THE CANTARELL OIL FIELD AND THE MEXICAN ECONOMY

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Abstract

Major oil fields have played an essential role in the global hydrocarbon supply, but the majority are now in decline. The Cantarell macro-reserve has produced significant volumes of hydrocarbons and brought countless benefits to the country, but starting in 2004, the exhaustion of the Cantarell supply began to affect the oil production platform. This research studies all of the factors that have had an impact on the performance of this macro-reserve, which are fundamental to explain the current state of affairs. The conclusion is that the management of the Cantarell oil field was less than optimal during the three time periods identified in the paper, as decisions were made on a non-technical basis, which contributed to the decline and the series of challenges facing the oil complex today. These difficulties could, in turn, be mitigated through the use of technology.

Keywords: Oil, Cantarell, hydrocarbons, Pemex, investment.

I. INTRODUCTION

Worldwide, major oil fields have been an economic boon. However, many of them are now in decline, which has prompted a search for solutions to prolong their lifespan or find alternative sources to meet the oil demand, such as the exploitation of non-conventional crude.

Cantarell has long been among the top 100 oil field complexes on the planet, at one point contributing 45% of worldwide production (Robelius, 2007: 77), but is now one of the reserves currently in decline (Sorrel *et al.,* 2012: 710). Cantarell has also been the source of the largest volumes of oil extracted in Mexico since the end of the 1970s. However, by the end of 2004, the supply began to become depleted, which led to a situation in which by mid-year, the oil field was only producing 15.4% of the historical production peak reached in December 2003. In light of this behavior, the question arises as to the rationale behind the speed of this decline. Some papers have sought to explain the performance of the giant oil field from a technical perspective, including documents published by Pemex, while others have taken a more institutional approach (Lajous, 2009), but none has thus far explored a structural analysis tied to the economic environment of the country and its influence on the management choices made.

This paper aims to analyze the performance of the Cantarell oil field over time and its role, as the cornerstone of the oil production platform, in Mexico's economic development. This text is divided into four sections. The first reviews the major factors that have affected the oil field's performance over time. The second recounts its recent history, aiming to identify the principal factors explaining the current state of affairs. The third section analyzes the principal challenges facing the oil field and its prospects for the future. Finally, this paper concludes that Cantarell has indeed been the origin of significant financial resources that have underpinned Mexico's economic growth, but inefficient management derived from a series of shortsighted decisions played a major role in its rapid decline and the challenges it now faces.

CANTARELL AND THE FACTORS THAT HAVE INFLUENCED ITS PERFORMANCE

Cantarell is the name that Petróleos Mexicanos (Pemex) gave to a cluster of oil wells located offshore in the bay of the Mexican state of Campeche, encompassing a surface area of around 21,000 square kilometers. It has been one of the most productive fields, producing the highest volumes of hydrocarbons and oil income Mexico has ever seen.

Reconnaissance works began offshore in 1966, but it was not until 1972 that conclusions were reached as to the extent of the onshore wells in the states of Chiapas and Tabasco, although the costs of exploration and drilling were six times as expensive as on the mainland. In the early stage, the structures for the Chac field were sketched out.[2] Exploitation of these fields began on June 23, 1979, in the oil discovery well called Cantarell 2095, which had a 974-meter impregnated column. That same year, average production at the Akal field reached 42 thousand barrels per day (mbd) per well, production commenced at the Nohoch field with a volume of 4.3 mbd, and the Kutz field was discovered. These events took place in an environment of high crude oil prices, thanks to the political plight of Iran and disputes between the members of the Organization of the Petroleum Exporting Countries (OPEC), among other reasons, all of which stimulated oil activities in Mexico.

Initial oil production at Cantarell averaged 88 mbd in 1979, but this figure skyrocketed to 611 mbd by 1980, thanks to progress made in the structural profile of the Campeche platform. In 1981, oil production peaked at 1,156 mbd through the exploitation of only 40 wells, essentially by injecting water into the reserve. High oil prices, mainly derived from the fact that the global oil supply was restricted due to the Iran-Iraq conflict, constituted the principal reason driving Pemex to raise the volume of crude produced, encouraging investment in the entire value chain of the national industry.

In 1982, Mexico ran into liquidity problems and the government was crippled by a swollen public finance deficit, but the production platform continued to ramp up, reaching 1.6 million barrels per day (mmbd) in an international oil market with a surplus supply. In 1983, an additional tax burden was imposed on Pemex, which began to have to pay the value added tax and the special tax on production and services, such that its fiscal contributions rose from 16% in 1981 to 43% of all public revenue in 1983. In the midst of public spending adjustments and efforts to reduce the fiscal deficit, investment in the state enterprise fell (Romo, 2010: 417-444). However, operations at Cantarell were prioritized within the Pemex portfolio, in particular, by increasing the number of producing wells.

