Downflows in Wells at the Mak-Ban Geothermal Field, Philippines

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ABSTRACT

The productive reservoir in the Mak-Ban Geothermal Field has been found to include both “shallow” and “deep” reservoirs that are separated by a low permeability formation called the Andesite Lava Marker (ALM) (also known as the LimBrigo barrier), which occurs at ~4,500 ft (~1,400 m) below sea level (bsl). The majority of the production wells are completed in and produce from both reservoirs and the separation of the two reservoirs has been manifested by the existence of intra-zonal flows under shut-in conditions. Historically, the intra-zonal flows have been seen as upflows and the overall production has been very stable. However, in recent years, it has been noted that there have been significant negative impacts to production which are believed to be caused by a relative increase in cooler fluid inflow from the shallow reservoir. This has resulted in both flow instability and downflows in wells under flowing conditions that have caused step-drops in individual well production capacity.

To evaluate the impact of the shallow fluid entries in more detail, recent downhole Pressure-Temperature-Spinner (PTS) and Pressure-Temperature (PT) surveys have been analyzed and wells that have developed downflow in their wellbores were identified. The downflows are easily identified because they are nearly isothermal and register negative spinner velocity. The mass flow rate and enthalpy of the downflowing fluid were estimated and used to assess its impact on the deep reservoir. Downflow temperatures range from 207°C to 250°C. Although this is not much cooler than the typical reservoir temperatures of 280°C to 320°C, the hydraulic head and higher density of the downflow have the capability to suppress production from the deep entry zones and this were determined as the main cause of the reduction of productivity in affected wells. The individual well downflows were calculated to be in the range of 10 to 200 kph (1.2 to 25.2 kg/s) which was considered too small to significantly cool down the deep reservoir or to have a significant impact on neighboring wells, given that the fluid is also injected at different depths in the deep reservoir. Numerical modeling studies show that there is little or no impact on neighboring wells provided the feed zones are more than 400 ft (122 m) apart. It is also possible that the mass flow rate of the downflowing fluid will increase as mass withdrawal from the deep reservoir continues and a separate numerical modeling study is being undertaken to address this issue. To better understand the dynamics of the downflow, both geochemical and production/injection data were evaluated. Current analysis showed that there is not a single model to explain why the downflows have started in individual wells, therefore, each well needs to be reviewed on a case-to-case basis.

To mitigate the downflows, alternatives are being investigated to determine what can be done to isolate the cooler fluid inflow zones and stop the downflows. Zonal isolation, where the slotted production liner is cut and pulled and replaced by a cemented blank casing, is the preferred method but this is not always possible due to well completion issues. It will be necessary to also develop alternative technologies, such as injection of resins or similar products to plug off the inflow zones located behind the liners. Although this may not result in a full plugging of the zone, it may reduce the inflow to the point where the well can continue to flow from the deep reservoir.

1. INTRODUCTION

The Mak-Ban (Makiling-Banahaw, also known as Bulalo) Geothermal Field (Capuno, *et al*. 2010) is located about 70 km southeast of Manila. The field has been on commercial production since 1979 (Figure 1), when the first 55 MW turbine generator was commissioned and by 1984 the installed capacity had reached 330 MW, with the addition of five 55 MW units. In the early to mid-1990s, an additional 80 MW of steam turbine capacity (i.e., 40 MW baseload and 40 MW standby) and 15.73 MW of binary units were also added. In 2002-2006, the initial four units installed were rehabilitated and their capacities were increased to 62.3 MW each, bringing the total installed capacity to 458.53 MW. The base-load capacity of Mak-Ban is considered to be 402 MW with 40 MW on stand-by. The binary plants, which have not been in operation since 2003, are not considered to be part of the baseload at the present time.

As shown in Figure 1, the “steam field capacity” has normally been maintained at or above the power plants’ design requirements by drilling make-up wells at various times. However, the last make-up well drilling campaign occurred in 2002 to 2004 when a total of 10 wells were drilled. In recent years, there has been a continuing decline in steam field capacity and average field generation, as of April 2014, is about 240 MW.

Many of the production wells in the Mak-Ban field are completed in and produce from both the “shallow” and “deep” reservoirs. These two reservoirs are separated by a low permeability formation called the Andesite Lava Marker (ALM) located at ~4,500 ft (~1,400 m) below sea level (bsl). This barrier limits the interaction between the reservoirs except through the wells and this has resulted in intra-zonal flows. In the past, this was usually manifested as up-flows, due to the two-phase conditions that can develop in the deep reservoir but more recently, cooler fluid inflows have been occurring from feed zones in the shallow reservoir which resulted in well instability and caused downflows to occur in a number of wells.

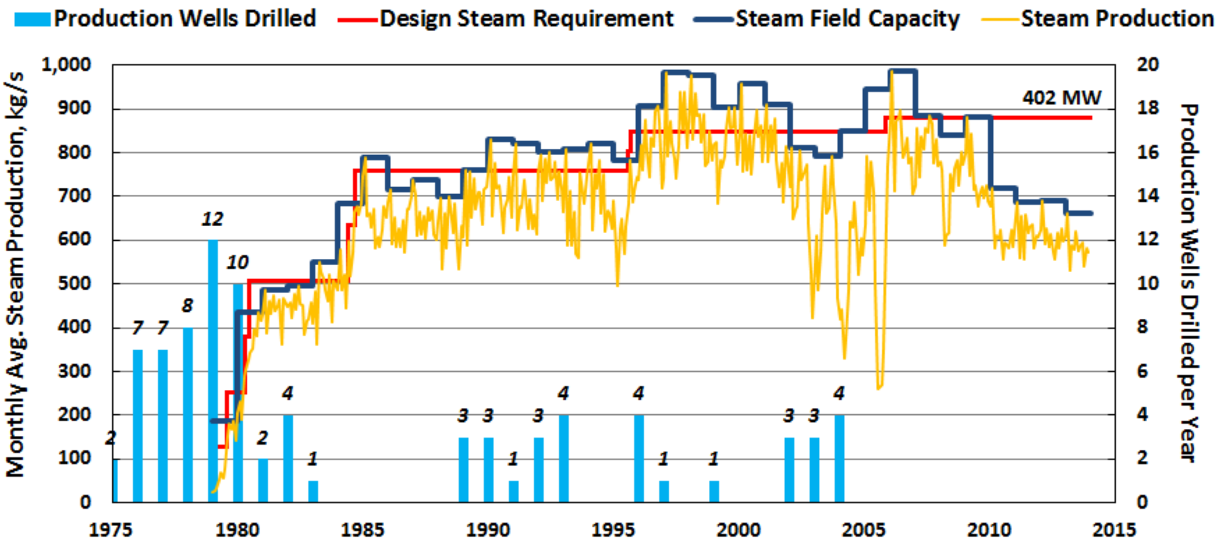

Figure 1: Field Production History Showing Production and Make-Up Well Drilling, Steam Field Capacity, Actual Steam Produced and Steam Required to Fully Load the Power Plants.

