A Novel “Smart Microchip Proppants” Technology for Precision Diagnostics of Hydraulic Fracture Networks

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Masoud Kalantari, Ph.D.

Associate Professor

The University of Kansas

U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

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Presentation Outline

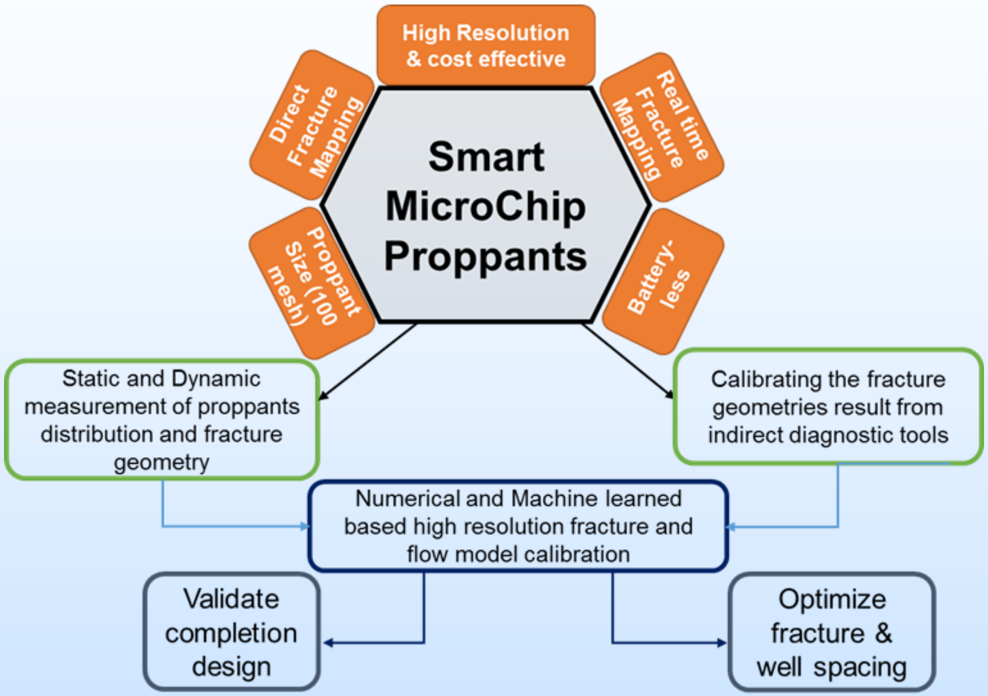
- Technology Background
- Benefit to the Program
- Technical Approach/Project Scope
- Accomplishments to Date
  - Laboratory testing of Smart Microchip Sensors
  - Building downhole tool to power the chips
  - Novel iGeoSensing Fracture Diagnostic tool
- Plans for future testing/development/ commercialization
- Organization Chart
- Gantt Chart

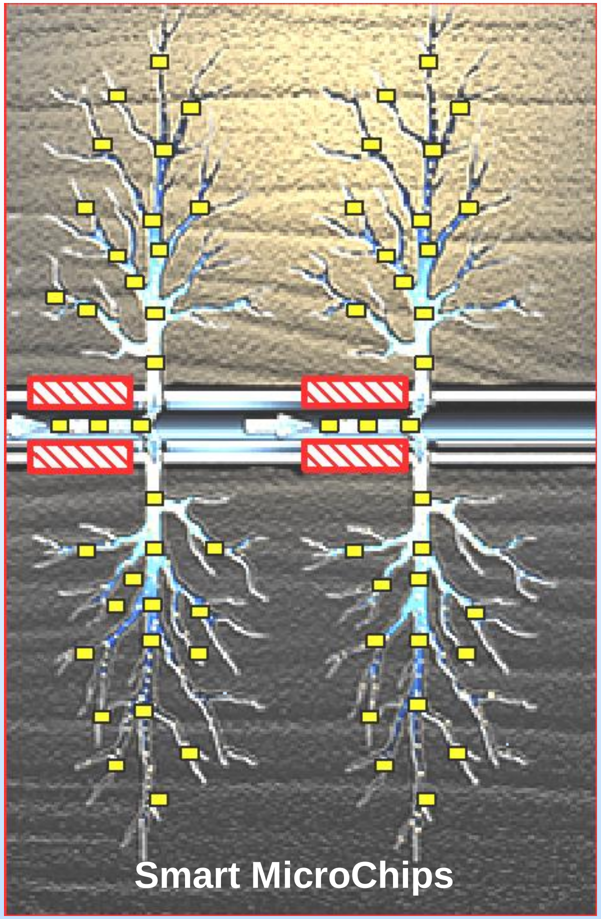
Program Overview

- Funding
  - (DOE:$2.49M and Cost Share:$1M)
- Overall Project Performance Dates:
  - October 2019-April 2024
- Project Participants
  - University of Kansas(Lead institution), UCLA, MicroSilicon Inc., and EOG Resources

  (Consultants: NSI Fracturing Inc and Confractus Inc)
- Overall Project Objectives
  - to develop and field test fine size and wirelessly powered smart MicroChip Proppants
  - to develop a closed-loop fracture diagnostic and modeling workflow using the collected data from Smart MicroChip Sensor to better characterize propped fracture geometry in real time.

Technology Background





Pilot Location:
Permian Basin, Yeso Field, Paddock Reservoir, NM
Cored interval 2594-2600 (6ft)

Technology Background

- The proposed technology responds to the current limited understanding of the near wellbore fracture properties.
- Smart MicroChip proppants map the geometry of a fracture network with a resolution of less than 1 ft.
- A downhole tool injects electromagnetic energy through the perforations.
- The sensor harvests energy from these electromagnetic waves activates an on-chip radio to communicate back with the down-hole tool.
- MicroChips change the frequency of the received signal and respond back in a different band.

Technology Background

- Frequency-shift technology enables the down-hole tool to separate the strong reflection caused by the reservoir from the signals generated by the MicroChips.
- Physics informed, Al based iGeoSensing platform on cloud enables real time processing of the transmitted signals to generate multiple realizations of HF geometries and generate the corresponding flow responses.

Benefit to the Program

Technology Impact:

- Reduces unconventional resources development cost by optimizing well spacing while minimizing the development related environmental footprint.
- Maintain the US leadership in unconventional energy development

Vision

Metric	State of the Art	Proposed
Resolution	50 ft	<1ft
Data streaming	Only during the hydraulic fracturing (HF)	Real time, during , after the HF job and during the production
Manufacturing cost	$10-100 per proppant	Few cents

MEMS (micro electro mechanical systems)

Technical Approach/Project Scope

Design and work plan

- experimental components:
  - ✓ build and calibrate novel Smart MicroChip Sensor in the lab environment
  - ✓ construct synthetic cores with different levels of fracture complexity for testing Microchips.
  - ✓ build a downhole logging tool to power the Smart MicroChip Sensor and assimilate their data
  - ✓ perform basic and comprehensive rock mechanical tests
  - ✓ conduct two fluid sensitivity testing-pH& Potassium Chloride (KCl) tests
  - ✓ Field Laboratory testing

Technical Approach/Project Scope

Design and work plan:

- computational components:
  - ✓ iGeoSensing platform development
  - interpret and map the received data from the “Virtual” Smart MicroChip Sensor by developing a new algorithms to process discrete points
  - real-time fracture mapping
  - real time proppant transport modeling
  - real time flow back and production history matching by coupling numerical and machine-learned models.

