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Thermopile Energy Harvesting for Subsurface Well Bore Sensors

FWP-20-022728

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Sandia National Laboratories

U.S. Department of Energy

National Energy Technology Laboratory

2022 Carbon Management and Oil and Gas Research Project Review Meeting – Carbon Storage

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Project Overview

- Funding
  - NETL funded project ($500K total)
- Period of Performance
  - Oct. 1, 2020 – Dec. 15, 2022 (extension obtained)
- Project Participants
  - Sandia National Laboratories
    - Charles Bryan (PI)
    - Thomas Dewers (hydrogeology; modeling and lab testing)
    - Jason Heath (hydrogeology; field test coordination)
    - Ramesh Koripella (power generation)
    - Jiann-cherng Su (engineering and design)
  - APS Technology Wallingford, CT (field test)

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:** Discussion with Farnsworth Unit Operator and Southwest CO_2 Partnership informed 1st prototype design; field test at APS Technology's Drilling Test Facility
- **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

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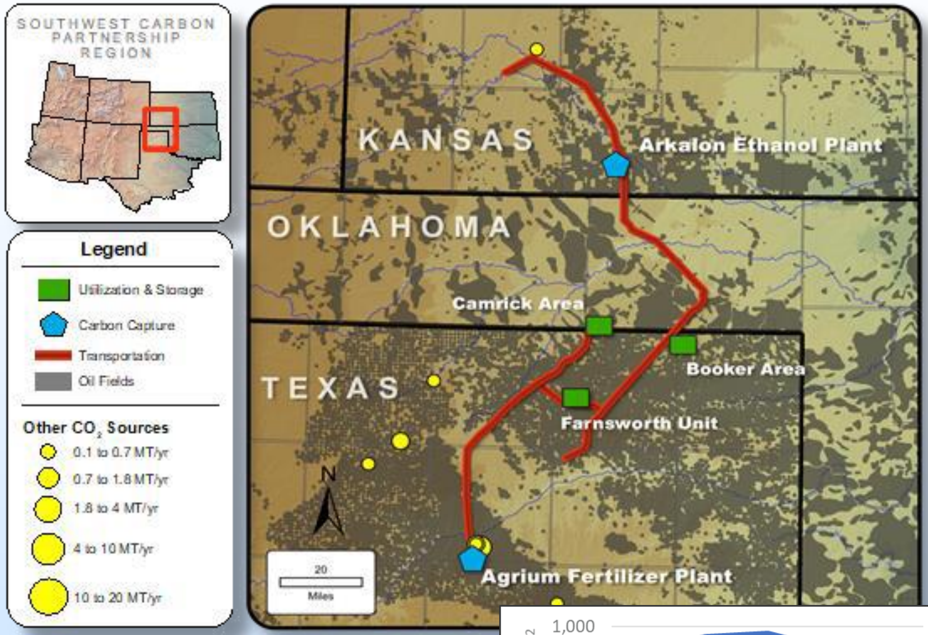
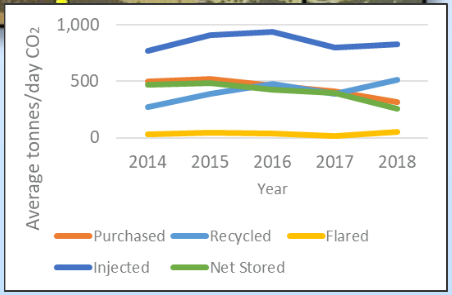
Subsurface CO_2 Sequestration

- 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 effectiveness of injection/storage operations
  - Accelerate development of commercial scale CO_2 storage sites while reducing technical risk, uncertainty, and cost
- 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 (TEGs)

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

General Approach

Concept 1: TEG modules mounted on production tubing

- Tool mounted in injection tubing. Tool length can be increased for additional power generation.
- Possibly use wire brush centralizers to increase heat transfer to the casing?

Pros:

- Can be emplaced in an existing hole
- Generates more power (higher thermal gradients) during thermal pulses

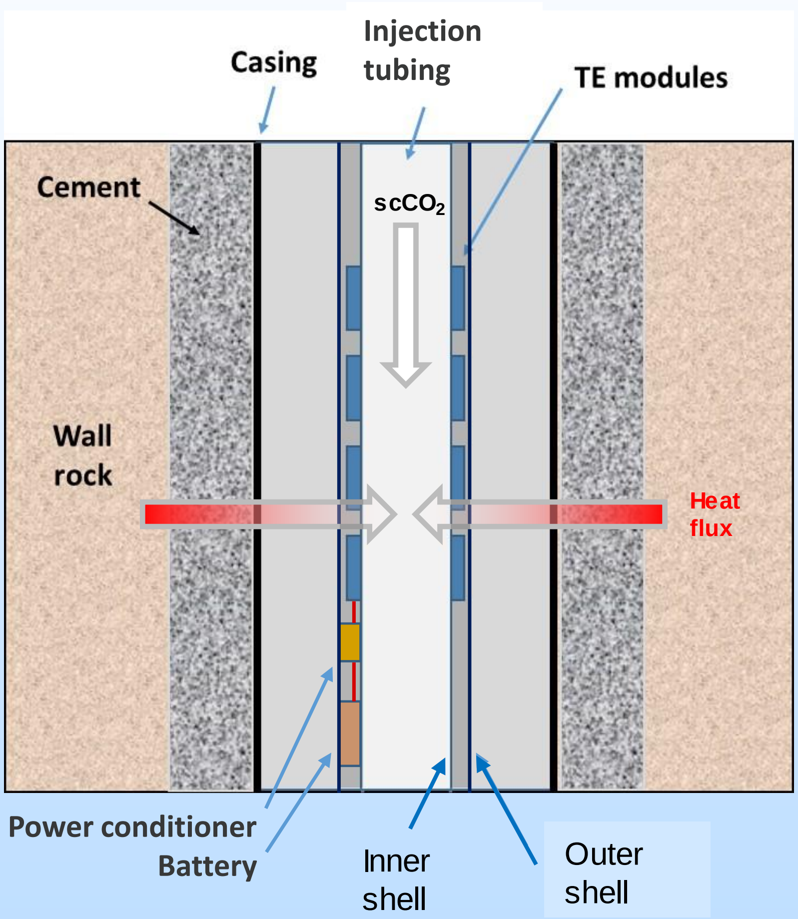
Cons:

- Limited to use with some types of sensors
  - Potential through-casing sensing includes temperature profiles and thermal conductivity, resistivity, potentially seismic/acoustic
  - Possible placement of sensors on the inside of the casing?
- Cannot power sensors on the outside of the casing.

