

**THE EAST SWAN HILLS UNIT WATERFLOOD OPTIMIZATION  
STUDY: A MULTI-DISCIPLINARY APPROACH**

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## ENHANCED OIL RECOVERY

# The East Swan Hills Unit waterflood optimization study: a multi-disciplinary approach

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## ABSTRACT

The East Swan Hills Unit No. 1 is located on the eastern flank of the Swan Hills Beaverhill Lake "A" and "B" Pools. The reservoir is now in an advanced stage of depletion like many of Alberta's oil reservoirs. Optimization of a geologically complex reservoir, such as is found in the Beaverhill Lake, is a major undertaking and requires a multi-disciplinary approach. To evaluate waterflood performance a study consisting of petrophysical data reduction, geological mapping, spreadsheet analysis of recovery and reservoir simulation was carried out. This paper highlights three major contributions which were essential in the analysis:

1. The significance of geological mapping which has identified layering/heterogeneity within the Swan Hills formation and the potential in the underlying Slave Point formation.
2. Manual waterflood calculations have enhanced the understanding of the reservoir and confirmed Slave Point production, prior to proceeding with numerical simulation.
3. The methodology used to simulate a multilayer reservoir under waterflood is described.

Incremental recovery is predicted by improved waterflooding in selected areas of the Unit. A program consisting of injection testing, production testing, single well tracers and selective cased-hole logging has been designed, prior to proceeding with field implementation.

## Introduction

The East Swan Hills Unit is located in the province of Alberta approximately 200 km northwest of Edmonton as shown in Figure 1. This field was discovered in early 1963 with primary production commencing in the same year. Commingled production is derived primarily from the Swan Hills formation as well as from the underlying Slave Point formation. There are 76 wells in the Unit. The field was produced by primary fluid expansion drive since there was no gas cap or no aquifer support. Unitization occurred in 1967 for the purposes of waterflooding. Peak oil production of 1959 m<sup>3</sup>/day occurred in 1969 after which oil production declined at 20% per year.

An aggressive workover program was initiated in 1984 to arrest the production decline. The program was successful as indicated by the oil production rate which has remained flat over the last five years. The current oil rate is 100 m<sup>3</sup>/day with a water cut of 90%. As the Unit was approaching its economic limit, it was concluded that a detailed reservoir engineering study should be carried out to determine if improved waterflooding could be achieved.

This paper documents the results of the study and the method-

ology used. The paper has been divided into three main sections: Geological - Petrophysical Studies, Conventional Reservoir Engineering Review and Reservoir Simulation. The Optimization Program developed from these three studies is then discussed. Finally, the conclusions of the paper are presented.

## Geological - Petrophysical Studies Method of Study

When the East Swan Hills pool was being developed and unitized a fairly simple geological model was used. Two reservoirs, the Swan Hills member and the Slave Point member were recognized. These became known colloquially as the "Light Brown" and "Dark Brown", respectively. The Light Brown member was known to be of substantially better reservoir quality; hence most development was aimed at this pay. The Slave Point contribution was considered insignificant in many areas of the reef. Subsequent work (see references) plus production performance reviews demonstrated that the reservoir was more complex. Up to eight zones were identified in the main Swan Hills reef bioherm. The last major geological study of the subject Unit predated these referenced studies. Consequently a complete geological re-evaluation was necessary.

The study concentrated on identifying detailed layering with a particular emphasis on establishing the degree of continuity that existed between the different segments of the reservoir. A complete computerized petrophysical evaluation was undertaken. The results of this analysis were used as the basis for identifying layers. The continuity of the layers was best identified with a series of cross sections which extended between all wells in the Unit. Maps were subsequently prepared showing porosity and permeability for each of the defined reservoir layers in the pool. Composite maps were compiled for the Swan Hills and the Slave Point members.

## Geology of Swan Hills (Light Brown Member)

The East Swan Hills Unit is located at the front of the main Swan Hills reef (Fig. 1) and extends northeastward for about 8 km into the lagoonal area between the Swan Hills and House Mountain reef build-ups.

In the area of the subject Unit, the Upper Devonian Swan Hills formation consists of light brown detrital limestone composed of fossil fragments and organic debris, much of which was derived from the adjacent reef. This material consists of coarse fragments of reef-building organisms with finer fragments of carbonate along with interbeds of lime mud or limy shale. Shoals of well sorted fragments comprise zones of high porosity and permeability. Low energy inter-shoal areas received finer sediments which formed less permeable rocks. Minor patch reefs which also developed in the area provided local sources for fossil debris.

A prominent tidal channel trends southwest across the central

**Keywords:** East Swan Hill, Geological-petrophysical, Reservoir engineering, Numerical simulation.

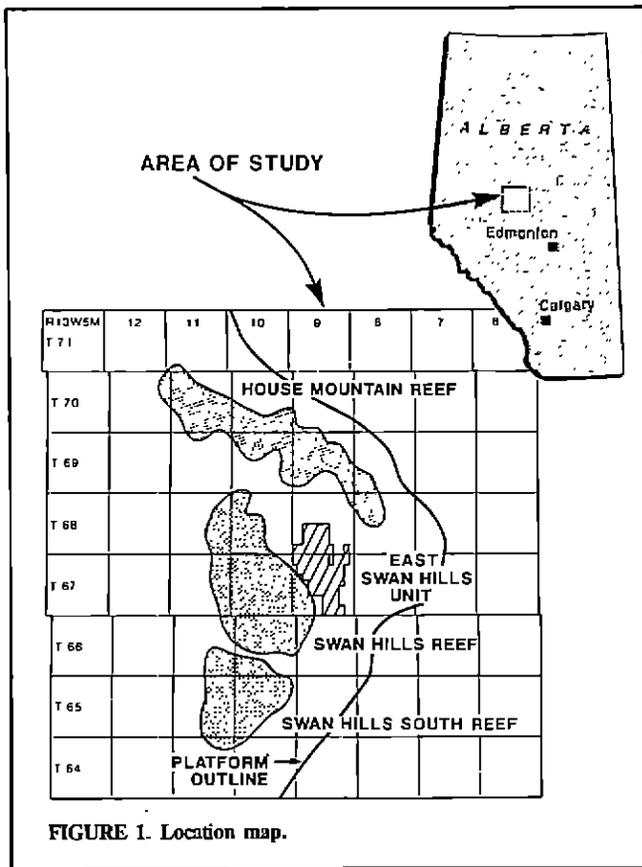


FIGURE 1. Location map.

