Liquid Tin Anode SOFC for Direct Coal Conversion: A System Perspective

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**Background, Objectives, Approach**

Liquid Tin Anode SOFC (LTASOFC) could revolutionize power generation from coal ...

- Liquid anode regeneration allows conversion of almost all fuel in LTASOFC: promises **high electrical efficiency** and **straightforward carbon capture**
- Is tolerant of many coal impurities (oxidizes sulfur as fuel): promises **robust operation**
- Eliminates expensive and gasifier, ASU, and gas turbines compared with IGCC: holding potential for **low cost**

... but it is at a very early stage of development.

- Basic feasibility has been proven in single cells and 2-cell stacks since 1990s
- Key data for coal conversion lacking, leaving key questions:
  - Can LASOFC be made sufficiently robust for reliable power generation?
  - Can power densities be raised to achieve acceptable cost?
  - Can the technology be scaled-up?

Thus DOE’s NETL wanted to understand the technical and economic potential for LTASOFC, as well as key challenges.
Strictly speaking the LASOFC is a metal-air fuel cell with continuous regeneration of the metal oxide produced.

**LTASOFC Operating Principle**

- Anode reactions are quite fast at 1000 °C operating temperature
- Potential for SnO₂ precipitation limits LTASOFC power density:
  - Drives high T (~1000°C)
  - Theoretically: 1-2% O²⁻
  - Practical operation shows lower limit (0.1 – 0.2%)

In equilibrium, the effects of the Sn reactions cancel out.
## LTASOFC Stacking Considerations

### LTASOFC Sn Reduction: Options

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<th>In-Situ</th>
<th>In-Stack</th>
<th>Central</th>
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<td><strong>Coal Feed</strong></td>
<td>Exhaust (H₂O, CO₂)</td>
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<tr>
<td>In-Situ Reduction (CO₂)</td>
<td>Direct Reduction</td>
<td>Sn + SnO₂</td>
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**In-Situ**
- + Can build up voltage
- + No direct contact coal / cells / tin stays in place
- Can build up voltage inside stack
- Cannot build up voltage inside stack
- Requires recirculation of large Sn volumes
- Requires recirculation of large Sn volumes
- Direct contact coal with stack
- Complex coal / ash handling per stack
- Poor control fuel conversion
- No on-stream tin quality mgmt
- Power density diffusion - limited

**In-Stack**
- + High conversion
- + Higher power density possible
- + Easiest thermal integration
- + Central coal / ash handling
- + High conversion
- + Tin quality management possible
- + Highest power density possible

**Central**
- + Central coal / ash handling
- + High conversion
- + Tin quality management possible
- + Highest power density possible

### LTASOFC Cell Voltage

**Graph**: Cell Voltage vs. Current Density (A/cm²)

- **Standard Potential**
- **OCV**
- **Electrode Polarization**
- **IR losses**

For perspective:
- Sn circulation: ~0.5 million tpd (cell voltage 0.65V/cell, max oxygen content in tin 0.2%)
- Impact of cell voltage build-up:
  - each micro-ohm of busbar resistance results in 15% I²R loss
  - Keeping I²R loss <1% would require >300 cm² cross-section for 20 cm long busbar
Preliminary analysis indicates that 60+% efficiency is feasible with LTASOFC with CCS, provided efficient thermal integration.

1. Ideal efficiency: unit activities
2. OCV figures in Nernst correction (anode and cathode side)
3. Stack losses comprise I2R losses, electrode polarization, mass transfer
4. Utilization of 97% is likely only achievable with anode gas recycle
5. HRSG/ST bottoming cycle heated by syngas purge, cathode air exhaust, and syngas cooling
6. Parasitics include power for fans, tin pump, amine units, and miscellaneous factors
The capital cost for an LTASOFC system would likely be $1400 - $2400 per kW, and a LCOE of around 70 $/MWh with CCS.

- Capital cost assumptions:
  - For stack modified from earlier analysis for Siemens tubular stacks
  - For tin reduction reactor, based on estimates for molten metal gasifiers (e.g. Hymelt, Hydromax)
  - Other system components scaled from DOE baseline IGCC

- LCOE analysis based on DOE baseline study

- Narrowing down the uncertainty on the stack and SnO2 reduction reactor is critical:
  - O/Sn
  - Thermal integration / losses
  - Power density
  - Tin flow control system

- From 2007 baseline with CO2 capture
- Coal conversion / SnO2 reduction reactor is listed as gasifier
LTASOFC could have the potential for high-efficiency, low-cost, clean coal power generation, but there are key uncertainties.

- Systems based on LTASOFC may be relatively simple and may achieve:
  - 60% electrical efficiency based on coal based on a high-efficiency fuel cell stack
  - >90% carbon capture by recycling unconverted anode tailgas
  - <10% increase in LCOE if stack cost can be kept to less than $750/kW

- There appear to be no fundamental showstoppers for LTASOFC at this point, but there are significant uncertainties about its viability as a coal-based power technology:
  - No thermodynamic limitation known that would prevent a LTASOFC from being realized, but the solubility of oxygen in molten tin must be better-understood
  - Basic technology challenges include:
    - Stack operation in presence of coal contaminants other than sulfur
    - Power density limitations, including the limitations imposed by the limited solubility of SnO2 in Sn(l)
    - Ability to break the conductive path through the flowing tin to allow voltage build-up in the stacks
  - In addition, a host of engineering challenges will have to be addressed:
    - Stability of materials under hostile conditions (temperature, molten metal, mechanical stresses, erosion)
    - Sealing of cells and components
    - Insulation to mitigate against unacceptable heat losses
    - Reactor engineering of the SnO2 reduction / coal conversion reactor

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