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AN UPDATED SURVEY OF NON-CONDENSIBLE GASES EVOLUTION AT LOS AZUFRES, MEXICO, GEOTHERMAL RESERVOIR

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ABSTRACT

Evolution and spatial distribution of non-condensible gases at Los Azufres geothermal field are reported. This reservoir has been under continuous exploitation since 1982. The observed evolution of gases is heterogeneous in different wells and, sometimes, an unpredictable and surprising evolution is observed. Simultaneously to fluid extraction, important amounts of low enthalpy liquid and air are reinjected into the reservoir. Nitrogen separates from the air mixture migrating to production zones following high permeability paths. We postulate an hypothesis in order to explain this evolution, that is related to the fractured and faulted reservoir's nature and to N_2 injection.

INTRODUCTION

Los Azufres, Mexico with 88 MWe installed, is the second geothermal field of the country, whose existence was known before Columbus times. The Los Azufres area was little studied in the 50's, when were carried out geochemical analysis of the existent fumaroles. After a long interruption, the studies were reactivated in 1972 and in 1977 the first producing wells were drilled, confirming the existence of an energy potential of considerable magnitude. The geology, geochemistry, geophysics and mineralogy of the field have been described and updated in several internal CFE reports and in some international publications (Gutierrez & Aumento, 1982; Nieva & Quijano, 1983; Dobson, 1984; Cathelineau et al., 1985; Nieva et al., 1987; Razo et al., 1989; Geotermia, 1991). Forty years ago, geological and geochemical studies were the first type of research that was carried out in this field.

Until today, more than 60 wells have been drilled to depths ranging between 627 and 3544 meters. The maximum measured temperature is 358 "C. The reservoir is formed by two sectors having different thermodynamic and mineralogical characteristics. The northern sector, known as Maritaro, is a liquid single phase reservoir, located between 200 and 2200 masl. It is characterized by an hydrostatic vertical profile at an average pressure of 90 bar and an average temperature of 300 "C.

The southern sector known as Tejamaniles, presents three different profiles: a shallow two-phase steam dominated stratum, located between 1800 and 2600 masl, at initial average conditions of 55 bar and 270 °C; an intermediate two-phase liquid dominated stratum, located between 400 and 1800 masl, at 100 bar and 300 "C; and a deep compressed liquid stratum, located between -50 and 400 masl, at 180 bar and 350 "C. Gases presence at this sector, has always been larger than in the northern zone.

In August 1982 began the field's commercial exploitation, when CFE installed five small plants of 5 MWe each, without condenser. Between 1986 and 1992, CFE installed four more plants of the same capacity and in 1988 a 50 MWe plant was constructed. Noncondensable gases [NCG] accompanying steam extraction at this field, is a compound typically formed by CO, (- 90.81 %), H_2S (~ 1.162%), H_2 (~ 0.026%), N_2 (- 0.773%), CH_4 (~ 0.012%), He (~ 0.0002%) and Ar (~ 0.122%). All figures are expressed as percentages of total gas weight. Carbon dioxide is the major constituent in all the wells, representing today, between 70% and 99% in weight.

Since the beginning of the field exploitation, it was detected that the steam phase had an heterogeneous composition (Quijano, Truesdell & Nieva, 1989), with a wide range of concentration values of NCG (from 2% to 8% in weight). The analysis of chlorides concentration showed that boiling processes were more intense in the southern zone than in the northern sector. Initial studies of the composition of phases in the reservoir (Nieva et al., 1983,1987; Quijano et al., 1987) showed that concentration of fluid volatile components such as CO, and deuterium will decrease with depth, while concentration of non-volatile components such as oxigen-18 and ion-chloride will increase. The highest CO, content was found in shallow wells with high steam quality.

At that time, it was predicted that CO, concentration in the total discharge of deep wells, small at the beginning, would tend to increase with the exploitation. In the shallow wells it was expected that CO, concentration would remain stable or diminished.

