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MASTER THESIS

Title: ANALYZING RESERVOIR THERMAL BEHAVIOR BY USING THERMAL SIMULATION MODEL

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ABSTRACT

ANALYZING RESERVOIR THERMAL BEHAVIOR BY USING THERMAL SIMULATION MODEL (SECTOR MODEL IN STARS)

It is observed that the flowing bottom-hole temperature (FBHT) changes as a result of production, injection or shutting the well down. Variations in temperature mainly occur due to geothermal gradient, injected fluid temperature, frictional heating and the Joule-Thomson effect. The latter is the change of temperature because of expansion or compression of a fluid in a flow process involving no heat transfer or work. CMG STARS thermal simulation sector model developed in this study was used to analyze FBHT changes and understand the reasons. Twenty three main and five additional cases that were developed by using this model were simulated and relation of BHT with other parameters was investigated. Indeed the response of temperature to the change of some parameters such as bottom-hole pressure and gas-oil ratio was detected and correlation was tried to set between these elements. Observations showed that generally FBHT increases when GOR decreases and/or flowing bottom-hole pressure (FBHP) increases. This information allows estimating daily gas-oil ratios from continuously measured BHT. Results of simulation were compared with a real case and almost the same responses were seen. The increase in temperature after the start of water and gas injection or due to stopping of neighboring production wells indicated interwell communications. Additional cases were run to determine whether there are BHT changes when initial temperature was kept constant throughout the reservoir. Different iteration numbers and refined grids were used during these runs to analyze iteration errors; however no significant changes were observed due to iteration number differences and refined grids. These latter cases showed clearly that variations of temperature don't occur only due to geothermal gradient, but also pressure and saturation changes. On the whole, BHT can be used to get data ranging from daily gas-oil ratios to interwell connection if analyzed correctly.

Keywords: bottom-hole temperature, bottom-hole pressure, gas-oil ratio, CMG STARS

XÜLASƏ

İSTİLİK İMİTASİYA MODELİ ƏSASINDA REZERVUARLARIN İSTİLİK REJİMİNİN ANALİZİ

Müəyyən olunmuşdur ki, quyudibi temperatur (BHT) hasilatın, su vurmanın və quyu hasilatının dayandırılmasının təsirləri nəticəsində dəyişir. Temeperaturdakı fərqliliklər əsasən geotermal qradient, quyuya vurulan məhlulun temeperaturu, sürtünmə istiliyi və Coul-Tompson effektindən irəli gəlir. Axırıncı sadalanan temepratur dəyişikliyi maye və qazın genişlənmə və ya sıxılma zamanı heç bir iş və ya istiliyin ötürülmədiyi axını prosesində baş verir. Bu dissertasiyada BHT dəyişikliklərini analiz etmək və səbəblərini araşdırmaq üçün CMG STARS termal simulyatorunu istifadə edilmişdir. Bu simulyatordan istifadə etməklə iyirmi üç əsas və beş əlavə ssenarilər yaradılmışdır və quyudibi temeperaturun başqa parametrlərdən asılılığı araşdırılmışdır. BHT-nin dəyişməsinin quyudibi təzyiq (FBHT) və neftin qazlılıq əmsalının (GOR) dəyişməsindən asılılığı qeydə alınmış və bu parametrlər arasında müəyyən əlaqənin qurulmasına çalışılmışdır. Müşahidələr göstərir ki, ümumilikdə BHT neftin qazlılıq əmsalının azalmasından və ya quyudibi axın təzyiqinin artmasından asılı olaraq artır. Bu məlumat quyudibi temperaturun davamlı ölçülməsi ilə neftin qazlılıq əmsalını təyin edilməsinə imkan verir. Simulyasiyanın nəticələri real sahə məlumatları ilə qarşılaşdırılmış və tamamilə eyni cavablar alınmışdır. Quyuya su və qaz vurmanın başlanılmasından və ya qonşu hasilat quyularında hasilatın dayandırılmasıdan sonra temperaturun dəyişməsi quyulararası əlaqənin olmasını göstərmişdir. Laydakı başlanğıc temeperaturu sabit saxlamaqla BHT-nin dəyişməsini öyrənmək üçün əlavə ssenarilər yaradıldı. Bütün bu ssenarilər yekunda onu göstərdi ki, temperatur dəyişməsi təkcə geotermal qradieyntdən yox həm də təzyiq və doyma əmsalının dəyişməsindən asılıdır. Ümumilikdə əgər düzgün analiz edilərsə, BHT gündəlik neftin qazlılıq əmsalından başlamış quyulararası əlaqəyədək sıralanan müxtəlif məlumatların alınmasında istifadə edilə bilər.

Açar kəlimələr: quyudibi temperatur, quyudibi təzyiq, neftin qazlılıq əmsalı, CMG STARS

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BHP	Bottom-hole pressure
BHT	Bottom-hole temperature
DTS	Distributed Temperature Sensing
GOR	Gas-oil ratio
STR	Sidetrack
WBS	Wellbore storage

INTRODUCTION

The temperature data has begun to be measured many years ago. First time temperature data was investigated for determining phase contacts, but it was unsuccessful because of small differences in thermal properties of oil and water. However, up to recent years temperature data wasn't used widespread in reservoir characterization. Nowadays the relation of temperature with many factors is revealed and applications are expanded. Also, new technology allowed very precise and continuous measurement of temperature. That is why fiber optic Distributed Temperature Sensing (DTS) is installed in many wells to measure temperature and as well as pressure continuously and accurately in the recent years.

DTS is a continuous and real-time measuring tool by which the problem is identified instantly and pro-active and effective measures are taken. It enables to monitor rapid temperature changes in a short period of time.

The temperature changes occur mainly due to Joule-Thomson effect, frictional heating and geothermal gradient. Joule-Thomson effect [1, 2, 3] is the temperature change as a result of expansion or compression in adiabatic process. This effect usually depends on magnitude and speed of pressure changes as well as the reservoir and fluid properties. The warming or cooling is based on the sign of Joule-Thomson coefficient that is related to pressure and temperature. Usually gases show cooling and oil/water warming effect upon pressure reduction.

The frictional heating [2] that is caused by the friction between producing fluids and reservoir rock is another reason for temperature changes. Since pressure gradient is not large from reservoir to perforations, frictional heating is a controlling factor on temperature inside reservoir rather than Joule-Thomson effect which dominates mainly at sandface and near wellbore region due to large pressure drops.

If there is no dip in the reservoir, we can neglect thermal gradient. However, in steeply dipping reservoirs the geothermal gradient will affect the temperature since the temperature increases towards the lower layers. Additionally, the temperature dependence on the direction of pressure support is observed, i.e. whether pressure support is up-dip or down-dip. If it is up-dip, the well drainage area skews up-dip resulting with cooling or vice versa. For this reason one may deduce from temperature records whether the voidage is from up-dip or down-dip.

Temperature data can be used in various applications ranging from identification of leaks to interwell communication. Producing/injection zones, fluid movement behind pipe, casing leaks, unwanted fluid entries, lost circulation zones, under-ground blow-outs and cement tops can be successfully deduced from wellbore temperature profile.

For transient tests only pressure information was used to determine reservoir properties. But some field examples showed the need of temperature transient analysis, for example, determining the end of welbore storage (WBS) in gas wells in the case of their underestimation or overestimation via pressure tests. As an example, in wells, where perforations were done only in a portion of productive interval, a short radial flow near the sandface followed by spherical flow is observed. In this case the decreasing trend of the pressure derivative curve can be interpreted either as an end of WBS or transition from radial to spherical flow. Flowmeters at sandface can be used for this purpose; however, the low flow rates may be not measured because of flow meter threshold. This causes incorrect estimation of the end of WBS which is important in test interpretations.

The usefulness of temperature data is observed in determining interwell communication. It is observed that when the production starts from a new well, it interferes with others and changes their flowing bottom-hole temperature (FBHT) trends. Temperature transient analysis gives us opportunity for qualitative estimation of permeability and skin factor based on delay times, like in pressure tests.

On the whole, temperature is an additional and valuable data and has a large potential in reservoir understanding and management. Using temperature data with pressure analysis for reservoir characterization will improve accuracy and decrease uncertainty.

This thesis work is mainly focused on revealing temperature-GOR and temperature-bottom-hole pressure relationships. The gas-oil ratio and pressure data inferred from temperature logs can be used as additional information and to check the measured values. Generally, any extra data about the reservoir, which is several kilometers below the surface, can greatly help to reduce uncertainties.

Usually getting information in reservoir engineering with great certainty is like looking for a needle in the haystack. Temperature may be used successfully for decreasing uncertainty.

It is also tried to find whether there was interwell communication between wells from temperature data by opening new wells and/or shutting existing wells in a study. Twenty eight cases were simulated in order to evaluate the impact of different parameters on temperature and analyze the extent of changes.

CHAPTER 1. REVIEW OF PREVIOUS INVESTIGATIONS

1.1 HISTORY

The relation of temperature with other parameters became interesting and various models have been developed. Even in 1930's Deussen and Guyod (1937) [4] described identifying the location of cement tops based on temperature increase due to heat of hydration.

Nowak (1953) [4] tried to determine injection profiles from shut-in temperatures. He assumed the areas between the shut-in temperature curve and its extrapolation is proportional to injection rates. However, this area is not only the function of injection rate per unit depth of pay zone, but also permeability. Steffenson and Smith (1973) concluded that quantitative interpretations of temperature profiles during shut-in are difficult due to lack of information about permeability and its distribution.

Bird (1954) [4] was a pioneer in interpretation of flowing temperature data. He neglected fluid heat storage capacity and derive an equation from simple heat balance. His Δ function is similar to Ramey's A-function.

Ramey (1962) presented wellbore temperatures and heat losses in non-flowing zones [5]. He assumed steady-state heat transfer between fluid and casing and unsteady-state heat transfer from casing into formation. He neglected vertical heat conduction from fluid to formation. Witterholt and Tixier (1972) and Romero-Juarez (1969) [5] used Ramey's asymptotic solutions to estimate a flow rate of different zones (both) and thermal conductivity (Romero-Juarez). The method of Squier et al. (1961) is very identical to Ramey's solution with the exception of boundary condition that assumes formation temperature is equal to earth temperature at very long radial distances. McKinley (1987) estimated flow rates of two zones by applying enthalpy balance and assuming same heat capacities for fluids of the two different production zones.

Sagar-Doty-Schmidt (1991) proposed a simplified model in which they developed a correlation for Joule-Thomson coefficient and kinetic energy terms from 392 two-phase flowing wells data [6].

Kabir (1996) showed wellbore/reservoir model for gas wells. Hasan did the same work for oil (1997) and two-phase flows (1998) [7]. Hasan-Kabir (2003) presented analytical model in order to find wellbore fluid temperature profile in gas wells during transient period [8]. Their model is intended to calculate BHP from wellhead pressure and this is a non-trivial work in the case of transient period. Izgec-Hasan-Kabir (2007) presented a new semi-analytical heat transfer model for coupled wellbore/reservoir system for transient period improved with variable earth temperature and numerical differentiation.

For steady-state gas flow Cullender and Smith (1956) [9] method of computing BHP from wellhead pressure is accurate for dry gas wells and Govier and Fogarasi method (1975) [9] for wet gas and two phase model.

Hutchinson (2007) investigated interwell communication of Chirag field (Azerbaijan) by using temperature data and got quite reasonable results.

1.2 CAUSES OF TEMPERATURE CHANGES IN RESERVOIR

Up to recent years the wellbore temperature is assumed to be equal to the reservoir temperature at that depth. However, in reality the temperature at sandface differs from original reservoir temperature during production, injection or shut-in. The geothermal effect, frictional heating, injected fluid temperature and Joule-Thomson effects are the main reasons of temperature changes in reservoir and wells.

1.2.1 GEOTHERMAL GRADIENT

The earth always loose heat from hot center to the cold earth crust by conduction and this causes geothermal gradient to occur. The geothermal gradient is the change of temperature per unit depth. Temperature at the earth's surface is dictated by the Sun and atmosphere, except where the flow of hot springs and lava are dominant. On the other hand, radioactive decay (80%) and planetary accretion (approximately 20%) are the main sources of internal heat of the earth [10]. Electromagnetic effects and tidal force also have minor effects on the internal heat. At the center of the earth, temperature and pressure may reach up to 7000 K and 360 GPa, respectively [10].

Geothermal gradient is not a straight line because of layers with different geological, petrophysical and thermal properties. It usually changes between 0.6ºF and 1.6ºF per 100 ft with an average value of 1ºF per 100 ft [3]. However high gradients (even up to 11°F/100 ft) are typical for the mid-ocean ridges and island arcs and low gradients are typical for tectonic subduction zones [11].

Oil and gas industries greatly deal with the geothermal gradient. Down-hole drilling and logging tools have to be made in such a way that they function in deep wells and tolerate high temperatures in areas where high gradient is observed. Geothermal gradients and temperatures play an important role in the generation of hydrocarbons in a source rock. Geothermal energy is the main source of energy in some areas with high geothermal gradients such as some regions in Iceland (regions where geothermal gradients ≥2.2°F/100 ft) [11].

Geothermal gradient may be neglected in reservoir that is not located in a large distance vertically. But in the case studied in this thesis work, the difference between top and bottom of the reservoir is 2299 ft in the North and 1320 ft in the South and it can not be neglected. This gives extra advantage in determining whether oil comes from top or bottom.

1.2.2 JOULE-THOMSON EFFECT

Joule-Thomson effect, also called Joule-Kelvin effect is the warming/cooling effect of fluids as a result of expansion or compression preceded by pressure change in adiabatic process. The magnitude of Joule-Thomson effect depends on fluid properties and amount of drawdown. The maximum drawdown usually occurs at sandface, and so maximum temperature change due to this effect usually corresponds to this point.

The Joule-Thomson coefficient is defined as temperature change per unit pressure at constant enthalpy.

$$\mu_{JT} = \left(\frac{\Delta T}{\Delta P} \right)_H \tag{1}$$

The warming or cooling is a function of the sign of Joule-Thomson coefficient. If it is negative, the temperature increases or vice versa. Generally high pressure oils and gases show warming effect, while low pressure gases show cooling. Ideal gases have zero Joule-Thomson coefficients.

STARS uses two different enthalpy models, which makes the J-T issue on STARS more complicated. For default water (enter zeroes for any enthalpy keywords) the enthalpy model is full P-T dependence via table look-up over the stated T and P ranges. The point here is that the H(T,P) function represents real water, especially water vapour, so the J-T effect should be seen in STARS for water component.

For all other components, and non-default water, enthalpy depends only on T. This is a good approximation for liquids and amounts to the ideal-gas approximation for gases/vapours. Consequently, the J-T effect will not be seen for these components.

1.2.3 FRICTIONAL HEATING

Frictional heating is a warming of reservoir fluids as a result of friction when fluids are passing through porous media. The magnitude of frictional heating strongly depends on the value of permeability, such as, it increases as permeability decreases.

In oil reservoirs both Joule-Thomson effect and frictional heating tend to warm the reservoir. However, in the gas reservoirs, the final temperature depends on the combination of Joule-Thomson cooling and frictional warming. Mainly at sandface and near wellbore region, where large pressure drops are observed, Joule-Thomson effect dominates, while away from wellbore region into the reservoir frictional heating is a controlling factor.

1.2.4 INFLUENCE OF INJECTION FLUID TEMPERATURE

Depending on the rate, time and temperature of injected cold fluid the reservoir cools gradually. It is obvious that injection fluid temperature tends to approach to the geothermal gradient as it moves along the wellbore and through the reservoir. However in the case of vast amount of cold fluid is injected, the fluid finds an opportunity to cool the reservoir radially as a function of time. The injected fluid forms a cold thermal front that equals approximately to the half of fluid front as shown in figure 1.1.

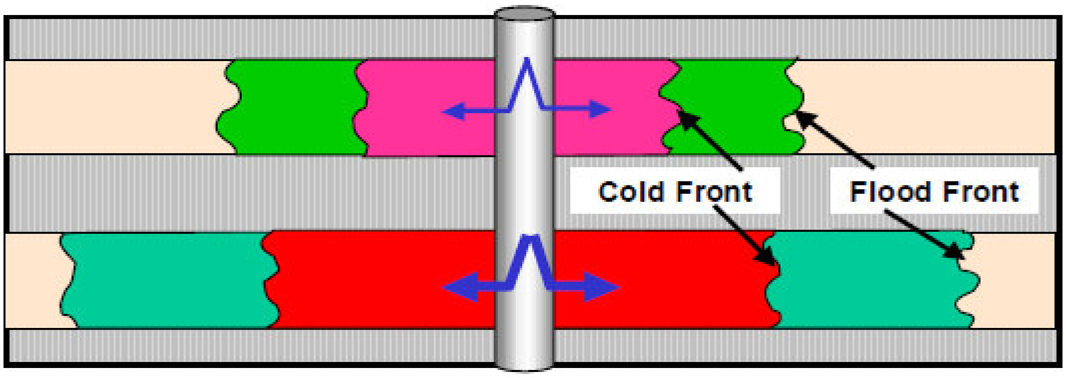

Figure 1.1 Radial injection of cold water [3]

At the producing end of the reservoir the temperature of produced injecting fluid will be cooler than the formation temperature depending on the rate, injecting temperature, zone thickness and distance of producer from injector after the arrival of injected fluid to producer. Since the thermal front is about half of flood front, producing of injected fluid is required for some time in order to observe thermal front reaches to producer. The time for arrival of thermal front to producing end decreases as the zone thickness decreases.

These temperature changes give opportunity to measure velocity of sweep between injector and producer by surveillance the thermal front movement in new drilled injection wells or in injection wells that was ceased for some time and started again.

1.3 TEMPERATURE EFFECTS ON THERMAL PROPERTIES

Heat capacity [12] increases with increasing temperature, while thermal conductivity [13] of most rock types show decreasing trends except glasses and vitreous materials. Thermal conductivities of liquid-saturated rocks decreases with temperature and reverse process occur in gas-saturated rocks [14]. Temperature has large effect on thermal diffusivity since diffusivity is the ratio of thermal conductivity to the product of density and isobaric heat capacity and since thermal conductivity decreases and heat capacity increases with temperature.

Formation thermal values are very difficult to get at high temperatures and pressures. Errors in thermal data can be even as high as 20% at temperatures greater than 1500°F [15]. The errors may be caused by thermal reactions at high temperatures. However, if the relationship of thermal properties with temperature is not taken into account, calculations may be wrong at large temperatures.

1.4 DATA GATHERING

1.4.1 PRODUCTION LOGGING TOOL (PLT)

Production Logging Tool (PLT) is used to get fluid data in order to have better reservoir management. It is useful in detecting leaks, problem zones, producing intervals and flow rates of oil, water and gas. PLT gives opportunity to identify the well problems and to correct them.

Production Logging Tool is consisted of pressure and temperature gauges, gamma ray, Casing Collar Locator (CCL) tool, flowmeter, spinner, density and capacitance tool [16]. Flowmeter is used to measure fluid flow rates. Depth correlation is made by CCL and gamma ray. CCL also identifies holes or perforations in the producing well. Capacitance tool is usually used for measuring water cut.

1.4.2 DISTRIBUTED TEMPERATURE SENSING (DTS)

The mechanism of DTS system is based on analyzing back-scattered laser light. The strength of reflected light depends on molecular vibration in optic fiber which in turn is a function of the temperature at the corresponding point. Reflected signals are interpreted at surface and converted into temperature profile.

Appropriately installed DTS can measure temperature with 1 meter increments and up to 12 kilometers from surface. The accuracy of temperature measurements may reach to 0.01°C.

DTS allows getting a real-time temperature data accurately without interruptions of ongoing operations. Flow profile can be deduced from these temperature measurements, especially in vertical and near-vertical wells. In deviated and horizontal wells it is difficult to identify fluid entry regions because of small changes in geothermal gradient. However, DTS can be successfully used to determine flow profile in wells deviated up to 75 degrees [17].

1.4.3 ADVANTAGES OF DTS OVER CONVENTIONAL PRODUCTION LOGGING TOOLS (PLTs)

DTS is an excellent measuring tool that minimizes ceasing of operations, especially during drilling where access to wellhead is limited. In the case of high flow rates, PLT measurements require reducing the rate, while in DTS measurements this is not a case. Reducing rates results unrepresentative flow distribution in multi-zone production together with the lost of production. Because the drawdown in each zone changes depending on producing flow rates. Reducing costs significantly is another advantage of DTS over conventional PLT. Last but not least, the risk of damaging people and equipment decreases as a result of decreasing well interventions.

1.5 WELLBORE TEMPERATURE PROFILE

Production and injection intervals, flow rates and different anomalies can be estimated from temperature surveillance during production, injection or shut-in. Deussen and Guyod [4] described identifying the location of cement tops based on temperature increase due to heat of hydration. Casing leaks and cross-flows can be identified by using wellbore temperature profile. The temperature surveys can reveal flow behind casing that is not possible with flow meter measurements. Based on cooling/warming effect of fluids, temperature is a good indicator of gas/water breakthroughs.

If the oil is produced from more than one interval, then the difference will be observed in their entry temperature. The upper part is colder than the lower part due to geothermal gradient, and as a result the fluid coming from upper zone will tend to cool the flowing stream. This phenomenon helps us to identify flowing intervals and even contribution of each interval to flow.

Many models have been derived in order to describe wellbore temperature profiles. One of the most important models is Ramey's. His equations sourced from energy balance and describe temperature profiles of wellbore at non-pay zones during water and gas injection. The following two equations are found for liquid and gas injection temperature profiles, respectively [18].

$$T_f(z,t) = az + b - aA + [T_s + aA - b]\, e^{-z/A} \tag{2}$$

$$T_f(z,t) = az + b - A(a \pm \frac{1}{778C_p}) + [T_s - b + A(a \pm \frac{1}{778C_p})]\, e^{-z/A} \tag{3}$$

Where, $T_f(z,t)$ is a fluid temperature distribution at any position and time in the wellbore. Plus sign is used for injection and negative sign is used for production. Also, a = geothermal gradient, °F/ft; b = surface geothermal temperature, °F; C_p = isobaric heat capacity of fluid, Btu/lb-°F; Ts = surface temperature, °F; A = relaxation distance, ft; z = distance from injection/production point, ft.

Witterholt and Tixier (1972) [5] suggested expression for A approximately by considering typical values of thermal conductivity of formation and heat capacity and density of water, i.e. $\lambda = 1.4$ Btu/ft-D-°F, $C_p = 1$ Btu/lb -°F and $\rho_w = 350$ lb/bbl. Thus,

$$A = 1.66 \times f(t) \times (\text{BPD of injection}) \tag{4}$$

f(t) in the equation above is a time function. Ramey found an approximate expression for this function.

$$f(t) = -\ln(\frac{1}{2}\sqrt{t_D}) - 0.2886 \tag{5}$$

However this solution becomes suitable at longer times, approximately one week. Because, after sufficient time temperature will be dominated by formation conditions and zero wellbore radius assumption of Ramey will almost have no effect on results. Witterholt and Tixier emphasized Ramey's linear f(t) solution to be very accurate at t>100 days [5].

There are two asymptotic solutions [5] of the Ramey equation for fluid temperature distribution depending on the values of A and z. The first asymptote occurs if z>>A. In this case $e^{-(z/A)}$ will approach to zero and the equation become:

$$T_f(z,t) = az + b - aA = T_e - aA \tag{6}$$

Where, T_f and T_e are fluid and earth temperatures, respectively.

It can be deduced from the equation above that, T_f is parallel to T_e if the A is very small compared to z and this usually occurs when the injection time is very short. Figure 1.2 shows flow rate and time dependence of asymptotes, respectively. Note that distances of asymptotes from geothermal temperature are directly proportional to flow rates and flowing times. When $A \rightarrow 0$, then $z \rightarrow \infty$ and $T_f \rightarrow T_e$ and so very far from injection point T_f is equal to T_e.

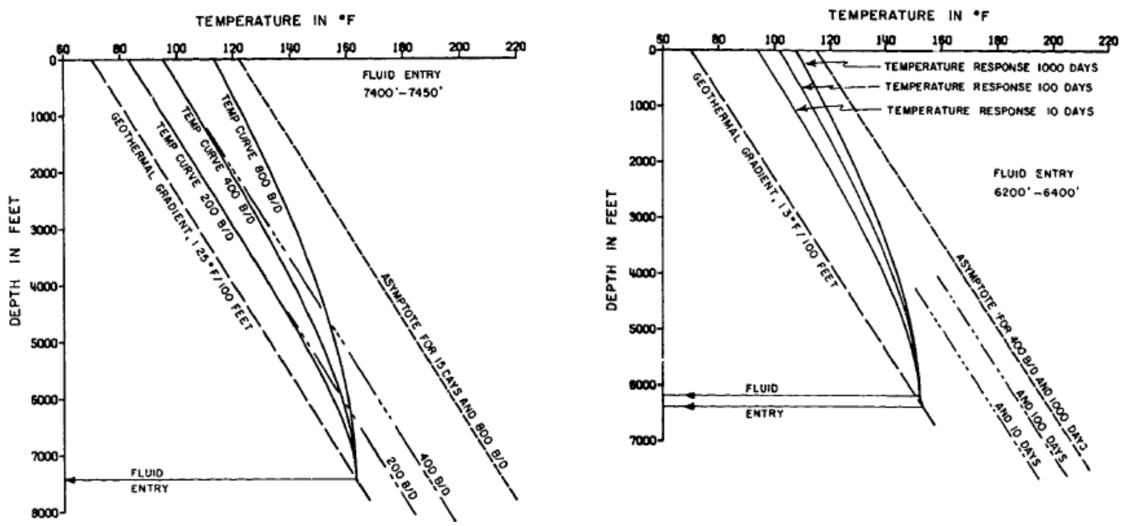

Figure 1.2 Effect of flow rate (left) and time (right) on first asymptote [5]

The second asymptote (figure 1.3) describes the situation when A>>z. In this case $e^{-(z/A)}$ approaches one and equation (2) becomes:

$$T_f(z,t) = az + T_s \qquad (7)$$

Where, T_s is surface injection temperature.

The second asymptote doesn't change with flow rate and time unlike the first one. It is fixed and greater likelihood to see this asymptote when flow rate and injection time increases as A increases with the increase of these parameters.

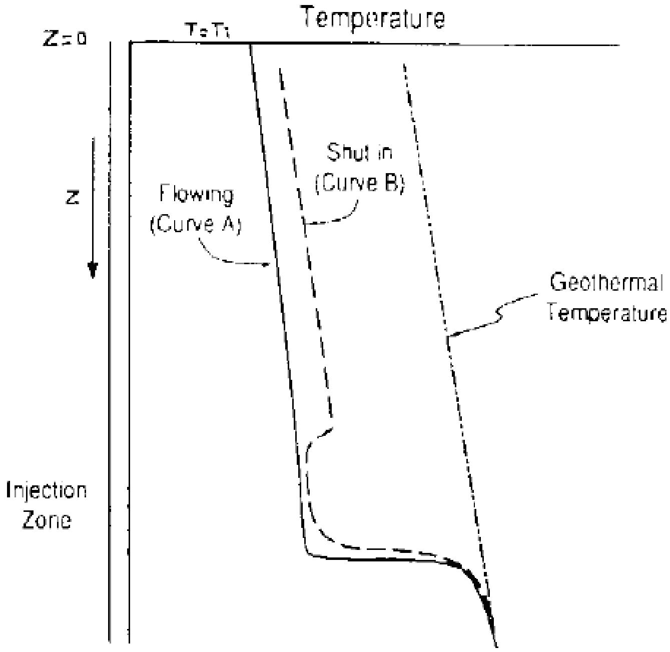

Figure 1.3 Second asymptote resulting from a single injection zone [5]

Flow rates to/from each zone during injection/production as well as identification of injection and production intervals can be inferred from temperature logs like flowmeter surveys. To do accurate analysis reservoir intervals should be distinct and at a distance of minimum 100 ft between them [19]. Accuracy increases when flow rates are low because temperature should reach its asymptote before it reaches the upper production zone. As can be seen from figure 1.2, there is small distance between geothermal gradient and asymptote at low flow rates and this distance decreases as the flow rate decreases.

The value A can be estimated from the difference between geothermal temperature and asymptote that are parallel to each other [19].

$$A \times \text{Geothermal gradient} = T_f - T_{Geothermal} \qquad (8)$$

Knowing reservoir and well properties, f(t) is calculated from Ramey's approximation. After finding A and f(t), equation (4) can be used to calculate flow rate in the case of water injection.

1.5.1 CROSS FLOW BETWEEN ZONES

During the time when the well is shut in, the flow of fluids to other zones can occur as a result of pressure difference at different intervals. In order to identify cross-flows and casing leakages well temperature profiles should be compared with geothermal gradient. Obtaining a representative geothermal gradient is important. Actually it is not a straight line as a result of different thermal properties of different layers.

The flow can be either through wellbore or behind casing. In both cases the direction and amount of flow can be determined by using temperature logs.

1.5.2 WATER INJECTOR ANALYSIS

The injected cold water cools the entire wellbore including non-permeable zones. This makes determining injection intervals and amount of injected water difficult. For this purpose the technique called "warm back" [3, 20] is used effectively. During the injection well shut in the temperature along the wellbore warms back and approaches to geothermal gradient. But warming effect and time will not be same at the non-permeable and permeable intervals. Because latter cool more deeply depending on the rate, permeability and rock and fluid thermal properties.

1.5.3 HOT SLUG VELOCITY MEASUREMENT

After the "warm back" period the reservoir is still cold while the water in the wellbore above the pay zone warms quickly by conduction from adjacent formation. When the injection starts again, the hot water slug in the tubing can be tracked and velocity can be measured and flow profile can be identified.

1.5.4 WATER-CUT AND GAS-CUT ZONE DETECTION USING TEMPERATURE

The temperature measurement can help to identify water and gas-cut zones, since the thermal properties of different fluids are not the same. The gas-cut or water-cut increase results in change in temperature of producing fluids and can be identified by continuous temperature monitoring.

The change in the amount of water production will change the reservoir rock relative permeability that alters flow rate which can be identified from temperature data. In the case of water-cut increase, the change in the down-hole flow rates can be determined via temperature logs and the zone from which increasing water-cut comes can be identified.

1.6 DETERMINING END OF WBS IN GAS WELLS

Some field examples show difficulties in identifying end of wellbore storage WBS from pressure and pressure derivative curves. As an example, in wells, where perforations were done only in a portion of productive interval, a short radial flow near the sandface followed by spherical flow is observed. In this case the decreasing trend of the pressure derivative curve can be interpreted either as an end of WBS or transition from radial to spherical flow.

Temperature transient analysis can help to identify WBS ending time in gas wells where Joule-Thomson effect causes temperature to drop below geothermal at sandface. When the well is shut in, Joule-Thomson effect disappears and temperature starts to increase. So the point where temperature changes from decreasing trend to increasing one indicates beginning of WBS (afterflow) in build-up tests in gas wells. On the other hand, frictional heating is observed after shut-in due to non-zero flow rate. When the flow rate becomes zero (i.e. end of afterfow) the frictional heating vanishes and temperature again changes into decreasing trend and approaches to reservoir geothermal temperature.

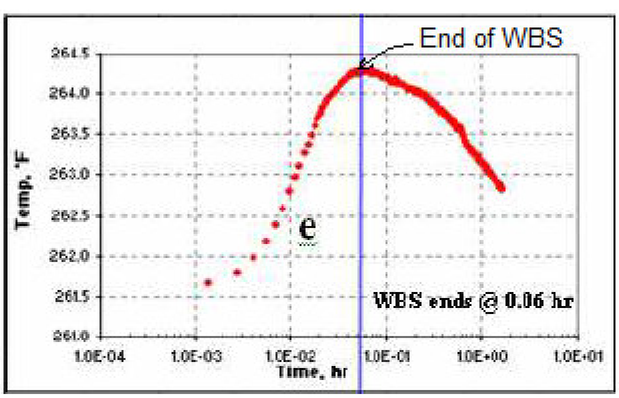

Figure 1.4 Identification of the end of WBS [2]

1.7 IDENTIFYING INTERWELL COMMUNICATION USING TEMPERATURE DATA

It is observed that interwell communication can be determined by Flowing Bottom-hole Temperature (FBHT) measurements due to interference delay times. The consistency of interference temperature delay times with pressure transient gives us opportunity to define interwell permeability. Temperature measurements can also provide us with the information of whether oil comes from up-dip or down-dip which is not possible with pressure transient analysis. If voidage occurs from down-dip, the flowing bottom-hole temperature increases and GOR decreases since the gas saturations and dissolved gases are lower at the bottom. When the oil comes from up-dip, vice-versa occurs.

1.7.1 CORRELATION BETWEEN FBHT AND FBHP

FBHT are mostly consistent with FBHP. FBHP usually changes in the same fashion as FHBT at the same time range. One advantage of FBHT over FBHP is that, FBHP is influenced from changes of flow regimes and chokes, while FBHT is not.

1.7.2 CORRELATION BETWEEN FBHT AND GOR

FBHT is inversely correlated to producing GOR, such as, FBHT decreases as the producing GOR increases. Correlation between FBHT and GOR gives opportunity to determine GOR using merely FBHT at times when production test is not conducted. Temperature decrease is also a function of a drawdown value for the same GOR change.

CHAPTER 2. REVIEW OF FIELD EXAMPLES

2.1 INTERWELL COMMUNICATION IDENTIFIED USING FBHT

The example below shows how producers of Chirag field have interwell communications. The Chirag field is located in the Caspian Sea, Azerbaijan part. Reservoir height is 1000 m and average pay-zone thickness is 130 m. The most productive intervals are Pereriv B and Pereriv D which have 20% porosity and 200 md permeability and 80 m total thickness [21].

2.1.1 INTERFERENCE OF PRODUCER A09Z WITH A20

A09Z and A20 are located at the south flank of Chirag field with a distance of 640 m between them [21]. The production started from A09Z in May, 2004 and flowing bottom-hole temperature showed a stable trend. When A20 put into production in December, 2005, the FBHT trend of A09Z changed significantly and stabilized on the other (cooler) trend after three months. This indicates that the drainage area of A09Z changed towards up-dip as a result of interference of A20. The delay time between the starting of A20 and changing the FBHT trend of A09Z was 5 days which was consistent with pressure transient analysis.

2.1.2 INTERFERENCE OF PRODUCERS A09Z, A19, A20 WITH A16

The wells A09Z, A19, A20 and A16 are on the south flank of the Chirag field [21]. The production from A16 started at January, 2002 and stable (warming) trend was observed due to strong down-dip aquifer support. The start of A09Z in May, 2004, A19 in December, 2004 and A20 in October, 2005 influenced the A16 FBHT trend. However the warming trend of A16 was stabilized again on the previous manner after some time, which indicates the existence of strong aquifer. The interference delay times were consistent with pressure transient analysis.

2.2 GAS EXPANSION AND EFFECT OF FRACTURES

Joule-Thomson effect assumes no heat transfer between formation and flowing fluid. This assumption is true if the expansion occurs only through a very small distance during the fluids enter the wellbore. However, in the case of high permeable fractures, expansion occurs before the gas reaches the wellbore and heat is transferred from formation into fluid.

The gas field example in Pennsylvania [22] shows the large effect of fractures on Joule-Thomson temperature. The reservoir pressure was 2615 psia and original reservoir temperature was 122ºF. Two temperature log measurements were done in two wells separately. The first well was producing with 1 MMscf/D and the second one with 6 MMscf/D. The temperatures in both wells were expected to be 10ºF due to Joule-Thomson effect. But measurements showed 48ºF in the first well and 120ºF in the second because of heat transfer which is assumed as zero in the Joule-Thomson definition.

This example indicates that fractures which have high permeability and surface area can behave as a heat exchanger. This event showed in example gives opportunity to evaluate permeability and fractures from temperature logs.

2.3 BOTTOM-HOLE TEMPERATURE AND GOR RELATIONSHIP, AZERI FIELD

Azeri-Chiag-Guneshli (ACG) is located in the Caspian region of Azerbaijan (figure 2.1). The Azeri field contains the South-East part of the structure and is operated by BP [23]. Oil is essentially produced from the formations of Pereriv B, C and D. The reserves are estimated to be 5-6 billion barrels and the thickness of oil column is approximately 1000 m. The angle of the reservoir is 35 and 20 degrees in the North and South flanks, respectively. The wells are highly deviated and able to produce with 50000 BOPD [23]. Sand production, high angle, large uncertainties, high gas-oil ratio in some wells are the major problems in Azeri field.

Figure 2.1 ACG field location [23]

A well P41 in Azeri was investigated to determine whether there is a relationship between BHT and GOR. Investigation was carried out in two stages, before and after water injection. In both cases the measured values of gas-oil ratio was plotted against BHT (figure 2.2). Plots indicated an excellent linear correlation between these parameters. In the case of pressure support the relationship showed slightly decreasing trend, while it declined sharply before water injection as can be seen from the slopes.

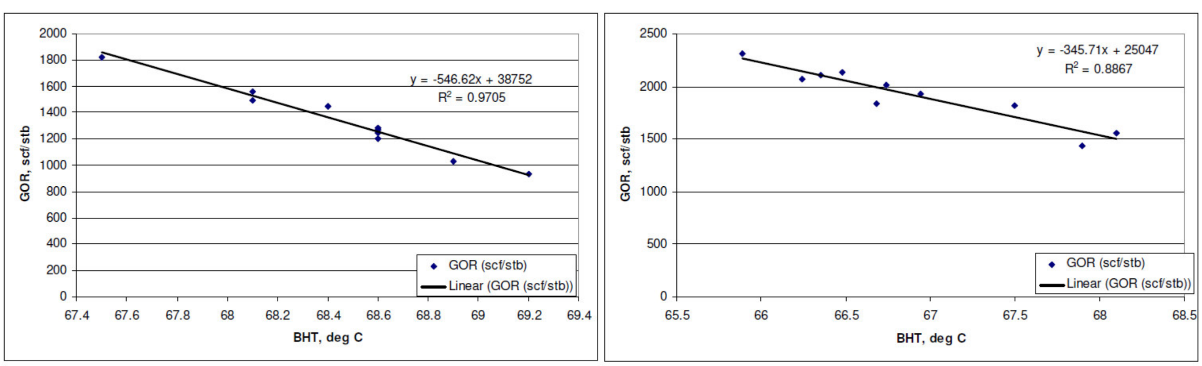

Figure 2.2 FBHT and GOR correlation before (left) and after (right) the water injection [24]

CHAPTER 3. METHODOLOGY OF ANALYZING RESERVOIR THERMAL BEHAVIOR

3.1 STATEMENT OF PROBLEM AND METHODOLOGY

Up to recent years the effect of temperature change due to production, injection and/or shut in was neglected. In most cases the temperature at the sandface was assumed to be equal to reservoir temperature. Upon improvement of surveillance technology these temperature changes became measurable and it was revealed that these changes have relation with some parameters such as well bottom-hole pressure and gas oil ratio. The influence of one well to the temperature of other neighbor well was also observed. In this thesis work the temperature at the perforations was simulated in the CMG STARS simulator for the six years time range. Different sensitivity studies were done to estimate the effect of different parameters, such as oil rate, water injection rate, drawdown pressure, GOR, wettability, etc. on temperature. The cases at which maximum and minimum temperature changes occurred were investigated to determine the extent of changes and analyze whether the changes are larger or smaller from the threshold values of DTS. Based on information from this work bottom-hole pressure and GOR were tried to be correlated with temperature for better reservoir management.

3.2 USE OF CMG STARS SOFTWARE

3.2.1 INTRODUCTION

CMG STARS is an advanced simulator for three-phase flow and multi-component fluids. It makes possible to simulate complex oil and gas recovery processes and complex geological formations, such as naturally and hydraulically fractured reservoirs. STARS is also an excellent tool for petroleum managers to increase production efficiency significantly. The processes that can be modeled with STARS are shown in table 3.1 below.

Table 3.1 Application areas of CMG STARS [25]

• **Thermal**	• **Geomechanics**
• Steam flooding • Cyclic steam • SAGD - (Steam Assisted Gravity Drainage) • ES-SAGD - (Expanding Solvent-Steam Assisted Gravity Drainage) • Thermal VAPEX • Hot water flooding • Hot solvent injection • Combustion (air injection) - HTO & LTO (High and Low Temperature Oxidation) - THAI (Toe-to-Heel Air Injection) • Electrical heating • Differential temperature water injection	• Compaction and subsidence • Rock failure • Dilation • Creep
• **Chemical**	• **Naturally and Hydraulically Fractured Reservoir**
• Gellation. simple or multi-stage, multi-component • Foams, emulsions and foamy oil • ASP (Alkaline-Surfactant-Polymer) flooding • Microbial EOR • VAPEX • Low salinity waterflooding • Reservoir souring	• Dual porosity - Multiple interacting continua - Vertical refinement • Dual permeability • Integrated to Pinnacle Technologies, Inc.'s FracProPT fracture design software • Integrated to Fracture Technologies Ltd.'s WellWhiz well, completion and fracture design software
• **Solids Transport and Deposition**	
• Fines transport • CHOP (Cold Heavy Oil Production) - Sand transport and production (Worm holes) • Asphaltene precipitation, flocculation, deposition and plugging • Wax precipitation	

STARS is also used to simulate non-oil and gas related applications including ground water movement, pollutant clean-up and recovery, hazardous waste disposal and re-injection, geothermal reservoir production, solution mining operations and near wellbore exothermic reactions.

3.2.2 DATA GROUPS

Keyword input system for building a model in STARS is composed of nine data groups. Each group has its own keywords. The order of keywords in the groups and the order of groups should be taken into account. The groups must be in the following order:

- Input/Output Control
- Reservoir Description
- Other Reservoir Properties
- Component Properties

- Rock-fluid Data
- Initial Conditions
- Numerical Methods Control
- Geomechanical Model
- Well and Recurrent Data

3.2.2.1 INPUT/OUTPUT CONTROL

Input/Output Control is composed of parameters which control the simulator's input and output activities including filenames, units, titles, choices and frequency of writing to both the output and SR2 file, and restart control. This data group doesn’t require any keywords. There is a default value for each keyword in this group that can be used.

3.2.2.2 RESERVOIR DESCRIPTION

Reservoir description section includes data describing the basic reservoir definition such as porosity, permeability, transmissibility, etc. and grid options. Grids can be Cartesian, cylindrical, variable depth/variable thickness or corner point. 2-D and 3-D models can be built with any of these grid options.

3.2.2.3 OTHER RESERVOIR PROPERTIES

“*END-GRID” keyword shows the end of “Reservoir Description” section and beginning of “Other Reservoir Properties”. This section is composed of data that describes other reservoir properties. These data include:

- Rock compressibility
- Reservoir Rock Thermal Properties
- Overburden Heat Loss Options

3.2.2.4 COMPONENT PROPERTIES

Component properties section contains component data which includes number of components in the oil/gas/water/solid phase, densities, critical pressures, molecular weights, K values, etc. of components. Figure 3.1 shows a component model with three components (water, oil and gas) in which two of them are in liquid phase and one is in aqueous phase.

```
*MODEL  3 3 2 1
*COMPNAME    'Water' 'Oil' 'Gas'
.
.
.
```

Figure 3.1 An example of component model

3.2.2.5 ROCK-FLUID DATA

Rock-fluid data includes relative permeabilities, capillary pressures and component adsorption, diffusion and dispersion. A set of relative permeability (water-oil and liquid-gas relative permeability) is the minimum data for this group.

3.2.2.6 INITIAL CONDITIONS

"*INITIAL" keyword is the first keyword of the "Initial Conditions" data group and comes immediately after the rock-fluid data. Initial pressure distribution is the only required data for this group.

3.2.2.7 NUMERICAL METHODS CONTROL

This data group controls the simulator's numerical activities such as time stepping, iterative solution of non-linear flow equations and the solution of resulting system of linear equations. There is no required data in "Numerical Methods Control" section and each keyword has a default value. The order of keywords is not important in this group.

3.2.2.8 GEOMECHANICAL MODEL

Geomechanical model section is optional entirely. The model options of this group are:

- Plastic and Nonlinear Elastic Deformation model
- Parting or Dynamic Fracture model
- Single-Well Boundary Unloading Model

3.2.2.9 WELL AND RECURRENT DATA

The Well and Recurrent Data section is composed of data and specifications that may change with time. Well and related data is the largest part of this section. The minimum required keywords and their critical ordering are indicated in figure 3.2.

```
*RUN
*TIME or *DATE    ** Starting time
*DTWELL           ** Starting timestep size

*WELL             ** Well definition (at least one set)
*INJECTOR or *PRODUCER
*INCOMP (injector only)
*TINJW  (injector, thermal only)
*OPERATE
*PERF or *PERFV

*TIME or *DATE    ** Stopping time
```

Figure 3.2 Minimum required keywords for Well and Recurrent Data group

A well is defined with a "*WELL" keyword and the well type must be specified with an *INJECTOR/*PRODUCER and *SHUTIN/*OPEN keywords before it is used by any other keyword.

