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PDC Bit Testing at Sandia Reveals Influence of Chatter In Hard-Rock Drilling

Polycrystalline diamond compact (PDC) bits have yet to be routinely applied to drilling the hard-rock formations characteristic of geothermal reservoirs. Most geothermal production wells are currently drilled with tungsten-carbide-insert roller-cone bits. PDC bits have significantly improved penetration rates and bit life beyond roller-cone bits in the oil and gas industry where soft to medium-hard rock types are encountered. If PDC bits could be used to double current penetration rates in hard rock, geothermal well-drilling costs could be reduced by 15 percent or more.

PDC bits exhibit reasonable life in hard-rock wear testing using the relatively rigid setups typical of laboratory testing. Unfortunately, field experience indicates otherwise. The prevailing mode of failure encountered by PDC bits returning from hard-rock formations in the field is catastrophic, presumably due to impact loading. These failures usually occur in advance of any appreciable wear that might dictate cutter replacement. Self-induced bit vibration, or "chatter", is one of the mechanisms that may be responsible for impact damage to PDC cutters in hard-rock drilling. Chatter is more severe in hard-rock formations since they induce significant dynamic loading on the cutter elements.

Chatter is a phenomenon whereby the drillstring becomes dynamically unstable and excessive sustained vibrations occur. Unlike forced vibration, the force (i.e., weight on bit) that drives self-induced vibration is coupled with the response it produces. Many of the chatter principles derived in the machine tool industry are applicable to drilling. It is a simple matter to make changes to a machine tool to study the chatter phenomenon. This is not the case with drilling. Chatter occurs in field drilling due to the flexibility of the drillstring. Hence, laboratory setups must be made compliant to observe chatter.

The Hard-Rock Drilling Facility (HRDF) at Sandia was modified with the addition of springs as shown in Figure 1 to allow the compliance of field drillstrings to be simulated. To be representative of field-drilling conditions, the range of parameters used in the experimental setup must reflect conditions that a drillstring equipped with a PDC bit might typically experience. Weight on bit (WOB), rotary speed, and the fundamental vibration modes of the drillstring are important parameters in the experimental design. The penetrating forces and surface speeds for the cutters on the test bit should be characteristic of what cutters experience in the field in comparable formations. The experimental setup is designed to make the fundamental frequencies of the test fixture as low as possible to simulate field drilling. Using this approach, chatter effects observed at the natural frequency of the test setup are representative of the system characteristics at frequencies which may be encountered in the field. Torsional compliance, also inherent in field drillstrings and of particular concern in PDC bit applications, was eliminated in this first phase for simplicity, but it will be addressed in future investigations.

Sandia conducted testing in Berea Sandstone, a soft formation, and Sierra White Granite, a hard rock representative of geothermal formations, to determine the conditions under which chatter originates. The tests involved drilling a series of holes at constant WOB and constant rotary speed while recording drilling parameters for post-test analysis. The peak-to-peak vibration of the drillstring was monitored by a displacement transducer. Drilling tests were conducted over a range of WOB values and rotary speeds to simulate a variety of conditions.

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One measure of chatter severity is the difference between the bit's peak-to-peak vibration and its depth-of-cut per revolution. This parameter, the "out-of-cut distance," is shown in Figure 2 for sandstone. This plot shows the relative amplitude of vibration at various WOB and rotary speed combinations. When the parameter is negative, the bit remains in the cut. Conversely, when the parameter is positive, the bit is bouncing completely out of the cut! The power spectral density for the data presented has the same general character suggesting that the out-of-cut parameter is indicative of the vibration energy resident in each of the operating conditions across the measurement range.

