High-Resolution 3D Acoustic Borehole Integrity Monitoring System

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U.S. Department of Energy

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Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
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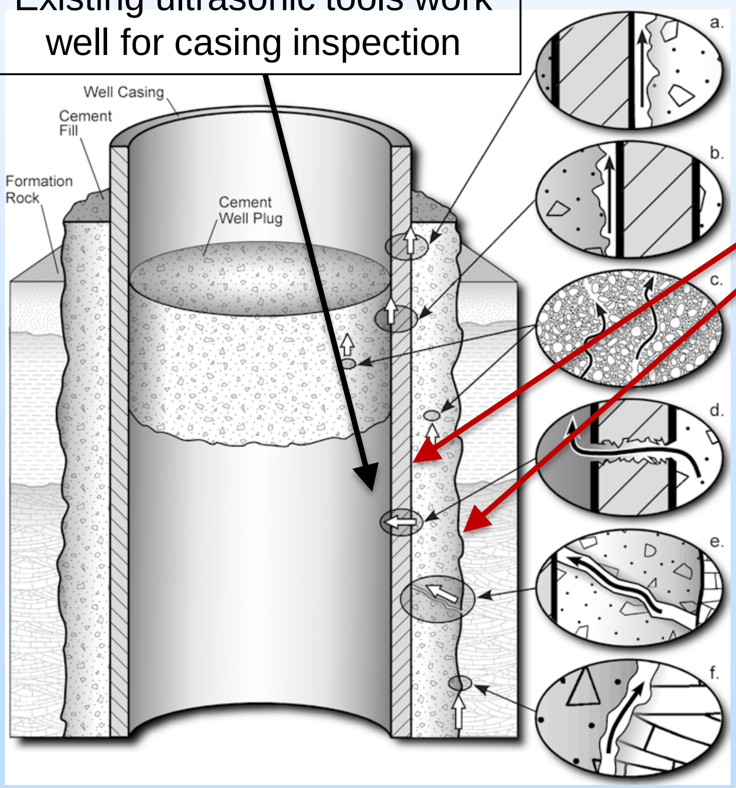
Presentation Outline

- Technical Status
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary

Technical Status

Develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

Existing ultrasonic tools work well for casing inspection



** Picture from S.E. Gasda, Environ Geol (2004) 46: 707-720*

Extend applicability to: (1) casing-cement interface, (2) cement-formation interface, and (3) out in the formation (up to ~ 3 meters).

Performed a comprehensive literature/existing technology study for wellbore integrity monitoring tools.

Comparison of existing techniques and the present approach

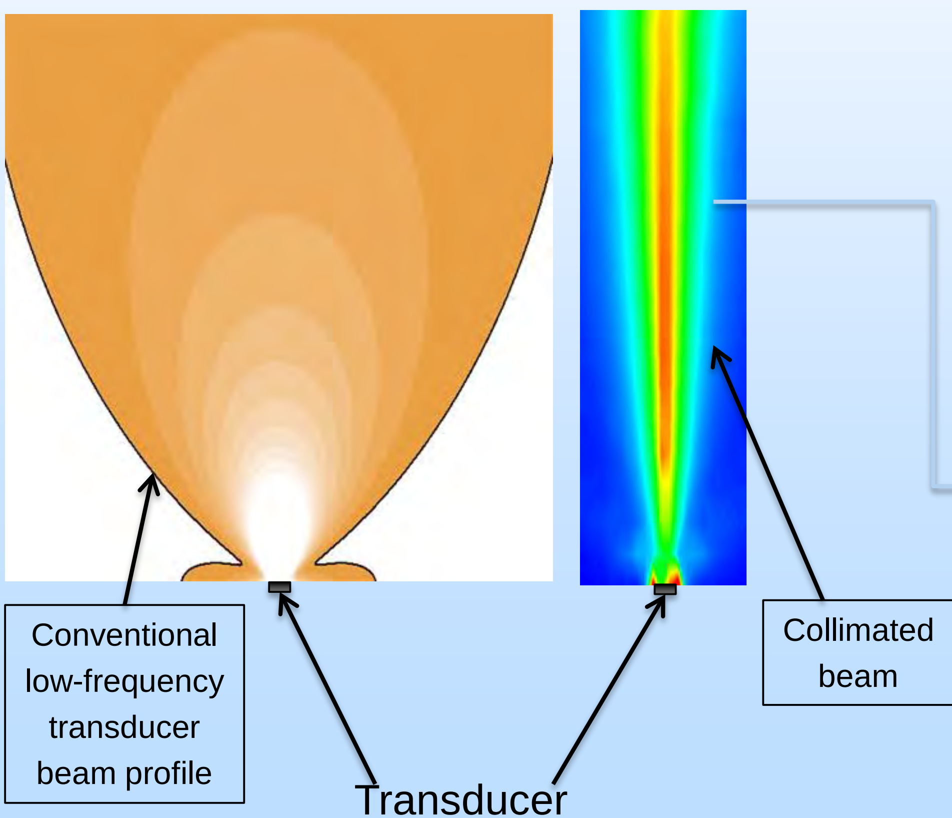
Method	Frequency (kHz)	Range (m)	Resolution (mm)
Sonic probe	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe	>250	casing	4-5

Technical Status

The Proposed Approach:

Novel technique that fills this technology gap.

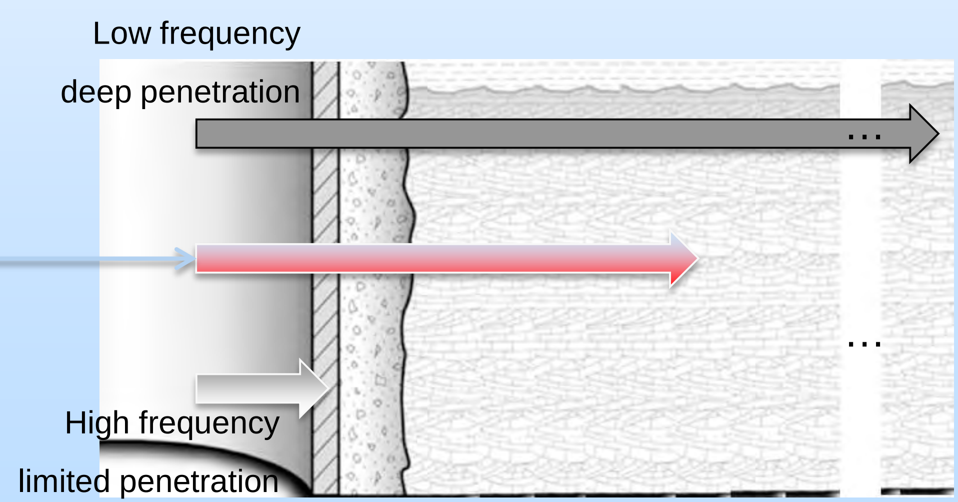
1. Collimated beam for increased resolution