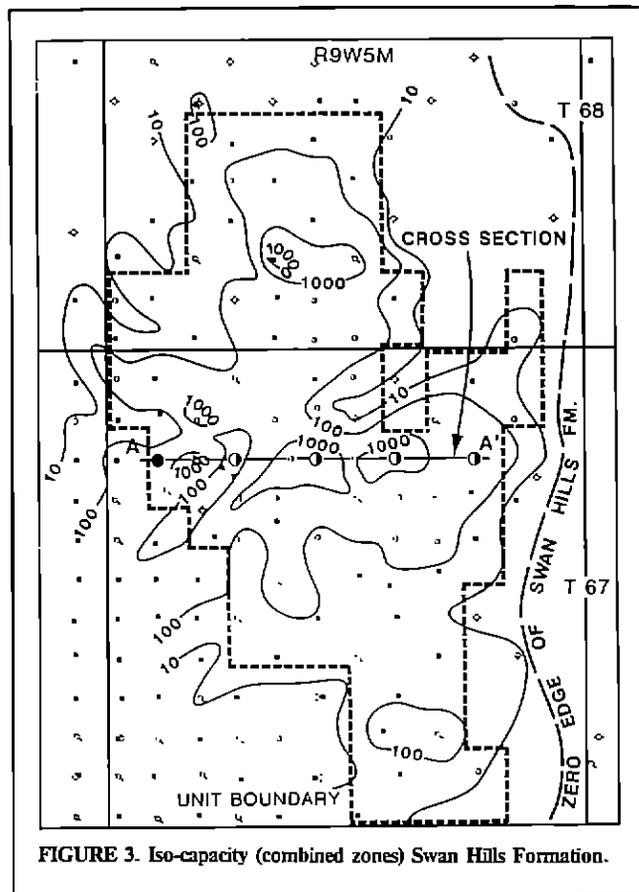


FIGURE 3. Iso-capacity (combined zones) Swan Hills Formation.

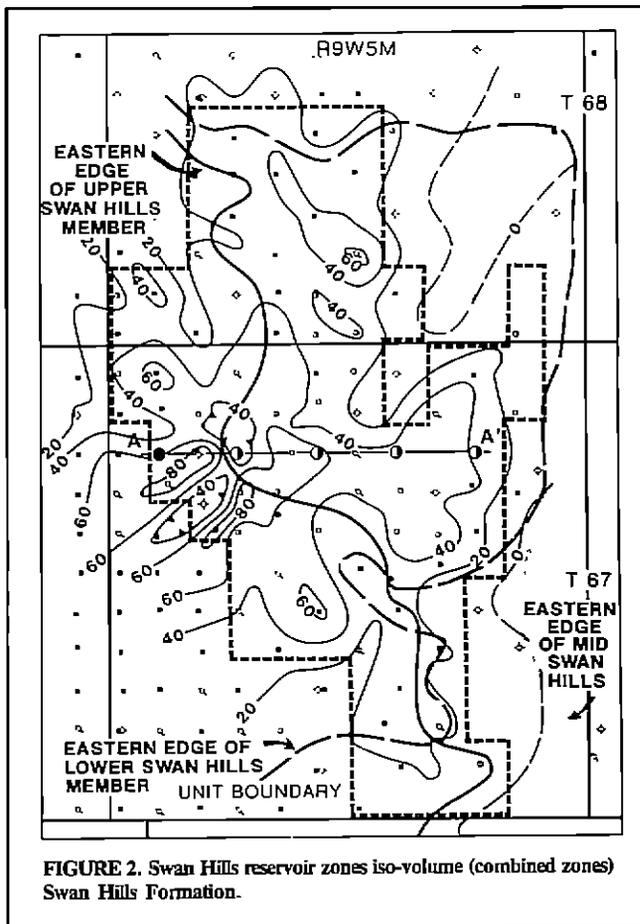


FIGURE 2. Swan Hills reservoir zones iso-volume (combined zones) Swan Hills Formation.

