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LIFE CYCLE OF GEOTHERMAL WELLS – EXPERIENCE IN MEXICO

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ABSTRACT

Last year 238 production and 26 injection wells were operating in Mexico at the geothermal fields of Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes, whose main data for 2011 are presented. Geothermal wells produced an average rate of 6882 tons per hour (t/h) of steam with a unitary production of 28.9 t/h. Between 1963 and 2011 almost 600 exploration, production and injection wells have been drilled in the country, at a national average depth of 2173 m. Form a statistic view, it can be concluded that the mean life-cycle of a production well in the country goes from 12 years in Las Tres Vírgenes and 13 in Cerro Prieto, to 42 years in Los Azufres and 57 years in Los Humeros. The main factors affecting the production life-time of the wells can be related to the wells themselves (casing collapses, thermal stress, circulation losses) or to specific characteristics of the geothermal reservoir (mainly scaling and corrosion). To deal with these problems and get the mentioned life-cycle, some types of workovers, like mechanical and chemical cleaning, sleeves and sidetracks, must be done at variable intervals and with distinct results and success rates.

1. GEOTHERMAL FIELDS

FIGURE 1: Location of the Mexican geothermal

There are four geothermal fields in operation for electricity generation in Mexico. They are Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes, located as shown in Figure 1. All fields and power units are owned and operated by the Comisión Federal de Electricidad (CFE), the federal utility in charge of the electric market in Mexico for public service. However, the steam-field and the power units are managed by distinct business units of CFE in each geothermal field.

Cerro Prieto is geologically located into a pull-apart basin related with the southern prolongation of the San Andreas faults system. The heat source is a thermal anomaly produced by the thinning of the continental crust in the basin. The geothermal fluids (a mix with 61% at liquid phase and 39% as vapor phase) are contained in sedimentary rocks (sandstones intercalated into series of shales) with a mean thickness of 2,400 meters (Gutiérrez-Negrín et al., 2010). It is the largest liquid-dominant geothermal field in the world and one of the oldest, since the first power units started to operate in April 1973. It lies practically just a few meters above the sea level.

The installed capacity is 720 MW composed of 13 power units of condensing type, which are four single-flash of 37.5 MW each, one 30-MW of single-flash and low-pressure type, four 110-MW double-flash (two 55-MW units in tandem each), and four single-flash of 25 MW each (the more recent units in operation). Two of the four 37.5-MW units are currently out of continuous operation being only eventually dispatched when some other power unit is under maintenance. These are Units 1 and 2 of the sector known as Cerro Prieto I (CP-I), which were the first units to be commissioned. Even though both are still operative, their steam consumption is higher than the more recent units. Thus, taking into account the reduction in the steam production experienced in the oldest portions of the field over the last few years, it was decided to use the declining steam to feed the most efficient units.

During 2011 the steam produced in the field was almost 40 million of metric tons, accompanied by 64.2 million tons of brine (CFE, 2011a). The annual average production rate is thus 4562 tons of steam per hour (t/h) and 7325 t/h of brine, i.e. 11,887 t/h of mix. Gross electricity generation produced with that amount of steam was 4547 gigawatt-hour (GWh) (CFE, 2011a), at a steam specific consumption of almost 8.8 tons per MWh, not so bad considering that age of most of the power units. However, the annual capacity factor in 2011 was only 72.1% (or 0.71) taking into account the installed capacity (720 MW) or 80.5% (0.85) considering just the effective capacity of 625 MW. Gross electric generation has been declining due to the increasingly reduced steam production. In 2008 generation was 5176 GWh with a capacity factor of 82%, and the steam production was 45.9 million tons (Gutiérrez-Negrín et al., 2011). Thus, in three years steam production dropped 12.9% and electric generation fell 12.2%. However, the steam specific consumption was similar in 2008 (8.82 t/MWh) (Gutiérrez-Negrín et al., 2011), which seems to indicate that in Cerro Prieto the power units are better managed than the steam-field.

Los Azufres is located in the central part of Mexico within the physiographic province of the Mexican Volcanic Belt (Figure 1) at 2,800 meters above the sea level (masl). It is a volcanic field whose heat source is the magma chamber of an extinct strato volcano known as the San Andrés volcano that is the highest peak in the area. Host rocks of the geothermal fluids are fractured andesites affected by locally important faults arranged into an E-W trend, which drive the movement of the subsurface fluids. Los Azufres is a steam-dominated field, with wells currently producing a mix of 75% steam and 25% brine on average. Around ten years ago the relation used to be 64% steam and 36% brine.