2. Low frequency for deeper penetration

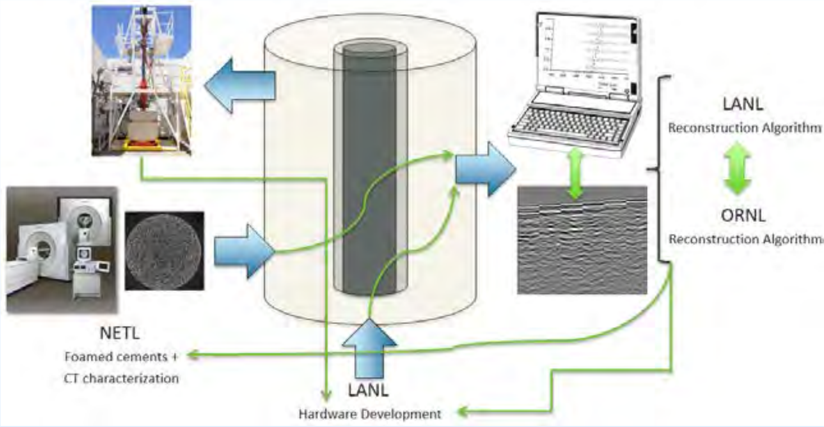
$$Attenuation \sim f^n$$

f = frequency, n = 1-2



Technical Status

Multi-lab project



Inter-lab collaboration and teaming arrangements/partnerships

- LANL: Develop acoustic source, imaging system, and image processing.
- NETL: Investigate acoustic metrics for foamed cements. Incorporate new metrics for wellbores in the field.
- ORNL: Explore different image processing approaches.
- SNL: Perform experiments in more realistic boreholes. Incorporate data from realistic borehole and compare resolution with lab experiments.

Technical Status

Foamed Cement Young's Modulus Prediction

A material model has been developed to compute the degree of hydration of Class H cement

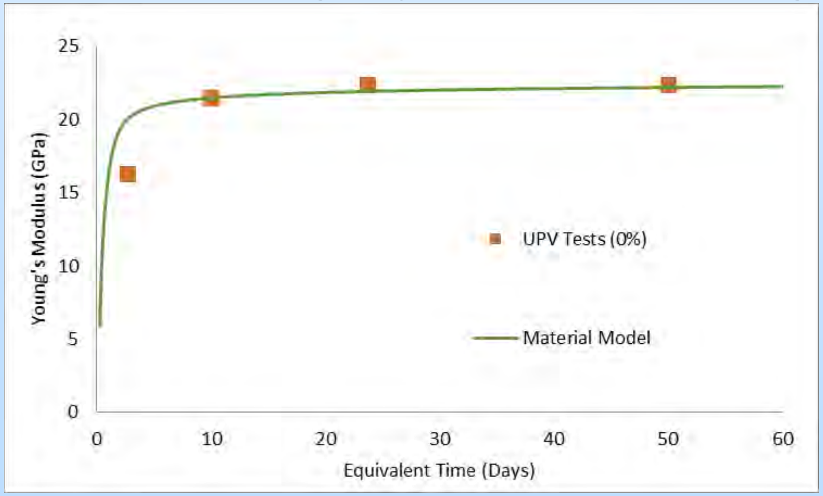
Table 1: Chemical Compositions of Class H Cement

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Blaine (m^2/kg)	C_3S	C_2S	C_3A	C_4AF
%	64.7	22.3	2.6	4.3	2.3	2.9	310	61.7	17.3	0	12.7

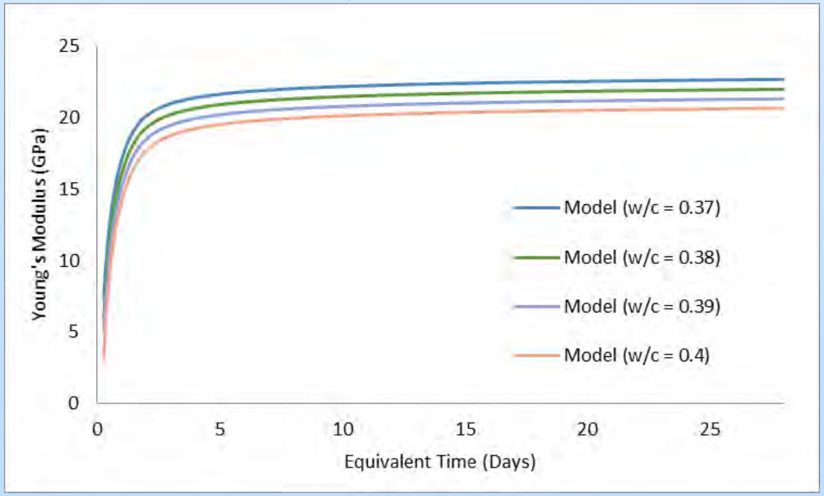
The early-age Young's Modulus of the Neat Class H Cement was measured using the Ultrasonic Pulse Velocity (UPV) method.

The material model was used to calculate the Young's modulus of the neat Class H cement.

The effective medium theory is the basis for the calculation of the Young's modulus which assumes the cement paste is a porous medium consisting of hydration products (C-S-H gel), pores, pore water and anhydrous cement.



