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Sandia National Laboratories

# Cyclic Thermal and Structural Testing of a Hot Particle Storage Bin

*G3P3 Award 34211 and 38711*

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# Overview

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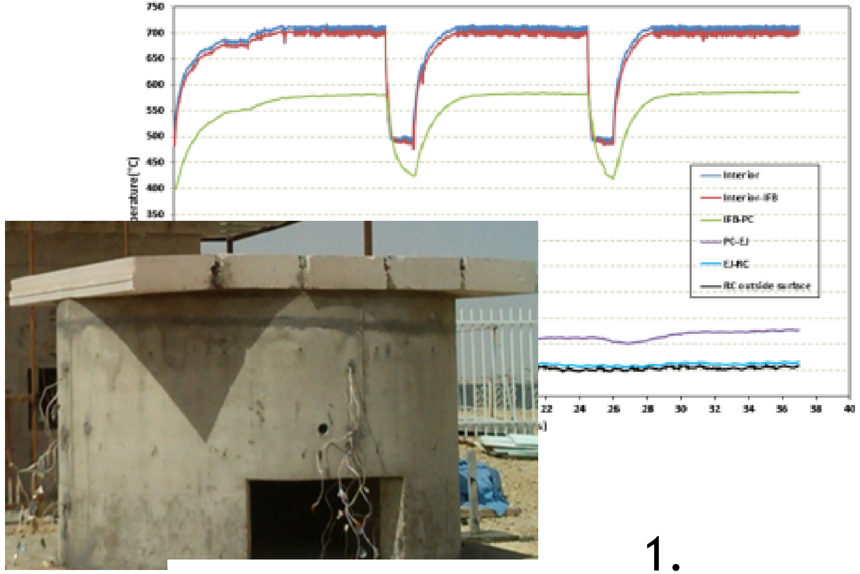
# Gen 3 Flowing Particle Storage Bin Modeling and Testing

El-Leathy et al 2014 – Tested 0.12 m$^3$ and ~8.3 m$^3$ storage bin.

Cyclic heating with air temperature heated to 800° C by gas.

Sment et al 2019 – Measure a single discharge and charge steel bin with 64 kg of particles at 800° C heated in a furnace.

Next steps seek to model and test the coupled transient charge-hold-discharge behavior with flowing particles over several cycles.



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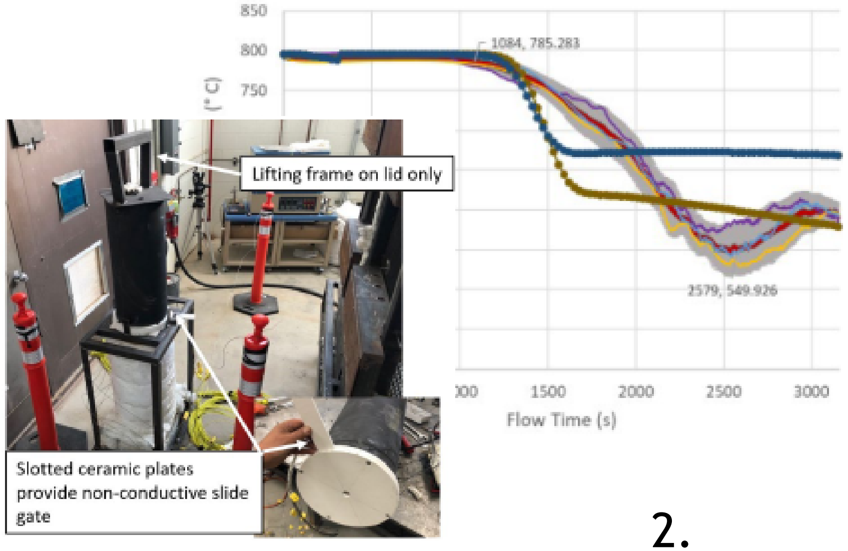



2.

1. El-Leathy, A., Jeter, S., Al-Ansary, H., Danish, S. N., Saeed, R., Abdel-Khalik, S., . . . Al-Suhaibani, Z. (2019). Thermal performance evaluation of lining materials used in thermal energy storage for a falling particle receiver based CSP system. *Solar Energy, 178*, 268-277. doi:https://doi.org/10.1016/j.solener.2018.12.047

2. Sment, J. N., Martinez, M. J., Albrecht, K. J., & Ho, C. K. (2020). *Testing and Simulations of Spatial and Temporal Temperature Variations in a Particle-Based Thermal Energy Storage Bin.* Paper presented at the ASME 2020 14th International Conference on Energy Sustainability, Denver, CO.