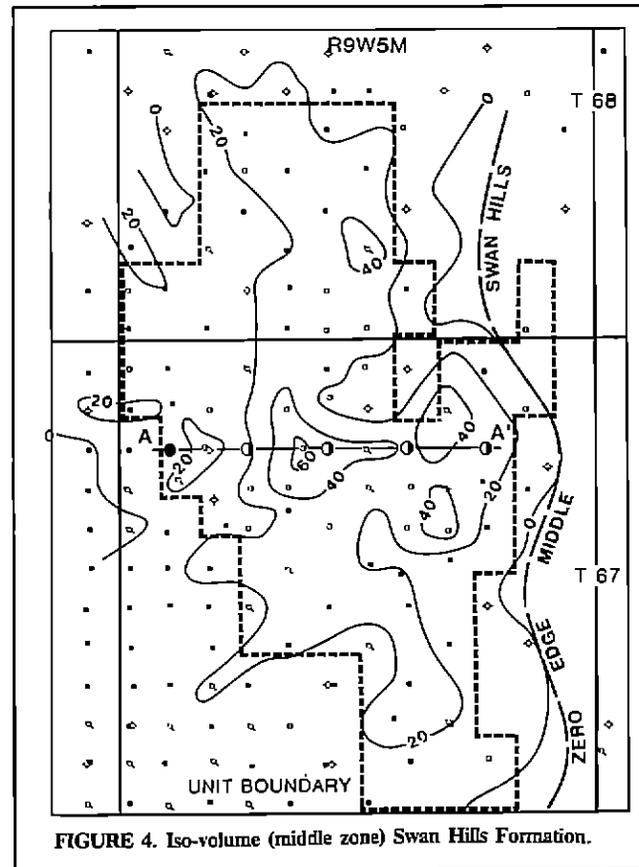
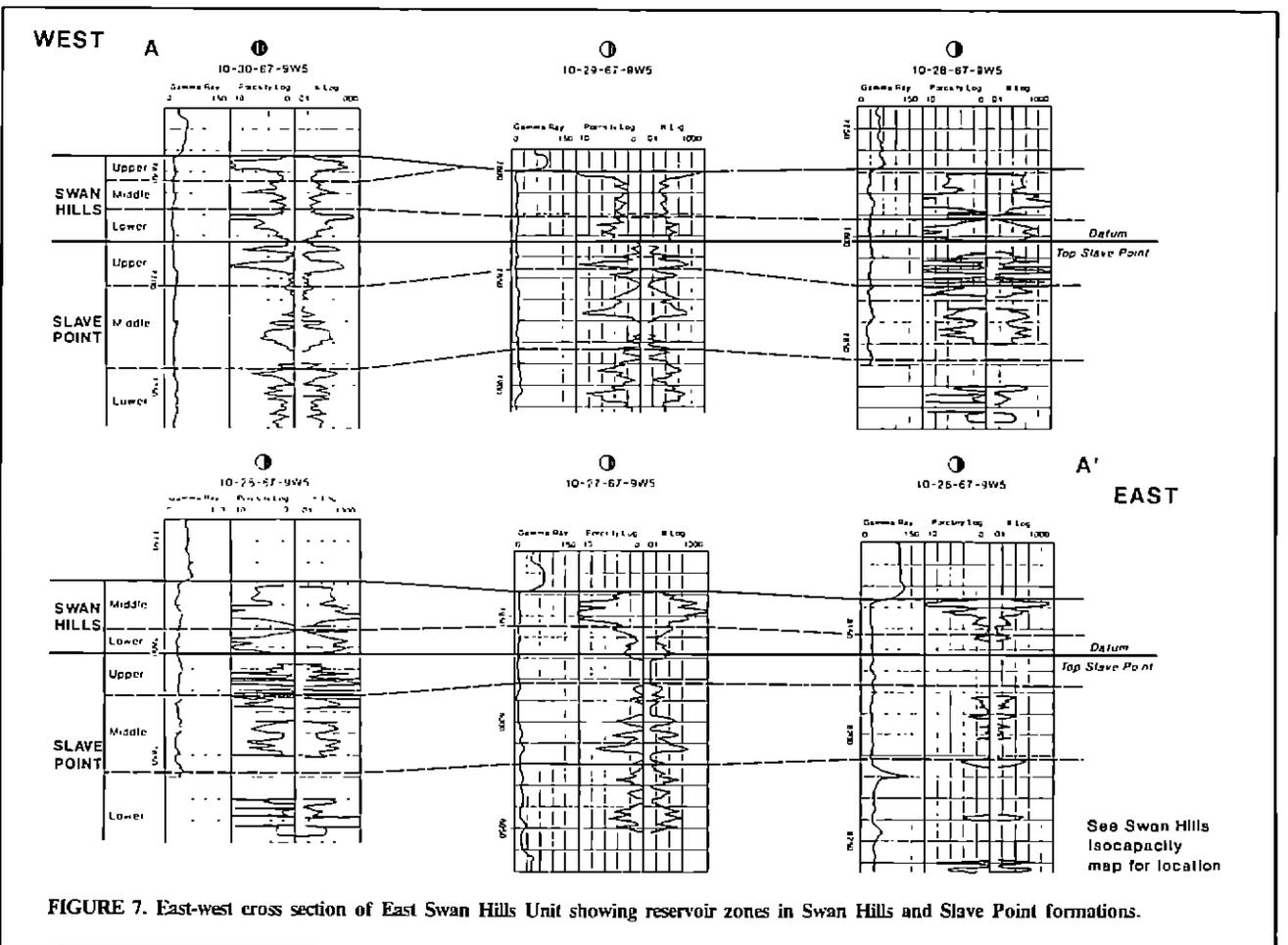
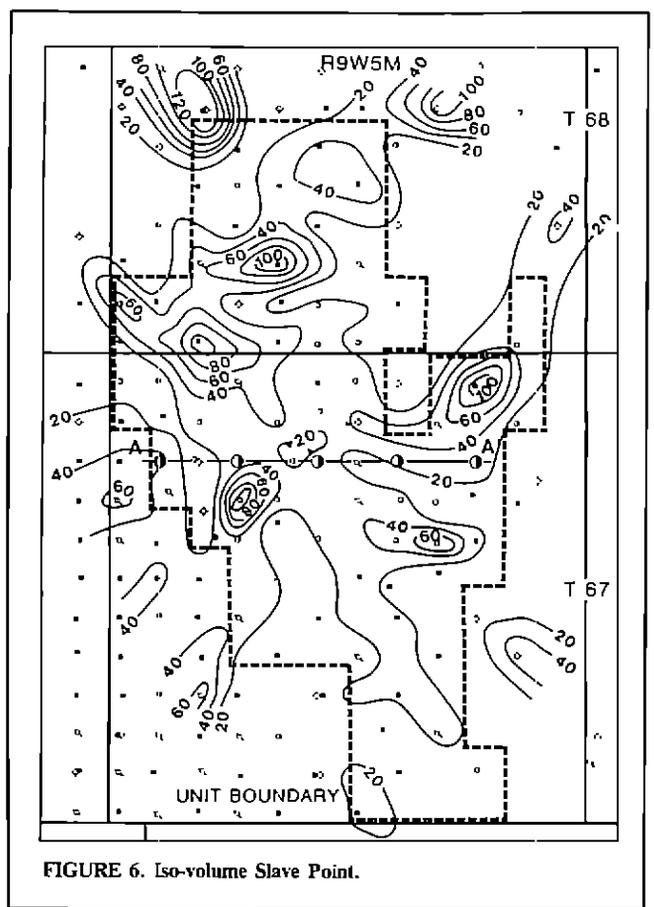
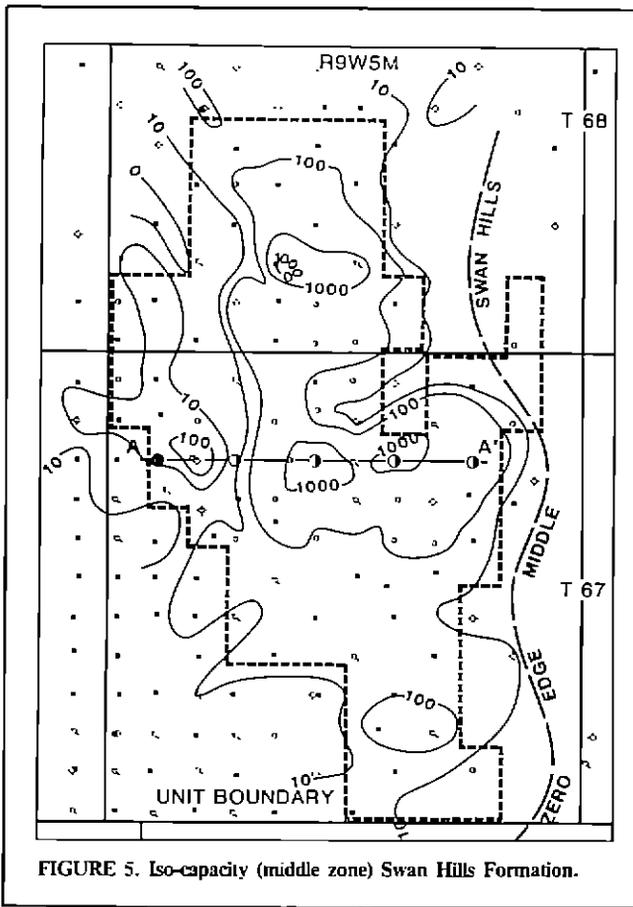


FIGURE 4. Iso-volume (middle zone) Swan Hills Formation.

part of the Unit, dividing the reservoir into northern and southern lobes. Some of the most porous and permeable rocks of the pool are adjacent to this feature. The tidal surge provided a cleaning

action along the flanks which removed fines. The channel was subsequently filled with fine sediments of low permeability.

Wave action also affected the sorting and deposition of the carbonate fragments. The seaward side of the reservoir exhibits im-



proved sorting and hence quality.

The Swan Hills formation ranges from 2 m in thickness in the eastern part of the Unit to a maximum of 14 m near the western boundary. This is in sharp contrast to the 110 m thickness of the main reef.

The Swan Hills formation was divided into three reservoir layers based on the cross sections made from the petrophysical analysis. These layers are separated by widespread thin shaly zones along with a significant thickness of dense rock. In some areas these tight zones are absent.

Maps of the reservoir properties include net pay, iso-volume and iso-capacity. Highlights of the mapping are discussed below:

Figure 2 shows the areal distribution of each of the three reservoir zones. The lower and middle zones have the widest distribution. The upper zone is located along the western edge of the Unit close to the main Swan Hills reef. The iso-volume (porosity height) of the total Swan Hills (all three layers combined) is also shown in Figure 2. A general decrease in reservoir volume from west to east can be seen across the Unit. A thin embayment projects from the northeast, dividing the pool into northern and southern lobes. This is the tidal channel.

Figure 3 shows the iso-capacity (kh) of the total Swan Hills. Note that the kh does not decrease to the east as does the pore volume. The highest capacity of the reservoir is located adjacent to the tidal channel.

Figure 4 shows the iso-volume of the Middle Swan Hills layer. A north-south, trending thick near the eastern part of the Unit is shown. The thickness is variable to the west toward the main reef.

Figure 5 shows the iso-capacity of the Middle Swan Hills layer. This map shows a trend of high-capacity reservoir adjacent to a southwest-trending embayment, similar to the trends in the total Swan Hills kh.

