FOSSIL ENERGY

DOE/BC/14994-9
OSTI ID: 9321

# A COMPARISON OF MASS RATE AND STEAM QUALITY REDUCTIONS TO OPTIMIZE STEAMFLOOD PERFORMANCE

SUPRI TR 108



By
Gregory L. Messner

July 1998

Work Performed Under Contract No. DE-FG22-96BC14994

Stanford University
Stanford, California

National Petroleum Technology Office
U. S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

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# Abstract

Many operators of steamdrive projects will reduce the heat injection rate as the project matures. The major benefit of this practice is to reduce the fuel costs and thus extend the economic life of the project. However, there is little industry consensus on whether the heat cuts should take the form of; (1) mass rate reductions while maintaining the same high steam quality, or (2) steam quality decreases while keeping the same mass rate. Through the use of a commercial three-phase, three-dimensional simulator, the oil recovery schedules obtained when reducing the injected steam mass rate or quality with time were compared under a variety of reservoir and operating conditions. The simulator input was validated for Kern River Field conditions by using the guidelines developed by Johnson, *et al.* (1989) for four steamflood projects in Kern River.

The results indicate that for equivalent heat injection rates, decreasing the steam injection mass rate at a constant high quality will yield more economic oil than reducing the steam quality at a constant mass rate. This conclusion is confirmed by a sensitivity analysis which demonstrates the importance of the gravity drainage/steam zone expansion mechanism in a low-pressure, heavy oil steamflood with gravity segregation. Furthermore, the impact of discontinuous silts and nonuniform initial temperatures within the steamflood zone was studied, indicating again that a decreasing mass rate injection strategy is a superior operating practice.

# Acknowledgements

Financial aid for this work was provided by Department of Energy Grant DE-FG22-96BC-14994 and by SUPRI-A Industrial Affiliates. This support is gratefully acknowledged. We also thank Texaco for permission to publish the data in this report.

# 1. Introduction

It is routine to reduce the heat injection rate in a steamflood project as it approaches the economic limit. The major benefit of this practice is to reduce the fuel costs and thus extend the economic life of the project. Furthermore, there is evidence that frequent reductions in the heat injection rate are both theoretically sound and economically advantageous in steamflooding operations (Vogel, 1984). There are two general approaches to accomplishing these reductions: (1) cutting the mas rate of the injected steam while maintaining the same high quality; and (2) reducing the steam quality while keeping the same rate. Interestingly, there appears to be no industry consensus on which heat reduction process should be applied under a given set of reservoir conditions, and operators will often follow different steam injection rate or quality strategies within the same field.

The purpose of this study is to examine the recovery consequences of reducing mass rates or steam qualities using a thermal reservoir simulation program. In addition to the insights gained, it was hoped that general guidelines could be developed which would help determine which heat reduction scheme should be applied under a given set of steamflood conditions.

# 2. Literature Review

Several investigators have studied the effect of varying the heat injection rate with time in thermal recovery projects. Chu and Trimble (1975) conducted a reservoir simulation study using a three-dimensional, three-phase numerical model (Coats, *et al.*, 1974). After history matching the oil recovery performance for a single pattern in the Kern River Field, they investigated the influence of varying the steam injection schedule. By using the concept of cumulative discounted net oil (CDNO) as the optimizing criterion, they found that the economic performance of a steamflood could be improved over the constant rate injection case by increasing the initial steam rate and then decreasing the steam rate with time. In all these cases, the steam quality was held constant at 70%. While they mentioned that further work was needed to determine the optimal variations of steam rates, a hyperbolic decline was superior to a linear variation. They also concluded that the improvements increased with sand thickness.

The work of Vogel (1984) provides a more theoretical foundation for placing the Chu and Trimble results in perspective. By assuming that steam override is instantaneous, he derived an analytical descending steam chest model using the equations for linear heat flow from an infinite plane. Inspection of his equations showed that the heat rate requirements in a steamflood should start high and then decline with time. Figure 1, reproduced from Vogel's paper, illustrates typical steam injection rate requirements using his method. These steam requirements decline in a somewhat hyperbolic manner. Although not explicitly expressed, Vogel appeared to assume that mass rates rather than steam qualities should be cut, because the key to his method involved estimating the rate of downward growth of the steam zone.

In a similar study, Neuman (1985) developed equations to predict steamflood performance with steam override. His approach enabled calculation of steam zone growth, oil displaced, and consequences of reduced heat injection. With these equations, a reasonable match of oil production was made for Chevron's 10-pattern steamflood in the Kern River Field, California (Oglesby, *et al.*, 1982 and Blevins and Billingsley, 1975). Like Vogel, Neuman also showed the benefits of decreased heat injection with time, but he stated that a reduction in steam quality is the preferred method. However, he did not present any field or theoretical evidence to support this assertion.

Other studies have supported reduced injection rates with time in steamfloods. Using scaled physical laboratory models and field data, Myhill and Stegemeier (1978) found that high initial steam injection rates were desirable to promote faster heating around the producers. After breakthrough, however, large amounts of heat were produced, indicating that injection rates should be reduced. Also, from a mathematical heat balance model, they demonstrated that oil-steam ratios were improved with increased steam quality. Farouq Ali and Meldau (1979) expanded upon these findings.

Spivak and Muscatello (1987) performed a reservoir simulation study of steamflooding in the South Belridge Field, Kern County, California. After peak oil production, they found that tapering the mass injection rate at constant quality, increased the oil-steam ratio over a constant injection rate case. The optimum taper rate was 10% per year. Furthermore, they showed that, for equivalent heat injection, tapering the steam quality was much less effective than tapering the mass rate. However, these comparisons were made for a layered reservoir model with no vertical communication, so steam override was not a factor.

In the field, reduced injection rates have been reported to be successful in several steamflood projects. In Kern River, Bursell and Pittman (1975) saw improved steam-oil ratios resulting from reduced steam injection rates in three steamflood pilots, presumably with steam at a constant high quality. Ault, *et al.* (1985) also reported economic success in reducing heat injection rates in two Kern River projects, but they accomplished these reductions by cutting the steam quality to approximately 10%.

There seems to be common agreement that the heat injection rate should be reduced with time. However, contradictory evidence exists over whether heat cuts should take the form of reduced rate at constant quality or reduced quality at constant rate. Since fuel consumption is the highest operating cost item in a steamflood, deciding how best to use that fuel is of great importance. The purpose of this work is to answer that question.

## 3. Methodology

This study relies heavily on a commercial three-phase, three-dimensional thermal simulation program (THERM) developed by Scientific Software-Intercomp (SSI). This program is capable of simulating steamflood, hot waterflood, cyclic steam and in-situ combustion processes and is fully implicit in the pressure, temperature, saturation and concentration terms. All simulation runs used a 9-point finite difference scheme which accurately handles reservoir heterogeneities and unequal grid spacings, and considerably reduces any grid orientation effect (SSI, 1988). All runs were made on a CRAY supercomputer.

For model input, the general guidelines developed for the Kern River Field by Johnson, *et al.* (1989) were incorporated. These include:

1. Kern River oil can be represented by a single-component, non-distillable heavy oil.
2. To induce the rapid steam overlay observed in the field, the vertical transmissibility at the injector is multiplied by 100 until 0.4 pore volumes (PV) of steam are injected.
3. A uniform set of relative permeability curve shapes and endpoints can be used.

Reservoir input data used in all of the following models are listed in Table 1. All cases comparing either mass rate or steam quality reductions have identical heat injection schedules.

One further point should be stressed here. The Johnson, *et al.* (1989) study successfully history matched the performance of high and low quality steamfloods using a uniform set of input guidelines. Not only were oil and water production rates and cumulatives matched; but also satisfactory predictions were achieved for steam breakthrough times, oil saturation profiles and temperature profiles. Successful history matching of several types of field data reduces the problem of non-uniqueness and indicates that the model is properly simulating the recovery mechanisms in low-pressure, heavy oil steamfloods. In a similar vein, this study will use several different operating scenarios and initial reservoir conditions to arrive at general conclusions regarding the preference of rate or quality reductions.

## 4. Discussion of Results

Several different types of reservoir settings and production schemes were studied to assess their effects on the economics of heat reduction operations. Each of these will be discussed in some detail.

### 4.1 One-Eighth of a Five-Spot Model

The first segment of this study involved using a one-eighth pattern element of symmetry to model a five-spot steamflood configuration. A $7 \times 4 \times 5$ parallel grid (Fig. 2) was set up for two homogeneous sand thicknesses, 40 and 80 feet. Table 2 lists input assumptions for these cases. The first set of runs assumed a 24% heat injection rate cut for two timing scenarios: (1) after two years of high quality, constant rate injection; and (2) at the high quality, constant rate economic limit, which was set to occur at a steam-oil ratio of 10.5. "High quality" in these cases means 52.5% of the steam mass is vapor at the sandface, a good average for Kern River operations. Key results from these simulation runs are shown in Figs. 3 and 4.

In brief, the recovery results for the 40 ft. reservoirs show that rate cuts at constant quality are superior to quality cuts at constant rate, no matter when the reduction in heat rate begins. Clearly comparing Figs. 3 and 4, it is better to start heat reduction sooner. The resulting total recoveries are about the same, but the operating costs would be significantly less.

For the 80 ft. reservoir case, the recoveries are also better for rate reduction compared to quality reduction. But clearly these differences are minor. In terms of practicality, we should recognize that we seldom see steam floods in sands that have as much as 80 ft. of homogeneous section. Later results will include cases where the systems are not homogeneous, but first we will discuss the effects of assumed relative permeability relationships and residual oil saturations.

## 4.2 Recovery Mechanisms and Sensitivity to Residual Oil Saturation and Relative Permeability Assumptions

From examining these simulation runs, it is clear that tapering mass rates promotes more rapid steam zone expansion. For example, in the 40 ft. example, the average steam saturation in the entire reservoir was 9.7% at the end of four years in the rate cut case. This is 34% higher than the quality cut case (7.1%). Furthermore, the rate case had 10% greater volumetric sweep of the steam zone.

These differences in steam zone expansion rates should be expected, since more steam vapor is injected in the rate cut case. However, the oil recovery differences suggest that steam zone expansion/gravity drainage is a more efficient recovery mechanism than hot water displacement. Looking at our input data, this idea is reasonable, given that at 225°F the residual oil saturation to liquid water ($S_{orw}$) is assumed to be 0.233, while the residual oil saturation to steam vapor ($S_{org}$) is only 0.05. These endpoint residual oil saturation (ROS) assumptions are extremely important in determining whether to reduce steam mass rates or qualities.

