Development and Evaluation of a Forward-looking Acoustic Camera for Opaque Media Tested at High Temperature and High Pressure

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***Abstract* - A prototype forward-looking acoustic camera for imaging of objects in optically opaque media has been developed and evaluated. Its imaging capability has been successfully verified under simultaneous exposure to a temperature of 125 degree Celsius and a pressure of 720 bar. The current maximum imaging distance is 45 cm. The camera builds upon technology developed for the oil & gas industry, but has potential applications in a variety of optically opaque environments, e.g. downhole geotechnical mapping of subsea vents and subsea mining. The pressure performance is by far superior to the conditions that are expected in subsea hydrothermal vents while the current temperature performance is satisfying for a subset of vents.**

Keywords—acoustics; imaging; high temperature; high pressure; downhole

1. INTRODUCTION

The objective of this work was to develop a prototype forward-looking acoustic camera able to image objects in optically opaque media. The origin was the need of the oil and gas industry for visual information from wells that are optically opaque due to mud, oil and sand.

In-well operations such as drilling, completion, maintenance, intervention, and abandonment require a range of custom-made tools developed by the industry. Failures of these tools might often lead to obtrusion of the borehole. In many situations, it is advantageous to visually see the source of the problem. Video cameras utilizing the visible part of the optical spectrum for downhole inspection have been in use for many years [1] but can not perform in opaque media as often is the case in oil and gas wells. This lack of visual information may lead to a more costly and time-consuming operation and longer production downtime. This can ultimately result in total loss of the well.

Ultrasonic imaging is used for a number of applications for visualization of objects in opaque media [2]. The main challenge was to achieve good acoustic performance within the restraints imposed by the dimensions and operating environment (temperature, pressure, types of media), and implementation of the electronics (temperature).

Tools for acoustic downhole imaging (televiewers) have been available for several decades, but solely for imaging of the borehole wall. To our knowledge, no commercial forward-looking acoustic alternatives existed at the onset of the camera prototype development in 2004. Today acoustic televiewers are capable of high temperatures and pressures, and both sideways and forward-looking ultrasonic imaging tools are commercially available or under development [3]-[5]. Tools based on alternative technologies, such as backscatter X-ray, also exists [6].

Although the prototype was developed based on the needs of the oil and gas industry, a modified version of the downhole acoustic camera may have promising future applications in a variety of optically opaque environments encountered in subsea mining and for mapping of high temperature underwater structures such as hydrothermal vents [8]-[9].

2. DOWNHOLE ACOUSTIC CAMERA CONCEPT

The forward-looking camera prototype is shown in Fig. 1 with (a) a picture of the assembled prototype and (b) schematics. The tool has an outside diameter of 10 cm, a length of 216 cm, and a total weight of 85 kg. The battery container may be removed from the main body during shipping, if a length below 2 m required for e.g. helicopter transport.

The core of the downhole acoustic camera is an ultrasonic transducer for use under harsh conditions at high temperature and high pressure. A polymer-free single-element piezoelectric transducer with a pressure compensated hull was designed and constructed. The transducer operates in pulse-echo mode while being rotated in a spiral pattern by a swivel joint run by a stepping motor. This enables forward-looking 3D imaging with the single-element transducer.

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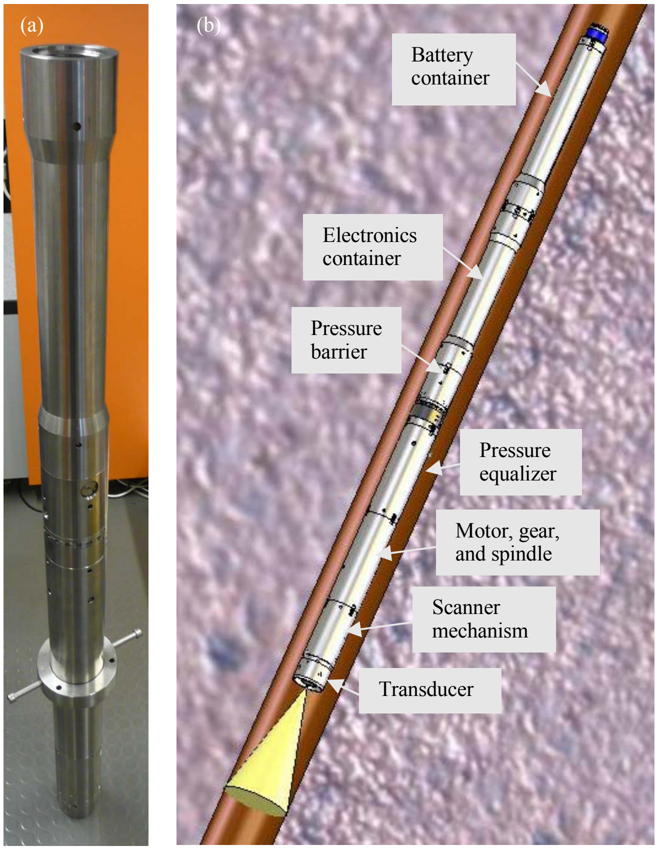