Figure 7 is an east-west cross section through the south lobe of the field. The continuity, as well as the termination of the reservoir layers, is shown in this diagram. The Upper Swan Hills layer is present only in the most westerly well. The third well from the left in the cross section illustrates the high reservoir volume and capacity in wells adjacent to the tidal channel. The most easterly well in the section shows low permeability in the Lower Swan Hills member.

## Slave Point (Dark Brown Member)

The Slave Point forms the widespread platform on which all of the Swan Hills reefs developed. It consists of a dark brown finely crystalline limestone with thin coralline zones.

The formation was subdivided into three zones, an upper, middle and lower for ease of reference. The three zones contain units which develop into patch reefs in certain areas and become fairly good reservoirs. The Slave Point varies in thickness from 26 m to 35 m in the East Swan Hills Unit. The variations in thickness of the entire member plus sub-layer suggests local small-scale structural movements; possibly caused by compaction and/or solution of the evaporites in the underlying Elk Point.

Figure 6 shows the Slave Point iso-volume (porosity-height). This map shows six small areas with thick reservoir development. A significant amount of oil has been produced from the Upper Slave Point member from the wells in the northwest part of Township 67-9W5M and the southwest of Township 68-9W5M. The remaining thick areas are not on production. There are no linear trends expressed in the mapping and the thicker porous areas probably represent isolated patch reefs. The northeast-southwest trending tidal channel present in the Swan Hills is also expressed in the Slave Point.

The Slave Point iso-capacity (kh) follows a pattern similar to the iso-volume map. The most prominent feature is the high-capacity area in the west-central part of the Unit.

The iso-volume of the Mid and Lower Slave Point were mapped as one unit since they varied in a similar manner. The four thick reservoir areas in the central part of the Unit occur in the Lower and Middle Slave Point. A minor thick zone is present in the extreme northeast. The iso-capacity highs are centred in the same areas as the iso-volume thicks. Each of the high-capacity areas has poten-

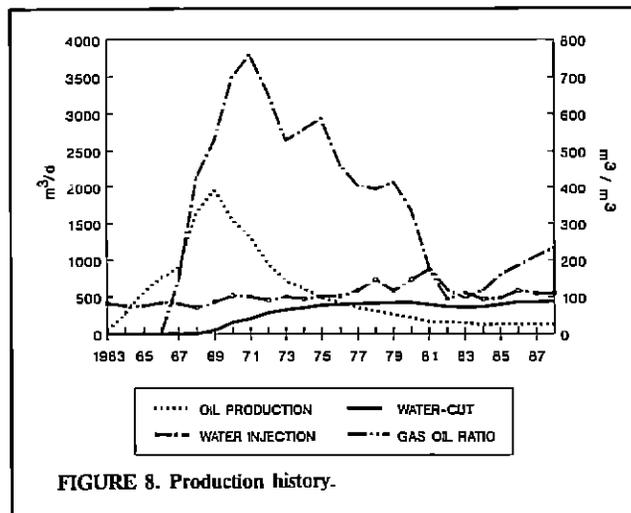


FIGURE 8. Production history.

tial for oil recovery through implementation of a waterflood program.

Figure 7 shows the variability of the Slave Point reservoir. The section further demonstrates that each thick reservoir area would require a separate waterflood program strategy.

## Geological Summary

The average reservoir parameters for the Swan Hills and Slave Point formations derived from the geological portion of the study were as follows:

Rock Properties	Swan Hills	Slave Point
Net Pay	5.3 m	6.9 m
Porosity	6.8%	4.1%
Perm. (k)	96.4 mD	37.6 mD
<b>Cutoffs</b>		
Porosity	2.0%	2.0%
Permeability	0.2 mD	0.52 mD

## Conventional Reservoir Engineering Review

A conventional reservoir engineering review was carried out prior to the commencement of modelling and was designed to gain a fundamental understanding of reservoir performance. The components of the review process included: (1) reviewing the Unit's historical production and injection record; (2) re-determination of the original oil-in-place (OOIP); (3) a spreadsheet waterflood pattern analysis. This was used to estimate depletion profiles and recovery for both primary and secondary production.

## Unit Historical Production/Injection Performance

The East Swan Hills field production history is depicted in Figure 8. Primary production, which started in 1963, peaked at a rate of 700 m³/day during 1967. Unitization was initiated specifically to start a pressure maintenance project. Water injection commenced during June of 1967. The waterflood has responded well as demonstrated by the peak oil production, which was achieved shortly thereafter, in 1969.

Water was injected in 11 injection wells (Fig. 9) which were irregularly spaced throughout the Unit. A majority of the water has been re-injected into three injectors, namely, 4-27-67-9W5M, 10-32-67-9W5M and 4-10-68-9W5M. The voidage replacement ratio for the Unit was in excess of 1.0. The re-injection of a majority of the produced water via three injection wells suggests that ineffective sweep has occurred, especially in the fringe areas of the Unit. The original reservoir pressure in the Swan Hills formation was 21 719 kPa. Pressure declined to just above the bubble point of 11 722 kPa under primary production. Areal variations in the reservoir pressure were identified. Currently the Unit is over-injected near

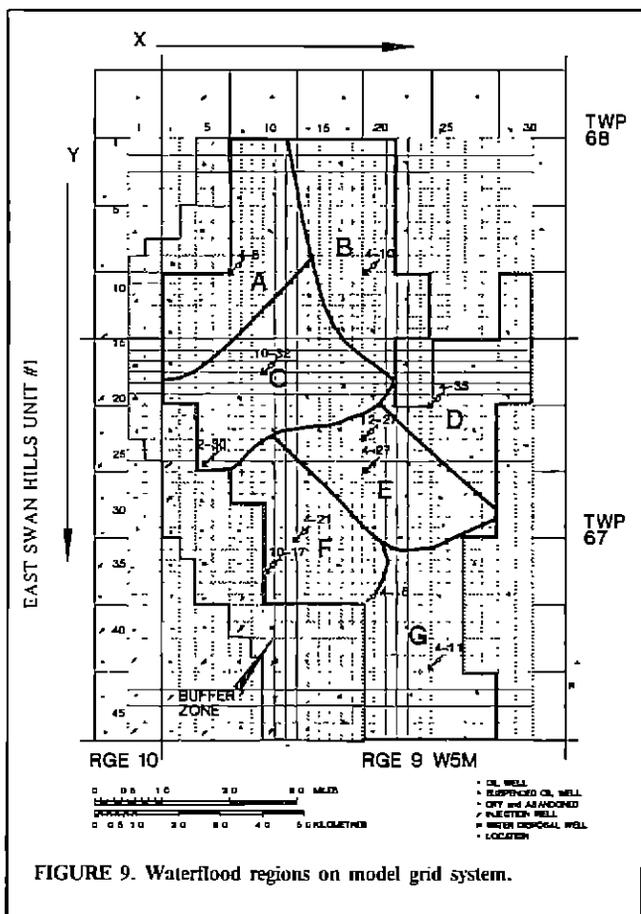


FIGURE 9. Waterflood regions on model grid system.

the above noted injectors with peak pressures in excess of 24 000 kPa. The lower permeability areas of the field were observed to have significantly lower pressures. The under-injected or lower pressure areas potentially may have by-passed oil which offers opportunity for improved waterflooding. The average pore volume weighted reservoir pressure at the end of 1988 in the Swan Hills formation was estimated to be 22 750 kPa.

