

# When Rocks Get Hot: Thermal Properties of Reservoir Rocks

For many years, thermal stimulation has been the leading method for enhanced oil recovery. Operators are using new techniques on heavy oil, tar sands, bitumen and oil shale to liberate a vast store of liquid energy that could provide transportation fuels for worldwide use for a century or more. Design of stimulation programs to produce these resources efficiently over long periods of time requires better understanding and measurement of thermal properties of rocks.

**Evgeny Chekhonin**  
**Anton Parshin**  
**Dimitri Pissarenko**  
**Yury Popov**  
**Raisa Romushkevich**  
**Sergey Safonov**  
**Mikhail Spasennykh**  
*Moscow, Russia*

**Mikhail V. Chertenkov**  
**Vladimir P. Stenin**  
*Lukoil*  
*Moscow, Russia*

*Oilfield Review* Autumn 2012: 24, no. 3.  
Copyright © 2012 Schlumberger.

For help in preparation of this article, thanks to Yevgeniya Gelman, Houston; and Sidney Green and Roberto Suarez-Rivera, Salt Lake City, Utah, USA.

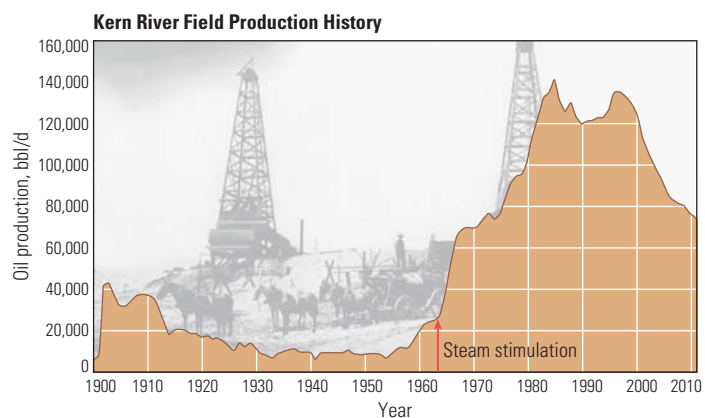
Micarta® is a trademark of Norplex-Micarta.

Plexiglas® is a registered trademark of ATOFINA.

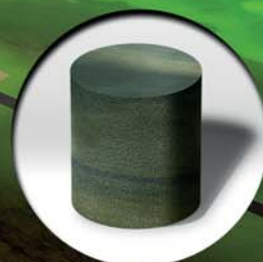
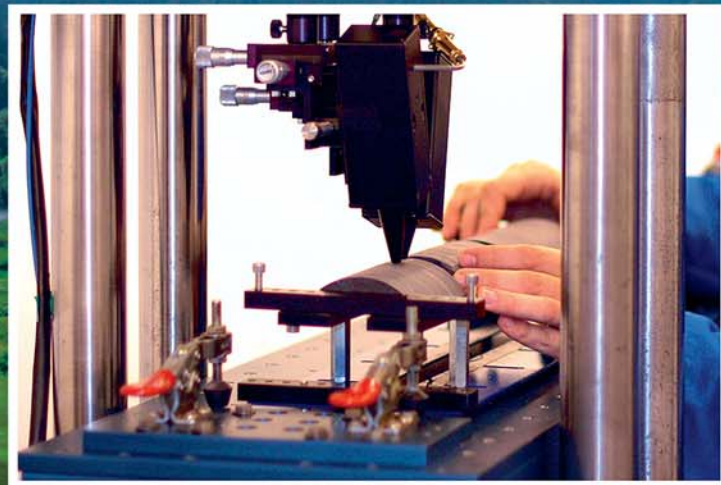
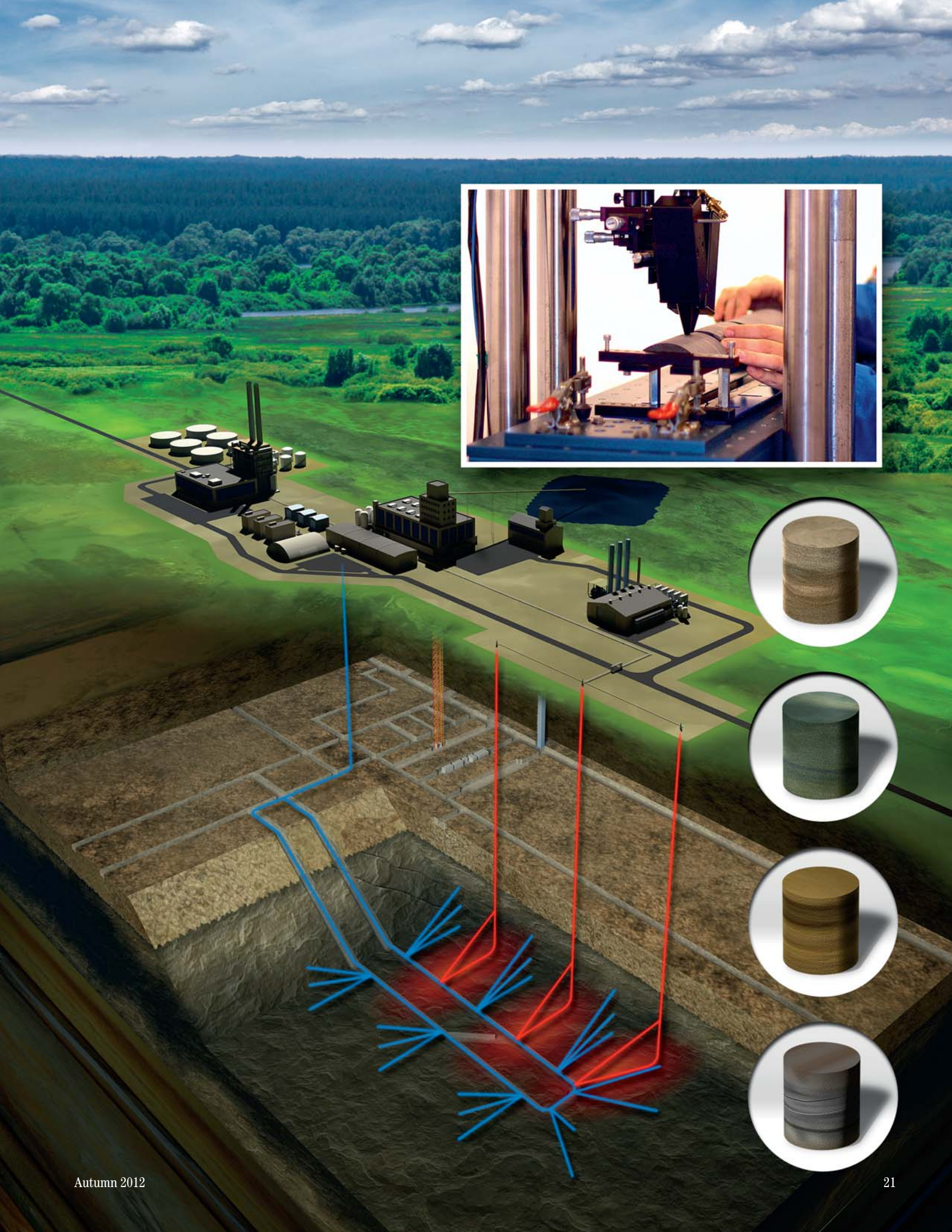
TerraTek is a mark of Schlumberger.

When reservoir fluid gets hot, its viscosity decreases, and a greater amount of fluid usually can be produced from the reservoir rock. Stimulation of conventional petroleum reservoirs with heat from injected steam or hot water has been practiced for more than 50 years with some

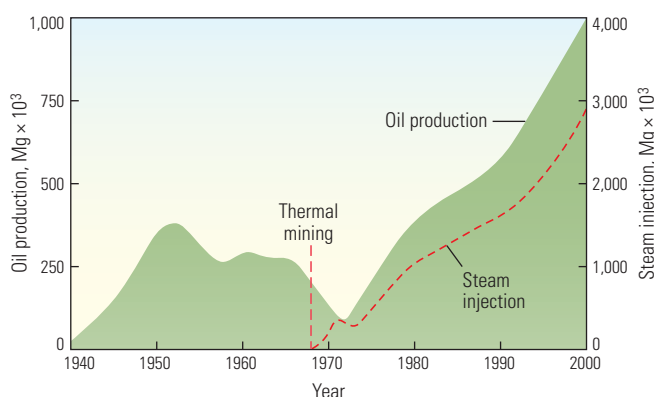
remarkable successes. At the Kern River oil field in California, USA, for example, a massive program of cyclic steam injection, starting in the 1960s, revived this supergiant field by increasing its production rate more than tenfold after it had stagnated for decades ([below](#)). Today, about



▲ Kern River field, operated by Chevron near Bakersfield, California, USA. Production of heavy oil at Kern River field peaked within its first 10 years of operation and went into a 50-year decline. A program of thermal EOR by cyclic steam injection, accompanied by intensive infill drilling, rejuvenated the field in the 1960s, with high production levels continuing today.







▲ Yarega oil field, operated by Lukoil near Ukhta in the Komi Republic, Russia. Primary production of oil from bitumen in the shallow Yarega field started in the 1930s and peaked in the early 1950s. Production was declining rapidly around 1970, when new programs of thermal mining by steam injection were introduced.

60% of world oil production attributed to methods of enhanced oil recovery (EOR) comes from thermal stimulation. For the future, heavy oil deposits, tar sands, bitumen and oil shale—unconventional resources that represent Earth's largest store of liquid fuels—are now being coaxed into releasing the oil they contain by highly evolved forms of thermal recovery.<sup>1</sup>

This article examines an important, but often overlooked, facet of thermal EOR—the thermal behavior of reservoir rocks. Heating reservoir fluids means also heating large volumes of rock. And, while engineers designing a stimulation program usually know the thermal properties of the fluids, thermal properties of formation rocks are

often only loosely constrained, even though these properties help determine project economics.

After a brief look at an unusual thermal recovery operation taking place in the Yarega heavy oil field in Russia, this article reviews the basic thermal properties of rocks and their measurement by often time-consuming conventional techniques. It also introduces a new measurement technique that employs optical sensors to rapidly quantify thermal properties of rock. Since the 1980s, scientists have scanned thousands of rock samples with this optical method, including igneous and metamorphic rocks from deep scientific boreholes around the world and, more recently,

sandstones, shales and carbonates from many petroleum reservoirs. The measurements have revealed important new results about the heterogeneity and anisotropy of thermal rock properties. Investigators are also finding intriguing correlations between thermal and other petrophysical properties.

Research on cores from Russian oil fields revealed surprising variability in reservoir thermal properties over spatial scales ranging from centimeters to tens of meters. Reservoir simulations show why it is important for engineers to understand this variability when they attempt to predict the outcome of thermal EOR. In the cases simulated, incorrect values caused estimates of key metrics for thermal stimulation to vary by up to 40% after just 10 years of production.

### Yarega Oil Field

The Yarega heavy oil field in the Komi Republic, Russia, illustrates the enormous potential of thermal EOR. Discovered in 1932, and now operated by Lukoil, Yarega lies in a prolific oil province west of the Ural Mountains called the Timan-Pechora basin (left). The reservoir holds large quantities of bitumen, a highly viscous, semisolid hydrocarbon formed during the process of petroleum generation. Natural bitumen occurs at depths shallower than 370 m [1,200 ft] in many Russian oil fields, where it constitutes a resource estimated at more than 16 billion m<sup>3</sup> [100 billion bbl] of oil. The pay zone in Yarega is at depths between 180 and 200 m [590 and 660 ft] and is composed of fine-grained quartz sandstone of Middle Devonian age, with a porosity of 20% to 25% and nearly 100% oil saturation.<sup>2</sup>

Production from the shallow reservoirs at the Yarega field resembles a mining operation. Operators have used several configurations to heat the reservoir with steam and extract the liberated fluids. In the most common scheme, developed in the 1970s and called the two-level, or two-horizon, system, steeply inclined steam injection wells, drilled from overlying chambers reached by conventional mine shafts, penetrate and heat the reservoir. Additional mine shafts lead to a second set of galleries near the bottom of the reservoir, from which gently sloping production wells are drilled upward into the oil-bearing layers.

The effect of thermal stimulation on production from the Yarega field has been dramatic. Before thermal mining began in the late 1960s, production in conventional wells drilled from the surface recovered barely 4% of the original oil in place. Thermal mining has raised the

average recovery to 33% and in some zones, to nearly 70%. Lukoil recently introduced new forms of steam-assisted gravity drainage (SAGD) at Yarega, which are expected to increase annual production to 3.5 million metric tons (3,500,000 Mg) [25 million bbl] of oil in the near future.<sup>3</sup>

### Thermal Rock Properties

Engineers often use reservoir simulations to design thermal EOR programs and predict the amount of additional oil attributed to thermal stimulation and its production rate over time at various wells in the field. To accomplish this, simulators employ sophisticated algorithms to compute the evolution of temperature and heat flow within a reservoir after stimulation. These two quantities—temperature and heat—are linked by the thermal properties of rocks and their pore fluids (see “Physics of Temperature and Heat,” page 24). The most important of these properties are volumetric heat capacity, thermal conductivity and thermal diffusivity. Volumetric heat capacity specifies the amount of heat required to raise the temperature of a unit volume of rock (and any pore fluids within) by one degree. Thermal conductivity determines where and how much heat flows in response to temperature differences in the reservoir. Thermal diffusivity determines the speed at which a temperature front moves through the reservoir.<sup>4</sup>

A fourth property, the coefficient of thermal expansion, links the thermal and mechanical responses of reservoir rocks by determining the amount by which a volume of rock expands as its temperature increases. Knowledge of this property is needed, for example, to assess changes in mechanical wellbore stability and in caprock integrity caused by changing temperature conditions in the reservoir.