Fig. 1. The assembled prototype. (a) Picture of prototype without battery container, and (b) schematics of the Downhole Acoustic Camera prototype.

The prototype camera is designed for complete autonomous and battery-powered operation while attached to a simple slickline. The actual imaging procedure are pre-programmed. Collected image data are pre-processed and stored on board until the camera is retrieved after end of mission. The data are then uploaded to a computer for further processing. On-line capability through wireline requires only the addition of an appropriate physical connector. A custom image processing software (USCam) was developed in order to capture the transducer's pulse-echo signals and process them according to the actual transducer position in order to create a visualization of the volume in front of the camera.

Mechanical design of the downhole acoustic camera is heavily influenced by the design of the acoustic transducer. In order to protect the transducer from the harsh environment, the transducer is housed inside a dome at the front of the instrument. The dome is filled with a pressure-equalized, low-loss, acoustically transparent liquid. Seven sections make up the tool, the first three sections being the transducer, the scanner mechanism and the motor, gear, and spindle. These sections enable the transducer to rotate, so that it is able to scan in a spiral pattern. A pressure equalizer and a pressure barrier follows in order to separate the pressure compensated sections, i.e. the electronics and battery containers, from the pressure-equalized sections.

3. Transducer design

A. *Attenuation measurements*

The main advantage of an acoustic camera to conventional optic cameras for downhole imaging is their ability to successfully operate in opaque fluids. However, there are also challenges related to imaging in opaque fluids for acoustic cameras, due to the increased attenuation in such fluids compared to e.g. water. To estimate the performance of ultrasonic transducers in fluids commonly encountered in oil wells, acoustic attenuation tests were conducted on water, mud, brine and crude oil.

A schematic of the measurement system is shown in Fig. 2. The dedicated measurement cell was filled with the fluid under investigation and given time to degas and temper. A 20 cycles sine burst was generated by an HP 33120A signal generator, emitted into the fluid by a Panametrics 1'' immersion transducer and received at the other end of the measurement cell by an identical transducer, before the signal was amplified and bandpass-filtered by a Krohn-Hite 3940 filter, and recorded by a LeCroy Wavesurfer 424 oscilloscope. The separation distance between the two immersion transducers was 76 mm.

Two different sets of transducers were used in the attenuation measurements, with 0.5 MHz and 1 MHz peak frequency. All measurements were carried out in room temperature. The attenuation relative to water was estimated in crude oil, NaCl brine, KCl brine, water-based mud (WBM) and oil-based mud (OBM) by dividing the measured voltage with the corresponding measured voltage in water. Note that only an estimate of the attenuation was obtained, as for example the effect of the different acoustic impedances of the liquids on the emitted and received energy was not accounted for. The measurement results of both the 0.5 MHz and 1 MHz transducers are presented in Fig. 3.

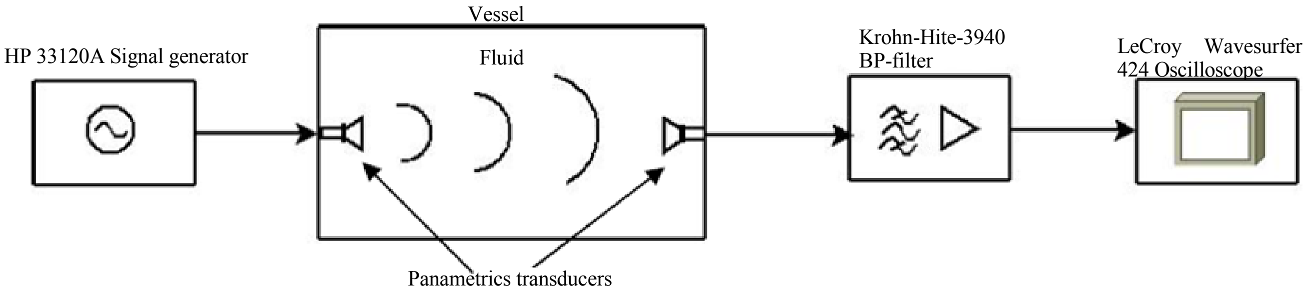

Fig. 2. A schematic overview of the measurement setup used for acoustic attenuation tests of relevant downhole fluids.