The gas oil ratio (GOR) has remained flat over the entire production history at about 100 m<sup>3</sup>/m<sup>3</sup>. There are two notable exceptions. The jump in 1969 coincides with the start of water production and commissioning of treaters. There was also an increase between 1978 and 1981 which was due to changes in facility operating practices and modifications at the central battery.

## Re-determination of the Original Oil-in-Place

The re-determination of the original oil-in-place was required because the geological study indicated several significant features. The pore volume would be affected by the changes to the tidal channel, the reservoir layers identified, and the recognition of increased Slave Point pore volume.

The volumetric OOIP was calculated both on a Unit wide basis and on a layer by layer basis. Both approaches yielded similar results. The new mapping indicated a 15% increase in the OOIP for the Swan Hills formation to 16.7 10<sup>6</sup> m<sup>3</sup>. A more substantial increase in the OOIP was calculated for the Slave Point formation. The OOIP in the Slave Point was revised to 12.2 10<sup>6</sup> m<sup>3</sup>, which represented a 47% increase over previous estimates.

As a check on the volumetric OOIP estimates a material balance calculation was done for the Swan Hills formation. Conventional wisdom held that the amount of Slave Point production was significantly smaller than the Swan Hills production. The Slave Point formation was therefore not included in the material balance estimate.

Reserve estimates obtained using the material balance technique were found to be sensitive to rock compressibility. It was judged that the material balance confirmed the volumetric estimates given

the accuracy of the data. The calculations were limited in that:

1. The East Swan Hills Unit is not a closed system. It is in direct communication with the Swan Hills Unit No. 1 along its western boundary.
2. The Slave Point had been excluded, as discussed previously.
3. No compressibility measurements were available. Rock compressibility had been estimated from correlations.

## Spreadsheet Analysis

All of the injection wells were examined to determine the reservoir properties (kh and porosity) and completion histories of the reservoir layers. It was found that all of the injection wells had one or two layers which would have taken the majority of injected fluid. Waterflood sweep areas were thus identified.

A spreadsheet was used to determine the recovery from each layer within the Swan Hills and Slave Point formations. The technique is illustrated in Figure 10. The layers identified in the previous section were used as a basis for this phase. Total well production and injection was allocated to individual layers based on the layer kh as a fraction of the well's total kh.

For each waterflood sweep area identified, reserves were calculated on a quarter section basis. Production from the dominant layer was tabulated on another spreadsheet as shown in Figure 11. Layers which were identified as receiving minimal pressure support were assigned a recovery factor of 5%. This was based on the actual cumulative primary recovery prior to waterflooding. This spreadsheet enabled the calculation of recovery factors within the waterflood pattern as well as providing an indication of the degree of oil migration that had occurred.

In general, the spreadsheet method of analyzing the waterflood performance within the Unit was in agreement with the results generated subsequently by numerical simulation. The two methods were not directly comparable since the spreadsheet method was layer specific whereas the simulation work was done on a total pay basis.

Estimated recoveries, as a percentage of the OOIP, for each of the layers in the Swan Hills formation are as follows: Upper 9.1%; Middle 29.7%; and Lower 32.7%. The total recovery to the end of 1988 within the Swan Hills formation is estimated to be 29.3% of the OOIP.

A sample recovery profile for the Middle Swan Hills layer is shown in Figure 12.

Waterflood recovery from the Slave Point formation is estimated to be 4.5% of the OOIP. Only one area in the Slave Point formation has received waterflood pressure support where recovery is estimated to be 21% of the OOIP.

Analysis of each of the waterflood sweep areas within the Unit enabled preliminary identification of areas where further waterflood potential exists.

## Reservoir Simulation

### Considerations in Model Construction

The major decisions in constructing the model were: (1) how to account for the boundary conditions (communication with the adjoining unit); (2) how to include the effects of the Slave Point; and (3) how to layer the model. These three factors are discussed in more detail in the following sections.

### Boundary

Four options were available to handle the boundaries:

1. Rigorously model the entire field (including offsetting units).
2. Model the entire field and input the Unit as a local grid refinement. The main field would be input with a very coarse grid.
3. Use an aquifer function.
4. Install a "buffer area" in the grid and use a series of injection and production wells.

Rigorously modelling the field was not realistically economic due to the large size of the Swan Hills Beaverhill Lake A and B pools. For local grid refinement, well production from the main pool would be summarized into large grid blocks, with the higher density sub-grid placed over the ESHU#1. This was judged to be uneconomic

WELLNAME	SWAN HILLS FORMATION			SLAVE POINT FORMATION	TOTAL CAPACITY	PRODUCTION CUMMULATIVE	ALLOCATED PRODUCTION PER ZONE (M3) (KH/TOTAL KH * CUM. PROD)			
	UPPER KH	MIDDLE KH	LOWER KH	KH	TOTAL KH	OIL (M3)	UPPER	MIDDLE	LOWER	SLAVE POINT
10-02-67-9WS	11.8	3	0	0.7 NP	12.1	26,709	5,000	21,709	0	0
04-03-67-9WS	0.1	23.6	0	67.9	23.6	38,617	0	38,617	0	0
10-03-67-9WS	0.7	42.6	0	13.9	56.5	103,209	0	97,818	0	5,391
03-10-67-9WS	0	181.4	0.9	6.2	188.5	28,542	0	27,467	136	939
10-10-67-9WS	0	96.9	0	21.3	118.2	69,857	0	57,269	0	12,588
INJECTOR 04-11-67-9WS	0	194.7	0.8	57.9	253.4	14,250	0	10,949	45	3,256
04-14-67-9WS	0	35.1	0.9	6.4	36.0	60,594	0	59,371	1,522	0

FIGURE 10. Production capacity of Swan Hills and Slave Point formations.

WELL	QUARTER SECTION	S.H. MIDDLE LAYER OOIP (M3)	S.H. MIDDLE LAYER ROIP (M3)	TOTAL PRODUCTION (M3)	ALLOCATED MIDDLE PRODUCTION	ALLOCATED SLAVE POINT PRODUCTION	REMAINING MIDDLE ROIP	MIGRATED MIDDLE ROIP	MIDDLE LAYER RECOVERY % OOIP
	NW 10	37,646	18,823				18,823		
10-10-67-9WS	NE 10	102,857	51,429	69,857	57,268	12,588	17,338	23,178	33.1%
03-10-67-9WS	SW 10	41,985	20,993	28,542	27,467	939		6,475	50.0%
	SE 10	84,706	42,353					(42,353)	50.0%
	NW 11	78,917	39,459					(39,459)	50.0%
04-11-67-9WS	SW 11	83,344	41,672	14,250	10,949	3,256		(30,723)	50.0%
	NW 3	57,263	28,632				28,632		0.0%
10-03-67-9WS	NE 3	73,460	36,730	103,209	97,813	5,391	7,346	68,434	40.0%
	NW 2	55,579	27,790					(27,790)	50.0%
10-02-67-9WS	NE 2	15,471	7,736	26,709	21,709	0		13,974	50.0%
04-14-67-9WS	SW 14	55,362	27,681	60,894	59,272	0	5,536	37,127	40.0%
TOTALS		686,590	343,295	303,461	274,483	22,174	77,675	8863	40.0%

( ) OIL MIGRATION FROM SPACING UNIT

\* CAPTURE FROM OUTSIDE UNIT

FIGURE 11. East Swan Hills Unit No. 1 summary of Swan Hills middle layer waterflood recovery.

since the summarization process would be time-consuming, and adding the larger grid with refinement would add to the required computation time. The use of an aquifer function would have been relatively easy to implement and therefore economic. However, the adjoining unit's pressure history varied considerably from the East Swan Hills Unit as the implementation of waterflood had occurred on a different schedule. It was expected that migration had reversed. This was supported by government field-wide pressure data. An aquifer function provides a "correcting" effect which could not match the variations in pressure history.

