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A Model for Predicting Rate and Volume of Oil Spill in Horizontal and Vertical Pipelines

Mode, A.W.[1] , Amobi, J.O[1*] and Salufu, S.O[2]
1 Department of Geology, University of Nigeria, Nsukka, Nigeria
2 Department of Petroleum Engineering, University of Ibadan, Nigeria wilfred.mode@unn.edu.ng[1], johnson.amobi@unn.edu.ng[1*],just4samuel@gmail.com[2]

Abstract
Accurate prediction of total quantity of oil spilled has become essential in designing bioremediation projects for effective remediation, cleanup and for proper assessment of oil polluted environments. The principle of conservation of energy was used to derive a simple analytical model to predict the rate and total volume of oil spills from both horizontal and vertical pipelines. The model was validated by comparing with laboratory measured results at various leakages, pressure and leakages radii. The results indicate that the model values match with the experimental values. The average standard deviation of the model from experimental values is $8.35x10^{-5}$ bbl while the absolute error ranges from $1.11x10^{-3}$ to $3.08x10^{-1}$, and the correlation coefficient value is 0.978. This fact suggests that the model should be utilized with a high degree of confidence to determine the rate of oil spills and total quantity of oil spill in both horizontal and vertical pipelines. The model would help in determining the corresponding quantity of microorganism required to design an effective bioremediation project, and to carry out proper assessment and evaluation of environmental impacts of oil spill in offshore, onshore, or shallow water environments.
Key words: Bioremediation, oil spill, environmental pollutants, flow rate

1. Introduction

An important parameter prior to the planning of bioremediation project in any environment (offshore, onshore, or swamp) where there is oil spillage is the ability of the environmental scientist and engineer to estimate the quantity or volume of oil spilled in that particular environment. Knowing the quantity of oil spilled will enable engineers and scientists to adequately culture or produce the required equivalent quantity of microorganism that will decompose and clean up organic environmental pollutants in the soil and water body (Farhadean, et. al., 2009).

Bioremediation often fails because the volume of oil spilled, is not known (U.S. Congress 1991, and Delaune, et. al., 1984). This makes the process of cleaning up of organic pollutants in the soil and water body difficult. Some of the bacteria employed in bioremediation include members of the genera *Pseudomonas, Flavobacterium, Arthrobacter*, and *Azobacter* (Bragg, et. al., 1993; Mendelssohn and Dianxin, 2003). These microorganisms usually release enzymes on the pollutants. Each enzyme controls one in a series of steps, called a pathway, by which a toxic organic pollutant is metabolized into nontoxic products. Different microorganisms may be used to perform different stages of a pathway, and if adequate quantity of bacterial that is required to release the equivalent quantity of enzymes that are meant to clean up the volume of oil spilled is not known, then bioremediation fails. The volume of oil spilled in an environment should therefore be known before bioremediation exercise commences in order to have an effective result. Knowing the volume of oil spilled, would also help environmental engineers and environmental scientists to fully evaluate the extent of environmental pollution in an area and the negative impact the spill from the pipeline could have on the environment.

Several conventional methods are used in detecting oil spill prior to environmental remediation. They include the traditional pressure drop method; which involves monitoring the pressure drop along a pipeline to detect if it is below the expected pressure required to flow the fluid along the pipeline and the use of harmless radioactive isotopes which are introduced into the pipeline while the points of escape along the pipeline are monitored (Mastandra, 1982). Both methods can detect the points of spill along the pipeline but cannot quantify the volume of oil spilled. Oil trajectory, oil module, and fate model are some of the recent models which are being used in managing oil spill problem (Nwilo and Badejo, 2005).These models only predict the trajectory (direction) of spill in a given area, the extent of spill spread and the speed of spill. In recent times, satellite and GIS are being used to monitor the occurrence of oil spill. It is very effective in identifying the exact time and exact location of oil spill along a pipeline in any area. However, there is need for a model that can predict the quantity of oil spill in both horizontal and vertical pipelines and also mitigate the uncertainties associated with bioremediation projects. Thus, this study is aimed at achieving the following objectives:

1. To develop an analytical mathematical model for estimating and predicting rate of flow of oil spilled from a pipeline and the volume of the spill,

2. To validate the model with empirical data obtained from repeated experimental values of volume of oil spill in the laboratory.