Since economic limits are built into the recovery comparisons, the shapes of the relative permeability curves should also have some influence on the recovery efficiencies. Changing the shapes and endpoints of these curves did have some effect on the results. The endpoint effect was the stronger of the two.

## 4.3 Validity of ROS and Relative Permeability Input Assumptions

A key factor influencing the recovery comparisons is the residual oil saturation to water and steam vapor. The ROS endpoint values used here are the same as those used by Johnson *et al.* (1989). The $S_{orw}$ values were based on laboratory coreflood experiments, and the $S_{org}$ endpoints were determined from both post-steamflood coring and laboratory corefloods. The low ROS to steam (0.05 PV) agrees with field results presented by other authors (Bursell and Pittman, 1975; and Blevins and Billingsley, 1975).

There are two major mechanisms by which steam vapor reduces oil saturation to very low values: (1) distillation, and (2) three-phase film flow with gravity (Hirasaki, 1989). These two phenomena were visually observed by Bruining, *et al.* (1984) during gravity-stable coreflood experiments. For longer flood times their residual oil saturations were below 0.10. These studies explain the low ROS's observed in steam-swept field cores, and tend to validate the $S_{org}$ endpoint values used herein.

As previously mentioned, the $S_{orw}$ endpoints were determined from laboratory measurements (Johnson, *et al.*, 1989). For 225°F, the $S_{orw}$ averaged 0.234, but the laboratory measurement scatter was significant. Other experimental work discussed by Prats (1982, Chapter 6) indicates that the $S_{orw}$ endpoint at higher temperatures tends to remain above 0.20. Thus the ROS endpoints to hot water used in this study appear to be realistic.

The relative permeability curves used in any reservoir simulation study are always subject to question, as recently explained by Saleri and Toronyi (1988). However, the chosen curves have been successfully used in history matching several steamflood projects (Johnson, *et al.*, 1989) and thus are within a reasonable uncertainty range.

In summary, the input assumptions which have the greatest impact on the comparison of rate and quality cuts, i.e., the ROS endpoints and the oil relative permeability curve to water, are considered to be quite reasonable. Thus, the conclusions regarding rate and quality reductions, appear to be valid. The behavior is consistent with observations by Vogel (1984) and Myhill and Stegemeier (1978). The primary recovery mechanism after steam breakthrough, is downward steam zone expansion with gravity drainage of heated oil. Cutting the rate but keeping the steam quality high will promote this effect. Cutting steam quality, and maintaining rate, depends on less efficient hot water displacement.

### 4.4 Multiple Pattern Model

In the previous model, it was implicitly assumed that all fluid flow was confined within the five-spot pattern. In an actual steamflood project, there will usually be some inter-pattern communication. For example, in the Kern River 10-pattern steamflood pilot, approximately 10% of the increased production came from hot production wells outside of the original project area (Blevins and Billingsley, 1975). Thus a multiple pattern model was constructed to incorporate asymmetric conditions. With less pattern confinement, it was thought that the recovery mechanisms identified in the confined model, might change in their relative importance.

The multiple pattern model consisted of a $16 \times 16 \times 3$ triangular grid representing one-eighth of 50 patterns covering 125 acres in a 60 ft. sand, and is similar to the model set-up described by Chu (1987). The reservoir conditions were identical to those of the single pattern model, except that the grid thicknesses were now 9, 18 and 33 ft, from top to bottom, with the injection wells completed only in the bottom layer. To initialize asymmetrical conditions the exterior 34 patterns were steamflooded for six years while the interior 16 patterns remained idle (Fig. 5). After steam stimulating the interior producers (Wells 1, 2 and 7), a steamflood was started in the interior 16 patterns, with steam injection rates of 331 BPD/well.

First, a test case of constant rate injection was run, and immediately apparent was the low oil recovery in the multiple pattern flood. Recovery was 48,000 bbl/pattern compared with 88,000 bbl from the single pattern after five years. Nevertheless, several years of economic oil production were attained in this model set-up. Figure 6 illustrates the oil recovery versus time for tapering the mass rates and steam qualities at two different decline rates. It is apparent that tapering the rate is significantly better than tapering the quality.

Interestingly, the recovery differences between the rate and quality cases are more pronounced than those in the confined model. At least part of this effect is due to the lower pressures in the multipattern model, which allow more steam zone expansion.

## 4.5 Comparison of Rate and Quality Reductions in Silty Sands

Both the single and multiple pattern models discussed so far have assumed homogeneous rock properties for the entire flood area. However, most steamflood projects are conducted in reservoirs with some degree of heterogeneity. For example, several Kern River steamfloods have been shown to have discontinuous shale layers within the displacement interval (Bursell and Pittman, 1975; and Blevins and Billingsley, 1975).

For this segment of the study, a $7 \times 4 \times 7$ grid was used to model one-eighth of a 2.5 acre, 60 ft. thick pattern. Input data are listed in Table 3. The presence of silts was simulated by altering the vertical fluid transmissibilities to correspond to a 2 ft. thick, 5 millidarcy shale layer. The first set of runs assumed one silt interbedded between grid layers 4 and 5, corresponding to a position 24 ft. below the top of the formation. Also, no shale was placed in the vicinity of the injection well, as illustrated in Fig. 7. This was done to create the maximum opportunity for steam override above the silt layer, as might result from a poor quality cement bond in the injector, and thus counteract the rate cut's main advantage seen in the clean sand cases: the downward steam zone expansion/gravity drainage recovery mechanism.

Figure 8 shows oil recovery vs. time for 10% and 30% per year taper rates beginning at 548 days into the project. Instead of the modest differences in recovery seen in Fig. 4, the mass rate reductions recover far more economic oil. Furthermore both the 10% and 30% per year taper cases are still producing economically after eight years of steamflooding, with a recovery over 60% of the OOIP indicated for the 10% case. The oil recoveries are well above those in the clean sand model. The reasons for these results will be discussed later.

For the second discontinuous silt model, three silt interbeds were placed in positions corresponding to 9, 24, and 48 ft. from the top of the 60 ft.. thick sand. The areal extent of the silts was assigned using a random number generator (Figs. 9-11). Like the one silt case, Fig. 12 shows that mass rate cuts are far more efficient in this model. Again, high economic oil recoveries are indicated.

These high recoveries need further discussion. Comparing Figs. 8 and 12 with Fig. 4, it is apparent that the sand/silt models recover significantly more oil than the homogeneous sand case. The saturation and temperature distributions show that the silt layers improve the vertical sweep of the steamflood by trapping steam below them. Figure 13 illustrates this phenomenon for the one silt model. On this cross-section, an additional steam zone lies under the silt layer. Thus, the silt layers accelerate the downward heating of the formation and extend the economic production time. Furthermore, high steam quality promotes this effect.

## 4.6 Preheated Reservoir Sands

Restine (1983) has pointed out that the productive section of the Kern River Field consists of a sequence of sands averaging 60 ft. in thickness and separated by continuous silt or clay layers. While these shaly layers may be impermeable to steam, the sands immediately above a steamflooded interval are heated by conduction. Restine discussed field results and simulation work, and he concluded that this preheating effect of upper sands is an important consideration in a steamflood operation.

To see the impact of reservoir preheating on the comparison of rate and quality cuts, a one-eighth pattern model with a $7 \times 4 \times 7$ grid was again used to simulate a steamflood in a 60 ft. thick sand. The reservoir conditions were identical to the discontinuous silts model (Table 3) except that the initial reservoir temperature varied with depth. This temperature relationship is illustrated in Fig. 14 and is similar to the field data presented by Restine (1983).

Table 4 summarizes the production results for clean and silty sand cases, and we see again that for the equivalent heat injection rate, one should cut the mass rate at constant quality. Note, however, that while the 30% per year tapers show large differences between rate and quality reductions, the 10% rate decreases yielded only modest inprovement (3-6% of OOIP). It is likely that the 10% rate cases were relatively overinjected with heat. Evidence of overinjection can be seen in the almost identical final oil recoveries for the 10% and 30% cases.

Another interesting result is the high ultimate oil recoveries seen in the clean sand cases with tapered injection rates. In the last section it was noted that the presence of discontinuous silts could increase recovery, in sands of uniform temperature, by hindering the gravity override of the steam and thus accelerating the downward heating of the formation. However, when a zone has already been heated by underlying conduction, this effect is minor; in fact, discontinuous silts in preheated sand steamfloods could actually reduce oil recovery by hindering gravity drainage due to reduced vertical permeabilities. This concept is suggested in the Table 4 data, where the clean sands produced slightly more oil than the silty sand cases when the mass rates were tapered.

## 5. Conclusions

Under a variety of reservoir and operating conditions, the oil recovery consequences of reducing the injected steam mass rate or quality with time have been compared with the help of a thermal simulator. Examination of the simulation results combined with the literature review leads us to the following conclusions:

1. Under the conditions assumed in this study, declining the steam injection mass rate at a constant high quality will recover more economic oil than reducing the steam quality at a constant mass rate. This result assumes equivalent heat injection for the two cases.
2. This constant steam quality strategy agrees with some researchers' observations that in heavy oil, low-pressure steamfloods with gravity segregation, the dominant recovery mechanism is gravity drainage of heated oil accompanied by downward steam zone expansion. High steam quality will promote this effect more than reducing steam quality, which depends on the less effective hot water displacement.
3. Based on cumulative discounted net oil (CDNO), steam injection should start at a high rate than taper with time for the most economic operating strategy. This observation is consistent with the results of Chu and Trimble (1975) and Vogel (1984).
4. Discontinuous silts within an otherwise uniform interval can enhance oil recovery by accelerating the downward heating of the formation. Furthermore, a reduced mass rate approach will be far superior to reducing the quality under these reservoir conditions.

5. If a reservoir sand has been preheated by an underlying steamflood, steam injection rate cuts with time appear to be even more effective than the same strategy in non-preheated reservoirs.

## Recommendations

These general conclusions do not answer the question of the best strategy for a given reservoir. The question is: "When should rate reductions occur, and at what decline rate?" Clearly this question can only be answered by making runs for the specific field case of interest. Such calculations would be quite important economically.

