IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 6, Issue 10 (Oct. 2016), ||V3|| PP 32-40

Analysis of production-decline data: Case of geothermal wells as renewable energy

Alfonso Aragón-Aguilar[1], Rosa M. Barragán[1], Víctor Arellano[1]†,
[1](*Instituto Nacional de Electricidad y Energía Limpias, Reforma 113, Col. Palmira, Cuernavaca, Morelos, México, CP 62490*)

Abstract: - Geothermal reservoirs could recover their conditions after a shut-down period by this reason are considered as renewable energy. In order to optimize the availability of this source, a sustainable exploitation strategy should always be designed. In contrast with oil systems which are practically isolated, geothermal reservoirs are open systems in which the flow of recharge due to the pressure drops is possible. Due to depth of geothermal reservoirs indirect methods based on monitoring data of wells are used to study their evolution. In this work, models widely used for the analysis of production decline data in oil wells have been adapted in order to include the analysis of geothermal wells. From them, important reservoir information needed to design optimal exploitation strategies is obtained. The analysis of production decline in wells is based either on analytical methods or on type curves fitting approaches. With the decline results of wells and considering their economic limit of production, the remaining useful life and the feasible reserves to be extracted from the source, can also be estimated. In this work the analysis of production decline methodology of wells is given and illustrative examples are discussed, highlighting the renewability of geothermal systems respect to oil reservoirs.

Keywords: - *Production decline analysis, Production characterization, Economic production limit, Renewability, Recharge entrance.*

I. INTRODUCTION

Geothermal energy has been classified as a renewable source in the long term since reservoirs would fully recover to their pre-exploitation state after an extended shut-down period [1]. Besides, electricity generation from geothermal resources reduces damage to the environment avoiding fuels burning and potential risks of their transportation and storage. Generally, is accepted as being an environmentally benign energy source. Currently, there are 24 countries in the world generating electricity from geothermal resources, with a total installed capacity of 10898 MW [2].

In this work we deal with both oil and geothermal reservoirs, which are natural resources classified as non-renewable and renewable sources, respectively. Non-renewable energies cannot be replenished in a short period time. The potential energy to be recovered from these two types of reservoirs is defined through their production capacity. The wells productivity tends to decline depending on the exploitation time and reservoir properties and the efficiency of wells is measured through their productivity index. The typical decline of wells is characterized as a decreasing trend of production over time until a non-sustainable limit of production is approached.

The production decline of a well is a function of both: the petro-physical properties of the reservoir, the exploitation rate and the recharge water entrance. For this reason, it is important to characterize the wells since the beginning and through their exploitation period. Assuming that every well, represents a punctual section of the reservoir, the consideration of various wells into the analysis allows the characterization of one section of the reservoir. In order to identify the productivity decline of wells, the behavior of production parameters should be investigated. In oil wells the variables used to evaluate their performance are: pressure, flow rates, oil/gas ratio, viscosity, density, etc. In geothermal wells the variables: pressure, flow rates, enthalpy, and water/steam ratio, among others are considered.

During the commercial exploitation stage, most of the production wells are incorporated to the operative systems, being difficult to shut them off, in order to evaluate them. For this reason, the monitoring data consisting of routine measurements in wells taken at the wellhead, are used to study their performance. This technique is suitable since when the wells operate continuously they eventually reach a pseudo-steady state. The wells behavior is related with the effects of exploitation on the reservoir. The technical considerations that support as representative of the reservoir are: 1) The mass extracted at reservoir conditions is the same than that in the surface the only difference is the steam fraction of fluids; 2) The reservoir pressure (p_e) which is used to obtain formation properties could be estimated through well simulation programs.

By correlating the productivity decline of wells to exploitation, it is possible to forecast wells performance. If in addition, the economic constraints for every well are included in the study, then the useful time-life, the total production capacity and the remaining reserve of wells can be obtained. Thus the results of decline studies can sustain exploitation strategies for every well while the generalization to the whole reservoir will support its development projects. Initially the methodology was designed to be applied in oil industry, then the purpose of this work is to show that the methodology is also suitable and hence can be extended to study aspects related to the renewability of geothermal systems.

One of the challenges to be faced when dealing with geothermal systems is to estimate how they behave regarding fluid extraction with respect to the recharge. In other words, the mass balance at reservoir, which consists in estimating by one hand the output of the system in terms of produced mass flow rates and by the other hand, the recharge inputs, both of them should nearly equilibrate to avoid overexploitation in the case that the mass extracted is higher than the input constituted by the recharge. When such condition is achieved the system under exploitation becomes a renewable system.