The remaining alternative was the use of boundary wells. One advantage that could be realized in modelling this reservoir was that, for the majority of the Unit's pressure history, the reservoir pressure was above the bubble point. The compressibility of the fluid system was therefore quite low. The pattern of waterflood sweep in the reservoir is thus not strongly affected by the over-all level of pressure. The "technical price tag" which came with this method was:

1. The boundary buffer area requires a larger grid.
2. The pore volume must be fixed. Typically this is a history match parameter.

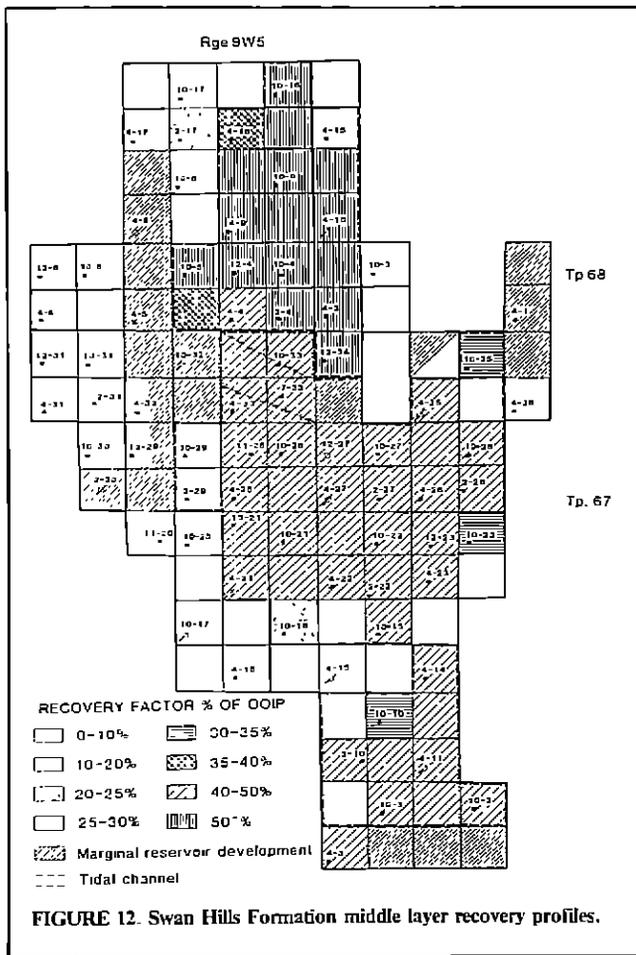
3. Matching the boundaries is a trial and error process — which could possibly be time-consuming.

4. Allocating the injection/production along the boundaries must be estimated.

The buffer area requirements were not onerous. Due to the physical shape of the Unit only two more rows in the grid were required. Due to the high proportion of wells cored, the pore volume control in the East Swan Hills Unit No. 1 was quite good. It was found subsequently that the last two factors were acceptable.

### Slave Point Production

As previously discussed there was considerable question at this stage of the study as to the magnitude of Slave Point production. The reservoir in this zone was discontinuous over large areas. It was therefore anticipated that the Slave Point would contribute to primary production, however, it would not show any positive response to waterflood. Because there was so many unknowns it was decided that including another layer in the model grid, based on a cumulative Slave Point map, could prove highly misleading. The best way to determine if the Slave Point was contributing sig-



nificantly was to try modelling without it. History matching would then be used to identify its effects.

## Layering

Although geological mapping had been prepared with three layers there were some problems associated with implementing this in the model. Three layers, with the areal size of the grid plus the potential for a Slave Point layer, would have required a very large model (over 5520 grid blocks). History matching detailed layers might be extremely difficult with the other major unknowns such as the Slave Point and a large boundary.

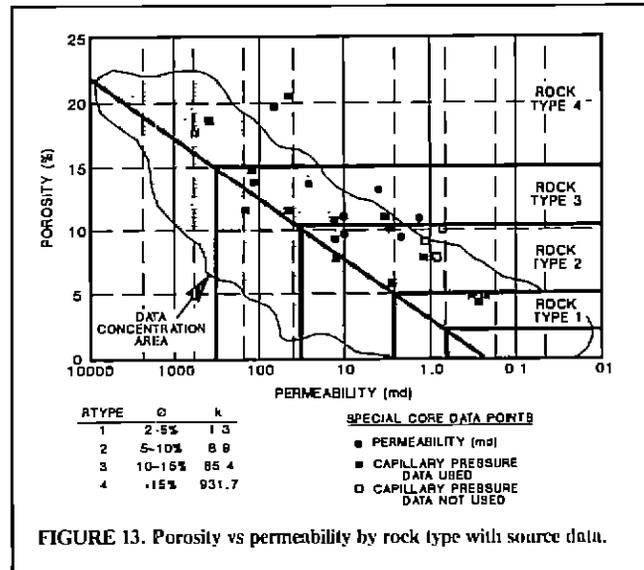
The available special core data, which was expected to provide relative permeability and capillary pressure data, came from wells in adjoining units. The lithologies were similar but not identical to the lithology found in the East Swan Hills Unit No. 1. When the permeability and porosity of the special core samples were compared against the same data derived from the conventional core analysis for the Unit, it was concluded that a skewed sample existed. This is shown in Figure 13. Although detailed layers had been identified, no precise rock properties could be tied to this description.

Accurately assigning production and injection to the layers based on completions also had the potential for errors. The cement bonds in the wells were old. Fresh water had been used for injection which could cause dissolution leading to communication. It was felt that selective completions, which would be input into the model, might prove to be misleading.

In view of the other major uncertainties in the modelling process, it was felt that the detailed geological layering was not appropriate at this stage. A "pseudo relative permeability" would be developed in the history match process.

## Grid System

The grid used is shown in Figure 9. The grid was designed to allow infill wells to be placed between the existing producers. The Unit



was developed on 64 hectare spacing and has not yet been completely infilled. Two layers were included in the model to account for possible gravity segregation effects.

The buffer zone used to account for boundary effects is shown as the shaded area in Figure 9. Wherever possible the buffer zone had been split off from inactive grid blocks through the lines between injectors in the adjoining unit. This was not possible in sections 31-67-9W5M and 6-68-9W5M. Injection and production for the wells along the edges were multiplied by a linear factor to account for their approximate contribution to the grid.

## History Matching Methodology

The methodology used is shown in Figure 14. The approach was to match the Unit as a whole first, then proceed to matching the individual wells. After a major change was made, it was necessary to iterate back and repeat the previous steps.