In May 1984, exploitation of the Ixtoc field began with an average production of 5.2 mbd. Moreover, in 1987, artificial exploitation systems (pneumatic pumping) were installed, which permitted the platform to maintain average production at 950 mbd. In those years, oil production acted as a counterweight to Mexico's weak financial situation, especially with regard to its public finances.

In the mid-1980s, the government began to liberalize the economy, followed by the privatization of public enterprises and economic deregulation in the years to come. They also preserved public spending cuts in order to reduce the financial deficit and increase the low investment in Pemex, which led to an adjustment process in the Pemex portfolio of activities. The rate of exploration operations was reduced and little attention was given to new investments in refining and petrochemicals, favoring oil exploitation, an area in which Cantarell's operations were especially noteworthy. This change in the Pemex business model took place in an environment of an excess supply of crude in the international oil market (Romo, 2011: 140).

In 1990, Mexico managed to renegotiate its foreign debt with favorable terms, reducing the financial pressure on the government and the liabilities of the state oil enterprise, which were also included in this renegotiation. However, the investment channeled towards Pemex only recovered slightly, although Cantarell was one of the principal destinations for these resources. Between 1991 and 1994, investment in the mega complex accounted for around one-fifth of all of Pemex's expenditures on exploration and production, with the principal goals being to add new reserves, maintain the production platform, increase the gas dehydration capacity, transport gas, and finish the Nohoch C. drilling platform. In August 1991, production began at the Chac field, and in February 1993, exploitation commenced at the Balam field, both of which experienced major changes in production in those early years.[3]

When the crisis broke out at the end of 1994, the financial situation of the government was affected once again, and new adjustments were made to public spending. However, unlike what happened in previous years, additional investments were channeled into exploitation, especially at Cantarell. The objective was to back the commitment agreed upon with international creditors, where oil was

granted as a guarantee for the loans obtained and to expand the flow of petrocurrency. In 1995, Pemex had maintained its production platform at above the 1.0 mmbd achieved since 1990, but with the new investment, it managed to average 1.3 mmbd between 1997 and 1999.

In 1996, Pemex implemented the Cantarell Optimization Project (POC) to maintain the production capacity of the wells and reduce maintenance costs, supported by the increased participation of private enterprises.[4] The following year, Pemex launched the so-called Productive Infrastructure Investment Projects with Deferred Expenditure Registration (PIDIREGAS), whose purpose was to channel even more resources to strategic projects for the state oil company. One of these was the Cantarell Project, aiming to improve its infrastructure and push production levels upwards[5] by injecting nitrogen. The justification for this decision was based on the fact that the energy for the field came primarily from the secondary gas cap and it was believed that more energy was needed to increase production, which could be obtained through this injection. This decision was controversial, because although it was made on the basis of the economic benefits it would bring, in light of the low price of nitrogen and the potential for reducing imports of natural gas (Lajous, 2009), it was criticized from a technical perspective by experts who believed the reinjection of natural gas to be the better choice (Garaicoechea, 2007: 4-6).

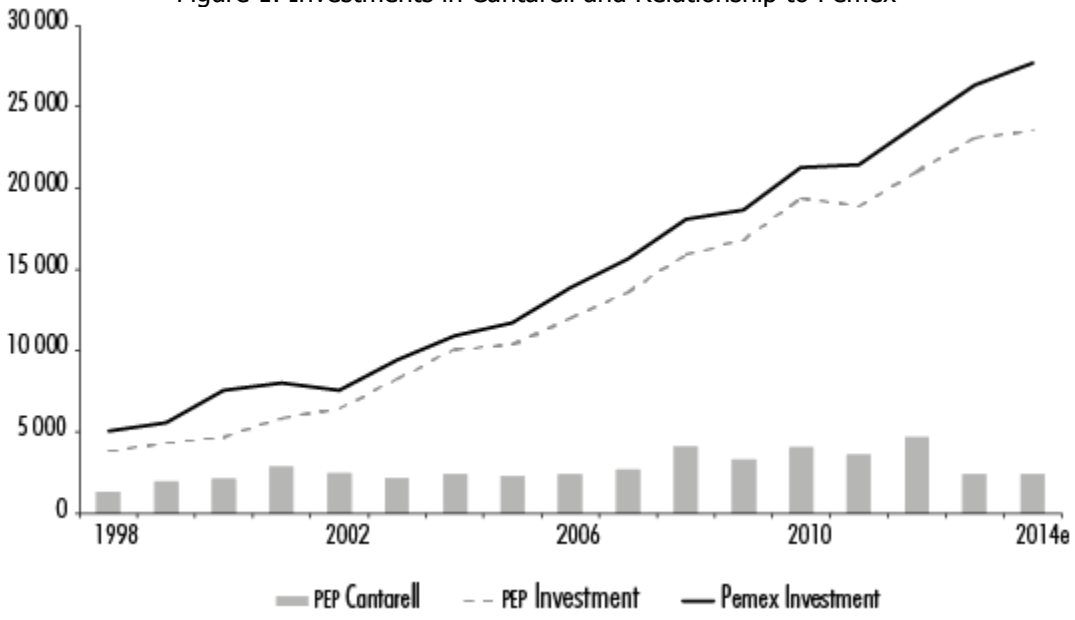
In an environment of low crude oil prices in the international market, which had persisted since 1998, and in a process of recovering from the two previous years, Pemex turned its attention primarily towards investing in Cantarell, together with investing in other projects to drive oil and gas production.[6] In 1998, the Sihil block was discovered, below Akal, which came with the potential for more than one billion barrels of crude oil equivalent (bbcoe), something like 5% of the original reserves of the Akal field (Barton, 2009/2010: 28).

