

**A NEW AND PRACTICAL METHOD FOR ZONE SELECTION IN HYDRAULIC FRACTURING
OPERATION: A CASE STUDY IN SIRRI-A RESERVOIR**

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Abstract. Hydraulic fracturing creates a high conductivity channel within a large area of formation and bypasses any damage that may exist in the near wellbore region. Moreover, it has been one of the major well stimulation techniques to increase well production. Accurate knowledge of parameters affecting fracture initiation pressure provides essential information to assess the identification of fracture initiation zones and hydraulic fracture strategies as well as completion design requirements. In order to study the feasibility of implementing this method, Sirri-A reservoir is selected and an extensive literature survey was carried out. Geomechanical model factors are calculated by poroelastic methods and normal stress regime ($\sigma_v > \sigma_H > \sigma_h$) is diagnosed for the reservoir rock. Based on the crucial factors such as in situ stress, porosity, water saturation and uniaxial compressive strength, best layers for hydraulic fracturing operation are selected and their fracture pressures are estimated. A simulation of hydraulic fracturing job in these zones and comparison of the results by predicting the production and investigating Net Present Value (NPV) for these cases is carried out. Using the results we decide which one of these candidates is the best case for a hydraulic fracturing operation.

Keywords. Hydraulic fracturing; geomechanical; petrophysics; zone; formation.

1. INTRODUCTION

Hydraulic fracturing has been used commercially as a stimulation technique in the petroleum industry. Such fracturing jobs are designed to stimulate production from reservoirs with low permeability (Soni, Pitroda and Bhavsar, 2015). This often involves pumping large amounts of fluid and solids (proppant), thus creating long fractures filled with proppant. A massive hydraulic fracturing (MHF) job may exceed one thousand cubic meters of fluid and one million kilograms of proppant. The fracture thus creates a high-permeability flow channel towards the wellbore which has a large drainage area towards the low-permeability formation (Perumalla, Santagati, Addis, Al-Mahrooqi, Curtino, Briner and Qobi, 2012).

In general, the main objectives of the hydraulic fracturing process are as below: (1) Increasing the flow rate of oil and/or gas from low permeability reservoirs. (2) Increasing the flow rate of oil and/or gas from wells that have been damaged. (3) Connecting the natural fractures and/ or cleats in a formation to the wellbore. (4) Decreasing the pressure drop around the well to minimize sand production. (5) Decreasing the pressure drop around the well to minimize problems with asphaltene and/or paraffin deposition. (6) Increasing the area of drainage or the amount of formation in contact with the wellbore. (7) Connecting the full vertical extent of a reservoir to a slanted or horizontal well.

In the field of rock mechanics, hydraulic fracturing is the process of injecting pressured water into a sealed bare borehole to induce tensile fracture in the rock (Perumalla, Moos, Bartoon, Finkbeiner, Al-Mahrooqi, Weissenback and Al-syabi, 2011). This fracturing process is characterized by the formation, growth, and coalescence of microcracks as well as the initiation and development of macroscopic faults.

Until 2013 four unsuccessful hydraulic fracturing treatments have been recorded in the Iranian oil industry (Kerahroodi, Sadegh, Masoud and Mahnaz, 2014). Hydraulic Fracturing Simulation of Mansouri Oil Field in Iran. *Turkish Journal of Engineering, Science and Technology*. 01. 44-54.). The three acid fracturing treatments had been done in a carbonate reservoir mostly composed of limestone in one Iranian oilfield and the single propped fracturing treatment was done in another carbonate reservoir. Studying the previous fracturing jobs shows that the lack of mechanical

properties and appropriate geotechnical knowledge can be major causes leading to failure.

The dimension and propagation characteristics of a hydraulic fracture are important information in design of fracturing operations. Knowing the properties of reservoir rock, fracturing fluid, and the magnitude and direction of in situ stresses, one seeks an accurate prediction of the dimension (opening width, length, and height) of the hydraulically induced fracture for a given pumping rate and time (Pak & Chan, 2008). Many fracture models have been developed for this purpose. The breakdown pressure is defined as the pressure required not only for fracture initiation but early propagation, since the identification of the fracture initiation pressures has proved not to be sufficient to determine if a zone could be fractured or not.