Technical Approach/Project Scope

Key milestones

Milestone Log			
Task	**Milestone Title**	**Planned Completion Date**	**Verification method**
Budget Period 1			
Task 4.1	Field Laboratory (Science Well) Site Selection and **Static data collection**	Q5-Completed	Presentation file
Task 5.5 and 5.6	Basic pilot well core analysis and Rock Mechanics testing	Q8	Report, Presentation files. Submitting raw and interpreted data
Subtask6.2	Constructing multiple synthetic fracture network models and building synthetic cores using 3D printing technology	Q8	Presentation and report files. 3D Printed Cores
Budget Period 2			
Subtask6.3	Test the imaging capability of MicroChip proppants with 3D printed synthetic cores	Q14	Demo and Presentation file
Subtask5.8	Smart Proppant Transport tests in Lab	Q14	Report, Presentation files. Submitting experimental and interpreted data
Subtask6.4	Test the MicroChip proppants in a high pressure and temperature lab environment	Q14	Demo and Presentation file
Subtask6.1	Build and calibrate novel smart MicroChip proppant sensors	Q14	Demo and Presentation file
Subtask 8.1	Construct a high-resolution simulation model	Q14	Demo, models and Presentation files
Budget Period 3			
Subtask 6.6	Build a downhole logging tool to power the Microchips and assimilate their data.	Q18	Demo and Presentation file
Subtask 6.7	Inject the MicroChip proppants into the formation (small-scale frac job) and validate survival of the chips.	Q18	Demo and Presentation file
Task 4.2	Field Laboratory –**Dynamic Data collection**	Q18	Presentation file
Subtask 6.8	Interpret and map the received data from the MicroChips- iGeoSensing Fracture Diagnostic Software Package Development (**i-GSFD** platform)	Q18	Demo and Presentation file
Task 7.0	Integration of near wellbore (microchip) and the other diagnostic tools through machine learning techniques	Q18	Demo, models and Presentation files
Task 8.0	Development of state-of-the-art integrated machine earning, analytical and numerical predictive fracture and flow models	Q18	Demo, models and Presentation files
Subtask 8.2	Develop extremely fine resolution fracture and flow simulation and machine learning model	Q18	Demo, models and Presentation files
Subtask 8.3	Develop new diagnostic plots and enhance analytical solutions/ type curves	Q18	Demo, models and Presentation files

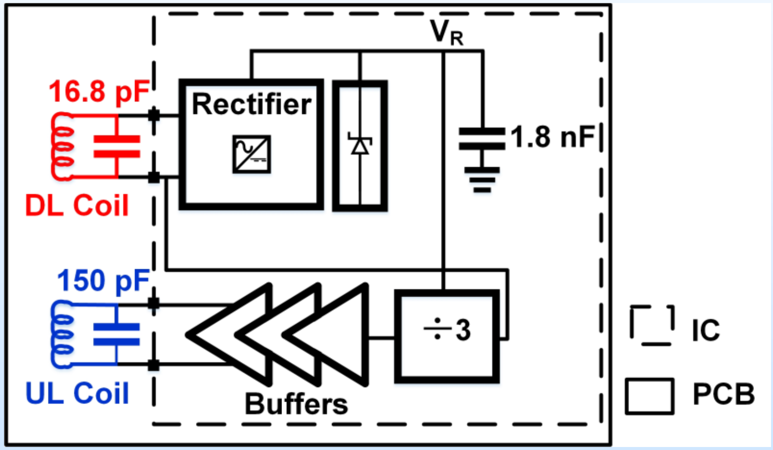
Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ demonstrated successful Coherent Radiation from a Swarm of Chips operating in GHz range
  - ✓ designed a 40MHz wirelessly powered tag to increase the depth of penetration
  - ✓ the 13.33 MHz signal generated by the divide-by-3 circuit is radiated wirelessly
  - ✓ the size of the PCB has been significantly reduced.
  - ✓ successful measurements are performed to demonstrate the communication with the PCB embedded with the chip while using small 8mm antennas.
  - ✓ an external transmitter is used to power the chip and communicates with it.
  - ✓ successful laboratory testing of Smart MicroChip Sensors for fracture mapping using a complex 3D printed synthetic core
  - ✓ successful laboratory testing of Smart MicroChip Sensor at 250 °C (482 °F)

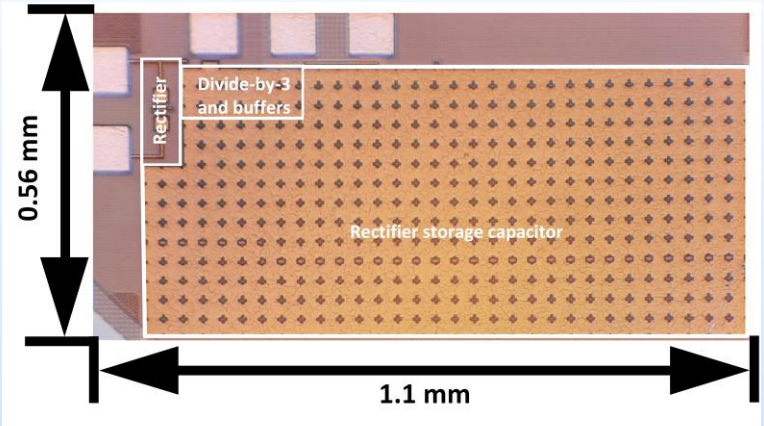
Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Coherent Radiation from a Swarm of Chips**

Block diagram of the initial chip



Localizer architecture

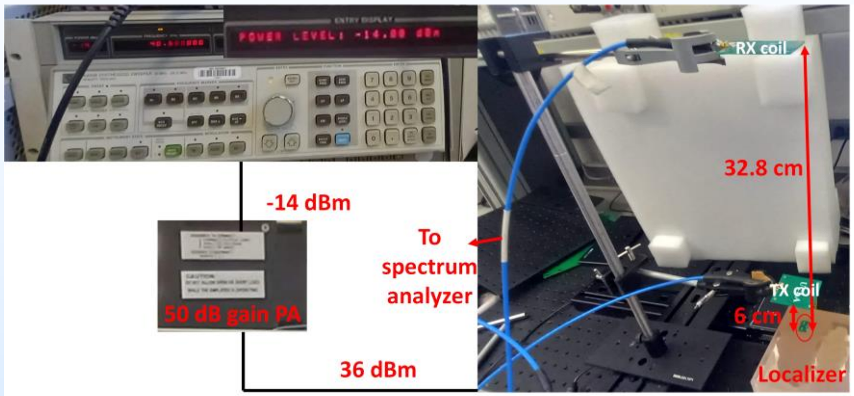


Die micrograph

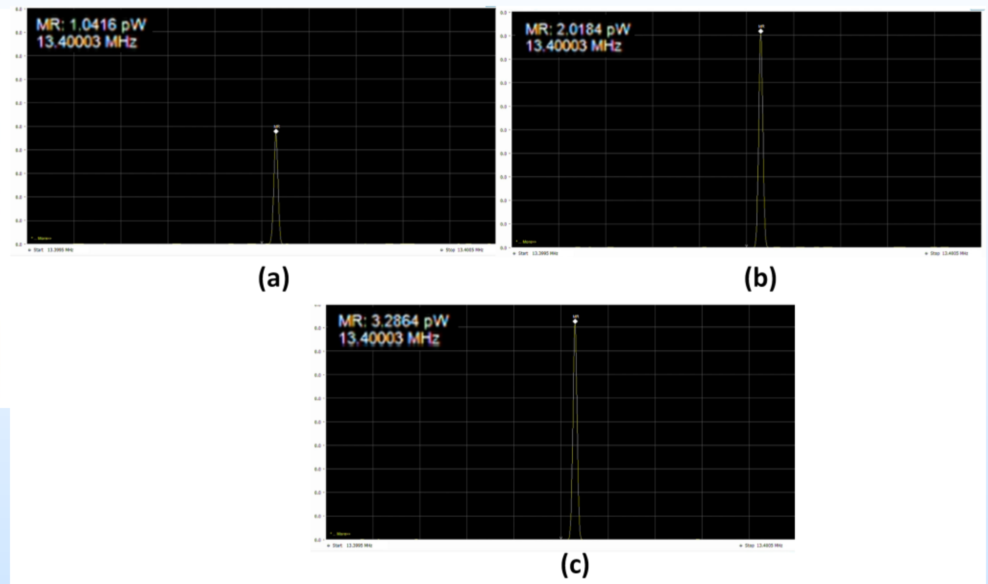
- A new technique is developed to <u>synchronize a swarm of sensor nodes at the RF domain</u> and produce coherent radiation from the sensor nodes to increase the amplitude of the reflected signal. That <u>data swarm is then converted into discrete chip positions.</u>
- A network is formed by an <u>array of microchips that are wirelessly powered</u>, and <u>upon activation, radiate back an RF signal</u>.

Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Smart Microchips functionality verification**



Measurement setup used for chip functionality verification

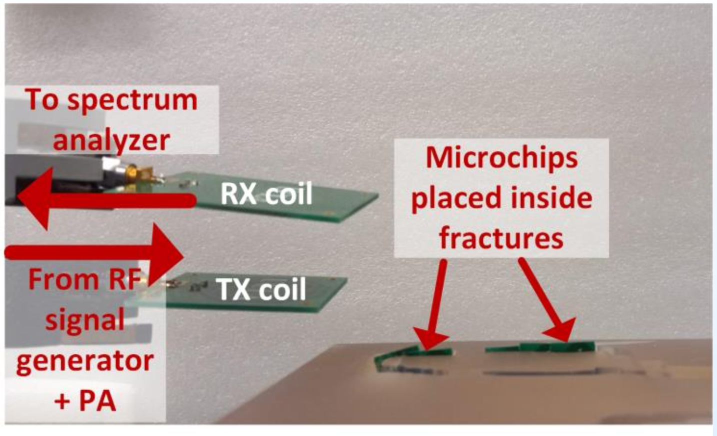


Received power from (a) one, (b) two, and (c) three localizers

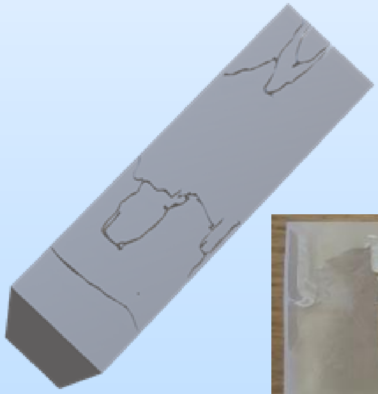
- Using the highest RF power available, the maximum operating range of the system is determined.
- In three different measurements, one, two and three localizers are placed on a surface such that they can be wirelessly powered by the same TX coil.
- The TX and RX coils are placed at a distance of 6 cm and 10 cm respectively from the localizers to transmit and receive signal from them.
- A Tektronix spectrum analyzer (RSA 306B) was used to measure the power received from the localizers.
- The power received at 13.56 MHz received from (a) one (b) two and (c) three localizers.
- The power received from two and three localizers is almost equal to twice and thrice of that received from one localizer, which verifies the fact that the signals transmitted by the localizers add up in a coherent manner.

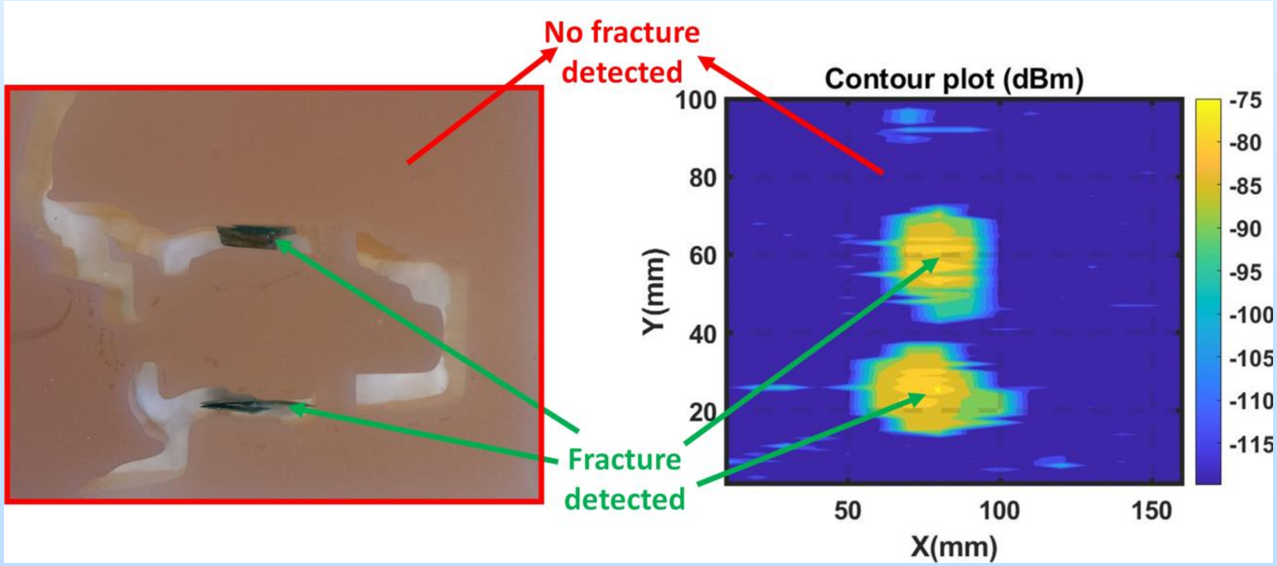
Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Fracture mapping verification**
    - using 3D printed synthetic cores with complex fracture geometry
    - The TX and RX coils are moved over the entire region that is desired to be mapped.
    - The fractures are mapped in the X and Y directions separately with a resolution of 1mm in the X and Y directions.