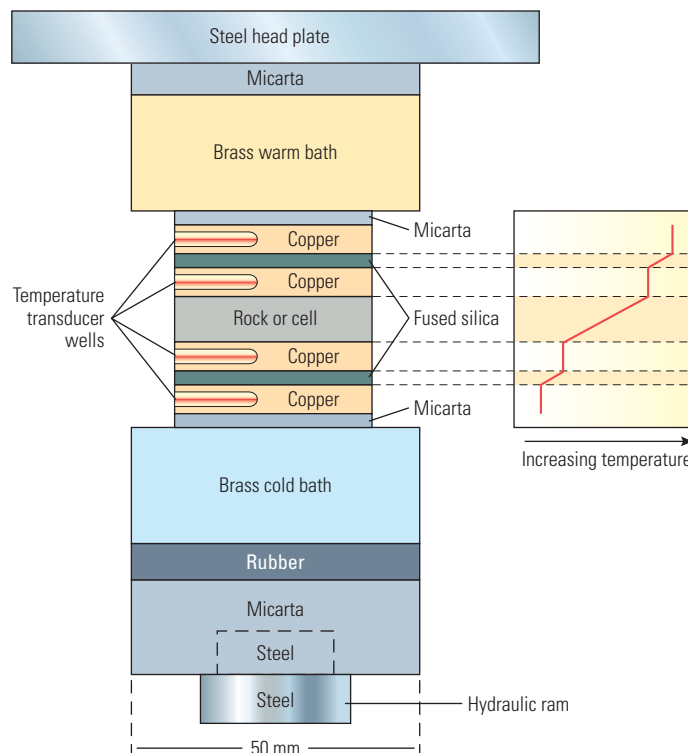
In the enormous volume of petrophysical data from geologic formations around the world, there are relatively few measurements of thermal properties of reservoir rocks made in the laboratory or in situ. As a result, engineers often calculate these thermal properties by using crude predictive models, without reference to actual measurements on core samples. This lack of thermal measurements represents a big gap in current knowledge of reservoir rock properties.

One reason for the lack of data is that it is difficult to measure thermal rock properties. The long-time standard for measuring thermal conductivity, the divided bar method, obtains the property by placing a disk-shaped sample of material between two cylindrical metal bars held at constant temperature (above right).

After a steady state is reached, the sample's thermal conductivity is estimated by comparing the temperature drop across its faces with the drop across those of reference materials of known conductivity flanking the sample. The divided

bar method defines the standard for accuracy in measuring thermal conductivity, but is time-consuming. The measurement of a typical cylindrical sample, 3 to 5 cm [1.2 to 2.0 in.] in diameter and 1 to 3 cm [0.4 to 1.2 in.] long, takes

(continued on page 27)



^ Measuring rock thermal conductivity. The divided bar method is the standard laboratory technique for determining rock thermal conductivity. The method sandwiches a disk-shaped rock sample between brass plates—two ends of a divided bar—held at different temperatures. The sample is flanked by disks of a reference material of known thermal conductivity; fused silica, with a thermal conductivity of 1.38 W/m<sup>2</sup>K, is a commonly used reference. After a steady state is reached, as indicated by steady temperatures in the transducer wells, the sample's thermal conductivity is determined by comparing the temperature drop across its length with the drop across the reference material. The hydraulic ram compresses samples for measurements under high pressure. (Adapted from Popov et al, reference 12.)

1. For more on Kern River and modern methods of thermal EOR: Curtis C, Kopper R, Decoster E, Guzmán-García A, Huggins C, Knauer L, Minner M, Kupsch N, Marina Linares L, Rough H and Waite M: “Heavy-Oil Reservoirs,” *Oilfield Review* 14, no. 3 (Autumn 2002): 30–51.  
Alboudwarej H, Felix J, Taylor S, Badry R, Bremner C, Brough B, Skeates C, Baker A, Palmer D, Pattison K, Beshry M, Krawchuk P, Brown G, Calvo R, Cañas Triana JA, Hathcock R, Koerner K, Hughes T, Kundu D, López de Cárdenas J and West C: “Highlighting Heavy Oil,” *Oilfield Review* 18, no. 2 (Summer 2006): 34–53.  
Allix P, Burnham A, Fowler T, Herron M, Kleinberg R and Symington B: “Coaxing Oil from Shale,” *Oilfield Review* 22, no. 4 (Winter 2010/2011): 4–15.  
Butler RM: *Thermal Recovery of Oil and Bitumen*. Englewood Cliffs, New Jersey, USA: Prentice Hall, 1991.  
For a comprehensive report on methods developed in the former Soviet Union: Bokserman AA, Filippov VP, Filanovskii VYu: “Oil Extraction,” in Krylov NA, Bokserman AA and Stavrovsky ER (eds): *The Oil Industry*

*of the Former Soviet Union: Reserves and Prospects, Extraction, Transportation*. Amsterdam: Gordon and Breach Publishers (1998): 69–184.

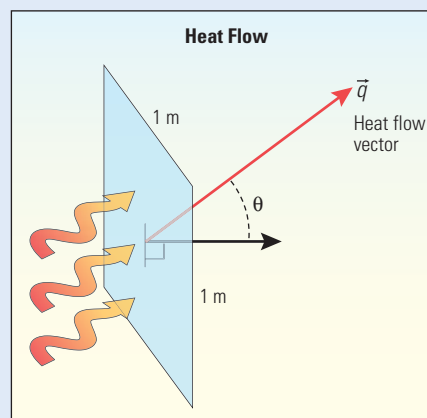
For a recent comprehensive review of enhanced recovery: Alvarado V and Manrique E: “Enhanced Oil Recovery: An Update Review,” *Energies* 3, no. 9 (2010): 1529–1575.

2. Mamedov YG and Bokserman AA: “Development of Heavy Oils and Natural Bitumens in the Former Soviet Union and Eastern and Central Europe: State-of-the-Art and Outlook,” *Proceedings of the Sixth UNITAR International Conference on Heavy Crude and Tar Sands*, Houston, February 12–17, 1995: 11–18.  
Chertenkov MV, Mulyak VV and Konoplev YP: “The Yarega Heavy Oil Field—History, Experience, and Future,” *Journal of Petroleum Technology* 64, no. 4 (April 2012): 153–160.
3. Chertenkov et al, reference 2.
4. The three thermal properties are not independent; thermal diffusivity is the ratio of thermal conductivity to volumetric heat capacity.

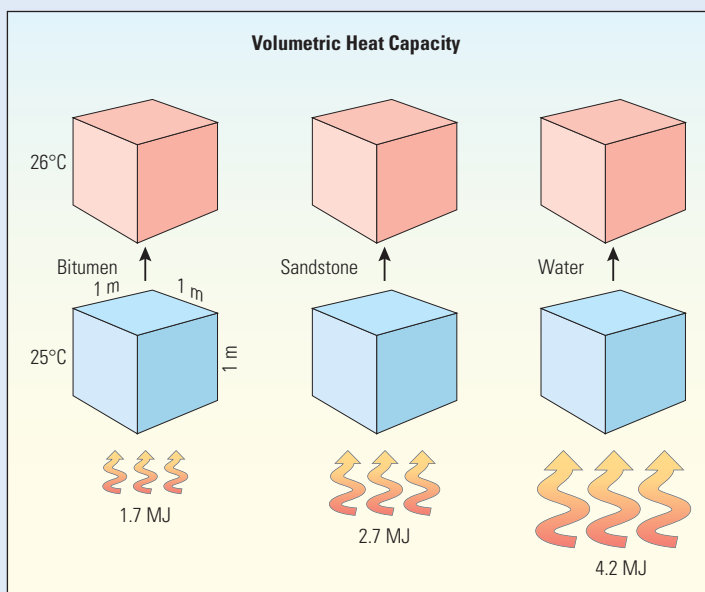
## Physics of Temperature and Heat

Thermal properties connect temperature and heat flow, which are fundamental concepts in physics and classical thermodynamics. Temperature is a measure of the average energy content of macroscopic bodies—solids, liquids and gases—while heat flow represents the transfer of thermal energy between bodies or regions at different temperatures. Temperature has its own basic SI unit, degrees kelvin ( $^{\circ}\text{K}$ ), with absolute zero ( $0^{\circ}\text{K}$ ) as the lowest possible temperature. In the commonly used Celsius scale ( $^{\circ}\text{C}$ ), the freezing point of water is taken as  $0^{\circ}\text{C}$ , placing absolute zero at  $-273.15^{\circ}\text{C}$ . A difference of one degree in either scale represents the same change in temperature.

Volumetric heat capacity, thermal conductivity, thermal diffusivity and the coefficient of thermal expansion are the main thermal properties of interest for engineers. Volumetric heat capacity (VHC) measures the amount of heat needed to raise the temperature of a unit volume ( $1\text{ m}^3$ ) of a substance by  $1^{\circ}\text{K}$  (below). The original unit of heat, the Calorie, was defined in 1824, by the French physicist and chemist Nicolas Clément, as the amount of heat needed to raise 1 kg of water by  $1^{\circ}\text{C}$ . The later discovery, by the English physicist and brewer James Prescott Joule, of the equivalence of heat and mechanical energy led to replacement of the Calorie as a basic physical unit by the derived unit for mechanical or kinetic energy,  $\text{kg m}^2/\text{s}^2$ —now called the



^ Heat flow. Heat flow is a vector quantity,  $q$ , whose magnitude, at any point in a material, gives the amount of thermal energy flowing per unit time across a surface of unit area oriented perpendicular to the vector direction. If the heat flow vector (red arrow) is oriented at an angle,  $\theta$ , to the surface, energy flow across the surface is reduced by the cosine of the angle.



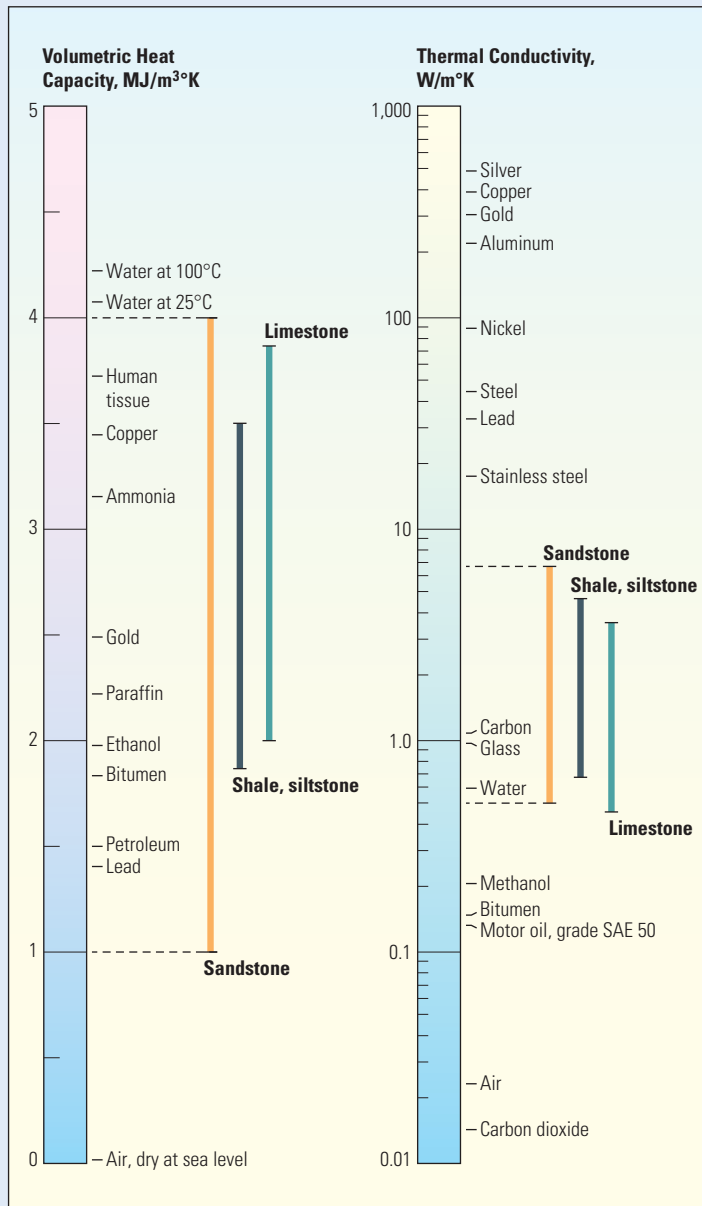
^ Volumetric heat capacity. Volumetric heat capacity is the amount of thermal energy in the form of heat needed to raise the temperature of a unit volume of material— $1\text{ m}^3$  in SI units—by  $1^{\circ}\text{K}$ , starting from a given temperature  $T_0$ . There can be no change of phase, such as melting, during the temperature rise. The volumetric heat capacity of dry sandstone typically falls between that of bitumen and water.

joule (J). Clément's Calorie, which is equivalent to about 4.2 kJ, survives today as the common unit for measuring the energy content of food. Since  $1\text{ m}^3$  of water weighs 1,000 kg, the volumetric heat capacity of water is about  $4.2\text{ MJ}/\text{m}^3\text{K}$ . The volumetric heat capacity of rocks is generally lower, in the range 1 to  $4\text{ MJ}/\text{m}^3\text{K}$  (next page, bottom left).