Field observations suggest that the breakdown pressure moves between the pressure requirements to overcome the minimum in-situ stress and the tensile strength of the materials, considering for both cases the additional pressure needed for early fracture extension.

Based on these, lower and upper bounds can be determined through the definition of the profiles related to: (1) Minimum insitu stress (2) Pressure required overcoming the tensile strength (3) early fracture extension pressure. The pressure requirements for fracture initiation are influenced not only by the far field stress but by the re-distribution of stresses around the well, tensile strength and mechanical properties of the materials.

Selection of suitable or target layer for hydraulic fracturing operation has its special challenges. Presentation of an accurate geomechanical model which saves the time and reduces the field attempts makes the selection of suitable layer possible. In order to prepare a geomechanical model, we need a wide range of data such as wire line logs, image logs, rock mechanics tests, drilling reports and data fracture analysis selection of suitable layer is done based on rock and fluid properties for instance porosity, water saturation and in situ stress. In this study we add the effect of uniaxial compressive strength (UCS) and the difference between horizontal stresses in order to accurate interval selection process.

The field under study consists of three reservoirs of Asmari, Bangestan and Khami, of which the first two are oil reservoirs and the latter, a gas reservoir. Located in a flat plain, the studied field has no

surface outcrop. This field, which is located in Zagros thrust-fold belt, has the same trend as the Zagros, namely the north-west and south-east. The Bangestan limestone unit consists of two formations, Ilam and Sarvak. The Sarvak formation is part of middle Cretaceous calcareous rocks. Lithology of the Ilam formation consists of limestone rocks with a regular stratification, in which there are thin interlayers of shale in some intervals. Here we select 2 zones for this study (one in Ilam formation and one in Sarvak) and using our flow work we simulate a fracturing job for each zone. The results show a very major difference in these zones.

2. MATERIALS AND METHODOLOGY

2.1. Geomechanical modeling

In order to develop mechanical earth model (MEM), elasticity coefficient must be calculated, first. These coefficients can be obtained using empirical relations and also well log measurements. To calculate elasticity coefficient, sonic and density logs were employed. The velocities of compression waves and shear waves depend on the density and the elastic properties of the rock as defined by the following characteristic equations.

The work flow that is designed for preparing the following study was divided in five main steps that include important factors influence the process of selection of the best layer for hydraulic fracturing operation in the Bangestan reservoir rock:

- Calculation of the elastic properties of rock such as dynamic and static Young's modulus and Poisson's ratio. The equations that are used in this section are fed by compressive and shear transient times. The transient times is calculated by sonic log data.
- Determination of main in situ stresses such as vertical stress or overburden stress, maximum and minimum horizontal stresses and make decision what type of stress regime exist in understudying area. Based on Anderson (1951), there are three different stress regimes exist:
 - a) Normal stress regime ($\sigma_v > \sigma_H > \sigma_h$)
 - b) Reverse stress regime ($\sigma_H > \sigma_h > \sigma_v$)
 - c) Strike Slip stress regime ($\sigma_H > \sigma_v > \sigma_h$)
- Safe mud window design. Undoubtedly, most of the problems we are faced during drilling operation (such as fishing, pipe sticking) are

related to the inappropriate mud weight selection. This window helps that the best mud weight select and reduces the cost of drilling beside the time that is saved.

- There are stresses in different directions such as radial, axial and tangential directions that are created after engineering constructions. The mentioned stress causes different types of failure in the borehole. In fourth step, these stresses are calculated and the type of failure is predicted also the minimum necessary pressure for hydraulic fracturing in layers is determined.
- Final step is simulation of hydraulic fracturing job in the reservoir and comparing the results by predicting the production and investigating Net Present Value (NPV) for cases. Finally decide which one of these candidates is the best case for a HF.