The net installed capacity in Los Azufres is 188 MW (gross installed capacity is 194.5 MW) composed of 14 power units, which are: one condensing of 50 MW, four condensing of 25 MW each, seven 5-MW of back-pressure type and two 1.5-MWe of binary cycle. The first power units were commissioned in 1982. During 2011 the steam production was 14.8 million tons with 5 million tons of brine (CFE, 2011b), and then the average production rate was 1688 t/h of steam and 568 t/h of brine, for a total mix production of 2256 t/h of geothermal fluids. Steam production in Los Azufres has been steady in the last few years, as it was practically the same (14.6 million tons) in 2008 (Gutiérrez-Negrín et al., 2010). Generation of electricity in 2011 was 1576 GWh (CFE, 2011b), at an annual capacity factor of 95.7% (gross) or 92.5% (net), one of the highest of all power units operating in Mexico that year but lower than in Los Humeros. The steam specific consumption in Los Azufres was 9.39 t/MWh, higher than in Cerro Prieto, but it is due to the operation of the back-pressure power units which are less efficient then the flash power units. However, it seems to mean that in Los Azufres the steam-field is better managed than the power units.

Los Humeros is another geothermal field of volcanic type, located also in the Mexican Volcanic Belt, over its eastern edge (Figure 1) at an average altitude of 2600 masl. The field has been developed within a Quaternary caldera, and then the heat source is the magma chamber that produced a couple of caldera collapses known as Los Humeros and Los Potreros. Los Humeros caldera is ellipsoidal with 21 km by 15 km in diameters, and was formed some 0.46 Ma ago. Los Potreros caldera is nestled into the first one, is also ellipsoidal with 10 km by 7 km in diameters and was formed around 0.1 Ma ago (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010).

Geothermal fluids are hosted by Miocene-Pliocene andesites that overlie a basement composed of metamorphic (calcareous skarn and hornfels, marble) sedimentary (limestones) and intrusive rocks (granite, granodiorite, tonalite and more recent diabasic and andesitic dikes). Los Humeros is a steam-dominant geothermal reservoir, producing a mix of 90% steam and 10% brine. Wells mainly produce steam with high enthalpy (more than 2000 kJ/kg) except the well H-1 that produces mainly water with enthalpy between 1100-1300 kJ/kg. Water is chemically homogeneous of type sodium-chloride to bicarbonate-sulfated with high content of boron. Some deep production wells drilled at a zone known as Colapso Central have presented acid, corrosive fluids. This zone coincides with the upflow of the geothermal system and the proximity to the magma chamber at depth (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010).

The net installed capacity in Los Humeros is 40 MW, composed of eight flash power units of back-pressure type of 5 MW each. The first units were commissioned in 1990 and the last one in 2008. There are two more power units of condensing, flash type currently under construction, with a net capacity of 25 MW each. These units are part of the Los Humeros II (phases A and B) project and are expected to be on line in this year (2012). When this happens, three of the 5-MW back-pressure units will be off-line and conserved as back-up units to be operated just during the maintenance periods of other operative units. So, the installed capacity in Los Humeros will increase to 90 MW, but the operative capacity is going to be 75 MW.

The steam production in Los Humeros in 2011 was 5.1 million tons, accompanied by 0.57 million tons of brine (CFE, 2011c). The annual average production rate was 581 t/h of steam and 65 t/h of brine, i.e. 646 t/h of mix, and it was a little higher than in 2008 when 4.8 million tons of steam were produced at an annual rate of 550 t/h (Gutiérrez-Negrín et al., 2010). Electric generation got with that amount of steam in 2011 was 335.6 GWh (CFE, 2011c), and then the annual capacity factor resulted in 95% (0.95). The capacity factor only can be higher than 100% (or higher than 1.0), if the power unit produced an output higher than its nominal plate capacity, what was the case in Los Humeros last year. In general terms, this is not a recommendable operation policy, since the power units can fail, which already happened in this same field in 2000-2001 (Gutiérrez-Negrín and Quijano-León, 2003). The steam specific consumption in Los Humeros was 14.4 t/MWh, the highest of all geothermal fields in Mexico, because in Los Humeros all the power units in operation are of back-pressure type, with much more less efficiency. Anyway it was a little lower than the specific consumption obtained in 2008 (15.4 t/MWh) (Gutiérrez-Negrín et al., 2010).