Significant negative impacts to production due to well instability and downflows have only been observed in recent years, starting with a drop in production noted in 2007 that was associated with small changes in steam production in a large number of wells. This was the first time that production in the Mak-Ban reservoir had been affected in this way and it brought into sharp focus the potential for productivity loss by (cooler) fluids entering the wells and causing instability. When production wells are negatively affected by inflows of shallow fluid, they can manifest a wide range of behaviors depending on the extent of the fluid encroachment. The usual patterns of behavior are as follows:

1) Increased brine production: When the slightly cooler fluids initially flow into the wellbore, they tend to be carried by the flow momentum from the deep feed zones and brine rate will increase without showing any significant change in well performance.

2) Flow fluctuations (no downflow): As the recharge fluid influx increases, it tends to build a water column in the wellbore. This will initially be resisted by the pressure from the deeper region. Fluctuations will be seen in the flowing wellhead pressure and, possibly, in the flow behavior as long as the struggle for dominance is being fought.

3) Wells become all-steam producers (downflow is occuring): If the build-up of the hydraulic column in the wellbore can overcome the pressure in the deeper zones, downflow will eventually be achieved and the well may change to an all-steam producer and this will generally result in a significant loss of productivity. Production wells then produce ≤20 kph (2.5 kg/s) steam as they are only producing from the shallow steam zone. In some cases, the steam production is less than expected, based on pre-downflow mass balance calculations, indicating that the cool inflows may also be affecting the steam zone productivity.

4) Well suddenly dies on line: This is the case when recharge fluids totally overcome the steam zone where productivity of the well is entirely cut-off.

In 2011 (Vicedo, 2012) and 2012, there were drops in production of ~400 kph (50 kg/s) each year; the majority of which were due to a small number of "problem" wells where downflows were determined to be the major cause. Lim (2012) identified 32 wells, producing a total of 1,100 kph (~140 kg/s) steam, that had or were at risk of losing production due to downflows; thus it is a significant threat to existing base production. In some wells, it may be possible to mitigate this threat by working over the wells to plug the inflow zones by cutting and pulling the slotted liner and replacing this with cemented blank casing, however, completion issues in other wells make it necessary to develop or adapt new technology, such as the use of diverters and epoxy-type materials, to provide a way of plugging zones behind the slotted liner.

The deep reservoir could also be at risk if the amount of downflow in the wellbores becomes significant or if the downflowing fluids are able to enter the deep reservoir through the ALM in significant quantities. This could happen if the pressure differential between the shallow and deep reservoirs reaches a critical level but to date, there is no evidence that this is a significant issue. However, continued surveillance, such as running regular PTS surveys and evaluating results from downhole chemical sampling and the chemical data from deep wells, will be needed to ensure that this issue can be addressed in a timely manner if it becomes more significant.

2. DOWNFLOWS IN WELLS

Since 2005, 23 two-phase producers in Mak-Ban have turned into all-steam producers resulting in an overall loss in steam supply of ~800 kph (~100 kg/s) or the equivalent of 44 MW. From analysis of downhole PT and PTS surveys, it was determined that 15 of the wells were affected by fluid entering one or possibly more shallow feed zones and flowing down into the deep feed zones, thus preventing all the deep feed zones below the topmost entry zone from flowing (Figure 2). In the other five wells, it is assumed that downflows are responsible as they exhibited similar changes in production, while in the remaining three wells, it is not clear as the wells are only completed in the shallow reservoir. In reviewing the locations of the wells that are experiencing downflows, it is apparent that the impacted wells are located all over the field (Figure 3).

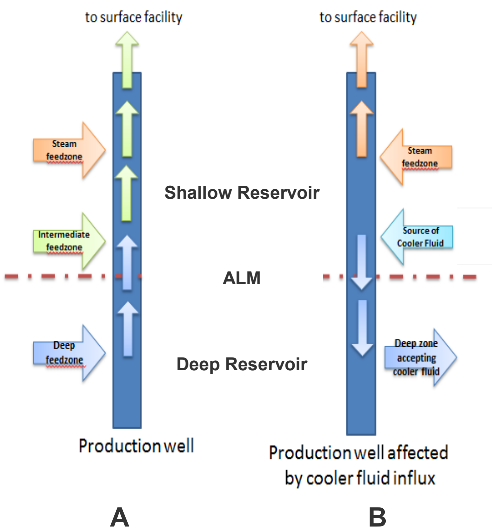

Figure 2. Normal Well Production Conditions (A) Compared to the Conditions After a Downflow Starts (B).

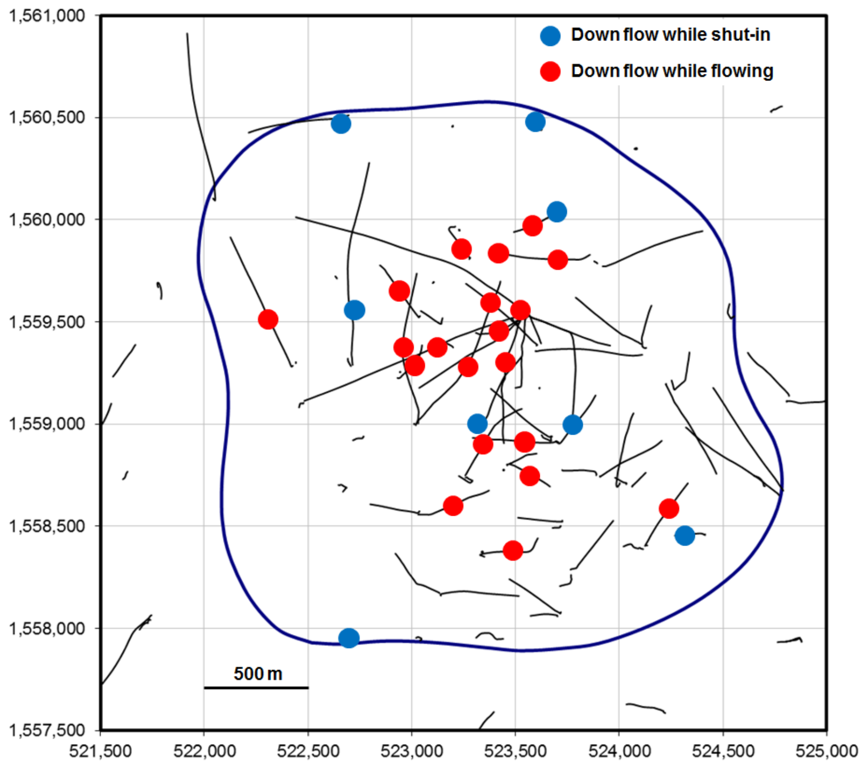

Figure 3: Locations of Wells With Identified Downflows Under Shut-In and Flowing Conditions