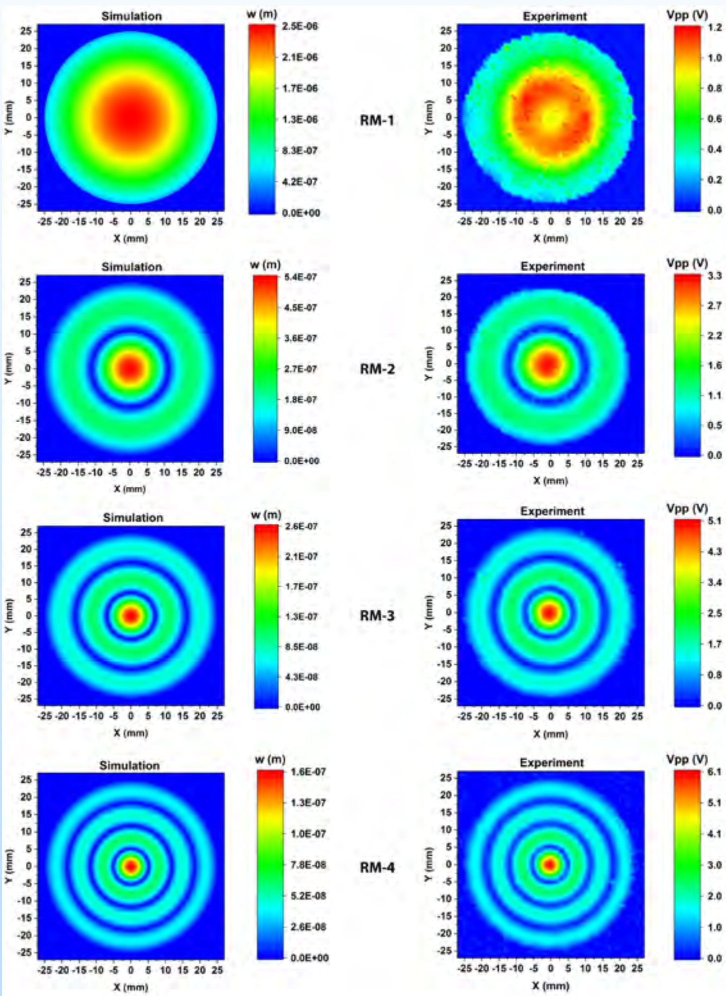
Young's Modulus of Neat (0%) Class H Cement Comparison (w/c = 0.38)



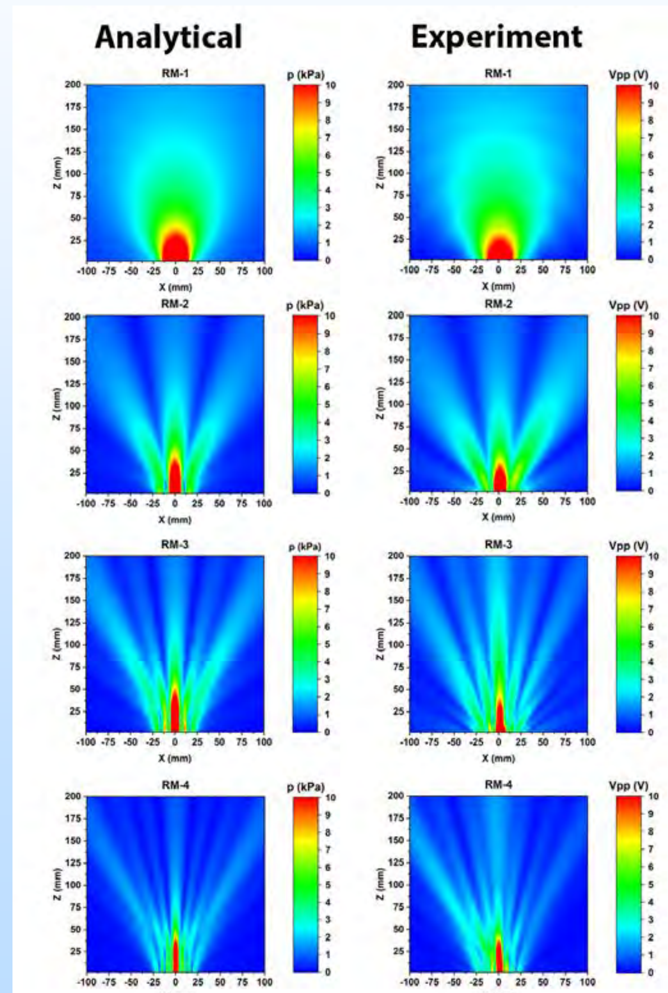
Effect of w/c ratio on Young's Modulus of Neat Class H Cement

Technical Status

Comparison of analytical and experimentally obtained out-of-plane displacement patterns of the radial modes

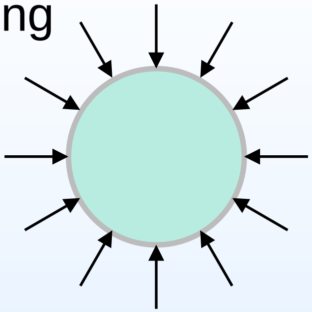


Comparison of analytical and experimentally obtained beam profiles from the radial modes

