

Title: THERMAL MODELING OF CORE SAMPLING IN  
FLAMMABLE GAS WASTE TANKS: PART II -  
ROTARY-MODE SAMPLING

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**Thermal Modeling of Core Sampling In Flammable Gas Waste Tanks:  
Part II -Rotary-Mode Sampling**

by  
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**ABSTRACT**

The radioactive waste stored in underground storage tanks at Hanford site includes mixtures of sodium nitrate and sodium nitrite with organic compounds. The waste can produce undesired violent exothermic reactions when heated locally during the rotary-mode sampling.

Experiments are performed varying the downward force at a maximum rotational speed of 55 rpm and minimum nitrogen purge flow of 30 scfm. The rotary drill bit teeth-face temperatures are measured. The waste is simulated with a low thermal conductivity hard material, pumice blocks. A torque meter is used to determine the energy provided to the drill string. The exhaust air-chip temperature as well as drill string and drill bit temperatures and other key operating parameters were recorded.

A two-dimensional thermal model is developed. The safe operating conditions were determined for normal operating conditions. A downward force of 750 at 55 rpm and 30 scfm nitrogen purge flow was found to yield acceptable substrate temperatures. The model predicted experimental results reasonably well. Therefore, it could be used to simulate abnormal conditions to develop procedures for safe operations.

**I. INTRODUCTION**

The management and storage of the waste accumulated from processing defense reactor irradiated fuels for plutonium recovery at the Hanford Site is one of the important environmental clean-up effort that engineers and scientist face today. There are 177 waste tanks, including 149 single-shell tanks and 28 double-shell tanks at the Hanford reservation.

Waste characterization activities are an important part of the waste management and environmental operations at the Hanford site. The rotary-mode core sampling is one of the method employed for obtaining full-depth core samples for hard wastes. A typical sampling operation involves setting a sampling truck, an exhauster, a nitrogen supply system, and a variety of support equipment on or near a waste tank. The sampling truck is positioned at the appropriate riser, and the DS with a sampler is inserted into the tank. The rotary-mode sampling method collects a waste sample that is withdrawn from the tank, transferred in a shielded receiver to a mobile x-ray system for preliminary examination, then into a cask for transport to the analytical laboratories for full characterization. The drilling/sampling sequence is repeated until a set of samples representing a full-depth core is acquired.

Wastes including mixtures of sodium nitrate and sodium nitrite with organic compounds can produce violent exothermic reactions when expose to heat sources. The temperature of the waste in the vicinity of the drill bit could be increased as a result of frictional heating or cutting.

The local runaway reactions in wastes can be prevented by establishing waste temperature limits. A temperature limit of 160 °C is established for waste reactivity in Ref. 1. The drill bit/waste interface temperatures in rotary-mode core sampling must not exceed this critical temperature limit. The power of the drilling truck is more than necessary to elevate the drill bit temperature above the critical waste temperature limit. Therefore, operating parameters, downward force, rotational speed, and nitrogen purge flow, need to be controlled under normal as well as abnormal conditions.

The study reported in this paper and Ref. 2 are performed to support the safety assessment of rotary and push-mode core sampling in flammable gas single-shell tanks (Ref. 1). This paper discusses the thermal modeling of the rotary-mode core sampling. The objective of the paper is to develop a thermal model for the drilling process. The model is aimed to determine the allowable maximum downward load, rotational speed, minimum nitrogen purge flow rate and penetration rate that can be safely applied without initiating a local hot spot (>160 °C).

## **II. DESCRIPTION OF ROTARY-MODE SAMPLING AND TESTING**

The description of the sampling is given in Part I of this paper. In this section components specific to the rotary-mode core sampling is discussed. The rotary mode drill bit depicted in Fig. 1 rotationally bores into the waste to produce a nominal 1-in.-diameter core sample and acts as the leading tip of the DS. The bit has a hollow-cored center section surrounded by cutting teeth and holes on the drilling surface for nitrogen purge flow. The commercially available unit (nominally 2.5-in. o.d.) is made of sintered-bronze matrix with tungsten chips.