The innovative contributions given in this work to the energy resources knowledge are as follows:

- It is demonstrated that the decline analysis methodology is suitable and can be used in both, oil and geothermal production wells and reservoirs.
- The methodology analysis can help studies on the renewability of geothermal system.
- The results of the decline trend allow estimate the reserve which can be recovered up to achieve the limit of useful life.
- It is emphasized in the importance to know the recharge water entrance in order to determine the appropriate exploitation rate for maintain a balance between both.

The objectives of this work are: a) to use the production decline methodology in wells that have overcome transient effects and, b) to characterize the reservoir through estimating the useful life, the total mass with possibility to be extracted and the remaining reserves.

II. BACKGROUND

The analysis of decline curves through the use of mathematical expressions was introduced by [3] and up to now, it is used widely with vast success. In the analysis [3] established the following types of production decline: Exponential, hyperbolic and harmonic. [4, 5] extended the use of type curves to the analysis of production data by combining in a theoretical way, the response of a well in a closed reservoir with the classic technique of decline curves.

The flow normalization technique to the decline analysis of wells based on production measurements was introduced by [6]. Modern methods for the production decline analysis [7, 8] show the combined use of type curves and the decline analysis concepts. The main difference between initials and some actual methods is that these latter take into account the well bottom pressure together with the production mass flow rates. A complete production analysis technique to be used in mature fields was proposed by [9], while results of decline analysis focused on reservoir characterization were presented by [10]. The techniques of production data analysis to predict the behavior of gas wells were developed by [11]. Different methodologies to analyze decline in geothermal reservoirs were discussed by [12].

III. THEORETICAL CONCEPTS

The methods more widely used to investigate the natural response of reservoirs to exploitation are based on production data of wells through decline analysis. The typical decline of wells is identified as a sharp decreasing trend in production until a non-sustainable limit is approached. When such condition is reached the wells are classified as marginal. Every well represents a portion of a larger area which corresponds to the reservoir. Depending on the individual behavior of each one of the wells, the production-decline correlation represents the general tendency of the reservoir. The equations to obtain the initial mass flow rate and the decline rate D were proposed by [3]:

$$q_i = \frac{kh(p_i - p_{wf})}{141.2\mu_o B_o \left[\ln\left(\frac{r_e}{r_{wa}}\right) - 0.5\right]} \tag{1}$$

$$D = \frac{2(0.000264)k}{\phi\mu_o C_t (r_e^2 - r_{wa}^2)\left[\ln\left(\frac{r_e}{r_{wa}}\right) - 0.5\right]} \tag{2}$$

where q_i is the initial flow rate, k is he permeability of the formation, h is the useful production thickness, p_i is the initial pressure, p_{wf} is the well bottom flowing pressure, $\square_o$ is the fluid viscosity, B_o is the volume factor of the fluid, r_e is the reservoir drainage radius and r_{wa} is the apparent radii of the well. The classic expression for decline analysis proposed by [3, 13, 14] is:

$$q = q_i e^{-Di} \qquad (3)$$

where q is the flow rate, D is the decline constant and t is time. By changing variables (D = b) in (3), it stands that for b = 0 the decline is exponential type, for b = 1 decline is harmonic type being these the limits of the type curves. For the cases where $0 < b < 1$ the decline is hyperbolic type. In order to estimate the accumulated production of the wells the following equation proposed by [14] is used:

$$Np = \frac{q_i}{D}\left(\log q_i - \log q\right) \qquad (4)$$

It is possible to represent (4) by a straight line in logarithmic scale by plotting the accumulated mass flow rate produced in the log scale. Due to that transition since steady-state to pseudo steady state is practically immediate; a natural extension of the decline type curves is combining these declinations in one graph. The decline during transient periods depends mainly on the near-well formation characteristics. Thus it is important to notice that the apparent radius of the well (r_{wa}) is used to obtain the formation properties. In addition, the decline type curves are suitable for wells with either positive or negative damage factor. The expressions for the non-dimensional parameters which are used in the decline analysis with type curves are:

For non-dimensional mass flow:

$$q_{Dd} = \frac{q(t)}{q_i} \qquad (5)$$

For non-dimensional time:

$$t_{Dd} = D_i t \qquad (6)$$

The equations to obtain the reservoir properties from non-dimensional mass flow and time are as follows. By using the dimensionless mass flow (q_D), the permeability (k) can be obtained:

$$q_D = \frac{141.2 q_o \mu_o B_o}{kh(p_i - p_{wf})} \qquad (7)$$

And by using the dimensionless time, the porosity (□) is obtained:

$$t_D = \frac{0.00634kt}{\phi \mu c_t r_{wa}^2} \qquad (8)$$

The first analysis methods using type curves applied to reservoirs were those, for transient pressure test [15, 16]. By using the same analogy, the superposition method [17] follows a similar procedure than that of the (log-log) type curves fitting, used to analyze pressure data for constant mass flow rate. It is advisable to make a general diagnosis of the behavior of the production history previous to perform the analysis. It is possible to fit data to an equation for extrapolating behavior to the future and make predictions on the production of the well for example to 1, 2, 5, 10 or more years.

.

By plotting the flow rate vs time, it is seen that the flow rate declines as the exploitation time increases. The variations of both production and pressures of the wells depend on the orifice diameter. In addition, when the production data of a well are plotted vs the cumulative production of extracted mass (Np) it is observed that the part of the curve that declines becomes to a straight line. From this line, extrapolations to estimate future behaviors can be made, so it is possible to identify two stages of declining evolution: The transient (in the initial stage of exploitation) and the pseudo stable trends of decline.

IV. PRACTICAL CASES

In order to illustrate the application of the declining analysis theory, some cases are presented using data of oil and geothermal wells.

IV.1. Oil well

An oil well produces in a low-permeability zone of a reservoir with a bottom hole flowing pressure of 800 psia (55.16 E^5 Pa). Fig. 1 shows the mass flow rate declining of the well. By using the well data and results of a transient pressure test, the following determinations are given:

1) The decline model of the production in the well, by extrapolating to the point in which the flow reaches 10 b/d (1.592 m^3/d) as the critic limit.
2) Through the use of decline data q_{oi} and D are calculated. Subsequently, by using the decline rate shown in Fig. 1, q is obtained.

3) Comparison is made between calculated q_{oi} and D of the step 2 and these obtained through (1) and (2) by using the results of the pressure tests.

In order to obtain a complete characterization of the test, a mass flow vs time graph (Fig. 1) is used as a base for a general diagnosis. After having a general conceptual understanding of the test, the more convenient model of flow declining is identified by using two graphical methods: 1) Log flow rate versus log time and, 2) Log flow rate versus time.

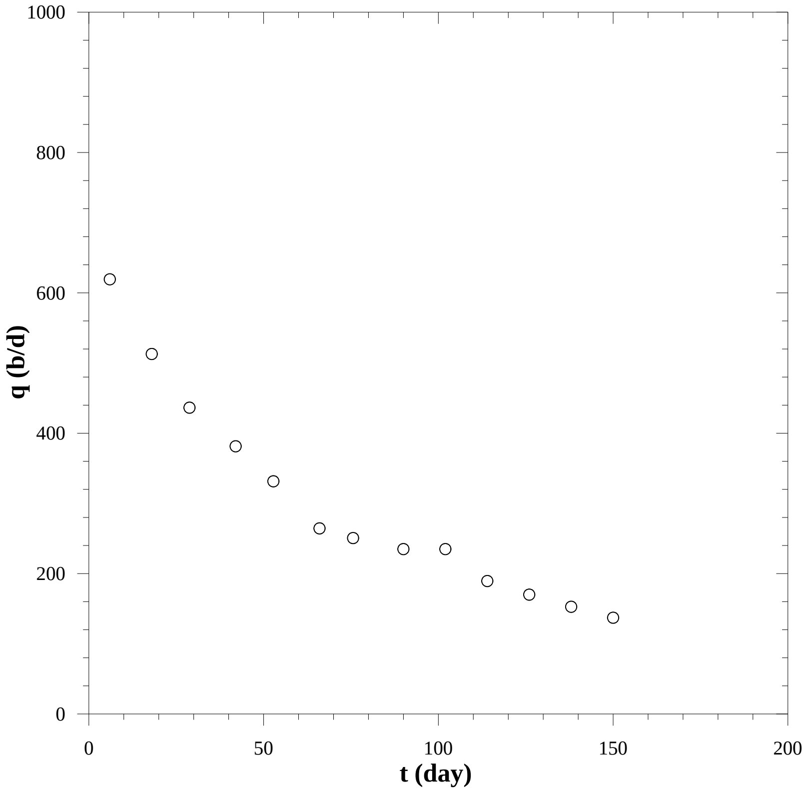

Figure 1. Graph of behavior of the volumetric flow vs time in an oil well.

