A RESERVOIR ENGINEER CHARACTERIZATION OF
THE AUSTIN CHALK TREND

A Thesis
by
HER-YUAN CHEN

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

December 1985

Major Subject: Petroleum Engineering
A RESERVOIR ENGINEER CHARACTERIZATION OF
THE AUSTIN CHALK TRENDS

A Thesis
by
HER-YUAN CHEN

Approved as to style and content by:

S. W. Poston
Steven W. Poston
(Chairman of Committee)

Ching H. Wu
(Member)

Robert R. Berg
(Member)

William D. Von Gonten
(Head of Department)

December 1985
ABSTRACT

A Reservoir Engineer Characterization of the Austin Chalk Trend. (December 1985)

Her-Yuan Chen, B.S., Taiwan Provincial College of Marine Science and Technology

Chairman of Advisory Committee: Dr. Steven W. Poston

Fracture trends and reservoir dual-characteristics are presented for a portion of the fractured Austin Chalk producing trend. The production histories of 1,235 wells from Giddings field covering portions of Lee, Burleson, Washington, and Fayette Counties were analysed by the technique of decline curve analysis. Production of the average Austin Chalk well is usually characterized by a two-stage exponential decline behavior -- an early rapid decline and a later slow decline. The average early decline rate is 200 to 300 %/year, and lasts about six months to one year. The averages are about 30 to 60 %/year for the later, less dramatic decline.

Methods to determine the dual-properties of a fractured system, based on Da Prat et al's model, are presented. The flow capacity, storage capacity, and expansibility of fracture or matrix, and certain dimensionless parameters defining a fractured system may be computed using multi-slope production data. A field example is given to illustrate the application of these techniques. The ratio of early to late decline rate, which is an index of the over-all capacity, is
usually 2.5 to 5.5. This ratio, coupled with the early production rates of a well, should aid in the forecasting of the future production of an Austin Chalk well.

Statistical analysis of well performance indicates no difficulty in finding oil in the Austin Chalk producing trend. However, areas of high fracture density must be encountered for a well to be highly profitable. A contour map of the iso-reserves was prepared for a better understanding of the fracture trend and reservoir characteristics. Besides the general northeast-southwest production trend, the map shows anomalies in the fracture system and reservoir characteristics.
ACKNOWLEDGEMENTS

I wish to thank Dr. Steven W. Poston, chairman of my advisory committee, for suggesting the thesis topic and for his support. The guidance of Dr. Poston was very helpful for the preparation and improvements of this thesis. He has contributed much to make this thesis possible.

I also wish to thank Dr. Ching H. Wu and Dr. Robert R. Berg, members of my advisory committee, for their assistance and discussion throughout this study.

I also appreciate the opinion, encouragement, and friendship from my fellow graduate students, particularly Thomas Blasingame and Tsaibao Kuo.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>GEOLOGY AND HYDROCARBON CHARACTERISTICS</td>
<td>3</td>
</tr>
<tr>
<td>PRODUCTION HISTORY AND BEHAVIOR</td>
<td>6</td>
</tr>
<tr>
<td>DECLINE CURVE ANALYSIS</td>
<td>12</td>
</tr>
<tr>
<td>Fracture Properties</td>
<td>14</td>
</tr>
<tr>
<td>Matrix Properties</td>
<td>15</td>
</tr>
<tr>
<td>Dimensionless Parameters Describing an Overall</td>
<td>16</td>
</tr>
<tr>
<td>Fractured System</td>
<td></td>
</tr>
<tr>
<td>Application of the Method</td>
<td>18</td>
</tr>
<tr>
<td>RESULTS AND DISCUSSION</td>
<td>22</td>
</tr>
<tr>
<td>Well Performance</td>
<td>22</td>
</tr>
<tr>
<td>Austin Chalk Fracture Trend</td>
<td>24</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>26</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>27</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>29</td>
</tr>
<tr>
<td>APPENDIX A STATISTICAL METHODS OF AVERAGING THE</td>
<td>31</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td></td>
</tr>
<tr>
<td>DECLINE PROPERTIES</td>
<td></td>
</tr>
<tr>
<td>APPENDIX B SHAPE FACTOR</td>
<td>35</td>
</tr>
<tr>
<td>VITA</td>
<td>38</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Well Status (up to June 1984)</td>
<td>6</td>
</tr>
<tr>
<td>2a</td>
<td>Classification of Austin Chalk Wells Based on Production Decline Shapes</td>
<td>10</td>
</tr>
<tr>
<td>2b</td>
<td>Statistical Summary of Austin Chalk Wells Based on Decline Types</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Reservoir Data for Example Problem</td>
<td>18</td>
</tr>
<tr>
<td>4a</td>
<td>Classification of Austin Chalk Well Profitability Based on Ultimate Reserves</td>
<td>23</td>
</tr>
<tr>
<td>4b</td>
<td>Statistical Summary of Austin Chalk Wells Based on Profitability Types</td>
<td>23</td>
</tr>
<tr>
<td>A1</td>
<td>Calculation of Statistical Average Value of the Initial Rates of Decline</td>
<td>32</td>
</tr>
<tr>
<td>A2</td>
<td>Calculation of Statistical Average Value of the Final Rates of Decline</td>
<td>33</td>
</tr>
<tr>
<td>A3</td>
<td>Calculation of Statistical Average Value of the Ratios of Initial to Final Decline Rate</td>
<td>34</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Austin Chalk Producing Trend</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Example of Production Decline Type I&lt;br&gt;(Well A-2-10 #1 D1, Lee, Texas)</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Example of Production Decline Type II&lt;br&gt;(Well D-4-4 #16 D3, Lee, Texas)</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Production Decline Curve for Example Problem</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>Iso-reserves Contour Map of Austin Chalk</td>
<td>in the map pocket</td>
</tr>
<tr>
<td>B1</td>
<td>Idealization of the Warren and Root Two-porosity Model</td>
<td>35</td>
</tr>
</tbody>
</table>
INTRODUCTION

