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The Worst Case Discharge Scenario

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Honors Thesis

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On April 20, 2010, a series of both engineering and management mistakes led to one of the darkest days in the history of the oil and gas industry. The Deepwater Horizon drilling rig, operated by Transocean and contracted by BP, caught fire after a blowout—eventually sinking completely April 22, 2010. Consequently, eleven crew members lost their lives during the explosion, along with additional workers in the wake of the cleanup. The well, which blewout during cementing operations, was believed to be leaking nearly 62,000 barrels of oil per day into the Gulf of Mexico as of final estimates based upon pressure analysis. As the reservoir pressure was depleted, this figure dipped to a final rate of 53,000 barrels per dayon July 15, 2010, the day the well was finally shut in. The total estimatedamount of oil spilled into the Gulf of Mexico was 4.9 million barrels of oil, per the "Flow Rate Technical Group," formed in response to the blowout. Some 800,000 barrels were recovered via the "tophat" placed upon the leaking well early in the summer before making it into the water, limitingthe total amount spilled into the Gulf to 4.1 million barrels of oil.

In order to give some contrast to the spill volume itself, consider the Exxon Valdez spill in March of 1989, another disaster caused by negligence and previously the largest in United States history.While sailing from Alaska to Long Beach, California, the oil tanker ran aground on Bligh Reef in Prince William Sound—while the captain was asleep. The estimated amount of oil spilled per the National Oceanic and Atmospheric Association, was 0.26million barrels of oil, less than 6% of the amount spilled during the BP Macondo well blowout. The Macondo disaster has and will forever change the arena of deepwater drilling (that occurring in greater than five hundred feet of water). Figures 1 and 2 below highlight the drastic difference in areal impact between the Exxon Valdez spill and the BP Macondo spill.The Exxon Valdez is believed to have affected at least 1,300 square miles of coastline, and 11,000 sqaure miles of open water, per Alaskan State estimates. The impact was far inferior to that of Macondo, even though it was in a different environment. No official coastal impact estimates have been made for the BP Macondo Blowout.Estimates of areal impact are around 70,000 square miles, or 33 million Tiger Stadiums.

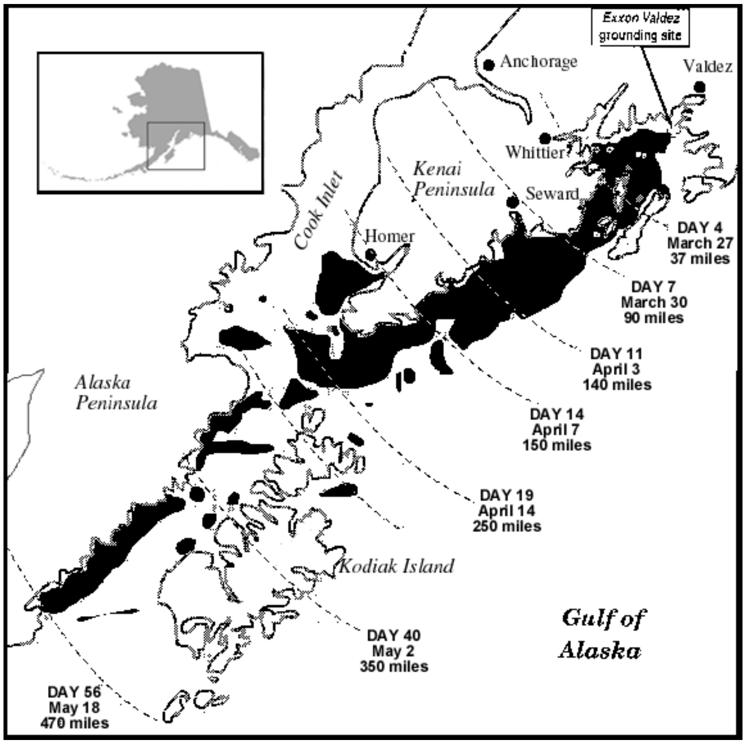


Figure 1.Areal Impact map of Exxon Valdez Oil Spill: ≈1,300 miles of coastline and ≈11,000 square miles of open water. http://www.evostc.state.ak.us/facts/spillmap.cfm

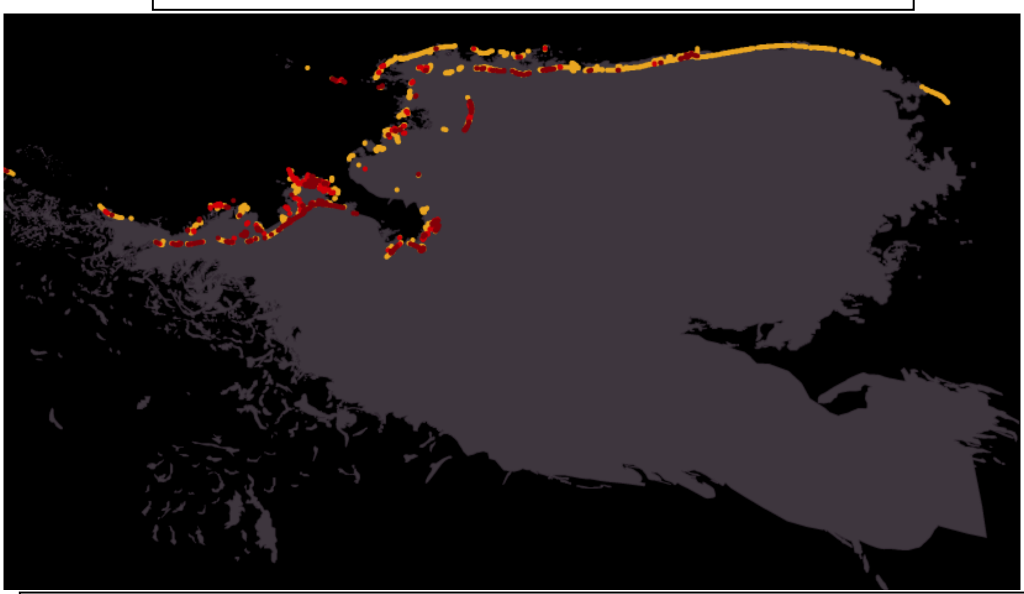


Figure 2.Areal and Coastal Impact of the BP Macondo Blowout: an estimate of the area covered in gray, an overlay of all of NOAA's oil trajectory maps, gives ≈70,000 square miles of open water affected. Red and yellow indicate oil landfall areas (Morgan City, LA to Panama City, FL), ≥ 1000 miles. http://www.nytimes.com/interactive/2010/05/27/us/20100527-oil-landfall.html

Immediately following the Macondo blowout, a six month moratorium was issued by Secretary of the Interior Ken Salazar, effectively, but temporarily banning deepwater drilling operations. In addition to this ban, it is has been made clear that new permits for deepwater drilling will be more difficult to obtain, and greater emphasis has been placed on the WCD, or Worst Case Discharge scenario. Note that the WCD for the BP Macondo well was 162,000 barrels per day, a great deal larger than the actual discharge rate estimated for the well, although the leakage rate was somewhat choked back by the collapsed riser.While the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE), formerly the Minerals Management Service (MMS), is requiring more information in regard to the well plan in order to issue permits, the main focus here will be upon the Worst Case Discharge calculation required by the BOEMRE. On June 18, 2010, the newly formed BOEMRE issued a notice to lessees,(NTL), No. 2010-N06, outlining "information requirements for exploration plans, development and production plans, and development operations," which "rescind[ed] the limitations set forth in NTL No. 2008-G04 regarding a blowout scenario and worst case discharge scenario." NTL No. 2008-G04 was released to lessees in April2008 in order to limit the amount of information required to obtain permitsin the outer continental shelf (OCS) areas. The main objective in issuing NTL No. 2010-N06, per the NTL itself, follows below:

> "Due to the explosion and sinking of the Deepwater Horizon, the resulting deaths of 11 people, and changing conditions caused by the BP Macondo prospect well that was being drilled by the Deepwater Horizon, the BOEM requires additional information concerning your planned activities [EPs, DPPs, or DOCDs].
>
> Pursuant to the regulations at 30 CFR 250.284 and 250.201(b), the BOEM may require you to submit additional information necessary to evaluate your proposed or existing plan or document. In accordance with the regulations, the BOEM may also require you to provide information to demonstrate that you have planned and have prepared to conduct your proposed activities in a manner that conforms with all applicable federal laws and regulations, is safe, conforms to sound conservation practices and does not cause undue or serious harm or damage to the human, marine, or coastal environment pursuant to 30 CFR 250.202. This NTL describes the information you must submit to the BOEM.
>
> The Secretary's Safety Measures Report, dated May 27, 2010, contains recommendations for immediate and long term requirements to improve

> the safety of oil and gas operations in shallow and deep waters. In light of the Safety Measures Report, the BOEM issued NTL No. 2010-N05, Increased Safety Measures for Energy Development on the OCS (Safety NTL). The Safety NTL requires you to submit additional safety information to BOEM."

While NTL No. 2010-N06 in essence does require the submittal of additional information and the repeal of NTL 2008-G04, its primary purpose is the alteration of the requirement of blowout scenario description with a worst case discharge scenario (WCD). The alteration basically consists of providing much more detail and information in regard to the WCD and blowout scenario. The new required information consists of first, a blowout scenario, per CFR 250.213(g) and 250.243(h). The potential blowout must be outlined with the well with highest potential hydrocarbon production noted. The estimated flow rate, total volume, and maximum duration (time) of the blowout. Other important possibilities, such as downhole bridging due to drawdown, and the possibility of the blowout to be stopped via surface techniques must be noted. A very important new item must be included as well—the evaluation of rig availability to drill a relief well, the constraints to be met by said rig, the time for said rig to come under contract, move to location, and complete the relief well. If a platform is near the drill site or near shore, the possibility of drilling the relief well from the platformor onshore must be evaluated as well (BOEM).

