Breaking Ground

Energy conservation and fracture complexity in plug-and-perf and ball-activated completions

One of the greatest challenges in the disciplines of geomechanics and petroleum engineering is the effective hydraulic stimulation of unconventional oil and gas reservoirs. Scientists and engineers aim to achieve this goal by quantitatively identifying the best methodologies for predictable and repeatable optimal extraction.

The current understanding of hydraulic fracturing has evolved through experiment and applications since the birth of industrial-scale hydraulic fracturing. From the first high-rate fluid injection to the more complex and integrated solutions of today, the industry can now discern limitations on fracture height, identify asymmetric fracture growth and model complex stress interactions in the deep subsurface.

Tying subsurface stress conditions and mechanical properties of rocks to physical processes allows us to quantify the dynamics of hydraulic stimulation. The goal is to identify the best methodology to stimulate the reservoir to maximize fracture network complexity.

Subsurface analysis shows that ball-activated multi-stage completion systems achieve more fracture complexity and surface area in the reservoir, resulting in higher drainage efficiency.

FRACTURE CHARACTERIZATION

Hydraulic fractures are typically modelled as a single fracture because only one set of treatment measurements is available. Nolte-Smith (Figure 1) uses treating pressure to discern hydraulic fracture dimensions. The surface pressure response, treatment rate and proppant concentration are translated into a single planar fracture with a corresponding height, length and width. This can be a gross oversimplification of the actual fracture complexity. Furthermore, it does not take into account continued deformation of the rock mass over a longer time period.

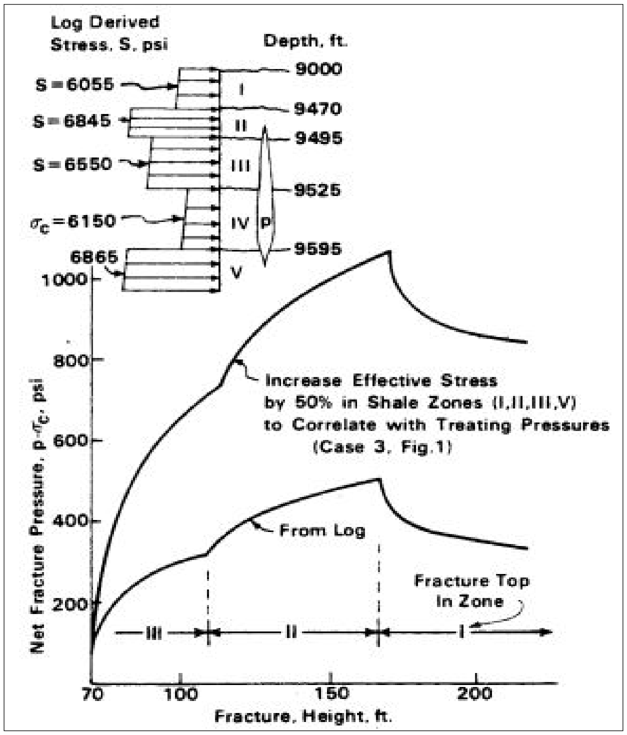

Figure 1: Interpretation of fracture height growth based on treating pressure. (SPE 8297)

During stimulation, the reservoir is forced to accommodate additional volume. Time-dependent strain of the rock mass is typically not considered once a stage has been sealed off in the wellbore and operations have moved on to the next stage. However, there are two common scenarios leading to different results regarding rock strain over time:

- A pressure decline is seen as a loss of hydraulic energy from the fracture as it changes from a mode of fracture propagation to one of fracture closure
- Closely spaced pressure signatures are seen, indicating initiation, breakdown and fracture propagation in successive stages, using ball-activated systems

In the plug-and-perf case, there is time lag associated with operations that makes it impossible to apply additional strain before energy loss and fracture closure begin. In the case of a continuous-pumping operation, the timing is such that stress is added to the system before the first initiated fracture is in a mode of closure.

Key mechanisms controlling stress re-distribution are the magnitude of the stress differential within the fracture relative to the minimum stress and the ability of the rocks to accommodate it through elastic and inelastic processes.

The controlling parameters that determine how the reservoir responds to elevated stress conditions will be the elastic moduli of the rocks, their brittleness, the ability to transmit fluid pressure (and volume) through leak-off, and the presence of natural fractures. In a lab experiment measuring creep strain (Figure 2), results show that irreversible strain occurs prior to complete failure.