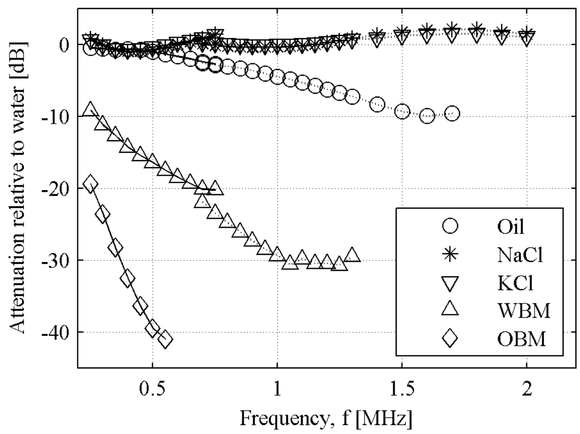

Fig. 3. Results for both the 0.5 MHz and 1 MHz transducers in dB relative to water.

It was observed that the attenuation in brine is approximately the same as in water for the investigated frequency range. Crude oil exhibits a somewhat higher attenuation than water, especially at higher frequencies. At 0.5 MHz the loss in crude oil is approximately 2 dB higher than in water, and at 1 MHz it is approximately 5 dB higher than water. Higher attenuation is observed in mud than in the other fluids, especially for oil-based mud at high frequencies. In OBM, the received signal could not be identified for frequencies above 0.5 MHz. For WBM, the attenuation is about 18 dB higher than water at 0.5 MHz and 30 dB higher than water at 1 MHz.

The choice of frequency in a downhole acoustic camera is a compromise between range and resolution. A higher frequency increases the resolution and decreases the range, while a lower frequency decreases the resolution and increases the range. In the final prototype design the resolution was emphasized, and an operating frequency of 1 MHz chosen for the transducer. The estimated attenuations indicate that imaging is possible at 1 MHz in water, brine and oil, but difficult in mud.

B. Acoustic transducer

The primary design goal was to maximize the transducer's tolerance to harsh conditions in terms of high pressure and high temperatures, while maintaining the acoustical performance. Robust mechanical design is required to withstand the high pressures downhole, and this limits the available transducer designs to either pressure compensation or a pressure resistant hull.

High temperatures influence the acoustical and mechanical properties of the polymers commonly used in ultrasonic transducers. Softening of the materials may result in deformation of crucial components. All materials expand according to their coefficient of thermal expansion, and materials with similar thermal expansion must be chosen to ensure that the acoustic coupling is maintained.

To create an image of the object in front of the camera, either a phased array transducer or a mechanically scanning transducer must be used. A phased array option requires more advanced on-board electronics and signal processing, and often depends on polymer materials in the design. A scanning transducer increases the mechanical complexity in the design by including a scanning mechanism.

Prior experience with successful development of several single element transducer for use in harsh conditions formed the basis for the design. A single element scanning solution was chosen, and a pressure compensated hull was preferred to a pressure resistant hull in order to achieve a thinner metal front and thus less ringing. The advantages of a well-proven robust and temperature resistant transducer design were deemed to outweigh the increased mechanical complexity of the moving parts.

The final transducer design is shown in Fig. 4. The transducer is pressure compensated, consisting of a single piezoelectric disk with a diameter of 41.6 mm, and a high-impedance solid backing material. The piezoelectric ceramic element in the transducer is 2 mm thick in order to achieve a resonance frequency at 1 MHz. Fluid is filled in the chamber behind the backing material, which together with small pistons allow for pressure compensation of the transducer. The piezoelectric disk is coupled to the front face of the transducer hull using pressure and silicone oil, and no additional impedance matching to the fluid is used. A plano-concave front face focus the acoustic waves at a distance of about 300 mm, thus increasing the performance of the transducer at said distance. The source sensitivity of the transducer at 1 MHz in water, measured at the focal point 30 cm, is 26 dB re 1 Pa/V @ 1 m, and the beam width is approximately 3°. The level of the first sidelobe is approximately -9 dB.

The front diameter is 49.8 mm and the overall length is 145 mm. It is mainly constructed of stainless steel and titanium, and weighs 1.3 kg. The transducer is mounted in a swivel joint and rotated by a stepping motor driven by the analog electronics. Operating in pulse-echo mode while rotating the transducer in a spiral pattern, the collected data can produce 3D-images of the object in front of the tool.