Considerable interest has been shown in producing oil from the Austin Chalk Formation in south and central Texas because of higher oil prices, increased demand, and improved fracturing technology during the past decade.\textsuperscript{1-4}

Oil was produced from fractures in the Austin Chalk as far back as 1930s with the discovery and development of Pearsall field, Frio County. Subsequent exploration and development extended northeastward along the inner Gulf Coastal Plain to Brazos County in east central Texas. Natural fractures must be found in order to produce a well on an economic basis due to the poor rock matrix characteristics.\textsuperscript{5-7} The number of fractures penetrated by an Austin Chalk well can dramatically affect the oil productivity between adjacent leases.\textsuperscript{1}

The importance of being able to find fractures and to define the fracture/matrix characteristics before drilling is evident. It is the objective of this paper to describe a portion of the Austin Chalk producing trend and the reservoir dual-characteristics by the technique of decline curve analysis. Production histories of 1,235 wells from Giddings field covering portions of Lee, Burleson, Washington, and

This thesis follows the style of the \textit{Journal of Petroleum Technology}
Fayette Counties were analysed. Production decline types, well performance, and a contour map of the iso-reserves are presented for a better understanding of the fracture trends and characteristics. Also, methods of evaluating the reservoir parameters of a fractured system are discussed and example computations are presented. The result will allow an operator to better describe and rate an individual property.
GEOLGY AND HYDROCARBON CHARACTERISTICS

The Austin Chalk was deposited in Late Cretaceous seas which at one time covered the Gulf Coast basin.\textsuperscript{5,6} The sedimentary section generally consists of a fine grained limestone with interbedded shale streaks. Typical X-ray analyses show the formation is composed of about 85% calcite, 5% quartz, 5% feldspar, and 5% mixed-layer illite-montmorillonite clay. The Austin Chalk has a medium hardness near surface but is much harder where it is penetrated at most producing depths. Subsequent deposition of younger sediments caused structural downwarping that fractured the older sediments along the basin margin. The fracturing helped to form the trend now being drilled and explored (Fig. 1).

The thickness of the Austin Chalk within the productive trend varies both along the strike and down dip direction.\textsuperscript{4,5,7} In Brazos County, the Austin Chalk is about 100 ft thick, while in Lee and Washington Counties the thickness has increased to 300 ft. The chalk thickness stays relatively constant along the strike until it reaches Gonzales County, where it again has decreased to a thickness of 200 ft. The chalk thickens again to the southwest, reaching 400 ft in Frio and LaSalle Counties.

Production depths range from 5,000 ft in Frio County to 7,000 ft in Dimmit County on the western end of the trend.\textsuperscript{8} To the east, Caldwell County has shallow production at 3,000 ft, while in Lee and
Burleson Counties production occurs at depths of more than 8,000 ft.

The matrix porosities typically range from 3 to 7%. Permeability is quite low, less than 0.1 md.\textsuperscript{5,6} In many cases, the permeability is not measurable. Core analysis indicates the presence of extensive natural vertical fractures. Some fractures can be described as hairline, while others are open to the extent that mineral growth of iron pyrite and CaCO\textsubscript{3} crystal has occurred.\textsuperscript{5} Thus, production may be aided by fractures that connect the sparse matrix pores with the permeable fracture systems.

The hydrocarbons in the Austin Chalk include those formed in place and those which were formed elsewhere and have migrated into the chalk.\textsuperscript{9} The nature of the hydrocarbon accumulation is related to depth.\textsuperscript{4,7} In general, oil gravity and gas-oil ratio increase as the production depth increases. The Austin Chalk appears to be water wet above depths of 7,000 ft. Production is found in conventional traps associated with up-to-the coast faults. At depths of 7,000 ft to 9,000 ft, oil fills the fractures and no water is found. Oil gives way to gas and condensate below a depth of 9,000 ft.
PRODUCTION HISTORY AND BEHAVIOR

Production records of 1,235 Austin Chalk wells (up to June 1984) from the Giddings field covering portions of Burleson, Lee, Washington, and Fayette Counties were collected and examined. The production curves obtained are the production rate vs time curve plotted on semilog graph paper. The area covered by this study is shown in Fig. 1.

The earliest date of production history was October 1960. However, the bulk of the production records encompassed the period from 1978 to 1983. Table 1 shows the well status compiled as of June 1984.

Table 1 - Well Status (up to June 1984)

<table>
<thead>
<tr>
<th>STATUS</th>
<th>NO. OF WELLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRY HOLES</td>
<td>105</td>
</tr>
<tr>
<td>SHUT IN</td>
<td>201</td>
</tr>
<tr>
<td>ACTIVE</td>
<td>929</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1235</td>
</tr>
</tbody>
</table>

As indicated in Table 1, 105 wells are dry holes, and 201 wells have been shut in. The remaining 929 wells are producing while most of these are being pumped to sustain production. As of June 1984, 65.8 MMBbl of oil have been produced.
The production behavior of the Austin Chalk wells was examined by decline curve analysis. Neither exponential or hyperbolic curves seem to represent the historical producing behavior of the Austin Chalk wells because of the unusual producing characteristics (or decline shape). Based on production decline shapes, five types of wells were classified as shown in Table 2a.