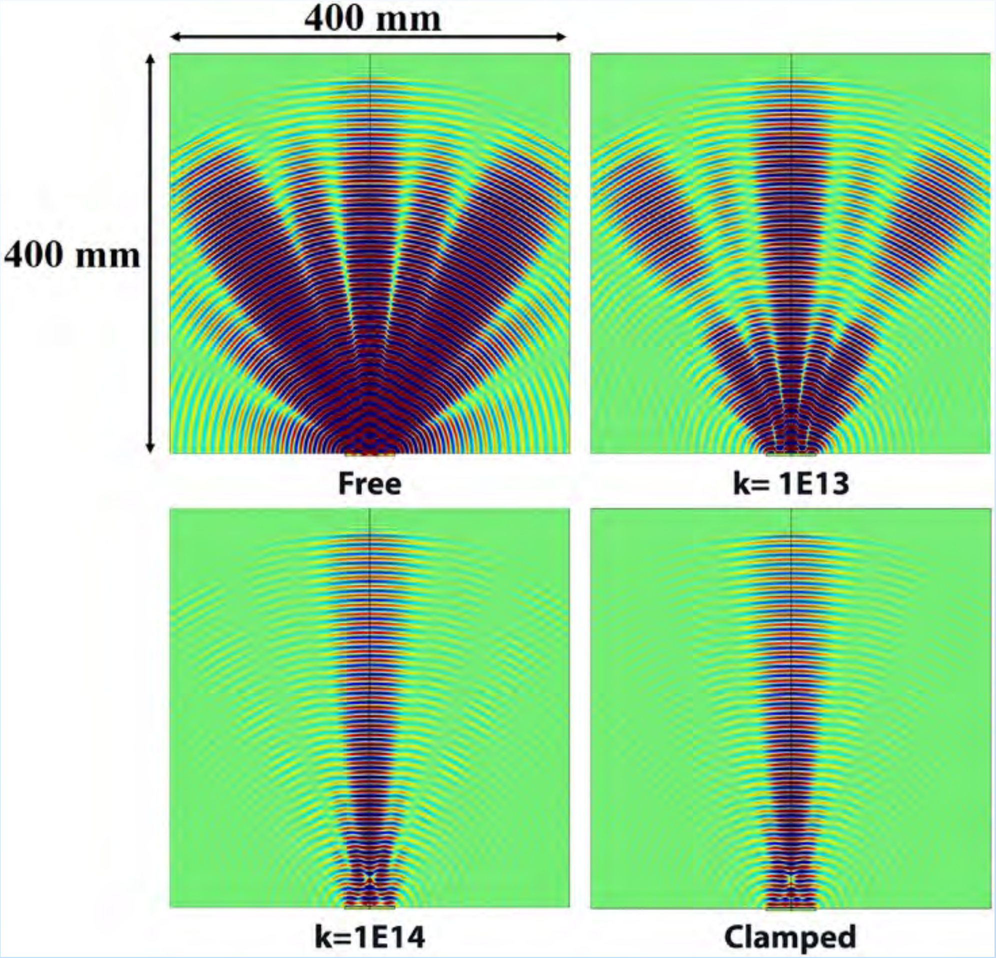


Technical Status

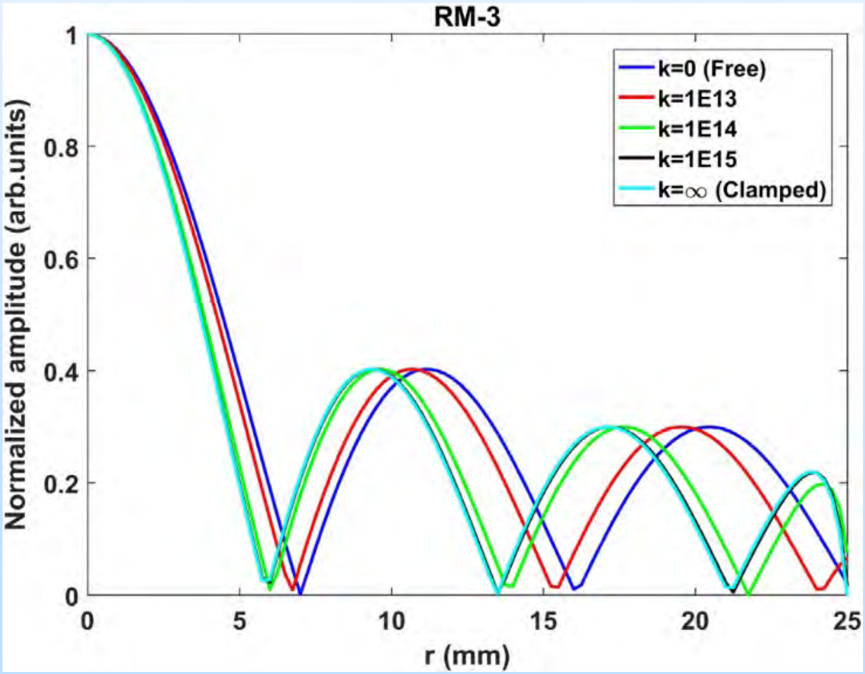
Effect of radial clamping on beam profile



Ultrasonic beam profiles in water generated by RM-3 at 161.8 kHz for different lateral stiffness k



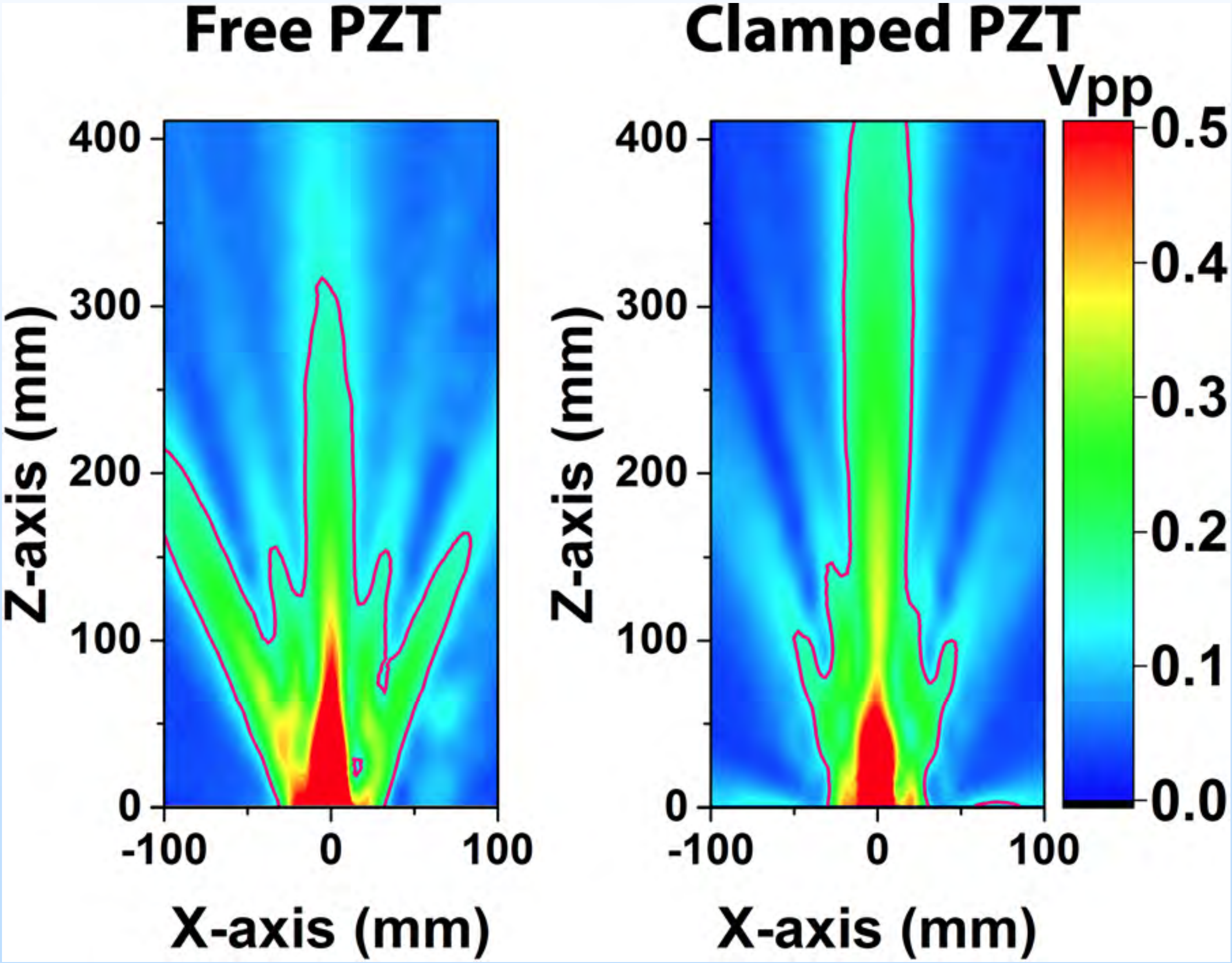
Normalized out-of-plane displacement on the surface of the disc for RM-3 for different lateral stiffness k (N/m3)