2.2. Elastic properties

Elastic properties such as static Young's modulus and Poisson's ratio are the main data we need. In better word poroelastic correlations are fed by this data. There are two references for calculation of elastic coefficient: (a) logging data, (b) empirical correlations. The two following correlations are specifically used to calculate the dynamic Young's modulus and Poisson's ratio base on the transient times that are gained by sonic log data:

$$\nu_d = \frac{\frac{1}{2} \left(\frac{\Delta t_c}{\Delta t_s} \right)^2 - 1}{\left(\frac{\Delta t_c}{\Delta t_s} \right)^2 - 1} \quad (1)$$

$$\Delta t_s = 1.7891 \Delta t_c + 7.622 \quad (2)$$

$$E_{Dynamic} = \frac{\rho_b \left[3 - 4 \left(\frac{\Delta t_s}{\Delta t_c} \right)^2 \right]}{\Delta t_s^2 - \Delta t_c^2} \quad (3)$$

Where ν_d is the dynamic Poisson's ratio, E_d is the dynamic Young modulus (psi), Δt_s is shear wave travel time (ft/s), Δt_c is compressional wave travel time (ft/s), ρ_b is the bulk density (gr/cm³) and ρ_{gr} is the grain density (gr/cm³). We have used a correlation that was developed in Bangestan reservoir to calculate the shear wave:

In the above equations, primary and secondary transient times are in km/s, and dynamic Young's

modulus is in Gpa. Generally, in the Bangestan reservoir rock, the range of Poisson ratio is 0.3–0.37 and for the understudying section Poisson’s ratio is 0.3. Since we could not use dynamic data in geomechanical models, it is essential to convert them to the static condition (Figure1).

Based on the existing empirical correlations for the under studying area:

$$\nu_{static} = \nu_{dynamic} \quad (4)$$

$$E_{Static} = 0.4145 E_{Dynamic} - 1.0593 \quad (5)$$

For hydraulic fracturing operation, we should consider three crucial conditions:

- The candidate layer should have low in situ stress.
- The candidate layer should have high porosity.
- The candidate layer should have low water saturation.

If the under studying layer has the three mentioned conditions at the same time, it will be a perfect candidate for our purpose. If any of the conditions were not true, we cannot select this layer as a suitable layer because of the near future problems that might be faced like water production problem. In the recent studies, all three of the above conditions had been used, but we also included the effect of other geomechanical factors such as UCS or the difference between the minimum and maximum horizontal in situ stresses.

UCS, which is the capacity of rock to withstand axially directed pushing forces, was calculated by the following empirical equation:

$$UCS = 135.9 e^{- (4.8 \phi)} \quad (6)$$

Here, UCS is in Mpa.

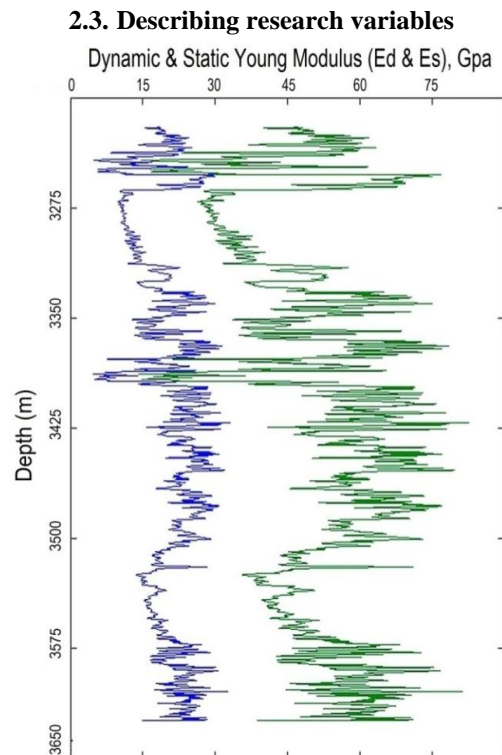
Based on experimental studies, rocks with the high UCS in the range of 159–207 Mpa have high strength against failure. Where UCS is weaker it means that rock has low level of strength and fracture formation is easier and vice versa. In other words, high UCS not only restricts fracture initiation but also makes some problems on the way to identify the suitable layer for hydraulic fracturing operation. One other use for UCS is when there is

no tensile strength. In this case, if UCS is estimated accurately, the tensile strength is equal to 1/10 to 1/12 times UCS (Figure2).