The data show that severe chatter occurs in sandstone. This implies that chatter can play a significant role in oil and gas drilling. However, no damage to the PDC cutters was observed throughout the sandstone testing. In accordance with the theory of chatter applied in the machine tool industry, our tests show that there are pockets of stability (i.e., WOB and RPM pairs) for which the vibration level is reduced. Figure 2 shows that a given WOB has preferential rotary speeds for the drilling configuration represented. Further, although not apparent from the data displayed here, the rate of penetration decreases in the presence of significant chatter. Alternatively, when the chatter level decreases the penetration rate increases. As expected, increasing the WOB at a given rotary speed acts to decrease the chatter. However, even at higher WOB some rotary speeds are better than others. The zigzag nature of the higher WOB data shown in Figure 2 is due to the excitation of higher-frequency vibration modes at increased WOB.

Important to geothermal drilling, Sandia's testing in Sierra White Granite produced chatter with much higher impact loading that lead to PDC cutter damage and failure. In fact, the quantity of PDC cutter failures limited the progress of the testing. Figure 3a is a photo of a PDC cutter that drilled 96 ft at 30 ft/hr under stable, non-chatter operating conditions that resulted in initial stages of wear. Figure 3b shows a cutter that drilled one ft at 10 ft/hr in Sierra White Granite under chatter conditions, resulting in bulk failure of the diamond table and carbide support. These results confirm that chatter is a significant problem when drilling in hard-rock formations. Controlling the level of chatter in the drillstring is crucial to using PDCs in geothermal drilling.

Sandia is pursuing multiple paths to reducing chatter. One approach is a high-speed data link to the bit. The level of vibration measured at the surface is attenuated from the vibration actually occurring at depth. If accurate dynamic conditions are known downhole, drilling parameters can be modified using feedback control to reduce the chatter level at the bit and improve the drilling process. Another approach is a downhole-controllable damper. Such a device would monitor the response of the bit and apply appropriate damping to reduce the chatter level, thereby reducing the impact loading of PDC cutters in hard-rock formations. Yet another approach is to use our drilling facility to characterize the shock environment that PDC bits must endure under nominal operating conditions. This information may be used to develop advanced cutters that are capable of surviving chatter in the hard-rock formations characteristic of geothermal drilling.

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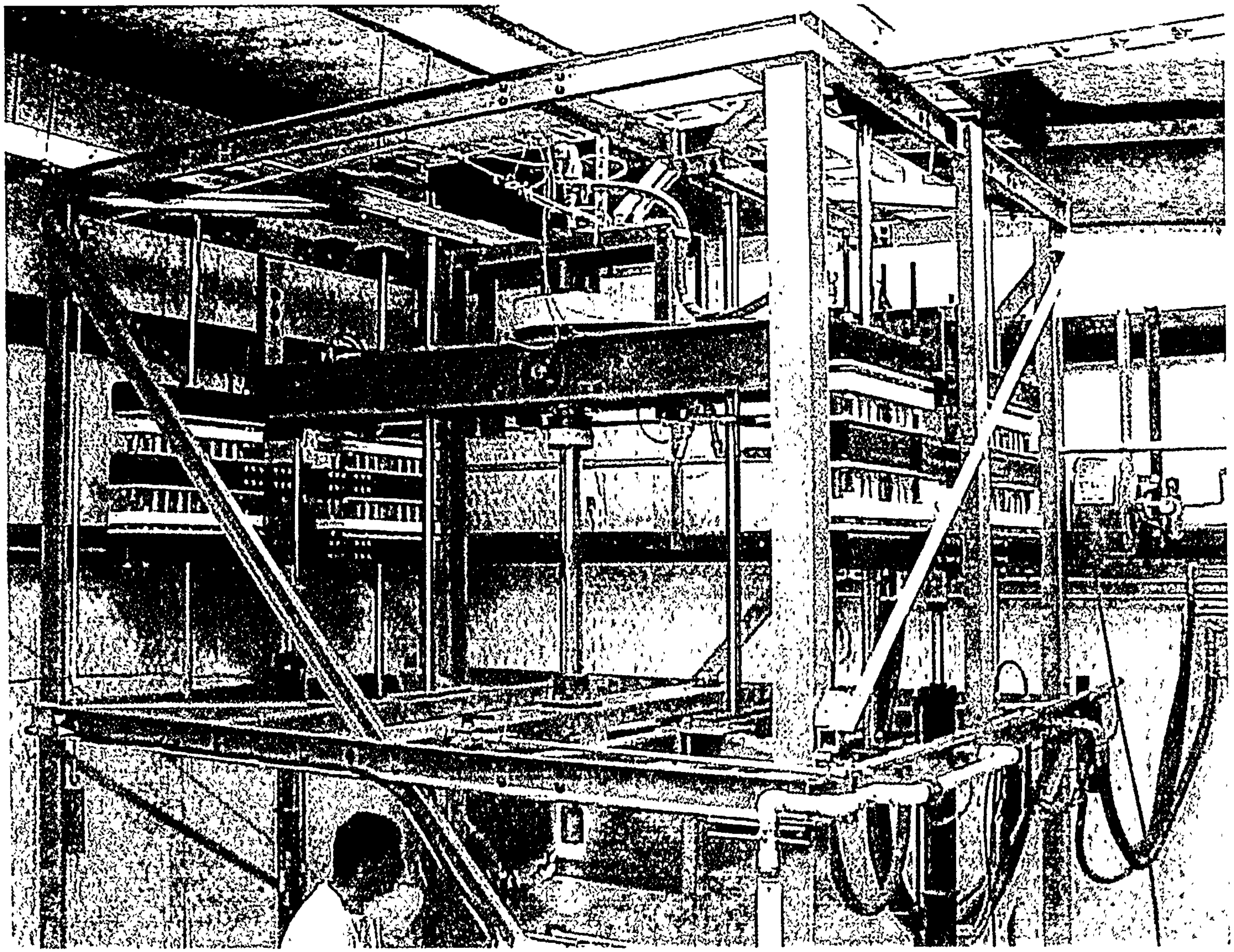