The next piece of information to be provided pursuant to the NTL is a description of all assumptions and all calculations performed in order to determine the worst case discharge scenario and volumes. This is required by 30 CFR 250.219(a)(2)(iv) [EPs] or 30 CFR 250.250(a)(2)(iv) [for DPPs and DOCDs]. These assumptions include, but are not limited to: well design, reservoir characteristics, pressure volume temperature (PVT) data, all analog reservoirs utilized, and the defense for utilization of the analog reservoirs. All calculations and models supporting the worst case discharge scenario (specifically an uncontrolled unconstricted blowout) must be included as well, in addition to a proposed or approved Oil Spill Response Plan (OSRP) based on the WCD. Lastly, all measures which may reduce the risk or chance of a blowout, measures that may aid in preventing a blowout, and measures that may allow effective

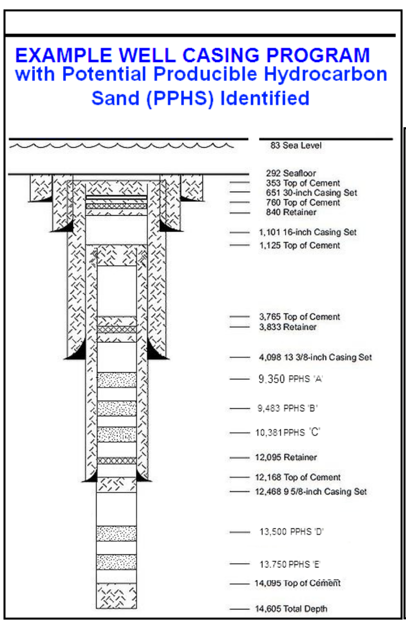
and early intervention in the event of a blowout—including the drilling of relief wells, must be included (BOEM).

The worst case discharge scenario must be calculated from all producible reservoirs open to the wellbore. Note that this may not be the target zone, or even zones near the target zone, but rather the compilation of the zones that are open to the wellbore at any one time and capable of flow. Any reservoir isolated by cement and casing is considered a non producible zone. A producible reservoir is defined by 30 CFR 250.116(b)(4) as a zone with a resistivity or induction log showing at least fifteen feet of producible sand (true vertical thickness). However, reservoirs of less than fifteen feet of producible sand occur, and those analog reservoirs must be considered. In order to determine the WCD, the collection of those reservoirs exposed to the open hole with the greatest discharge potential must be considered and potential flow rates predicted. It is important to note that an open hole interval with no restrictions must be considered when making the WCD calculations. Even more important to note is that gas and gas condensate reservoirs are not exempt from WCD calculations, and must be considered.

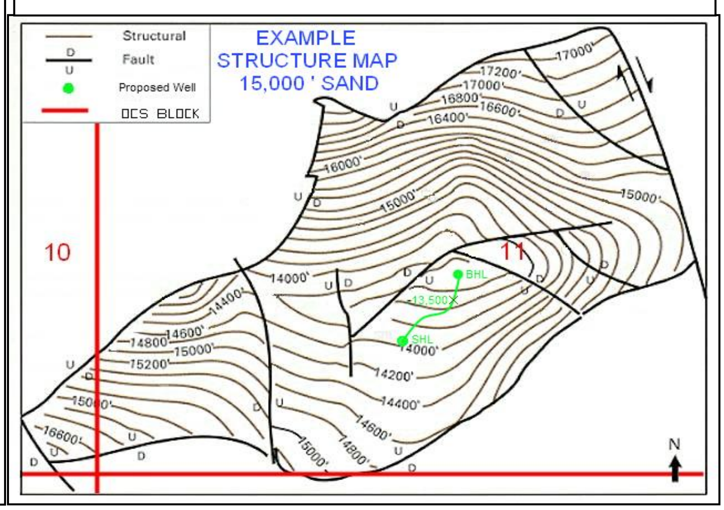
Additionally, information must be provided other than the WCD calculation. A wellbore diagram accompanied by a well cross section with casing program, hole sizes, and proposed directional survey must accompany the WCD. All geologic information, including structure maps, seismic information, maximum drainage area, drive mechanism, and hydrocarbon net sand must be included as well. Reservoir fluid data must be provided: PVT data, fluid characteristics (oil and gas), and any analog reservoir data utilized. Also, all input and output files of any software programs utilized, including the flowing bottom hole pressures at each wellbore diameter change and at the seafloor wellhead, and the total production rate at the wellhead on the seafloor. Note that the assumption is made that the BOP is NOT attached to the wellhead for WCD calculation purposes (BOEM).

As of August 10, 2010, BOEMRE had compiled a list of FAQ's as an addendum to the NTL. These highlighted several important constraints concerning the NTL: Development and Production Plans (DPPs), Exploration Plans (EPs), and Development and Coordination

Documents (DOCDs) are affected in all water depths, not only those in 500’ of water or greater; the Gulf of Mexico, Pacific, and Alaskan OCS areas are all affected; and all plans or Applications for a Permit to Drill (APDs) submitted after June 18, 2010. The information required by the NTL is not required if: an APD was approved before June 18, 2010, drilling of waterflood, injection, disposal, or relief wells, drilling operations or activities necessary to safely shut in, abandon, decommission, or complete a well, and any and all activities which do not require an APD. Note that sidetracks are covered under the initial APD as long as those sidetracks do not cross into another OCS block. Expected turn time on the end of BOEMRE is somewhat addressed in the FAQ section. It is pointed out by BOEMRE that each design is site specific, and each will take a different amount of time. A way to expedite their evaluation is to provide “a robust response.” BOEMRE also goes on to state that they will not notify of approval of submitted documents, but rather notify if additional documents are needed. Lastly, the BOEM states that they will not necessarily use the same data used by companies to calculate the WCD of a particular proposal, as they “have proprietary data that may not be available to [the operator],” and may “…use that data as an analog. ”(BOEM).Below an example WBD and structure map provided in BOEMRE NTL No. 2010-06, demonstrating the level of detail BOEMRE is expecting in the WCD portion of submitted applications.



Left: Figure 3. An example Wellbore Diagram
Below: Figure 4. An example structure map, both provided by the BOEMRE in NTL No. 2010-N06.



On September 22, 2010, a committee within the Society of Petroleum Engineers, chaired by Tim Magner of Chevron, released a memo, entitled "*Guidance for Complying with BOEM NTL No. 2010-N06 on Worst Case Discharge for Offshore Wells*," outlining how companies can best and most thoroughly comply with the new BOEMRE regulations. The memo focuses primarilyon the Worst Case Discharge calculations, and is intended to be a guideline for each individual company to use, but it is up to each and every company to submit what they believe to be the required information pertaining to their WCD calculation. Further, this document outlines the potential consequences of not submitting the required information—BOEMRE interpreting their own WCD calculation results as the true calculation. Also, this document highlights the fact the BOEM requires both hard and electronic copies of documents to be submitted. The BOEM has been somewhat murky on what is the most efficient and explicit way to submit the required information for review(as well as what is actually required), though it has stated that weekly updates will be given on what may have caused certain approvals to be returned to the operator and not approved (SPE 1-6).

This SPE document outlines how to perform the WCD discharge calculation by four major steps: Step 1—"Evaluate all potential hydrocarbon bearing intervals in each section of the hole to be drilled and determine the Uncontrolled Flow for each hole section following the guidelines described below. The hole section with the highest Uncontrolled Flow Rate scenario will be considered the Worst Case Discharge Scenario for reporting"; Step 2—"Estimate the time required to drill a relief well for the hole section to be considered for Worst Case Discharge Scenario reporting"; Step 3—"For thehole section considered as the Worst Case Discharge Scenario for reporting, provide a single rate profile for production decline or depletion for all zones including those which may be commingled"; and Step 4—"From the flow rate projection in Step 3, calculate the total potential spill volume over the time required to kill the well" (SPE 5).

The primary focus of Step 1 is to determine the uncontrolled flow for each hole section within the well. The premise of this calculation is that the hole is fully drilled, and all hole sections both open to flow and whose fluids can commingle are considered in the calculation. Of course, BOEMRE has previously challenged the inclusion of water sands, and thus the inclusion of water sands and resulting commingled flow rate must be supported by strong offset/analog reservoir data. Clearly, the inclusion of these zones may result in virtually no oil flow resulting

from the blowout initially, but once the water zone depletes, hydrocarbon production will begin. As far as estimating the well flowrate, the recommendation is to make the best technical estimate possible with the data available.The SPE committee recommends that the hole section with the highest uncontrolled rate be considered, rather than the section with the highest volume. The possibility of a zone with a very high initial rate but quickly depleting is possible, and here a higher volume formation with a lower, but more stable flow rate and pressure will begin flowing and compose the majority of the uncontrolled flow (SPE 3-6).