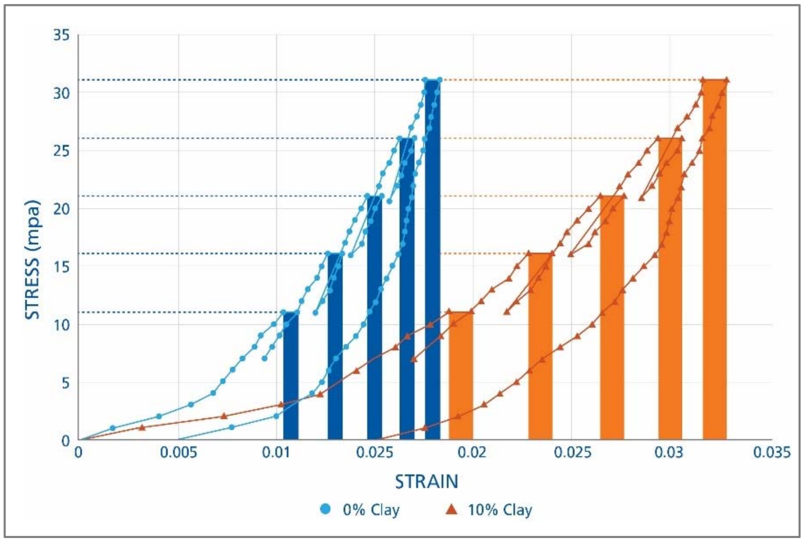

Figure 2: Laboratory test results for creep strain of clay cores. Strain continues under a constant load. This indicates that a significant percent of strain experienced in each loading and unloading cycle is inelastic.

To observe key differences between completion methodologies, a step-by-step analysis of plug-and-perf and ball-activated completions for two successive stages in a single well is described. The processes and time parameters at each step highlight how operational differences have impacts on geomechanics, stress distribution, and fracture complexity, which ultimately correlates to reservoir drainage.

Geomechanics of Plug-and-Perf Completions

After perforating the first stage, slurry enters the reservoir, forcing it to accommodate additional fluid and proppant. This manifests as a fracture, as well as added pressure along the fracture face and the stress shadow extending out into the surrounding rock. Stress is not static at this point—it is transmitted into the formation surrounding the fracture, and dissipates in several ways: leak-off, elastic, and inelastic strain of the rock. These are the active mechanisms of the stress shadow, where dynamic, time-dependent stress and strain occur.

At this point in the treatment, the stress mechanisms at work are identical for plug-and-perf and ball-activated completions systems. Following stimulation of the first stage in a plug-and-perf job, key differences in operations and energy conservation come into play.

The well is flushed to displace proppant remaining in the wellbore, ensuring that wireline tools are not obstructed. Tools for the next stage are pumped down using additional fluid that displaces proppant from the fractured interval. While the specific volume of fluid and impact of overflush varies depending on the operator's program, these operations occur during a crucial time frame where energy is being lost from the fracture system.

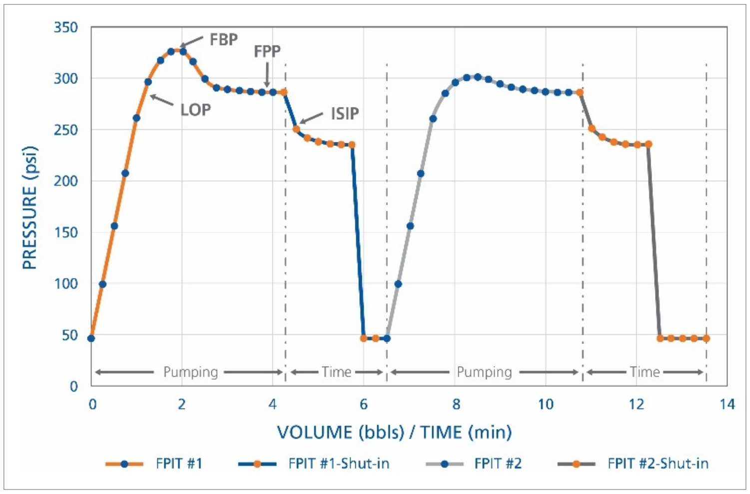

Figure 3: Idealized hydraulic fracture treatment plot for plug-and-perf, showing leak-off point, formation breakdown, fracture propagation (FPP) and ISIP. Pressures below FPP correspond to fracture closure.

