Thermopile Energy Harvesting for Subsurface Well Bore Sensors

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Sandia National Laboratories

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Presentation Outline

- Background and Project Overview
- Technical Status and Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary
- Appendix

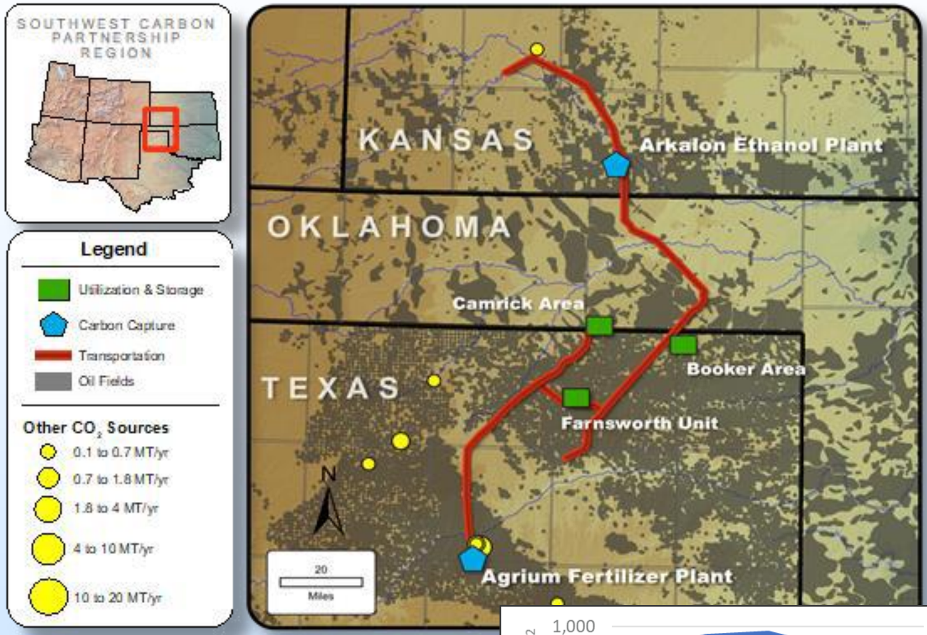
Project Overview

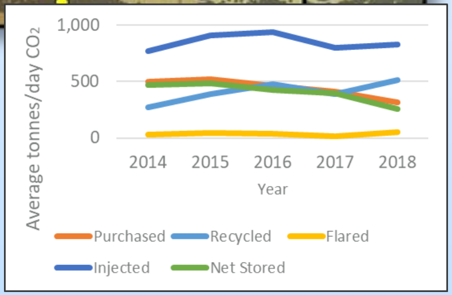
Problem Statement

- **Motivation:** *In situ* power harvesting required for use of downhole autonomous sensors for real-time, long-term monitoring of CO_2 plume movement/permeance, wellbore health, and induced seismicity
- **Objective:** Develop thermoelectric generators (TEGs) as downhole power sources for sensors to perform *in situ* real-time long-term downhole monitoring
- **Main research questions:** What TEG designs will meet power needs of *in situ* sensors? Material design/requirements to survive downhole environments? Cost?
- **Industry involvement:** Nothing formal currently, but ongoing discussions with the operator of the Farnsworth Unit EOR-CO_2 storage site for field testing and validation
- **Ties to Priority Research Directions of the Mission Innovation CCUS Workshop:** Downhole thermopile arrays for power harvesting potentially address these PRDs,
  - PRD S-2: Understanding Dynamic Pressure Limits for Gigatonne-scale CO_2 Injection – *in situ* monitoring to assess pressure build-up
  - PRD S-3: Optimizing CO_2 Injection by Control of Near-Well Environment – *in situ* real-time monitoring may enable rapid intervention
  - PRD S-4: Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure – multiple thermopile arrays may enable integrated, simultaneous monitoring of caprocks, reservoirs, and USDWs
  - PRD S-5: Realizing Smart Monitoring to Assess Anomalies and Provide Assurance – *in situ* power harvesting supports autonomous sensor systems
  - PRD S-9: Establishing, Demonstrating, and Forecasting Well Integrity - power harvesting enables sensors for continual long-term monitoring of trends in hydrodynamic and material behavior

Subsurface CO_2 Sequestration

- Subsurface sequestration is the only viable option for reducing industrial emissions of CO_2
- DOE's large-scale pilot programs (e.g., Southwest Regional Partnership, SWP) were established to:
  - Obtain baselines for monitoring efforts
  - Monitor the effectiveness of injection and storage operations
  - Provide test-beds for injection, storage, and monitoring operations
- Need for improved understanding of CO_2 movement within reservoir/caprock, and potential leakage pathways along the wellbore.
- Collection of long-term data via downhole sensors will allow application of "big data" concepts to better quantify the long-term stability and safety of subsurface CO_2 sequestration





Disposition of CO_2 per day at Farnsworth Unit, TX (courtesy M. Cather, NMT)

All sensors require power, many must be outside of the casing—how to power them, charge batteries? We propose powering via downhole power harvesting with thermoelectric generators (TEG)

General Approach

In situ power harvesting is required to support a wireless downhole system of autonomous sensors. This project evaluates use of thermoelectric generators (TEGs) attached to casing or tubing to generate substantial power (e.g., 10's of Watts) via power harvesting.