In the first four years of the PIDIREGAS scheme, an annual average of two billion dollars were channeled to the Cantarell complex. In early 2000, the infrastructure was upgraded to optimize gas exploitation and to expand drilling operations;[7] nitrogen injections also commenced. Starting in 2002, the portfolio of projects for the exploration and exploitation of oil and natural gas was expanded, including the notable Ek-Balam field, which was included in the Cantarell complex. As such, the average annual investment rose to 2.4 bd between 2002 and 2007 and 3.8 bd between 2008 and 2013, representing the highest volumes ever invested in the state enterprise (see Figure 1), whose central pillar consisted of increasing the number of wells.[8]

In December 2003, Cantarell hit a production peak of 2.2 mmbd, primarily thanks to the Akal field, which contributed 95.2% of the total amount exploited at the complex (see Figure 2). At that point in time, Mexico reached an all-time high in crude production. This giant field accounted for nearly two-thirds of the national total and even reached number one in offshore production in the world, as well as the number two macro producer, second only to the Saudi Arabian field Ghawar. In fact,

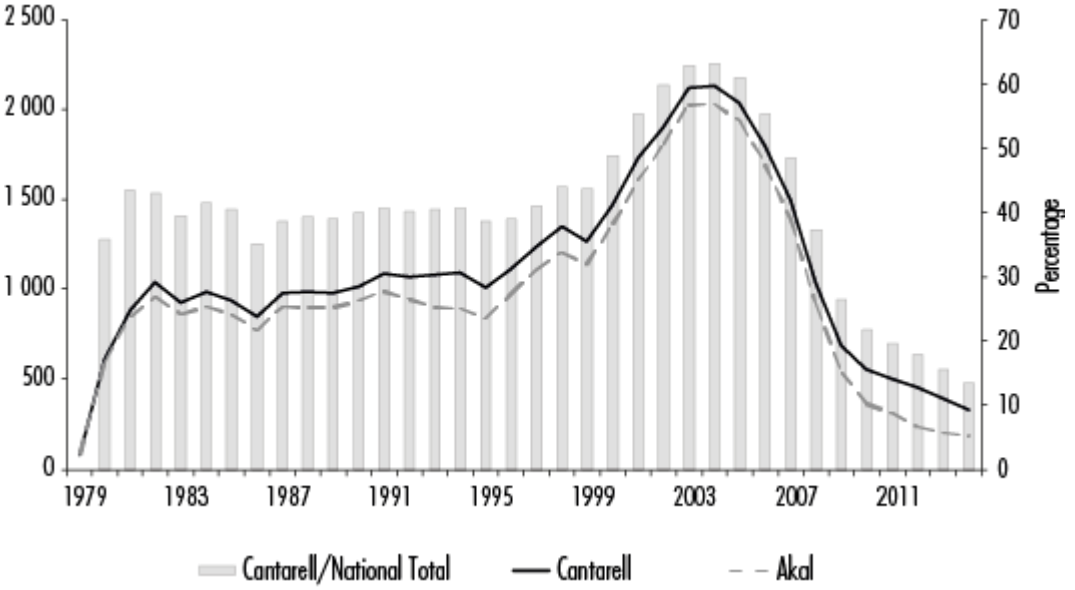
Cantarell averaged 2.3% of the global oil supply between 2000 and 2003, after having maintained a percentage of only 1.4% between 1980 and 1999.

Figure 1. Investments in Cantarell and Relationship to Pemex



Source: Created by the author based on data from Pemex.

Figure 2. Oil Production at Cantarell. Thousands of Barrels Per Day.



Source: Created by the author based on data from Pemex.

