Development of a Geothermal Well Inspection Camera
With Active CO₂ Cooling

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ABSTRACT

A downhole camera for geothermal well inspection has been developed and is on the verge of deployment for the first time. The camera employs a unique cooling system powered by solid/liquid carbon dioxide (CO₂, dry ice) to keep critical camera components cool in wells up to 250°C. The tool can be operated in either a forward-looking mode, to provide images of wellbore objects such as lost tools and twisted-off drill pipe; or a side-looking mode, to provide images of the wellbore wall, including fractures, lithology, and casing damage or scaling. The tool has been designed and built, laboratory tests are underway, and field tests are planned for the near future. This paper focuses on the design and fabrication of the tool, including a detailed analysis that predicts the thermodynamic behavior of the CO₂ cooling system, optics modeling for optimizing the camera’s optical design, adaptation of commercial video imaging systems, development of software for de-coning and enhancing images taken through a conical mirror, and incorporation of a recently developed high-temperature microprocessor.

The Need for Wellbore Imaging at Geothermal Temperatures

There are good reasons to conduct video imaging of a geothermal wellbore during every phase of its life. For example, lost tools or twisted-off drill pipe experienced while drilling a well may require visual inspection to plan corrective actions. After the well is drilled and cleaned, images measuring the size and orientation of production fractures in the open hole sections of the well would be highly valued. Finally, during the production life of a well, the well casing or production tubing may become bent, damaged, or scaled. Visual inspection of damaged casing would aid in corrective action. For these and other reasons, there is a strong market for well-logging camera tools. However, existing oil-well and water-well logging tools cannot take the heat of a geothermal well because small solid-state video sensors do not operate at geothermal temperatures.

Figure 1. Simplified schematic of the Geothermal Well Inspection Camera in both the side-looking and forward-looking modes.
temperatures. The geothermal well owner wanting images inside a well must first cool the well. Needless to say, pumping cold water down a geothermal well is expensive. It is also damaging to the well, subjecting it to large changes in thermal expansion, damaging well casing and/or fracturing the hot rock supporting the well. For these reasons, few geothermal well operators will risk video-image logging of their wells. The work presented here offers a solution to this problem.

**Design of the High-Temperature Camera**

A simplified schematic of the geothermal well inspection camera is shown in Figure 1. Two modes of camera operation are shown. The first is the side-looking mode, where the camera looks through a 45° conical mirror, allowing a longitudinal slice of the wellbore wall to be imaged. The second is the forward-looking mode, where a view down the axis of the wellbore is taken, providing images of misfortunes such as stuck drill pipe, lost tools, and collapsed casing. Changing the mode of operation is accomplished by simply changing the attachment on the lower end of the camera. Specialized software developed for this tool unwraps the circular, distorted image taken with the conical mirror and produces a panoramic-type image of a 360° slice of the wellbore wall. This allows close, detailed inspection of wall features such as fractures, lithology, and cracked, corroded, or scaled casing and slotted liners.

The camera’s video chip and lens are mounted on the end of a heat sink, facing downward. This heat sink is part of an active cooling system powered by the vaporization of solid/liquid CO₂ (dry ice). This cooling is needed because video chips, due to inherent physical limitations, do not operate above 105°C, and image quality is significant degraded at even lower temperatures. Other camera-related electronics, such as the image processor and non-volatile memory (SD cards), are mounted on the sides of the heat sink. The entire camera compartment is housed behind an annular sight glass window that not only seals against wellbore fluids but also has a built-in annular light tunnel that segregates the incoming imaged light from the outgoing light that illuminates the target. The outgoing light is provided by a ring of 24 circuit-mounted LED lights mounted inside the pressure window.

The CO₂ cooling system uses dry ice to pre-cool the system hardware and camera compartment prior to tool deployment, and to actively cool the camera compartment when it is inside a well. At sea-level pressures, solid CO₂ sublimates to gas at a temperature of -78.5°C, so all solid dry ice commonly encountered is, by definition, at or below this temperature. Each pound of dry ice absorbs 246 Btu of heat as it sublimates to gas and another 25 Btu or so as the gas warms up to room temperature. So 4 pounds of dry ice would absorb roughly 1100 Btu as it sublimates and warms up to room temperature. If just 10 pounds of steel containment surrounding the dry ice were initially chilled to the dry ice temperature, it would absorb another 100 Btu or so as it heats up to room temperature.