Concept 2: TEG modules mounted on casing

- Can power sensors outside the casing; however, requires new borehole for installation

Concept 1

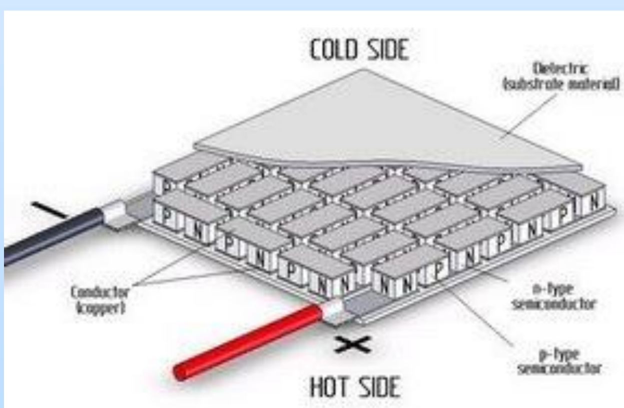


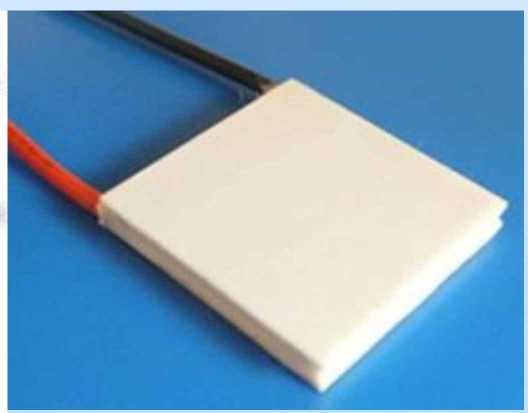
Planned Work

1. **Thermal-hydrologic modeling to determine relevant heat fluxes** ✓
   - Used to size thermo-electric generator (TEG) 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 thermal bridge 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**
   - System designed (machining is out for bid)
   - Field tests planned for Oct.-Nov. at **APS Technology (Wallingford, CT)**

Thermoelectric Generators

- TEGs directly convert heat flux 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.



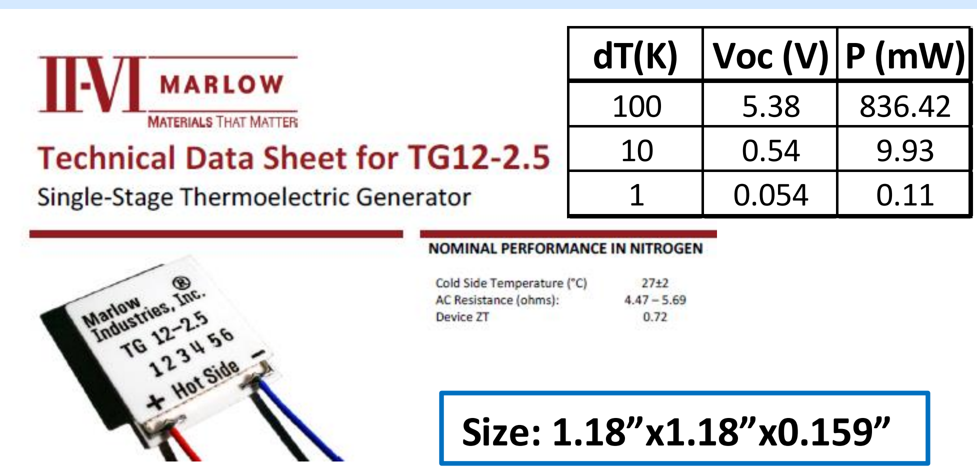


- Dense alumina substrates on the top and bottom. Edges are sealed to protect the TE elements.
- Heat source and heat sink are attached to the top and bottom with good thermal interface material for efficient heat transfer.

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:



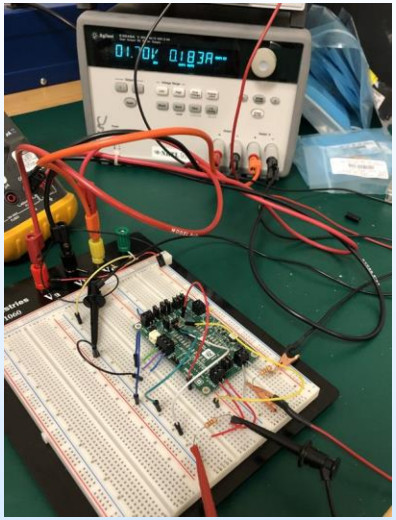
dT(K)	Voc (V)	P (mW)
100	5.38	836.42
10	0.54	9.93
1	0.054	0.11

- 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

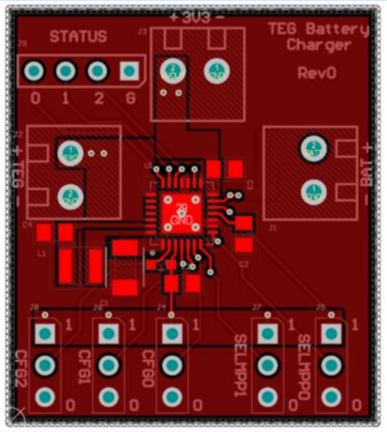
Power Conditioning and Battery Management

- 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. Tested at room T/high T (100°C) conditions.
- Card for benchtop testing was designed, built, and tested