By fitting data to a straight line, the slope and the interception to the origin are obtained. The origin intercept allows q_i to be obtained while the declining rate is given by the slope D. The fitting of data provides a straight line defined by (3) from which, q_i and D are:

q_i = 675 b/d (107.46 m^3/d)

D = 1.598 (b/d)/month [0.254 (m^3/d)/month]

As no measurements of historical production are available, the parameters of (3) can also be determined from reservoir data. With (1) and (2) and data from transient pressure tests q_i and D are obtained.

By substituting values in (1) and (2) both the initial flow rate (q_i) and the decline (D) can be calculated.

$$q_{oi} = \frac{0.392(121)(5790 - 800)}{141.2(0.46)1.36\left[\ln\left(\frac{1490}{11.75}\right) - 0.5\right]} = 617\left(\frac{b}{d}\right) = 98.23\left(\frac{m^3}{d}\right)$$

$$D = \frac{2(0.000264)0.392}{0.101(0.46)(1.09(10^{-6}))(1490^2 - 11.75^2)\left[\ln\left(\frac{1490}{11.75}\right) - 0.5\right]}(3600)$$

D = 1.526 (b/d)/month [0.243 (m^3/d)/month]

As can be seen q_i and D values calculated with Arps equation [3], compare fairly well with the values obtained from equations proposed by [13]. The important issue is that this methodology provides criteria on the interval of the parameters involved in the decline of the well.

By using the production data, the economic limit of production (Fig. 2) and the cumulative production volume (Fig. 3) of the well are obtained. From Fig. 2, it is also inferred that for the same declining rate, the critical limit for the flow (10 b/d) is being attained in approximately 5000 days. In order to have a more precise estimation of this time period, it is advisable to use the history of production of the well and the analytical method. According this approach, the extrapolated values are fitted to an equation and rearranging variables, the time (t) is calculated as follows:

$$t = \frac{10 - 248.0056}{-0.049032} = 4854(days) = 161.8(months)$$

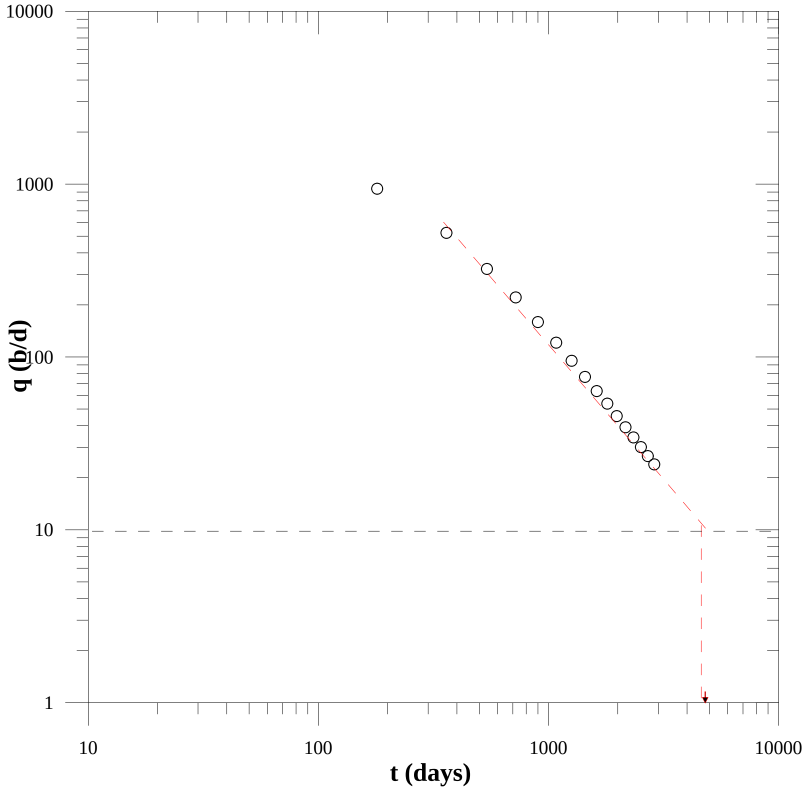

Figure 2. Log of the flow rate vs log of time for the analyzed well [18] used for determining the useful life of the well at the economic limit of production.