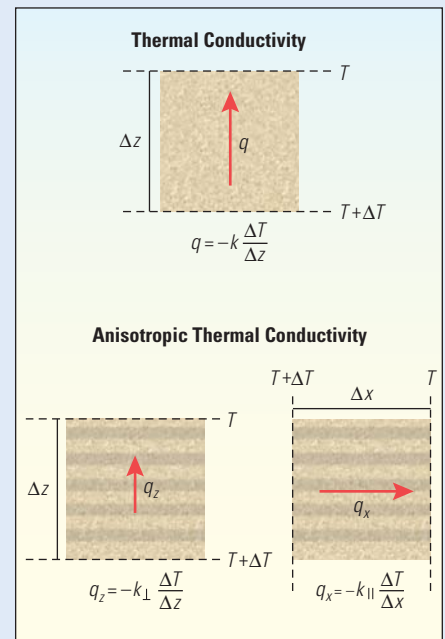
Temperature differences drive the flow of thermal energy—the flow of heat (above). Like the flow of fluid or electrical current, heat flow has both magnitude and direction and is therefore represented as a vector quantity. The magnitude of the heat flow vector gives the amount of thermal energy per second crossing a surface of unit area oriented perpendicular to the direction of the vector. The units of heat flow are thus energy per unit time per unit area, or power per unit area and are conventionally taken as watt per square meter ( $\text{W}/\text{m}^2$ ).

Thermal conductivity provides the quantitative connection between heat flow and temperature differences (right). It can be defined by considering a cube of homogeneous material with a temperature difference between two opposite faces. The amount of heat flowing through the cube, from the high- to low-temperature faces, is

proportional to the temperature difference divided by the distance between the faces. The constant of proportionality is the thermal conductivity, which thus has units of  $\text{W/m}^\circ\text{K}$ . The thermal conductivity of water is about  $0.6 \text{ W/m}^\circ\text{K}$ . The thermal conductivity of rocks is generally higher, in a range from about  $0.5$  to  $6.5 \text{ W/m}^\circ\text{K}$ .

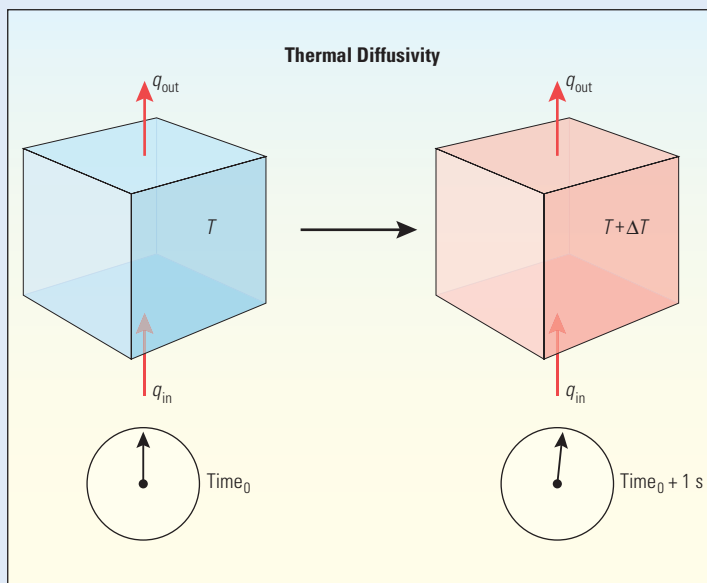


▲ Thermal properties of common materials.

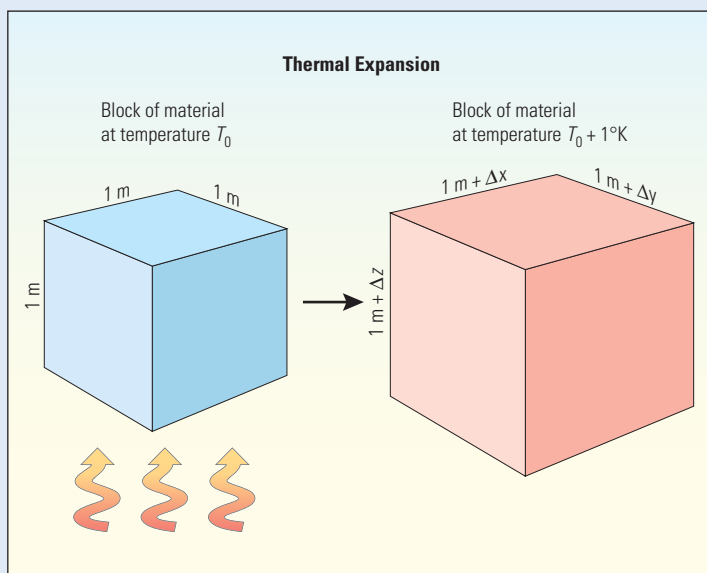


▲ Thermal conductivity. Thermal conductivity relates temperature gradients and heat flow. A block of material with a temperature difference  $\Delta T$  across two opposing faces separated by a distance  $\Delta z$  sustains a heat flow whose magnitude is proportional to the temperature difference divided by the distance (top). The proportionality constant is the block's thermal conductivity  $k$ . Many materials display anisotropic thermal conductivity, in which temperature differences placed across different pairs of opposing faces of a cube result in different magnitudes of heat flow (bottom). Thermal anisotropy is common in finely layered materials, such as rocks, where the thermal conductivity parallel to layers ( $k_{\parallel}$ ) is up to 50% higher than thermal conductivity perpendicular to layers ( $k_{\perp}$ ).

Some materials, including rocks, exhibit macroscopic thermal anisotropy; for example, different numerical values for thermal conductivity result from measurements across different pairs of opposing faces on a cube of the material. The simplest type of thermal anisotropy, common in rocks, arises when the material has a layered structure at fine scales. The thermal conductivity in the direction perpendicular to the layering is generally lower than the conductivity in any direction parallel to the layering.



▲ Thermal diffusivity. Thermal diffusivity controls the rate at which temperature rises in a uniform block of material when more heat is flowing into the block than flowing out. If an initial temperature gradient is established between the block and its surroundings, the heat fluxes in and out are determined by the block's thermal conductivity, while the temperature rise caused by the heat imbalance is determined by the block's volumetric heat capacity. Thermal diffusivity is thus the ratio of thermal conductivity to volumetric heat capacity.



▲ Thermal expansion. The coefficient of thermal expansion measures a fractional change in linear dimension of a uniform cube for a unit temperature rise. Each side of the cube may expand by a different amount in anisotropic materials.

Volumetric heat capacity and thermal conductivity combine to determine a third thermal property, called thermal diffusivity (left). Imagine a cube of uniform material with more heat flowing in through the bottom face than is flowing out through the top face. The difference in the two flows is the rate at which heat is being added to the cube, which will cause its temperature to rise. Since the rate of heat flow is determined by the material's thermal conductivity and the temperature increase by its volumetric heat capacity, the rate of temperature increase is obtained by dividing the thermal conductivity by the volumetric heat capacity. This ratio, called thermal diffusivity, governs the speed at which temperature changes propagate through a material.

Temperature is not the only property that changes when a cube of material is heated: Most substances also expand. The rate of linear expansion—defined as the fractional increase in length of a cube's sides per unit temperature rise—is called the coefficient of linear thermal expansion (below left). The thermal expansion of reservoir rocks provides an important link between the thermal and mechanical responses of the reservoir during thermal EOR.

Thermal conductivity, heat capacity, thermal diffusivity and the coefficient of thermal expansion are properties that apply to macroscopic chunks of matter. The concepts break down when applied to individual atoms or molecules of a substance. Like all macroscopic properties—including petrophysical properties such as porosity, permeability and electrical conductivity—thermal properties may vary from point to point in a rock formation and depend on its temperature and pressure.

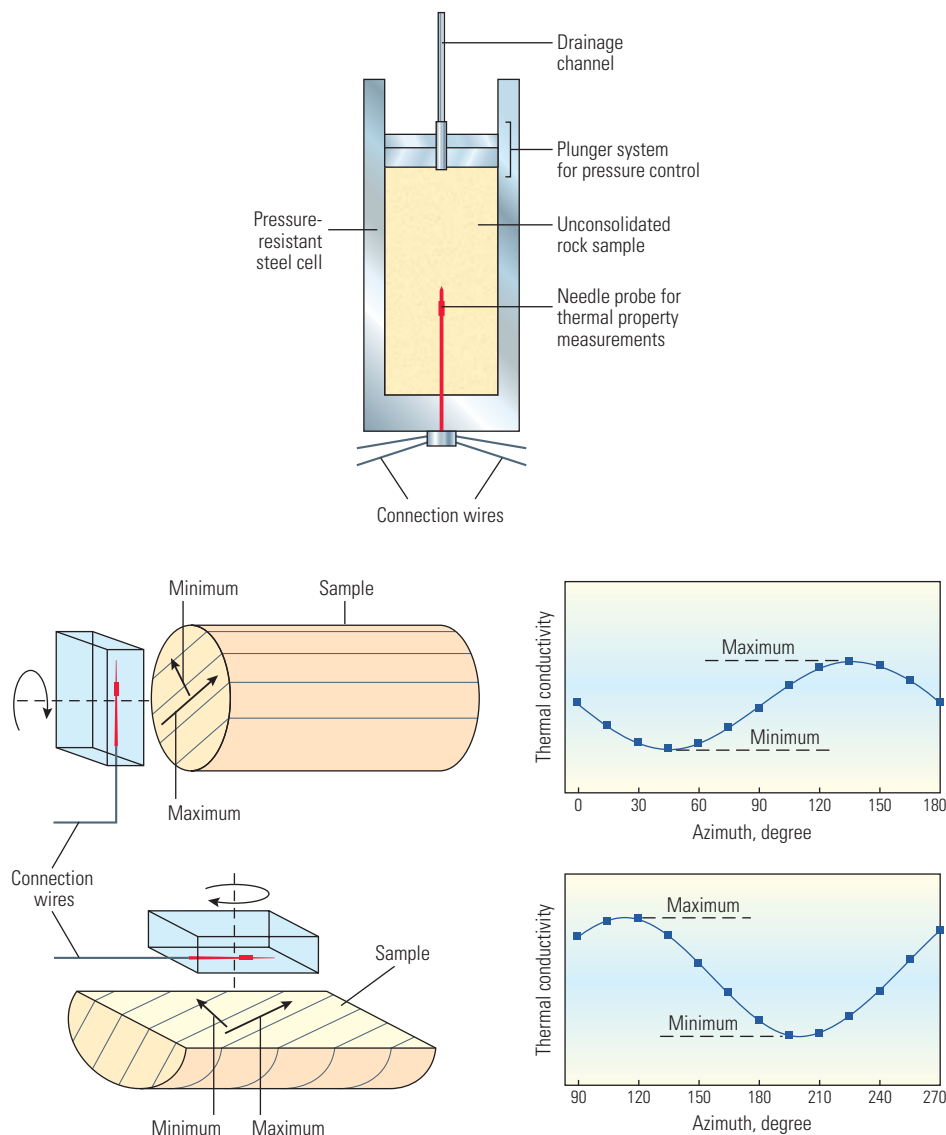


about 10 to 15 minutes. In addition, laboratory technicians must spend an hour or two cutting, trimming and polishing the disk to ensure good thermal contact with the heating bars. This last step is difficult to complete with fractured or poorly consolidated reservoir rocks.<sup>5</sup>

Alternatives to the steady state method are transient methods in which a scientist applies a pulse of heat to the sample, usually with a needle-shaped probe, and records the temperature response at one or more locations on the sample (right). Thermal conductivity or diffusivity is then calculated from a theoretical model that predicts how the material should respond in the given configuration. One configuration of this transient line source method, which is useful for measuring loose samples such as unconsolidated sediments and soils, applies the pulse of heat along a thin wire that carries a temperature sensor at its midpoint. This wire is inserted, like a hypodermic needle, into the material and measures the temperature as a function of time. In another configuration, a scientist places the needle-shaped probe with its sensor on the flat top of a cylindrical core and records this surface's temperature response to a pulse of heat.<sup>6</sup>

Because thermal conductivity relates two directional quantities, the temperature gradient and the heat flow vector, its value may depend on the direction of measurement, for example, on the direction of the temperature gradient imposed on a sample. The line source method provides a convenient way of characterizing directional dependence: Any variation of the temperature response as the needle is rotated through various directions on the surface of the core indicates that its thermal conductivity is anisotropic—heat flows preferentially in certain directions through the rock.

The most common form of anisotropy in crustal rocks is the result of features such as thin layers or oriented fractures that determine the directional characteristics of a rock's bulk physical properties. The simplest example is fine layering or bedding, which is present in nearly all clastic reservoir and source rocks—sandstones and shales—and distinguishes the direction perpendicular to the layers from the directions parallel to the layers. This type of anisotropy induced by layering—also called transverse isotropy, axial anisotropy or cross anisotropy—may be present in sedimentary and igneous rocks permeated by thin oriented fractures, and in metamorphic rocks that have been compressed strongly in



^ Measuring thermal conductivity of unconsolidated or anisotropic materials. The line source method determines thermal conductivity by placing a thin probe with a heating element and temperature sensor in contact with a sample. A theoretical model predicting the temperature response to a pulse of heating is used to calculate the sample's thermal conductivity. For unconsolidated samples, the probe is inserted, like a hypodermic needle, inside the material (top). For solid rocks, the probe is attached to the bottom of a Plexiglas block placed on the surface of the sample. For laminated samples cut at an angle to the measurement surface, the response of the probe changes as it rotates through various directions (bottom). Variations in response with angle may be used to determine the thermal anisotropy of layered rocks.

5. Beck A: "A Steady State Method for the Rapid Measurement of the Thermal Conductivity of Rocks," *Journal of Scientific Instruments* 34, no. 5 (May 1957): 186–189.
- Pribnow DFC and Sass JH: "Determination of Thermal Conductivity for Deep Boreholes," *Journal of Geophysical Research* 100, no. B6 (June 10, 1995): 9981–9994.
- Beck AE: "Methods for Determining Thermal Conductivity and Thermal Diffusivity," in Haenel R, Rybach L and Stegena L (eds): *Handbook on Terrestrial Heat Flow Density Determination*. Dordrecht, the Netherlands: Kluwer (1988): 87–124.
6. Jaeger JC: "The Measurement of Thermal Conductivity with Cylindrical Probes," *EOS Transactions American Geophysical Union* 39, no. 4 (1958): 708–710.