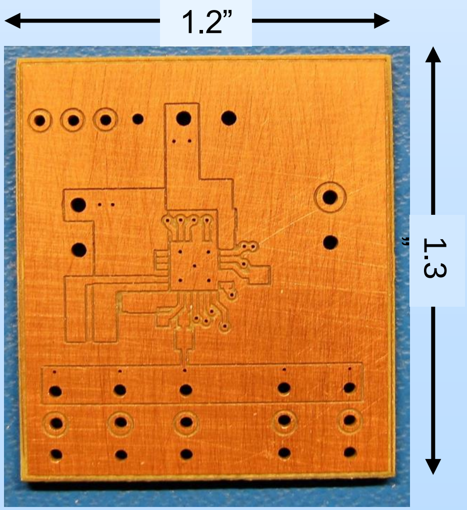
Testing power conditioner



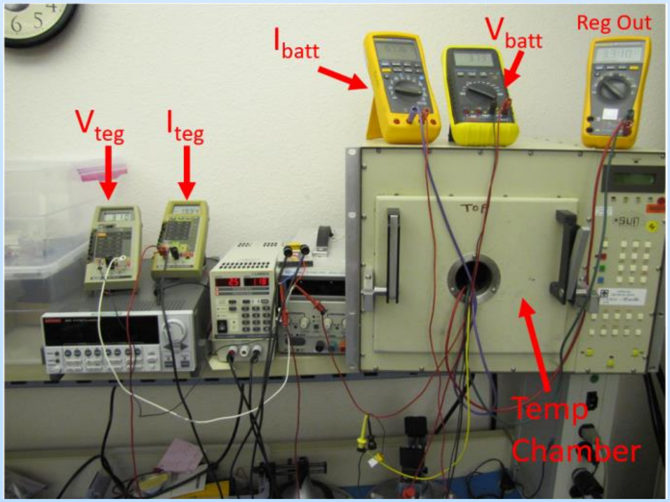
Board schematic



Printed board

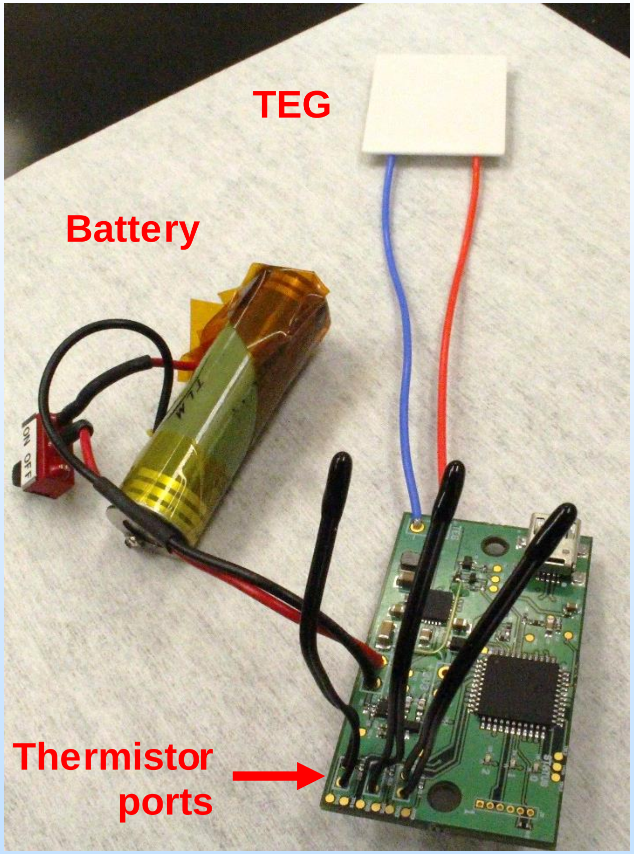


Testing at elevated temperatures

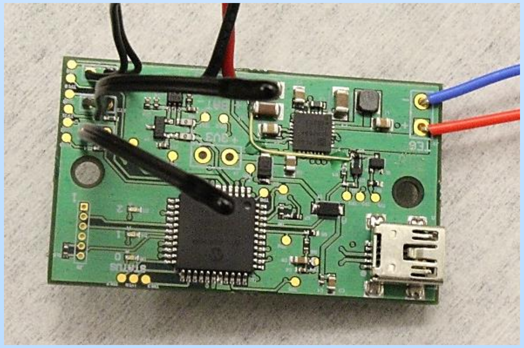


Power Conditioning and Battery Management

- Card for downhole test designed, built, and tested. Includes:
  - Power conditioning chip
  - Memory and microprocessor for data management
  - Battery leads
  - Thermistor ports (3) for monitoring temperatures
  - Programmed for field test to monitor and store power generation and thermistor temperature data
- Battery:
  - Tadiron TLM-1520HPM selected and tested, will be in field demo.
  - AA-sized; rechargeable; up T-range up to 85°C



Top



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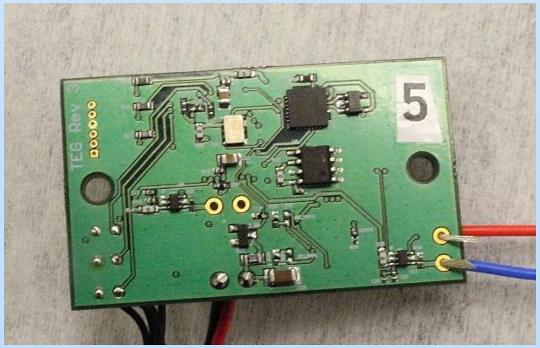
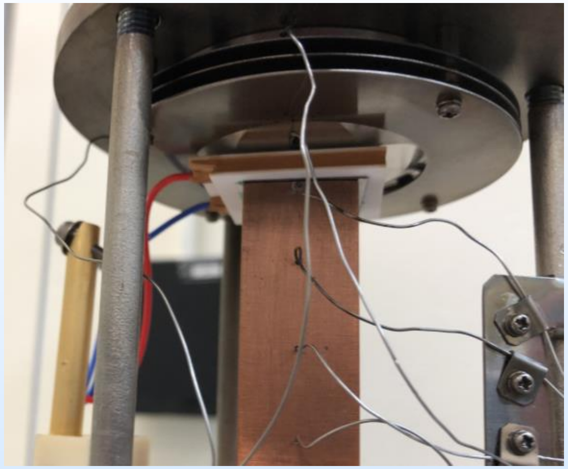