Carbon dioxide emitted by the Los Azufres geothermal power plants, represents the fifth part of the same gas produced by a thermopower plant having the same capacity. However, due to the 50 MWe plant technology, the turbine can only accept a maximum amount of NCG lower than 3% in weight. It **is** well known since 1929 (Kestin, 1980), that noncondensable gases diminish the efficiency of the turbine, reducing notably both, the condensation and the global transfer heat coefficients. This combined effect causes the efficiency of the geothermal power cycle to decrease. For this reason it is particularly important to observe the evolution of those gases. At the same time, their careful study allows the inference of important details on the fluid transport in the reservoir.

SPATIAL DISTRIBUTION OF NCG

Systematic measurements of NCG began at Los Azufres in 1984. Few **data** were obtained between 1981 and 1983. In 1984 the systematic use of gas chromatography was introduced in the field, to measure the concentration of elements present in the NCG. Figures 1 and **2** synthesize the initial and final state of NCG spatial distribution. The **data** were measured by the technical personnel of the Los Azufres field, by direct sampling in wells at **8** bar of separation pressure, between 1981 and 1996. The two-dimensional contours were obtained through a Kriging type interpolation method, using a linear variogram. After several essays, this tool turned out to be the most appropriate for the type of data we analysed. Coordinates of figures are referred to those of well A10, whose absolute coordinates are: X= 322,000.3, Y=2,186,615.7 in the system of Mercator.

Figure 1 shows the state of NCG concentration between 1981 and 1984 when the first measurements were carried out and the reservoir was in its early exploitation stage. It is appreciated that at the beginning there was two relative maxima in the field, reflecting the existence of two natural rich zones of NCG (> 8% in weight); both were located in the southern portion of the reservoir. The first one correspond to the position of wells with the hghest steam quality, **A17** and A36 at the West. The second one was related to well A18 at the East, having little vapor. Toward the north, NCG concentration diminished and was notably