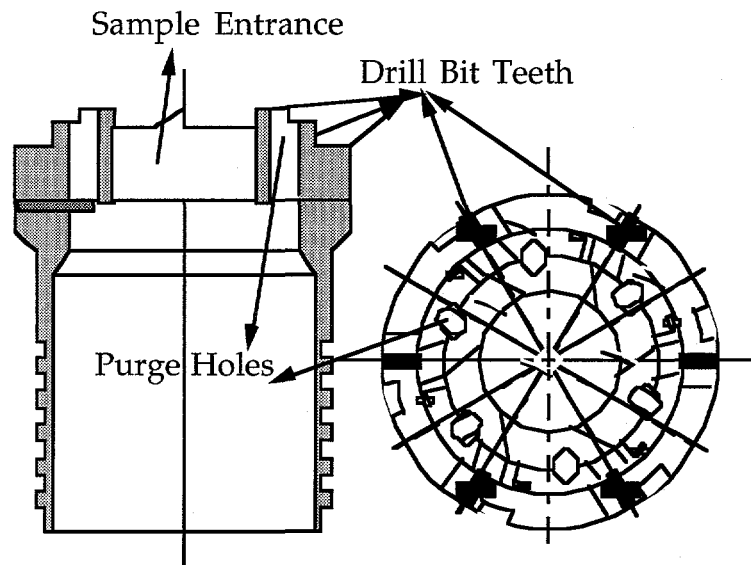


Fig. 1. Sketch of rotary-mode drill bit.

Testing was carried out with a drill rig discussed in the companion paper (Ref. 2). Two calibrated K type-thermocouples were mounted by silver soldering on the cutting faces of the inner and outer tooth. The air and waste simulant (pumice blocks) temperatures were also measured at several places. Thermocouples were characterized before and after testing.

The rotational velocity and the applied downward force was recorded manually. The rotational speed was measured with a proximity sensor which counted the teeth on a sprocket rotating with the drill string. The bit position is also recorded with A Celesco string potentiometer.

The purge flow rate was calculated with data from a flow meter, type K thermocouple, and a pressure gage. The torque was measured in real time with a inductively coupled device from Wireless Data Corporation (Model 1200B). This unit monitors strain from an instrumented section of drill string and converts the resulting output to foot-pounds. The instrumentation and accuracy is given in Table 1.

Tests are performed using a waste simulant that was selected as pumice blocks. The material properties of pumice is estimated and summarized in Ref. 1. The density times the specific heat products for the waste simulant used by various researchers at Hanford and the pumice block are within three percent of each other. Thus, the energy storage terms are very comparable. The thermal diffusivity coefficient of the pumice block tends to be less than that of the simulant.

Each test was performed with a new (sharp teeth) bit. Pumice blocks are stacked to allow multiple runs with one set up. Block temperature was checked between runs to provide a consistent starting point, and all runs were started a minimum of about

one inch into the pumice block to minimize any cooling effect from surrounding air.

**TABLE 1  
INSTRUMENTATION AND ACCURACY**

| <b>Item</b>   | <b>Range and Accuracy</b>  |
|---|--|
| Position Indicator<br>Celesco PT10140A                | 24 in. $\pm$ 0.1 in.(initially) and $\pm$ 0.01 in.<br>(during testing) |
| Downward Force<br>Toledo/Mett Mdl 8140                | 0-2000 lb $\pm$ 2 lb   |
| Nitrogen Purge Flow Rate<br>Hedland 647060 Flow meter | 10-60 cfm -> 5% error at 30 scfm                                       |
| Thermocouples K type                                  | 0-300 °C $\pm$ 2°C   |
| Marsh Bourdon Tube Pressure Gage                      | 0-1000 psia $\pm$ 2% full scale  |
| Torque Wrench   | 0-1200 in-lb $\pm$ 2 in-lb   |
| Torque Wrench (Electronic)                            | 15-250 ft-lb $\pm$ 1 ft-lb   |

The typical test involved following steps.

1. Zero torque cell and down force scale; verify thermocouple inputs are consistent with ambient temperature conditions.
2. Lower bit to pumice block; zero vertical position transducer, set down force, verify block temperature, and check/adjust purge flow rate in concert with vacuum attachment to plastic enclosure.
3. Raise bit; start/verify drill string rotation.
4. Lower bit to pumice block; monitor/adjust downward force as required during test run.
5. Continue test for several minutes until a maximum temperature is clearly evident or follow prescribed scenario.

### **III. EXPERIMENTAL RESULTS**

Table 2 summarizes the performed tests and their conditions (see Ref. 3 for details). Details of test description is available in Ref. 3. Test 16 will be used in benchmarking the model. Test results obtained from Test 16 are summarized in Figs. 2 and 3 and explained briefly below.