# Heat Kernel Model Validation

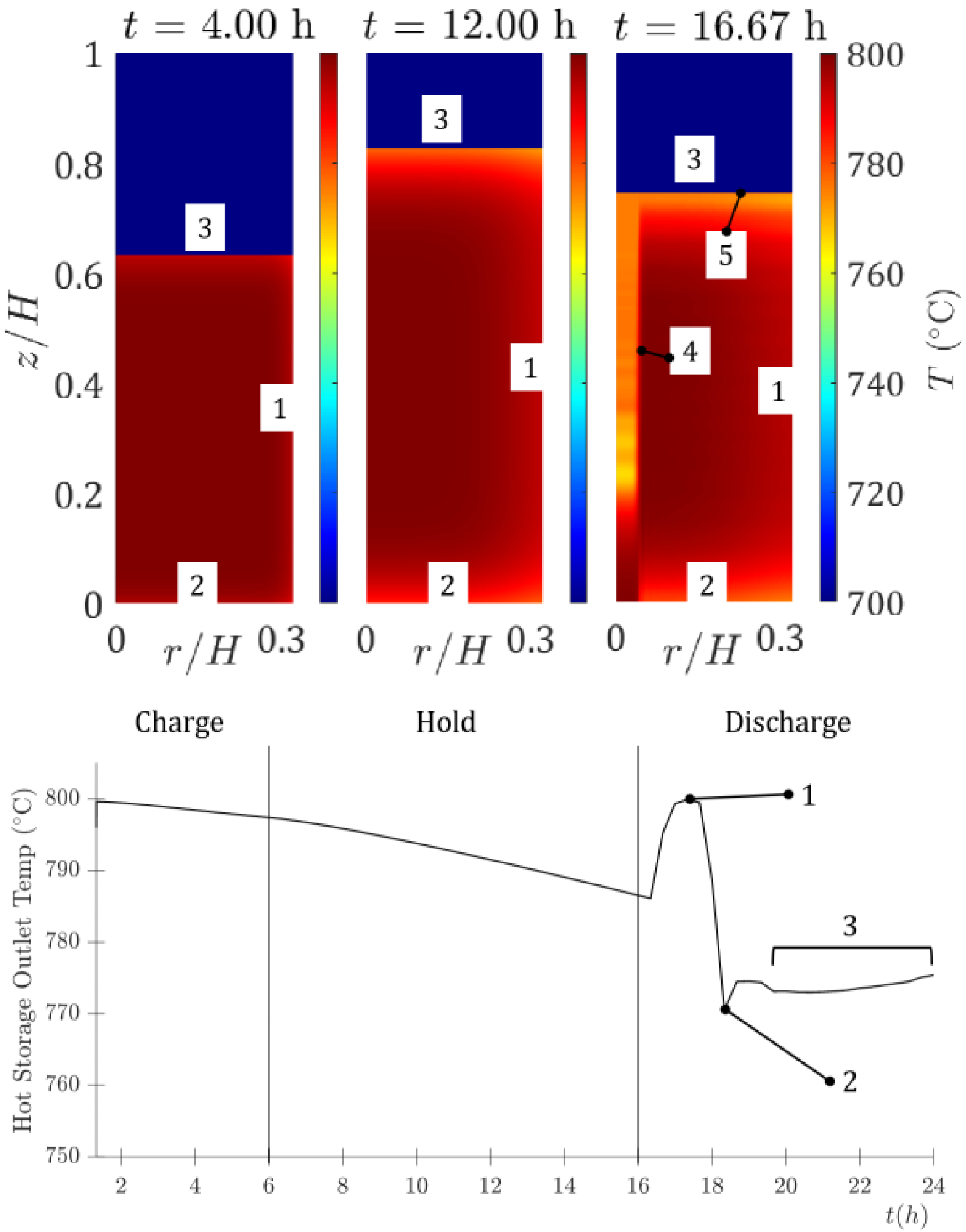
Plewe et al 2020, 2021 couples the charge-hold-discharge operational modes.