4. IMAGING PERFORMANCE

The performance of the downhole acoustic camera has been tested in water, mud, brine and crude oil. Initial tests of the imaging performance were conducted at ambient pressure and temperature, providing information about capabilities and limitations of the downhole acoustic camera in relevant fluids. Testing of the imaging performance in distilled water at high temperature and high pressure was conducted at a later stage and compared to the measurements at ambient temperature and pressure.

The main components of the measurement setup (Fig. 5) were the assembled prototype (excluding battery and electronics containers) and a measurement tube containing the measurement fluids and the target for the acoustic imaging, a reflector spindle. The reflector spindle placed in the center of the measurement tube consisted of an 80*80 mm plate with an M20 shackle attached to one side.

Fig. 4. The high-pressure high-temperature transducer.

The software system USCam was developed to communicate with and program the tool, perform signal processing, and present the acquired data. Online image acquisition is possible if the prototype is connected to an external computer. This is achieved through a serial cable for testing and development. The prototype has been designed for preprogrammed slickline operation, but only addition of a physical connector for wireline is necessary to achieve online operation. USCam is used to initialize offline image acquisition. The camera is then programmed to acquire images on a future date and time, while running on batteries.

The camera rotates the ultrasound transducer in a spiral pattern and for a set of positions on this spiral a pulse/echo ultrasound signal is produced. The data from the camera only contain this set of ultrasound signals, and the USCam software must then process these signals to create a visualization of the volume in front of the camera. The volume is presented as 2D cross sections in a 3D viewport. The processed data can also be exported as a ".raw" file for more advanced volume visualization with a third party software package. A screenshot of the USCam software during imaging performance testing is shown in Fig. 6.

During the signal processing, an approximate sound velocity for the medium is needed to compute the geometries correctly. A background noise threshold is set, which determines the minimum energy level of the signal to be included in the dataset when generating the image. A smoothing filter and an edge enhancement routine are included, and should be tuned for increased image quality.

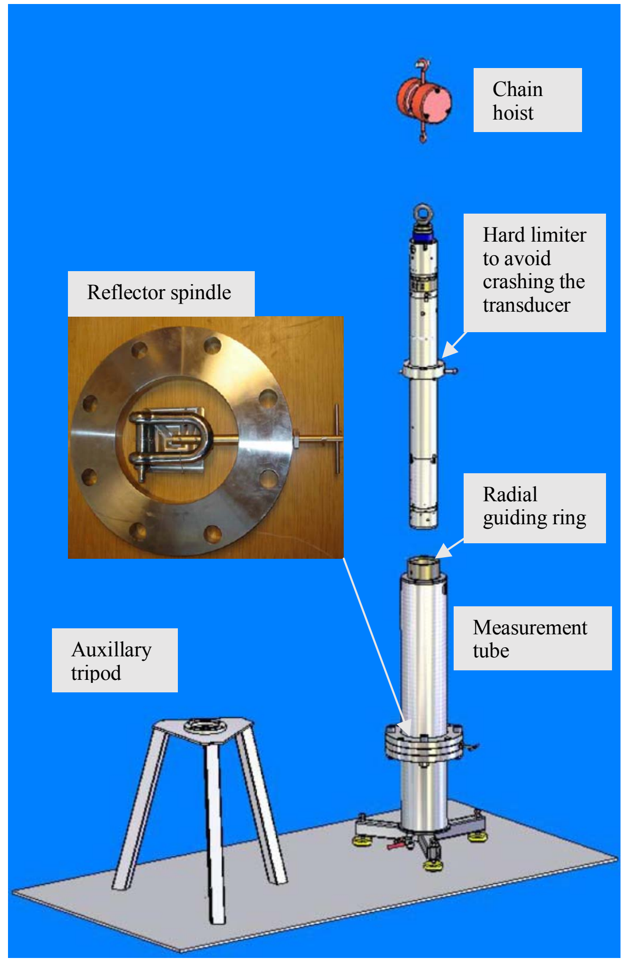

Fig. 5. Imaging measurement setup. A picture of the reflector spindle showing the shackle is inset.

First fresh water was used as test fluid to establish a baseline measurement for the other measurements. To investigate the imaging feasibility for each fluid, manual measurements were conducted using an oscilloscope. A full image was obtained and analyzed in the regions with sufficiently strong signals. This measurement cycle was repeated until the capability/limitation was established for all fluids. An overview of the test results are given in TABLE I.