To put these numbers into perspective, consider that such a system would absorb roughly 1200 Btu of heat before it reaches room temperature over a 4-hour period. That would be an average heat absorption rate of 300 But/hr, which is 6% of the cooling capacity of a typical 5,000 Btu/hr AC window unit for a small room. Our analysis, detailed below, shows that if such cooling power is efficiently concentrated on the video chip and other temperature-sensitive components, it should be adequate to keep those electronics cool enough for the time necessary to run a downhole log.

An important part of the tool’s CO₂ cooling system is the CO₂ pressure control system. This system regulates the pressure in the cooling system to keep the pressure there as low as possible, in order to both enhance safety and improve the efficiency of the CO₂ cooling process. The CO₂ gas released by the vaporizing dry ice during the cooling process must be safely contained within the tool and/or safely expelled from the tool when possible. The pressure containment system is designed to safely withstand a maximum expected internal pressure of 3,000 psi, and two pressure relief/check valves are used to vent the CO₂ gas from the tool whenever the internal pressure exceeds the external pressure by 10-50 psi. High pressures in the dry ice chamber degrade the efficiency of the heat absorption process, and the process stops completely upon reaching the CO₂ supercritical pressure of 70.5 atm (1036 psi). So maintaining the lowest possible pressure at all times during the cooling cycle is necessary.

In a deep, liquid-filled wellbore, however, the elevated pressure surrounding the tool does not allow for CO₂ venting. The pressure control system therefore contains sufficient volume to maintain the CO₂ pressure below the supercritical pressure during the entire vaporization process using a specified mass of dry ice. This arrangement maximizes the amount of heat absorbed by the gas as the solid/liquid CO₂ vaporizes at increasing pressure.

Situated above the pressure control system are the wellbore pressure transducer and the wellbore temperature probe. A transducer for measuring the CO₂ system pressure is also included at this location.
Above these transducers are the electronics chassis and pressure barrel for the electronics that do not require heat shielding. These so-called “barefoot” electronics include a high-temperature microprocessor, wireline modem, and associated components that provide communication and data transfer capabilities between the camera and the operator at the surface. A complete description of these electronics is provided below.

**Predicted Downhole Performance**

To determine the feasibility of using dry ice for active cooling in a downhole tool, a detailed transient thermal model of the cooling system was developed using a lumped-parameter approach. Major components of the tool concept shown in Figure 1 were modeled as nodes in a thermal network, each with their individual properties such as configuration, dimensions, mass, density, specific heat, thermal conductivity, and normal emissivity. The equations describing heat absorption by the various nodes and heat transfer between the different nodes were then developed.

The transport and thermodynamic properties needed to solve these equations vary as a function of the state, temperature, and pressure of the CO$_2$ in various parts of the cooling system. By developing an understanding of the thermodynamic processes that occur in such a closed system, a relationship between pressure and temperature was established that allows these properties to be calculated at any given time in the transient analysis. The necessary equations were derived by fitting polynomial curves to experimental data found in the literature for CO$_2$.

The heat transfer, transport-property, and thermodynamic equations were programmed into an Excel spreadsheet and solved using iterative numerical techniques coded in visual basic subroutines. The spreadsheet allows the transient thermal behavior of the tool to be simulated over a wide range of different design specifications and operating conditions.

Results for a typical camera configuration are shown in Figure 2. For this simulation, it was assumed that the cooling system was first pre-cooled to a temperature of −78.5°C by placing a quantity of dry ice in the containment tube and allowing it to completely vaporize and vent to the atmosphere. A specified 0.75 kg load of dry ice was then assumed to be sealed into the tool before sending it downhole. It was assumed that the trip downhole would take one hour (e.g., 6,000-ft depth at 100 ft/min running-in-speed), at which time the exterior tool temperature would be 250°C. This temperature was the design wellbore temperature specification for this project.

The results of the simulation predict that it would take 4.04 hours at depth for the entire 0.75 kg of solid/liquid CO$_2$ in the tool to completely vaporize, at which point the cooling system would shut down. The system pressure would be 70.5 atm (1036 psi), and the CO$_2$ vapor temperature would be 29.6°C. The camera compartment temperature is predicted to be 34.5°C, with the compartment still under a vacuum.