3.3 SECTOR MODEL DESCRIPTION

Sector model is an anticline and has different characteristics in North and South flanks. The dimensions of the model are 34440 ft in length, 9840 ft in width and 209.6 ft in thickness. The top of model is located at 8531 ft and continues to 9851 ft in South flank and 10830 ft in North flank. There is a 1036 ft difference in water-oil contact at flanks which is 9431 ft and 10467 ft in the South and North flanks, respectively. The reference pressure is 4370 psi at a reference depth of gas-oil contact (8650 ft). Model has 8 producers (4 in South and 4 in North flank), 4 sidetracks of South flank wells and 3 injection wells (2 water and 1 gas injection). Water is injected from South and gas from crest. The injected gas tends to flow into North flank rather than South. The location of injection and production wells is described in figure 3.3.

Since the sector model has a big difference in depth between top and bottom, temperature shows large variations along the K direction (figure 3.4). It is 132.01 ºF at the top and increases 1ºF per 100 ft.

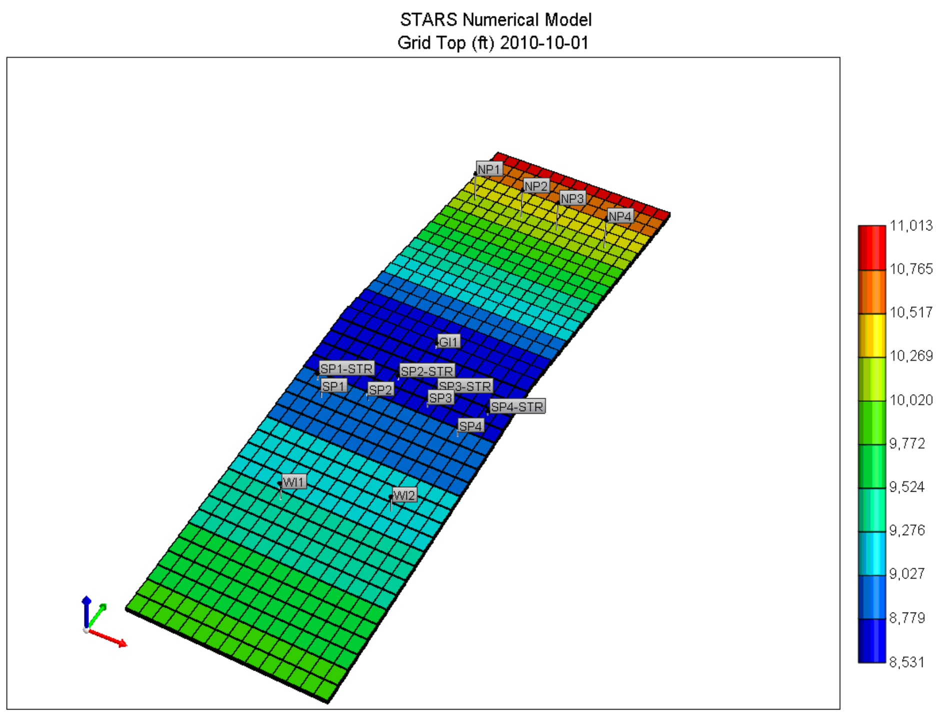

Figure 3.3 Location of production and injection wells in sector model [29]

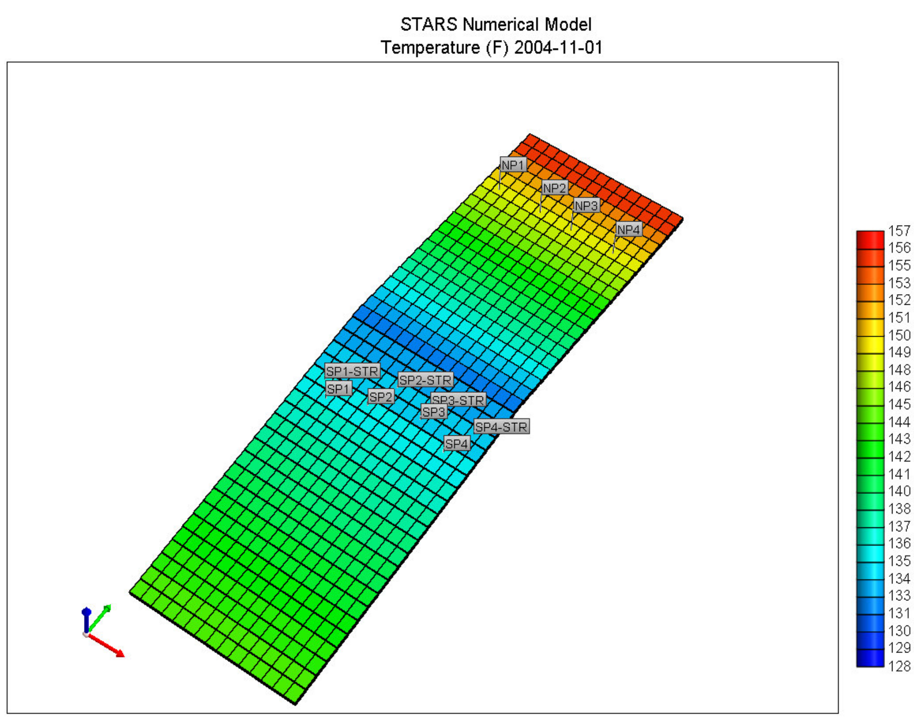

Figure 3.4 Initial temperature distribution of sector model [29]

Pressure changes between 4360 and 5301 psi throughout the model (figure 3.5).

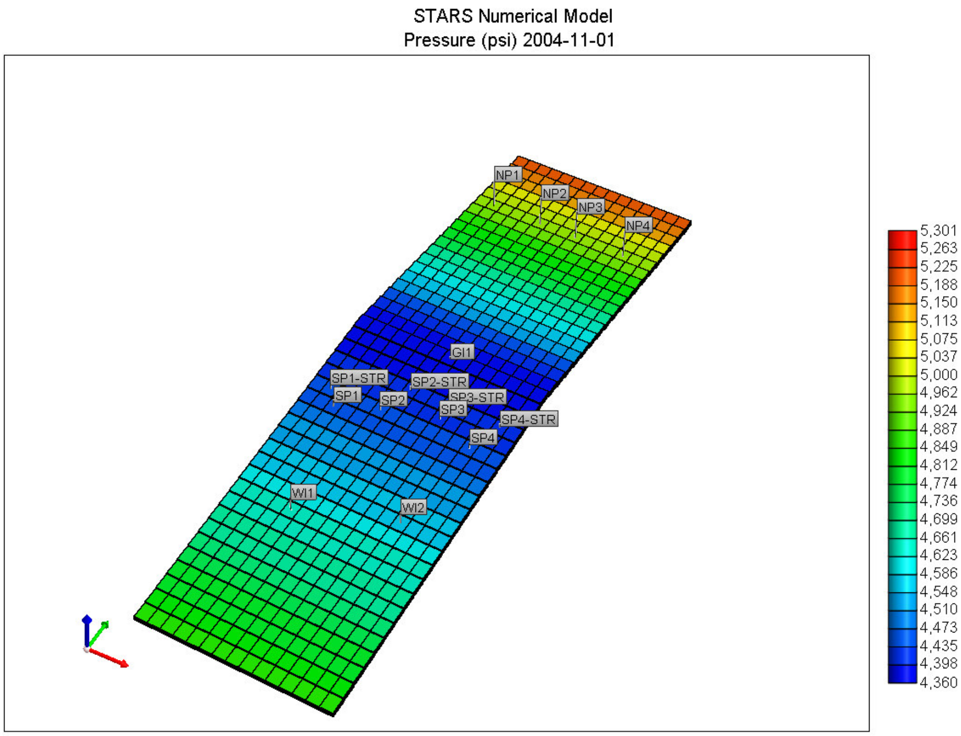

Figure 3.5 Initial pressure distributions of sector model [29]

There are total 5030 grids in the model; 15 in direction I, 42 in direction J and 8 in direction K. Cartesian grid system was used with dimensions of 656x820x26.2 ft.

Porosity and permeability values for all grids are not constant. Figures 3.6, 3.7, 3.8 and 3.9 below show the porosity, permeability, net-to-gross ratio and initial saturation distributions throughout the model, respectively.

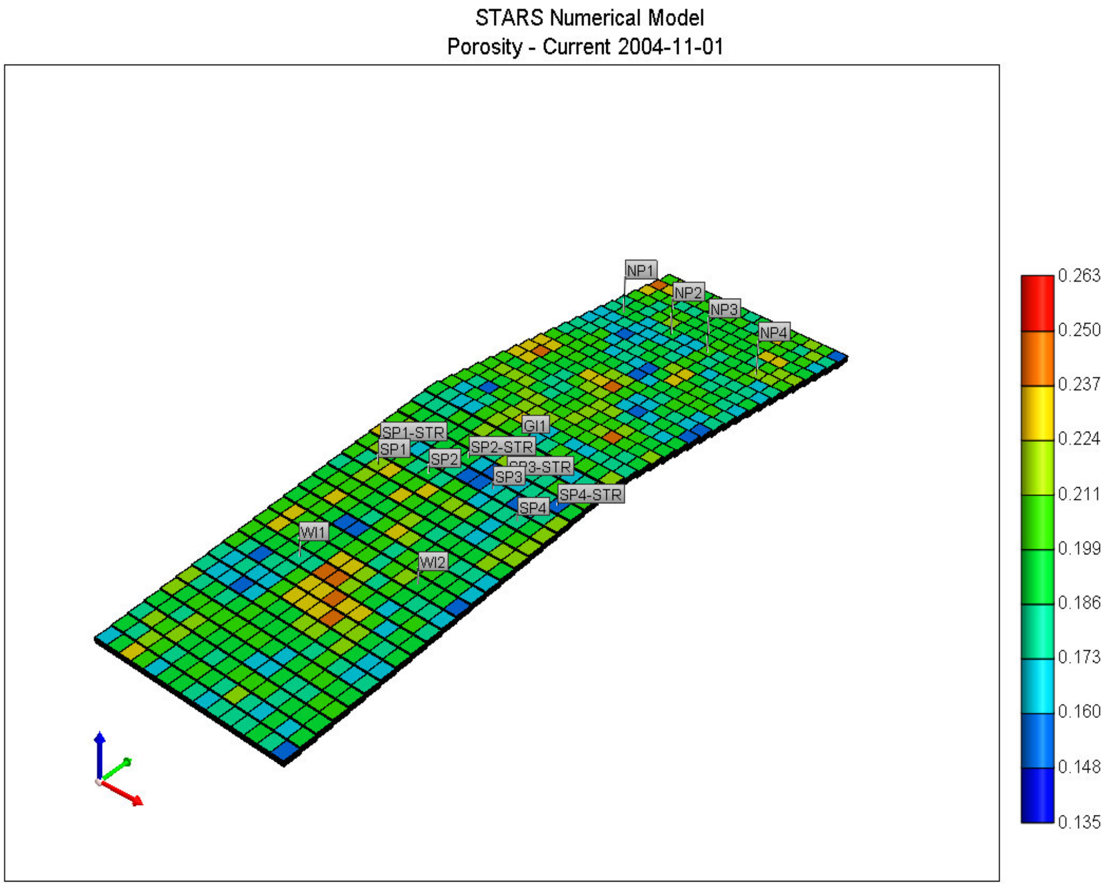

Figure 3.6 Porosity distribution [29]

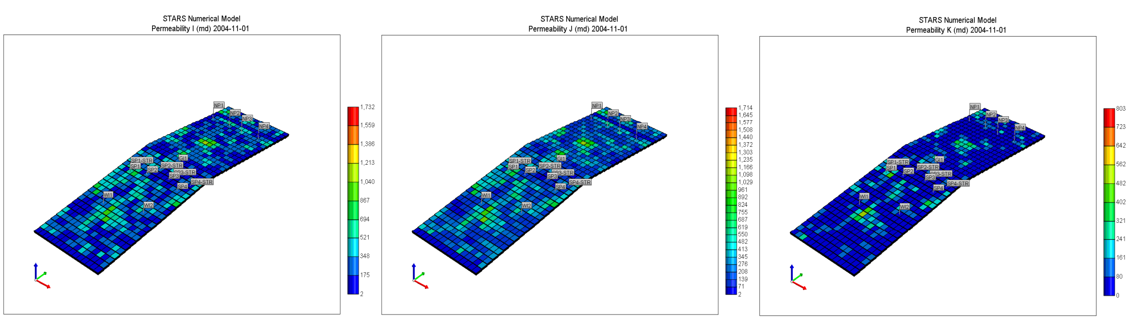

Figure 3.7 Permeability distributions in I, J and K direction [29]

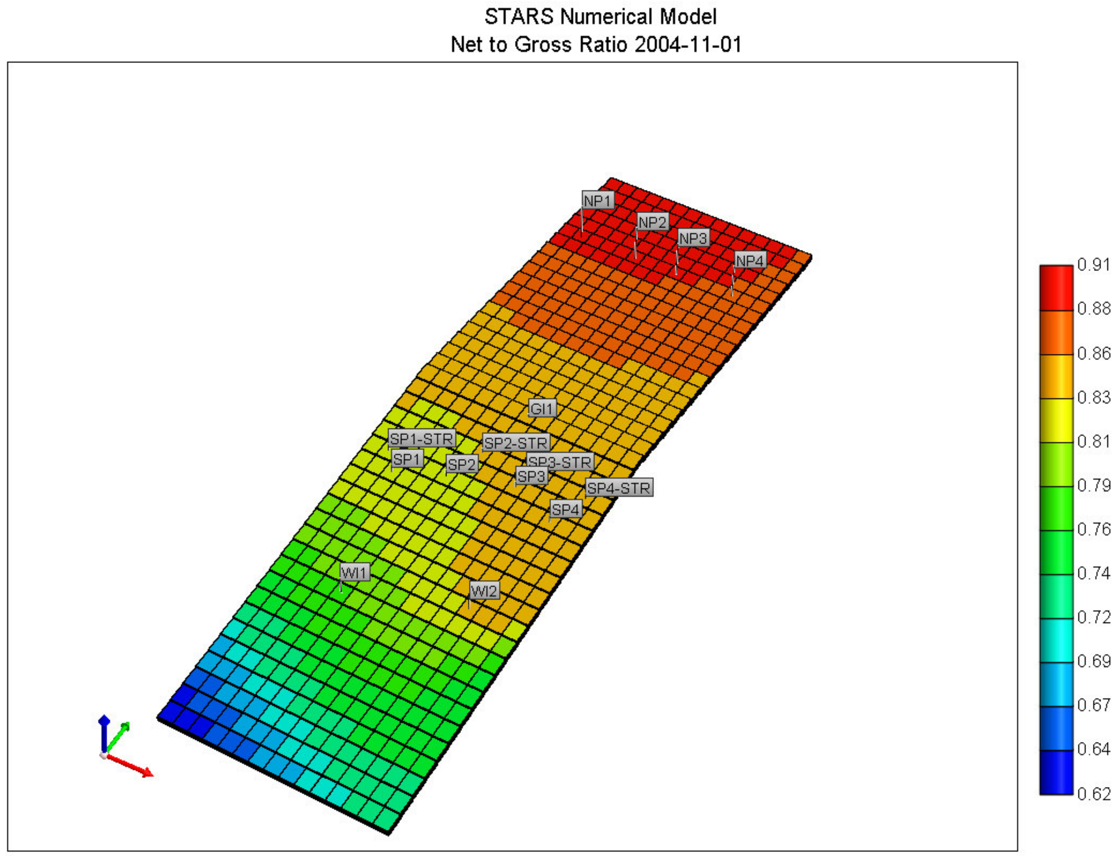

Figure 3.8 Net-to-gross distributions [29]

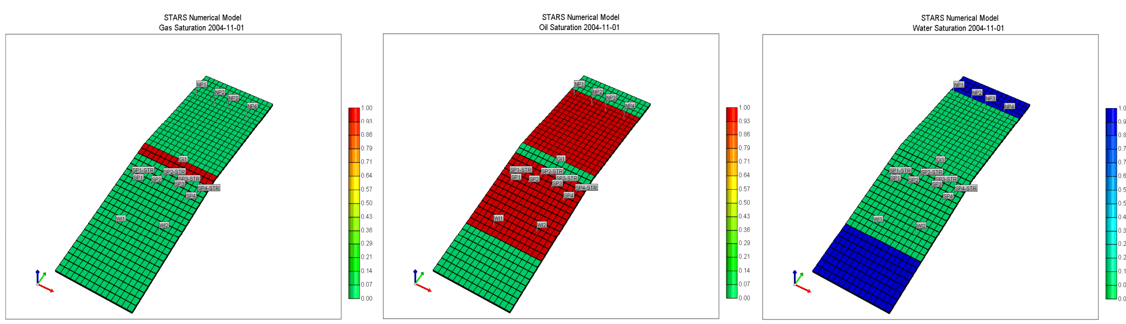

Figure 3.9 Initial saturation distributions of gas, oil and water

There are two sets of relative permeability data; one for North flank and one for South flank.

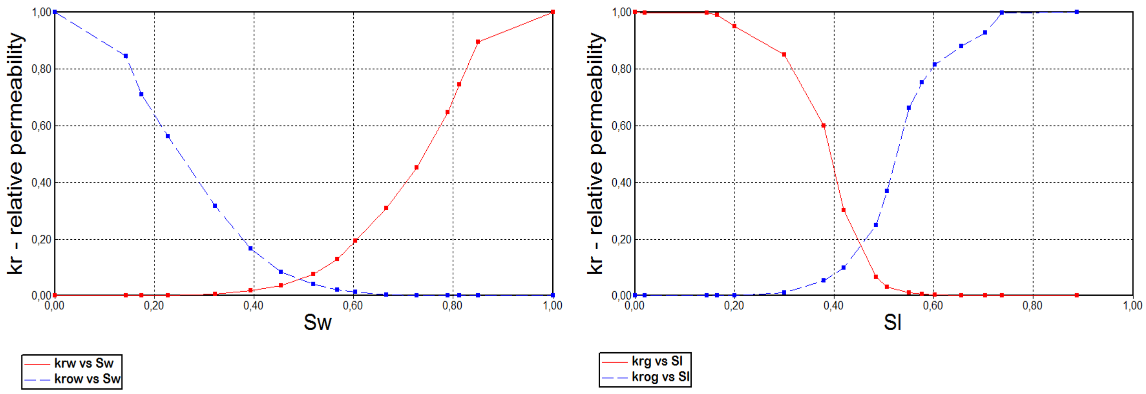

Figure 3.10 Relative permeabilities to water and oil (left) and to gas and oil (right) in the North flank [29]

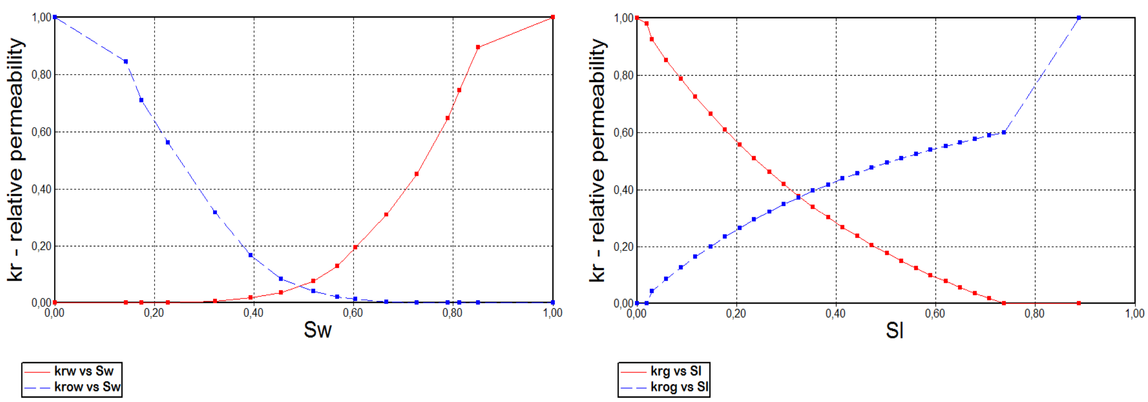

Figure 3.11 Relative permeabilities to water and oil (left) and to gas and oil (right) in the South flank [29]

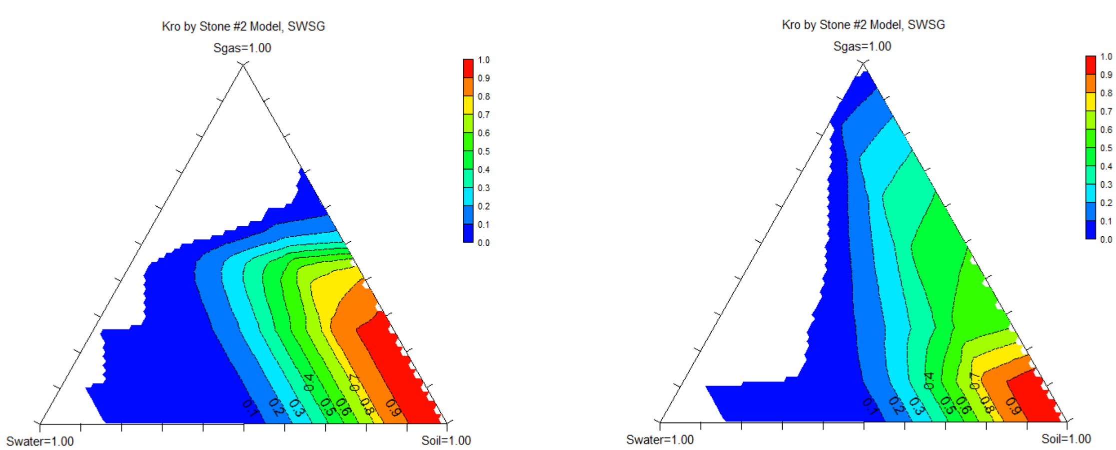

Figure 3.12 Three phase oil relative permeabilities in the North (left) and South flank (right) [29]

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1 DESCRIPTION OF THE METHOD FOR ANALYSIS

Twenty three cases for different scenarios and additional five cases were run in the CMG STARS simulator to observe temperature changes depending on different parameters. Well bottom-hole pressure, bottom-hole temperature, gas-oil ratio data were investigated at production wells and this section mainly deals with the relation of temperature with FBHP and GOR. Additionally, production and injection wells were shut in for some period and opened again to estimate its effect on temperature and to determine the inter-well interaction through temperature data. The simulated cases are:

- Case 1 – Base case (without injection)
- Case 2 – Base case (with injection)
- Case 3 – High oil rate
- Case 4 – Low oil rate
- Case 5 – High GOR
- Case 6 – Low GOR
- Case 7 – Low water injection rate
- Case 8 – High water injection temperature (from 20ºC to 30ºC)
- Case 9 – Changing location of water injection wells (up)
- Case 10 – Maximum drawdown pressure = 100 psi
- Case 11 – Maximum drawdown pressure = 150 psi
- Case 12 – Maximum drawdown pressure = 200 psi
- Case 13 – Maximum drawdown pressure = 250 psi
- Case 14 – High GOR, maximum drawdown pressure = 100 psi
- Case 15 – High GOR, maximum drawdown pressure = 150 psi
- Case 16 – High GOR, maximum drawdown pressure = 200 psi
- Case 17 – High GOR, maximum drawdown pressure = 250 psi
- Case 18 – Low GOR, maximum drawdown pressure = 100 psi
- Case 19 – Low GOR, maximum drawdown pressure = 150 psi
- Case 20 – Low GOR, maximum drawdown pressure = 200 psi
- Case 21 – Low GOR, maximum drawdown pressure = 250 psi
- Case 22 – Intermediate wet reservoir
- Case 23 – Oil wet reservoir

Additional cases:

- Case 24 – T = const in the reservoir, no injection, iterations = default (15)
- Case 25 – T = const in the reservoir, no injection, iterations =20
- Case 26 – T = const in the reservoir, no injection, iterations =30
- Case 27 – T = const in the reservoir, no injection, grids refined (all grids are divided into two in the j direction except where wells exist)
- Case 28 – T = const in the reservoir, with injections

4.2 BASE CASE ANALYSIS

Sector model has total 15 wells; twelve of them are production and three are injection. Two water injection wells are located at the South flank and gas is injected from crest. North flank owns 4 production wells (NP1, NP2, NP3 and NP4) (figure 4.1). These wells are close to water-oil contact and gravity is the main drive system for these wells. There were 4 production wells (SP1, SP2, SP3 and SP4) in the South flank initially. After beginning of injection, sidetracks which shifted the drainage area of wells towards gas-oil contact were drilled (figure 4.2).

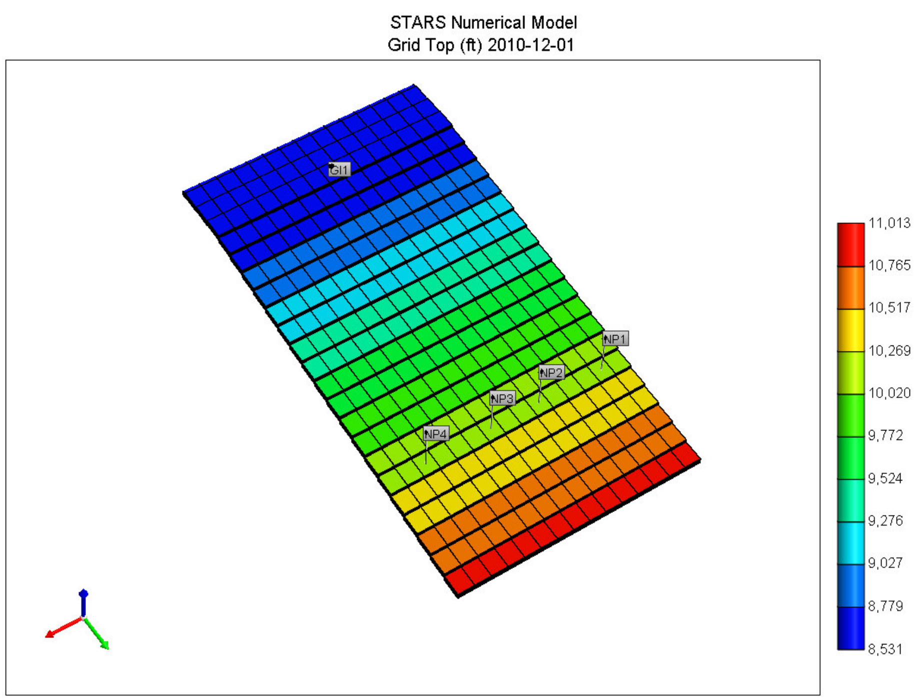

Figure 4.1 Location of wells at the North flank

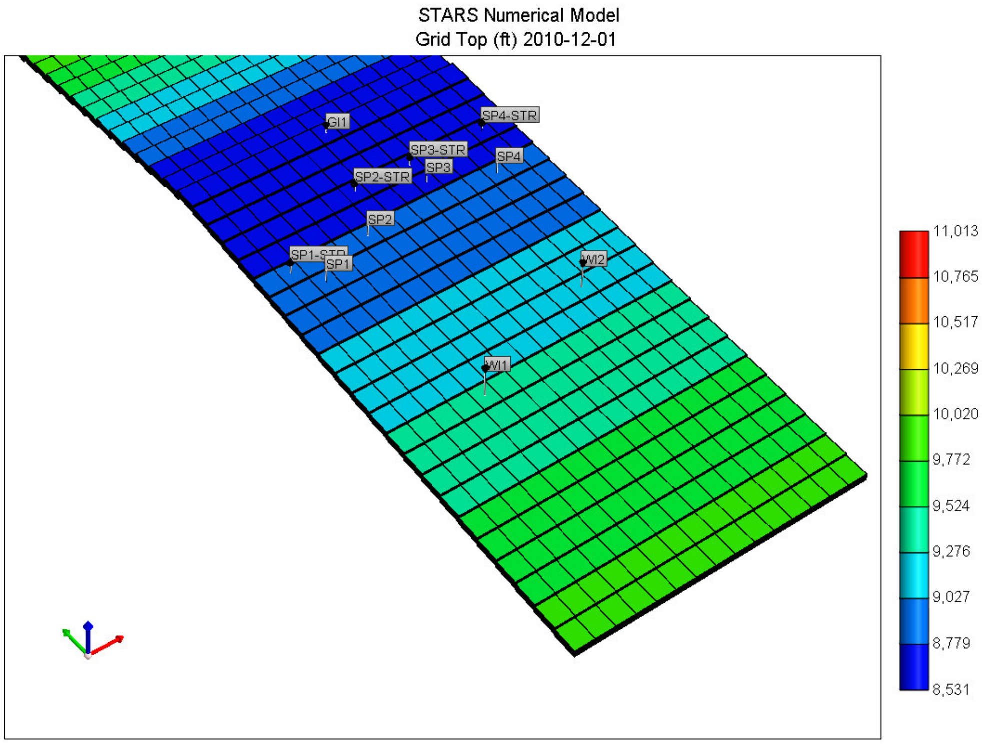

Figure 4.2 Location of wells at the South flank

The wells produced with the constant rate of 23 MSTB/day in the base case. The limit of injection rates were 65 MSTB/day for water injection wells and 35 MMscf/day for gas injection well. The starting days of wells are shown in table 4.1.

Table 4.1 Starting dates of wells

Wells	Beginning date
NP1, NP2, SP1	2005-02-01
NP3	2005-04-01
SP2	2005-07-02
SP3	2005-11-01
SP4	2006-01-01
NP4	2006-04-01
GI1	2006-07-02
WI1	2006-10-01
WI2	2007-01-01
SP1-STR	2007-04-01
SP2-STR	2007-06-01
SP4-STR	2007-08-01
SP3-STR	2007-10-01

Base case was run in two steps; with only production wells and no injection wells in the first step and with water and gas injection wells in the second step.

Temperatures analyzed in this study correspond to temperatures in blocks where the production wells are located in. So, the word "bottom-hole temperature" in the text means block temperatures rather than temperatures inside the wellbore.

4.2.1 NORTH FLANK WELLS ANALYSIS

In this section the North flank wells are discussed and injection wells are not taken into account at the first run. The wells in the North flank are located near the water-oil contact as shown in the figure 4.1. Figure 4.3 shows the temperature response of these wells during six years of production time. The different lines in the temperature graphs show temperatures of 8 different layers for the given wells. The temperature trends of 4 North flank wells are similar to each other due to their close location. As seen from the figure temperature shows a sharp decreasing trend from beginning of production to October, 2006 in all North flank wells and decreased approximately 1.6-2ºF during 21 months. However, beyond this date the sharp decreasing trend changed into less decreasing trend. After this point temperature began to decrease slowly and it changed only 0.4-0.8ºF during the following 4 years. When we analyze well bottom-hole pressure we see the shape of pressure curve is almost the same with temperature changing trend (figure 4.4). Beginning of slow decrease after October, 2006 is also case for bottom-hole pressure.

Why did this happen? Upon analyzing GOR data it becomes obvious that the date of October, 2006 corresponds to the date when bubble-point pressure was reached and solution GOR (R_s) decreased from constant value of 1596 scf/STB (figure 4.5). No any increase in producing GOR in North wells was observed from beginning of bubble-point to the almost end of simulation that may be due to the high critical gas saturation and/or vertical movement of separated gas as a result of dip angle in the North flank. Only at the end of 2010 GOR changed its slope and became approximately constant and this was resulted a very little increase in the decreasing trend of pressure and temperature. The latter proves the interrelation of BHT, BHP and GOR.

The wells NP2 and NP3 deliberately were shut in for 10 days to evaluate the shut-in effect on temperature trend. NP2 was shut down in September, 2005 and NP3 in April, 2008. This ten day's period indeed affected temperature 0.05-0.06ºF in NP2 and 0.02-0.035 ºF in NP3 approximately, while pressure increased 127 and 119 psi as a result of shut-in, respectively.

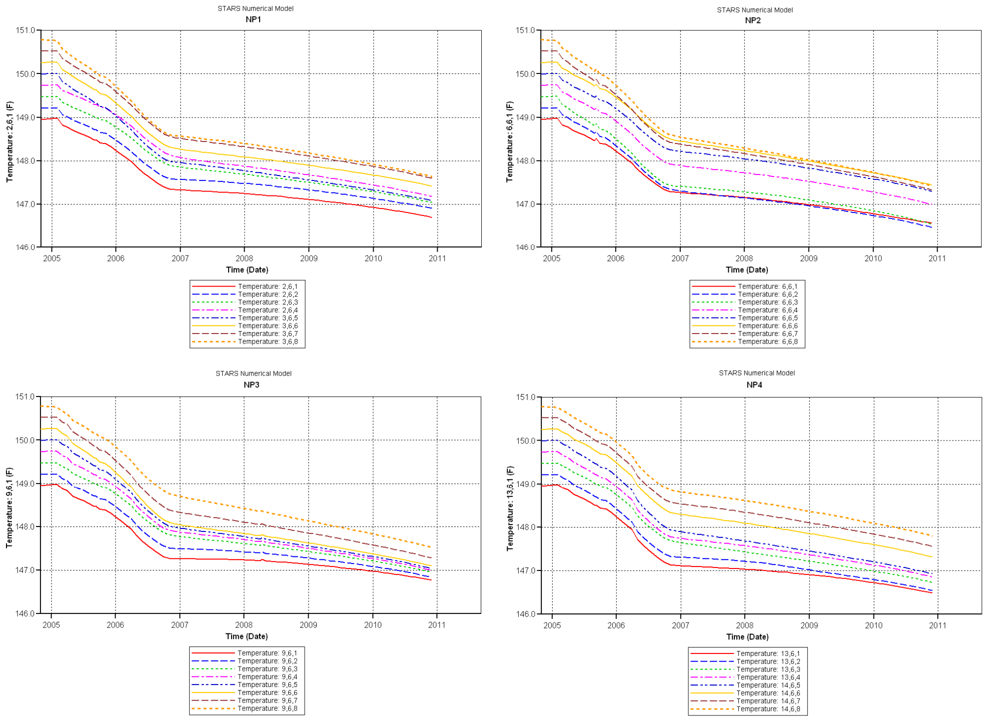

Figure 4.3 Temperature responses of North flank wells (base case without injections)

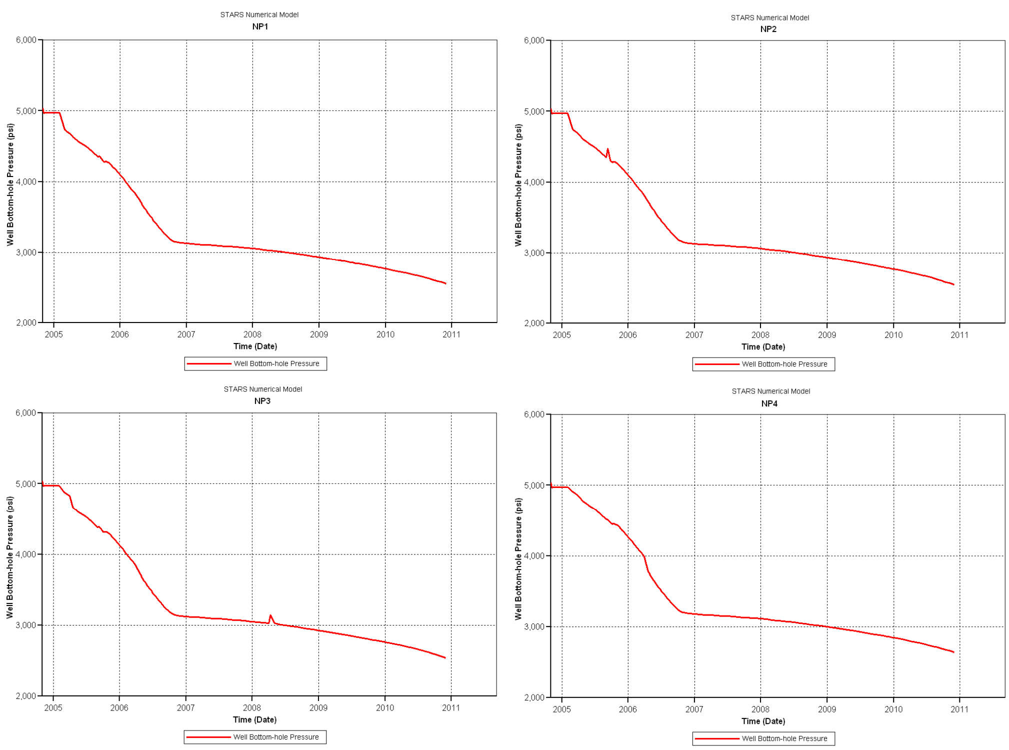

Figure 4.4 Bottom-hole pressure of North flank wells (base case without injections)

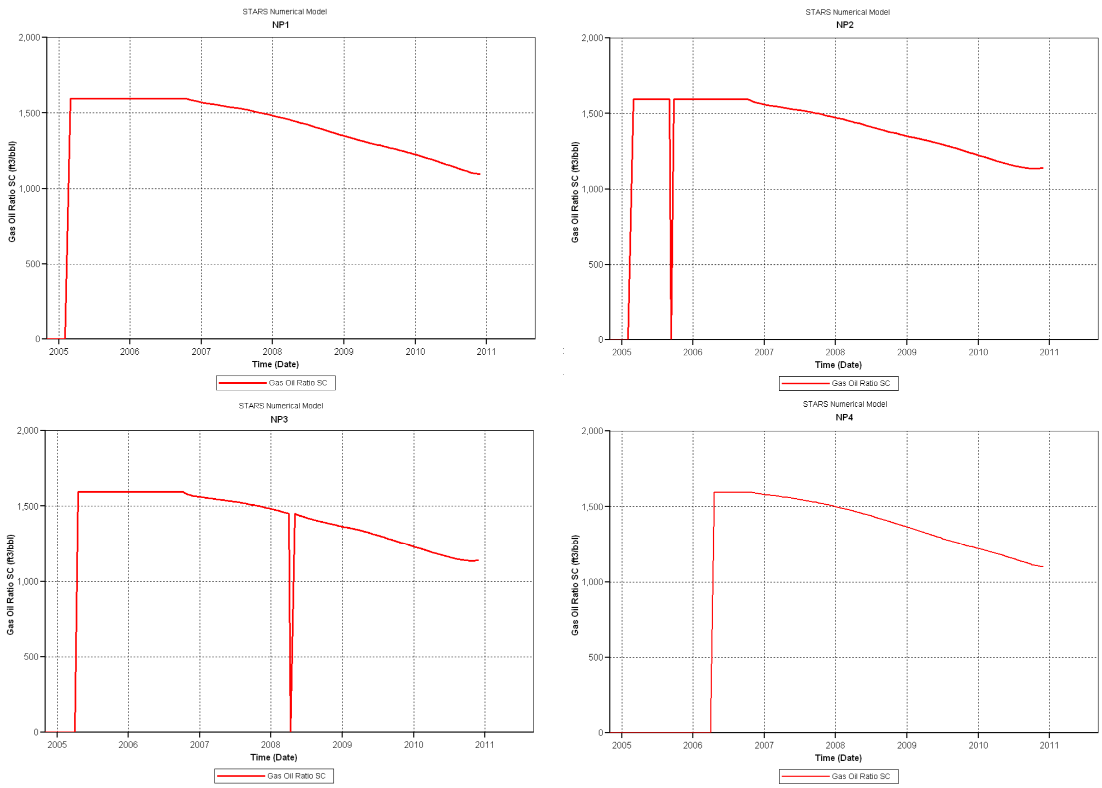

Figure 4.5 Gas-oil ratio of North flank wells (base case without injections)

When taking the injection into account we can see temperature decreases in the same fashion as it was in the first case. However after bubble-point the degree of change was something different, although it was the same before saturation pressure. The decrease in temperature was approximately 0.26-0.29ºF less than the no-injection case during the last 4 years. The reason is the pressure maintenance by injection wells, especially by gas injection well. North flank wells have no communication with water injection wells, since they are at the opposite flanks. The temperature trend was also agreed with pressure data that approached to constant after start of injection. The pressure at the end of simulation was approximately 338 psi higher compared to no-injection case. Variation in gas-oil ratio was also observed in the second case and GOR showed slow decrease which indicates influence of gas injection well.

