. Hong et al, J. Electrochem. Soc., 166(2), 2019
500 hrs Getter Transpiration Test
Contaminated air
intrinsic and extrinsic impurities

Getter

Clean Air to SOFC Stack
Capture of intrinsic and extrinsic contaminants from both BOP and Stack has been demonstrated

- Ashish Aphale, Aman Uddin, Boxun Hu, Su Jeong Heo, Junsung Hong and Prabhakar Singh, ECS, 2018
Thermal Stability of Cr getters

High temperature *in-situ* XRD performed on SrNiOx powder for 40h

![XRD spectra for 850°C and 1000°C](image)

- SrNiOx maintains phase stability below sintering temperature of 900°C
- Sintering SrNiOx above 950°C leads to dissociation into separate SrO and NiO phases
- Volume expansion and pulverization is observed above 950°C sintering temperature

VESTA and COD utilized for crystallographic representation

XRD analysis after sintering

- [SrNiOx](https://example.com/srxniyoz)
- [Chromium Getter for Solid Oxide Fuel Cells](https://example.com/srofuelcells)

*Ashish Aphale, Aman Uddin, Boxun Hu, Su Jeong Heo, Junsung Hong and Prabhakar Singh, Synthesis and Stability of SrxNiyOz Chromium Getter for Solid Oxide Fuel Cells*, ECS, 2018
Chromium Capture Validations

Transpiration Tests

Without getter

With getter

Getter concept also validated independently by industries

Advanced Getter: Stability and Performance

The stability of SNO is improved using SrCO₃ passivation layer while the ability to capture Cr vapor is maintained.

The LSM/YSZ/Pt half-cell exposed to 3% H$_2$O/air in the presence of Cr & SO$_2$ vapor with SMO getter shows a stable performance in I-t curve.