Table 2b shows the statistical summary of Austin Chalk wells based on decline types classified in Table 2a. Of 1,235 wells, 294 wells (23.8%) are Type I, and 397 wells (32.2%) are Type II. There are 166 wells belong to Type III and comprise 13.4%, and 273 wells are of Type IV, and comprise 22.1%. The remaining 105 wells (8.5%) are dry holes. Examples of Type I and II wells are illustrated in Figs. 2 and 3 respectively.

Type I and II are the typical production behavior of a fractured system in which the contrast between fracture and matrix flow capacities is large.\textsuperscript{2,5,10,11} Together, they comprise 56.0% (691 wells) of the total wells analysed. The average initial rate of exponential decline usually is 200 to 300 \%/year (Table A1, Appendix A) and lasts for about six months to one year. This rapid decline in rate indicates fracture production dominates. The transition stage which followed the initial decline (Type I well) reflects the transfer of fracture production dominance to matrix production dominance. The average final rate of decline, which characterizes the dominance of matrix production, is found to be 30 to 60 \%/year (Table A2, Appendix A). For Type III wells, the ratio of flow capacities in the matrix and
Table 2a - Classification of Austin Chalk Wells Based on Production Decline Shapes

<table>
<thead>
<tr>
<th>CLASSIFICATION</th>
<th>DESCRIPTION OF DECLINE SHAPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>The flow rates show a fairly rapid decline initially, then gradually change to the eventually steady and slow exponential decline (Fig. 2).</td>
</tr>
<tr>
<td>II</td>
<td>The initial rapid decline is followed immediately by the steady and slow decline in rates, resulting in two distinct exponential decline rates (Fig. 3).</td>
</tr>
<tr>
<td>III</td>
<td>A single exponential decline for a sufficient long production period without characteristics found in Types I and II.</td>
</tr>
<tr>
<td>IV</td>
<td>No decline type can be observed due to short production history, or radically changing production.</td>
</tr>
<tr>
<td>V</td>
<td>Dry holes.</td>
</tr>
</tbody>
</table>

Table 2b - Statistical Summary of Austin Chalk Wells Based on Decline Types

<table>
<thead>
<tr>
<th>DECLINE TYPE*</th>
<th>NO. OF WELLS</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>294</td>
<td>23.8</td>
</tr>
<tr>
<td>II</td>
<td>397</td>
<td>32.2</td>
</tr>
<tr>
<td>III</td>
<td>166</td>
<td>13.4</td>
</tr>
<tr>
<td>IV</td>
<td>273</td>
<td>22.1</td>
</tr>
<tr>
<td>V</td>
<td>105</td>
<td>8.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1235</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* The decline types are those classified in Table 2a.
in the fracture is small, hence only one single decline rate is noticeable.

Obviously, the initial decline (and the transition stage) does not represent the final state of depletion. Extrapolation of the initial decline or transition stage may lead to erroneous results when decline curve analysis is applied.
DECLINE CURVE ANALYSIS

No effort was attempted to fit the whole historical production life of a well since most of the Austin Chalk production is from fractured system, and production decline is multi-slope in behavior. Remaining reserves were calculated by fitting and extrapolating the final decline stage. Total reserves were then obtained by adding back the production before the final stage. The computer program of decline curve analysis for calculating rate of decline and ultimate reserve is provided by Poston and Blasingame,\textsuperscript{12} and performed on an IBM PC. The economic limit was assumed to be 100 bbl/mo.

The rate of production decline is related to field, fracture, and fluid properties.\textsuperscript{10,11,13-16} Da Prat et al.\textsuperscript{11} found from decline curve analysis of a naturally fractured reservoir the flow rate drops rapidly at first, and then becomes almost constant for a long period. Finally a final decline takes place. These characteristics were found for a finite no-flow outer boundary reservoir producing at constant pressure. The initial rapid drop in rate (short times), which represents the fracture dominance production, is a function of \( r_{eD} \), \( t_D \), and \( \omega \) (Eq. 1).

\[
q_D(t_D) = \left[ \frac{1}{\ln(r_{eD})-3/4} \right] \cdot \exp \left[ \frac{-2}{r_{eD}^2(\ln(r_{eD})-3/4)/\omega} \cdot \frac{t_D}{\omega} \right]
\]

(Eq. 1)

For long times, the flow rate depends on one more additional parameter, \( \lambda \) (Eq. 2).
\[
q_0(t) = \left[ \frac{r_e^2 - 1}{2} \right] \lambda \cdot \exp \left[ \frac{-\lambda t}{1 - \omega} \right]
\]

(2)

The flow rate stays constant (transition stage, fracture/matrix production) until the exponential term in the Eq. 2 dominates which indicates the final rate decline of matrix production dominance. The flow rate and duration of the transition stage depends strongly on the matrix/fracture permeability ratio, \( \lambda \).