Las Tres Vírgenes is also a volcanic field, located not at the Mexican Volcanic Belt but in the middle of the Baja California peninsula (Figure 1). The field has been developed inside a Quaternary volcanic complex of the same name, and its heat source seems to be the magma chamber of the youngest and southernmost strato volcano of the complex. The field has a liquid-dominant geothermal reservoir with wells producing a mix of 24% steam and 76% water (the highest proportion of liquid phase of all Mexican geothermal fields in operation). Geothermal fluids are contained into intrusive rocks (mainly granodiorite), fractured and faulted by the tectonic activity in the zone.

The installed capacity in Las Tres Vírgenes is only 10 MW with two condensing, flash units of 5 MW each that started to operate in 2002, thus being the most recent and smallest geothermal field in Mexico. The steam production in this field was only 0.62 million tons in 2011, but the water production was a little more than 2 million (CFE, 2011d), at annual average rates of 71 t/h of steam, 230 t/h of brine and 301 t/h of mix. Three years ago the steam production was 0.55 million tons (Gutiérrez-Negrín et al., 2010), so there has been an improvement of 13% in the last few years. The gross electric output in this field was 46.6 GWh in 2001 (CFE, 2011d), representing an annual capacity factor of only 53% (0.53), the lowest in Mexico for geothermal power plants but still higher than that obtained in 2008 (47%) (Gutiérrez-Negrín et al., 2010). The gross steam specific consumption resulted in 13.4 t/MWh, which has been steady in the last few years but results higher for condensing, flash units. This seems to mean that the steam-field is better managed than the power units in this field.

2. GEOTHERMAL WELLS

Production wells in the Cerro Prieto geothermal field were 172 on annual average during 2011, with maximum of 175 during September and minimum of 166 in November. There were also 16 injection wells in operation fluctuating between 14 in September to 18 in February through May (CFE, 2011). It is worth to mention that only around 30% of the brine is injected in Cerro Prieto, the rest being disposed in a 14.3 square kilometers solar evaporation pond. Taking into account the total production of steam and water in the field over 2011, on average each production well produced 69.1 t/h of mix, of which just 26.5 t/h were steam. Unit steam production per well has dropped from 39.3 t/h in 2003 to 31.3 t/h in 2008 (Gutiérrez-Negrín et al., 2010) and then to 26.5 t/h in 2011 –a loss of 12.8 t/h or 32% per well in nine years.

In the Los Azufres field there were 39 production wells in operation along 2011, with minimal monthly variations to one more or less, and 6 injection wells (CFE, 2011b). In this field all the brine is sent back to the reservoir. The average production per well results to be 43.3 t/h of steam and 14.6 t/h of brine, or 57.9 t/h of mix. This unitary production is a more or less the same in the last nine years: 44.6 t/h of steam in 2003 and 42.8 t/h in 2008 (Gutiérrez-Negrín et al., 2010), which means that the management of the field has been steady in spite of the reduction in the brine share of the mix.

On average, the production wells in Los Humeros were 23 during 2011, with little variation along the year. There were also 3 injection wells to dispose all the scarce brine produced (CFE, 2011c). Unitary production per well is 25.3 t/h of steam and just 2.8 t/h of water on average, even though most of the brine is produced just by one well –the well H-1. The unitary steam production in Los Humeros seems to be declining, since it was 30.3 t/h in 2003 and 27.5 t/h in 2008 (Gutiérrez-Negrín et al., 2010), representing a reduction of 5 t/h of steam per production well, equivalent to 16.5% along the last nine years.

Finally, there were four production wells operating on average in the Las Tres Vírgenes geothermal field during 2011, practically with no variations along the year. One injection well was disposing the water into the reservoir most part of the year, but 2 injection wells were operating during the last quarter (CFE, 2011d). Annual average production per well was 17.8 t/h of steam and 57.5 t/h of water, which is the lowest steam unitary production of the Mexican fields. Unitary steam production per well dropped almost 15% from 20.9 t/h obtained in 2008 and is comparable to that of 2008 (17.6 t/h) (Gutiérrez-Negrín et al., 2010).

The main mentioned data on geothermal wells in operation in Mexico during 2011 are summarized in Table 1.

