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Report May 2018 - High-Resolution 3D Acoustic Borehole Integrity Monitoring

Quarterly Research Performance Progress Report

Federal Agency and Organization: Office of Fossil Energy (FE); National Energy Technology Laboratory (NETL); Geologic Storage Technologies

Recipient Organization: [Los Alamos National Laboratory](#)

Project Title: [High-Resolution 3D Acoustic Borehole Integrity Monitoring](#)

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EXECUTIVE SUMMARY

SubTER Topic 1. Wellbore Diagnostics and Integrity Assessment

Real-time, in-situ, high spatial resolution (sub-cm) imaging of the near-borehole environment would revolutionize wellbore diagnostics and integrity assessment by direct observation of defects. It is becoming increasingly apparent, that better understanding of the near-wellbore environment is required to meet the safety and operational needs in challenging environments such as those present in subsurface energy extraction (geothermal) and storage (CO₂ sequestration) applications. Therefore, it is important to have a more robust ability to image the near-borehole and reliably detect defects.

It was proposed to further develop and improve our advanced 3D imaging system to evaluate casing defects (e.g. corrosion) and cement quality in either open- or cased-borehole with the ultimate goal to develop a commercially deployable technology. The system consists of a unique acoustic source (LANL) and advanced inversion techniques for image processing (LANL, ORNL). This system will provide comprehensive borehole integrity monitoring with improved resolution over existing techniques. As an application of this imaging system, we will characterize the effectiveness of next-generation wellbore completion technology (NETL, SNL), and will demonstrate that, unlike current technology, the proposed approach can successfully characterize foamed cements.

The first 6 months of the project were dedicated to Phase 1: Feasibility study. Assess feasibility of the high-resolution 3D imaging technique for wellbore integrity applications, across multiple industries (geothermal, CO₂ sequestration, oil & gas, nuclear repository).

ACCOMPLISHMENTS & MILESTONE UPDATE

Project Status Summary:

Task	Title	Planned Completion Date	Completion Date or % completion
1	Investigation of existing technology	03/31/2018	100%
2	Define metrics	03/31/2018	100%
3	Industry partners/technology maturation plan	03/31/2018	100%

Task 1. Investigation of existing technology

1. Planned Activities:

Baseline performance of existing technologies, validated through elicitation of industry input, case studies, and/or literature review.

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2. Actual Accomplishments:

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

Literature study:

Wellbore integrity is crucial for geothermal energy production. It is necessary to monitor wellbore integrity throughout the life cycle of production/injection wells. The existing techniques for wellbore integrity monitoring include optical, electrical and acoustic imaging.

Optical imaging uses photographic camera for visual inspection and recording of downhole completion conditions [Prensky, 1999]. It is capable of directly obtaining a high-resolution color image of the wellbore wall for fracture identification or casing inspection. The direct-imaging technology has only limited use because of the operational requirement of a transparent borehole fluid or in air holes, which are often impractical. The other drawback of optical imaging is that the technique can detect only fractures on the inner surface.

Acoustic imaging makes use of acoustic reflectivity to detect the changes of surface roughness and fractures in the wellbore wall. Acoustic waves travel through the drilling fluid and undergo partial reflections on the borehole wall. Reflected pulses are received by a transducer. The amplitudes and travel times of the reflected pulses are influenced by several factors, such as fractures, vugs, breakouts on the borehole walls, and acoustic impedance between the fluid and the borehole walls [Zemanek et al., 1970; Massiot et al., 2015]. The wellbore televiewer can provide a 360° image in an open or cased hole. The principle limitation of current state-of-the-art of this technique is that it uses only acoustic reflections, and can detect only the inner surface of the wellbore walls.

Electric imaging identifies fractures by contrasts in conductivity between the fracture and the adjacent borehole wall. The images are produced by placing pads with arrays of electrodes maintained at a constant electrical potential against the borehole wall, and measuring the current drop as the electrodes travel along the borehole wall. Data from multiple electrodes are combined to produce electrical conductivity images [Davatzes and Hickman, 2005]. Electric imaging tools have proved superior to the acoustic imaging in the identification of some structural features and rock properties in depth. However, acoustic imaging can reveal a higher resolution on the wellbore surface [Davatzes and Hickman, 2005].

