Hydraulic Optimization Worksheet
for MS Excel – All Versions subsequent to 5.0

1. Introduction.

2. Data Input.
   
   Header.
   Bit Information.
   Mud Information.
   Casing Program.
   P.D.M./Turbine.
   Drill String Design.
   System Losses.
   Bit Hydraulics.
   Annular Hydraulics.

3. Hydraulic Optimization.

4. Units of Measure and Formulas.

5. Sample Worksheet.

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INTRODUCTION:

The Hydraulic Optimization Worksheet (HOW) is a spreadsheet based program that can provide the user with bit and other drilling related hydraulic calculations at two separate depths, in most units of measure.

HOW allows the user to determine optimum bit nozzle selection or flow rates for the entire length of a bit run, simultaneously, without a lengthy process of re-entering data.

There are nine sections to HOW. The first six sections are for data input and are labeled as: Header, Bit Information, Mud Information, Casing Program, PDM/Turbine, and finally, Drill String Design.

The final three sections, labeled as System Losses, Bit Hydraulics, and Annular Flow Characteristics detail hydraulic results for the beginning and end points of the bit run.

The non-data input area of the worksheet is sealed to prevent changes to any formulas and the diskette has been virus-scanned and permanently write protected.

The basic information needed to use HOW:

- Units of Measure to be used in calculations.
- Bit type and size and estimated nozzle sizes.
- Variations in mud rheology and flow rates from Depth In to Depth Out.
- Casing design from surface to current casing point.
- Drill string design, from the kelly to the bit.
- PDM or Turbine use and it’s specifications.
- MWD tool use and it’s specifications.

The sample at the end of this manual is based on the following:

- The operator wants to drill from below the shoe to 7,750’ in one run.

- Mud rheology (mud weight, plastic viscosity, and yield point) is fixed. Flow rates of 800 to 900 gpm are required. Standpipe pressure cannot exceed 3,000 psi.

- A steerable assembly is to be used, with a pressure drop of 350 psi across the PDM and 150 psi across the MWD tool. As the PDM uses a mud lubricated bearing assembly, so mud by-pass rate will increase during the run.

The objective is to determine optimum nozzle size and flow rates for the entire run.
HEADER

In this section, data is entered into four cells only. These cells provide a log of who and what the calculations were made for. They are not linked to any other cells and calculations will not be affected if no data is entered.

BIT INFORMATION

This section details the bit information and jet sizes to be used. Data is entered into eight cells only, up to a maximum of 4 nozzles. The cells containing the bit diameter and jet sizes are linked to other cells, thus calculations will be affected if no data is entered.

Jet sizes are entered in 32’s of an inch. Blank nozzles are entered as 0, 9/32’s as 9, 18/32’s as 18, and so on.

For the purpose of these instructions, three 18’s have been entered. If you are not sure what jet sizes are going to be used, enter a best guess. Entries can be changed in a matter of seconds once the remaining sections have been completed.

MUD INFORMATION

This section details mud rheology and flow rates for the two depths hydraulics are calculated for.

The purpose of using two data sets is to allow a balance in hydraulic optimization over the length of the run. For example, in most wells as depth increases, flow rate will decrease as mud weight increases. HOW allows the user to input the change in rheology and flow rates between the beginning and end of a bit run.

Units of Measure are entered into cells M8, P8, R8, and T8. Mud information is entered into cells M9, M11, P9, P11, R9, R11, T8, and T11. All of these cells are linked to other cells, thus calculations will be affected if no data is entered. Plastic Viscosity and Yield Point must be above “0”.

In the sample, rheology remains static while flow rate increases.

CASING PROGRAM

This section details the casing program from surface to just above where the bit is to first start drilling.

The purpose of two rows of casing data is to allow for Open Hole vs Cased Hole diameters and the effects of using a liner hanger. An open hole is slightly larger than
the ID of the casing just above it. And the annular flow characteristics on a well with a 7” liner hung from 9 5/8” casing will change drastically.