TEG Testing

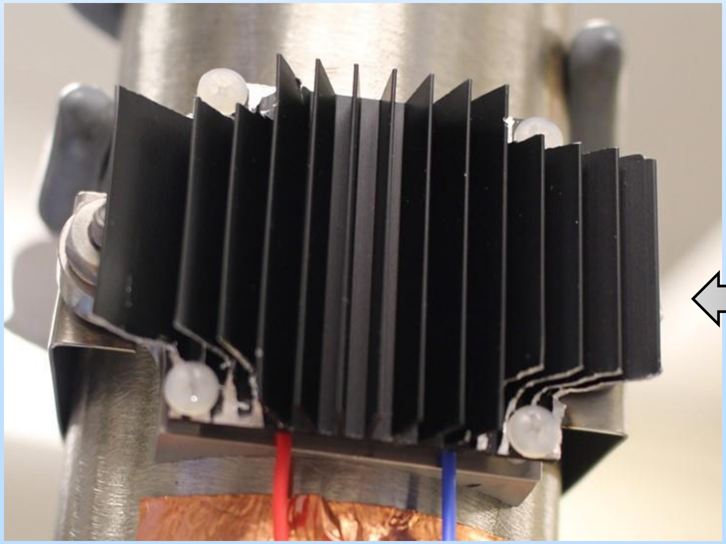
Ambient Pressure Benchtop Tests

- TEGs (BiTe-based) 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

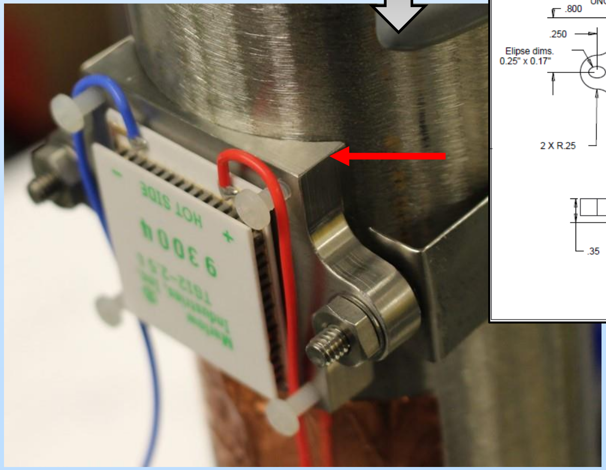
Testing TEG efficiency

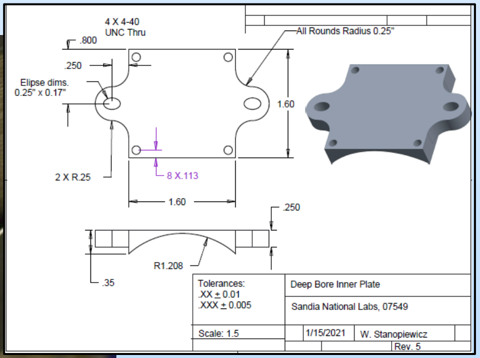


Testing TEG with mount and heat sinks



TEG mount

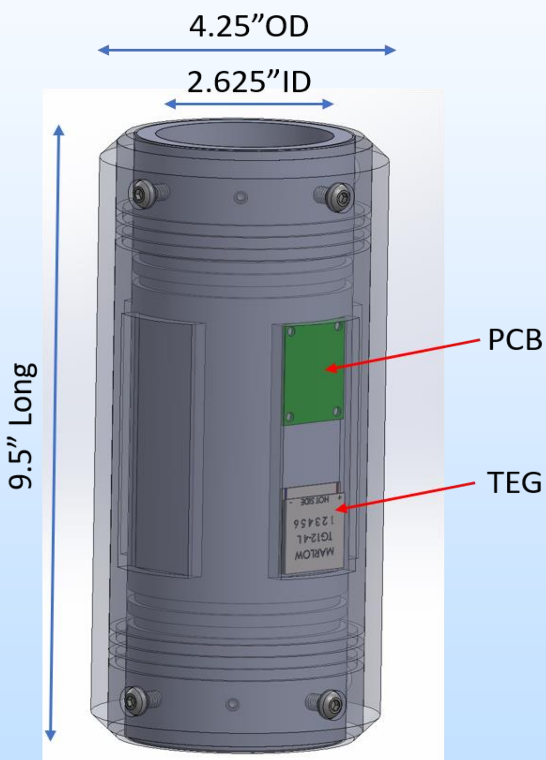


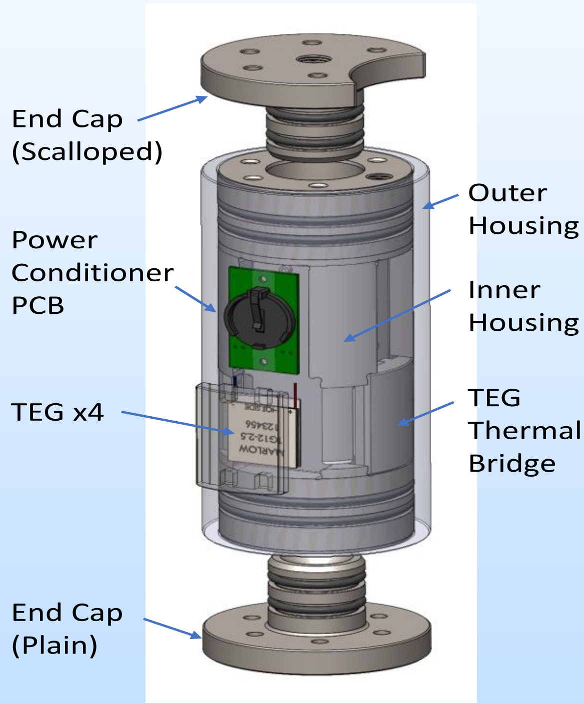


Benchtop Testing of High P/T Prototype

To test TEGs, power conditioner board, and batteries; to aid in system design for field prototype; and to exercise/validate COMSOL models

Schematic of prototype high pressure power generation module for benchtop testing





As-built lab prototype

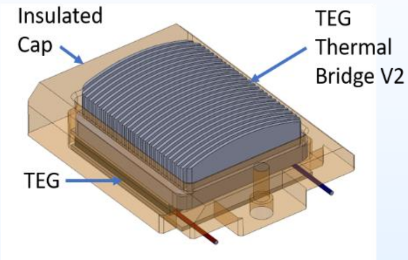
Basic design—inner and outer cylindrical shells, with TEGs and supporting electronics in between. In the field, it will be inserted between tubing sections.

As-built prototype for laboratory testing—end caps are for lab test setup only.