At the end of 2004, as the Akal field became depleted, Cantarell began to decline, in spite of the strategies implemented, investments made, and participation of private enterprises.[9] The oil production decline ran counter to the increase in natural gas production between 2004 and 2009. One driver behind this behavior, in addition to the reorganization of the fluids at the field, was the increase in nitrogen production, which by mid-2014 accounted for just over half of its total natural gas production. The fall in hydrocarbon production at Cantarell was compensated for by increases from other projects (Ku-Maloop-Zaap, Litoral Tabasco, and some fields in the Southern Region). In 2006, Pemex implemented additional measures to push exploitation at the macro field[10] and prevent further declines in crude production,[11] but these were largely unsuccessful, as production continued to fall. In 2008, when the Kambesah field was discovered and international oil prices reached a historical peak, Mexico enacted changes to the legal framework for the state oil enterprise to allow it to expedite its operations to procure goods and services,[12] make use of Comprehensive Exploration and Production Contracts, and initiate Corporate Governance efforts. The National Hydrocarbons Commission (CNH) was created and the powers given to the Ministry of Energy were revised, a situation that limited the management capacity of the oil company, because it subjected the enterprise to greater oversight, control, and governmental follow-up,[13] which in turn further complicated decision-making with regard to projects at the oil company, especially those taking place at the Cantarell complex.

THE CURRENT SITUATION OF CANTARELL

As of mid-2014, the Cantarell complex[14] consisted of the Nohoch, Chac, Akal, Kutz, Ixtoc, Takín, Ek, Balam, Sihil, Kambesah, and Után fields, of which the latter was not producing. With the exception of the Kambesah and Ixtoc fields, Cantraell produces heavy crude oil ranging from 12° to 24° API (American Petroleum Institute), with a high content of sulfur and metals. The reservoir rock is clastic limestone and dolomitized carbonates, naturally fractured with high permeability and porosity.

In general, the Cantarell fields have high rock permeability, broad thickness of impregnated rock, and are located in strips of water no greater than 100 meters and at depths of up to more than 3,000 meters. It is considered a mature reserve, so its oil production is obtained with a high percentage of water and rapid progress of contact with gas, which has led to a smaller oil window, (Morales *et al.,* 2014), varying from 60 to 100 meters.

The original volume of hydrocarbons contained at the Cantarell complex at the end of 2013 was about 42.6 billion barrels of crude oil equivalent (bbcoe), 2.1% lower than the figure in 2002. This puts the complex in the range of a super-giant field (Ivanhoe and Leckie, 1993: 87-91), although the CNH has designated it as a "compartmentalized" field (Comisión Nacional de Hydrocarburos, 2013: 87).

Similarly, as of the end of 2013, the total 3P reserves of hydrocarbons was around 5.3 bbcoe, which was 53% lower than what was reported in 2002. However, what was most alarming is the behavior of 1P reserves, which fell from 9.0 to 2.2 bbcoe, a situation that runs contrary to the international trend by which the growth in reserves tends to be highest in the largest, oldest, and in particular, onshore fields (UK Energy Research Centre, 2009: 58). This decline in the proven reserves at Cantarell is a reflection of the production obtained, but also of the administrative problems plaguing the reservoir and its depletion,[15] which has translated, among other factors, into water invasion. In turn, the drop in reserves was a key factor in driving the diversification of the project portfolio at the state oil company, including its incursion into deepwater operations, mature fields, and complexes, such as the Tertiary Gulf Oil Project (previously known as Chicontepec).

Of the total proven reserves of oil, both liquid and condensate, the reserves located at the Akal field were the most important as of the end of 2013, with 75% of the total at the Cantarell complex and accounting for 16.9% of the national supply. The Akal field has 2P and 2P reserves, but it is also the field that has experienced the greatest depletion of proven reserves over the years.

The number two field in terms of oil reserves was Sihil, followed by Ek, Ixtoc, and Kutz, which together account for nearly one-fifth of the total 1P reserves of the complex. The fields with the highest total reserves (3P) were Sihil, Ek, and Balam. It will be impossible to reverse the downward trend of the remaining hydrocarbon reserves at Cantarell, unless an autonomous block is discovered. Between 2001 and 2012, the discoveries reported in the three wellsUtán-1, Sihil-5, and Ixtoc-22 added 223 mmbo of 3P reserves, of which a little over half corresponded to 1P reserves—102.2 mmbo and 73 billion cubic feet (bcf) of natural gas—. Nor have major volumes of proven reserves been added due to revisions.

Towards the end of 2014, crude oil production at the Cantarell Asset amounted to 351mbpd, although the Akal field was depleted more rapidly than expected ULuhnow, 2007). For this reason, its contribution to national oil production plummeted from a maximum in March 2005 of 65.5% to 14.7% in September 2014. Additional oil production from the Sihil,[16] Ek, and Ixtoc fields, the result of the increase in the number of producing wells—especially in the first two cases since 2009—[17] was a relative compensation for the decline of the Akal field. These three fields ended up contributing around 43% of the total crude production of the complex, after contributing only 1% in 2004. In turn, the Chac, Balam, and Kutz fields began to be depleted (see Table 1).