2. Materials and methods

Simple analytical equations were derived from principles of fluid mechanics with scientific assumptions to mimic pressure, velocity and the forces that act along a pipeline. Experimental work was conducted in the laboratory under laminar flow condition in order to generate empirical data to validate the effectiveness of the analytical equations that were derived. About 2bbl of diesel oil was flown through a horizontal pipeline of about 16ft. A total of five holes were created along the pipe at different points in order to allow oil to spill from the holes. A pump was connected to the pipe and the inlet pressure was measured as well as the pressure at the five leaking points along the pipe, using six manometers. Graded containers were placed at each leaking point to collect the quantity of oil that spills out. The time for the oil to spill was measured by stop watch. The diameters of the leaking holes were measured with vernier calipers and the density of the oil was measured. The laboratory units of all the measured parameters were converted to field units. Empirical values were used to validate analytical values using the trends of parameters predicted and those measured in the laboratory.

3. Development of Model

The model was developed based on the following assumptions:

1. Laminar flow
2. Incompressible fluid
3. Surface area of leak is assumed circular in nature
4. Average radius of the leak radii is taken as the radius of the leak.

By applying the principle of conservation of energy, pressure along a pipeline at a particular point (Fig. 1) can be given as:

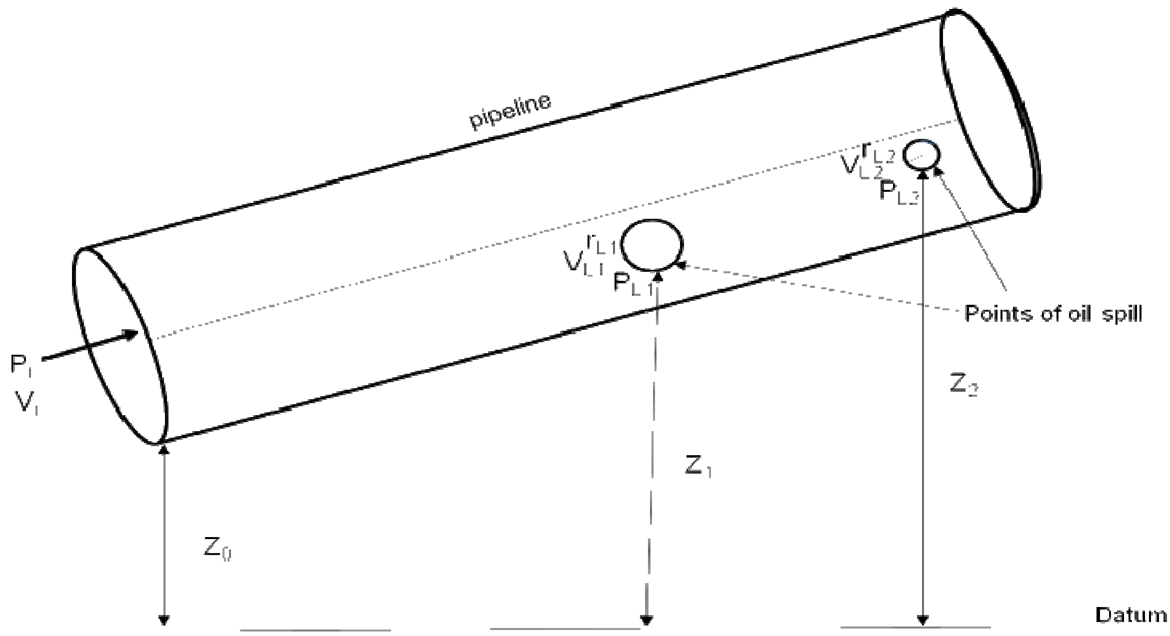

Fig. 1: Inclined pipeline showing points of oil spill.