Wave Motion, vol. 76, (2018), pp. 19-27 and Proceedings of SPIE, vol. 10170, (2017), Article no. 1017024

Technical Status

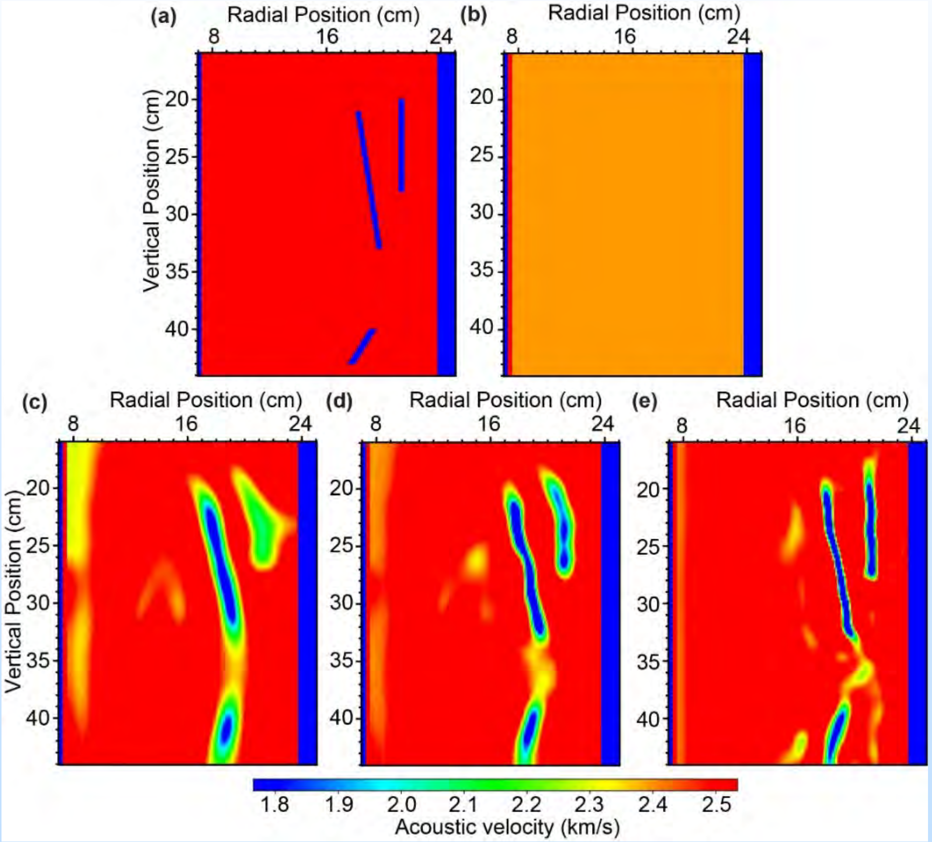
Beam profile in water for the 3rd radial mode RM-3; free transducer (left) and clamped transducer (right)



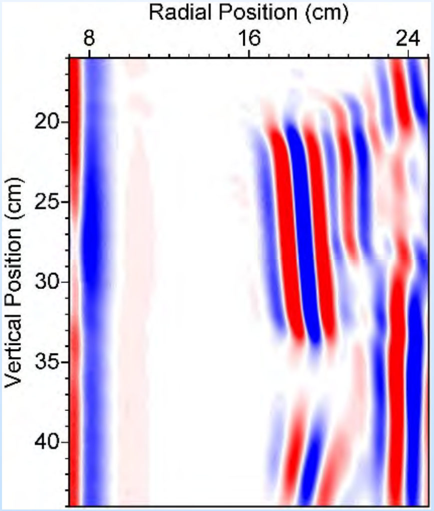
Appl. Phys. Lett., vol. 110, issue 6, (2017), 064101

Technical Status

Experimental concrete barrel with LANL's 3D imaging prototype in a borehole located at the center of the concrete barrel

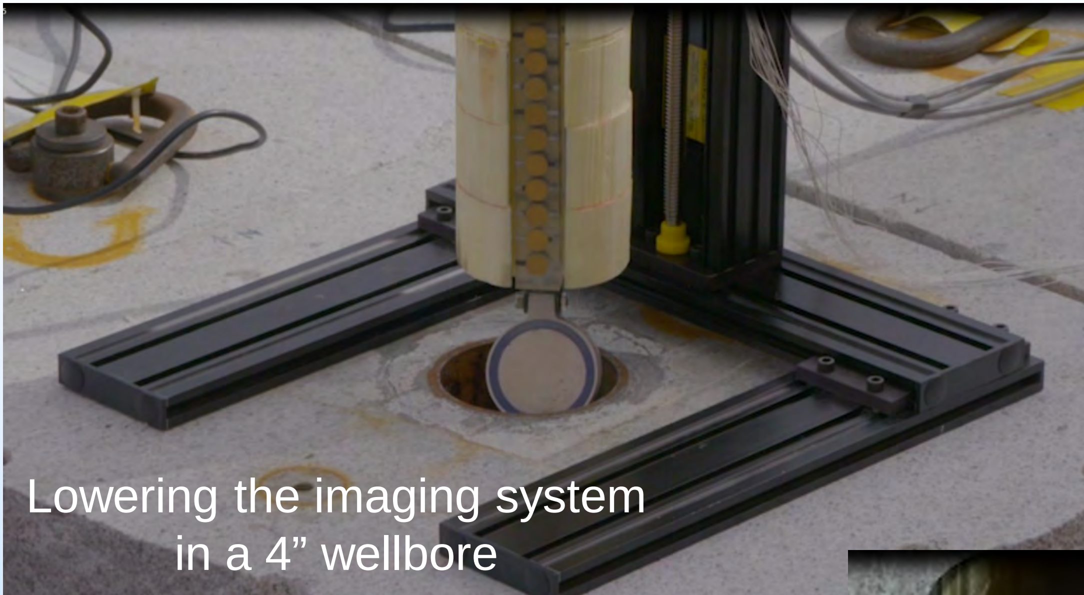


(a) Velocity model based on experimental data; (b) Initial velocity model used for full-waveform inversion; (c-e) Results of full-waveform inversion obtained using the center frequencies of 29 kHz (c), 42 kHz (d), and 58 kHz (e).