In summary, in mid-2014, the Cantarell Asset was contributing around 13% of the total crude produced in Mexico and one-third of total heavy crude, as well as 34.2% of cumulative historical oil production as of the end of 2013.

Table 1. Oil Production at Cantarell Fields.* Thousands of Barrels Per Day

Año	*Cantarell*	*Akal*	*Balam*	*Chac*	*Ek*	*Ixtoc*	*Kutz*	*Nohoch*	*Sihil*	*Takín*
Origin to 1989	843	852				5.8		58		
1990-1999	843	994	24	38	9	8		73		
2000	1 471	1 361	18	18	3	12		59		
2001	1 731	1 604	20	22	2	11	14	68		
2002	1 901	1 805	13	17	1	11	9	46	2	
2003	2 122	2 028	14	20	1	11	13	26	9	
2004	2 137	2 038	11	17	1	11	12	41	6	
2005	2 036	1 938	6	12	2	13	12	36	19	
2006	1 802	1 701	7	12	6	14	12	34	16	
2007	1 491	1 389	10	13	17	12	11	28	12	
2008	1 040	925	12	12	18	12	11	24	19	7
2009	685	543	10	12	28	11	10	18	35	18
2010	558	370	7	14	50	11	21	14	60	11
2011	501	314	5	9	47	15	19	12	66	14
2012	454	234	7	6	42	23	13	6	110	12
2013	440	203	9	10	51	29	3	8	110	8

* All fields that Pemex reports as part of the Cantarell Asset for administrative purposes were considered.

Note: Up until 2013, Kambesah produced 10 thousand barrels per day and Után did not produce at all, as it only had natural gas reserves.

Source: CNH.

The exploitation pattern at Cantarell has not followed that of the other giant fields, which tend to have a prolonged plateau period (ASPO, 2001: 5), as its annual rate of decline was 20.3% between

2006 and 2011, which contrasts with the international practice for this type of macro-reserve (of between 4% and 6%), or those located offshore, estimated at 10% (Höök, 2009: 2268).[18] Pemex justified the production decrease at Cantarell associated with its phase of maturity as a result of the "…increase in the percentage of water and salt content in the crude currents…(and because)…the thickness of the oil in the field is increasingly reduced and in some parts, the channels of gas and water in the wells are higher…(and)…the effect of extracting gas in the transition zone in the production of water and oil…" (Pemex PEP, 2012a: 5), a situation that led to the closure of certain wells[19] and the building of infrastructure to manage this water.

The oil recovery factor at Cantarell, defined as the ratio between the cumulative production and the original volume of total reserves (3P), was 36.4% as of the end of 2013, a level similar to the global average of 35% (Babadagli, 2007: 222) and one of the highest in the country,[20] but it escalated since 2002, when the figure was at 23.5% due to the effect of increasing production and fewer new reserves.

Natural gas production at the Cantarell Asset maintained a stable ratio to barrel of oil extracted since the beginning of its exploitation until 2006, equivalent to 7.4% of natural gas per barrel of oil obtained—measured in barrels of crude oil equivalent—, but since 2007, it began to rise to 34%, until reaching an average of 39% between 2009 and 2013, a situation that can be attributed to the aforementioned decision to inject nitrogen gas and reinject the sour gas, beginning in July 2004. In this way, associated natural gas production rose gradually, from 566 mmcfd in 2000 to a peak of 1,627 mmcfd in 2008, to culminate at 1,002 mmcfd in 2013.

However, much of the production was nitrogen gas, because the ratio between nitrogen gas and natural gas produced went from 18% in 2007 to 148% in 2013. Pemex was not prepared to deal with this increase in gas production, because it did not have the appropriate infrastructure for this level of exploitation, nor the capacity to separate out the nitrogen, a situation that led to two problems:

1. The contamination of the natural gas—with nitrogen—generated pressure from major consumers to offer discounts on firsthand prices. In response to this request, and two years delayed in commencing operations,[21]Pemex had to develop schemes to handle the nitrogen and build a nitrogen-eliminating plant at the Gas Processing Complex in Pemex City, Tabasco, with processing capacity of 630 mmcfd.[22]
2. Increasing amounts of gas were released into the atmosphere as a result of flares starting in 2001,[23] a problem that was exacerbated over time,[24] leading the National Hydrocarbons Commission (CNH) to declare that this "was endangering" the optimal exploitation of Cantarell.[25] This problem also entailed not only an opportunity cost of exploiting natural gas for Pemex, but also additional spending, because the wasted gas was taxed in the same

manner as the gas channeled for sale, a rather unreasonable situation, because it was the government that decided not to invest in infrastructure for its management.