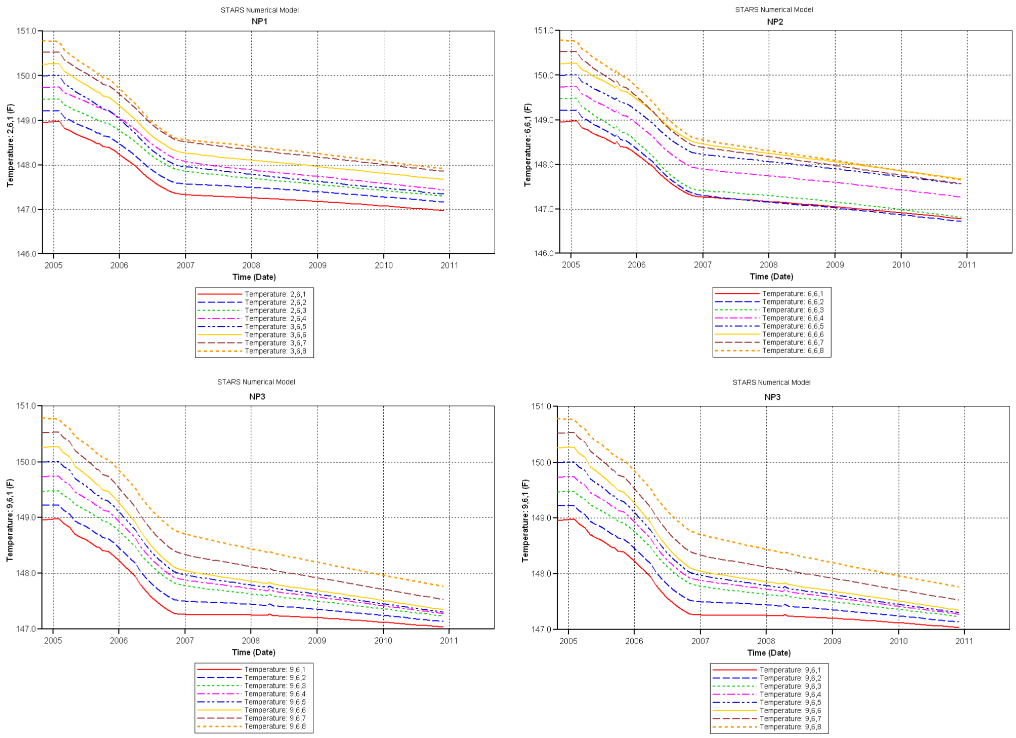

Figure 4.6 Temperature responses of North flank wells (base case with injections)

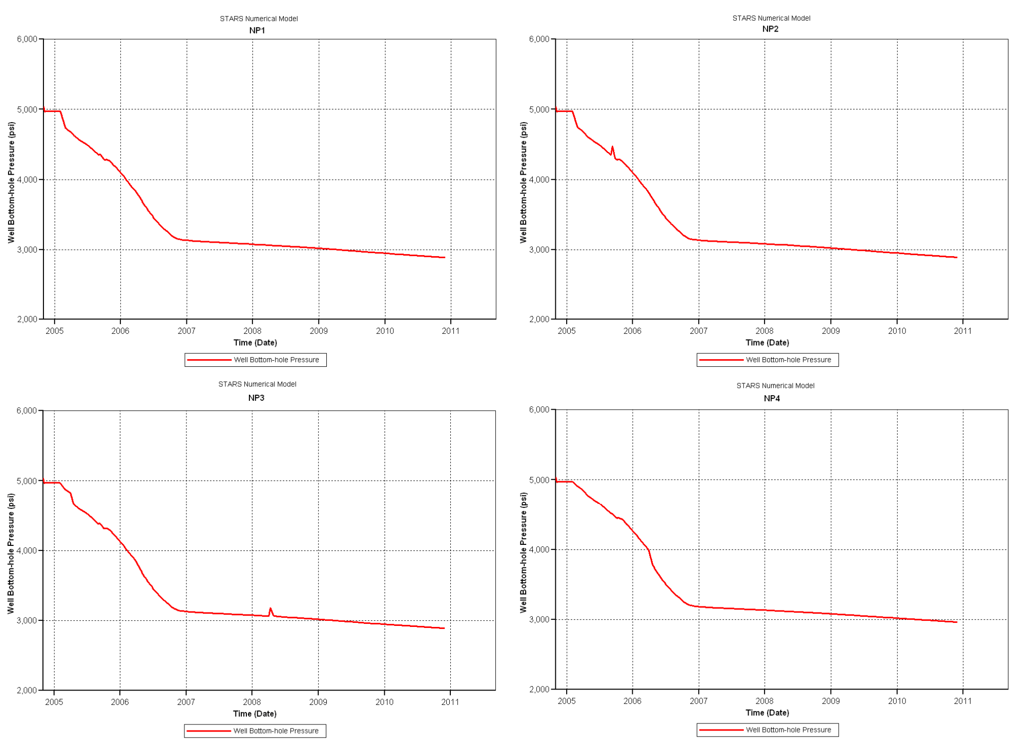

Figure 4.7 Bottom-hole pressure of North flank wells (base case with injections)

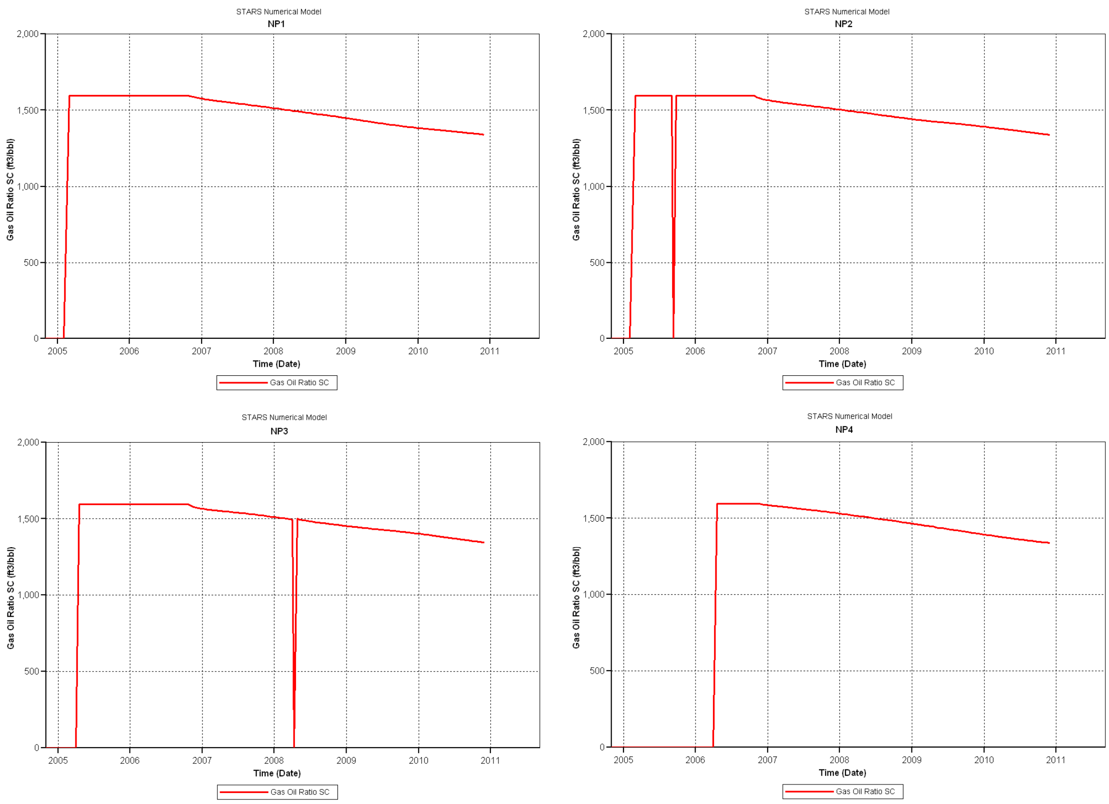

Figure 4.8 Gas-oil ratio of North flank wells (base case with injections)

4.2.2 SOUTH FLANK WELLS ANALYSIS

Unlike North flank wells South flank wells are located near oil-gas contact. SP1, SP2, SP3 and SP4 were closed after about two years production and sidetrack wells (SP1-STR, SP2-STR, SP3-STR and SP4-STR) were opened and these new wells skewed drainage area towards up-dip. Firstly base case without injections was analyzed. In the case of no injection the shape of BHT (figure 4.9a and 4.9b) and BHP (figure 4.10a and 4.10b) curves for the South wells are almost the same similar to North flank wells. Sharp decreasing trend of temperature and pressure changed after bubble-point (September-October, 2006) and slope decreased. When sidetracks were opened main wells showed an increase in pressure and temperature, while the reverse occurred in sidetrack wells. However, after few days previous trends were again rebuilt. Upon analyzing GOR graphs (figure 4.11a) it can be seen that gas-oil ratio increased at SP2 and SP3 wells due to free gas in July, 2006 and May, 2006, respectively. But this change wasn't reflected at pressure or temperature trend. From the beginning of mid 2008 gas-oil ratio of all sidetrack wells showed increasing trend and an effect of this increase can be seen on pressure and temperature graphs such as a small increase in the slopes of pressure and temperature trends was observed. At the end of 2010 a sudden increase in pressure/temperature in some wells, especially in SP3, SP2-STR and SP3-STR occurred. When looking the model, it can be seen that these wells are located at the upper part of the South flank. GOR graph explains this sudden change; the SP2-STR and SP3-STR were closed due to high gas-oil production that also affected SP3.

a)

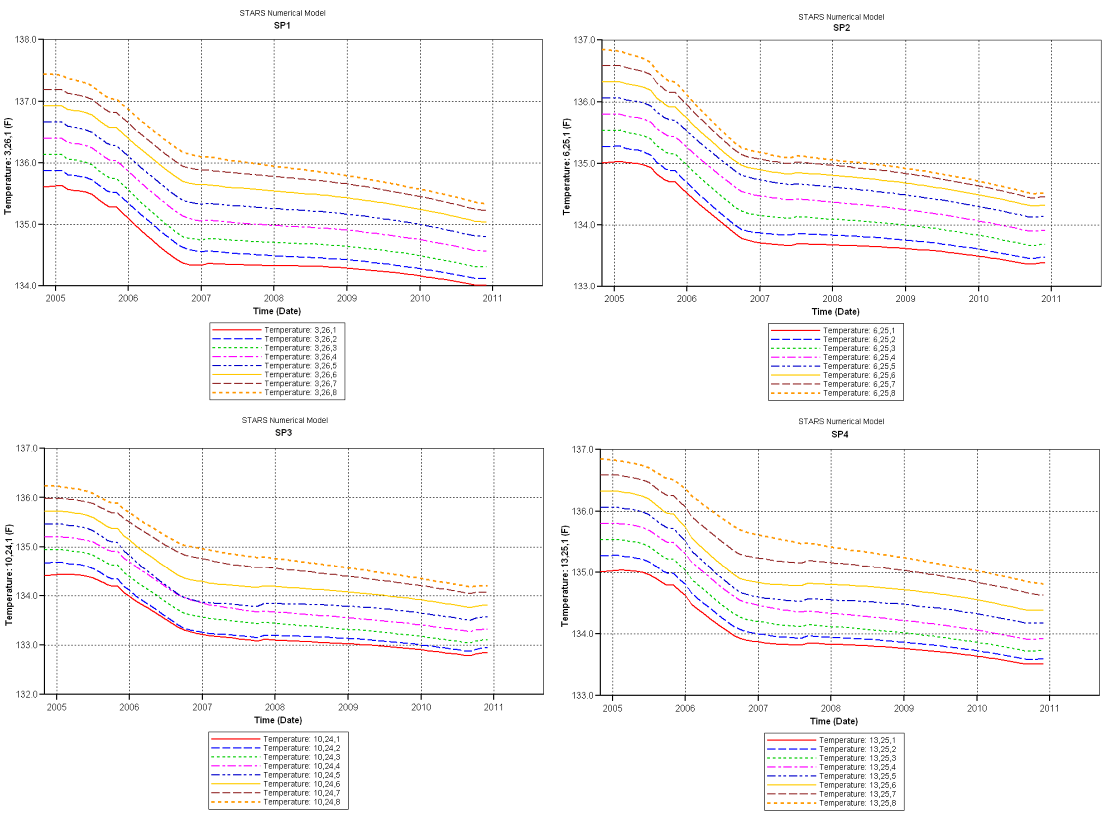

Figure 4.9 a) Temperature responses of SP1, SP2, SP3 and SP4; b) Temperature responses of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections)

b)

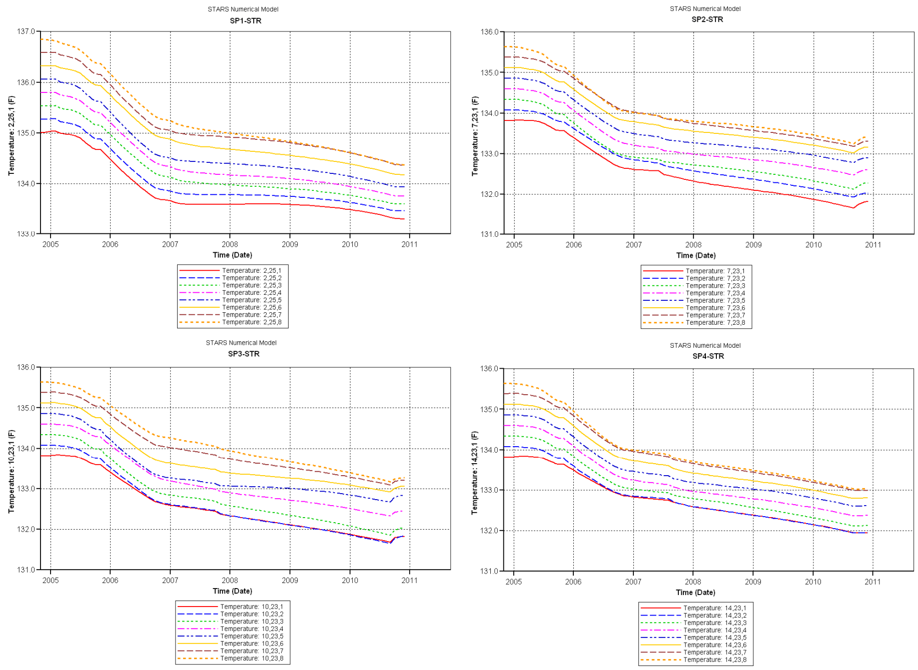

Figure 4.9 a) Temperature responses of SP1, SP2, SP3 and SP4; b) Temperature responses of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections) (continued)

a)

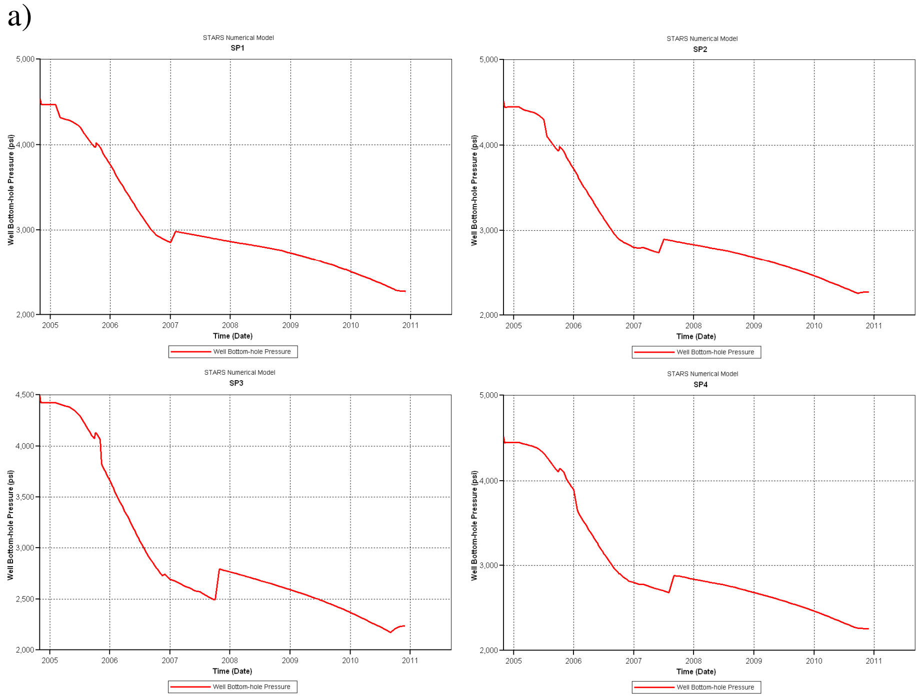

Figure 4.10 a) Bottom-hole pressure of SP1, SP2, SP3 and SP4; b) Bottom-hole pressure of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections)

b)

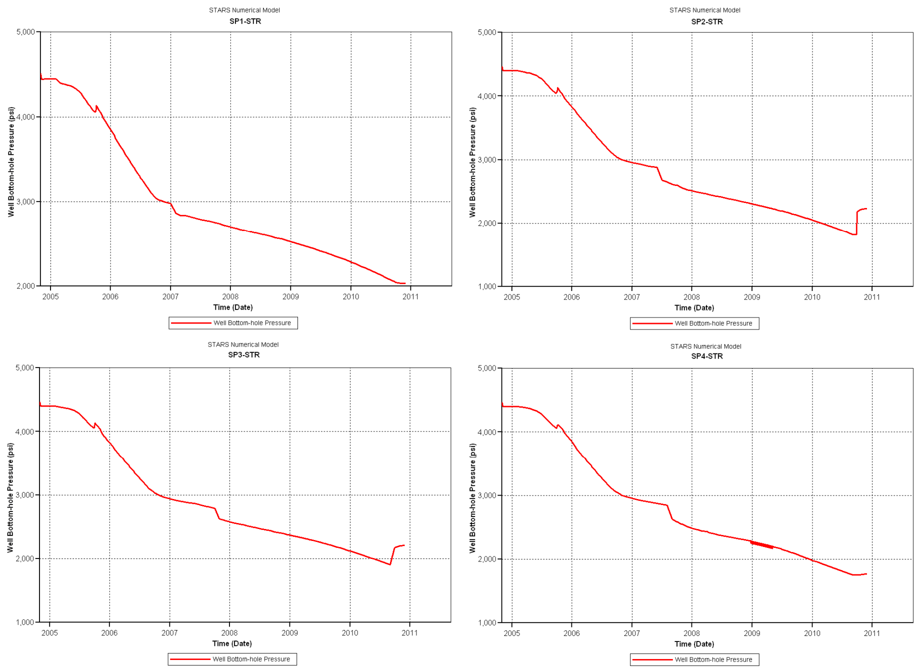

Figure 4.10 a) Bottom-hole pressure of SP1, SP2, SP3 and SP4; b) Bottom-hole pressure of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections) (continued)

a)

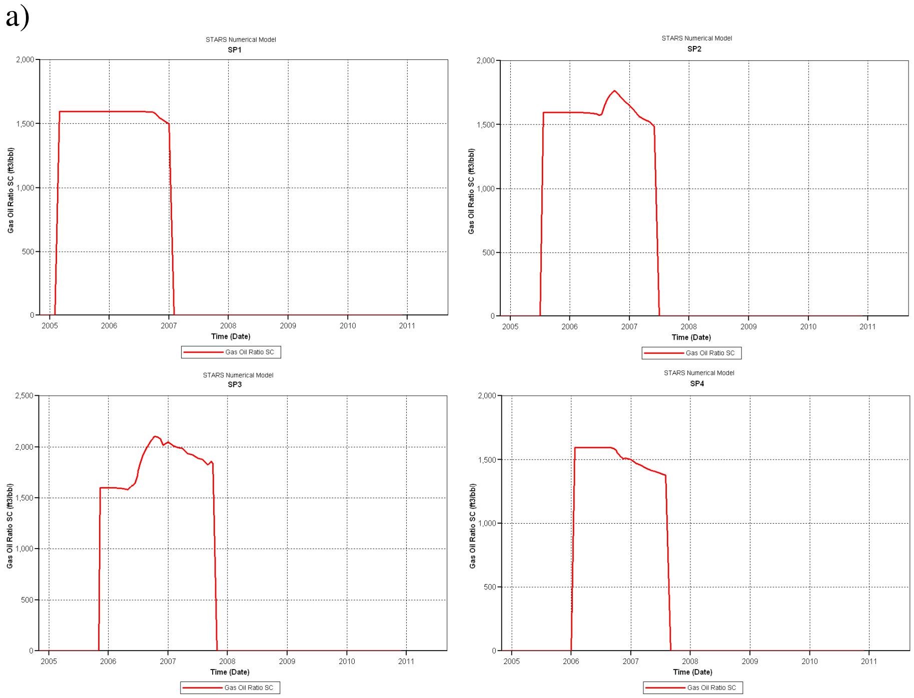

Figure 4.11 a) Gas-oil ratio of SP1, SP2, SP3 and SP4; b) Gas-oil ratio of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections)

b)

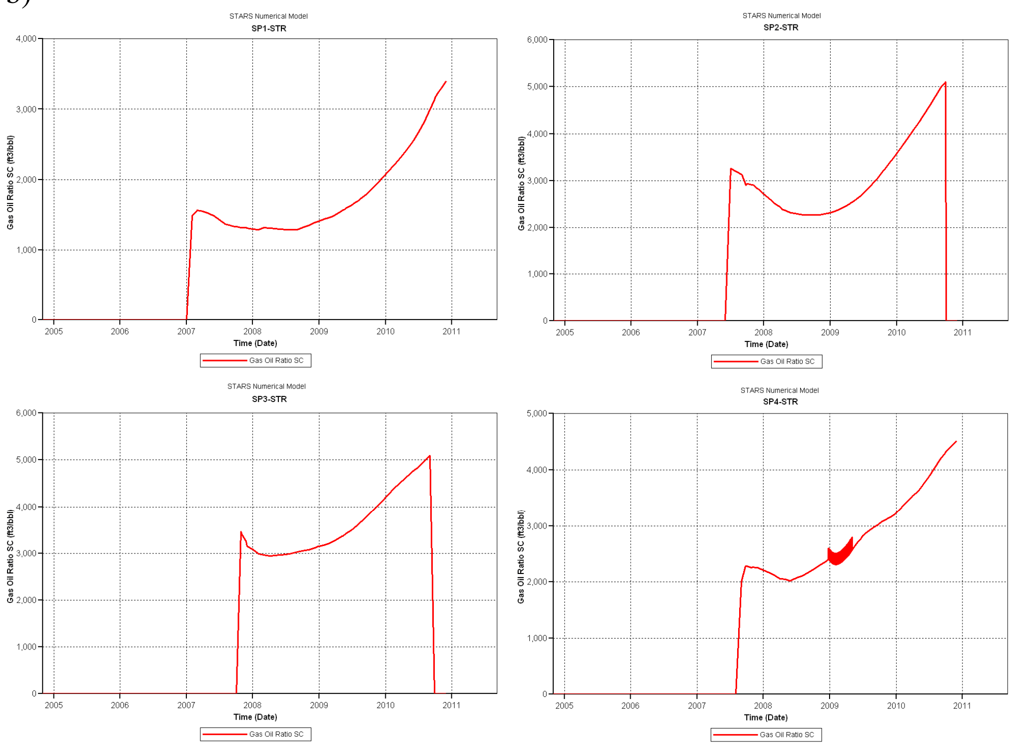

Figure 4.11 a) Gas-oil ratio of SP1, SP2, SP3 and SP4; b) Gas-oil ratio of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case without injections) (continued)

When running base case with injection wells, temperature behaved differently and even sharp decreasing trend changed into slightly increasing trend (figure 4.12a and 4.12b). After beginning of injection, wells changed their drainage area towards South (producing warmer fluids) because of high pressure support by water injection wells and 0.1-0.6ºF increase in temperature was observed in South flank wells. Gas injection mainly affects North part of sector model.

Gas-oil ratio of SP1, SP2, SP3 and SP4 were not affected by injection largely because these main wells were shut in approximately about the time of beginning of injection and sidetracks started production. However the GOR became constant in SP1-STR and SP4-STR and started to decrease in SP2-STR and SP3-STR due to injection pressure support while it was increasing in the “no injection” case (figure 4.14b).

When sidetracks were opened, the increase in temperature and pressure in main wells and decrease in sidetracks were observed (figure 4.12a, 4.12b, 4.13a and 4.13b). The previous trends were again rebuilt a few days later. Pressure decreased 150-300 psi in sidetrack wells after the start of injection to the end of simulation. However this value was approximately 1000 psi for "no injection" case in the same time range. Since injection provided extra energy and production was stopped in SP1, SP2, SP3 and SP4, pressure in these wells became above bubble-point and stayed approximately at constant value (figure 4.13a). Deliberately closed water injection well (WI2) for a month in August, 2008 made BHT and BHP to decrease and GOR to increase. This relation between BHT, BHP and GOR was seen throughout the simulation and may be used for a better reservoir management.

a)

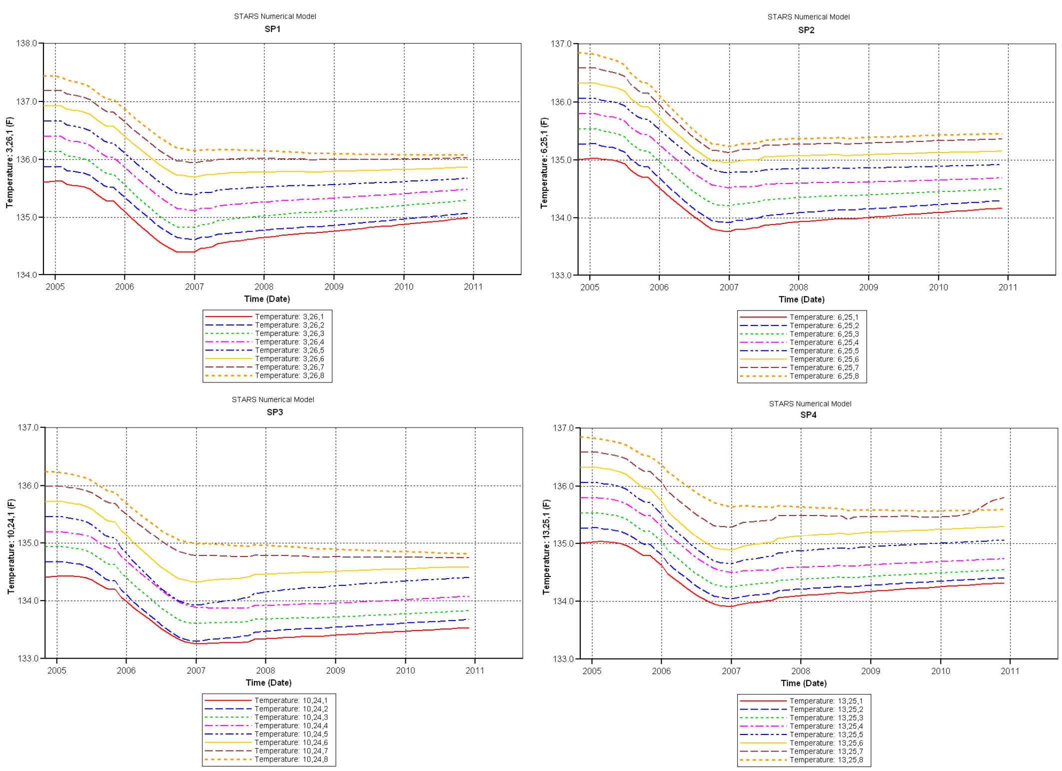

Figure 4.12 a) Temperature responses of SP1, SP2, SP3 and SP4; b) Temperature responses of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections)

b)

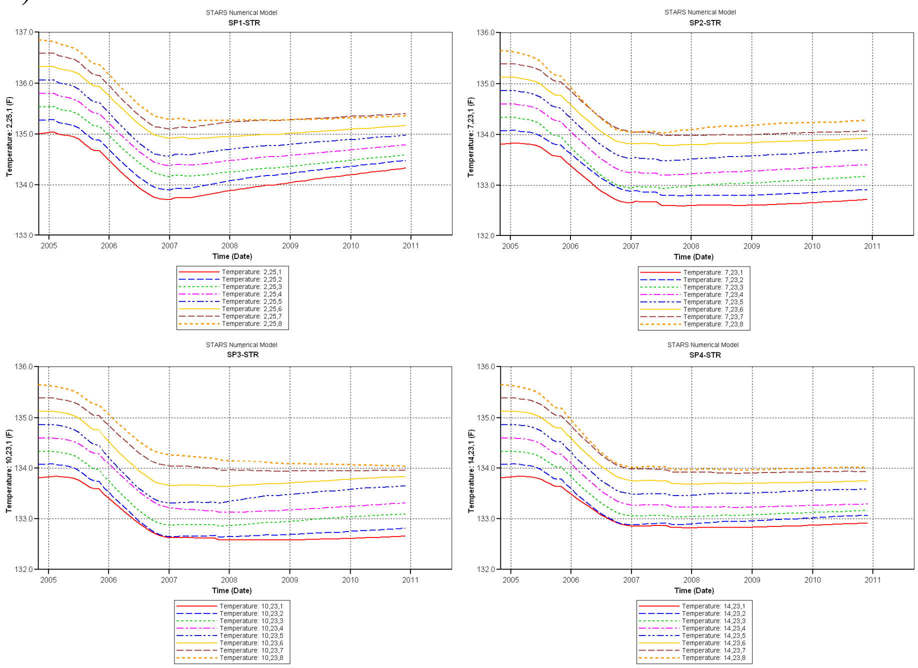

Figure 4.12 a) Temperature responses of SP1, SP2, SP3 and SP4; b) Temperature responses of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections) (continued)

a)

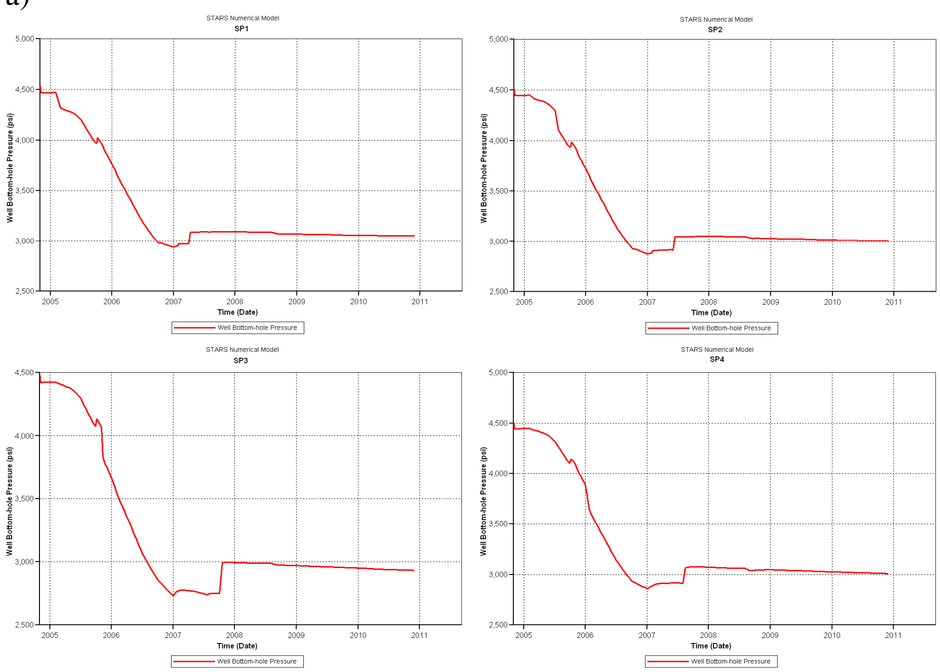

Figure 4.13 a) Bottom-hole pressure of SP1, SP2, SP3 and SP4; b) Bottom-hole pressure of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections)

b)

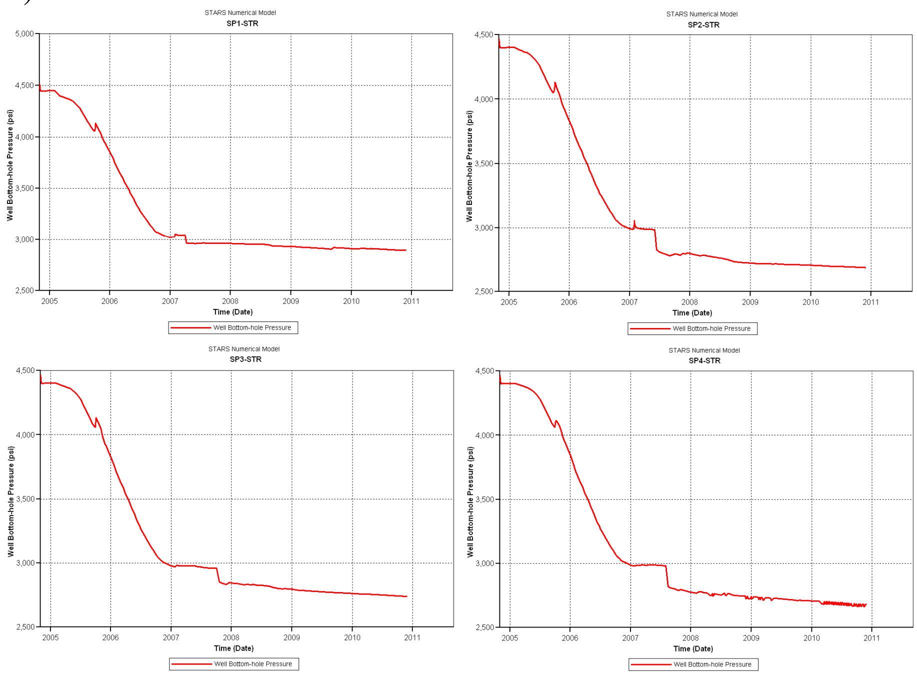

Figure 4.13 a) Bottom-hole pressure of SP1, SP2, SP3 and SP4; b) Bottom-hole pressure of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections) (continued)

a)

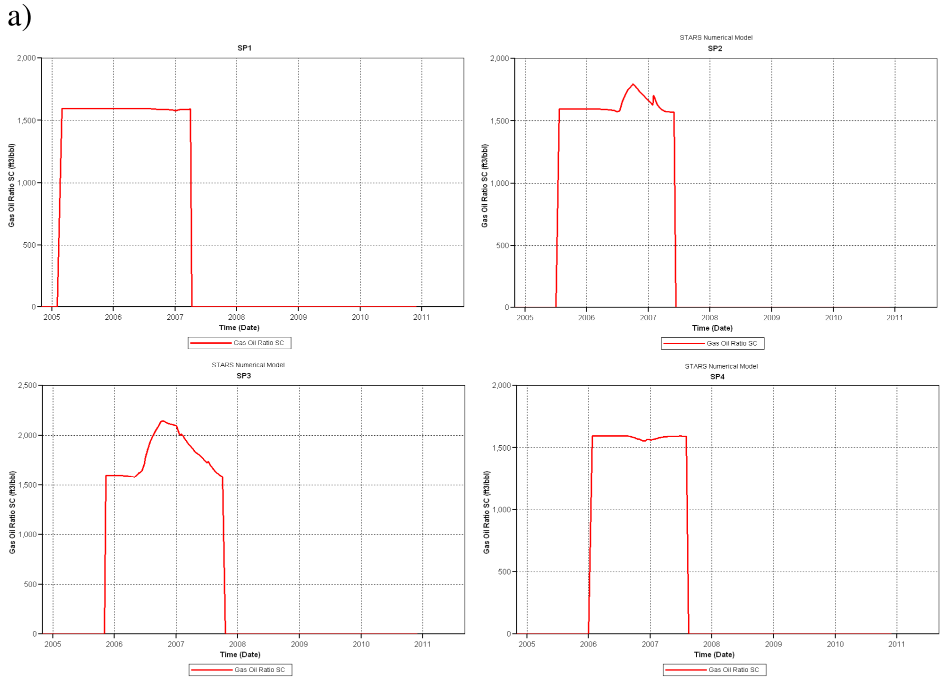

Figure 4.14 a) Gas-oil ratio of SP1, SP2, SP3 and SP4; b) Gas-oil ratio of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections)

b)

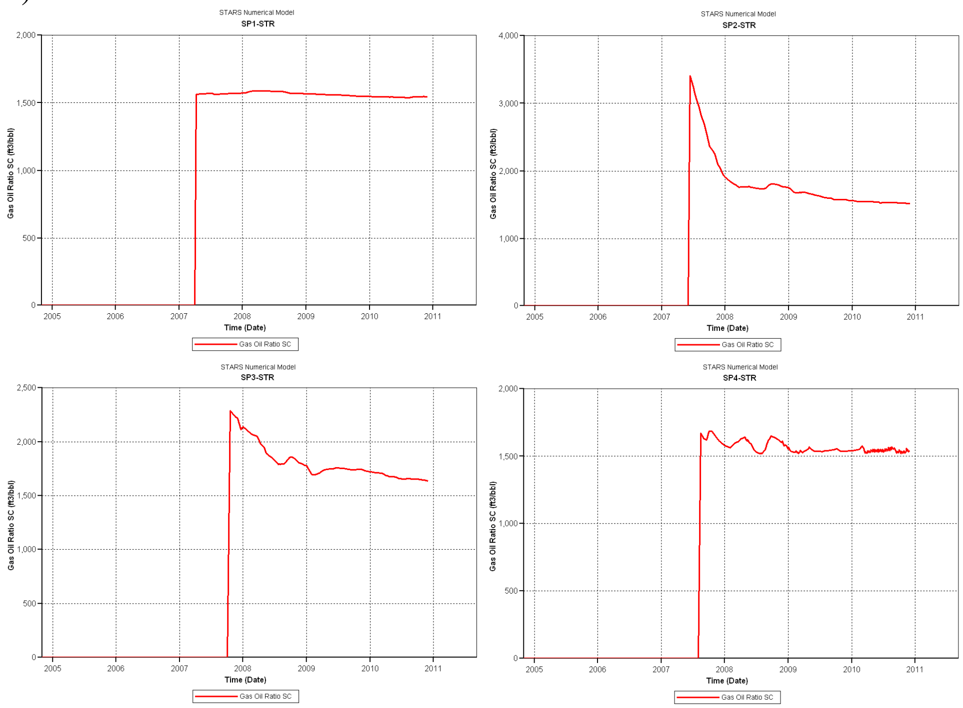

Figure 4.14 a) Gas-oil ratio of SP1, SP2, SP3 and SP4; b) Gas-oil ratio of SP1-STR, SP2-STR, SP3-STR and SP4-STR (base case with injections) (continued)

Figures 4.15 and 4.16 below show 3-D temperature distributions and figures 4.17 and 4.18 gas, oil and water saturations at the end of simulation for case 1 and case 2, respectively.

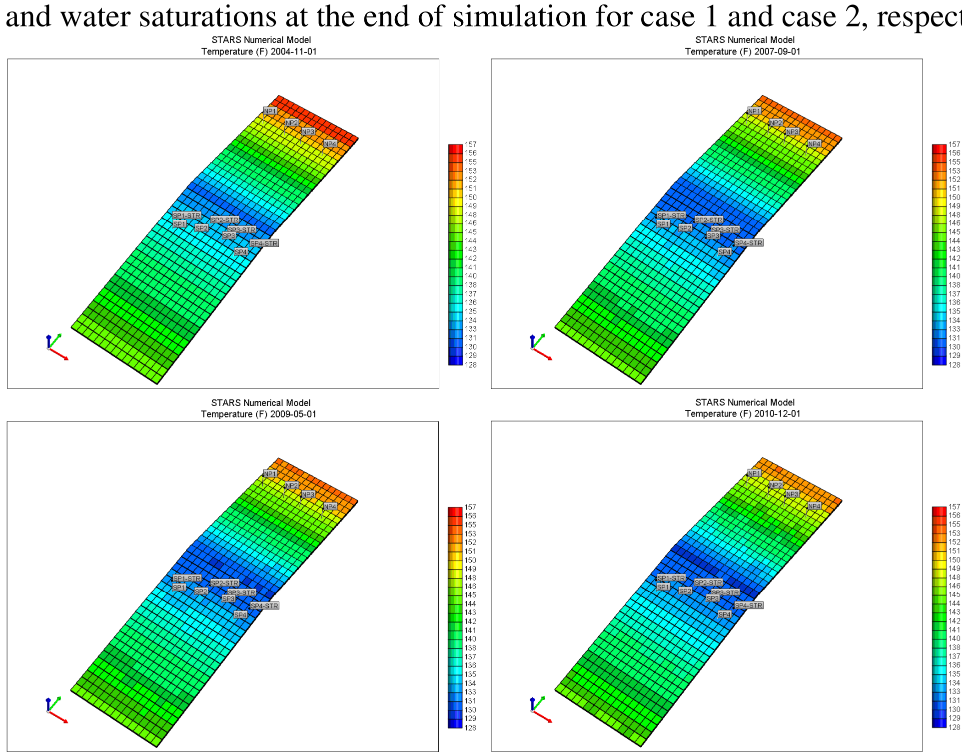

Figure 4.15 3-D temperature distributions in the base case with no injection

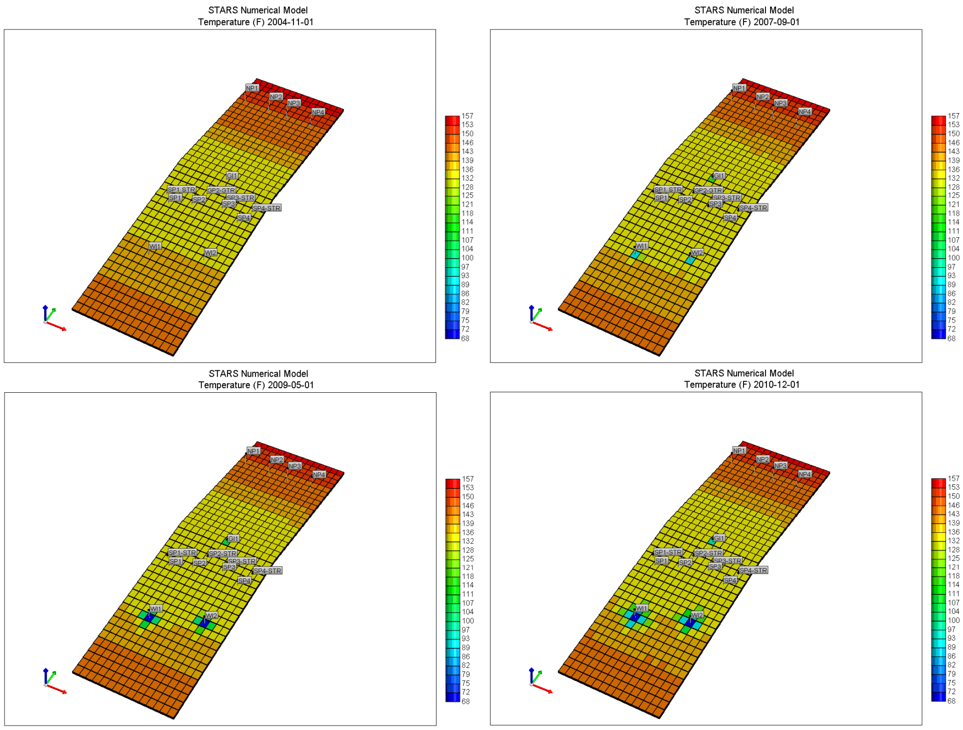

Figure 4.16 3-D temperature distributions in the base case with injection

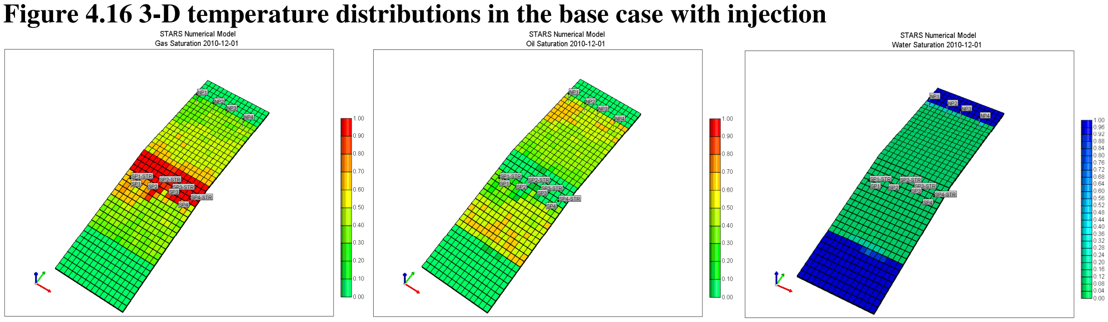

Figure 4.17 Gas, oil and water saturation at the end of simulation (base case without injection)

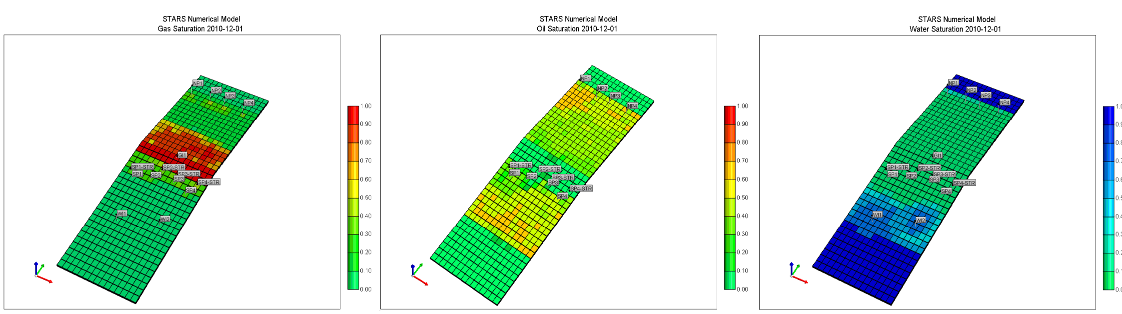

Figure 4.18 Gas, oil and water saturation at the end of simulation (base case with injection)

In this section we saw that the shape of temperature trend is almost the same with pressure graph in the "no injection" case. In base case with injection these trends were not demonstrated exactly the same shape; however the direction and date of change were coincided in both BHT and BHP. In most cases temperature increased when GOR dropped. On the whole, the base cases obviously showed the interaction of BHT with BHP and also GOR which is the result of pressure change. The relation above may be used as additional information for a particular well or even it gives opportunity to determine interwell communication.

4.3 COMPARING SIMULATION RESULTS WITH A REAL CASE (AZERI FIELD)

In this section simulation results will be compared with the behavior of West South Azeri wells. There are 5 production and 3 injection (2 water injector and 1 gas injector) wells in the West South Azeri [2]. P3, P10, P11, P15 and P8 are producers, P12 and P16 are water injectors and P31 is the gas injection well. Wells are produced from single layer except P11 (it produces from Pereriv B and D). Figure 4.19 shows the location of West South Azeri wells.

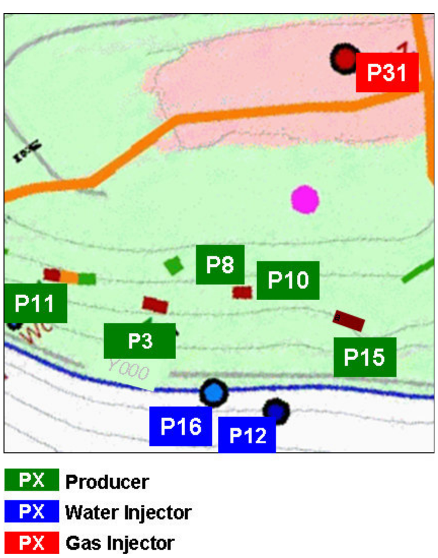

Figure 4.19 Wells in West South Azeri [24]

The temperature response of P3 and P10 to injection wells will be discussed in this section. After water injection (P12) started, the increase in BHT and BHP was observed, while GOR decreased from 1000-1200 scf/STB to the 800 scf/STB [2]. Stopping of injection at the end of October, 2008 influenced P3 well reversely and BHT and BHP dropped and GOR showed increasing trend. In May, 2008 BHT started to increase in P3 that maybe caused by pressure support from P31 gas injection well.

Water injection had also impact on P10 well. The effect of drop in GOR and as well as increase in pressure in this well was felt after a time lag of one month, maybe because of offset location of P10 to P12. However, BHT responded to P12 approximately just from the beginning of injection due to warmer fluid production from down-dip which caused by water push. P10 gave the same reaction to the ceasing of water injection in October, 2008 as it was in P3. When P12 started again to injection, decrease in GOR and increase in BHT was observed. No clear impact of P31 gas injection well on both P3 and P10 was seen during the analyzed time.