- Von Herzen R and Maxwell AE: "The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method," *Journal of Geophysical Research* 64, no. 10 (October 1959): 1557–1563.
- Waite WF, Gilbert LY, Winters WJ and Mason DH: "Estimating Thermal Diffusivity and Specific Heat from Needle Probe Thermal Conductivity Data," *Review of Scientific Instruments* 77, no. 4 (April 2006): 1–5.
- Woodside W and Messmer JH: "Thermal Conductivity of Porous Media. I. Unconsolidated Sands," *Journal of Applied Physics* 32, no. 9 (September 1961): 1688–1699.
- Woodside W and Messmer JH: "Thermal Conductivity of Porous Media. II. Consolidated Rocks," *Journal of Applied Physics* 32, no. 9 (September 1961): 1699–1706.



one direction and, as a result, have acquired a distinctive planar fabric.<sup>7</sup>

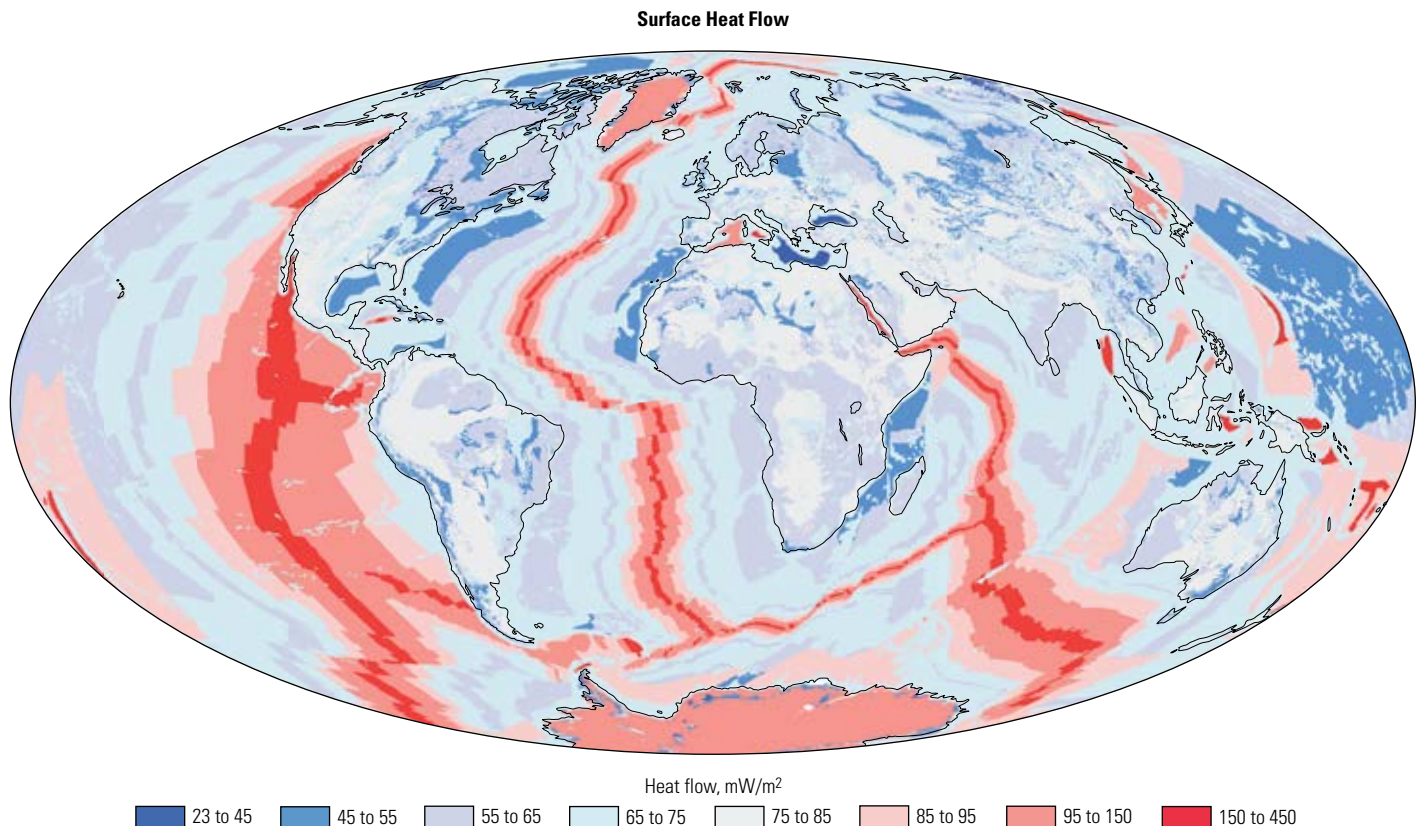
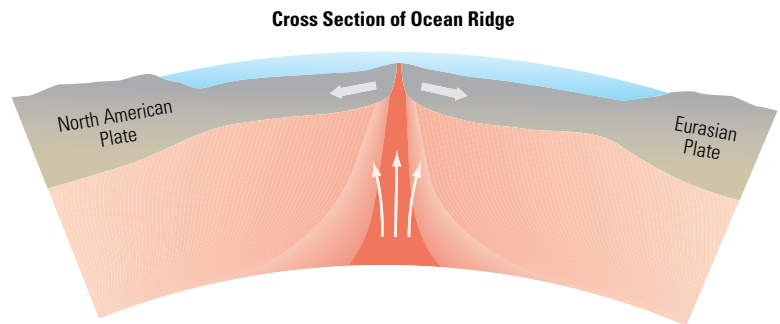
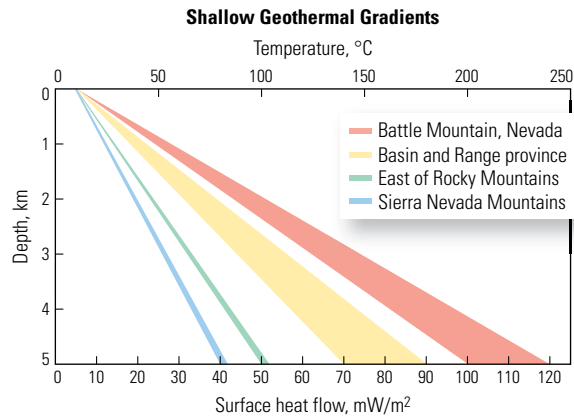
In finely layered rocks, the value of thermal conductivity in the direction perpendicular to the layers—and therefore the heat flow for a given temperature drop—is usually 5% to 30% lower than its value in directions parallel to the layers; in some rocks, the difference is as high as 50%. The physics and mathematics of thermal anisotropy are similar to those of electrical

anisotropy, which is critical to the proper evaluation of laminated reservoirs.<sup>8</sup>

### Measuring Thermal Properties by Optical Scanning

Most of the fundamental science of rock thermal properties was carried out in two waves. The first took place in the 1930s, when scientists began to unravel the thermal structure of Earth's interior; the second occurred during the years of the plate

tectonics revolution of the 1960s and 1970s, when scientists recognized that the Earth's internal heat and its flow to the surface were driving forces of global tectonics. Much of the latter research was devoted to mapping heat flow through ocean basins, which shows the thermal signature of convection patterns in the Earth's deep interior (*below*).<sup>9</sup> Scientists study thermal rock properties as a necessary component for heat flow determination and to understand the

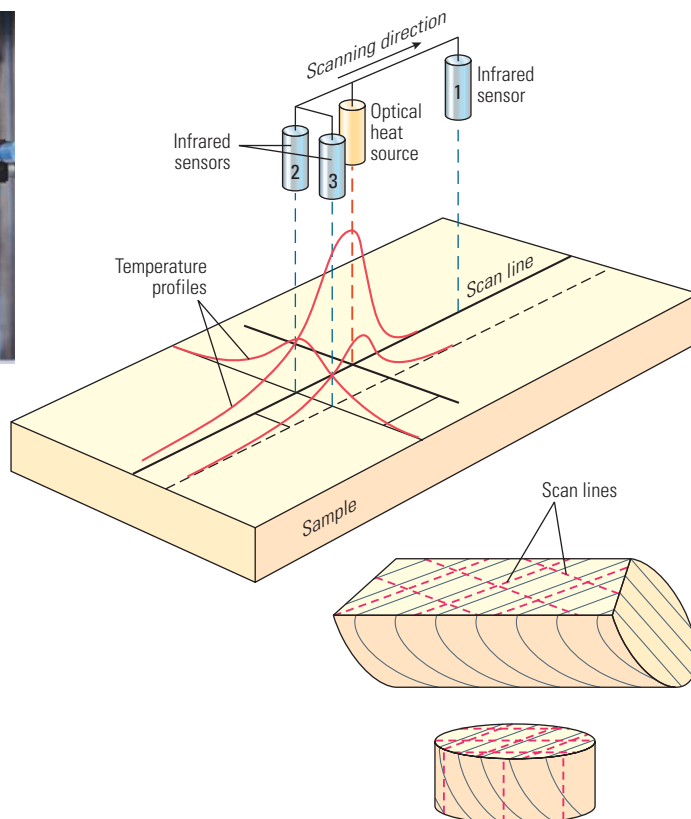


^ Earth's surface heat flow. Flow of heat from the Earth's deep interior to the surface is a driving force of global tectonics. A map of surface heat flow highlights ocean ridges, where magma derived from partial melting of the upper mantle rises to the surface to create new oceanic crust (*bottom*, adapted from Davies and Davies, reference 9). To produce this map, Davies and Davies compiled nearly 40,000 measurements, from which correlations of heat flow with geologic regions were derived to extend the discrete measurements using a digital map of global geology. At ocean ridges (*top right*), heat flow is dominated by convection—the movement of hot material (white arrows) from depth to the surface. Over the continents, average heat flow is determined by the geothermal gradient—the variation of temperature with depth—and the thermal conductivity of crustal rocks. The graph shows geothermal gradients in the shallow crust for several regions of the US (*top left*). Each geothermal gradient corresponds to a different value of surface heat flow.

potential of geothermal energy. Beginning in the 1980s, researchers looked at thermal properties of sedimentary rocks to provide input to model the thermal history of basins in early quantitative attempts at petroleum system modeling.<sup>10</sup>

These lines of research converged in a study of thermal and other petrophysical measurements on rocks from deep scientific boreholes, including the 12,262-m [40,230-ft] Kola Superdeep Borehole in the Soviet Union, the deepest hole ever drilled. The work was driven by the recognition that thermal properties measured along the track of long scientific boreholes were much more heterogeneous than previously imagined. Scientists realized that new methods were needed to characterize the thermal properties of rocks, including better methods of measuring these properties in situ, as well as laboratory methods that worked more rapidly and at higher resolution on smaller core samples.<sup>11</sup>

In the 1990s, scientists from Russia, Germany and the US participated in a joint study of major laboratory methods for measuring thermal conductivity, focusing on cores from the superdeep KTB borehole in Germany.<sup>12</sup> One method in this study used an optical device developed in the early 1980s in the former Soviet Union. Unlike prior techniques for measuring thermal properties, the optical method is contactless—no sensor touches the material; instead, the device uses remote optical thermal sensors to scan the sample surface for the thermal signature of a constant, focused heat source (right). The source and sensors move together along the sample—a core, for example—in a fixed arrangement that



^ Principle of the optical scanning method. Optical scanning provides a fast, contactless method of measuring thermal properties (*top right*). This method determines thermal conductivity and thermal diffusivity by heating a spot on the sample with a moving optical heat source—a laser or focused electric light (*top left*). Three infrared sensors, moving in tandem with the source, measure temperature at the surface of the sample. Sensor 1 is situated ahead of the heat source along the scan line to register surface temperature before the sample is heated. Two trailing sensors register the temperature rise induced by the heating: Sensor 2 measures along the scan line, and Sensor 3, along a parallel line (dashed black). A theoretical model predicting the temperature at these two locations as a function of time is used to calculate the thermal conductivity and thermal diffusivity at various locations under the scan line. By scanning the sample in three different directions, the method can determine anisotropic thermal properties of laminated rocks (*bottom right*).

7. Transverse isotropy, axial anisotropy and cross anisotropy are synonymous terms referring to the particular directional character of materials in which properties have the same values in all directions parallel to planes of isotropy and different values perpendicular to or crossing the planes of isotropy; this perpendicular direction is the axis of cylindrical symmetry.
8. Thin oil-bearing layers in laminated reservoirs significantly increase the resistance to current flow, but only in the direction perpendicular to the beds. A resistivity logging tool that measures resistance in directions parallel to the beds generally will not detect the presence of oil. For more on the anisotropy of finely layered formations: Anderson B, Barber T, Leveridge R, Bastia R, Saxena KR, Tyagi AK, Clavaud J-B, Coffin B, Das M, Hayden R, Klimonts T, Minh CC and Williams S: "Triaxial Induction—A New Angle for an Old Measurement," *Oilfield Review* 20, no. 2 (Summer 2008): 64–84.
9. The earliest systematic studies of Earth's surface heat flow were a series of papers in the late 1930s: Anderson EM: "The Loss of Heat by Conduction from Earth's Crust," *Proceedings of the Royal Society of Edinburgh* 60, part 2. Edinburgh, Scotland: Robert Gran and Son, Ltd. (1939–1940): 192–209.  
Benfield AE: "Terrestrial Heat Flow in Great Britain," *Proceedings of the Royal Society of London A* 173, no. 955 (December 29, 1939): 428–450.

Krige LJ: "Borehole Temperatures in the Transvaal and Orange Free State," *Proceedings of the Royal Society of London A* 173, no. 955 (December 29, 1939): 450–474.