Perforating the next stage creates a new leak-off path for excess pressure from the previous stage's fracture. Excess stress in the fracture can equalize within the wellbore and the reservoir. This equalization, or redistribution of stress, allows for fracture closure.

As seen in Figure 3, events such as initial shut-in pressure (ISIP) are indicative that the closure process is underway. In some wireline operations, pressure is bled off from the well to convey the tools. This tends to accelerate fracture closure because it allows the net pressure to drop under the minimum horizontal stress.

Wireline operations in the well have resulted in two distinct geomechanical impacts. The near-well fracture network has been overflushed by up to 2-3 wellbore volumes and the pressure leak-off or net pressure equalization between open points of communication with the formation and the well have allowed the closure process to begin. Focused stress dissipates, resulting in a loss of hydraulic fracture width over the entire fracture face, as well as closure of fractures near the well where proppant was overflushed. The net effect of this change in the proppant distribution and stress dynamics are shorter, fewer complex fractures, with less near wellbore conductivity.

The plot of treatment parameters in Figure 4 again shows the time gap and energy loss between treatment stages as well as slightly elevated treating pressures as new stages are added. This elevation of treating pressure is in part due to the stress shadow effects in the reservoir.

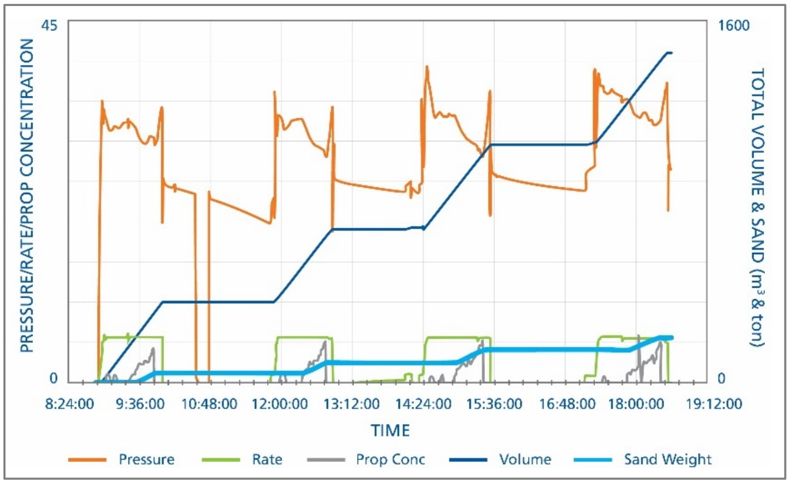

Figure 4: Surface pressure recording of a 4-stage plug-and-perf treatment. Pressure drops correspond to energy losses and onset of fracture closure.

Net Impacts of Small Energy Losses

From the perspective of net stress, the amount of pressure in excess of the minimum stress that is required to propagate a fracture is small. Taking this step-by-step accounting of stress distribution and the realization that the in-situ stress field has only been exceeded by this small amount, it is apparent that small losses in energy from the area of interest can have tremendous impacts. The fractures are allowed to close, rather than retaining stress in the reservoir to promote longer term strain in the form of tip extension and additional shear fractures between primary hydraulic fracture wings.

GEOMECHANICS OF BALL-ACTIVATED COMPLETIONS

In ball-activated completions, a sliding sleeve shifts open, and the hydraulic fracture is initiated. The fractured rock is subject to the same stresses and parameters as the plug-and-perf treatment. The fluid rate, fluid type and proppant concentration are identical.

Following the treatment, a small volume of spacer fluid is pumped down the well, followed immediately by the actuation ball for the next stage. The spacer and ball are then followed by the fracturing fluid for the next stage. These operations occur continuously, and addition of fluid to the system (and energy) is uninterrupted.