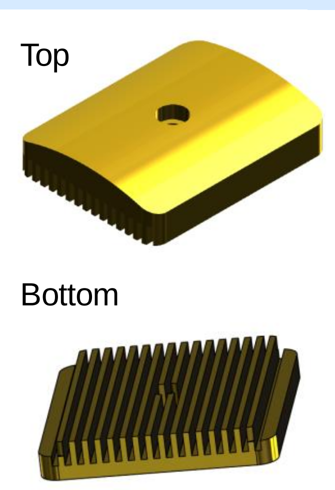
Benchtop Testing of High P/T Prototype

Effect of TEG cap and base design (final version)

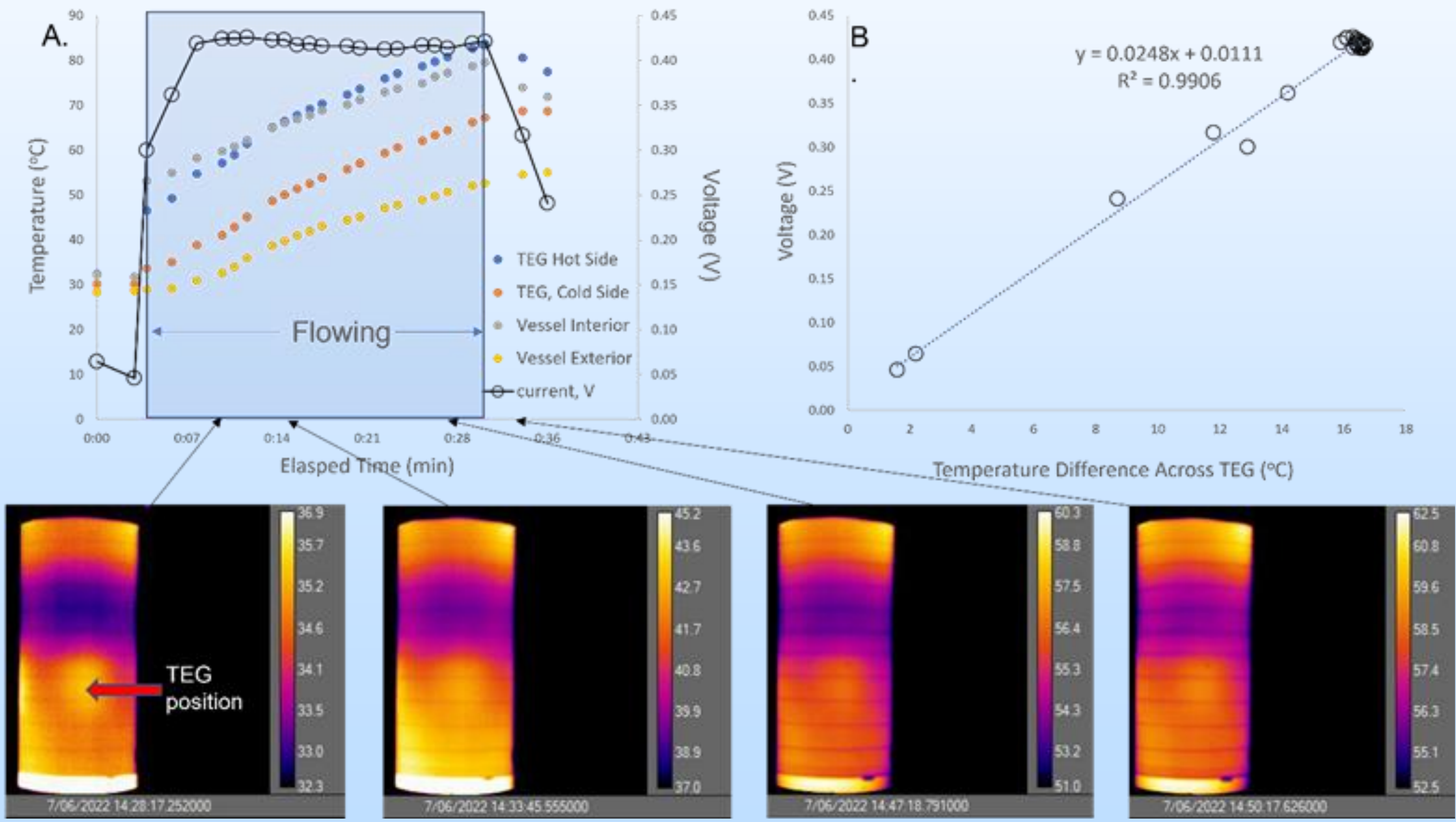
Version 2 cap and base



Version 3 caps



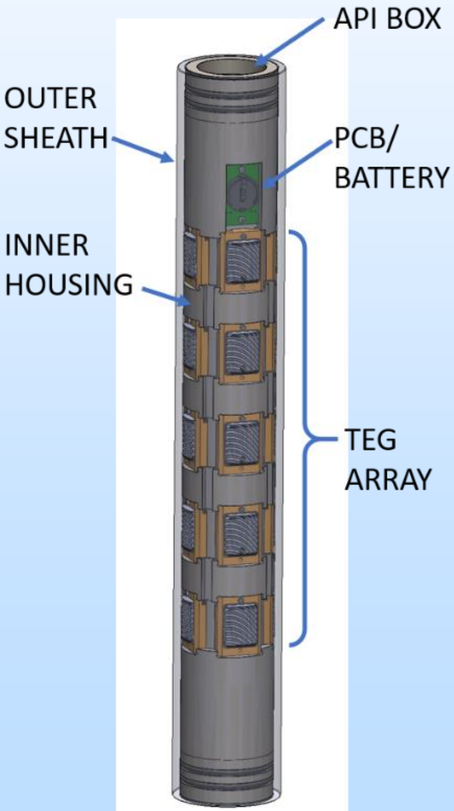
Improved design. Heat preferentially transferred through TEG and thermal bridge



