MEASUREMENT AND ANALYSIS OF CHATTER IN A COMPLIANT MODEL OF A DRILLSTRING EQUIPPED WITH A PDC BIT

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ABSTRACT
Typical laboratory testing of Polycrystalline Diamond Compact (PDC) bits is performed on relatively rigid setups. Even in hard rock, PDC bits exhibit reasonable life using such testing schemes. Unfortunately, field experience indicates otherwise. In this paper, we show that introducing compliance in testing setups, provides better simulation of actual field conditions. Using such a scheme, we show that chatter can be severe even in softer rock, such as sandstone, and very destructive to the cutters in hard rock, such as Sierra White Granite.

INTRODUCTION
Chatter in PDC bits has gained a great deal of attention recently. This is caused by the recognition that the primary mode of failure of PDC cutters in hard rock is that of catastrophic failure caused by impact loading. Typically this mode of failure takes place in advance of any appreciable wear that may dictate cutter replacement. Since chatter is a phenomenon in which the drillstring becomes unstable and excessive sustained vibrations ensue, it is considered one of the primary suspects in this mode of failure. A great deal of theoretical work has been performed in an effort to understand this phenomenon as it applies to PDC bits [see for example Elsayed et al., 1997]. Many of the concepts were borrowed from the metal cutting industry, where chatter has been recognized and studied for decades. The problem as it applies to PDC bits drilling in rock is more difficult to analyze. For a theory to be tested on a machine tool, one goes to the laboratory and uses a similar machine for that purpose. Should the test require changes, it is a simple matter to do so. The basic dynamics of the machine is the same, and any changes can be made relatively quickly. On the other hand, a drillstring changes its dynamic characteristics as drilling gets deeper. Should a change in bit or in drillstring configuration is required, the whole length must be extracted before any changes can be made. Moreover, rock properties are different than those of metal. One of the complicating factors is that rock is less homogeneous than metal.

Due to the difficulties expressed above, laboratory testing must be configured in such a way as to approximate field drilling conditions as much as possible. One major area is the compliance of the drilling setup. Typically laboratory rigs are stiff. Tests to evaluate cutter wear and bit performance are generally performed with limited chatter. This chatter takes place at higher frequencies than those experienced in the field [Elsayed, 1999]. In this work, this situation was addressed by adding compliance to the drilling apparatus as discussed below. Drilling tests were performed where the weight-on-bit (WOB), rate of penetration (ROP), rotational speed, and vibration characteristics are measured. The testing procedure and analysis of the results are presented in the following sections.
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Albuquerque, New Mexico. The SNL/NM Environmental Restoration Project is currently excavating the Classified Waste Landfill (CWLF) as a Voluntary Corrective Measure (VCM). The CWLF consists of a series of disposal trenches and pits that were used for disposal of classified weapons components (SNL/NM, 1997).

This paper describes some of the history of the project, the rationale for excavating the landfill, the status of the project, and then discusses the various processes for managing the material exhumed and the emphasis on recycling to minimize generating regulated waste that would have to be disposed at permitted landfills.

Site Location and History
The CWLF is located in the eastern portion of Technical Area II (TA II). The landfill proper covers approximately 1.5 acres, but is included in a suspect area that encompasses nearly 3.5 acres.

Classified material reportedly was buried at the CWLF from the early 1950s through 1987, but disposals may have started as early as 1947.

Based on historical records and interviews, the typical disposal method consisted of excavating trenches and emplacing unneeded classified materials collected from throughout SNL/NM, then backfilling each trench section to bring it to grade (Jerome, 1989). Besides the trench method of disposal, some deep pits were dug with a clamshell excavator. After each disposal event, a marker was placed on the surface at the approximate midpoint of each cell and labeled with the cell designation. After disposals ended in 1987, the landfill was designated an environmental restoration site.

Project Justification
The landfill is being concurrently characterized and excavated to mitigate its potential to pose hazards to human health and the environment. The following factors and assumptions were used as the basis for excavating the landfill:

- Because of the landfill subsidence over time, classified materials were subject to exposure and possible retrieval by unauthorized entities.

- The site contains hazardous and radioactive materials that pose a threat of release, particularly by uncontrolled intrusive activities.

- There is the potential for the site to have contributed to low-level groundwater contamination beneath TA II.

- The landfill location interferes with future plans for the area.

- Because of the heterogeneous and discrete nature of the waste, traditional assessment approaches would not fully characterize the nature and extent of contamination. A defensible risk assessment analysis would not be possible and unplanned releases of contaminants to the environment could occur.
• Significant long-term cost savings can be realized by accelerating the cleanup voluntarily through the VCM option. The alternative is following the traditional path from site characterization, through a corrective measures study, to final implementation of a corrective measure, with an accompanying series of long regulatory review cycles.