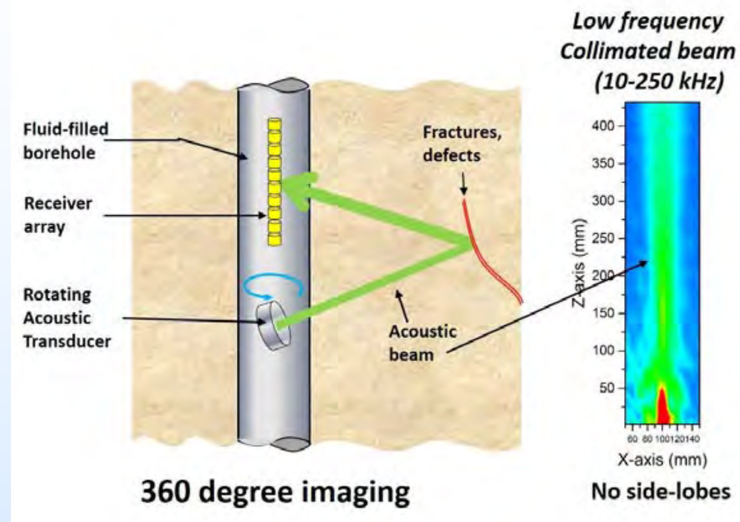


Least-squares reverse-time migration image obtained using synthetic ultrasonic data and the velocity model of full-waveform inversion

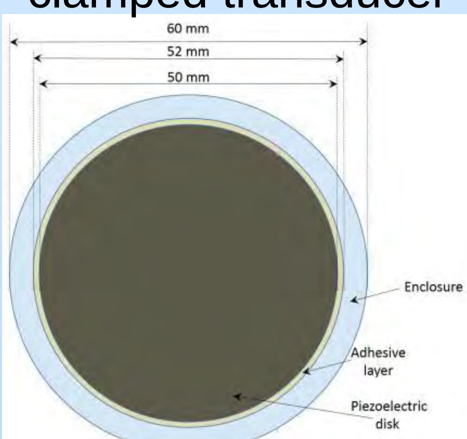
Technical Status



Lowering the imaging system in a 4” wellbore



Drawing of front face of clamped transducer



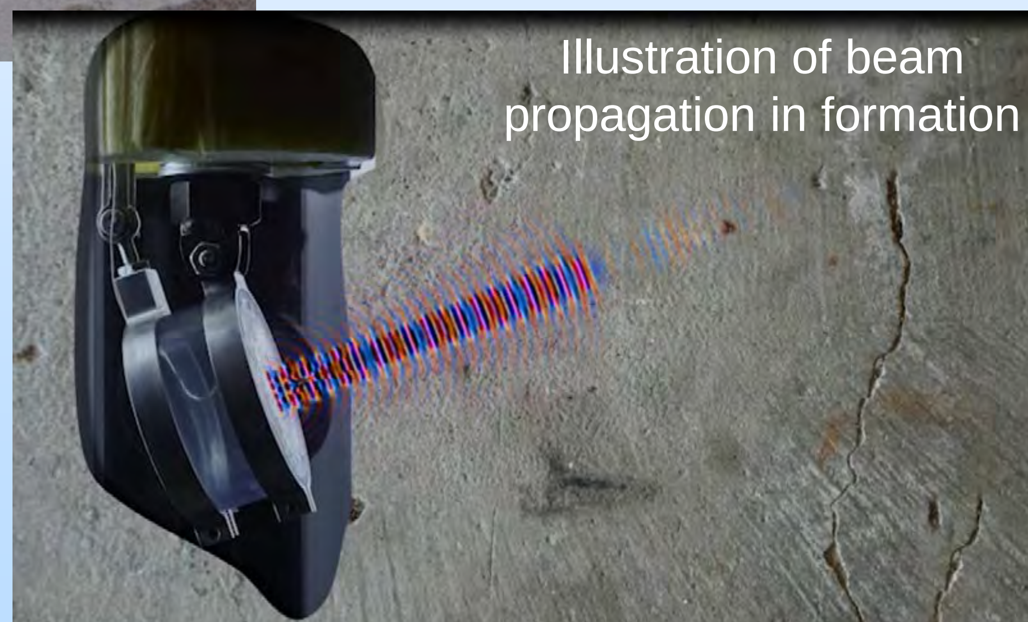
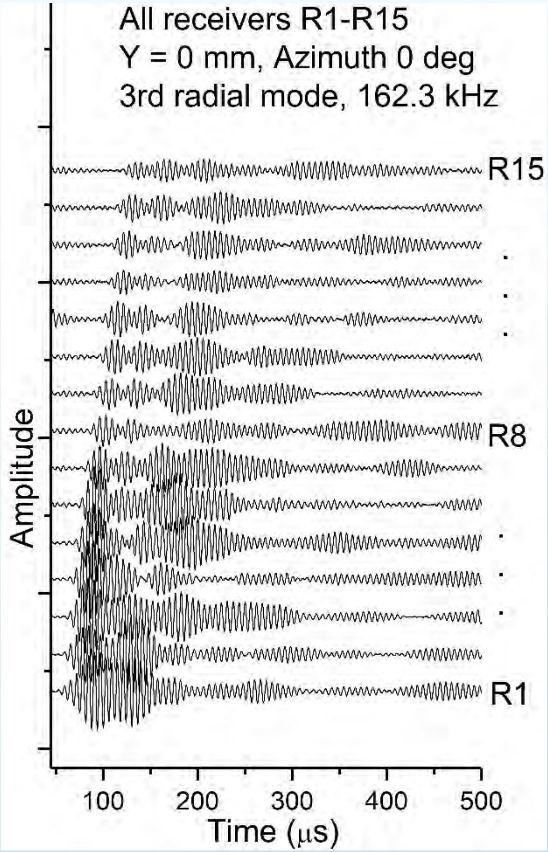
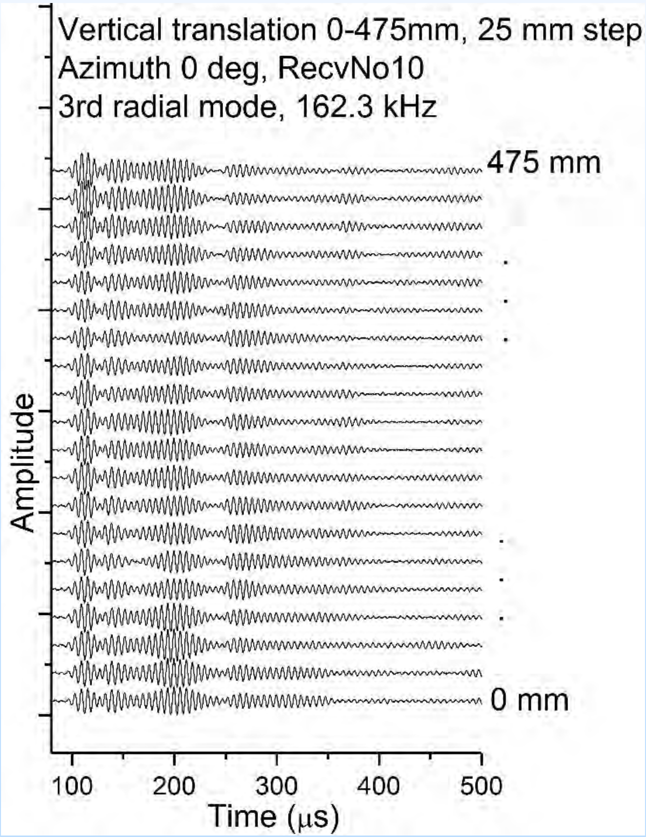