The validation of this model requires a test apparatus with:

- three operational modes: charge, hold, discharge
- particles in funnel flow
- multiple cycles
- Adjustable mass flow rates and temperatures

The model will be evaluated on three characteristic points:

1. Maximum at core discharge
2. Minimum when slug of cool particles at top layer exit
3. Average of “plateau”.
    - Flow channel gradually widens



# Test Overview

- SNL is building a test stand capable of heating ≤750 kg particles to ≤900° C in an electric furnace.
- Slide gates on electric actuators then control the flow of heated particles into a small -scale replica of the G3P3 storage bin instrumented with thermocouples and strain gauges.
- The particles then flow into catch bin where they can be lifted back to furnace for reheating.
  - Particles can be lifted in receiving bin with a crane or recirculated through the falling particle receiver

charging bin
with heat transfer
tubes

bucket lift and test stand next to falling particle receiver

charging bin in furnace

test storage bin

# Test Objectives

1. Validate transient thermal models for UT at Austin
2. G3P3 Mechanical stress
3. G3P3 instrumentation methodology
4. G3P3 thermal performance

# Geometric and Dynamic Scaling of Test Bin

TES scaling parameters can be identified in our models or using the Buckingham Pi Theorem:

$$T(Fo, \bar{z}, \bar{r}) = f(Re, Pr, Bi)$$

***Re***: Reynolds number describes momentum transfer and advection during discharge.

***Pr***: Prandtl/Peclet number describes advection and diffusion of heat inside of the bin.

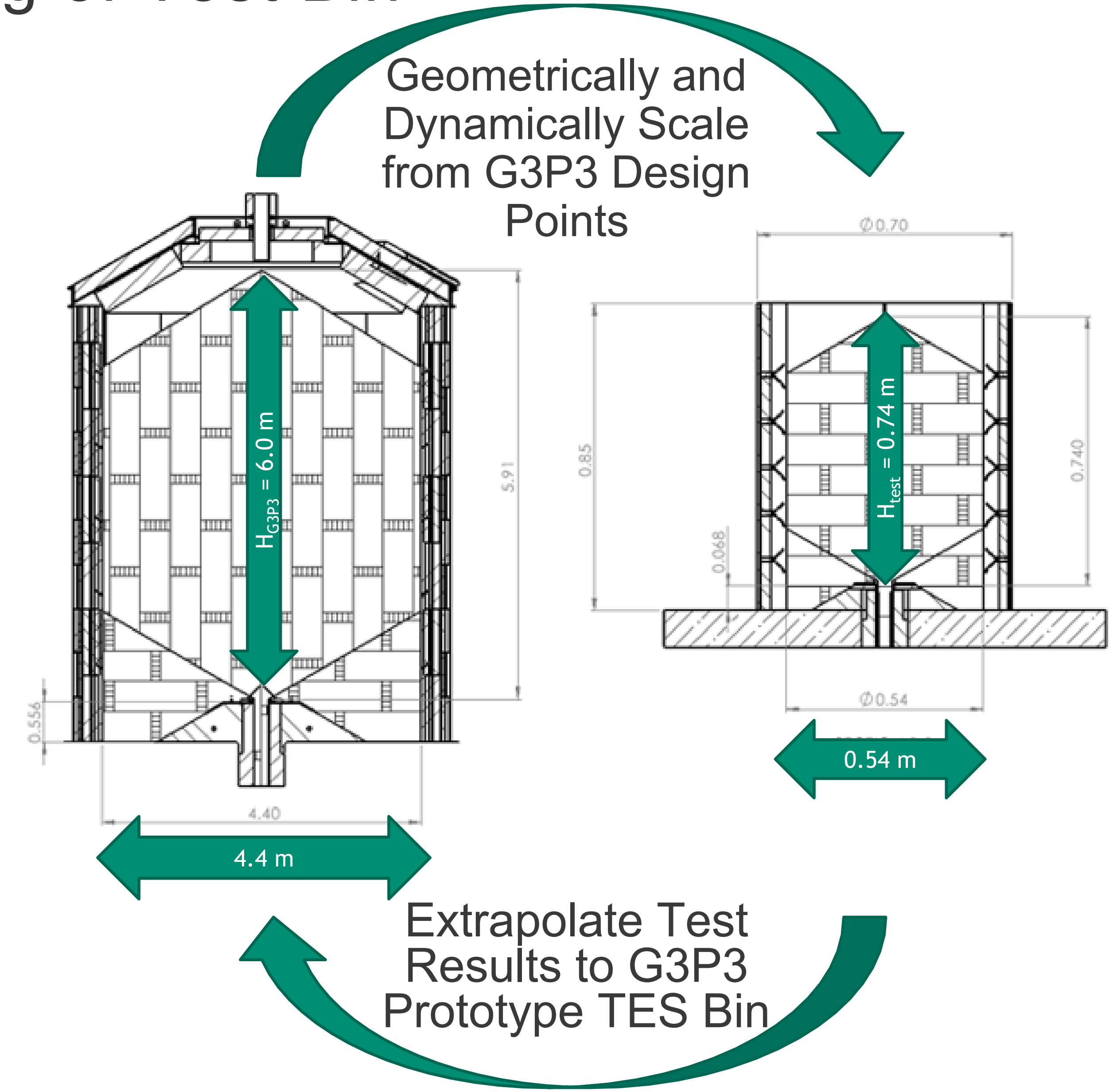
***Bi***: Biot number describes the conduction and convection resistance in the insulation layers.