The total of geothermal wells drilled in the Cerro Prieto geothermal field since exploration started in this field in 1963 is around 402, including exploration, production and injection wells, with data as of December 2010. Combined long of all these wells is estimated to be of almost 963 kilometers (Table 2). These estimates come from the data reported for 2008 (Gutiérrez-Negrín et al., 2010) added with recent internal data from CFE for 2009 and 2010 (Alvarado, 2011, personal communication). The average depth for geothermal wells in Cerro Prieto can be estimated in 2392 m, but the deepest geothermal well in this field is 4400 m (Gutiérrez Negrín et al., 2010).

Wells drilled in the Los Azufres field, including also exploration, production and injection, are estimated to be 88 with total combined long of 139.3 km, as of December 2010. The average depth of those wells is 1583 m, as reported in Table 2, which is considerably less than the average in Cerro Prieto. In Los Humeros there have been drilled 45 wells with different purposes (exploration, production, injection) at an average depth of 2179 m, which is deeper than in Los Azufres but shallower than in Cerro Prieto. Eleven wells were drilled in Las Tres Vírgenes up to December 2010, with an average depth of 2037 m, similar to the average of Los Humeros wells (Table 2).

The Cerritos Colorados geothermal field was drilled in the eighties and the CFE was preparing the construction and installation of the first back-pressure units when it was asked to suspend the development activities by the local government, in order to remediate and mitigate the environmental impacts caused in the forest where the field is located. CFE carried out an extensive mitigation program, but since then the project has remained suspended (Gutiérrez-Negrín et al., 2002). Other potential zones in Table 2 are around 12 geothermal zones in diverse portions of the country where the CFE drilled exploration wells looking for new developments, including recently the Tulecheck zone, near Cerro Prieto.

TABLE 1: Main data on geothermal wells operating in Mexico in 2011

Averages in 2011	**CP**	**LAZ**	**LHM**	**LTV**	**Total**
Production wells in operation (number)	172	39	23	4	238
Injection wells in operation (number)	16	6	3	1	26
Steam production rate (t/h)	4562	1668	581	71	6882
Water production rate (t/h)	7325	568	65	230	8188
Steam production per well (t/h)	26.5	43.3	25.3	17.8	28.9
Brine production per well (t/h)	42.6	14.6	2.8	57.5	34.4

CP: Cerro Prieto, LAZ: Los Azufres, LHM: Los Humeros, LTV: Las Tres Vírgenes.

TABLE 2: Total geothermal wells drilled in Mexico from 1963 to 2010

Geothermal field	**Wells (no.)**	**Total long (km)**	**Average depth per well (m)**
Cerro Prieto	402	961.7	2392.2
Los Azufres	88	139.3	1582.9
Los Humeros	45	98.1	2178.9
Las Tres Vírgenes	11	22.4	2036.8
Cerritos Colorados	13	23.1	1776.9
Other potential zones	38	52.6	1384.9
Total	**597**	**1297.1**	**2172.8**

3. LIFE-CYCLE OF PRODUCTION WELLS

The life-cycle of a production well varies in each field, and even from one to other region of the same field in the case of a large field as Cerro Prieto. Thus, in order to get a statistical, general average of the expected life-cycle we prepared the Table 3, encompassing a period of ten years (2001-2010). The first row in each field reports the average number of production wells in operation during the year. The second row shows the number of the so called make-up wells drilled during the year, which are wells drilled to replace production wells that finished their life-cycle. The third row presents the proportion of replaced wells compared to the total of production wells in operation. The last column presents the averages during the ten-years period examined.

TABLE 3: Production wells in operation and number of make-up wells drilled in 2001-2010

Field and wells	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2001-2010
Cerro Prieto											
A) Production wells	130	138	149	151	162	165	169	167	164	167	156
B) Make-up wells	9	8	9	17	17	5	0	11	15	18	11
B/A (%)	6.9%	5.8%	6.0%	11.3%	10.5%	3.0%	0.0%	6.6%	9.1%	10.8%	**7.0%**
Los Azufres											
A) Production wells	24	15	29	35	37	36	39	39	39	40	33
B) Make-up wells	3	0	0	0	0	2	0	0	1	2	1
B/A (%)	12.5%	0.0%	0.0%	0.0%	0.0%	5.6%	0.0%	0.0%	2.6%	5.0%	**2.4%**
Los Humeros											
A) Production wells	9	11	17	18	18	17	19	20	20	21	17
B) Make-up wells	0	0	0	0	0	0	0	3	0	0	0
B/A (%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15.0%	0.0%	0.0%	**1.8%**
Las Tres Vírgenes											
A) Production wells	2	3	2	2	2	1	2	3	3	4	2
B) Make-up wells	0	0	0	0	0	0	1	0	0	1	0
B/A (%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	62.4%	0.0%	0.0%	28.6%	**8.5%**