If the tool were immediately pulled out of the hole over the next one hour, it would reach the surface 6.1 hours after loading it with dry ice, and the camera compartment temperature would never exceed 61.5°C during the entire time. If the CO$_2$ gas within the system were for some reason not vented to the wellbore as the tool was brought back uphole, the 56-atm (823-psi) pressure that remained in the tool after cool-down could be safely vented at the surface.

**Optical Design**

Extensive optical modeling was performed to allow key design elements of the camera system to be optimized. The equations that describe light pathways as they reflect off a target, through the lens of a camera, and onto the pixel grid of the video chip were derived and expanded to include the effects of reflecting off a conical mirror. The resulting model allows us to predict the: target resolution (pixel count per unit target area), focusing requirements, lens location within the tool, and mirror placement; as a function of the: lens focal point, video chip size, pixel density, pressure window diameter, and...
wellbore diameter. As illustrated in Figure 3, optical testing was conducted using several camera platforms and set-ups. This effort was successful in determining that the minimum image size acceptable for high-quality images of a wellbore wall is 5 Mpixels. This knowledge, in turn, was used to guide the selection of an optimal camera platform for the geothermal tool.

**Camera System Design**

The camera tool design places the camera image sensor inside the cooled camera compartment. The image sensor is a silicon integrated circuit (IC) with millions of very small light-sensing transistors. The actual IC is only a square centimeter in size. As such, using the CO2 to keep this small device cool seems like an easy solution to a difficult problem.

The original idea was that the remaining electronic circuits needed to support the camera image sensor would be made using high-temperature (HT) silicon-on-insulator (SOI) integrated chips designed for use in commercial aircraft engine controls. In particular, the system design would take advantage of a new HT SOI device, the RelChip™ RC10001. The RC10001 is the first 32-bit microprocessor designed as a HT SOI device. This technology can operate up to 300°C+. The plan was to allow the RC10001 and other HT SOI circuits to operate at ambient well temperatures, avoiding active cooling of much of the tool. The RC10001 would use the power of a 32-bit processor to interface to the camera image sensor and transmit image data to the surface using image compression techniques.

Like all great plans, there developed a need to alter this one. As the first RC10001’s became commercially available, RelChip determined the operating frequency of the RC10001 was limited to only 5 MHz at 250°C. Although this speed is entirely adequate for most downhole logging needs, it is a problem for the camera system because the slowest acceptable read rate on commercial image sensors is 6 MHz at normal temperatures. The image captured by the image sensor’s light-sensitive transistors must be read and moved to electronic memory quickly, as silicon ‘dark’ currents will corrupt the image over time and, especially, at elevated temperatures. It is because of these dark currents that image sensors cannot operate at geothermal temperatures.

Unfortunately, at 5 MHz, the RC10001 cannot directly interface with the camera image sensor. In fact, we found that we need a processor frequency around 20 MHz to properly interface with the image sensor and store each pixel reading as it is read from the image sensor. An alternative approach was necessary.

A large number of options were considered. The two receiving the most consideration (and effort) were based on using commercially available public-domain camera interfaces: the Arduino and the BeagleBone. Both of these systems require increasing the number of components that must be housed in the cooled camera compartment.

The Arduino system has a huge base of public-domain software. The system is taught at many high school robotic classes worldwide. The basic Arduino system uses a 16-MHz, 8-bit processor. Camera manufacturers wanting to supply the Arduino market provide the camera with a built-in interface to the Arduino system. This camera interface is a high-speed image compression chip, which converts the 5-Mpixel image to a JPEG image using a 20:1 compression.

Figure 4 shows a commercially available camera from UCTronics®. This is a 5-Mpixel camera with a replaceable lens. The chip below the camera is the interface chip which downloads the camera image and performs the conversion to a much larger image.
smaller JPEG image. The JPEG compression is reasonable for camera images looking downhole; however, for images of the wellbore wall using the cone mirror, the resolution of the compressed JPEG images is too poor to see much detail.

After a significant effort to make the Arduino camera system work, a second, faster processor system was considered. The BeagleBone uses a 1-GHz micro-processor system and supports a bare-bones camera module with a USB interface. Like the Arduino, it is also in the public domain. It is essentially a credit-card-size computer running Linux. The BeagleBone does have a significant overhead, which make fitting it into the tool more difficult. The much faster BeagleBone system can grab full 5-Mpixel images. The tradeoff is the increased heat generated by the support electronics.