2.1 Downflow Mechanism

For downflows to occur, it is necessary for the intermediate feed zones (Figure 2) to develop a higher "potential" than the deep feed zones in order to both reverse the normal wellbore flow (A) and overcome the pressure in the deep reservoir. This means that the pressure at the intermediate feed zone (plus the hydrostatic head in the wellbore) must be higher than the deep feed zone reservoir pressure so that the downflowing fluid can enter the deep reservoir. The hydrostatic head is a function of fluid density and is therefore a function of the inflow temperature, i.e., a lower temperature (higher density) downflowing fluid will result to a greater hydrostatic head. Hence, if the shallow recharge fluids are causing both pressure support and cooling in the shallow reservoir, these will increase the potential for downflows to occur.

Analysis of historical downhole pressure survey data indicates that the deep reservoir pressure drawdown over the past 35 years has been ≈150 psi (10.3 bar) greater than in the shallow reservoir (Figure 4). Based on this data and an assumed inflow temperature of 450°F (232°C), the potential difference between the shallow and deep reservoirs has been calculated and the basic condition for downflows to occur (shallow potential > deep potential) has been satisfied since the early 2000s. However, individual well conditions, such as feed zone temperatures, pressures and permeabilities, are also important factors in determining whether downflow will actually occur or not. It is therefore very difficult to determine the "trigger" condition that allows downflow to start in any particular well. If the well is producing from the deep zones, then the shallow inflow fluid also needs to overcome the momentum of the rising column and reverse the flow. In some cases, the onset of the downflow was preceded by an upset or abnormal condition, such as a plant or separator station shutdown, that caused a perturbation in the wellhead pressures and was sufficient to change the dynamics in the wellbore. However, in most cases, there was no upset condition and the possible "trigger" was not apparent.

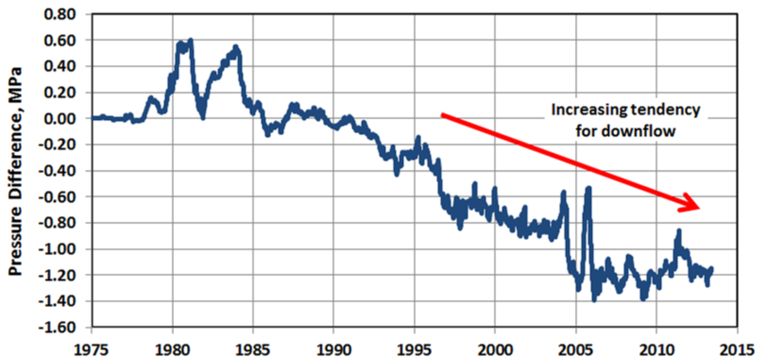

Figure 4. Historical Pressure Difference Between the Shallow and Deep Reservoirs.

2.2 Downflow Identification

Qualitative and quantitative analyses and review of downhole shut-in PT and flowing PTS surveys of all production wells in Mak-Ban were undertaken to determine which wells have or are being affected by downflows, either under shut-in or flowing conditions, including when downflows started in these wells. The main characteristic to look for initially was the presence of isothermal sections in the well temperature profiles as this normally indicates downflow conditions. It is also possible that the isothermal profiles could indicate upflow conditions if the fluid in the well is single-phase but this is less likely.

As mentioned above, based on this analysis, 15 wells were identified as currently having downflows under flowing conditions and an additional 8 wells have downflows under shut-in conditions. It was also determined that fluid downflow had occurred in a few wells even during the early years of production. For instance, the 1989 shut-in PT survey of Bul-66 showed it had a downflow from 3,100 ft (945 m) to 7,000 ft (2,134 m) Measured Depth (MD) as indicated in the temperature profile in Figure 5.

In the case of Bul-66, the temperature of the downflow is 450°F (232°C) and occurs below the water level. The isothermal temperature profile is the major indication that a downflow condition is occurring and, in this case, is not considered to be an upflow for two reasons, namely, 1) the temperature of the fluid is cooler that the deep reservoir temperature (>500°F or 260°C) and 2) the wellbore pressure is greater than the known reservoir pressure at depth.

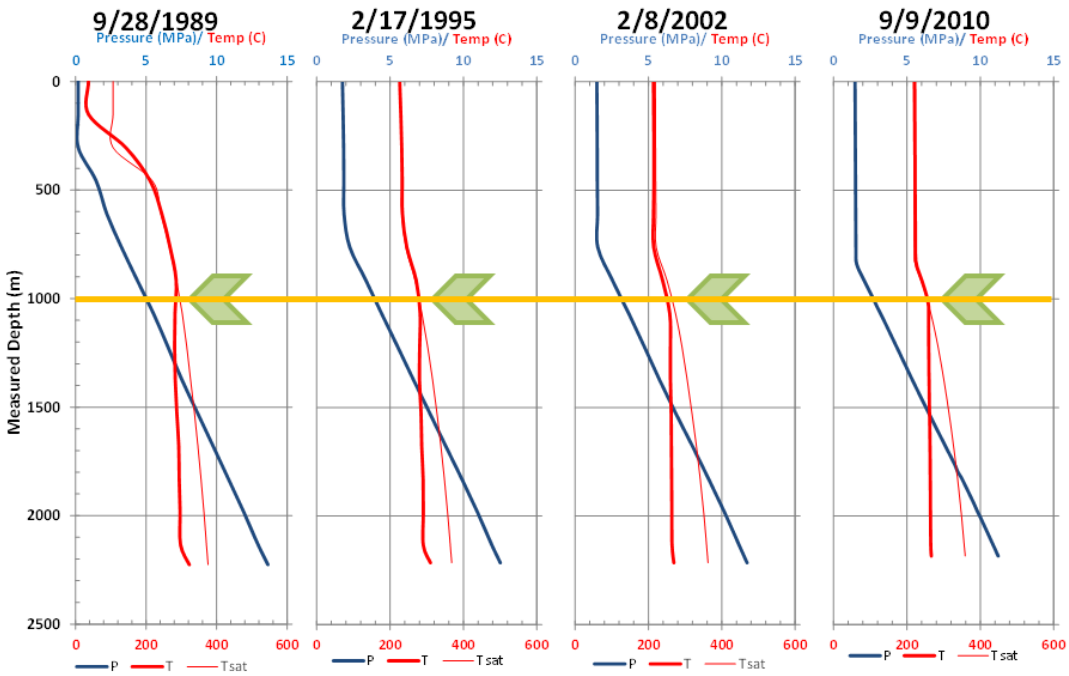

Figure 5. Repeat Shut-In PT Surveys in Bul-66 Showing Continued Evidence of Downflow Over Time.