A) Number of production wells in operation during the year (rounded to unit).
B) Number of make-up wells drilled in the year, excluding wells to feed new power units as in the case of Los Azufres in 2002-2003 (seven wells drilled for the Los Azufres II project) and Los Humeros in 2010 (two wells for the Los Humeros II project).
Figures in the last column are the averages for the decade, rounded to unit.
Prepared with unpublished data from the drilling department of the GPG, CFE.

Make-up wells drilled in each year, and their annual percentages related to the production wells in operation, presents wide variations. In the case of Cerro Prieto, the number of make-wells can be as low as zero in 2007 and as high as 17 in 2004 and 2005. These variations are due to the administrative process needed to drill any new wells in the Mexican fields, rather than to variations in the behavior of the wells or the geothermal reservoir. Since all these fields are managed by CFE and this is a governmental utility, the construction of new wells is made by contracts awarded by international bids that must comply with the federal laws on the matter. The CFE's geothermal division prepares the technical specifications and conditions, asks for the budget, convenes the bid, declares the winner, signs the contract, supervises the drilling, and accepts and pays for the works. The process is often delayed and/or cancelled by several technical, economic or administrative causes, and then it is difficult to have a similar amount of replacement wells in each calendar-year.

Anyway, the averages along the decade are rather representatives of the need of replacement wells related to the wells in production. For Cerro Prieto, the annual average of make-up wells in that period is 11 (actually 10.9), representing 11% of the annual average of wells in production over the same period (156). This means that seven out of 100 wells in production will end their life-cycle each year, and then all the 100 production wells shall finish their production life in a little more than 15 years. Of course, this is a statistical data that cannot be applied to every production well. In addition, each well is distinct. However, as a general approach it can be considered that the life-cycle of an average production well in Cerro Prieto is 15 years, based on the need of replacement wells.

Other approach to the life-cycle of production wells in Cerro Prieto, perhaps more realistic, is analyze the number of wells effectively retired from the steam-supply system in each year and compare to the number of wells in production. Table 4 presents this information for the last six years.

TABLE 4: Production wells in operation and retired in Cerro Prieto in 2006-2011

Production and dead wells	2006	2007	2008	2009	2010	2011	Average 2006-2011
A) Wells in production	165	169	167	164	167	172	**167**
B) Wells retired (dead wells)	12	10	19	19	19	27	**18**
Proportion B/A (%)	7.3%	5.9%	11.4%	11.6%	11.4%	15.7%	**10.6%**

Thus, according to Table 4 in the last six years an average of 18 (actually 17.7) production wells must be retired annually from a total 167 (actually 167.3). That means that 10.6 wells out of 100 finish their life-cycle every year, and that all the wells shall be dead in 10.5 years. Of course, it must be taken in mind that production wells are retired of the production system and officially declared dead when their production reaches some minimum that not necessarily is zero. But from this approach, the average life-cycle for the Cerro Prieto wells in the last years can be established in 10.5 years.

Therefore, it seems reasonable to define the average production life of the Cerro Prieto in 13 years in round figures, which is the approximately the mean between 15.3 and 10.5. What providences have to be taken to get that life-cycle is other matter that we discuss in the next section.

For the Los Azufres field, things are quite different. Just one make-up well (actually 0.8) per year is necessary to replace the 33 (33.3) wells that were in production on average along 2001 through 2010. This represents 2.4% per year, meaning that the total of production wells shall be finished in a little more than 42 years. With the already mentioned reserves for the Cerro Prieto case, we can say therefore that the average life-cycle of a production well in Los Azufres is 42 years.

The annual average of make-up wells in Los Humeros and Las Tres Vírgenes, reported as zero in Table 3, is actually 0.3 and 0.2, respectively, for the decade. Making similar assumptions and taking the same reserves for both fields, it is possible to mention that the average life-cycle for a production well in Los Humeros is 57 years, and 12 years in Las Tres Vírgenes.

