

Title: THERMAL MODELING OF CORE SAMPLING IN
FLAMMABLE GAS WASTE TANKS: PART I -PUSH-
MODE SAMPLING

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Thermal Modeling of Core Sampling In Flammable Gas Waste Tanks: Part I -Push-Mode Sampling

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ABSTRACT

The radioactive waste stored in underground storage tanks at Hanford site is routinely being sampled for waste characterization purposes. The push-and rotary-mode core sampling is one of the sampling method employed. The waste includes mixtures of sodium nitrate and sodium nitrite with organic compounds that can produce violent exothermic reactions if heated above 160 °C during core sampling. A self-propagating waste reaction would produce very high temperatures that eventually result in failure of the tank and radioactive material releases to environment.

A two-dimensional thermal model based on a lumped finite volume analysis method is developed. The enthalpy of each node is calculated from the first law of thermodynamics. A flash temperature and effective contact area concept were introduced to account the interface temperature rise. No maximum temperature rise exceeding the critical value of 60 °C was found in the cases studied for normal operating conditions. Several accident conditions are also examined. In these cases it was found that the maximum drill bit temperature remained below the critical reaction temperature as long as a 30 scfm purge flow is provided the push-mode drill bit during sampling in rotary mode. The failure to provide purge flow resulted in exceeding the limiting temperatures in a relatively short time.

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 scientists face today. There are 177 waste tanks, including 149 single-shell tanks and 28 double-shell tanks at the Hanford reservation. Some of these tanks generate/retain/release hydrogen/ammonia/nitrous oxide with considerable amounts.

The radioactive waste stored in underground tanks can be sampled by several means to provide physical, chemical, and radionuclide data. Push and rotary-mode core sampling are one of the method employed to obtain full-depth core samples. The push mode is used for liquids and sludges, while the rotary mode is used

primarily with salt cake. For either sampling mode, a sampling truck, an exhauster, a nitrogen supply system, and a variety of support equipment is set up on or near the tank to be sampled.

Wastes including mixtures of sodium nitrate and sodium nitrite with organic compounds can produce violent exothermic reactions when exposed to heat sources. The temperature of the waste in the vicinity of the rotary or push-mode drill bit could be increased as a result of frictional heating or generation of waste chips. The local runaway reactions in wastes can be prevented if the bit temperature is limited to 160 °C (Ref. 1). The power of the drilling truck is more than necessary to elevate the drill bit temperature above the critical waste temperature limit. Therefore, drilling/sampling operating parameters such as downward force, rotational speed, and nitrogen purge flow (only rotary-mode) are needed to be controlled under normal as well as abnormal conditions.

The work discussed in this paper and Ref. 2 are performed to support the safety assessment of push-mode and rotary-mode core sampling in flammable gas single-shell tanks (Ref. 1). This paper discusses the thermal modeling of the push-mode core sampling. The objective of the paper is to develop a thermal model for push-mode core sampling process that could be used to develop procedures ensuring safety. The model is aimed to determine the allowable maximum downward load that can be safely applied to the drill string without initiating a local hot spot (>160 °C) causing a local exothermic waste reaction. The test set up and procedure is same for both push-and rotary mode tests. Section II describes the sampling and push-mode equipment. Section II presents the thermal model and its assessment. Conclusions are given in Section III.

II. DESCRIPTION OF PUSH-MODE SAMPLING AND TESTING

The basic core sampling system required for retrieving waste samples consists of the sampling truck, the portable exhauster, the N₂ supply system, the generator, and associated equipment. Primary components associated with the sampling truck include the grapple hoist assembly, the shielded receiver with remote latch unit, the drill string, the nitrogen system, and the change-out assembly.¹ Associated equipment includes the x-ray machine, cask stand and truck, power distribution trailer, and support vehicles.

The drill string assembly is comprised of the drill bit and core barrel assembly, mated to multiple, interconnected drill rods. The drill string transmits power from the drill rig and quill rod to the drill bit. The string provides containment for purge and hydrostatic head gases.

The core sampler assembly, is a mechanical device that is used to collect and retain the waste sample. After a sample stroke, the sampler is transferred from the drill string to the shielded receiver, then to a cask for shipment to the analytical laboratory. The core sampler assembly, fundamentally consists of the quadralatch,

the pintle rod attached to a piston, the housing assembly, and a rotary valve. Latched into the core barrel assembly, the sampler provides a seal to prevent waste from entering the drill string. The sketch of core sampling is illustrate in Fig. 1. More details of the sampling process is available in Ref. 1 and not relevant to this paper.