This test is conducted with a downward force of 750 lbf, a rotational speed of 55 rpm, and a purge flow of 30 scfm. There are 4 different phases in this test. The first phase end at about 120 second at which the drill bit penetration stops. The torque within 60 second is nearly constant with some oscillations. The drill bit temperature increases exponentially when the penetration rate is nearly constant. After 60 seconds, perhaps because of teeth are getting dull, the penetration rate decreases and torque starts to decrease slightly. The drill bit temperature levels off. The air

temperature continues to increase. The control of downward force is not perfect and the downward force somewhat increases from 600 lbf to 800 lbf in this period.

**TABLE 2  
TEST CONDITIONS**

| Test ID    | Downward Force (lbf) | Rotational Speed (rpm) | Nitrogen Purge Flow (scfm) | Drill Bit Condition | Simulant |
|------------|----------------------|------------------------|----------------------------|---------------------|----------|
| RETMP-09   | 1170                 | 55                     | 0                          | Sharp               | Pumice   |
| RETMP-10   | 1170                 | 55                     | 0                          | Sharp               | Pumice   |
| RETMP-10A  | 1170                 | 55                     | 0                          | Dull                | Pumice   |
| RETMP-10B  | 1170                 | 55                     | 0                          | Dull                | Pumice   |
| RETMP-11   | 1170                 | 55                     | 0                          | Sharp               | Pumice   |
| TORQTST-5  | 1170                 | 55                     | 0,20,30                    | Sharp               | Pumice   |
| TORQTST-6  | 1170                 | 55                     | 20                         | Sharp               | Pumice   |
| TORQTST-7  | 1170                 | 55                     | 20                         | Sharp               | Pumice   |
| TORQTST-9  | 650                  | 30                     | 30                         | Sharp               | Pumice   |
| TORQTST-10 | 1170                 | 55                     | 21                         | Sharp               | Pumice   |
| TORQTST-11 | 900                  | 55                     | 30                         | Sharp               | Pumice   |
| TORQTST-12 | 900                  | 55                     | 30                         | Sharp               | Pumice   |
| TORQTST-14 | 750                  | 55                     | 30                         | Slug therm.         | Pumice   |
| TORQTST-16 | 750                  | 55                     | 30                         |                     | Pumice   |
| TORQTST-17 | 750                  | 55                     | 30                         | 4 plugged holes     | Pumice   |
| TORQTST-19 | 750                  | 30                     | 30                         | 4 plugged holes     | Pumice   |
| TORQTST-20 | 900                  | 55                     | 30                         | 4 plugged holes     | Pumice   |
| TORQTST-21 | 750                  | 55                     | 30                         | 4 plugged holes     | Pumice   |
| TORQTST-22 | 650                  | 55                     | 30                         | 4 plugged holes     | Pumice   |
| TORQTST-23 | 750                  | 55                     | 30                         |                     | Steel    |

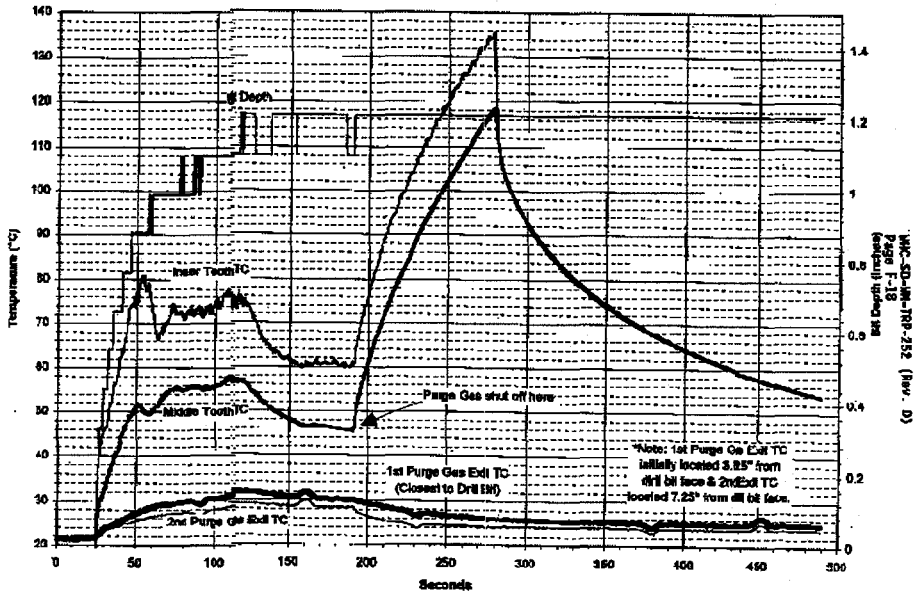
The second phase starts with no penetration at 120 and ends at 190 seconds. In this period, the drill bit slides on the pumice and the drill power is consumed by frictional heating. The air and drill bit temperatures, force, rotational speed and torque approaches to steady-state values in this period. The drill bit cools off because the applied torque decreased.

