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FRICTIONAL HEATING AND CONVECTIVE COOLING OF POLYCRYSTALLINE DIAMOND DRAG TOOLS DURING ROCK CUTTING

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MASTER

ABSTRACT

A numerical-analytical model is developed to predict temperatures in stud-mounted polycrystalline diamond compact (PDC) drag tools during rock cutting. Experimental measurements of the convective heat transfer coefficient for PDC cutters are used in the model to predict temperatures under typical drilling conditions with fluid flow. The analysis compares favorably with measurements of frictional temperatures in controlled cutting tests on Tennessee marble. It is shown that mean cutter wearflat temperatures can be maintained below the critical value of 750°C only under conditions of low friction at the cutter/rock interface. This is true, regardless of the level of convective cooling. In fact, a cooling limit is established above which increases in convective cooling do not further reduce cutter temperatures. The ability of liquid drilling fluids to reduce interface friction is thus shown to be far more important in preventing excessive temperatures than their ability to provide cutter cooling. Due to the relatively high interface friction developed under typical air drilling conditions, it is doubtful that temperatures can be kept subcritical at high rotary speeds in some formations when air is employed as the drilling fluid, regardless of the level of cooling achieved.

DISCLAIMER

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INTRODUCTION

Over the past several years, considerable interest has been focused on drag-type drill bits employing polycrystalline diamond compact (PDC) elements. Although these bits have been most successful in drilling relatively soft formations [1], work has been underway at Sandia National Laboratories to investigate the potential of PDC bits in the more severe environments typical of geothermal drilling.

Unsealed roller bits have limited lives in such environments, and conventional sealed roller bits cannot be used in many geothermal reservoirs due to temperature limitations on seals and lubricants [2]. The fact that PDC bits require no bearings or seals makes them particularly attractive for geothermal drilling, especially at the high rotational speeds typical of downhole motors. The high penetration rates and long lives achieved with PDC bits in certain formations further suggest that geothermal drilling costs might be reduced if PDC bits can be developed for this application.

The inherent characteristics of drag bits impose high frictional heating on PDC cutters. The purpose of the present study was to investigate the thermal characteristics of PDC elements mounted on tungsten carbide studs in order to understand the driving parameters behind the thermal response of these cutters. The incentive for understanding these parameters is to permit steps to be taken to keep cutter operating temperatures as low as possible. The need for achieving this goal is illustrated by an examination of the wear characteristics of PDC cutters at various operating temperatures.

Below 750°C, the primary mode of wear of PDC cutters is microchipping of the sintered diamond. It has been shown [3] that the intensity of this wear increases with sliding speed, presumably due to the increased temperatures associated with higher speeds. Evidence indicates that this increased wear rate is caused by a decrease in the hot hardness of individual diamond crystals with increasing temperature.

Above 750°C, the wear mode changes from microchipping to more severe thermal deterioration and whole-grain pullout. This is caused by stresses resulting from differential thermal expansion between the diamond and residual metal inclusions along the diamond grain boundaries, which lead to intergranular cracking and grain boundary failure.

By 800°C, the hot hardness of the tungsten carbide stud is severely degraded, leading to accelerated wear of the stud itself, which even at low temperatures has a wear rate greater than that of sintered diamond. For temperatures above 950°C, the tungsten carbide (WC) is susceptible to plastic deformation and flow under applied surface shear.

In this study, we therefore establish 750°C as the maximum safe operating temperature of PDC-WC cutters but recognize that even below this temperature, wear rate can be significantly reduced by maintaining operating temperatures as low as possible. The major objective of the present study was to identify parameters which can be controlled to achieve this goal.

Approach

Numerical modeling of PDC cutters was performed to compute local temperatures for assumed frictional heating and convective cooling rates. Referring to Figure 1, the assumptions used in this thermal modeling are:

1) The PDC cutter is two dimensional. Analysis shows that this assumption does not introduce significant error.

2) The cutter is in constant contact with the rock surface, implying that a constant frictional heat flux is imposed at the cutter-rock interface. The cutter receives a fraction α of this heat flux,

$$q_1 = \alpha Q_f/A_w = \alpha \mu F_n V/A_w \quad (1)$$

and the rock receives a fraction $(1 - \alpha)$ of the heat flux,

$$q_2 = (1 - \alpha) Q_f/A_w = (1 - \alpha)\mu F_n V/A_w \quad (2)$$

One of the tasks of this study was to evaluate the energy partitioning fraction, α.

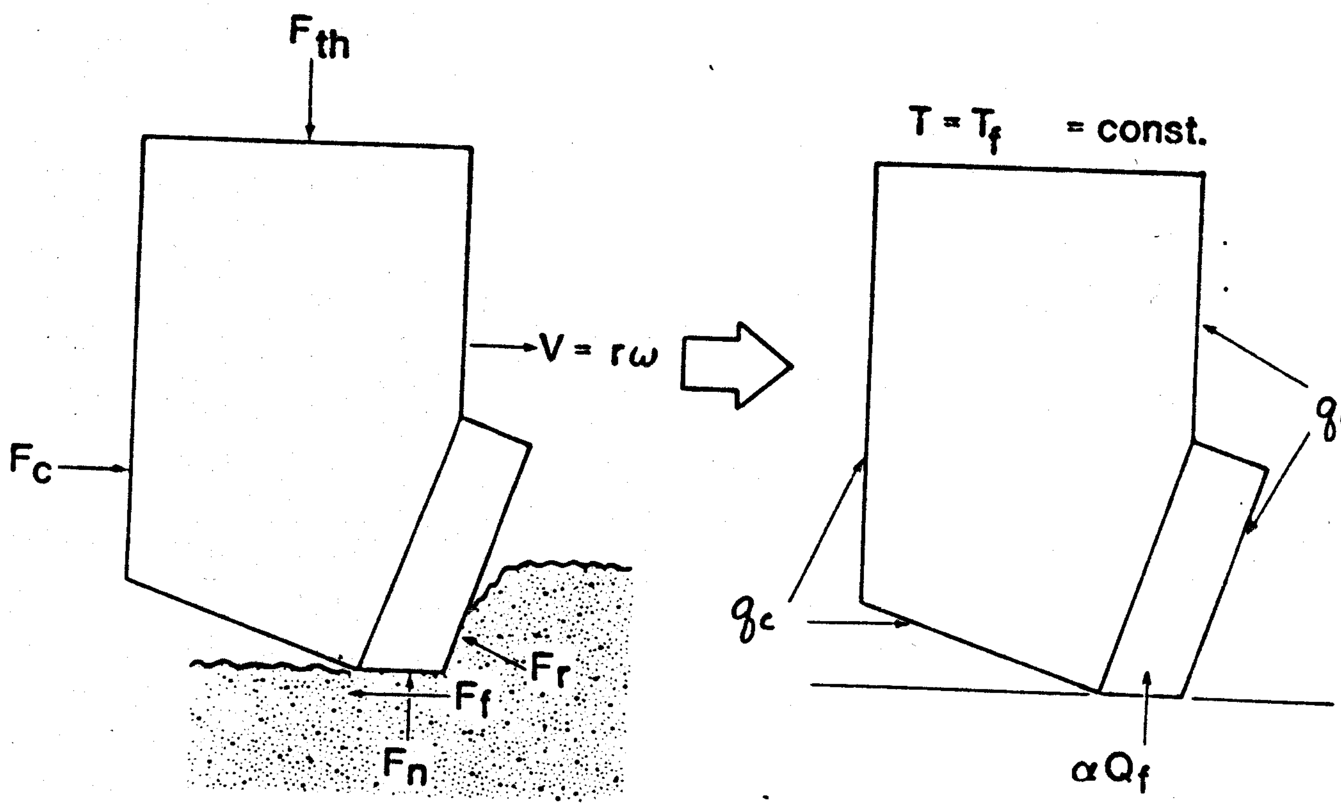

Figure 1. Forces and heat fluxes acting on a PDC cutter

3) Constant convective cooling occurs at the exposed lateral surfaces,

$$q_c = h(T_s - T_f) \tag{3}$$

One of the tasks of this study was to measure the convective heat transfer coefficient, h.

4) No convective cooling of the rock surface occurs. This assumption, necessary to evaluate α, does not introduce appreciable error due to the relatively low thermal conductivity of rock.

5) The top of the PDC cutter is fixed at the fluid temperature. The bit is thus assumed to act as a heat sink and is vigorously cooled by the fluid.

6) Thermal properties are not temperature-dependent. The following thermal properties were employed: k_{PDC} = 5.43 W/cm°C; k_{wc} = 0.42 W/cm°C; k_2 = 0.02 W/cm°C; χ_2 = 0.01 cm^2/s.

Separate thermal models were developed for the three cutter configurations shown in Figure 2, corresponding to severely worn, moderately worn, and mildly worn cutters. For the mildly worn cutter, the wearflat includes only the diamond layer of the PDC element. For the moderately worn cutter, the wearflat includes the diamond layer and the tungsten carbide material in the PDC element. For the severely worn cutter, the wearflat extends across a major portion of the tungsten carbide stud itself.