Furthermore, the difference between minimum and maximum horizontal stresses is another critical factor that even a small diversity between these two stresses makes some problems in the controlling of stress orientation. In other words, we cannot make fracture in a desirable direction. In other words in homogeneous media, where horizontal stresses are very close to each other, control the direction of the fracture is difficult and this media are stable. This is very useful in wellbore stability issue.

It is generally accepted that stress variation between pay zone and adjacent layers is the most important controlling factor for creating fracture height containment. Both the target layer and adjacent layers have critical role in layer selection process because if adjacent layers are weak, it will causes fracture propagate into them which results in the water production problem. Water cut is definitely undesirable since two to three separator phases are needed for its treatment that causes more expenses with a non-profitable production. Basically, adjacent layers should be characterized by high in situ stress and low porosity so that they can act as barrier layers.

Figure1. Dynamic and static Young’s modulus



To get the geomechanical model, firstly, calculate the magnitude of the main stresses, which are those vertical stresses on the plane that their shear stresses are zero. They are defined as maximum main stress (S1), intermediate main stress (S2) and minimum main stress (S3) (Figure3). The vertical stress (σ_v) is one of those, so the two other main stresses are minimum horizontal stress (σ_h) and maximum horizontal stress (σ_H) (Fjaer, Holt, Horsrud, Raaen, & Risnes, 2008) (Al-Ajmi, & Zimmerman, 2006).

Vertical stress or overburden stress is determined by the below formula:

$$\sigma_\theta = \int_0^z \rho(z) g dz \cong \bar{\rho} g z \quad (7)$$

Here, $\rho(z)$ is the rock density and the function of depth. The average magnitude of density has been equaled by 2.56 (gr/cm³). Finally, overburden or vertical pressure is calculated by integrating all available density logs.

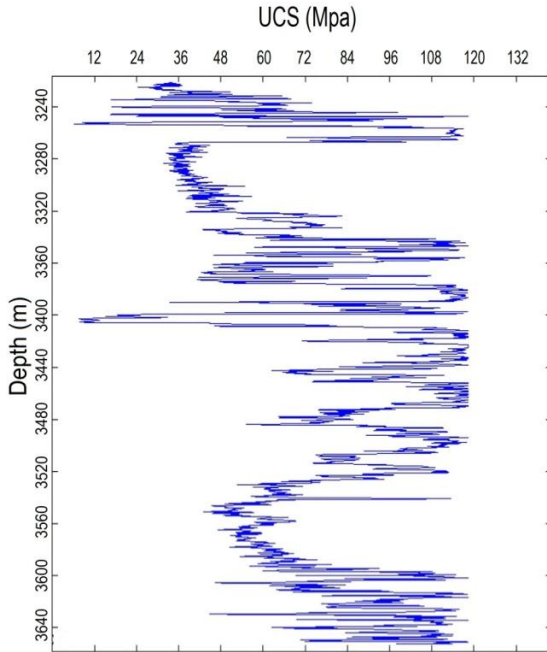


Figure2. UCS (Mpa)

