HIGH POWER MICROHOLE TURBODRILL & BIT for DRILLING with COILED TUBING

DOE Project No. DE-PS26-04NT15480

Smith Neyrfor

Houston, TX

March 14, 2007

Bob Radtke, TII
Dave Conroy, SII

PREFACE

- "To economically recover gas from deep reservoirs we need to learn how to drill smaller boreholes more rapidly and less expensively."

  Steve Holditch, Schlumberger fellow.

- Coiled tubing drilling required low weight on bit and becomes increasing economical with higher rotary speeds.

THE TEAM

TECHNOLOGY INTERNATIONAL, INC. (TII)

- Bob Radtke
- Dave Glowka
- Glenn Corser

Smith Neyrfor (SII)

- Dave Truax
- Dr. Dave Conroy
- Dr. Man Mohan Rai

AGENDA

- 1:00P Introductions
- 1:10P Catoosa Field Testing of 2-7/8" Turbine and 4-1/8” Drill Bits
- 1:20P Prototype Turbodrill Design
  - NASA Ames Hydraulic Modeling

  2:30P Coffee Break
- 2:45P Drill Bit Design
  - Cutter Finite Element Thermal Modeling
  - Cutter Fabrication
- 4:00P Manufacture Two Prototype 2-7/8" Turbine and Drill Bit TurboDrills and Drill Bit
- 4:15P Field Testing
- 4:30P Discussion
- 5:00P Adjourn

OBJECTIVES

- Developing and testing an effective downhole drive mechanism and a novel drill bit for drilling with coiled tubing
  - An improved Turbodrill that can deliver higher power at 1100 to 2200 RPM and low weight-on-bit
  - A more durable drill bit that will employ high-temperature cutters to drill hard and abrasive rock in 3½-inch boreholes

BENEFITS TO THE INDUSTRY

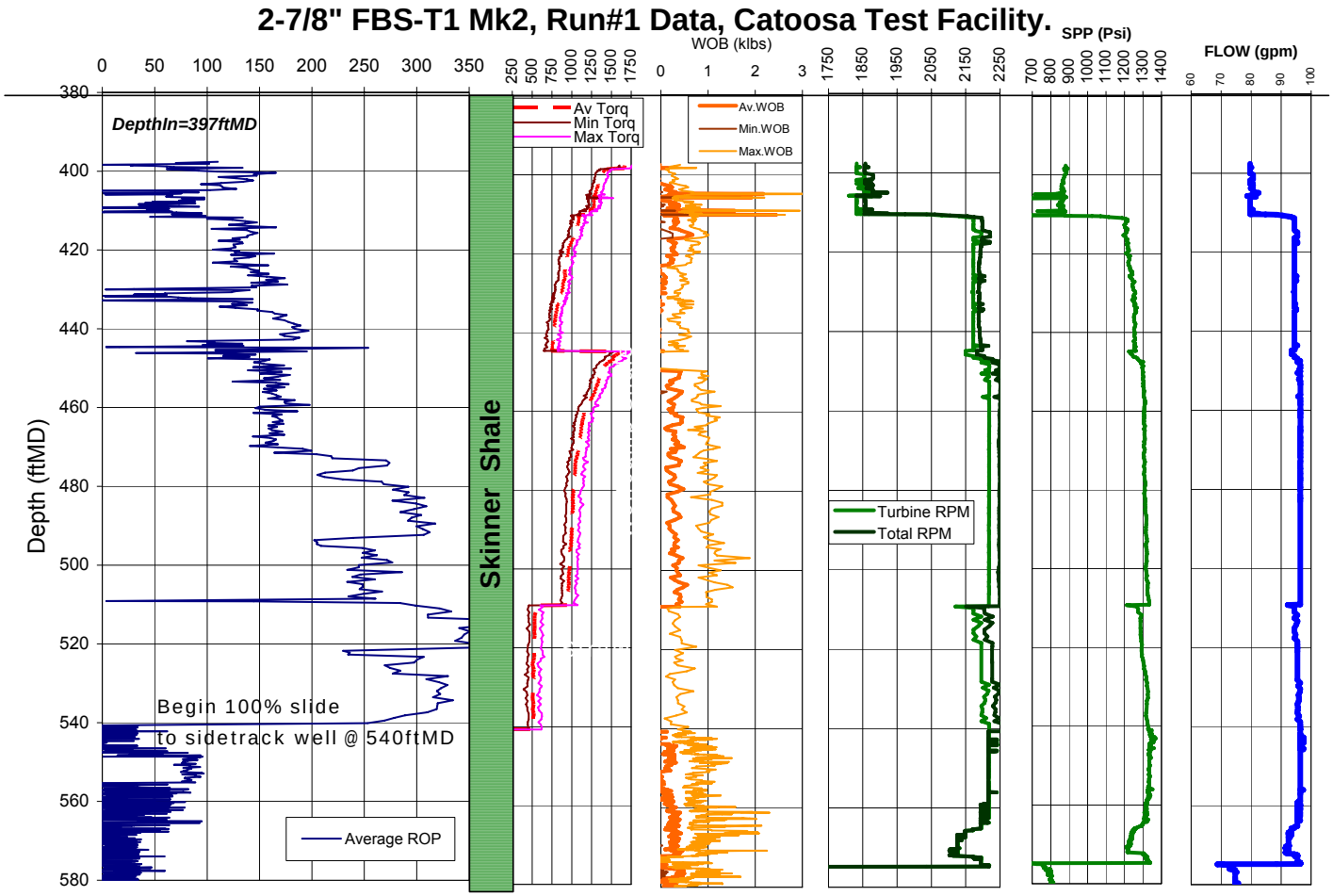
- Shorter higher power 2-7/8” Turbodrill for directional drilling
  - Better utilization of hydraulic budget
- Dedicated directional coil drill bit
  - For drilling rather than to just clean-out hole
  - Learning combination of materials needed
  - With low available WOB, ROP is RPM sensitive

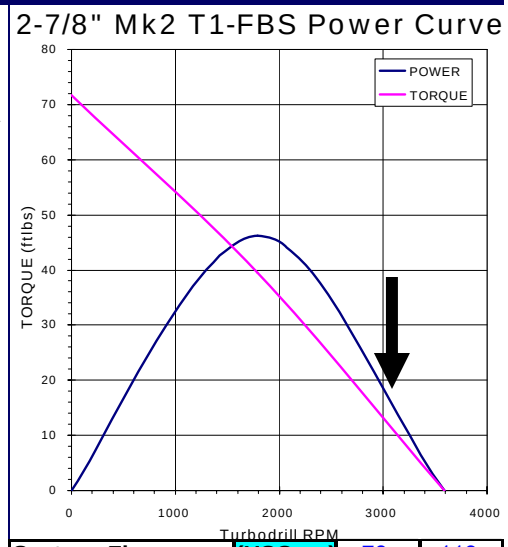
PROJECT PLAN

- Phase I: Design
  - Catoosa Field Test of 2-7/8” Turbodrill
  - Higher Power Turbodrill
    - Turbine Blade Design
    - Bearings
    - Seals
  - Drill Bit Design
    - Cutter Finite Element Thermal Modeling
    - High Temperature Cutter Fabrication
- Phase II: Manufacturing and Testing Prototype Turbodrill and High Temperature Drill Bit

PHASE I - GTI CATOOSA FIELD TEST FACILITY

CATOOSA FIELD TEST#1, BASELINE 2-7/8" TURBODRILL

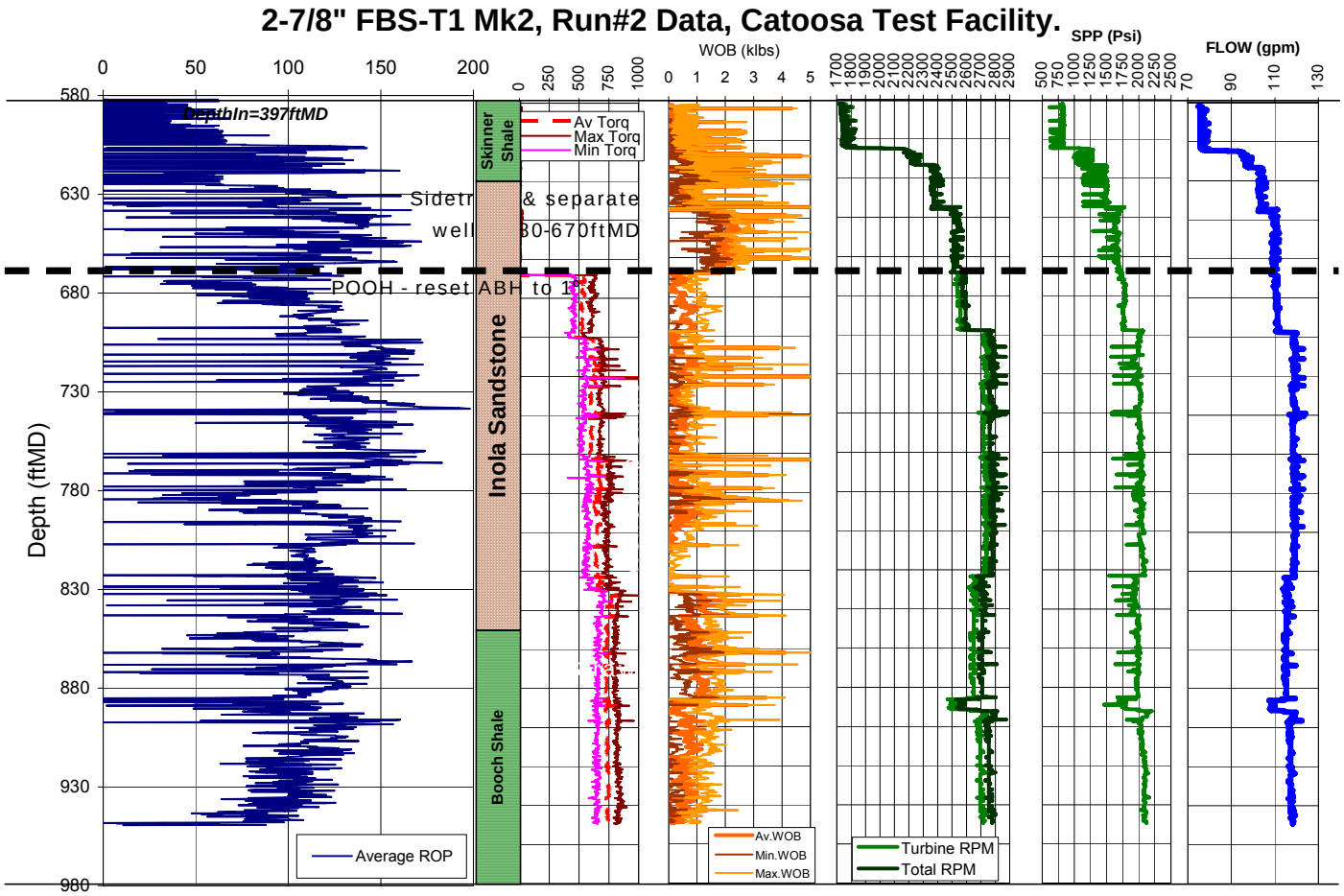


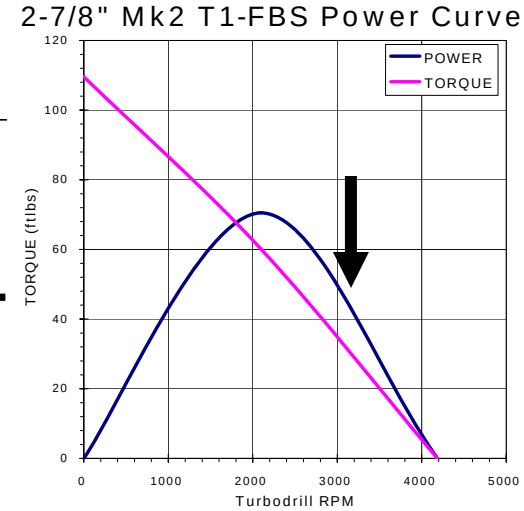


System Flow	(USGpm)	78	113
Mud Type	(-)	wbm	wbm
Mud Weight	(PPG)	8.80	8.80
Surface Pressure	(p.s.i.)	879	2004
Turbine Pressure	(p.s.i.)	665	1395
Bit Pressure	(p.s.i.)	15	31
AMB Bearings	(PVu)	0.66	1.90
AMB Springs	(%)	27	53
Nominal Speed	Rpm	1794	2599
Nominal Torque	(Lb.Ft.)	44	93
Stall Torque	(Lb.Ft.)	80	169
Power	(Hp)	15	46
Hydraulic Thrust	(Lbf)	2122	4224
Mech. Horsepower	(Hp/in2)	1.13	3.44

- **Turbo-PDC drilled 184ft @ 42.8ft/hr** *(WOB=1klbs, 91gpm, RPM=2070, hHp/in^2=1.9)* Shale (UCCS=6-9kPsi) dominated sequence with sandstone (UCCS=~9kPsi) intervals; Drilled out of common casing until BHA clear of shoe.
- **Sidetracking operations (ABH=2º) @ 540ftMD to build 7º from vertical and hold tangent in order to create separation before beginning ROP trials.**