Numerical simulation was performed with the finite difference code, CINDA [4], over the following ranges of operating conditions:

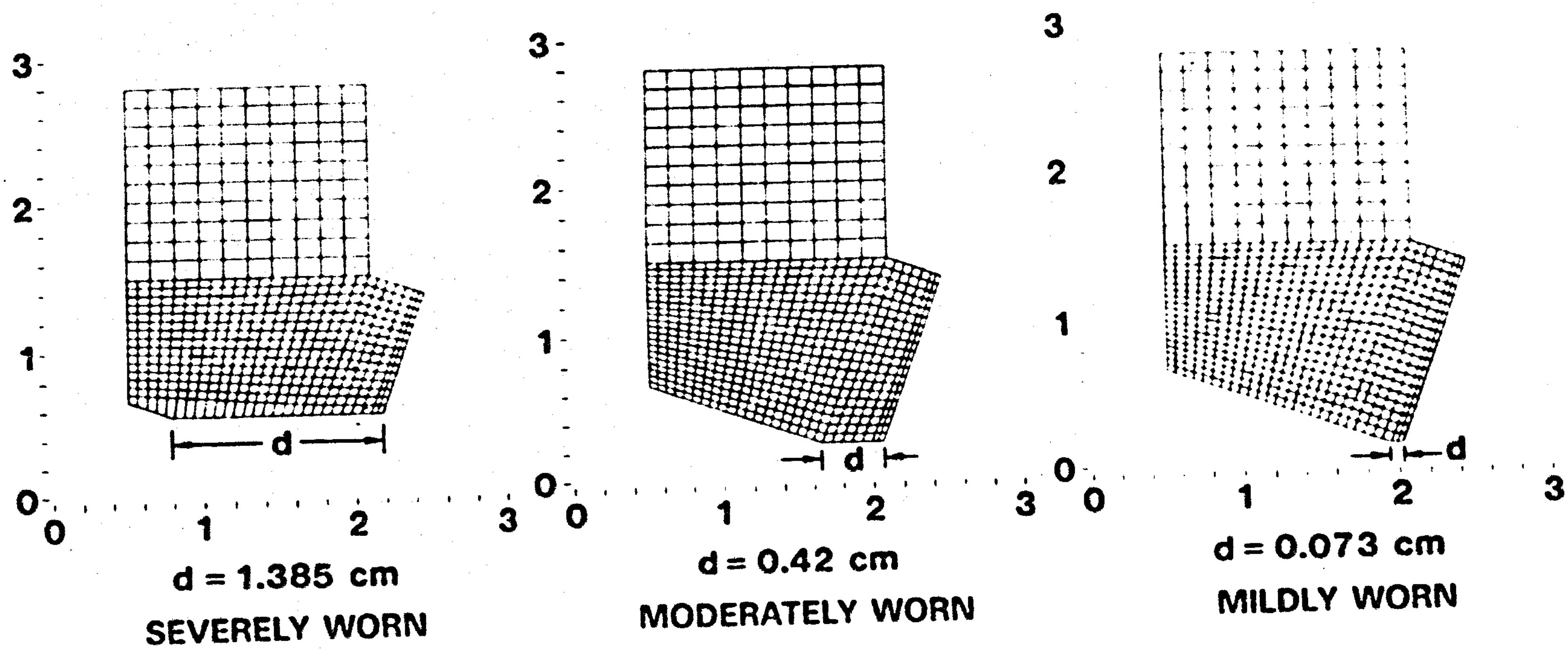

Figure 2. Finite difference models for thermal analysis

$$q_1 = 250 - 5000 \text{ W/cm}^2$$

$$h = .001 - 10 \text{ W/cm}^2 \cdot °C.$$

Typical results are shown in the isotherm plots of Figures 3 and 4.

Figure 3 shows typical results for a moderately worn tool. Note that a maximum temperature of 370°C is achieved near the center of the wearflat. Under the same conditions, the severely worn cutter shown in Figure 4 reaches a maximum temperature of 850°C. This greater thermal response is attributed to two factors. First, the more severely worn tool has a greater wearflat area and, hence, greater total frictional heating for a given imposed heat flux. Secondly, as wear increases, the fraction of the total wearflat area composed of diamond decreases. Since diamond has a thermal conductivity which is thirteen times that of tungsten carbide, the thermal diffusion characteristics change with wear. The result is that the more severely worn the tool becomes, the less able it is to conduct heat away from the wearflat region.

A further point to recognize about the isotherm plots is that extremely high thermal gradients exist across the wearflat. Such gradients probably contribute significantly to the wearflat heat checking and cracking observed under certain conditions.

Using computed results such as those seen in Figures 3 and 4, the mean wearflat temperatures were computed for each wear and operating condition. The results are plotted in Figure 5 in the form

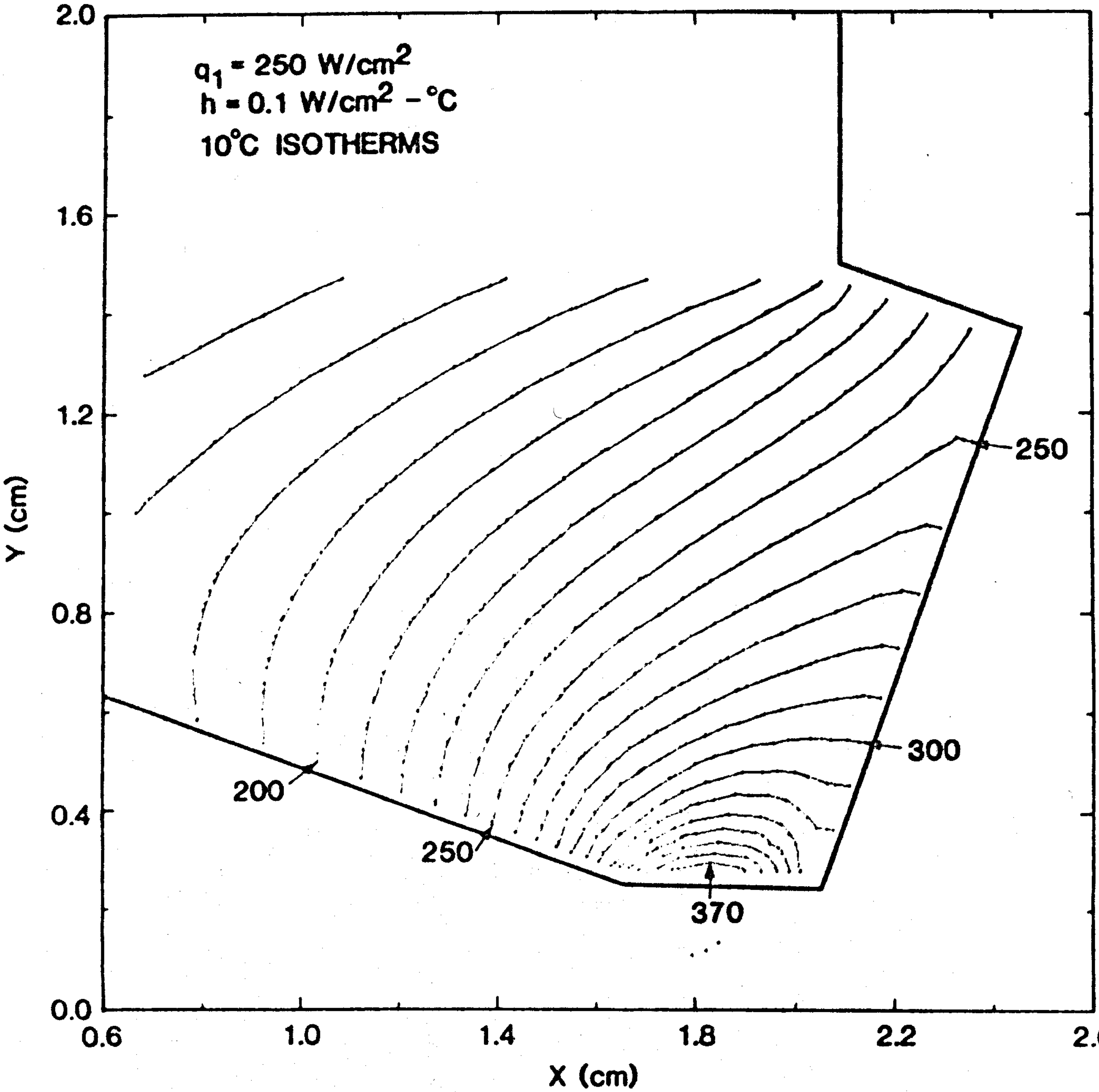

Figure 3. Typical results of numerical simulation for a moderately worn tool (T_f = 80°C)