In regard to selecting analog reservoir data, the best course of action is too select a nearby analog reservoir completed in similar lithology. BOEMRE seems to favor those analogs based on nearby, similar lithology formations. If no nearby analogs are available within the company, it is suggested within the document to consider industry wide database analogs to utilize; however, this data is generally proprietary and not available to the company applying for the permit, leaving the company in a “catch-22”. But, accuracy here is key: any inconsistencies in PVT properties or gradients should be clearly addressed. Note that the BOEMRE has a great deal of internal data from many formations which to utilize. BOEMRE has such a great deal more data to consider than each individual company due to it retaining such a large amount of proprietary data—which may seem unfair to the company, unless one considers that BOEMRE is part of the Department of the Interior, and charged with protecting the public. The WCD scenario should be based on the hydrostatic column of water or atmospheric pressure at sea level, if drilling from an existing platform. If drilling from any mobile drilling rig, it is assumed the rig and riser are both removed from the wellhead, and all well control equipment has failed and provides no barrier to flow. In this case, the hydrostatic pressure at the mudline is to be considered (SPE 3-6).

In the second step of the SPE committee’s guidelines, the company must make a recommendation as to how long it would take to drill a relief well to the particular section of the hole selected as the Worst Case Discharge scenario location. This time estimate should include three primary components: “days to secure a rig, de-mobilize/mobilize and be ready to drill at the relief site, time to drill the relief well and intersect the blowout well at the base of the previous casing point, and the days [required] to [both] kill and cement the blowout well” (SPE 7). Specific estimation of days to drill the well to TD and days to effectively complete the well is required as well (SPE 7).

The third step in the guidelines from the committee is to provide a rate profile for the WCD scenario production decline. The primary requirements from the BOEM are flow rates, total spill volume, and total time elapsed before the well is killed. Several methods exist to generate this profile: analog reservoir data/analytical analysis, material balance analysis, and reservoir simulation (the latter two restricted to those reservoirs with "well-defined geologic models). The SPE committee, with emphasis on expediting the entire permit approval process, recommends utilization of the first method mentioned, analog reservoir data/analytical analysis. Further, if the decision is made to use a bounded model, maximum drainage area, demonstration of fitting structure maps, and demonstration of fitting interpreted lithological reservoir boundaries must be shown. When modeling with production data, all data supporting that particular pressure decline and coupled cumulative production, such as history match data and reservoir performance history must be included. For all other modeling, data supporting all assumptions and estimates must be included (SPE 5-7).

The final step in the provided committee guidelines is to calculate the total spill volume to be reported in the Worst Case Discharge calculation. As per BOEMRE guidelines, the definition of the total spill volume is the total sum of production from the well before it is successfully killed and flow stopped. This number is to be reported in stock tank barrels of oil. This volume, as well as the uncontrolled flow rate, the time required to drill and cement a relief well, and the determined rate profile from the WCD report will be utilized further in each individual company's Oil Spill Response Plan (OSRP). The outline of the OSRP, required by BOEMRE, is not addressed in detail in this report (SPE 6-7).

As an addendum, the SPE committee provided a recommended submission outline, ordering all documentation that must be provided to BOEMRE. Also provided is an outline of all data requirements. This basic submission outline consists of six main parts: an introduction and summary of results and calculations, discussion of well/prospect and summary of well plan, detailed description of worst case discharge scenario rates and spill volumes, documentation for the worst case discharge scenario as previously discussed, list of attached displays and input/output files, and all maps and cross sections. The recommended list of specific data requirements for those sections not included in the Worst Case Discharge Scenario is comprised of merely a geological and offset well discussion that clearly displays the justification not to include the particular hole sections in the WCD calculation. For those sections to be included,

the following data is appropriate: all reservoir characteristics, reservoir pressure and temperature data, drive mechanisms present, drainage area and depletion rates, wellbore completion configurations, casing and open hole sizes, casing and open hole absolute roughness, production history, static and flowing pressures and temperatures, mechanical skin damage, water intrusion, coning, formation sloughing, bridging, pressure-volume-temperature characteristics, and the hydrostatic pressure present (seawater gradient assumed 0.445 psi/ft). No specific requirement for different hydrocarbons with respect to volume are included, though all fluid properties of different reservoir fluids must be included. This documentation guidance, while not legal nor technical tender, is a great help to all companies who must submit plans to BOEMRE, and consequently influenced my approach to building the WCD calculation (SPE 8-14).

The effects of the Macondo blowout were further reaching than the coastlines and waters of the Gulf of Mexico. The resulting stiffened requirements issued by the BOEMRE left many smaller independents operating in the Gulf of Mexico Deepwater arena with quite the daunting proposition. Even mid-majors and majors had some difficulty meeting and deciphering the newly released guidelines and requirements. Smaller companies, by virtue of their size and overhead, could not and cannot bear the financial risks of a major corporation, and therefore typically operate as minority partners in the Deepwater Gulf of Mexico. However, these smaller companies still had to meet all requirements set forth by the BOEMRE, in addition to procuring all necessary insurance policies based upon the WCD scenarios calculated. In an effort to assist both the majors and independents, an SPE committee was formed to outline the necessary requirements, and was summarized in the previous pages.

Larger companies have the resources to obtain and utilize software packages that BOEMRE seems to prefer to perform the necessary WCD calculations needed. Because these software packages are fairly expensive, and often require annual payments, at least to receive the latest upgrades, smaller operators are left at a disadvantage. The objective of this work is to formulate and develop a generic spreadsheet that would allow smaller operators to more easily comply with the NTL, or at the very least perform a “first pass” at the calculations. While this sheet is not perfect and does not fit all wells perfectly, it is a great starting point for those companies unsure of the exact method appropriate for calculating the WCD for the BOEMRE, and to understand the data that the BOEMRE requires to support the calculations.

Structure of the BOEMRE Example WCD Calculation Sheet:

The constructed spreadsheet draws from the examples provided by the BOEMRE in the NTL No. 2010-N06, the methods discussed in the SPE committee memo previously mentioned, and additional information not contained in either. The spreadsheet was formatted in Microsoft Excel, and consists of twelve individual tabs.

For the purpose of this report, an example well with five open layers is considered. The example well data will be provided in the figures that follow. These data come from class assignments, a survey of SPE literature and various assumptions made by the author. The data is not meant to be representative of any particular well or field, rather, the data used is meant only to show the capability of the spreadsheet. In addition to the reservoir data considered, the primary piece equipment data to remember is the smallest flow diameter—the 7” production casing.

The Equipment tab is the first one in the sheet, and displays the number and description of the casing/liner strings to be utilized within the well. Also, the location (OCS Area and Block) and lease and plan numbers are input, as well as the water depth at the drilling site. Below is a snapshot of the equipment tab. While only three casing section spaces are listed, more strings and their respective descriptions can be added, or rather must be added below if present. The sections are currently blank for example purposes; however, these sections will be filled in with example data in the sample sheet addendum. Also, it is important to notice the installed date for the casing strings, as this sheet can be utilized and filled in as casing is set in the hole. Setting Depths and the date set in hole should be filled in as casing is set, in order to maintain an accurate picture of the downhole equipment present in the well at any given time. Future work here is to include the performed Pressure tests on the casing or liner strings, and the methods to do so, to the right.

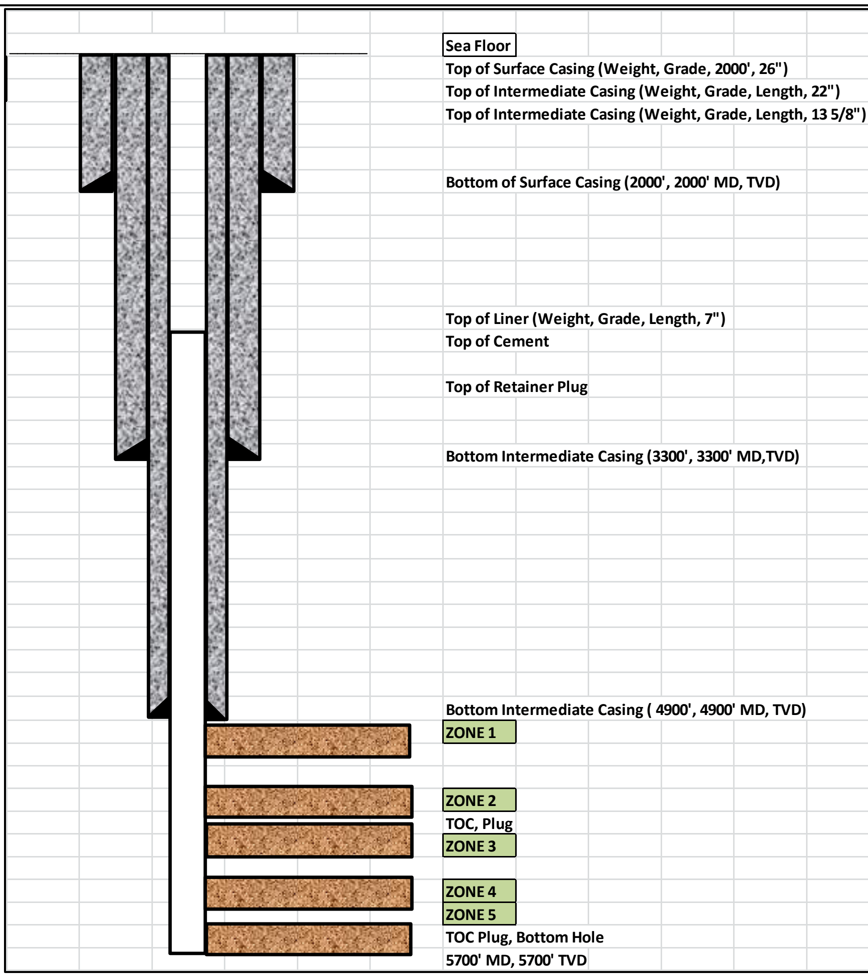
Following the Equipment tab on the next page, the next tab of the spreadsheet follows. This is the Wellbore Diagram tab. This tab gives accurate information regarding all equipment and fluid in the hole as well as the formations to be encountered downhole. Keeping this diaram up to date is very important in regard to having accurate knowledge of all equipment downhole.