2.3 Downflow Rate Calculation

Temperature isotherms seen in PT or PTS surveys indicate fluid movement in the wellbore, either upward or downward but the direction of flow is not always readily distinguishable unless the temperature is low enough (<480°F or 250°C) to reveal that it is most likely to be a downflow. The temperature isotherms seen in the wells identified as having downflows from the flowing PTS surveys range from 415 to 480°F (213 to 250°C) and these were proven to be downflows from analysis of the spinner surveys, which showed that the fluid was moving down the well.

The PTS surveys can also be used to estimate the rate of downflow (provided that there is more than one survey) by analyzing the cross-plot between spinner rotations (rotations per second, *rps*) vs. line speed as discussed and presented in Syms (1980) and Spielman (1994). In PTS convention, line speed is positive when logging down and negative when logging up. At zero *rps*, the tool is moving at the same speed as the fluid. Positive *rps* indicates that the fluid is moving down the well (downflow) relative to the tool while negative *rps* designates fluid is moving up the well (upflow) relative to the tool.

The volumetric flow rate can then be determined by multiplying the computed fluid speed, which is equivalent to the line speed at zero rps, by the effective area of the wellbore and the result can then be easily converted to its equivalent mass flow rate.

A sample calculation is provided below representing the estimate of downflow rate for Bul-88 based on its flowing PTS on 29 November 2011. The results of the four PTS surveys run while logging up and down the well at line speeds of 140 fpm (42 m/min) and 200 fpm (61 m/min), are shown in Figure 6.

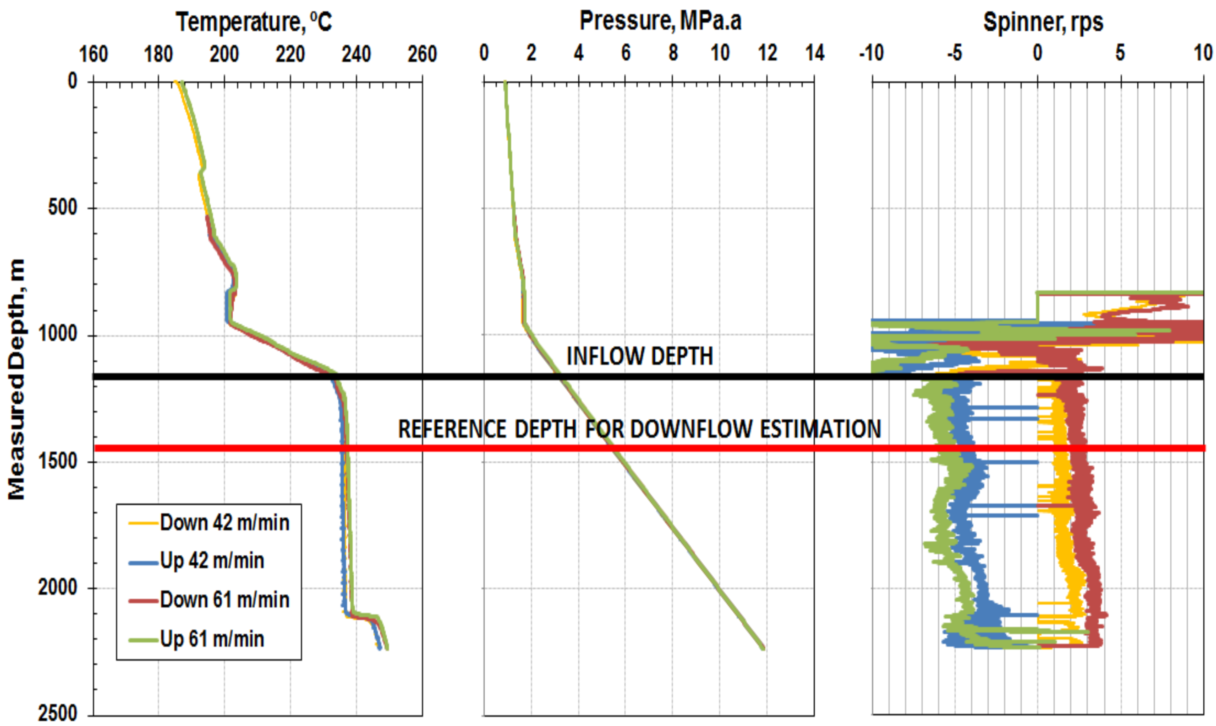

Figure 6. Bul-88 PTS Surveys on 29 November 2011

The PTS surveys showed that there was a significant inflow occurring at 3,900 ftMD (1,180 mMD) and this was flowing down the well, as indicated by the different responses at the various line speeds. Note that the response is also not unifrom down the well, possibly due to changes in well diameter and the possibility of additional inflows. The spinner responses at 4,750 ftMD (1,450 mMD) were used to obtain the information necessary for the downflow estimation and the data are summarized in Table 1 and shown as a cross-plot in Figure 7.

Table 1. Line Speed and Spinner Rotation Data From the Bul-88 PTS Surveys

Line Speed, fpm (m/min)	Spinner Response, rps
140 (42)	1.5
-140 (-42)	-4.5
200 (61)	2.3
-200 (-61)	-5.5

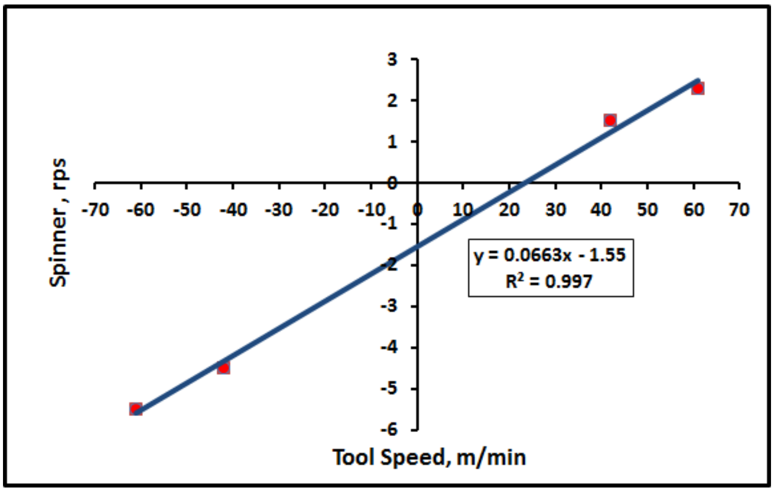

Figure 7. Cross-Plot of Tool Speed and Spinner Velocity, Bul-88.