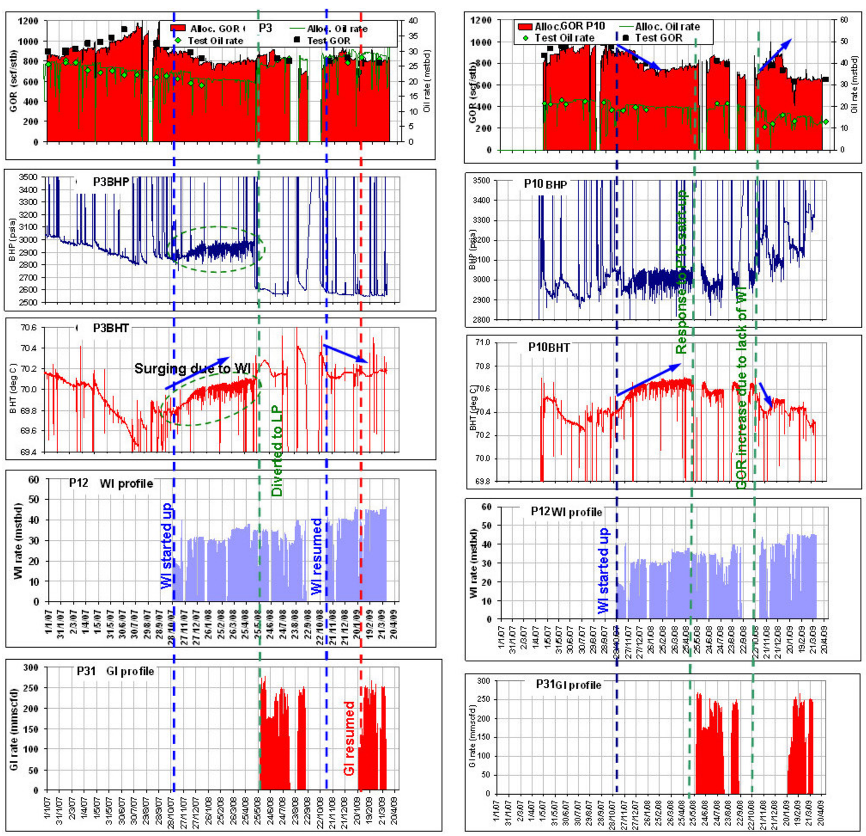

Figure 4.20 Analyzing P3 (left) and P10 (right) wells behavior [24]

When comparing the responses of two West South Azeri wells with simulation results, exactly same behavior can be observed. In both cases BHT increased as a result of pressure support by injection and GOR decreased. The reverse impact was seen when injection was ceased. This is a very valuable result that can be used to check the quality of data and even to determine gas-oil ratio in high GOR wells where test separators are limited with the certain amount of gas and well rates should be decreased during the test. The latter causes some money and time losses to company. Using of BHT, BHP and GOR relationship as additional information is very logical since all modern wells are equipped with continuous temperature gauges now. All of these may decrease the frequency of production tests and save time and money as a result.

4.4 GENERAL VIEW OF SIMULATED CASES

Different cases were analyzed to estimate the influence of some parameters, such as oil rate, initial solution GOR, wettability, amount of drawdown pressure, and water injection rate and location on BHT. Tables A.1 to A.3 in appendix A show average temperatures in the North and South flank for each case from beginning of production to the end of simulation. For simplicity only one layer of each well (layer 2) was taken into account during averaging. The degree of effect of each parameter was plotted on figures 4.21 to 4.48.

Information from these figures indicates great influence of varied oil rates on temperature. In base cases wells were produced with a constant rate of 23 MSTB/day. To evaluate the impact of rate changes on BHT cases with higher (30 MSTB/day) and lower (15 MSTB/day) rates were run and compared with the base case. These runs indicated that the lowest oil rate causes the smallest temperature change.

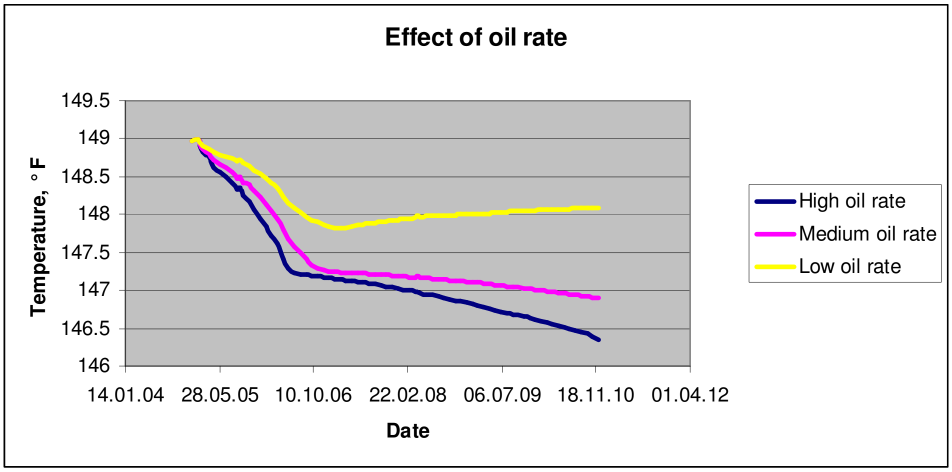

Figure 4.21 Effect of oil rate on temperature in North flank

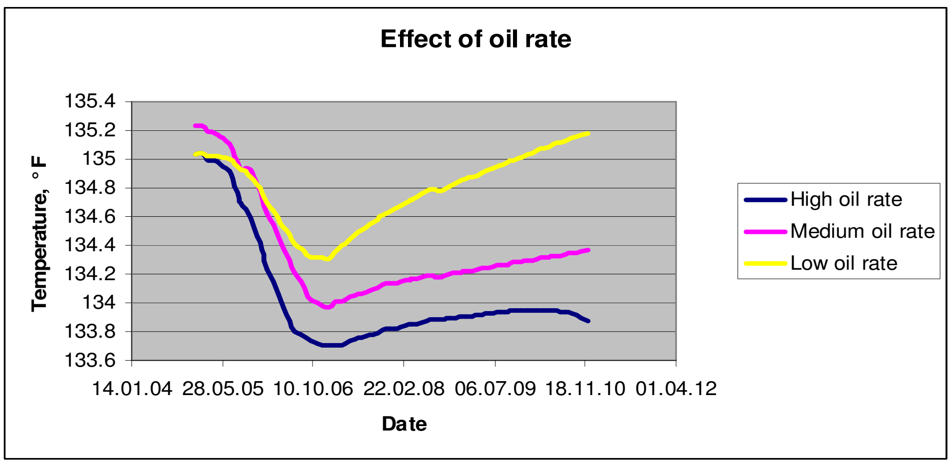

Figure 4.22 Effect of oil rate on temperature in SP1, SP2, SP3 and SP4

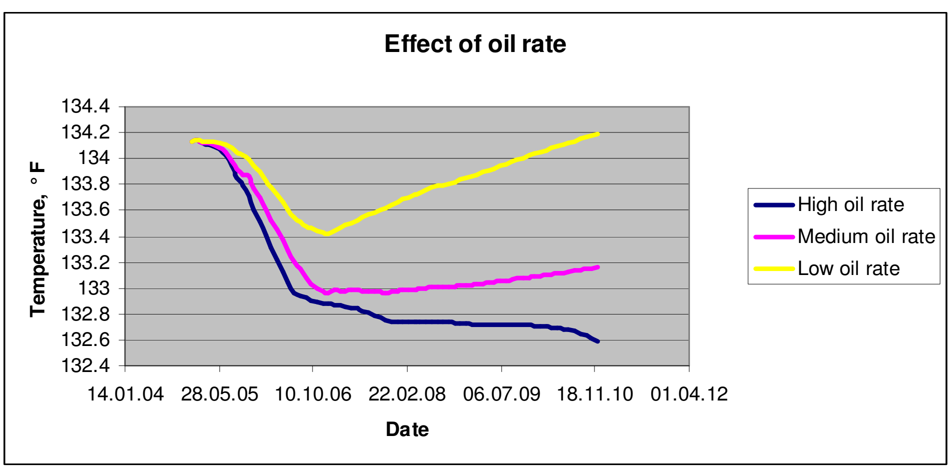

Figure 4.23 Effect of oil rate on temperature in sidetracks

The large effect of initial solution GOR was also seen in both flanks. It was deliberately changed from 1596 scf/STB to 2254 scf/STB and 1037 scf/STB in case 5 and 6, respectively. As a result changes became larger as the initial solution GOR decreases (so the API gravity decreases).

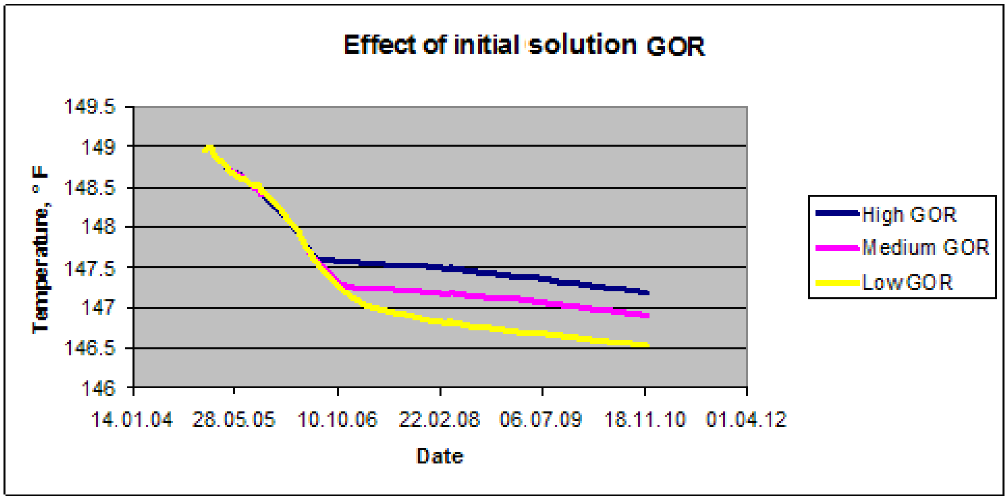

Figure 4.24 Effect of initial solution GOR on temperature in North flank

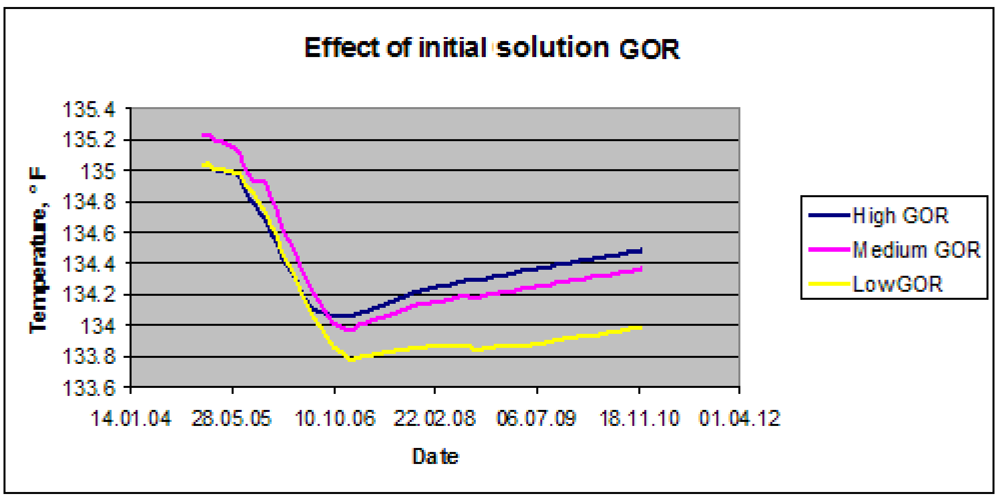

Figure 4.25 Effect of initial solution GOR on temperature in SP1, SP2, SP3 and SP4

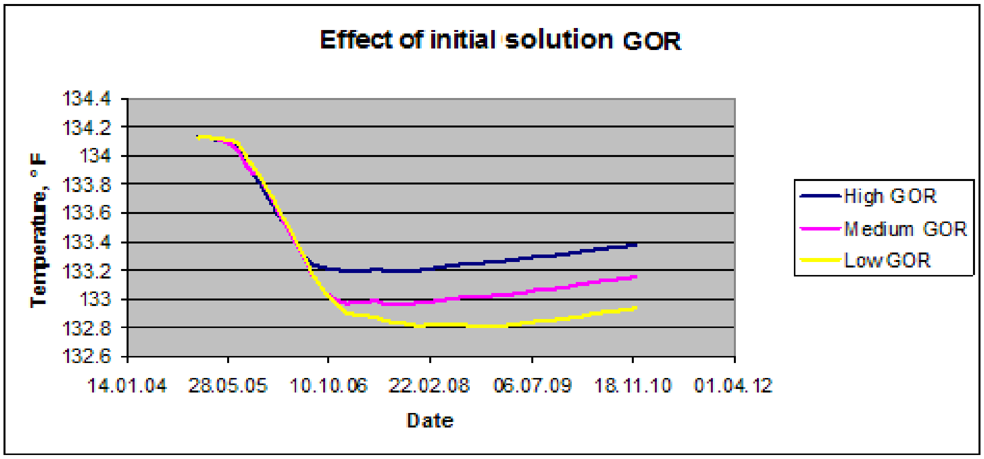

Figure 4.26 Effect of initial solution GOR on temperature in sidetracks

To determine the effect of wettability, relative permeabilities of sector model were changed and run as intermediate and oil wet reservoir which was water wet in the base cases. However these changes didn't influence temperature so much, only a slight decrease was observed in the "oil wet" case in North flank and in the "water wet" case in sidetrack wells. There were no significant effects of wettability on main wells in the South flank.

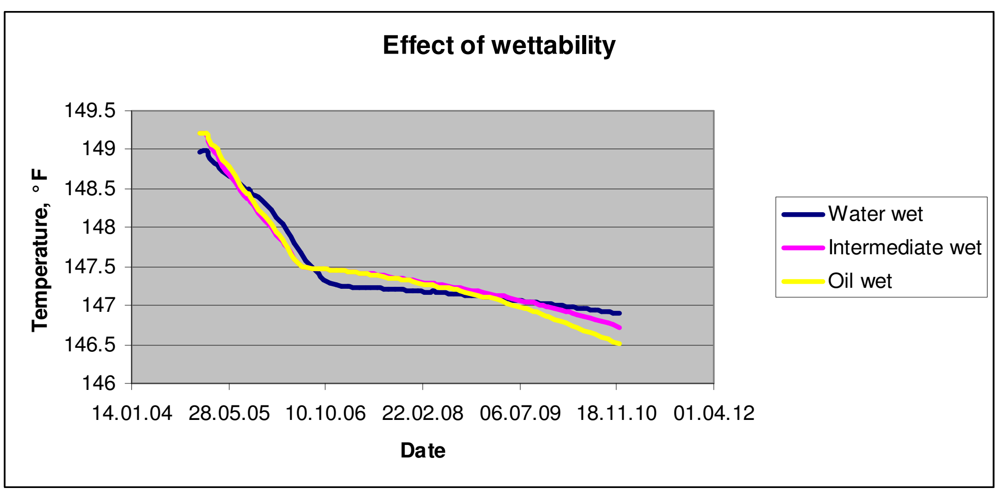

Figure 4.27 Effect of wettability on temperature in North flank

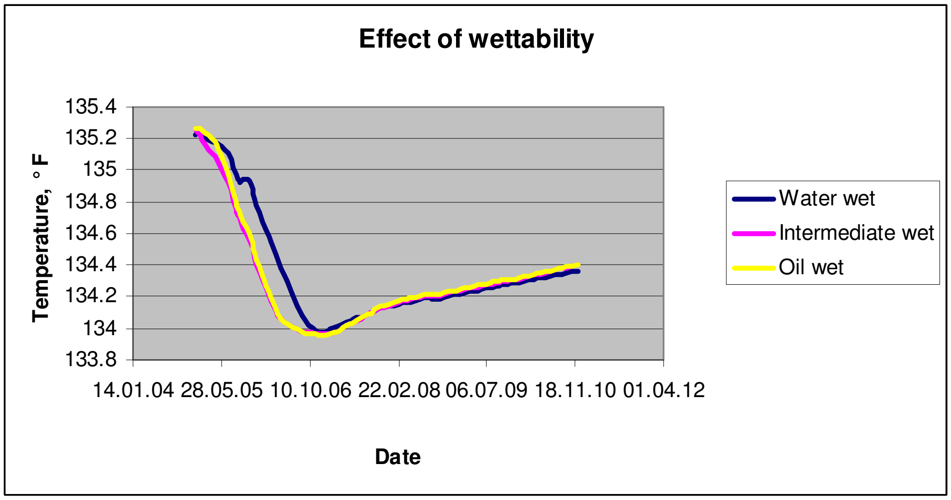

Figure 4.28 Effect of wettability on temperature in SP1, SP2, SP3 and SP4

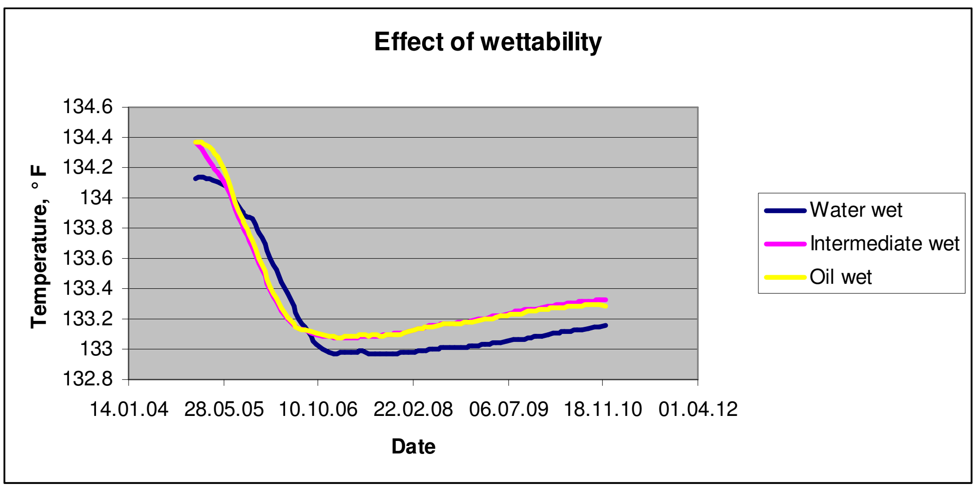

Figure 4.29 Effect of wettability on temperature in sidetracks

In cases 10 through 13, the field was produced with a drawdown pressure of 100 psi, 150 psi, 200 psi and 250 psi, respectively. In all wells temperature showed direct relationship with drawdown pressure and highest change was observed when drawdown pressure was 250 psi.

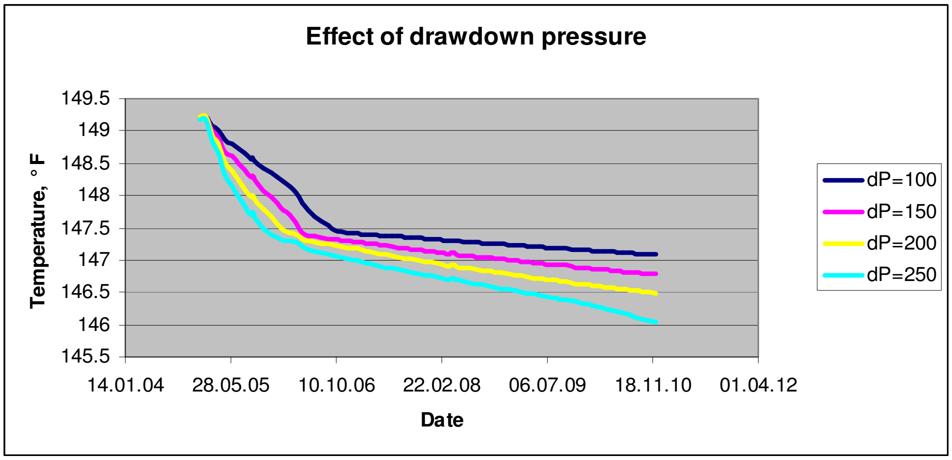

Figure 4.30 Effect of drawdown pressure on temperature in North flank

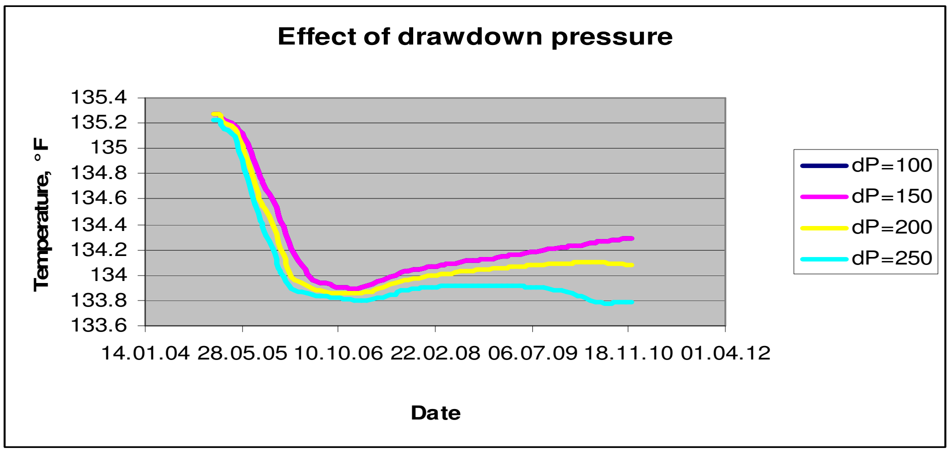

Figure 4.31 Effect of drawdown pressure on temperature in SP1, SP2, SP3 and SP4

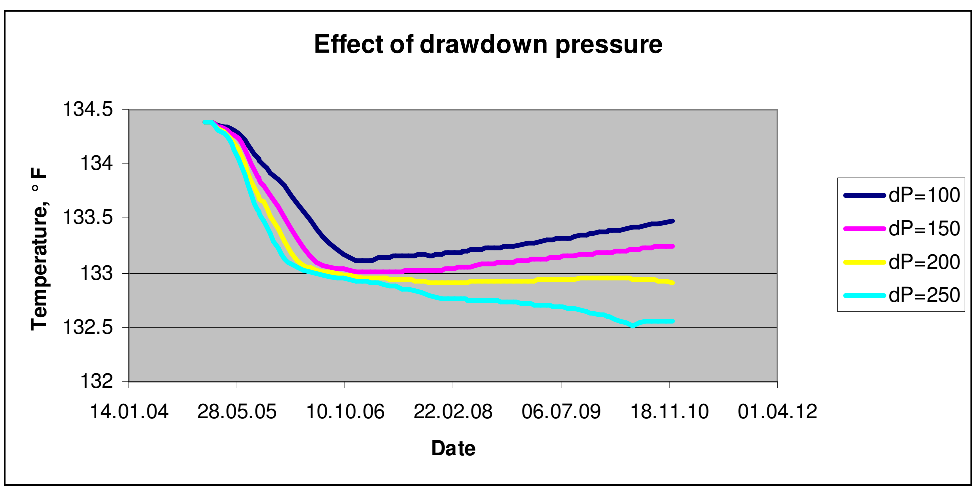

Figure 4.32 Effect of drawdown pressure on temperature in sidetracks

In base cases the impact of injection on temperature was revealed. But how the rate of injection impact of injected water? In order to answer this question, maximum limit of water injection of 65 MSTB/day was reduced to 32.5 MSTB/day. The changing rate of water mainly affected South flank because of location of injection wells. High water injection rate maintained pressure and subsequently BHT more effectively. It also skewed drainage area towards more South.

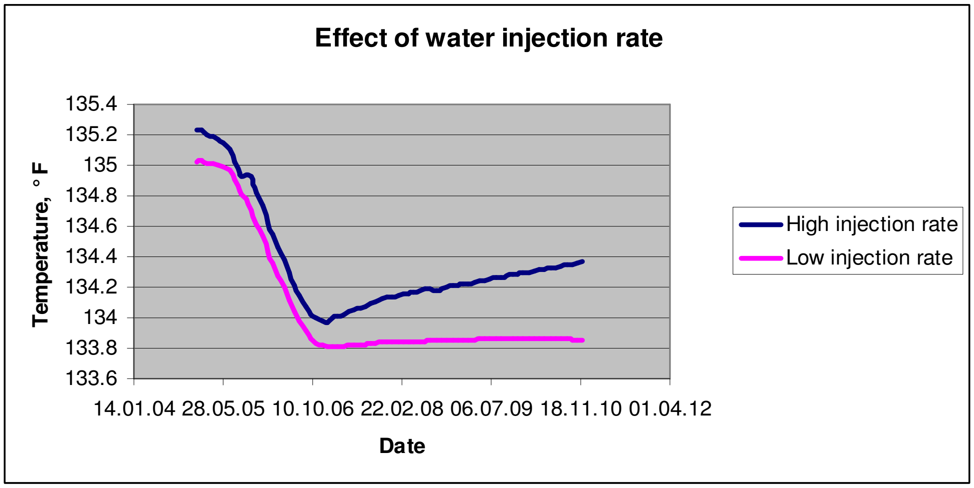

Figure 4.33 Effect of water injection rate on temperature in SP1, SP2, SP3 and SP4

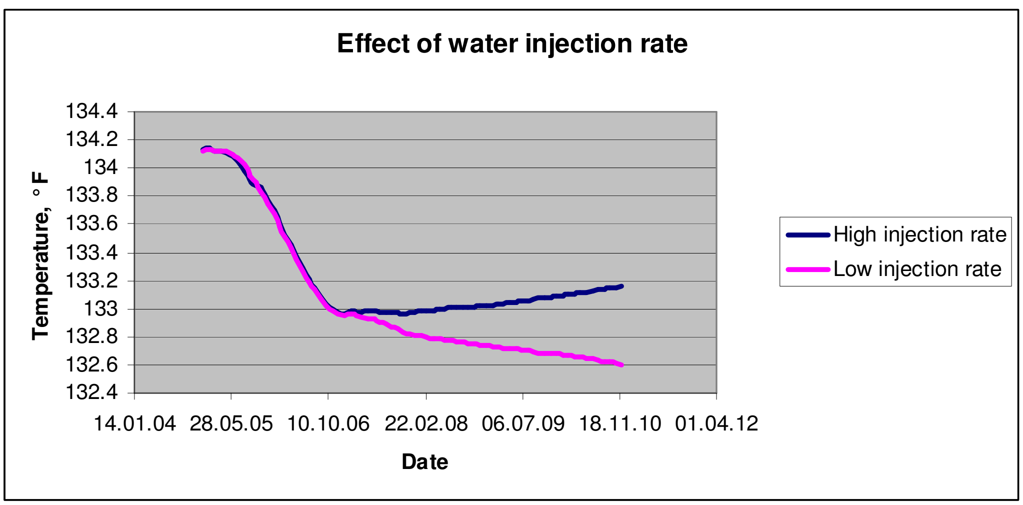

Figure 4.34 Effect of water injection rate on temperature in sidetracks

When injected water temperature was raised from 68°F to 86°F, little temperature variations was observed in sidetracks and almost no changes were occurred in main South wells. In case 9 water injection wells were moved up in the J direction deliberately. However, shifting the location of injection wells up didn't impact the temperature so much and behaved exactly in the same way as the heated water injection case.

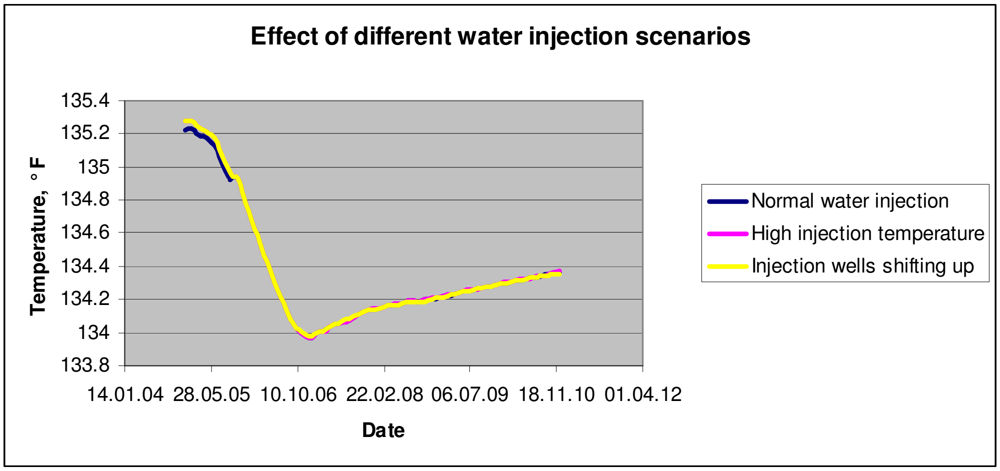

Figure 4.35 Effect of different water injection scenarios on temperature in SP1, SP2, SP3 and SP4

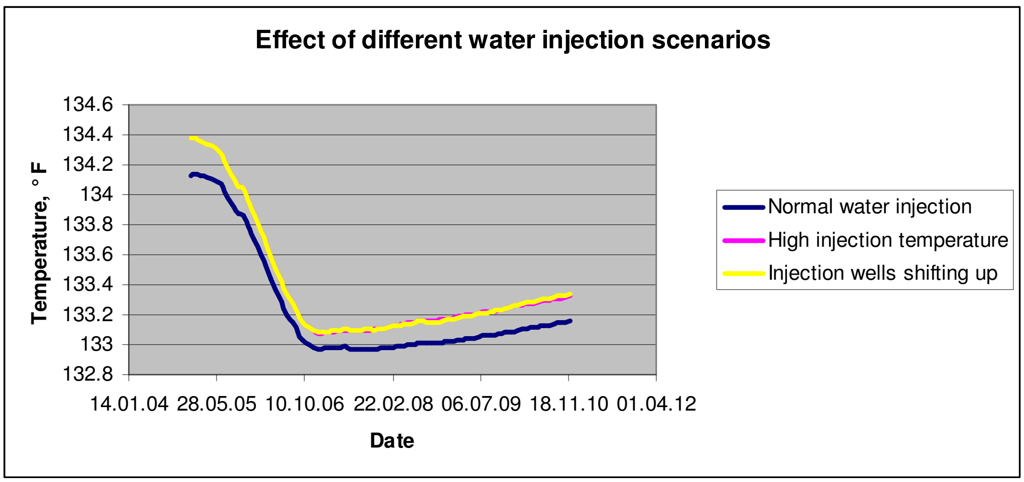

Figure 4.36 Effect of different water injection scenarios on temperature in sidetracks

Combinations of initial solution GOR and maximum drawdown pressure were run in eight cases (from case 14 to case 21). The maximum BHT change occurred in the case of lowest initial GOR and highest drawdown pressure.

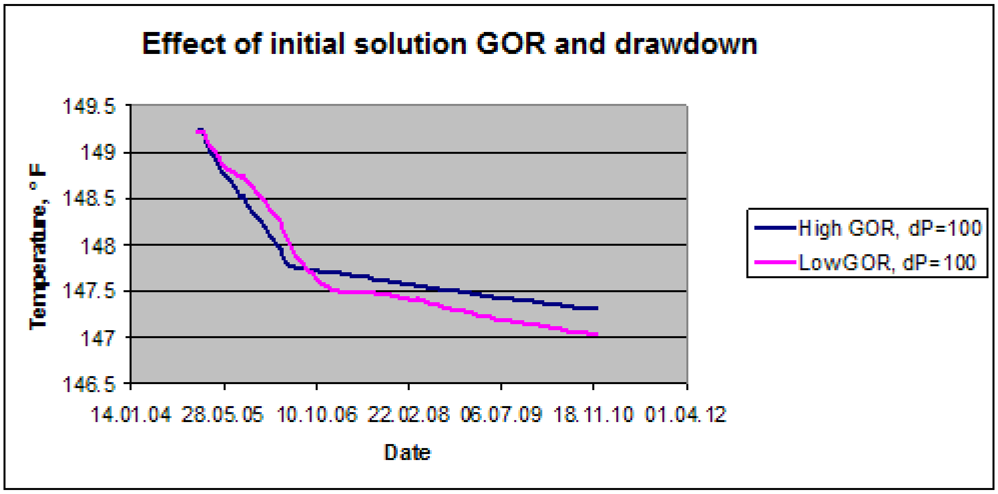

Figure 4.37 Effect of initial solution GOR and drawdown (100 psi) on temperature in North flank

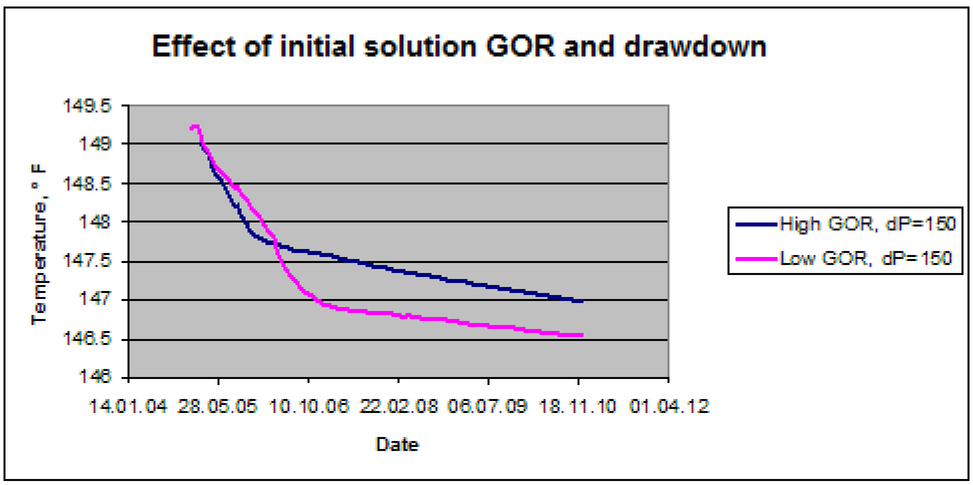

Figure 4.38 Effect of initial solution GOR and drawdown (150 psi) on temperature in North flank

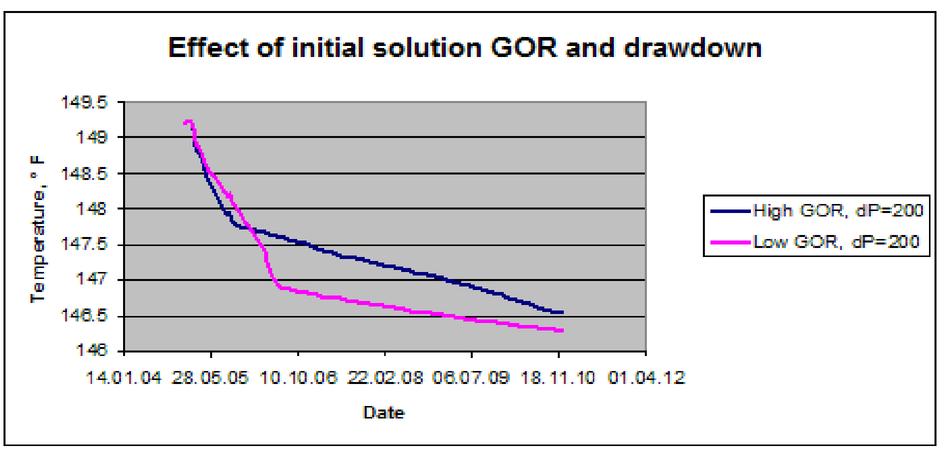

Figure 4.39 Effect of initial solution GOR and drawdown (200 psi) on temperature in North flank

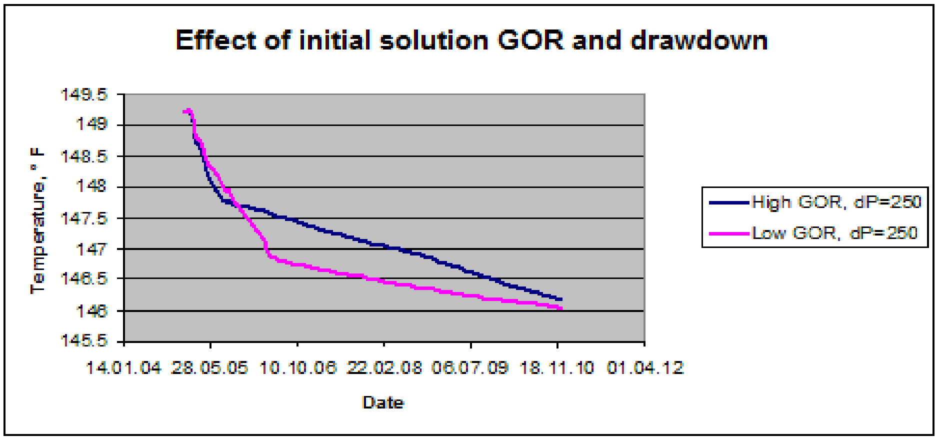

Figure 4.40 Effect of initial solution GOR and drawdown (250 psi) on temperature in North flank

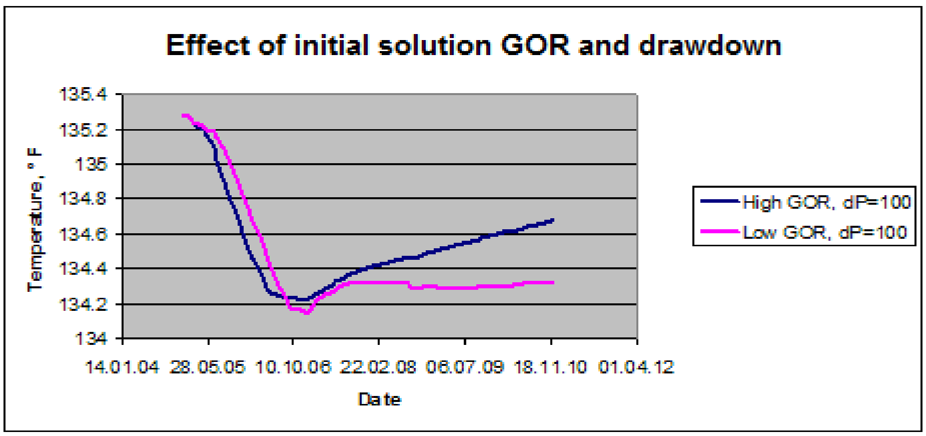

Figure 4.41 Effect of initial solution GOR and drawdown (100 psi) on temperature in SP1, SP2, SP3 and SP4

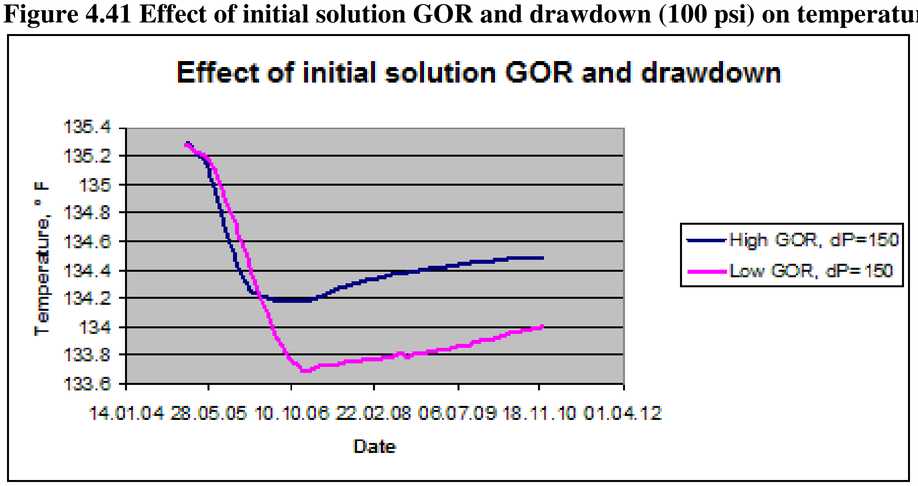

Figure 4.42 Effect of initial solution GOR and drawdown (150 psi) on temperature in SP1, SP2, SP3 and SP4

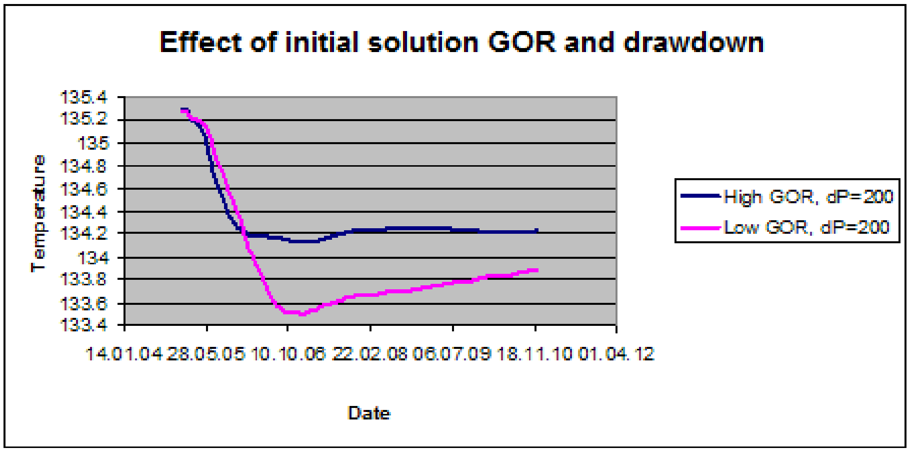

Figure 4.43 Effect of initial solution GOR and drawdown (200 psi) on temperature in SP1, SP2, SP3 and SP4

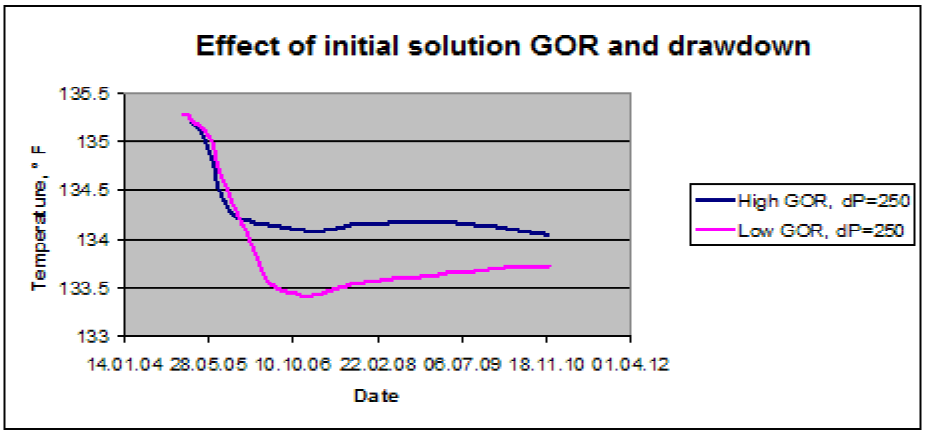

Figure 4.44 Effect of initial solution GOR and drawdown (250 psi) on temperature in SP1, SP2, SP3 and SP4

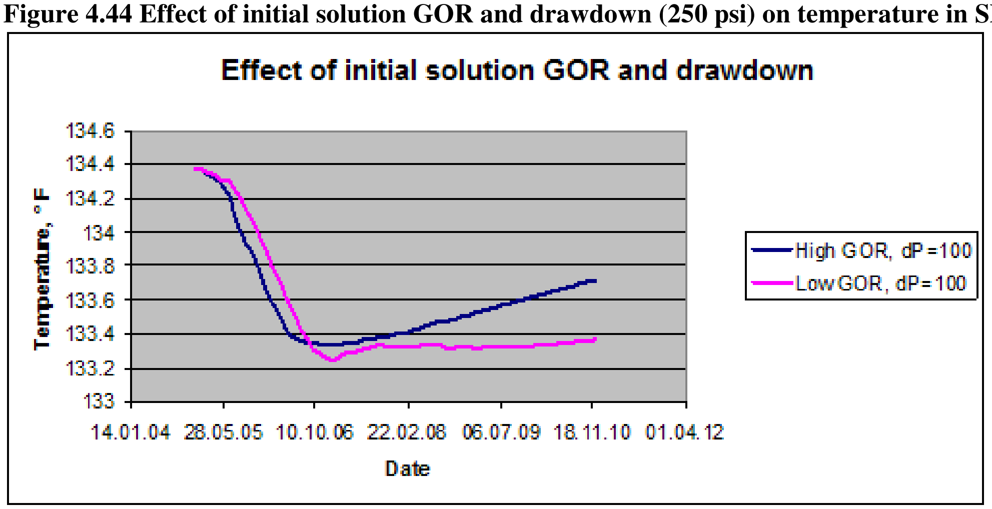

Figure 4.45 Effect of initial solution GOR and drawdown (100 psi) on temperature in sidetracks

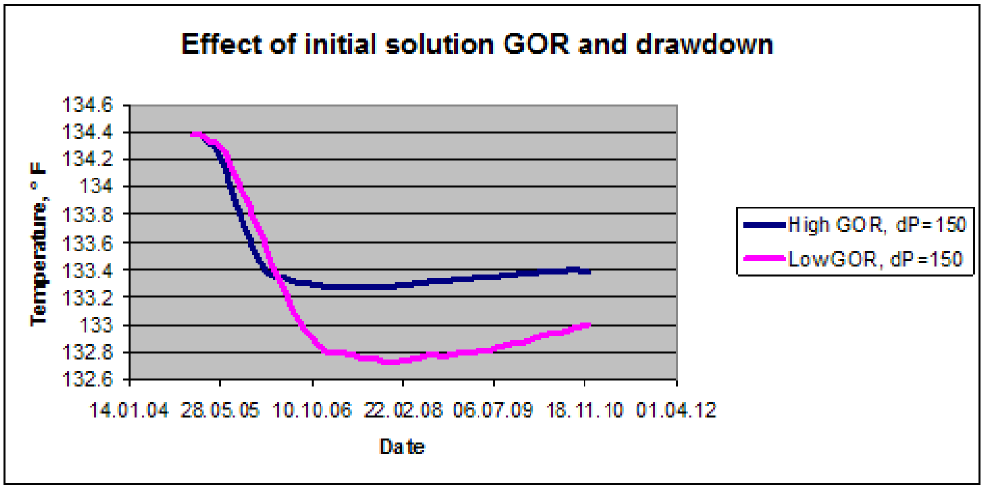

Figure 4.46 Effect of initial solution GOR and drawdown (150 psi) on temperature in sidetracks

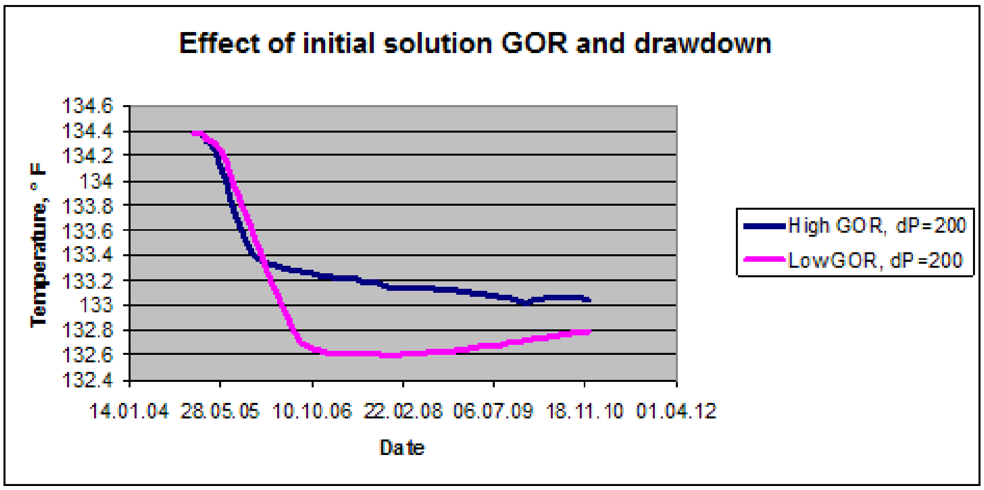

Figure 4.47 Effect of initial solution GOR and drawdown (200 psi) on temperature in sidetracks

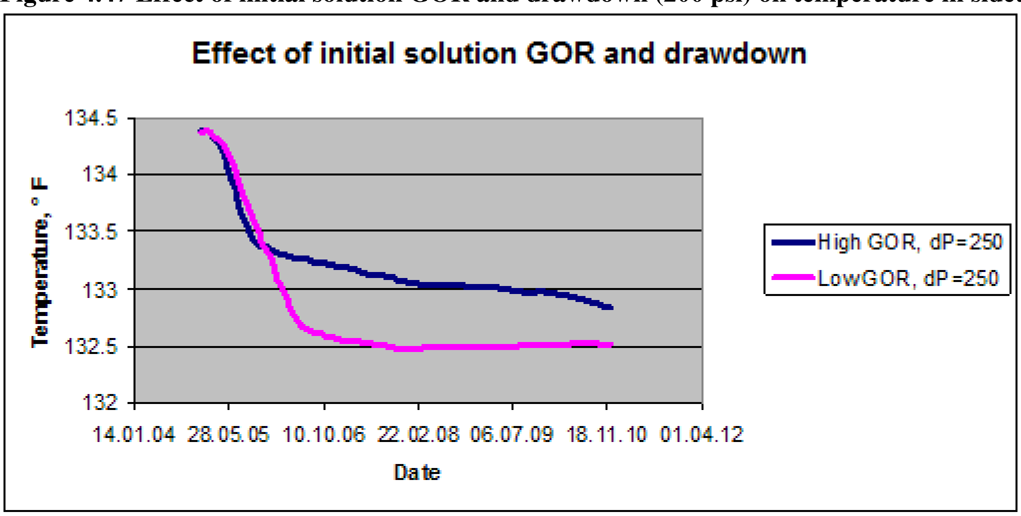

Figure 4.48 Effect of initial solution GOR and drawdown (250 psi) on temperature in sidetracks

4.4.1 MAXIMUM AND MINIMUM TEMPERATURE CHANGES

Analyzing the extent of temperature variations was revealed maximum changes in case 21 (low initial solution GOR and drawdown=250 psi) in the South flank and in case 1 and case 21 in the North flank. The minimum changes were observed in case 4 (low oil rate) in both flanks. In the case of low injection rate (15 MSTB/day) temperature showed smaller decreasing trend compared to higher oil rates (23 MSTB/day and 30 MSTB/day) up to the start of injection. The degree of change was 1.2°F in North wells and 0.7-0.75°F in the South flank. When injection wells were opened temperature began to increase because of high pressure support, especially in South wells (0.8-0.9°F) in case 4. Maximum changes corresponded to 3°F and 1.8-2°F in the North and South flanks, respectively, when the initial solution GOR was low and drawdown pressure was the highest. Additionally, main case without injections also caused large temperature decrease in the South flank. When investigating the extent and reasons of temperature variations, it can easily be seen that pressure is the most influential factor on changes. More decrease in the North flank rather than south was also occurred due to the lack of connection with water injection wells. Maximum and minimum changes observed when drawdown is maximum and minimum (low oil rate), respectively. So a good relationship can be set between pressure and temperature and this can help greatly to better reservoir management.