Good imaging capabilities were achieved for water and brine in the range 150 mm to 400 mm. Medium imaging capabilities was achieved for crude oil in the range 150 mm to 250 mm. No images could be obtained in mud. The achieved range is comparable to and exceeding the range of competing technologies, where these are stated [5]-[6]. It is assumed that the other technologies also have limited imaging capabilities in mud due to the increased attenuation.

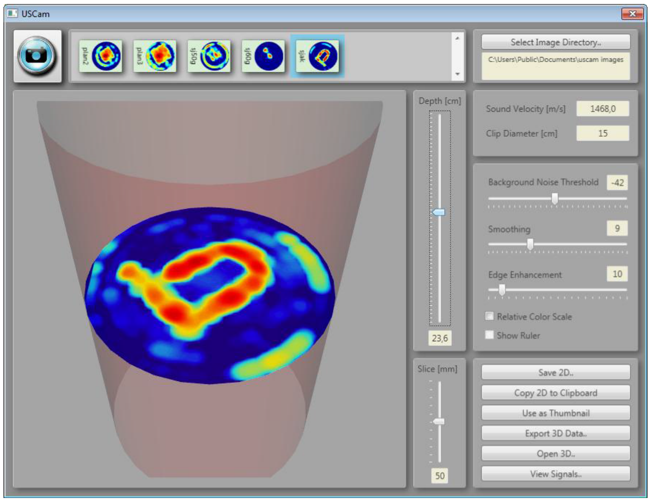

Fig. 6. Screenshot from the USCam software.

5. Functional Testing under Extreme Temperatures and Pressure

Substantial environmental testing of the downhole tool and its individual parts were conducted to ensure that the Downhole Acoustic Camera prototype would withstand the harsh conditions it would be subjected to. The in-house tests, covering vibration, temperature and pressure, were designed to ensure that the requirements of a future qualification run would be met.

Random vibration tests following the procedure of ISO 13628-6 [7], but limited to a 5 minute test period, were performed on the pressure compensated parts and the electronics with successful results. Functional temperature tests of the electronics and the transducer were first performed at temperatures up to 85 °C. After an electronics upgrade, the tests were repeated at 120 °C. No mechanical defects were found after running the tests, and the electronics and transducer retained functional with respect to their mechanical and imaging capabilities during the tests, but indicated a slight decrease in image quality at higher temperatures. A combined temperature and pressure test of the transducer were conducted in a purpose-built chamber filled with distilled water, with pressure exceeding 690 bar and a maximum temperature of 120 °C. Transducer operation were investigated during testing, and no significant decline in performance was observed during or after the test was conducted. Similar pressure and temperature tests of the pressure equalization and prototype main body revealed the need for larger pressure channels for the pressure equalization, a smaller stepper motor and a few other mechanical improvements. After the modifications, a new test was conducted successfully.

Pressure and temperature tests of the complete prototype were performed prior to the electronics temperature upgrade, and the electronics module was therefore left outside the pressure and temperature. The test cycle started at ambient temperature and pressure, pressure was then increased to above 690 bar and held constant while the temperature was increased to above 120 °C over the span of a few hours.

TABLE I. Camera capability/limitation matrix established from image analysis.

[green]	**Good** (Clear shape/contour of the shackle)
[blue]	**Medium** (Reasonable good shape/contour of shackle)
[yellow]	**Limited** (Reflection obtain, but only medium image quality)
[orange]	**Poor** (Reflection observed, but it does not resemble a shackle)
[red]	No signal/image
[white]	No picture taken

Distance	Water	NaCl- and KCl-Brine	Crude oil	WBM	OBM
112 mm	[yellow]	[yellow]	[yellow]	[red]	[red]
150 mm	[green]	[green]	[blue]	[white]	[white]
200 mm	[green]	[green]	[blue]	[red]	[red]
250 mm	[green]	[green]	[blue]	[white]	[white]
300 mm	[green]	[green]	[yellow]	[white]	[red]
350 mm	[green]	[green]	[orange]	[white]	[white]
400 mm	[green]	[green]	[orange]	[white]	[white]
450 mm	[blue]	[blue]	[orange]	[white]	[white]
490 mm	[white]	[yellow]	[white]	[white]	[white]

Pressure was then reduced to 10 bar, and increased again to above 690 bar. Finally, both temperature and pressure were decreased to ambient condition. At each point in the test diagram, the prototype was programmed to capture images. The transmission medium was distilled water, and the object to be depicted was an M20 shackle. In Fig. 7 the captured images at ambient pressure and temperature and at 720 bar and 125 °C are shown. It is seen that the tool is fully functional at maximum temperature and pressure, and that the image quality is comparable to that at ambient conditions. No damage was observed on the housing or pressure-equalizing components after the test, and the test was considered successful. Additional tests were performed successfully at a lower temperature, 80 °C and 690 bar, so that the un-upgraded electronics could be included.