## Saturation Function Changes

The initial run simulated a massive over-pressuring of the reservoir. Analysis of the production prediction showed that insufficient water was being produced. To reconcile the predictions, major changes to the relative permeability curves were required. Two successive iterations were made as shown in Figure 15.

The effects of layering had not been included in the reservoir grid and a change to the saturation functions to account for layering/heterogeneity was expected. The changes to the relative permeability curves were considered fairly radical. A review of papers and government submissions showed that similar modifications were required in history matching other Beaverhill Lake reservoirs. Two implications were derived from this observation; first, the similarity of results indicates that the fundamental reason for this could be quantified and second, that the changes were reasonable. Quantifying the physics of the displacement in the reservoir could be achieved by detailed layering, scaling up studies, or geostatistical modelling.

The changes resulted in a match of the Unit average water production. However, the pressure history of the Unit was still not correct.

## Matching Boundary Effects

Two possible effects could be responsible for the pressure discrepancy. First, the boundary and second, unaccounted for Slave Point pore volume. At this stage it was still not possible to identify which of the above was correct. It was decided to again continue without including the Slave Point.

A series of pseudo injection and production wells were installed in the buffer area. The wells were grouped together using a gathering centre. Production and injection targets were set for the group to manipulate the Unit pressures. Matching was done on a trial

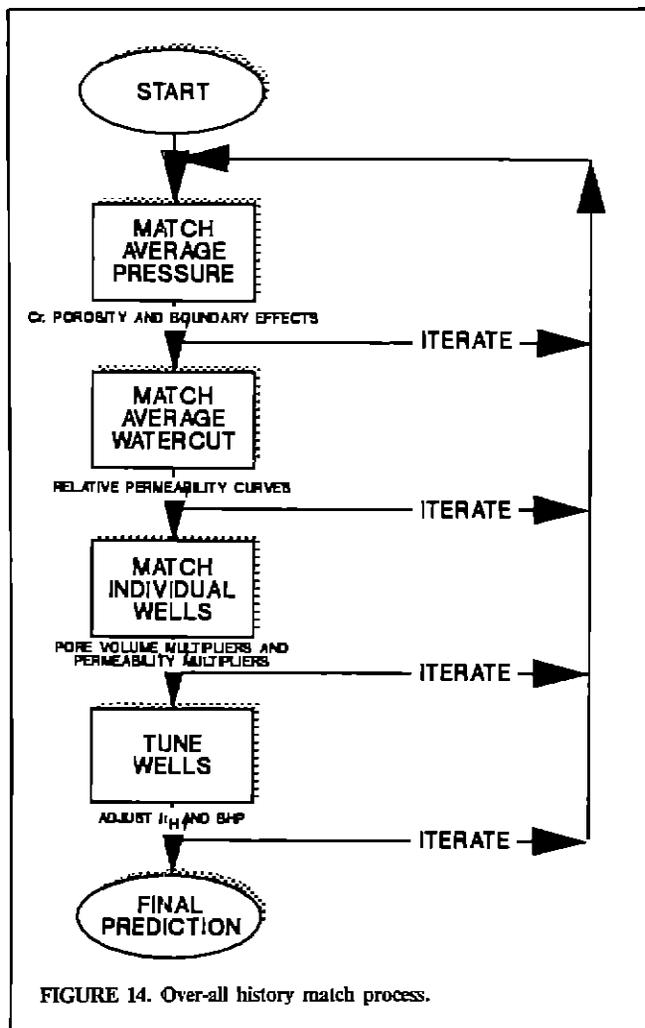


FIGURE 14. Over-all history match process.

and error basis by stringing together a series of restart runs. An equivalent of two runs was all that was required to achieve a match.

Figure 16 shows the average Unit pressure vs the average pool pressure derived from the ERCB published performance graphs. This approach is not rigorous, but it does indicate that the input boundary corrections are plausible.

With the average production and pressures for the Unit in order, it was possible to examine the individual wells in detail. Significant variations in performance were observed. Simulated water breakthroughs occurred in some areas up to 12 years earlier than the actual production history. To correct this would require drastic changes to the pore volume of over 200% which, across large areas, could not be justified. It was felt that the volumetrics were quite accurate.

Comparison with mapping yielded a correlation between mapped Slave Point pay and the problem areas in the model. It was now apparent that the Slave Point would have to be included.

## Slave Point Inclusion

Possible methods of including the Slave Point were:

1. Adjust production to subtract out the Slave Point production.
2. Create artificial increases in the Swan Hills volume.
3. Include a separate layer for the Slave Point.

Significant drawbacks existed with the first two methods and the latter was chosen.

The Slave Point pay was digitized as a layer and included in the model. The next run showed improvement in the previously identified problem areas, however, a deterioration in the history match occurred for other wells.

The Slave Point was not continuous in most areas of the Unit. Therefore many individual wells, with Slave Point pay, would drain only a small area. The next modification was to set the transmissi-

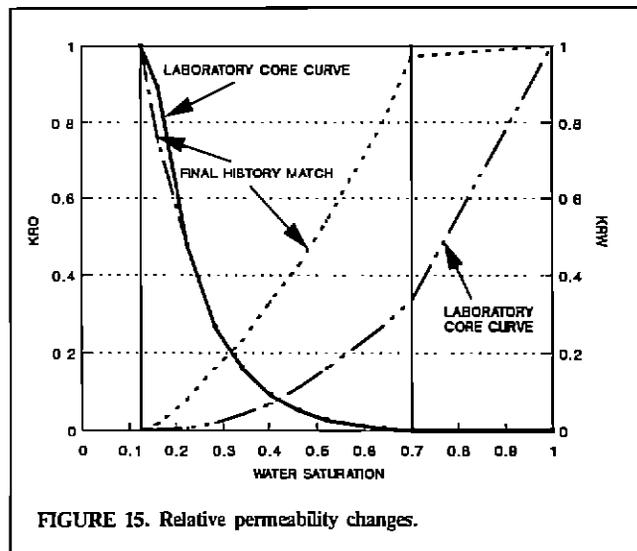


FIGURE 15. Relative permeability changes.

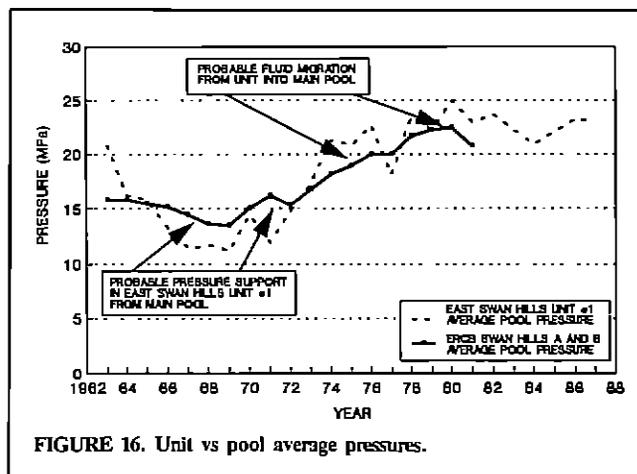


FIGURE 16. Unit vs pool average pressures.

bilities to zero over the discontinuous areas. Production would then only occur from the grid block pore volume in which a well was completed. This improved the history match in both the continuous and discontinuous areas of Slave Point pay.