CATOOSA FIELD TEST#2, BASELINE 2-7/8” TURBODRILL

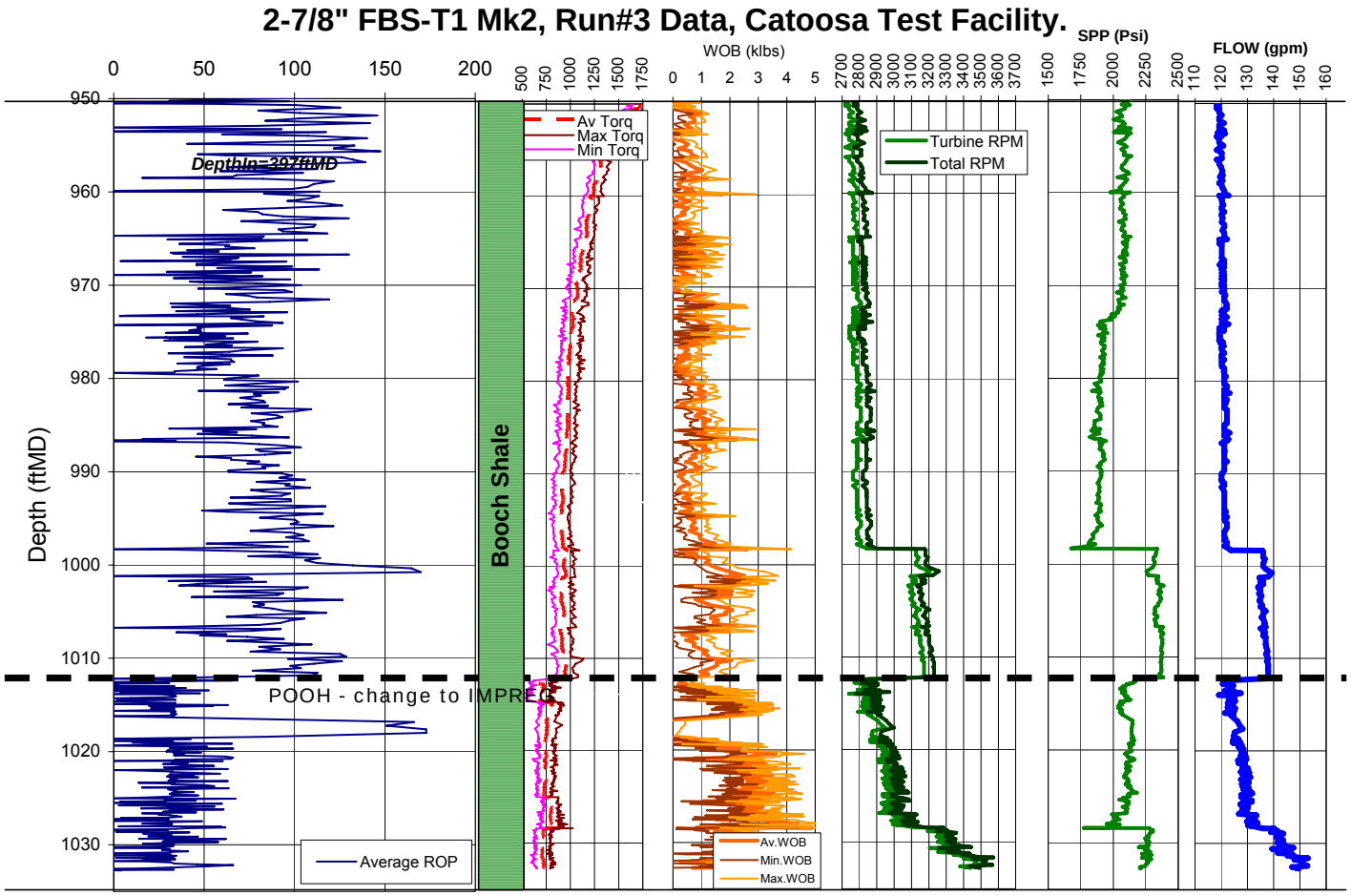


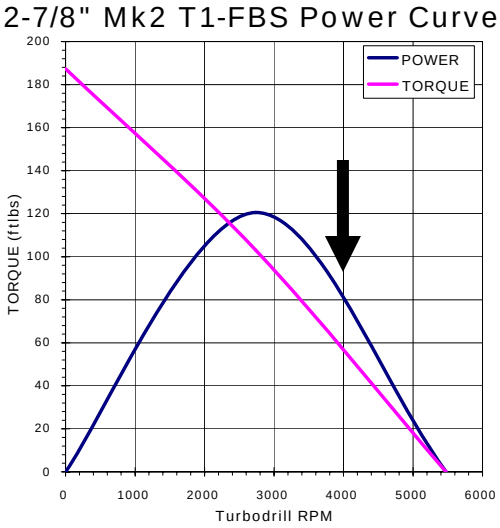


System Flow	(USGpm)	91	117
Mud Type	(-)	wbm	wbm
Mud Weight	(PPG)	8.80	8.80
Surface Pressure	(p.s.i.)	1185	2129
Turbine Pressure	(p.s.i.)	905	1495
Bit Pressure	(p.s.i.)	20	33
AMB Bearings	(PVu)	1.02	2.10
AMB Springs	(%)	35	57
Nominal Speed	Rpm	2093	2691
Nominal Torque	(Lb.Ft.)	60	100
Stall Torque	(Lb.Ft.)	110	181
Power	(Hp)	24	51
Hydraulic Thrust	(Lbf)	2813	4514
Mech. Horsepower	(Hp/in2)	1.80	3.82

- **Turbo-PDC drilled 368ft @ 42.1ft/hr** *(WOB=1-2klbs, 117gpm, RPM=2691, hHp/in^2=3.8)* Shale (@118ft/hr 3.8hHp/in^2, UCCS=6-9kPsi) and sandstone (@126ft/hr 3.82hHp/in^2, UCCS=9-12kPsi) sequence; 100% rotation with 1ºABH and PDC.

CATOOSA FIELD TEST#3, BASELINE 2-7/8" TURBODRILL





System Flow	(USGpm)	119	132
Mud Type	(-)	wbm	wbm
Mud Weight	(PPG)	8.80	8.80
Surface Pressure	(p.s.i.)	1993	2638
Turbine Pressure	(p.s.i.)	1547	1903
Bit Pressure	(p.s.i.)	34	42
AMB Bearings	(PVu)	2.20	2.98
AMB Springs	(%)	58	71
Nominal Speed	Rpm	2737	3036
Nominal Torque	(Lb.Ft.)	103	127
Stall Torque	(Lb.Ft.)	187	231
Power	(Hp)	54	73
Hydraulic Thrust	(Lbf)	4662	5689
Mech. Horsepower	(Hp/in2)	4.02	5.49

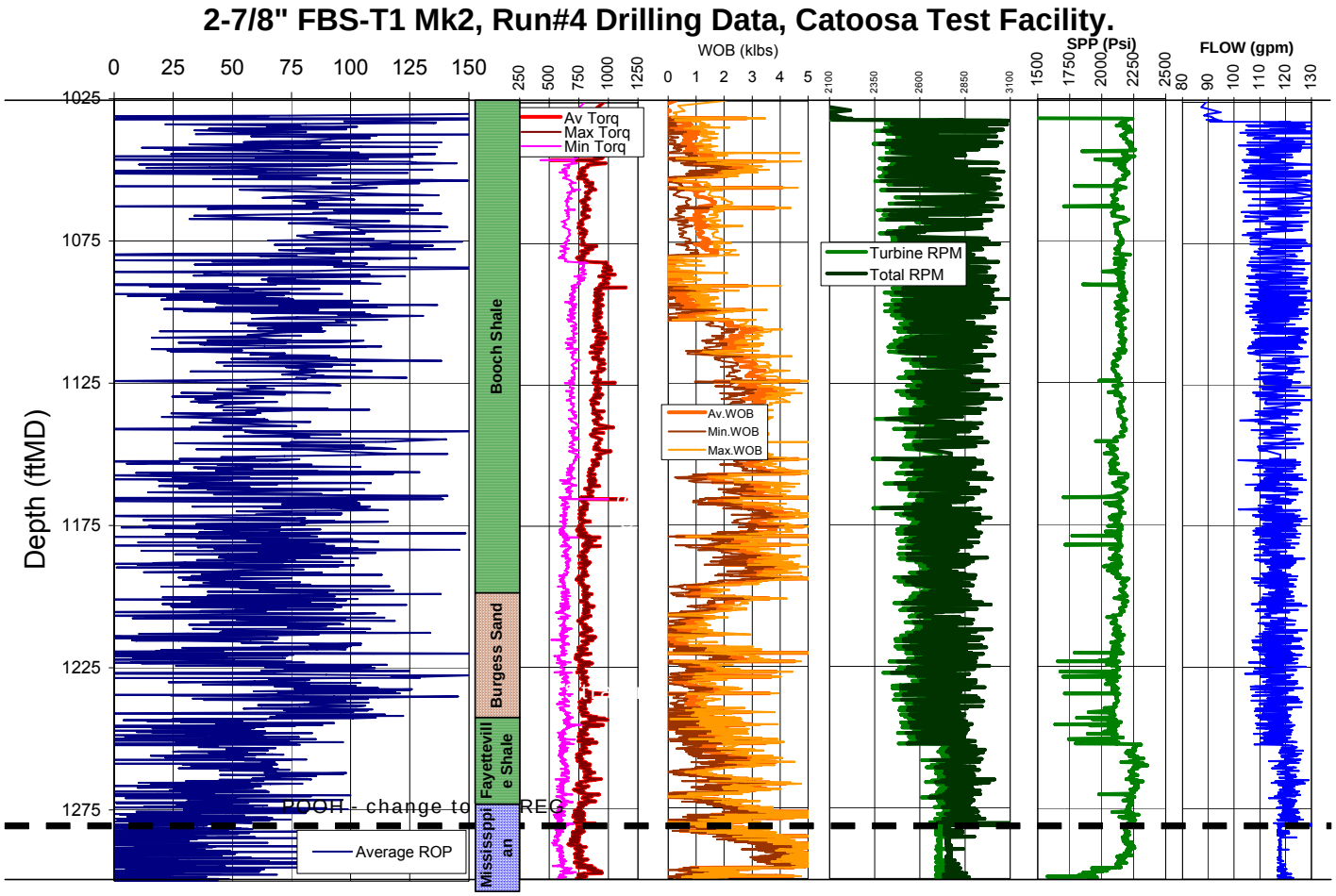
Turbo-PDC drilled 62ft @ 78.5ft/hr *(WOB=1klbs, 122gpm, RPM=2887, hHp/in^2=4.1)*

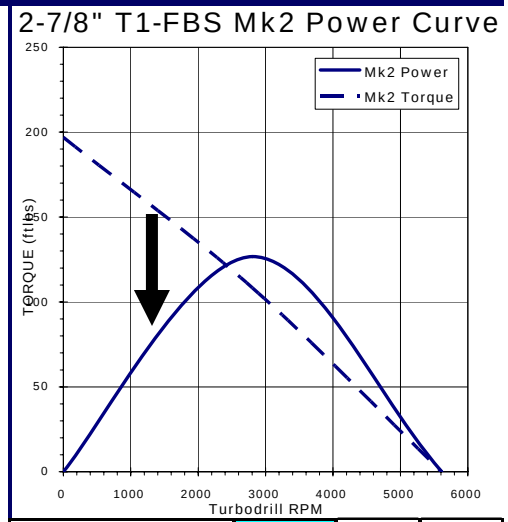
Shale (UCCS=6-9kPsi) dominated sequence with sandstone (UCCS=9-12kPsi) intervals; POOH for impreg @ 1012ftMD for comparative ROP trial.

- **Turbo-Impreg drilled 20ft @ 20.4ft/hr** *(WOB=2-3klbs, 128gpm, RPM=3000, hHp/in^2=5.4)*

  Shale (UCCS=6-9kPsi) dominated sequence with sandstone (UCCS=9-12kPsi) intervals

CATOOSA FIELD TEST#4, BASELINE 2-7/8" TURBODRILL





System Flow	(USGpm)	122	132
Mud Type	(-)	wbm	wbm
Mud Weight	(PPG)	8.80	8.80
Surface Pressure	(p.s.i.)	2092	2638
Turbine Pressure	(p.s.i.)	1626	1903
Bit Pressure	(p.s.i.)	36	42
AMB Bearings	(PVu)	2.37	2.98
AMB Springs	(%)	61	71
Nominal Speed	Rpm	2806	3036
Nominal Torque	(Lb.Ft.)	108	127
Stall Torque	(Lb.Ft.)	197	231
Power	(Hp)	58	73
Hydraulic Thrust	(Lbf)	4890	5689
Mech. Horsepower	(Hp/in2)	4.33	5.49

Turbo-PDC drilled 240ft @ 47.3ft/hr *(WOB=2klbs, 117gpm, RPM=2737, hHp/in^2=4.3)*

Shale (UCCS=6-9kPsi) dominated sequence with sandstone (UCCS=9-12kPsi) intervals; Tagged top Mississippian Limestone (UCCS=27-30kPsi) before POOH for impreg.

- **Turbo-Impreg drilled 20ft @ 15.8ft/hr** *(WOB=3klbs, 118gpm, RPM=2781, hHp/in2=5.4)*

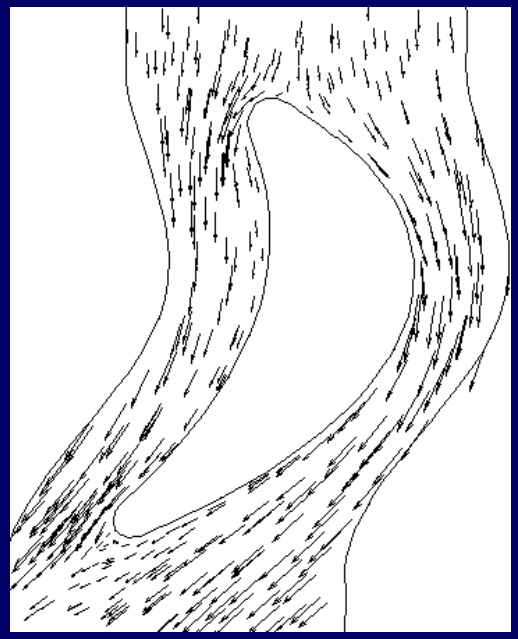
  Mississippian Limestone (27-30KPsi) sequence with shale (UCCS=18-21kPsi) intervals

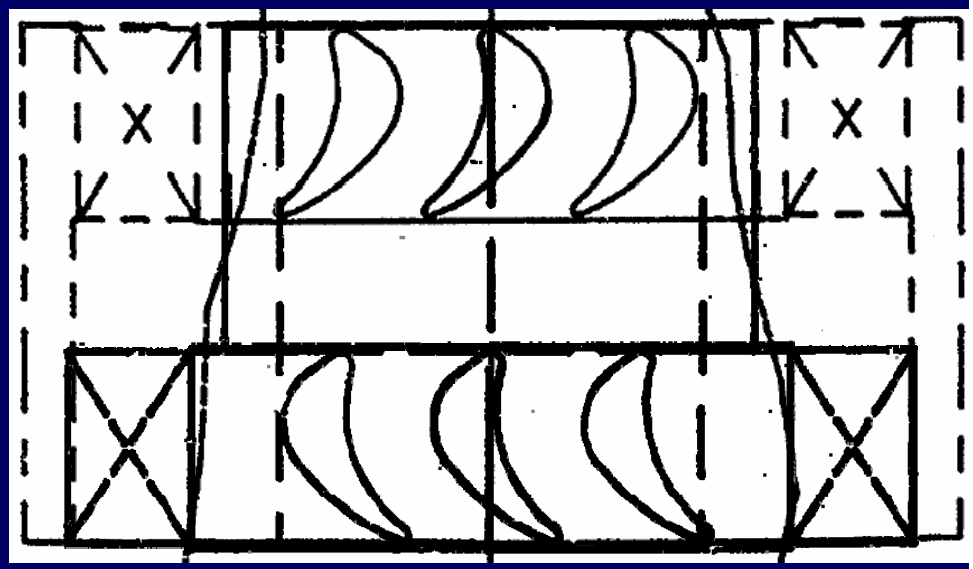
HIGH POWER TURBODRILL DESIGN

- Design Process of Blade Profile
  - Fluid dynamics modeling
  - Blade shape optimization
  - Dynamometer testing
  - Bearing and Seal Testing
- Performance Comparisons

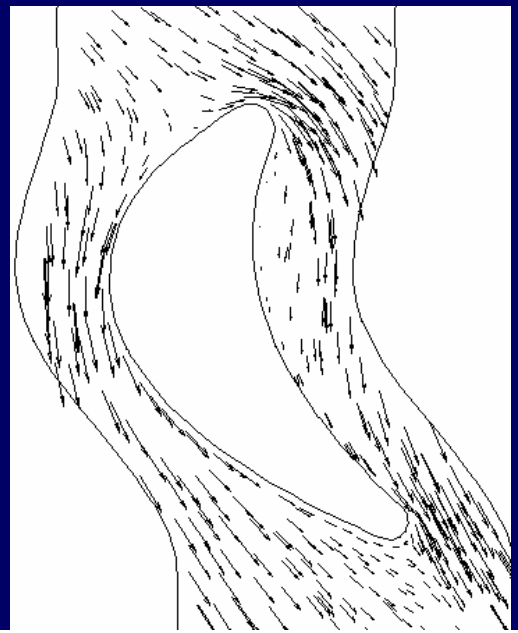
PHASE I – BASELINE MK2 BLADE MODEL

STATOR





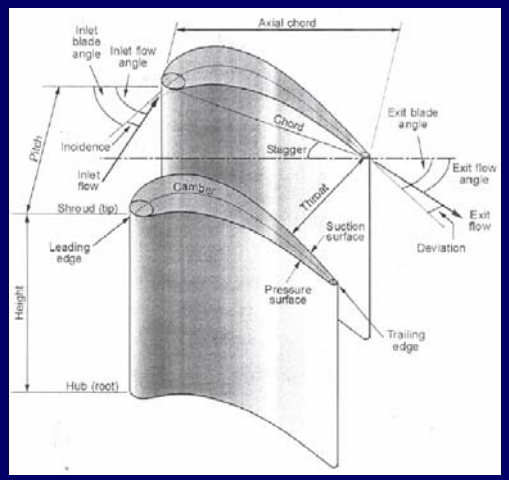
ROTOR

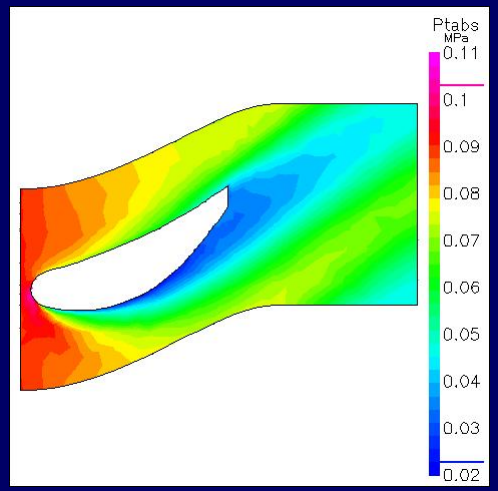


With turbine at 2000Psi, 120gpm

- **Power = 58hp** *(=4.3hHp/in²)*
  Nominal Torque = 108ft-lbf
- **Nominal Speed = 2806RPM**
- **Axial Thrust = 4890lbf**
- **Total Efficiency = 44.9%**