Differences in stress mechanisms in ball-activated operations begin when the second ball lands on the seat. Stress is at a maximum, and the timing of the next fracture is at a unique point in the

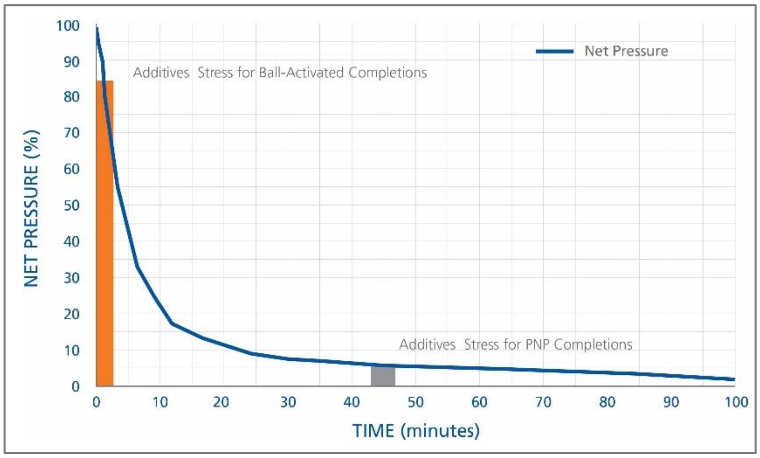

Figure 5: Conceptual depiction of percentage of net pressure available in the reservoir that is additive at the time of fracture initiation in the subsequent stage. Bars indicate stress concentrations for ball-activated & plug-and-perf systems.

evolution of stress that can only be capitalized on by using continuous pumping completion systems. Figure 5 shows the decline in net stress over time, and highlights the differences in additive stress available during fracturing in subsequent stages for ball-activated and plug-and-perf. Stress redistribution from wireline operations is eliminated, whereas stress accommodation mechanisms are maximized and retained in the stimulated rock.

Stress Shadow Impacts During Ball-Activated Stimulation

Since ball-activated completions are in a continuous mode of fracture propagation by virtue of the uninterrupted addition of fluid volume to the system, the stress shadow interactions between sequentially created fractures is maximized. The second hydraulic fracture further alters the stress state and the stress shadows associated with each fracture have an additive effect on the rock mass between the two fractures. Figure 6 depicts how energy is conserved in the reservoir and is maintained at magnitudes that exceed the fracture gradient.

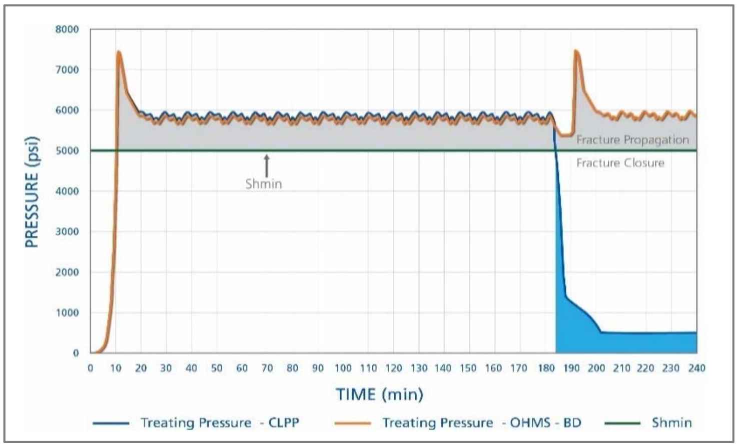

Figure 6: Conceptual energy distribution differences between ball-activated and plug-and-perf systems. S_{hmin} is depicted as the threshold for propagation and closure "modes" for hydraulic fractures.

At the point of the second fracture, both fracture systems with high retained stress concentrations undergo the process of stress distribution to the surrounding rock. From this volumetrically static point, the dynamic processes underway are not yet complete. Stresses in the hydraulic fractures still exceed the minimum stress magnitude and processes in the reservoir are acting to relieve and redistribute the induced stress concentration.

The effect of the stress shadows is additive on the volume of rock situated between the two fractures. Stress shadows imposed by each fracture will vary in intensity as a function of distance from the main fracture. The rocks within the stress shadow and near the fracture face are in an altered stress state resulting in strain hardening. Under elevated stress conditions, the rocks near and at some distance from the fracture face behave more stiffly since they are closer to their elastic limits.

The result is that the rock is more susceptible to the initiation of shear fractures as the reservoir equalizes the elevated stress condition. With the added formation of shear fractures extending into the rock mass from the main hydraulic fracture, stress relaxation through inelastic processes becomes a key mechanism for leak-off, especially in tight formations where fluids cannot readily move through the matrix or natural fractures are absent.