## Nomenclature

| | | |
|---|---|---|
| CDNO | = | Cumulative discounted net oil, bbl |
| CWE | = | Cold water equivalent volume of steam |
| $k_{rg}$ | = | Gas relative permeability, dimensionless |
| $(k_{rg})_{ro}$ | = | Gas (steam) relative permeability at residual oil saturation, dimensionless |
| $(k_{ro})_{iw}$ | = | Oil relativbe permeability at irreducible water saturation, dimensionless |
| $k_{rog}$ | = | Oil relative permeability in a gas (steam/oil system, dimensionless |
| $k_{row}$ | = | Oil relative permeability in a gas (steam/oil system, dimensionless |
| $k_{rw}$ | = | Water relative permeability, dimensionless |
| $(k_{rw})_{ro}$ | = | Water relative permeability at residual oil saturation, dimensionless |
| $n_g$ | = | Exponent for gas relative permeability calculation, dimensionless |
| $n_{og}$ | = | Exponent for oil relative permeability calculation in a gas (steam)/oil system, dimensionless |
| $n_{ow}$ | = | Exponent for oil relative permeability calculation in a water/oil system, dimensionless |
| $n_w$ | | Exponent for water relative permeability calculation, dimensionelss |
| OOIP | = | Original oil in place, bbl |
| ROS | = | Residual oil saturation |
| $S_{iw}$ | = | Irreducible water saturation, fraction PV |
| $S_{org}$ | = | Residual oil saturation to steam fraction |
| $S_{orw}$ | = | Residual oil saturation to steam, fraction pv |
| $T$ | = | Temperature, degrees Fahrenheit |

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TABLE 1

RESERVOIR DATA USED IN ALL SIMULATION RUNS

Reservoir Description

| | |
|---|---|
| Rock heat capacity, Btu/ft$^3$-°F | 35.0 |
| Rock thermal conductivity, Btu/ft-D-°F | 25.6 |
| Overburden heat capacity, Btu/ft$^3$-°F | 39.0 |
| Overburden thermal conductivity, Btu/ft-D-°F | 27.6 |
| Rock compressibility, psi$^{-1}$ | 0.000735 |
| Initial pressure at top of reservoir, psia | 40 |

Oil Properties

| | |
|---|---|
| Heat capacity, Btu/lbm-°F | .50 |
| Thermal Expansion, °F$^{-1}$ | .00039 |
| Compressibility, psi$^{-1}$ | .5 X 10$^{-5}$ |

Relative Permeability Curve Shape and End Point Data (See Appendix A)

$n_w$ = 1.94

$n_{ow}$ = 2.24

$n_{og}$ = 1.20

$n_g$ = 2.58

$(k_{rg})_{ro}$ = 0.46 (all temperatures)

| TEMP, °F | $S_{iw}$ | $S_{orw}$ | $S_{org}$ | $(k_{rw})_{ro}$ | $(k_{ro})_{iw}$ |
|---|---|---|---|---|---|
| 50 | 0.515 | 0.400 | 0.400 | 0.0486 | 0.751 |
| 225 | 0.590 | 0.234 | 0.050 | 0.0558 | 0.575 |
| 400 | 0.665 | 0.229 | 0.050 | 0.0630 | 0.400 |

## TABLE 2

### RESERVOIR DATA USED IN ONE-EIGHTH PATTERN MODEL

| | | |
|---|---|---|
| Model and grid | 1/8 of 5-spot<br>X x Y x Z: 7 x 4 x 5 | |
| Vertical Grid Thickness | 40' Sand | 80' Sand |
| Z = 1 | 5 ft | 5 ft |
| Z = 2 | 5 ft | 10 ft |
| Z = 3 | 10 ft | 15 ft |
| Z = 4 | 10 ft | 20 ft |
| Z = 5 | 10 ft | 30 ft |
| Distance between injector and producer, ft | 233.35 ( 2.5 Acre Pattern) | |
| Initial reservoir temperature °F | 85 | |
| Porosity, % | 31 | |
| Initial water saturation, % | 55 | |
| Initial oil saturation, % | 45 | |
| Initial gas saturation, % | -0- | |
| Horizontal permeability, md | 3,000 | |
| Vertical permeability, md | 2,700 | |
| Oil viscosity @ 80°F, cp | 7,500 | |
| Oil viscosity @ 300°F, cp | 8.38 | |

Injectors completed in the bottom 30' of zone
Producers completed throughout thickness

$P_{wf}$ = 25 psia

$P_{inj}$ varies according to injectivity
Injected fluid enthalpies set at 366°F

TABLE 3

RESERVOIR DATA USED IN MODEL WITH DISCONTINUOUS SILTS

| | |
|---|---|
| Model: grid | 1/8 of 5-spot pattern<br>2.5 acres<br>X x Y x Z: 7 x 4 x 7 |
| Distance between injection and producer, ft | 233.35 |
| Initial Reservoir Temperature, °F | 85 |
| Porosity, % | 31.0 |
| Initial Water Saturation, % | 55 |
| Initial Oil Saturation, % | 45 |
| Initial Gas Saturation, % | 0 |
| Horizontal Permeability, md | 3500 |
| Vertical Permeability, md | 3150 |
| Oil Viscosity, cp 80°F | 7175 |
| 300°F | 7.40 |

Vertical Grid Thickness

| | |
|---|---|
| Z = 1 | 3′ |
| Z = 2 | 6′ |
| Z = 3 | 6′ |
| Z = 4 | 9′ |
| Z = 5 | 12′ |
| Z = 6 | 12′ |
| Z = 7 | 12′ |
| | 60′ Total |

Injector completed in bottom 3 layers
Producer completed in all layers

TABLE 4

COMPARISON OF OIL RECOVERIES
FOR TAPERING INJECTION RATES/QUALITIES
IN PREHEATED 60' SANDS

| CASE | OIL RECOVERY AT THE E. L., % OOIP | LIFE, YEARS |
|---|---|---|
| Clean Sand | | |
| 1. 10%/Yr Taper | | |
| Rate | 63.4 | 4.25 |
| Quality | 57.4 | 3.50 |
| 2. 30%/Yr Taper | | |
| Rate | 63.3 | 5.75 |
| Quality | 46.2 | 3.00 |
| One Shale | | |
| 1. 10%/Yr Taper | | |
| Rate | 62.5 | 3.75 |
| Quality | 59.7 | 3.75 |
| 2. 30%/Yr Taper | | |
| Rate | 61.8 | 5.0 |
| Quality | 46.7 | 3.4 |
| 3 Random Shales | | |
| 1. 10%/Yr Taper | | |
| Rate | 61.9 | 4.0 |
| Quality | 58.3 | 3.75 |
| 2. 30%/Yr Taper | | |
| Rate | 61.1 | 5.5 |
| Quality | 45.0 | 3.15 |

TAPERING INJECTION SCHEDULE
FOR PREHEATED SAND CASES

| TIME, DAYS | 10%/YR RATE TAPER BPD | 10%/YR QUALITY TAPER % | 30%/YR RATE TAPER BPD | 30%/YR QUALITY TAPER % |
|---|---|---|---|---|
| 0-183 | 331 | 52.5 | 331 | 52.5 |
| 183-548 | 300 | 43.885 | 245 | 28.59 |
| 548-913 | 271 | 35.82 | 182 | 11.07 |
| 913-1278 | 245 | 28.59 | 142.17 | 0 |
| 1278-1643 | 222 | 22.20 | 142.17 | 0 |
| 1643-2008 | 201 | 16.36 | 142.17 | 0 |
| 2008-2373 | 182 | 11.08 | 142.17 | 0 |
| 2373-2738 | 164 | 6.07 | 142.17 | 0 |

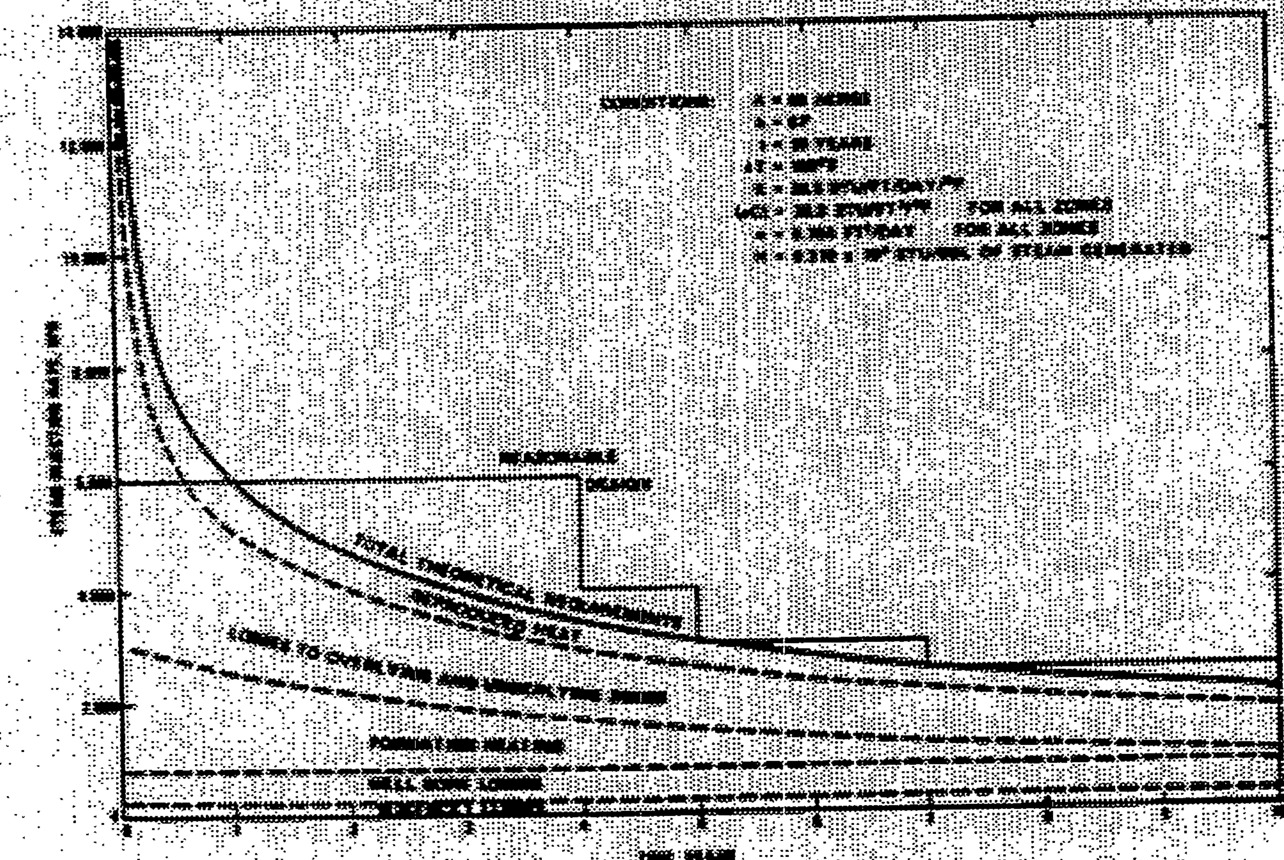


Figure 1. Theoretical steam requirements using planar heat flow model (Vogel, 1984).