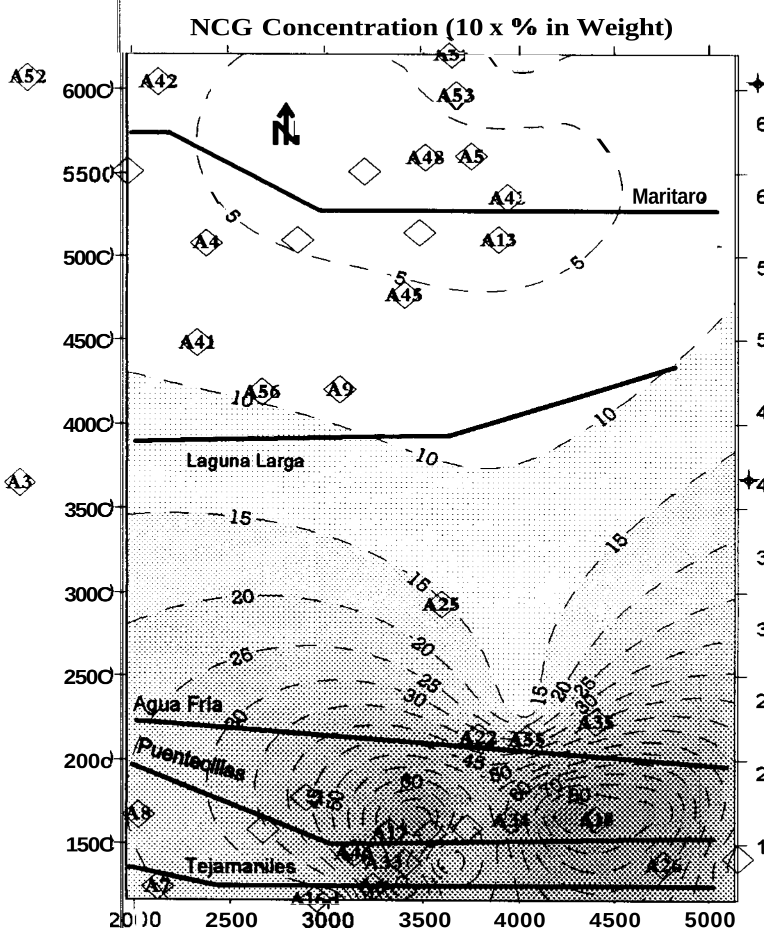


Fig. 1.- Spatial Distribution of Total Gases 1981-1984

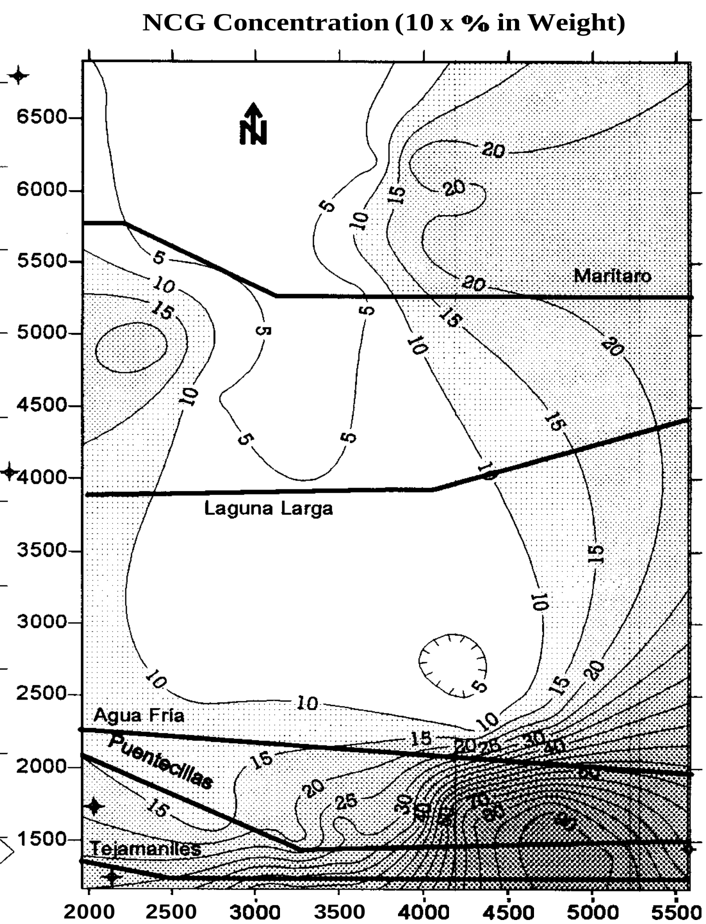
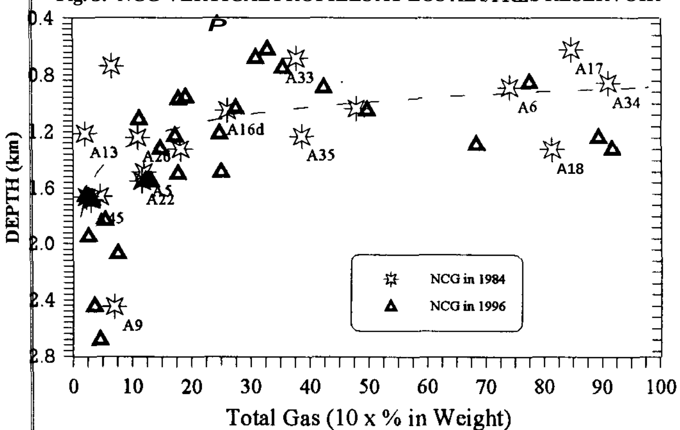


Fig. 2.- Spatial Distribution of Total Gases in 1996

minor than in the southern sector, Certain E-W alignment existed, corresponding to faults oriented W-E. It is also observable a N-S gradient originated by the lowest NCG concentration in the north and by the highest in the south.