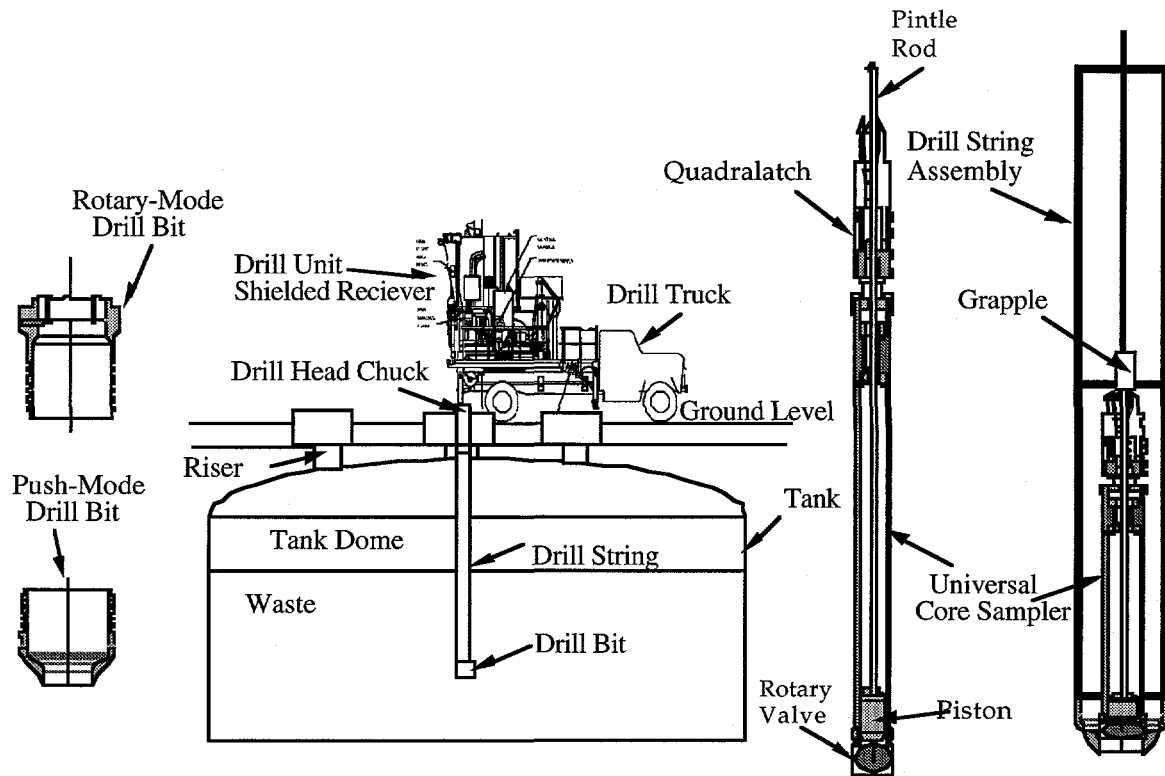


Fig. 1. Sketch of Core Sampling

The push mode drill bit schematically represented in Fig. 2 has an 18° tapered bore, and the sharp-edged, smooth-sided bit is designed to move vertically through liquid and sludge wastes. The bit has a nominal 1-in. i.d. and 2.25-in. o.d. and acts as the leading edge of the drill string into the push mode sampler. The 60-degree cone has a nominal one-inch core-sampling hole on the symmetry axis. A stainless-steel version of this bit is used in testing. The push-mode core barrel, when screwed onto the drill bit, forms an assembly that houses the core sampler.

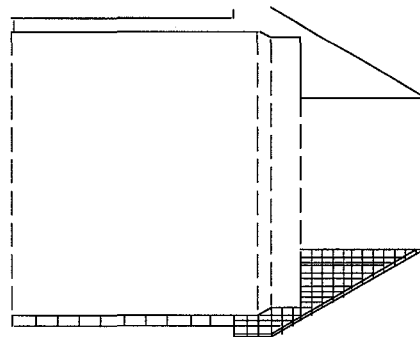


Fig. 2. Schematic view of push bit finite-differencing mesh.