General Information									
Plan Number	OCS Area	OCS Block	Lease Number						
####	TST	191	######						

Wellbore Data		
Water Depth at proposed location:	2000	ft

Casing Data								
Interval Number	Hole Size	Size Casing	Weight	Grade	Setting Depth MD	Setting Depth TVD	Installed (Y,N)	Date Installed
Surface	26 1/2	26			2000	2000	Y	
Intermediate	16	13 5/8			3300	3300	Y	
Intermediate	9	7			4900	4900	Y	
Production Liner							N	

Above: Figure 5. Equipment Tab, Example BOEMRE WCD Calculation spreadsheet.



Prepared By:	Noah McGill
Date:	9/30/2010

Date of Installation of Casing	
Surface	10/31/2010
Inermediate	11/10/2010
Inermediate	11/26/2010

Date of Cement	
Surface	10/31/2010
Inermediate	11/10/2010
Inermediate	11/26/2010
Bottom Hole	
Bottom Plug	
Retainer	

Tubing (Y,N)	N
Size	2.375
Weight	
Grade	H-40

Drillpipe	
Size	
Weight	
Grade	

Full String (Y or N)	N
Liner (Y or N)	Y

Above: Figure 6. Well Bore Diagram Tab, Example BOEMRE WCD Calculation spreadsheet.

All wellbore information, including drillpipe, tubing, casing, cement, and plug data, or any work that has been or is currently being completed or had been completed on the well which altered the first formal diagram in any way can be entered here.

The next tab in the spreadsheet gives a broad overview of the reservoir geology, and its incorporation into the Worst Case Discharge Scenario Calculation. Each producible zone to be encountered within the well should be described, no matter the flow potential (high or low) or flow fluid (oil or water). However, zones with less than 15’ of pay only need to be considered if there are analog reservoirs producing from such intervals. Formation top (Total Vertical Depth (TVD), Measured Depth (MD)) and base (TVD, MD) should be input, height open to flow, total thickness, and drainage area must be described as well. Most importantly, the decision whether to include the zone in the WCD Calculation (Y or N) must be given here, with both ample and specific justification for doing so. BOEMRE will check and recheck this particular decision, and will most likely reject it without proper documentation. Lastly, at the bottom of the sheet, it must be noted the top and bottom of the zone (in MD) to be utilized in the WCD calculation. A diagram of this sheet is found below:

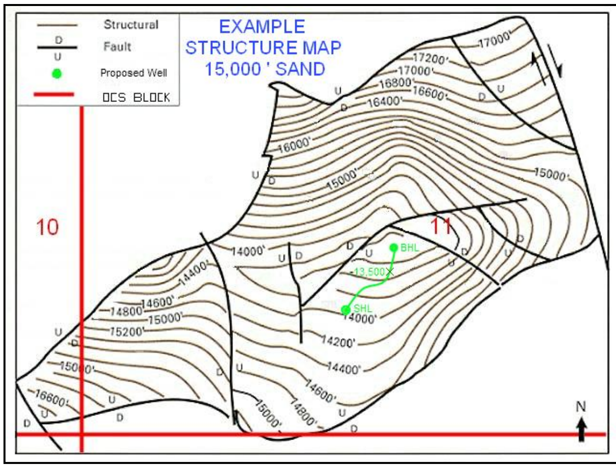
Geologic Data

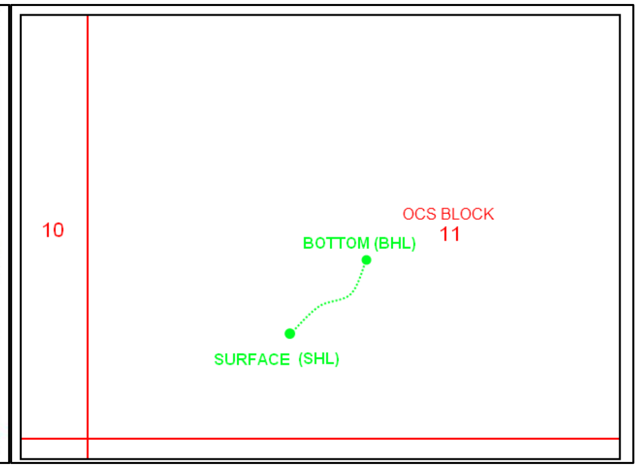
Sand Name	Top		Base		Height	Sand Thickness	Drainage Area	Used in WCD (Y,N)?	If N, Why not?
	MD	TVD	MD	TVD					
Zone 1	5000	5000	5100	5100		100		Y	
Zone 2	5110	5110	5210	5210		100		Y	
Zone 3	5225	5225	5325	5325		100		Y	
Zone 4	5375	5375	5475	5475		100		Y	
Zone 5	5480	5480	5580	5580		100		Y	

Hole Interval Used in WCD Calculation	Top MD	Bottom MD
	4900	5580

Above: Figure 7. Overview Tab, Example BOEMRE WCD Calculation spreadsheet.

The next two tabs in the sheet are the Well Plan and Structure Map. Both of these items are critical information which must be submitted to BOEMRE. Below, find an example well plan and Structure Map provided on BOEMRE’s website:





Above Left: Figure 8. Example Structure Map, contained in the FAQ pertaining to NTL 2010-N06.

Above Right: Figure 9. Example Well Location Map, contained in the FAQ pertaining to NTL 2010-N06. http://www.gomr.boemre.gov/homepg/regulate/regs/ntls/2010NTLs/10-n06-FAQs.pdf

Following the Structure Map tab begins the Worst Case Discharge Calculation. The spreadsheet is broken down in such a manner that each individual zone is given its own individual tab and sheet, provided it is to be included in the WCD calculation. All the characteristics specific to the individual reservoir are input here, including but not limited to the following: initial pressure, initial temperature, permeability, drainage area, thickness, porosity, skin, drive mechanism, and fluid data (oil—bubble point pressure, oil formation volume factor, viscosity, compressibility, API Gravity, static oil fluid gradient, and RSI; gas—condensate API Gravity, gas specific gravity, yield, gas static fluid gradient, D-turbulence flow factor, gas viscosity, and gas formation volume factor). For analysis using transient flow, some other vital data is needed: distance to reservoir boundary, wellbore radius, GOR, specific gravity of total fluid, and separator conditions. Time for flow to stabilize is also an important data point needed for transient analysis. Each zone's flow is calculated by both Transient and Vogel flow equations, in addition to the oil/water hydrostatic column existing above the well during Worst Case Scenario situations. These conditions (Worst Case Scenario) are defined as: the well completely open to flow without any obstructions or well control equipment at the mudline and a skin = 0. This hydrostatic calculation is important, as it describes the minimum pressure needed to be generated by the reservoir to flow openly, and are the last pressures considered in the IPR/TPR plot generated for each zone. An example hydrostatic calculation is given below:

Hydrostatic Column (in psi)= (Water Depth from ocean surface) * (**0.445** psi/ft) + (Depth to Zone from Mudline) * (**0.443** psi/ft) * (**Specific Gravity** of Formation Fluid)

Note that the 0.445 psi/ft is the assumed pressure gradient due to salt water, and the gradient of 0.443 psi/ft is the pressure gradient due to fresh water. A multiplication of this gradient with the gravity of the formation fluid will give the pressure gradient due to the formation fluid. Next, each zone's flow was calculated via transient flow. The following equations were utilized to complete this analysis:

$$q_o = \frac{kh(P_r - P_{wf_s})}{162.6 B_o \mu_o \left[log\left(\frac{kt}{\phi \mu C_t r_w^2}\right) - 3.23 + 0.87S \right]}$$

Where $t < t_{stab}$ in hours. Note that all nomenclature for equations presented in this thesis follow in the Appendix A.

$$t_{stab} = 948 \left(\frac{\phi \mu_o C_t r_e^2}{k} \right)$$

This transient flow analysis was completed for each individual zone, varying the parameters of P_{wfs}, B_o, and of course, P_r. Each zone had a singular P_r, and the P_{wfs} and B_o were altered for each individual zone according to those specific reservoir properties. Below is an example of the Transient Flow Calculation. To the left are the reservoir parameters, in the middle are the transient flow parameters, and to the right is the P_{wfs}, P_{hydro} (Due to Brine and Oil), B_o, and the flow rate, Q_o. A macro was utilized to calculate B_o, due to the repetitive nature of the calculation for individual zones. It is important to realize that the primary purpose of the spreadsheet is to demonstrate flow from multiple zones, and the reservoir parameters listed below were the assumptions made, and resulted in the flow rates and WCD to follow. These values are NOT from an actual reservoir. Note here that this is only an individual zone calculation, not affecting ones above and below it. The example Zone Tab follows on the next page.

Below Left: Figure 10. Zone 2 Tab, Example BOEMRE WCD Calculation spreadsheet.

Reservoir Data

Sand Name:	Zone 5	5400 ft

Note: These numbers are for demonstration/example only.