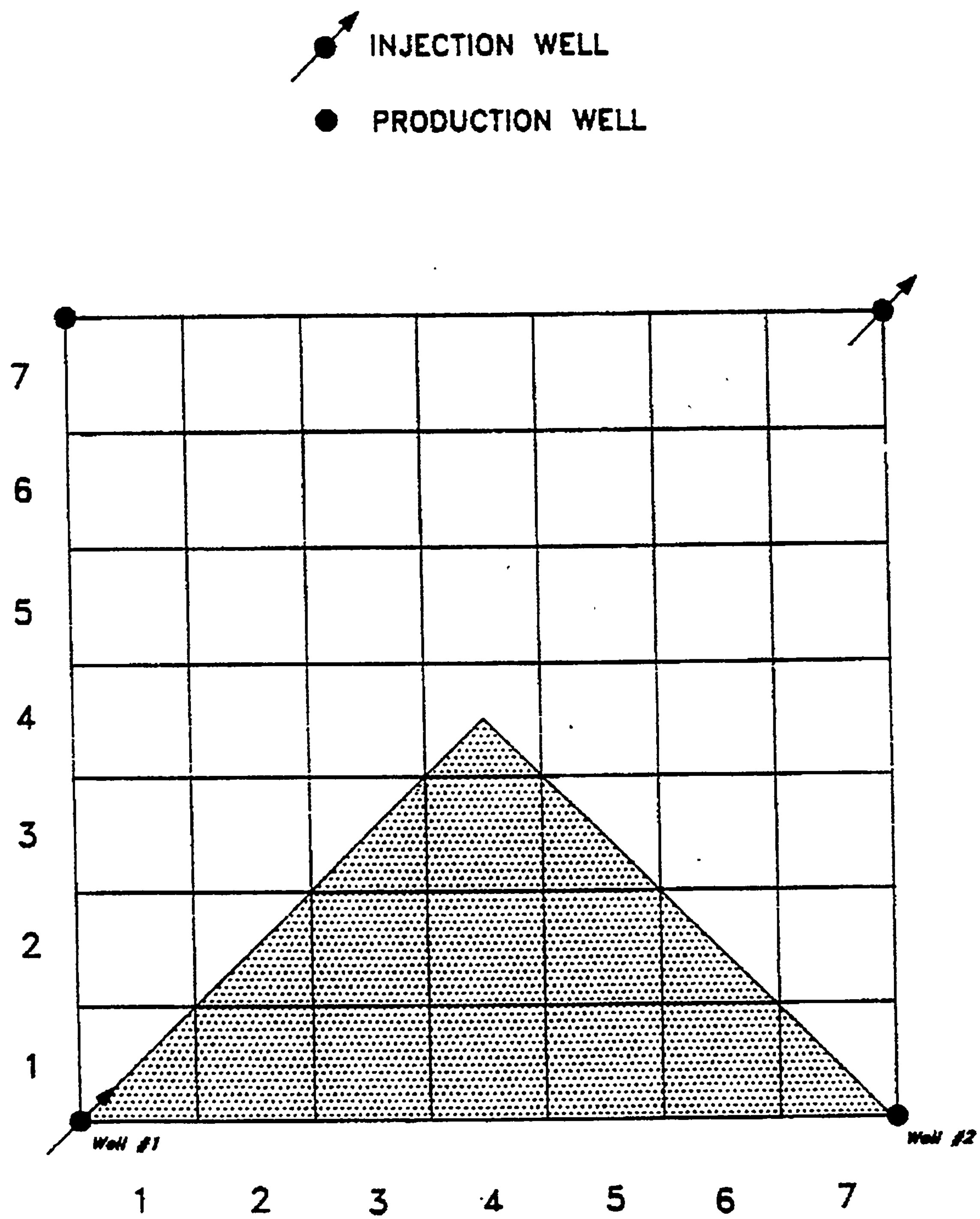


Figure 2. One-eighth of a five-spot pattern, areal view of parallel grid.

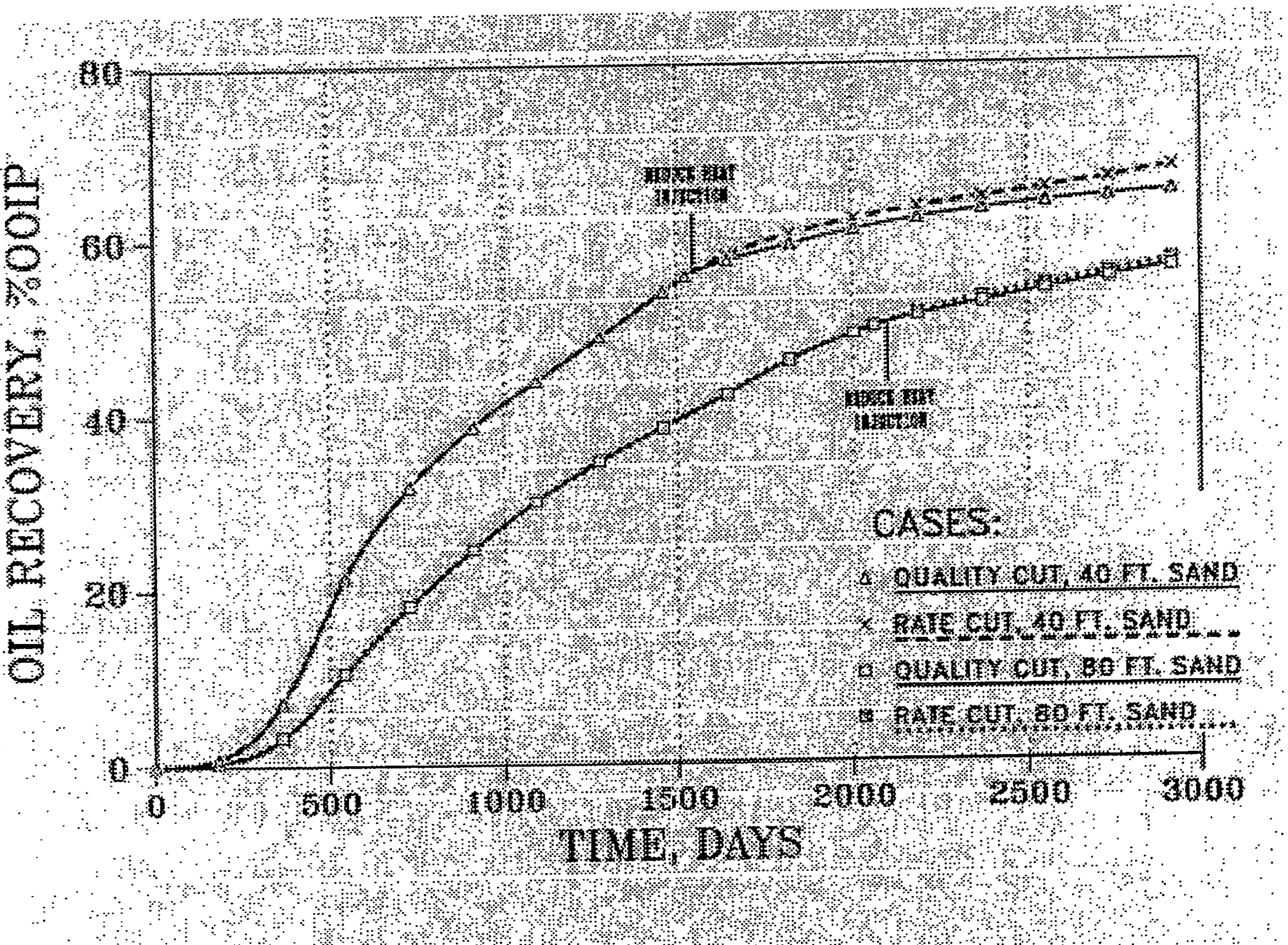


Figure 3. Oil recovery vs. time. One-eighth pattern model. Heat injection reduction at the E.L.