In Eqs. 1 and 2, \( \omega \) is a dimensionless parameter relating the storage of the fracture to that of the combined system

\[
\omega = \frac{(\varrho Vc)_f}{(\varrho Vc)_f + (\varrho Vc)_m}
\]

(3)

and \( \lambda \) is the dimensionless matrix to fracture permeability ratio which governs interporosity flow

\[
\lambda = \alpha \frac{k_m}{k_f} r_w^2
\]

(4)

where \( \alpha \) is the interporosity flow shape factor in ft\(^{-2}\). The rest of the terms are defined in the Nomenclature.

Both equations indicate an exponential decline in production rates. By numerical inversion, Da Prat et al. showed the two solutions can be combined to analyse the production behavior of a two-porosity system. Eqs. 1 and 2 are modified to evaluate the dual characteristics
of the Austin Chalk.

Fracture Properties

The fracture depletion equation (initial decline, Eq. 1), which all the variables are expressed in dimensionless terms, has the dimensional form of

\[
q(t) = \frac{0.00708 \ k_f h (P_i - P_{wf})}{Bu (ln(r_e/r_w) - 3/4)} \cdot \exp \left[ \frac{-5.274 \ (10^{-4}) \ k_f t}{r_e^2 (ln(r_e/r_w) - 3/4) (\phi Vc)_f u} \right]
\] (5)

As mentioned earlier, the decline in rates as indicted in Eq. 1 or 5 is exponential in nature. Upon comparing Eq. 5 with the general form of the exponential decline equation

\[
q(t) = q_i e^{-dt}
\] (6)

it is seen that the extrapolated initial rate \( q_{if} \) is

\[
q_{if} = \frac{0.00708 \ k_f h (P_i - P_{wf})}{Bu (ln(r_e/r_w) - 3/4)}
\] (7)

The decline rate \( d_f \), which is the slope of the decline curve on semilog paper, is

\[
d_f = \frac{5.274 \ (10^{-4}) \ k_f}{r_e^2 (ln(r_e/r_w) - 3/4) (\phi Vc)_f u}
\] (8)
Note that the initial rate defined by Eq. 7 is usually not the actual initial rate of a well. It is the initial rate when the reservoir is under pseudo-steady state condition. Hence it must be extrapolated from rate decline curve at \( t=0 \).

It is clearly seen that Eqs. 7 and 8 can be rearranged or combined to evaluate fracture flow capacity \( k_fh \), fracture storage capacity \((\varphi V_c)_f\) and fracture expansibility \((k/\varphi V_c)_f\). Rearranging Eq. 7 yields the fracture flow capacity

\[
k_f h = \frac{141.2 \ q_{if} Bu (\ln(r_e/r_w))^{-3/4}}{p_i - p_{wf}}
\]  

Rearranging Eq. 8 yields fracture storage capacity

\[
(\varphi V_c)_f = \frac{5.274 \times (10^{-4}) \ k_f}{d_f \mu r_e^2 (\ln(r_e/r_w))^{-3/4}}
\]  

and expansibility

\[
\left[ \frac{k}{(\varphi V_c)} \right]_f = 1.896 \times (10^3) \ d_f \mu r_e^2 (\ln(r_e/r_w))^{-3/4}
\]  

Matrix Properties

Same procedures can be applied to the matrix depletion equation (Eq. 2) which describing the production behavior of the transition and
final stages of a fractured reservoir. The equations obtained which define the matrix flow capacity \( k_m h \), storage capacity \((\phi V_c)_m\), and expansibility \((k/\phi V_c)_m\) are

\[
k_m h = \frac{282.5 \ q_{im} B \mu}{(p_i - p_{wf})(r_e^2 - r_w^2) \alpha}
\]

(12)

\[
(\phi V_c)_m = \frac{2.637 \times 10^{-4} \ \alpha \ k_m}{d_m \mu}
\]

(13)

and

\[
\left[ \frac{k}{(\phi V_c)_m} \right] = \frac{3.792 \times 10^3 \ d_m \mu}{\alpha}
\]

(14)

Dimensionless Parameters Describing an Overall Fractured System

With the properties obtained above, the Warren and Root dimensionless parameters\(^\text{17}\) defining the behavior of a naturally fractured system -- fracture storage parameter \( \omega \) and matrix/fracture permeability ratio \( \lambda \), then can be computed with Eqs. 3 and 4 respectively. Most modern studies of two-porosity systems (including the study of Da Prat et al.) are based on the Warren and Root model.
Terms involving fracture/matrix storage capacity, interporosity flow capacity, and interporosity flow shape factor can be related to the rates of decline and \( r_e/r_w \) ratio. Eqs. 11 and 14 may be combined to form

\[
\frac{1}{\alpha r_w^2} \frac{(k/\phi V_c)_f}{(k/\phi V_c)_m} = \frac{1}{2} \frac{d_f}{d_m} \left( \frac{r_e}{r_w} \right)^2 \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} \right] \tag{15}
\]

Eq. 15 allows both the initial and final exponential decline rates observed on a production curve of a two-porosity system to be combined for a better evaluation of the over-all reservoir characteristics. The only data required in addition to production records is the \( r_e/r_w \) ratio. "Over-all capacity" will be named for the term calculated by Eq. 15. The equation permits the estimation of three important parameters of a fractured reservoir, interporosity flow shape factor, matrix/fracture flow capacity, and matrix/fracture storage capacity. Note that the over-all capacity is dimensionless and equivalent to \((1/\lambda)(1/\omega - 1)\). If \( r_e/r_w \) ratio is constant, then this dimensionless term would be a function of \( d_f/d_m \) ratio only.