The estimated cumulative production in the well was 499650 barrels (79544 m^3); while assuming an economic limit of production for the well of 10 (b/d) [1.592 (m^3/d)], the maximum production volume can be extrapolated from the graph in Fig. 3. Thus, for this case results slightly above 525000 barrels (83580 m^3) are seen, which could be assumed as the total reserve of the well. Therefore, the well has declined approximately 95.2 % in 2 880 days. The maximum recoverable production which is also related to total reserve can be estimated by using the cumulative produced volume together with the volumetric flow of the well. This graph can be used for estimating the reserve which could be extracted before the well reaches the economic limit of the production. Fig. 4 shows the superposition of the production values, flow and time in a log-log scale, on the type curve [3]. In order to identify which of the type curves better fits the measured data both graphs should have the same scale.

IV.2. Geothermal well

In order to illustrate the use of the decline analysis techniques in geothermal wells, the production data of a Mexican geothermal well is given in Fig. 5 [19]. In this figure the production history of the well over 340 months is shown along with the wellhead pressure and the discharge orifice diameter over time. Fig. 5 is useful to make a general diagnostic of the data and their possible use for decline analysis; it is seen that between months 160 and 200 the well is shut in, which causes an abrupt increase in wellhead pressure even reaching that measured at static conditions. However, when the well is reopened using an orifice diameter similar to that has operated before be shut off, it was found that the mass flow rate is slightly higher (about 5%) than that recorded previously. This evidences that the shutting caused a small recovery of the well, although it maintained its decline tendency, after reopening.

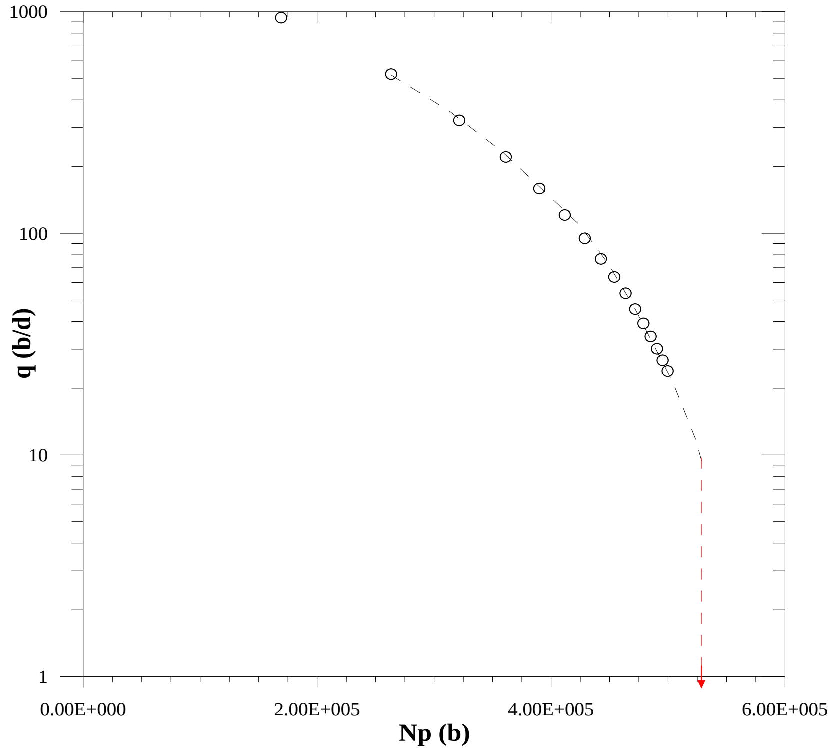

Figure 3. Log of volumetric flow (q) vs cumulative produced volume of the well (Np).