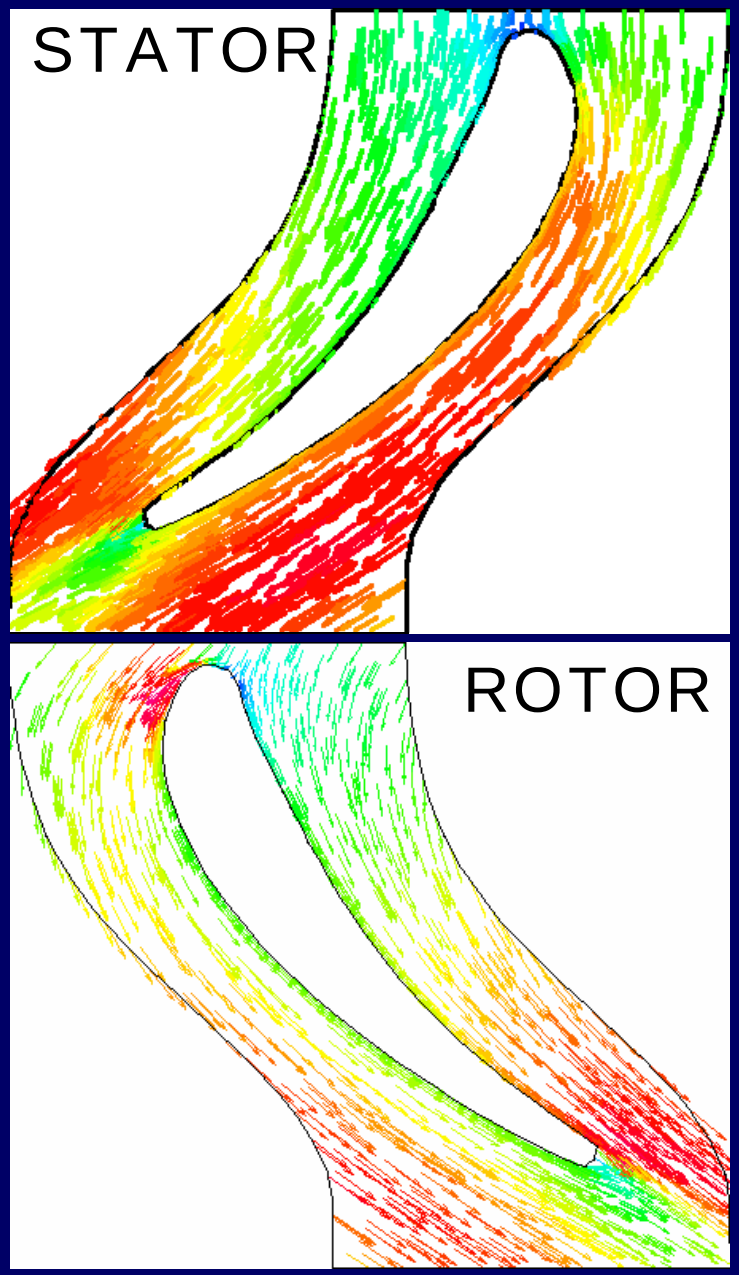
Phase II - TURBINE BLADE MODELS

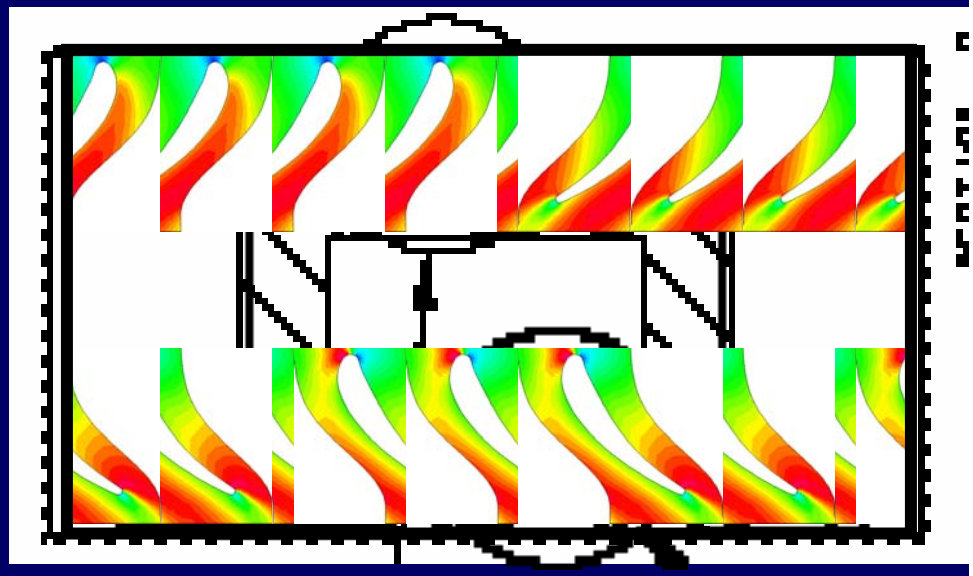




- **Computational Fluid Dynamics**
- **Response Surface Methodology**

Phase II - NASA BLADE MODEL





With turbine at 2000 Psi, 120 gpm

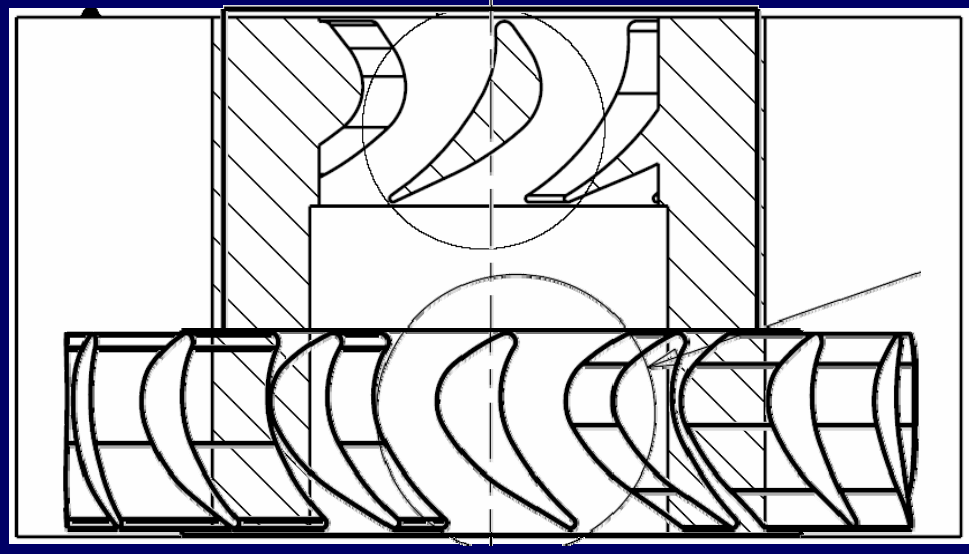
- **Power = 90.8hp** *(=6.8hHp/in2)*
  (+32hp ≡ +55%)
- **Nominal Torque = 190ft-lbf**
  (+82hp ≡ +76%)
- **Nominal Speed = 2500RPM**
  (-300RPM ≡ -11%)
- **Axial Thrust = 2937lbf**
  (+1953 ≡ +40%)
- **Total Efficiency = 84.8-85.5%**

Phase II - Neyrfor Blade Model

Blade

Modeling

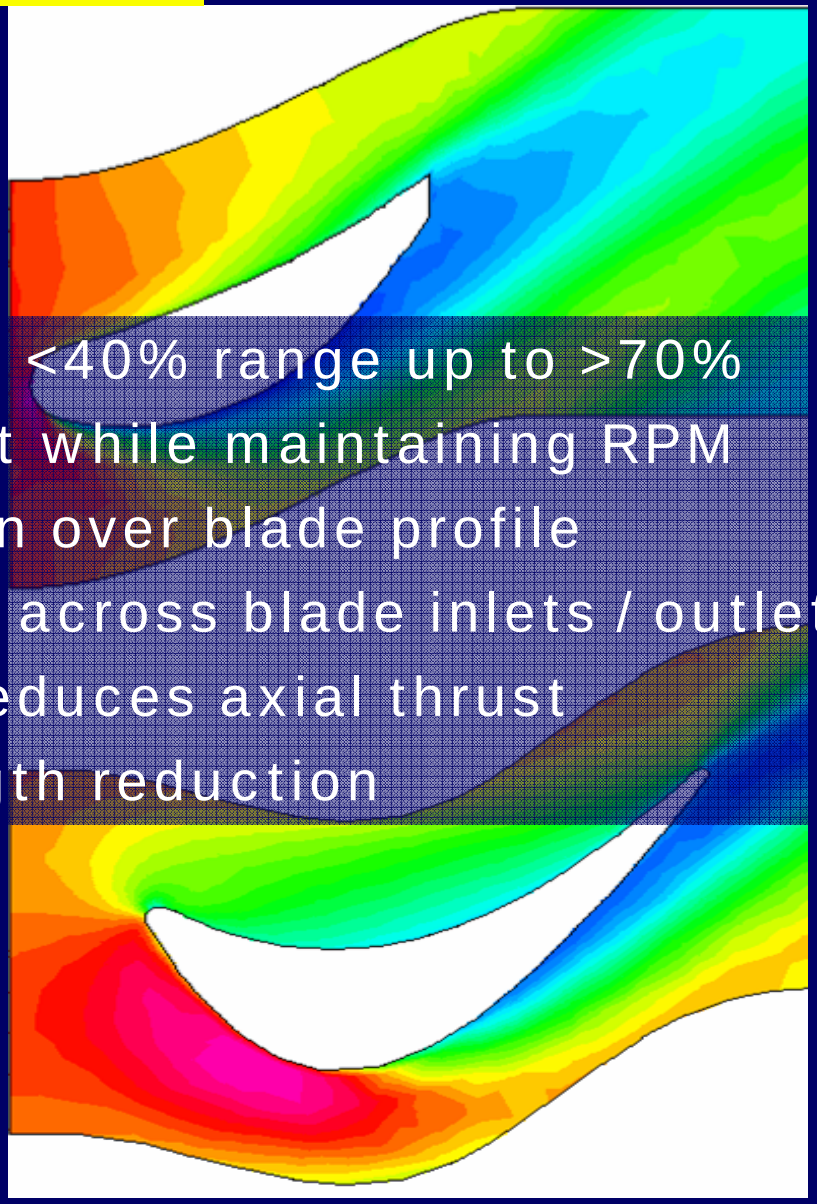
Incomplete



With turbine at 2000Psi, 120gpm

- **Power = ~120hp** *(=8.9hHp/in2)*
  (+62hp ≡ +107%)
- **Nominal Torque = 310ft-lbf**
  (+202hp ≡ +187%)
- **Nominal Speed = 1175RPM**
  (-1631RPM ≡ -58%)
- **Axial Thrust = ~1630lbf**
  (+3260 ≡ +67%)
- **Total Efficiency = 87.8-88.5%**

PHASE II – TURBO-BLADE DEVELOPMENT CONCLUSIONS



- Improve tool efficiency from <40% range up to >70%
- Raise nominal torque output while maintaining RPM
- Reduce fluid separation over blade profile
- Maintain or lower pressure drop across blade inlets / outlets
- New impulse design reduces axial thrust
- Overall tool length reduction

Single- and Multiple-Objective Optimization

With
Differential Evolution and Neural Networks

Man Mohan Rai
Exploration Technologies Directorate
NASA Ames Research Center
Moffett Field, CA-94035

Seminar at Smith-Neyrfor / Technology International
Houston, Texas

March 14, 2007

NASA AMES TURBINE BLADE DESIGN METHODOLOGY

- Dr. Man Mohan Rai Presentation
  - Overhead slides contained in three .pdf files available from Bob Radtke at (radtke@kingwoodcable.com).

POTENTIAL AREAS FOR TURBODRILL REDESIGN

- Smith Neyrfor/Technology International assessment shows separated flow on first rotor
  - Run case where the same blade design is used for the both the stator and rotor
  - Redesign first rotor to reduce flow separation
  - Investigate possibility of turbodrill design with three distinct airfoil sections
    - First stator row (distinct) followed by repeating rotor and stator rows
  - Investigate performance with 3-D blade designs
- Design for performance robustness
  - Assess performance of various airfoil sections at off design conditions
  - If necessary, redesign to reduce performance sensitivity to changing operating conditions

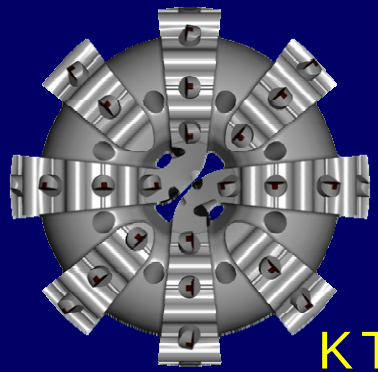
REMAINING TASKS

- Phase I: Design
  - Catoosa Field Test of 2-7/8” Turbodrill
  - Higher Power Turbodrill Blade
    - Bearings and Seals
    - Turbine Blade (Fluid Dynamics)
    - ARC Optimization and Geometry Modeling Algorithms
  - Drill Bit Design
    - Finite Element Thermal Modeling
    - High Temperature Cutter Fabrication
- Phase II: Manufacturing and Testing Prototype Turbodrills and High Temperature Drill Bits

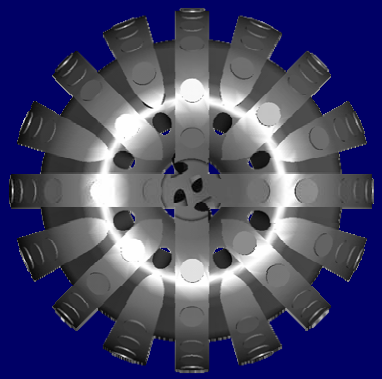
SMITH FIELD TEST DRILL BITS

IMPREGNATED DESIGN OPTIONS

KT503



KT703



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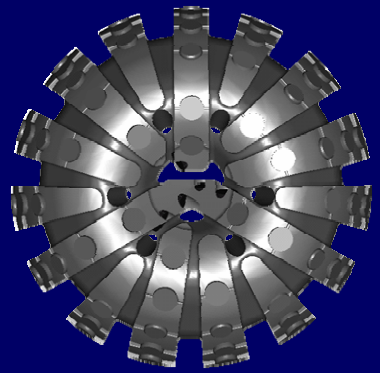

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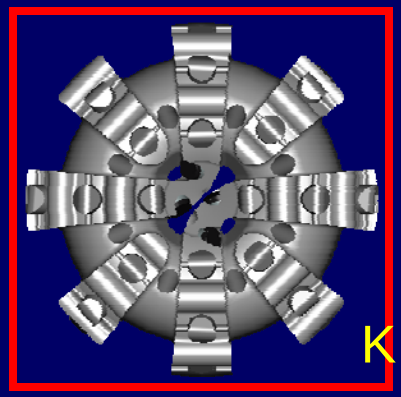
K503



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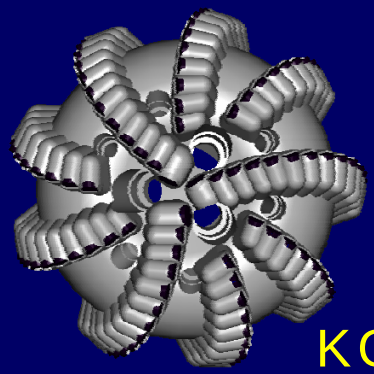