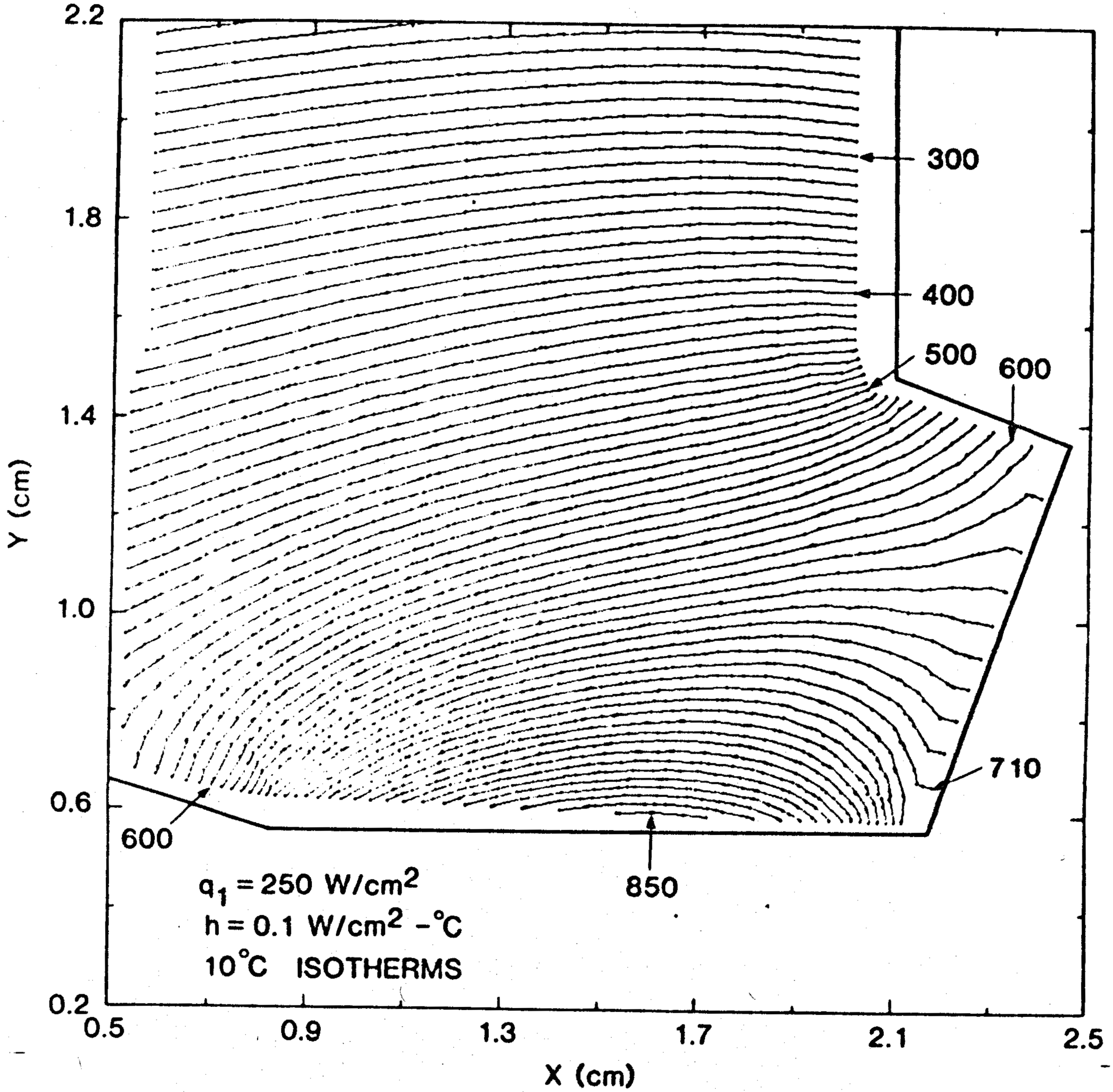

Figure 4. Typical results of numerical simulation for a severely worn tool (T_f = 80°C)

$$f = \frac{\overline{T}_w - T_f}{q_1} \tag{4}$$

as a function of h.

Figure 5 again illustrates that for a given heat input, thermal response increases with cutter wear. A second point to be made is that convective cooling can significantly reduce the thermal response of moderately and severely worn tools over the range h = 0.01 - 10 W/cm^2•C; however, convective cooling above 10 W/cm^2•C provides essentially no further reduction in mean wearflat temperatures. This is due to the fact that once cooling reaches this level, the limiting factor becomes the thermal conductivity of the cutter material. In other words, the cutter material simply cannot conduct heat away from the wearflat to the convecting surfaces fast enough to further reduce the wearflat temperatures. It is thus concluded that the maximum beneficial cooling rate which can be achieved by cooling the exposed cutter surfaces lies in the range of h = 5 - 10 W/cm^2•C.

Thus far, the computed temperatures presented are the results of assumed frictional heating rates. In order for these results to be useful in predicting temperatures for a given environment, the frictional heating rate must be determined according to equation (1). This requires a determination of the energy partitioning fraction α. This is accomplished with the following analysis.

The solution for the temperature field about a band source

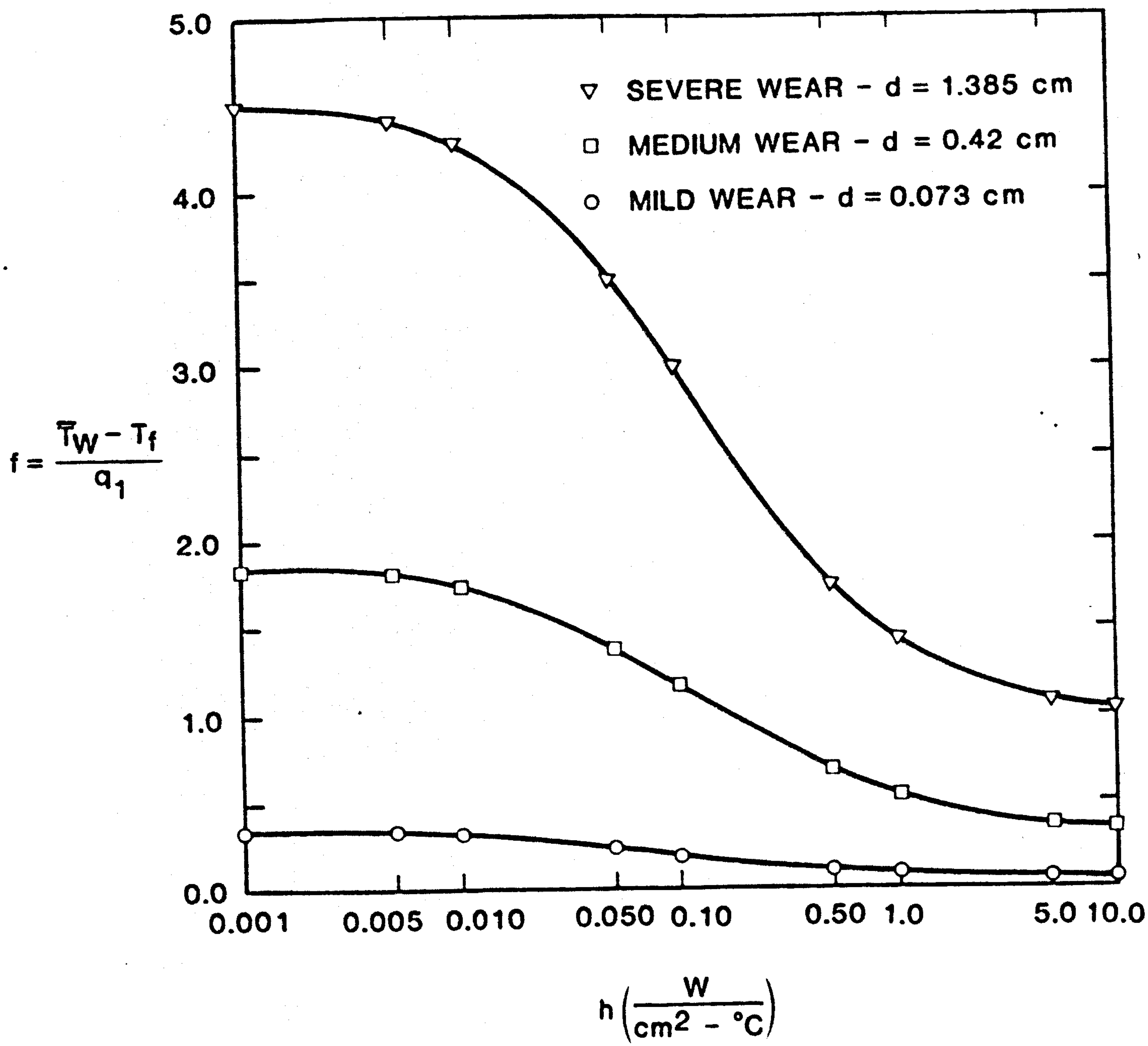

Figure 5. Computed thermal response of PDC cutters

of heat moving over a semi-infinite, constant property solid, such as rock, is given by Jaeger [5] for the case where no heat is lost from the surfaces not in contact with the heat source. For a band heat source of width d, moving at a speed typical of the sliding speeds experienced by PDC cutters in the downhole environment, the mean temperature rise of the rock at the sliding interface is given as

$$\overline{\theta}_r = \frac{4q_2}{3\sqrt{\pi}k_2}\left(\frac{X_2 d}{V}\right)^{1/2} \tag{5}$$

The temperature of the rock and the PDC cutter at the sliding interface are assumed equal due to their intimate contact at the wearflat area. Assuming the undisturbed rock temperature near the surface of the wellbore is equal to the circulating fluid temperature, the equality of the sliding interface temperatures ~~is equivalent to~~ takes the form

$$\overline{\theta}_r = \overline{T}_w - T_f \tag{6}$$

Substituting equations 1, 2, 4, and 5 into equation 6 gives the final result

$$\alpha = \left[1 + \frac{3\sqrt{\pi}k_2}{4}\left(\frac{V}{dX_2}\right)^{1/2} f\right]^{-1} \tag{7}$$