4. FACTORS AFFECTING THE LIFE-CYCLE OF PRODUCTION WELLS

There are several factors influencing the production-life of the wells, but in general they can be grouped into two broad types: factors more related to the well itself and factors related to the behavior and characteristics of the geothermal reservoir. Some factors related to the wells are shared by all the fields and others are site-specific meanwhile factors depending on the reservoir are specific to each field.

The main factors related to the wells can be listed as follows.

Casing collapses. Several production wells in Cerro Prieto experience the collapse along the casing. Collapses can occur due to a poor cementing job when the casings were originally cemented. During drilling, some wells have to be encased in zones with high losses of circulation, and then geothermal fluids can occasionally contaminate the grout and modify their physical characteristics, leaving a weak spot in the cementation and impoverishing the isolation that prevents contact of fluids of lower temperature. This increases the possibility of causing thermal stress resulting in mechanical failure. Of course, a routine measure after cementing is to run a cement-log in the well to evaluate the quality of the cement, particularly in a two-stage cementation, but sometimes is uncertain whether the primary cementing was adequate or not. To prevent the problem in Cerro Prieto, it has been started to use light cement slurries for cementing some casings (13 3/8” and 7” in diameter), with density of 11 ppg instead of the usual 14 ppg, which has increased the cement effectiveness. The problem of poor cementing also has eventually occurred in the other geothermal fields.

Thermal stress**.** The change in temperature produced when it is necessary to cool a well carries the risk of inducing mechanical damage in the casings by thermal shock. A similar effect can occur when is necessary to manipulate the operating valves and/or to change the orifice-plate of production, due to fast changes in flow and pressure. This problem has occurred mainly in wells of the Cerro Prieto field.

Circulation losses. This is a problem occurring during the initial construction of the well that can reduce its further production life. Most wells drilled in Mexico use mud as circulation fluid, even at the depths where the production zones are expected. Mud is based on bentonite, and then when circulation is lost bentonite and some drilling cuttings can invade the formation and prevent production or reduce the productive life of the well. Even though this used to be a problem exclusive for the Mexican volcanic fields, in the last few years is also a problem in Cerro Prieto. Measures to prevent or mitigate this problem include the use of KCl and polymeric fluids instead of bentonite, use of near-balanced drilling, and use of seals based on mineral and organic fibbers, which are being implemented in Cerro Prieto.

Factors affecting the well's life-cycle more related with the reservoir features include changes in some variables like enthalpy, and reservoir pressure and temperature. These changes are a consequence of the resource management, the natural recharge and the extraction and injection rate. But some special factors of this type are the following.

Scaling. The silica scaling is a recurring problem in Cerro Prieto and may occur inside the well to produce reductions in the production diameter or may occur in the reservoir in the vicinity of the well, depending on where takes place the phase-change from liquid to steam (flash). The silica deposit rate increases proportionally with the content. At concentrations higher than 800 ppm of SiO_2 the deposition rate increases remarkably, which is often the case of the Cerro Prieto brines. No wells in the other Mexican fields experience this silica scaling, but in the Las Tres Vírgenes field the scaling problem in production wells is caused by calcite, even though the problem is already under control using acid to prevent the calcite deposition.

Corrosion or 'acid' wells. Corrosion is caused by acid and the high content of dissolved salts in the production fluid and directly affects the well casings causing mechanic damage. This is a problem particularly severe in the production zone of the field sector known as CP-IV, where the deep wells produce acid fluids ($pH < 5$). The origin of these acid fluids has been explained because this sector of the field is closer to the heat source, and the magmatic fluids tend to acidize the deep geothermal fluids. But anyway, corrosion is a main factor to reduce the life-cycle of the deep wells located in that sector.

As mentioned before, production wells drilled in the Colapso Central area of the Los Humeros field produce also acid fluids when they are drilled at more than 1800 m depth. In this case the formation of low pH fluids has been explained as a post-exploitation process related to the migration of deep magmatic volatile species, which is induced by the extraction of fluids and by the proximity of the magma chamber in this area. In the past deep wells located in that area had to be repaired by plugging the deep production zones with cement to prevent the mixing of deep fluids transporting magmatic volatiles and shallow fluids. The CFE also decided that further wells to be drilled in the Colapso Central shall be shallow enough to avoid the deeper production zones. That solved the problem but also reduced the production rate of those wells by more than a half (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010).