Significantly less boundary influx was required at this stage to match the Unit's pressure history. An experiment was also run with a relaxation of the changes to the relative permeability curves. This was not successful.

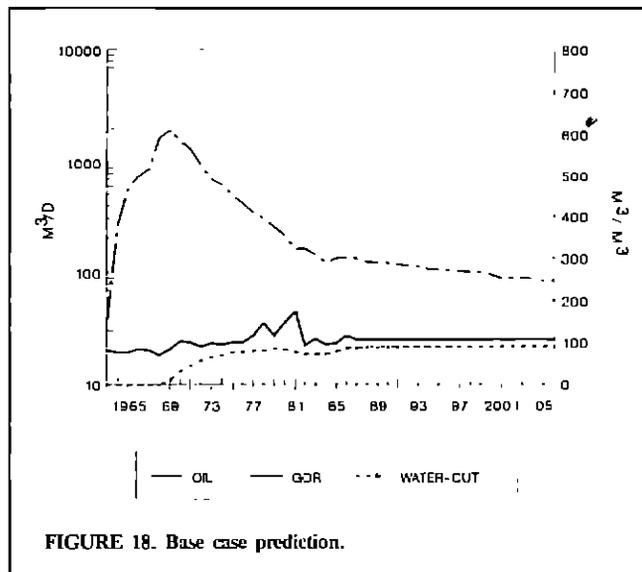
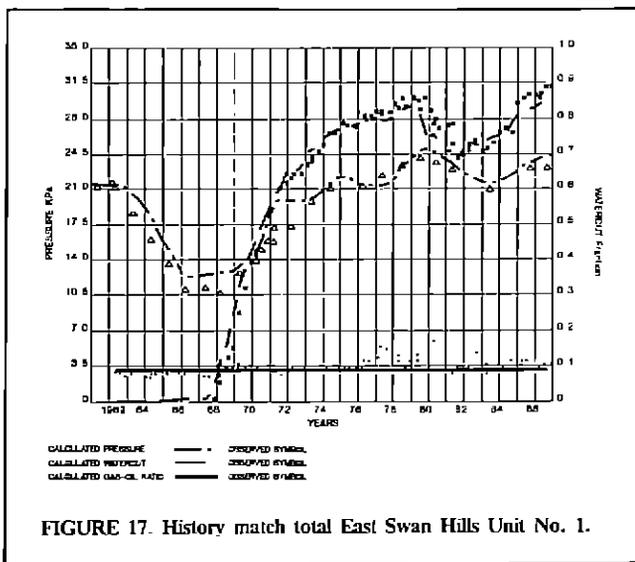
## Pore Volume Adjustments

A number of areas required some pore volume adjustment in the Swan Hills. The areas which caused the most difficulty were where the Swan Hills and Slave Point had high quality pay. In particular, one well was very sensitive to the proportion of injection between the two zones. The effect of continuity was difficult to resolve. It was ultimately recommended that some field logging should be done to confirm the history match changes.

## Tidal Channel

After all of the above changes the wells in sections 33-67-09W5M and 3-68-09W5M still showed a perplexing trend. The watercuts would dip after breakthrough in the simulator, even though this performance was not seen in the actual data. No reasonable changes in pore volume or permeability could correct this effect. Analysis of the saturation arrays showed that the reversals in watercuts were caused by the movements of three different flood fronts.

A tidal channel had been mapped across the Unit and extended into the adjoining unit. Pay and permeability were further reduced in the eastern part of the tidal channel within the Unit. This resulted in successful history matches in the problem sections as the flood front from the south was effectively cut off.



The extent of the tidal channel was thus verified from reservoir simulation.

## Reduction In Layers

A full run of the model took a considerable period of time to execute. A trial run was therefore made with the Swan Hills reduced to one layer. This decreased run times substantially. The history match was affected on only two wells. One well improved considerably and the other was negatively affected. The latter problem was corrected with other adjustments. Further modelling was completed with the reduced layering.

## Sensitivities

A sensitivity to rock compressibility was conducted, however, changes to boundary rates were found to have a greater effect.

## Final Boundary Adjustments

A final iteration on the boundary conditions was required to correct the pressure match in the latter part of the production history. These changes did not affect the watercuts, but did alter the overall levels of pressure. The final history match for the Unit is shown in Figure 17.

## History Match Summary

The history match resulted in cumulative errors of  $-15.4\%$  for total water produced,  $-5.2\%$  of cumulative gas produced. The character of the trends in water production and pressure also match well.

The history match process has increased the understanding of the East Swan Hills Unit in the following ways: (1) The degree of heterogeneity/layering which exists. (2) The approximate magnitude of boundary migration. (3) Confirmation of the positive contribution of the Slave Point. (4) The extent and location of the tidal channel. (5) Areas of potential have been identified within the Swan Hills. (6) Areas identified from the geological study as having potential in the Slave Point have been confirmed.

## Predictions

Only the base case prediction which is shown in Figure 18 has been made to date. The simulation shows a flattening of the trend in the latter part of the life of the Unit. The final suite of predictions will be completed after the proposed field tests have been finished.

Over-all, after detailed review of all of the individual well plots, the prediction is felt to be slightly optimistic. The watercuts are slightly lower than actuals. For comparison between other depletion schemes, this is not judged to be serious. The over-all recovery was estimated at  $32.2\%$  with the existing waterflood scheme.

## Optimization

### Identification of Areas for Optimization

The results of the two engineering studies were combined to identify improved recovery potential. The spreadsheet analysis and the simulation complemented each other.

Nine potential optimization areas were identified for the middle layer in the Swan Hills formation and seven areas for the lower layer. Improved waterflooding within the Swan Hills formation is estimated to increase recovery by  $5\%$  of the OOIP.

Successful waterflooding of the Slave Point has been demonstrated in the northwest portion of the Unit. The areas shown in Figure 19 have similar reservoir parameters and are now considered waterflood candidates. Improved waterflooding in the Slave Point is expected to increase recovery by  $6\%$  of the OOIP.

### Optimization Programs

The waterflood optimization program has been divided into two phases. Phase 1 is a combination of investigative work and reactivation of suspended producers which is expected to secure an immediate increase in oil production. Phase 2 will follow-up information gained in Phase 1 to further optimize waterflooding and includes higher risk optimization.

#### Phase 1

The following investigative techniques have been proposed: (1) Water injection tests will be made to evaluate the potential success of converting selected wells to injection.

(2) Single well tracers have been recommended for residual oil determination.

(3) Production logging has been selected for some wells to confirm the condition of casing and cement bond.

(4) Spinner surveys have been selected to confirm the injection profiles in complex areas of the reservoir.

(5) Recompletions will be done to establish zonal isolation.

The Phase 1 program includes the low-risk optimization opportunities. Reactivation of suspended wells is expected to add an additional  $30 \text{ m}^3/\text{day}$  of oil ( $5 \text{ m}^3/\text{day}/\text{well}$  in 6 wells).

#### Phase 2

Phase 2 includes infill drilling, recompletion and conversion of suspended producers to injectors as shown in Figure 20. The existing water injection system will also have to be upgraded in certain areas. Each component of Phase 2 has been ranked based on risk assessment. Completion of the entire program will be based on the success of the previous components.