From the data, the best-fit equation is determined and this was used to estimate various parameters. For this case, it can be seen that the velocity is positive at zero rps and the rps is negative at zero velocity, which indicate that there is a downflow in the well.

Spinner, rps = 0.0663 * line speed (m/min) -1.55

when *velocity* is zero, rps intercept is -1.55

when *rps* is zero, *velocity* intercept is 1.55/0.0663 = 24 m/min (77 fpm)

>>>> (+ ➔ downflow)

To compute for the amount of downflow:

mass flow rate = unit constant*(cross-sectional area)*(fluid velocity)*(density)

Diameter of liner	9.625 (0.244)	inches (m)
Effective x-sectional area	0.5053 (0.0469)	sq. ft. (sq. m.)
fluid velocity (x-intercept)	**24 (77)**	**m/min (fpm)**
volumetric flow	1.1 (38.73)	Cm/min (CF/min)
mass flow	**15 (120)**	**kg/s (kph)**

The outside diameter of the production liner is assumed to be the effective diameter of the production hole. It approximately represents the average diameter of the hole section and the inside diameter of the liner.

Based on the flowing PTS on 29 November 2011, the downflow in Bul-88 was calculated to be ~120 kph (15 kg/s) which enters the well at 3,900 ftMD; 1,180 mMD (2,850 ftbsl; 870 mbsl). This downflow entry zone is located below two prolific steam zones at 2,550 ftMD; 777 mMD (1,527 ftbsl; 465 mbsl) and 2750 ftMD; 840 mMD (1,724 ftbsl; 525 mbsl) and this has still allowed Bul-88 to continue to produce over 220 kph (27.8 kg/s) of steam despite preventing all feed zones below its entry depth from producing. There may also be a small inflow of hot fluid at 6,900 ftMD; 2,100 mMD (5,826 ftbsl; 1,776 mbsl) before all fluid exits the wellbore at the bottom permeable entry.

Similar analyses have been conducted in 11 of the wells that have been found to have downflows under flowing conditions. From the results, the total cumulative downflow has been determined to be about 1,100 kph (~140 kg/s) or an average of 100 kph (12.6 kg/s) per well. Assuming this rate applies to all the 20 wells with downflow, the current total rate of downflow is ~2,000 kph (~250 kg/s).

3. EXAMPLE WELL REVIEW (BUL-88)

Detailed well reviews have been undertaken for most of the production wells affected by downflows to better understand the impact of the cool inflows on well productivity and, also, how the downflow could be mitigated in the future. Bul-88 is a well with sufficient data to illustrate the analytical workflow used, show the different reservoir processes that have occurred and how these affected the well.

3.1 Bul-88 Background and Production Data

Bul-88 was completed as a directional "big hole" (with 13-⅜-in production casing) on 25 March 1992 to a total depth of 7,445 ft. MD; 2,270 mMD (6,391 ft; 1,948 mbsl) and with production casing shoe set at 2,175 ftMD; 663 mMD (1,155 ftbsl; 352 mbsl). This well started producing in August 1992 and has continued to be a reliable producer and is presently the biggest producer in the Mak-Ban field. Steam deliverability decline has been moderate at ~4% since 1998 and this decline rate did not change when the well turned to an all-steam producer in January, 2011 (Figure 8), as shown by the change in discharge enthalpy. Note that this is not the usual behavior of wells affected by downflows as productivity normally drops significantly but the steam zone at Bul-88 has unusually high productivity.

The well historically produced at a relatively stable 700 to 800 BTU/lb enthalpy indicating production mainly from the deep zones (Figure 8). When the discharge changed to all-steam in January 2011, the flowing wellhead pressure dropped from 175 psig (12 bar.g) to 125 psig (8.6 bar.g) and this resulted in improved production from the steam zone – unlike typical wells with cooler fluid downflow.

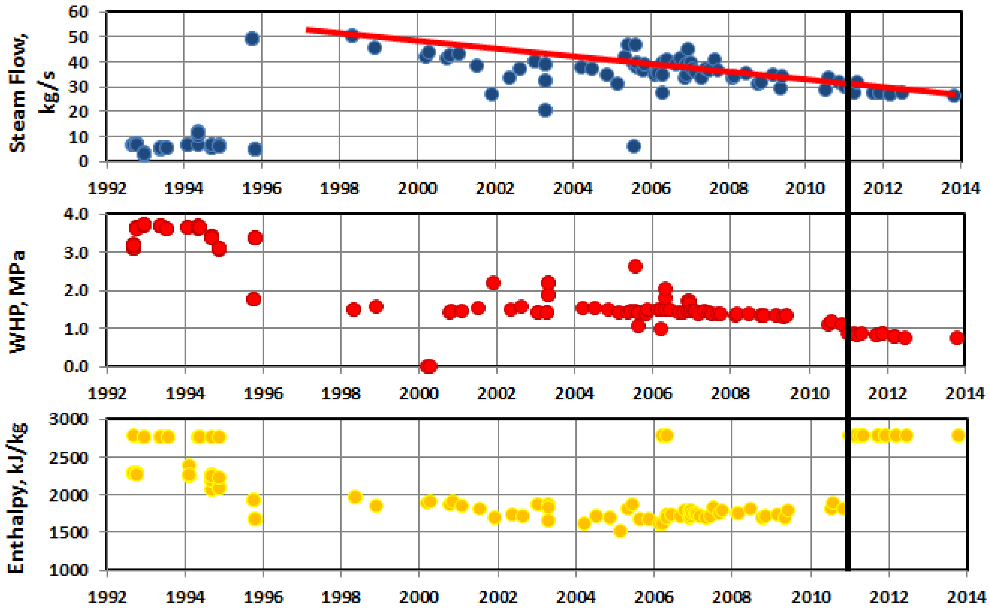

Figure 8. Historical Production Data of Bul-88.

3.2 Analysis of Downhole Conditions

From analysis of downhole PT surveys under shut-in conditions and PTS surveys under flowing conditions, it was possible to determine that Bul-88 has changed from initially having upflows in the well to finally having a downflow under flowing conditions. Based on available data, the well history can be split into the following three periods:

1) 1992 - 1998: upflow under both shut-in and flowing conditions;
2) 1998 - 2011: downflow under shut-in conditions, with upflow from the deep reservoir under flowing conditions; and
3) 2011 – present: downflow under both shut-in and flowing conditions.