Eqs. 9-15 indicate the dual-characteristics of a fractured system can be evaluated from the extrapolated initial production rates and the rates of decline of a multi-slope production curve.
Application of the Method

In order to illustrate the use of the equations presented above, the producing history shown in Fig. 3 is examined. No other well data are available, hence the average properties of Giddings field (Table 3) are used for calculation.

Table 3 - Reservoir Data for Example Problem

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial reservoir pressure</td>
<td>3,800 psi</td>
</tr>
<tr>
<td>Initial GOR</td>
<td>1,050 cf/bbl</td>
</tr>
<tr>
<td>Oil gravity</td>
<td>40 °API</td>
</tr>
<tr>
<td>Temperature</td>
<td>225 °F</td>
</tr>
<tr>
<td>Well spacing</td>
<td>40 acres</td>
</tr>
</tbody>
</table>

Fig. 4 shows the estimated initial and final decline rates and the extrapolated initial production rates. The oil viscosity is estimated to be 0.26 cp. The drainage radius calculated from 40-acre spacing is 745 ft. The producing well pressure is assumed to be zero, since the well is kept pumped off. Wellbore radius is assumed to be 0.25 ft.

The fracture flow capacity is determined with Eq. 9:

\[ k_f h = \frac{141.2 \times (433)(0.26)(\ln(745/0.25)-3/4)}{(3800 - 0)} \]

\[ = 30.3 \text{ md-ft} \]
Fig. 4 - Production Decline Curve for Example Problem
Assuming \( h = 40 \text{ ft} \), then

\[
k_f = \frac{30.3}{40} = 0.76 \text{ md}
\]

From Eq. 10, the fracture storage capacity is

\[
(gVc)_f = \frac{5.274 \times 10^{-4}(0.76)}{(2.05/365/24)(0.26)(745^2)(\ln(745/0.25)-3/4)}
\]

\[
= 1.6 \times 10^{-6} \text{ psi}^{-1}
\]

The fracture expansibility is

\[
\left[ \frac{k}{gVc} \right]_f = \frac{0.76}{1.6 \times 10^{-6}} = 4.8 \times 10^5 \text{ md-psi}
\]

which also can be computed from Eq. 11.

The matrix properties are characterized by the final decline stage. From Eq. 12, the flow shape factor-matrix permeability product is

\[
\alpha k_m = \frac{282.5 (133)(0.26)}{(40)(3800-0)(745^2-0.25^2)}
\]

\[
= 1.2 \times 10^{-7} \text{ md-ft}^{-2}
\]

If \( k_m \) can be obtained from core analysis, \( \alpha \) can be computed. The value of \( \alpha \) may yield information about the fracture spacing and matrix
geometry (Appendix B). \(^{17}\)

With the value of \(\alpha k_m\), the matrix storage capacity is obtained from Eq. 13 as

\[
(\phi V_c)_m = \frac{2.637 \ (10^{-4})(1.2 \times 10^{-7})}{(0.693/365/24)(0.26)} = 1.5 \times 10^{-6} \text{ psi}^{-1}
\]

Eqs. 3 and 4 may be used to compute the dimensionless parameters of fracture storage \(\omega\) and matrix/fracture permeability ratio \(\lambda\) as follow

\[
\omega = \frac{(1.6 \times 10^{-6})}{(1.6 \times 10^{-6}) + (1.5 \times 10^{-6})} = 0.52
\]

and

\[
\lambda = \frac{(1.2 \times 10^{-7})(0.25^2)}{0.76} = 1.0 \times 10^{-8}
\]

The dimensionless over-all capacity can be computed either by Eq. 15 or by \((1/\lambda)(1/\omega -1)\). A value of over-all capacity equal to 0.9 \(\times 10^8\) was obtained for this example.
RESULTS AND DISCUSSION

Well Performance

The total reserves obtained from decline curve analysis are classified into five profitability groups based on ultimate reserves\(^4\) as shown in Table 4a.

Table 4b shows the result of a statistical analysis of Austin Chalk wells based on well profitability classified in Table 4a. Those wells which are relatively "new" (i.e., still in fracture depletion stage) and show relative high current production rate (about 5,000 bbl/mo) are not analysed due to the danger and uncertainty discussed earlier. The economic limit applied in this study is 100 bbl/mo.

As indicated in Table 4b, of 1,235 wells, 43.9% (542 wells) are classified as unprofitable, 11.6% (143 wells) are marginally profitable, 11.5% (142 wells) are profitable, and 19.4% (240 wells) are highly profitable. Noted that, only 63 of the 1,235 wells (5.1%) are dry holes. Considering the large number of wells drilled and the large area covered by the Austin Chalk productive trend (at least 300 mi long, 15 mi wide), obviously it is not difficult to find oil in this trend. However, it is obvious from this study, areas of high fracture density must be encountered for a well to be highly profitable. The result is further clarified by plotting the iso-reserves contour map as shown in Fig. 5 (in the map pocket). Highly productive spots are
sparsely distributed in the area. Thus, the Austin Chalk production can be generally described as "low risk, low yield". The future of Austin Chalk play is still controlled by oil price.