Knowledge of vertical profile of the minimum horizontal stress is one of the most important parameters in a hydraulic fracturing. The minimum horizontal stress (σ_h) can be determined by different methods such as hydraulic fracture method, leak-off test method, macro-fracture test method and mini-fracture test method. However, the leak-off test method is much more common in comparison with the other methods. Hubbert & Willis (1957)

presented a comprehensive study on hydraulic fracturing. They found that not only the induced fracture propagates perpendicular to the minimum horizontal stress, but also the work had done to keep a fracture open is appropriate to the stress, which is perpendicular to the fracture plane and try to close the fracture. In this study, poroelastic correlations have been done instead of the mentioned tests, in order to calculate the magnitude of horizontal stresses:

$$\sigma_h = \frac{\theta_s}{1-\theta_s} (\sigma_v - \alpha_B P_p) + \alpha_B P_p + \frac{\theta_s E_S}{1-\theta_s^2} \varepsilon_1 + \frac{E_S}{1-\theta_s^2} \varepsilon_2 \quad (8)$$

$$\sigma_H = \frac{\theta_s}{1-\theta_s} (\sigma_v - \alpha_B P_p) + \alpha_B P_p + \frac{\theta_s E_S}{1-\theta_s^2} \varepsilon_2 + \frac{E_S}{1-\theta_s^2} \varepsilon_1 \quad (9)$$

Here, σ_h is minimum horizontal stress; σ_H is maximum horizontal stress; P_p is pore pressure; ε_1 and ε_2 are strains due to tectonic forces in maximum and minimum directions and considered 1 and 1.5, respectively.

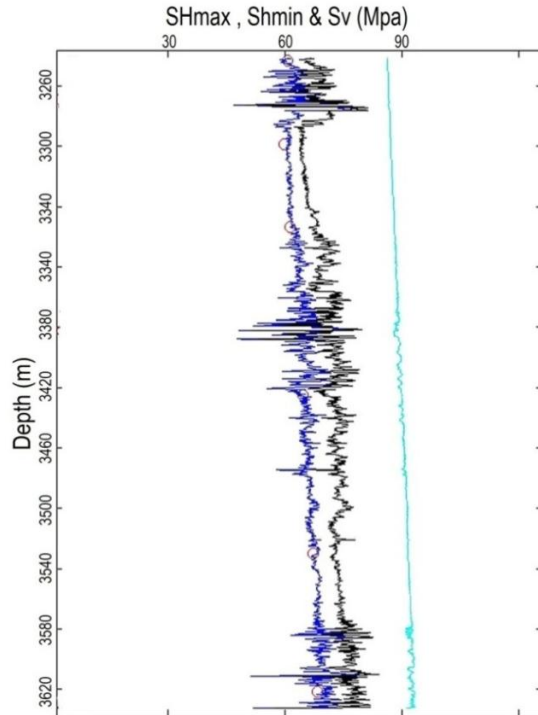


Figure3. Minimum and maximum horizontal stresses

2.4. Safe mud window design

Now, in this step, it is possible to design and sketch the mud window by using the pore pressure and minimum horizontal stress data. The window helps us to select suitable mud weight. Safe mud window shows that if the mud pressure is lower than pore pressure then the well will kick and fluid flow into the hole. Also if the mud pressure is higher than minimum horizontal stress, then induced tensile failures will occur during drilling operation and minor mud loss will happen.

The best domain for the safe mud window is between pore pressure and the minimum horizontal stress. From the geomechanical point of view, safe mud window allows the well to avoid tensile failures or pipe sticking that is caused by mud weight. Furthermore, it prevents the shear failures to occur because of low mud weight. Calculations for these cases show safe mud window which includes pressure in domain between 35 and 55 MPa ($35 < P_w < 55$).

2.5. Breakdown pressure

Drilling a borehole will alter the in situ principal stresses, the vertical stress (S_v) and the maximum and minimum horizontal stresses (S_{Hmax} and S_{Hmin}), in such a manner as to maintain the rock mass in a state of equilibrium. This leads to a stress concentration around the well. In a linear elastic material, the largest stress concentration occurs at the borehole wall. Therefore, breakdown is expected to initiate at a pressure higher than the least horizontal stress (Legarth, Huenges, & Zimmermann, 2005) (Hibbeler & Rae, 2005).