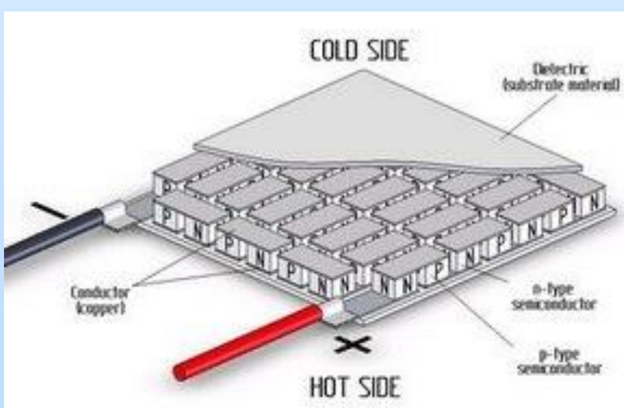
- **We are evaluating use of TEGs—thermopile arrays—to harvest energy from:**
  - Intermittent pumping to produce a transient higher gradient, charging a battery
  - *Any location along the length of the wellbore* (e.g., reservoir unit, caprock, overlying aquifer)
- **Our primary focus is power generation—other research groups are working on sensor development**
  - TEG designs based on sensor power needs
  - TEGs will be attached to 1) production tubing or 2) casing outer wall
- **Thermopile arrays themselves can be used as sensors; also evaluating this**
  - *Temperature profiles* (e.g., profiles shift due to CO_2 saturation changes & thermal blanketing)
  - *Thermal gradient into-out of borehole*—a function of near-field / far-field thermal conductivity
    - Indirect measurement of CO_2/brine saturation in wall rock or casing cement or of near well-bore leakage/movement of CO_2

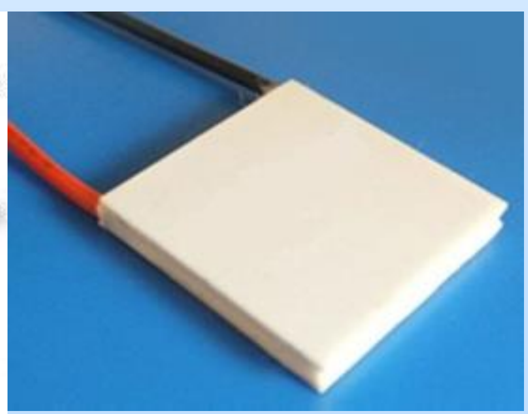
Planned Work

1. **Thermal-hydrologic modeling to determine relevant heat fluxes**
   - Used to size thermo-electric generator (TE) arrays, determine power generation, assess steady-state and transient heat flow, and plan benchtop experiments
2. **Bench-scale testing of TEGs**
3. **Perform benchtop thermal hydrologic testing**
   - Optimize TEG and heat sink designs
   - Develop integrated TEG power system
   - Develop and validate power generation and thermal-hydrologic models
   - Test use of TEGs as sensors
     - Temperature changes, thermal pulse decay
     - Changes in near-field and far-field thermal conductivity due to changing brine/CO_2 saturation
4. **Design, build and test field-sized TE systems**
   - Potential path forward: attached-to-tubing thermopile validation at Farnsworth Unit, less likely is thermopiles outside casing, as that requires drilling of a new well

Thermoelectric Generators

- TEGs directly convert heat into electric power.
- Thermoelectric modules consists of several P-type and N-type thermoelectric legs connected in series or series-parallel combination.
- Solid-state heat engines with no moving parts. Robust and very reliable in long-life applications.
- Efficiencies are low, but ideally suited for energy harvesting applications.
- Thermoelectric generator takes advantage of the Seebeck Voltage. When a temperature differential is maintained across a thermoelectric couple, a voltage is generated. Current can be drawn by connecting a load.

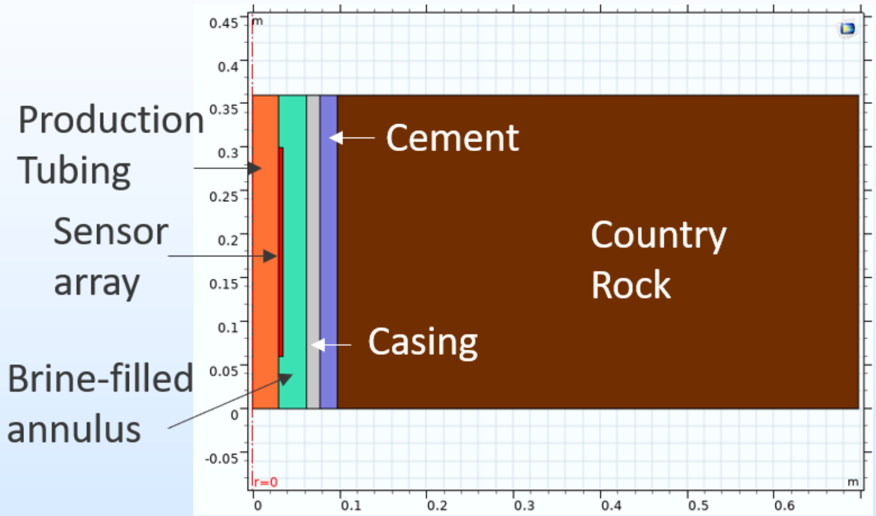


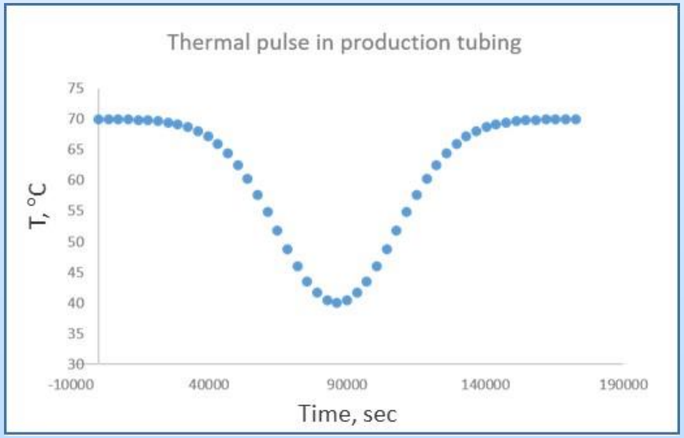


- Dense alumina substrates on the top and bottom. Edges are sealed to protect the TE elements.
- Heat source and heat sink are attached to the top and bottom with good thermal interface material for efficient heat transfer.

