From: mark_sogge@usgs.gov
Sent: Monday, October 11, 2010 2:34:17 PM
To: pahsieh@usgs.gov
Subject: Draft report - MKS feedback

ttachments: Attachment

Hi Paul,

This was exactly the type of report I was thinking of - straightforward, short, and to the point. Nicely done!

I of course do not have the technical background to comment on the modeling itself, but I have a few comments/questions/edits in the attached version. I have also sent a copy to Dan Maclay, leader of the Reservoir Modeling Team, so he can give us feedback on the proprietary/business confidential data issue.

The next step would be peer-review. Do you have any suggestions for technical experts (internal or external) who might be able to conduct a quick peer-review? One thought I had was to ask Don Maclay or some of the DOE folks from the Nodal Analysis Team. But I welcome suggestions for other alternatives, if you have them.

Mark

Mark Sogge
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From: Paul A Hsieh/WRD/USGS/DOI
To: Mark K Sogge/DO/USGS/DOI@USGS
Date: 10/08/2010 09:40 PM
Subject: draft report

Hi Mark,

Here is the draft report. Please send me your comments on what needs to be modified, and what are the next steps.

Regards,
Paul[attachment "hsieh_report_10-8-10_draft.doc" deleted by Mark K Sogge/DO/USGS/DOI]

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Computer simulation of Reservoir Depletion and Oil Flow from the Macondo Well Following the Deepwater Horizon Incident

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By Paul A. Hsieh

Open-File Report 2010–xxxx

U.S. Department of the Interior
U.S. Geological Survey

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Figure 6. Simulated volumetric flow rate of oil in stock tank barrels per day. The origin of the time axis corresponds to April 20, 2010, the date of the Deepwater Horizon blowout.

Computer simulation of Reservoir Depletion and Oil Flow from the Macondo Well Following the Deepwater Horizon Incident

By Paul A. Hsieh

Abstract

A computer model was developed to simulate reservoir depletion and oil flow from the Macondo well following the Deepwater Horizon incident. Reservoir and fluid properties used in the model are based on: (1) information provided by BP personnel during meetings in Houston, Texas, and (2) calibration by history matching to wellhead shut-in pressures measured during the Well Integrity Test. In the model simulation of the 86-day period from the blowout to shut in, the simulated reservoir pressure at the well face declines from the initial reservoir pressure of 11,850 psi to 9,500 psi. The simulated volumetric flow rate of oil declines from 60,000 stock tank barrels per day to 50,000 stock tank barrels per day. The simulated total volume of oil discharge is 4.6 million stock tank barrels. After shut in, the simulated reservoir pressure recovers to 10,400 psi. The pressure does not recover back to the initial pressure due to reservoir depletion from 86 days of oil discharge.

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Comment [MKS1]: These are not exactly the same as the beginning 62,000 and ending 53,000 BPD values in the final FRTG-DOE estimate. But is it this relative difference that drove the depletion rate used by for the final estimate?

Comment [MKS2]: Are there uncertainty or "error" ranges for this, ar-d the daily estimates?

Comment [MKS3]: Good section!

Background

The computer simulation described in this report was undertaken to support the work of the Flow Rate Technical Group, a group of scientists and engineers lead by U.S. Geological Survey Director Marcia McNutt to estimate the flow of oil from the Macondo well following the Deepwater Horizon blowout incident. Much of the work of the Flow Rate Technical Group was carried out prior to July 15, 2010, when the Macondo well was shut in to begin the Well Integrity Test. The computer simulation described in this report was carried out to analyze the pressure data obtained during the Well Integrity Test in order to gain additional knowledge of the Macondo well and the oil reservoir. Of particular interest is an assessment of reservoir depletion resulting from oil flow during the 86 days from blowout to shut in. The computer simulation also provides estimates of oil flow rates, which can be used for comparison with the estimates by the Flow Rate Technical Group.

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A significant amount of information (for example, reservoir and fluid properties) used in the development of the reservoir model described in this report was provided by BP personnel at meetings in Houston, Texas during the period from late June to early August, 2010. Much of the information is unpublished, and therefore citations could not be provided in this report. Instead, this report focuses on documenting the procedure for developing the reservoir model.