Table 4a - Classification of Austin Chalk Well Profitability Based on Ultimate Reserves

<table>
<thead>
<tr>
<th>PROFITABILITY TYPE</th>
<th>RESERVES (Mbb1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry holes</td>
<td>0.0</td>
</tr>
<tr>
<td>Unprofitable</td>
<td>0.0 - 35.0</td>
</tr>
<tr>
<td>Marginally profitable</td>
<td>35.0 - 60.0</td>
</tr>
<tr>
<td>Profitable</td>
<td>60.0 - 100.0</td>
</tr>
<tr>
<td>Highly profitable</td>
<td>&gt; 100.0</td>
</tr>
</tbody>
</table>

Table 4b - Statistical Summary of Austin Chalk Wells Based on Profitability Types

<table>
<thead>
<tr>
<th>PROFITABILITY TYPE*</th>
<th>NO. OF WELLS</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry holes</td>
<td>105</td>
<td>8.5</td>
</tr>
<tr>
<td>Unprofitable</td>
<td>542</td>
<td>43.9</td>
</tr>
<tr>
<td>Marginally profitable</td>
<td>143</td>
<td>11.6</td>
</tr>
<tr>
<td>Profitable</td>
<td>142</td>
<td>11.5</td>
</tr>
<tr>
<td>Highly profitable</td>
<td>240</td>
<td>19.4</td>
</tr>
<tr>
<td>&quot;New wells&quot;</td>
<td>63</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1235</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

* The profitability types are those classified in Table 4a.
Austin Chalk Fracture Trend

With almost all production coming from natural fractures plus the facts of low porosity and permeability of matrix, chances of finding oil are enhanced if the largest concentration of natural open fractures can be located. Conversely, it is quite natural to relate productivity, hence ultimate recovery, to fracture intensity and orientation (or pattern).

Fig. 5 shows the iso-reserves contour map. The map is prepared in the hope of locating favorable fracture areas or directions in the Austin Chalk trend. As indicated in Fig. 5, the main productive trend runs in a northeast-southwest direction. The trend should approximate the main fracture trend of the Austin Chalk formation. Some good production spots are found in opposite pairs (or more) to the main alignments or in parallel pairs (or more) along the main alignment. There are some high production areas running 45 to 90° to the main productive trend. Observation of two sets of fractures with two different (degrees) of angles in the cores of good oil producing area have been reported.5

While the iso-reserves map indicates oil production comes from northeast-southwest trending fractures, it is quite difficult to tell the more localized directions of the favorable areas or high fracture intensity areas for possible best production.
It should be noted that Fig. 5 shows the production distribution along the main producing trend, but not necessary the fracture density distribution. As mentioned earlier, finding fractures does not always foretell a producing well. Fractures may be so intensive or interconnected in some areas, that oil migration by adjacent production has already occurred. In some updip areas near Pearsall field, operators have found the fractures but most of the oil had already migrated downdip to earlier producing wells.²

The fracturing of Austin Chalk may due to sinking of the Gulf Coast geosyncline, fault-related brecciation, or textural fractures which are not directly related to faulting.⁵ If Fig. 5 represents the fracture density distribution, smaller, more localized events causing fracturing seem to be key for the highest fracture intensity.

While Fig. 5 does not necessarily represent the natural fracture distribution, it can aid the operators in selecting future sites of stimulating wells to intersect the largest possible production areas. In addition, it may reflect the irregular pattern of fluid flow paths, which is important information when dealing with enhanced recovery.
CONCLUSIONS

As a result of this study the following general conclusions can be drawn:

1. Production of fractured Austin Chalk wells is characterized by a two-slope exponential decline behavior -- an early rapid decline and a late slow decline.

2. The average values of decline rates are 200 to 300 %/year for initial decline and 30 to 60 %/year for final decline.

3. Under favorable conditions, one should be able to evaluate the flow capacity, storage capacity, expansibility, fracture storage parameter, matrix/fracture permeability ratio, and over-all capacity from the production data of a fractured system.

4. The ratio of early to late decline rate has the average value of 2.5 to 5.5. Coupled with the initial rates of a well, this ratio should aid in the forecasting of the future production of an Austin Chalk well.

5. An Austin Chalk well can be described as "low risk, low yield". Areas of high fracture density must be encountered for a well to be highly profitable.

6. The reservoir shows a somewhat anomalous fracture system and characteristics inspite of the general northeast-southwest direction of production trend.
NOMENCLATURE

\[ B \quad = \quad \text{formation volume factor, RB/STB} \]
\[ c \quad = \quad \text{compressibility, 1/psi} \]
\[ d \quad = \quad \text{rate of decline, 1/hour} \]
\[ h \quad = \quad \text{formation thickness, ft} \]
\[ k \quad = \quad \text{permeability, md} \]
\[ P_i \quad = \quad \text{initial reservoir pressure, psi} \]
\[ P_{wf} \quad = \quad \text{flowing wellbore pressure, psi} \]
\[ q \quad = \quad \text{flow rate, STB/D} \]
\[ q_D \quad = \quad \text{dimensionless flow rate, } \frac{141.2 \ q_b \mu}{k_f h (P_i - P_{wf})} \]
\[ r_{eD} \quad = \quad \text{dimensionless outer boundary radius, } r_e/r_w \]
\[ r_w \quad = \quad \text{wellbore radius, ft} \]
\[ t \quad = \quad \text{time, hours} \]
\[ t_D \quad = \quad \text{dimensionless time, } \frac{2.637 \times 10^{-4} \ k_f t}{((\varphi V_c)_m + (\varphi V_c)_f) \mu r_w^2} \]
\[ V \quad = \quad \text{ratio of total volume of medium to bulk volume, } V_f + V_m = 1 \]
\[ \alpha \quad = \quad \text{interporosity flow shape factor, ft}^{-2} \]
\[ \mu \quad = \quad \text{viscosity, cp} \]
\[ \varphi \quad = \quad \text{porosity, fraction} \]
\[ \omega \quad = \quad \text{dimensionless fracture storage} \]
\[ \lambda \quad = \quad \text{dimensionless matrix/fracture permeability ratio} \]
Subscripts