The measurement setup used for fracture mapping

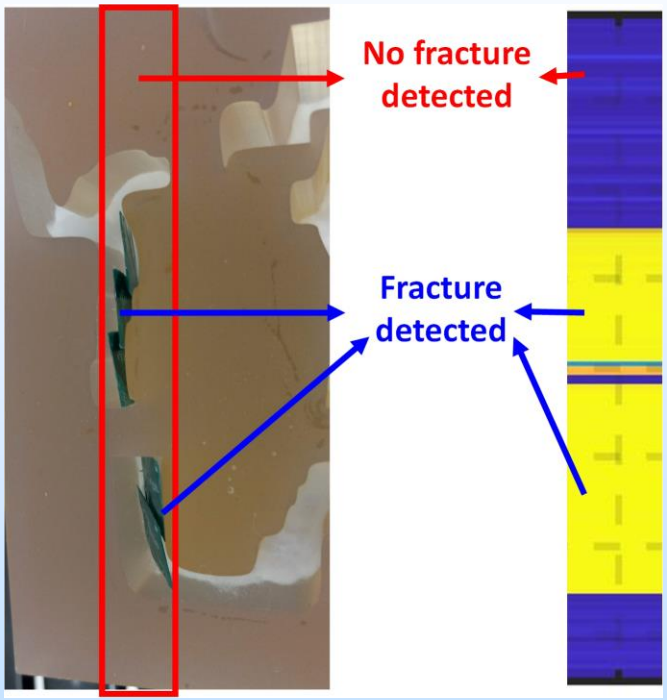




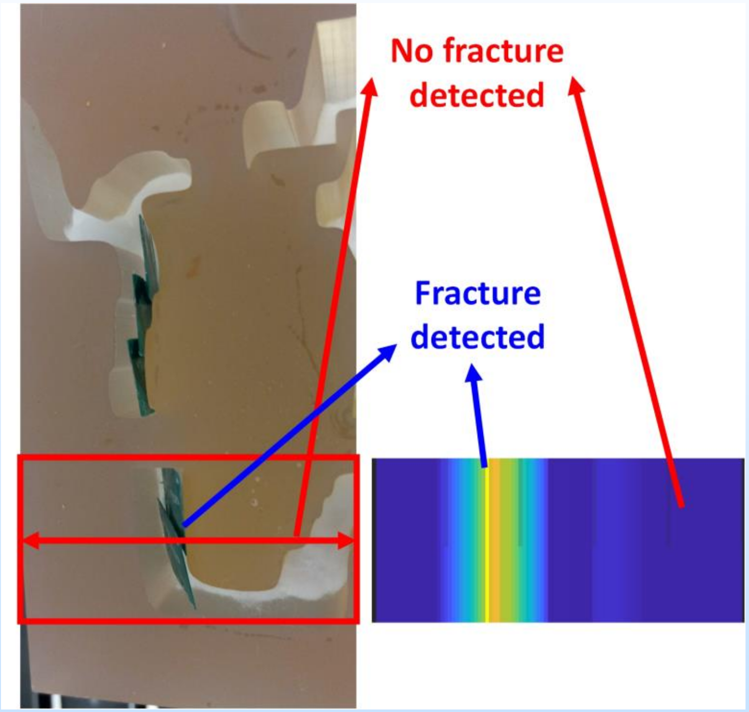
2D fracture mapping results

Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Fracture mapping verification**



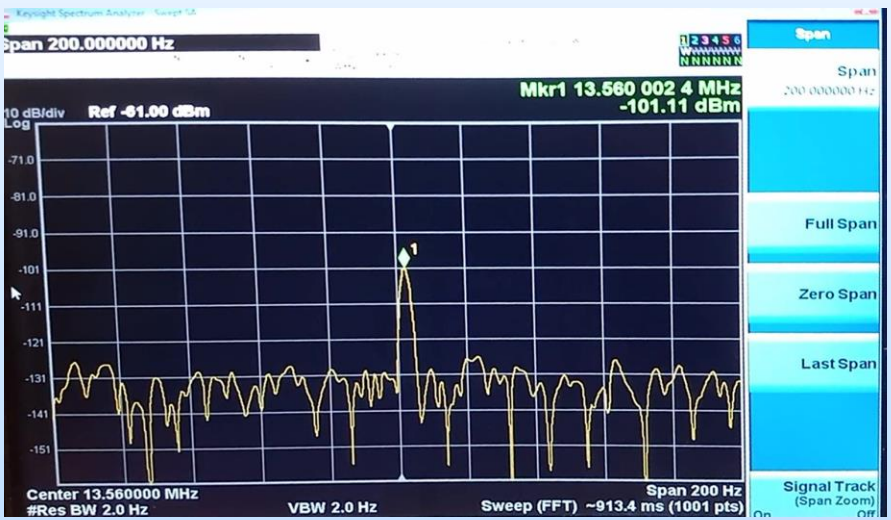
1D fracture mapping results for y-direction.
The red box indicates the region that was mapped.



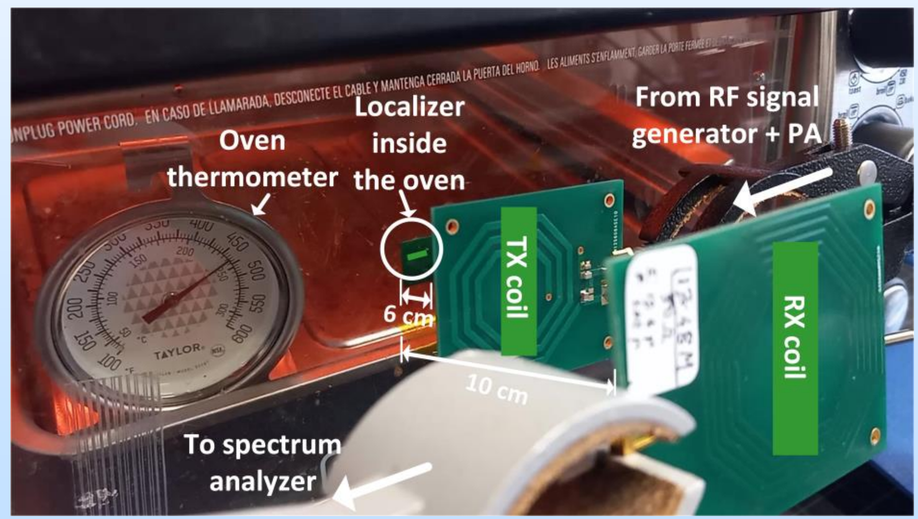
1D fracture mapping results for x-direction.
The red box indicates the region that was mapped.

Progress and Current Status of Project

- **Build and calibrate novel Smart MicroChip Sensor**
  - ✓ **Very high temperature verification**
  - the functionality of the localizers is verified at high temperatures (250 °C (482 °F))
  - the localizer is placed inside a microwave oven and heated. The temperature inside the oven is measured by an oven thermometer.
  - The RX coil connected to the spectrum analyzer is placed such that it receives the signal from the localizer



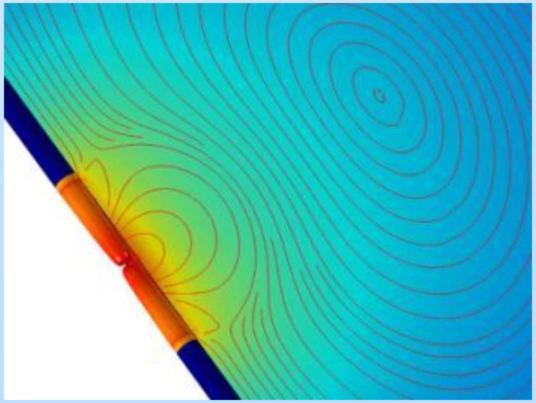
Received signal at 250 °C (482 °F)



Measurement setup for verification at high temperatures

Progress and Current Status of Project

- **Build a downhole logging tool to power the Smart MicroChip Sensor**
  - Specifications of the downhole tool have been completed. It will use a "horn" shaped antenna that approximates a resonant dipole and has optimized mechanical configuration for borehole geometry.
  - All deployed chips will be charged at the same frequency (~40MHz) and they will all respond at the same frequency (~13MHz).
  - A mockup of the antenna has been constructed for lab use
  - We tested the chips with a downhole tool and and confirmed that it can activate the chips with an antenna.