Inlet Pressure + Pressure of oil column + kinetic energy = constant

$$P_i + \rho g Z_0 + \tfrac{1}{2} m V_i^2 = K \quad (1)$$

$$\tfrac{1}{2} m Vi^2 = mgh \quad (2)$$

Therefore, $$h = \frac{1}{2g} Vi^2 \quad (3)$$

Since $P = \rho gh$ (4)

Substitute eq. (3) in (4) thus kinetic energy becomes:

$$Ke = \frac{1}{2}\rho Vi^2$$

Therefore eq. (1) becomes;

$$P_i + \rho g Z_0 + \frac{1}{2}\rho V_i^2 = K$$

$$P_i + \rho g Z_0 + \frac{1}{2}\rho V_i^2 = P_L + \rho g Z_1 + \frac{1}{2}\rho V_L^2 \quad (5)$$

Where,

P_i = Inlet pressure
ρ = Density of the oil
g = Acceleration due to gravity
V_i = inlet velocity
P_L = Leakage pressure
Z_0 = Height of the inlet pressure from the reference point
Z_1 = Height of the leak at point one along pipeline
Z_2 = Height of the leak at point two along pipeline
r_{L1}= Radius of leak at point one along pipeline
r_{L2}= Radius of leak at point two along pipeline

For Horizontal Pipe:

For horizontal pipe, eq. 5 will be;

$$P_i + \frac{1}{2}\rho V_i^2 = P_L + \frac{1}{2}\rho V_{L1}^2 \quad (6)$$

Therefore velocity of leak VL_1 will be;

$$V_{H_{L1}} = \sqrt{\frac{2\left[\left(P_i + \frac{1}{2}\rho V_i^2\right) - P_L\right]}{\rho}} \quad (7)$$

$$F \alpha \eta r_L V_L$$

Therefore $F = K\eta r_L V_L$ (8)

Where $K = 6\pi$

$$F = 6\pi r_L \eta V_L \quad (9)$$

Assumption: Leak surface is circular in nature

Therefore, $F = \pi r_L^2 P_L$ (10)

Sub eq. 10 in eq. (9) to have;

$$\pi r_L{}^2 P_L = 6\pi r_L \eta V_L \quad (11)$$

$$\eta = \frac{\pi r_L{}^2 P_L}{6\pi r_L V_L} = \frac{r_L P_L}{6V_L} \quad (12)$$

Sub eq. (7) in (12)

$$\eta = \frac{r_L P_L \sqrt{\rho}}{6\sqrt{2\left[\left(Pi + \frac{1}{2}\rho V_i^2\right) - P_L\right]}} \quad (13)$$

Flow rate of oil spill from pipe is given by:

$$Q_{H_{os}} = \frac{\pi r_L{}^4 \rho g}{8T_p \eta} \quad (14)$$

Sub eq. (13) in (14)

Therefore,

$$Q_{H_{os}} = \frac{\pi r_L{}^4 \rho g}{8T_p} X \frac{6\sqrt{2\left[\left(P_i + \frac{1}{2}\rho V_i^2\right) - P_L\right]}}{r_L P_L \sqrt{P}} \quad (15)$$

Rate of oil spills, Q_{Hos}

$$Q_{os} = \frac{6\pi r_L^3 \rho g \sqrt{2\left[\left(P_i + \frac{1}{2}\rho V_i^2\right) - P_L\right]}}{8T_p P_L \sqrt{\rho}} \quad (16)$$

Inlet velocity can be express as

$$Vi = \frac{\sqrt{2P_i}}{\sqrt{\rho}} \quad (17)$$

If eq. 17 is substituted in eq. 16, then flow rate for horizontal pipeline will become:

$$QH_{os} = \frac{6\pi r_L^3 \rho g \sqrt{2(2P_i - P_L)}}{8T_p P_L \sqrt{\rho}} \quad (18)$$

If the pipeline contains more than one leaking point, Q_{THos} is given by:

$$Q_{THos} = \frac{6\pi \rho g}{8T_P \sqrt{\rho}} \sum_{i=1}^{n} r_{Ln}^3 \frac{\sqrt{2(2P_i - P_{Ln})}}{P_{Ln}} \quad (19)$$