Again, UM are entered in cells B16 and D16 and casing data is entered into cells B17, B18, D17, D18, F17, and F18. All of these cells are linked to other cells, thus calculations will be affected if no data is entered. If a single casing size is used from the lower-most casing point back to surface, enter the data on both rows.

**PDM/TURBINE**

This section details the use, if any, of a downhole PDM or Turbine. UM are entered into cells B23, D23, and F23. PDM specifications and anticipated wear rate is entered into cells B24, D24, F24, D27, and F27.

All of these cells are linked to other cells, conditional on the indicated use or non-use of the PDM or Turbine. If the “Y” option is chosen, any dependent calculations will be affected if data is not entered into remaining cells.

The purpose of this section is to allow accurate calculation of the effects of using a PDM or Turbine with mud lubricated bearings (the design of the vast majority of all downhole motors and turbines).

*By-pass is defined as the amount of drilling fluid vented into the annulus from below the PDM without going through the bit. It is determined by comparing the cross sectional area of the drive shaft ID to the cross sectional area of the clearance between the rotating and stationary radial bearings*

If you are not sure what these are, enter your best guess. Again, this information can be changed once the remaining data sections are completed.

**DRILL STRING DESIGN**

This section details the individual components of the drill string. UM and data can be entered into cells I20 to I28, K17 to K28, M17 to M28, P17 to P28, R18, and T17.

Drill string descriptions must be entered in the format shown (the first three letters of each entry must match one of the four available options).

In the event that all eleven data rows are not needed, as in the above example, use the SPACEBAR once to remove a previous entry, starting from the bottom row up.

In the event that more than eleven data rows are required, consolidate components, such as cross-over subs, by combining them with the item either above it or below it. This is also applicable for components with minor diametrical changes.
If the user indicates that a PDM is to be used, its entire length must be either completely outside or completely inside the casing. In the above example, casing is set from 0 to 1,990 feet. At Depth In, the Drill String is 2,083.5 feet in length, which put the PDM’s entire length of 27.5 feet outside the casing.

If the entire PDM is not completely inside or outside the casing, the spreadsheet does not pick up the correct OD when calculating Annular Flow Characteristics. This condition does not apply to any other Drill String component.

A ‘section’ is defined as a change in the type of component (DP to HWDP to COL), a change in OD of components, or a change from Open Hole to Cased Hole. Thus, in the above sample, there are four sections. At Depth In, there are two sections for the BHA (part in Open Hole and part in Cased Hole), one for the HWDP, and a final section for the drill pipe.

If you are not sure what these are, enter your best guess. Again, this information can be changed once additional information becomes available.

**SYSTEM LOSSES**

This section details pressure losses, component by component, based on the information into the previous sections. There is no data to be entered this section.

The user should verify that Calculated Standpipe Pressure (CSP) for Depth In and Depth Out does not exceed the maximum rating for the rig.

**BIT HYDRAULICS**

This section specifies UM to be used in this, the previous, and the following sections, and details the calculations for Bit Hydraulics at Depth In and Depth Out.

Cells T40 and T47 are highlighted red. These cells are critical in the optimization process. We strongly recommend a minimum jet nozzle velocity of 300 ft/sec or a minimum bit hydraulic energy of 3.0 hhp per square inch of hole bottom (3.0 hsi).

Although not directly related to bit hydraulics, data can be entered in cells K42, R42, K49, and R49. The data entered into these cells allow cutting velocity and slip rate to be calculated.

**ANNULAR FLOW CHARACTERISTICS**

This section details Annular Hydraulics, section by section, from TD back to Surface, for Depth In and Depth Out. There is no data to be entered this section.
Laminar flow is preferable to Turbulent flow. However, one of the primary factors determining flow characteristics is mud rheology, which is almost always a function of drilling requirements and usually not subject to change in the optimization process.