For the hydraulic fracturing study, consequently, stresses at the borehole wall are the ones that must be compared against a failure criterion (Zoback, Barton, & Wiprut, 2003) (Economides, & Nolte, 2002). According to the Kirsch solution, the stresses at a vertical borehole wall are given by:

$$\sigma_r = P_w \quad (10)$$

$$\sigma_\theta = \sigma_{Hmax} + \sigma_{Hmin} - 2(\sigma_{Hmax} - \sigma_{Hmin}) \cos 2\theta - P_w \quad (11)$$

$$\sigma_z = \sigma_\theta - 2\theta(\sigma_{Hmax} - \sigma_{Hmin}) \cos 2\theta \quad (12)$$

Where σ_r is the radial stress, σ_θ is the tangential stress, σ_z is the axial stress, P_w is the internal

wellbore pressure, and ν is the Poisson ratio of the rock. The angle θ is measured clockwise from the σ_{Hmax} direction (x-axis). Since there are no shear stresses, σ_r , σ_θ and σ_z are principal stresses that can be directly introduced into a failure criterion.

Table1. Mohr–Coulomb criterion for fracture pressure in vertical wellbores

	σ_3	Borehole tensile failure will occur if
TVER	σ_θ	$P_w \geq 3 \sigma_{Hmin} - \sigma_{Hmax} - P_p - T$
THOR	σ_z	$P_w \leq 3 \sigma_{Hmin} - \sigma_{Hmax} - \sigma_v - 2\nu(\sigma_{Hmax} - \sigma_{Hmin})$
TCYL	σ_r	$P_w < P_p + T$

There are numerous failure criteria that have been developed. The Mohr–Coulomb criterion is the simplest, and the most used in practice (table1). This criterion is appropriate for vertical wells. The fracture pressure estimated by Mohr-Coulomb failure criteria (TVER) is given in Figure 4.

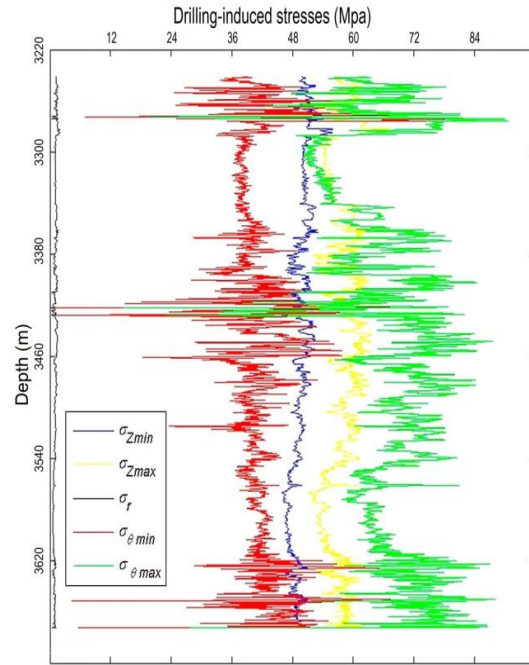


Figure4. Drilling-induced stresses around the well

3. RESULTS AND DISCUSSION

In order to study the effect of hydraulic fracturing on the production of Zone1 and Zone2 formations separately, two hydraulic propped fractures have

been designed for the well. Systematic design procedures are available based on the so-called two-dimensional models (2D) focus on the optimization of fracture length and width, assuming one can estimate a value for fracture height, while so-called pseudo three dimensional (p-3D) models suitable for multi-layered reservoirs aim to maximize well production by optimizing fracture geometry, including fracture height, half-length and width at the end of the stimulation treatment. The proposed p-3D approach to design integrates four parts:

- 1) Containment layers discretization to allow for a range of plausible fracture heights
- 2) The Unified Fracture Design (UFD) model to calculate the fracture half-length and width
- 3) The PKN or KGD models to predict hydraulic fracture geometry and the associated net pressure and other treatment parameters, and, finally
- 4) Linear Elastic Fracture Mechanics (LEFM) to calculate fracture height.