5. WORKOVERS

Some measures to prevent problems reducing the life-cycle of the wells were mentioned in each case in the previous section. But when the problem has already occurred, the first step is to fix the well and try to recover the steam production lost or reduced. Workover on wells of the volcanic Mexican fields are quite exceptional, excepting in certain specific problems experienced in the past in Los Humeros and Las Tres Vírgenes. The reason is the long and more or less steady life-cycle of the standard production well. However, in Cerro Prieto well workover is a constant activity, as usual as the make-up well drilling.

The wells repaired in the last six years in Cerro Prieto and the recovery of steam in each year are presented in Table 5, along with the total of operative wells already included in Table 4. Fluctuations from one to other year reflects the administrative conditions mentioned before regarding the drilling contracts, as long as the workovers are also subjected to the same regulations. However, in the six-year period reported an average of 7 production wells were repaired annually, gaining a steam recovery of 37 t/h per repaired well. In average, 4.3% of the production wells in operation must be repaired every year. That could be interpreted as if a production well would require a workover only after 24 years of productive life, but the reality is not all the declining or dead wells are able to be repaired, and in some cases is more efficient to drill a new replacement well. As a matter of fact, the workover policy in Cerro Prieto, lead by the reservoir engineering area, has been to repair only those declining or dead wells located in the most productive zones of the reservoir (Rodríguez y Pérez, 2011).

TABLE 5: Production wells in operation and retired in Cerro Prieto in 2006-2011

Data	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Average 2006-2011**
A) Wells in production	165	169	167	164	167	172	**167**
B) Wells repaired	3	16	6	0	9	9	**7**
Proportion B/A (%)	1.8%	9.5%	3.6%	0.0%	5.4%	5.2%	**4.3%**
Recovered steam production (t/h)	117	576	264	0	270	333	**260**
Recovered steam per well (t/h)	39	36	44	0	30	37	**37**

Main types of workovers are described below.

Mechanical cleaning

This is the simplest and cheapest workover. Sometimes is just the first step for a more complicated workover, but in other times it is good enough to recover steam production (or injection capacity). Mechanical cleaning operations are done either with a conventional rig or with a coiled tubing unit, and consist of the well recognition, calibration and cleaning of the casings to remove basically soft silica deposits or material from the formation in some less frequent cases. It can be done not only for production wells but also for injection wells.

Sleeve

This is a more complicated workover, when a severe damage (collapse or other mechanical damage) is recognized in the well casing. It needs a conventional rig and consists in the recovery of the damaged parts (if possible) and the installation of a casing of smaller diameter to cover the damaged part of the original casing (Figure 2, left).

Sidetrack

This is an even more complex, risky and costly operation than the sleeve, and also requires a conventional rig. Sidetracking is decided when a complete block is detected in some part of the casing, that cannot be removed or extracted. It consists of making a conventional deviated hole in the well, starting above the block and continuing up the original depth or beyond, and then place or cement another casing to protect the new hole (Figure 2, right).