Figures 6 and 7 show the values of α obtained for the assumed rock properties. Note that the fraction of frictional heat conducted into the cutter decreases with cutter wear and

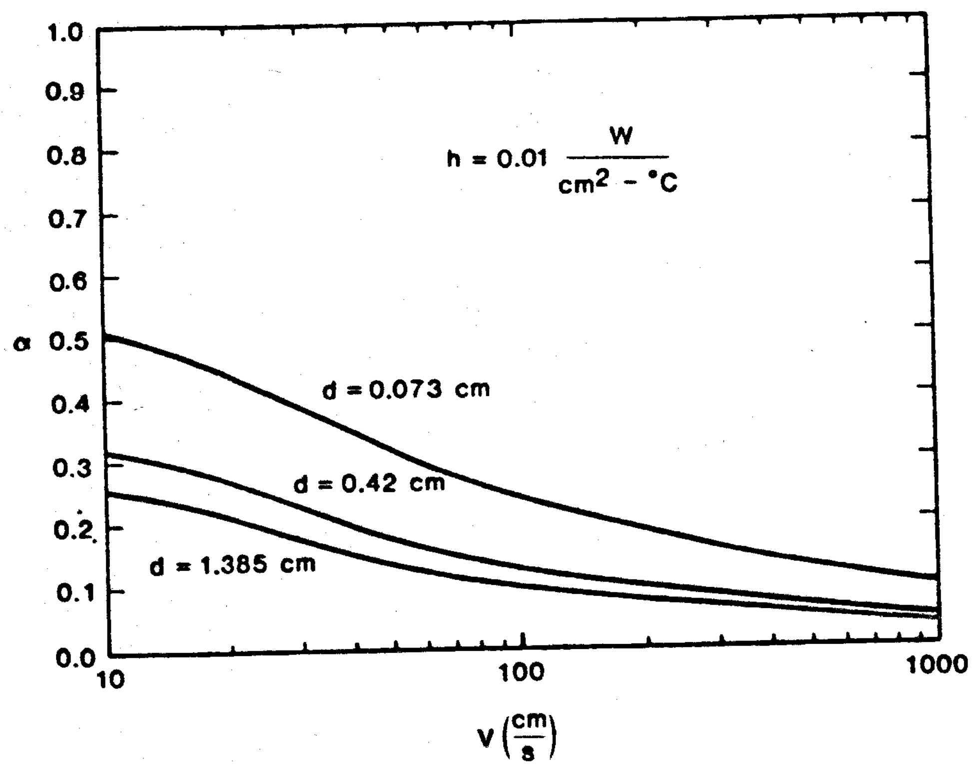

Figure 6. Energy partitioning fraction for low cooling rate

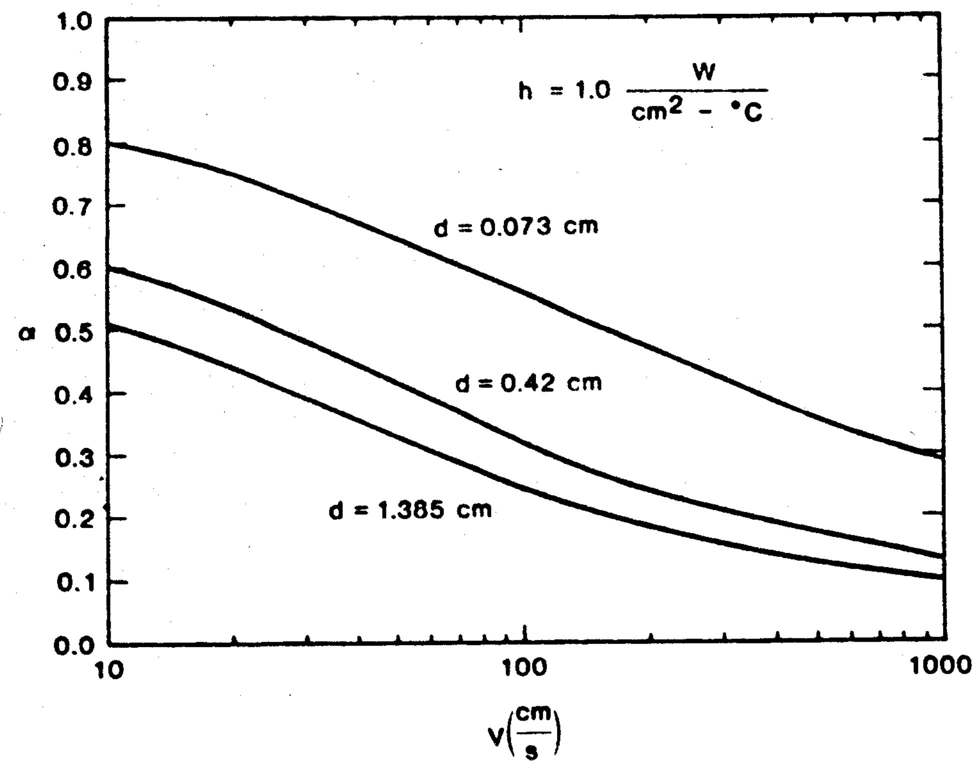

Figure 7. Energy partitioning fraction for moderate cooling rate

sliding speed but increases with convective cooling.

Now that an expression for the energy partitioning fraction has been derived, an equation can be established with which the predicted mean cutter wearflat temperature can be determined for a given environment. Combining equations (1) and (4) gives the result

$$\bar{T}_w - T_f = q_1 f = \frac{\alpha \mu F_n V}{A_w} f, \tag{8}$$

where α is determined from equation 7, and f is determined from Figure 5 as a function of h. The parameters μ, F_n, V, A_w, and h are functions of the assumed environment. The following two sections discuss determination of the parameters μ and h.

Determination of the Friction Coefficient

Since the mean wearflat temperature rise is directly proportional to the friction coefficient, as seen in equation 8, determination of representative values of μ for a given condition is required to accurately predict PDC operating temperatures. Measured values of μ for a variety of conditions are compiled from various sources and presented in Figure 8.

Note that rather high friction coefficients are measured for the dry conditions typical of air drilling. Simply wetting the rock surface reduces friction to a certain extent. Directing liquid jets at the cutter-rock interface reduces friction substantially. It is thus concluded that an important role of liquid drilling fluids with PDC bits is reducing friction and,

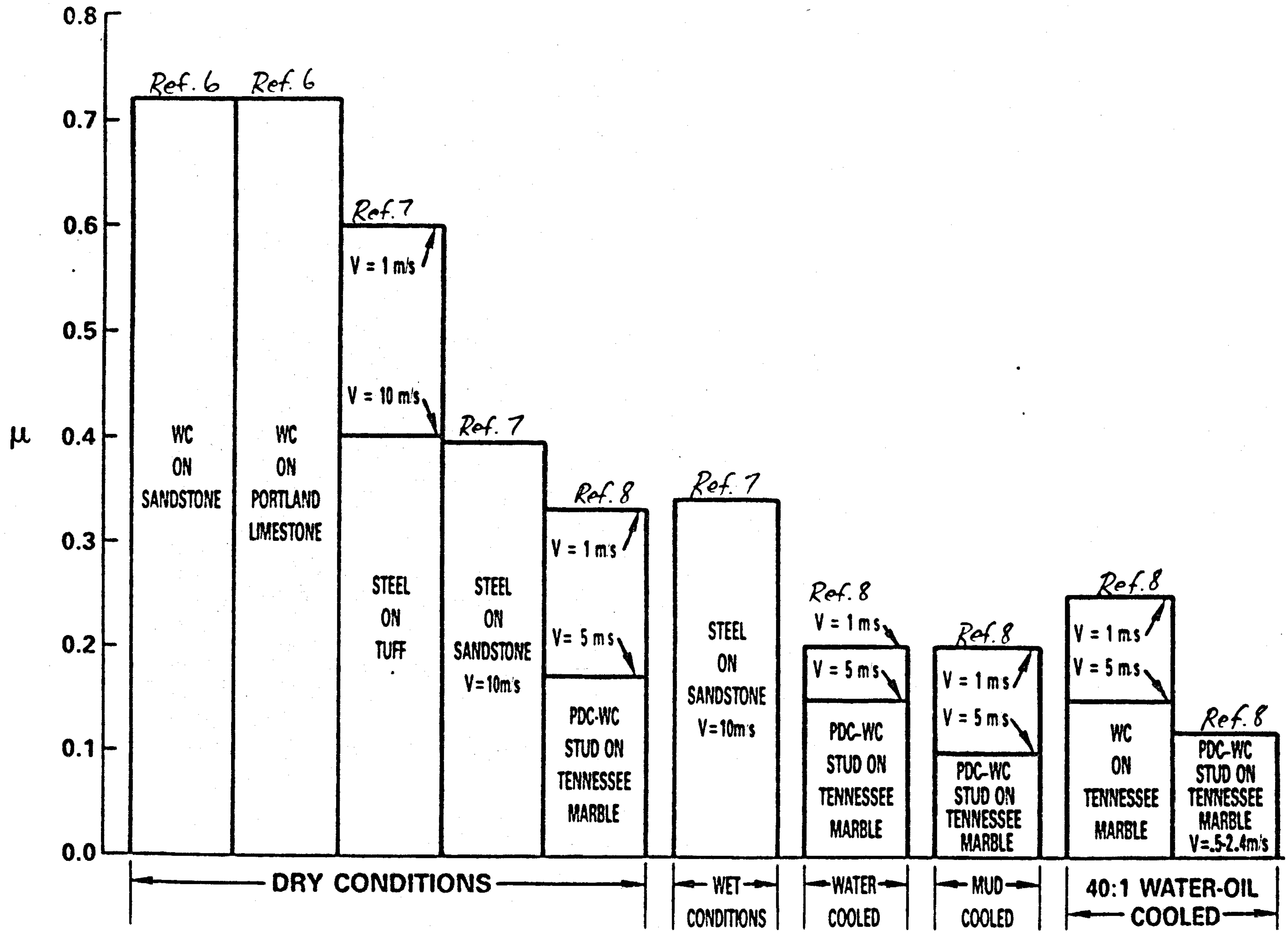

Figure 8. Measured friction coefficients for various sliding pairs

therefore, frictional heating of the cutters. The cause of the reduction in friction coefficient with sliding speed is not yet clearly understood, but work is continuing, to both understand this phenomenon and to measure friction coefficients for a larger matrix of rock types, fluid types, and sliding speeds [8].