Bullard EC: "Heat Flow in South Africa," *Proceedings of the Royal Society of London A* 173, no. 955 (December 29, 1939): 474–502.

Birch AF and Clark H: "The Thermal Conductivity of Rocks and Its Dependence on Temperature and Composition, Part I," *American Journal of Science* 238, no. 8 (August 1940): 529–558.

Birch AF and Clark H: "The Thermal Conductivity of Rocks and Its Dependence on Temperature and Composition, Part II," *American Journal of Science* 238, no. 9 (September 1940): 613–635.

Many researchers contributed to mapping surface heat flow over the globe and unraveling its relation to plate tectonics. For more: Sclater JG and Francheteau J: "The Implications of Terrestrial Heat Flow Observations on Current Tectonic and Geochemical Models of the Crust and Upper Mantle of the Earth," *Geophysical Journal of the Royal Astronomical Society* 20, no. 5 (September 1970): 509–542.

The most recently published compilation of surface heat flow data: Davies JH and Davies DR: "Earth's Surface Heat Flux," *Solid Earth* 1, no. 1 (February 22, 2010): 5–24.

10. Brigaud F, Chapman DS and Le Douaran S: "Estimating Thermal Conductivity in Sedimentary Basins Using Lithologic Data and Geophysical Well Logs," *AAPG Bulletin* 74, no. 9 (September 1990): 1459–1477.

McKenna TE, Sharp JM Jr and Lynch FL: "Thermal Conductivity of Wilcox and Frio Sandstones in South Texas (Gulf of Mexico Basin)," *AAPG Bulletin* 80, no. 8 (August 1996): 1203–1215.

For more on petroleum system modeling: Al-Hajeri MM, Al Saeed M, Derks J, Fuchs T, Hantschel T, Kauerauf A, Neumaier M, Schenk O, Swientek O, Tessen N, Welte D, Wygrala B, Kornpil D and Peters K: "Basin and Petroleum System Modeling," *Oilfield Review* 21, no. 2 (Summer 2009): 14–29.

11. Orlov VP and Laverov NP (eds): *Kola Superdeep Well: Scientific Results and Research Experience*. Moscow: Technoneftegaz, 1998 (in Russian).

Burkhardt H, Honarmund H and Pribnow D: "Test Measurements with a New Thermal Conductivity Borehole Tool," *Tectonophysics* 244, nos. 1–3 (April 15, 1995): 161–165.

12. Popov YA, Pribnow DFC, Sass JH, Williams CF and Burkhardt H: "Characterization of Rock Thermal Conductivity by High-Resolution Optical Scanning," *Geothermics* 28, no. 2 (April 1999): 253–276.

KTB is the Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland, or German Continental Deep Drilling Program. For more on the KTB borehole: Bram K, Draxler J, Hirschmann G, Zoth G, Hiron S and Kühr M: "The KTB Borehole—Germany's Superdeep Telescope into the Earth's Crust," *Oilfield Review* 7, no. 1 (January 1995): 4–22.

allows the first sensor to register the ambient surface temperature under laboratory conditions. After a spot on the surface has been heated by the source—either a laser or a focused electric light—one or two trailing sensors record the rise in temperature along lines parallel to the trace of the heated spot.<sup>13</sup>

Optical scanning uses tailored theoretical models to determine thermal properties from the

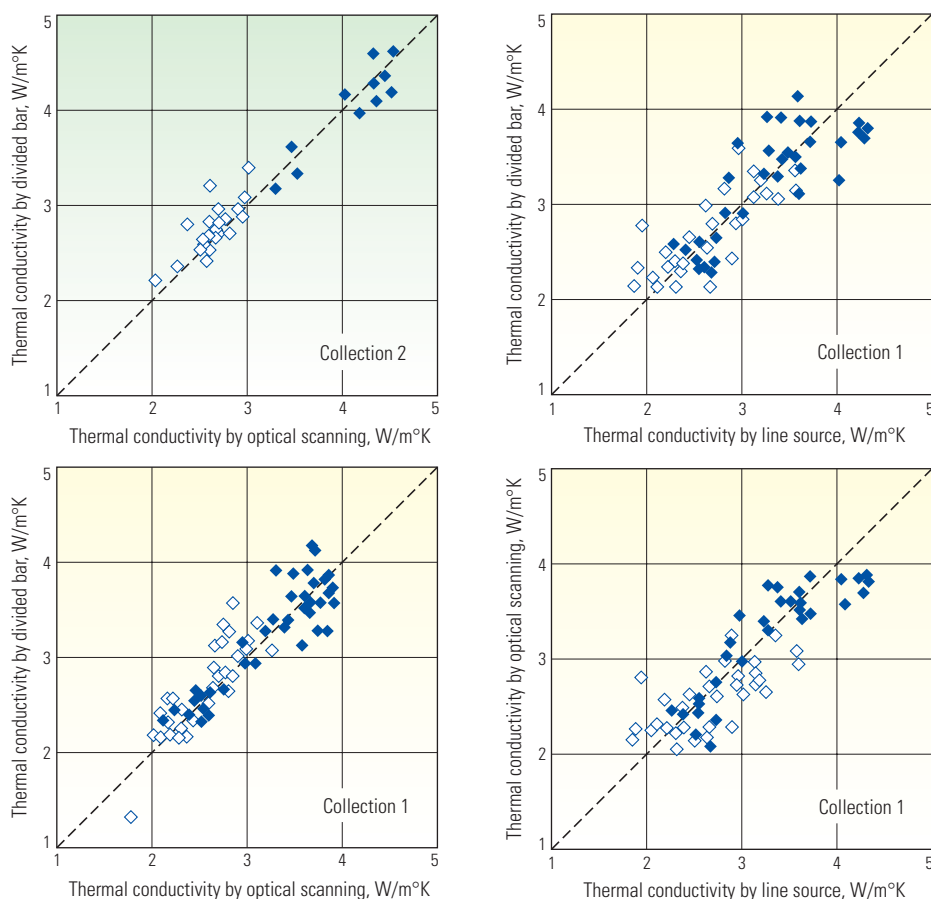
recorded temperature profiles. According to a model for the arrangement with two thermal sensors flanking the heat source, the maximum temperature rise seen by the trailing sensor is directly proportional to the source power, in watts, and inversely proportional to the product of the source-sensor separation and the sample's thermal conductivity. This model can be inverted for the unknown thermal conductivity, given the mea-

sured temperature rise, source-to-sensor distances and source power. Alternatively, thermal conductivity can be determined by comparing the temperature rise in the sample with that in a standard material of known conductivity placed next to it in the scan line. Another common configuration adds a second trailing sensor offset from the main scan line and uses two different standards flanking the sample to determine both thermal diffusivity and thermal conductivity. Aligning the axis of the scan along various directions through the rock allows characterization of the thermal conductivity of an anisotropic sample; full characterization requires scans along three distinct directions lying in two nonparallel planes.

Nearly all of the core samples from the KTB borehole were crystalline metamorphic rocks, chiefly amphibolites and gneisses, possessing a distinctive foliation and requiring measurement of thermal conductivity parallel and perpendicular to their planar fabric.<sup>14</sup> The joint international study of cores from the KTB borehole demonstrated that measurements of thermal properties by optical scanning compare well in precision, or repeatability, and in accuracy with measurements made by the divided bar and line source methods (left). The divided bar measurements were conducted with a device maintained and continually improved since the late 1960s by the US Geological Survey; the line source measurements were conducted with a unit specially constructed at the Technische Universität Berlin to work on cores from deep scientific wells. Differences between optical scanning and divided bar measurements averaged 2.1%, with a standard deviation of 6.5%; the closest agreement was for measurements in directions parallel to rock foliation. Differences between optical scanning and line source measurements were generally less than 5%.<sup>15</sup>

The accuracy and reliability of thermal properties measured by optical scanning have since been confirmed on thousands of core samples. Many of these cores come from deep scientific wells drilled into large impact structures such as the Puchezh-Katunki impact structure in Russia, the Ries impact structure in Germany, the Chesapeake crater in the US and the Chicxulub crater in Mexico.<sup>16</sup> This work established that optical scanning measurements can be accurate to within 1.5% for thermal conductivity within the range 0.1 to 50 W/m<sup>2</sup>K and to within 2% for thermal diffusivity in the range  $0.1 \times 10^{-6}$  to  $5 \times 10^{-6}$  m<sup>2</sup>/s. The remote sensing and nondestructive nature of optical scanning allows easy, repeated testing of samples of a variety of sizes; the laboratory instrument used in the scientific studies characterizes samples from 1 to 70 cm [0.4 to 28 in.] long.

Optical scanning measurements are also relatively immune to the shape and quality of the sample

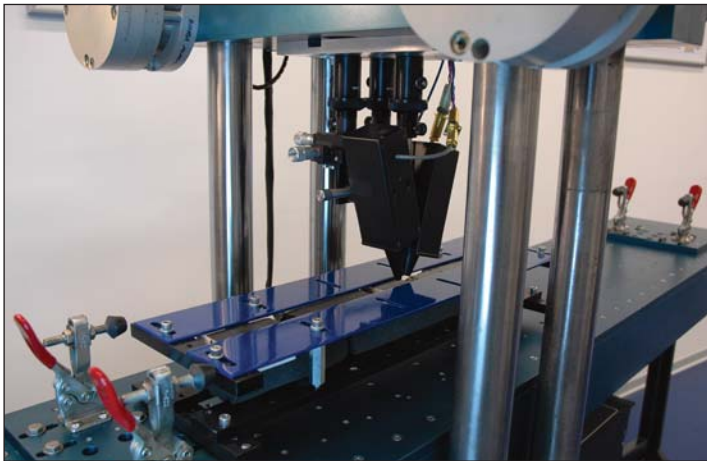


▲ Thermal properties of rock samples from the superdeep KTB borehole. A study of core samples from the KTB borehole in Germany (top) demonstrated that measurements of thermal conductivity by optical scanning compare well with measurements made by the divided bar and line source methods. The crossplot at upper left, for example, shows good agreement between optical scanning measurements of thermal conductivity and divided bar measurements on 36 different samples cut from the KTB cores. Scientists prepared this collection so that the same physical rock sample could be used in both instruments. The remaining crossplots compare one method against another when two different rock samples are cut from the same core. Open diamonds represent measurements in the direction parallel to the rock foliation; solid diamonds represent measurements perpendicular to the foliation. (Adapted from Popov et al, reference 12.)



surface, tolerating up to 1 mm [0.04 in.] of roughness with little loss of accuracy. The scan speed is routinely set between 1 and 10 mm [0.04 and 0.4 in.] per second, which usually allows a throughput of about one sample per minute. Slower speeds and a smaller distance between the heating spot and temperature sensor enlarge the measurement's depth of investigation, which can be up to 3 cm in samples with moderate to high thermal conductivity.

A new instrument developed at Schlumberger Moscow Research Center and engineered at the Schlumberger Innovation Center in Salt Lake City, Utah, USA, has further refined the specifications for rapid, high-resolution optical measurement of thermal properties (right). This instrument for rock profiling, housed at TerraTek Rock Mechanics and Core Analysis Services laboratory, can detect heterogeneity in thermal conductivity and thermal diffusivity—or volumetric heat capacity, as calculated from these two quantities—with a resolution better than 0.4 mm [0.016 in.] at a core scanning velocity of 3.0 mm/s [0.12 in/s] (below right).<sup>17</sup>



Parameter	Value
Thermal conductivity range	0.2 to 6.0 W/m <sup>2</sup> K
Thermal diffusivity range	(0.1 to 2.5) × 10 <sup>-6</sup> m <sup>2</sup> /s
Accuracy of thermal conductivity	4%
Accuracy of thermal diffusivity	5%
Spatial resolution in rock profiling	Better than 0.4 mm
Scanning velocity	3.0 mm/s

▲ High-resolution optical scanner at the Schlumberger Innovation Center in Salt Lake City, Utah.

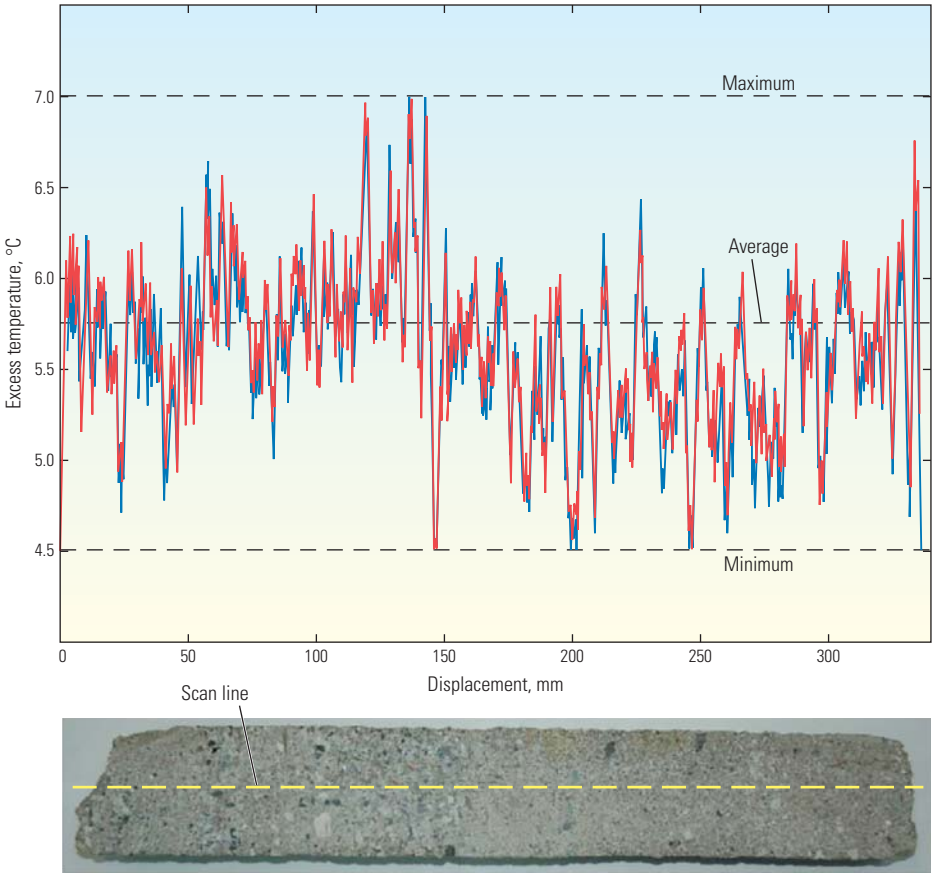
13. Popov Yu A: "Theoretical Models for Determination of the Thermal Properties of Rocks on the Basis of Movable Sources of Thermal Energy, Part I," *Geologiya i Razvedka* (Geology and Prospecting) no. 9 (September 1983): 97–105 (in Russian).  
 Popov Yu A: "Theoretical Models for Determination of the Thermal Properties of Rocks on the Basis of Movable Sources of Thermal Energy, Part II," *Geologiya i Razvedka* (Geology and Prospecting) no. 2 (February 1984): 81–88 (in Russian).  
 Popov Yu A: "Peculiarities of the Method of Detailed Investigations of Rock Thermal Properties," *Geologiya i Razvedka* (Geology and Prospecting) no. 4 (April 1984): 76–84 (in Russian).