	Value	Analog Utilized	Source
Initial Pressure (Pr)	9200		
Initial Temperature (F)	175		
Permeability (mD)	500		
Drainage Area (Ac)			
Thickness (ft)	100		
Drive Mechanism	Depletion		
Skin	0		

Fluid Data

Oil

	Value	Analog Utilized	Source
Bubble Point Pressure	5000		
Boi	1.4987986		
Oil Viscosity	20		
Compressability	7.50E-07		
API Gravity	35		
Static Oil Fluid Gradient			
RSI			
Porosity	0.3		

Gas

	Value	Analog Utilized	Source
Condensate API Gravity			
Gas Specific Gravity			
Yield			
Static Gas Fluid Gradient			
D-Turbulence Flow Factor			
Gas Viscosity			
BG			

t_stab	34.128
t (t<t_stab)	25
re=	2000
rw (flowing ID)=	3.047
API	35
Separator Temp	70
Separator Pressure	100
Sg	0.667
GOR	1000

Brine Hydro	Oil Hydro	
890	1595.597	2485.5974

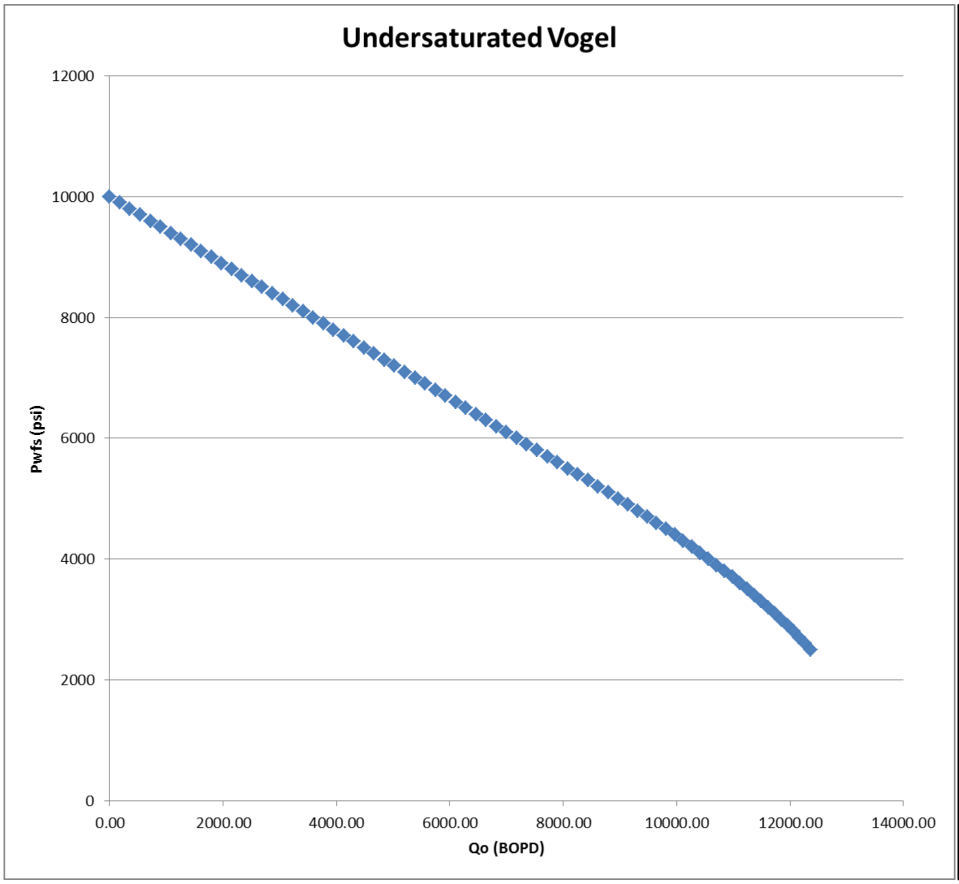
IPR	5		IPR 5	Vogel
Pwfs	**Phyrdo**	**Bo**	**Qo**	**Qo**
9200	2485.5974	1.498799	0.0000000	0.0000000
9100	2485.5974	1.499357	179.0337124	179.0337124
9000	2485.5974	1.499928	358.0674247	358.0674247
8900	2485.5974	1.500512	537.1011371	537.1011371
8800	2485.5974	1.50111	716.1348494	716.1348494
8700	2485.5974	1.501722	895.1685618	895.1685618
8600	2485.5974	1.502348	1074.2022741	1074.2022741
8500	2485.5974	1.502989	1253.2359865	1253.2359865
8400	2485.5974	1.503646	1432.2696989	1432.2696989
8300	2485.5974	1.504319	1611.3034112	1611.3034112
8200	2485.5974	1.505008	1790.3371236	1790.3371236
8100	2485.5974	1.505715	1969.3708359	1969.3708359
8000	2485.5974	1.50644	2148.4045483	2148.4045483
7900	2485.5974	1.507184	2327.4382606	2327.4382606
7800	2485.5974	1.507947	2506.4719730	2506.4719730
7700	2485.5974	1.50873	2685.5056854	2685.5056854
7600	2485.5974	1.509534	2864.5393977	2864.5393977
7500	2485.5974	1.510361	3043.5731101	3043.5731101
7400	2485.5974	1.51121	3222.6068224	3222.6068224
7300	2485.5974	1.512083	3401.6405348	3401.6405348
7200	2485.5974	1.51298	3580.6742471	3580.6742471
7100	2485.5974	1.513903	3759.7079595	3759.7079595
7000	2485.5974	1.514854	3938.7416718	3938.7416718
6900	2485.5974	1.515832	4117.7753842	4117.7753842
6800	2485.5974	1.51684	4296.8090966	4296.8090966
6700	2485.5974	1.517879	4475.8428089	4475.8428089
6600	2485.5974	1.51895	4654.8765213	4654.8765213
6500	2485.5974	1.520055	4833.9102336	4833.9102336
6400	2485.5974	1.521195	5012.9439460	5012.9439460
6300	2485.5974	1.522372	5191.9776583	5191.9776583
6200	2485.5974	1.523588	5371.0113707	5371.0113707
6100	2485.5974	1.524845	5550.0450831	5550.0450831
6000	2485.5974	1.526145	5729.0787954	5729.0787954
5900	2485.5974	1.527491	5908.1125078	5908.1125078
5800	2485.5974	1.528884	6087.1462201	6087.1462201
5700	2485.5974	1.530327	6266.1799325	6266.1799325
5600	2485.5974	1.531823	6445.2136448	6445.2136448
5500	2485.5974	1.533375	6624.2473572	6624.2473572
5400	2485.5974	1.534986	6803.2810696	6803.2810696
5300	2485.5974	1.53666	6982.3147819	6982.3147819
5200	2485.5974	1.5384	7161.3484943	7161.3484943
5100	2485.5974	1.54021	7340.3822066	7340.3822066
5000	2485.5974	1.542095	7519.4159190	7519.415919
4900	2485.5974	1.542095	7698.4496313	7691.889836
4800	2485.5974	1.542095	7877.4833437	7861.270051

These transient calculations were completed for Zones 1-5. Next, the undersaturated Vogel IPR was considered to express the flow from each zone. The equation utilized to complete this analysis is shown below:

$$\frac{q - q_b}{q_{max} - q_b} = 1 - 0.2\left(\frac{P_{wf}}{P_b}\right) - 0.8\left(\frac{P_{wf}}{P_b}\right)^2$$

Where q_b is the flow rate at the bubble point (this value can be obtained from Darcy's Law), q_{max} is the maximum flow from the well, occurring at P_{wf} =0, and P_{wf} is the flowing BHP of the well. The maximum flow rate considered for this work occurs at a surface flowing pressure equivalent to the seawater hydrostatic column. Some production data giving a clue of this potential

maximum flow rate for a Vogel IPR may be available (it can be derived with any P_{wf} vs. q data). Figure 11 is a graph showing anundersaturated Vogel IPR.



IPR 5	Vogel
	Qo
	0.0000000
	179.0337124
	358.0674247
	537.1011371
	716.1348494
	895.1685618
	1074.2022741
	1253.2359865
	1432.2696989
	1611.3034112
	1790.3371236
	1969.3708359
	2148.4045483
	2327.4382606
	2506.4719730
	2685.5056854
	2864.5393977
	3043.5731101
	3222.6068224
	3401.6405348
	3580.6742471
	3759.7079595
	3938.7416718
	4117.7753842
	4296.8090966
	4475.8428089
	4654.8765213
	4833.9102336
	5012.9439460
	5191.9776583
	5371.0113707
	5550.0450831
	5729.0787954
	5908.1125078
	6087.1462201
	6266.1799325
	6445.2136448
	6624.2473572
	6803.2810696
	6982.3147819
	7161.3484943
	7340.3822066
	7519.415919
	7691.889836
	7861.270051
	8027.556563
	8190.749372
	8350.848479
	8507.853884
	8661.765585
	8812.583585
	8960.307881
	9104.938476
	9246.475367
	9384.918556
	9520.268043
	9652.523827
	9781.685908
	9907.754287
	10030.72896
	10150.60994
	10267.39721
	10381.09078
	10491.69064
	10599.19681
	10703.60927

Right: Figure 11. Graphical Display of Undersaturated Vogel IPR and associated rates , contained in each Zone tab; Example BOEMRE WCD Calculation spreadsheet.