Amount of oil that spills from horizontal pipeline is given by:

$$V_{Hos} = QTHosXt$$

$$V_{Hos} = \frac{6\pi r_L^2 \rho g t \sqrt{2\left[\left(P_i + \frac{1}{2}\rho V_i^2\right) - P_L\right]}}{8T_p P_L \sqrt{\rho}} \quad (20)$$

If eq. 17 is substituted in eq. 20 volume of oil spill in horizontal pipeline will be:

$$V_{Hos} = \frac{6\pi r_L^2 \rho g t \sqrt{2(2Pi - P_{Ln})}}{8T_p P_L \sqrt{\rho}}$$

Therefore, the total quantity of oil spill in horizontal pipeline is:

$$V_{HTos} = \frac{6\pi \rho g}{8Tp\sqrt{\rho}} \sum_{i=1}^{n} \frac{t_n r_{Ln}{}^3 \sqrt{2(2Pi - P_{Ln})}}{P_{Ln}} \quad (21)$$

For Vertical Pipe:

For vertical pipe, eq. 8 will still remain without any part being altered:

$$P_i + PgZ_0 + \frac{1}{2}\rho V_i^2 = P_L + \rho g Z_i + \frac{1}{2}\rho V_L^2$$

Therefore,

$$V_{VL} = \sqrt{\frac{2\left[\left(P_i + PgZ_0 + \frac{1}{2}\rho V_i^2\right) - \left(P_L + \rho g Z_1\right)\right]}{\rho}} \quad (22)$$

Sub eq. (20) in eq. (12)

Therefore

$$\eta = \frac{r_L P_L}{6V_L} X \frac{\sqrt{\rho}}{\sqrt{2\left[\left(P_i + \rho g Z_0 + \frac{1}{2}\rho V_i^2\right) - \left(P_L + \rho g Z_1\right)\right]}}$$

$$\eta = \frac{r_L P_L \sqrt{\rho}}{6V_L \sqrt{2\left[\left(P_i + \rho g Z_0 + \frac{1}{2}\rho V_i^2\right) - \left(P_L + \rho g Z_1\right)\right]}} \quad (23)$$

When eq. (23) is sub in eq. (14), then rate of oil spill from vertical pipe is given as:

$$Q_{Vos} = \frac{6\pi r_L^3 \rho g V_L \sqrt{2\left[\left(P_L + \rho g Z_0 + \frac{1}{2}\rho V_i^2\right) - \left(P_L + \rho g Z_1\right)\right]}}{8T_p P_L \sqrt{\rho}} \quad (24)$$

If eq. 17 is substituted in eq. 24, therefore rate of oil spill from a vertical pipe is modified to:

$$Q_{Vos} = \frac{6\pi r_L^3 \rho g V_L \sqrt{2\left[(2Pi + \rho g Zo) - (PLn + \rho g Zn)\right]}}{8T_p P_n \sqrt{\rho}} \quad (25)$$

Therefore, total rate of oil spills along a vertical pipe is given by:

$$Q_{VTos} = Q_{vos1} + Q_{Vos2} + Q_{Vos3} + \ldots\ldots\ldots\ldots\ldots Q_{Vosn}$$

$$Q_{VTos} = \frac{6\pi\rho g}{8Tp\sqrt{\rho}} \sum_{i=1}^{n} \frac{r_{Ln}^3 V_{Ln} \sqrt{2\left[(2P_i + \rho g Z_0) - (P_{Ln} + \rho g Z_n)\right]}}{P_{Ln}} \quad (26)$$

Therefore the volume of oil spills or quantity of oil spills from vertical pipe is given by:

$$V_{vos} = Q_{Vos} \; X \; t \quad (27)$$

$$V_{Vos} = \frac{6\pi r_L^3 \rho g V_L t \sqrt{2\left[(2Pi + \rho g Z_o) - (P_{Ln} + \rho g Z_n)\right]}}{8T_p P_n \sqrt{\rho}} \quad (28)$$

Therefore total volume of oil spills from vertical pipe is given by:

$$V_{vTos} = V_{vos1} + V_{vos2} + V_{vos3} + \ldots\ldots\ldots\ldots + V_{vosn}$$

$$V_{vTos} = \frac{6\pi\rho g}{8Tp\sqrt{\rho}} \sum_{i=1}^{n} \frac{r_{Ln}^3 V_{Ln} t_n \sqrt{2\left[(2P_i + \rho g Z_0) - (P_{Ln} + \rho g Z_n)\right]}}{P_{Ln}} \quad (29)$$

3.1. Validation of the Developed Model

For validation purpose, the volumes of oil spill, estimated and predicted by the model from the five leaking points in the pipeline were compared with the experimental data in Table 1.