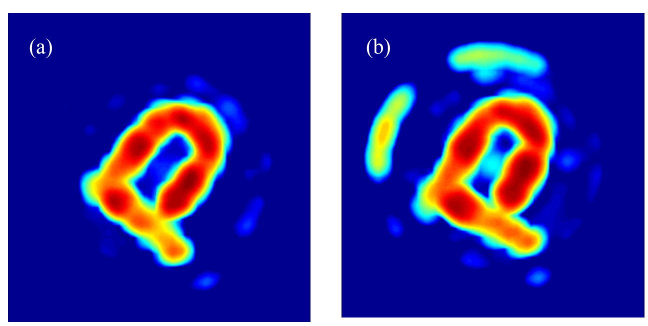

Fig. 7. Picture of shackle generated by the Downhole Acoustic Camera. (a) At 1 bar and 20 °C, and (b) at 720 bar and 125 °C.

6. SUMMARY AND CONCLUSIONS

The development of a forward-looking acoustic camera for downhole imaging is presented. The technology is based on a single piezoelectric transducer mechanically steered to obtain an image of obstacles in e.g. an oil well. The acoustic camera prototype has been successfully tested at 720 bar and 125 °C. Imaging performance at 1 MHz was also preliminary verified for a range of reproducible liquids as water, brine (NaCl and KCl), crude oil, and drilling mud. Good results were obtained when imaging objects in water, brine (range 150-490 mm) and crude oil (range 150-250 mm).

The development of the Downhole Acoustic Camera prototype was initiated because there was no tools available for acoustic downhole imaging at the time, and there was a clear demand for this type of technology. Today there are alternative commercially available tools such as Archer SPACE [4], and tools still under development, such as Sonasearch Acoustic Camera [5] and Visuray VR90 (X-ray backscattering) [6]. However, most competitors are designed for shorter ranges than the Downhole Acoustic Camera prototype.

The principles of the Downhole Acoustic Camera prototype are extremely simple and robust and may have promising applications within downhole geotechnical mapping, exploration of hydrothermal vents, and subsea mining.

Future work will aim at shortening the overall length or to modularize the mechanical design. This will allow for a more agile physical layout for operation in narrow and winding structures, such as in subsea hydrothermal vents. Addition of an appropriate connector will allow for wireline operation. Extension of the operating temperature range is necessary in order to allow for operation in a wider range of hydrothermal vents.

REFERENCES

[1] J. R. Tague and G.F. Hollman, “Downhole video: a cost/benefit analysis,” SPE/AAPG Western Regional Meeting, Long Beach, California, 19-22 June, 2000.

[2] W. S. Gan, *Acoustical Imaging: Techniques and Applications for Engineers*. John Wiley & Sons Ltd, 2012.

[3] Anon., “ABI 85-92 – High temperature acoustic televiewer,” Advanced Logic Technology, 2004. [Online]. Available: http://www.alt.lu/pdf/ABI85.pdf

[4] Anon., “Captured by SPACE – 3D perspective on well performance,” Archer, 2014. [Online]. Available: http://archerwell.com/content/uploads/2014/10/BR-US-SPACE-25092014.pdf

[5] Anon., “Acoustic Camera – High Resolution Imaging Tool,” Sonasearch, 2009. [Online]. Available: http://www.sonasearch.com/R&D/AcousticCamera/acoustic_camera.pdf

[6] M. Spannuth et al., “X-ray backscatter imaging in an oil well,” SPE Annual Technical Conference and Exhibition, Amsterdam, The Netherlands, 27-29 October, 2014.

[7] Anon., “ISO 13628 - 6, Petroleum and natural gas industries - Design and operation of subsea production systems - Part 6: Subsea production control systems,” ISO Standard, 2005.

[8] R. B. Pedersen et al., “Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge,” Nature Communications, vol. 1, pp. 126, 2010.

[9] P. Linke et al., “In situ measurement of fluid flow from cold seeps at active continental margins,” Deep Sea Research Part I: Oceanographic Research Papers, vol. 41 (4), pp. 721-739, 1994.