The nitrogen flow is turned off at the beginning of the third period. Frictional heating is continued with almost constant force, torque and rotational speed until 275 seconds. After this time, rotation is stopped while force is continued to applied until system cools down.

## V. MODELING

The general conduction heat transfer equation is solved numerically for the bit geometry. The coordinate system is fixed to the drill bit; therefore, the drilled material is moving (in effect flowing) with respect to the grid. Therefore, as the bit

TORQTS16 - STANDARD BIT IN PUMICE BLOCK  
 Drill Bit and Exit Purge Gas TC's & Depth  
 (760 lbf, 56 RPM, 30 SCFM)



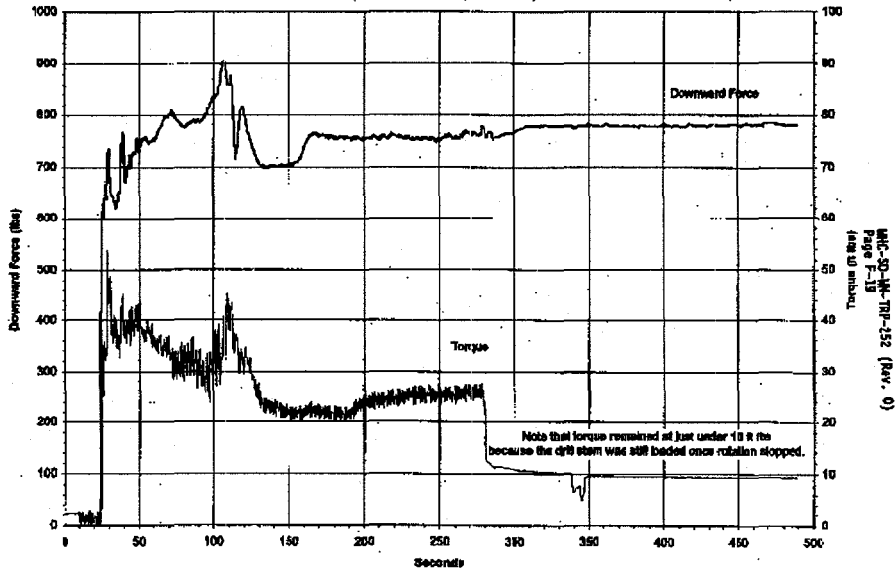
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Fig. 2

TORQTS16 - STANDARD BIT IN PUMICE BLOCK  
 Downward Force & Torque  
 (760 lbf, 56 RPM, 30 SCFM)



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Fig. 3.

penetrates, an additional term is added to the drilled material heat transfer solution. In effect, this is a steady state, constant property, incompressible flow solution. The material that “flows” through the upper boundary of the drilled material is added to the gas flow.

The approximated heat transfer process during drilling is illustrated in Fig. 4.