Starting in 2007, gas flaring and venting began to increase in a context of high fuel prices, reaching maximum exploitation of 65.8% in 2009, equivalent to a total of unexploited gas of nearly 680 million cubic feet per day (mmcfd). In response to this problem, the CNH approved and published technical provisions to prevent or reduce gas flares and venting during hydrocarbon exploration and exploitation works.[26] As a result, the state enterprise had to build additional infrastructure for gas recovery or reinjection into the field, as other major measures. Starting in October 2011, the state company began to meet its goals for the gas exploitation index of 96.6% set by the CNH, achieving 97.5%, as of the end of December 2012, but in a context of lower overall natural gas production. The estimate of the losses due to gas flares at the Cantarell complex amounted to nearly 1.3 bd between 2009 and 2012.[27]

The total value of the hydrocarbons obtained at the Cantarell Asset as of the end of 2013 added up to approximately 445 bd, which entailed a major contribution to national oil proceeds,[28] as the production costs were low from the time exploitation began until the early years of the last decade. In effect, the original cost of production was 2.50 dollars per barrel (db), and starting in 2000, with the recovery processes implemented, this cost rose to between 3.50 and 4.50 db, until it began to average a little over 7.7 db between 2010 and 2012.[29] Operations also became more expensive as it became increasingly complex to access additional hydrocarbon sources and build the infrastructure required to do so.[30]

Of the value of the income obtained throughout the lifespan of the Cantarell Asset, nearly 73% was earned between 1998 and 2013, a time period during which nearly 42 bd were invested, which meant a little over 7.3 dollars in proceeds for each dollar invested.

It should be pointed out that, taking into account the behavioral pattern of an offshore field, between 2004 and 2012, the state enterprise missed out on something like 70 bd (see Figure 3),[31] by virtue of the fact that its rate of decline was higher than that of the other giant fields.

In addition, throughout the entire lifetime of Cantarell, the complex has lacked an optimal management strategy and has failed to take into account the conditions of supply and demand in the international oil market. Instead, the state enterprise exploited the resources, without optimizing income, in response to a market offering attractive prices. The 1990s bore witness to the worst correlation in this sense.

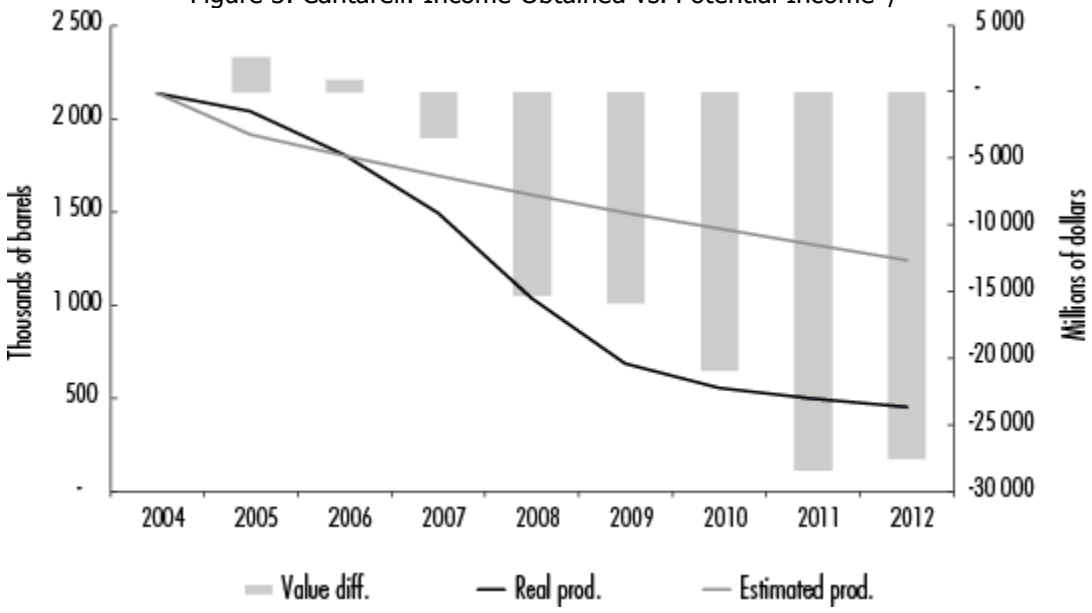
WHERE IS CANTARELL GOING?