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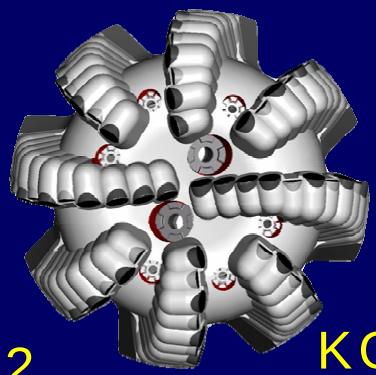


KGR730

Aggressive Design & Materials

THE SOLUTION
THE ENDURUS™ DIAMOND

- High Temperature Wear Resistance
- High Attachment Shear Strength
- Highest Fracture Resistance

EFFECT OF PDC CUTTER SPEED ON WEAR

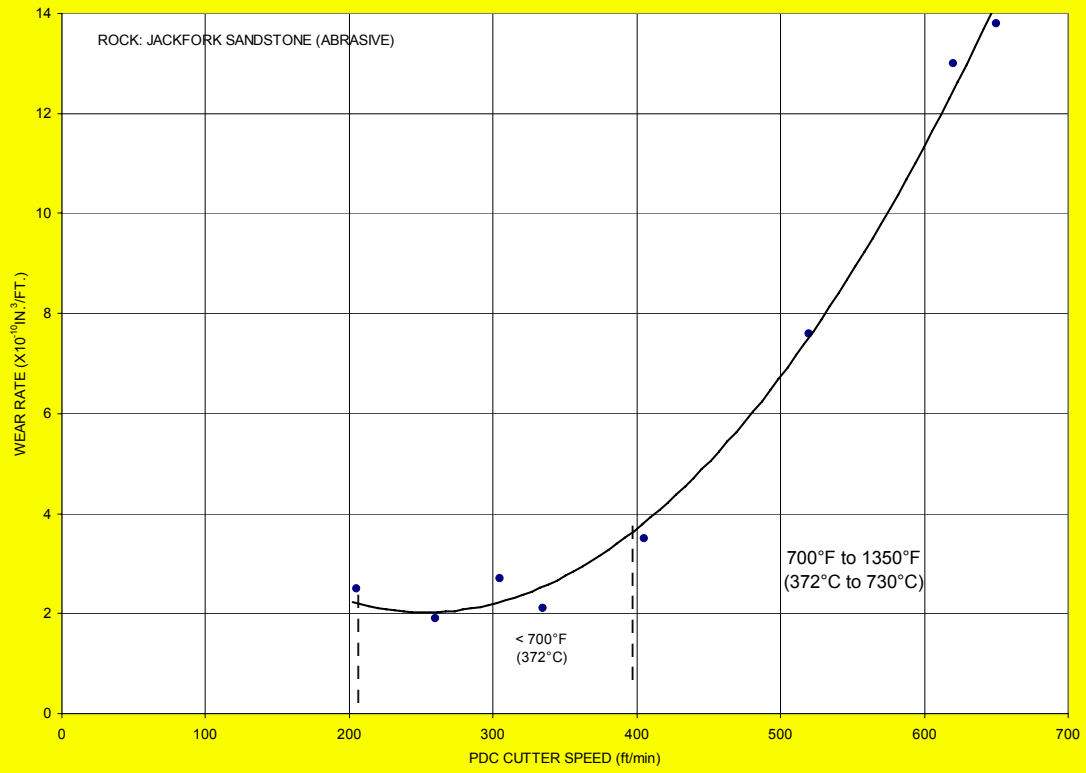


FIGURE 2: EFFECT OF PDC CUTTER SPEED ON WEAR

EFFECT OF TEMPERATURE ON TSP AND PDC WEAR RATE

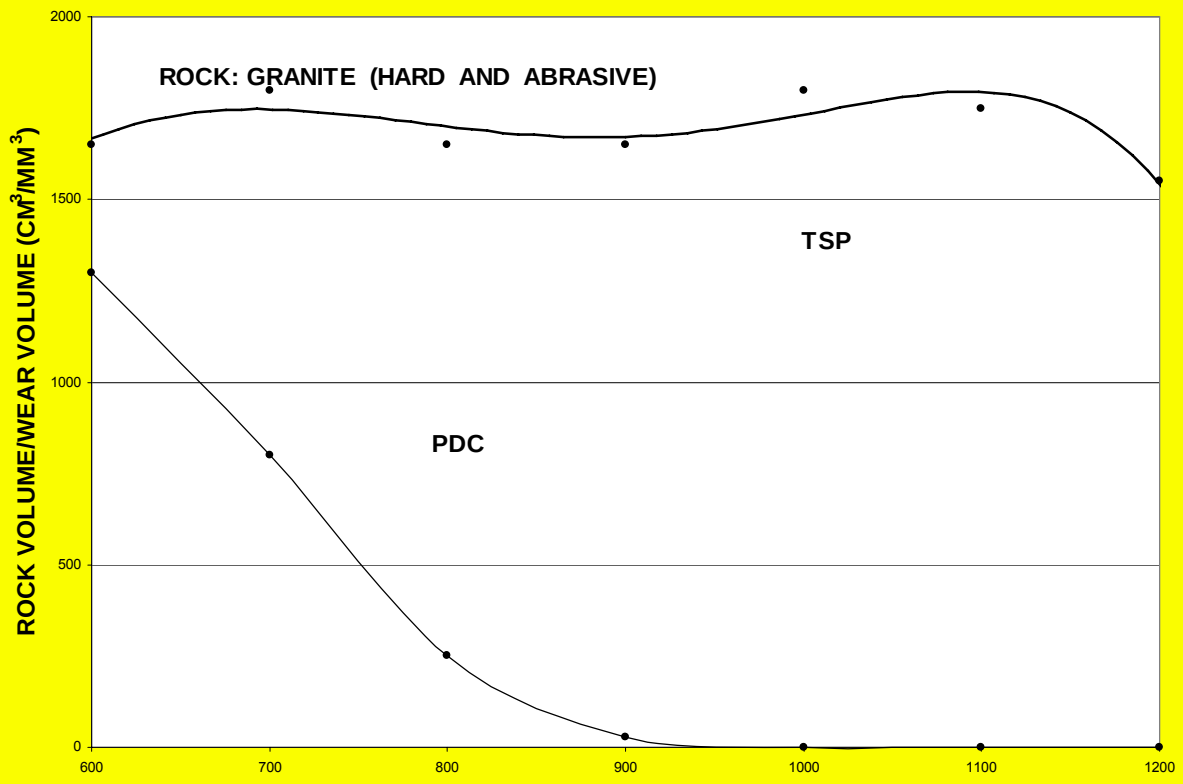


FIGURE 1: EFFECT OF PDC AND TSP CUTTER TEMPRATURE ON WEAR RATE

RELATIVE ROP OF DRILL BIT TYPES WITH INCREASING ROTARY SPEEDS

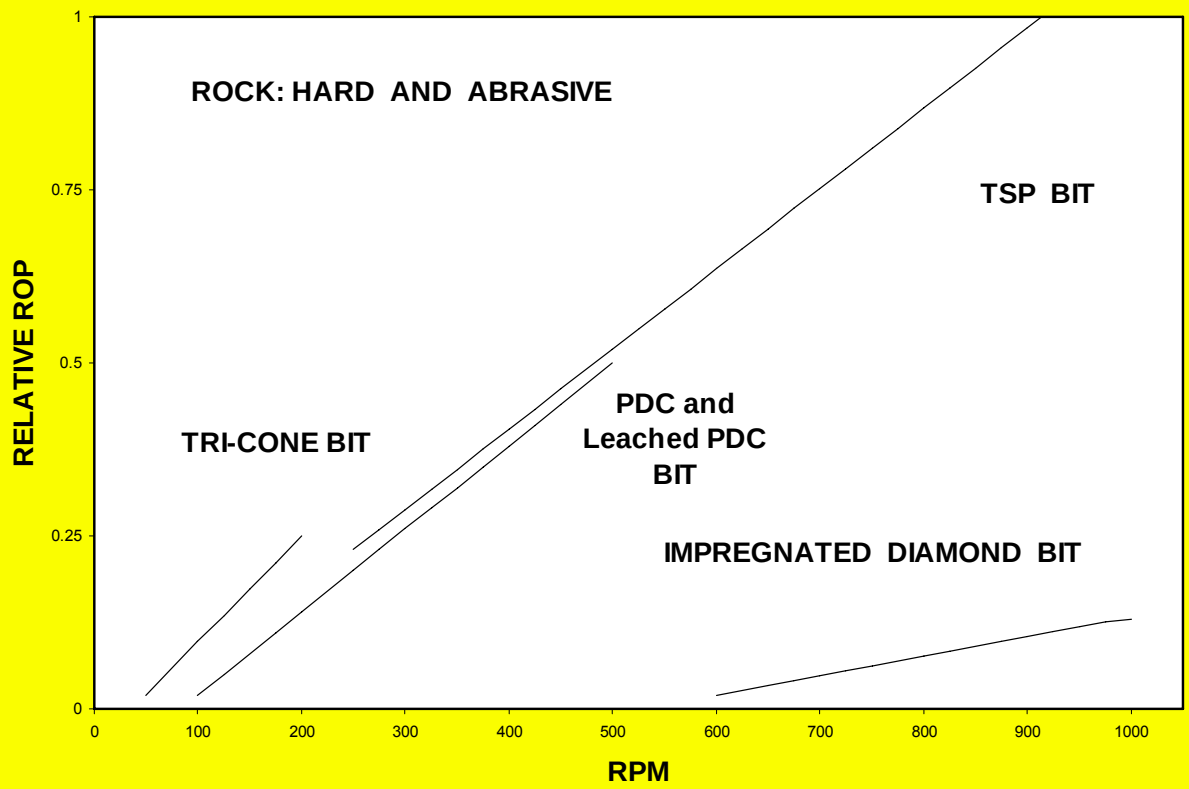
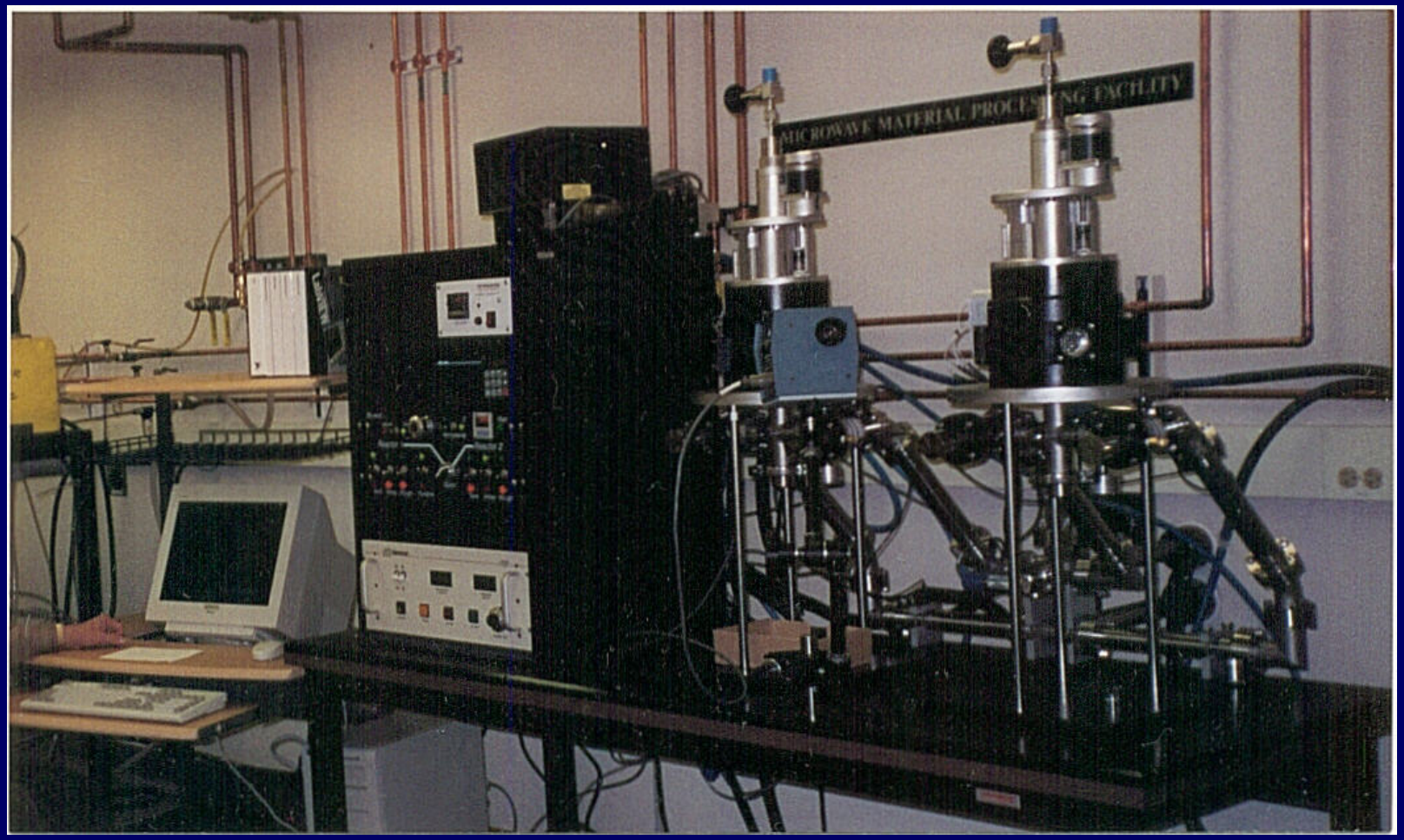


FIGURE 3: EFFECT OF BIT TYPE AND RPM ON RELATIVE ROP

MICROWAVE BRAZING



NASA 2002 SPACE ACT AWARD for INNOVATION

National Aeronautics and
Space Administration

Certificate of Recognition

Presented to

Robert P. Radtke

For the creative development of a technological contribution which has been determined to be of significant value in the advancement of the space and aeronautical activities of NASA, and is entitled:

Microwave Technique for Brazing Diamond Drill Bits

Chairperson, Inventions and Contributions Board

January 7, 2002
Date

HIGH POWER TURBODRILL BIT

Thermal and Mechanical Performance Modeling

March 14, 2007

Dave Glowka
Red Rock Research, Inc.