The next step in the analysis was to sum the flow rates from each individual zone. The limiting factors considered here were only the seawater hydrostatic column above the mudline, and the flowing backpressure generated by each zone. More simply put, reservoirs of a higher flowing pressure will flow singularly until that particular flowing pressure is lowered enough to allow another reservoir, of a lower pressure, to flow into the wellbore. Therefore, we will initially have flow from the highest pressure zone open to the wellbore only, with zones of lower pressures slowly coming onto production as the higher pressure zones are depleted. Also, the possibility of a zone of higher pressure flowing into a zone of lower pressure is not considered here. All flow from zones goes to the mudline at surface. An example of the summation of each zone's flow, contained in the Transient and Undersaturated Vogel/Transient tabs is shown below:

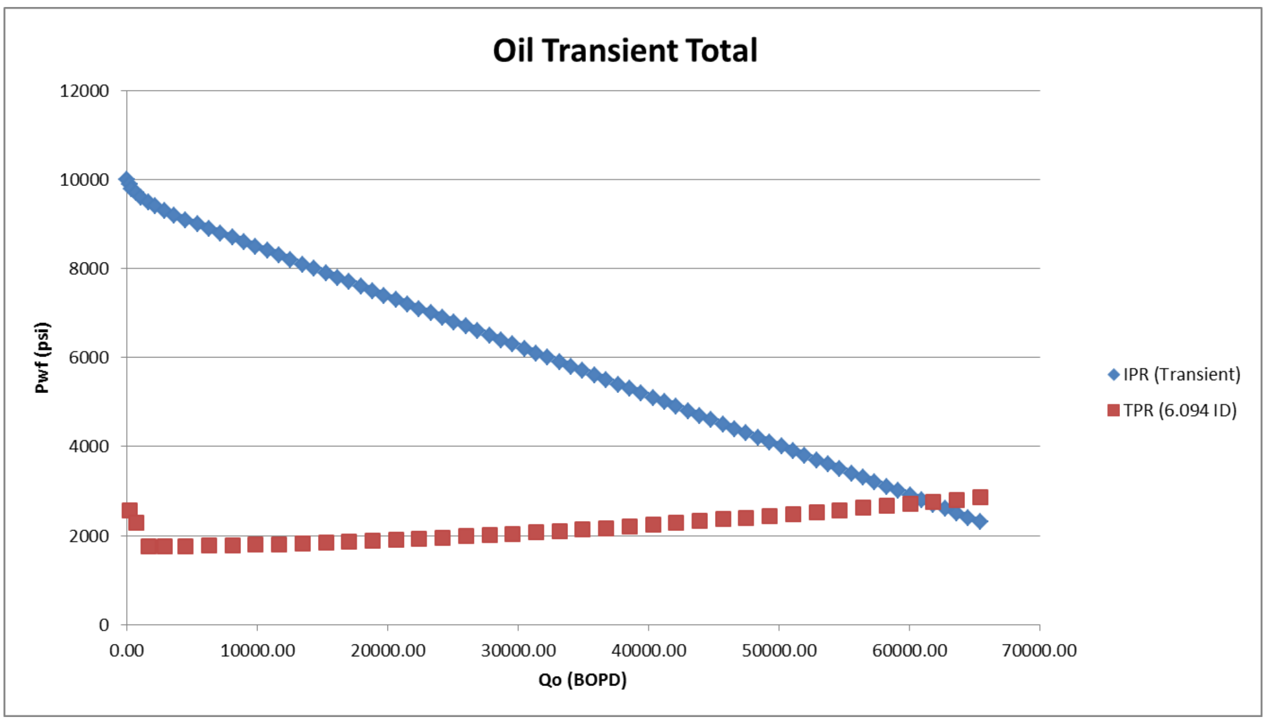
IPR	1		IPR	2		IPR	3		IPR	4		IPR	5	
Pwfs	Bo	Qo	Pwfs	Bo	Qo	Pwfs	Bo	Qo	Pwfs	Bo	Qo	Pwfs	Bo	Qo
10000	1.494739088	0.0000000	10000	[redacted]		10000	[redacted]		10000	[redacted]		10000	[redacted]	
9900	1.495210087	179.5199483	9900	[redacted]		9900	[redacted]		9900	[redacted]		9900	[redacted]	
9800	1.49569085	359.0398965	9800	1.495691	0.0000000	9800	[redacted]		9800	[redacted]		9800	[redacted]	
9700	1.496181686	538.5598448	9700	1.496182	179.4057132	9700	[redacted]		9700	[redacted]		9700	[redacted]	
9600	1.496682914	718.0797930	9600	1.496683	358.8114264	9600	1.496683	0	9600	[redacted]		9600	[redacted]	
9500	1.497194867	897.5997413	9500	1.497195	538.2171396	9500	1.497195	179.2867957	9500	[redacted]		9500	[redacted]	
9400	1.497717893	1077.1196896	9400	1.497718	717.6228528	9400	1.497718	358.5735913	9400	1.497718	0	9400	[redacted]	
9300	1.498252356	1256.6396378	9300	1.498252	897.0285660	9300	1.498252	537.860387	9300	1.498252	179.1629017	9300	[redacted]	
9200	1.498798635	1436.1595861	9200	1.498799	1076.4342792	9200	1.498799	717.1471826	9200	1.498799	358.3258034	9200	1.520055	0
9100	1.499357126	1615.6795343	9100	1.499357	1255.8399924	9100	1.499357	896.4339783	9100	1.499357	537.4887051	9100	1.521486	179.0337124
9000	1.499928243	1795.1994826	9000	1.499928	1435.2457057	9000	1.499928	1075.720774	9000	1.499928	716.6516069	9000	1.522975	358.0674247
8900	1.500512418	1974.7194308	8900	1.500512	1614.6514189	8900	1.500512	1255.00757	8900	1.500512	895.8145086	8900	1.524527	537.1011371
8800	1.501110106	2154.2393791	8800	1.50111	1794.0571321	8800	1.50111	1434.294365	8800	1.50111	1074.97741	8800	1.526145	716.1348494
8700	1.50172178	2333.7593274	8700	1.501722	1973.4628453	8700	1.501722	1613.581161	8700	1.501722	1254.140312	8700	1.527834	895.1685618
8600	1.502347937	2513.2792756	8600	1.502348	2152.8685585	8600	1.502348	1792.867957	8600	1.502348	1433.303214	8600	1.529599	1074.202274
8500	1.502989098	2692.7992239	8500	1.502989	2332.2742717	8500	1.502989	1972.154752	8500	1.502989	1612.466115	8500	1.531444	1253.235986
8400	1.503645807	2872.3191721	8400	1.503646	2511.6799849	8400	1.503646	2151.441548	8400	1.503646	1791.629017	8400	1.533375	1432.269699
8300	1.504318639	3051.8391204	8300	1.504319	2691.0856981	8300	1.504319	2330.728344	8300	1.504319	1970.791919	8300	1.535398	1611.303411
8200	1.505008193	3231.3590687	8200	1.505008	2870.4914113	8200	1.505008	2510.015139	8200	1.505008	2149.954821	8200	1.537521	1790.337124
8100	1.505715101	3410.8790169	8100	1.505715	3049.8971245	8100	1.505715	2689.301935	8100	1.505715	2329.117722	8100	1.539751	1969.370836
8000	1.506440026	3590.3989652	8000	1.50644	3229.3028377	8000	1.50644	2868.588731	8000	1.50644	2508.280624	8000	1.542095	2148.404548
7900	1.507183667	3769.9189134	7900	1.507184	3408.7085509	7900	1.507184	3047.875526	7900	1.507184	2687.443526	7900	1.542095	2327.438261
7800	1.507946756	3949.4388617	7800	1.507947	3588.1142641	7800	1.507947	3227.162322	7800	1.507947	2866.606427	7800	1.542095	2506.471973
7700	1.508730067	4128.9588099	7700	1.50873	3767.5199773	7700	1.50873	3406.449118	7700	1.50873	3045.769329	7700	1.542095	2685.505685
7600	1.509534415	4308.4787582	7600	1.509534	3946.9256905	7600	1.509534	3585.735913	7600	1.509534	3224.932231	7600	1.542095	2864.539398
7500	1.510360658	4487.9987065	7500	1.510361	4126.3314038	7500	1.510361	3765.022709	7500	1.510361	3404.095133	7500	1.542095	3043.57311
7400	1.511209703	4667.5186547	7400	1.51121	4305.7371170	7400	1.51121	3944.309504	7400	1.51121	3583.258034	7400	1.542095	3222.606822
7300	1.512082507	4847.0386030	7300	1.512083	4485.1428302	7300	1.512083	4123.5963	7300	1.512083	3762.420936	7300	1.542095	3401.640535
7200	1.51298008	5026.5585512	7200	1.51298	4664.5485434	7200	1.51298	4302.883096	7200	1.51298	3941.583838	7200	1.542095	3580.674247
7100	1.513903493	5206.0784995	7100	1.513903	4843.9542566	7100	1.513903	4482.169891	7100	1.513903	4120.746739	7100	1.542095	3759.707959
7000	1.514853877	5385.5984478	7000	1.514854	5023.3599698	7000	1.514854	4661.456687	7000	1.514854	4299.909641	7000	1.542095	3938.741672
6900	1.515832431	5565.1183960	6900	1.515832	5202.7656830	6900	1.515832	4840.743483	6900	1.515832	4479.072543	6900	1.542095	4117.775384
6800	1.516840426	5744.6383443	6800	1.51684	5382.1713962	6800	1.51684	5020.030278	6800	1.51684	4658.235445	6800	1.542095	4296.809097
6700	1.517879212	5924.1582925	6700	1.517879	5561.5771094	6700	1.517879	5199.317074	6700	1.517879	4837.398346	6700	1.542095	4475.842809
6600	1.518950219	6103.6782408	6600	1.51895	5740.9828226	6600	1.51895	5378.60387	6600	1.51895	5016.561248	6600	1.542095	4654.876521
6500	1.520054972	6283.1981890	6500	1.520055	5920.3885358	6500	1.520055	5557.890665	6500	1.520055	5195.72415	6500	1.542095	4833.910234
6400	1.52119509	6462.7181373	6400	1.521195	6099.7942490	6400	1.521195	5737.177461	6400	1.521195	5374.887051	6400	1.542095	5012.943946
6300	1.522372298	6642.2380856	6300	1.522372	6279.1999622	6300	1.522372	5916.464257	6300	1.522372	5554.049953	6300	1.542095	5191.977658
6200	1.523588437	6821.7580338	6200	1.523588	6458.6056754	6200	1.523588	6095.751052	6200	1.523588	5733.212855	6200	2.542095	5371.011371
6100	1.524845468	7001.2779821	6100	1.524845	6638.0113886	6100	1.524845	6275.037848	6100	1.524845	5912.375757	6100	3.542095	5550.045083
6000	1.526145491	7180.7979303	6000	1.526145	6817.4171019	6000	1.526145	6454.324644	6000	1.526145	6091.538658	6000	4.542095	5729.078795
5900	1.527490747	7360.3178786	5900	1.527491	6996.8228151	5900	1.527491	6633.611439	5900	1.527491	6270.70156	5900	5.542095	5908.112508
5800	1.528883639	7539.8378269	5800	1.528884	7176.2285283	5800	1.528884	6812.898235	5800	1.528884	6449.864462	5800	6.542095	6087.14622
5700	1.530326742	7719.3577751	5700	1.530327	7355.6342415	5700	1.530327	6992.185031	5700	1.530327	6629.027363	5700	7.542095	6266.179932
5600	1.531822821	7898.8777234	5600	1.531823	7535.0399547	5600	1.531823	7171.471826	5600	1.531823	6808.190265	5600	8.542095	6445.213645
5500	1.533374846	8078.3976716	5500	1.533375	7714.4456679	5500	1.533375	7350.758622	5500	1.533375	6987.353167	5500	9.542095	6624.247357
5400	1.534986014	8257.9176199	5400	1.534986	7893.8513811	5400	1.534986	7530.045418	5400	1.534986	7166.516069	5400	10.5421	6803.28107
5300	1.536659771	8437.4375681	5300	1.53666	8073.2570943	5300	1.53666	7709.332213	5300	1.53666	7345.67897	5300	11.5421	6982.314782
5200	1.538399835	8616.9575164	5200	1.5384	8252.6628075	5200	1.5384	7888.619009	5200	1.5384	7524.841872	5200	12.5421	7161.348494
5100	1.540210225	8796.4774647	5100	1.54021	8432.0685207	5100	1.54021	8067.905805	5100	1.54021	7704.004774	5100	13.5421	7340.382207
5000	1.54209529	8975.9974129	5000	1.542095	8611.4742339	5000	1.542095	8247.1926	5000	1.542095	7883.167675	5000	14.5421	7519.415919
4900	1.54209529	9155.5173612	4900	1.542095	8790.8799471	4900	1.542095	8426.479396	4900	1.542095	8062.330577	4900	15.5421	7698.449631
4800	1.54209529	9335.0373094	4800	1.542095	8970.2856603	4800	1.542095	8605.766192	4800	1.542095	8241.493479	4800	16.5421	7877.483344
4700	1.54209529	9514.5572577	4700	1.542095	9149.6913735	4700	1.542095	8785.052987	4700	1.542095	8420.656381	4700	17.5421	8056.517056
4600	1.54209529	9694.0772060	4600	1.542095	9329.0970867	4600	1.542095	8964.339783	4600	1.542095	8599.819282	4600	18.5421	8235.550768
4500	1.54209529	9873.5971542	4500	1.542095	9508.5028000	4500	1.542095	9143.626579	4500	1.542095	8778.982184	4500	19.5421	8414.584481
4400	1.54209529	10053.1171025	4400	1.542095	9687.9085132	4400	1.542095	9322.913374	4400	1.542095	8958.145086	4400	20.5421	8593.618193
4300	1.54209529	10232.6370507	4300	1.542095	9867.3142264	4300	1.542095	9502.20017	4300	1.542095	9137.307987	4300	21.5421	8772.651905
4200	1.54209529	10412.1569990	4200	1.542095	10046.7199396	4200	1.542095	9681.486966	4200	1.542095	9316.470889	4200	22.5421	8951.685618
4100	1.54209529	10591.6769472	4100	1.542095	10226.1256528	4100	1.542095	9860.773761	4100	1.542095	9495.633791	4100	23.5421	9130.71933
4000	1.54209529	10771.1968955	4000	1.542095	10405.5313660	4000	1.542095	10040.06056	4000	1.542095	9674.796693	4000	24.5421	9309.753043
3900	1.54209529	10950.7168438	3900	1.542095	10584.9370792	3900	1.542095	10219.34735	3900	1.542095	9853.959594	3900	25.5421	9488.786755
3800	1.54209529	11130.2367920	3800	1.542095	10764.3427924	3800	1.542095	10398.63415	3800	1.542095	10033.1225	3800	26.5421	9667.820467
3700	1.54209529	11309.7567403	3700	1.542095	10943.7485056	3700	1.542095	10577.92094	3700	1.542095	10212.2854	3700	27.5421	9846.85418
3600	1.54209529	11489.2766885	3600	1.542095	11123.1542188	3600	1.542095	10757.20774	3600	1.542095	10391.4483	3600	28.5421	10025.88789
3500	1.54209529	11668.7966368	3500	1.542095	11302.5599320	3500	1.542095	10936.49454	3500	1.542095	10570.6112	3500	29.5421	10204.9216
3400	1.54209529	11848.3165851	3400	1.542095	11481.9656452	3400	1.542095	11115.78133	3400	1.542095	10749.7741	3400	30.5421	10383.95532
3300	1.54209529	12027.8365333	3300	1.542095	11661.3713584	3300	1.542095	11295.06813	3300	1.542095	10928.937	3300	31.5421	10562.98903
3200	1.54209529	12207.3564816	3200	1.542095	11840.7770716	3200	1.542095	11474.35492	3200	1.542095	11108.09991	3200	32.5421	10742.02274
3100	1.54209529	12386.8764298	3100	1.542095	12020.1827848	3100	1.542095	11653.64172	3100	1.542095	11287.26281	3100	33.5421	10921.05645
3000	1.54209529	12566.3963781	3000	1.542095	12199.5884981	3000	1.542095	11832.92851	3000	1.542095	11466.42571	3000	34.5421	11100.09017
2900	1.54209529	12745.9163263	2900	1.542095	12378.9942113	2900	1.542095	12012.21531	2900	1.542095	11645.58861	2900	35.5421	11279.12388
2800	1.54209529	12925.4362746	2800	1.542095	12558.3999245	2800	1.542095	12191.5021	2800	1.542095	11824.75151	2800	36.5421	11458.15759
2700	1.54209529	13104.9562229	2700	1.542095	12737.8056377	2700	1.542095	12370.7889	2700	1.542095	12003.91441	2700	37.5421	11637.1913
2600	1.54209529	13284.4761711	2600	1.542095	12917.2113509	2600	1.542095	12550.0757	2600	1.542095	12183.07732	2600	38.5421	11816.22502
2500	1.54209529	13463.9961194	2500	1.542095	13096.6170641	2500	1.542095	12729.36249	2500	1.542095	12362.24022	2500	39.5421	11995.25873
2400	1.54209529	13643.5160676	2400	1.542095	13276.0227773	2400	1.542095	12908.64929	2400	1.542095	12541.40312	2400	40.5421	12174.29244
2300	1.54209529	13823.0360159	2300	1.542095	13455.4284905	2300	1.542095	13087.93608	2300	1.542095	12720.56602	2300	41.5421	12353.32615