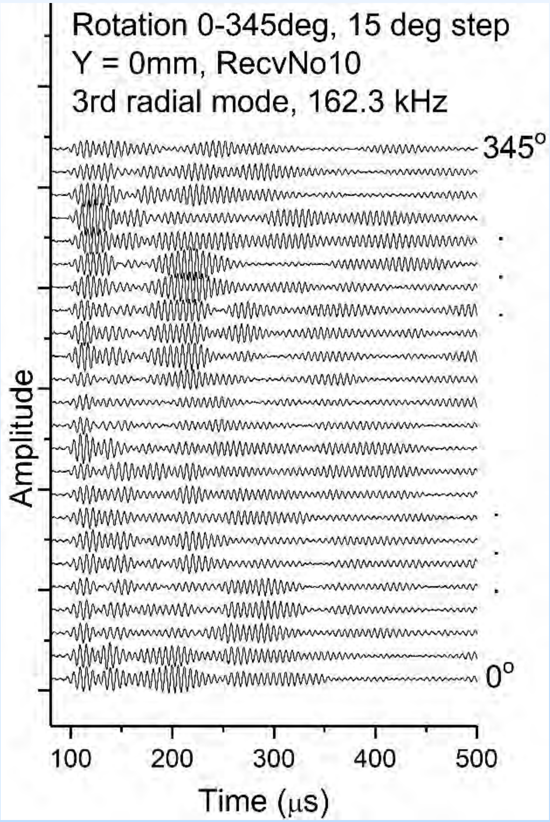
Illustration of beam propagation in formation

Technical Status

Performed quick scans on granite blocks
360 deg rotation, and 475 mm vertical span
15 deg and 25 mm step size







Accomplishments to Date

- Performed a comprehensive literature/existing technology study for wellbore integrity monitoring tools
- Identified potential partner for further developing the proposed technique
- Refined hardware (ACCObeam – Acoustic Collimated beam)
- Refined software for faster measurement and analysis
- Performed theoretical prediction on foamed cement Young's modulus with different hydration degrees
- Started acquiring data in granite with embedded defects (wall thinning, casing eccentricity, channeling, delamination)

Lessons Learned

- Research gaps/challenges.
  - Small issues with hardware packaging for experiments in granite
- Unanticipated research difficulties.
  - N/A
- Technical disappointments.
  - N/A
- Changes that should be made next time.
  - Closer interaction with technical members of the team

Synergy Opportunities

Possible future collaboration identified in several different areas of interest to the CO_2 sequestration/FE community: Hydraulic Fracturing/Simulation Diagnostics, Intelligent Monitoring Systems/Integration, Associated CO_2 Storage, Well Integrity and Zonal Isolation, Geophysics for CO_2 Storage, Oil and Gas Fundamental Science, Geomechanics for CO_2 Storage, Wellbore Integrity and Mitigation, etc.

For this session, "Well Integrity and Zonal Isolation":

– Nonlinear Acoustic Methods for the Detection and Monitoring of CO_2/Brine Leakage Pathways in Wellbore Systems - Los Alamos National Laboratory- Carly Donahue (Rice)
  - Combination of linear acoustic/imaging data with nonlinear acoustics can lead to complementary information for better characterization of leakage pathways in wellbore systems.

– Embedded Sensor Technology Suite for Wellbore Integrity Monitoring - National Energy Technology Laboratory - Paul Ohodnicki (Albenze)
  - Embedding a system of low-frequency collimated beam transmitter-receiver can help in identification of certain types of defects. Improved investigation range and lateral resolution are the key advantages of our imaging system.

– Autonomous Monitoring of Wellbore Integrity Applying Time Reverse Nonlinear Elastic Wave Spectroscopy (TR NEWS) and Fiber Optic Sensing and Communication – LANL - Paul Johnson (Rice)
  - Complementary information can be obtained, with improved range and resolution. That implies additional adaptation for integration of our system in an autonomous system.