Another question is that, can we measure these small changes? Threshold value of modern DTS equipments is very low and variations in our cases can easily be measured. Maybe it is difficult to estimate daily changes, but trends can be determined. Comparing these trends with pressure, the quality of BHP and subsequently GOR data can be checked and uncertainties can be reduced significantly.

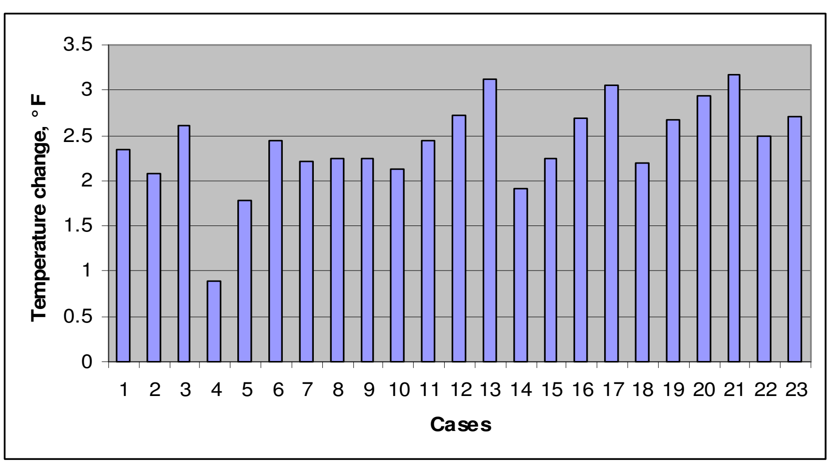

Figure 4.49 The extent of temperature change in the North flank

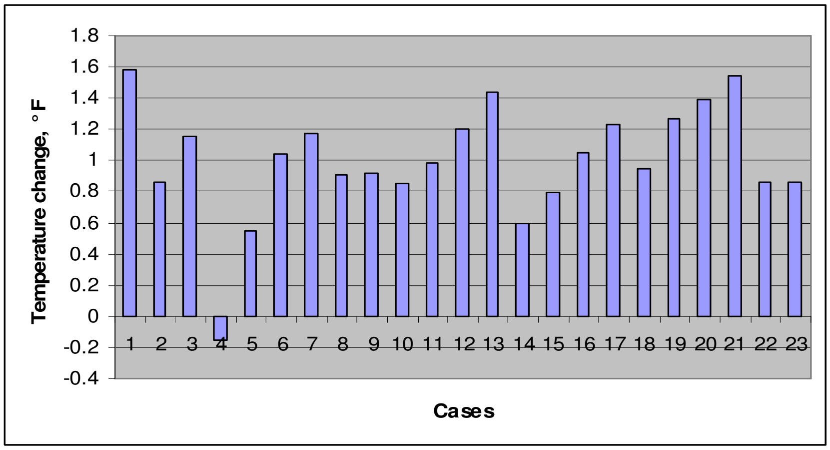

Figure 4.50 The extent of temperature change in SP1, SP2, SP3 and SP4

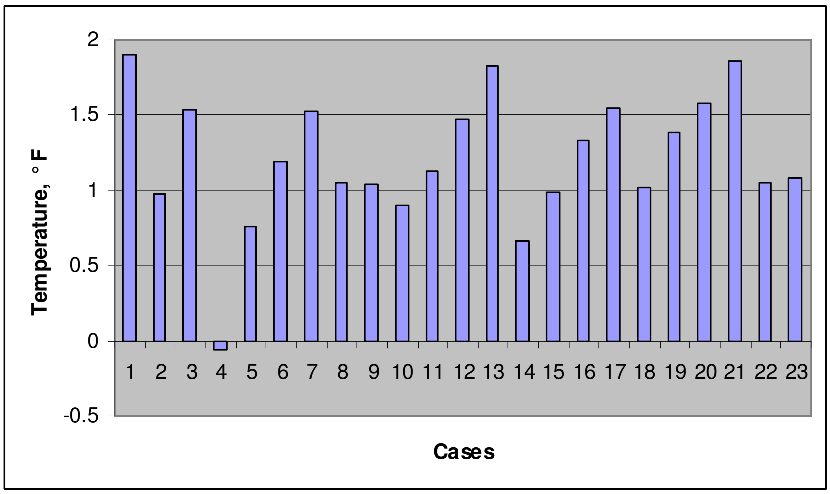

Figure 4.51 The extent of temperature change in sidetracks

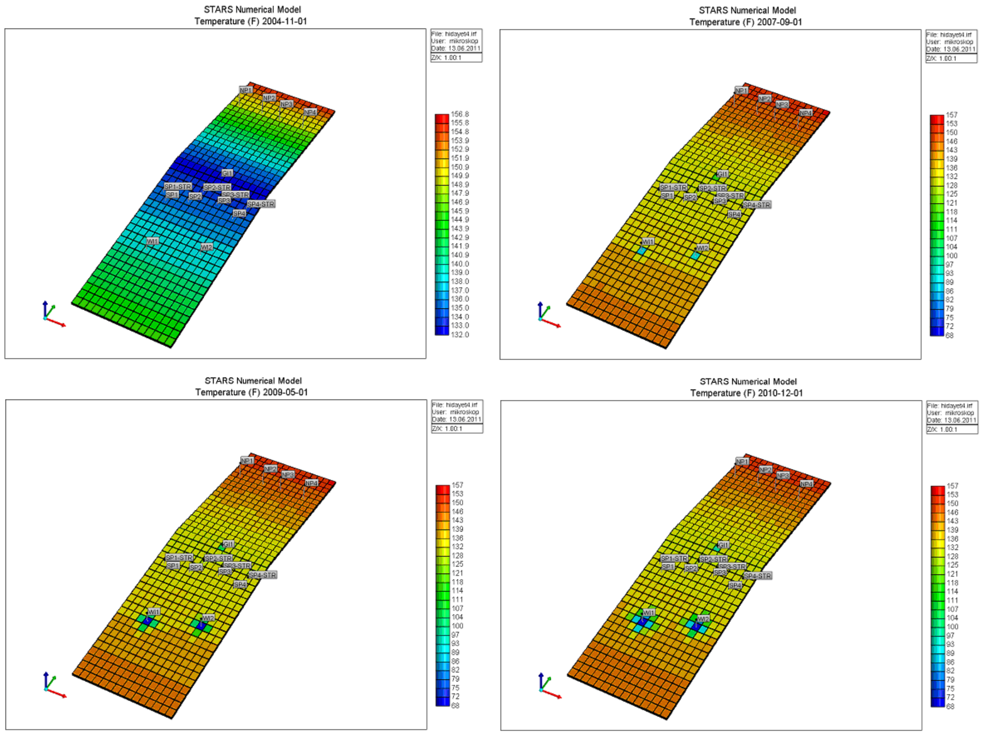

Figure 4.52 3-D temperature distributions of case 21

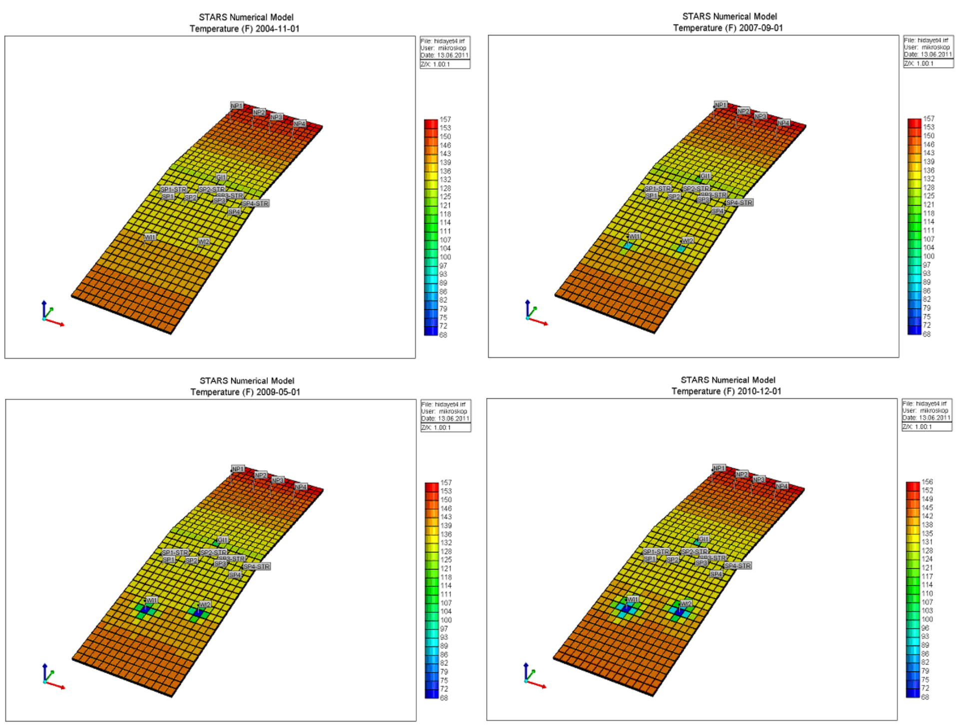

Figure 4.53 3-D temperature distributions of case 4

4.5 ADDITIONAL CASES

To determine whether the temperature changes as a result of reasons apart from geothermal gradient, additional cases were run. In these runs temperature was kept constant throughout the reservoir and in order to prevent external influence on reservoir temperature, injection wells were not opened. The results showed changes in temperature as it was in the previous cases. However there was still a question in mind; did temperature change due to iteration errors or not? To answer this question two extra runs with different iterations and one run with refined grids were done. These runs made it obvious that changes in temperature were not due to iteration errors. Although some variations from case 24 were observed in "refined grids" case, these variations were very small and can easily be neglected. These cases showed the relationship of BHT with BHP and subsequent GOR change.

The extent of temperature changes in additional cases were very similar to the previous cases and even temperature decreased more in South flank compared to case 1 (figure). When giving attention to initial temperatures, it can be seen that temperature was 149-151ºF in North wells and 133.8-137.5ºF in South wells initially. This value corresponds to 141ºF in additional cases which is higher than the temperature of South flank wells of case 1. This information made it clear that the degree of change in BHT is also a function of initial temperature.

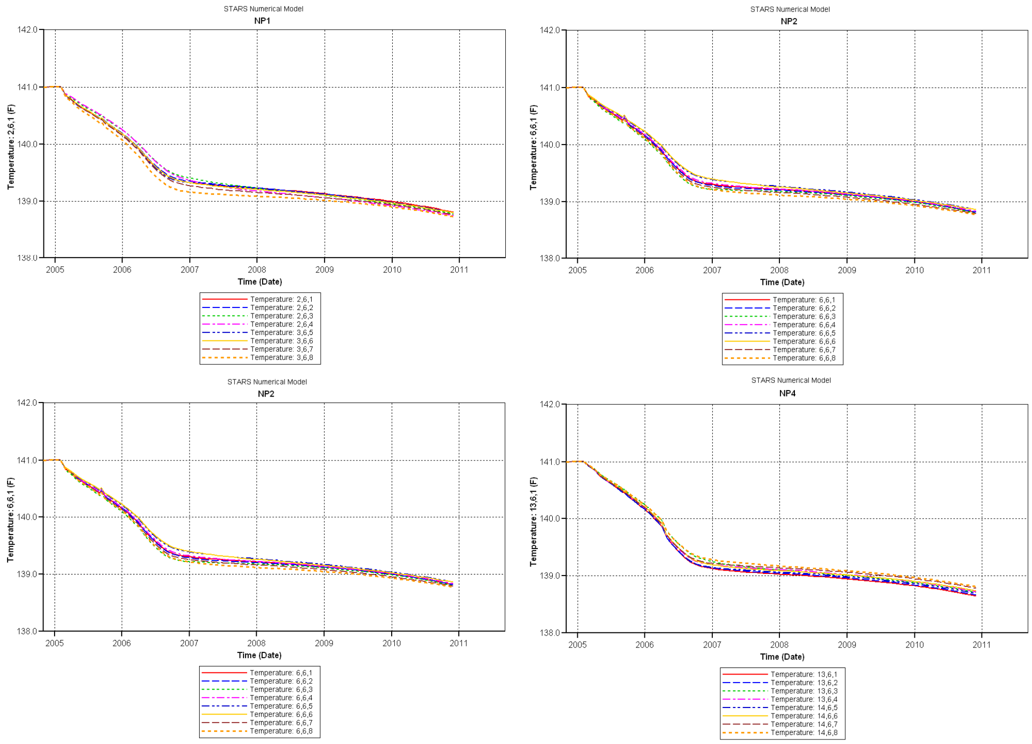

Figure 4.54 Temperature responses of North flank wells (case 24)

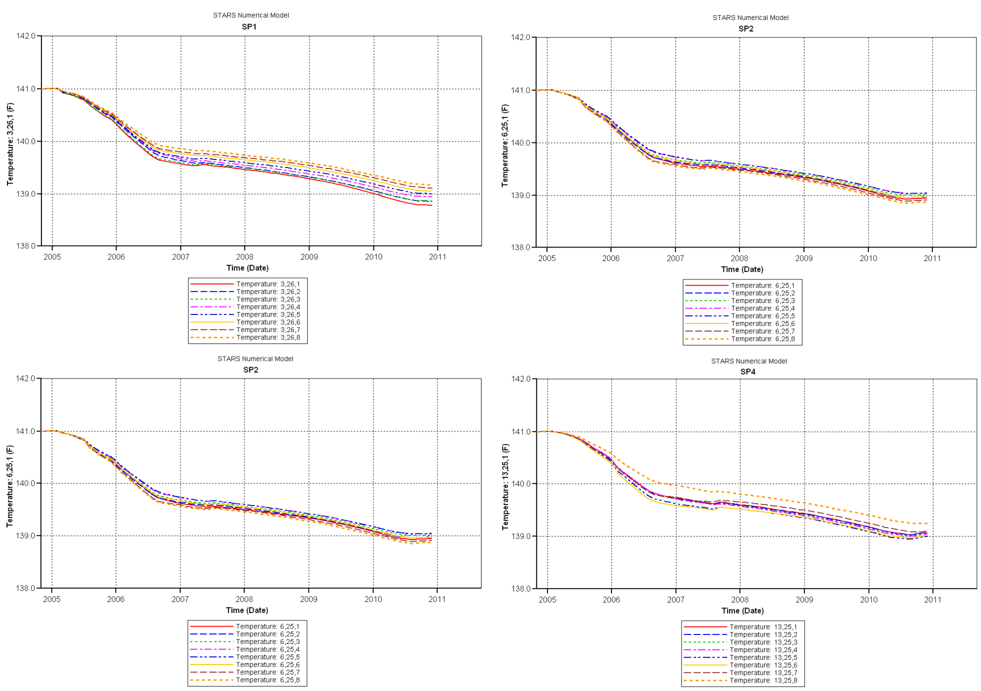

Figure 4.55 Temperature responses of SP1, SP2, SP3 and SP4 (case 24)

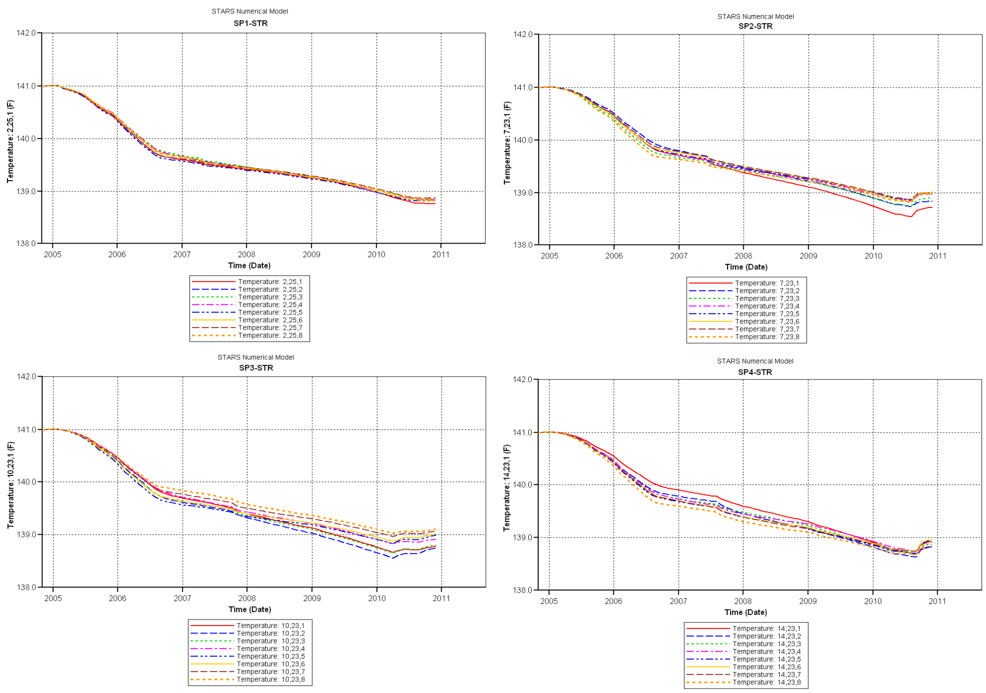

Figure 4.56 Temperature responses of SP1-STR, SP2-STR, SP3-STR and SP4-STR (case 24)

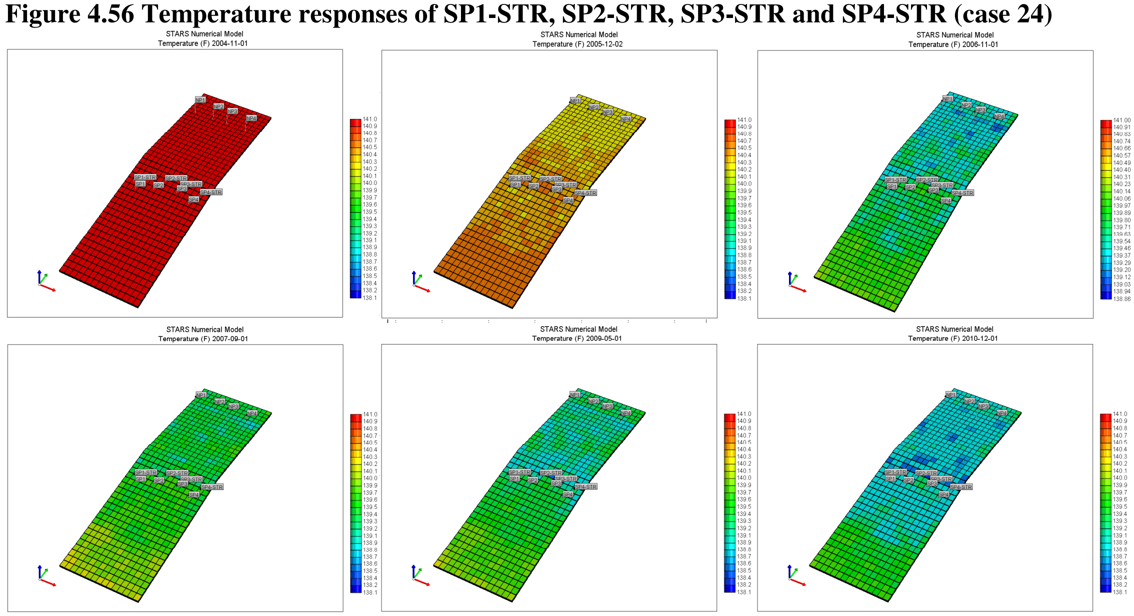

Figure 4.57 3-D temperature distributions in the case 24

Almost no difference in bottom-hole pressure was seen when comparing additional cases with case 1. However GOR showed some variations; such as in North wells GOR started to decrease some time later after reaching bubble-point, while it occurred just after saturation pressure in base cases.

Also SP4-STR well was closed due to high gas production which was not the case for case 1. Based on this information it becomes clear that initial temperature and GOR are interrelated and change in one of them affects the other one.

In the case of injection into reservoir with constant temperature (case 28), BHT was not behaved as it was in case 24; in North wells it showed less decreasing trend and even became constant in South wells after start of injection. This case again makes it clear that there is a strong relationship between BHT and BHP.

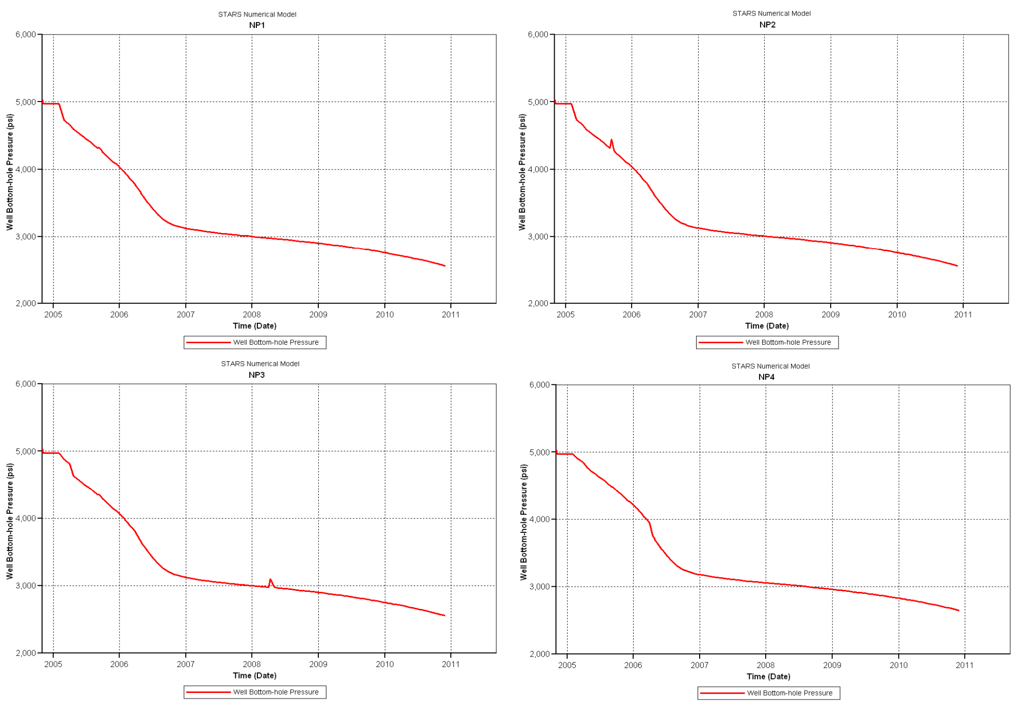

Figure 4.58 Bottom-hole pressure of North flank wells (case 24)

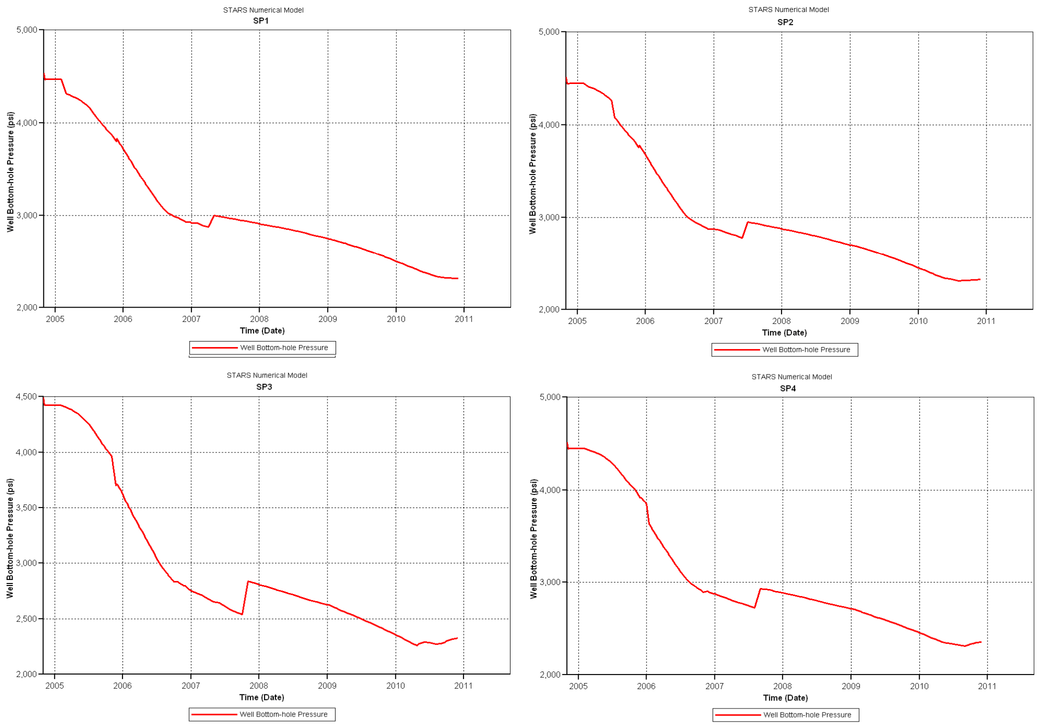

Figure 4.59 Bottom-hole pressure of SP1, SP2, SP3 and SP4 (case 24)

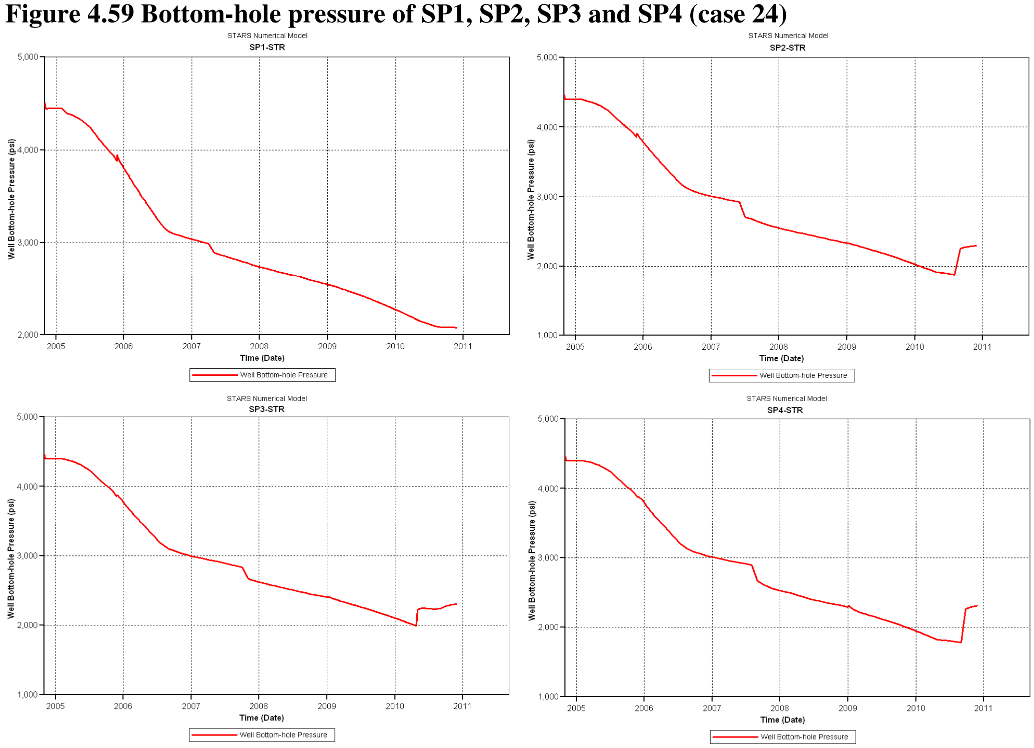

Figure 4.60 Bottom-hole pressure of SP1-STR, SP2-STR, SP3-STR and SP4-STR (case 24)

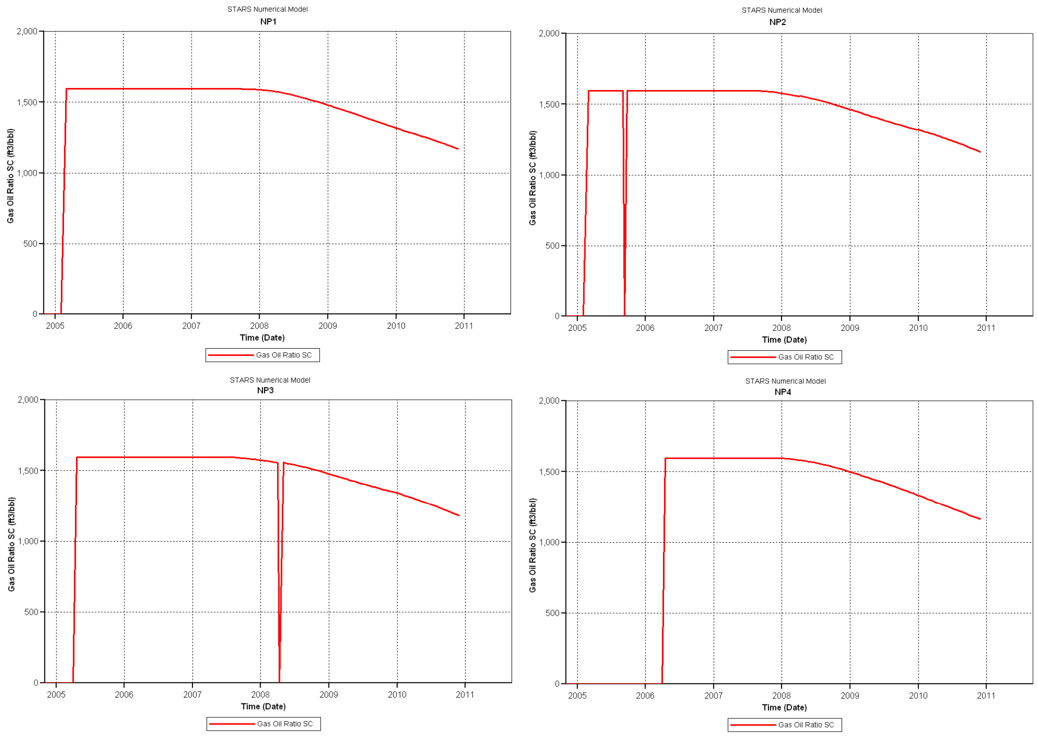

Figure 4.61 Gas-oil ratio of North flank wells (case 24)

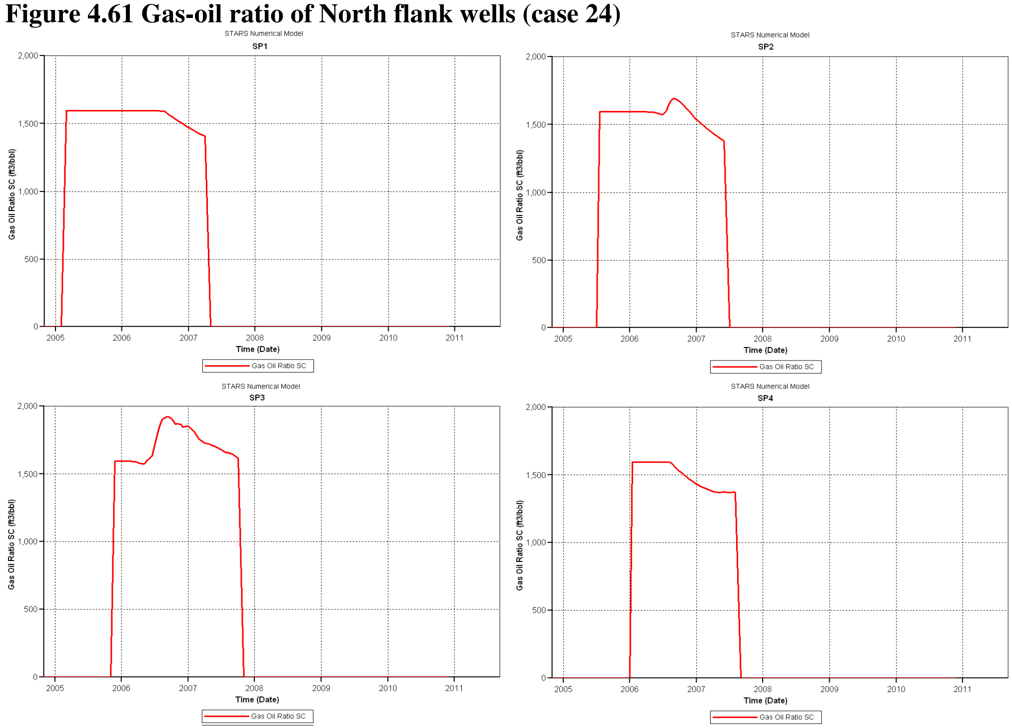

Figure 4.62 Gas-oil ratio of SP1, SP2, SP3 and SP4 (case 24)

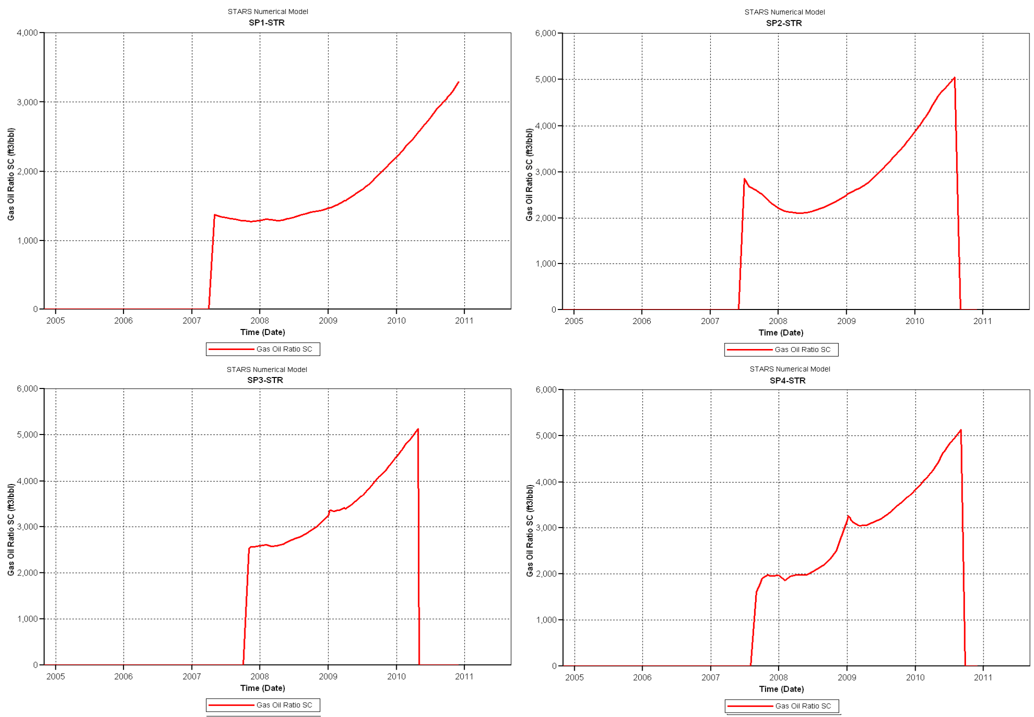

Figure 4.63 Gas-oil ratio of SP1-STR, SP2-STR, SP3-STR and SP4-STR (case 24)

4.6 BHT, BHP AND GOR RELATIONSHIP

In all simulated cases the reaction of well bottom-hole temperature to pressure variations was observed. BHT increased in the case of external pressure support by fluid injection and dropped when the BHP showed decreasing trend. That is why the largest temperature changes corresponded to the case of maximum drawdown pressure. NP1 well was analyzed as an example to North flank wells from the beginning to the end of simulation and a very good relationship between bottom-hole temperature and pressure was observed in this well in base cases both with and without injection (figure 4.65). Same good relationship was also obtained for SP1-STR well in no-injection case (figure 4.66).

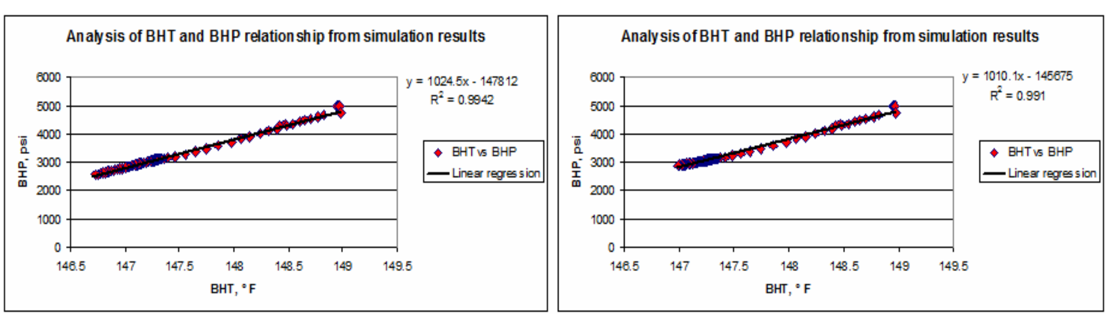

Figure 4.64 Analysis of BHT and BHP relationship in NP1 well for case 1 (left) and case 2 (right)

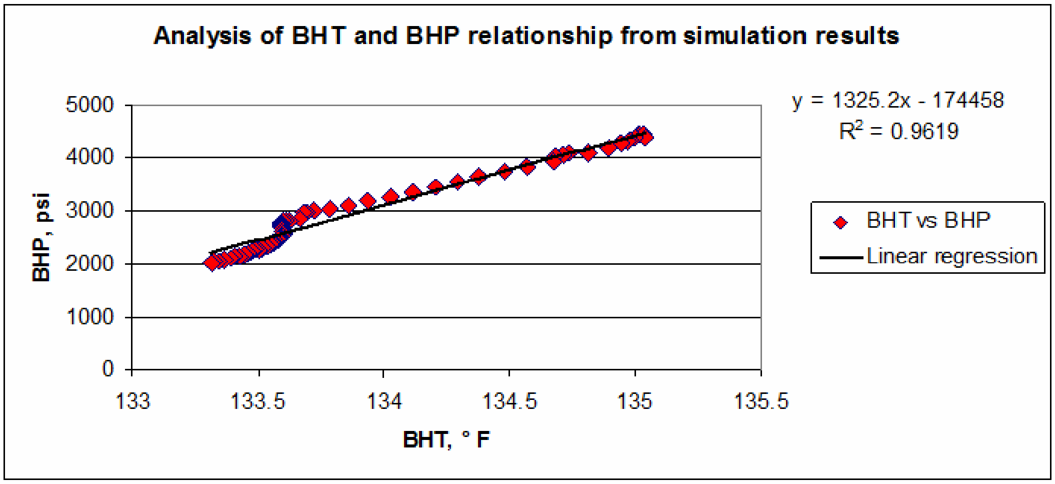

Figure 4.65 Analysis of BHT and BHP relationship in SP1-STR well for case 1

However, when analyzing SP1-STR for case 2, different behavior in BHT and BHP correlation is seen; there are two good linear relationships as can be seen from figure 4.67. Intersection point corresponds to the start of injection from injection wells. Firstly, temperature and pressure decreased as a result of production. After beginning of injection, temperature changed its trend and started to increase. The decrease in the slope of pressure trend was also observed and BHP approached to nearly constant value. If case 2 is analyzed separately for the "before injection" and "after injection" cases, two perfect relationships between bottom-hole temperature and pressure can be observed.