III. MODEL

Two-dimensional transient simulations was developed and performed to quantify the local temperature rise from frictional heating in push mode sampling. Because the push-mode sampling involves metal-to-waste sliding, an analysis of the temperature rise caused by frictional heating was considered.

Frictional heating is a function of the force normal to the sliding interface, the relative velocity between the two sliding surfaces, and the coefficient of friction. Assuming vertical orientation and radially isotropic waste properties at the point of sampling, there is no normal load on the inside surface. In addition, the sample hole is actually tapered (1.06 inches at the upper end), so we assume no "rubbing" on the inside surface.

The estimation of peak temperatures requires calculating the nominal surface temperature distribution resulting from frictional heating over the entire apparent contact area and calculating the "flash temperature rise;" the results are then added together. See Ref. 3 for additional discussion of frictional heating and the concept of a flash temperature rise.

The waste is assumed to flow relative to the bit parallel to the conical bit surface. Thus, both axial penetration and radial displacement of waste are accounted for in a one-dimensional flow problem. No compaction (densification) is modeled.

The bit is axisymmetric, so a two-dimensional r-z model is appropriate. Detailed temperature distributions, both spatially and as a function of time, are calculated. A lumped-parameter approach assumed that the nodes are small enough (considering temperature gradients, etc.) to be well characterized by their average behavior. The model uses node enthalpy (denoted as h , units are J) for the state variables, so the time derivatives are power terms (J/s or W), based on local energy balances. Temperatures are extracted from the enthalpies as needed.

Within the solid bodies (bit and waste), conduction coupling with temperature-dependent properties and variable meshing is used. The model has to support the calculation of rotary operation of a push bit, so convective cooling (or heating, depending on local conditions) from the nitrogen purge flow is included as an option, both inside the drill string and in the push-bit interior. Those surface nodes of the bit and waste in contact are coupled with a "contact resistance" model, allowing heat to flow across the interface in either direction as dictated by the instantaneous temperature distribution. This model assumes conduction over the real contact area, A_r , and radiation between the two surfaces for that fraction of the apparent contact area, A_a , not in contact. For purposes of these analyses, A_r is

assumed to be 10% of A_a , which should give a conservative estimate of bit-to-waste heat transfer for contact between these types of materials. Frictional heating was applied over the apparent contact region. Because frictional heating occurs throughout the volume "worked" in sliding contact, the heat was deposited within the surface nodes. It was assumed that the applied force was uniform over the conical surface, and local relative surface velocities determine the local heat source. The frictional heat source was partitioned between the bit and waste as recommended in Ref. 4 proportional to the square root of the product of specific heat capacity, density, and thermal conductivity for the materials in contact. This model results in approximately 85% of the total frictional heat source being deposited in the stainless-steel bit. The higher thermal conductivity of the copper-based alloy results in nearly 90% of the total frictional heat source being deposited in the copper-based bit.

The finite-difference meshing used is quite fine, dictated by the attempt to closely match the real geometry. A cross section of the bit, with the finite-difference mesh displayed, can be seen in Fig. 2. The noncylindrical nature of the near-surface nodes required to match the conical geometry is accommodated by geometric shape factors. The waste is difficult to treat adequately in a lumped-parameter calculation, because the low thermal conductivity leads to large temperature gradients.

As currently modeled, long transients lead to elevated temperatures throughout the modeled waste zone, even though the zone is surrounded by "cooler" waste. This effect may be removed in later applications, but it is conservative (outer boundary has a high thermal resistance, leading to over-prediction of waste temperatures). The resulting model has 313 separate nodes (103 in the push bit; 10 in the threaded sleeve; 50 in the DS; and 150 in the waste).

The model was developed and solved within the architecture of the Los Alamos Systems Analysis (LASAN) code package.⁵ LASAN materials properties and convective cooling routines were applied directly. The model nonlinear ordinary differential equations are solved simultaneously with a fully implicit integration algorithm. Temperature-dependent material properties are used throughout. The maximum surface temperature was saved at each time step along with user-defined list variables and plot variables. Details of the model and the analyses reported here can be found in Reference 6.