Reservoir Model

Reservoir Geometry and Conditions

The Macondo well produces oil from an oil reservoir known as M56. According to drilling logs, the M56 oil reservoir consists of three oil-producing sand layers. The top of the reservoir is penetrated by Macondo well at a depth of approximately 18,000 ft TVDSS (True Vertical Depth Sub Sea). The combined thickness of the three oil-producing sand layers is approximately 90 ft. Analysis of seismic data suggest that these oil-producing sands are submarine channel fills, with a longitudinal axis approximately in a northwest-southeast orientation. The initial reservoir pressure is 11,850 psi. Reservoir temperature is approximately 240° F. The estimated volume of "original oil in place" is 1.1×10^8 stock tank barrels (stb). The bulk volume of reservoir containing the oil can be estimated by

$$V_b = \frac{V_o B}{\phi(1 - S_w)}, \quad (1)$$

where

V_b is the bulk volume of reservoir containing the oil,

V_o is the volume of original oil in place,

B is the formation volume factor,

ϕ is porosity, and

S_w is water saturation.

Using reservoir properties given in Table 1, the bulk volume of reservoir containing the oil is computed to be 7.68×10^9 ft^3.

In the model, the oil reservoir is represented by a long, narrow channel having a rectangular cross section (Figure 1). The vertical thickness (b) of the channel is 90 ft. The horizontal length (L) and width (W) are initially unknown and are estimated by history matching. However, because $L \times W \times b$ must equal V_b, L and W are related by

$$L \times W = \frac{V_b}{b} = \frac{7.68 \times 10^9 \text{ ft}^3}{90 \text{ ft}} = 8.53 \times 10^7 \text{ ft}^2 \quad (2)$$

The reservoir is assumed to be a closed system. In other words, all six faces of the channel are impermeable boundaries. Within the reservoir, the Macondo well location, as defined by the coordinates (x_w, y_w), is initially unknown and is estimated by history matching.

Mathematical Formulation

The equation of oil flow in the reservoir is given by (Matthews and Russell, 1967)

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = \frac{\phi \mu c}{k} \frac{\partial p}{\partial t}, \quad (3)$$

where

p is pressure,

c is compressibility,

k is permeability,

μ is oil viscosity,

x, y are Cartesian coordinates in the horizontal plane, and

t is time.

In applying equation 3 to the reservoir, the following conditions are assumed:

1. Flow of oil is under single-phase and isothermal conditions,
2. Reservoir properties (permeability, porosity, and compressibility) are homogeneous,
3. Permeability and viscosity are independent of pressure, and
4. Permeability is isotropic.

The compressibility is computed as

$$c = (1 - S_w)c_o + S_w c_w + c_f, \qquad (4)$$

where

c_o is oil compressibility,

c_w is water compressibility, and

c_f is effective formation (or pore) compressibility.

Except for permeability, values of reservoir and fluid properties used in the reservoir model are given in Table 1. Permeability is estimated from history matching.

The volumetric flow rate of oil from the reservoir through the Macondo well and exiting the blowout preventer is modeled by the equation (see Figure 2)

$$Q^2 = C(p_w - \Delta - p_e), \qquad (5)$$

where

Q is volumetric flow rate of oil at reservoir conditions,

C is a coefficient of pressure loss through the well,

p_w is the reservoir pressure at the well face,

Δ is the pressure correction to account for the elevation difference between reservoir and the exit point at the blowout preventer, and

p_e is the ambient pressure at the exit point of the blowout preventer.

The pressure correction Δ is computed by (see Figure 2)

$$\Delta = G_o(d_r - d_e), \quad (6)$$

where

G_o is the oil pressure gradient in the well,

d_r is the depth of the reservoir, and

d_e is the depth of the exit point at the blowout preventer.

For the Macondo well flow calculation, G_o is taken to be 0.246 psi/ft, d_r is 18,000 ft TVDSS, and d_e is 5,000 ft TVDSS. Therefore, Δ is computed to be 3,198 psi. The ambient pressure at the exit point of the blowout preventer, p_e, is 2,231 psi. The volumetric flow rate of oil at surface (stock tank) conditions is computed by dividing Q by the formation volume factor B.

The Q^2 term in Equation 5 is based on the assumption that flow is turbulent in the well. The value of the coefficient C is initially unknown and is estimated by history matching. In the reservoir simulation, C is kept constant in time for the entire period of well flow. This assumes that the changes in outlet configuration, such as cutting of the riser pipe, do not significantly impact the oil flow rate.