The present effect of reservoir's exploitation on NCG concentrations, between 1984 and 1996, is shown in figure No. 2. From 1984 up to 1996, there is a tendency of the NCG to increase toward the East, following a slightly SE direction, in both zones of the field. Something very interesting is observed in the S-N profile: particularly in the southern zone, the gases increment has a markedly growing trend in that direction, but restricted to the y-coordinates of 1250 m and 2000 m. It is observed that NCG concentration gradient is aligned in two portions following the orientation of two main faults system, Puentecillas (A17, A34, A18) and Agua Fría (A22, ASS, A35). In the northern zone there is a minor increment, but observing the same trend and conserving a similar profile between the y-coordinates of 5500 and 6000 m (Fig. **2).** NCG concentration gradient follows the same orientation as Laguna Larga and Maritaro faults (A42, A19, A43).

Fig. 3.- NCG VERTICAL PROFILES AT LOS AZUFRES RESERVOIR

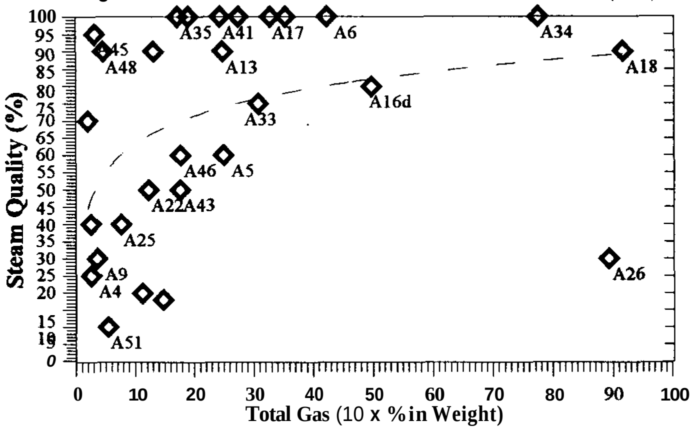


During the analyzed period 1984-1996, the content of gases in both zones has maintained a similar vertical profile, as an inverse function of depth (Fig. **3).** At major depth the gas amount is minor; while in shallow zones, the gas concentration increases. Exceptions happen in some wells located in zones of low gas content toward the West of the field. **A** vertical 800 m thickness stratum exists in the southern sector, located between 600 and 1400 m depth, where NCG concentration is greater than 2%, reaching values up to 9% in weight (Fig. **3).**

NCG CONCENTRATION *AND* THERMODYNAMICS OF WELLS

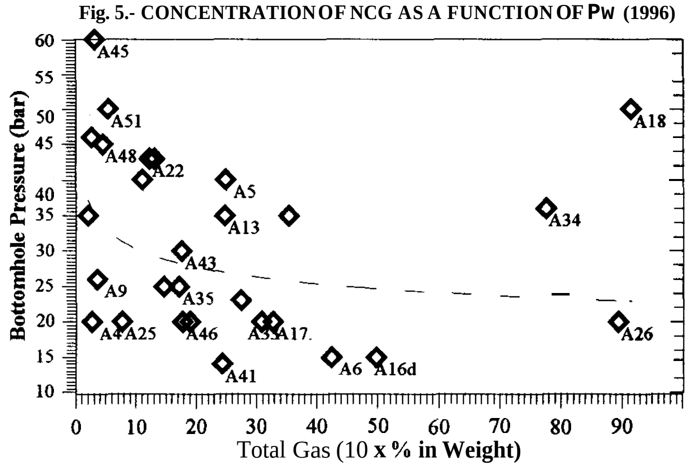
Thermodynamic conditions of producing wells, have a close relationship with gases presence. The general trend is that wells having rich or growing gas concentrations (NCG > 2% in weight), have high steam quality (Xv *2* 75%, Fig. 4). Wells with poor and constant gas concentrations (1% ≤ NCG ≤ 2%) have lower and constant steam qualities (Xv ≤ 50%). Some exceptions can **be** noticed in wells that have been little exploited, located in the center of the northern sector: A45, A48, A32. Wells with small amounts of gas (NCG < 1%) could have any thermodynamic condition (Figs. 4 **and** 5).