14. Foliation is the layered fabric—the orientation, arrangement and texture of minerals, grains and other constituents in rock—of metamorphic rocks that have been strongly compressed in one direction.

15. Popov et al, reference 12.

16. Popov Yu, Pohl J, Romushkevich R, Tertychniy V and Soffel H: "Geothermal Characteristics of the Ries Impact Structure," *Geophysical Journal International* 154, no. 2 (August 2003): 355–378.  
 Popov Yu, Romushkevich R, Korobkov D, Mayr S, Bayuk I, Burkhardt H and Wilhelm H: "Thermal Properties of Rocks of the Borehole Yaxcopoil-1 (Impact Crater Chicxulub, Mexico)," *Geophysical Journal International* 184, no. 2 (February 2011): 729–745.  
 Mayr SI, Burkhardt H, Popov Y, Romushkevich R, Miklashevskiy D, Gorobtsov D, Heidinger P and Wilhelm H: "Physical Rock Properties of the Eyreville Core, Chesapeake Bay Impact Structure," in Gohn GS, Koeberl C, Miller KG and Reimold WU (eds): *The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes*. Boulder, Colorado, USA: The Geological Society of America, Special Paper 458 (2009): 137–163.  
 The Chicxulub crater is believed to be an imprint of the catastrophic asteroid impact that ended the age of dinosaurs. For more: Barton R, Bird K, García Hernández J, Grajales-Nishimura JM, Murillo-Muñetón G, Herber B, Weimer P, Koeberl C, Neumaier M, Schenk O and Stark J: "High-Impact Reservoirs," *Oilfield Review* 21, no. 4 (Winter 2009/2010): 14–29.

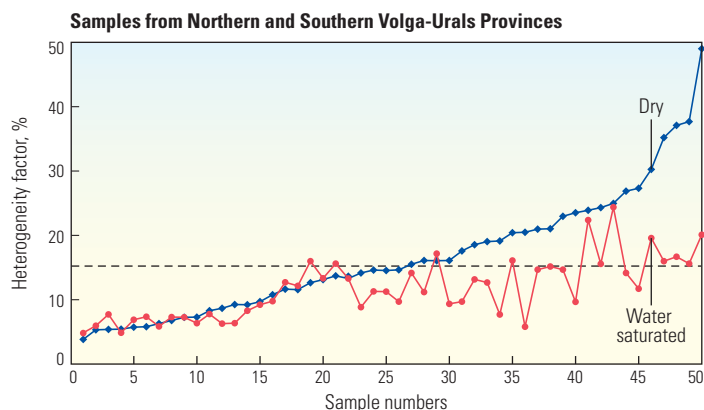
17. Popov Yu, Parshin A, Chekhonin E, Gorobtsov D, Miklashevskiy D, Korobkov D, Suarez-Rivera R and Green S: "Rock Heterogeneity from Thermal Profiles Using an Optical Scanning Technique," paper ARMA 12-509, presented at the 46th US Rock Mechanics/ Geomechanics Symposium, Chicago, June 24–27, 2012.



▲ Resolution and repeatability of optical scanning. Two optical scans (red and blue, top) of a gravelly sandstone core illustrate the strong heterogeneity of thermal properties in rocks and the repeatability of optical measurements. Excess surface temperature—the temperature rise measured along a scan line (yellow, bottom) after heating by the laser—is proportional to thermal conductivity. The difference between the maximum and the minimum, divided by the average, gives a measure of property heterogeneity.



^ Core samples from Russian oil provinces. Scientists have compared thermal conductivity measured by high-resolution optical scanning with other petrophysical properties on more than 8,000 core samples of sedimentary rocks from various petroleum provinces in Russia. The collection was supplemented by samples from deep scientific boreholes and oil fields in Germany, Mexico and the US.



^ Heterogeneity of thermal conductivity and porosity. Heterogeneity of rock thermal properties is closely related to variations in porosity. In this plot, 50 clay-rich limestone samples, studied under dry and water-saturated conditions, are arranged in order of increasing heterogeneity as measured under dry conditions (blue). Heterogeneity is quantified as the difference between the maximum and minimum thermal conductivities measured along a scan line, divided by the average value along the line. When this heterogeneity factor of a dry sample is less than about 15%, it changes by only a few percent when the sample is saturated with water and scanned again (red). When the heterogeneity factor of a dry sample is greater than 15%, it generally changes dramatically after water saturation. Scientists traced this effect to large spatial variations of porosity in samples with dry heterogeneity factors above 15%. (Adapted from Popov et al, reference 12.)

## Thermal Properties of Reservoir Rocks:

### A Growing Database

Because scientists are now better able to measure thermal properties, new avenues of petrophysics are opening up. Like many rock properties, thermal conductivity depends in complex ways on the composition and distribution of minerals in the rock matrix and fluids in its pore space. Studies going back to the 1950s have provided data on this dependence, but until recently such studies were limited by measurement techniques that were unable to resolve layers and fractures at scales finer than a few centimeters. Moreover, conventional techniques cannot determine thermal conductivity and diffusivity simultaneously and have difficulty characterizing unconsolidated rocks and core samples and plugs saturated with brine, oil or gas.<sup>18</sup>

Optical scanning avoids nearly all of the obstacles hindering accurate, routine determination of thermal rock properties. This method enabled a large petrophysical study of more than 8,000 samples, including sedimentary rocks of various lithologies, ages and geologic settings from eight geologic regions, to uncover new connections between thermal rock properties and the usual staples of petrophysical reservoir evaluation: porosity, permeability, electrical conductivity, acoustic velocity and fluid saturation.<sup>19</sup>

Most of the cores in this study came from basins in petroleum provinces of the former Soviet Union (above left). Scientists measured the thermal conductivity of all samples under both dry and fluid-saturated conditions, and the high-resolution scans revealed several key features of this diverse collection.

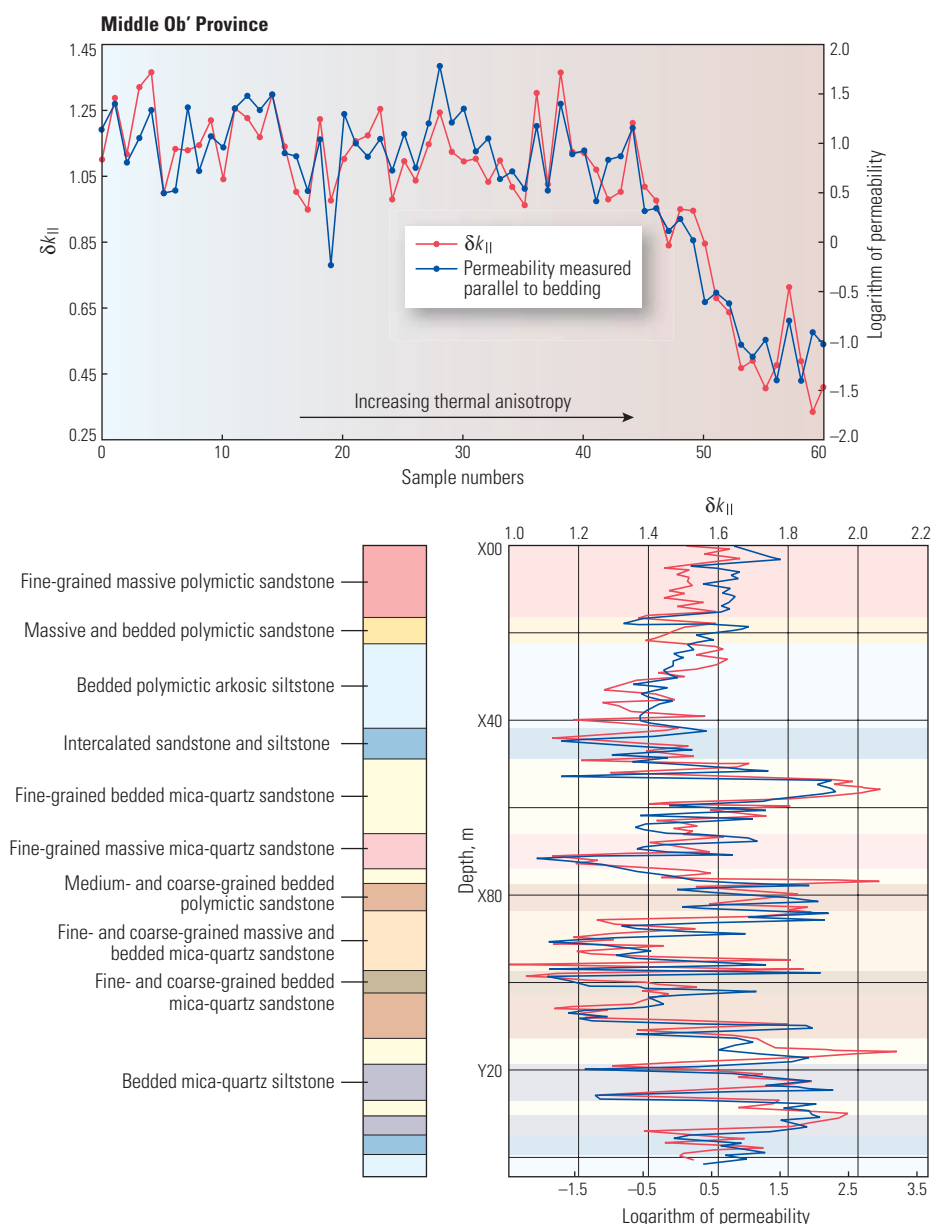
Scientists first discovered a wide variation of thermal properties within individual dry samples. A simple measure of heterogeneity within a sample is the difference between the maximum and minimum thermal conductivity measured along a scan line, divided by the average conductivity along the same line. This heterogeneity factor, expressed as a percentage, characterizes the range of conductivity in the sample as seen by optical scanning. Measured on dry samples, the factor varied from about 4% to 50% for rocks in the collection (left).

Second, and more interesting, was that the heterogeneity factor went no higher than about 15% when measured on samples saturated with water. This result could be explained by higher values of porosity in samples whose heterogeneity factor, when dry, was above about 15%. Void space, or air, has essentially zero thermal conductivity, in contrast to most solid rock, and is distributed in a complex way at scales below the

resolution of the optical scans—about 1 mm. When its low thermal conductivity is averaged with that of the rock matrix, void space has large effects on the result because an optical scan senses low and high values of conductivity depending on whether the heated spot contains more or less pore space. In contrast, when pore space is saturated with water, whose thermal conductivity is relatively close to that of solid rock, its effect on the average thermal conductivity is much less significant.

Scientists have known for some time that changes in thermal properties are caused by the opening of microscopic cracks and fissures in rock samples brought from high pressure deep underground to atmospheric pressure at the surface.<sup>20</sup> But high-resolution optical scans confirmed the importance, for thermal properties, of even small variations in natural porosity in sedimentary rocks. The threshold of 15% to 20% in the heterogeneity factor is significant: When variations along a scan line remain below this level on dry samples, saturating the rock with water does not change the measured range of scanned conductivity values. In such rocks, heterogeneity along a scan line arises directly from variations in composition or mineralogy of the rock matrix.

Optical scans have also revealed that anisotropy may be a key to unlocking new relationships among thermal and other petrophysical properties. One example is the relationship between thermal conductivity and permeability (right). These two properties depend not only on the amount of pore space, but also on its distribution through the rock volume—in isolated pores or in connected pathways. When compared on a collection of rock samples, permeability and thermal conductivity often show a wide scatter. But when the samples are limited to rocks with a heterogeneity factor above 20%—that is, to samples in which thermal conductivity is strongly affected by pore fluids—there appears to be a direct correlation between permeability and the percentage change in thermal conductivity in going from dry to water-saturated conditions. The relationship is strongest when both thermal conductivity and permeability are measured parallel



▲ Anisotropic thermal conductivity and permeability. Most sedimentary rocks have anisotropic thermal properties: Thermal conductivity measured in a direction parallel to the layering generally is 5% to 50% higher than its value measured perpendicular to the layering. Moreover, the value measured in each direction changes in going from dry to water-saturated conditions. The degree of thermal anisotropy and its change with fluid saturation are both related to permeability (top). Samples with higher thermal anisotropy generally have lower permeability. Moreover, the percentage change in thermal conductivity parallel to layering when going from dry to water-saturated conditions—a quantity labeled  $\delta k_{||}$  in these plots—closely tracks the logarithm of permeability. Measurements on core samples collected throughout a 140-m [450-ft] depth interval in the Middle Ob' province of Russia show that this correlation holds across different lithologies (bottom). (Adapted from Popov et al, reference 19.)