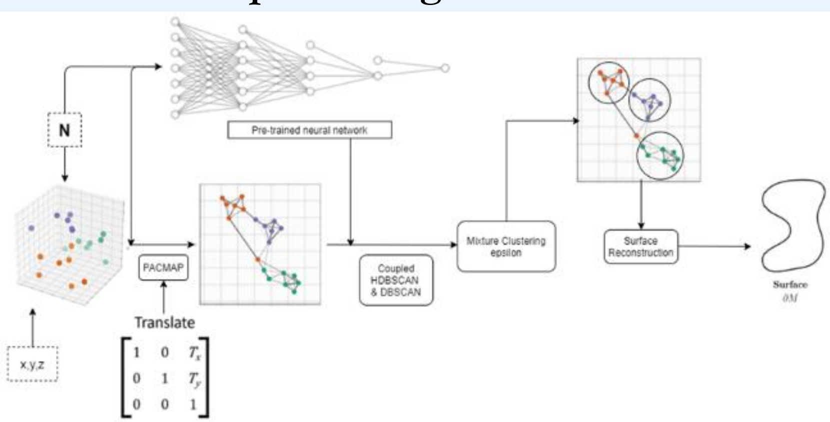
Progress and Current Status of Project

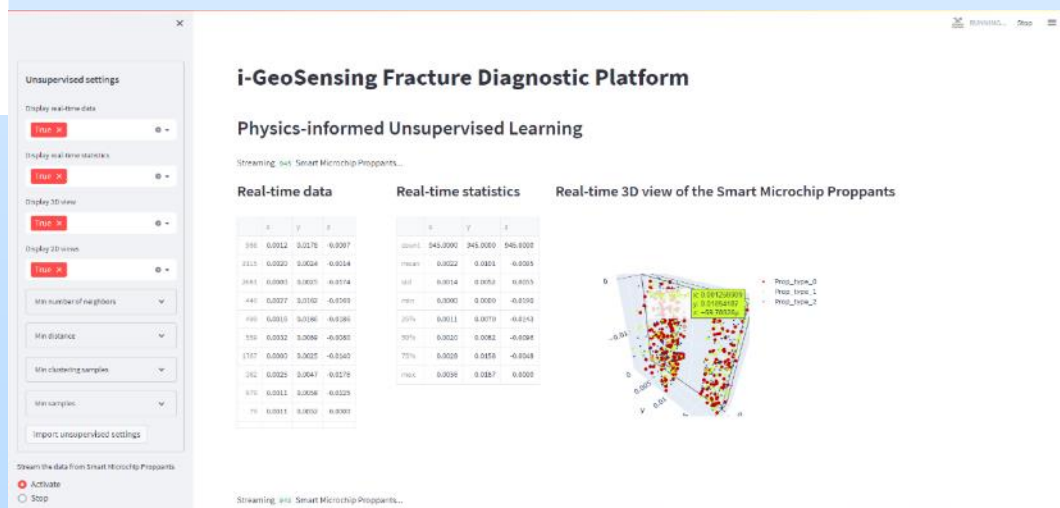
- **Build a downhole logging tool to power the Smart MicroChip Sensor**

Progress and Current Status of Project

iGeoSensing Fracture Diagnostic Software Package Development

- **Unsupervised Learning module:**
  - –Fully functional unsupervised clustering using triplet UMAP-HDBSCAN-DBSCAN and clustering stability control using Mixture clustering Epsilon
  - –Proven accuracy via synthetic environment testing
  - –Post-processing and transfer results to the Supervised Learning module





Progress and Current Status of Project

iGeoSensing Fracture Diagnostic Software Package Development

•Supervised Learning module:

–A “data pipeline” with the following components:

  –Design of Experiments: Pre-process and identify the fracture networks embedded in the available core sample images

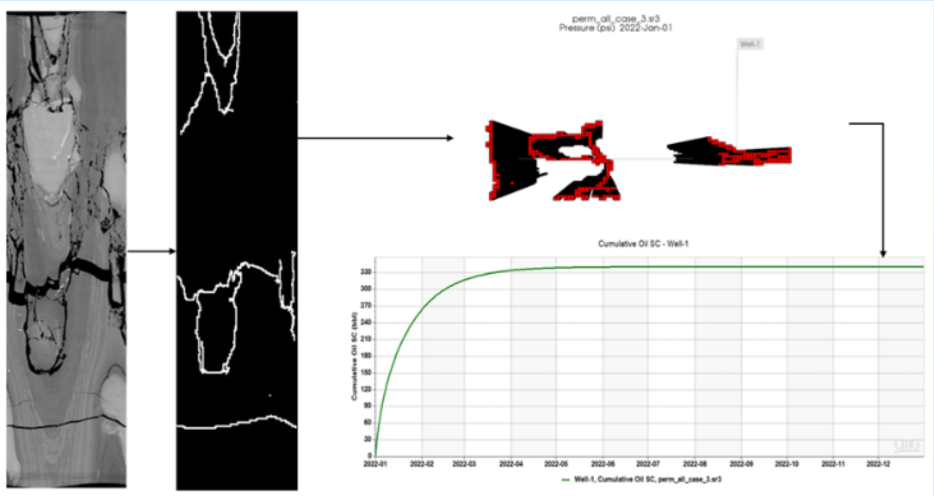
  –Grid Fracture Network: Convert the embedded fracture networks into “grid” fracture network data (i.e., including reservoir properties)

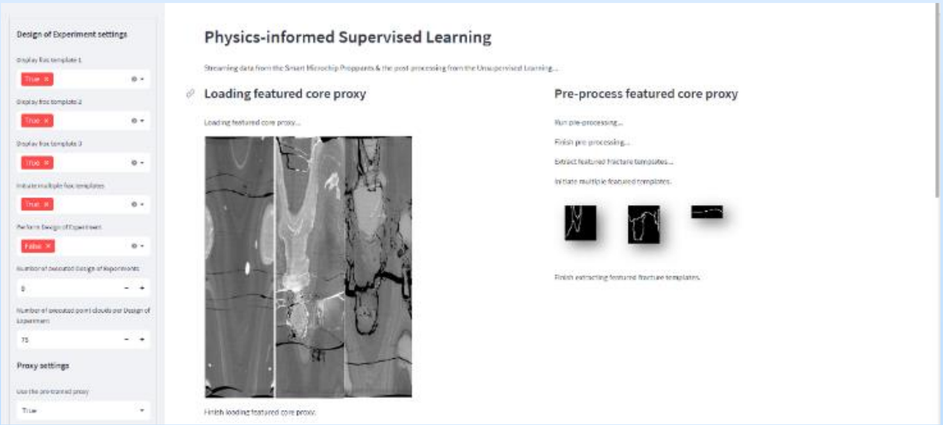
  –Flow simulator: Generate multiple synthetic simulation cases from the “grid” fracture network data

–Supervised proxy modeling options:

  –Graph Neural Network (the secondary proxy deployment)

  –Point Net (the main proxy deployment)