Using TEGs for Downhole Power Harvesting (COMSOL Example)

- Wellbore mock-up based on 3" production tubing, 5.5" OD casing, cement-filled annulus between casing and rock
- Examine a thermal pulse over two days (1.8×10^5 s) associated with pumping cold $scCO_2$ into a 70°C reservoir (properties modelled after Farnsworth)
- Thermopile array composed of 0.24 m long cylindrical shell of 1 commercial module consisting of 125 BiTe TE couples mounted on exterior of production tubing
- *Really a best-case example involving thermal gradients associated with spring-type heat fins mounted on casing interior*

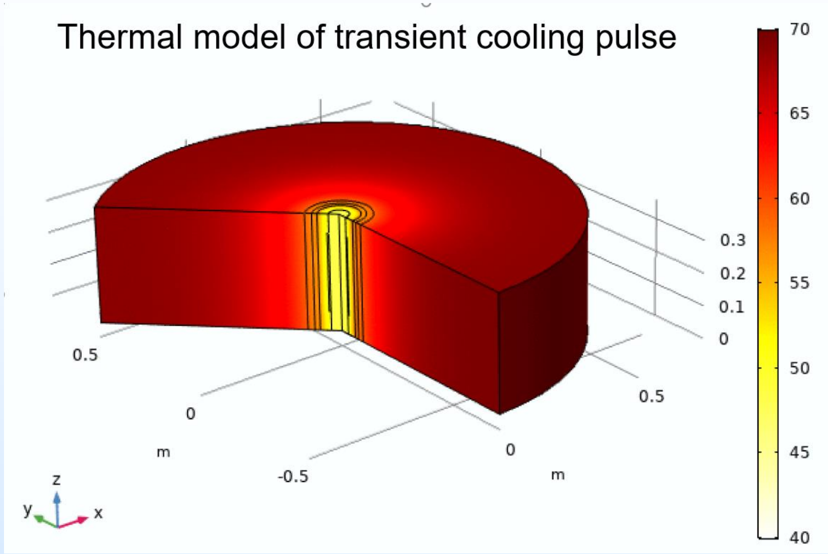


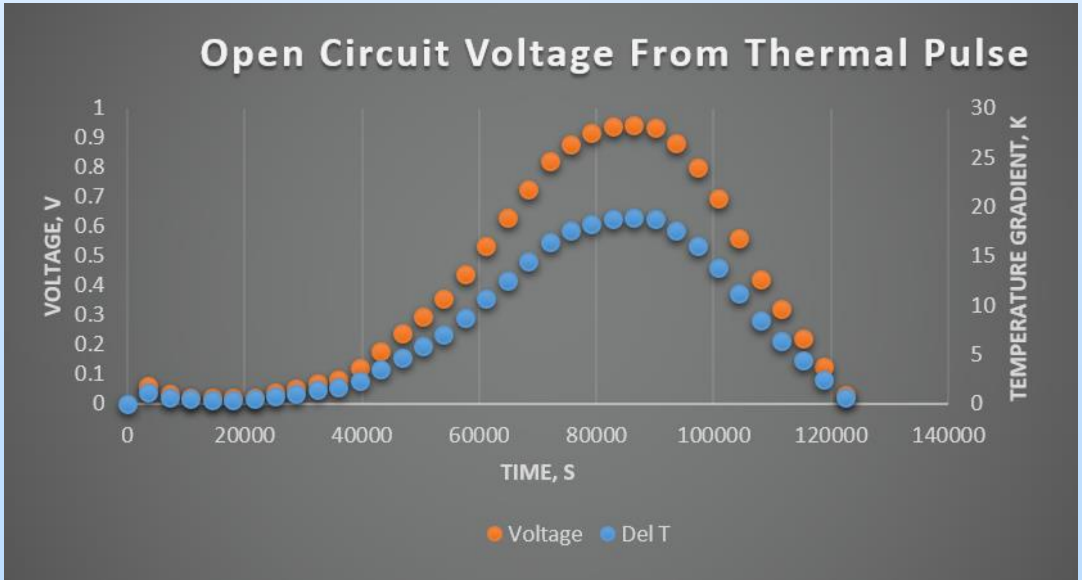


Using TEGs for Downhole Power Harvesting (COMSOL example)

Model:

- Reservoir initially at 70°C, cools near wellbore then returns to far-field T
- Spike in voltage produced by thermal pulse
- Assume 125 TE couples in 1 shell module with Seebeck coefficient of 400 mV/K





Heat flux through the TEG during and after the pulse is converted to electricity.

Thermoelectric Module

- Open circuit voltage of a TEG; $V_{oc} = S_{p\text{-}n} * dT * N$

  where $S_{p\text{-}n}$ is the Seebeck coefficient of a P-N thermoelectric couple (for a BiTe-based TEG module,
  $S_{p\text{-}n}$ ~400 uV/K); dT is the temperature differential across the TE couple; and N is the number of TE couples in the module.

- We are using commercial TEG modules consisting of 125 couples (BiTe material); expected V_{oc} and maximum Power output for 1 module at different dT are:

II-VI MARLOW
MATERIALS THAT MATTER

Technical Data Sheet for TG12-2.5

Single-Stage Thermoelectric Generator

dT(K)	Voc (V)	P (mW)
100	5.38	836.42
10	0.54	9.93
1	0.054	0.11

NOMINAL PERFORMANCE IN NITROGEN

Cold Side Temperature (°C)	27±2
AC Resistance (ohms):	4.47 – 5.69
Device ZT	0.72

Size: 1.18”x1.18”x0.159”

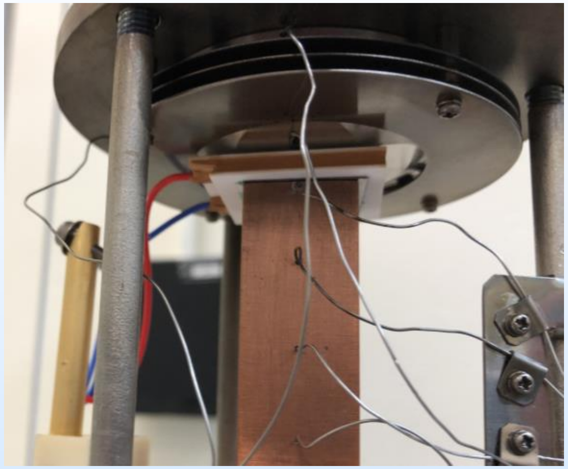
- Power output depends on the load, so load optimization is required. For max power, V_{load} ~ ½ V_{oc}
- To generate sufficient power/voltage, several TEG modules will be connected in series or parallel configuration.
- V is proportional dT and P is proportional to dT^2