Status of the Excavation
As of late October 1999, the excavation phase of the project was 77% complete. The pace of excavation is controlled by weather, available space, the type of material excavated, and fluctuations in the size of the field crew. If storage space and weather permit, a backlog of material to be sorted and characterized is generated to allow operations to continue during inclement weather. It is estimated that excavation will be complete by July of 2000. Then a geophysical survey will be performed to ensure that all buried debris is removed and final verification samples will be collected in the bottom of the excavation. These tasks, along with backfilling the excavation and disposition of the material excavated, should be completed by February of 2001.

MATERIAL EXCAVATED AND DISPOSITION

Classified Material
Approximately 90% of the landfill contents is still considered classified from a national security standpoint. Therefore, in addition to managing any hazards posed by the excavated artifacts themselves, they must be adequately secured to prevent the loss of classified nuclear weapon design information. The material includes weapon components from the many different weapon systems with which SNL/NM was involved in a design or test capacity. Hundreds of different parts are being found, from very small electronic components to molds weighing thousands of pounds for shaping metal pieces. Complete weapon mock-ups also are being excavated that were used to test weapon assemblies or used for training purposes. Production versions and a wide variety of prototype models of every type of component from the different weapon systems are being recovered.

As the material is excavated, it is surveyed and sorted several times to separate classified artifacts from unclassified artifacts and waste items. The classified components are then grouped by type and scheduled for demilitarization. The demilitarization process renders the material unclassified. In some cases, the process is as simple as throwing a component into a large shredder that produces a mulch of plastic and metal fragments. The larger assemblies are more complex and once their internal structure is understood, must be disassembled to remove any radioactive components or hazardous materials such as batteries, capacitors, lead-containing ceramics, or mercury switches.

The mulched remains of the classified components are then sent to a smelter in Arizona where common and precious metals are extracted. The common metals include steels, magnesium, aluminum, copper, lead, and tin. Because many components contain very
high quality electronics, precious metals such as gold, silver, platinum, and palladium can be recovered. The sale of these metals returns some funding to SNL/NM to support the demilitarization process.

Not all the classified weapon components are demilitarized. Some weapon mock-ups or components being excavated are from weapon systems that are no longer in the U.S.'s nuclear stockpile. These items have some historical value and are being released to the classified weapons display at the KAFB Nuclear Weapons Training School.

A joint Los Alamos National Laboratory and SNL/NM training program preparing specialized response teams for explosive and nuclear incidents are using other weapon mock-ups.

Unclassified Material
Unclassified material, primarily composed of various metals, comprises approximately 10% of the landfill contents. This category is primarily metal shapes or parts that were never classified or are no longer considered classified. In some cases unclassified metal casings are separated from classified assemblies for recycle. Unclassified metals have recoverable value and are easily recycled. The types of metal with recoverable value include cast iron, stainless steel, aluminum, magnesium, copper, brass, and carbon steel. Once the metal is separated from the classified components and certified to be free of radioactive contamination, it is loaded into roll-off containers for disposition by a local metal recycling contractor.

Some components or assemblies that are no longer classified but have some historical value and are still in good shape are released to the National Atomic Museum on KAFB for display.

Classified Waste
Classified Components: A number of classified components recovered from the landfill are radioactively-contaminated as a result of past testing or from their materials of construction. Examples are radioactive contamination from depleted uranium, corroded thoriated metal skins, or breached radioactive sources containing tritium, nickel-63, radium, or americium. If disassembly or decontamination cannot minimize the radioactive contamination, the entire component must be considered waste. Many components also contain capacitors, batteries, electronic components, explosive switches, mercury, or lead solder that add a hazardous component to the waste. In some cases these items are removed in the dismantling process where any material with recoverable value is separated before an item is destroyed to eliminate the classification issue.

Classified Soft Waste: Also considered classified waste are parts or models of wood, plastic, paper, or foam whose shape and association with a specific weapon system render them classified. This category is referred to as “classified soft” waste. Material in this category generally has no radioactive contamination or chemical hazards but must be managed as classified waste. The “classified soft” waste has no significant recoverable value and is of a very heterogeneous nature. Therefore, when the absence of radioactive
or chemical hazards is confirmed, it is cut or shredded into small pieces to render it unclassified. The debris is then sent to a local landfill as solid waste. One unusual example of this type of waste was thousands of reels of magnetic tape used to store classified design information. While there were no hazards associated with the tapes, the material had to be surveyed to verify the absence of radioactive material and then shredded to DOE standards for classified information.