**HYDRAULIC OPTIMIZATION**

Bit hydraulics are usually optimized either for optimum jet impact force or optimum hydraulic horsepower, both of which were based on percentage of pressure loss that occurs through the bit. In older issues of the I.A.D.C. Drilling Manual, it stated that optimum jet impact force was achieved when 48% (+ 0%) of total system losses occurred at the bit. Optimum hydraulic horsepower was achieved when 65% (+ 0%) of total system losses occurred at the bit.

Drilling results worldwide clearly demonstrate significantly increased drilling rates when jet nozzle velocities of 330 feet per second or minimum hydraulic energy level of 3.0 hsi are achieved.

Assuming that the data has been entered as per the previous sections, the first course of action is to verify that no typographical errors have been made. This can be done by checking the screen or by printing a hard copy. We recommend printing a hard copy.

- Check each data entry section on the hard copy for errors. Pay particular attention to the Mud Information section and the reported Depths In & Out at the bottom of the Drill String Design section.

Data entry errors of any type will be most apparent in one or more of the last three sections. If under Flow Rate for example, you entered 8,000 instead of 800, it will be very apparent in either the System Losses, Bit Hydraulics, or Annular Flow Characteristics sections.

Also, if you have used an unacceptable Unit of Measure, a multiplication factor of “0” will result in a “0” answer in one or more of the final three sections.

Once you have checked and corrected any typographical errors that may have been made, you are ready to proceed with optimization.

The following steps can all be followed on the computer’s monitor. We do not recommend continually printing new copies unless you want a record of the various changes.

Mud rheology is usually set by drilling requirements. Most of the time you will only be able to vary nozzle sizes. However, many operators will allow a slight variation in Flow Rate in order to improve bit hydraulics.
Check the System Losses. If total CSP is within the rig’s maximum rating, then mud energy levels can be increased by increasing Flow or decreasing TFA.

If total CSP exceeds the rig’s maximum rating, you will have to use larger nozzles or a lower flow rate.

Check the Bit Hydraulics. If the results for both Depths are acceptable, try some changes anyway to see if results can be improved on.

Verify that the pressure loss at the bit does not exceed the rating for the PDM or Turbine being used. Typically, motor suppliers do not exceed 500 to 750 psi.

Verify that bit hydraulics at Depth Out have not been sacrificed to the benefit of bit hydraulics at Depth In.

Enter any new nozzle sizes (or Flow Rate) and re-check the CSP and Bit Hydraulics until you are satisfied with the results.

Print your final hard copy.

FORMULAS AND UNITS OF MEASURE

Following are the primary formulas, acceptable units of measure, and conversion factors used in calculating the system losses, bit hydraulics, and annular flow characteristics.

The formulas were originally developed using imperial units, thus if the units of measure are entered in the original imperial units, the spreadsheet uses a default conversion factor of 1 in the conversion process. Otherwise, conversion is extended to six decimal places where applicable.

The formulas are available from a variety of publications. However, two of the best sources are the IADC Drilling Manual and a publication titled Formulas for Drilling, Production and Workover by Norton J. Lapeyrouse.

Not shown are the ‘secondary’ formulas that match the correct parameter(s) to the correct calculation, or formulas that sum a column.

**Total Flow Area**

\[ \text{Total Flow Area} = (\pi \cdot ((\text{ND}/32)/2)^2) + (\pi \cdot ((\text{ND}/32)/2)^2) + (\pi \cdot ((\text{ND}/32)/2)^2) + (\pi \cdot ((\text{ND}/32)/2)^2) \]

**Jet Nozzle Pressure Loss - Depth In (with no by-pass)**

\[ \text{Jet Nozzle Pressure Loss} = (\text{MW} \cdot \text{FR}^2)/(10858 \cdot \text{TFA}^2) \]
Jet Velocity - Depth In (with no by-pass)
\[=\frac{(0.32\times FR)}{TFA}\]