TEG Testing

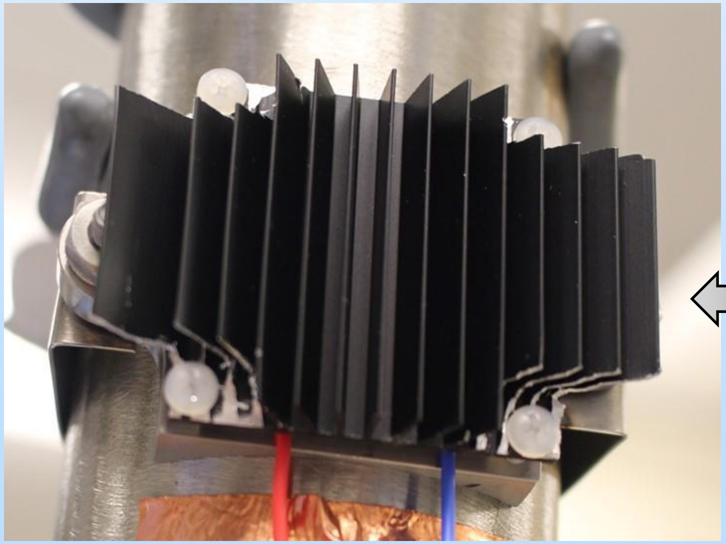
Ambient Pressure Benchtop Tests

- TEGs identified and purchased
- Steel mount designed and machined
- Heat fins (for testing purposes) purchased
- Testing (low P) to determine efficiency and function completed; used to calibrate COMSOL power generation models

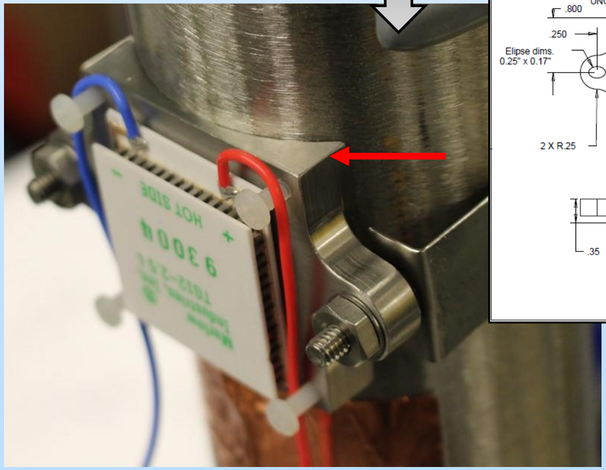
Testing TEG efficiency

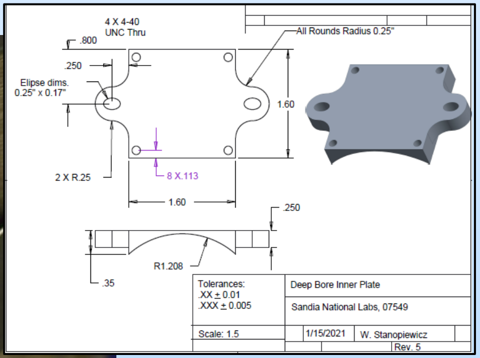


Testing TEG with mount and heat sinks



TEG mount

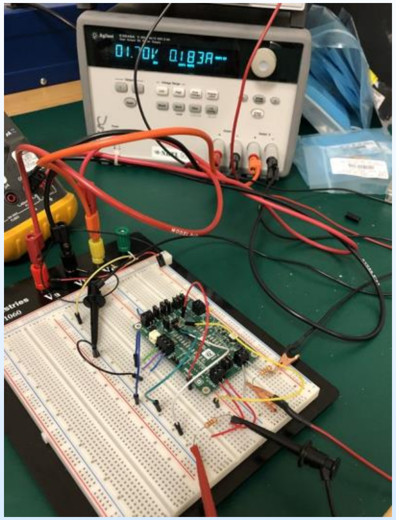




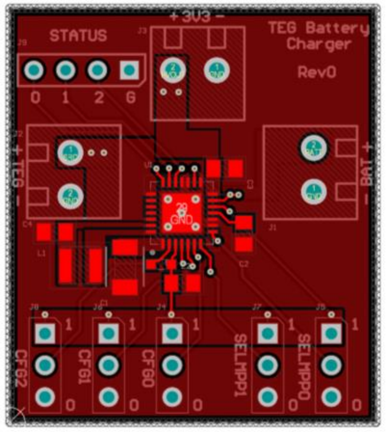
Power Conditioning and Battery Management

- TEG voltage/current vary with heat flux; directly powering sensors is difficult.
- Solution: Store the energy in a battery, which can then be used to power sensors. Power management circuitry is required to condition the TEG power output and charge the battery.
- Power conditioning chip identified/purchased. Testing at room T/high T (100°C) conditions completed.
- Card for benchtop testing designed and being built