Fig. 4- CONCENTRATION OF NCG AS A FUNCTION OF Xv (1996)



At this moment there is a clear correlation of gases in steam dominated two-phase wells (75% ≤ Xv ≤ 90%): NCG concentration grows as a logarithmic function of *steam* quality (Fig. 4). The exception is found at well ***A26*** in the southern sector, which is seemingly in a region naturally rich in gases. Its high NCG content could also be explained as a direct effect of injection in that portion of the reservoir. This correlation does not apply in single steam phase wells, whose quality exceeds Xv > 90%. In such wells, several NCG concentrations could exist. It also *seems* to exist **an** inverse relationship between bottomhole temperature & pressure and gases (Fig. 5): NCG concentration diminishes when pressure and temperature increase. The exceptions correspond to wells with natural **high** NCG content (A18 and A34) in the southern sector.

Fig. 5.- CONCENTRATION OF NCG AS A FUNCTION OF Pw (1996)

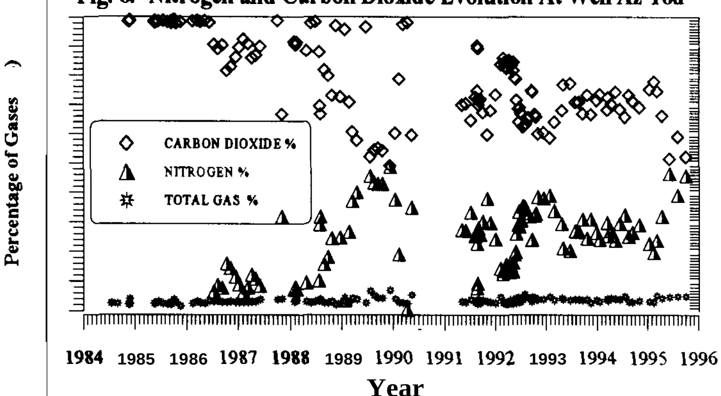


INFLUENCE OF ATMOSPHERIC NITROGEN ON NON-CONDENSIBLE GASES DISTRIBUTION

At Los Azufres, reinjection of waste liquid is carried out parallel to the exploitation of the field. Simultaneously, injected water drags air toward the reservoir through the injection wells (Home et al., 1989; Suárez, et al., 1992). The air arrives to deep reservoir zones and breaks down into its primary elements. Oxygen reacts immediately, combining with another components in the formation, probably within the injector wells neighbourhood. On the other hand, Nitrogen and Argon, inert gases, are freely displaced from zones of injection to production sectors. The concentration of these two gases, have exhibited a marked increment in several producing wells. In some wells, the increase has been exponential, with a factor between 4 and 6, approximately, on the percent of initial weight. The molar quotient N_2 / Ar has been falling with time (Tello, E., 1996), reaching in some cases the same value as in the atmosphere (83.6).

The NCG increment has generally maintained the percent of CO_2. But reinjection accompanied by air is contributing to increase the total gases due to the extra amount of atmospheric N_2. Therefore reinjection causes an increment of NCG in some wells and pushes the reservoir gases in the same direction (Fig. 2), following preferential trajectories, obviously related to **high** permeability paths. Figure 6 illustrates the evolution of N_2 & CO_2 concentrations at well A16d, one of the oldest wells of the field. It is clearly observed that the displacement of CO_2 in the total percent of NCG, is a reflection of N_2 concentration. When NCG concentration increases, as a direct effect of injection, there is an increment of N_2 that results in the simultaneous decrease of CO_2; and viceversa (Fig. 6).