Jet Impact Force - Depth In (with no by-pass)
\[=(0.000516\times MW\times FR\times JV)\]

Jet Impact Force per Square Inch of Hole Bottom - Depth In (with no by-pass)
\[=\left(\frac{MF}{(\pi)((BD/2)^2)}\right)\]

Bit Hydraulic Energy - Depth In (with no by-pass)
\[=\left(\frac{(BP\times FR)}{1714}\right)\]

Bit Hydraulic Energy per Square Inch of Hole Bottom - Depth In (with no by-pass)
\[=\left(\frac{HP}{(\pi)((BD/2)^2)}\right)\]

Equivalent Circulating Density - Depth In (with no by-pass)
\[=\left(\frac{((0.052\times MW\times DT)+AP)}{(0.052\times DT)}\right)\]

Drill Stem Pressure Loss - Depth In (first component)
\[=\left(\frac{ (((0.000061\times MW\times DP\times FR^{1.86})/(EID^{4.86})) + ((0.0000765\times PV^{0.18}\times MW^{0.82}\times FR^{1.82}\times DP)/(EID^{4.82}))}{2} \right)\]

Annular Pressure Loss, Laminar Flow - Depth In (first component)
\[=\left(\frac{(DP\times YP)}{(225\times (CF-OD)^2)} + \frac{(AV/60)\times DP\times PV}{(1500\times (CF-OD)^2)}\right)\]

Annular Pressure Loss, Turbulent Flow - Depth In (first component)
\[=\left(\frac{ (((0.00000014327\times MW\times DP\times AV^2)/(CF-OD)) + ((0.0000765\times PV^{0.18}\times MW^{0.82}\times FR^{1.82}\times DP)/(CF-OD)^{3}\times (CF+OD)^{1.82}))}{2} \right)\]

Annular Velocity Depth In (first component)
\[=\left(\frac{(24.5\times FR)}{(CF^2-OD^2)}\right)\]

Critical Annular Velocity - Depth In (first component)
$$=(((1.08*PV)+(1.08*\sqrt{PV^2+(9.26*(CF-OD)^2)*YP*MW}))/\left(MW*(CF-OD)\right))\times 60$$

Cutting/Chip Slip Rate - Depth In

$$=\left((0.45*(\frac{PV}{MW*\text{R42}}))\times\left(\sqrt{\frac{36800}{(\frac{PV}{MW*\text{R42}})^2}}\times \text{R42} \times (\frac{K42}{MW}-1)+1\right)\right)-1$$

Where:

- **AP** = Annular Pressure Loss
- **AV** = Annular Velocity over Component
- **BD** = Bit Diameter
- **BP** = Bit Pressure Loss
- **CF** = ID of Casing
- **DP** = Drill Pipe Length
- **DT** = Depth
- **EID** = Equivalent ID of Drill Pipe
- **FR** = Flow Rate
- **HP** = Hydraulic Horsepower
- **JV** = Jet Nozzle Velocity
- **MF** = Mud Impact Force
- **MW** = Mud Weight
- **ND** = Jet Nozzle Size
- **OD** = OD of Component
- **PV** = Plastic Viscosity
- **TFA** = Total Flow Area
- **YP** = Yield Point of Mud

Units of Measure (UM) must be entered in lower case as per boldface type in the following table. If the unit of measure is not entered as required, the applicable calculation will be factored by 0 and a 0 will result.

UM are listed in the approximate order in which they are used in the worksheet.