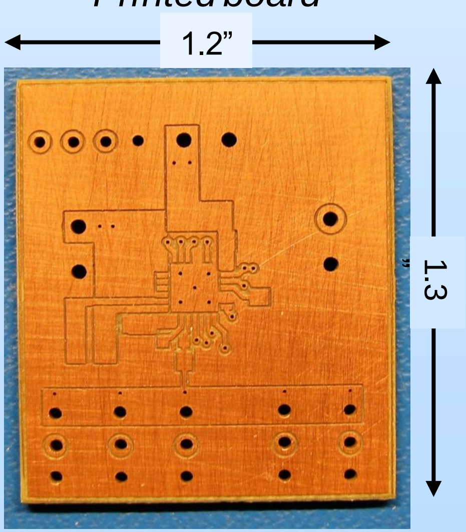
Testing power conditioner



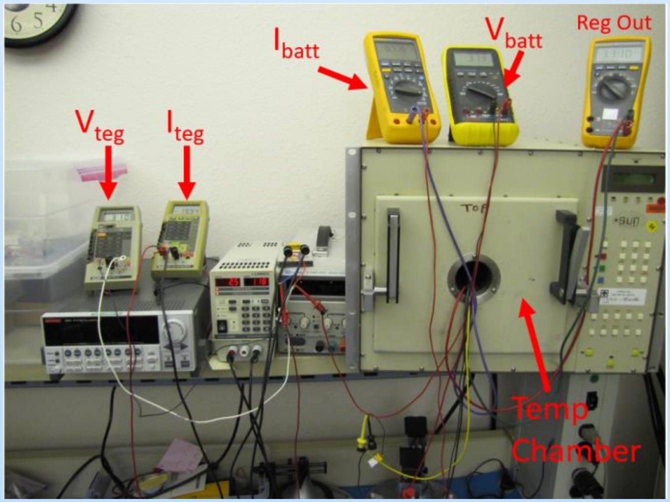
Board schematic



Printed board



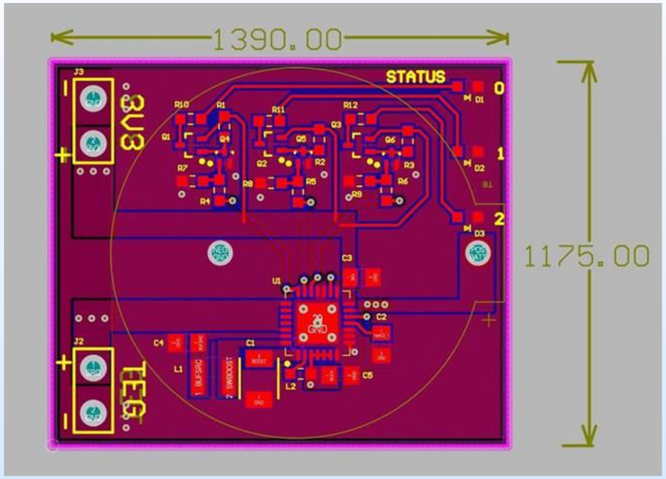
Testing at elevated temperatures



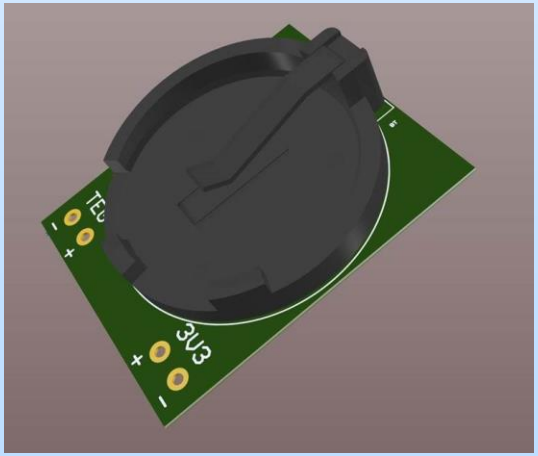
Power Conditioning and Battery Management

- Preliminary card for downhole use designed. Includes:
  - Power conditioning chip
  - Memory and microprocessor for data management
  - Battery (rechargeable coin cell)
- Simplified card for lab testing has been built
- *Batteries are the biggest challenge:*
  - Limited options for high-temperature, rechargeable batteries

Schematic for downhole power conditioner/battery



Top



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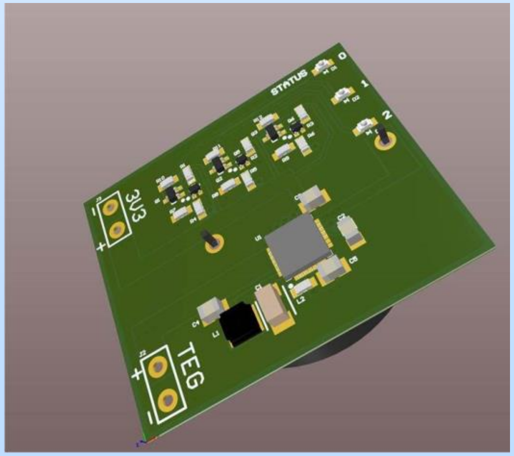
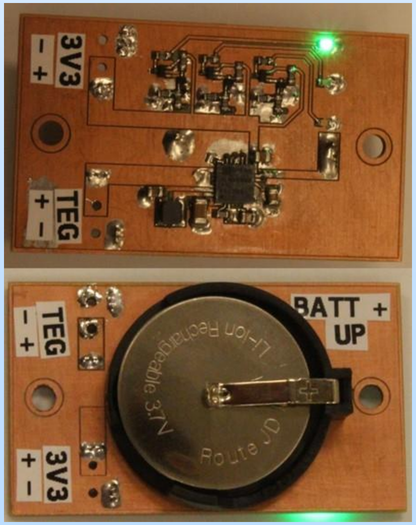