A more streamlined table is presented in **APPENDIX A**, in a comparison table. Only three main competitors are presented, with a detailed comparison of different parameters of interest, e.g. frequency, collimation resolution.

Tools available on the market:

Technique	Company	Range	Frequency	Resolution	Notes
FMI – Fullbore Formation Microimager	Schlumberger	30 inches	N/A	5 mm both	Temp 175 C/pressure 20 ksi/ 80% of borehole in 8 inch hole coverage

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IBC – Imaging Behind Casing	Schlumberger	Casing-formation interface	~200 kHz	102 mm vert 30 mm azimuth	Good for low-impedance cements/ produces SLG maps / can possibly see casing position within borehole
CBL – Cement Bond Log (multiple tools)	Schlumberger	Casing-cement interface	20 kHz	Poor - ~.91m	Mostly for evaluation of cement-casing interface/ 260 C / 30 ksi
USI – Ultrasonic Imager	Schlumberger	Casing-cement interface	200 – 700 kHz	30 mm lateral ² 15.24 cm vert	177 C/ 20 ksi
UBI – Ultrasonic Borehole Imager	Schlumberger	Full Borehole, all standard sizes	250, 500 kHz	“high”	Not influenced by mud type, advanced software
OBMI – Oil-Based MicroImager	Schlumberger	3.5 in	N/A	Features as small as 1 cm	Microresistivity imaging in nonconductive oil-based systems
ARI – Azimuthal Resistivity Imager	Schlumberger	~100 in?	N/A	8 inches vert/ 60° azimuth angle for 1 inch standoff	177 C/ 20 ksi/ resistivity
AIT - Array Induction Imager Tools (multiple)	Schlumberger	10-90 in	N/A	.61m or .30m smooth borehole	125 C- 260 C/ 15 – 30 ksi/ 3600 feet per hour log speed/ resistivity
Isolation Scanner Tool	Schlumberger	Casing and annulus up to 3 in	~200kHz	1.52 cm vert	177 C/ 20 ksi/ 563 feet per hour log speed
Sonic Scanner	Schlumberger	formation	wide	<1.82 m	177 C/ 20 ksi

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XMAC F1	Baker Hughes	100 feet	Low frequency dipole source	low	232 C/ 30 ksi/ 50 feet per minute log speed/ 4.5 in minimum borehole size/ features don't need to intercept borehole
Array Dielectric eXplorer formation evaluation service	Baker Hughes	6 in	N/A (“multiple”)	3 in	150 C/ 20 ksi/ Mostly for determining mobility of oils and porosity values as well as hydrocarbon saturation/ Acquires permittivity and conductivity data/ 5.875 inch min borehole diameter
High-Resolution Vertilog	Baker Hughes	5.3 in to 9.425 in depending on hole diam (casing tool)	N/A	?	175 C/ 15 ksi/ Uses Hall effect sensors for magnetic flux leakage detection/ has minimum operating distance from tool
Digital MagneLog (DMAG)	Baker Hughes	Casing	multi	?	Designed to detect wall thickness changes by measuring magnetic field shift
Acoustic Cement Bond Log	Baker Hughes	Casing-Cement Interface	?	?	177 C/ 17 ksi/ 2.38 in min casing
Imaging Caliper Log	Baker Hughes	Casing	N/A (mechanical)	.003 in azimuth .14 in vertical at 11 $\frac{11}{16}$ in casing	150 C/ 15 ksi/ resolution strongly dependent on borehole size. Listed resolution is best, worst is .013 in azimuth, .28 in vertical