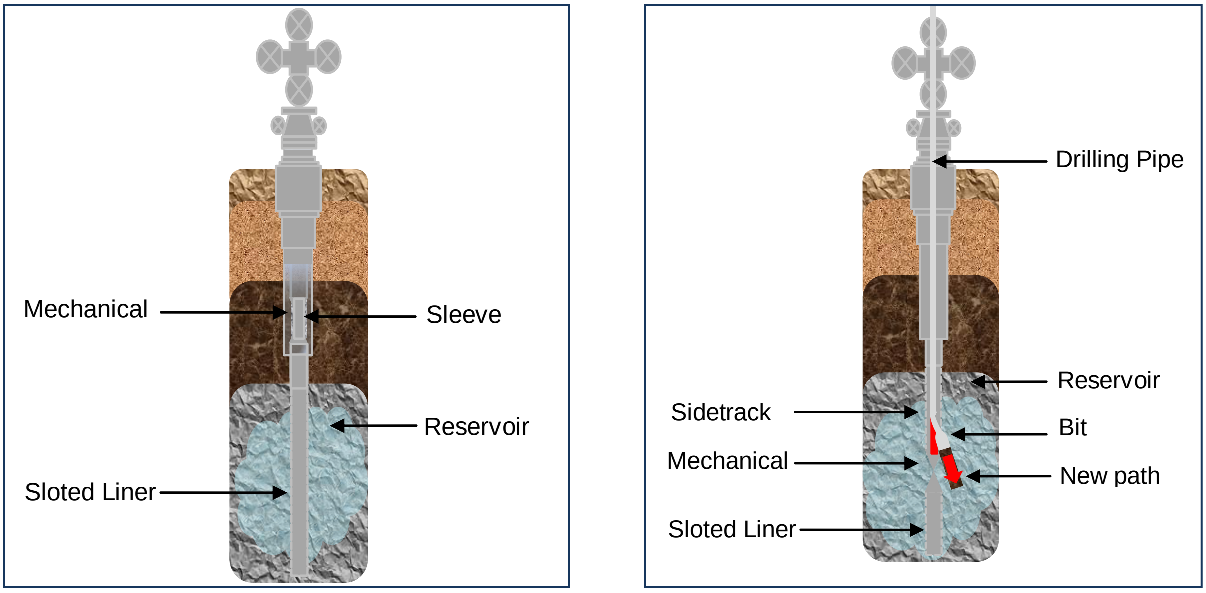

FIGURE 2: Schemes of sleeves and sidetracks in geothermal wells

Chemical cleaning (matrix stimulation)

22 production and injection wells in the volcanic fields of Mexico have been stimulated since 2000 by the CFE using the matrix acidizing technique, to improve the production or injection capacity reduced by the mud lost during their drilling or by further silica or calcite scaling. Only 3 of those 22 workovers were failed, having obtained improvements between 13 and 540% over the original conditions (Flores-Armenta and Gutiérrez-Negrín, 2011). Some of the acidized wells in Los Azufres and Los Humeros cannot be considered as workovers sensus stricto, because they were originally poor producers or injectors, but the experience in these fields have led to try the same procedure to repair some of the Cerro Prieto wells, starting with the well 307 with excellent results. This workover can be done either with a conventional drilling rig or a coiled tubing unit, to inject a mix of acids at previously chosen depths.

Following are some cases of workovers and results presented just as examples, being interesting to note that some wells have been repaired more than once like E-11 and 609 included in Table 5.

6. CONCLUSIONS

The life-cycle of a geothermal well is determined by several factors, some depending on the design, construction and operation of the well itself, and some related to the general features of the geothermal field. Some of them are common to any well, and some are very site-specific. Some factors, finally, can be prevented or at least mitigated with the proper technical measures, but in a few cases Mother Nature prevails. The Mexican experience on this matter, based on almost 40 years of drilling geothermal wells, include remarkable successes but also not less remarkable fails. This experience indicates that the mean life-time of production wells can be as short as 12 or 13 years in Las Tres Vírgenes and Cerro Prieto, respectively, or as long as 42 and 57 years in Los Azufres and Los Humeros, respectively. In Cerro Prieto, the biggest liquid-dominant geothermal reservoir in the world, almost 11% of the wells have to be retired every year, demanding to drill 11 replacement wells and to repair 7 more, while in The Geysers there are some steady production wells that have been flowing since the sixties almost with the same production. Of course, they are distinct reservoirs (The Geysers is dry-steam for a start), and have been rather differently managed along the years.

TABLE 5: Some examples of workovers and practical results in Mexican fields

Field	Well	Type of workover	Year	Previous condition	Results
CP-I	E-11	Sleeve	1985	0 t/h steam	55 t/h steam
		Sidetrack	1990	8 t/h steam	25 t/h steam
CP-II	616	Sidetrack	1996	21 t/h steam	40 t/h steam
CP-II	E-24	Sidetrack	2004	11 t/h steam	35 t/h steam
CP-III	609	Sleeve	1996	35 t/h steam	55 t/h steam
		Mechanical cleaning	2000	20 t/h steam	60 t/h steam
		Sidetrack	2003	15 t/h steam	30 t/h steam
CP-IV	410	Sidetrack	2006	41 t/h steam	62 t/h steam
LAZ	Az-15	Acid stimulation	2000	340 t/h injection	450 t/h injection
LTV	LV-11	Acid stimulation	2002	12 t/h steam	35 t/h steam
LAZ	Az-8	Acid stimulation	2005	180 t/h injection	410 t/h injection
LAZ	AZ-68D	Acid stimulation	2008	10 t/h steam	64 t/h steam
LHM	H-1D	Acid stimulation	2010	6 t/h steam	45 t/h steam
LTV	LV-6	Acid stimulation	2010	0 t/h steam	25 t/h steam
LAZ	Az-51	Acid stimulation	2010	17 t/h steam	42 t/h steam

CP: Cerro Prieto, LAZ: Los Azufres, LHM: Los Humeros, LTV: Las Tres Vírgenes.

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