Determination of the Heat Transfer Coefficient

Due to the complexity of the fluid flow field around a PDC cutter, it was concluded that experimental work was needed to determine typical heat transfer coefficients for this application. The results of this work, reported previously in references 9 and 10, are repeated in Figure 9 for reference.

These data were obtained with water at crossflow velocities typical of the mean radial flow velocities achieved across the face of a stud-mounted PDC bit. Under these conditions, the measured values of h lie approximately in the range 0.5-1.0 $W/cm^2 °C$ for different locations on the cutter.

It is useful to examine these results for the purpose of drawing conclusions about the effects of various parameters on convective cooling. Note that the heat transfer correlations shown in Figure 9 are of the standard form

$$h \propto \frac{k_f}{D}\left(\frac{\rho_f u D}{\mu_f}\right)^n \left(\frac{c_f \mu_f}{k_f}\right)^m \qquad (9)$$

where $n \sim 0.3 - 0.6$ and $m \sim 0.3$. Although these correlations have not yet been validated for fluids other than water, it is of interest to examine the effects, as defined by equation (9),

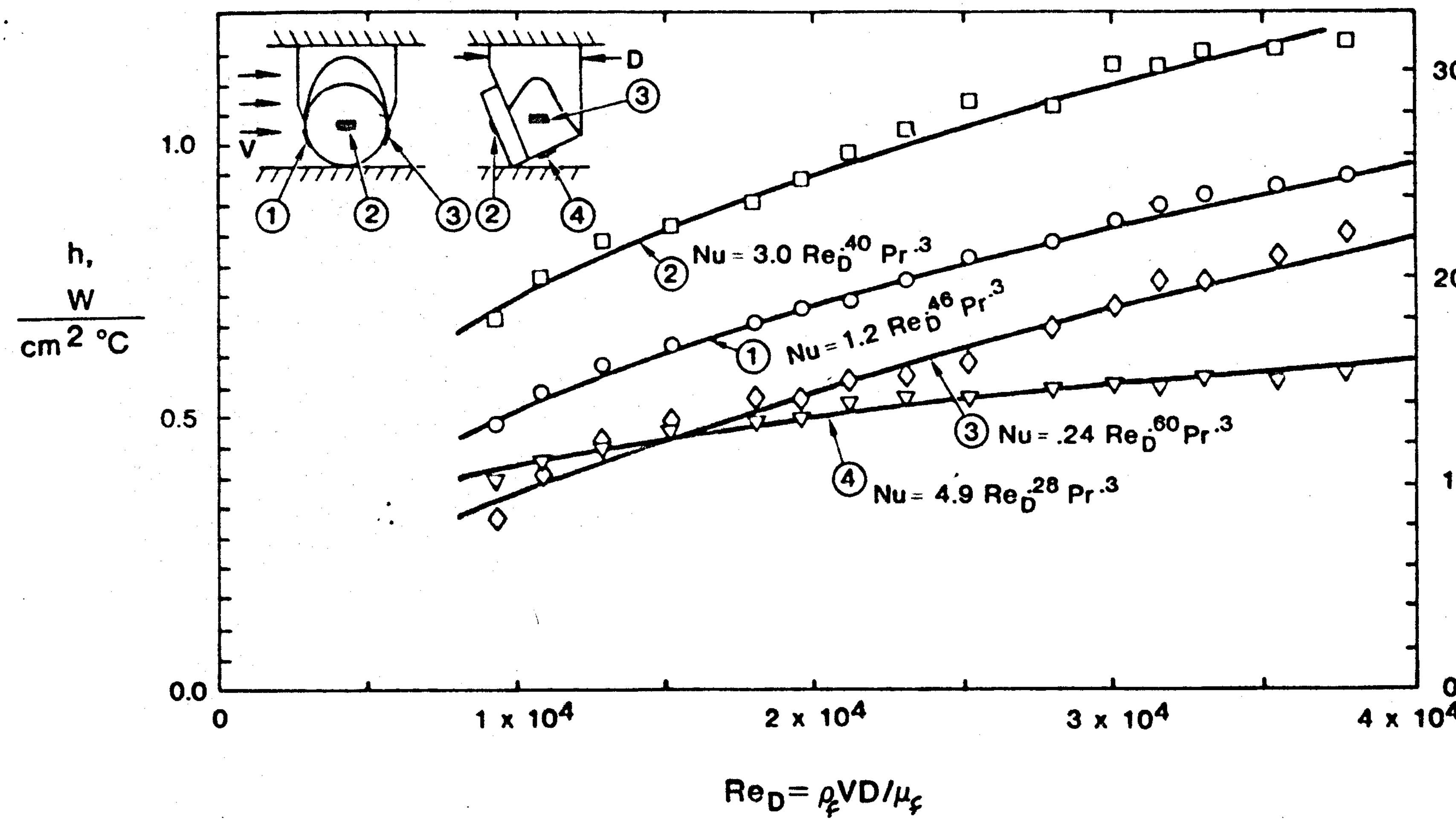

Figure 9. Measured heat transfer coefficients for a single PDC cutter in uniform crossflow of water (References 9 and 10)

of varying different parameters. It is unlikely that the form of these correlations would change with fluid type; thus, the following conclusions should be at least qualitatively correct.

Due to the small change in k_f and c_f and the significant reduction in the ratio ρ_f/μ_f which occurs when "mudding up," it is concluded that the use of drilling muds rather than water actually reduces convective cooling slightly.

Similarly, the extremely low values of ρ_f/μ_f and k_f for air suggest that the use of air as the drilling fluid significantly reduces cutter cooling. In fact, a quantitative extrapolation of the correlations of Figure 9 estimates heat transfer coefficients with air to be on the order of 0.05 $W/cm^2 \cdot {}^\circ C$. It is therefore concluded that typical air drilling operations provide essentially no beneficial cooling to PDC cutters.

Short of the development of an inexpensive, low viscosity, high density, and high thermal conductivity drilling fluid, which would not be attractive from the standpoints of chip removal and borehole pressure control, the only apparent means whereby convective cooling can be increased is through modification of the hydraulic design to provide higher local velocities past the cutters.

Reducing the bit body-rock clearance by matrix mounting the PDC elements or countersinking the studs can effectively double the mean radial flow velocities; however, this relatively small increase in velocity increases convective cooling only slightly, to a value of 1.5 - 2.0 $W/cm^2 \cdot {}^\circ C$ with water.

On the other hand, directing 0.64 cm (0.25 in.) nozzles at the cutters with only 2400 kPa (350 psi) would impinge 70 m/s jets on the cutters, providing heat transfer coefficients on the order of 5 $W/cm^2 \cdot C$ with water. This arrangement would place the convective cooling in the range of the maximum beneficial cooling rate established earlier for exposed cutter surfaces.

It has been suggested that individual cutters on bits may not be in continuous contact with the rock during bit rotation because of drill stem flexing and cutter interaction. If this is the case, jets directed at the cutter could further reduce time-averaged wearflat temperatures by directly cooling the wearflat and more effectively lubricating the sliding interface. Further work is required to validate the above extrapolations and interpretations of equation 9, to determine if direct jet impingement would tend to erode PDC cutter assemblies, and to assess the wearflat damage potential of thermal shock resulting from alternating rapid cooling and heating of the wearflat.

Comparison of Predicted and Measured Wearflat Temperatures

Single point cutting tests to measure cutter operating temperatures have been performed by Hibbs [8] on a vertical turret lathe using preground Stratapax® cutters and Tennessee marble. These cutters had measureable wearflat areas corresponding approximately to the moderately worn condition examined in this study. The cutters were instrumented with miniature thermocouples at locations very near the wearflat surface, at the compact-stud braze joint, and in the stud. The precise locations of the thermocouple junctions are shown in Figure 10. A water-soluble oil (40:1 water to oil) coolant jet was directed to impinge on the leading circular face of the cutter. Steady-state temperature measurements were made for flow rates of 0.4 L/s (6.3 gpm) and 0.09 L/s (1.4 gpm), resulting in predicted heat transfer coefficients of approximately 1.0 and 0.5 $W/cm^2 \cdot C$, respectively, based on the data of Figure 9. Cutting speeds for the tests were 1.12 m/s (221 ft/min) and 0.44 m/s (87.1 ft/min). The depths of cut were set at 0.005 cm and 0.015 cm.

