Applying insulative coating technologies from oil and gas to advance geothermal drilling

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Geothermal wells present competing temperature challenges

- Geothermal wells are typically drilled into high-temperature reservoirs of 150^{o}C (302^{o}F) or greater
- Operators want to keep the produced reservoir fluids hot to maximize thermal energy at the surface
- Operators want to keep drilling fluids and downhole tools cool to avoid damage and expensive downtime for repairs
- Maintaining the cooling effect of drilling fluids is critical

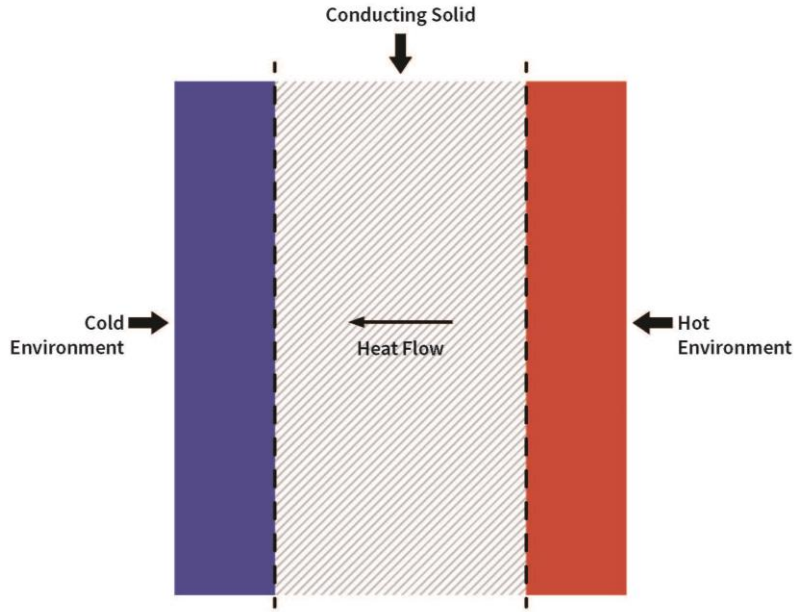
Thermal conductivity holds the key to temperature control

- The thermal conductivity (TC) of a material is a measure of its ability to conduct heat
- Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity

Material	Thermal Conductivity (W/mK)
Diamond	1,000
Copper	401
Aluminum	237
Carbon steel	45
Water	0.5918
Polyurethane foam	0.03