Although many oil fields around the world are becoming depleted, researchers estimate that there are still considerable volumes of hydrocarbons to be recovered, as only 1% extra in these types of fields would be equivalent to between 20 and 30 billion barrels of oil additional.[32]

By the end of 2013, the original volume of hydrocarbon reserves available at Cantarell consisted primarily of oil (around 92%). Cantarell's importance resided in the fact that it represented 14.8% of the national total of the original volume of oil reserves; that is, the third-highest area of resources, topped only by the reservoirs of the Tertiary Gulf Oil Project (30.7%) and Ku-Maloop-Zaap (15%), as well as one-fifth of the 1P oil reserves and 16% of the 3P reserves.

Although the production potential of Cantarell has been exploited, especially at the Akal and Chac fields, there are still hydrocarbon reserves to be extracted, especially if we look at the recovery factors of other nations, where up to 46% recovery factors have been observed (Jan Kjärstad, 2009: 451) or the rates achieved in the North Sea. In fact, Pemex is forecasting the recovery of, between 2013 and 2050, an oil volume of 2,641 mmb of oil and 1,436 bcf of natural gas, projects for which it plans to invest nearly 35 billion dollars in the Cantarell and Ek-Balam projects.[33]

Figure 3. Cantarell: Income Obtained vs. Potential Income*/



**/ Refers to a comparison between the value of volumes obtained and the volumes determined through international practices with a decline rate of 6%.*
Source: Created by the author based on Pemex data.

Besides continuing to exploit Akal, which has the majority of proven oil reserves, there is potential at the Sihil, Ek, Balam, and Kambesan fields, which contain 17% of the proven reserves of the complex and low cumulative production. The Kutz, Ixtoc, and Nohoch fields contain 6% of the total proven oil reserve and also present certain potential, because their recovery factor was below 20% (see Table 2).

Among the challenges continuing to face the exploitation of hydrocarbons at Cantarell are the following: increasing knowledge about the profile of the fields, in particular, the damage to the formation of crude reservoirs; improving the management of contact with water, especially at the Akal field; adding new production areas; neutralizing the effects of gas production in wells; optimizing management and disposal of water and gas produced; implementing a secondary recovery system through double displacement for the Akal field, as well as raising the management efficiency of the facilities operating production volumes up to five times higher than what was obtained at the end of 2012. For example, at the Akal field, there are estimates (Rodríguez de la Garza, 2013) indicating that it could increase its oil recovery by an additional 10%. However, the critical point to raise the recovery factor is the profitability of the operations, which, in turn, is determined by operational efficiency, productivity, and international oil prices.

Table 2. Proven Reserves (1P) at Cantarell, 2013

Field	*Remaining 1P Reserve*		*Oil, Liquids, and Condensate*		*Natural Gas*	
	mmbcoe	Recovery Factor*	mmbo	Recovery Factor*	bcf	Recovery Factor*
Akal	1 666.2	42.2%	1 467.10	41.5%	1 037.9	50.2%
Balam	60.3	10.2%	57.2	10.3%	15.7	9.6%
Chac	20.3	34.1%	18.8	34.3%	7.8	31.6%
Ek	127.8	11.3%	124.3	11.3%	18.4	9.3%
Ixtoc	75.5	17.0%	62.4	17.0%	68.3	17.1%
Kambesah	29.4	2.4%	26.3	2.5%	16.2	1.7%
Kutz	8.6	16.2%	7.9	16.3%	3.6	15.2%
Nohoch	14.5	30.6%	13.5	30.7%	5	29.7%
Sihil	176.2	8.1%	165.7	8.1%	55.2	8.8%
Takín	7.8	22.2%	7.6	22.0%	1.3	35.3%
Után	2.8	0.0%	-	n. s.	14.4	0.0%
Total	2 189.4	37.1%	1 950.9	36.4%	1 244.0	44.0%

* Refers to the recovery factor of 3P reserves out of the original volume; n.a.: not applicable; n.s.: not significant; mmbcoe: Millions of barrels of crude oil equivalent; mmbo: Millions of barrels of oil; bcf: billions of cubic feet.

Source: Created by the author based on CNH data

According to the methodology used, which employed an exponential model of decline (Arps, 1944: 228-247), based on equations up to the third degree, the production forecast for Cantarell was calculated up to the year 2025 (see Table 3). The results comparing these estimates (see Figure 4) with those reported by Pemex PEP are as follows. Both cases point to a production downturn; however, the estimates in this paper indicate that oil production will fall at a lower speed than what has been predicted by Pemex, as a result of the potential success of the exploitation strategies that have been implemented and investments made in recent years, particularly in the Akal field, and the possibility to use improved recovery techniques.