A comparison of the experimental and theoretical results is shown in Figure 11. The experimental temperatures plotted are the average of the measurements from thermocouple locations A and B in Figure 10. Since the friction coefficient was not measured in these tests, and since the depth of cut was extremely small, the friction force, F_n, was assumed equal to the total cutting force, F_c (see Figure 1).

It is seen that even with the difficulty in accurately measuring the true wearflat frictional temperatures, the theoretical predictions are quite close to the measured data. The temperatures indeed increase linearly with increased frictional heating, and the rate of increase is greater for the lower flow rate, as predicted, because of the decreased cooling. Furthermore, the predicted temperatures are generally higher than the measured values, probably because the true friction force, F_n, is somewhat less than the cutting force, F_c, used in calculating the heating rate. Even though the amount of data available for

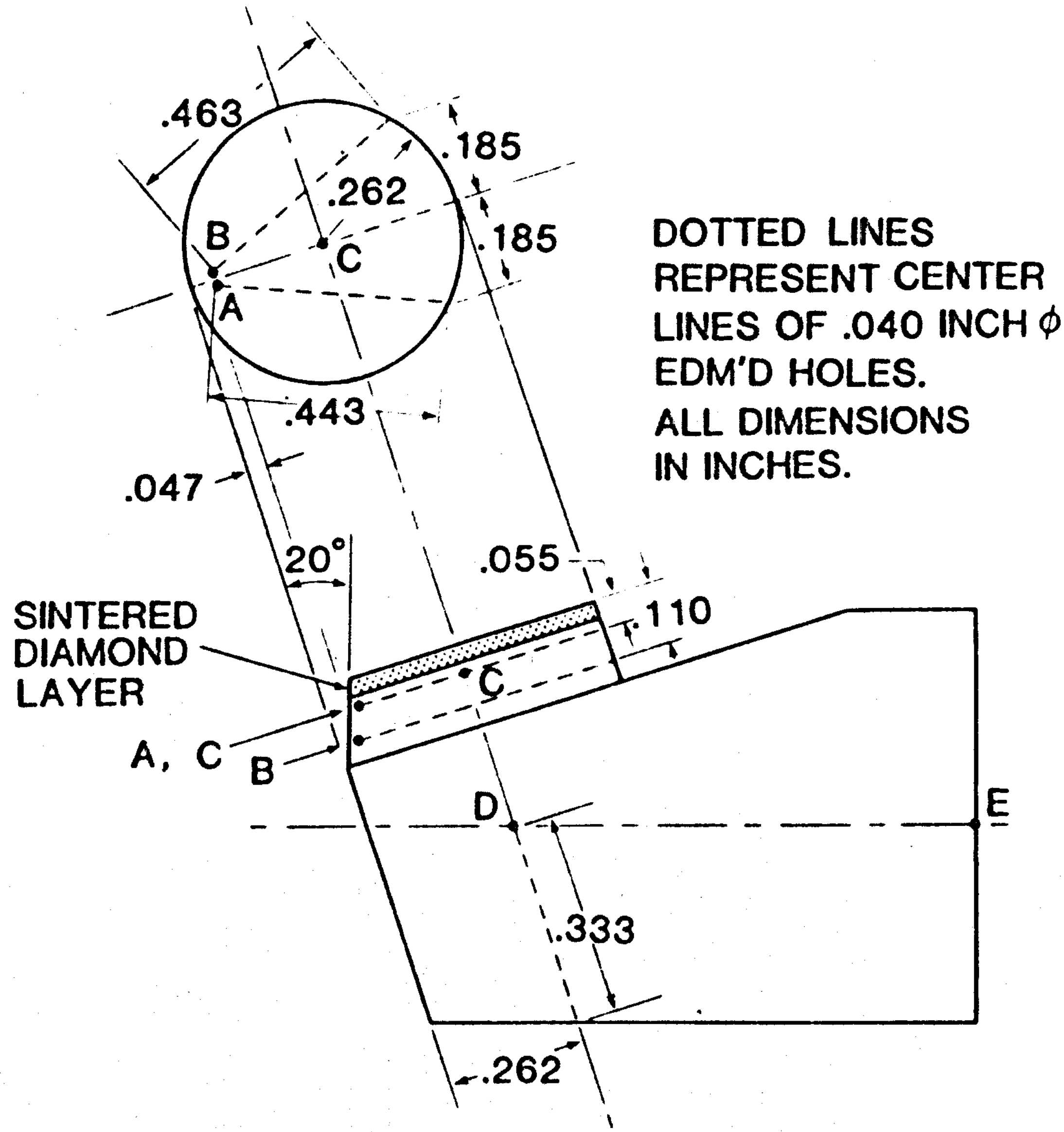

Figure 10. Thermocouple locations in PDC cutter instrumented for temperature measurements (Reference 8)

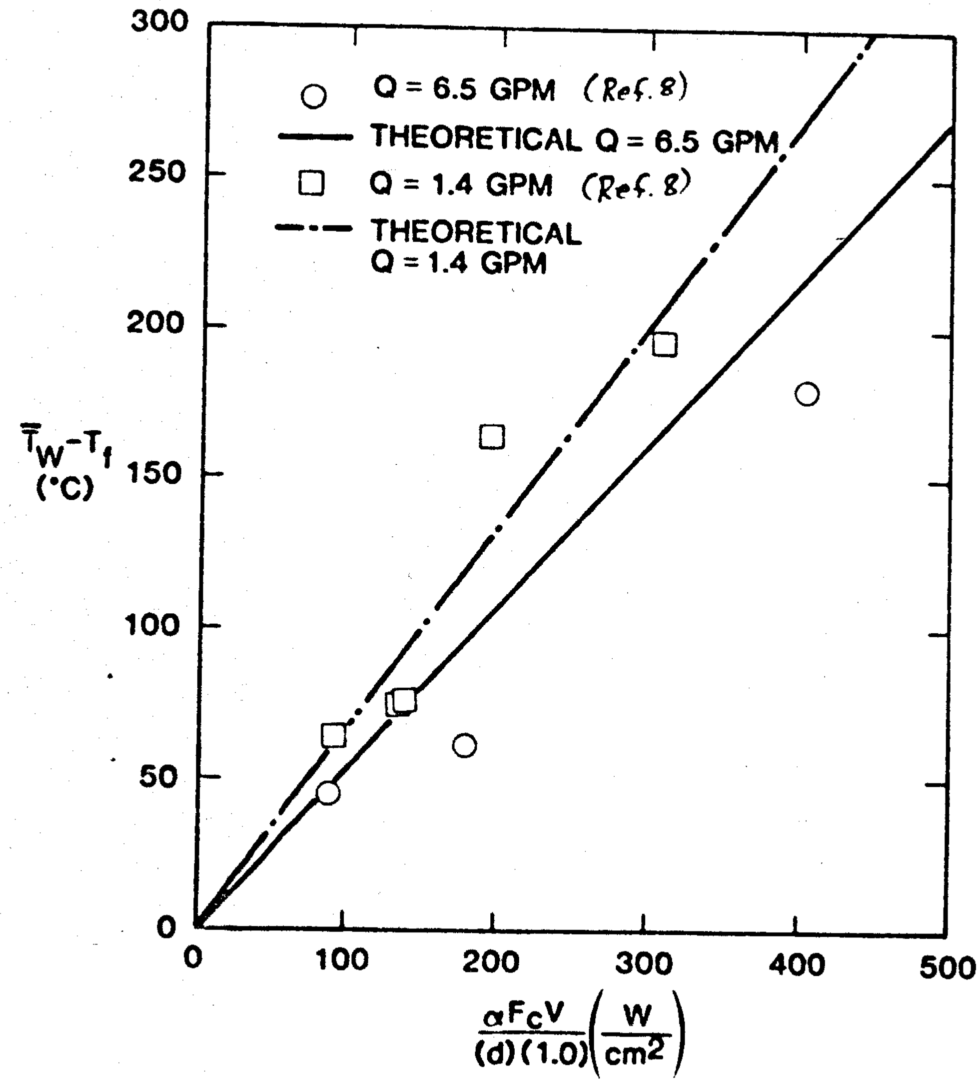

Figure 11. Comparison of predicted and measured wearflat temperatures

comparison is as of yet small, the comparison with the general theory developed for PDC cutters is encouraging for the use of the analytical model as a predictive tool.

Predicted Temperatures for Typical Operating Conditions

The theory developed in this study was used to predict temperatures for typical operating conditions in the downhole environment. These results are presented in Figures 12, 13, and 14. In all of these figures, we examine the effects of various parameters on the mean wearflat temperature of a PDC cutter mounted near the periphery of a 40-cutter, 8-3/4 inch bit. This location for the cutter was chosen to permit the use of a simple relationship between bit rotational speed and cutter sliding speed, namely

$$V(m/s) \sim \omega(RPM)/100 \qquad (10)$$

Shown in Figure 12 are the results for high bit rotational speed, low cooling, and low friction. These conditions are not necessarily representative but are chosen for this case to make the following point about weight on bit: for a given weight on bit, a mildly worn cutter runs hotter than a more severely worn cutter. This is due to the fact that total frictional heating is directly proportional to weight on bit, but heat flux (heat input per unit area) is inversely proportional to wearflat area. A mildly worn tool thus experiences greater heat flux for a given weight on bit and, therefore, achieves higher operating temperatures.