Higher heat transfer

Lower heat transfer

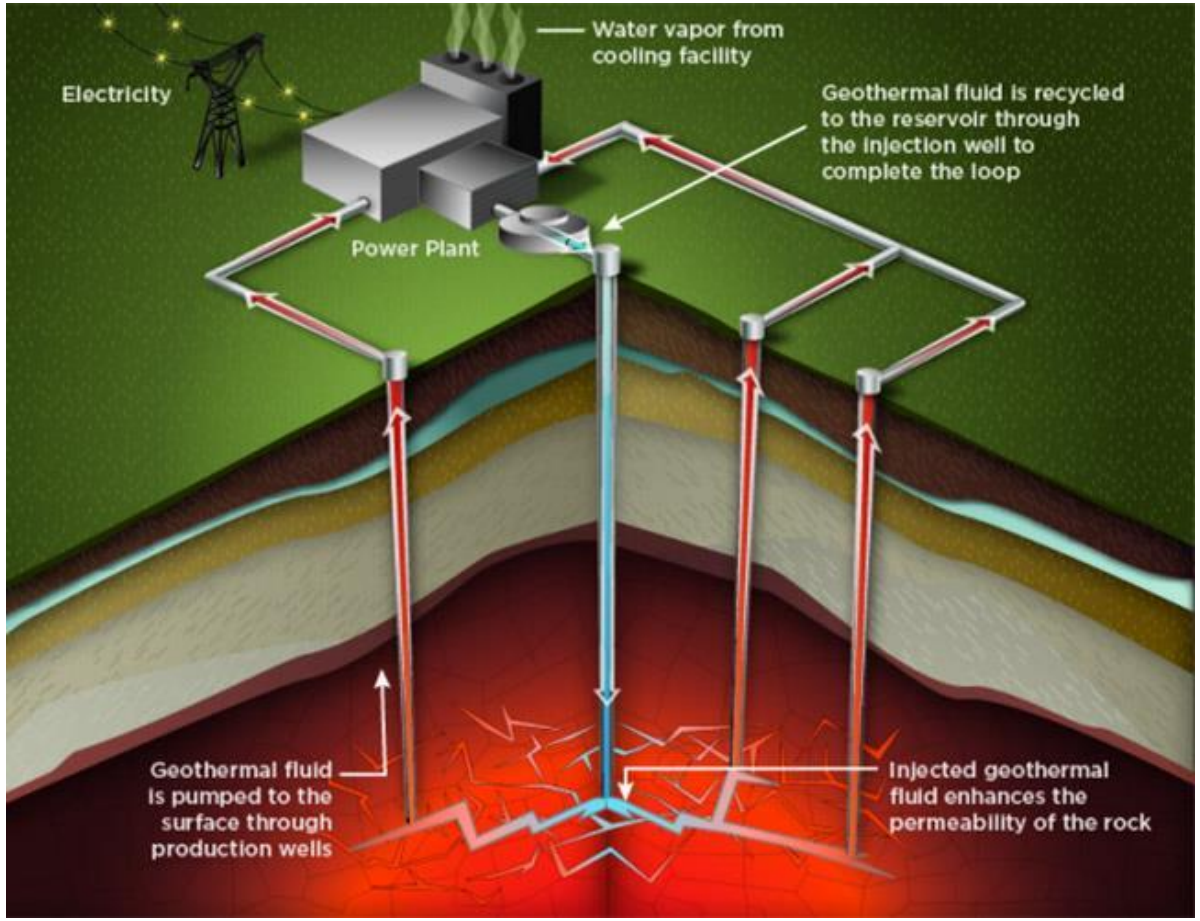


Low thermal conductivity coating development had its start in oil and gas

- High-temperature fields can damage downhole tools and affect drilling rates
- Long laterals increase exposure time to high temperatures
- NOV has over 75 years of experience developing coatings for operating in aggressive oil and gas applications
- NOV has recently developed an insulating drill pipe coating for extreme temperature oil and gas wells

New geothermal developments are drilling deeper and hotter

- Enhanced geothermal systems are being developed to drill deeper and into reservoirs at 200°C (392°F) or greater
- Drilling long, multilateral, closed-loop systems keeps drill string and tools exposed to high T reservoirs for extended periods
- Colder drilling fluids, less than 120°C (248°F), desired to protect sensitive electronics
- **Target: Develop a coating with a thermal conductivity of 0.5 W/mK or less**



Development plan for low-conductivity coatings for geothermal

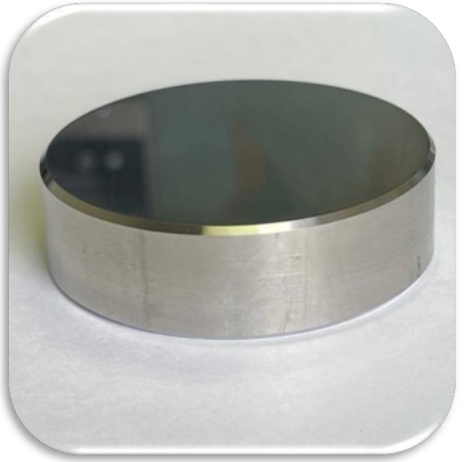
- Establish thermal conductivity and properties of current drillpipe coatings for oil and gas
- Adjust coating formulation to decrease thermal conductivity if necessary
- Ensure applicability of new coating formulation in current manufacturing facilities
- Verify the new coating maintains required chemical and corrosion performance

Testing methodology and equipment

- ASTM – E1530-19 Primary measurement of thermal resistance/thermal conductivity for solids, such as metals, polymers, composites and paste (-20 °C to 310 °C)
- The calculation of thermal conductivity from measurement of thermal resistance is the most accurate method of testing the true thermal conductivity of heterogeneous materials
- The steady-state measurement of thermal resistance represents the full sample thickness and mature heat transfer properties

Thermtest™ GHFM – 01 – Guarded Heat Flow Meter

Test Coupons



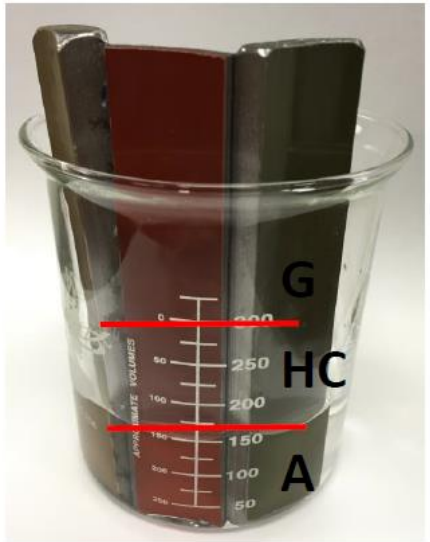
Testing methodology and equipment (cont.)