For the first period (1992 - 1998), surveys conducted under both flowing (F) and shut-in (SI) conditions indicate that upflow was occurring in the well, which was typical for Mak-Ban (Figure 9). The upflow conditions were indicated by the two-phase pressure gradient, the associated changes in fluid temperature and the results from the spinner log on 13 October 1992 which showed that flow was dominated by the deep zones in the well, with only a small contribution from shallow steam zones.

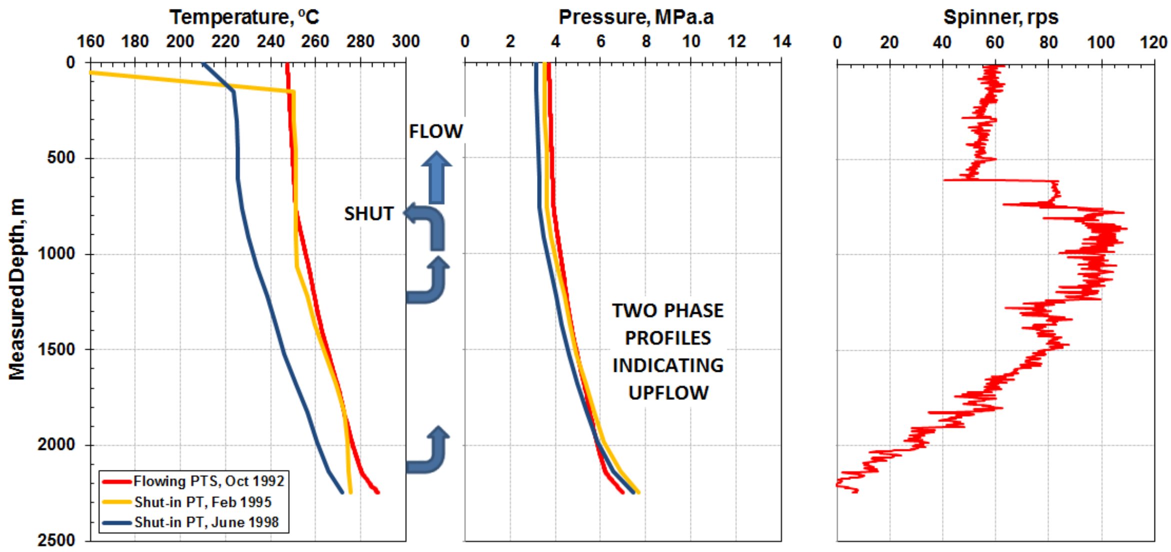

Figure 9. Shut-In PT and Flowing PTS Surveys From 1992 to 1998.

The shut-in PT survey conducted on 6 June 1998 indicated that the well was still upflowing even under shut-in conditions but a similar survey conducted on 8 September 1998 showed that a downflow had developed from ~4,000 to 7,000 ftMD (1,219 to 2,134 mMD) under shut-in conditions as indicated by changes in both temperature and pressure conditions (Figure 10); this downflow was later confirmed by a similar survey conducted on 21 November 2003. It is interesting to note that the pressures at the inflow depth at 4,000 ftMD (1,219 mMD) are very similar under both upflow and downflow conditions suggesting that the well was likely to be sensitive to relatively small changes in operating conditions. The inflow temperature in 1998 was 470 to 480°F (243 to 249°C).

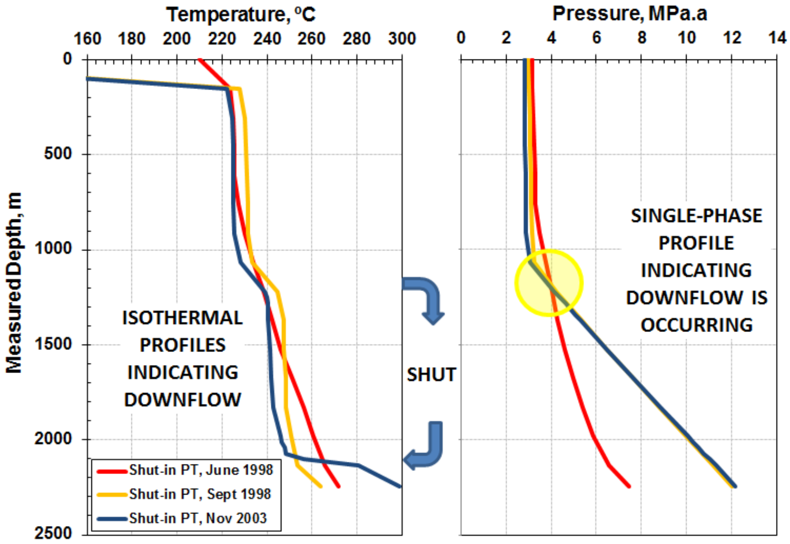

Figure 10. Bul-88 Shut-In PT Surveys in 1998 and 2003.

PTS surveys conducted in 2001 and 2002 showed that Bul-88 was still able to produce from its deep feed zones under normal production conditions even though it is experiencing downflow under shut-in conditions (Figure 11).

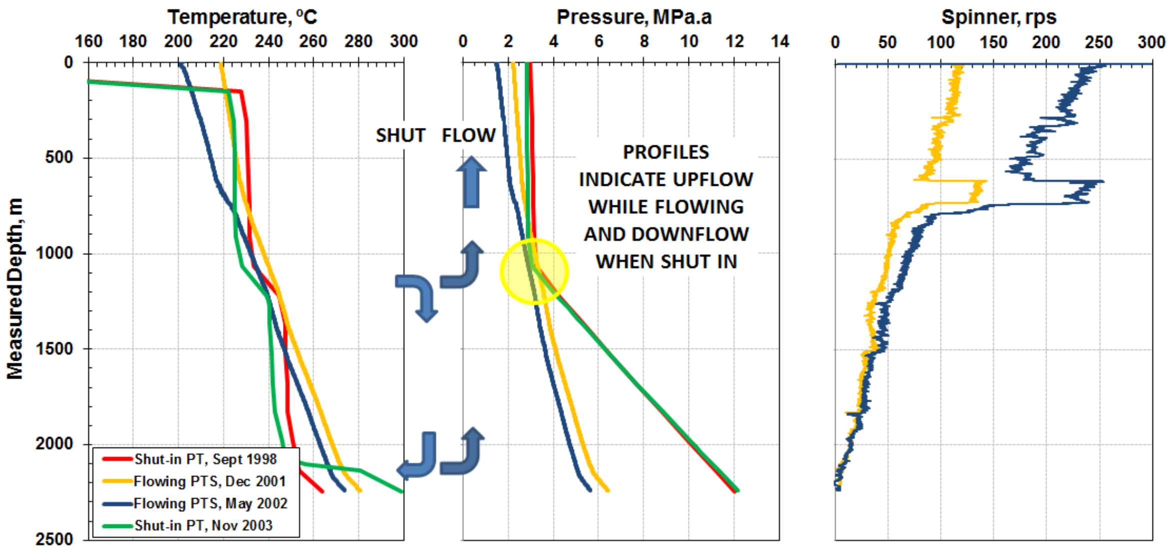

Figure 11. Bul-88 Shut-In PT and Flowing PTS Surveys From 1998 to 2003.