The rocks have low compressibility and small pores, so the only way to accommodate new volume is to break. The benefits of this process are added fracture complexity and improved drainage efficiency through greater fracture surface area.

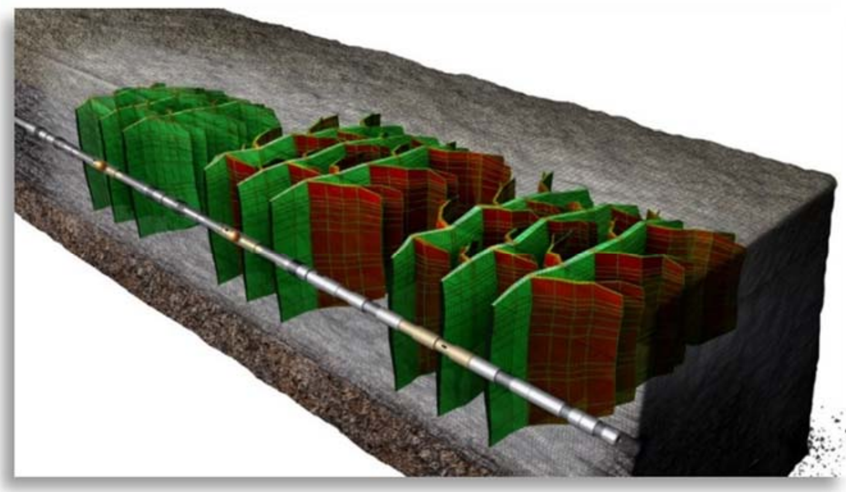

Figure 7: Maximized fracture complexity and drainage from a ball-activated completion. Green represents fractures created from initial treatment. Red represents fractures generated from ongoing stress shadow interactions.

Case Study

A study from a group of wells in the Montney formation of the Western Canada Sedimentary Basin[1] indicates fundamentally different geomechanical processes in plug-and-perf and ball-activated completions.

The ball-activated completions in the study achieved higher estimated ultimate recovery (EUR) by more than 40% compared to the operator's plug-and-perf completions.

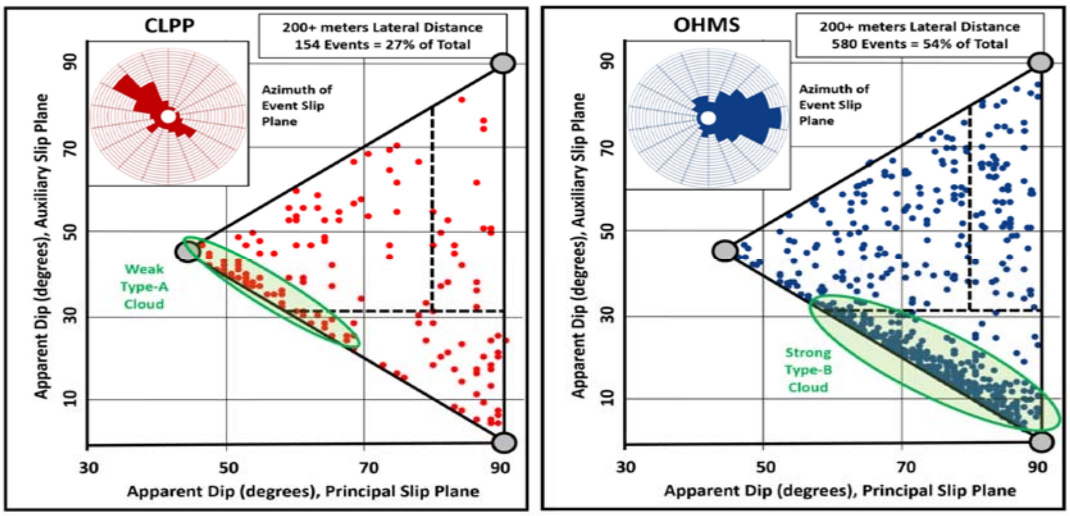

Figure 8: Microseismic focal mechanism comparison for plug-and-perf and ball-activated completion systems in the Montney Formation. (SPE 174955)

In addition to the production study, analysis of microseismic interpretations showed distinctive differences between the events recorded in each type of completion. The study's conclusions include the following:

- A significantly greater number of seismic events occurred in wells using ball-activated completions systems, and larger magnitude microseismic events occurred at all distances from the well

[1] Reimer, J., Ng, M., Dusterhoft, B., Birkelo, B., & Hlidek, B. (2015, September 28). Comparing Openhole Packer Systems with Cemented Liner Completions in the Northern Montney Gas Resource Play: Results From Microseismic Monitoring and Production. Society of Petroleum Engineers. doi:10.2118/174955-MS

- Strong fracture complexity was evident in the wells using ball-activated completions systems—this failure pattern was not evident in the plug-and-perf wells
- Lower magnitude focal mechanisms in plug-and-perf wells indicated that these treatments followed pre-existing fracture pathways rather than developing new planes of failure in the reservoir.

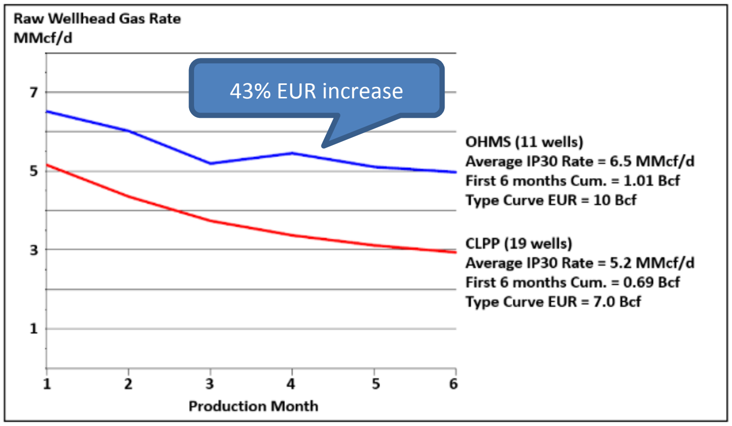

Figure 9: Six-month production comparison between plug-and-perf and ball-activated completions systems showing 43% increase in EUR. (SPE 174955)

The 43% increase in production of ball-activated wells (Figure 9) is directly related to the development of new fractures identified in microseismic data.

Conclusion

With a better understanding of fracture stress, operators can promote shear fracture development without impinging on fracture development in successive stages by optimizing treatment delivery and stage spacing. Capitalizing on the additive interactions of multiple stress shadows constitutes an alternative mechanism for leak-off in the reservoir through the initiation of fractures after stimulation is complete.

In plug-and-perf completions, the nature of the stop and start operations allows net stress to drop below the minimum stress through equalization within the wellbore and the formation. This leads to a stress state that is in a mode of fracture closure and a less than optimal reservoir stimulation.

In ball-activated completions, the stress in the reservoir generated by the fracturing fluid in the completed stage is maintained and the subsequent hydraulic fracture further alters the stress state. The stress shadows associated with each fracture have an additive effect on the rock mass between the two fractures, leading to added fracture complexity, greater fracture surface area, and improved drainage efficiency.

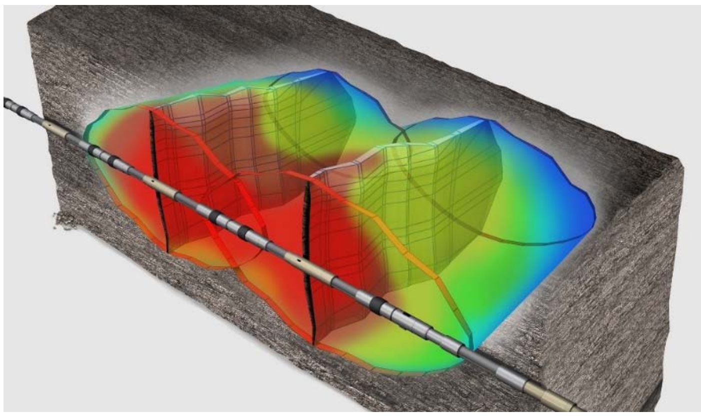

Figure 10: Conceptual depiction of stress shadow interactions and additive effects of elevated stress conditions in the rock mass surrounding two hydraulic fractures.

FURTHER RESOURCES

Packers Plus is a completion technology company dedicated to providing high quality solutions that work the first time. To this end, Packers Plus offers systems for a variety of applications, including cemented liner, open hole, and high pressure and high temperature applications.

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