OBJECTIVES

- Develop a technique for calculating TSP cutter temperatures on a high-speed drill bit
- Quantify any thermal advantage of TSP vs PDC cutters
- Develop a technique for predicting the performance and wear of a high-speed TSP drill bit

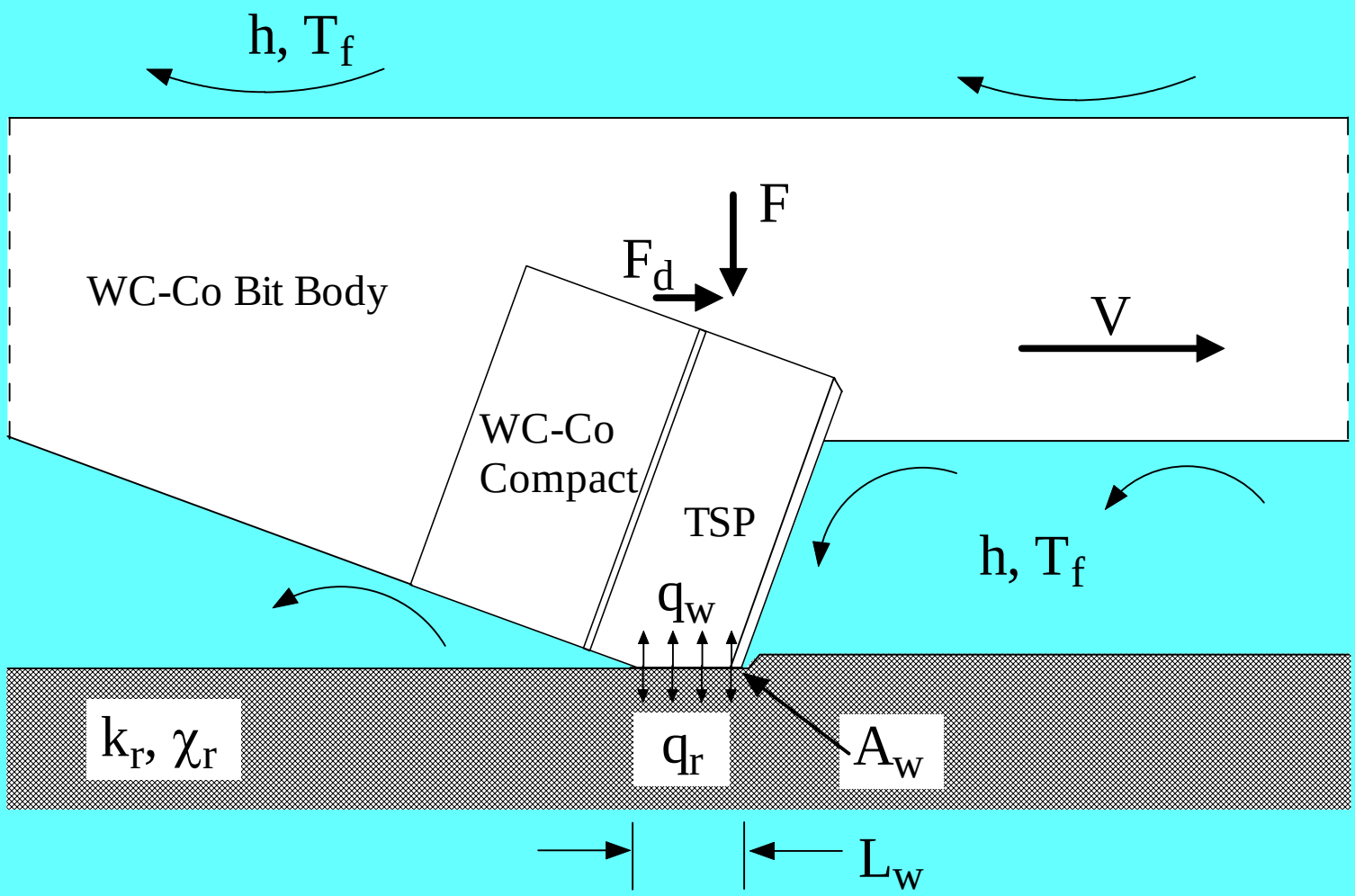
THERMAL MODELING OF TSP CUTTERS

- Based on analysis and numerical modeling method first used by in 1980 by Sandia National Laboratories
- Two-dimensional finite-element numerical models were constructed and run with