IV. RESULTS

To perform an integral "reasonableness check" on the numerical model, it was applied to a push mode sampling test reported by WHC.⁶ In this test, a somewhat different bit designated XB393, was used to core sample simulated wastes using the push mode. The XB393 bit has a cone-shaped body, but it features cutting teeth on the conical surface. The exact dimensions, hence surface area and mass, are not known at this time. The simulation used the

push bit model shown earlier in Fig 2. The location of the bit thermocouple was not reported in Ref. 6, so a number of model locations were examined looking for similar behavior. The maximum loading and penetration depth were reported. The experimental plots featured waste temperatures at different depths, bit temperature, and penetration depth as a function of time. The penetration curve was used to develop a table of penetration rates as a function of time. There was a sharply lower slope in the first 10 seconds of the bit temperature curve, and it was assumed that the down force ramped from 0 to maximum load over that 10-s period. All other code parameters were held as described above. The waste simulant in this test was at a considerably higher initial temperature than the bit (60°C versus 18.5°C), causing heat transfer from the waste to the bit.

Figure 3 shows the peak surface temperature calculated for the bit, and the temperature at a "likely" location for a thermocouple (interior to the bit, but near the surface and away from the core sampling mechanism), along with the reported "bit temperature." The time response of the "likely thermocouple location" is similar to that reported for the bit temperature, and the temperature agreement is quite good. The shape of the peak surface temperature can be related to changes in the penetration rate (hence heating rate) at 20 s and 35 s, and the termination of penetration at 180 s. These results support the use of the value of 0.5 for the friction factor, and the 90% reduction in conduction heat transfer across the bit/waste interface.

Reference 6 suggests that "the increase in the drill temperature is caused entirely by the conduction of heat from the hotter simulant to the cooler drill." To test this conclusion, the case was rerun with the waste and bit at the same initial temperature to separate the frictional heating effect from the effect stated in the report. The key result of this simulation is shown in Fig. 4, where a rise in bit temperatures of a few degrees can be attributed to frictional heating. The rise is, however, quite small. Again, the shape can be attributed to the ramp-up in down force from 0 to 10 s, the initial penetration of the bit over the first 5 s, and the changes in penetration rate mentioned above.

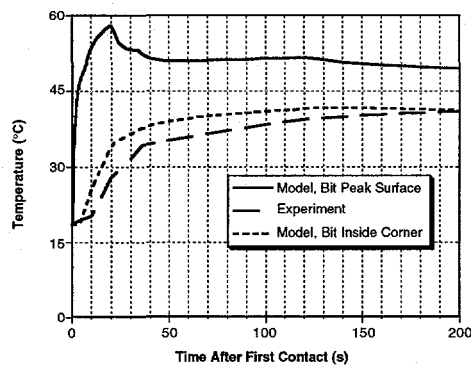


Fig. 3. Comparison of predicted and measured peak bit temperatures.

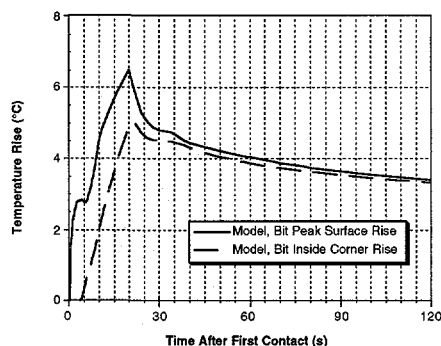


Fig. 4. Estimated temperature rise.

The first model applications were to pure push mode sampling. To bound the thermal response, a down force of 5500 lb. was used for all analyses. The penetration rate was varied from 0.75 in./min, to 25 in./min, to the bounding drive limit of 50 in./min. This set of analyses artificially assumes that the waste provides just enough resistance to require the maximum available down force at all penetration rates. The friction coefficient between the waste and bit was held constant at 0.5. The value of 0.5 is considered reasonable for dry waste layers and conservative for "soft" sludge layers. These conditions result in total frictional heating of 2.2 W, 74.7 W, and 149.5 W for the three cases. Because the waste rheology would be very different for these three conditions, thermal coupling between the waste and bit was restricted by a contact resistance to conservatively estimate the peak temperature. All cases were run from an isothermal initial condition of 22°C, but the results are presented here in the more generic terms of temperature rise.

Each case was run to a simulation time required to insert the bit the 19-inch length of a drill-string section at the assumed penetration rate. An example of temperature rise curve is given in Fig. 5 and the other results are summarized in Table 1. The calculated peak temperature rise did not exceed the maximum allowable temperature riser of 60°C (see Ref. 1) for any case.