18. Early studies of the thermal properties of fluid-saturated porous rocks include the following:

Asaad Y: "A Study of the Thermal Conductivity of Fluid Bearing Porous Rocks," PhD thesis, University of California, Berkeley, USA, 1955.

Zierfuss H and van der Vliet G: "Laboratory Measurements of Heat Conductivity of Sedimentary Rocks," *AAPG Bulletin* 40, no. 10 (October 1956): 2475–2488.

Somerton WH: "Some Thermal Characteristics of Porous Rocks," *Petroleum Transactions, AIME* 213 (1958): 375–378.

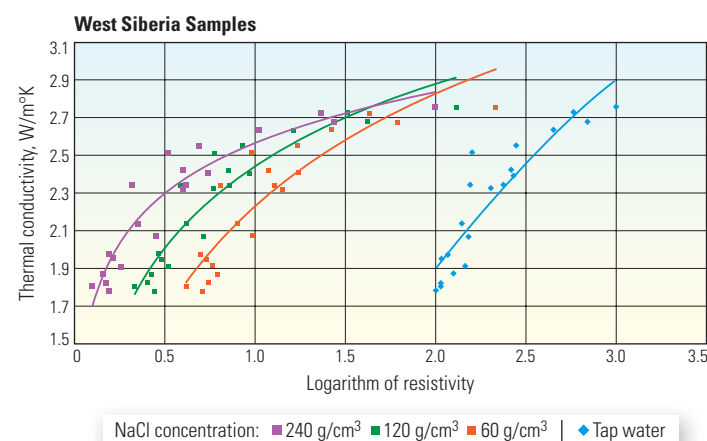
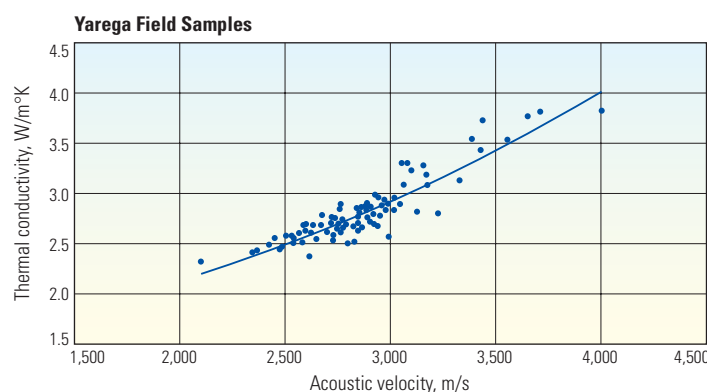
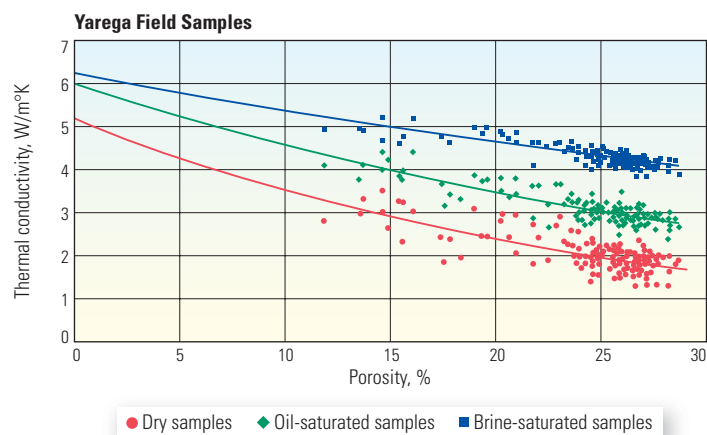
A large, published compilation of thermal rock properties is maintained by the US Geological Survey: Robertson EC: "Thermal Properties of Rocks," Reston, Virginia, USA: US Geological Survey, Open File Report 88-441 (1988).

19. Popov Y, Tertychnyi V, Romushkevich R, Korobkov D and Pohl J: "Interrelations Between Thermal Conductivity and Other Physical Properties of Rocks: Experimental Data," *Pure and Applied Geophysics* 160, no. 5–6 (2003): 1137–1161.

20. Walsh JB and Decker ER: "Effect of Pressure and Saturating Fluid on the Thermal Conductivity of Compact Rock," *Journal of Geophysical Research* 71, no. 12 (June 15, 1966): 3053–3061.

Pribnow D, Williams CF, Sass JH and Keating R: "Thermal Conductivity of Water-Saturated Rocks from the KTB Pilot Hole at Temperatures of 25 to 300°C," *Geophysical Research Letters* 23, no. 4 (February 15, 1996): 391–394.





▲ Correlation of thermal conductivity with porosity, acoustic velocity and electrical resistivity. Thermal conductivities of samples from the Yarega field show good correlation with porosity (*top*) and acoustic velocity (*center*). The solid lines in the top two panels are based on best least-squares fits to the measurements for curves with an exponential dependence of thermal conductivity on porosity or on acoustic velocity. Measurements on samples from western Siberia (*bottom*) show a correlation between thermal conductivity and resistivity. The solid lines in the bottom plots are best fits to the measurements for curves with a logarithmic dependence of thermal conductivity on the logarithm of resistivity.

to any layering. A conclusion of the large study of samples from Russian oil fields was that a specific relative change of thermal conductivity—defined as the percentage change in thermal conductivity in the direction parallel to layering when going from dry to water-saturated conditions—may be the single most important thermal property for the petrophysical characterization of reservoir rocks.<sup>21</sup>

Understanding these subtleties enabled scientists to discern new correlations relating thermal conductivity to porosity, acoustic velocity and electrical resistivity (*left*). These functional mappings hold promise in both directions: Going from the standard petrophysical properties to thermal conductivity opens the possibility of detecting changes in thermal properties far from the wellbore by remote geophysical sensing with electrical or seismic methods; going in the reverse direction enables high-resolution optical scans to explore the petrophysical heterogeneity of rocks at both macroscopic and microscopic scales. Thermal rock properties may also help to quantify this multiscale heterogeneity in the evaluation of unconventional reservoirs such as gas shale.<sup>22</sup>

### Thermal Properties at Reservoir Conditions

Optical scanning provides rapid measurements of thermal properties under normal laboratory conditions—ambient temperature and atmospheric pressure. To calibrate these measurements to conditions in the reservoir, a special chamber was built at the Schlumberger Moscow Research Center to study the influence of elevated temperature and pressure on thermal properties (*next page*). The new device employs a variation of the line source method to determine thermal conductivity and diffusivity at temperatures up to 250°C [480°F] and at pressures up to 200 MPa [29,000 psi]. Pore pressure in the sample and axial and lateral components of confining stress can be varied independently within the chamber.<sup>23</sup>

Thermal conductivity and diffusivity usually have an inverse relationship with temperature. For example, under an increase of temperature from 25°C to 100°C [77°F to 212°F], thermal conductivity in core samples from the Yarega oil field decreased by 50% while thermal diffusivity decreased by 70%. A suite of measurements on samples selected from different reservoir rocks determined average trends for changes in thermal properties with temperature, which were then applied to all measurements in the database.

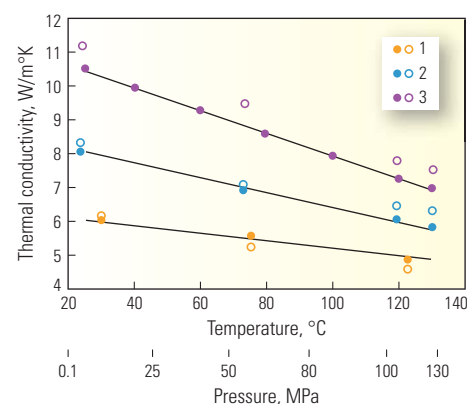
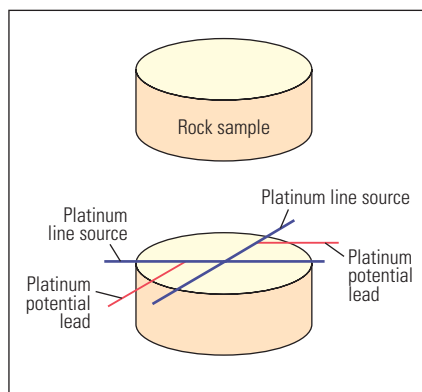
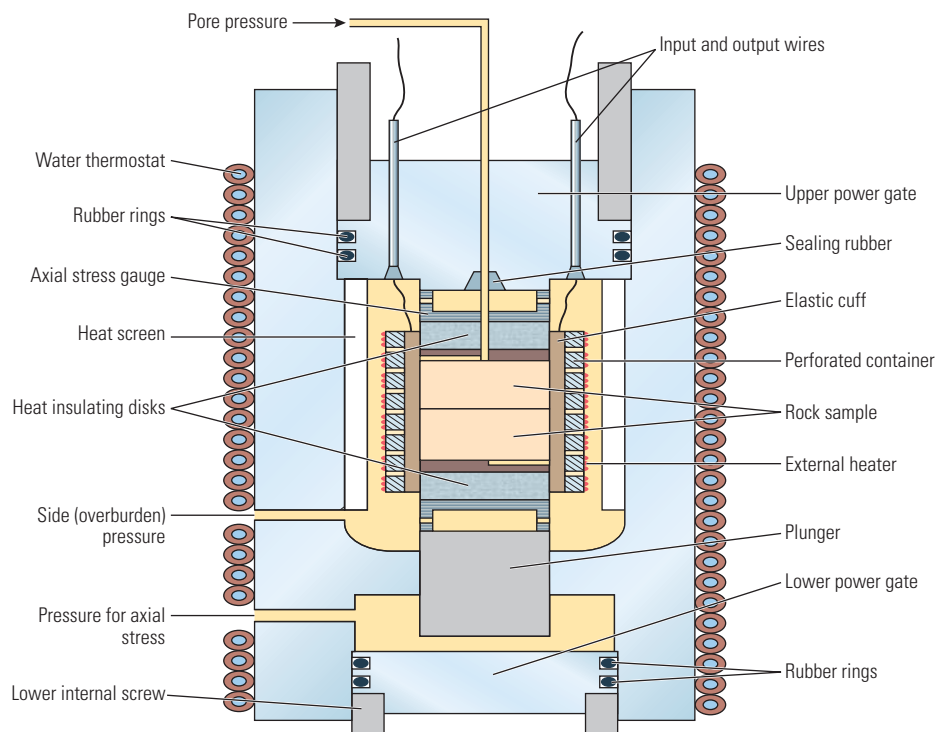
To connect thermal and mechanical properties, a new instrument was developed at the Schlumberger Moscow Research Center to measure the thermal expansion of core samples over a range of typical reservoir temperatures. The instrument, which uses a standard test method called a quartz-rod dilatometer, accommodates either cube-shaped samples or standard cylindrical core plugs used in petrophysical studies—3 cm in diameter and length—and can measure anisotropic thermal expansion coefficients by orienting the same sample in different positions. This measurement technique gives results that are more consistent than conventional approaches in which thermal expansion along a variety of directions is measured on three different samples cut from the same rock core. A typical measurement sequence, which takes up to 12 hours, determines the coefficient of thermal expansion at temperatures from 20°C to 300°C [70°F to 572°F] in temperature steps of 20°C.<sup>24</sup>

A second instrument at TerraTek provides thermal expansion measurements at elevated pressure. The device accommodates dry or saturated cylindrical plugs 5 cm [2 in.] long and 2.5 to 3.8 cm [1 to 1.5 in.] in diameter. The specimen can be loaded axially and radially in two directions and subjected to a maximum hydrostatic confining stress of 27 MPa [3,900 psi]. The device measures thermal expansion coefficients at temperatures up to 200°C [400°F] in a few temperature steps.<sup>25</sup>

### Thermal Properties in Russian Heavy Oil Fields

Since its introduction in the 1980s, the optical scanning method has measured thermal properties of more than 80,000 rock samples. About 10% of the samples come from 15 oil and gas fields in Russia.<sup>26</sup> This growing database of reservoir thermal properties is beginning to change the way petrophysicists regard the importance of heterogeneity in EOR processes.

Thermal rock properties measured by scans of more than 500 cores from the production zone and surrounding formations at Yarega field, for example, showed variations up to 150% over distances of a few meters. The largest variations correlated generally with changes in lithology, but the degree of heterogeneity in individual dry samples was not expected. Moreover, differences in thermal conductivity and diffusivity of up to



^ Measuring thermal properties at high temperature and pressure. Scientists at Schlumberger Moscow Research Center constructed a chamber (top) to determine rock thermal properties at reservoir conditions. The measurement cell (bottom left), which employs a version of the line source method, was calibrated on quartz crystals, a material with well-known anisotropic thermal properties. Measurements (bottom right) indicate that values for the thermal conductivity along the principal axes (1, 2 and 3) of the quartz thermal conductivity tensor measured at different temperatures and pressures with the new instrument (solid circles) compare well with published results (open circles). (Adapted from Popov et al, reference 23.)