In addition to the high-resolution images, the BeagleBone will provide a thumbnail image to the HT processor, provide additional high-resolution measurements, and package the data into packets that are transmitted to the HT processor for final processing and transmission. The real-time transmission will include the thumbnail images and pertinent measurements such as wellbore temperature and pressure, along with diagnostic measurements to aid in determining the real-time performance of the deployed system. The BeagleBone will store the high-resolution images downhole on a micro-SD card. After a log, the high-resolution images will be processed by PermaWorks software to enable the user to review the log in high resolution. By highlighting the areas of interest determined during the real-time collection of thumbnail sketches, the software will filter the data to provide the user a quick look at the area of interest in high resolution shortly after deployment.

As mentioned earlier, the deployment logging speed is assumed to be approximately 100 ft/min. This is adequate to enable the user to know that the system is working and to determine when the area of interest is close at hand, thereby enabling the wireline operator time to slow down appropriately to ensure clear images are taken at and near the area of interest. Many times, the exact location of concern is not known, and having real-time images is imperative to ensure that the area of interest is properly covered.

**Barefoot HT SOI Electronics Module**

The hot side of the tool will be running HT SOI electronics which are capable of continuous operation at or above our target temperature of 250°C. The high-temperature electronics perform two functions: communication with the camera and surface, and high-temperature sensing. The basic building block is a chip set built around the RC10001 from RelChip (see Figure 6). The chip set is a circuit constructed for use in any number of future geothermal logging and drilling tools. This will provide a key technology to other geothermal system builders in the future.

Under this configuration, the user programs the RC10001 operating program within the EEPROM. Once the tool powers up, the program is moved to the RAM (Random Access Memory) for fast execution. The above circuit have 50 pins for connecting to the outside world. This allows for expanding the RAM or downloading the operating program from a PC. Also, reducing the system from 238 total pins to 50 pins means that the system is much easier for use in the limited commercial production runs found in the geothermal industry, where hand soldering is usually required.

The core contains an analog switch and ADC to gather data from four channels. The RAM provides additional code and data storage, while the EEPROM stores boot code, calibration constants and non-volatile data. Once these units are combined into a MCM, only 7-9 signal pins are required. Four channels of pressure and temperature data are gathered. A real-time clock in the microcontroller time stamps data.

The RC10001 has a large number of built-in functions needed for building complete logging tools such as the geothermal well inspection camera. Below is a short list of built-in hardware, all of which are under control of the programmer and have access through the 50-pin package.

**RC10001 Built-In Hardware Functions:**

1. UART – Used for communication between the RC10001 and other system microprocessors or an external computer as a PC being operated by a reservoir engineer.
2. PWM – Used for controlling external electrical power as needed to power other electronics or heavy loads such as electric motors.
3. SPI – A common communication between microprocessors and sensor hardware, such as 3-axis inclination sensors for a MWD tool or a simple pressure measurement.
4. **I2C** – A common communication using only two wires for slower-accessed sensors or system functions such as backup flash memory.

5. Internal real time clock for tagging data as collected.

6. Timers for counting spinners for flow measurement or gamma count rates for a gamma tool.

Perma Works has also developed general serial communication software within the RC10001 for driving camera images or other types of data up a 600°F-rated mono-conductor logging cable. Bit rates are programmable up to 200Kbit/sec, depending on the length of the logging cable.

Many existing camera systems use low-temperature, high-end coaxial cable, not logging cable. These systems are limited to depths less than 4000-ft inside cold water wells. Our camera electronics are designed to be consistent with standard wireline logging systems found on approximately 70% of existing logging trucks, without modification or the purchase of expensive surface equipment.

This tradeoff greatly reduces the operating cost of our camera and eliminates the depth limitation, but the image update is slower because of the losses inherent to a long single-conductor wireline.

Shown in Figure 7 are measured losses through a 12,800-ft mono-conductor wireline mounted on a logging truck. With this 600°F-rated wireline, the bandwidth starts to roll off at 10.1KHz at room temperature. Our receiver can operate with a -30db loss of signal allowing room temperature operation up to ~200KHz or a FSK data rate around 30 KBaud.

Additional testing not presented here, however, suggests this same cable at 250°C would have its bandwidth and data transmission rate reduced by 50%. The electrical resistance of any metal conductor increases with increasing temperature, thereby reducing the bandwidth. In addition to this loss, a 600°F-rated cable uses a nickel-clad copper-center conductor. The nickel cladding, which protects the copper from caustic gasses inside the hot geothermal well, also greatly increases the wire’s EMF (electro-magnetic force). EMF fights against any oscillating signal inside the wire, thereby reducing the cable’s bandwidth. By making the communication system user-programmable at the surface, we will be able to attain the greatest image transfer rate based on the logging cable’s length and type of construction.