MODFLOW Implementation

The U.S. Geological Survey model known as MODFLOW-2000 (Harbaugh and others, 2000) is used to simulate oil flow in the M56 oil reservoir. Although MODFLOW-2000 is originally designed to simulate the flow of groundwater in aquifers, it can be readily adapted for simulating flow of oil in reservoirs under single-phase and isothermal conditions. The fluid flow equation solved by MODFLOW-2000 is analogous to Equation 3, and can be written as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S_s}{K}\frac{\partial h}{\partial t}, \quad (7)$$

where

h is hydraulic head,

K is hydraulic conductivity, and

S_s is specific storage.

For simulating oil flow, the quantities h, K, and S_s are computed as

$$h = \frac{p}{\rho_o g} + z, \tag{8}$$

$$K = \frac{\rho_o g k}{\mu}, \tag{9}$$

$$S_s = \rho_o g \phi c, \tag{10}$$

where

ρ_o is oil density,

z is vertical elevation above a given datum, and

g is gravitational acceleration.

Figure 3 is a map view showing an example finite-difference grid of the oil reservoir, which is represented by one model layer. The cell containing the Macondo well has a horizontal dimension of 1 ft by 1 ft. The cell size increases away from the well to a maximum size of 100 ft. The simulation time step is 0.2 day.

History Matching

The parameter estimation program PEST version 10 (Doherty, 2004) is used to perform history matching—the adjustment of model parameters so that simulated pressures matches measured pressured. PEST implements a nonlinear least-squares regression method to estimate model parameters by minimizing the sum of squares of the differences between measured and simulated pressures:

$$\Phi = \sum_{i=1}^{N} (p_i^{mea} - p_i^{sim})^2 \tag{11}$$

Where

N is the number of measurements.

p_i^{meas} is the the i^{th} measured pressure, and

p_i^{sim} is the i^{th} simulated pressure.

PEST uses the Gauss-Marquardt-Levenberg method to minimize Φ. Details of this method are given in the PEST user's manual (Doherty, 2004).

The pressure data used for history matching were measured during the Well Integrity Test, which began on July 15, 2010. At 2:20 pm Central Daylight Time, the final turn on the choke was closed and the Macondo well was shut in. Wellhead pressures were measured by two pressure gages installed in the sealing cap. For history matching, wellhead pressures measured by the gage known as "PT-3K-2" are used. The simulated wellhead pressure is calculated by subtracting the Δ value of 3,198 psi (see Equation 6) from the simulated reservoir pressure at the well face to adjust for the 13,000 ft elevation difference between the M56 reservoir and the pressure gage.

Figure 4 is a Horner plot showing the measured and simulated wellhead pressures during the Well Integrity Test. The horizontal axis of the Horner plot shows the quantity $(t_p + \Delta t)/\Delta t$, where t_p is the period of oil flow (86 days), and Δt is the time since shut in. Note that on the horizontal axis, time increases to the left. The left-most pressure measurement in the plot was taken on July 29, 2010, which is 14 days after shut in. Figure 4 shows that the simulated pressures closely match the measured pressured. The model parameter values estimated by history matching are given in Table 2.

Simulation Results

Reservoir Depletion

Figure 5 shows the simulated reservoir pressure at the Macondo well face. The origin of the time axis corresponds to April 20, 2010, the date of the Deepwater Horizon blowout. The initial reservoir pressure is 11,850 psi. Immediately after the blowout, the simulated pressure drops rapidly to approximately 11,000 psi and then follows a steady decline to 9,500 psi on day 86, just prior to shut in. After shut in, the simulated pressure recovers and eventually stabilizes at

10,400 psi. The pressure does not recover back to the initial pressure due to reservoir depletion from 86 days of oil discharge.

Oil Flow Rate

Comment [MKS4]: Are there uncertainty or error ranges associated with the output in this type of modeling?

Figure 6 shows the simulated volumetric flow rate of oil for surface conditions (expressed in stock tank barrels per day). The simulated initial volumetric flow rate of oil is 60,000 stock tank barrels per day. As the reservoir depletes, the flow rate decreases to 50,000 stock tank barrels per day on day 86, just prior to shut in. The simulated total volume of oil discharge over the 86-day period from blowout to shut in is 4.6 million stock tank barrels.

Conclusions

A computer model was developed to simulate reservoir depletion and oil flow from the Macondo well following the Deepwater Horizon incident. Reservoir and fluid properties used in the model are based on: (1) information provided by BP personnel during meetings in Houston, Texas, or (2) calibration by history matching to wellhead shut-in pressures measured during the Well Integrity Test. In the model simulation of the 86-day period from the blowout to shut in, the simulated reservoir pressure at the well face declines from the initial reservoir pressure of 11,850 psi to 9,500 psi. The simulated volumetric flow rate of oil declines from 60,000 stock tank barrels per day to 50,000 stock tank barrels per day. The simulated total volume of oil flow is 4.6 million stock tank barrels. After shut in, the simulated reservoir pressure recovers to 10,400 psi. The pressure does not recover back to the initial pressure due to reservoir depletion from 86 days of oil discharge.