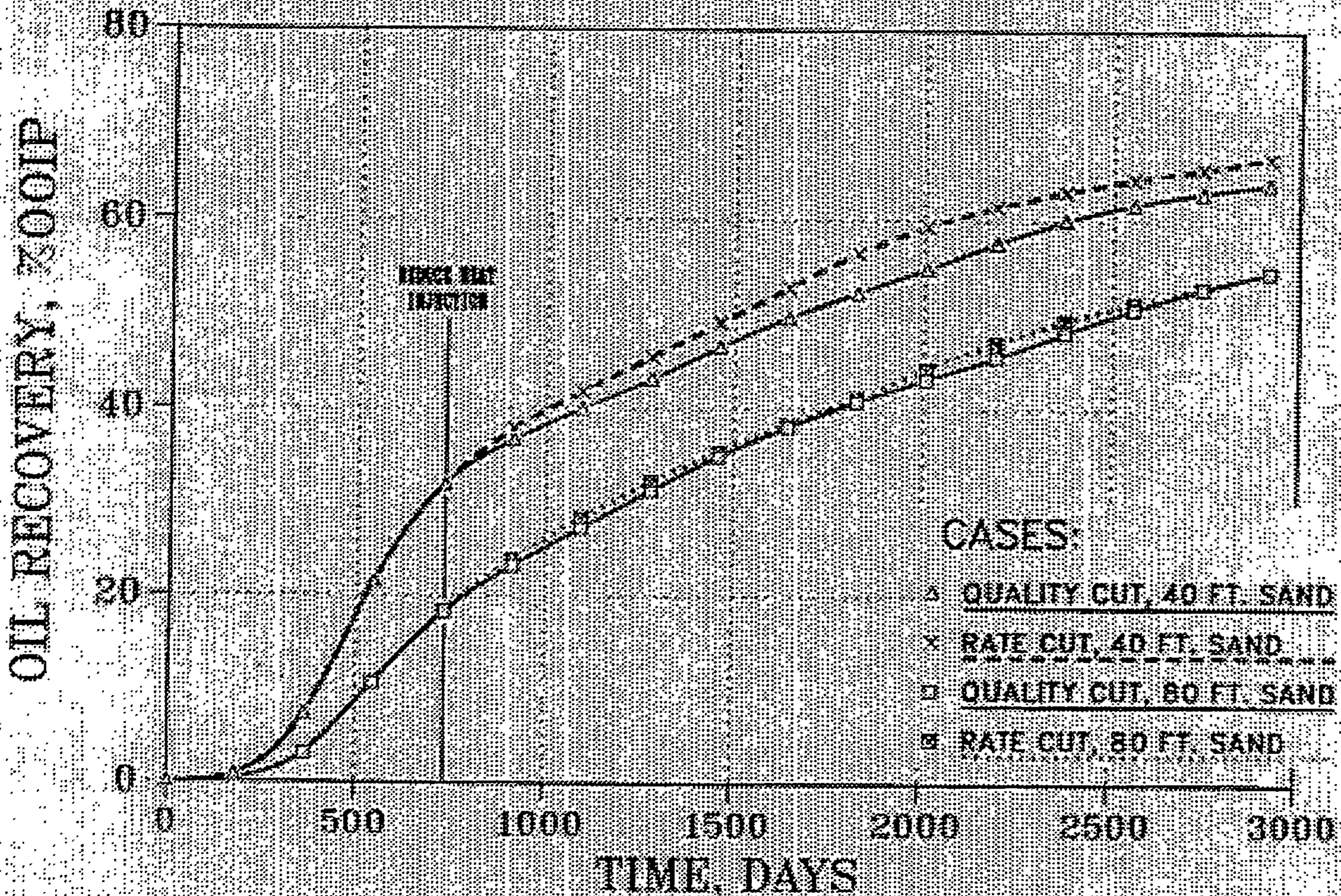


Figure 4. Oil recovery vs. time. One-eighth pattern model. Heat injection in Year 3.

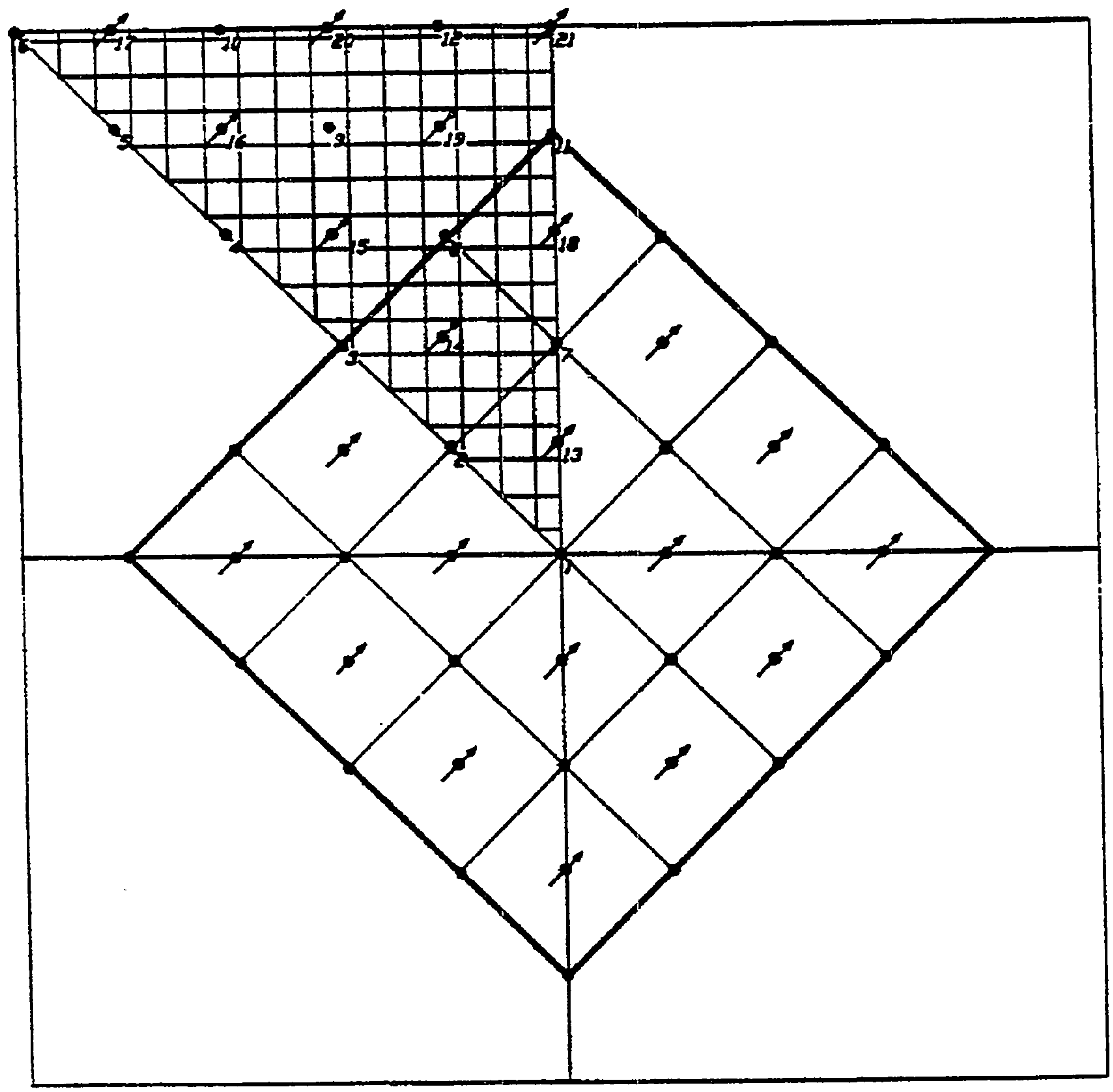


Figure 5. Multipattern model configuration sixteen patterns surrounded by previously steamflooded reservoir.

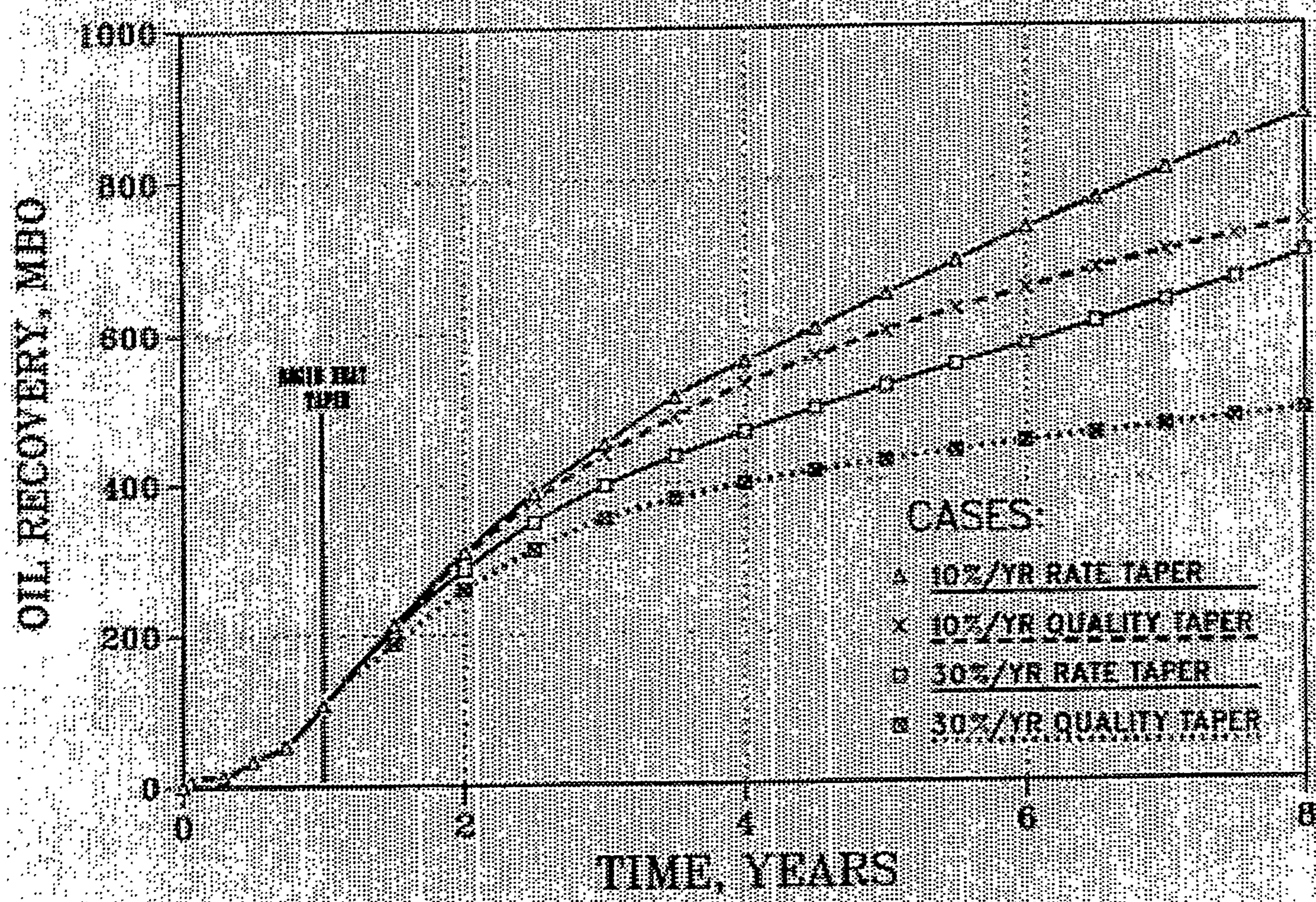


Figure 6. Oil recovery vs. time numerical model -- field case (sixteen) patterns). Heat injection taper starting in Year 2.