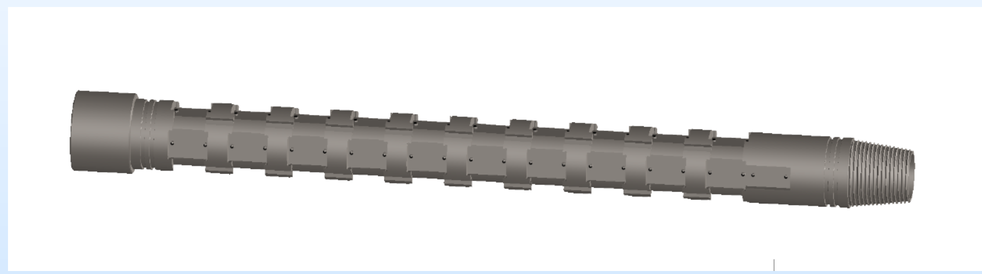
High P/T Packaging for Downhole System

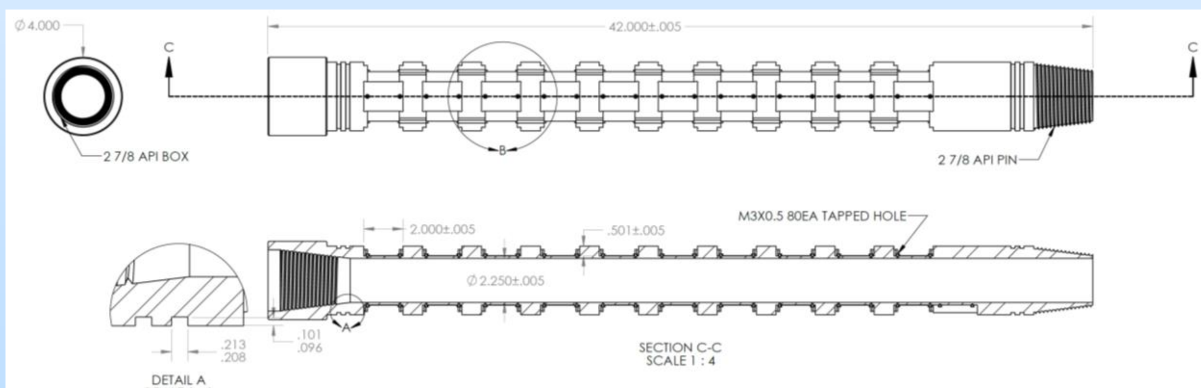
General concept: Similar to lab prototype. Hollow sleeve design, encapsulating TEGs, batteries, and support electronics. *Insert into tubing string via API pin/box.*

Schematic of the field-deployable thermopile energy generation system.



Engineering sketch. The system will hold ~40 TEGs, plus the power conditioning board and the battery. The outer sheath is not shown.





Request for quote for machining sent out, awaiting reply. Schedule is to build and assemble by 10/15/22

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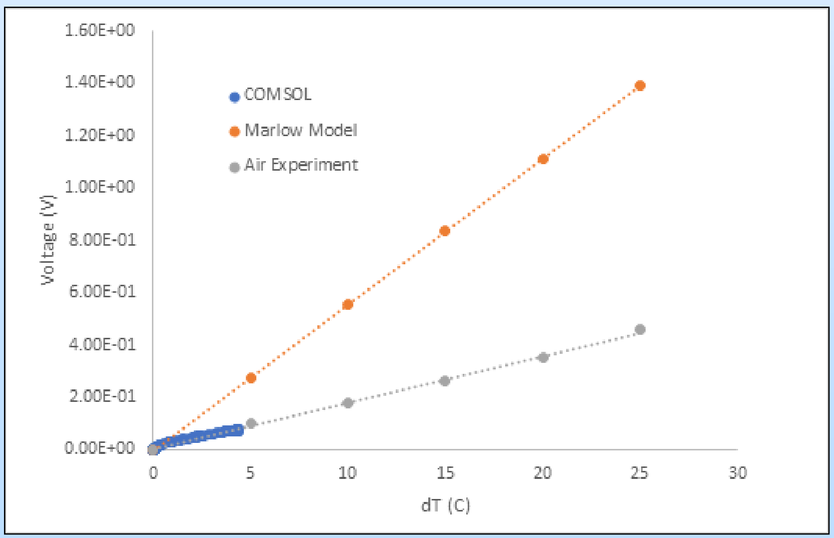
COMSOL models of TEG ambient tests