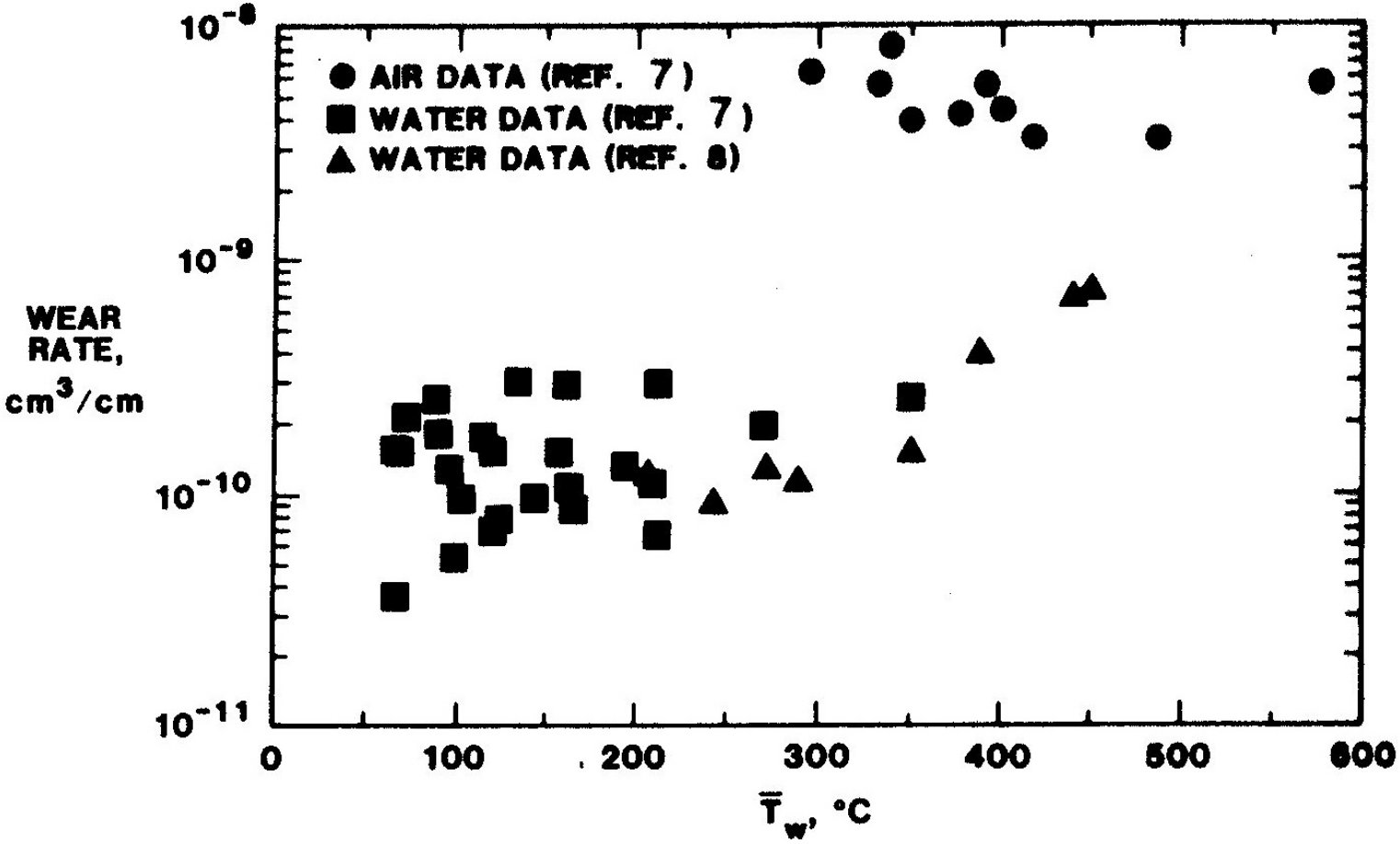
  - 9-mm TSP cutter geometry

  - Temperature-dependent thermal properties

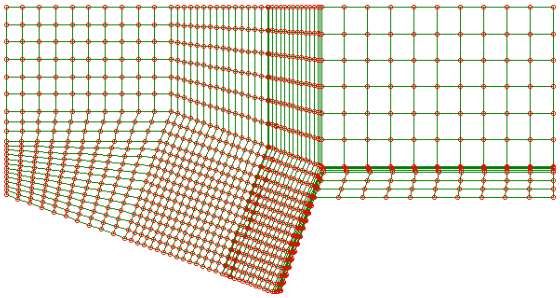
DRAG CUTTER on a DRILL BIT



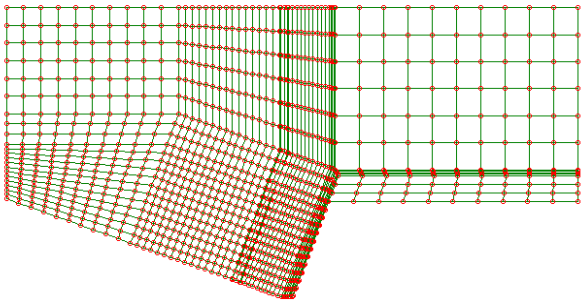
PDC CUTTER WEAR DATA



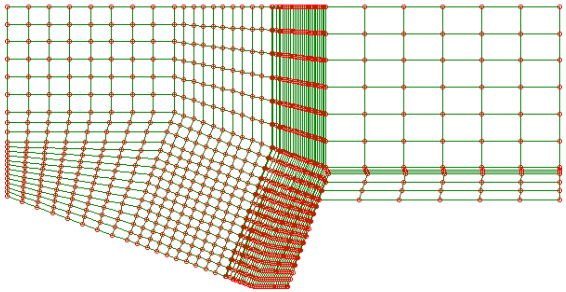
FOUR LEVELS of WEAR MODELED



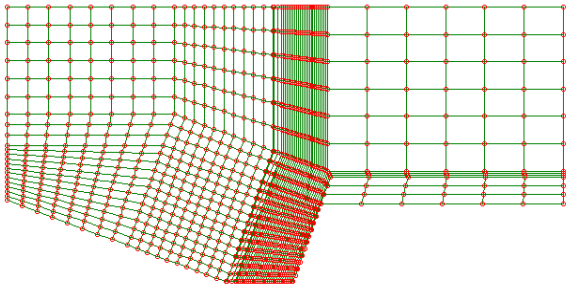
L_w = 0.38 mm



L_w = 0.68 mm



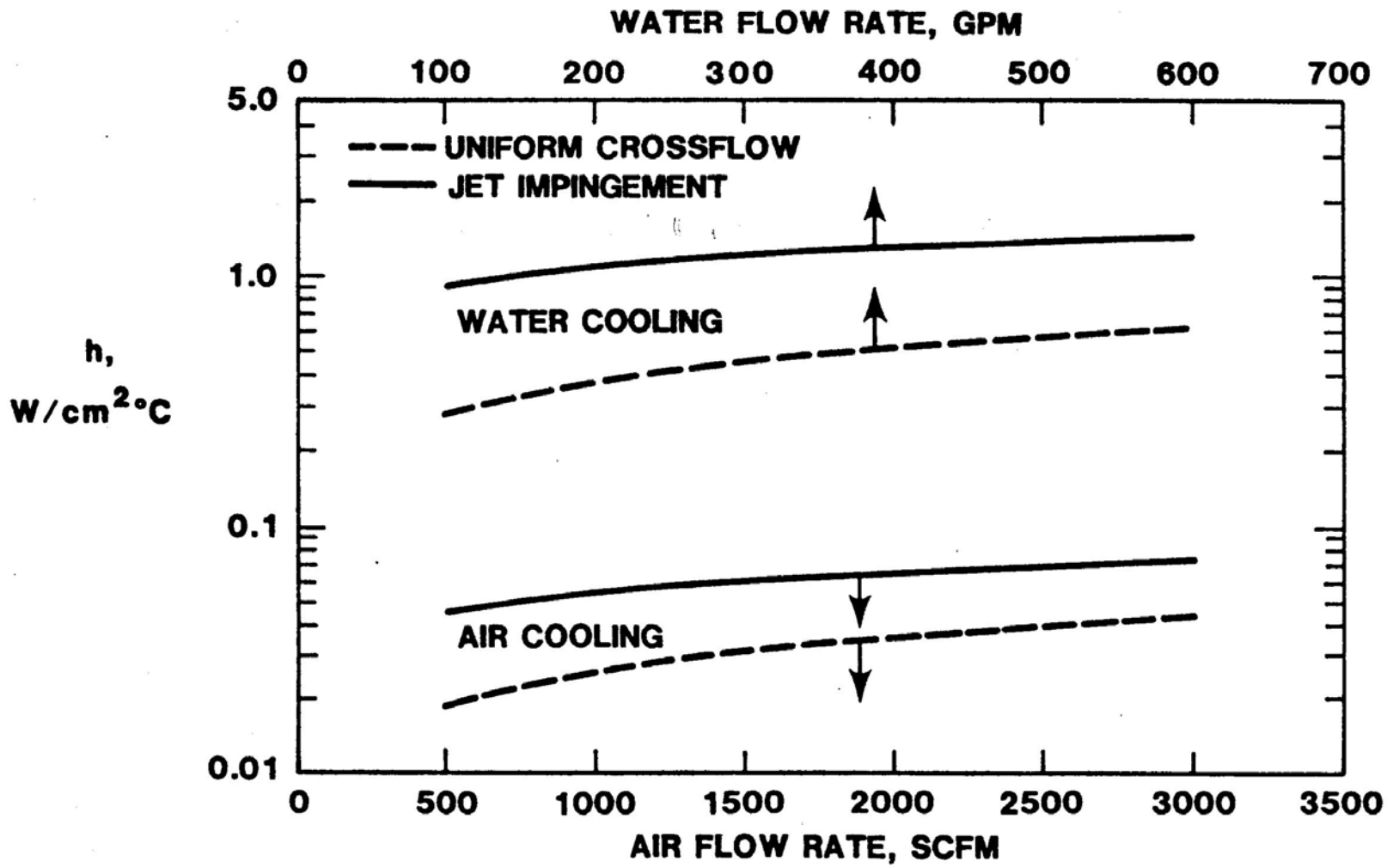
L_w = 2.18 mm



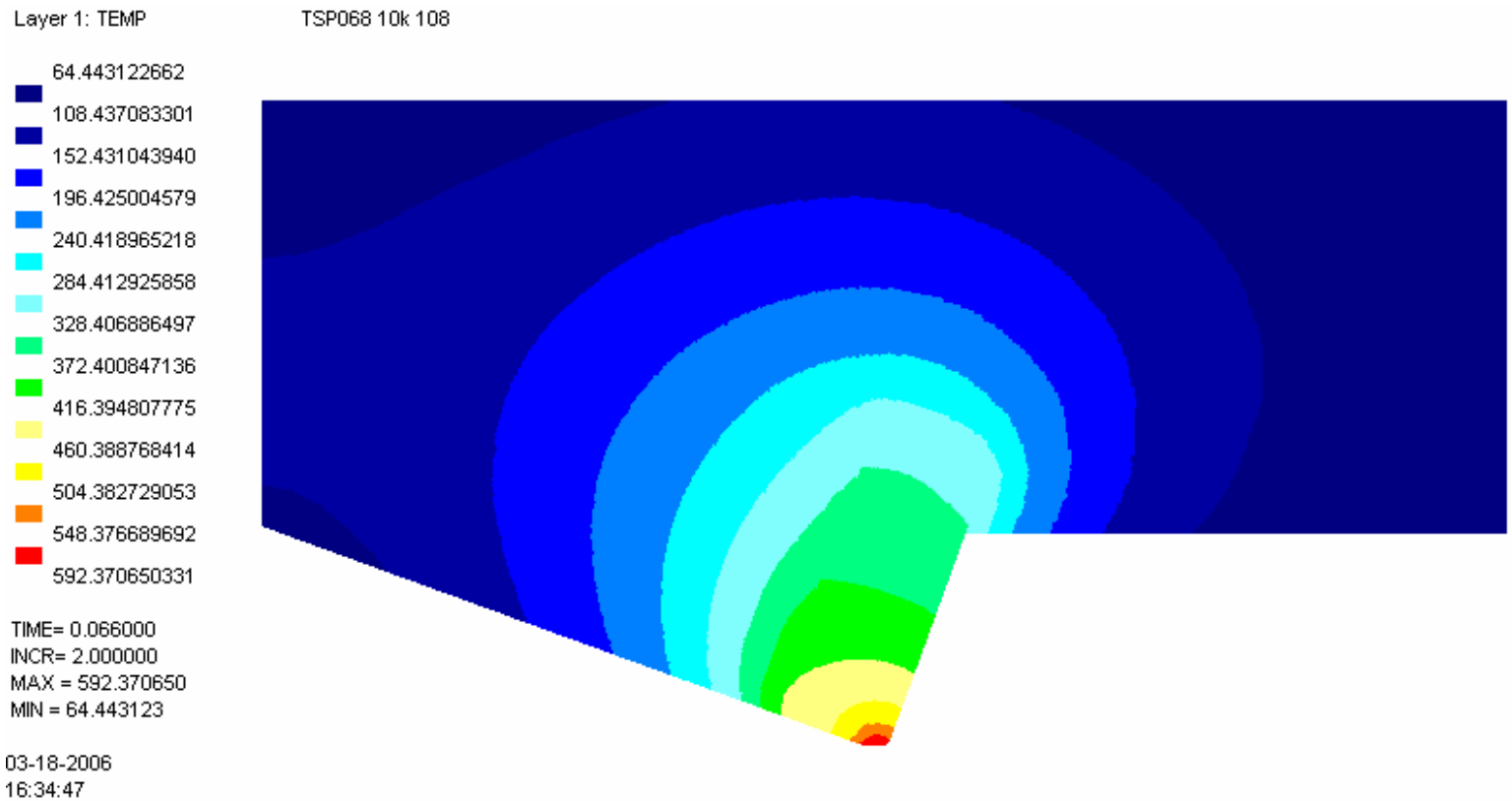
L_w = 4.37 mm

ESTIMATING WEARFLAT HEAT FLUX

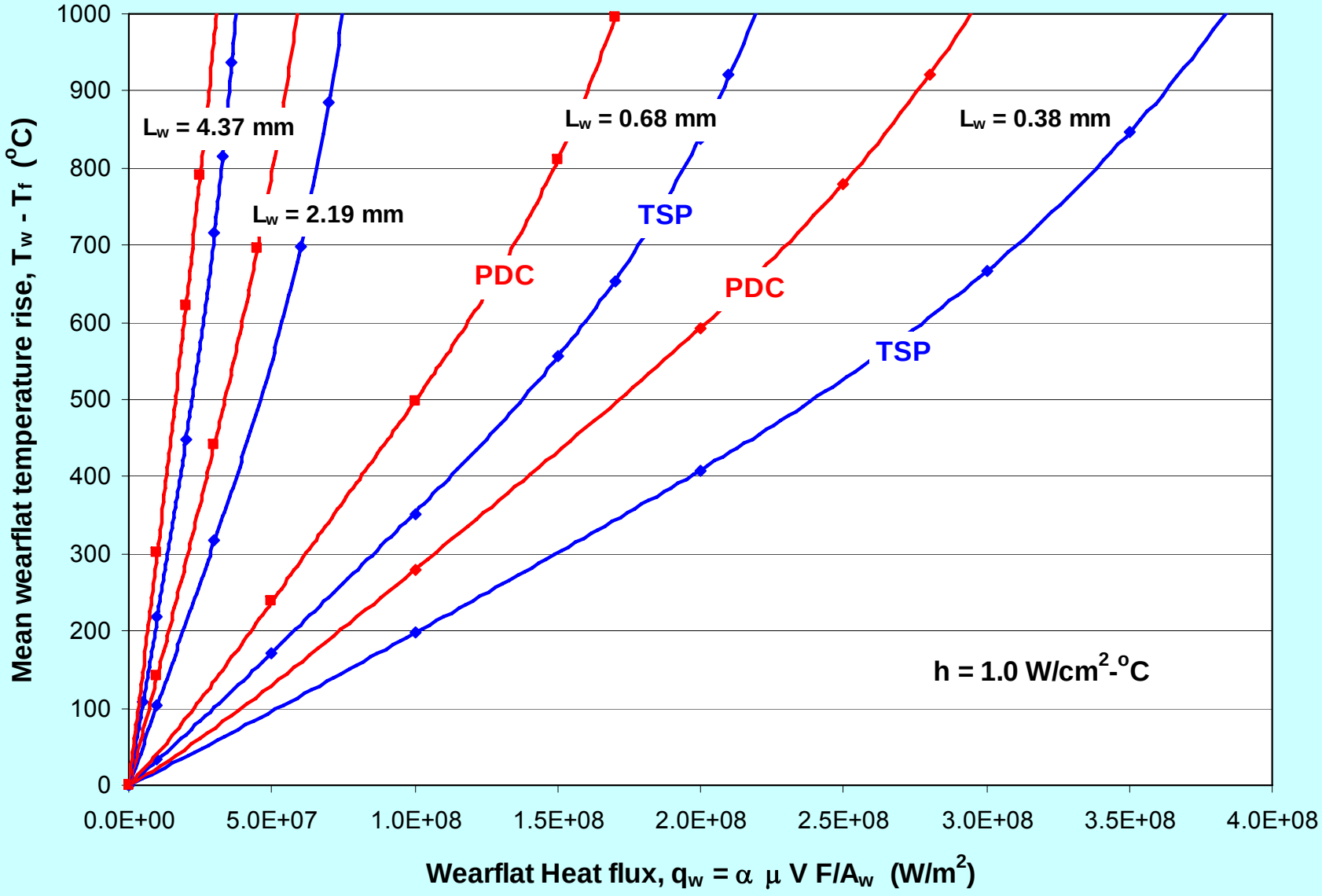
Total Frictional Heating at Wearflat, $Q = F_d V = \mu F V$			
Heat Flow into Cutter Wearflat, $Q_w = \alpha Q = \alpha \mu F V$			
Heat Flux into Cutter Wearflat, $q_w = Q_w/A_w = \alpha \mu V F/A_w$			
Possible Range in Wearflat Heat Flux			
Energy partitioning fraction, α	0.2	0.9	
Friction coefficient, μ	0.03	0.30	
Cutter velocity, V	0.5	12	m/sec
Cutter penetrating stress, F/A_w	35	700	MPa
Wearflat heat flux, q_w	**1.1E+05**	**2.3E+09**	**W/m^2**


WATER FLOW RATE, GPM
0
100
200
300
400
500
600
700
5.0
1.0
0.1
0.01
h,
W/cm²°C
UNIFORM CROSSFLOW
JET IMPINGEMENT
WATER COOLING
AIR COOLING
0
500
1000
1500
2000
2500
3000
3500
AIR FLOW RATE, SCFM

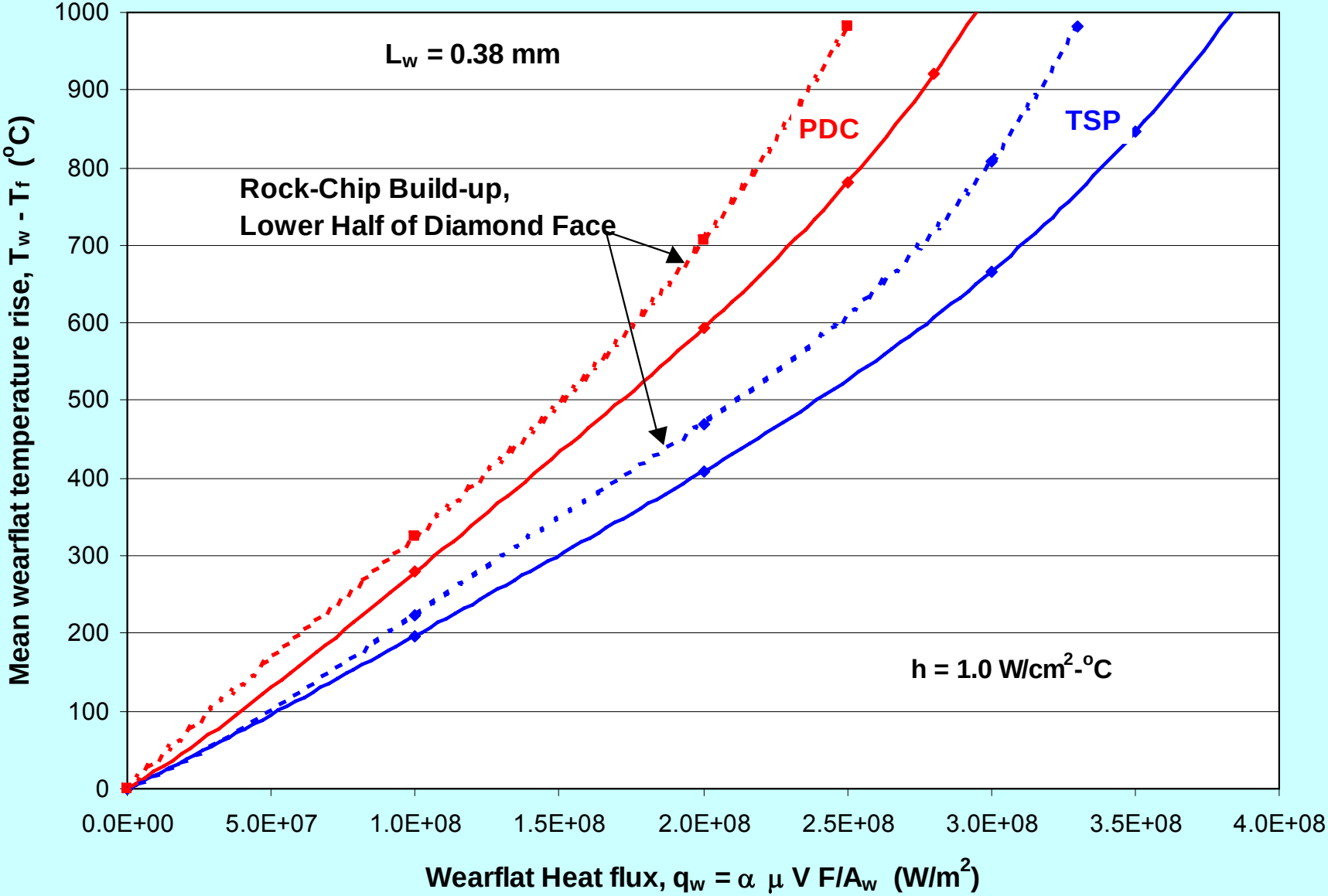
TYPICAL FE TEMPERATURE CALCULATIONS



CALCULATED TEMPERATURES for TSP and PDC CUTTERS



EFFECTS of ROCK-CHIP BUILDUP on DIAMOND FACE



TSP BIT PERFORMANCE MODELING

- **Based on PDCWEAR computer code developed in 1986 by Sandia National Laboratories**
- **Code was updated to include new thermal response equations for TSP cutters**
- **Glenn Corser of Applied Design and Technology developed user-friendly GUI and database management routines to facilitate use of the code**
- **New software is called *DragBit***

DragBit

Results Selection

BtRn	Depth	MW(	WFA
24	662.1	15	0.0230
25	763.75	17	0.0281
26	778.48	17	0.0290
27	794.35	17	0.0300
28	817.41	17	0.0314
29	827.18	17	0.0320

Get Results

Wearflat Area Thresholds (in**2)

Worn Thld	Thld Depth	Worn Out Thld	Thld Depth
.016	504.50	.0314	817.41

Export Results

Plot Control

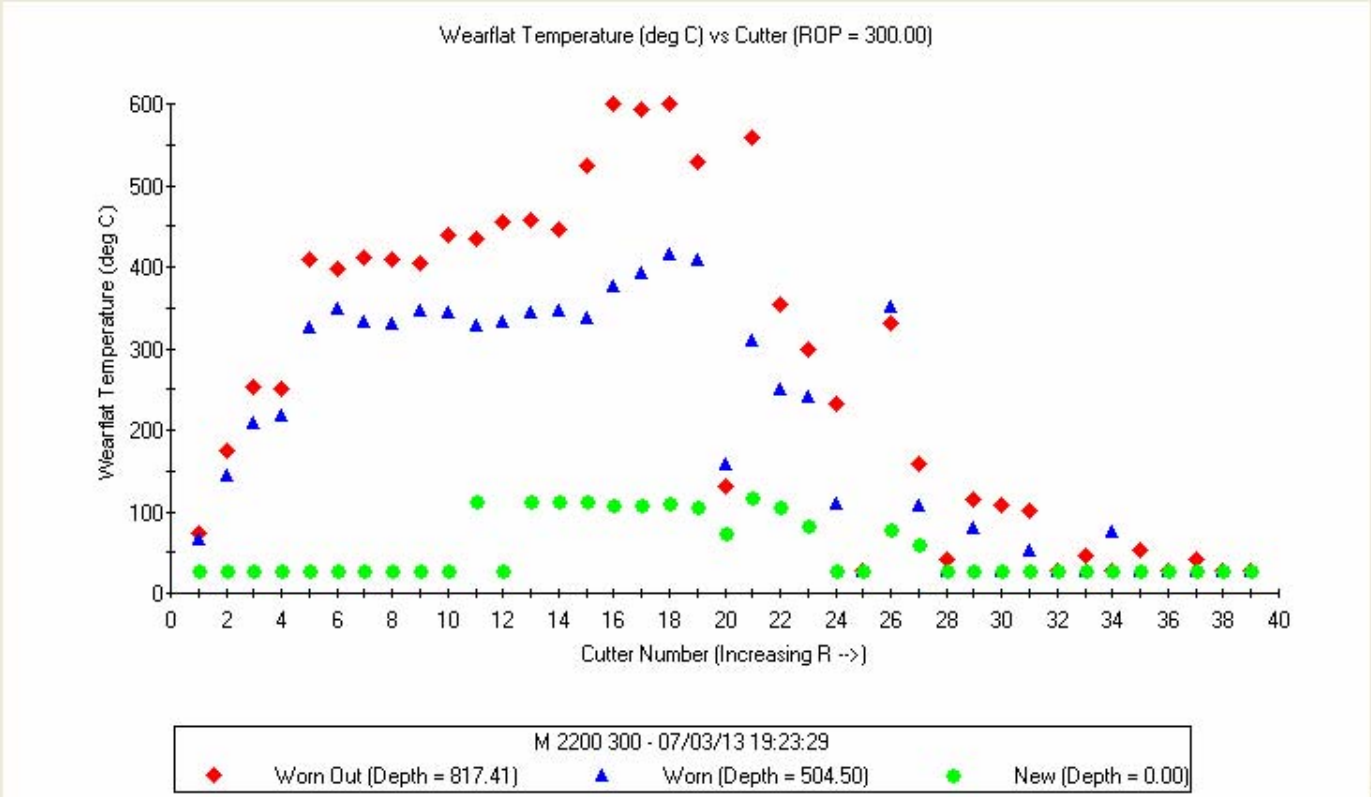
**Geometry/Rock vs Cutter by RO

Plot | Print | Print All

**Enter parameters for these selections in new dialog after you click Plot

Open | Open | Open | Open | Open

(deg C) vs Cutter (By ROP) | Effective Depth of Cut (in) vs Cutter (By ROP) | Max Wear Cutter vs Depth | Predicted Cutter Wear Distribution | Bit Run Summary



Bit Design | Wear Configuration | Operating Conditions | Processing and Review | **Analysis/Plotting** | Parameter Management

Get/Save Designs

Design Name: M 2200 300

Design Description: M 2200 300

Clear All/Start New Design | Open Database | Make New Database | Save Design To Database

Database: C:\Program Files\DragBitGUI\DragBitDB-07-03-11_09-27-03.mdb

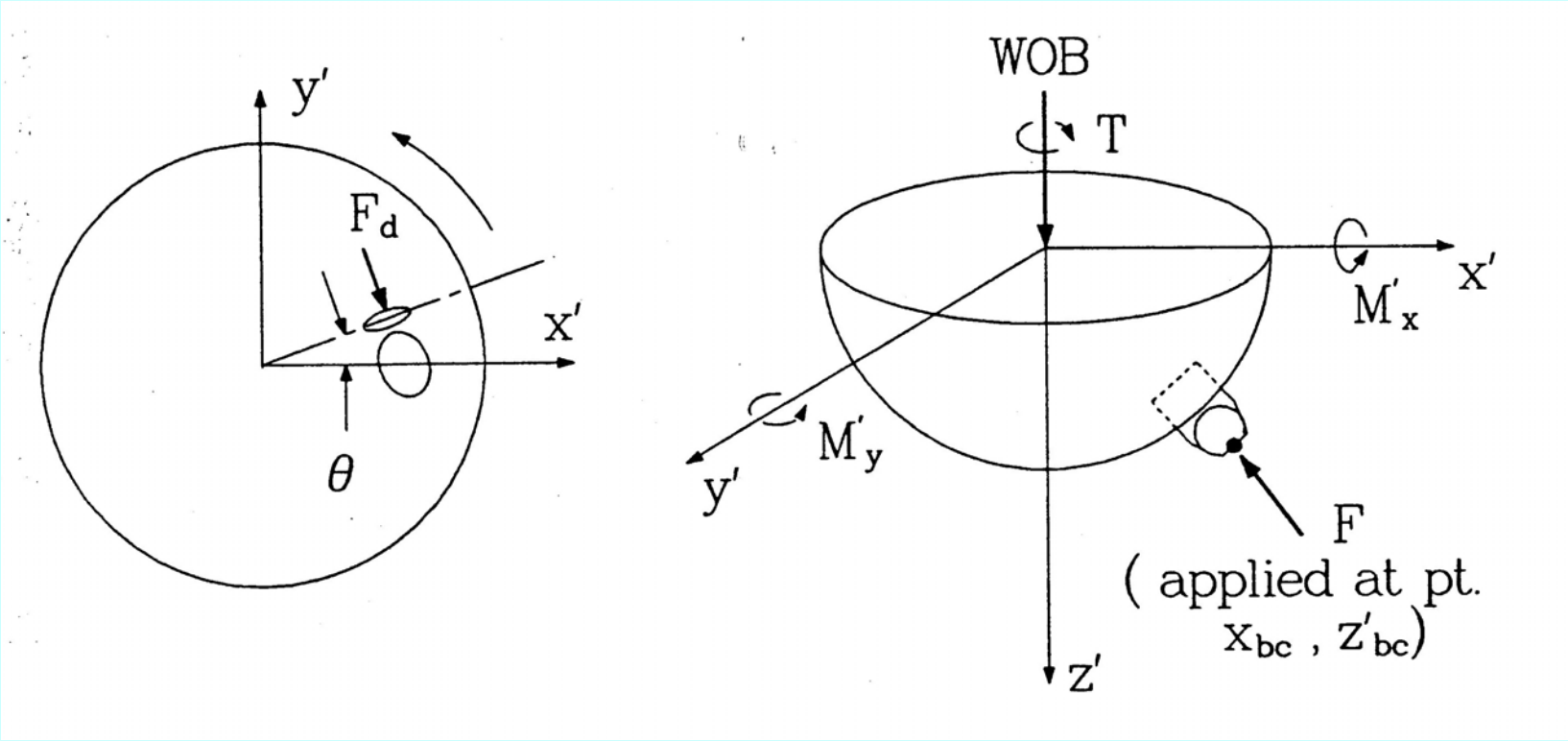
Browse

Design Name	Design Description	Save Date	Parameter Set
Use - Del to remove from DB\Dbl Click to retrieve			
M 2200 300	M 2200 300	2007/03/11 19:24:37	Default
M 2200 500	M 2200 500	2007/03/11 19:59:28	Default
M 300 30	M 300 30	2007/03/11 19:00:24	Default
M 3000 300	M 3000 300	2007/03/11 19:44:57	Default