**Mud Density**

- pounds mass per gallon = **lbm/gal** or **ppg**
- pounds mass per cubic foot = **lbm/ft3** or **pcf**
- kilograms mass per cubic meter = **kg/m3**
- kilograms mass per liter = **kg/l**
- specific gravity = **sg**
- kiloPascals per meter = **kpa/m**

**Plastic Viscosity**
centiPoise = cp @ 1.0
Pascal•sec = pa = 0.001

Yield Point

pounds force per 100 square feet = lbf/100ft² @ 1.0
Pascal = pa = 0.478803

Flow Rate

gallons per minute = gpm @ 1.0
cubic feet per minute = ft³/min = 0.133681
barrels per minute = bpm = 0.0238095
cubic meters per minute = m³/min = 0.0037854
liters per minute = lpm = 3.785412

Casing OD and ID

inch = in @ 1.0
millimeter = mm = 25.4
centimeter = cm = 2.54

Casing Length

feet = ft = 1.0
meter = m = 0.3048

PDM or Turbine OD

inch = in @ 1.0
millimeter = mm = 25.4
centimeter = cm = 2.54

PDM or Turbine Length

feet = ft = 1.0
meter = m = 0.3048

PDM or Turbine Pressure Drop

pounds force per square inch = psi @ 1.0
kiloPascal = kpa = 6.894757
kilograms force per square centimeter = kgf/cm² = 0.070307

Drill String OD and ID
<table>
<thead>
<tr>
<th>Conversion</th>
<th>Symbol</th>
<th>Factor</th>
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<tbody>
<tr>
<td>inch =</td>
<td>in</td>
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</tr>
<tr>
<td>millimeter =</td>
<td>mm</td>
<td>25.4</td>
</tr>
<tr>
<td>centimeter =</td>
<td>cm</td>
<td>2.54</td>
</tr>
</tbody>
</table>

**Drill String Length**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>feet =</td>
<td>ft</td>
<td>1.0</td>
</tr>
<tr>
<td>meter =</td>
<td>m</td>
<td>0.3048</td>
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</table>

**Drill String Weight**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pounds mass =</td>
<td>lbm</td>
<td>1.0</td>
</tr>
<tr>
<td>kilograms =</td>
<td>kg</td>
<td>0.453592</td>
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</tbody>
</table>

**Bit Pressure Drop**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pounds force per square inch =</td>
<td>psi</td>
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</tr>
<tr>
<td>kiloPascal =</td>
<td>kpa</td>
<td>6.894757</td>
</tr>
<tr>
<td>kilograms force per square centimeter =</td>
<td>kgf/cm²</td>
<td>0.070307</td>
</tr>
<tr>
<td>bar =</td>
<td>bar</td>
<td>0.068948</td>
</tr>
</tbody>
</table>

**Jet Nozzle Velocity**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>feet per second =</td>
<td>fps or f/s</td>
<td>1.0</td>
</tr>
<tr>
<td>meters per second =</td>
<td>mps or m/s</td>
<td>0.3048</td>
</tr>
</tbody>
</table>

**Mud Impact Force**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pounds force =</td>
<td>lbf</td>
<td>1.0</td>
</tr>
<tr>
<td>newton =</td>
<td>newt or n</td>
<td>4.448222</td>
</tr>
<tr>
<td>kilogram force =</td>
<td>kgf</td>
<td>0.453592</td>
</tr>
</tbody>
</table>

**Hydraulic Energy**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydraulic horsepower =</td>
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<td>1.0</td>
</tr>
<tr>
<td>kilowatt =</td>
<td>kw</td>
<td>0.746043</td>
</tr>
</tbody>
</table>

**Cutting Density**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pounds mass per gallon =</td>
<td>lbm/gal or ppg</td>
<td>1.0</td>
</tr>
<tr>
<td>pounds mass per cubic foot =</td>
<td>lbm/ft³ or pcf</td>
<td>7.480519</td>
</tr>
<tr>
<td>kilograms mass per cubic meter =</td>
<td>kg/m³</td>
<td>119.8264</td>
</tr>
<tr>
<td>kilograms mass per liter =</td>
<td>kg/l</td>
<td>0.1198264</td>
</tr>
</tbody>
</table>
specific gravity = \( sg \) = 0.1198264
kiloPascals per meter = \( kpa/m \) = 1.175096

Cutting Diameter

inch = \( in \) @ 1.0
millimeters = \( mm \) = 25.4