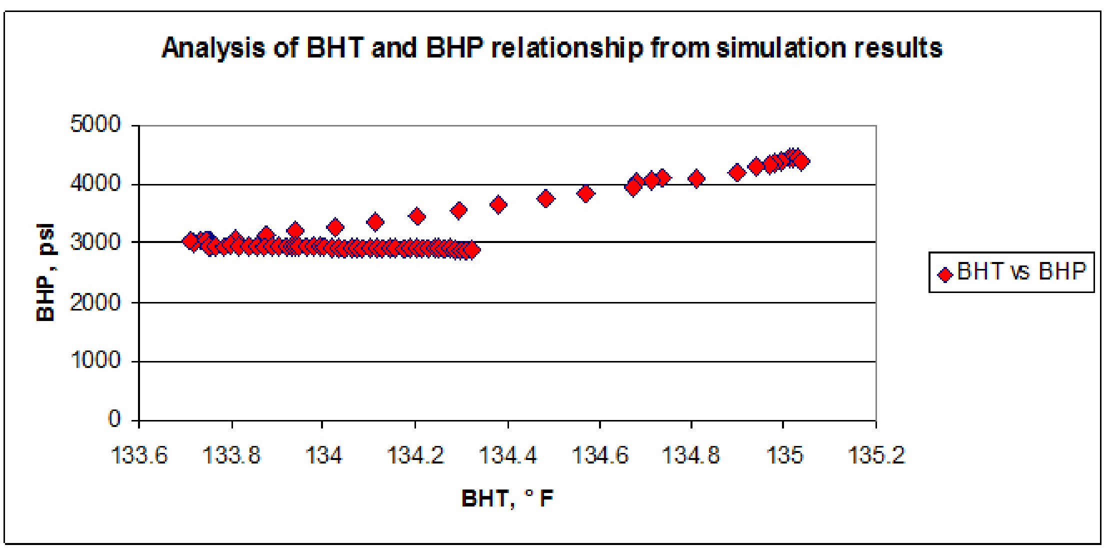

Figure 4.66 Analysis of BHT and BHP relationship in SP1-STR well for case 2

The another important fact is that GOR also responded to BHP and BHT changes in most cases and behaved inversely to them; when BHP increased GOR dropped from high value to low value. When analyzing main case without injection (case 1) as an example, a good relationship of GOR with BHT and BHP in North wells and South sidetrack wells can be seen. South main wells were closed early and no any clear relation of GOR with BHT was detected during short production life of these wells. In sidetrack wells, especially in SP1-STR (in case 1) the increase in GOR towards the end of simulation was seen from BHT data more clearly rather than from BHP. The relationship resulted from simulation was also agreed by a real field case (GOR decreased as a result of BHP and BHT increase). To analyze the relationship between BHT and GOR in more detail the data of SP1-STR well was plotted on figure 4.68 as an example for base cases (case 1 and case2). In both cases the plots indicated a good relation between the discussed parameters which showed inverse liner relationship similar to the given field example (field example 3). Plotted data covers almost all production life of SP1-STR in case 1 and from March, 2008 to September, 2010 in case 2.

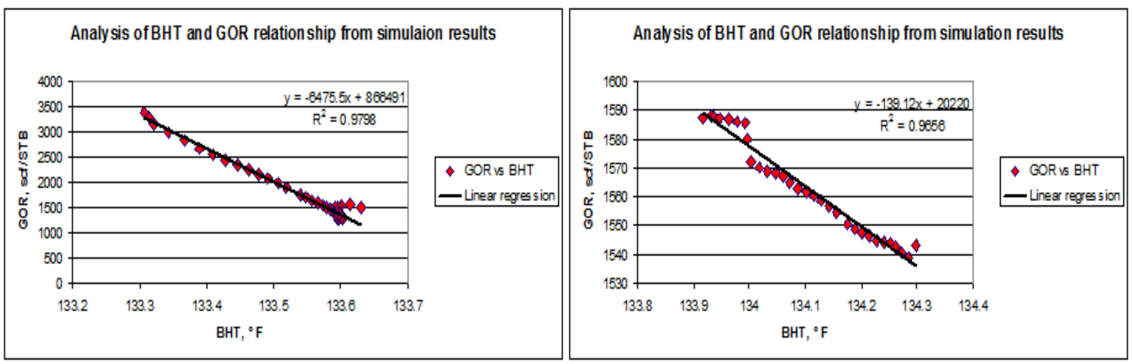

Figure 4.67 Analysis of BHT and GOR relationship in SP1-STR well for case 1 (left) and case 2 (right)

NP1 well as an example to North flank wells was also analyzed in respect to bottom-hole temperature and gas-oil ratio correlation from bubble-point up to the end of simulation (figure 4.69). In both case 1 and case 2, a good linear relationship was obtained throughout the plotted data.

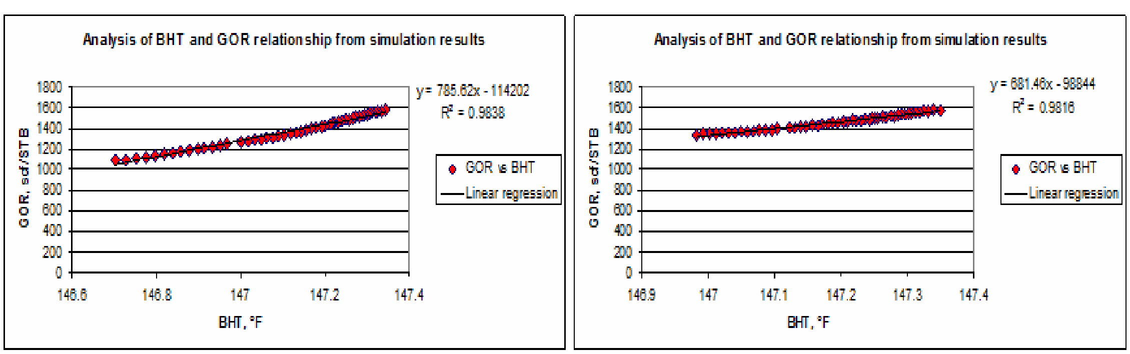

Figure 4.68 Analysis of BHT and GOR relationship in NP1 well for case 1 (left) and case 2 (right)

The GOR relationship with BHT may be an excellent source of data and used as additional information to reduce uncertainties or may be applied to determine real-time gas-oil ratio by using continuously measured BHT data in the case of further study on this topic. As it is mentioned, temperatures analyzed in this study correspond to temperatures in blocks where the production wells are located in. Maybe more perfect relationship between BHT and GOR can be established if temperatures are measured inside the wellbore in real field cases. On the whole, analyzing BHT relationship with BHP and GOR for a particular reservoir may significantly help to manage the field and optimize production.

4.7 INTERACTION BETWEEN WELLS VIA BHT

When analyzing different cases, it was clear that changes in temperature not only affect the particular well, but also neighboring wells. In the case of closing the well NP2 for ten days, the impact was seen in NP1 and NP3, such as small increase in temperature in these wells was observed. When comparing case 1 and case 2, the large effect of injection wells on South producers became obvious. Bottom-hole temperatures in the South wells increased after the start of injection as a result of pressure support and drainage area shifting towards warmer fluids. In the case of injection well 2 was ceased in August, 2008, the impact was seen in the South wells and small temperature drop was occurred in these wells. The obtained results were very similar to the responses of wells in West South Azeri field.

Furthermore, bottom-hole temperature may have a good potential to be used in transient analysis as the pressure data (to check the quality of data obtained from BHP or just doing analysis independently). Also interwell permeability may be determined from temperature communication between wells due to the lag times.

CONCLUSIONS

Twenty three main and five additional cases that were developed by using CMG STARS sector model were simulated and relation of BHT with other parameters was investigated. Temperature data variations were analyzed in these thesis and responses of temperature to bottom-hole pressure and gas-oil ratio was detected. In most cases BHT dropped as the BHP decreased and/or GOR increased. This is a good relationship and excellent source of data for better reservoir management and optimizing production. The conclusions that were drawn during this study are:

- Different cases were simulated by changing some parameters, such as oil rate, initial solution gas oil ratio, drawdown pressure, wettability, etc and compared with the base cases. It was observed that the maximum and minimum changes in temperature occurred in the case of highest drawdown pressure (250 psi) and lowest oil rate (15 MSTB/day), respectively.

- In all cases temperature responded to changes in pressure. In the lack of pressure support temperature showed sharp declining trend, while it increased slightly in the case of fluid injection into reservoir. Based on the high sensitivity of bottom-hole temperature to pressure changes as discussed in this study, anomalies in pressure can be identified and the quality of data obtained from BHP can be checked.

- In most cases GOR variations were reflected on temperature data and generally they behaved reversely to each other. Base cases in the example of SP1-STR and NP1 wells were investigated and good linear relationship was found between bottom-hole temperature and gas-oil ratio. This relationship may be applied to determine real-time gas-oil ratio by using continuously measured BHT data in the case of further study on this topic. Additionally BHT may be used effectively in measuring GOR in wells where gas-oil ratio is very high and test separators are not able to handle such amount of gas.

- When fluid injection was started/ceased or some production wells were closed/opened, an impact was felt on the other wells in respect of BHT. It gave opportunity to detect interwell communication between wells.

- In addition to these, bottom-hole pressure has potential to do temperature transient analysis and this can reduce the frequency of pressure tests which means saving time and money as a result. Interwell permeability may be estimated from the interaction of wells via BHT data.

On the whole, any extra data has a great importance in reservoir engineering and can help to reduce uncertainties to a great extent. Almost all modern wells equipped with continuous DTS equipment and so bottom-hole temperature can be used for this purpose successfully.

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APPENDIX A

AVERAGE TEMPERATURES FOR DIFFERENT CASES

Table A.1 Average temperatures in the North flank for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2005	148.9712	148.9712	148.9712	148.9712	148.9729	148.9699	148.9654	149.2173	149.2173	149.2173	149.2173	149.2173	149.1681	149.2189	149.2189	149.2189	149.2189	149.2159	149.2159	149.2159	149.2159	149.212	149.211
01.02.2005	148.9806	148.9806	148.9806	148.9806	148.9831	148.979	148.976	149.2193	149.2193	149.2193	149.2193	149.2193	149.1716	149.2218	149.2218	149.2218	149.2218	149.2177	149.2177	149.2177	149.2177	149.1889	149.2125
01.03.2005	148.8635	148.8635	148.8278	148.9062	148.8626	148.8574	148.8607	149.0989	149.0989	149.0751	149.0018	148.9311	148.8393	149.0576	148.9642	148.8747	148.7844	149.0907	149.0132	148.9448	148.8791	149.0263	149.0737
01.04.2005	148.8108	148.8108	148.7539	148.8744	148.8058	148.7999	148.8114	149.041	149.041	149.0057	148.8936	148.7877	148.6693	148.9765	148.8759	148.7642	148.6512	149.0341	148.9285	148.8337	148.7408	148.9296	149.0015
01.05.2005	148.7157	148.7157	148.6246	148.8163	148.7037	148.7008	148.7231	148.9416	148.9416	148.8715	148.6892	148.5238	148.3414	148.8402	148.6662	148.4863	148.3094	148.9367	148.7596	148.6059	148.4583	148.782	148.8736
01.06.2005	148.6621	148.6621	148.5513	148.7874	148.6735	148.6494	148.6749	148.8832	148.8832	148.8016	148.6027	148.3737	148.1481	148.7671	148.5648	148.3219	148.0985	148.8552	148.6722	148.4949	148.3134	148.678	148.7742
02.07.2005	148.6103	148.6103	148.5008	148.7649	148.6311	148.6119	148.6355	148.8269	148.8269	148.735	148.5044	148.2387	147.9816	148.6997	148.4475	148.1655	147.9405	148.7977	148.6016	148.3979	148.1832	148.578	148.6574
01.08.2005	148.549	148.549	148.4242	148.7401	148.5741	148.5709	148.5886	148.7613	148.7613	148.6593	148.3923	148.1049	147.8296	148.6091	148.3201	148.0215	147.8207	148.7704	148.5225	148.2922	148.055	148.4801	148.5403
01.09.2005	148.4763	148.4763	148.3326	148.7064	148.4963	148.515	148.5219	148.6846	148.6846	148.5736	148.2726	147.9722	147.6929	148.5054	148.1878	147.8955	147.7566	148.7213	148.4321	148.1753	147.9205	148.3757	148.4294
11.09.2005	148.4922	148.4922	148.3528	148.7198	148.5103	148.5354	148.5381	148.6982	148.6982	148.5894	148.2984	148.0141	147.7393	148.5211	148.2177	147.9481	147.7673	148.7398	148.4578	148.2081	147.9672	148.3843	148.4362
01.10.2005	148.4195	148.4195	148.2513	148.6771	148.4287	148.4636	148.4616	148.6242	148.6242	148.5051	148.1802	147.8925	147.6048	148.4264	148.0882	147.8146	147.7268	148.6732	148.3621	148.082	147.8209	148.2911	148.3379
01.11.2005	148.3965	148.3965	148.166	148.637	148.3468	148.3863	148.3793	148.5976	148.5976	148.4196	148.0741	147.785	147.4792	148.3395	147.9704	147.7603	147.6987	148.6019	148.2693	147.9605	147.6918	148.192	148.2387
02.12.2005	148.32	148.32	148.058	148.587	148.2705	148.3058	148.2945	148.5175	148.5175	148.3445	147.9755	147.6675	147.3919	148.2656	147.8689	147.7303	147.6798	148.5308	148.175	147.8455	147.5749	148.0978	148.1406
01.01.2006	148.233	148.233	147.9491	148.5387	148.1882	148.2246	148.2087	148.4275	148.4275	148.2868	147.8835	147.5589	147.3406	148.182	147.7963	147.7129	147.6649	148.4612	148.0799	147.7397	147.4679	148.0038	148.0398
01.02.2006	148.1384	148.1384	147.8328	148.4769	148.1037	148.1375	148.1155	148.3298	148.3298	148.2092	147.7801	147.4633	147.3109	148.0937	147.7632	147.6993	147.6505	148.3858	147.9805	147.6273	147.3671	147.9086	147.935
01.03.2006	148.0493	148.0493	147.7281	148.4166	148.0264	148.055	148.0277	148.2383	148.2383	148.1354	147.6881	147.4151	147.295	148.0344	147.7499	147.6883	147.638	148.317	147.8903	147.5262	147.2613	147.8228	147.842
01.04.2006	147.9531	147.9531	147.6138	148.3495	147.9468	147.9593	147.932	148.1395	148.1395	148.0559	147.5917	147.3892	147.2814	147.9625	147.7389	147.6774	147.6245	148.2422	147.7923	147.4182	147.1439	147.7348	147.7492
01.05.2006	147.7961	147.7961	147.419	148.2402	147.7971	147.7984	147.7755	147.9825	147.9825	147.8815	147.4098	147.3306	147.2043	147.7927	147.6975	147.6339	147.5748	148.0791	147.5637	147.1403	146.8939	147.5954	147.6041
01.06.2006	147.6773	147.6773	147.2873	148.1546	147.6921	147.6727	147.6567	147.8636	147.8636	147.7691	147.3784	147.3053	147.1656	147.7584	147.6785	147.6102	147.5431	147.9641	147.4203	146.9855	146.8459	147.5197	147.5196
02.07.2006	147.5711	147.5711	147.2291	148.0778	147.6179	147.5565	147.5525	147.7572	147.7572	147.6721	147.3607	147.2829	147.1363	147.746	147.662	147.5883	147.5136	147.8665	147.3064	146.9105	146.8152	147.4949	147.4944
01.08.2006	147.477	147.4847	147.2117	148.02	147.5998	147.4601	147.4692	147.6702	147.6702	147.5983	147.3464	147.2631	147.1108	147.7369	147.6471	147.5671	147.4854	147.7844	147.2198	146.8772	146.7909	147.4835	147.4828
01.09.2006	147.3856	147.4059	147.1993	147.9705	147.5913	147.374	147.3912	147.5904	147.5904	147.5316	147.3332	147.2457	147.0882	147.7281	147.6326	147.5463	147.4592	147.7123	147.1444	146.8556	146.7699	147.4748	147.4739
01.10.2006	147.3095	147.3376	147.1892	147.9253	147.5847	147.2959	147.324	147.5209	147.5209	147.4734	147.3218	147.2293	147.0662	147.7198	147.6194	147.5267	147.4354	147.6495	147.0874	146.8391	146.7505	147.4674	147.4662
01.11.2006	147.2668	147.2818	147.1796	147.9008	147.5794	147.2225	147.2727	147.4626	147.4641	147.436	147.3106	147.2121	147.0427	147.7114	147.6062	147.5076	147.4088	147.5926	147.0395	146.8246	146.7295	147.4601	147.4586
01.12.2006	147.2536	147.2598	147.1705	147.8695	147.5743	147.1599	147.2552	147.4387	147.4402	147.4193	147.2999	147.1941	147.0196	147.7038	147.5932	147.4881	147.3809	147.5575	146.9882	146.8096	146.7094	147.4532	147.4513
01.01.2007	147.2452	147.2499	147.1612	147.842	147.5693	147.105	147.2463	147.4271	147.4279	147.4087	147.2887	147.1739	146.9964	147.696	147.5802	147.4653	147.3516	147.5251	146.9464	146.7939	146.6901	147.4458	147.4434
01.02.2007	147.2385	147.2429	147.1523	147.8239	147.5645	147.0618	147.2395	147.4182	147.4187	147.4009	147.2768	147.1547	146.9749	147.6885	147.5672	147.4425	147.3255	147.5013	146.9206	146.7797	146.6731	147.4382	147.4351
01.03.2007	147.2331	147.2377	147.1436	147.8204	147.56	147.0284	147.2343	147.4111	147.4113	147.3945	147.2644	147.1371	146.9547	147.6816	147.5534	147.4212	147.3021	147.487	146.9036	146.7665	146.6571	147.431	147.4271
01.04.2007	147.2275	147.2326	147.1337	147.829	147.5549	147.0023	147.2292	147.4039	147.4039	147.3881	147.25	147.1178	146.9329	147.6736	147.5366	147.3992	147.2782	147.4832	146.8899	146.7529	146.6398	147.4225	147.4175
01.05.2007	147.2222	147.2279	147.1236	147.8422	147.5499	146.9835	147.2245	147.397	147.3973	147.3818	147.2358	147.1	146.912	147.6658	147.5196	147.379	147.2553	147.4834	146.8788	146.7399	146.6231	147.4137	147.4076
01.06.2007	147.2166	147.2232	147.1126	147.8564	147.5444	146.9681	147.2195	147.39	147.3904	147.3749	147.2223	147.0819	146.8906	147.6575	147.5021	147.359	147.2324	147.4825	146.8683	146.7271	146.6066	147.4042	147.3964
01.07.2007	147.211	147.2187	147.1017	147.8684	147.5389	146.9509	147.2148	147.383	147.3835	147.3682	147.2087	147.0647	146.8704	147.6492	147.4856	147.3402	147.2104	147.4802	146.8587	146.7148	146.591	147.3943	147.3851
01.08.2007	147.205	147.214	147.0901	147.8797	147.5333	146.931	147.2095	147.3759	147.3764	147.3607	147.1951	147.0472	146.8499	147.6397	147.4692	147.3213	147.1881	147.4769	146.8495	146.7026	146.5749	147.3835	147.373
01.09.2007	147.1987	147.2092	147.0783	147.89	147.5273	146.9113	147.2041	147.3686	147.3692	147.353	147.1819	147.0298	146.8296	147.6295	147.4534	147.3026	147.1658	147.4717	146.8407	146.6909	146.5588	147.3722	147.3604
01.10.2007	147.1923	147.2044	147.0665	147.9	147.5214	146.8937	147.1985	147.3613	147.362	147.3453	147.1694	147.013	146.8101	147.6192	147.4383	147.2847	147.1442	147.4659	146.8324	146.6796	146.5434	147.3607	147.3477
01.11.2007	147.1852	147.1991	147.0534	147.91	147.5151	146.8761	147.1922	147.3539	147.3544	147.3374	147.1569	146.996	146.7899	147.6083	147.4232	147.2663	147.1218	147.4567	146.8243	146.6675	146.527	147.3485	147.3341
01.12.2007	147.178	147.1938	147.0403	147.9197	147.5087	146.8604	147.1859	147.3462	147.3469	147.3299	147.1448	146.9795	146.7707	147.5975	147.4087	147.2485	147.1006	147.4446	146.8166	146.6556	146.5111	147.3362	147.3206

Table A.1 (continued) Average temperatures in the North flank for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2008	147.1699	147.1882	147.026	147.9307	147.5019	146.8451	147.1789	147.3381	147.3388	147.3221	147.1324	146.9628	146.7515	147.5865	147.3942	147.2306	147.0785	147.4315	146.8087	146.6432	146.4947	147.3232	147.3063
01.02.2008	147.1613	147.1823	147.0113	147.9402	147.4948	146.8313	147.1715	147.3297	147.3305	147.3144	147.1202	146.9461	146.7328	147.5758	147.38	147.2128	147.0566	147.4179	146.8007	146.6307	146.4784	147.3102	147.2913
01.03.2008	147.1527	147.1766	146.9971	147.9487	147.4881	146.8196	147.1642	147.3213	147.3222	147.3074	147.109	146.9307	146.7159	147.566	147.3668	147.1959	147.0354	147.4053	146.7931	146.619	146.4633	147.2977	147.2772
01.04.2008	147.1432	147.1704	146.9815	147.958	147.4808	146.8067	147.156	147.3119	147.313	147.2999	147.0971	146.9145	146.6983	147.5559	147.3531	147.1781	147.0128	147.392	146.7848	146.6065	146.447	147.2842	147.2619
11.04.2008	147.1494	147.1775	146.9906	147.9858	147.4863	146.8385	147.1625	147.3181	147.3191	147.3038	147.1024	146.9211	146.7049	147.5589	147.3575	147.1842	147.0201	147.4136	146.7913	146.6144	146.4561	147.2904	147.269
01.05.2008	147.1366	147.1655	146.9682	147.9738	147.4739	146.8048	147.1486	147.305	147.3062	147.2944	147.088	146.9023	146.6851	147.5478	147.342	147.164	146.9946	147.3866	146.7791	146.5979	146.4352	147.2754	147.2522
01.06.2008	147.1249	147.1583	146.9507	147.9794	147.4658	146.7883	147.1387	147.2941	147.2954	147.2865	147.0756	146.8853	146.6668	147.5377	147.3279	147.1451	146.9698	147.37	146.7696	146.5845	146.4177	147.2605	147.234
01.07.2008	147.1143	147.1516	146.9339	147.9871	147.4582	146.7766	147.1296	147.2839	147.2852	147.2793	147.064	146.8701	146.6497	147.5285	147.3147	147.127	146.9457	147.3571	146.7609	146.5722	146.4018	147.247	147.2179
01.08.2008	147.1028	147.1446	146.9166	147.9943	147.45	146.7662	147.1199	147.2731	147.2745	147.2719	147.0523	146.8542	146.6318	147.5192	147.3016	147.1084	146.9208	147.3446	146.752	146.56	146.3859	147.2332	147.2008
01.09.2008	147.0913	147.1392	146.9011	147.9955	147.4426	146.7578	147.11	147.2639	147.2653	147.2649	147.0431	146.8407	146.6154	147.5114	147.2907	147.0931	146.8984	147.3307	146.7438	146.5501	146.373	147.2202	147.1846
01.10.2008	147.0797	147.1333	146.8862	147.9935	147.4349	146.7496	147.1004	147.2548	147.2565	147.2583	147.0337	146.8281	146.5983	147.5047	147.2795	147.0778	146.8765	147.3136	146.7367	146.5415	146.3611	147.2072	147.1683
01.11.2008	147.0674	147.1258	146.8681	147.9943	147.4263	146.7388	147.0901	147.2438	147.2456	147.251	147.0223	146.813	146.5806	147.4959	147.2666	147.0599	146.8501	147.2966	146.728	146.5294	146.3463	147.1935	147.1507
01.12.2008	147.055	147.1184	146.8505	147.9991	147.4178	146.7289	147.0797	147.2331	147.235	147.2441	147.0114	146.7986	146.5634	147.4874	147.2543	147.0427	146.8238	147.2829	146.7196	146.5179	146.3324	147.1796	147.1333
01.01.2009	147.0416	147.1105	146.8322	148.0061	147.4089	146.7195	147.069	147.2221	147.224	147.2369	147.0002	146.7839	146.5456	147.4788	147.242	147.0245	146.7957	147.2702	146.7108	146.5062	146.3185	147.1648	147.1146
01.02.2009	147.0279	147.1026	146.8134	148.0045	147.3998	146.7097	147.0577	147.2111	147.213	147.2297	146.9892	146.7692	146.5279	147.4704	147.2294	147.0058	146.7671	147.252	146.7019	146.4947	146.3044	147.1497	147.0952
01.03.2009	147.0153	147.0952	146.7965	148.0046	147.3916	146.7011	147.0472	147.2011	147.2031	147.2232	146.9792	146.7561	146.5118	147.4628	147.218	146.9885	146.7407	147.2372	146.6939	146.4845	146.2918	147.1358	147.0761
01.04.2009	147.0008	147.0868	146.7778	148.0097	147.3822	146.6918	147.0353	147.19	147.1921	147.2159	146.9681	146.7417	146.494	147.4543	147.2055	146.9692	146.7112	147.2244	146.6852	146.4732	146.2781	147.1199	147.0542
01.05.2009	146.9865	147.0784	146.7595	148.015	147.373	146.683	147.0235	147.1793	147.1814	147.2089	146.9574	146.7278	146.4764	147.446	147.1934	146.9497	146.6822	147.2133	146.6766	146.4623	146.2649	147.1043	147.0316
01.06.2009	146.9715	147.0697	146.7407	148.0203	147.3633	146.6743	147.0111	147.1683	147.1704	147.2019	146.9465	146.7136	146.4578	147.4375	147.1811	146.9291	146.6524	147.2019	146.6678	146.4512	146.2514	147.0878	147.0079
01.07.2009	146.9565	147.061	146.7224	148.0258	147.3538	146.666	146.9989	147.158	147.1597	147.1951	146.9361	146.7001	146.4392	147.4294	147.1692	146.9086	146.6234	147.1912	146.6594	146.4406	146.2386	147.0712	146.9847
01.08.2009	146.9407	147.0519	146.7038	148.0313	147.344	146.6576	146.986	147.1469	147.1487	147.1883	146.9257	146.6862	146.4195	147.4212	147.1571	146.8867	146.5934	147.1802	146.651	146.4299	146.2255	147.0533	146.96
01.09.2009	146.9245	147.043	146.6852	148.0366	147.3341	146.6493	146.973	147.1357	147.1376	147.1815	146.9154	146.6726	146.3993	147.4133	147.145	146.8639	146.5632	147.169	146.6428	146.4194	146.2127	147.0346	146.9348
01.11.2009	146.8915	147.0241	146.6485	148.0467	147.3144	146.6333	146.9459	147.1137	147.1156	147.1677	146.8955	146.6462	146.3584	147.3975	147.1218	146.8167	146.5041	147.1477	146.6265	146.3995	146.1885	146.9967	146.8827
01.12.2009	146.8749	147.0147	146.6307	148.0513	147.3046	146.6253	146.9325	147.1027	147.1048	147.1609	146.8858	146.6336	146.3372	147.3898	147.1108	146.793	146.4752	147.1373	146.6187	146.3897	146.177	146.9778	146.8563
01.01.2010	146.8572	147.0049	146.6119	148.0555	147.2945	146.6171	146.9184	147.0915	147.0936	147.1541	146.8762	146.6206	146.3148	147.3819	147.0992	146.7679	146.4469	147.127	146.6108	146.3801	146.1656	146.9578	146.828
01.02.2010	146.8394	146.9951	146.5938	148.0596	147.2843	146.609	146.9041	147.0802	147.0824	147.1473	146.8664	146.6081	146.2915	147.3741	147.0878	146.7423	146.4195	147.1165	146.6032	146.3704	146.1539	146.9375	146.7992
01.03.2010	146.8226	146.9861	146.5769	148.0635	147.2751	146.6016	146.8912	147.07	147.0722	147.1411	146.8577	146.5965	146.2701	147.367	147.0774	146.7195	146.3954	147.107	146.5964	146.3617	146.1435	146.919	146.7729
01.04.2010	146.8035	146.9761	146.5577	148.0678	147.2649	146.5932	146.8769	147.0587	147.061	147.1346	146.8481	146.5839	146.2457	147.3592	147.0662	146.6945	146.3695	147.097	146.5892	146.3529	146.1321	146.8983	146.7434
01.05.2010	146.7844	146.9665	146.5386	148.0714	147.2551	146.585	146.8629	147.0476	147.05	147.1281	146.8389	146.5718	146.2214	147.3517	147.0553	146.6709	146.3446	147.0878	146.5822	146.3438	146.1216	146.8779	146.7152
01.06.2010	146.7642	146.9564	146.5174	148.0741	147.2449	146.5765	146.8485	147.0362	147.0387	147.1214	146.8294	146.5595	146.1955	147.344	147.0442	146.6473	146.3189	147.0784	146.5752	146.3346	146.1105	146.8566	146.6852
01.07.2010	146.7443	146.9466	146.4969	148.0763	147.235	146.5682	146.8343	147.025	147.0277	147.1151	146.8203	146.5475	146.1697	147.3365	147.0334	146.6249	146.2944	147.0695	146.5685	146.3258	146.1002	146.8362	146.6567
01.08.2010	146.7233	146.9364	146.4738	148.0787	147.2248	146.5595	146.8194	147.0135	147.0163	147.1086	146.8109	146.5351	146.1437	147.3289	147.0224	146.6027	146.2688	147.0601	146.5617	146.3168	146.0894	146.8142	146.6273
01.09.2010	146.7019	146.9261	146.4484	148.0809	147.2145	146.5507	146.8044	147.002	147.0057	147.1023	146.8015	146.5228	146.1169	147.3213	147.0113	146.5808	146.243	147.0503	146.5549	146.3078	146.0789	146.7919	146.5978
01.10.2010	146.68	146.9162	146.4217	148.0831	147.2045	146.5422	146.7898	146.9908	146.9946	147.0962	146.7932	146.5109	146.0917	147.3139	147.0004	146.5613	146.2179	147.0405	146.5484	146.2992	146.0688	146.7701	146.5693
01.11.2010	146.6576	146.9059	146.3909	148.0853	147.1942	146.5337	146.7745	146.9793	146.9832	147.09	146.7841	146.4985	146.067	147.3063	146.9892	146.5415	146.192	147.0308	146.5418	146.2904	146.0584	146.7476	146.5399
01.12.2010	146.6338	146.8959	146.3574	148.0876	147.1842	146.5252	146.7595	146.9681	146.972	147.0839	146.7753	146.4859	146.0434	147.299	146.9784	146.5232	146.1674	147.0211	146.5355	146.2819	146.0485	146.7257	146.5117

Table A.2 Average temperatures in SP1, SP2, SP3 and SP4 for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2005	135.0299	135.2267	135.0299	135.0299	135.0318	135.0288	135.0247	135.2759	135.2759	135.2759	135.2759	135.2759	135.2267	135.2778	135.2778	135.2778	135.2778	135.2748	135.2748	135.2748	135.2748	135.27	135.268
01.02.2005	135.0383	135.2292	135.0383	135.0383	135.0407	135.0371	135.035	135.2769	135.2769	135.2769	135.2769	135.2769	135.2292	135.2794	135.2794	135.2794	135.2794	135.2758	135.2758	135.2758	135.2758	135.2285	135.2693
01.03.2005	135.0114	135.1996	135.0035	135.024	135.0114	135.0097	135.0112	135.2459	135.2459	135.2434	135.224	135.2063	135.1498	135.2351	135.2277	135.211	135.1931	135.2448	135.2321	135.2176	135.2034	135.1617	135.2312
01.04.2005	135.0032	135.1857	134.9909	135.0223	134.9964	135.0069	135.0066	135.2312	135.2312	135.2274	135.2004	135.1751	135.1189	135.2168	135.2046	135.1813	135.1531	135.2332	135.2178	135.1993	135.1794	135.1087	135.2069
01.05.2005	134.9951	135.1723	134.976	135.0204	134.9869	135.0029	135.0015	135.2168	135.2168	135.2107	135.1686	135.1263	135.0501	135.2011	135.1682	135.116	135.0562	135.2191	135.2004	135.1743	135.1402	135.067	135.1644
01.06.2005	134.9743	135.1461	134.9484	135.0143	134.9851	134.9936	134.9903	135.1898	135.1898	135.1752	135.1248	135.0238	134.9087	135.1571	135.0971	134.984	134.8903	135.1925	135.169	135.1224	135.053	135.0003	135.0896
02.07.2005	134.9386	135.1051	134.9129	135.0042	134.9539	134.9787	134.9682	135.148	135.148	135.1224	135.0331	134.8984	134.762	135.0988	134.9919	134.8437	134.7396	135.1834	135.1159	135.0333	134.9275	134.9257	134.9768
01.08.2005	134.8602	135.016	134.8109	134.9693	134.8749	134.9178	134.9027	135.064	135.064	135.0249	134.8841	134.7168	134.5607	134.9842	134.8295	134.6604	134.5256	135.1369	134.9986	134.8735	134.7312	134.8128	134.8551
01.09.2005	134.7946	134.9454	134.7229	134.9364	134.8026	134.8594	134.8355	134.993	134.993	134.9442	134.7681	134.5869	134.4247	134.889	134.7055	134.5288	134.3919	135.0777	134.904	134.7491	134.5851	134.7169	134.757
11.09.2005	134.7741	134.9234	134.695	134.9246	134.7795	134.839	134.8141	134.9708	134.9708	134.9186	134.7337	134.5514	134.3867	134.8606	134.6703	134.4896	134.3561	135.0568	134.8749	134.7098	134.5416	134.6884	134.7264
01.10.2005	134.7464	134.94	134.6532	134.9115	134.7374	134.7991	134.7742	134.94	134.94	134.872	134.6728	134.5115	134.3184	134.8125	134.6019	134.4207	134.3045	135.016	134.8253	134.6343	134.4638	134.6341	134.6718
01.11.2005	134.7418	134.9306	134.5854	134.8777	134.6841	134.7392	134.71	134.9306	134.9306	134.8025	134.5878	134.3961	134.2094	134.7579	134.5047	134.3337	134.2581	134.9544	134.7425	134.526	134.3505	134.5589	134.5998
02.12.2005	134.6354	134.8177	134.459	134.8223	134.594	134.6414	134.6137	134.8177	134.8177	134.7355	134.4733	134.2555	134.0606	134.6621	134.3889	134.2595	134.2203	134.8705	134.6212	134.3843	134.1975	134.4444	134.4771
01.01.2006	134.5603	134.7386	134.368	134.7729	134.5242	134.5717	134.5404	134.7386	134.7386	134.6719	134.3775	134.1561	133.9811	134.585	134.311	134.2397	134.2037	134.8047	134.5272	134.2823	134.1112	134.3654	134.3903
01.02.2006	134.4523	134.6257	134.2368	134.6959	134.4314	134.4677	134.434	134.6257	134.6257	134.5717	134.2506	134.0171	133.9136	134.4845	134.2512	134.2043	134.1782	134.7107	134.3994	134.1335	133.9528	134.2533	134.2716
01.03.2006	134.3753	134.5446	134.1504	134.6423	134.3694	134.3917	134.3572	134.5446	134.5446	134.5016	134.1669	133.9617	133.8841	134.4401	134.2401	134.1901	134.1673	134.646	134.3119	134.0372	133.842	134.1763	134.1954
01.04.2006	134.2961	134.4611	134.0589	134.5844	134.3008	134.3082	134.2777	134.4611	134.4611	134.4372	134.0825	133.939	133.867	134.3696	134.2196	134.1792	134.1623	134.5748	134.2204	133.9364	133.7292	134.1123	134.1258
01.05.2006	134.2178	134.3792	133.9655	134.5282	134.2284	134.2263	134.1996	134.3792	134.3792	134.3613	134.0128	133.9168	133.8536	134.3019	134.2096	134.1763	134.1522	134.499	134.134	133.8415	133.621	134.0599	134.0636
01.06.2006	134.1372	134.2949	133.8744	134.47	134.1555	134.1416	134.1185	134.2949	134.2949	134.2805	133.9627	133.8952	133.8424	134.2625	134.2006	134.173	134.1435	134.4201	134.0436	133.7393	133.5444	134.0251	134.0278
02.07.2006	134.0572	134.2107	133.8035	134.4125	134.1059	134.0569	134.0415	134.2107	134.2107	134.2037	133.9435	133.8805	133.8376	134.2519	134.1938	134.167	134.1344	134.3433	133.9552	133.642	133.5136	134.0063	134.0069
01.08.2006	133.9829	134.1447	133.7748	134.3771	134.0903	133.9957	133.983	134.1447	134.1447	134.1513	133.9342	133.8709	133.831	134.2458	134.1901	134.1622	134.1271	134.2849	133.8882	133.5752	133.4896	133.9934	133.9938
01.09.2006	133.9073	134.0773	133.7549	134.34	134.0789	133.9312	133.9199	134.0773	134.0773	134.0931	133.9217	133.863	133.8254	134.2405	134.1908	134.1569	134.1192	134.2288	133.8239	133.5396	133.4671	133.9817	133.9814
01.10.2006	133.8498	134.0203	133.7344	134.3141	134.0681	133.8669	133.8656	134.0203	134.0203	134.0413	133.9077	133.8581	133.8196	134.234	134.1882	134.151	134.1108	134.1752	133.7775	133.5216	133.4515	133.9717	133.9704
01.11.2006	133.8181	133.9967	133.718	134.3195	134.0636	133.8371	133.8355	133.9967	134.0026	134.0234	133.8994	133.8579	133.8127	134.2284	134.1869	134.1459	134.102	134.1704	133.747	133.5145	133.437	133.9658	133.9633
01.12.2006	133.8002	133.9816	133.7075	134.315	134.0621	133.8079	133.822	133.9818	133.9881	134.0117	133.8963	133.8547	133.8066	134.229	134.1866	134.1414	134.0942	134.1616	133.7148	133.511	133.4285	133.963	133.9607
01.01.2007	133.7852	133.9723	133.7011	134.3096	134.063	133.7785	133.8122	133.9725	133.9778	134.0053	133.8956	133.8551	133.8023	134.2321	134.1879	134.1381	134.088	134.1471	133.6854	133.5049	133.4235	133.9619	133.9597
01.02.2007	133.7817	133.9988	133.7031	134.3513	134.0703	133.7905	133.8136	133.998	133.9941	134.0352	133.901	133.8574	133.8	134.2431	134.1917	134.1363	134.0824	134.185	133.6981	133.5126	133.4239	133.9679	133.9663
01.03.2007	133.772	134.0083	133.7069	134.3809	134.0812	133.7978	133.8143	134.008	134.0061	134.0617	133.9127	133.8639	133.8006	134.2581	134.1992	134.1369	134.0788	134.2211	133.7144	133.525	133.4332	133.9786	133.9777
01.04.2007	133.7614	134.02	133.7141	134.4124	134.0942	133.803	133.8117	134.0197	134.026	134.0804	133.929	133.8745	133.8055	134.2755	134.2103	134.1409	134.0777	134.2479	133.7248	133.5401	133.4455	133.992	133.9921
01.05.2007	133.7538	134.0398	133.7342	134.4468	134.1149	133.8185	133.8196	134.0396	134.0446	134.0937	133.9512	133.8932	133.8194	134.2973	134.2282	134.1564	134.0918	134.2605	133.73	133.5636	133.4664	134.0139	134.0153
01.06.2007	133.7475	134.0506	133.7428	134.4742	134.1276	133.8221	133.8194	134.0503	134.0545	134.1046	133.9649	133.904	133.8261	134.3128	134.2403	134.1633	134.0921	134.2737	133.7318	133.5753	133.4785	134.0289	134.031
01.07.2007	133.749	134.066	133.7579	134.5048	134.1454	133.8302	133.8238	134.0659	134.0699	134.1239	133.9845	133.9233	133.8414	134.333	134.2582	134.1804	134.1109	134.2968	133.7419	133.5943	133.4984	134.0506	134.0534
01.08.2007	133.7428	134.0729	133.7634	134.5291	134.1565	133.8285	133.8218	134.0728	134.0768	134.1326	133.9959	133.9341	133.848	134.346	134.2689	134.1877	134.1197	134.3094	133.7429	133.6037	133.5075	134.0634	134.0664
01.09.2007	133.7454	134.0942	133.7834	134.5612	134.1767	133.8437	133.83	134.0946	134.0976	134.1476	134.0153	133.9516	133.8748	134.3652	134.2854	134.2058	134.1417	134.3222	133.7552	133.6272	133.5308	134.0859	134.0896
01.10.2007	133.74	134.1043	133.7896	134.5833	134.1878	133.8455	133.8296	134.1043	134.1071	134.1551	134.0276	133.9619	133.8827	134.3779	134.2955	134.2137	134.1505	134.3309	133.7591	133.6415	133.5415	134.099	134.1032
01.11.2007	133.7455	134.1248	133.809	134.6124	134.2075	133.8568	133.8376	134.1256	134.127	134.1602	134.0417	133.9732	133.8916	134.3906	134.3077	134.2236	134.159	134.3277	133.7609	133.6515	133.5532	134.1232	134.1283
01.12.2007	133.7411	134.1326	133.8166	134.6339	134.2177	133.8569	133.8376	134.1344	134.1338	134.164	134.0486	133.9792	133.8949	134.399	134.3153	134.2268	134.161	134.3262	133.7615	133.6545	133.5585	134.1347	134.1405