\( D \quad = \quad \text{dimensionless} \)

\( f \quad = \quad \text{fracture} \)

\( i \quad = \quad \text{initial} \)

\( m \quad = \quad \text{matrix} \)
REFERENCES


12. Personal communication from Dr. S.W. Poston and T. Blasingame, Texas A&M University.


APPENDIX A

STATISTICAL METHODS OF AVERAGING

THE PRODUCTION DECLINE PROPERTIES

The average values of initial and final decline rates, and the ratios of initial to final decline rate are calculated as follows.

The data under consideration are classified into classes or ranges. The number of occurrences and the frequency (or percentage) of the data in each range are calculated. The arithmetic mean is defined by

\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i F_i}{n} \quad (A1)
\]

and the standard deviation by

\[
S = \left[ \sum_{i=1}^{n} (x_i - \bar{x})^2 F_i \right]^{1/2} \quad (A2)
\]

where \(\bar{x}\) = arithmetic mean

\(x_i\) = class mark (value of variable at mid-point) of i-th-class interval or range

\(F_i\) = frequency for i-th-class interval, fraction

\(S\) = standard deviation

\(n\) = number of class intervals.
The statistical analysis of the initial and final decline rates, and the ratio of initial to final decline rate are summarized in Table A1, A2, and A3 respectively. Only Type I and II wells (decline type, Table 2a) are analysed.

<table>
<thead>
<tr>
<th>RANGE (%/YEAR)</th>
<th>MID-VALUE OF RANGE</th>
<th>NO. OF WELLS</th>
<th>FREQUENCY (FRACTION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 100.0</td>
<td>50.0</td>
<td>26</td>
<td>0.04</td>
</tr>
<tr>
<td>100.0 - 200.0</td>
<td>150.0</td>
<td>193</td>
<td>0.28</td>
</tr>
<tr>
<td>200.0 - 300.0</td>
<td>250.0</td>
<td>195</td>
<td>0.28</td>
</tr>
<tr>
<td>300.0 - 400.0</td>
<td>350.0</td>
<td>88</td>
<td>0.13</td>
</tr>
<tr>
<td>400.0 - 500.0</td>
<td>450.0</td>
<td>77</td>
<td>0.11</td>
</tr>
<tr>
<td>500.0 - 600.0</td>
<td>550.0</td>
<td>57</td>
<td>0.08</td>
</tr>
<tr>
<td>600.0 - 700.0</td>
<td>650.0</td>
<td>23</td>
<td>0.03</td>
</tr>
<tr>
<td>700.0 - 800.0</td>
<td>750.0</td>
<td>21</td>
<td>0.03</td>
</tr>
<tr>
<td>&gt; 800.0</td>
<td>850.0</td>
<td>11</td>
<td>0.02</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>691</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Average = 312.37  
Standard deviation = 179.49
Table A2 - Calculation of Statistical Average Value of the Final Rates of Decline

<table>
<thead>
<tr>
<th>RANGE (%/YEAR)</th>
<th>MID-VALUE OF RANGE</th>
<th>NO. OF WELLS</th>
<th>FREQUENCY (FRACTION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 20.0</td>
<td>15.0</td>
<td>15</td>
<td>0.02</td>
</tr>
<tr>
<td>20.0 - 30.0</td>
<td>25.0</td>
<td>80</td>
<td>0.12</td>
</tr>
<tr>
<td>30.0 - 40.0</td>
<td>35.0</td>
<td>108</td>
<td>0.16</td>
</tr>
<tr>
<td>40.0 - 50.0</td>
<td>45.0</td>
<td>112</td>
<td>0.16</td>
</tr>
<tr>
<td>50.0 - 60.0</td>
<td>55.0</td>
<td>96</td>
<td>0.14</td>
</tr>
<tr>
<td>60.0 - 70.0</td>
<td>65.0</td>
<td>66</td>
<td>0.10</td>
</tr>
<tr>
<td>70.0 - 80.0</td>
<td>75.0</td>
<td>42</td>
<td>0.06</td>
</tr>
<tr>
<td>80.0 - 90.0</td>
<td>85.0</td>
<td>39</td>
<td>0.06</td>
</tr>
<tr>
<td>90.0 - 100.0</td>
<td>95.0</td>
<td>34</td>
<td>0.05</td>
</tr>
<tr>
<td>100.0 - 110.0</td>
<td>105.0</td>
<td>23</td>
<td>0.03</td>
</tr>
<tr>
<td>110.0 - 120.0</td>
<td>115.0</td>
<td>14</td>
<td>0.02</td>
</tr>
<tr>
<td>120.0 - 130.0</td>
<td>125.0</td>
<td>11</td>
<td>0.02</td>
</tr>
<tr>
<td>130.0 - 140.0</td>
<td>135.0</td>
<td>9</td>
<td>0.01</td>
</tr>
<tr>
<td>140.0 - 150.0</td>
<td>145.0</td>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>&gt; 150.0</td>
<td>155.0</td>
<td>32</td>
<td>0.05</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>691</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Average = 62.71
Standard deviation = 34.92
Table A3 - Calculation of Statistical Average Value of the Ratios of Initial to Final Decline Rate