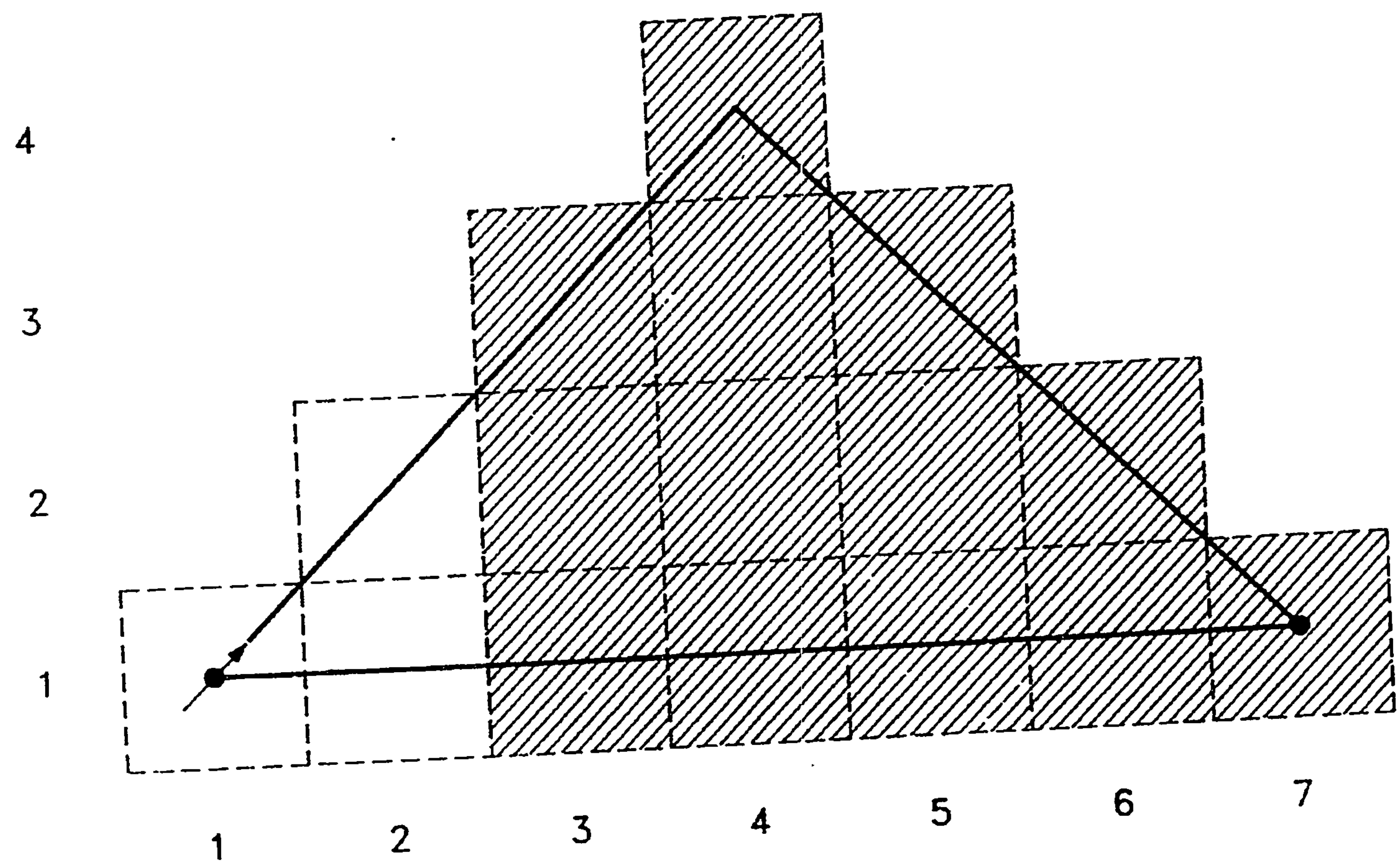


Figure 7. Location of silt between Layers 4 and 5, one silt model (24 ft. from top, 36 ft. from bottom).

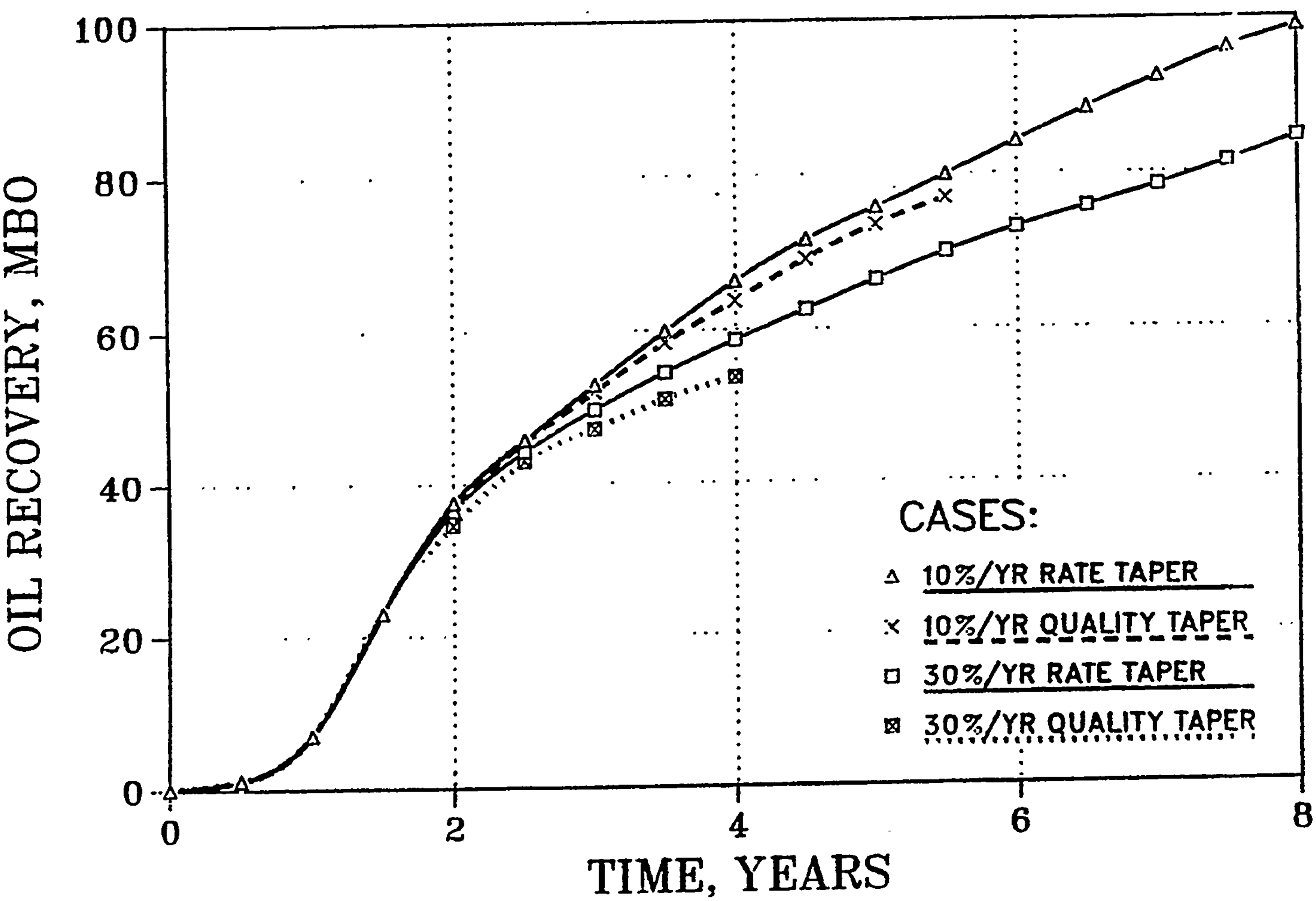


Figure 8. Oil recovery vs. time to the E.L. One-eighth pattern model. Heat injection taper starting at 548 days. One discontinuous silt in the 60 ft. sand.