Table A.2 (continued) Average temperatures in SP1, SP2, SP3 and SP4 for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2008	133.7367	134.1405	133.8253	134.6556	134.2281	133.8571	133.8383	134.1425	134.141	134.1693	134.0563	133.986	133.8997	134.4073	134.3232	134.2311	134.1638	134.3253	133.764	133.6585	133.565	134.1454	134.1516
01.02.2008	133.7326	134.148	133.8329	134.6758	134.2382	133.8579	133.8396	134.1501	134.1483	134.1748	134.064	133.9942	133.9038	134.4153	134.3316	134.2352	134.1669	134.3244	133.7675	133.6646	133.5711	134.1554	134.162
01.03.2008	133.7286	134.1546	133.8397	134.6945	134.2475	133.8586	133.8411	134.1569	134.1549	134.1799	134.0713	134.0009	133.9072	134.4231	134.3392	134.2386	134.1694	134.3238	133.7719	133.6702	133.5772	134.1644	134.1713
01.04.2008	133.7246	134.1616	133.8481	134.7145	134.257	133.8596	133.8426	134.1638	134.1616	134.1866	134.0792	134.0076	133.9106	134.4318	134.3484	134.2423	134.1726	134.323	133.7785	133.6766	133.5832	134.1736	134.181
11.04.2008	133.7232	134.164	133.8507	134.721	134.26	133.8601	133.843	134.1661	134.1636	134.1889	134.0818	134.0099	133.9117	134.4346	134.3511	134.2434	134.1734	134.323	133.7807	133.679	133.5852	134.1766	134.1841
01.05.2008	133.7208	134.1686	133.8562	134.7343	134.266	133.8613	133.8441	134.1708	134.1677	134.1937	134.0874	134.0148	133.9137	134.4408	134.3564	134.2455	134.1753	134.3233	133.7857	133.6835	133.5892	134.1824	134.1901
01.06.2008	133.7164	134.1765	133.865	134.7548	134.2751	133.864	133.8454	134.1786	134.1742	134.2015	134.0958	134.0217	133.9165	134.45	134.3646	134.2488	134.1785	134.3243	133.7943	133.6908	133.5961	134.1911	134.199
01.07.2008	133.7124	134.1844	133.873	134.7744	134.284	133.8669	133.8468	134.1863	134.1808	134.2096	134.104	134.0279	133.9189	134.4588	134.3723	134.2511	134.1813	134.3252	133.8024	133.6978	133.6029	134.1993	134.2073
01.08.2008	133.7078	134.1923	133.8812	134.7928	134.2932	133.8696	133.8484	134.1941	134.188	134.218	134.1122	134.0347	133.9212	134.4677	134.38	134.2539	134.1843	134.3256	133.81	133.7049	133.6092	134.2077	134.2155
01.09.2008	133.7029	134.1839	133.8841	134.7767	134.2947	133.8455	133.8489	134.1847	134.1793	134.2039	134.1129	134.0376	133.9197	134.4659	134.3836	134.2548	134.1864	134.2899	133.794	133.7018	133.6108	134.2033	134.2111
01.10.2008	133.6971	134.1894	133.8864	134.7927	134.2989	133.8456	133.8492	134.1904	134.1847	134.214	134.1156	134.0388	133.9176	134.4704	134.3861	134.255	134.1878	134.2923	133.7981	133.7036	133.6119	134.2082	134.2153
01.11.2008	133.6905	134.1981	133.8909	134.8144	134.3069	133.8516	133.8502	134.1993	134.1935	134.2254	134.1225	134.0423	133.9161	134.48	134.3913	134.2548	134.1884	134.2968	133.8071	133.7109	133.6163	134.2166	134.2237
01.12.2008	133.6837	134.2059	133.896	134.8332	134.3152	133.8557	133.8516	134.2073	134.2014	134.2352	134.13	134.0468	133.9155	134.4892	134.3971	134.255	134.1885	134.299	133.815	133.7189	133.6223	134.2246	134.2319
01.01.2009	133.6762	134.2138	133.9015	134.8521	134.3234	133.8596	133.8535	134.2154	134.2096	134.2449	134.1377	134.0516	133.9153	134.4981	134.4031	134.2553	134.1882	134.3006	133.8223	133.7267	133.6285	134.2326	134.2402
01.02.2009	133.6687	134.2196	133.9063	134.8603	134.3307	133.8579	133.8542	134.2212	134.2161	134.2521	134.1437	134.0551	133.9138	134.5065	134.4082	134.2543	134.1862	134.2939	133.827	133.7335	133.6335	134.2391	134.2469
01.03.2009	133.6619	134.2252	133.9105	134.8717	134.3374	133.86	133.8556	134.2269	134.2226	134.2584	134.1499	134.0586	133.9129	134.5134	134.4129	134.2539	134.1848	134.2918	133.8309	133.7398	133.6383	134.2454	134.2533
01.04.2009	133.6539	134.2326	133.9158	134.8883	134.3451	133.8654	133.8576	134.2344	134.2303	134.2671	134.1574	134.0629	133.9122	134.5216	134.4184	134.2542	134.1827	134.2921	133.8374	133.7471	133.6454	134.2524	134.2605
01.05.2009	133.6457	134.2396	133.9207	134.9041	134.3529	133.8711	133.8595	134.2415	134.2376	134.2747	134.1646	134.0672	133.9108	134.53	134.4237	134.2538	134.1797	134.2931	133.8444	133.7539	133.6508	134.2593	134.2674
01.06.2009	133.6366	134.2468	133.9257	134.9217	134.361	133.8773	133.8614	134.2489	134.245	134.2822	134.1722	134.0718	133.9091	134.5391	134.4291	134.2526	134.1757	134.2941	133.8525	133.7612	133.657	134.2663	134.2744
01.07.2009	133.6267	134.2535	133.9302	134.9389	134.3688	133.8828	133.863	134.2555	134.2516	134.2882	134.1797	134.0761	133.9067	134.5474	134.4343	134.2506	134.1702	134.2951	133.8605	133.7683	133.6633	134.2729	134.281
01.08.2009	133.616	134.2603	133.9344	134.9556	134.3766	133.8883	133.8645	134.2623	134.2584	134.2942	134.1872	134.0802	133.9029	134.5556	134.4395	134.248	134.163	134.2958	133.8687	133.7754	133.6692	134.2796	134.2876
01.09.2009	133.6049	134.2666	133.9379	134.9715	134.3833	133.8937	133.8656	134.2686	134.2656	134.3008	134.1946	134.0834	133.8982	134.5633	134.4444	134.2445	134.1537	134.2963	133.8772	133.7822	133.6752	134.2863	134.2943
01.11.2009	133.5808	134.279	133.9434	135.0005	134.3977	133.9058	133.8665	134.2815	134.28	134.3167	134.2087	134.0896	133.8851	134.5784	134.4531	134.2336	134.1438	134.299	133.8956	133.7956	133.6863	134.2995	134.3071
01.12.2009	133.568	134.2856	133.9452	135.0157	134.4046	133.9121	133.8666	134.2881	134.2868	134.3251	134.2157	134.0922	133.8763	134.5863	134.4573	134.2261	134.1439	134.3007	133.9038	133.8026	133.6916	134.3062	134.3134
01.01.2010	133.5539	134.2925	133.9466	135.0314	134.4118	133.9182	133.8665	134.2949	134.2933	134.3338	134.2232	134.0946	133.8655	134.5948	134.4616	134.2162	134.1394	134.3026	133.9122	133.8097	133.6968	134.3133	134.3201
01.02.2010	133.5395	134.2992	133.9479	135.0466	134.419	133.924	133.8663	134.3016	134.3001	134.3422	134.2304	134.0966	133.8528	134.6029	134.4661	134.2229	134.1327	134.304	133.9207	133.8169	133.7013	134.3208	134.3272
01.03.2010	133.5257	134.3054	133.9483	135.0605	134.4254	133.9288	133.866	134.3075	134.3059	134.3494	134.2368	134.0981	133.8392	134.61	134.47	134.2228	134.1257	134.3049	133.9279	133.8226	133.7053	134.3277	134.3338
01.04.2010	133.5102	134.3116	133.9478	135.0754	134.4323	133.9344	133.8656	134.3139	134.3122	134.3568	134.2436	134.0991	133.8216	134.6177	134.4743	134.2196	134.1173	134.3067	133.9361	133.8281	133.7092	134.3357	134.3412
01.05.2010	133.4946	134.3177	133.9462	135.0887	134.4386	133.9403	133.8649	134.3201	134.318	134.3644	134.2498	134.0992	133.8026	134.6248	134.4779	134.2169	134.1081	134.3089	133.9444	133.8341	133.7127	134.3437	134.3488
01.06.2010	133.4782	134.324	133.943	135.102	134.445	133.947	133.864	134.3264	134.3242	134.3727	134.2562	134.0986	133.7816	134.6322	134.4808	134.2178	134.0981	134.3125	133.9535	133.8406	133.7163	134.3521	134.3564
01.07.2010	133.4617	134.3305	133.9385	135.1154	134.451	133.954	133.8628	134.3329	134.3292	134.3812	134.2623	134.0977	133.782	134.6395	134.4831	134.218	134.0889	134.3159	133.9624	133.8476	133.7198	134.3603	134.364
01.08.2010	133.444	134.3376	133.9318	135.129	134.4576	133.9609	133.8613	134.34	134.3346	134.3904	134.2693	134.0962	133.7802	134.6474	134.4852	134.2185	134.0798	134.3186	133.9709	133.8545	133.7227	134.3689	134.3718
01.09.2010	133.4253	134.3446	133.9225	135.1432	134.464	133.9676	133.8595	134.347	134.3394	134.3992	134.2762	134.0932	133.7823	134.6555	134.4867	134.22	134.0712	134.3204	133.979	133.8614	133.725	134.3778	134.3795
01.10.2010	133.4288	134.3512	133.9111	135.1569	134.4712	133.9743	133.8571	134.3536	134.3447	134.4072	134.2823	134.089	133.7842	134.6632	134.4874	134.222	134.0629	134.3226	133.9864	133.868	133.7267	134.387	134.3874
01.11.2010	133.44	134.3582	133.896	135.1706	134.4779	133.9811	133.854	134.3605	134.3499	134.4154	134.2885	134.0836	133.7869	134.6709	134.4873	134.2244	134.0543	134.3256	133.9939	133.8744	133.7272	134.397	134.396
01.12.2010	133.4463	134.3648	133.8786	135.1841	134.4845	133.9879	133.8505	134.3668	134.3557	134.4236	134.2947	134.0764	133.7904	134.6784	134.4869	134.2268	134.0461	134.3284	134.0014	133.8805	133.727	134.4071	134.4044

Table A.3 Average temperatures in sidetracks for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2005	134.1299	134.1299	134.1299	134.1299	134.1318	134.1289	134.1248	134.376	134.376	134.376	134.376	134.376	134.376	134.3779	134.3779	134.3779	134.3779	134.3749	134.3749	134.3749	134.3749	134.3699	134.3676
01.02.2005	134.1382	134.1382	134.1382	134.1382	134.1406	134.1371	134.1351	134.377	134.377	134.377	134.377	134.377	134.377	134.3794	134.3794	134.3794	134.3794	134.3758	134.3758	134.3758	134.3758	134.3269	134.3693
01.03.2005	134.1231	134.1231	134.1187	134.1319	134.1221	134.1241	134.1232	134.3559	134.3559	134.3541	134.34	134.3276	134.3124	134.3456	134.3465	134.3359	134.3241	134.3553	134.3493	134.3406	134.332	134.2724	134.3427
01.04.2005	134.1157	134.1157	134.1073	134.1306	134.1073	134.1223	134.1194	134.3418	134.3418	134.3389	134.3181	134.2985	134.2821	134.331	134.3221	134.3043	134.2814	134.3446	134.3358	134.3233	134.3088	134.2116	134.3174
01.05.2005	134.1073	134.1073	134.092	134.1284	134.1026	134.118	134.1139	134.3266	134.3266	134.3215	134.2876	134.2437	134.2022	134.3114	134.2829	134.2322	134.1732	134.3297	134.3172	134.2957	134.265	134.1705	134.2718
01.06.2005	134.085	134.085	134.0687	134.1218	134.096	134.1079	134.1017	134.2974	134.2974	134.2824	134.2351	134.1371	134.0486	134.2645	134.205	134.0921	134.0025	134.3006	134.2834	134.2376	134.168	134.1003	134.193
02.07.2005	134.0479	134.0479	134.0246	134.1112	134.0646	134.0913	134.0781	134.2532	134.2532	134.227	134.1375	134.0045	133.8977	134.2028	134.0963	133.9504	133.8495	134.3008	134.2246	134.141	134.0351	134.026	134.0741
01.08.2005	133.9804	133.9804	133.9394	134.0839	133.994	134.0426	134.0236	134.1789	134.1789	134.1391	134.005	133.8474	133.7183	134.0982	133.9513	133.7964	133.6676	134.2568	134.1202	134.0015	133.8661	133.9259	133.9693
01.09.2005	133.9162	133.9162	133.8499	134.0507	133.9227	133.983	133.9558	134.1073	134.1073	134.0584	133.8892	133.7188	133.5826	134.003	133.8281	133.6618	133.5307	134.1935	134.025	133.8764	133.7205	133.8301	133.8714
11.09.2005	133.8962	133.8962	133.8225	134.0391	133.9001	133.9625	133.9347	134.085	134.085	134.0326	133.8551	133.6842	133.5445	133.9748	133.7935	133.6225	133.493	134.1717	133.9958	133.8368	133.6777	133.8022	133.8413
01.10.2005	133.8733	133.8733	133.7893	134.0301	133.8593	133.9229	133.8959	134.0575	134.0575	133.9863	133.7953	133.6471	133.4735	133.9275	133.7252	133.5526	133.4339	134.1299	133.9484	133.7616	133.6017	133.7485	133.7883
01.11.2005	133.8658	133.8658	133.7156	133.9929	133.8103	133.864	133.8326	134.0449	134.0449	133.9166	133.7105	133.5263	133.3564	133.879	133.6276	133.461	133.3813	134.0675	133.8628	133.6532	133.4884	133.6735	133.7172
02.12.2005	133.7684	133.7684	133.6052	133.9487	133.7291	133.7786	133.7478	133.9389	133.9389	133.8632	133.6074	133.397	133.2221	133.7835	133.522	133.3881	133.3544	133.9896	133.7499	133.526	133.3526	133.5687	133.6028
01.01.2006	133.6959	133.6959	133.515	133.8958	133.6604	133.7111	133.6766	133.8595	133.8595	133.793	133.5073	133.2931	133.1302	133.7045	133.4391	133.3635	133.3381	133.9229	133.655	133.4225	133.2736	133.4893	133.515
01.02.2006	133.6037	133.6037	133.4014	133.829	133.5828	133.6258	133.5866	133.7591	133.7591	133.7035	133.3981	133.1793	133.0766	133.6171	133.3806	133.3442	133.3214	133.839	133.5438	133.2955	133.1291	133.3905	133.4119
01.03.2006	133.5277	133.5277	133.3139	133.7778	133.5217	133.5518	133.5104	133.678	133.678	133.6333	133.3125	133.1065	133.0514	133.5738	133.3627	133.3298	133.3059	133.7753	133.4565	133.1964	133.017	133.3144	133.3366
01.04.2006	133.4473	133.4473	133.2209	133.721	133.4488	133.4678	133.4299	133.593	133.593	133.5713	133.226	133.0718	133.0289	133.4996	133.3464	133.3155	133.291	133.7032	133.3646	133.0941	132.9017	133.2534	133.2729
01.05.2006	133.3667	133.3667	133.1301	133.6654	133.3748	133.3831	133.3494	133.5085	133.5085	133.4901	133.155	133.0497	133.011	133.4289	133.3343	133.3029	133.2772	133.625	133.2753	132.9953	132.7912	133.1988	133.207
01.06.2006	133.2847	133.2847	133.0379	133.6073	133.3022	133.2957	133.2666	133.4216	133.4216	133.4074	133.0927	133.0299	132.9938	133.3814	133.3229	133.2909	133.2631	133.5452	133.1827	132.8919	132.7003	133.1599	133.1666
02.07.2006	133.2044	133.2044	132.9638	133.5494	133.2493	133.21	133.1892	133.3373	133.3373	133.3281	133.0682	133.0132	132.9782	133.3664	133.3133	133.28	133.2502	133.467	133.0941	132.7928	132.6566	133.1361	133.1415
01.08.2006	133.1313	133.1459	132.9394	133.5168	133.2347	133.1511	133.134	133.2745	133.2745	133.2758	133.0552	133.003	132.9675	133.357	133.3067	133.2726	133.2412	133.4107	133.0261	132.7229	132.6325	133.1215	133.1269
01.09.2006	133.057	133.0833	132.921	133.4792	133.2235	133.0875	133.0722	133.2087	133.2087	133.2181	133.0432	132.9925	132.9559	133.3495	133.2993	133.2651	133.2312	133.3545	132.9612	132.6796	132.6103	133.108	133.1138
01.10.2006	132.9998	133.0282	132.9056	133.4607	133.2152	133.0248	133.0178	133.1507	133.1507	133.1664	133.0323	132.9825	132.9455	133.3434	133.2929	133.2572	133.2211	133.3004	132.9149	132.6566	132.5926	133.0965	133.1027
01.11.2006	132.9645	132.9953	132.8926	133.4452	133.2092	132.9811	132.9804	133.1143	133.1183	133.1367	133.0229	132.9728	132.9346	133.3382	133.2869	133.2494	133.2104	133.2821	132.8719	132.6409	132.577	133.0873	133.0935
01.12.2006	132.9449	132.9758	132.8823	133.4304	133.2044	132.942	132.9647	133.0923	133.096	133.1176	133.016	132.9642	132.9244	133.335	133.2816	133.242	133.2005	133.2613	132.832	132.6287	132.5644	133.0802	133.0866
01.01.2007	132.9293	132.9633	132.8737	133.4184	133.2011	132.9057	132.9525	133.0774	133.0807	133.1053	133.0108	132.957	132.9153	133.3333	133.2775	133.2353	133.1909	133.2403	132.7968	132.6189	132.5542	133.0745	133.0812
01.02.2007	132.9082	132.9832	132.867	133.4388	133.1998	132.8945	132.9622	133.0885	133.0792	133.1145	133.0081	132.952	132.9075	133.3345	133.2747	133.2297	133.1821	133.2538	132.7881	132.6154	132.5463	133.0716	133.0784
01.03.2007	132.8953	132.9767	132.8626	133.4596	133.2009	132.8883	132.9485	133.0862	133.0819	133.1282	133.0093	132.9489	132.9014	133.3386	133.2738	133.2254	133.1745	133.2728	132.789	132.6159	132.5423	133.072	133.0791
01.04.2007	132.8835	132.9788	132.8601	133.4839	133.2041	132.883	132.9403	133.0881	133.0941	133.1403	133.0138	132.9483	132.8968	133.3461	133.2753	133.2223	133.1673	133.2919	132.7905	132.6201	132.5421	133.075	133.0824
01.05.2007	132.8738	132.9793	132.8486	133.5042	133.2033	132.875	132.9295	133.0899	133.0943	133.1381	133.0067	132.9348	132.8734	133.3493	133.2682	133.2062	133.1357	133.2885	132.7716	132.6138	132.5219	133.0756	133.083
01.06.2007	132.865	132.9854	132.8502	133.5277	133.2096	132.8743	132.9255	133.097	133.1008	133.1482	133.0146	132.9411	132.8732	133.3591	133.2753	133.2075	133.1313	133.3012	132.7721	132.6216	132.5299	133.084	133.0916
01.07.2007	132.8362	132.971	132.8154	133.544	133.1967	132.8524	132.9005	133.0904	133.0948	133.1508	133.0091	132.9285	132.849	133.3605	133.2713	133.1917	133.1254	133.3096	132.7569	132.6081	132.513	133.0807	133.0872
01.08.2007	132.822	132.971	132.8076	133.5652	133.1998	132.8452	132.8904	133.0933	133.0981	133.1584	133.0169	132.9308	132.8462	133.3691	133.2778	133.1912	133.1303	133.3221	132.7561	132.6111	132.516	133.0869	133.0926
01.09.2007	132.7983	132.9679	132.7854	133.5828	133.1958	132.833	132.8722	133.0917	133.0969	133.1595	133.017	132.9223	132.8277	133.3743	133.2762	133.1812	133.1146	133.3234	132.7467	132.6078	132.5019	133.085	133.0887
01.10.2007	132.7797	132.9716	132.7754	133.6027	133.1981	132.8303	132.8598	133.0971	133.1012	133.1672	133.0271	132.9236	132.824	133.3853	133.2834	133.1801	133.1142	133.3329	132.7495	132.6177	132.5031	133.0938	133.0952
01.11.2007	132.7479	132.9659	132.7486	133.6212	133.1919	132.8184	132.8328	133.0944	133.098	133.1604	133.0206	132.9036	132.7859	133.3848	133.275	133.1532	133.0717	133.3198	132.7293	132.5916	132.4737	133.0918	133.0897
01.12.2007	132.7299	132.9697	132.7439	133.6417	133.1954	132.8166	132.8211	133.1022	133.103	133.1646	133.0214	132.9027	132.7741	133.3909	133.2776	133.1441	133.0603	133.3215	132.7296	132.589	132.4689	133.1006	133.0974

Table A.3 (continued) Average temperatures in sidetracks for different cases

Dates \ Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01.01.2008	132.713	132.9752	132.7408	133.6627	133.2013	132.8157	132.8117	133.1104	133.1099	133.1712	133.0283	132.9036	132.7663	133.3988	133.2814	133.1396	133.0528	133.3237	132.7308	132.5911	132.47	133.1102	133.1072
01.02.2008	132.6979	132.9798	132.7391	133.682	133.2068	132.8158	132.8041	133.1181	133.1174	133.1773	133.0345	132.904	132.7619	133.4069	133.2853	133.1368	133.0478	133.3256	132.7334	132.5955	132.472	133.1195	133.1169
01.03.2008	132.6836	132.9836	132.7385	133.7	133.2124	132.8159	132.7977	133.1248	133.1233	133.183	133.0406	132.9056	132.7584	133.4156	133.2891	133.1349	133.0443	133.3274	132.7374	132.5998	132.4745	133.1282	133.1255
01.04.2008	132.6694	132.9875	132.7388	133.7193	133.218	132.8163	132.7909	133.1294	133.1288	133.1904	133.0476	132.9086	132.7551	133.4251	133.294	133.1334	133.0417	133.3291	132.7442	132.605	132.4768	133.1373	133.1344
11.04.2008	132.6648	132.9893	132.739	133.7258	133.22	132.8165	132.7885	133.1317	133.1303	133.193	133.0501	132.9105	132.7543	133.4281	133.2955	133.133	133.0409	133.3298	132.7465	132.6073	132.4776	133.1404	133.1375
01.05.2008	132.6565	132.9919	132.7393	133.7387	133.2242	132.8173	132.7843	133.1353	133.1343	133.1984	133.055	132.9136	132.7526	133.4343	133.2983	133.1325	133.0397	133.3314	132.7518	132.6107	132.4788	133.146	133.143
01.06.2008	132.6429	132.9972	132.7396	133.7584	133.2301	132.8192	132.7778	133.1429	133.14	133.2073	133.0653	132.9176	132.7505	133.4457	133.3025	133.1317	133.038	133.334	132.7611	132.6171	132.4805	133.1545	133.1515
01.07.2008	132.6303	133.0025	132.7397	133.7773	133.2351	132.8218	132.7719	133.1509	133.146	133.2168	133.0756	132.9209	132.7486	133.4575	133.3069	133.1306	133.036	133.3364	132.7701	132.6236	132.4823	133.1626	133.1591
01.08.2008	132.6171	133.008	132.7394	133.7945	133.2406	132.8244	132.7658	133.1596	133.1531	133.2268	133.0847	132.9236	132.7462	133.4679	133.3113	133.129	133.0346	133.3384	132.7792	132.6299	132.4837	133.1709	133.1665
01.09.2008	132.6039	133.0065	132.7379	133.7863	133.2434	132.8112	132.7597	133.1557	133.1491	133.2231	133.0884	132.9238	132.7418	133.4722	133.3137	133.1267	133.0335	133.3139	132.7715	132.6303	132.4838	133.1699	133.1673
01.10.2008	132.591	133.0058	132.7346	133.7982	133.2443	132.8063	132.7537	133.1541	133.1476	133.2271	133.0909	132.9222	132.7365	133.4761	133.3145	133.1239	133.0322	133.3115	132.7684	132.6297	132.4819	133.1712	133.1667
01.11.2008	132.5771	133.0096	132.7304	133.818	133.2473	132.808	132.7478	133.1586	133.1519	133.238	133.0963	132.9211	132.7298	133.4857	133.3167	133.1192	133.0295	133.3151	132.7738	132.6331	132.4827	133.1768	133.1714
01.12.2008	132.5634	133.0145	132.7274	133.8363	133.2516	132.8105	132.7425	133.1651	133.1579	133.2489	133.1022	132.9217	132.7237	133.4957	133.3201	133.1143	133.0257	133.318	132.7792	132.6378	132.4834	133.1834	133.1775
01.01.2009	132.5489	133.0198	132.7253	133.8549	133.2566	132.8139	132.7371	133.1724	133.1647	133.2603	133.1085	132.9232	132.7181	133.5061	133.3237	133.1095	133.0212	133.3204	132.7856	132.6444	132.4851	133.1907	133.1842
01.02.2009	132.5349	133.0224	132.7209	133.8621	133.2596	132.8111	132.7288	133.1767	133.17	133.2695	133.1132	132.923	132.7106	133.5154	133.3263	133.1031	133.0142	133.3139	132.7892	132.6483	132.4833	133.1952	133.1883
01.03.2009	132.5221	133.0288	132.7214	133.8743	133.2663	132.8142	132.7252	133.1848	133.1773	133.2776	133.1192	132.9256	132.7076	133.5248	133.3304	133.1003	133.0104	133.3131	132.7932	132.6542	132.486	133.2026	133.195
01.04.2009	132.5077	133.0349	132.721	133.8914	133.2726	132.8193	132.7211	133.1917	133.1849	133.288	133.1256	132.9284	132.7034	133.5349	133.3347	133.0968	133.0054	133.3144	132.8001	132.6606	132.4887	133.2107	133.2025
01.05.2009	132.4935	133.0407	132.7203	133.9073	133.2777	132.8245	132.7166	133.1975	133.1921	133.2962	133.1321	132.9309	132.6986	133.5444	133.3388	133.0926	132.9995	133.3162	132.8075	132.6678	132.4922	133.2183	133.2094
01.06.2009	132.4778	133.0469	132.7195	133.9246	133.2829	132.8301	132.7119	133.2044	133.1995	133.3054	133.1382	132.9334	132.6927	133.5548	133.3431	133.0877	132.9925	133.318	132.816	132.6745	132.4952	133.2258	133.2163
01.07.2009	132.4613	133.0527	132.719	133.9417	133.2881	132.8354	132.7073	133.2107	133.2069	133.312	133.1442	132.9357	132.6862	133.5642	133.3471	133.0819	132.9842	133.3197	132.8249	132.6817	132.4986	133.233	133.2228
01.08.2009	132.4444	133.0585	132.7183	133.9583	133.2934	132.8407	132.7023	133.217	133.2145	133.3194	133.1502	132.938	132.6785	133.5741	133.3513	133.0751	132.974	133.3213	132.8344	132.6886	132.5017	133.2402	133.2294
01.09.2009	132.4269	133.0642	132.7172	133.9745	133.2991	132.8458	132.6971	133.2226	133.2218	133.3279	133.156	132.9402	132.6696	133.5837	133.3553	133.0672	132.9618	133.3225	132.8441	132.6945	132.5044	133.2474	133.2358
01.11.2009	132.391	133.0757	132.7145	134.0047	133.3094	132.8569	132.6861	133.2362	133.2359	133.347	133.167	132.9441	132.6478	133.6025	133.3628	133.0472	132.9688	133.3264	132.8649	132.7067	132.5094	133.2611	133.2476
01.12.2009	132.372	133.0817	132.7122	134.0201	133.3151	132.8625	132.6807	133.2438	133.243	133.3569	133.1726	132.9456	132.6344	133.6117	133.3666	133.0351	132.9744	133.3284	132.8736	132.7129	132.5114	133.2676	133.2533
01.01.2010	132.3514	133.0879	132.7093	134.0359	133.3202	132.8682	132.6749	133.251	133.2526	133.3671	133.1788	132.9467	132.6183	133.6212	133.3707	133.0205	132.9712	133.3307	132.8839	132.7194	132.5135	133.2743	133.259
01.02.2010	132.3305	133.0944	132.7058	134.0512	133.3251	132.8739	132.6692	133.2584	133.262	133.3771	133.1854	132.9473	132.6	133.6303	133.3748	133.0483	132.9634	133.3328	132.8945	132.7254	132.5151	133.2808	133.2646
01.03.2010	132.3106	133.1008	132.7023	134.0653	133.3295	132.8788	132.6641	133.2657	133.2704	133.386	133.1911	132.9472	132.5817	133.6384	133.3777	133.0497	132.9545	133.3346	132.9038	132.7309	132.5163	133.2865	133.2691
01.04.2010	132.2879	133.1075	132.6976	134.0808	133.3347	132.8844	132.6584	133.2723	133.279	133.3954	133.1976	132.9465	132.5591	133.6472	133.3807	133.0476	132.943	133.3372	132.9141	132.7387	132.5175	133.2925	133.2738
01.05.2010	132.2652	133.1132	132.6923	134.0946	133.3395	132.8901	132.6527	133.2781	133.2869	133.4049	133.2037	132.945	132.535	133.6557	133.3834	133.056	132.9305	133.34	132.9241	132.7462	132.5184	133.2981	133.2781
01.06.2010	132.2412	133.1189	132.685	134.1087	133.3442	132.8965	132.6466	133.2843	133.2952	133.4148	133.21	132.9427	132.5082	133.6644	133.3857	133.0592	132.9164	133.3437	132.9347	132.754	132.5194	133.3036	133.2817
01.07.2010	132.2167	133.1251	132.6762	134.1227	133.3487	132.9029	132.6404	133.2904	133.3028	133.4247	133.2163	132.9396	132.5369	133.6729	133.3877	133.0593	132.9028	133.347	132.9449	132.7613	132.52	133.3085	133.285
01.08.2010	132.1903	133.1315	132.6649	134.1368	133.3532	132.9099	132.6336	133.2967	133.3102	133.4351	133.2231	132.9357	132.55	133.6817	133.3893	133.0576	132.8883	133.3497	132.9548	132.7684	132.5201	133.3133	133.2876
01.09.2010	132.1623	133.1381	132.6507	134.1512	133.3578	132.9168	132.6267	133.3032	133.3165	133.4451	133.2301	132.9305	132.5552	133.6904	133.3901	133.0556	132.874	133.3515	132.9644	132.7749	132.5195	133.3174	133.2895
01.10.2010	132.2055	133.1445	132.6346	134.1652	133.3623	132.9236	132.6193	133.3095	133.3232	133.4539	133.2359	132.924	132.5554	133.6987	133.3899	133.0538	132.8602	133.3539	132.9728	132.7806	132.5184	133.3206	133.2905
01.11.2010	132.2255	133.1511	132.6144	134.1792	133.367	132.9305	132.6112	133.3153	133.3295	133.4634	133.2418	132.9157	132.5544	133.7071	133.3889	133.0516	132.846	133.3572	132.9825	132.7863	132.5165	133.3229	133.2899
01.12.2010	132.2311	133.1576	132.5914	134.193	133.3715	132.9372	132.6027	133.3212	133.3359	133.4729	133.2475	132.9057	132.5532	133.715	133.3869	133.0491	132.8327	133.3605	132.9921	132.7915	132.5141	133.3235	133.287