Table 1: Results of the experimental and predicted volume of oil spill.

Leaks	Pi (Psi)	PL (Psi)	rL (ft)	Vi (ft/d)	VL(ft/d)	Tp (ft)	h (ft)	ρ (lb/bbl)	t (d)	Vexp (bbl	Vpred(bbl	QHos (bbl
1	10.2	0.0035	0.0033	0.57	0.01	0.0098	0.057	62	0.00165	0.0029	0.002008	1.216675
2	10.2	0.0029	0.0033	0.57	0.0097	0.0098	0.057	62	0.00242	0.0031	0.003554	1.468422
3	10.2	0.0041	0.0033	0.57	0.0115	0.0098	0.057	62	0.0012	0.00126	0.001246	1.03861
4	10.2	0.0047	0.0033	0.57	0.012313	0.0098	0.057	62	0.0006	0.000543	0.000544	0.906008
5	10.2	0.0023	0.0033	0.57	0.008614	0.0098	0.057	62	0.00482	0.00889	0.008924	1.851516

The statistical analysis results were compared with the predicted values by the model at various leakage pressure conditions shown in figures 2, 3 and Table 2.

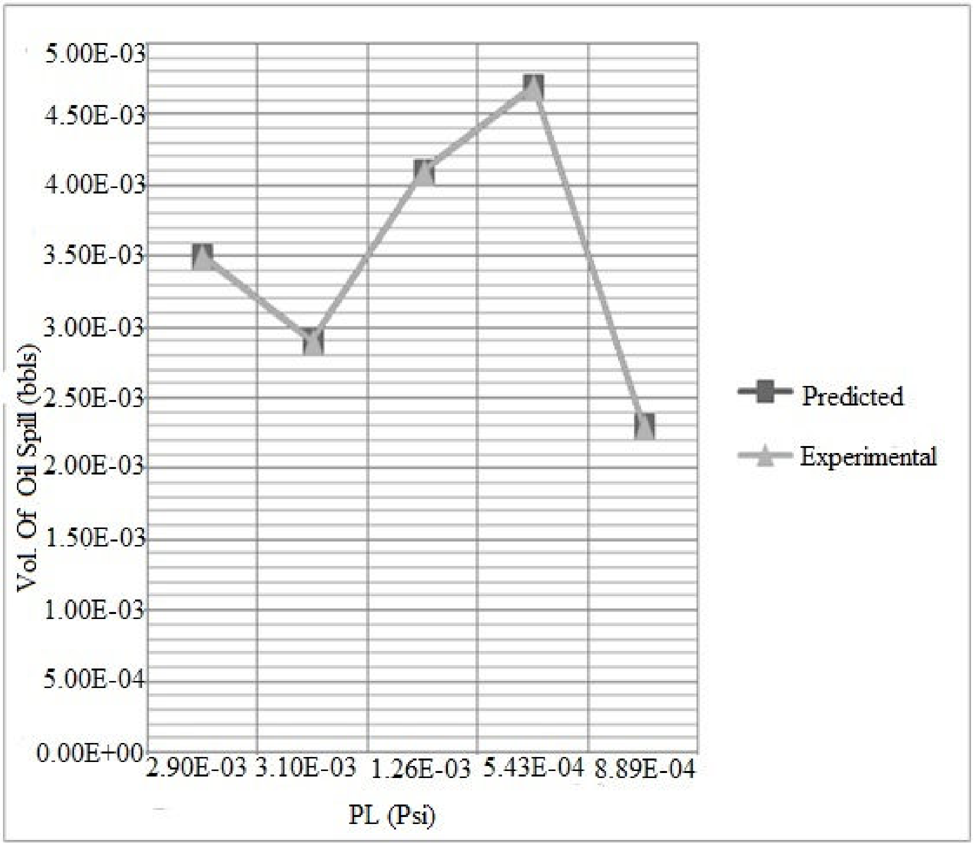

Fig. 2: Comparison of the experimental and predicted values.