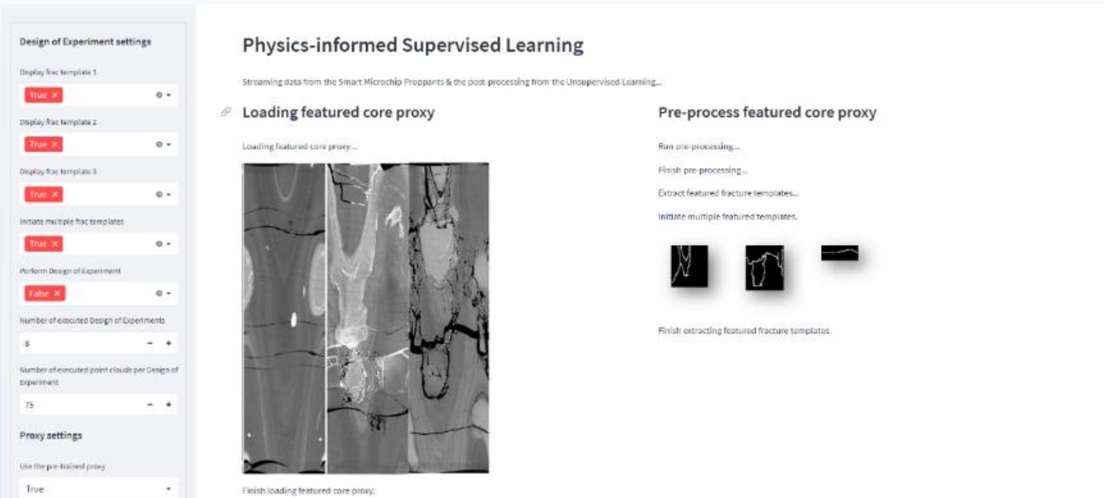


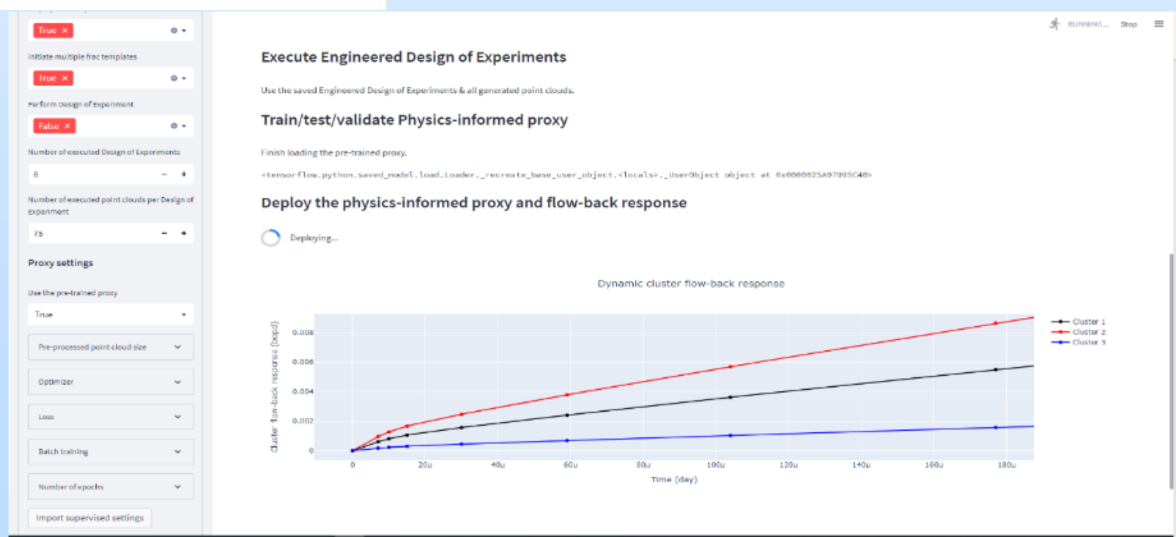


Progress and Current Status of Project

iGeoSensing Fracture Diagnostic Software Package Development

•Supervised Learning module:





Plans for future testing/development/ commercialization

- In this project, once the Smart MicroChips proppant tested in the lab, we go for the field trial.
- The developed smart Microchips are expected to interface with existing indirect hydraulic fracturing diagnostics to improve understanding of hydraulic fracture geometry.
- It helps the operators to maximize the return from their unconventional reservoir operation.
- It also helps to reduce the environmental footprints and will help in better designing the EOR system for unconventional reservoirs.
- Additionally, regulation agencies can benefit from using this technology to monitor and consequently minimize HF operation issues.
- A low-cost approach and partnership with EOG will aid in transitioning technology to commercial deployment if successful.
- The technology can be further tested in other DOE-sponsored Science wells as well as oil and gas operators' core assets.
- This technology can be further developed to measure pressure and detect phases

Outreach and Workforce Development Efforts or Achievements (If Applicable)

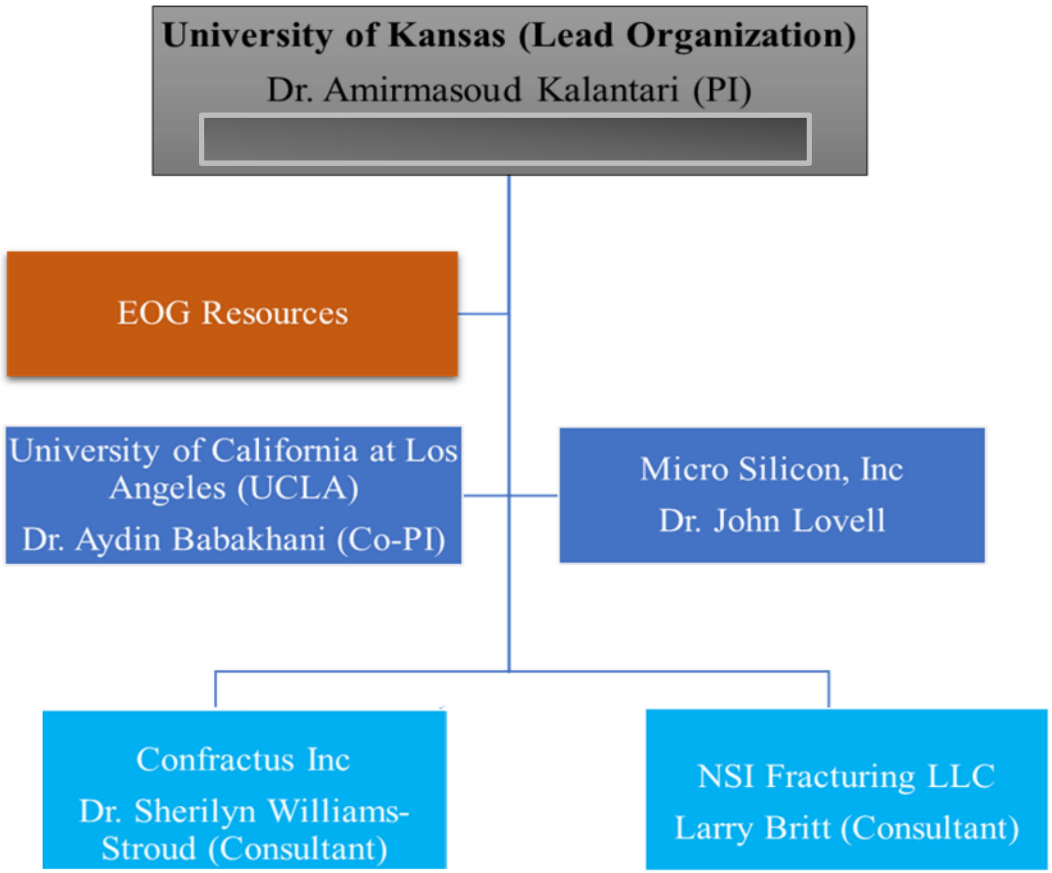
- Outcome of this research has been presented in multiple SPE, IEEE conferences.
- Workforce Development –
  - ✓ Training 6 Ph.D. students and research associate

Summary Slide

- Successful laboratory testing of Smart MicroChip proppants
  - ➢ Energy harvesting verification
  - ➢ Microchip functionality verification
  - ➢ Coherent power combining verification
  - ➢ Fracture mapping
  - ➢ High temperature functionality verification

- We are looking into an alternate antenna design using multiple planar antennas to efficiently communicate with microchips through the downhole tool
- Significant progress on iGeoSensing web-based platform development
  - ➢ Working on improving the functionality and the user interface