**Unclassified Waste**

**Batteries:** Over the years SNL/NM has performed extensive battery research and development for applications in nuclear weapons. The batteries power the weapons during the arming and detonation sequences. Over the operating life of the landfill, thousands of batteries from the research effort were disposed. The batteries coming from the landfill are no longer considered classified. Nickel-cadmium batteries, one of the major by-products of the battery research, are recycled for their metal content.

SNL/NM also developed many types of thermal batteries. There is currently no recoverable value from the thermal batteries. The thermal batteries are designed for one-time use and are activated by a small explosive charge or squib that mixes the battery components, initiating a chemical reaction that delivers the required voltage and amperage. The thermal batteries must be tested, or in some cases X-rayed, to verify that the explosive charge is fired before disposal. Thermal batteries contain a variety of heavy metals and in some cases have asbestos as an insulator, so they must be disposed as hazardous waste. In the few cases where batteries are unfired, each charge is fired by battery experts in a controlled environment. Reliability data on battery longevity is compiled by battery research groups when the batteries are fired. Thermal batteries are sorted by type, verified free of radioactive material, and packaged for disposal.

**Capacitors:** Capacitors, used to store electrical potential for discharge at a specific moment in certain weapon components, are another unclassified waste stream with no recoverable value. Capacitors of all shapes and sizes are being excavated from the landfill. Because of the potential for polychlorinated biphenyls in the oil contained in the capacitor layers, each type of capacitor must be characterized for disposal. The primary hazardous component of the capacitors is lead solder used for connections and to seal the containers. As with all material from the landfill, each capacitor must be surveyed to verify that it is free from radioactive contamination and therefore does not constitute radioactive waste.

**Soft Waste:** Another unclassified waste stream from the landfill is referred to as “soft” waste. This includes wood, paper, foam, and plastics that were used for packaging material placed in the landfill and were not directly associated with weapon components. Because of the potential for radioactive contamination in the landfill, the high cost of surveying all the material for radioactive contamination, and the absence of any recyclable value, the soft waste is characterized as low-level radioactive waste and disposed in a permitted landfill. To reduce the number of drums sent for disposal, the soft waste is compacted to achieve greater than a 3:1 volume reduction.
Miscellaneous Waste: Efforts are made during the excavation process to minimize the generation of waste soil. Some of the soil excavated is contaminated due to close proximity to contaminated components. However, by careful segregation of soil around contaminated artifacts, the amount of soil that must be treated as waste can be minimized. Of the approximately 35,000 cubic yards of soil excavated to date, less than 0.2% must be packaged for disposal at an approved landfill.

One of the smaller waste streams is asbestos fabric used as insulation in some test assemblies. This material is identified during the excavation process and separated for packaging and disposal in a permitted landfill.

Operational Waste
Another source of waste generated by the excavation project is operational waste. This includes all the personal protective equipment (PPE) and other consumables used by project personnel. To minimize the amount of PPE entering the waste stream, personnel wear reusable coveralls that are laundered by a commercial laundry if not contaminated or sent to a radioactive laundry service if they contain radioactive material. Another waste minimizing step is having personnel wear reusable chemical boots that can be decontaminated rather than disposable boot covers.

Waste oil from the heavy equipment is recycled, as is all the cardboard packaging from supplies used by the project and used office paper. Aside from those items with some definite recoverable value, the project also generates a certain amount of PPE, packaging materials, and other debris which increase the volume disposed as waste to the local landfill.

DISCUSSION

If recycling much of the material from the landfill were not a viable option at the beginning of the project, the excavation of the Classified Waste Landfill would not be possible. Disposal options for some classified waste streams simply do not exist. This lack of permitted disposal sites and the high cost of disposing of regulated waste support the implementation of waste minimization practices.

Over 1.3 million pounds of material have been excavated since the beginning of the project. Of that total, approximately 12% consist of material that must be disposed as hazardous, radioactive, or mixed radioactive and hazardous waste. If the project did not actively promote waste minimization practices, that percentage would be much higher.

Significant efforts are made to separate uncontaminated components or soil from contaminated material to minimize waste generation. This careful segregation process is the basis of effective waste minimization because the sorting reduces the volumes of each type of waste. If the recycle option cannot be exercised for a specific material from the landfill, an extensive waste characterization process must be undertaken. Included in this characterization are surveys and sampling along with the inventorying, packaging, data
management, transportation, sometimes treatment processes, and handling costs that are incurred before disposal fees are assessed. Simply defaulting to a waste category such as radioactive, hazardous, or mixed radioactive and hazardous waste is often not a cost-effective solution in the long term.

ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

REFERENCES