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References Cited

Doherty, John, 2004, PEST model-independent parameter estimation user manual, 5th Edition: Watermark Numerical Computing, variously paged, accessed October 5, 2010, at http://www.pesthomepage.org/Downloads.php.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p., accessed October 5, 2010, at http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf.

Matthews, C.S., and Russell, D.G., 1967, Pressure Buildup and Flow Test in Wells: New York, Society of Petroleum Engineers of AIME.

Table 1. Reservoir and fluid properties used in reservoir model. Values are given for reservoir conditions.

Reservoir or Fluid Property	**Value Used in Reservoir Model**
Formation volume factor, B	2.35
Porosity, ϕ	0.21
Effective formation (or pore) compressibility, c_f	1.2×10^{-5} psi^{-1}
Oil viscosity, μ	0.168 cp
Oil compressibility, c_o	1.46×10^{-5} psi^{-1}
Oil density, ρ_o	35.46 lb/ft^3
Water saturation, S_w	0.1
Water compressibility, c_w	3.0×10^{-6} psi^{-1}

Table 2. Values of model parameters estimated from history matching. See Figure 1 for definition of L, W, x_w, and y_w.

Model Parameter	**Estimated Value from History Matching**
Horizontal length of reservoir, L	19,400 ft
Horizontal width of reservoir, W	4,400 ft
X-coordinate of Macondo well, x_w	2,200 ft
Y-coordinate of Macondo well, y_w	1,900 ft
permeability, k	515 millidarcy
Coefficient of pressure loss in well, C	3.34×10^6 (barrel/day)^2/psi

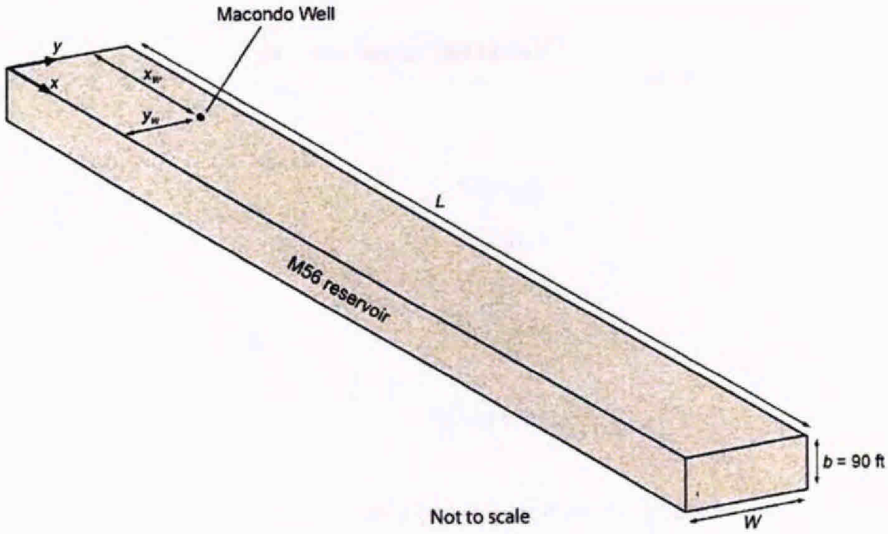

Figure 1. Oblique view of the M56 reservoir.