By matching the non-dimensional parameters that govern the TES dynamics as best as possible, we can extend our test results to the G3P3 system.

Challenges:

- Can't scale the particle diameter (i.e. bulk material and thermal properties)
- Manufacturing constraints limit the accuracy of insulation layer scaling.
  - Difficult to scale conduction and convective losses

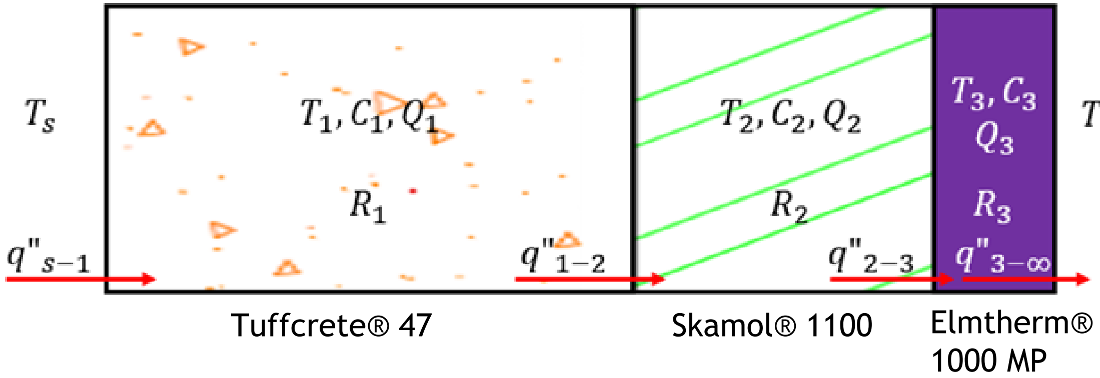
Solution: We will use a validated model to select the hot storage hold time to make up for differences in heat loss coming from incomplete scaling effects.