Project Summary

– Key Findings:
  - There are no commercial acoustic sources that provide a collimated beam over a frequency range of 10–250 kHz in a small package that works in different media
  - Developed robust operation software, speeding up data collections to a factor of at least 10 times
  - Developed improved acoustic source, significantly more powerful than its predecessor (which was based on nonlinear acoustics)

– Next Steps:
  - Further refine acoustic source for deeper penetration
  - Enhance receivers sensitivity
  - Image processing and technique refinement for faster collection/analysis
  - Enhance capabilities for foamed cements

Publications

– Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903
– Wave Motion, 2018, vol. 76, p. 19-27
– Appl. Phys. Lett., 2017, v. 110, issue 6, p. 064101
– Proceedings of SPIE, 2017, v. 10170, p. 1017024
– 1 manuscript in preparation (sandstone characterization)

– 1 conference paper in print – Rock Mechanics
– 1 conference paper submitted – Nondestructive Evaluation

– 1 non-provisional patent (Resonance-based Nonlinear Source)
– 1 non-provisional patent (Bessel-like Acoustic Source)
– 1 provisional patent (Imaging Technique with Low-frequency Beam)

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Project benefits statement:

  The research project is developing a Borehole Integrity Monitoring System to reduce the risk of release of CO_2 around the well casing and cement. The technology, when successfully demonstrated, will provide an improvement over current wellbore diagnostics and integrity assessment techniques. This technology contributes to the Carbon Storage Program's effort of improving reservoir storage efficiency while ensuring containment effectiveness.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - The main objective of this project is to develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment, with the ultimate goal to develop a commercially deployable technology.
  - Wellbore integrity monitoring and characterization of the near wellbore environment are in need of novel technologies for better, faster and safer characterization methods. Some of the goals of these methods are: (1) improved resolution, (2) extended characterization range, and (3) in-situ/real-time monitoring. We are planning to work in parallel to address all these three requirements, such that we can provide a complete solution for wellbore diagnostics and integrity assessment.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives:
    - We are looking into providing a complete solution for wellbore diagnostics and integrity assessment. As mentioned on a previous slide, this technology contributes to the Carbon Storage Program’s effort of improving reservoir storage efficiency while ensuring containment effectiveness.

Project Overview

Goals and Objectives

- Project goals and objectives in the Statement of Project Objectives.
  - Identify the success criteria for determining if a goal or objective has been met:
    - Identified and assessed existing commercial technology.
    - Determined resolution for channeling outside casing.
    - Performed successful tests on wellbores with foamed cements, with similar resolution as for neat cements.
    - Progress toward tool ruggedization for work in adverse conditions.
    - Demonstrated progress toward experimental technique and image processing refinement.
    - Improved detection range through foamed cements (these are more attenuating than neat cements).
    - ***Final success metrics**: Prototype in field functionality similar to the one observed in tests in the laboratory.*

Organization Chart

- Describe project team, organization, and participants.
  - LANL: Develop acoustic source, imaging system, and image processing.
  - NETL: Investigate acoustic metrics for foamed cements. Incorporate new metrics for wellbores in the field.
  - ORNL: Explore different image processing approaches.
  - SNL: Perform experiments in more realistic boreholes. Incorporate data from realistic borehole and compare resolution with lab experiments.

Gantt Chart

Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Phase 1 - Feasibility study												
Task 1 – Investigation of existing technology		M2										
Task 2 – Define metrics	M1											
Task 3 – Industry partners/technology maturation plan												
	GoNoGo1											
Phase 2 - Evaluate method on more complex wellbore environments												
Task 1 - Channeling outside casing			M3									
Task 2 - Hardware/software refinement												
Task 3 - Speed-up measurement & analysis												
Task 4 - Method testing on more complex wellbore environments				M4								
Task 5 - Foamed cements manufacturing												
Task 6 - CT of foamed cements												
Task 7 - Acoustics metrics of foamed cements												
Task 8 - Tests on simulated wellbores with foamed cements				M4								
			GoNoGo2									
Phase 3 - Extend method beyond wellbore												
Task 1 - Acoustic source improvement					M5							
Task 2 - Receivers enhancement												
Task 3 - Ruggedized tool							M7					
Task 4 - Image processing refinement						M6						
Task 5 - Technique refinement								M8				
Task 6 - Enhance capabilities for foamed cements												
							GoNoGo3					
							GoNoGo4					
Phase 4 - Technology Development and Verification												
Task 1 - Prototype development									M9			
Task 2 - Prototype verification at lab scale and in field											M11	
Task 3 - Hardware/software enhancement and refinement										M10		

Go/No-Go1 (end Q2Y1)
Tabulate commercial 3D imaging techniques for borehole integrity
- no commercial technologies for high-res 3D imaging technology with similar depth of penetration (~3 m) and resolution (< 5 mm)

Go/NoGo2 (end Y1)
Detect defects at the cement-formation interface, with high resolution- defects detection at the cement-formation interface with a resolution of at least 5 mm

Go/No-Go3 (end Y2)
Tool survival in adverse conditions of corrosiveness, high temperature and high pressure (brines, 250°C, 45 kpsi)
- imaging system can survive in adverse conditions of temperature, pressure and corrosiveness

Go/No-Go4 (end Y2)
Imaging capabilities out in the formation, up to 3 meters
- defects/features (up to ~ 3m) can be resolved in the received signal

Legend shaded areas:
Completed
In works

Bibliography

Peer reviewed publications generated from the project:

- Chen, Y., Gao, K., Davis, E.S., Sinha, D.N., Pantea, C., and Huang, L., 2018, Full-waveform inversion and least-squares reverse-time migration imaging of collimated ultrasonic-beam data for high-resolution wellbore integrity monitoring. Appl. Phys. Lett., v. 113, issue 7, p. -, available at: aip.scitation.org *in print*

- Chillara, V.K., Pantea, C., and Sinha, D.N., 2018, Radial modes of laterally stiffened piezoelectric disc transducers for ultrasonic collimated beam generation. Wave Motion, vol. 76, p. 19-27, available at: www.sciencedirect.com/science/article/pii/S0165212517300938

- Chillara, V.K., Pantea, C., and Sinha, D.N., 2017, Low-frequency ultrasonic Bessel-like collimated beam generation from radial modes of piezoelectric transducers. Appl. Phys. Lett., v. 110, issue 6, p. 064101, available at: aip.scitation.org/doi/10.1063/1.4975800

- Chillara, V.K., Pantea, C., and Sinha, D.N., 2017, Coupled electromechanical modeling of piezoelectric disc transducers for low-frequency ultrasonic collimated beam generation. Proceedings of SPIE, v. 10170, p. 1017024, available at: spie.org/Publications/Proceedings/Paper/10.1117/12.2262195