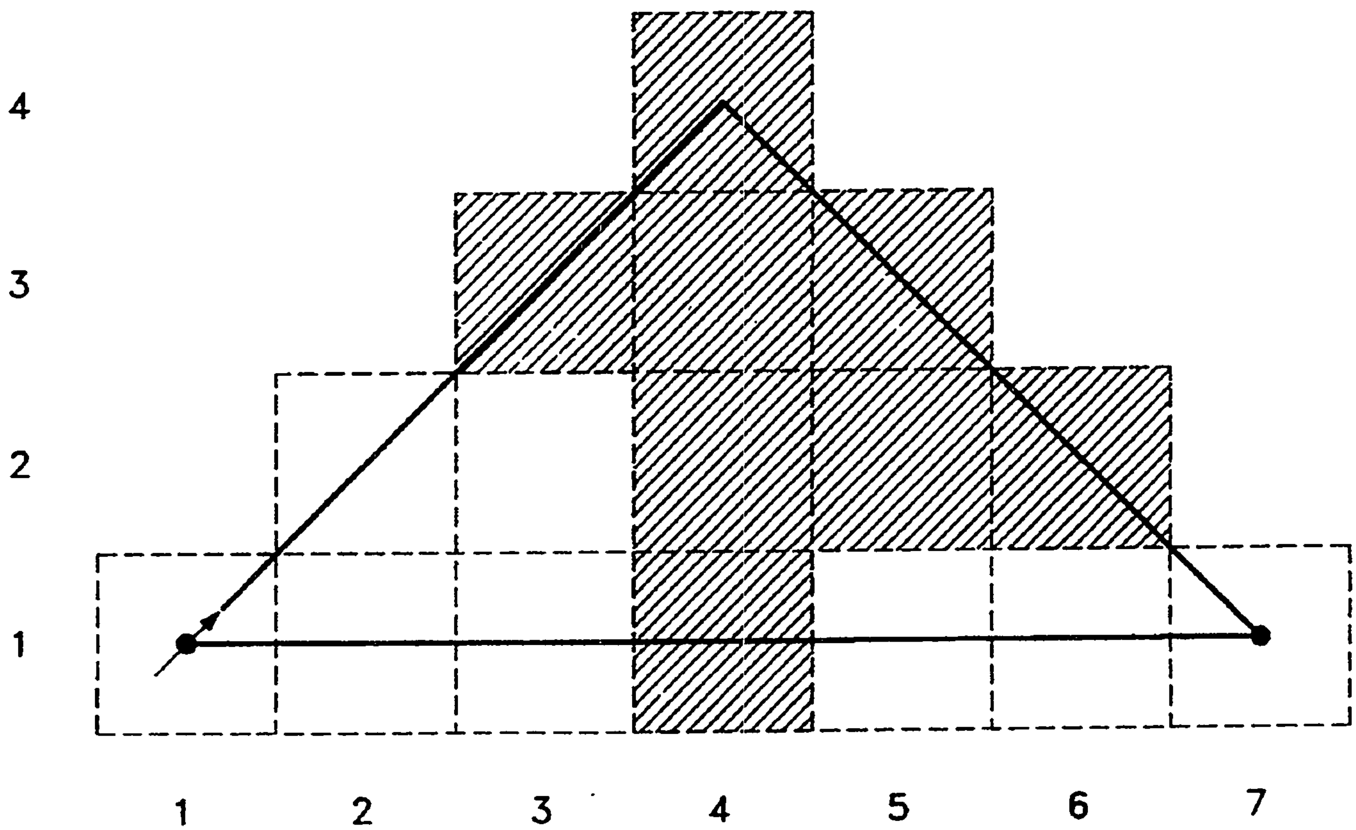


**Figure 9. Location of silts between Layers 2 and 3, three-silt model (9 ft. from top).**

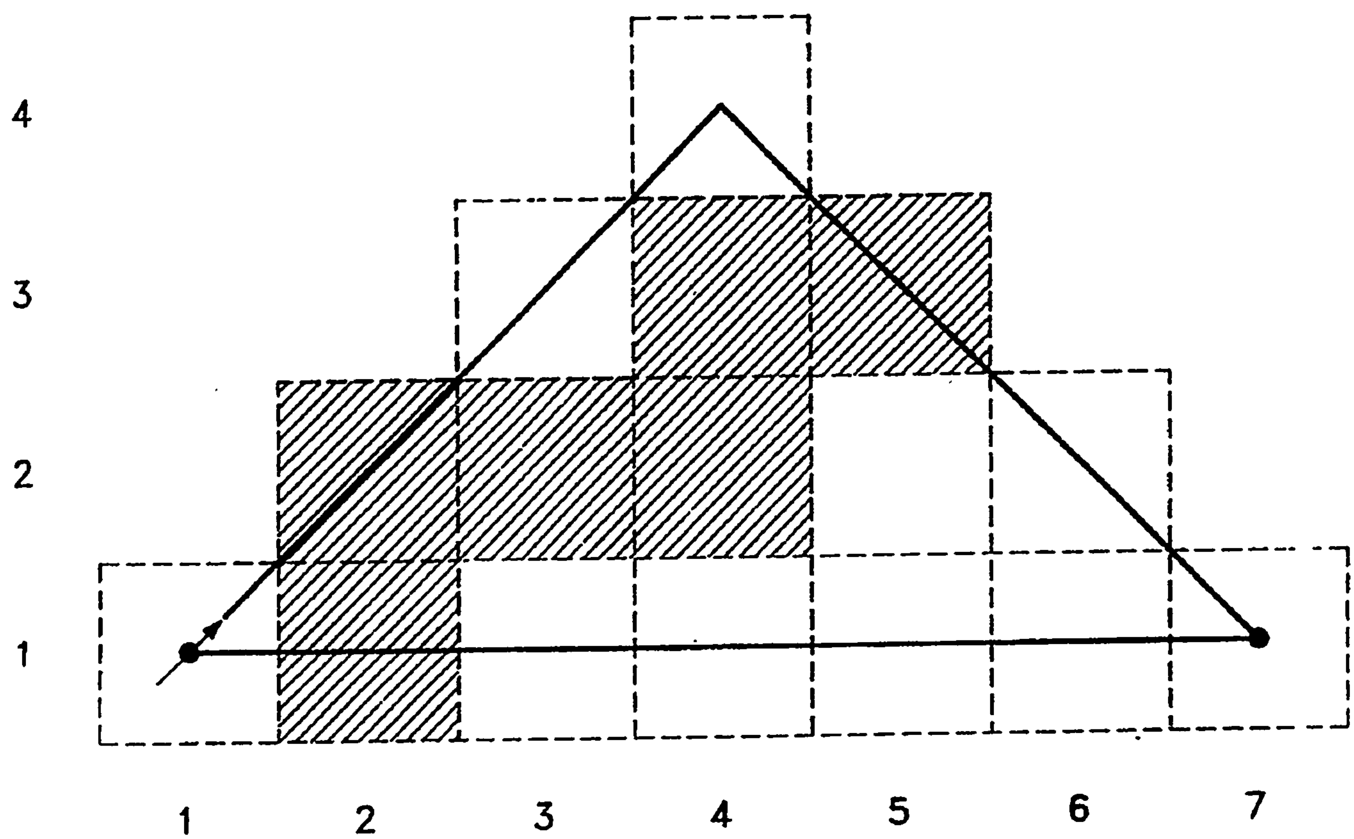


**Figure 10. Location of silt between Layers 4 and 5, three-silt model (24 ft. from top).**

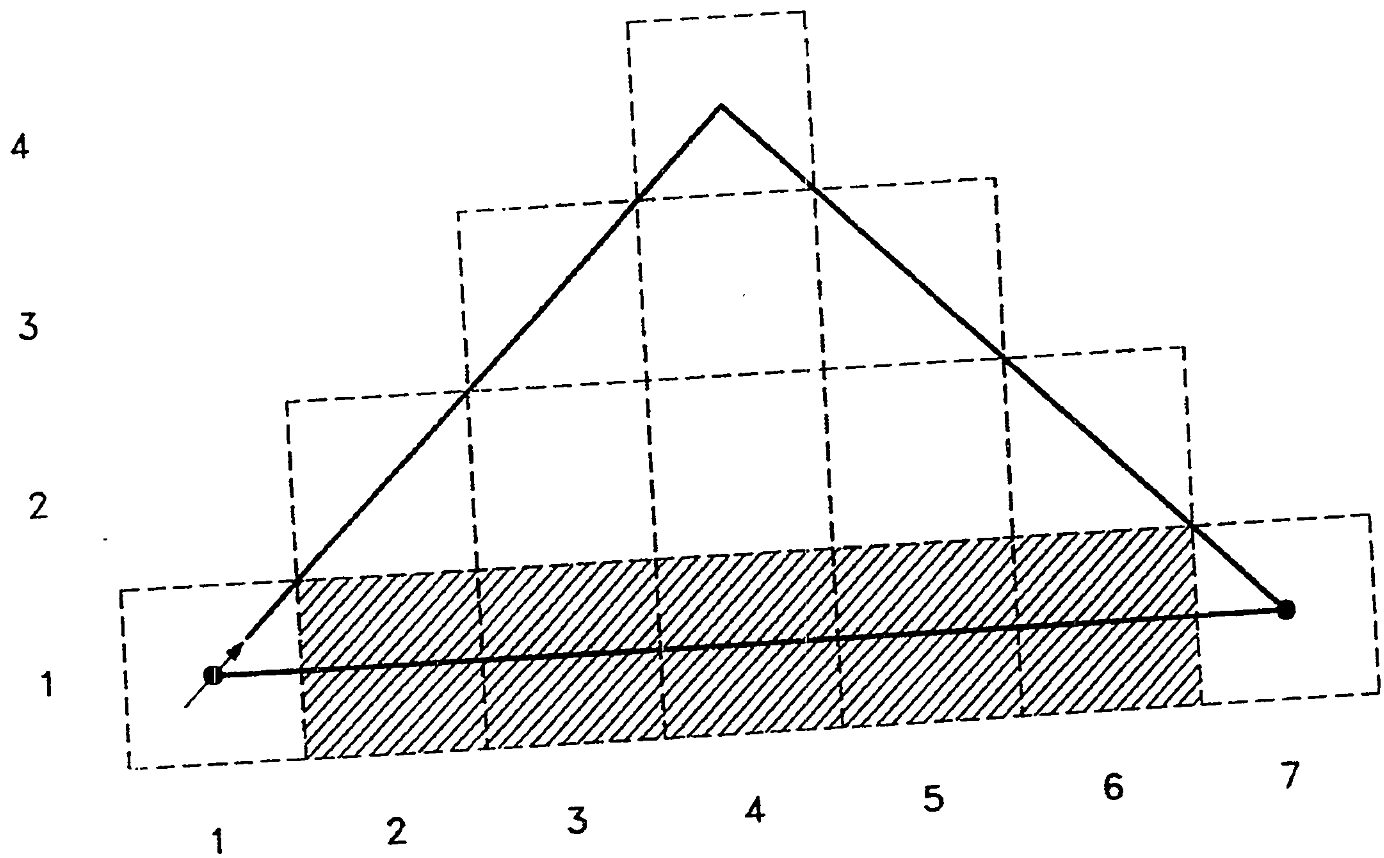


Figure 11. Location of silt between Layers 6 and 7, three-silt model (48 ft. from top).