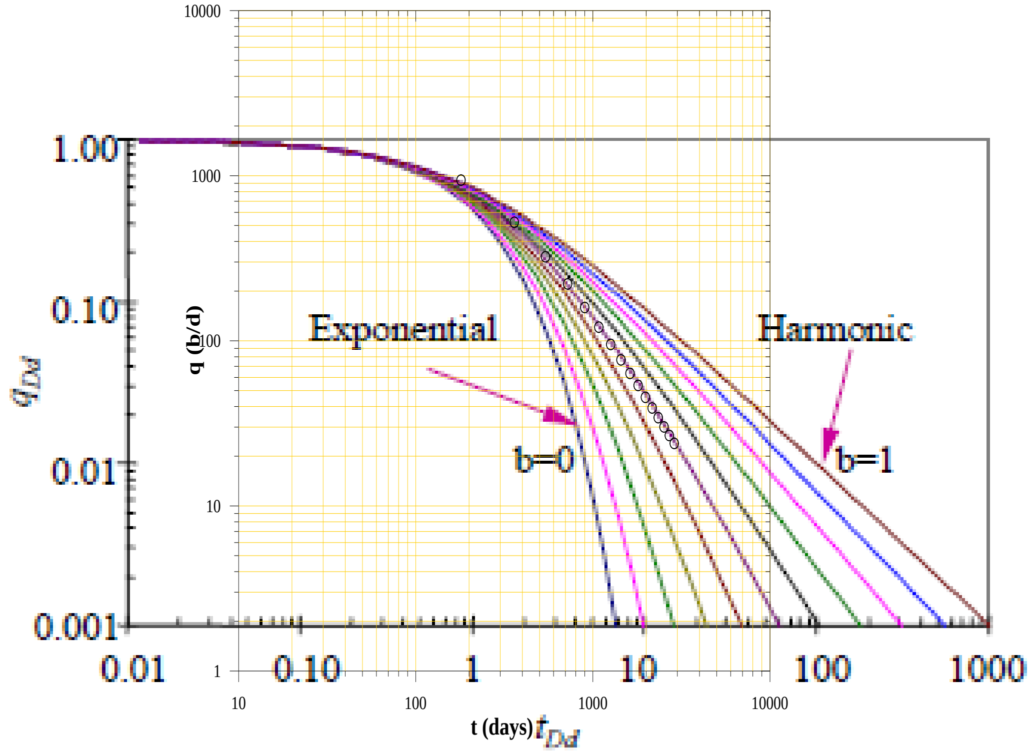

Figure 4. Comparison and fitting the production data with the declining type curve.

Fig. 6 shows the production data vs time of the well. One of the interesting uses of this graph is to estimate the time will take for the well to reach its economic production limit by considering the decline tendency. The economic production limit for geothermal wells is taken as 10 (t/h) and 7 bar (7E^5 Pa) of pressure, such conditions are considered to be enough to generate at least 1 MW of electricity. Thus, according to this information and by extrapolating in Fig. 6 it is seen that this time approximately is 495 months.

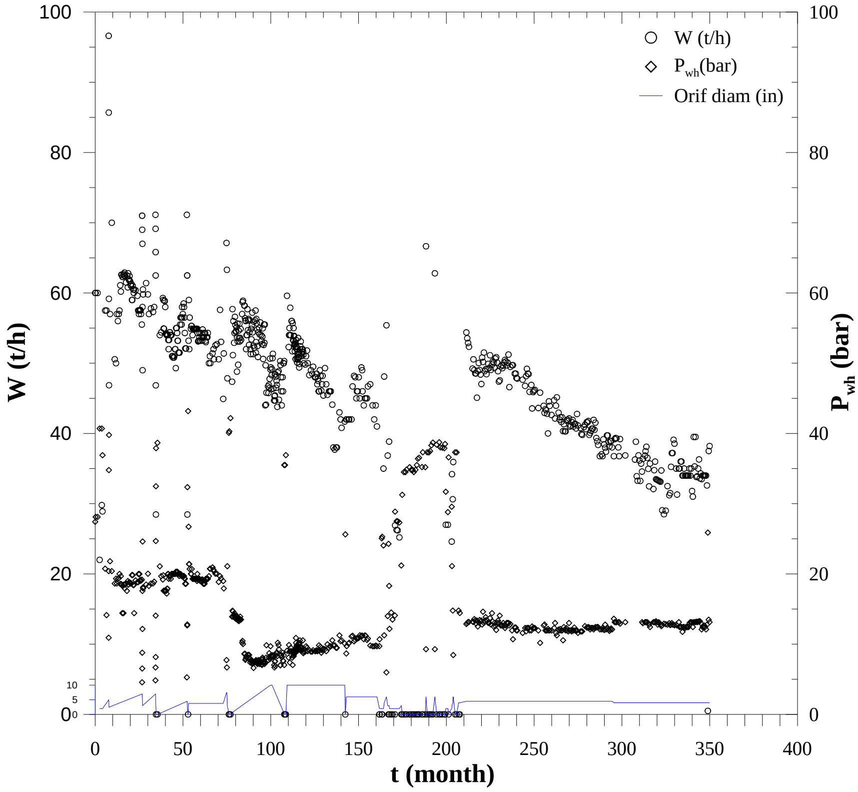

Figure 5. Graph of mass production, wellhead pressure and diameter of the discharge orifice vs time, taken from [19].