Total	IPR	TPR (6.094)
Pwf	Q	P
10000	0.0000000	
9900	179.5199483	2567
9800	359.0398965	
9700	717.9655580	2293
9600	1076.8912194	
9500	1615.1036766	1758
9400	2153.3161337	
9300	2870.6914925	1761
9200	3588.0668514	
9100	4484.4759226	1765
9000	5380.8849938	
8900	6277.2940650	1772
8800	7173.7031362	
8700	8070.1122073	1780
8600	8966.5212785	
8500	9862.9303497	1792
8400	10759.3394209	
8300	11655.7484921	1805
8200	12552.1575633	
8100	13448.5666345	1821
8000	14344.9757057	
7900	15241.3847769	1831
7800	16137.7938481	
7700	17034.2029193	1858
7600	17930.6119905	
7500	18827.0210617	1879
7400	19723.4301329	
7300	20619.8392041	1902
7200	21516.2482753	
7100	22412.6573465	1927
7000	23309.0664177	
6900	24205.4754889	1952
6800	25101.8845601	
6700	25998.2936312	1979
6600	26894.7027024	
6500	27791.1117736	2008
6400	28687.5208448	
6300	29583.9299160	2038
6200	30480.3389872	
6100	31376.7480584	2069
6000	32273.1571296	
5900	33169.5662008	2101
5800	34065.9752720	
5700	34962.3843432	2135
5600	35858.7934144	
5500	36755.2024856	2170
5400	37651.6115568	
5300	38548.0206280	2205
5200	39444.4296992	
5100	40340.8387704	2242
5000	41237.2478416	
4900	42133.6569128	2280
4800	43030.0659840	
4700	43926.4750552	2319
4600	44822.8841263	
4500	45719.2931975	2363
4400	46615.7022687	
4300	47512.1113399	2400
4200	48408.5204111	
4100	49304.9294823	2441
4000	50201.3385535	
3900	51097.7476247	2484
3800	51994.1566959	
3700	52890.5657671	2527
3600	53786.9748383	
3500	54683.3839095	2571
3400	55579.7929807	
3300	56476.2020519	2617
3200	57372.6111231	
3100	58269.0201943	2663
3000	59165.4292655	
2900	60061.8383367	2710
2800	60958.2474079	
2700	61854.6564791	2757
2600	62751.0655503	
2500	63647.4746214	2805
2400	64543.8836926	
2300	65440.2927638	2854

Above: Figure 12. Transient Flow Tab, with each zone and the summation. Example BOEMRE WCD Calculation spreadsheet.