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					when casing is 8 inches.
Segmented Bond Tool (SBT)	Baker Hughes	Casing-Cement interface	Ultrasonic range	3 in vertical	177 C/ 20 ksi/ Insensitive to heavy borehole fluids and moderate tool eccentricity
Radial Analysis Bond Log (RAL)	Baker Hughes	Casing-Cement Interface	?	Similar to other CBL	177 C/ 20 ksi/ can detect microannulus
Integrity eXplorer Cement Evaluation	Baker Hughes	Casing-Cement Interface	?	?	177 C/ 20 ksi/ electromagnetic-acoustic transducer sensor/ the service can provide measurements in air-filled boreholes and gas-cut mud systems/ 4.5 in minimum casing size
STAR Imager	Baker Hughes	Into Reservoir ?	N/A	.2 inch both	177 C/ 20 ksi/ Conductive mud only, resistivity imaging/ 6 in min borehole/ EARTH imager does oil-based muds
Circumferential Borehole Imaging Log	Baker Hughes	?	250 kHz	?	3.625 in diameter tool/ https://www.bakerhughes.com/products-and-services/evaluation/openhole-wireline-services/geology/circumferential-borehole-imaging-log
Ultrasonic Explorer Imaging Service	Baker Hughes	?	250 kHz	“high”	177 C/ 20 ksi/ 4.5 in min borehole size

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GeoXplorer Imaging Service	Baker Hughes	Near-wellbore	N/A	.8 in vert .3 in azimuth	177 C/ 25 ksi/ Nonconductive mud systems/ 7 in min borehole/ 79% in an 8-in. (203-mm) borehole coverage
Wellbore Geometry Instrument (WGI) Measurement Service	Baker Hughes	Casing only	N/A	1 in vert	
MR eXplorer	Baker Hughes	2.1-3.8 in	~500-1000 kHz (magnetic resonance)	high	175 C/ 20 ksi/5.875 in min borehole size/ Targeted towards permeability and porosity measurements and characterize oil
Circumferential Acoustic Scanning Tool (CAST)	Halliburton	Casing and Cement	?	1.8° azimuth openhole 3.6° casedhole, .3 in vert	175 C/ 20 ksi/ 5 in borehole min/ DeepSuite CAST-XR 35 ksi
Multifinger Imaging Tool (MIT)	Halliburton	Casing	N/A	?	177 C/ 20 ksi/ resolution similar to competitors, completely mechanical
Acoustic Conformance Xaminer® (ACX™)	Halliburton	Casing and Cement?	?	high	Used to triangulate leak sources
Electromagnetic Pipe Xaminer® V (EPX™ V) Tool	Halliburton	Casing only	N/A	.015 inch accuracy defect detection	177 C/ 15 ksi/ Used exclusively to characterize extent of damage in casing after already being picked up by another method

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Xaminer® Sonic Imager Service (also Full Wave Sonic Tool (FWS))	Halliburton	formation	low?	Low?	177 C/ 20 ksi/ Measures formation p-wave velocity using farthest-spaced monopole/ Mostly measures slowness
Radial Cement Bond Log (RCBL™)	Halliburton	Cement-Formation Interface	?	?	Similar capabilities to other CBL tools
SPACE Panorama	Archer	Casing	3.5 MHz	.39 in vert 1.25° azimuth	150 C/ 15 ksi
ABI-40 Televiewer/WellCAD	Advanced Logic Technology	2" to 20" diameter depending on mud conditions	~1.2MHz	Caliper Resolution: 0.08 mm	Logging Speed: 3 to 24 ft/min Samples/revolution: up to 360

3. **Explanation of Variance:** N/A

4. **Plans for Next Quarter:** Task 1, *Investigation of existing technology*, is complete. However, if anything new shows up on the market, we will perform the same comparison between our technology and any new one.

Task 2. Define metrics

1. **Planned Activities:**

Identify key performance metrics that will be used to judge success in subsequent phases of the project.

2. **Actual Accomplishments:**

Identified key performance metrics, defined previously in the proposal.

Year 1

3rd quarter progress measure: Determined resolution for channeling outside casing.

4th quarter progress measure: Performed successful tests on wellbores with foamed cements, with similar resolution as for neat cements.