- Physical Properties
  - Hydraulic Improvement / Surface Roughness
  - Abrasion Resistance
  - Chemical Resistance (immersion and autoclave performance)
  - Impact Resistance
  - Flexibility

Autoclave Testing

In-House Testing

Autoclave Testing Capabilities	
Maximum temperature	288°C [550°F]
Maximum pressure	689.5 bar [68.9 MPa]
Maximum test duration (hours)	N/A
Sample limit*	10
Aqueous test solutions	brine; tap water
Hydrocarbon test solutions	UP mix(toluene/varsol); customer specified test solution
Test gases	CO_2; CH_4; H_2S
H_2S gas conc. limit (% volume)	15



Development plan delivers low conductivity coating for geothermal

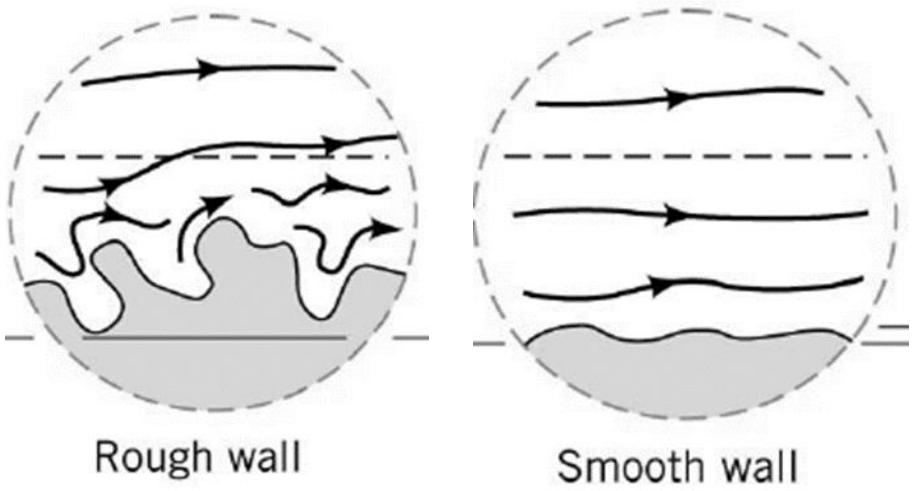
- Benchmark coating had a thermal conductivity of 0.8360 W/mK – exceeded 0.5 W/mK baseline
- Iterative coating development/testing protocol resulted in an optimized coating with TC of 0.1808 W/mK
- Optimized coating maintained desirable physical properties, including corrosion resistance, deposit mitigation, hydraulic improvement