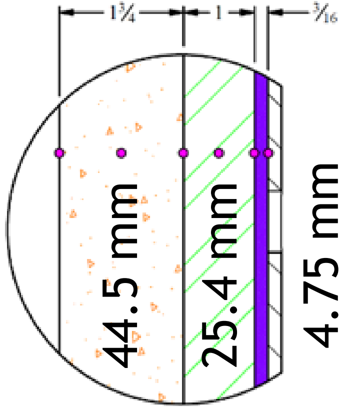


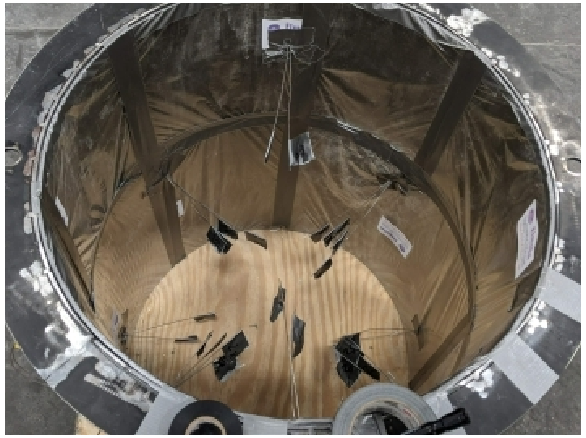
# Instrumentation

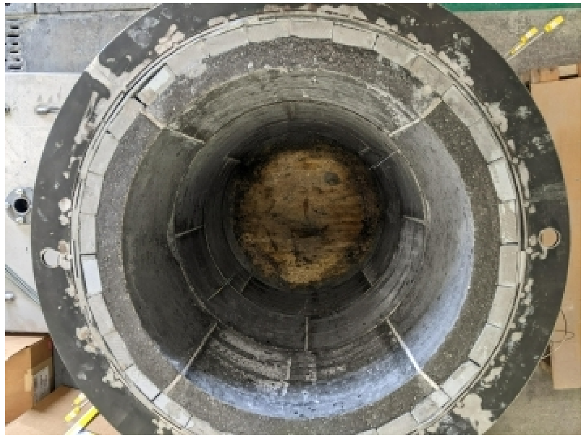
Hypothesis 1: The thermal storage and heat loss in the insulation layers can be approximated with a lumped thermal resistance and capacitance network as described in Plewe et al 2021

Thermocouples at every surface interface



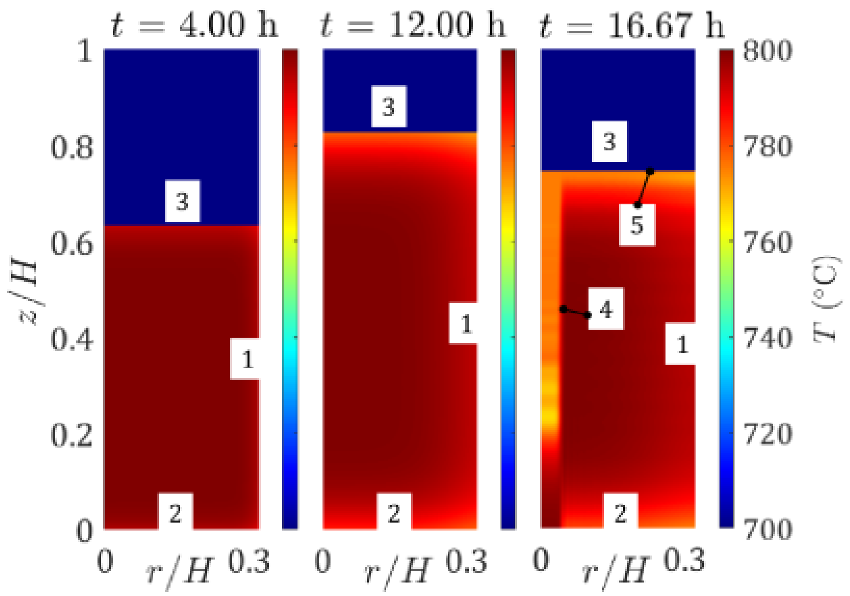





# Instrumentation

Hypothesis 2: The particle temperatures throughout the bin are described by the semi-analytic heat kernel model for 5 partial domains described in Plewe 2020:

1. Cylindrical region particle-to-wall contact
2. Particle to floor
3. Top surface of particle bed to air
4. Center flow channel to non-flowing region
5. Boundary of flowing region on top surface to stationary region




Key boundaries used in Plewe model

Thermocouples in test bin

# Instrumentation

Hypothesis 3: The particle outlet temperatures over three operational modes can be modeled using the semi-analytic methods described in Plewe et al 2021

Three thermocouples will be placed radially very near the center of the outlet pipe

One thermocouples will be placed near the perimeter of the outlet pipe and additionally in between to verify radial gradients modeled by Mario Martinez (Sment 2019)

Steel wire welded to plate will be used to hold in place

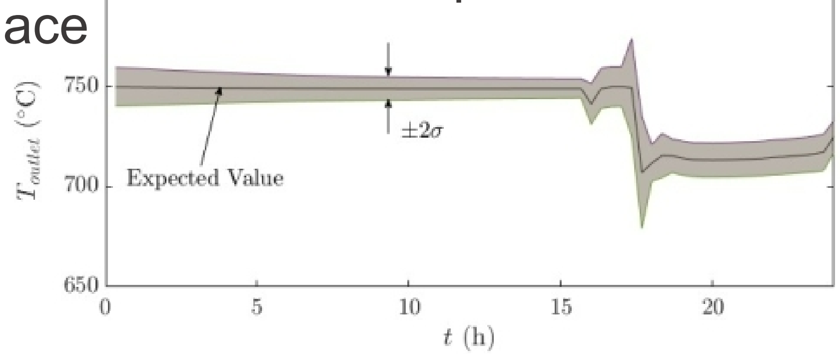



Figure: Modeled outlet temperatures with variation based on mass flow and inlet temperature perturbations