In 2003, shut-in PT surveys on 15 July and 21 November confirmed the downflow under shut-in conditions; the 21 November 2003 PT survey indicated an inflow temperature of 465°F (240°C) at 4,000 ftMD (1,219 mMD) (Figure 11).

In January 2011, Bul-88 began to permanently produce dry steam. A flowing PTS survey conducted on 29 November 2011 confirmed cooler fluid downflow was occurring under flowing conditions and this has stopped production from the deep feed zones (Figure 12). The inflow temperature was measured at ~455°F (235°C) suggesting that there had been further cooling since 2003. The rate of downflow, as calculated using the method described in Section 4.3, was 15 kg/s (120 kph).

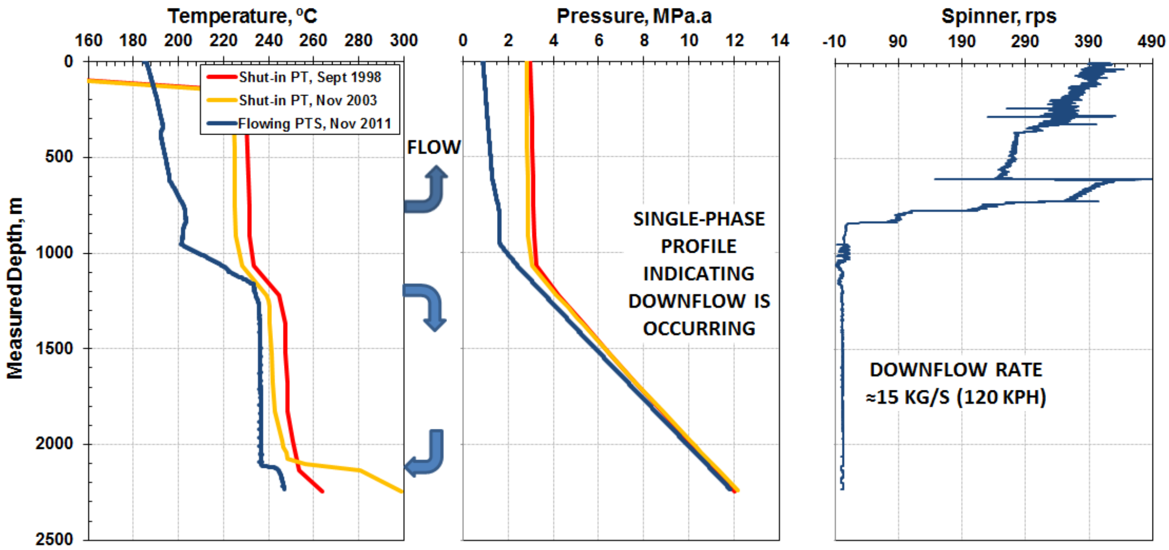

Figure 12. Bul-88 PTS Survey in November 2011 Showing Cooler Fluid Downflow Under Flowing Conditions.

4. THERMAL EFFECTS ON THE DEEP RESERVOIR

A simple process model was constructed using the TOUGH2 reservoir simulator to investigate the potential impact of the downflows on the deep reservoir and check if there is likely to be a significant thermal effect on the production feed zones in nearby wells. Using a process model was considered to be more appropriate than using the full fieldwide numerical model as the process model can better evaluate individual wells because it only considers a sub-section of the larger model and can therefore be constructed using smaller block sizes.

The overall xyz dimensions of the process model are 2500 ft x 2500 ft x 500 ft (760 m x 760 m x 150 m) and this is divided into a uniform set of grid blocks with dimensions of 50 ft x 50 ft x 50 ft (15 m x 15 m x 15 m). The grid blocks are therefore significantly smaller than the average 300 ft x 400 ft x 500 ft (90 m x 120 m x 150 m) dimensions of the grid blocks used in the full field model. The initial conditions in the model are single phase water at 580°F (304°C), which is consistent with the average conditions in the deep reservoir at Mak-Ban.

The model was used to check the sensitivity of the cooling ("thermal footprint") in the reservoir to various parameters, including variation in "MINCing" of the grid blocks (single porosity, double porosity and one fracture block with four levels of matrix sub-gridding), fracture spacing, various outer boundary conditions, distance between the injection source (well with downflow) and neighboring production well and pressure gradient across the model. The "thermal footprint" is the area significantly impacted by thermal breakthrough of the downflowing fluid. Production wells located inside the "thermal footprint" are therefore likely to be significantly affected by the downflow and possibly become non-commercial

An example of the model output is shown in Figure 13 and for this particular run, the injection and production blocks are located 500 ft (150 m) apart, the injection and production flow rates were set equal at 100 kph (12.6 kg/s) and continued for a period of 10 years, the outer boundary condition is constant pressure and each grid block is divided into one fracture and four matrix sub-blocks (MINC5). The results show that under these conditions, a 100 kph (12.6 kg/s) fluid downflow at 425°F (220°C) exiting into the deep reservoir would result in a thermal footprint after 10 years, with a radius of 400 ft (122 m). However, it is also apparent in these results that the shape of the thermal footprint is being affected by the presence of the constant pressure outer boundaries that provide recharge to the production well and this counters the effect of injection. Reversing the locations of the injection and production blocks also did not change the results significantly.

Therefore, although one of the major conclusions from the process modeling study is that provided the injection source and a neighboring production well feed zone are more than 400 ft (122 m) apart, then cooling should not be significant, the results are strongly dependent on boundary conditions, including local pressure gradients around the injection source as they control how the fluid moves away from the well and through the reservoir (streamline modeling). For example, if a neighboring well is in a higher pressure area, then it is less likely to be impacted than if it is in a lower pressure area.