In drilling, however, it is generally recognized that, after an initial "break-in" period, weight on bit must be increased as the bit wears in order to maintain a given penetration rate. If we assume that the required weight on bit increases linearly with wearflat area so as to maintain a constant contact pressure, F_n/A_w, between the cutter and the rock, then the dashed line shown in Figure 12 is followed as the bit wears. It is thus seen that cutter operating temperatures increase with bit wear under these conditions. In Figures 13 and 14, it is therefore assumed that maintaining the penetration rate achieved with a mildly worn bit at 2000 lb_f WOB requires 11,500 lb_f WOB with a moderately worn bit and 38,000 lb_f WOB with a severely worn bit.

Figure 13 presents predicted mean wearflat temperatures for the lowest measured friction coefficient reported to date, i.e., $\mu = 0.12$, corresponding to a PDC-WC stud sliding on Tennessee marble with water-oil coolant/lubricant. Assuming a downhole drilling fluid temperature of 150°C, not uncommon in geothermal drilling, the maximum safe operating limit, established earlier in this paper, corresponds to the value $\bar{T}_w - T_f = 600°C$. It is seen that under these conditions, safe operating temperatures are maintained for all three wear conditions up to at least 1000 RPM. It should be remembered, however, that wear rate increases rapidly with temperature even below the maximum safe limit, and we should therefore expect rather high wear rates at higher rotational speeds for at least the severely worn tool. Note also that convective cooling has only a moderate effect in reducing cutter temperatures.

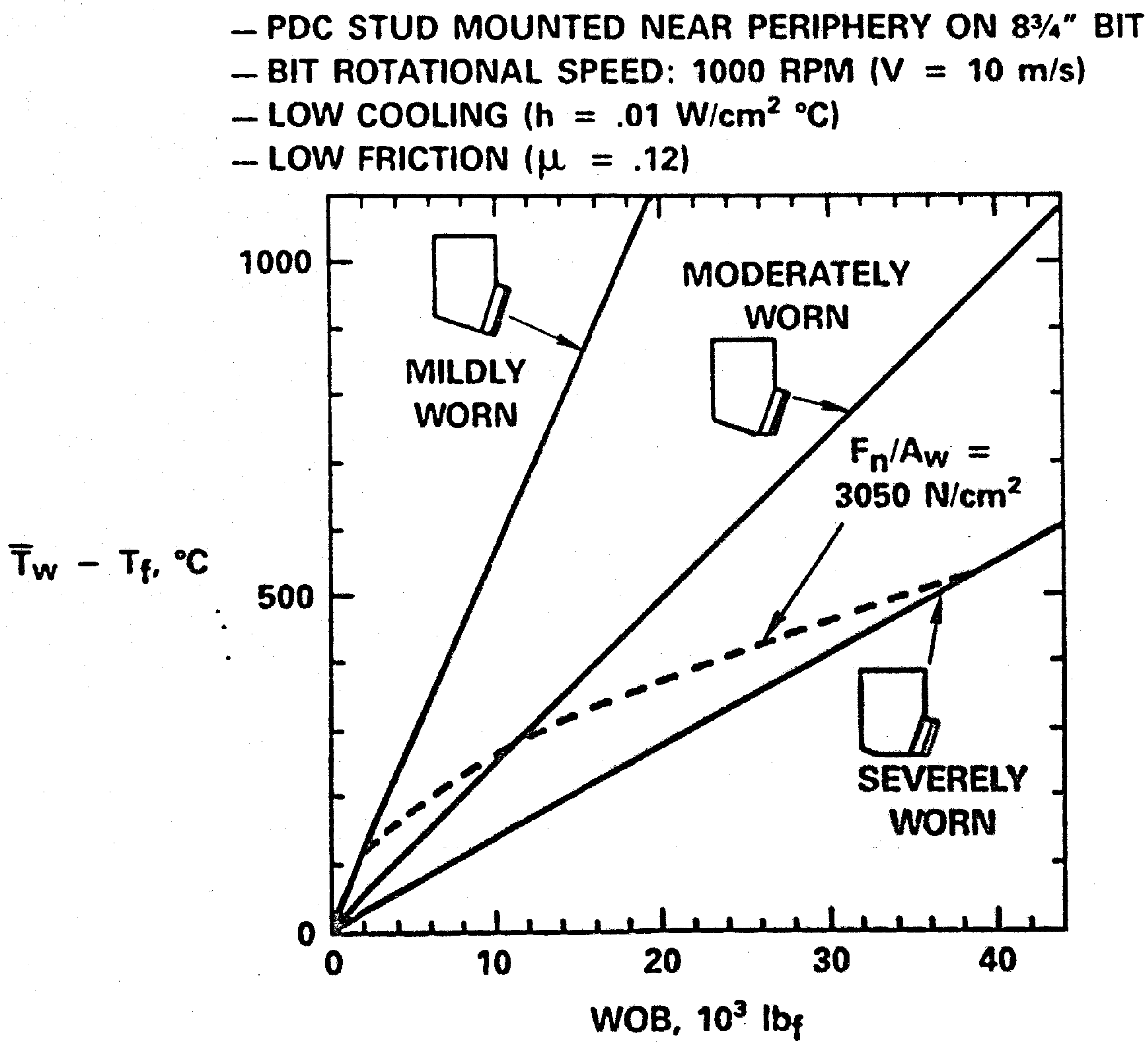

Figure 12. Computed mean wearflat temperatures as a function of weight on bit (WOB)

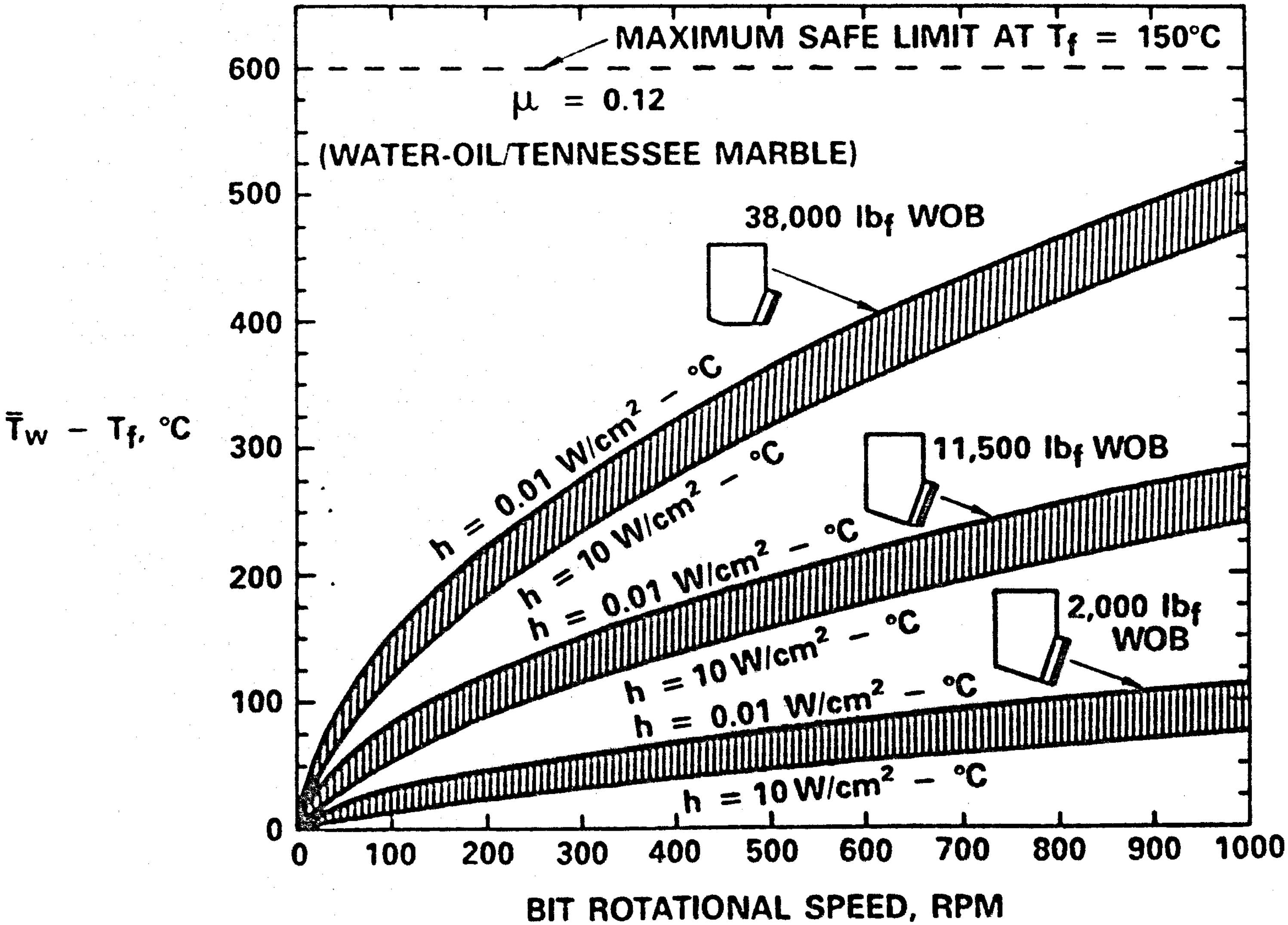

Figure 13. Computed mean wearflat temperatures for a low friction condition

Figure 14 presents predicted mean wearflat temperatures for the highest measured friction coefficient reported to date, i.e., $\mu = 0.72$, corresponding to a tungsten carbide slider on sandstone under the dry conditions typical of air drilling. In this case, only the mildly worn tool is maintained at a safe operating temperature over an appreciable portion of the range in bit rotational speed. Furthermore, it should be recognized that the downhole drilling fluid temperature could easily be higher with air, depending on the formation temperature. This would effectively reduce the maximum safe operating limit shown in Figure 14.