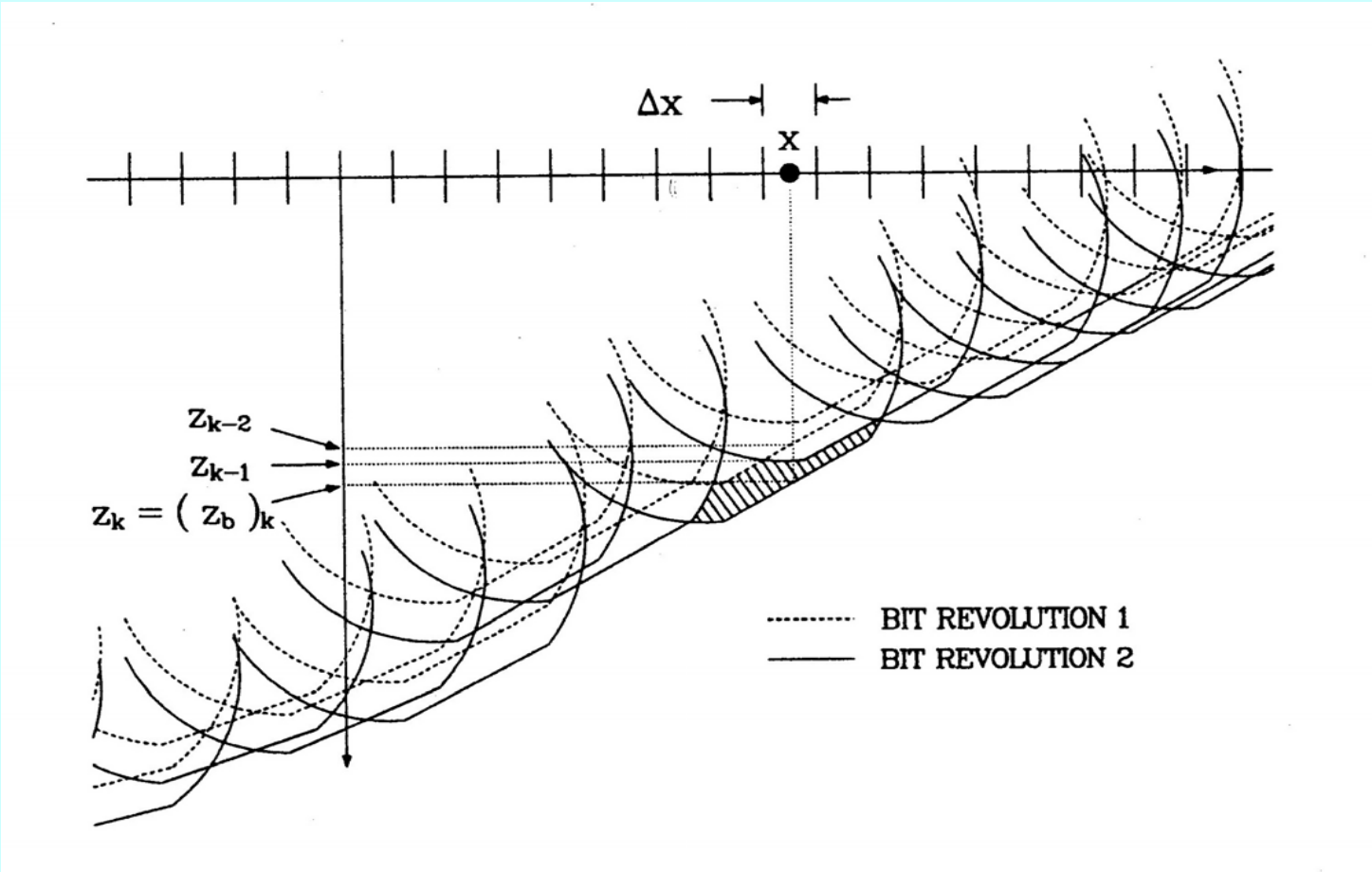
Show Status Window

start | DragBit | M 300 30 Bit Results.xls | Microsoft PowerPoint ... | DragBit | 7:24 PM

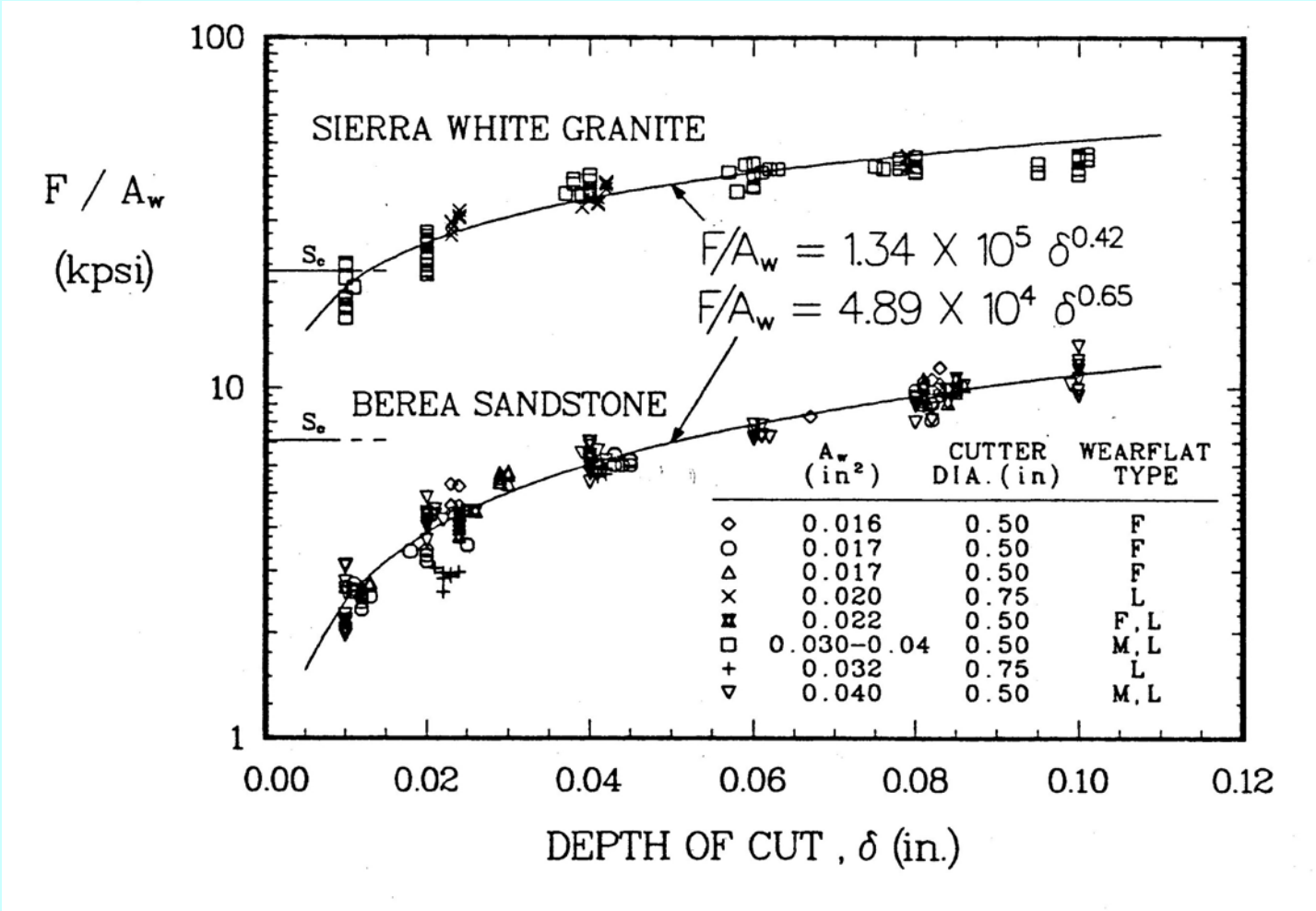
DRILLING FORCES and MOMENTS on a DRAG BIT