Phase 2 SMART milestone – Go/No-Go2 (end of year 1): Detect defects at the cement-formation interface, with high resolution (5 mm, or better). Key technical risk: acoustic signal can get trapped in the metal casing, which can lead to minimal acoustic energy transmission behind the casing. Risk minimization: we are using an acoustic source with unique properties (recently patented, with more patents pending). We proved in the past that our low frequency collimated acoustic beam, with the right choice of frequencies (avoiding tube modes), can penetrate successfully through metal casing, and we are planning to further improve the source, and also the receivers, for better signal-to-noise

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ratio. *Success metric:* defects detection at the cement-formation interface with a resolution of at least 5 mm.

Year 2

2nd quarter progress measure: Progress toward tool ruggedization for work in adverse conditions.

3rd quarter progress measure: Demonstrated progress toward experimental technique and image processing refinement.

4th quarter progress measure: Improved detection range through foamed cements (these are more attenuating than neat cements).

Phase 3 SMART milestone (end of year 2): Go/No-Go3: Tool survival in adverse conditions of corrosiveness, high temperature and high pressure (brines specific to geothermal wells, at temperatures of at least 250C, and high pressures of 45 kpsi); Go/No-Go4: Imaging capabilities out in the formation, up to 3 meters. Key technical risk 1: tool cannot survive the adverse conditions of corrosive media, high temperature and high pressures. Risk 1 minimization: in the past, we have developed an acoustic-based sensor that can withstand the aforementioned adverse conditions, and we are planning to leverage on the past knowledge. Key technical risk 2: limited penetration in the formation. Risk 2 minimization: we are planning (tasks 1 and 2), to further enhance the acoustic source and the receivers, such that (1) more power can be transmitted in the formation, and (2) smaller/noisier signal can be detected. Success metric 1: imaging system can survive in adverse conditions of temperature, pressure and corrosiveness. Success metric 2: defects/features (up to ~ 3m) can be resolved in the received signal.

Year 3

2nd quarter progress measure: 1st version of the prototype is functional in laboratory tests.

Final success metrics:

Prototype in field functionality similar to the one observed in tests in the laboratory.

3. **Explanation of Variance:** N/A
4. **Plans for Next Quarter:** This task, *Define metrics*, is complete. If any additional input is received, either from collaborators, the program side, or competition, this will be taken into account and will be incorporated in our technology.

Task 3. Industry partners/technology maturation plan

1. Planned Activities:

Identify industry partners and use cases for the tools to be further developed in subsequent phases, and provide a technology maturation plan.

2. Actual Accomplishments:

Identified Chevron as potential future partner for further developing the proposed technique. Obtained Support Letter from Chevron, on two different occasions: once when the proposal was submitted, and when we submitted an R&D100 application.

Technology maturation plan is reflected in the work proposed in the third year:

- Develop an engineering prototype. The prototype has to meet the standards required for CO₂ sequestration and geothermal industry, in terms of resistance

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- to corrosion, high temperature and high pressure.
 - Develop robust operation & analysis software, for near real-time 3D imaging by speeding up the measurement and analysis process.
3. **Explanation of Variance:** N/A
 4. **Plans for Next Quarter:** N/A. Work towards Technology Maturation will be performed in the third year.

PROJECT MANAGEMENT

Issues, Risks, and Mitigation (If Applicable): N/A

Changes in Approach (If Applicable): N/A

Key Personnel (If Applicable): N/A

Recipient Requests for DOE Attention (If Applicable): N/A

PROJECT OUTPUT

Publications (If Applicable): N/A

Technologies/Techniques (If Applicable): The main focus of this project is the development of a unique acoustic source that consists of a collimated beam of low frequency, with a bandwidth between 10 and 150 kHz. The source will be able to rotate azimuthally for 360 deg, move vertically along the borehole, and vary angle of incident beam with respect to borehole axis, such that the environment around the borehole is fully investigated. The acoustic source, incorporated in a logging tool, equipped with appropriate receivers, can provide information in several areas: mapping of the borehole shape and borehole casing, cement bond quality logging, mapping of the area around the borehole, fault detection, fracture detection, porosity mapping, fluid saturation mapping, fluid flow paths, etc.