To left are the individual flow rates from each zone, with the total flow rate on the right. Blacked boxes indicate the pressure in the particular zone cannot overcome the currently flowing zones, and therefore will not contribute to overall rate. The lowest pressure considered at the sand face is 2300 psi. This is because the hydrostatic of the brine is 890 psi, and the hydrostatic of the shallowest oil column, 5000', is 1477 psi, for a total of 2367 psi..This step was repeated for the flow rates given by the Undersaturated Vogel IPR analysis, with similar results obtained.

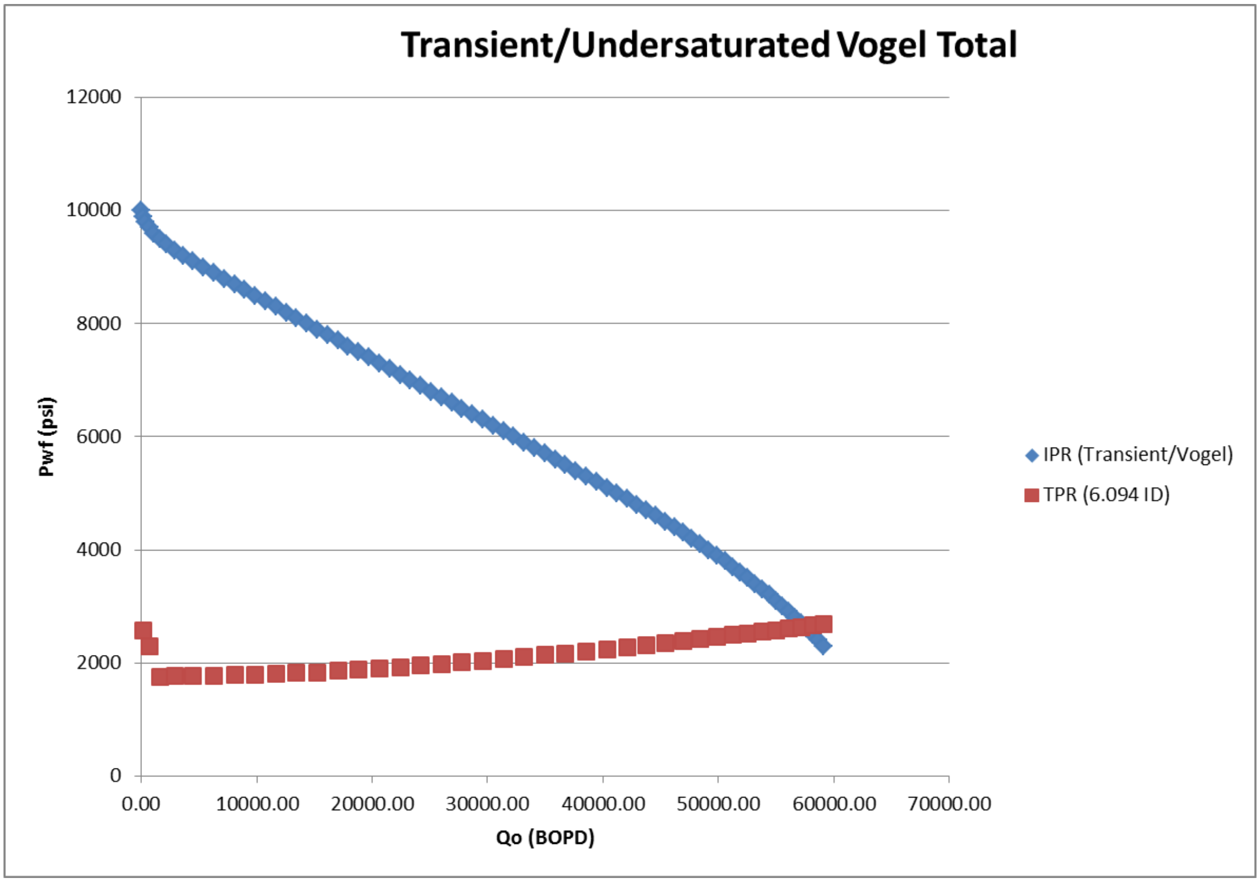
Finally, once all IPR calculations were completed, TPR analysis was done for outflow performance. The correlation considered in the sheet was Beggs and Brill, and utilized to represent flow inside of 7" casing (6.094" ID), a more common casing encountered in the Gulf of Mexico region. Note that for the WCD, there is no drillpipe or tubing in the well, and flow is directly up through the interior casing. Upon completion, these TPRs were graphed with the IPRs previously generated. The resulting nodal analysis plot for the initial conditions of the well provides the estimated flow rate for the WCD as the intersection of the IPR and TPR. That is, these graphs will yield the absolute worst case discharge from the well at early times, or before any reservoir pressure had been drained. These nodal plots are shown below for both Oil Transient and Undersaturated Vogel/Transient IPRs.Oil Transient flow is included below, and only applies above bubble point. The WCD for this case is 61000 BOPD. Bubble Point for this case is below 2400 psi.



Note that the plot to be used for WCD purposes here is the Undersaturated Vogel/Transient Plot. This plot is transient flow above bubble point, and Undersaturated Vogel flow below the bubble point, a more realistic situation.

At the intersection of the TPR and IPR, we have our worst case discharge scenario. The transient flow IPR is the better estimate of well performance at early well times than the pseudo-

steady state option put forth in the SPE document.We see that the WCD for this particular scenario below is about 56,500 BOPD. The next item considered is how to best estimate flow from the well for a significant period of time. Below is a nodal plot containing the Transient/Undersaturated Vogel IPR with the same TPR as in the Transient Flow plot. However, this plot may be more accurate at later times, once the addition of more IPRs (utilizing depleted reservoir pressures) are added. If we cross the bubble point, this IPR is more accurate.



Above: Figure 14. Total Undersaturated Vogel Nodal Plot, Example BOEMRE WCD Calculation spreadsheet. This would be the WCD for the example, as we see the intersection after bubble point, making this IPR the correct one.

reservoir pressure is lowered due to depletion. The best way to do this is generate multiple IPRs versus the same TPR, as previously mentioned, and determine the stepwise flow as pressure is depleted (considering volume over time). This chart, in conjunction with the WCD spreadsheet can be utilized to determine the overall discharge from the well as pressure is depleted. Any reasonable pressure step can be considered, but the smaller the step, the more accurate the flow

rate and overall discharge estimate.The well discharge must be considered at least as long as the time period required to drill a relief well as stated in the NTL.

Conclusions and Recommendations

The primary purpose of this project was to formulate and develop a spreadsheet to aid smaller, independent operators, and allow them to more easily comply with NTL 2010-N06. This spreadsheet is a good starting point in generating WCD estimates. For simple analysis, the sheet is very effective, and the spreadsheet can handle more complicated scenarios. Note thatsome BOEMRE approved factors that may lower the rate are not considered here (i.e. skin, water intrusion, bridging, etc.), as they were not considered the "Worst Case Scenario," but can be incorporated. These factors have been previously mentioned and discussed on pages 10-11. This spreadsheet gives guidance into the stepwise procedure to produce accurate WCD estimations, especially for smaller independent companies in the oil and gas industry. This sheet operates in much the same way as more complicated software packages in generating a WCD, with many of the same data inputs. Additional items to consider are how to handle condensates, especially which TPR correlations to utilize, the role of making PVT properties more accurate, and incorporating an aquifer;different TPR correlations and inputs of PVT properties can be incorporated into the spreadsheet in its current state. Here, the black oil transient model was used, which yielded accurate WCD estimates. Further, more thorough information about the WCD requirements can be found online www.boemre.gov.

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Appendix A

Nomenclature:

k = oil permeability, mD

h = wet vertical thickness, ft

μ_o = viscosity, cp

B_o = formation volume factor, rb/STB

t = time of interest; t <t_{stab}, hrs

t_{stab} = time for pressure transient to reach r_e, hrs

ϕ = porosity, fraction

C_t = total system compressibility, psi^{-1}

r_w = wellbore radius, ft

r_e = drainage radius, ft

S = skin factor (dimensionless)

P_r= Average reservoir pressure

P_{wfs} = Flowing pressure at sandface

P_{wf} = Flowing well pressure

P_b = Bubble point pressure

q = flow rate, bbl/day

q_b = flow rate at bubble point pressure

q_{max} = maximum flow rate from well, at P_{wf} = 0.

Some Spill Notes:

- Explosion occurred April 20,2010.
- Transocean Horizon sunk April 22, 2010.
- 60,000-62,000 bbl/day accepted discharge rate between April 20 and July 15 capping.
- BP's WCD: 162,000 bbl/d (permit to drill).
- Total spill volume: 4.9 MMBO (Flow Rate Technical Group)
- Previous largest U.S. spill, Exxon Valdez, was 6% the size and 16% of the area.
- However, nearly the same mileage of coastline affected due to environment differences.