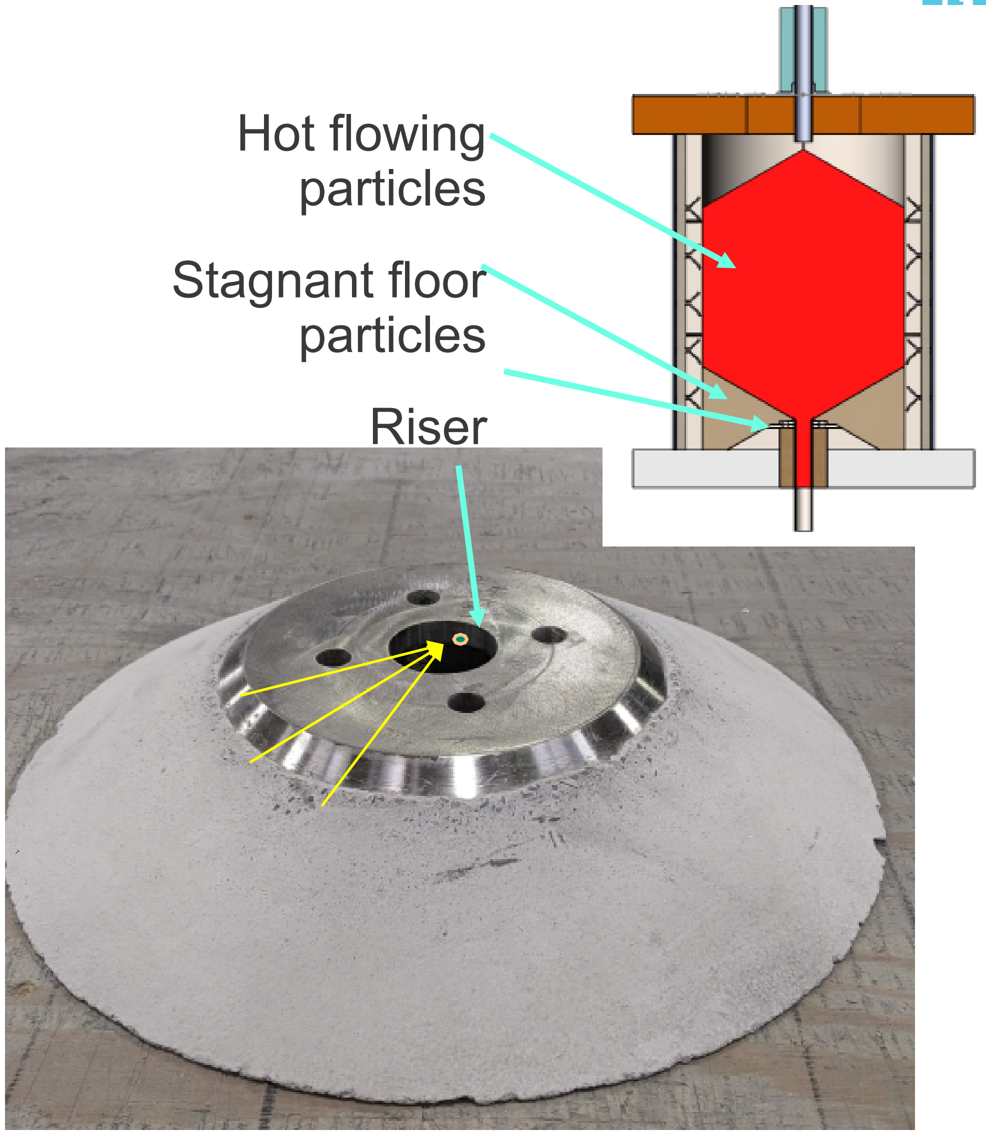



Figure: Outlet riser is used to create a thicker body of stagnant particles on the floor to reduce the temperature of the concrete slab.