Organization Chart



Gantt Chart

Task Title	Start Date	End Date	Budget Period 1				Budget Period 2				Budget Period 3			
			Including NCE				Including NCE							
			Q5	Q6	Q7	Q8	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18
Task 1: Project Management and Planning	Q1	Q16												
Task 2.0: Workforce Readiness for Technology Deployment	Q1	Q16												
Task 3.0: Data Management Plan	Q1	Q16												
Decision Point														
Task 4.1: Field Laboratory (Science Well) Site Selection and Static data collection	Q1	Q5												
Task 4.2: Field Laboratory –Dynamic Data collection	Q14	Q16												
Task5 Preliminary & basic core work	Q5	Q7												
Task 5 Detailed Rock Mechanics Testing	Q5	Q8												
Subtask 5 Additional project testing (Fluid sensitivity and Un-propped crack tests)	Q9	Q11												
Subtask 5.8 Smart Proppant Transport tests in Lab	Q13	Q14												
Subtask 6.1: Build and calibrate novel smart MicroChip proppant sensors	Q1	Q14												
Subtask 6.2. Constructing multiple synthetic fracture network models and building synthetic cores using 3D printing technology	Q2	Q8												
Subtask 6.3: Test the imaging capability of MicroChip proppants with 3D printed synthetic cores	Q7	Q13												
Subtask 6.4: Test the MicroChip proppants in a high pressure and temperature lab environment.	Q10	Q14												
Subtask 6.6: Build downhole logging tool to power the Microchips and assimilate their data.	Q1	Q16												
Subtask 6.7: Inject the MicroChip proppants into the formation (small-scale frac job) and validate survival of the chips.	Q13	Q18												
Subtask 6.8: Interpret and map the received data from the MicroChips - iGeoSensing Package	Q13	Q18												
Task 7.0: Integration of near wellbore (microchip) and the other diagnostic tools through machine learning techniques	Q13	Q18												
Task 8.0: Development of state-of-the-art integrated machine earning, analytical and numerical predictive fracture and flow models	Q12	Q18												
Subtask 8.2: Develop extremely fine resolution fracture and flow simulation and machine learning model	Q12	Q18												
Subtask 8.3: Develop new diagnostic plots and enhance analytical solutions/ type curves	Q12	Q18												
Report and presentation	Q1	Q18												

Appendix

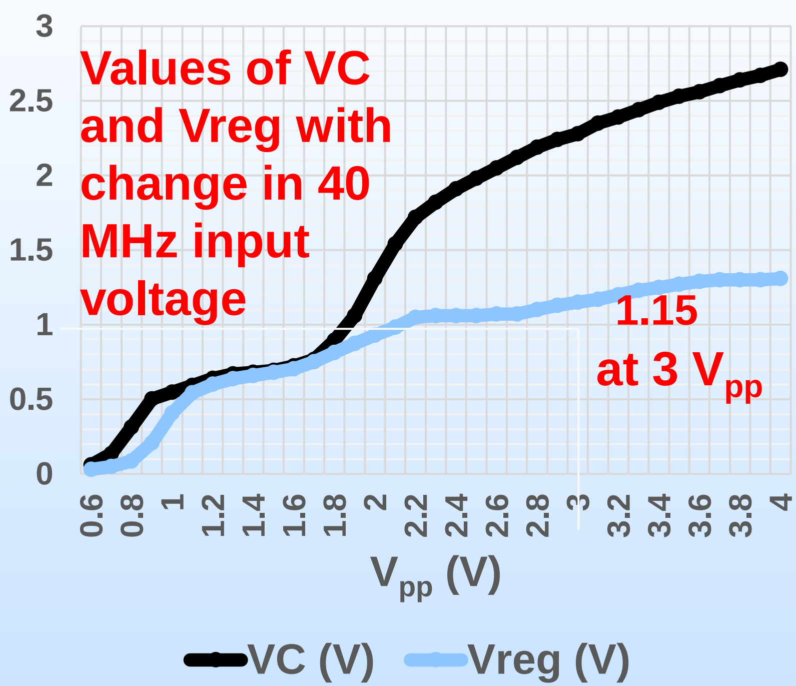
Technology Background

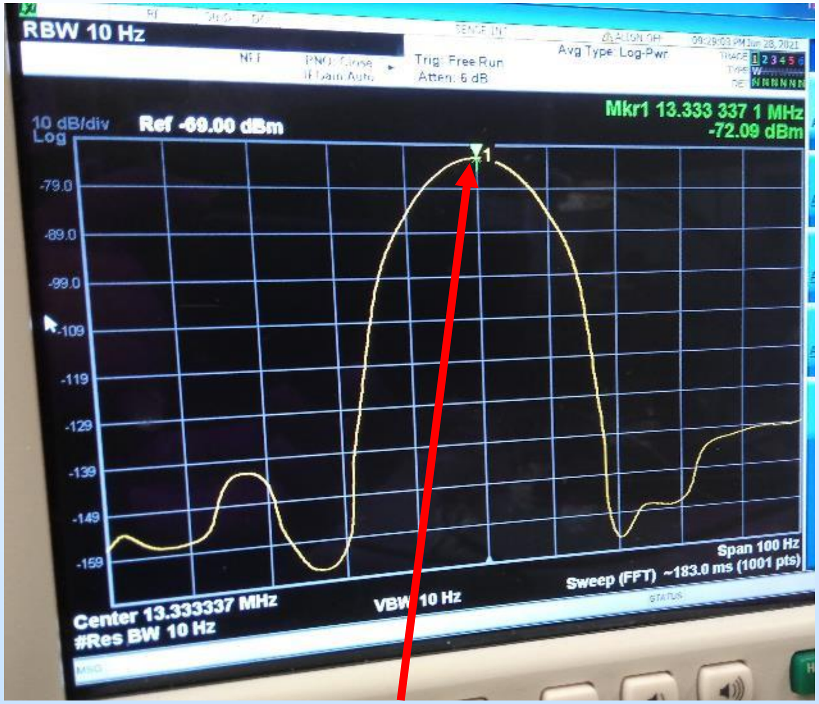
Technical Challenges:

- to miniaturize the smart microchip proppants to 100 mesh.
  - risk mitigation strategy:
    - ✓ use 180 nm CMOS technology to build the smart proppants. If we can't fit the entire electronic components in 100 mesh using 180 nm CMOS process, we will use smaller CMOS nodes such as 22 nm or 16 nm to reduce the size of the active components (transistors) by a factor of larger than 10.
- Antenna size (or on-chip inductor) used to harvest electromagnetic energy.
  - risk mitigation strategy:
    - ✓ ultrathin and flexible antennas such as nanowires. In this case, the core of the active circuitry will be integrated and fit within 100 mesh

Progress and Current Status of Project

Measurement results

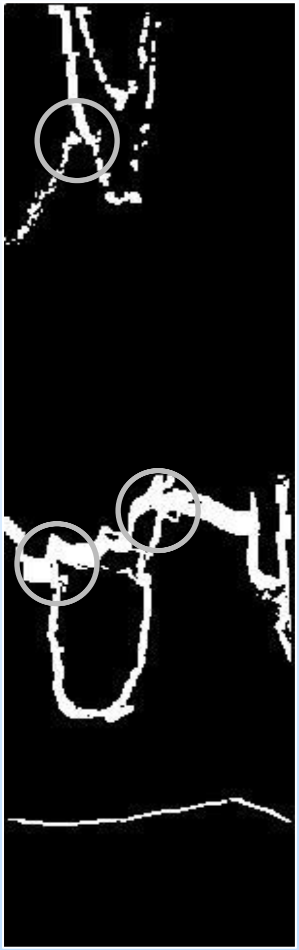




Measured 13.33 MHz output tone of -72.09 dBm for a 40 MHz input of 3 V_{pp}

Progress and Current Status of Project

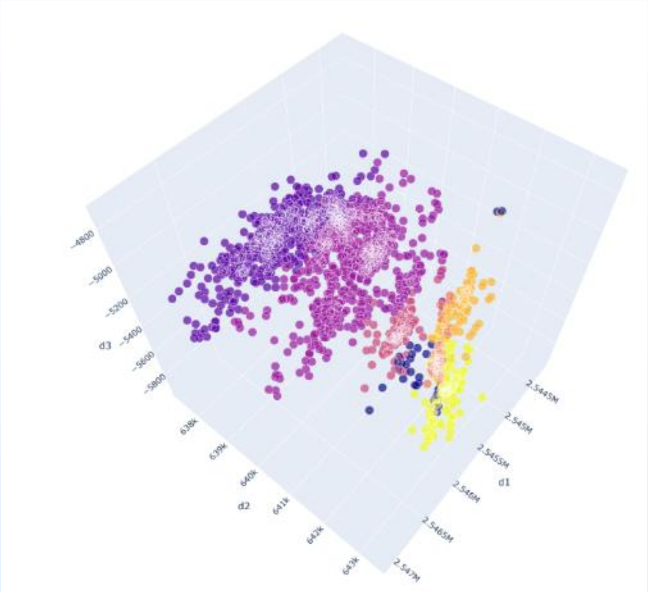
- **Challenges from "joint" locations for the current i-GSFD**
  - 2D projection of the 3rd synthetic fracture network, highest complexity level
  - Critical locations are circled: "joints" of different child fractures in a child fracture network, extreme proximity
  - These "joint" locations makes the i-GSFD performance challenging
  - Low-dimensional projection algorithms (t-SNE, or UMAP used in i-GSFD) are designed to separate the data using the proximity information in the data & preserve the data's local and/or global structure