Results showed that the fast insertions do not approach thermal equilibrium. These results have a "flash temperature rise" added to the maximum nominal surface temperatures. The flash temperature rise for each case was not significant for these bit speeds. The temperature rise for copper-based bits is always less than for stainless-steel bits, but the difference may be less than anticipated. One reason lies with the model for distributing the total frictional heat between the two bodies, which deposits a higher percentage of the heat source in the higher conductivity material.

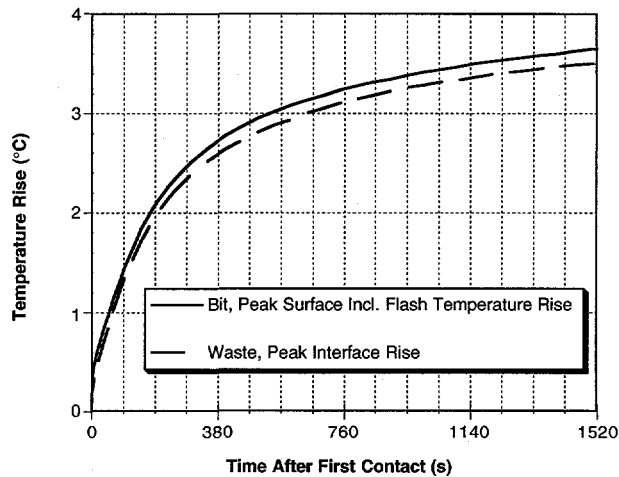


Fig. 5. Peak temperature rise in push mode sampling at a penetration rate of 0.75 inch/minute using a stainless-steel bit.

If a hard waste layer is encountered during push mode sampling, the bit may be changed and rotary mode operations undertaken. It has been postulated that a push bit might be inadvertently reinstalled and rotated. Analyses were performed to quantify the thermal response to such operations. Two cases were examined. Because there are operational limits on the minimum nitrogen flow and penetration rate, it was assumed that continued operation in this mode required continuing penetration and 30 scfm of nitrogen flow. This case is not expected to occur because the use of push-mode drill bit with the rotary-mode core sampler will not permit nitrogen to flow through the drill bit. However, for completeness it is presented in this appendix. The bit was rotated at a steady 55 rpm with a 750-lb down force. The penetration rate here was assumed to be 0.75 in./min.

**Table 1
Drill Bit Maximum Temperature Rise During Push-Mode Sampling**

V= 55 rpm, F=5500 lbf				
Case	Drill Bit Material	Penetration rate (in./min.)	Maximum Temp. Rise Inc. Flash Temp. (°C)	Waste Peak Interface Rise (°C)
1	Stainless Steel	0.75	3.6	3.4
2	Copper-based	0.75	2.6	2.5
3	Stainless Steel	25	18.4	13.5
4	Copper-based	25	16.2	14
5	Stainless Steel	50	24.5	16
6	Copper-based	50	22.2	18.8

Table 2 summarizes results. The calculated flash temperature rise in this case is 8°C. Here, the higher thermal conductivity of the copper-based bit greatly aids the transfer of heat from the bit surface, where it is deposited, to the bit interior where it is convectively transferred to the nitrogen flow. To evaluate the time available to sense inadequate nitrogen flow for rotary operation, the above calculations were rerun with the nitrogen flow set to zero. (As in the case above, heat transfer to the waste was enabled in the model). It can be seen that the temperature rise remains below 60°C for approximately 70 s for a stainless-steel bit and for approximately 85 s for the copper-based bit.

Table 2
Results of Rotating Push-Mode Drill Bit

$V_p = 0.75$ in./min and $V = 55$ rpm, $F = 750$ lbf				
Case	Drill Bit Material	Nitrogen Flow Rate (scfm)	Maximum Temp. Rise (°C)	Time to reach ΔT of 60 (°C) (s)
1	Stainless Steel	30	55	-
2	Copper-based	30	41	-
3	Stainless Steel	0	-	70
4	Copper Based	0	-	85

IV. CONCLUSIONS

The analyses show that frictional ignition from nominal push mode sampling is unlikely. Even for a conservative set of boundary conditions and loading assumptions, the peak temperature rise remains less than 60°C. A postulated accident with rotary operation of a push mode bit was also examined. If conditions necessary for continued rotary operation are assumed, the peak temperature rise remains less than 60°C. Calculations also show that a significant time period (70 s or more) would exist in rotary operation of the push mode sampling bit with no nitrogen flow before the peak temperature rise exceeds 60°C, allowing time to sense low flow and terminate rotation.

V. REFERENCES

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