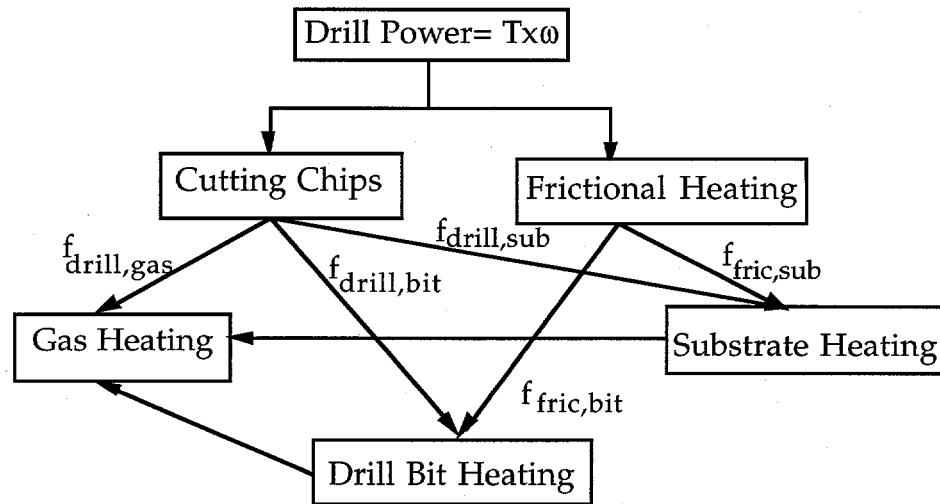


Fig. 4. Heat Transfer Process During Drilling

The drill power, which can be obtained from applied torque and rotational speed, is assumed to be consumed as thermal energy into chips created as a result of cutting,  $Q_{drill}$ , and frictional heating to the substrate and the drill bit,  $Q_{fric}$ .

$$Q_{tot} = T\omega = Q_{drill} + Q_{fric},$$

where

$$Q_{drill} = E_{sp} / (P \times A_{drill}) \quad \text{and} \quad Q_{fric} = f \times F \times \omega \times 2\pi r.$$

$P$  is the penetration rate,  $A_{drill}$  is the cross sectional area of the material removed,  $f$  is the coefficient of friction, and  $r$  is the effective radius.  $E_{sp}$  is the specific energy of the drilled material that is defined as the mechanical energy input per unit volume of material removed. In the rock drilling literature this quantity is called as specific energy while similar quantity is referred as unit horse power in the literature of machining.

Estimation of  $E_{sp}$  is difficult for materials those not characterized well such as nuclear wastes. However, if the torque is considered as an input parameter,  $Q_{drill}$  can be calculated as the difference between  $Q_{tot}$  and  $Q_{fric}$ . Giving the penetration rate and  $Q_{drill}$ ,  $E_{sp}$  than can be estimated.

Some fraction of the mechanical energy spend to remove the material is redistributed between the drill bit and substrate as discussed below. As shown in Fig. 4, the fractional splitting of  $Q_{\text{drill}}$  and  $Q_{\text{fric}}$  into their coolant gas, bit, and substrate components are introduced. The resulting energy deposition fractions are expressed in terms of fractions as given below,

$$Q_{\text{gen,bit}} = f_{\text{drill,bit}}Q_{\text{drill}} + f_{\text{fric,bit}}Q_{\text{fric}} ,$$

$$Q_{\text{gen,sub}} = f_{\text{drill,sub}}Q_{\text{drill}} + f_{\text{fric,sub}}Q_{\text{fric}} , \text{ and}$$

$$Q_{\text{gas}} = f_{\text{drill,gas}}Q_{\text{drill}} ,$$

$$f_{\text{drill,bit}} + f_{\text{drill,sub}} + f_{\text{drill,gas}} = 1 ,$$

$$f_{\text{fric,bit}} + f_{\text{fric,sub}} = 1 .$$

These fractions are yet to be determined from proper test data. The gas temperature is obtained from the following equation

$$T_{g_k} = \frac{1}{\dot{m}C_{p_k}} \left( \dot{m}_{k-1}C_{p_{k-1}}T_{g_{k-1}} + \dot{m}_{\text{chip}_k}C_{p_{\text{chip}}}T_{\text{sub}} + Q_{w_k} + Q_{\text{gas}_k} \right)$$

where:  $\dot{m}_k = \dot{m}_{k-1} + \dot{m}_{\text{chip}_k}$  .

$Q_w$  is the heat transfer between the solid surfaces and coolant and used both in the conduction solution and to calculate the gas temperature.  $Q_{\text{gas}}$  is the energy deposition directly into the gas from the chips and  $T_{\text{sub}}$  is the temperature of the substrate at the location where the chips are being generated. Also, as chips are added to the flow caused by drilling, the specific heat and other properties of the flow are adjusted. It is assumed that the gas and chips mix uniformly and come instantaneously to equilibrium.

The flow solution is solved separately from the conduction solution. The flow solution is obtained by setting up a nodal 1-D flow path based on a path-through system. Specified at each node are the node length, flow area, hydraulic diameter, the heat transfer area, and the surface temperature of the conduction nodes that surround the flow node. The heat transfer between the flow and conduction nodes is then given by the standard internal flow relations.