Figure 1. Sandia's Hard-Rock Drilling Facility Modified to Include Axial Compliance.

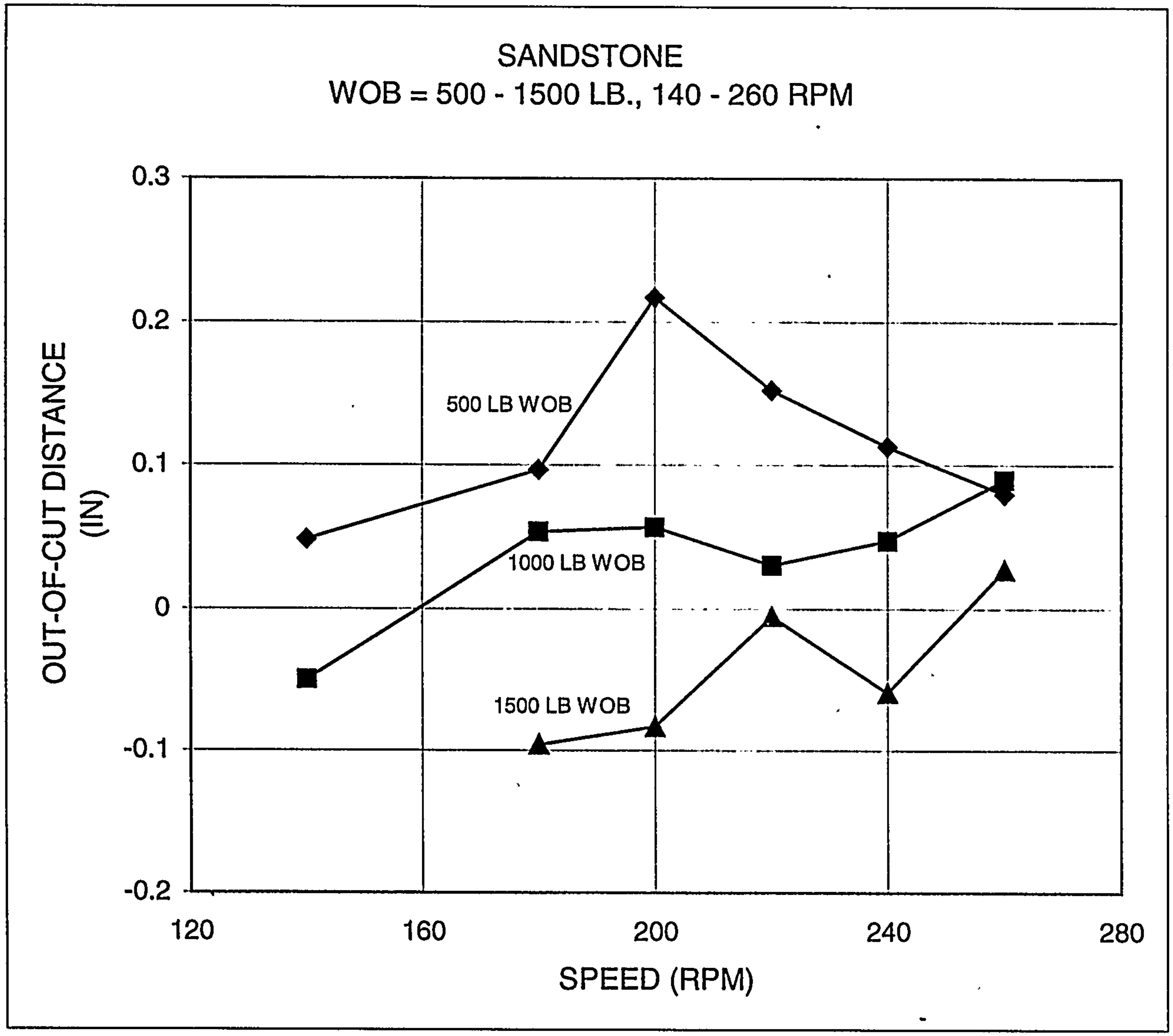

Figure 2. Bit Vibration Measurements from Drilling Tests in Berea Sandstone.

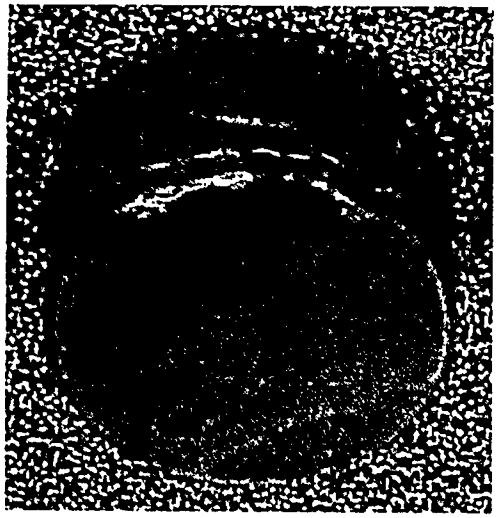

Figure 3a. Lightly-worn PDC at Stable Drilling Condition
(96 ft of Sierra White Granite at 30 ft/hr, 2000 lb. WOB and 100 RPM).

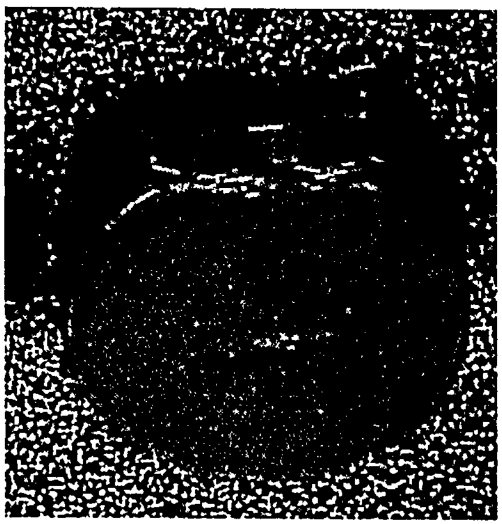

Figure 3b. Failed PDC in Chatter Conditions
(1 ft of Sierra White Granite at 10 ft/hr, 1500 lb. WOB and 140 RPM).