Fig. 6.- Nitrogen and Carbon Dioxide Evolution At Well Az-16d



FLUID TRANSPORT THROUGH FAULTS

Fluid in wells showing the major amount of NCG (A18 and A34), flashes inside the formation, presenting a high pressure drop and segregation of phases. Gases have a natural tendency to follow the steam phase, moving easily through fissures. The produced fluids in these wells, flow mainly through the fractures. The behavior of wells is very different at each zone and the reinjection effect contributes to modify their behavior in different ways, according to the reached vertical stratum. The injection at well A7 in the southern sector is carried out, at least partially, in the two-phase zone; while at well A8 injection is seemingly carried out in the compressed liquid region.

Well A16d produces fluid from the Tejamaniles fault, while A17 produces from the Puentecillas fault. A16d is a two-phase well dominated by vapor, and since 1992 it tends to become a steam single phase well. It has a deviated completion and produces from an interval located between 850 and 1050 meters depth, inside the two-phase zone dominanted by liquid. Well A17 produces almost pure vapor with an average enthalpy of 2770 kJ/kg. It has a very short open liner between 613 and 627 m depth, penetrating partially the highest steam saturation natural stratum. Well A16 located in the same zone, is a two-phase well with very little steam quality (~ 15%). It produces from a reservoir portion close to the crossing of two main faults, Agua Ceniza and Tejamaniles, through a liner openned between 1101 and 1322 m depth.

Those three wells represent the three main production strata of the southern sector, at different thermodynamic conditions. The three have in common, in conjunction with A37 and A46, the hghest N_2 concentration (> 10% in weight) in that portion of the reservoir. Well A33, located between Puentecillas and Tejamaniles faults, has a short open liner between 645 and 683 m depth. In August 1988, this well produced 98 T/h of fluid with 10 T/h of liquid, a steam quality of 90%, and an enthalpy of 2428 kJ/kg. In December 1989 the same well produced 154 T/h of fluid With 90 T/h of liquid, its steam quality was 42% and its enthalpy 1280 kJ/kg. Vapor production at this well decreased 50% in 16 months. Nitrogen dissolved in the fluid has presented a similar behavior as in well A17: in July 1986, it had 0.43% of N_2 in weight; in December 1988, N_2 had increased until 2.6% in weight and in August 1989, N_2 constituted 3.11% in weight.

Every information available indicates that N_2 migrates following the main faults direction (Fig. 1), increasing the total NCG concentration. Under these conditions, the evolution and displacement of both, CO_2 and N_2, are valuable indicators of the communication between several zones of the reservoir, leaving during their trajectory, the traces of high permeability paths related to faults and fractures.

CONCLUSIONS

- Steam phase at Los Azufres reservoir, has an heterogeneous composition, showing a wide range of NCG concentration values between 1% to 9% in weight. The general observed tendency is that at major depth the gas amount is minor; while in shallow zones, the gas concentration increases, with some exceptions.

- Wells having rich or growing gas concentrations greater than 2% in weight, have high steam quality, greater than 75%. Wells with poor and constant **gas** concentrations ($1\% \leq NCG \leq 2\%$) have steam qualities lower than 50%. Some exceptions occur in wells that have been little exploited. Wells with very small amounts of gas ($NCG < 1\%$) could have any thermodynamic condition.

- There seems to exist **an** inverse relationship between bottomhole temperature & pressure and gas content: NCG concentration diminishes when pressure and temperature increase.

- Injection modifies field's geochemistry. Reinjection of waste liquid accompanied by ***air*** is contributing to increase the **total gases** due to the extra amount of atmospheric N_2. Reinjection causes an increment of NCG concentration in some wells and pushes the reservoir noncondensable gases toward the production zones, changing their current spatial distribution.

- It is clearly observed that the displacement of CO, in the total percentage of NCG, is a direct reflection of N_2 concentration. When NCG concentration increases, there is an increment of N_2, diminishing simultaneously the percentage of CO, , and viceversa.

- Under these conditions, the evolution and displacement of both, CO, and N , are valuable indicators of the communication between several zones of the reservoir, showing the traces of high permeability paths related to faults and fractures.

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