Progress and Current Status of Project

- **Software trial: Fracture network clustering, DAS-based synthetic case**

- **Ongoing work:**
  - ✓ Tentative modification of i-GSFD to scope with highly–complexed fracture networks
  - ✓ Automatic coupling between i-GSFD and a numerical simulator engine (as CMG)
  - ✓ Solve the "joints" in complexed fracture networks using Trajectory Clustering (as TRACLUS)
  - ✓ Dynamic use of i-GSFD (i.e. real-time fracture mapping)
  - ✓ Compare between the "ground-truth" (i.e. synthetic) fracture networks and the predicted networks dynamically using statistical analysis.
  - ✓ Construct ML-based modelling proxy for uncertainty analysis using the capability of controlling commercial simulator engine in i-GSFD



Progress and Current Status of Project

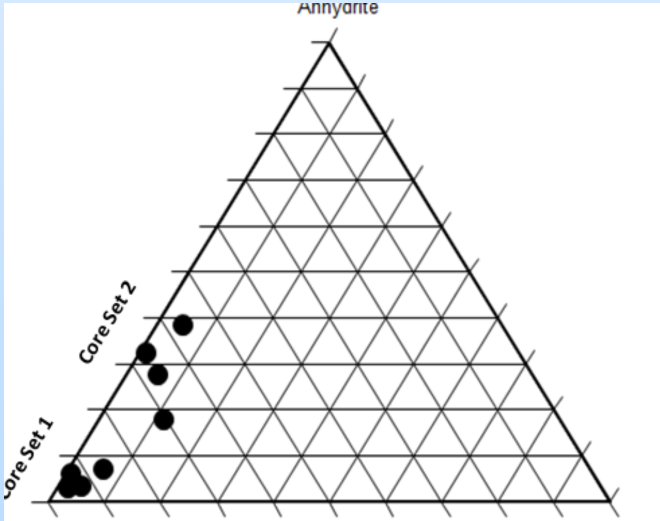
Field Laboratory (Science Well) Site Selection and Static data collection

- We worked with EOG resources to identify multiple locations for the field pilot testing.
  - ✓ Permian Basin, Yeso Field, Paddock Reservoir, NM is selected for field trial (Boyd State #15H Eddy County, New Mexico)
  - ✓ 6ft of core and logs were obtained from the pilot well (Boyd XState)

Progress and Current Status of Project

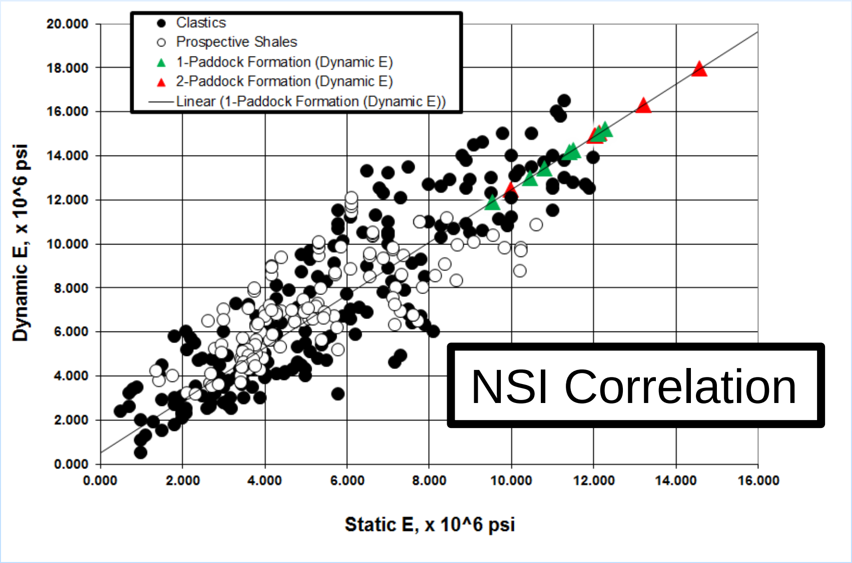
Geomechanical Evaluation, Un-propped Crack Test, Fluid Sensitivity Test, and Embedment Test

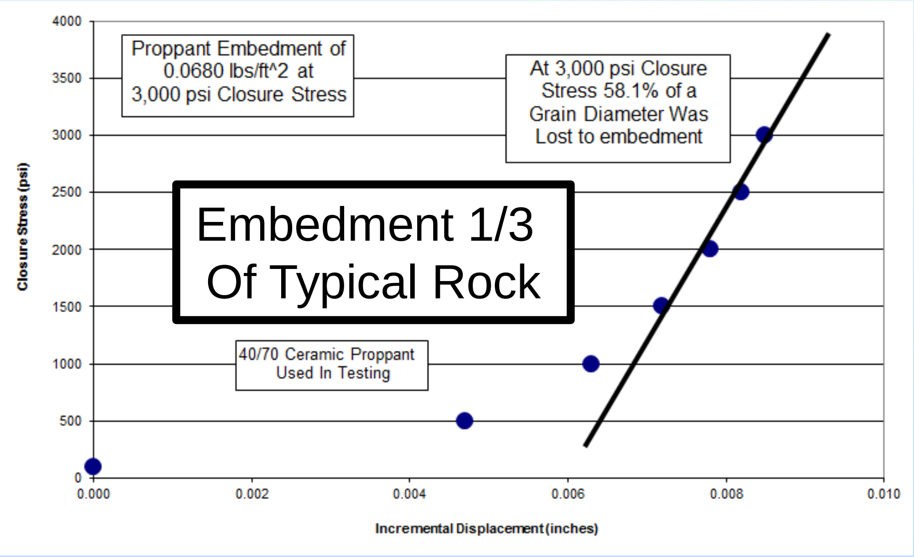
- **Core Analysis (Boyd State) Site Selection**
  - ✓ Permian Basin, Yeso Field, Paddock Reservoir, NM is selected for field trial
  - ✓ 6ft of core and logs were obtained from the pilot well (Boyd XState)
  - ✓ Shows Paddock Reservoir is A Dolomite W/ Anhydrite



Progress and Current Status of Project

- **Core Analysis (Boyd State) Site Selection**
  - ✓ Conducted Ultrasonic Velocity Tests For Dynamic Young's Modulus
    - Used NSI Correlation To Estimate Static Young's Modulus
    - Average E_{static}= 11.7 x 10^6 psi (Ranged From 9.5-14.6 x 10^6 psi)
    - Little Shear Anisotropy (Averages 4.8 Percent)
    - Paddock Formation Very Brittle W/ Little Proppant Embedment





Progress and Current Status of Project

- **Core Analysis (Boyd State) Site Selection**
  - ✓ Conducted Fluid Sensitivity & Un-Propped Crack Tests
    - ▪ Little Fluid Sensitivity To KCL Concentration
    - ▪ Un-Propped Crack Maintains Conductivity
    - ▪ Paddock Formation Is Very Brittle
    - ▪ Good Water Frac Candidate Assuming Low Leak-Off