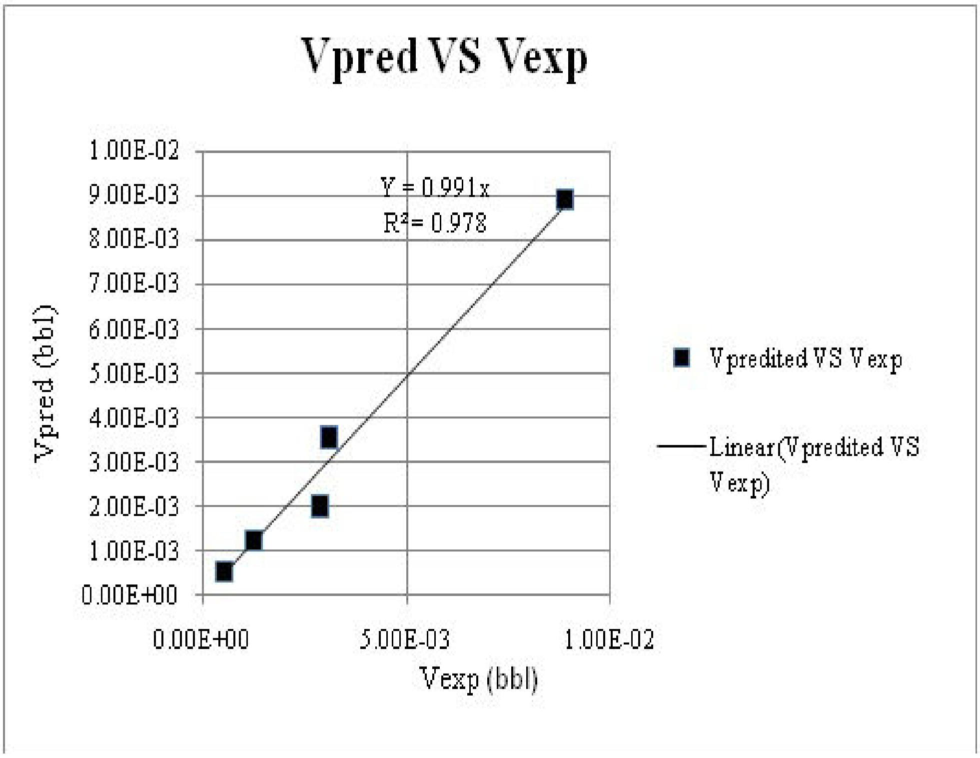

Fig. 3 Cross plot of the experimental and predicted values.

Table 2: Error analysis in predicted volume of oil spill.

Leaks	Ei	Emax	AAPRE	AD	AAD
1	-3.08E-01	0.307754	0.093978	8.35E-05	1.78E-04
2	1.46E-01	0.146317			
3	-1.08E-02	0.010848			
4	1.11E-03	0.001114			
5	3.86E-03	0.003859			

The statistical criteria used for error analysis include the following:
Average deviation:

$$AD = \frac{1}{N}\sum_{i=1}^{n}\left(Exp_i - \Pr ed_i\right)$$

Average absolute deviation:

$$AAD = \frac{1}{N}\sum_{i=1}^{N}\left|Exp_i - \Pr ed_i\right|$$

Maximum error:

$$E_{\max} = \underset{i=1}{\overset{N}{Max}}\left|E_i\right|$$

Where

$$E_i = \left[\frac{V_{vos}\ predicted - V_{Hos}\ Experimental}{V_{Hos}\ Experimental}\right]$$

i= 1, 2, 3 ….N.
Average absolute percentage relative error

$$AAPRE = \left(\frac{1}{N}\right)\sum_{i=1}^{N}\left|E_i\right|$$

4. Results and discussion

The volumes of oil spill predicted by the proposed model show good agreement with experimental values as shown in Figures 1, 2, and 3. This is shown not only in the value of the correlation coefficient (R^2=0.978) and the results of the error analysis in Table 2; it also indicate that the model is closest to the experimental values and therefore more reliable both for predicting volume of oil spill and rate of oil spill from both horizontal and vertical pipes in any given environment where there is oil spillage.