The aim is to find convergence of fracture height and net pressure. Net pressure distribution plays an important role when the fracture is propagating in the reservoir. In multi-layered reservoirs, the net pressure of each layer varies as a result of different rock properties.

To do so, we used Frac-pro software. After selecting the fluid and proppant, and considering the conditions of the reservoir the fracture was designed without crossing the barrier zones and with an injection rate of 20 bbl/min. Table2 shows the criteria for hydraulic propped fractures designing. In Figures 3, the results of the simulation for two zones have been shown.

Table 2. The criteria for hydraulic fractures designing

Fracture criteria	Zone1	Zone2
Fracture conductivity (FCD)	2	2
Proppant concentration	22 ppg	22 ppg
Upper barrier	3288 m	3533 m
Lower barrier	3387 m	3597 m
Reservoir Area	1 km ²	1 km ²

The hydraulic fracturing is designed in accordance to what is predicted and the Net Present Value

(NPV) is investigated. Since the purpose of the well stimulation is to increase the profile by accelerating the production or the recovery, the economic investigations must be considered as the most important parameters in deciding the simulation, the kind of stimulation and the other aspects of the treatment. In order to predict the production, the pseudo-3D model that is located in FracproPT software has been used. Cumulative oil production was calculated for 8 years after making this fracture for the zone1 and zone2. Figure5 shows the estimated cumulative oil production of these zones in non-fractured and fractured case. Figure6 shows the NPV analysis for both zones which resulted from the simulation. The comparison of the results showed that the NPV which resulted from the operation in the zone1 is almost two times greater than that of the zone2.

4. CONCLUSION

In this paper, the stresses were determined using the poroelastic method and based on petrophysical data. Stress regime existing in the borehole is of normal type and the fracture propagation is in a vertical plane. The breakdown pressure was determined based on the Mohr–Coulomb criterion. The most important parameters in hydraulic fracturing candidate well selection are the reservoir permeability and porosity, construction of an accurate stress profile and evaluation of the fracture containment. Stress gradient, percentage of water saturation and porosity indicate that, in this reservoir, the zone1 (a sub-layer in Ilam formation) and zone2 (a sub-layer in Sarvak formation) are good candidates for hydraulic fracturing. Finally, the production prediction and NPV which would result from the hydraulic fracturing operation of these two formations have been simulated and investigated base on pseudo 3D model in Frac-pro software.

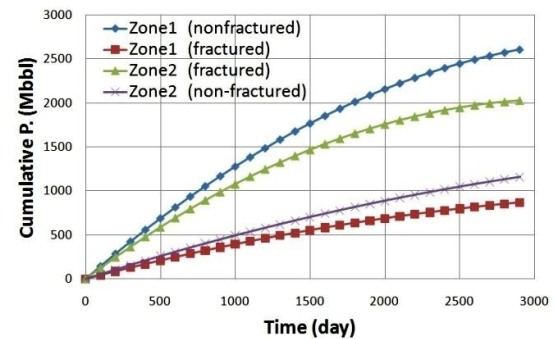


Figure5. Estimated cumulative oil production of zones in non-fractured and fractured case

The comparison of the results showed that the NPV which would result from the operation in the zone1 is almost two times greater than that of zone2. Also hydraulic fracturing treatment for the case study shows that the hydraulic fracturing job for this reservoir is feasible with respect to geomechanics and economics but for Iran it is not feasible due to lack of primary requirements.

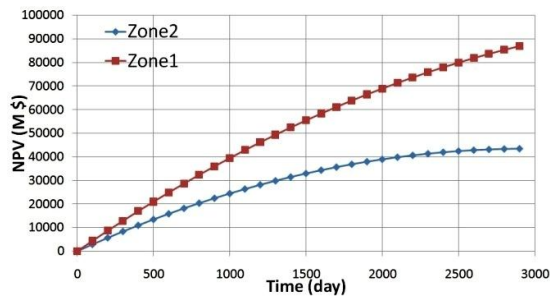


Figure 4. The NPV analysis from making a hydraulic fracture into the zone1 and zone2

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