Hydraulic Improvement

TK™-340TC and TK™-18TC

Primary Factors Influencing Flow Inside of Pipe

- Velocity
- Viscosity
- Pipe Geometry
- Surface Roughness

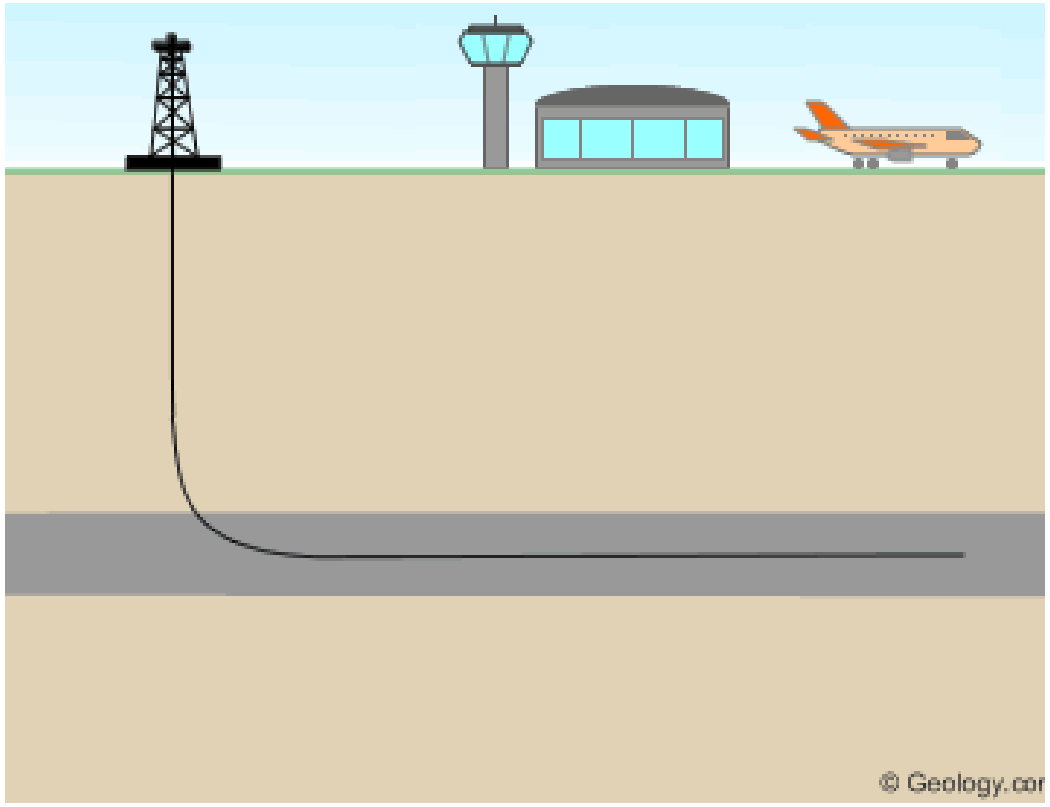


	$R_{Z(DIN)}$, microns (Nominal)	$R_{Z(DIN)}$, inches (Nominal)
Tube-Kote Coated Pipe	2 to 10 (4)	0.0000786 to 0.000393 (0.000157)
Bare Carbon Steel Tubing	30 to 40 (35)	0.00118 to 0.00157 (0.00138)
Bare 13Cr Tubing	30 to 60 (45)	0.00118 to 0.00236 (0.00177)
GRE Liners	12 to 16 (14)	0.000472 to 0.000630 (0,000551)
TK-340TC/18TC	2.68	0.0001055

Low Thermal Conductivity Coating Development

Traditional Oil and Gas - TK-340TC

- Coating performance in line with company models
- Bottom hole temperatures ~ 425°F (218°C)
  - Long laterals at temperature
- >120,000 feet (>36,576 meters) drilled
- >50 bottom hole assemblies (BHAs) saved
- Reduced the number of trips



Testing the optimized coating in the field

- The optimized coating was applied to drill pipe to drill a single well in New Mexico, USA
  - ~18,000 ft (~5.5 km) drilling distance in granite
  - Bottomhole temperature of ~250^{o}C
  - Local geothermal gradients in the region can exceed 50^{o}C/km
  - Measurement-while-drilling (MWD) tools measured temperature at the bit, while temperature sensors located in various parts of the drill string recorded annular fluid temperatures
  - Downhole temperatures would be used to validate the operator's transient thermodynamic model and confirm that drilling fluid could be maintained below the 120^{o}C target temperature (for protecting downhole tools from temperature failures)

Field results validate coating performance

- Drillpipe coated with new insulated coating helped
  - Drill a total of 18,000 ft at bottomhole temperatures up to 250°C (480°F)
  - Keep mud temperatures below 95°C (203°F) for the duration of the drilling run
  - Stay well below operator's target temperature threshold of 120°C (248°F) to prevent BHA damage
  - Maintain temperatures at BHA well below the estimated rock temperature along the drilling interval, which matched closely with the operator’s model

Active & upcoming projects

- Geothermal
  - Geretsried – Electricity generation and heating
  - Hanover – Heating
- Oil & Gas
  - Haynesville & Eagle Ford Shale HPHT (200°- 232°C)

Conclusions

- Thermal conductivity holds the key to optimizing geothermal drilling – drillstrings with low thermal conductivity keep drilling fluid and tools cooler for longer
- Low conductivity coatings originally developed for oil & gas can be easily modified/refined for drilling long multilaterals in deeper, hotter geothermal reservoirs
- Thorough testing and refinement of coatings delivered a low TC coating (<0.5 W/mK target) that maintained superior corrosion, chemical, and hydraulic performance
- Field testing confirmed—new coating kept mud below 120^{o}C threshold to protect BHA tools while drilling 18,000-ft geothermal well
- Encouraged by early successes, operators are placing more insulated drill pipe orders to continue field trials

Acknowledgements

- Thank you to NOV for their support and efforts in alternate energy
- Thanks to our various oil & gas and geothermal customers who continue evaluating low TC, insulated drillpipe in their extreme temperature drilling operations
- Thank you to NOV's scientists, laboratory technicians, and manufacturing centers for consistently designing and delivering low TC coatings that meet the demands of deeper, hotter reservoirs

Thank you!

Any questions?