5. Conclusions

A new model has been developed from inlet pressure, leakage pressure, density of spilled oil, and radius of leaking points. This model can be applied universally to the determination of quantity of oil spilled and the rate of oil spill, from both horizontal and vertical pipeline into any given environment (offshore, land and shallow water). The proposed model has been successfully validated and compared with experimental values with average absolute percentage relative error of 9%, average deviation of $8.35x10^{-5}$ bbl and correlation coefficient of 0.978 ($R^2 \approx 1$).This model will enable, environmental engineers and scientists to successfully evaluate the extent and magnitude of environmental impact of oil spill in any environment where there is oil spillage from a pipeline. It would also enhance the estimation of the quantity of bacteria (microorganism) required in bioremediation to clean up any volume of oil spill in an environment. Unlike the existing models and methods this model can evaluate the volume of the spill, rate of spill at any leaking point along the pipeline, and the pressure and velocity of the spill at each point of leakage along the pipeline.

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References

Bragg, J. R., Prince, R. C., Hamer, E. J. and Atlas, R. M. 1993. Effectiveness of bioremediation for the Exxon Valdex oil spill, Nature*,* Vol.368, pp.413-418.
Delaune, R. D. , Smith, C. J. , Patrick, W. H. , Fleeger W. J., and Tolly, W. D. Effect of oil on salt Mandbiota: Method of restoration of Environment. *Pollution* Vol.36, pp.207-227.
Farhadian, M., Duchez, D., Vachelard, C., and Larroche, C. 2009. Accurate quantitative
determination of monoaromatic compounds for the monitoring of bioremediation processes, *Bioresources Technology*, Vol.100, pp.173-178.
Mastrandra, R. J. 1982. Petroleum pipeline detection study, *Science Application Incorporation,* 101 Continental Bulevad, El Segundo, CA. 184pp.
Mendelssohn I. A. and Dianxin. L. 2003.Development of bioremediation for oil spill clean-up in Coastal wetland. *United States Department of Interior Mineral Management Service,* Gulf of Mexico OCS – MMS, 34pp.
Nwilo, P. C., and Badejo, O. T. 2005. Oil spill problem in the Niger Delta. *International Oil Spill Conference,* Miami, Florida, USA, 105pp.
U.S. Congress, Office of Technology Assessment.1991. Bioremediation for Marine Oil Spills— Background Paper, OTA-BP-O-70 .Washington, DC: U.S. Government Printing Office, 36pp.

Glossary

P_i	Inlet pressure, Psi
V_i	Inlet Velocity of fluid, ft/d
P_L	Leakage pressure, Psi
V_L	Velocity of spill, ft/d
F	Force at leaking point, Psi-ft^2
r_L	Radius of Leakage, ft
Q_{Hos}	Flow rate of oil spill in horizontal pipe, bbl/d
Z	Depth of pipe from a given datum, ft
Q_{THos}	Total Rate of oil spill in horizontal pipeline, bbl/d
Q_{Vos}	Rate of oil spill in vertical pipeline, bbl/d
Q_{TVos}	Total rate of oil spill in vertical pipeline, bbl/d
V_{Hos}	Volume of oil spill in horizontal pipeline, bbl
V_{THos}	Total Volume of oil spill in horizontal pipeline, bbl
Vv_{os}	Volume of oil spill in vertical pipeline, bbl
V_{TVos}	Total volume of oil spill in a vertical pipeline, bbl
T_p	Pipeline thickness, ft
t	Time of oil spill, d
g	Acceleration due to gravity
AAD	Average absolute volume of oil spill deviation
AD	Average of volume of oil spill deviation
AAD	Average absolute volume of oil spill deviation
E_{max}	Maximum error
E_i	Percentage error

Greek Symbols

π	Pie
η	Coefficient of Viscosity of oil, Psi/ft^2
ρ	Density of oil, lb/cuft