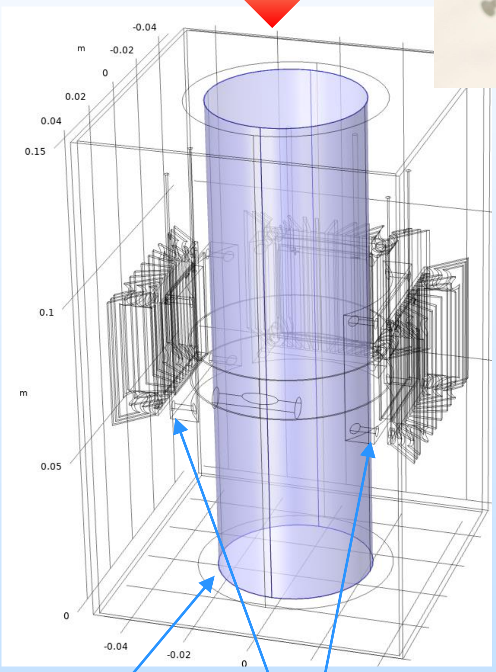
Model for low-P test system developed

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

Modelled Array Voltage Matches Measured Values

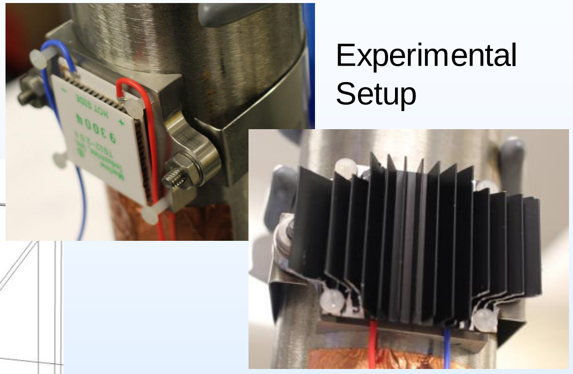


Hot air



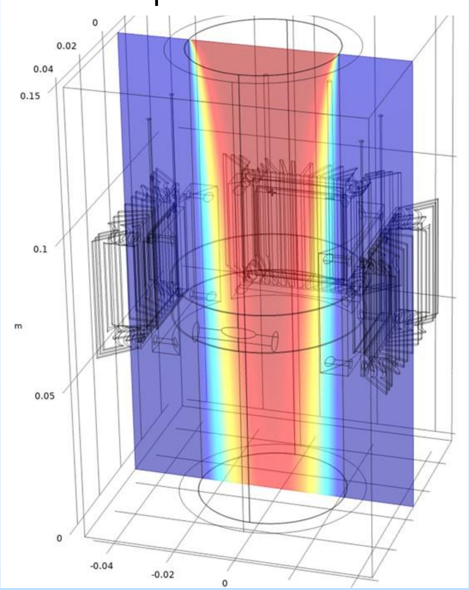
Steel tube

TEGs with mounts and heat sinks



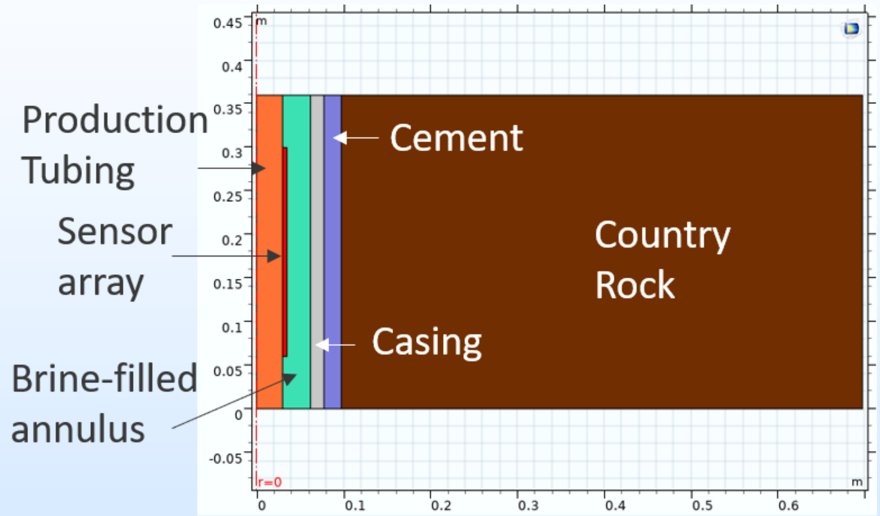
Experimental Setup

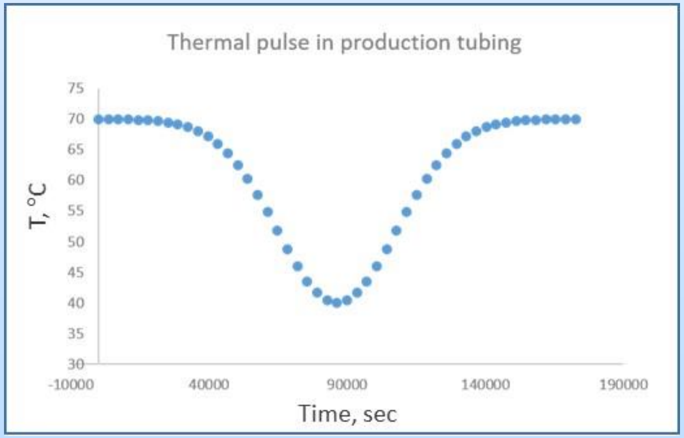
Temperature Profile



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 site)
- 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*

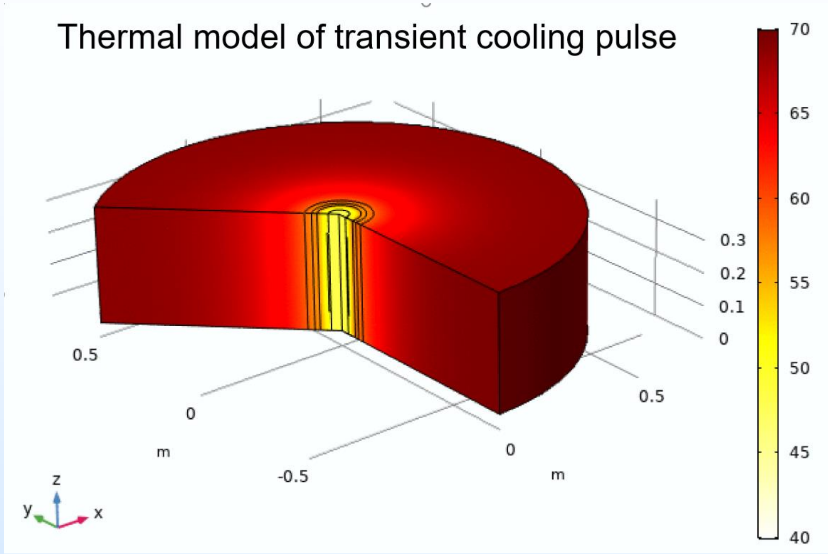


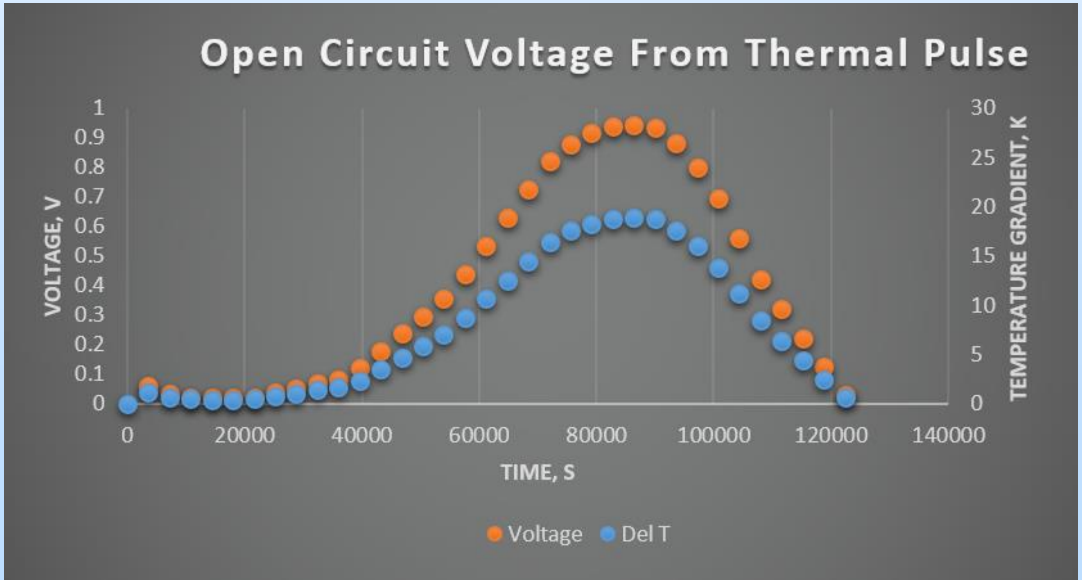


Using TEGs for Downhole Power Harvesting (COMSOL example)

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.