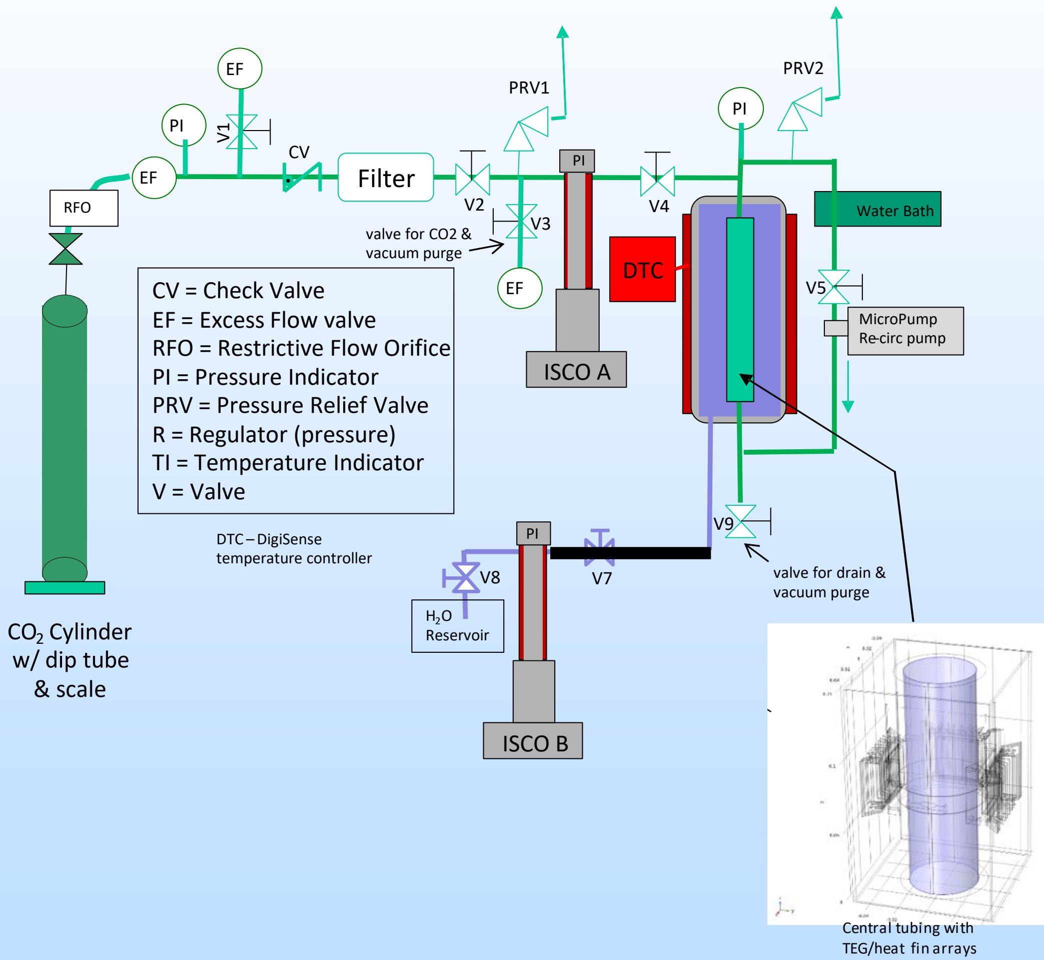


Card for high P/T lab testing

Benchtop High P/T Testing

- Robustness/survivability testing
  - Verify component operation at downhole P-T
  - Test TEGs, power conditioner, batteries
  - Pressure system being assembled: Pressure Safety Data Package (PSDP) in progress
  - System packaging for benchtop and downhole use designed and being built.
- Testing at simulated field conditions:
  - Exercise/validate COMSOL model
  - Aid in system design for field use

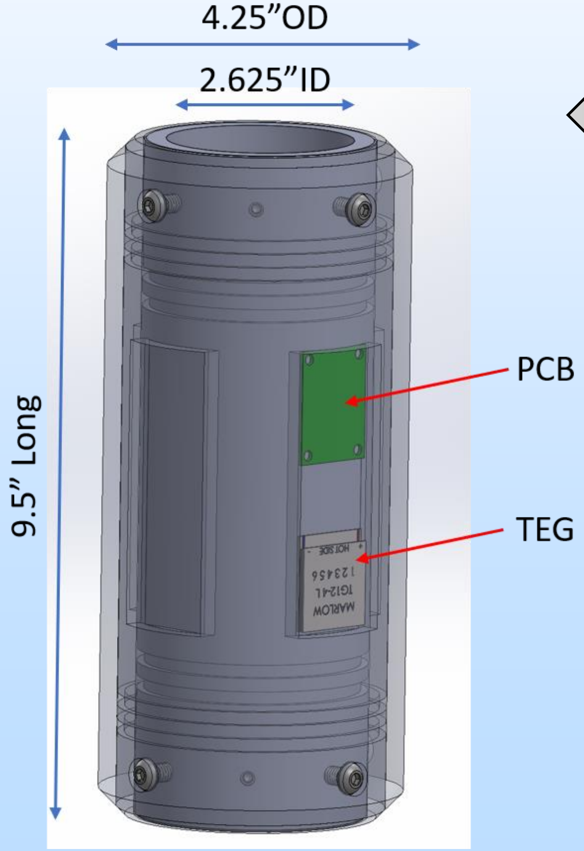
TEG High Temperature/ High Pressure Apparatus



High P/T Packaging for Downhole System

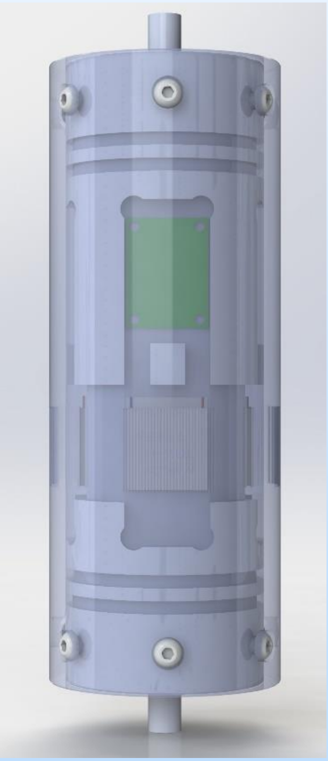
General concept: Hollow sleeve design, encapsulating TEGs, batteries, and support electronics