In the Mak-Ban field at the present time, there is no documented evidence that downflowing wells are having any significant thermal effect on neighboring wells. This may be due to the spacing between feed zones in the production wells being generally greater than 400 ft (122 m), even in the shallower regions of the deep production reservoir. The other factor which reduces the likelihood of thermal effects is that the flows from the 15 wells are being distributed through the deep reservoir at different depths rather than being concentrated at the same depth.

5. MITIGATION PLANS

For the current wells with downflows, there is an urgent need to evaluate different alternatives and come up with appropriate options to mitigate the downflow both to regain deep production, and to avoid possible negative impact to the deep reservoir in the future. For now, the existing technology of zonal isolation that has been implemented in two wells involves cutting and pulling out the production liner and running and cementing blank casing across the inflow zones. However, it is only possible in half of the wells that are presently being affected. The remainder of the wells have secondary tiebacks, which means that the slotted liners cannot be cut and pulled out, and it will therefore be necessary to develop alternative technologies, such as, injection of resins or similar products to plug off the inflow zones located behind the liners. Although this may not result in fully plugging the cool fluid entry zones, it may reduce the inflow to the point where the well can continue to produce from its feed zones in the deep reservoir.

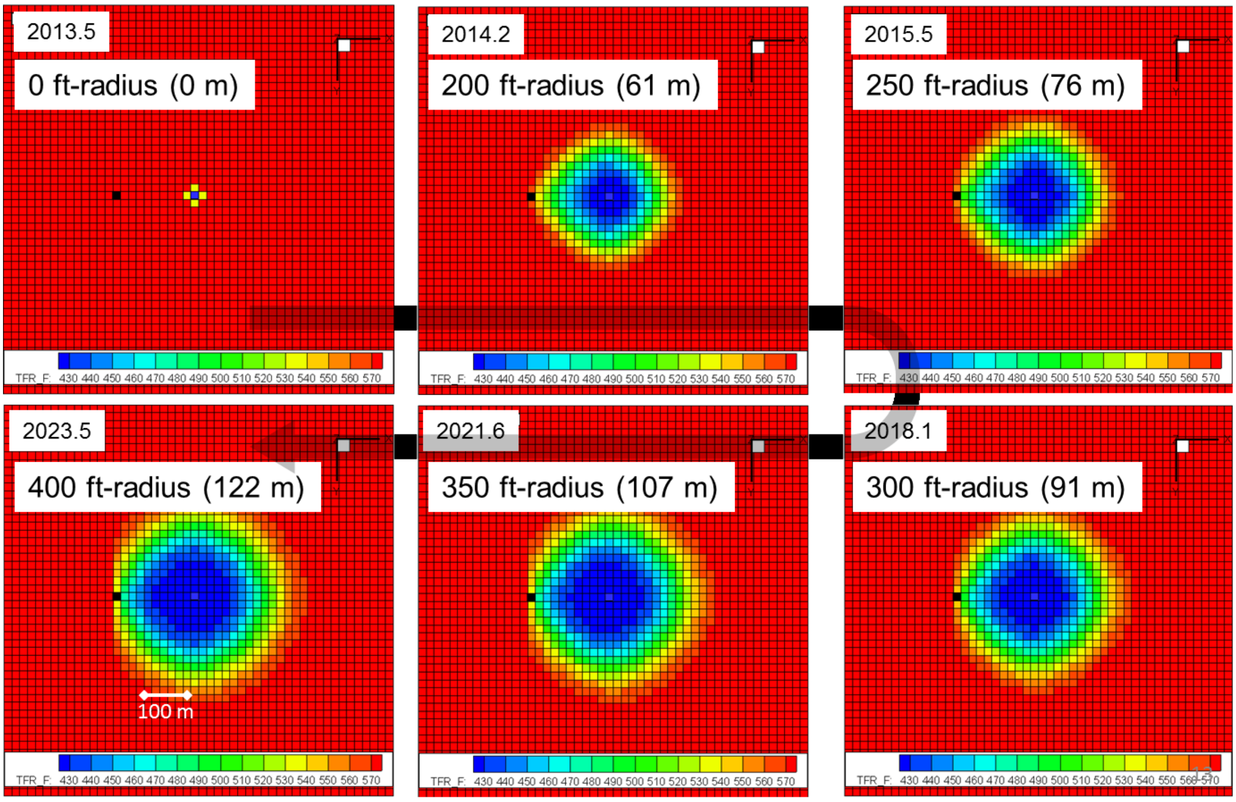

Figure 13. Evolution of Thermal Footprint Through Time Between Downflowing Well (center point) and a Producer (black square). In 10 years (from 2013 to 2023), the "thermal footprint" radius expands up to 400 ft (122 m).

6. CONCLUSIONS

The major conclusions from this study are as follows:

- In the past, shallow cooler fluid inflows have not had significant negative impact on production and have been part of the production at the wellhead but, in recent years, the entry of these fluids into the wells is causing instability in production and losses in well productivity due to downflows.
- The downflows are significantly impacting the productivity of the affected wells but there is no clear evidence of negative impacts to neighboring wells to date based on existing limited data. The estimated total downflow rate at the present time is about 2,000 kph (250 kg/s) which is roughly 30% of the total mass withdrawal from the deep reservoir.
- All wells with both shallow and deep feed zones are at risk of developing a downflow which may result in a significant loss of productivity. Wells need to be evaluated on a case-to-case basis to determine if cool fluid downflow will occur as downflow is dependent on a variety of well properties (i.e., temperatures, pressures, productivity indexes, etc.), although, in most cases, there may be some signs (say, from downhole survey data and geochemistry data) that may indicate its onset.
- Well instability and downflows occur due to the increasing potential difference between the shallow and deep reservoirs, which has weakened the ability of the deep fluids to carry the shallow fluids out of the well.
- The measured temperatures at the shallow inflows have been found to average 450°F (232°C) which indicates that there has not been significant cooling of the shallow reservoir.
- When the cooler fluid downflows and exits the wellbore into the deep reservoir, it will heat up (again) thus lessening its negative impact to the deep reservoir and/or neighboring wells. Process modeling indicated that there should be no significant thermal breakthrough as long as neighboring wells are located at least 400 ft (122 m) from the exit depth of a downflowing well, which is the case at the present time.
- Of the 20 wells that have been identified as having downflows, nine have no secondary tie-back and can possibly be worked over by cutting and pulling the slotted liner and running cemented blank casing over the shallow inflow zones. This should then allow the deep zones in these wells to produce again and thereby recover some of their lost production. For the remaining wells, development of new technology, such as the use of resins and diverters, will be needed to allow zones to be plugged off through the slotted liners.

7. REFERENCES

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