21. Popov et al, reference 19.

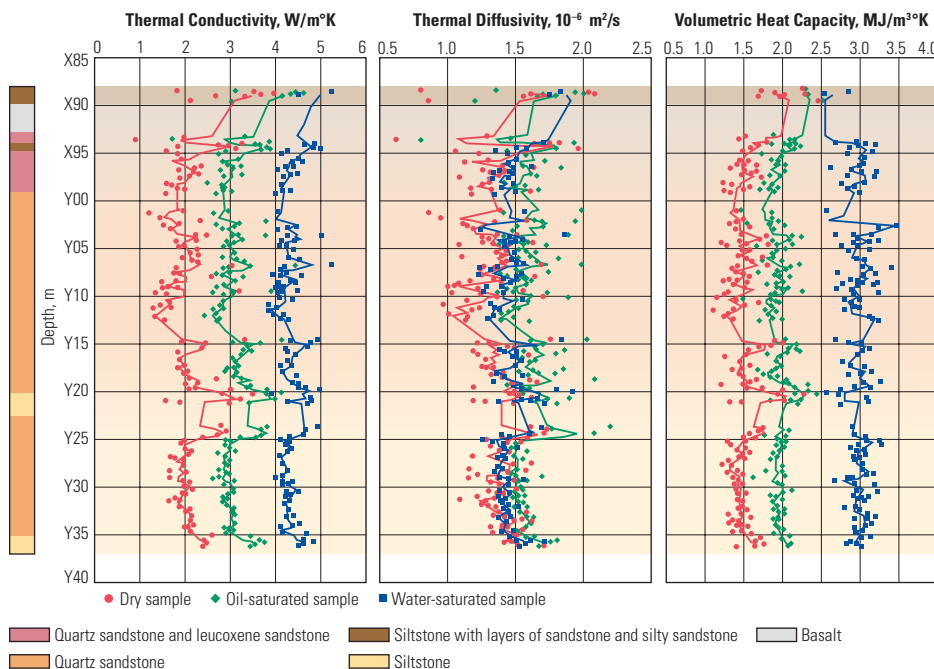
22. Popov et al, reference 17.

23. Popov YA, Spasennykh MY, Miklashevskiy DE, Parshin AV, Stenin VP, Chertenkov MV, Novikov SV and Tarelko NF: "Thermal Properties of Formations from Core Analysis: Evolution in Measurement Methods, Equipment, and Experimental Data in Relation to Thermal EOR," paper CSUG/SPE 137639, presented at the Canadian Unconventional Resources and International Petroleum Conference, Calgary, October 19–21, 2010.

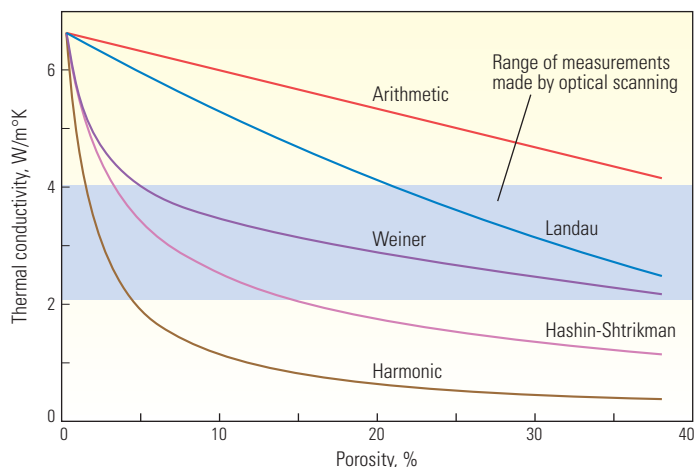
24. Popov Yu, Parshin A, Miklashevskiy D and Abashkin V: "Instrument for Measurements of Linear Thermal Expansion Coefficient of Rocks," paper ARMA 12-510, presented at the 46th US Rock Mechanics/ Geomechanics Symposium, Chicago, June 24–27, 2012. ASTM International: "Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer," West Conshohocken, Pennsylvania, USA, ASTM E228-11, April 2011.

25. Popov et al, reference 24.

26. Popov et al, reference 23.



^ Variation of rock thermal properties. Thermal properties at the Yarega oil field show large variations—up to 150%—over a 50-m [166-ft] interval covering the depths of thermal mining. Each data point represents a separate core sample measured under various conditions. Colored lines represent moving averages of the data. (Adapted from Popov et al, reference 23.)



^ Models of rock thermal properties. Reservoir engineers use predictive models called mixing laws to calculate a rock's bulk thermal conductivity as a function of porosity from the conductivities of the solid matrix and saturating fluid. Each model employs different assumptions about the distribution of pore space. Predictions of standard mixing laws for oil-saturated quartz sandstones, with matrix thermal conductivity of 6.6 W/m²K and varying porosity, overlap the range of thermal conductivities measured by optical scanning of oil-saturated sandstones from the Yarega oil field (blue shading), but can differ from actual values for specific samples by more than 100%.

120% were observed among nearly identical rock samples saturated with air, oil or water (left).

Overall, the ranges of thermal properties seen in the Yarega study ran from 0.8 to 5.2 W/m²K for thermal conductivity and from 1.1 to 3.4 MJ/m³K for volumetric heat capacity. Coefficients of linear thermal expansion, measured on samples from Yarega under reservoir conditions, varied by more than a factor of two, from  $8 \times 10^{-6}$  to  $17 \times 10^{-6}$  per °K.

This variation far exceeds what had been observed in previous studies. Optical scanning and complementary measurements are revealing, possibly for the first time, the natural variability of thermal properties in reservoirs—caused either by natural heterogeneity in rock texture, mineral and organic composition, or by changes in fluid saturation, temperature and pressure. All these factors affect the flow of heat into the reservoir and therefore the production forecasts for a thermal recovery project.

## Precise Design and Control of Thermal EOR

Estimating the economics of thermal EOR requires that operators accurately predict the amount of additional hydrocarbon that will be produced from a field and the production rates of wells following stimulation by a given amount of heat. The thermal properties used in these reservoir simulations are often derived from theoretical models, called mixing laws, that estimate the combined thermal properties of a volume of rock and pore fluid from the volume fractions of its constituents.<sup>27</sup>

27. The bulk physical properties of a composite material generally cannot be precisely calculated without knowledge of the microscopic distribution of its constituents. Mixing laws are mathematical combinations of the constituent properties to estimate bulk properties. Examples are the weighted arithmetic mean, weighted harmonic mean, weighted geometric mean and Hashin-Shtrikman model.

For more on mixing laws see: Berryman JG: "Mixture Theories for Rock Properties," in Ahrens TJ (ed): *Rock Physics & Phase Relations: A Handbook of Physical Constants*. Washington, DC: American Geophysical Union (1995): 205–228.

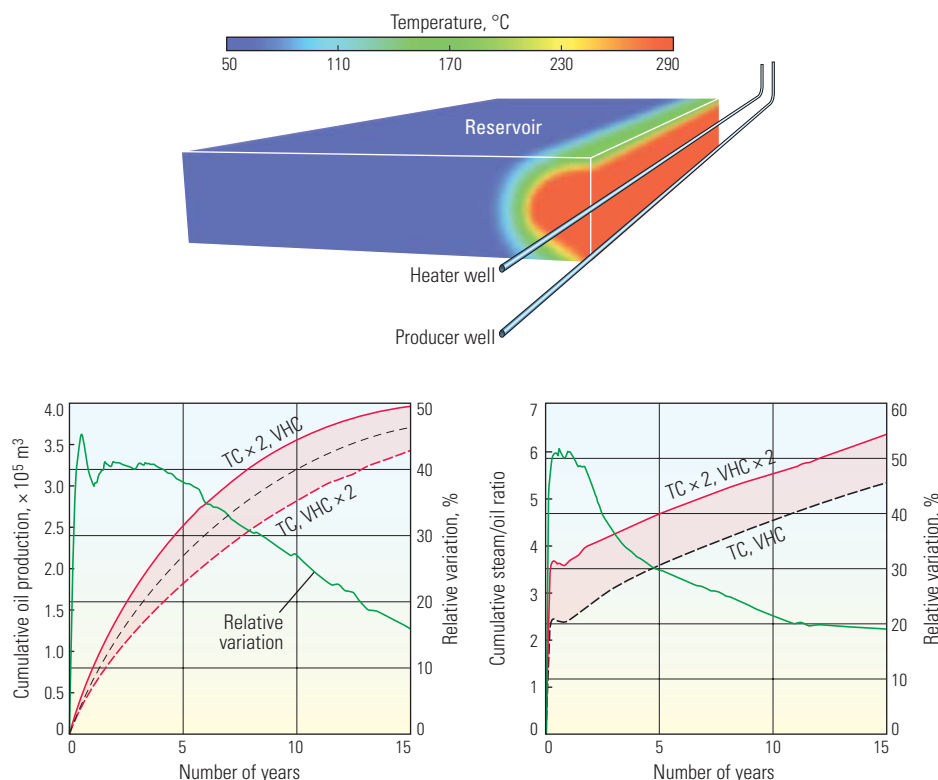
Zimmerman RVV: "Thermal Conductivity of Fluid-Saturated Rocks," *Journal of Petroleum Science and Engineering* 3, no. 3 (1989): 219–227.

28. Popov Y, Parshin A, Ursegov S, Taraskin E, Chekhonin E, Andrianov N, Bayuk I and Pimenov V: "Thermal Reservoir Simulation: Thermal Property Data Uncertainties and Their Influence on Simulation Results," paper WHOC12-291, presented at the World Heavy Oil Congress, Aberdeen, September 10–13, 2012.

29. For more on cementing: Boissault JM, Guillot D, Bourahla A, Tirila T, Dahl T, Holmes C, Raiturkar AM, Maroy P, Moffett C, Pérez Mejía G, Ramírez Martínez I, Revil P and Roemer R: "Concrete Developments in Cementing Technology," *Oilfield Review* 11, no. 1 (Spring 1999): 16–29.

30. For more on asphaltene: Akbarzadeh K, Hammami A, Kharrat A, Zhang D, Allenson S, Creek J, Kabir S, Jamaluddin A, Marshall AG, Rodgers RP, Mullins OC and Solbakken T: "Asphaltenes—Problematic but Rich in Potential," *Oilfield Review* 19, no. 2 (Summer 2007): 22–43.





▲ Sensitivity of a SAGD operation to reservoir thermal properties. In SAGD operations (*top*), steam is injected into a heater well and oil is produced from a producer well. Predictions of the performance over time of a SAGD operation—in terms of cumulative oil production (*bottom left*) and cumulative steam/oil ratio (*bottom right*)—vary with the modeled thermal properties of the reservoir zone. The base scenario (dashed black line) is modeled with an assumed, or measured, average volumetric heat capacity (VHC) and thermal conductivity (TC) for the reservoir zone. Variation in cumulative oil production from the base scenario is determined, on the low side, by doubling volumetric heat capacity (*left*, dashed red line), thereby reducing the temperature rise for a given amount of injected heat. Variation in oil production on the high side is determined by doubling thermal conductivity (*left*, red line), thereby increasing the speed at which the temperature rise at the heater well propagates into the reservoir. Increasing thermal conductivity or volumetric heat capacity drives the cumulative steam/oil ratio higher (*right*, red line) than its value in the base scenario (dashed black line). Relative changes (green) in oil production and steam/oil ratio in these different scenarios are as high as 40% in the early years of production and persist at levels above 20% for 10 years or more. (Adapted from Popov et al, reference 28.)

Values of thermal conductivity obtained from standard mixing laws may be compared with experimental results obtained by optical scanning ([previous page, bottom](#)). Although the mixing laws provide helpful bounds, the predicted values may differ from measured values by more than a factor of two. Similar large discrepancies are found between the default settings for thermal conductivity and volumetric heat capacity programmed in most reservoir simulators and the average values calculated from the database of measured thermal properties maintained at the Schlumberger Moscow Research Center.<sup>28</sup>

A simplified model of a SAGD process illustrates the importance of using accurate rock properties in simulations of thermal EOR ([above](#)). This

model has two horizontal wells crossing a 150-m by 500-m by 25-m [490-ft by 1,640-ft by 80-ft] pay zone of uniform thermal and production properties, typical of tar sand reservoirs. The key metrics for a SAGD operation are the cumulative oil production (COP) and the cumulative steam/oil ratio (CSOR), which is the volume ratio of steam input to oil produced. This ratio largely determines efficiency of a steam injection process. Simulations in which the thermal conductivity and volumetric heat capacity were varied by factors of up to two—to reflect a range of uncertainties in reservoir properties—show production scenarios with relative deviations in COP and CSOR of 20% to 50% persisting over the duration of the simulated SAGD operation.

The economic implications for the various scenarios differ dramatically from one another and, given the typical life of an EOR project, have long-term consequences. Production predictions based on empirically derived thermal rock properties may provide field operators with realistic expectations for returns on capital investments.

## Other Applications

Many oilfield processes other than thermal stimulation may benefit from operators having accurate knowledge of thermal properties surrounding the wellbore. A cementing operation, for example, has to maintain pressure in the annulus between the casing and the formation in the narrow range between formation pore pressure and formation fracture pressure. This requirement holds over the full length of the wellbore from the start of the job until the cement fully cures. Since the curing process can raise the temperature of the slurry by more than 100°C [180°F], pressure and temperature in the annulus may be strongly affected by the thermal response of the surrounding rock and its pore fluids. Knowing the actual values of thermal properties in a formation helps operators determine the best choice of cement mixtures and additives.<sup>29</sup>

Another important process governed in part by the temperature regime near the wellbore, and therefore by the surrounding distribution of thermal properties, is the precipitation of asphaltenes, which can choke off production by clogging flow pathways. Knowing where asphaltenes are likely to precipitate helps engineers design better well completions.<sup>30</sup>

Petroleum production is essentially a thermomechanical process. Modern reservoir simulators calculate the pressure, volume and temperature changes accompanying mass and heat transfer during production or testing, but they often use average values of thermal properties, usually based on point measurements on cores, to characterize the entire reservoir. The growing database of measurements made possible by optical scanning shows that thermal rock properties vary significantly at both macroscopic and microscopic scales. Understanding the effects of heterogeneity in scaling up from high-resolution thermal scans of cores to full reservoir simulations is a fundamental challenge for engineers constructing the next generation of reservoir models.

—MO