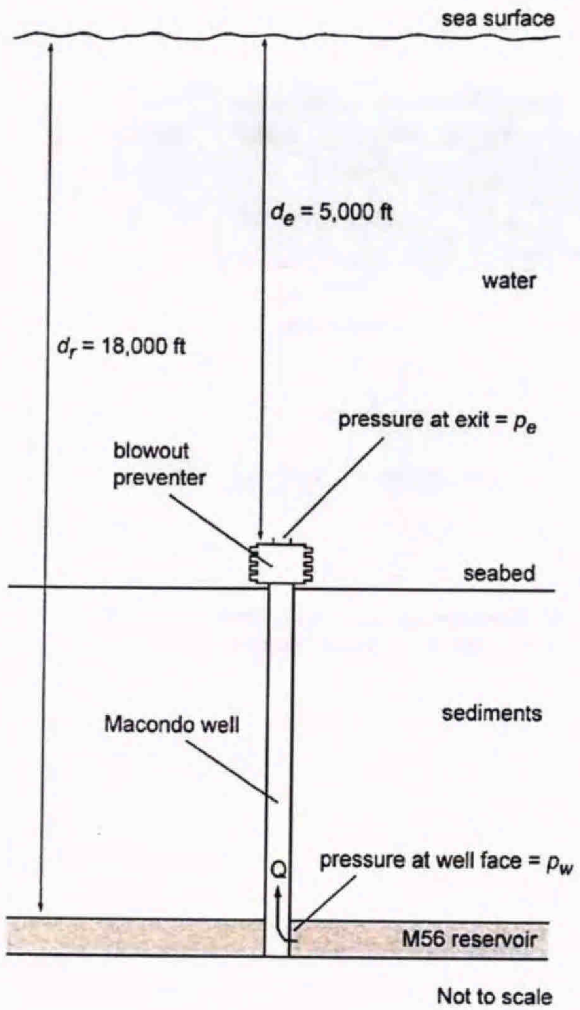

Figure 2. Schematic vertical section showing flow of oil from M56 reservoir through the Macondo well and exiting at the top of the blowout preventer.

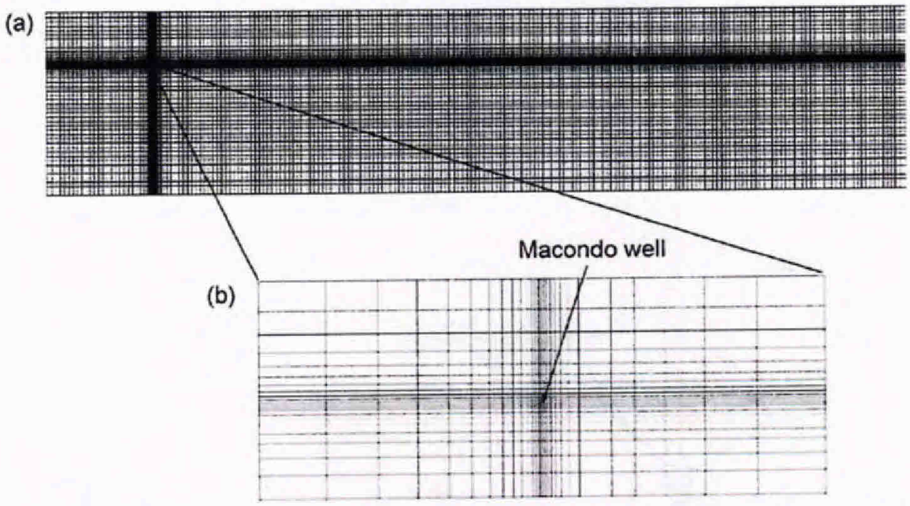

Figure 3. Map view of an example finite-difference grid of the oil reservoir. (a) Entire grid. (b) Detailed view of a small portion of the grid in the vicinity of the Macondo well.

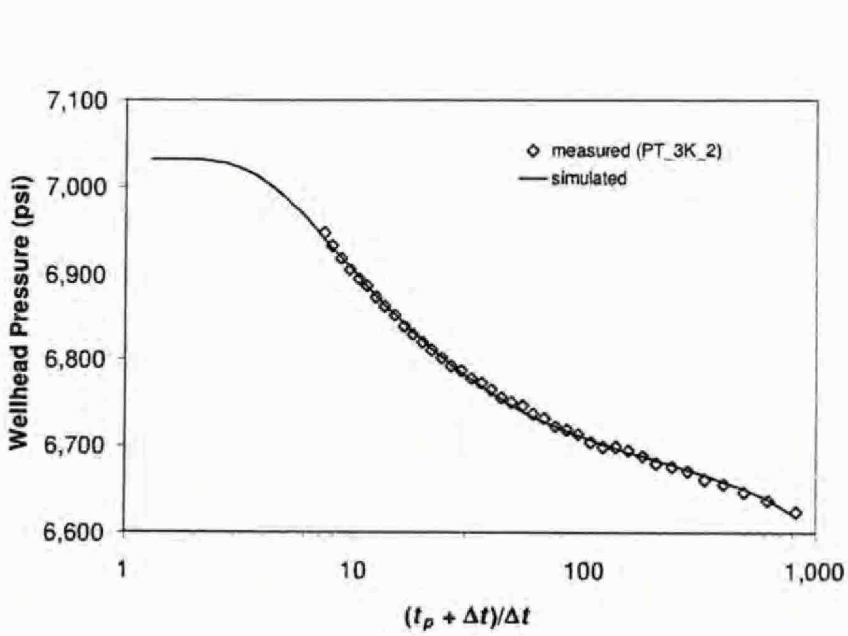

Figure 4. Horner plot of simulated and measured wellhead pressure during Well Integrity Test. t_p is the period of oil flow, which is 86 days. Δt is time since shut in. Note that time increases to the left on the horizontal axis.