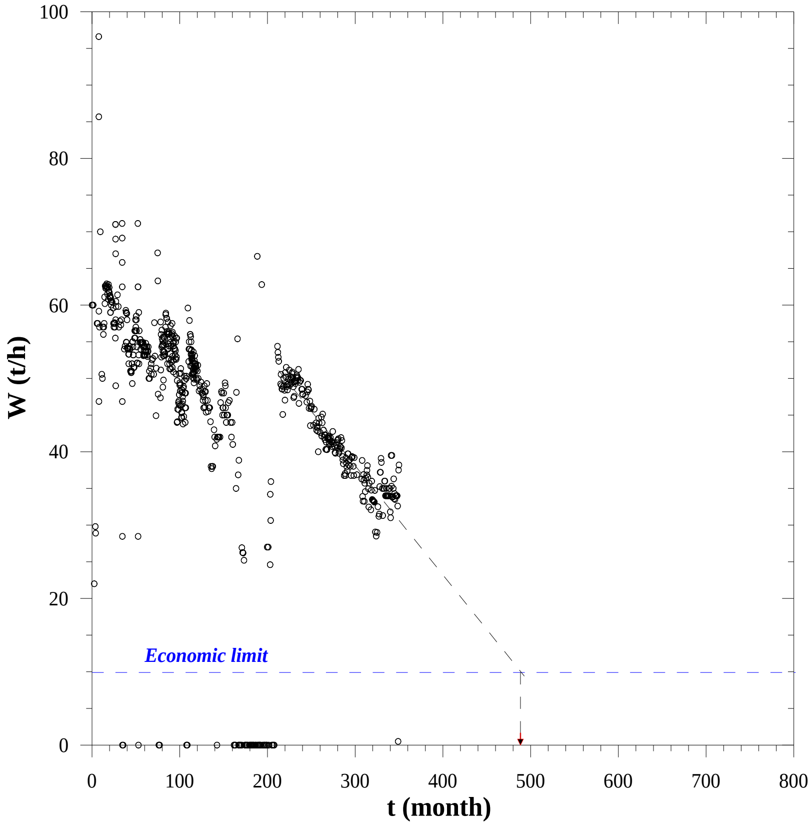

Figure 6. Graph of mass flow rate vs time, used to determine the economic limit of the well.

By fitting the decline data for the last section (from the month 210) of the plot in Fig. 6, the following expression was obtained:

$$W = -0.14636\,(t) + 82.148$$

From this extrapolation, the calculated time for W = 10 (t/h) is 492 months. The initial volumetric flow (q_i) and the initial decline (D_i) are estimated by substituting the obtained values in (5) and (6):

$$q_i = \frac{40}{0.56} = 71\left[\frac{t}{h}\right] \quad \text{and} \quad D_i = \frac{0.79}{300} = 0.0026\left[\frac{t}{h}\right] = 0.078\left(\frac{\left[\frac{t}{h}\right]}{month}\right)$$

Similar graph to that of Fig.3 (W vs Np) is used for determining the remaining reserve. The fit of the last part of decline data provides in terms of Np and W the following expression:

$$W = -4.87913E^{-6}(N_p) + 82.183583$$

For determining the Np value as W function the expression is:

$$Np = \frac{W - 82.1836}{-4.8791E^{-6}}$$

Using W=10 in the last equation, $N_p = 14.794E^6$ (t). This represents the total reserve of the well.

As a summary, the results obtained from the analysis developed, provide support for designing exploitation strategies of the wells and making predictions on their future behavior. The variables obtained from the analysis allow an understanding of the well performance and its productivity while results from every well can be interpreted together to understand the reservoir behavior. Table 1 gives a summary of the results and their impact on field exploitation strategies.

V. CONCLUSION

The production decline analysis constitutes a useful tool to characterize both oil and geothermal reservoirs. Although the methodology of analysis decline was developed for oil systems, in this work is shown that also can be used for geothermal systems. The analyzed geothermal well recovered its condition to its pre-exploitation state after a shut-down period, this behavior sustains the scenario that geothermal energy to be a renewable resource. The adequate combination of mass flow, accumulated production and the time are a technical support for extrapolating the wells behavior, determine their economic useful life, the remaining reserves of the resource and projects development for field expansion. By establishing the production economic limits of wells, and of the reservoir, it is possible to predict its useful life.

Table 1. Summary of data obtained from the production decline analyses which are useful to individual characterization of wells.