- Slightly reduced-scale version being built for high P/T benchtop testing



Preliminary design for downhole use

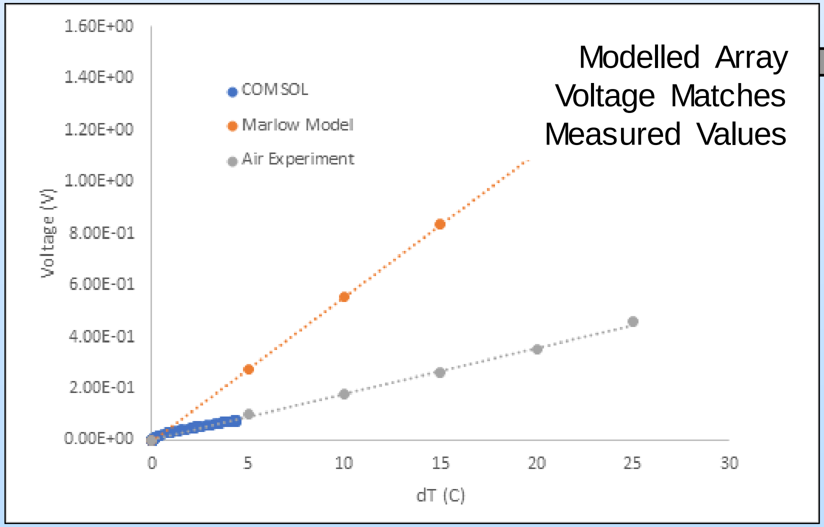
Design for benchtop testing

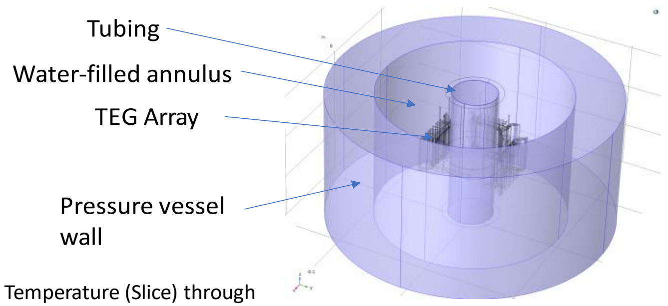


COMSOL Modeling of TEG Performance

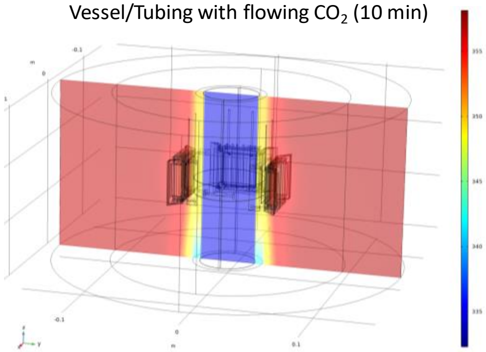
High P/T Benchtop Testing Setup

- Model for low-P test system developed
  - Models heat flow, TEG power generation (voltage/current)
  - Includes all system components (TEGs, tubing, mount, heat fins)
  - Fitting to measured data used to calibrate power generation model
-

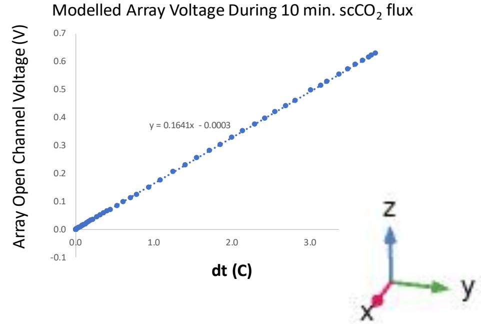




Modelled Temperature (Slice) through Vessel/Tubing with flowing CO_2 (10 min)



Modelled Array Voltage During 10 min. $scCO_2$ flux



Accomplishments to Date

- Completed acquisition and ambient testing of TEGS for down-hole use.
- Developed and tested of power conditioning circuitry for down-hole use. Prototype of actual circuit board built for high P/T lab testing.
- Preliminary packaging design completed, and a lab-scale unit is in production for high P/T testing
- COMSOL models for TEG performance/power generation
  – Model for ambient TEG test system calibrated/validated against lab data
  – Model of high P/T test system developed (will be finalized once system packaging is finalized)
  – Preliminary model developed for downhole power generation in response to thermal pulses
- Discussions with possible field site (SWP Farnsworth site) in progress.
  – Possible boreholes identified
  – Full set of borehole component dimensions, downhole conditions, pump schedules, etc. have been made available.

Lessons Learned

- Largest issue remaining: options for high-temperature rechargeable batteries are very limited. Current choices are only good to 60-70°C, or are too large for this application. Continuing to work this issue.

Synergy Opportunities

- Wireless downhole sensors for real-time, long-term monitoring of CO_2 plume movement/permeance, wellbore health, and induced seismicity require a power source. *TEGs provide a method for powering sensors by pumping fluids down the borehole and harvesting energy from the resulting thermal pulse.*
- Power/data transmission to wireless sensors is beyond the scope of this project (we focus only on power generation); however, a possible technology has been identified and may be lab-tested.
- Southwest Regional Partnership (SWP): possible field testing at Farnsworth EOR site.

Project Summary

In situ power harvesting is required for use of wireless downhole sensors. TEGs are a possible solution for downhole power generation, harvesting power from thermal pulses generated by intermittent pumping of cool or heated fluids down the borehole.

<u>Status</u>

- System designed
  - TEGs identified and tested
  - Power conditioning circuitry designed and tested
  - Batteries for energy storage (?)
  - High P/T packaging designed and being built for testing
- Benchtop testing
  - Ambient pressure testing completed (establish TEG efficiencies and performance at elevated temperatures)
  - High P/T testing to establish survivability and downhole performance of system and packaging (end-of-FY milestone)
- COMSOL modeling of TEG power generation
  - Modeling of ambient pressure benchtop tests completed (calibrate and validate power generation model)
  - Preliminary models of benchtop high P/T test apparatus completed (modifications required for final geometry/packaging).
  - Preliminary models of power generation in downhole pumping scenarios completed (modifications required for final geometry/packaging).
- Field Testing: Ongoing discussions with SWP Farnsworth site
  - Well geometries, downhole conditions, pump schedules obtained
  - 2 possible wells identified for testing in FY22

Project Summary

Next Steps:

- Complete laboratory testing at elevated P/T
- Build prototype unit for field testing
- Coordinate with field site and plan field test
- Complete downhole field test in FY22