# G3P3 Design Viability Testing

## Derisk the G3P3 TES design:

- Thermal shock of wall materials
  - 200° C is expected rise through receiver
- Detection of ratcheting
- Expansion joint sealant viability
- Sloped riser viability
- Conductivity near steel shotcrete anchors
- Platimum Silicone Rubber seals for construction joints in slab
- Fondag® concrete under thermal gradient
- Particle penetration or breach

Table: thermal cycling and shock regimen in air prior to particle testing

| Standard Dry-Out | | Thermal Cycling | | Thermal Shock | |
|---|---|---|---|---|---|
| Temp. (°C) | Hold (hr) | Range (°C) | Rate(°C/hr) | Temp. (°C) | Hold Time |
| 100 | 3 | 20-800 | 40 | 200 | 1 hr |
| 150 | 3 | 800-20 | 200 | 400 | 1 hr |
| 300 | 3 | 20-800 | 40 | 600 | 1 hr |
| 425 | 3 | 800-20 | 200 | 800 | 1 hr |
| 650 | 3 | 20-800 | 40 | 20 | - |

# Next Steps:

Test matrix for model validation is shown in the table.

- D Optimal partial factorial
- >80% power for 3 factors with 12 runs
- *3 margin tests

Test bin will be preheated to 550° C in two stages prior to testing

Nominal operation times:

- Charge = 7.6 minutes
- Hold = 12.7 minutes
- Discharge = 10.1 minutes

Testing was delayed due to issues with steel supply but will commence in October 2022.

| Run | Inlet Temperature (°C) | Mass Flow Rate in (kg/s) | Hold Time (minute) | Mass Flow Rate Out (kg/s) |
|---|---|---|---|---|
| 0-A | 225 | 0.5 | 12.7 | 0.5 |
| 0-B | 550 | 0.5 | 12.7 | 0.5 |
| 1 | 762 | 0.5 | 12.7 | 0.5 |
| 2 | 762 | 0.5 | 12.7 | 1 |
| 3 | 762 | 1 | 12.7 | 1 |
| 4 | 775 | 0.5 | 12.7 | 0.5 |
| 5 | 788 | 0.5 | 12.7 | 1 |
| 6 | 788 | 1 | 12.7 | 0.5 |
| 7 | 788 | 1 | 12.7 | 1 |
| 8 | 788 | 0.5 | 12.7 | 0.5 |
| 9 | 775 | 1 | 12.7 | 1 |
| 10 | 762 | 1 | 12.7 | 1 |
| 11 | 762 | 1 | 12.7 | 0.5 |
| 12 | 762 | 1 | 12.7 | 0.5 |
| 13* | 800 | 0.5 | 12.7 | 0.5 |
| 14* | 825 | 1 | 12.7 | 1 |
| 15* | 850 | 0.5 | 12.7 | 0.5 |

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# Thank you!

# Test Overview

- The bin is sized to have the same height to diameter ratio to preserve the ratio of particle volume in the flow channel to the non-moving volume.
- Dynamic scaleing (Re, Bi, Pr) (dynamic and geometric scaling of experiments)
- Choosing the charge and discharge mass flow rates:
- The Reynolds number of the flowing particles along the top surface is preserved with respect to the reference velocity at the bin outlet
  - Scale pipe diameter
  - Increase the particle velocity at the outlet to create proportional parody of the Reynolds number to the ratio of pipe diameters.
  - $T_{out} = f(Re, Pr)$
  - $u_{\infty,test} = \frac{d_{G3P3} u_{\infty,G3P3}}{d_{test}}$
  - $\dot{m} = u_{\infty,test} A_{pipe} \rho_b$
- The bin holds ≤ 250 kg for three consecutive charge-hold-discharge cycles
- The bin cycle will be proportional to G3P3 with a 7.6 min charge, 12.7 min hold, and 10.1 min discharge.
  - Choose a hold time: The Biot number will be smaller than G3P3 because of the identical heat transfer coefficient at the exterior layer and the discrete availability of insulation material thicknesses on market. Therefore the hold times are being extended such that the amount of heat loss is equivalent for the smaller Biot number
  - 2, we can choose a outlet insulation thickness to match heat transfer to concrete slab.The inlet and outlet flow rates are 0-1.5 kg/s
- Scaling insulation $\dot{q} = f(Bi)$
  - $Bi = \frac{Uh}{k_p}$,
-