**Image Enhancement and Compression**

Images captured by the video chip are stored in full on the micro-SD card in the camera compartment for later processing and analysis. Highly compressed, “thumb-nail” images are processed and encoded by the RC10001 high-temperature microprocessor for transmission to the surface through a single-conductor wireline. Images taken with the camera in the forward-looking mode are relatively straight-forward to interpret. Images taken through the conical mirror, however, show a highly distorted view of the wellbore wall. Consequently, software algorithms have been developed that “de-cone” the circular, distorted image to produce a panoramic-type image of a 360° slice of the wellbore wall.

![Figure 7. Signal amplitude losses in a 12,800-ft mono-conductor wireline at room temperature.](image1)

![Figure 8. Image taken with USB camera through a 45° conical mirror.](image2)

![Figure 9. Conical mirror image after applying de-coning algorithm.](image3)
Shown in Figures 8 and 9 are an example of a BeagleBone cone image and the resulting de-coned image. Notice that the image is quite detailed in the bottom half of the de-coned imaged, which corresponds to the outer perimeter of the conical mirror. The image quality degrades moving up the cone because the adjacent wall image is compressed into a smaller mirror surface area.

Perma Works’ software combines the images with depth data, allowing the creation of a composite view that make the best use of the outer perimeter of the conical mirror. When the tool is moved slowly over a critical area, very high fidelity is achieved for the entire section.

**Mechanical Envelope Design and Fabrication**

The pressure housing needed to contain the camera and all its systems was designed for a maximum working pressure of 5,000 psi at a maximum temperature of 250°C. The mechanical complexity of the tool and several inherent characteristics of the CO₂ cooling process of the tool are responsible for the tool’s rather large size: 2-7/8 inches (73 mm) diameter and 17.6 ft (5.4 m) long. The tool weighs approximately 250 lb. It contains over 25 custom-designed and machined parts as well as dozens of commercially available components. As of this writing, it has been successfully assembled and is ready for laboratory testing.

The parts of the tool exposed to wellbore fluids are made of either 17-4 PH or Nitronic 60 stainless steel. Component connections with external joints are sealed with double O-rings where possible, using perfluorelastomer O-rings with a maximum temperature rating of 320°C and extreme chemical resistance. The pressure window through which images are taken is a solid borosilicate glass window with an integrated annular light section and an external sapphire shield for scratch resistance. The window’s duplex stainless steel body is welded in place in the lower end of the camera body.

Commercial bowspring assemblies are used to centralize the tool, one at the top and one near the bottom of the tool. They can be adjusted for optimal squeeze for different wellbore diameters.

**Laboratory Testing**

Laboratory testing of several tool components and systems was performed during development of the tool. Extensive testing of the pressure relief/check valves was conducted in a laboratory process that used dry ice to provide pressurized gas for performance testing. As of this writing, a vacuum test of the camera compartment and barefoot electronics compartment is planned by drawing a vacuum on the space and monitoring its vacuum pressure for several hours after the vacuum pump is disconnected. Low-level pressure tests of the CO₂ containment system will also be conducted by loading the assembled tool with dry ice and monitoring its internal pressure as the dry ice vaporizes and the pressure relief/check valves are engaged.

Upon completion of the tool electronics, they will be installed in the pressure housings, the tool will be wired, and extensive laboratory tests will be conducted to characterize the tool’s performance and the quality of the images produced.

**Field Testing Plans**

As of this writing, field tests are currently being planned for the geothermal well inspection camera. The first test will be in a low-temperature water well, which will provide a low-level pressure test of the mechanical enclosure and a test of the camera’s optical performance under benign conditions. A geothermal well with a producing temperature of 150-200°C will then be selected, and several tests of the tool will be conducted there.

**Summary**

Significant analysis has been conducted during the development and design of the geothermal well inspection camera. Computational models have been developed, laboratory tests of tool components and systems have been conducted, and extensive design optimization has been undertaken to produce a tool that is safe and reliable. If shown effective in this application, the CO₂ cooling system developed for this tool may prove useful in other high-temperature logging applications.

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