Note also that increased convective cooling could have a much greater effect in this high friction case; however, cooling greater than approximately 0.25 $W/cm^2 \cdot C$ probably cannot be practically achieved with air, even if air jets directly impinge on the cutters. It can be concluded from comparison of Figures 13 and 14 that, although liquid drilling fluids provide greater convective cooling than air, the major beneficial role of liquids in reducing cutter operating temperatures is in lubricating the sliding interface and reducing frictional heating.

Summary of Major Conclusions

1) Very high thermal gradients can develop at the wearflat of PDC cutters, and these probably contribute greatly to the heat checking and cracking observed under certain operating conditions.

2) Increasing the thickness of the diamond layer relative

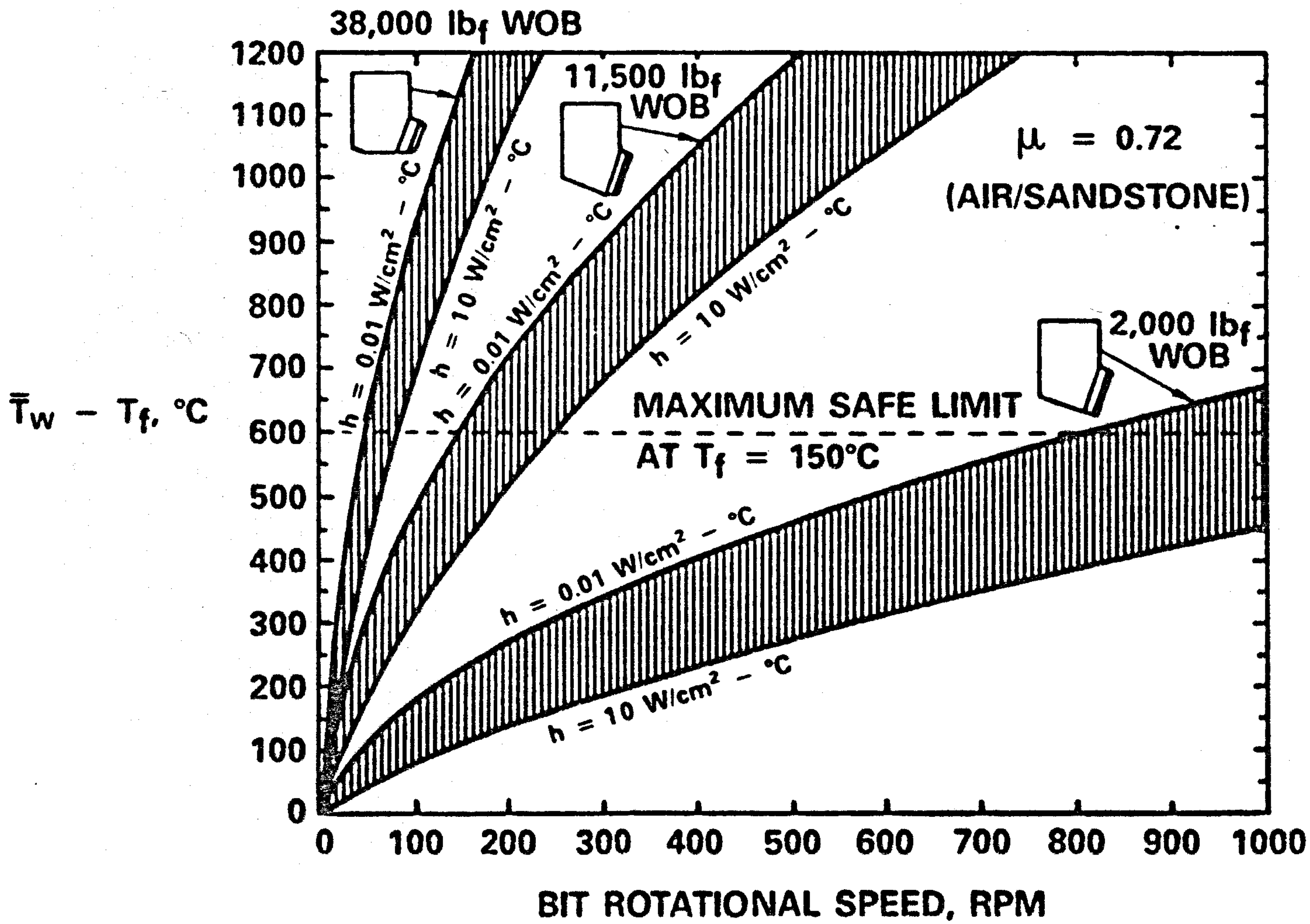

Figure 14. Computed mean wearflat temperatures for a high friction condition

to the total thickness of the compact may reduce thermal deterioration by improving the diffusion characteristics of the compact.

3) The mean wearflat temperature rise of a PDC cutter above the ambient fluid temperature is directly proportional to friction coefficient and weight on cutter. It increases at a rate proportional to approximately the one-half power of sliding speed and decreases at a non-linear rate with increased convective cooling. For a given contact pressure between the cutter and the rock, temperature increases with increasing cutter wear.

4) Convective cooling greater than 10 $W/cm^2 {}^\circ C$ does not further reduce wearflat temperatures due to the limited thermal conductivity of the cutter material; thus the maximum beneficial cooling rate lies approximately in the range 5-10 $W/cm^2 {}^\circ C$.

5) Mean radial flow across the face of a PDC bit provides cooling rates with water which are about 1/5 of the maximum beneficial value.

6) Low pressure water jets directed at the cutters should provide cooling rates which lie within the range of the maximum beneficial value.

7) "Mudding up" reduces convective cooling slightly.

8) Typical air drilling operations provide essentially no cutter cooling.

9) The ability of liquid drilling fluids to reduce friction is far more important in reducing operating temperatures than their ability to provide cutter cooling.

10) For certain combinations of conditions, particularly

when air is the drilling fluid, the wearflat operating temperatures of PDC cutters can exceed the maximum safe level of 750°C. Even below this level, bit life can be significantly increased if operating temperatures can be reduced by improving cutter cooling and lubrication.

Nomenclature

A_w = cutter wearflat area = d(1.0) - cm^2 (in^2)

c_f = fluid specific heat - kJ/kg - °C (Btu/lb_m°F)

d = cutter wearflat length - cm (in)

D = diameter of PDC stud - cm (in)

f = function defined in equation 4 and Figure 5 - cm^2°C/W (ft^2 hr °F/Btu)

F_c = cutting force - N (lb_f)

F_f = friction force = μF_n - N (lb_f)

F_n = normal force - N (lb_f)

F_r = rock reaction force - N (lb_f)

F_{th} = thrust force - N (lb_f)

h = convective heat transfer coefficient - W/cm^2°C (Btu/hr ft^2°F)

k = cutter material thermal conductivity - W/cm°C (Btu/hr ft°F)

k_f = fluid thermal conductivity - W/cm°C (Btu/hr ft°F)

k_2 = rock thermal conductivity - W/cm°C (Btu/hr ft°F)

PDC = polycrystalline diamond compact

q_c = convective cooling heat flux - W/cm^2 (Btu/hr ft^2)

q_1 = frictional heat flux into cutter - W/cm^2 (Btu/hr ft^2)

q_2 = frictional heat flux into rock - W/cm^2 (Btu/hr ft^2)

Q_f = frictional heat rate = $\mu F_n V$ - W (Btu/hr)

r = radial location of cutter on bit - cm (in)

T_f = ambient fluid temperature - °C (°F)

T_s = exposed cutter surface temperature - °C (°F)

$\bar{T}_w$ = mean cutter wearflat temperature - °C (°F)

u = local fluid velocity past cutter - m/s (ft/s)

Nomenclature cont.

V = cutter sliding speed - m/s (ft/min)

WC = tungsten carbide

WOB = weight on bit - N (lb_f)

α = energy partitioning fraction = $q_1/(q_1 + q_2)$

$\overline{\theta}_r$ = mean temperature elevation of rock at sliding interface - °C (°F)

μ = friction coefficient between cutter and rock = F_f/F_n

μ_f = fluid dynamic viscosity - Pa-s (cP)

ρ_f = fluid density - kg/m^3 (lb_m/gal)

χ_2 = thermal diffusivity of rock - cm^2/s (ft^2/hr)

ω = bit rotational speed - rad/s (RPM)

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