## VI. MODELING RESULTS

The model has been benchmarked versus two separate experimental tests: TORQTST16 and TORQTST23. TORQTST23 (which involves drilling into steel),

contains reliable temperature measurements below the drilling surface. Initially, the energy deposition fractions (and to a small extent the material properties) were varied so that the experimental and computational results matched for each case separately. A fixed set of parameters was then determined combining the results of the two cases.

The model was, then, used to calculate temperatures for three additional tests: TORQTST15, TORQTST17, and TORQTST18. No model parameters were adjusted in assessing the model against these three tests. The calculated results conform fairly well with the experimental results for each test, especially considering the uncertainty in the experimental measurements. The results for some of these calculations are shown in Fig. 5. The calculated results are plotted alongside the experimental bit temperature. The experimental gas flow temperatures are not plotted, but they conform within  $1^{\circ}\text{C}$  of the calculated temperatures. TORQTST23 involved drilling into a steel slug; the experimental and calculated temperatures in the slug are also plotted for this case. The agreement between experimental measurements and calculated data for tests TORQTST15, 17, and 18 indicates that this model can be used for further parametric analysis.

The primary result of the heat transfer analysis is the maximum substrate temperature as a function of time and drilling conditions. The substrate temperature limit has been set at  $150^{\circ}\text{C}$ ; therefore, the model was used to determine how long it would take to reach this temperature under specific drilling conditions. The time to reach  $120^{\circ}\text{C}$  was also calculated to provide a conservative number. The time to reach each temperature was calculated as a function of torque, penetration rate, and initial waste temperature. The material properties were taken to be the same as for the experimental pumice, which is assumed to be a bounding condition (i.e. the waste is expected to have a higher specific heat and a lower specific energy).

All of the results are obtained for a down force of 750 lb, a drill speed of 55 rpm, and a purge gas flow rate of 30 scfm. For this calculation, it was conservatively assumed that all of the energy goes into the bit and substrate (i.e., none goes directly to the gas). These results are plotted for the  $150^{\circ}\text{C}$  limit in Figs. 6 and 7. On the plots, any condition to the lower left of a given line will produce a maximum temperature below  $150^{\circ}\text{C}$ .

Fig. 8 plots that maximum allowable torque as a function of penetration rate that will not result in exceeding the  $150^{\circ}\text{C}$  limit. This data can be used to determine the optimum limits in terms of torque, penetration rate, and time for the drilling process.

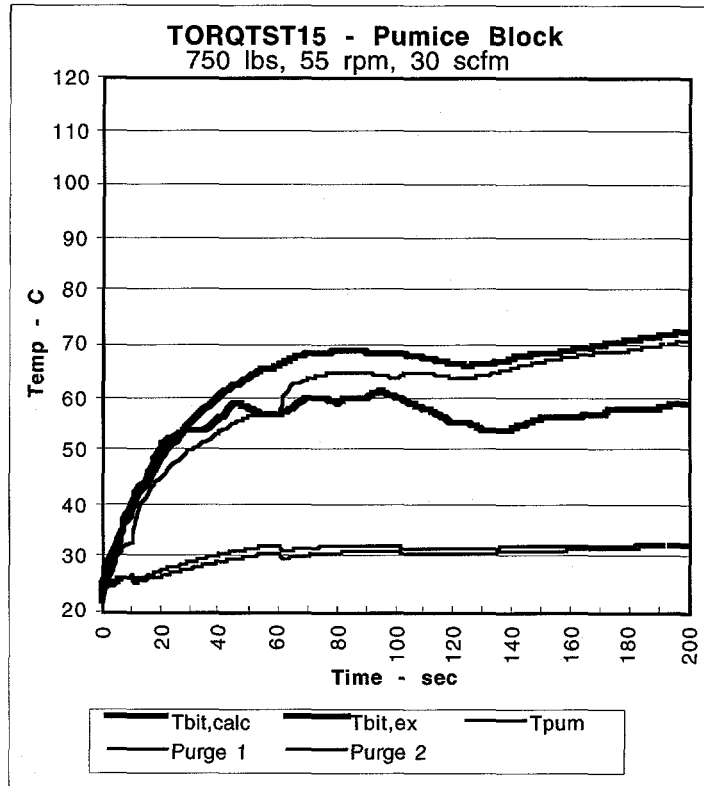


Fig. 5(a). Comparison of calculated and measured temperatures of Test 15.