Appendix

Benefit to the Program

Sandia National Laboratories

- Project addresses ***3 Major Goals of the Carbon Storage Program:***
  1. Wellbore Integrity & Mitigation – thermopile *in situ* power harvesting for wellbore monitoring
  2. Storage Complex Efficiency and Security – thermopiles span reservoir/caprocks/USDWs
  3. Monitoring, Verification, and Accounting and Assessment – real-time on-demand confirmation
- Project benefits statement:

The project develops autonomous downhole thermopile arrays for *in situ* power harvesting. Solution for real-time to long-term monitoring Carbon Storage Program Goals on wellbore health, CO_2 storage efficiency, and storage permanence. Lab/field validation by Year 2 support Testing and Monitoring Plans (UIC-VI requirements), ensuring 99 percent CO_2 storage (Storage Complex Goal), & global reservoir-caprock-USDW monitoring (Wellbore/MVA Goal). Thermopiles improve over battery-based embedded sensors ***by scaling in arrays for abundant remote power***. Designs include in-series thermopiles to power tailored sensor suites for pressure, stain, acoustic, and chemical measurements within or outside wellbores. Thermopile depth profiles of temp. and bulk conductivity measure time-lapse CO_2 saturation for storage/sweep efficiency.

Project Overview

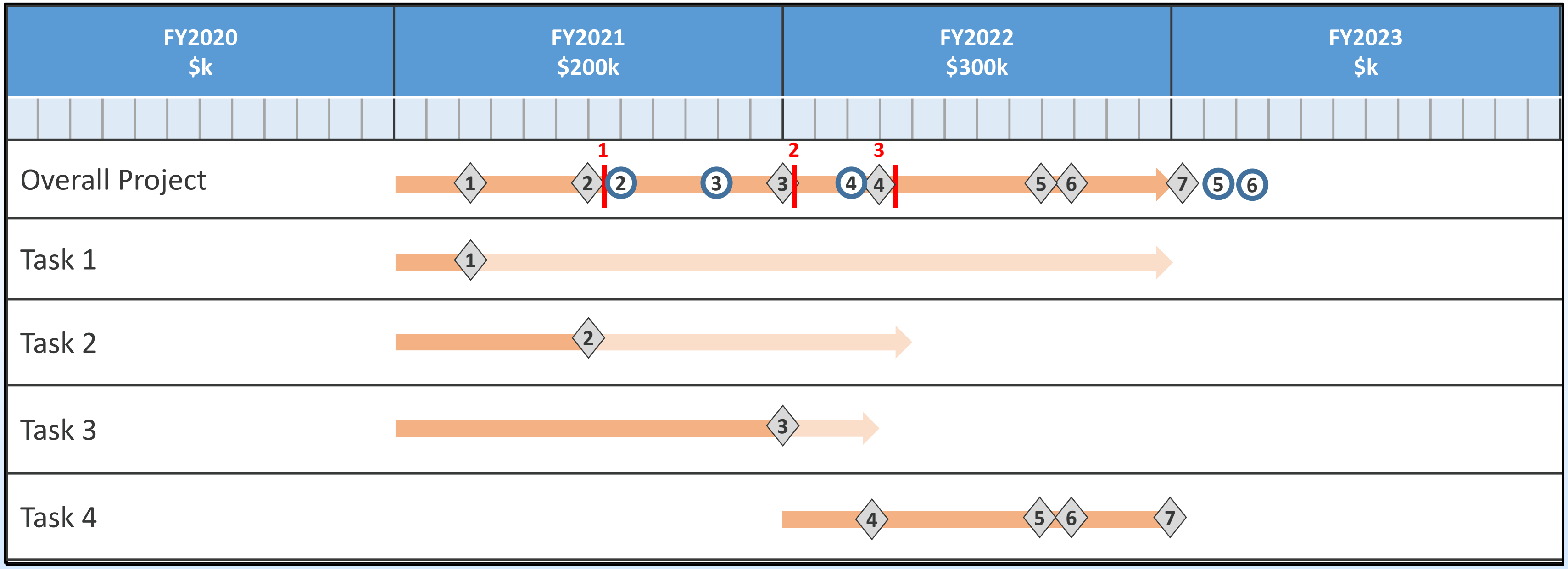
Goals and Objectives

- Funding (DOE and Cost Share):
  - DOE: $500K ($200K FY21/$300K FY22)
- Overall Project Performance Dates
  - Oct. 2020 to Sep. 2022; FY21: theory & lab tests; FY22: field validation
- Project Participants: Sandia w/NMT (potentially SWP or CarbonSAFE)
- Overall Project Goals & Objectives in Statement of Project Objectives:
  - Develop thermopile arrays for in situ data capture & transmission
  - Determine if thermopile materials will survive downhole environments
  - Assess economics of scaling arrays for reservoir/caprock/USDW monitoring
- How do project goals and objectives relate to the program goals and objectives?
  - Goal success criteria include lab demonstration of power generation, and field validation of scalability of thermopile arrays; supports monitoring Program Goals

Organization Chart

- Principal team members are all at Sandia National Laboratories
  - Charles Bryan, P.I.: project oversight, integration
  - Ramesh Koripella: power system development and integration
  - Tom Dewers: COMSOL modeling at field and lab scales, high pressure system development and testing
  - Jason Heath: interface with field sites, support field-scale thermal-hydrologic modeling
  - Others: Adam Foris, packaging; Derek Heeger and Jeff Frank, power management
- Southwest Regional Partnership on Carbon Sequestration (SWP) (contact Mr. George El-kaseeh). Ongoing discussions about a possible field test at the Farnsworth site.

Gantt Chart



Milestones:

1. Complete project management and planning documents.
2. Complete Thermal-hydrologic simulations required to design/size thermopile array for benchtop tests
3. Build benchtop testing systems and complete benchtop tests
4. Identify a field site and partner for testing
5. Complete large-scale thermopile arrays for field testing
6. Initiate field testing
7. Final Report.

Chart Key

TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

Go / No-Go

1. Do thermal-hydrologic calculations indicate that heat flux (thermopile energy output) will be sufficient for the planned use? Will the designed thermoelectric generators be economic?
2. Did benchtop testing determine that thermopile use is feasible?
3. Has a field site/partner been identified?

Acknowledgements

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