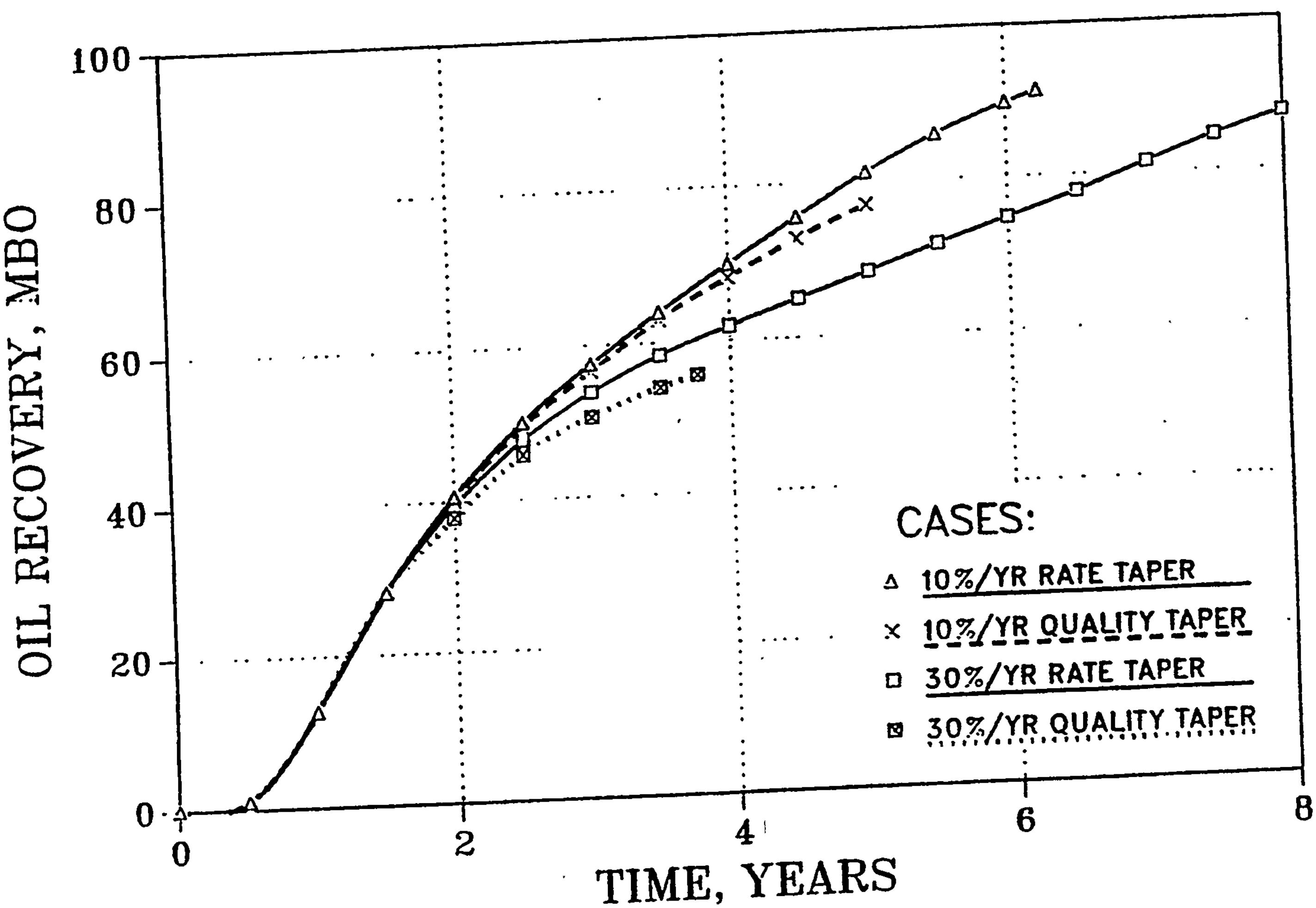


Figure 12. Oil recovery vs. time to the E.L. One-eighth pattern model. Heat injection taper starting at 548 days, 3 random silt layers, 60 ft. sand.

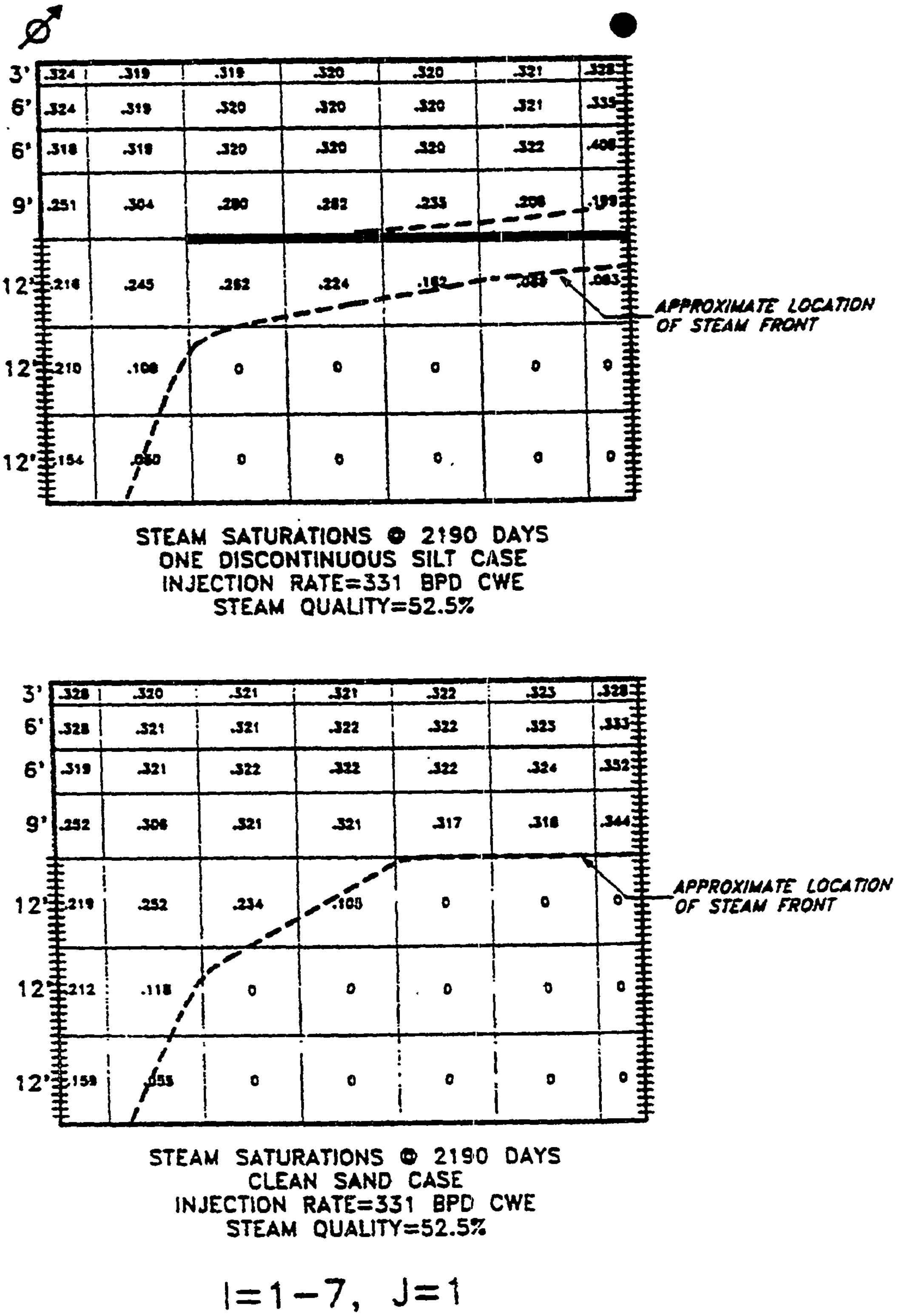


Figure 13. Comparison of steam saturation profiles for clean and silty sands.

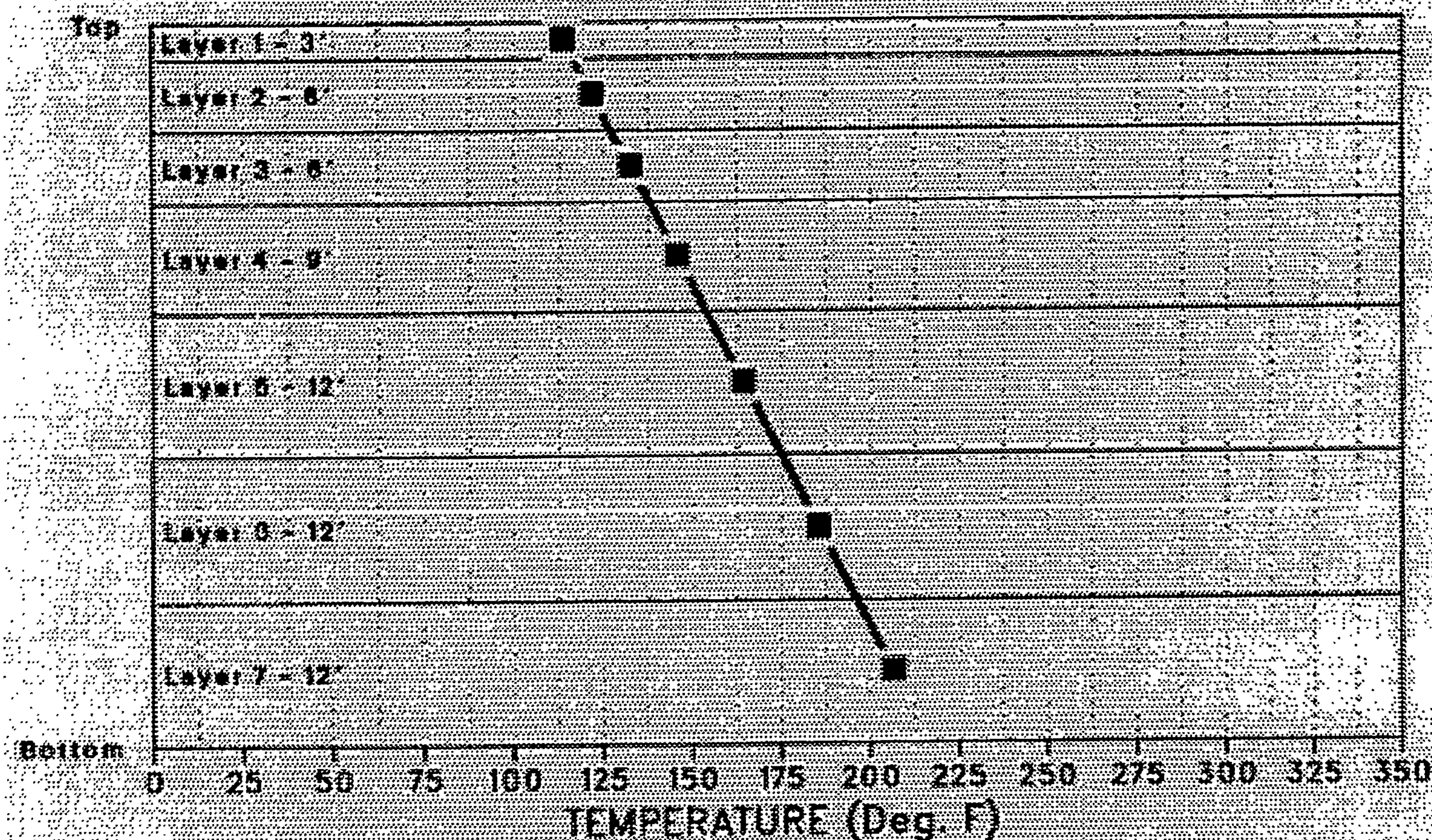


Figure 14. Initial temperature profile for 60 ft. preheated sand.