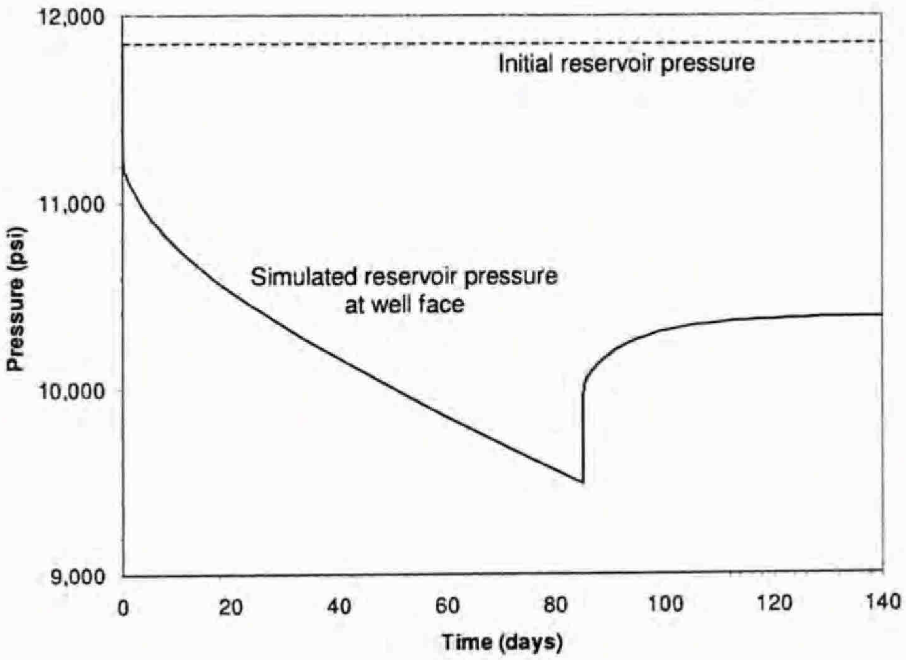

Figure 5. Simulated reservoir pressure at the well face. The origin of the time axis corresponds to April 20, 2010, the date of the Deepwater Horizon blowout.

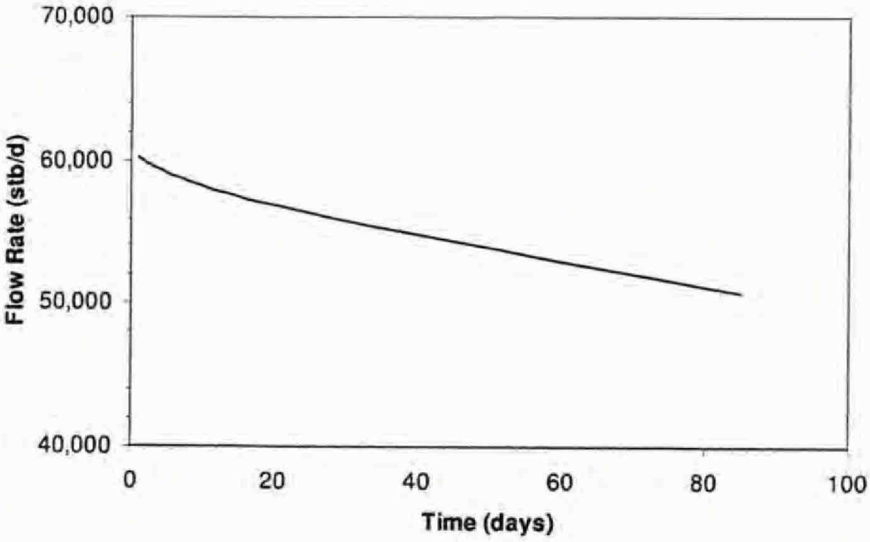

Figure 6. Simulated volumetric flow rate of oil in stock tank barrels per day. The origin of the time axis corresponds to April 20, 2010, the date of the Deepwater Horizon blowout.