	Initial flow rate q_i		D_i Decline rate		Total reserve		Useful life	Remaining reserve	
Oil well	(brl/d)	(m^3/d)	(b/d)/month	(m^3/d)/month	(b)	(m^3)	(month)	(b)	(m^3)
	1333	212.21	0.15	0.024	525000	83580	161.8	25350	4035.7
Geothermal well	W_i(t/h)		(t/h)/month		10^6(t)		(month)	10^6(t)	
	71		0.078		14.8		492	4.8	

Where q_i is the volumetric flow and W_i the mass flow, both of them for the time t = 0, D_i is the initial decline rate.

VI. ACKNOWLEDGEMENTS

This work was developed under support of the project IIE/14454 "Técnicas y métodos de análisis, al estado del arte de declinación de la producción en sistemas geotérmicos mexicanos y sus efectos predictivos", The authors express their gratitude by the support to authorities of INEEL (Instituto Nacional de Electricidad y Energías Limpias-México).

REFERENCES

[1] M O´Sullivan, M. Yeh, and W. Mannington, Renewability of geothermal resources, *Geothermics, 39(4),* 2010, 314-320

[2] R Bertani, Geothermal power generation in the world 2005-2010 update report, *Geothermics, 41*, 2012, 1-29.

[3] J. J. Arps, Analysis of decline curves, *Transactions of the American Institute of Minning, Metallurgical and Petroleum Engineers, 160*, 1945, 228-247.

[4] M.J. Fetkovich, M.E. Vienot, M.D. Bradley, U.G. Kiesow, Decline-curve analysis using type curves – Case histories, *Society Petroleum Engineers, Formation Evaluation, paper SPE 13169*, 1987, 637– 656.

[5] M.J. Fetkovich, E. J. Fetkovich, M. D. Fetkovich, Useful concepts for decline forecasting reserve estimation and analysis, *SPE 28628, 60th Annual Technical Conference SPE*, Nueva Orleans, LA, USA, 1994, 217–232.

[6] S.K. Sanyal, A. J. Menzies, P. J., Brown, K. L. Enedy, S. A. Enedy, A systematic approach to decline curve analysis for the Geysers steam field, California, *Geothermal Resources Council, Transactions* 1989, 13, 415-421.

[7] T.A. Blasingame, T. L. McCray, W. J. Lee, Decline curve analysis for variable pressure drop/variable flow rate systems, *Paper SPE 21513 Gas Technology Symposium, SPE,* Houston TX, USA, 1991.

[8] R.G. Agarwal, D. C. Gardner, S. W. Kleinsteiber, D. Fussel, Analyzing well production data using combined type curve and decline curve analysis concepts, *Paper SPE 49222, Reservoir Evaluation and Engineering*, 1999, 2, 478-486.

[9] R. Gaskari, S. D. Mohagheghi, J. Jalali, An integrated technique for production data analysis with application to mature fields, *SPE 100562, Gas Technology Symposium, SPE, Calgary, Alberta, Canada,* 2006.

[10] D. Mata, R. Gaskari, S. D. Mohagheghi, Field wide reservoir characterization base on a new technique of production data analysis: Verification under controlled environment, *Eastern Regional Conference and Exhibition, Society of Petroleum Engineers, SPE 111205, Lexington, Kentucky, USA.* 2007.

[11] A Bahadori, Analysis gas well production data using a simplified decline curve analysis method, *Chemical Engineering Research and Design*, *90*, 2012, 541–547.

[12] A Aragón-Aguilar, R. M. Barragán, G. V. Arellano, Methodologies for analysis of productivity decline: A review and application, *Geothermics*, *48*, 2013, 68-79.

[13] M J Fetkovich, Decline curve analysis using type curves, *Journal of Petroleum Technology*, 1980, 1065-1077.

[14] J J Arps, Estimation of primary oil reserves, *Trans. AIME, 207,* 1956, 182-191.

[15] R G Agarwal, R. Al-hussainy, H. J. Jr. Ramey, An investigation of wellbore storage and skin effect in unsteady liquid flow: I. Analytical treatment, *SPEJ,* 1970, 279-290.

[16] R C Earlouger, K. M. Kersh, Analysis of short-time transient test data by Type-curve matching, *Journal Pet. Tech.*, 1974, 793-800.

[17] H.C. Slider, *Worlwide practical petroleum reservoir engineering methods* (Tulsa Oklahoma, EUA, Penn Well Books, 1983).

[18] M. Golan, C. H. Whitson, *Well performance* (Second edition Trondhiem, Noruega: Tapir Akademiske Forlag, 2003).

[19] G V Arellano, M. A. Torres, R. M. Barragán, Thermodynamic evolution of the Los Azufres México geothermal reservoir, from 1982 to 2002, *Geothermics, 34,* 2005, 592-616.