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. Circuit boards built for both lab and field testing
- Lab-scale built and tested; field-scale prototype is in production
- 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.
- Field site identified, APS Technology.
  - Contract for testing in place.
  - Test plan complete
    - Survivability test in pressure vessel
    - Shallow borehole pumping test (deep borehole for $scCO_2$ testing not available).
    - Test scheduled for late October to early November.

Lessons Learned

Issues that arose:

- Batteries—limited choices for small, high-temperature batteries
  - Coin cell capacitors: large temperature range but low capacity
  - Tadiron batteries (AA size): lower temperature range (up to 85°C), moderate capacity; recently became available in the desired size
- Field testing—options limited.
  - Requires pulling tubing from an existing hole; potential damage to tubing or hole leads to high liability at $scCO_2$ injection sites.
  - Even at commercial testing sites, borehole availability is limited to shallow holes (no $scCO_2$ testing).
  - Difficulty in obtaining equipment rentals when oil prices are high.

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, possible technologies include:
  - Ultrasound transmission though tool wall/casing
  - RF transmission?
  - Hard-wiring
- If the opportunity presents itself (e.g., another project pulling tubing), piggyback to perform a real $scCO_2$ injection test at relevant depths.

Project Summary

TEGs are a possible solution for powering downhole sensors, harvesting power from thermal pulses generated by intermittent pumping of cool or heated fluids.

Status—the following tasks completed:

- System designed
  - TEGs purchased and tested
  - Power conditioning circuitry designed and tested
  - Batteries for energy storage identified, purchased, and tested
  - Benchtop prototype designed and built
  - Field prototype designed
- Benchtop testing
  - Ambient pressure testing completed (establish TEG efficiencies/performance at elevated T)
  - Benchtop prototype tested; resulted in system redesign to improve heat flow
- COMSOL modeling of TEG power generation
  - Modeling of ambient pressure benchtop tests and high P/T benchtop apparatus completed (calibrate and validate power generation model)
  - Preliminary models of downhole pumping scenarios completed (modeling of field test and real scCO_2 injection conditions with final geometry/packaging still to be done)

Project Summary

Next Steps:

- COMSOL modeling of field test, real $scCO_2$ injection conditions
- In parallel, conduct field test
  - Build prototype unit for field testing by Oct. 15, 2022
  - Complete downhole field test in Oct./Nov. 2022
- Final Report, Dec. 2022

Plans for future testing/development/commercialization

- Highly scalable system: Overall design of thermopile energy harvesting tool is easily scaled to at least a full section of tubing (28-40 feet).
- Transfer power from energy harvester → sensors? (ultrasound, RF)
- Data transmission?

Acknowledgements

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Appendix

Benefit to the Program

- 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

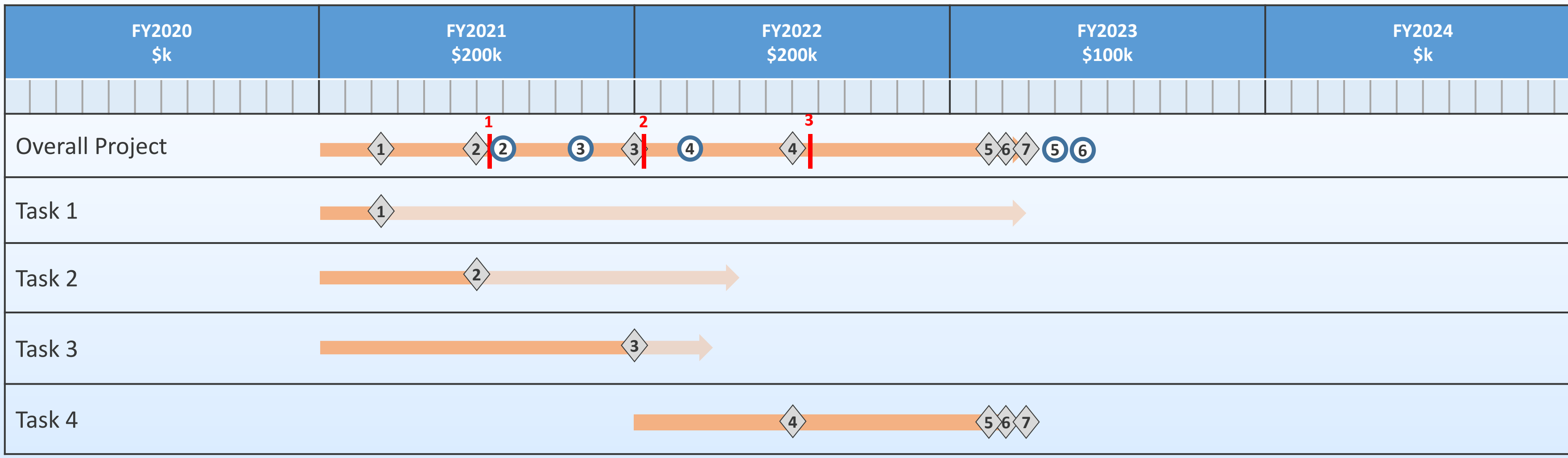
Goals and Objectives

- Funding (DOE and Cost Share):
  - DOE: $500K ($200K FY21/$300K FY22)
- Overall Project Performance Dates
  - Oct. 2020 to Dec. 2022; FY21: theory & lab tests; FY22: field validation
- Project Participants: Sandia w/APS Technology (field test site)
- 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, Jiann-cherng Su packaging; Derek Heeger and Jeff Frank, power management
- APS Technology, Wallingford CT (field test site)
  - Carl Perry

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?