EFFECTIVE DEPTH of CUT



MEASURED SINGLE-CUTTER PENETRATING STRESSES

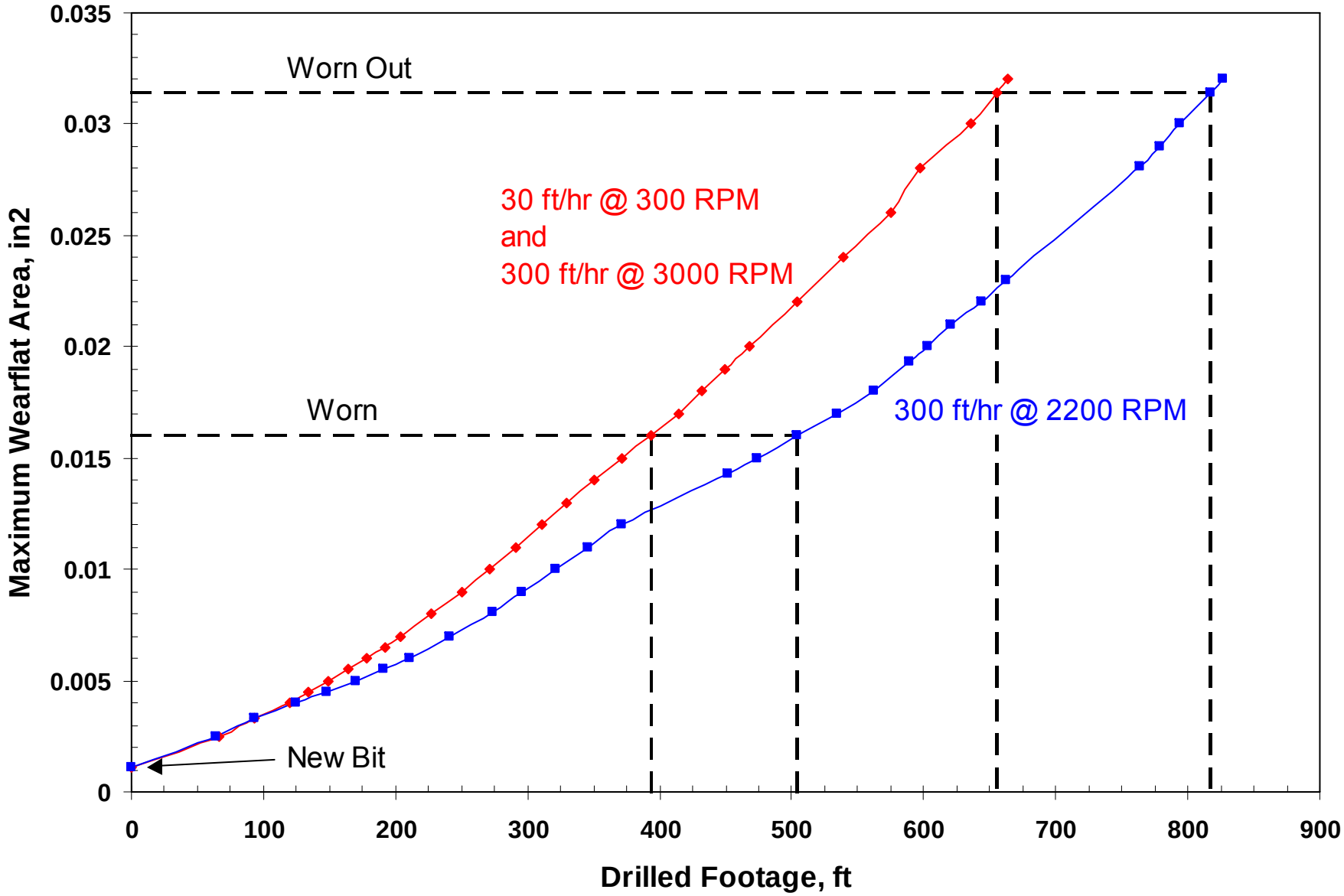


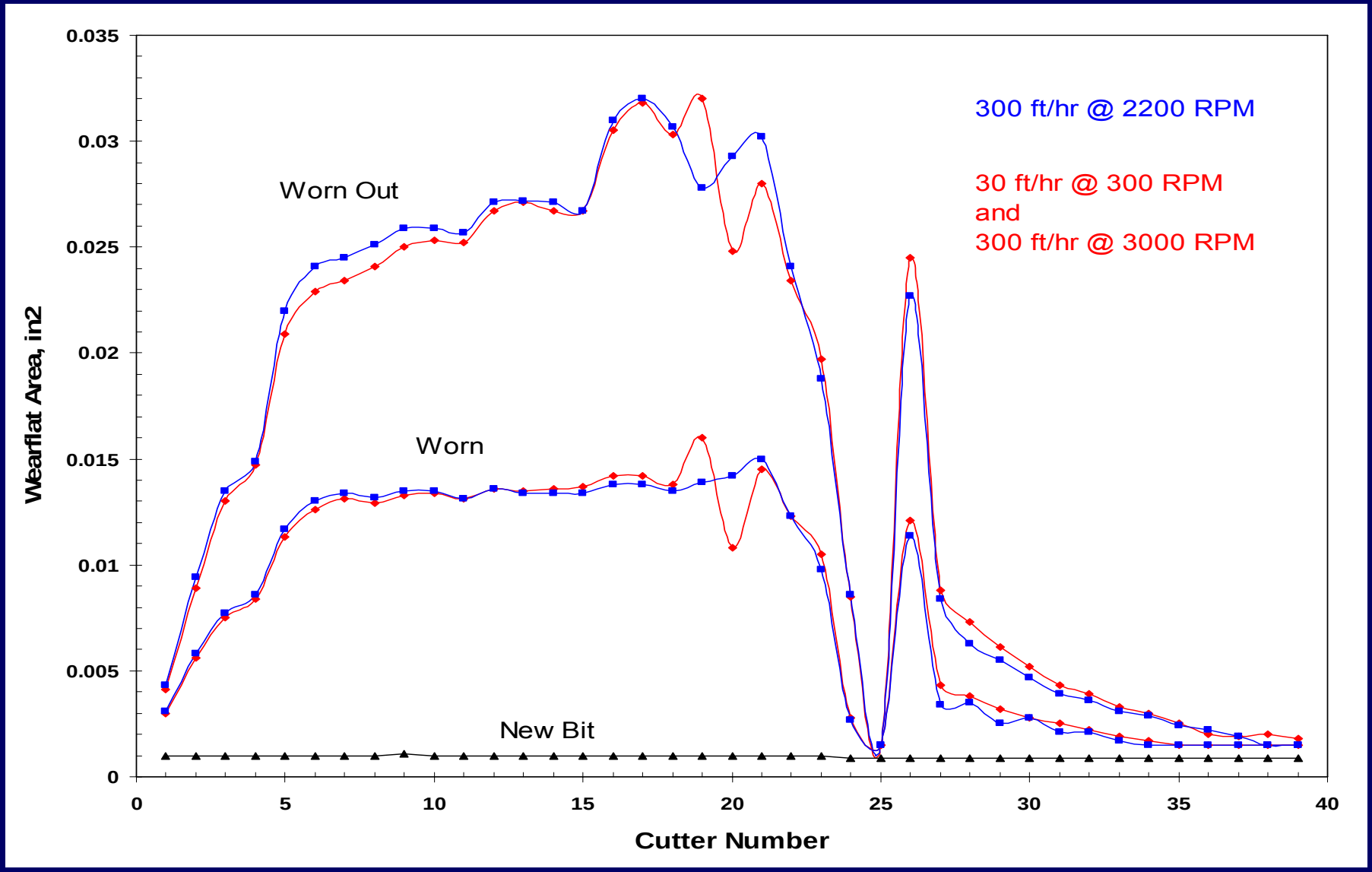
ANALYSIS OF THE 4-1/8” M09 BIT

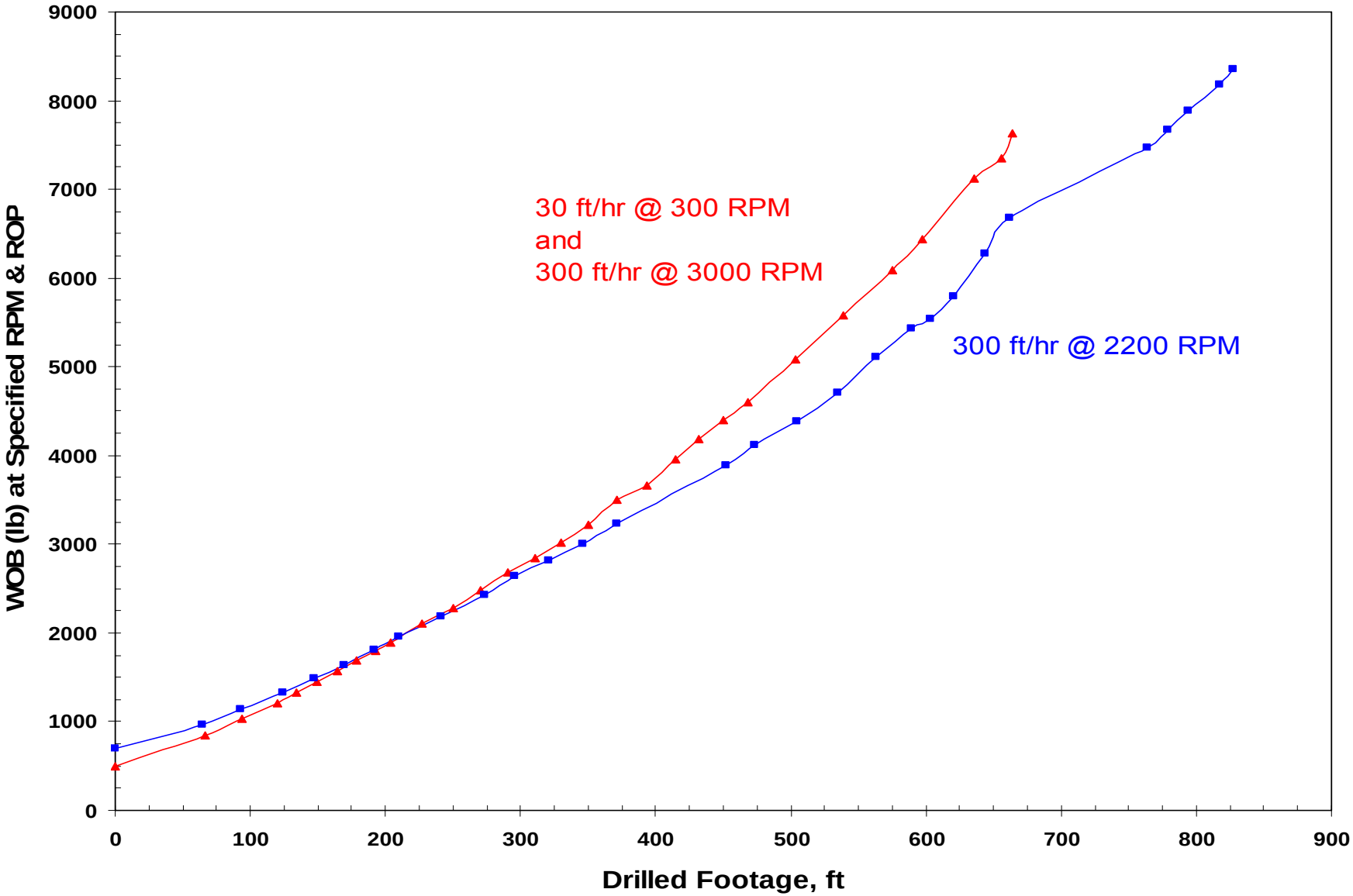
- GeoDiamond bit drawing dated 8/6/98
- 39 cutters arranged in 9 blades
- Multiply-redundant cutter layout, especially near gage
- 9-mm TSP cutters assumed in analysis

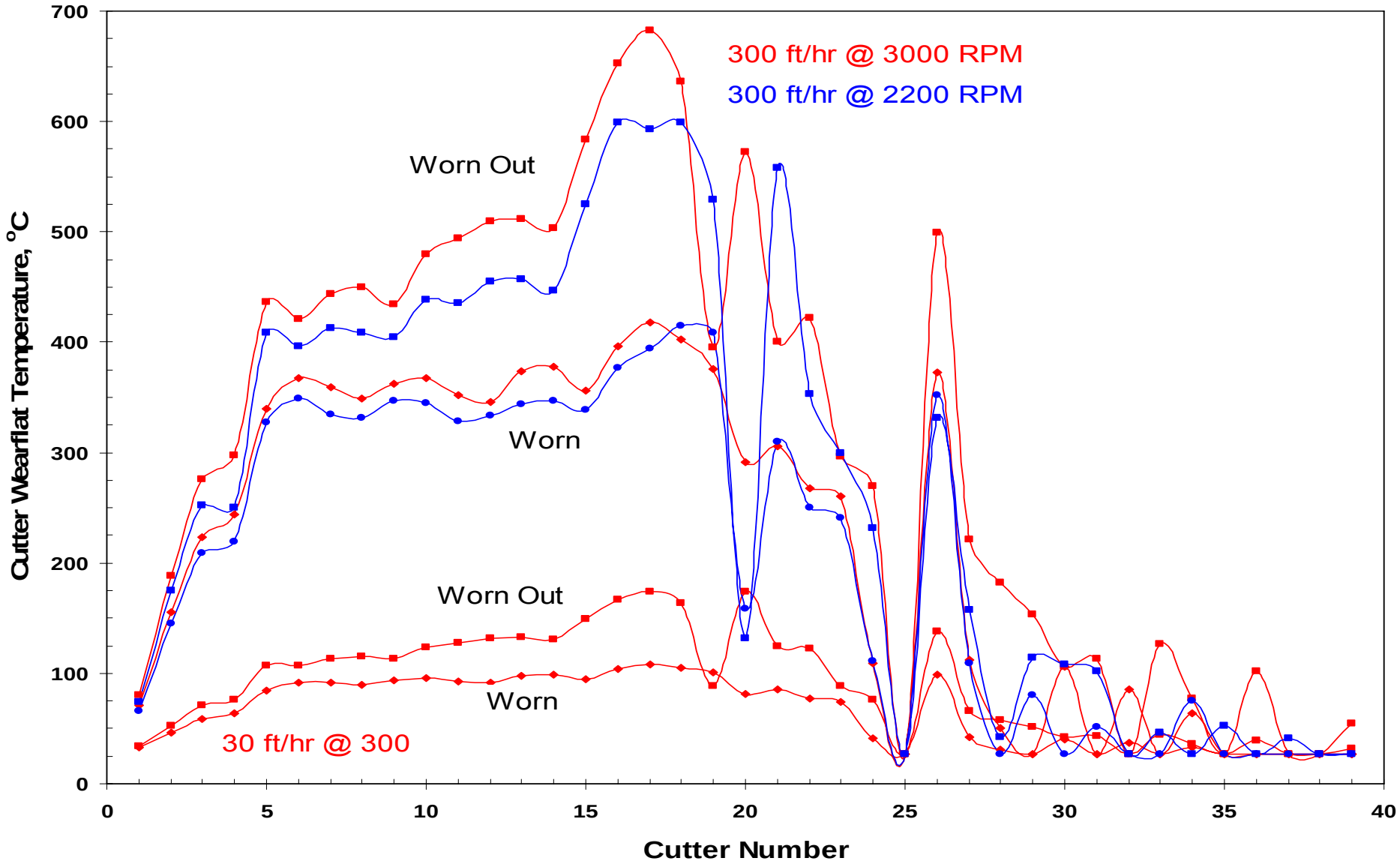
SIMULATED DRILLING CONDITIONS

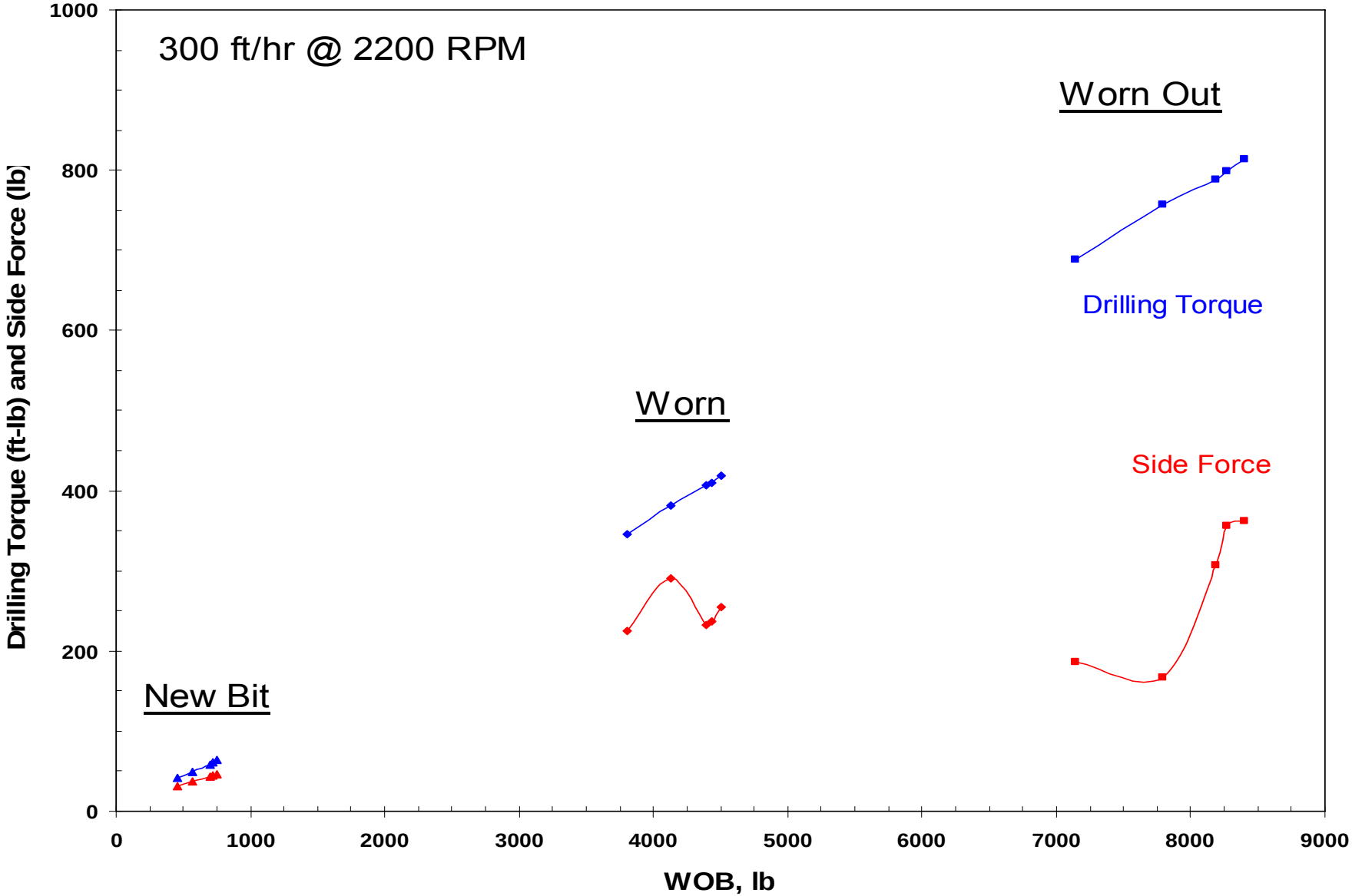
- Sierra White Granite
- 300, 2200, and 3000 RPM
- 30 and 300 ft/hr ROP
- Typical drilling mud cooling rates


Worn Out
Worn
New Bit
30 ft/hr @ 300 RPM
and
300 ft/hr @ 3000 RPM
300 ft/hr @ 2200 RPM
Maximum Wearflat Area, in2
Drilled Footage, ft
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
100
200
300
400
500
600
700
800
900


0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Wearflat Area, in2
0
5
10
15
20
25
30
35
40
Cutter Number
Worn Out
Worn
New Bit
300 ft/hr @ 2200 RPM
30 ft/hr @ 300 RPM
and
300 ft/hr @ 3000 RPM


9000
8000
7000
6000
5000
4000
3000
2000
1000
0
WOB (lb) at Specified RPM & ROP
0
100
200
300
400
500
600
700
800
900
Drilled Footage, ft
30 ft/hr @ 300 RPM
and
300 ft/hr @ 3000 RPM
300 ft/hr @ 2200 RPM


300 ft/hr @ 3000 RPM
300 ft/hr @ 2200 RPM
Worn Out
Worn
Worn Out
Worn
30 ft/hr @ 300
Cutter Wearflat Temperature, °C
Cutter Number
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
35
40


300 ft/hr @ 2200 RPM
Worn Out
Drilling Torque
Worn
Side Force
New Bit
Drilling Torque (ft-lb) and Side Force (lb)
WOB, lb
0
200
400
600
800
1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

SUMMARY OF THERMAL MODELING WORK

- TSP cutters run significantly cooler than PDC cutters due to:

  - Thicker diamond layer

  - Higher thermal conductivity

- Thermal response functions have been calculated for both cutter types for a variety of downhole conditions
- DRAGBIT™ code has been developed to predict bit performance for TSP and PDC cutters
- Preliminary analysis of 4-1/8” high-speed bit has been completed

ACCOMPLISHMENTS

Catoosa test provided benchmarks for Phase II prototype advanced turbodrill testing.

- **Turbo-PDC Drilling** **1hHp/in^2 ~ 10ft/hr**
- **Turbo-Impreg Drilling** **1hHp/in2 ~ 4ft/hr**

Phase II - Prototype Advanced Turbodrill

Redesign of turbine power stage blades with the objective of:

–Higher pressure drop per stage (pressure = turbo-power

–50% power stage length reduction (50% length reduction of turbine power section and a 30% reduction for the whole turbodrill)

–13% increase in mechanical output efficiency

CONCLUSIONS

- GTI Catoosa Field Test Provided Baseline Turbodrill ROP
- Turbodrill Redesigned for Higher Power in a Shorter Tool – Alpha and NASA Blades
- A More Durable High Speed Fixed Cutter Drill Bit Design with DRAGBIT™
- Phase II Field Test will compare ROP of Baseline and Two Higher Power TurboDrills