APPENDIX B

PVT PROPERTIES OF SECTOR MODEL

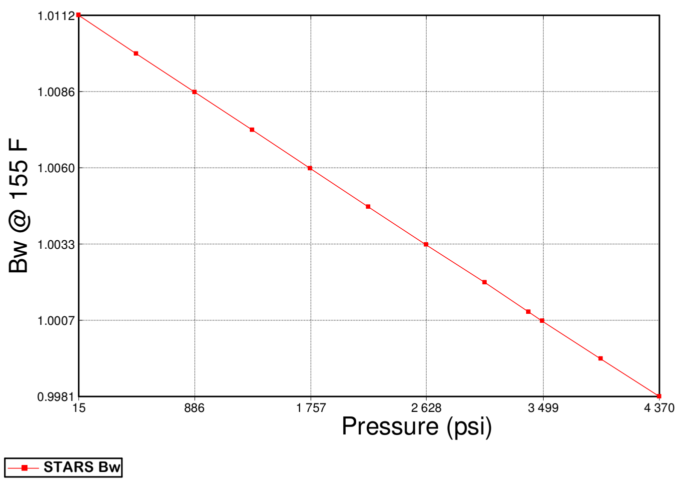

Figure B.1 Water formation volume factor at 155°F

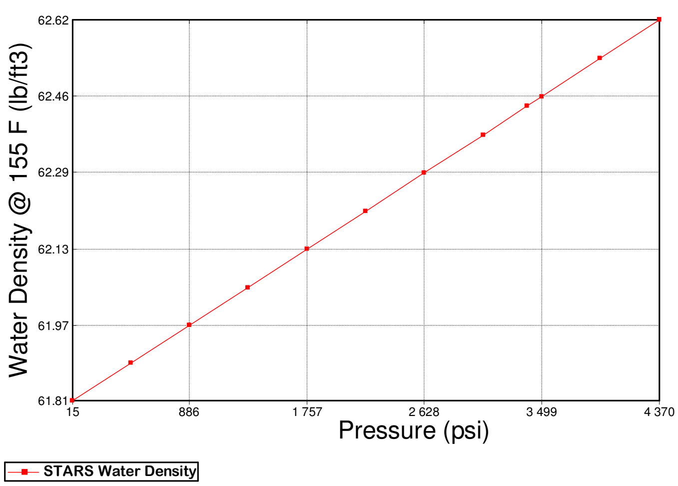

Figure B.2 Water density at 155°F

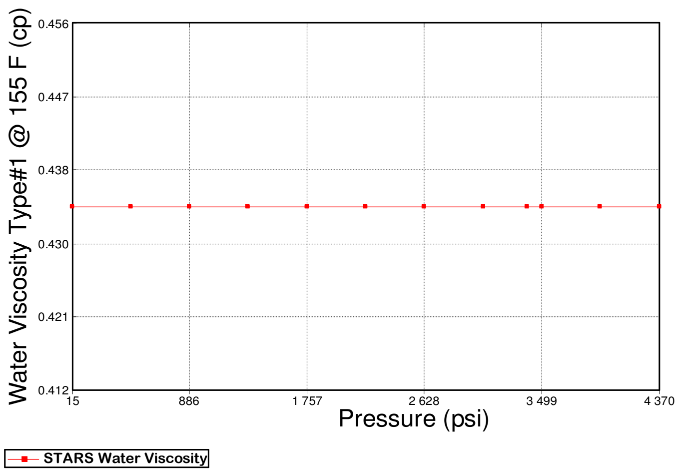

Figure B.3 Water viscosity at 155°F

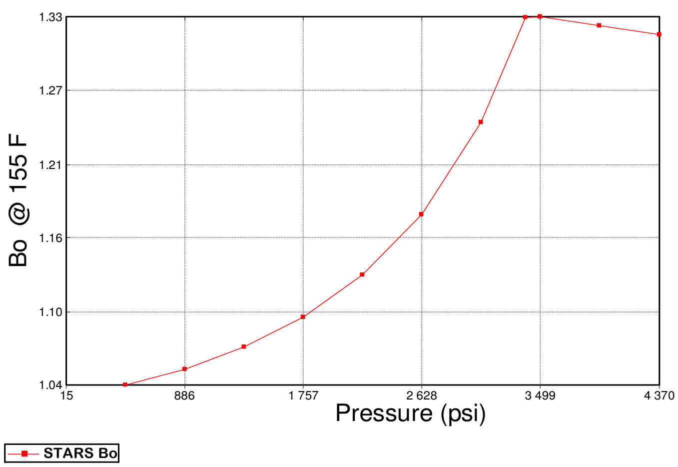

Figure B.4 Oil formation volume factor at 155°F

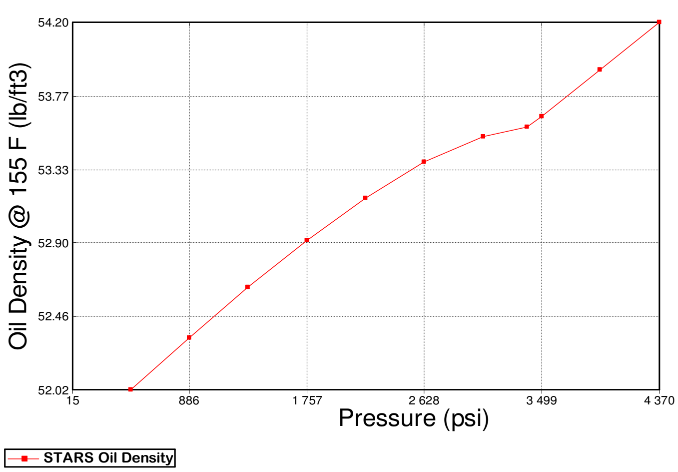

Figure B.5 Oil density at 155°F

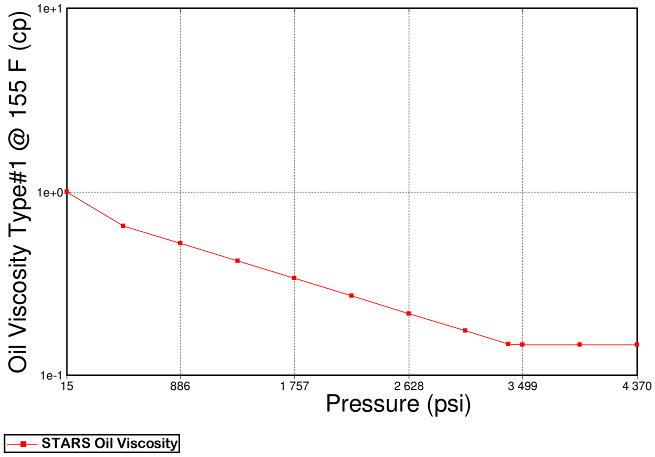

Figure B.6 Oil viscosity at 155°F

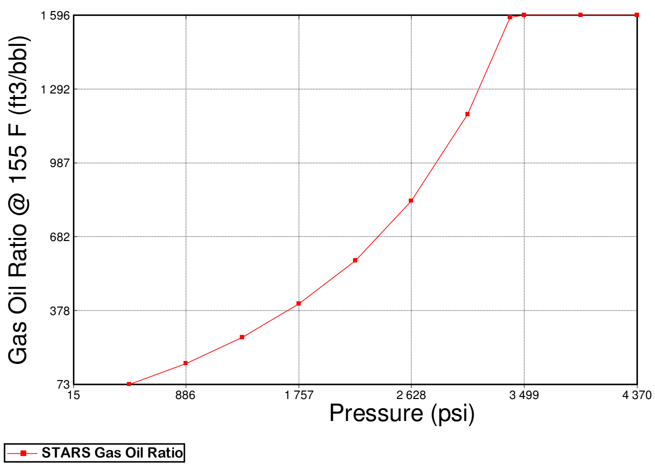

Figure B.7 Gas-oil ratio at 155°F

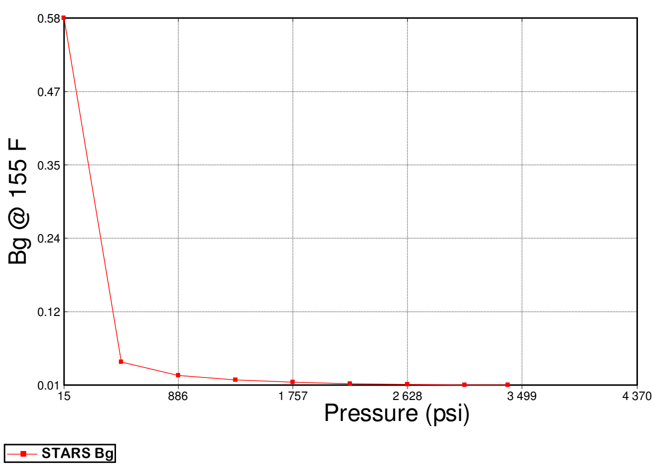

Figure B.8 Gas formation volume factor at 155°F

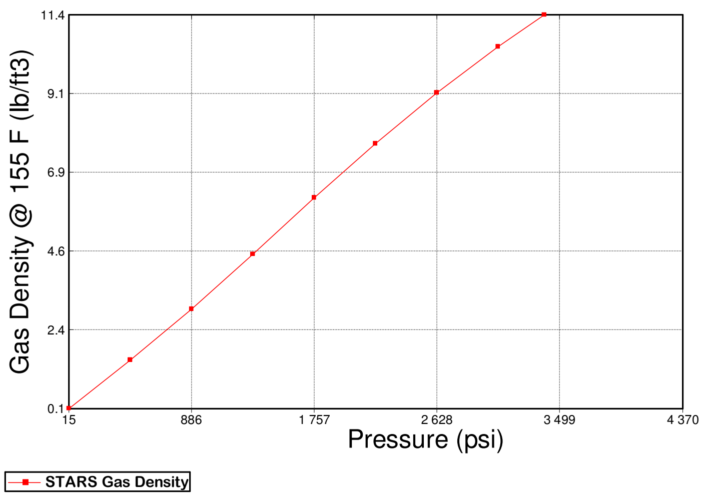

Figure B.9 Gas density at 155°F

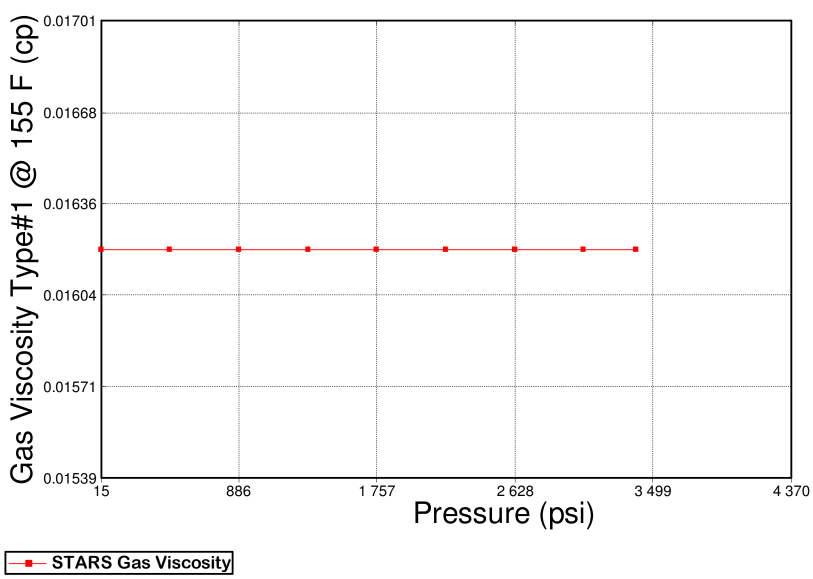

Figure B.10 Gas viscosity at 155°F

APPENDIX C

3-D TEMPERATURE DISTRIBUTIONS AT THE END OF SIMULATION FOR OTHER CASES

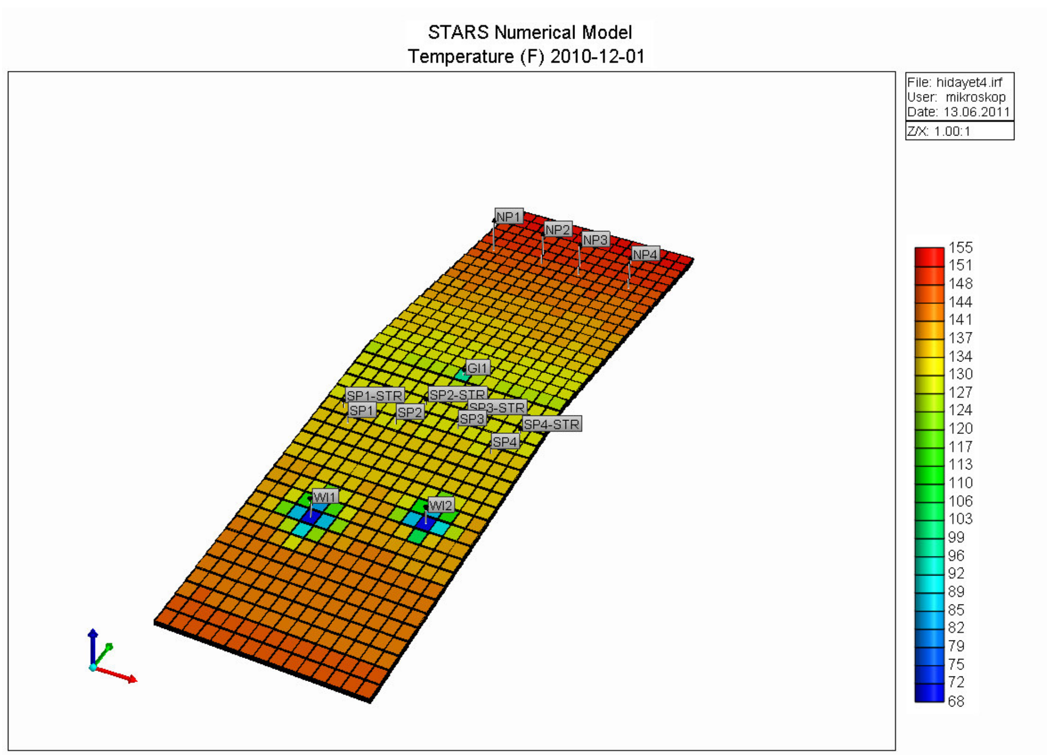

Figure C.1 3-D temperature distributions for case 3

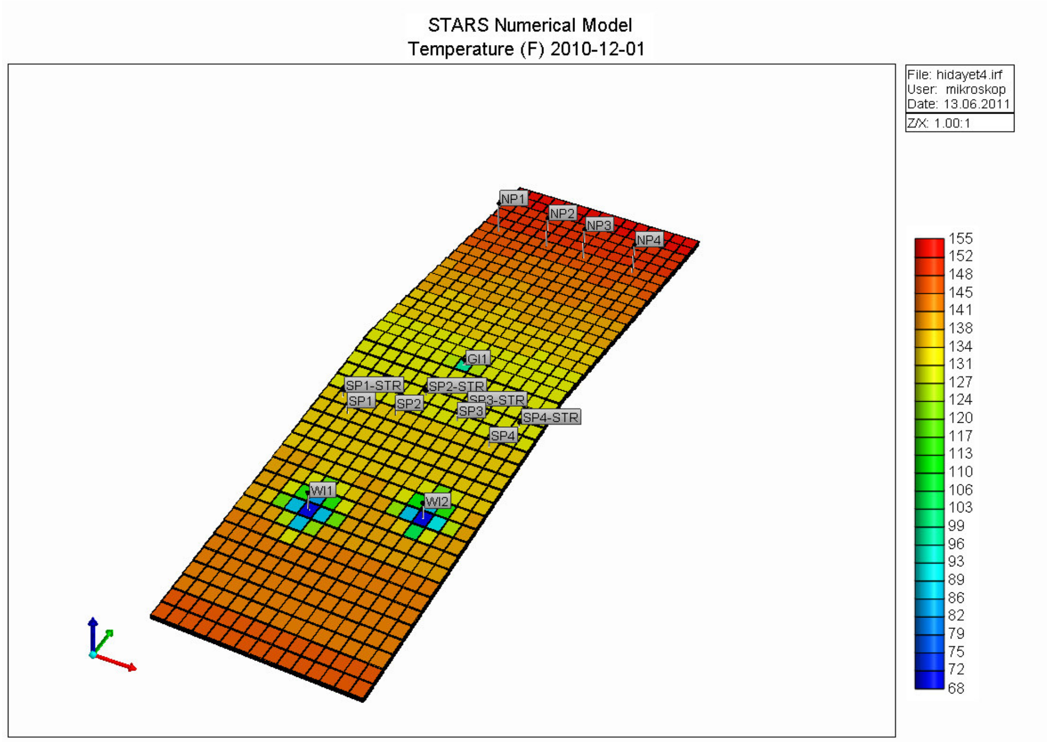

Figure C.2 3-D temperature distributions for case 5

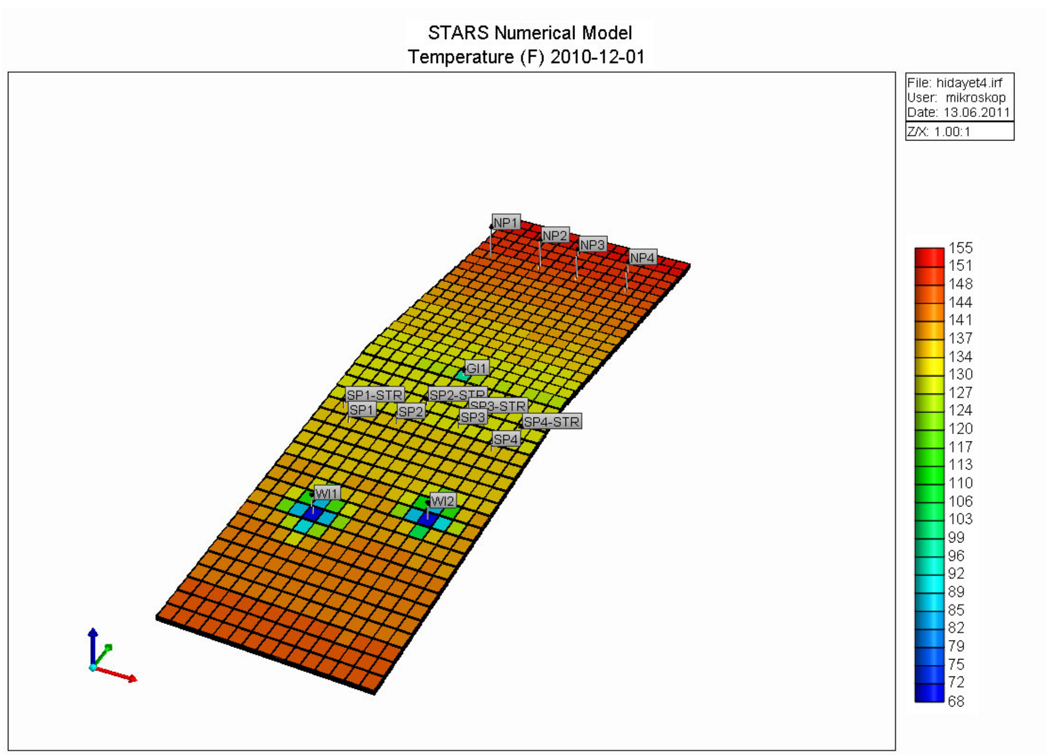

Figure C.3 3-D temperature distributions for case 6

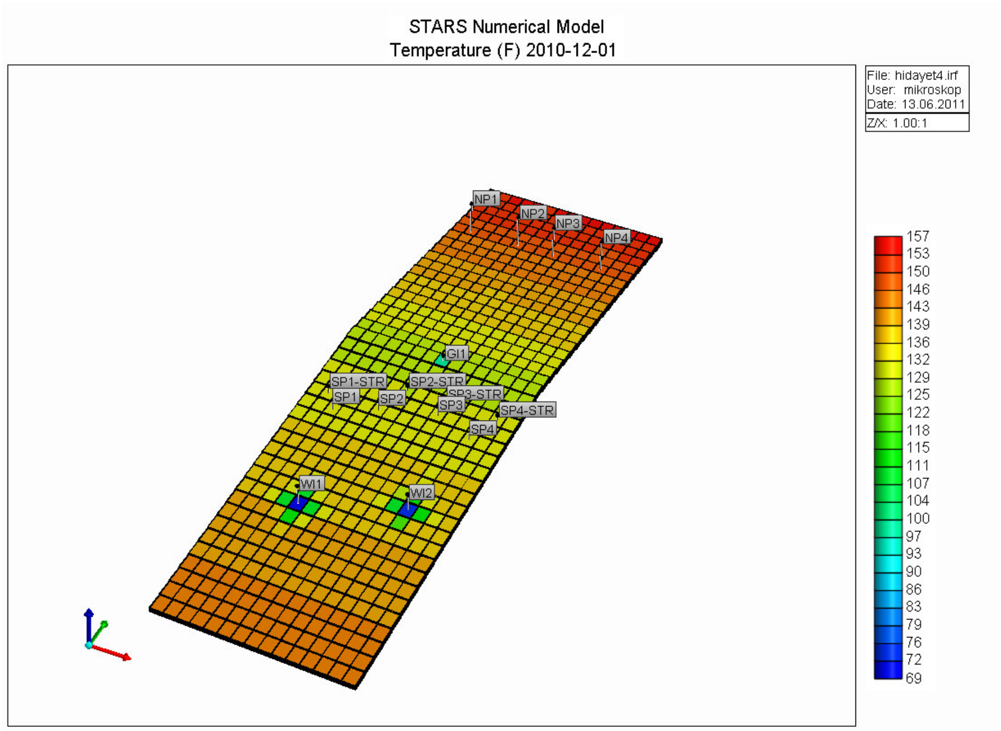

Figure C.4 3-D temperature distributions for case 7

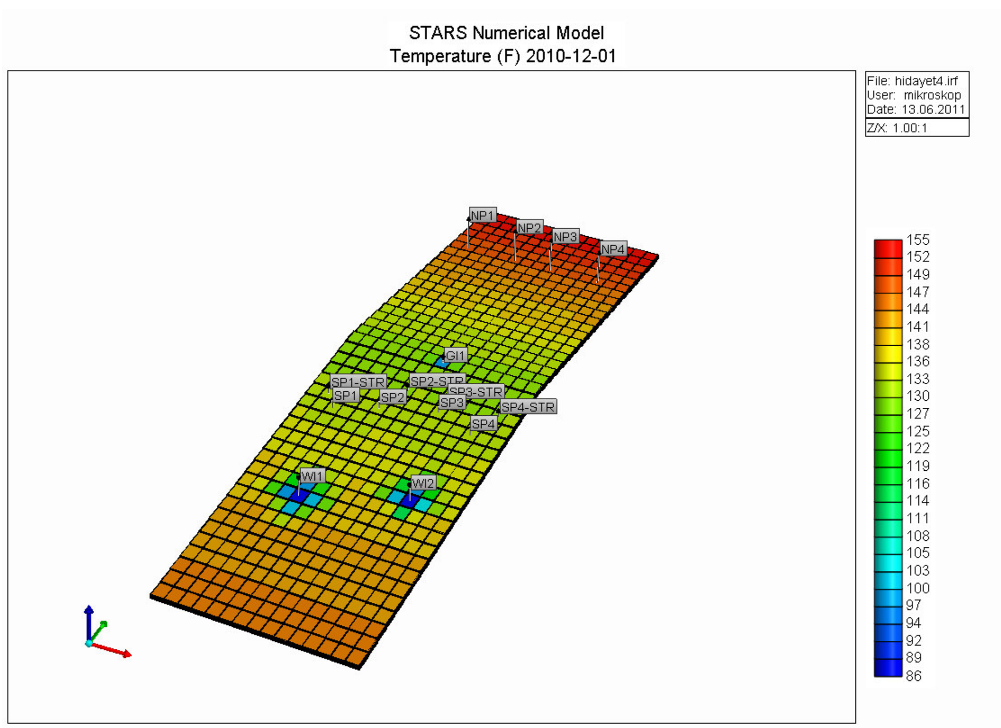

Figure C.5 3-D temperature distributions for case 8

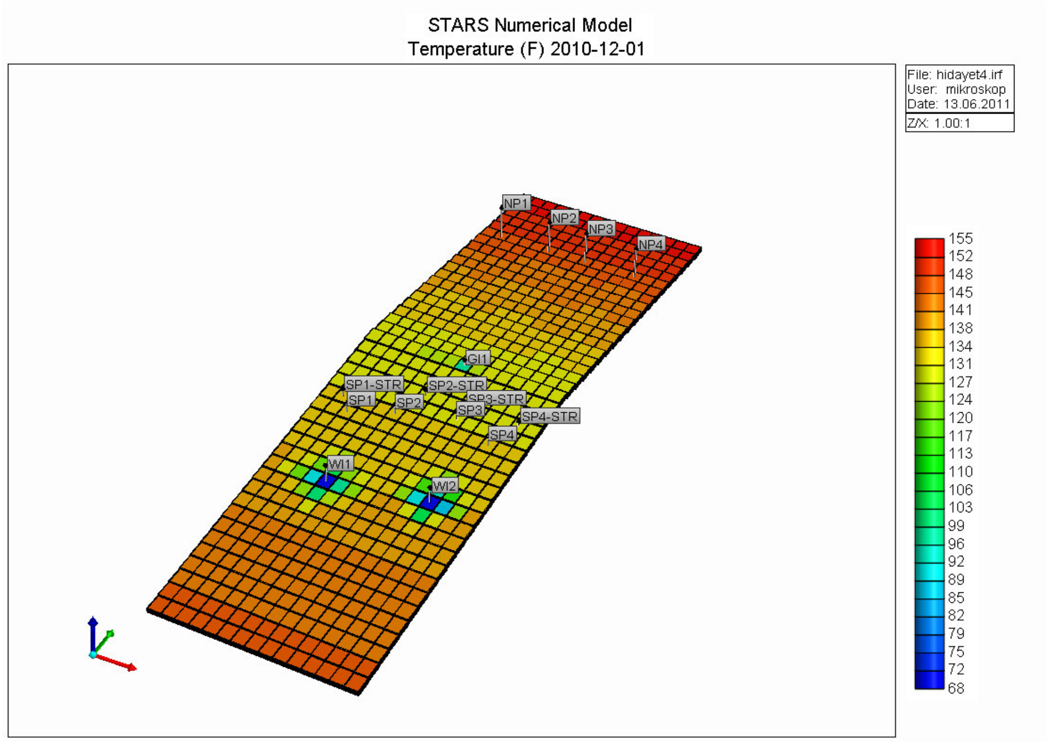

Figure C.6 3-D temperature distributions for case 9

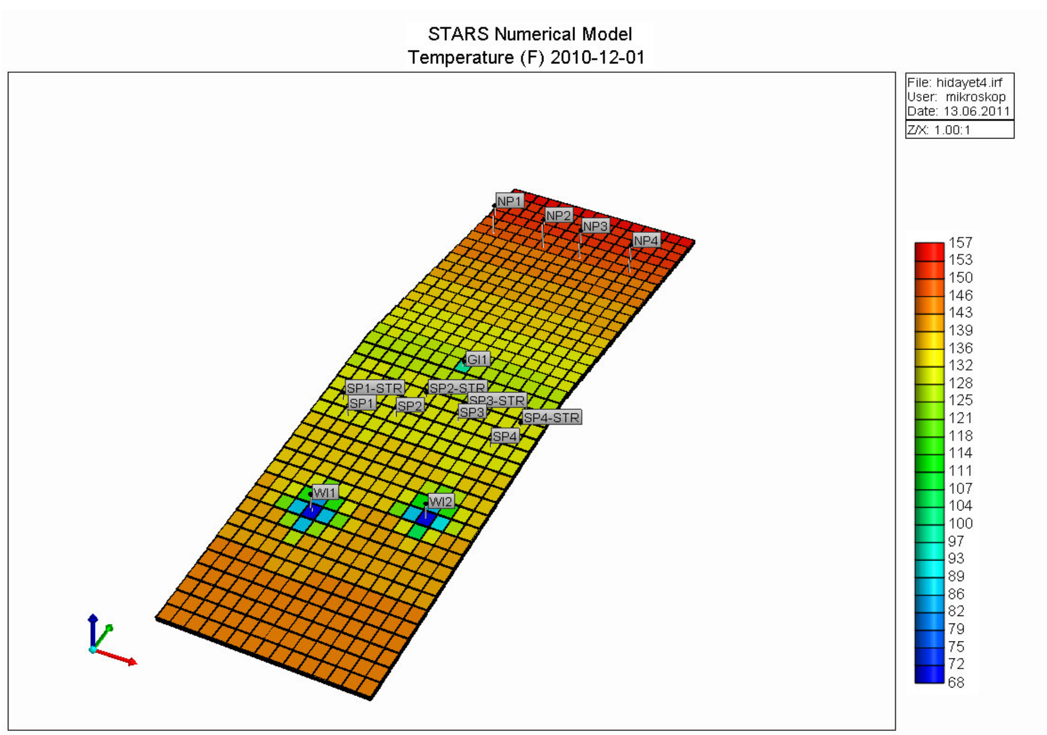

Figure C.7 3-D temperature distributions for case 10

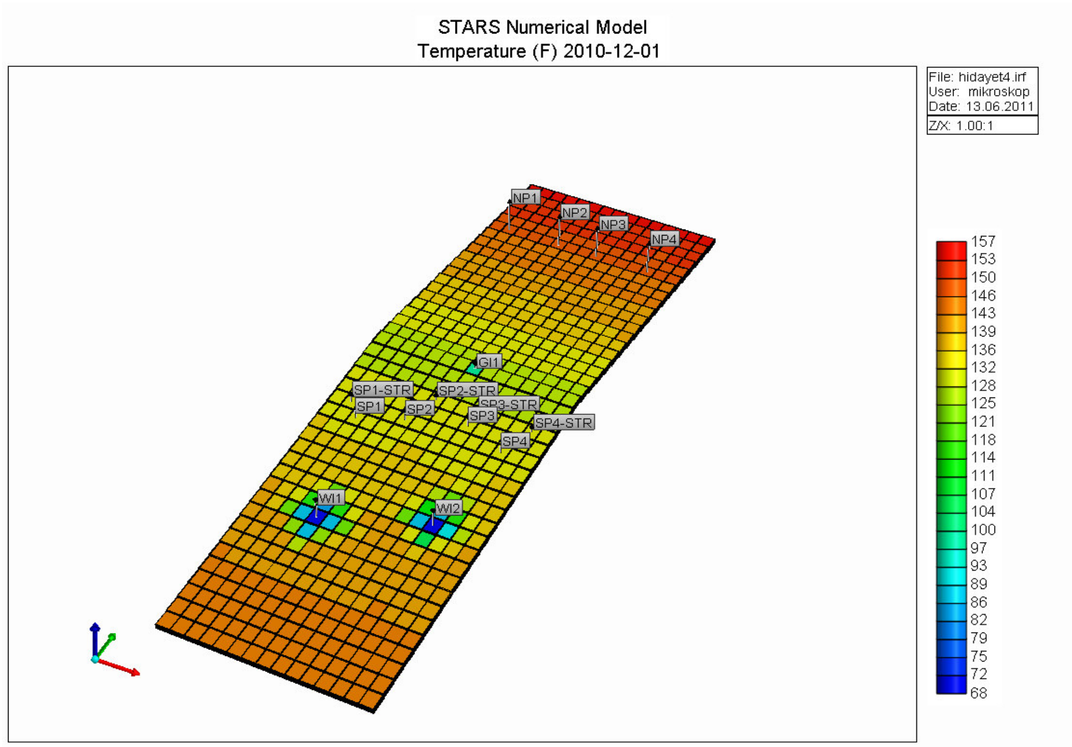

Figure C.8 3-D temperature distributions for case 11

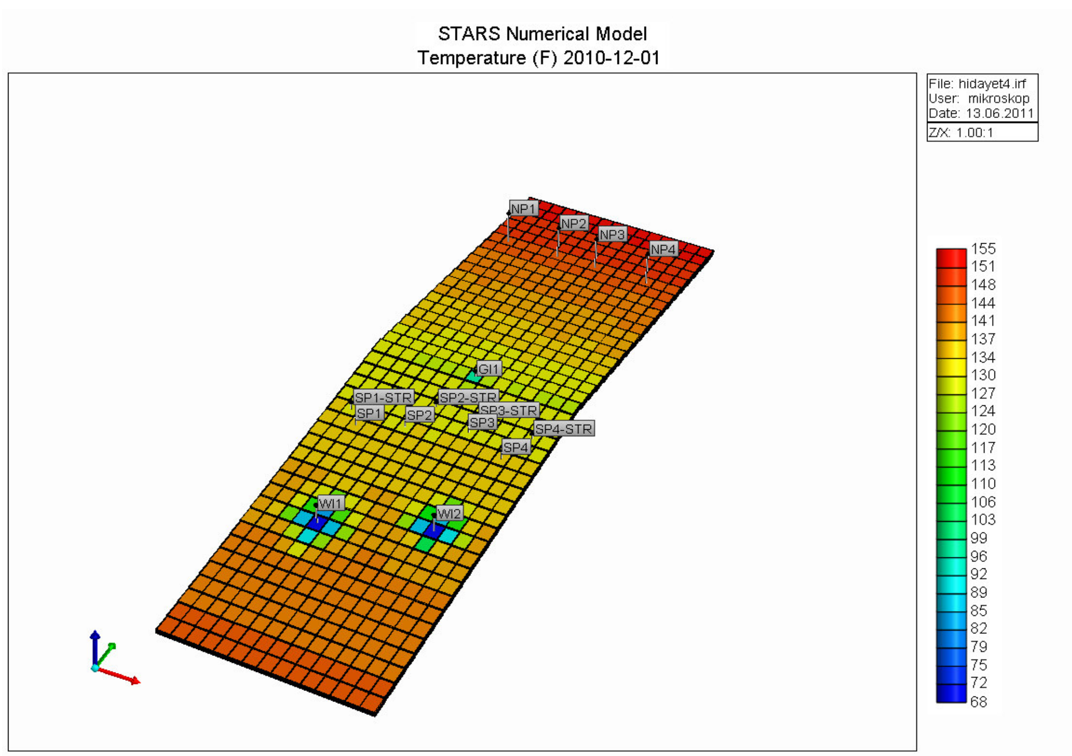

Figure C.9 3-D temperature distributions for case 12

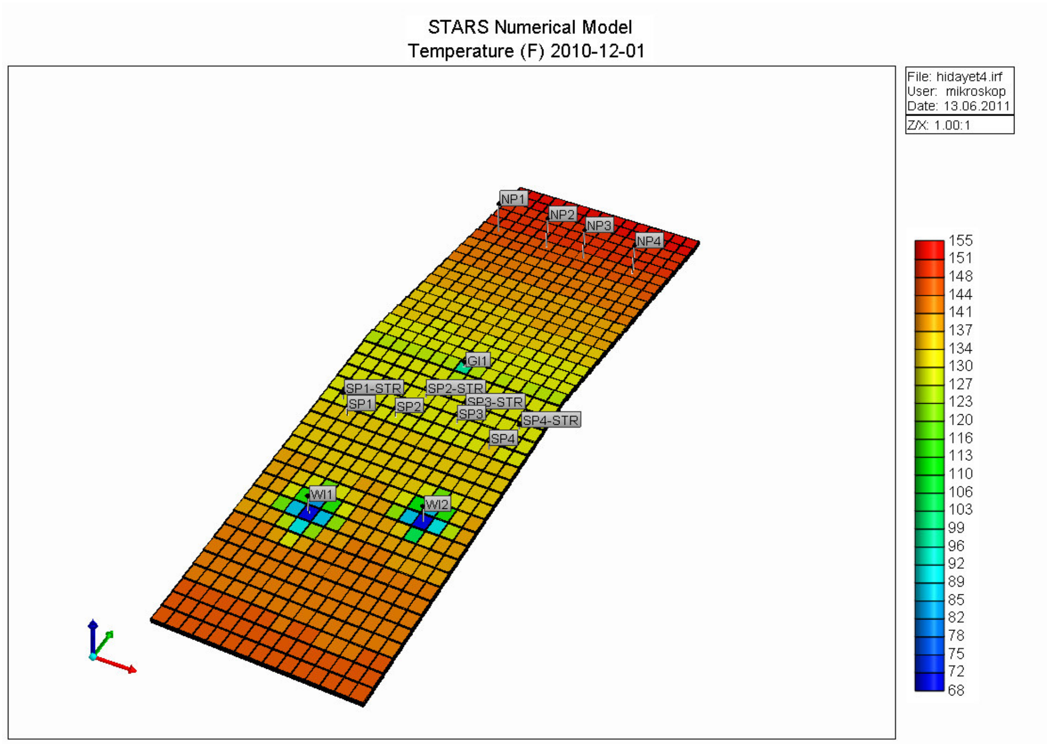

Figure C.10 3-D temperature distributions for case 13

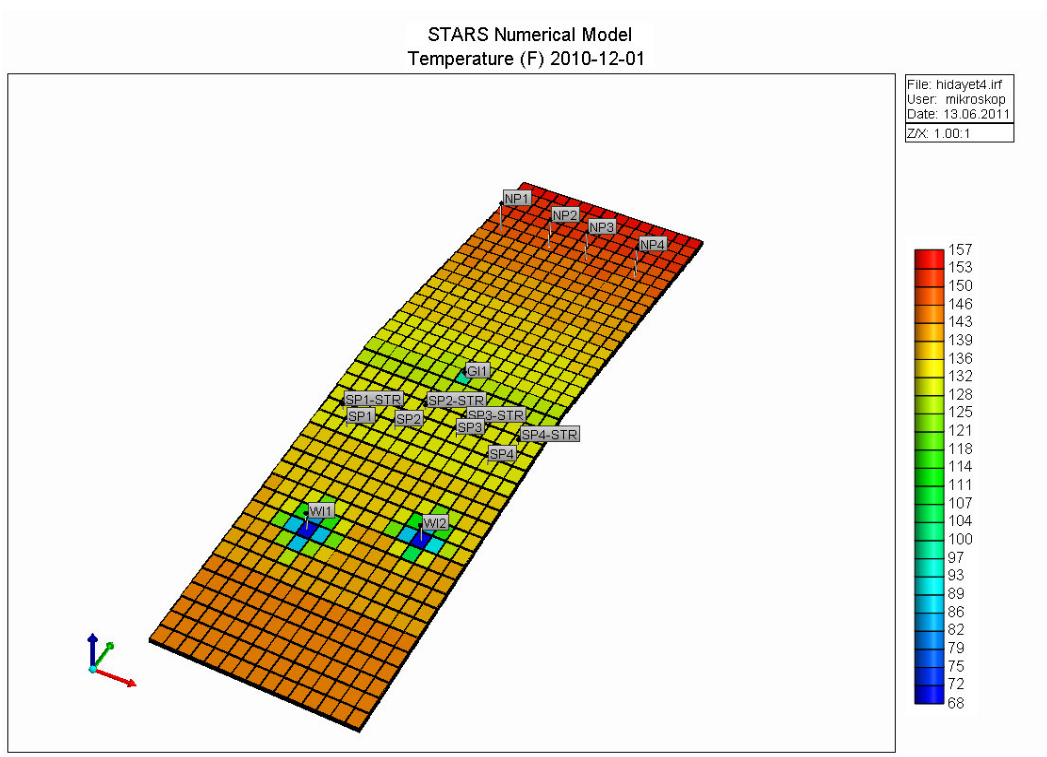

Figure C.11 3-D temperature distributions for case 14

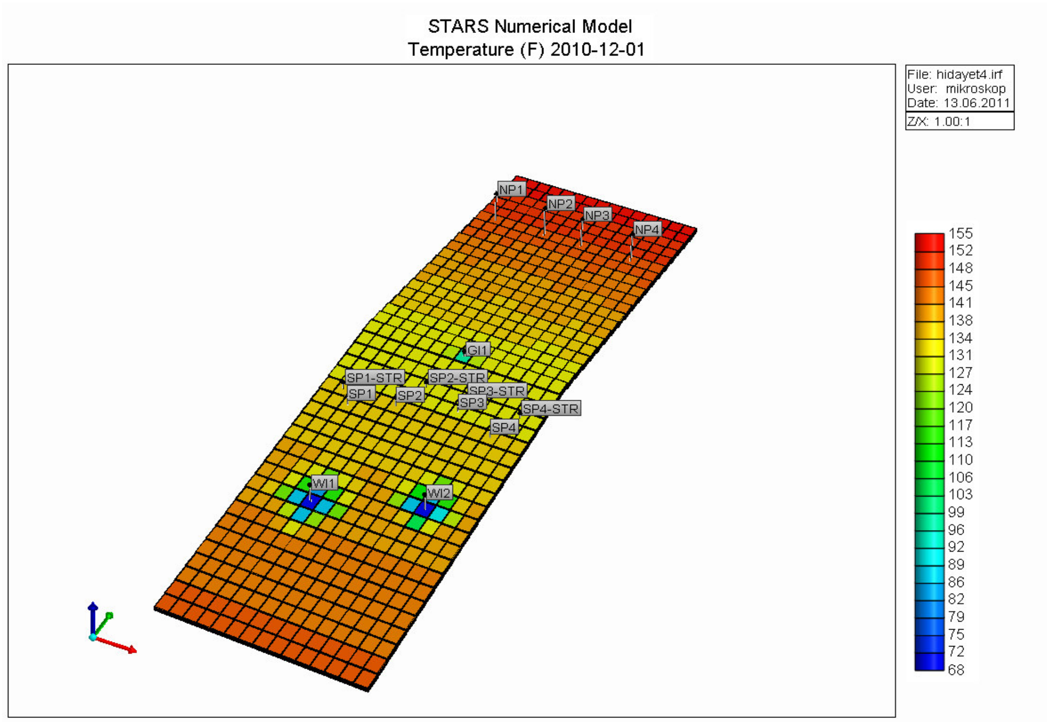

Figure C.12 3-D temperature distributions for case 15

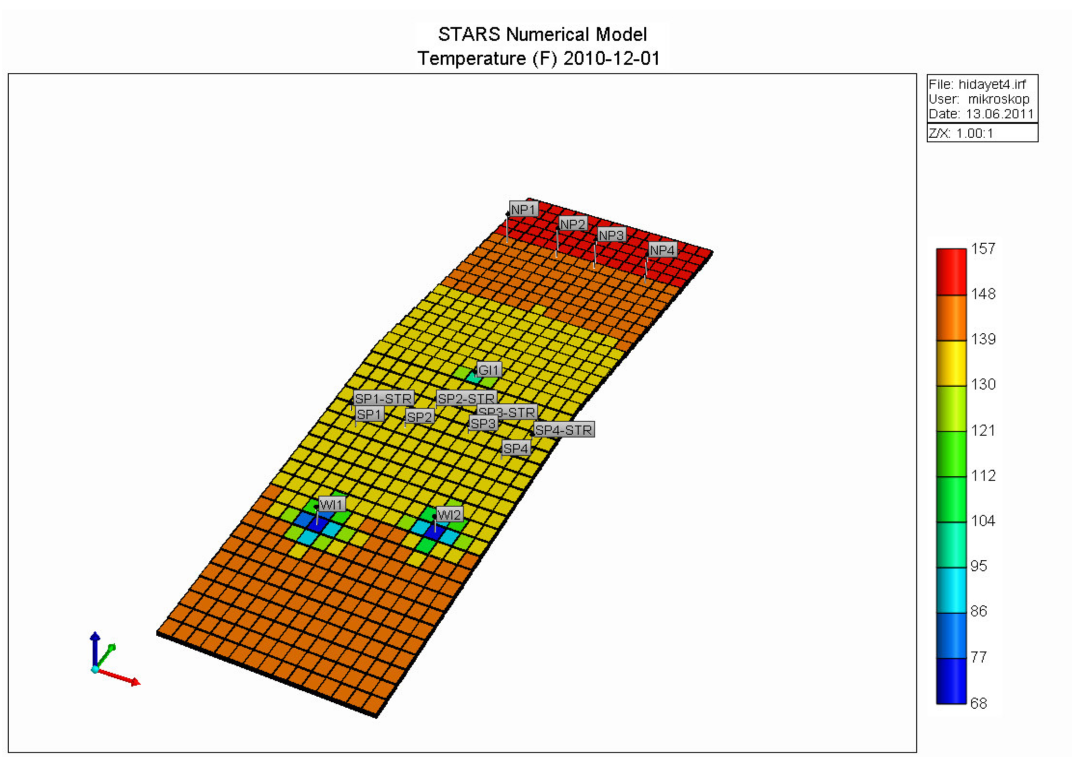

Figure C.13 3-D temperature distributions for case 16

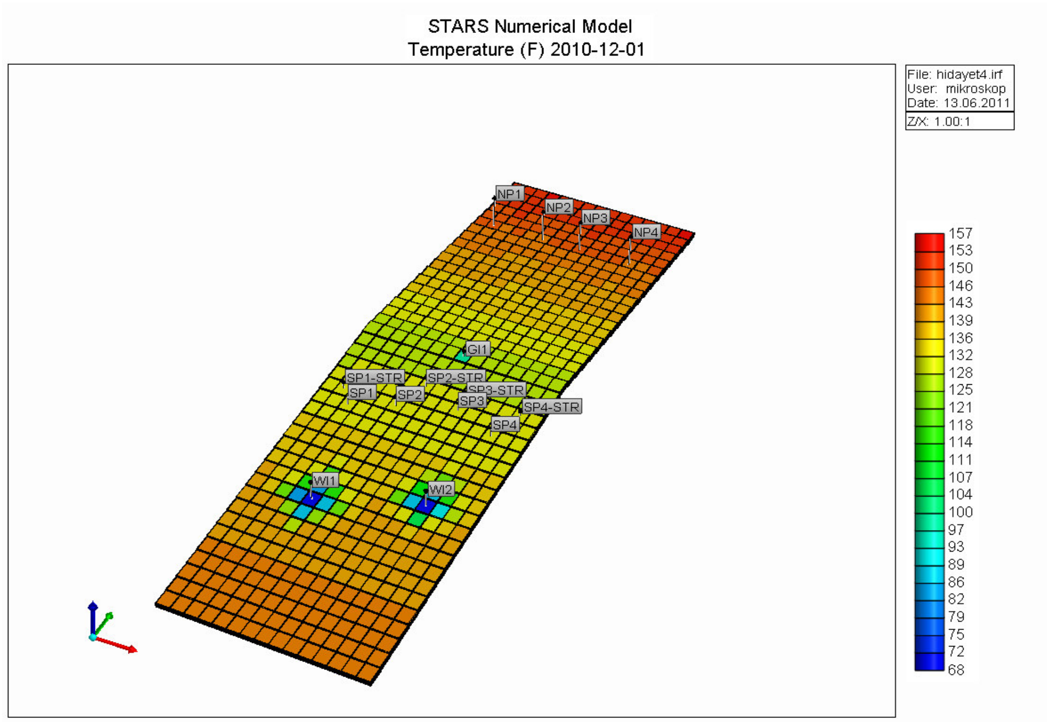

Figure C.14 3-D temperature distributions for case 17

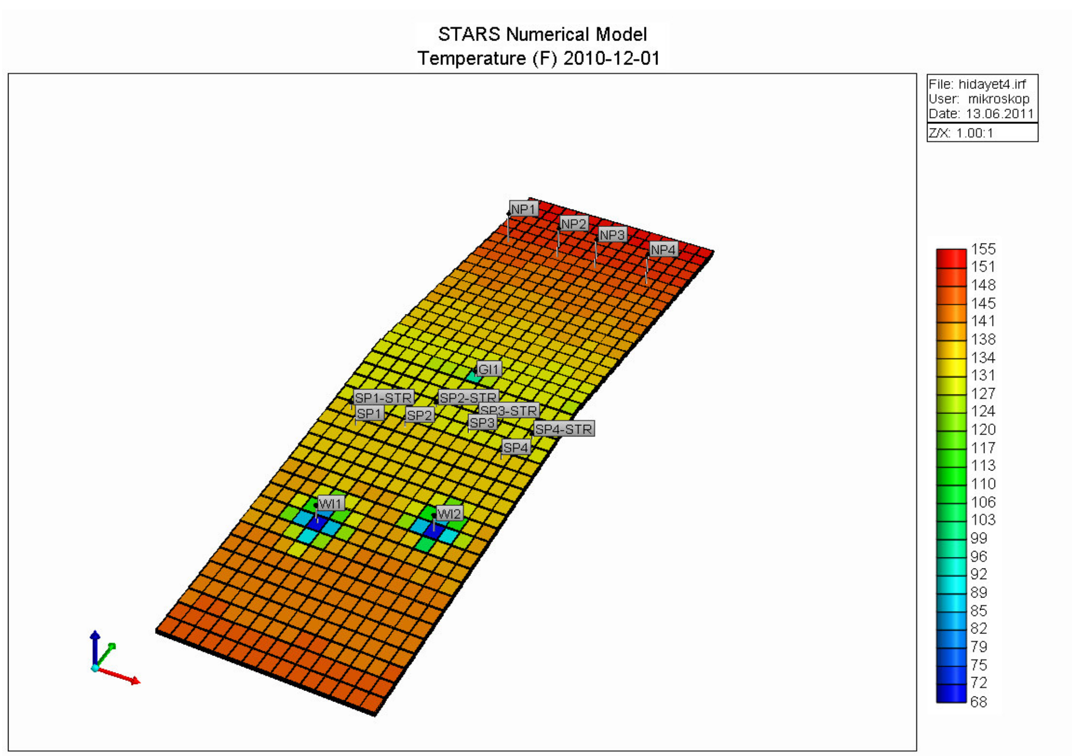

Figure C.15 3-D temperature distributions for case 18

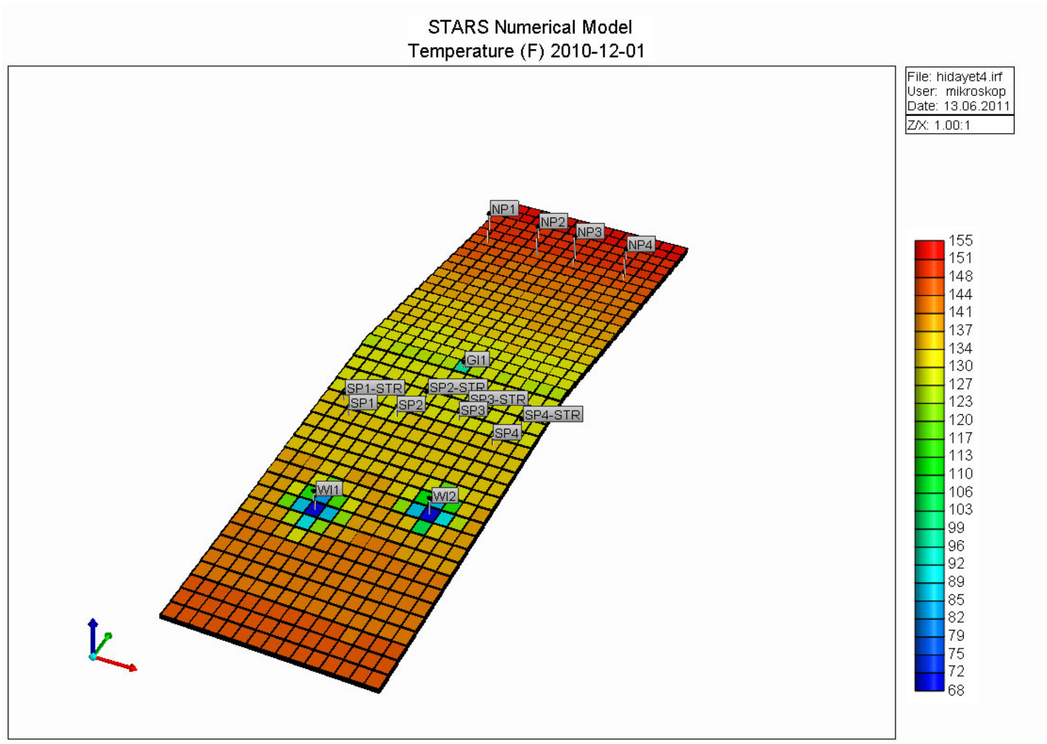

Figure C.16 3-D temperature distributions for case 19

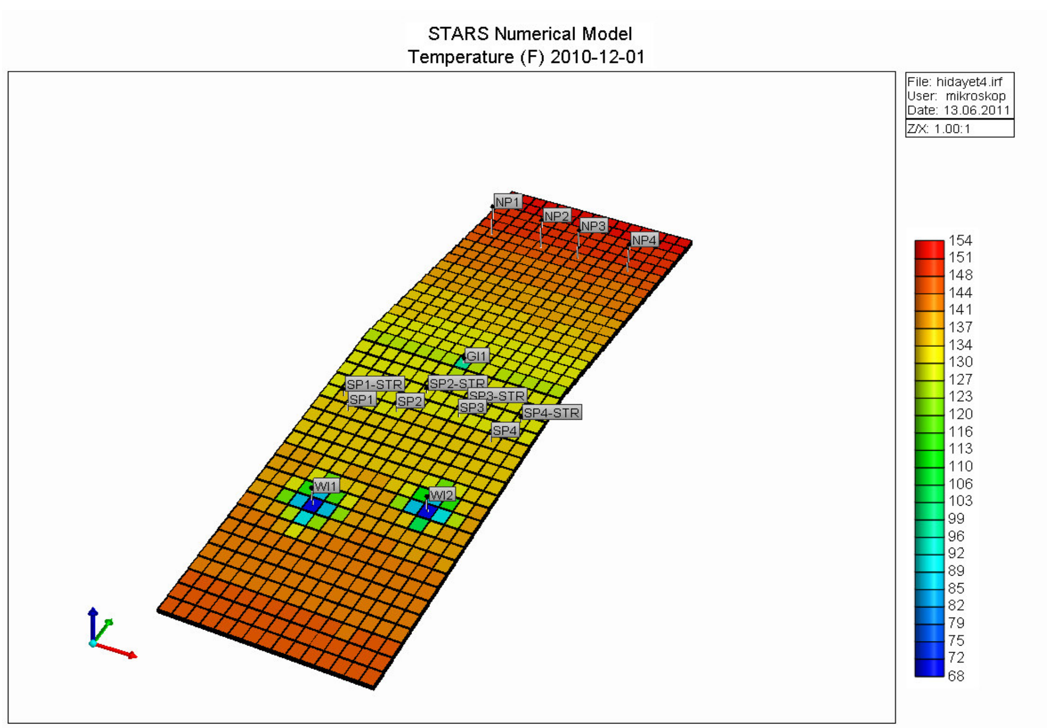

Figure C.17 3-D temperature distributions for case 20

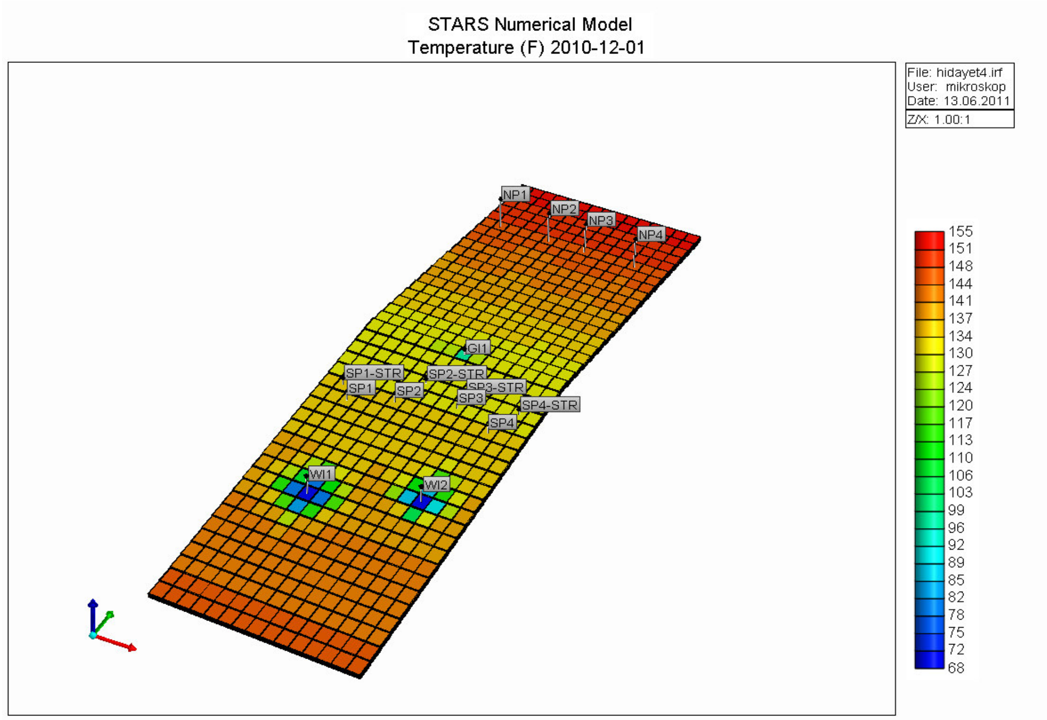

Figure C.18 3-D temperature distributions for case 22

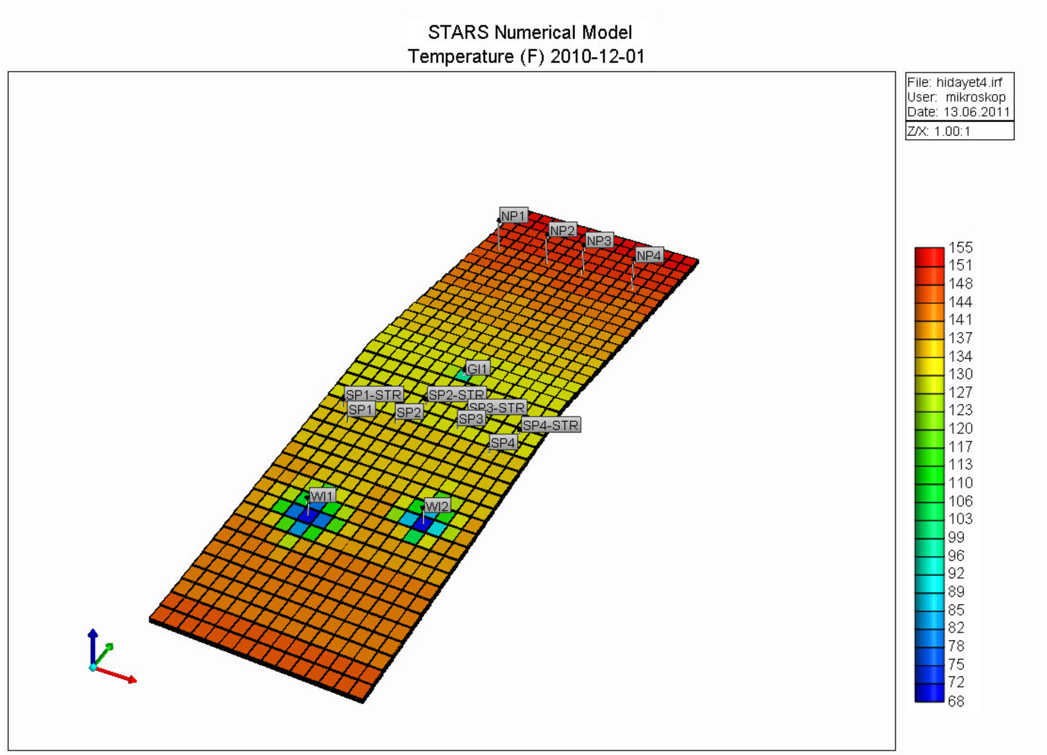

Figure C.19 3-D temperature distributions for case 23