<table>
<thead>
<tr>
<th>RANGE (%/YEAR)</th>
<th>MID-VALUE OF RANGE</th>
<th>NO. OF WELLS</th>
<th>FREQUENCY (FRACTION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.0</td>
<td>1.5</td>
<td>56</td>
<td>0.08</td>
</tr>
<tr>
<td>2.0 - 3.0</td>
<td>2.5</td>
<td>100</td>
<td>0.14</td>
</tr>
<tr>
<td>3.0 - 4.0</td>
<td>3.5</td>
<td>109</td>
<td>0.16</td>
</tr>
<tr>
<td>4.0 - 5.0</td>
<td>4.5</td>
<td>99</td>
<td>0.14</td>
</tr>
<tr>
<td>5.0 - 6.0</td>
<td>5.5</td>
<td>79</td>
<td>0.11</td>
</tr>
<tr>
<td>6.0 - 7.0</td>
<td>6.5</td>
<td>49</td>
<td>0.07</td>
</tr>
<tr>
<td>7.0 - 8.0</td>
<td>7.5</td>
<td>49</td>
<td>0.07</td>
</tr>
<tr>
<td>8.0 - 9.0</td>
<td>8.5</td>
<td>39</td>
<td>0.06</td>
</tr>
<tr>
<td>9.0 - 10.0</td>
<td>9.5</td>
<td>27</td>
<td>0.04</td>
</tr>
<tr>
<td>10.0 - 11.0</td>
<td>10.5</td>
<td>19</td>
<td>0.03</td>
</tr>
<tr>
<td>11.0 - 12.0</td>
<td>11.5</td>
<td>13</td>
<td>0.02</td>
</tr>
<tr>
<td>12.0 - 13.0</td>
<td>12.5</td>
<td>8</td>
<td>0.01</td>
</tr>
<tr>
<td>13.0 - 14.0</td>
<td>13.5</td>
<td>5</td>
<td>0.01</td>
</tr>
<tr>
<td>14.0 - 15.0</td>
<td>14.5</td>
<td>13</td>
<td>0.02</td>
</tr>
<tr>
<td>&gt; 15.0</td>
<td>15.5</td>
<td>26</td>
<td>0.04</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>691</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Average = 5.76
Standard deviation = 3.53
APPENDIX B
SHAPE FACTOR

The shape factor $\alpha$ was introduced in the two-porosity model proposed by Warren and Root\textsuperscript{17} in 1963. Their model is considered the forerunner of modern interpretation of two-porosity systems and has been the subject of further study.

The idealized two-porosity model proposed by Warren and Root (Fig. B1) was based on the following general assumptions:

![Diagram of actual reservoir and model reservoir with labels: VUGS, MATRIX, FRACTURE, MATRIX, FRACTURES, ACTUAL RESERVOIR, MODEL RESERVOIR.

Fig. B1 - Idealization of the Warren and Root Two-porosity Model

a. The material containing the primary porosity is homogeneous and isotropic, and is contained within a systematic array of identical, rectangular parallelepipeds.
b. All of the secondary porosity is contained within an orthogonal system of continuous, uniform fractures which are oriented so that each fracture is parallel to one of the principal axes of permeability. The fractures normal to each of the principal axes are uniformly spaced and are of constant width. A different fracture spacing or a different width may exist along each of the axes to simulate the proper degree of anisotropy.

The assumed model implies heterogeneity on a macroscopic scale. It may also be considered homogeneous if the dimensions of the homogeneous blocks are small in comparison with the dimensions of the reservoir.

\( \alpha \) was given by Warren and Root as a function of block shape and size as

\[
\alpha = \frac{4n(n+2)}{\xi^2}, \quad (B1)
\]

where \( n \) = number of normal sets of fractures = 1, 2, 3, and

\( \xi \) = characteristic dimension of heterogeneous region.

If the dimensions of the parallelepiped are \( a, b, \) and \( c, \) the equivalent value of \( \xi \) can be estimated from the surface-volume ratio:

\[
\xi = \frac{3abc}{(ab+bc+ca)}, \quad n=3 \quad (B2)
\]
\[ \ell = \frac{2ab}{(a+b)}, n=2 \] (B3)

\[ \ell = a, n=1 \] (B4)

Note that if \( a=b=c \), then \( \ell = a = b = c \).

The Warren and Root model is a highly idealized representation of the actual physical conditions existing in a naturally fractured reservoir. The use of a regularly shaped matrix block and fracture system is a mathematical convenience. Therefore, calculated value of \( \alpha \) may have little relationship with the existing physical fracture spacing.
VITA

Name: Her-Yuan Chen

Born: May 22, 1955
Pingtung, Taiwan, ROC

Parents: Mr. and Mrs. Cheng-Fu Chen

Permanent Address: 30-6 Lin-Sen Road
Pingtung, Taiwan, Republic of China 900

University: Taiwan Provincial College of Marine
Science and Technology, Keelung,
Taiwan, Republic of China
Bachelor of Science Degree in
Marine Science and Technology (July 1977)

Texas A&M University
College Station, Texas
Master of Science Degree in
Petroleum Engineering (December 1985)

Member: Society of Petroleum Engineers of AIME