Status Reports (If Applicable): N/A

Media Reports (If Applicable): N/A

Invention Disclosures (If Applicable): N/A

Patent Applications (If Applicable): submitted patent on low-frequency collimated acoustic source: SIMPLE BESSEL-LIKE COLLIMATED SOUND BEAM GENERATOR

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Licensed Technologies (If Applicable): [N/A](#)

Networks/Collaborations Fostered (If Applicable): [N/A](#)

Websites Featuring Project Work or Results (If Applicable): [N/A](#)

Other Products (If Applicable): [N/A](#)

Awards, Prizes, and Recognition (If Applicable): [N/A](#)

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APPENDIX A – COMPARISON MATRIX

Parameter	ACCObeam	Standard borehole sonic probe, e.g. BARS SCHLUMBERGER	Ultrasonic probe, e.g. UBI SCHLUMBERGER	SPACE Panorama ARCHER
Frequency	10-250 kHz	0.3-8 kHz	250, or 500 kHz	3.5 MHz
Comments: Low frequency is needed for deeper penetration, but conventional low-frequency sources have a very large beam spread, which decreases resolution. Our approach provides a low-frequency beam that is still collimated and has no side lobes.				
Penetration Range	3 m	15 m	Casing (< 10 mm)	Casing only
Comments: ACCObeam is collimated and has a much longer investigation range than other high-frequency sources, which leads to good understanding of both the borehole and the surrounding environment. Although it does not currently penetrate as far as standard probes, ACCObeam's collimation means that it surpasses standard probes in critical ways, namely imaging resolution (ACCObeam's resolution is 60-100 times better than standard sonic probes) and power efficiency. ACCObeam is also adaptable for numerous other applications.				
Resolution	3-5 mm	300 mm	4-5 mm	10 mm
Comments: ACCObeam has the deep penetration advantage of a low-frequency source, but it maintains the same resolution as higher-frequency sources. This resolution is critical because even small fractures, delaminations, and other defects can lead to catastrophic failure of a borehole.				
Collimation	< 6 deg	Monopole/dipole >180 deg	< 15 deg	< 6 deg
Comments: Our source has a very similar collimation/beam spread as its high-frequency competitors, even though it generates a low-frequency beam that penetrates much deeper than any high-frequency source. Please note the huge difference when compared with the standard borehole sonic probe.				
Cost	\$	\$\$\$\$	\$\$\$\$	\$\$\$\$
Comments: All other products are offered as a service/package operated by a specific company, so the cost of using their source is thousands of dollars. ACCObeam costs \$50-\$200 to manufacture and is compatible with virtually any imaging software or hardware.				
Imaging through highly attenuating materials	Y	Y	N	N
Comments: The only other product able to image clearly and beyond casing in highly attenuating media (such as concrete, drilling mud, rock, and bone) is the low-frequency standard borehole sonic probe.				

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However, standard probes have an extremely low spatial resolution and can miss important small features. On the other hand, our source works well in highly attenuating media while maintaining the resolution characteristic of high frequency.				
Parameter	Your product	Standard borehole sonic probe, e.g. BARS Schlumberger	Ultrasonic probe, e.g. UBI Schlumberger	SPACE Panorama Archer
Size	Small/compact	Large	Small/compact	Small/compact
Comments: ACCObeam is similar in size to high-frequency sources, but much smaller than a typical low-frequency source.				
Collimated beam at multiple frequencies	Y (several)	N	N	N
Comments: The UBI ultrasonic probe can provide either a somewhat collimated 250 kHz beam or a more collimated 500 kHz beam, but our source images at numerous frequencies ranging from 10–250 kHz while maintaining a tight collimation.				
Simple manufacturing process	Y	N	N	N
Comments: ACCObeam's design requires radial clamping, achieved by gluing a piezoelectric transducer into casing made of any strong material. Comparative technologies require filler material and a small matching inductor for "loading" the back of the transducer, making the packaging process more sophisticated.				
Images through various media	Y	N	N	N
Comments: No competing source can be used to image in assorted media. Since our source operates at a low frequency, it can transmit or receive in liquids, solids, gases, and air.				
Frequency hopping	Y	N	Y (limited)	N
Comments: ACCObeam supports as many as 4-10 frequencies, while the UBI has only two selectable frequencies.				

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