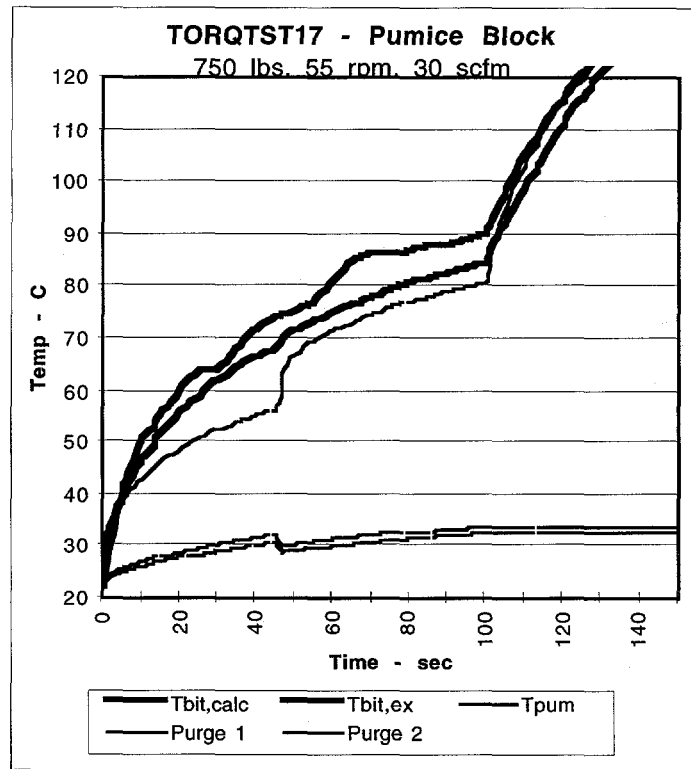


Fig. 5(b). Comparison of calculated and measured temperatures of Test 17.

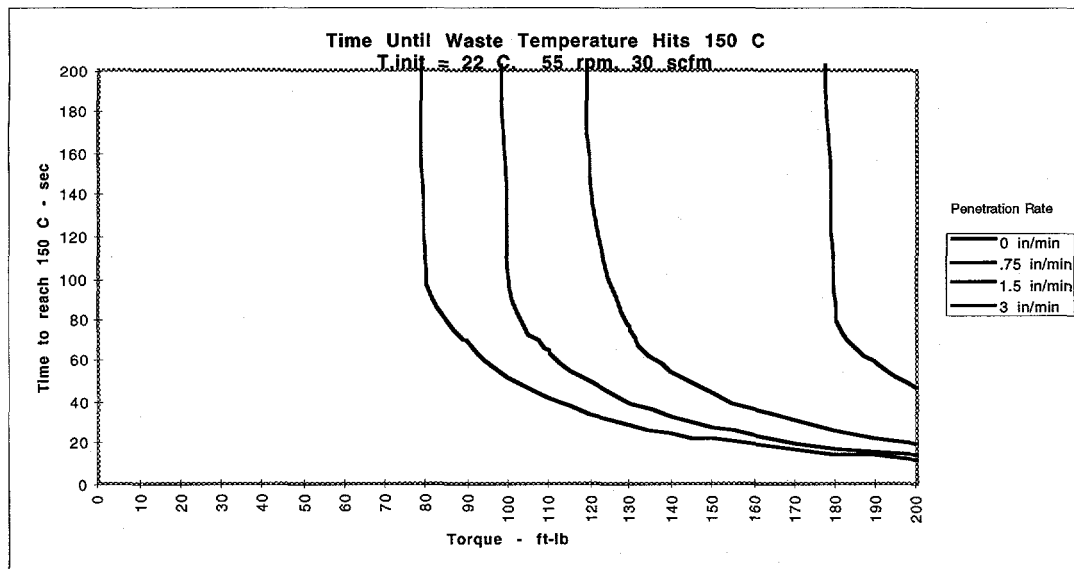


Fig. 6. Time to reach 150°C as a function of torque for various penetration rates and an initial temperature of 22°C.

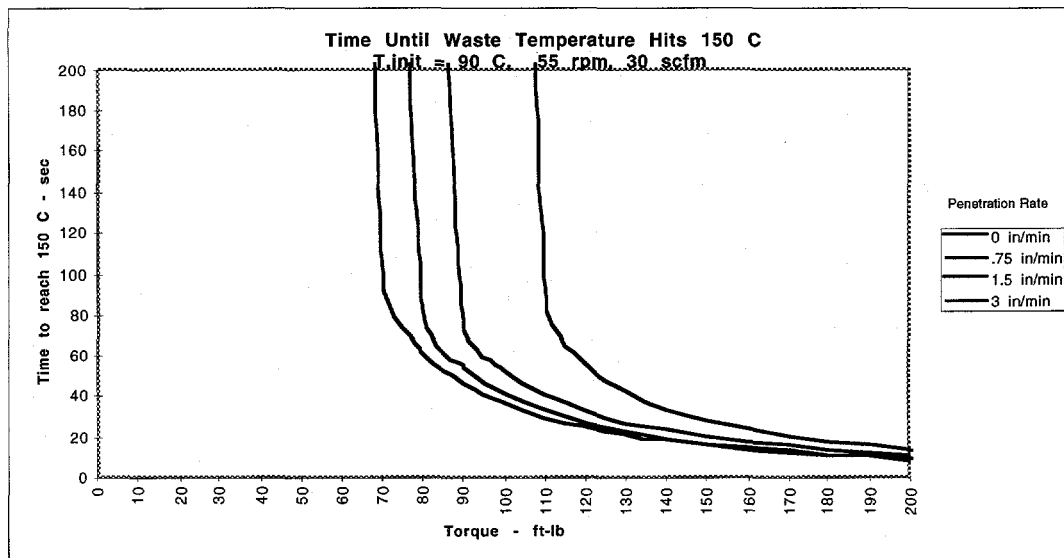
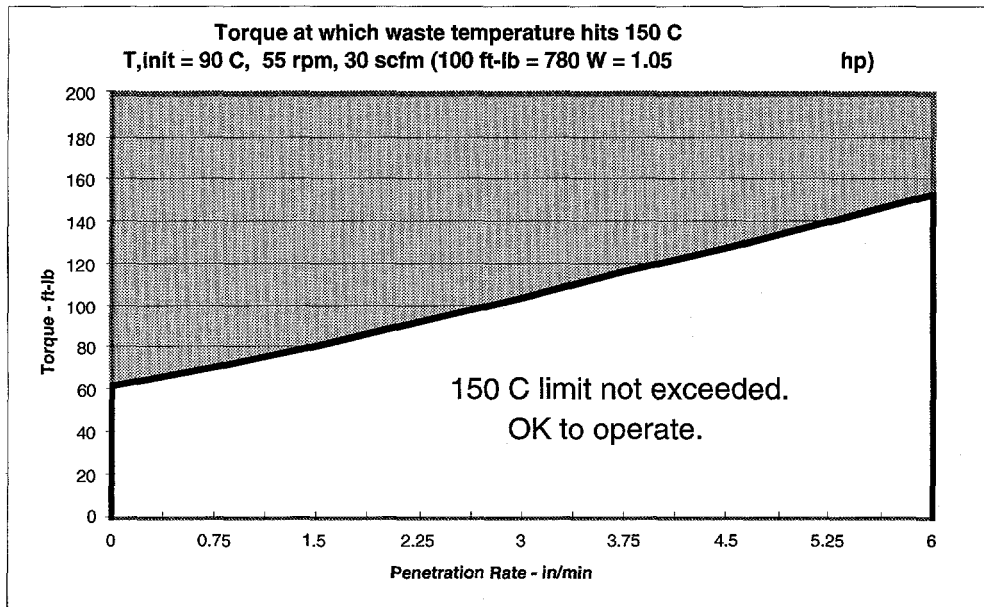


Fig. 7. Time to reach 150°C as a function of torque for various penetration rates and an initial temperature of 90°C.

## VII. CONCLUSIONS

Experimental and analytical results showed that the drill bit surface temperature can be limited by 150 °C if the downward force is less than 750 lbf, the rotational speed is less than 55 rpm, the nitrogen flow rate is higher than 30 scfm and the penetration rate is higher than 0.75 in./min. The model predicted the experimental results reasonably well. Therefore it can be used to study abnormal transient conditions to develop procedures for safe operations.



**Fig. 8. Torque at which waste temperature reaches 150°C as a function of penetration rate.**

## VII. REFERENCES

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