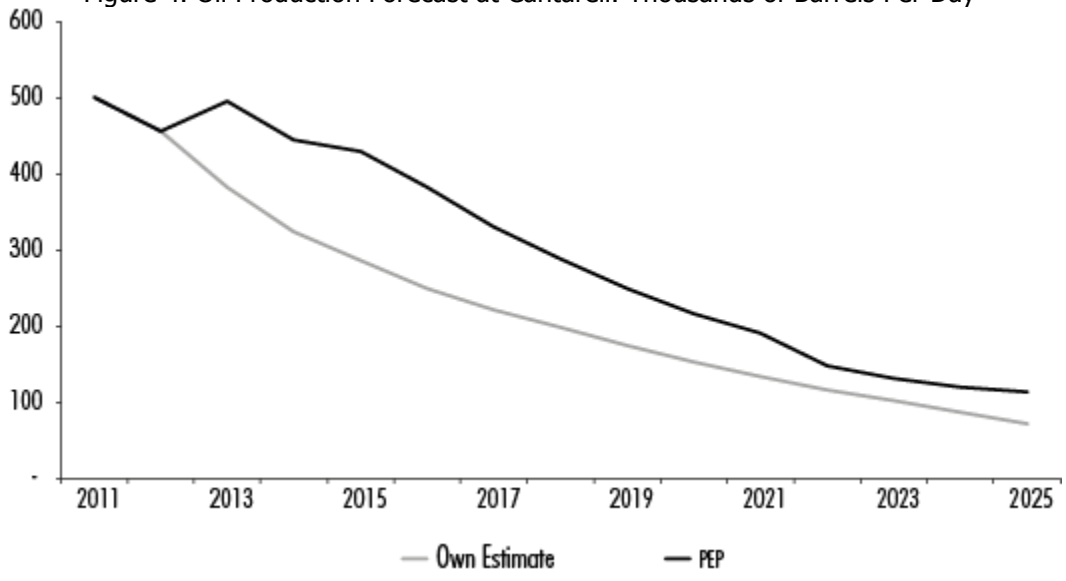
Table 3. Base Criteria for Projected Oil Production at Cantarell Fields

Field	*% of Original Volume Extracted*		*Function or Argument for Calculation*	*Observation*
	2012	2025		
Akal	34	35	y = 14.905e-0.092x	R^2 = 0.8284
Sihil	7	24	Annual rate of decline of 11% since 2014	
Hohoch	19	20	y = 37.599e-0.154x	R^2 = 0.8901
Kutz	17	22	y = 10.328e-0.252x	R^2 = 0.8692
Ixtoc	18	26	y = 0.0155x + 4.755	
Ek	10	27	y = -0.1445x2 + 3.7358x - 5.7058	
Chac	36	40	y = 14.905e-0.092x	R^2 = 0.8284
Balam	11	22	y = -0.0003x4 + 0.0173x3 - 0.3148x2 + 1.459x + 7.4792	Function adjusted to a volume of 112 mmb
Kambesah	0%	n.d.	n.d.	n.d.

n.d.: no data available.

Source: Created by the author based on Pemex data.

Figure 4. Oil Production Forecast at Cantarell. Thousands of Barrels Per Day



Source: Pemex PEP and own estimates.

CONCLUSIONS

Cantarell, and particularly the Akal field, has been one of the major sources of oil proceeds for Mexico, which has had a positive impact on the primary energy supply, the inflow of foreign currency in return for exported Maya crude, as well as the knowledge and experience accumulated by the oil industry, and specifically at Pemex.

Cantarell played a significant role as a heavy oil supplier to the world until the middle of the last decade, and has gained the designation of a super-giant oil field. Since the very beginning, it has been a priority for investment in the oil industry in light of its high profitability, derived from low operating costs and the vast oil and natural gas reserves available. However, its operations have been subject to government and corporate decisions that have undermined its optimal exploitation. In particular, its performance can be divided into three distinct phases, in which the common denominator has been the requirement to abide by the financial needs of the governmental administrations and support the economic situation of the country:

1. The first phase encompasses the time from when exploitation began to the end of the 1990s. During this period, Pemex's operations were essentially focused on oil exploitation at Cantarell, regardless of the conditions of supply and demand in the international oil market.
2. The next phase runs from the end of the 1990s until the oil production peak in 2003. This period is characterized by an increase in investment allocated to Cantarell by the government and the implementation of various strategies, including the use of nitrogen to increase pressure. The government's decision was partially retracted in light of the risk of losing a major source of income.
3. The final phase commences in 2004, where, in spite of the investment resources channeled to Cantarell, the fields began to decline, particularly Akal, seeing losses in productivity and efficiency, and facing greater complications to access the oil.

Oil production at Cantarell will continue for at least the next two decades, and the decline will persist, although it could be mitigated with the use of technology to broaden the geological knowledge of the fields and their profiles, strengthen the recovery methods used—especially at the Akal field—, as well as the allocation of additional financial resources.

In summary, the decision to exploit an oil field of the size of Cantarell should be made with priority given to technical choices and market strategies, rather than as a function of short-term government policies. In particular, one of the big questions still up for debate is the effectiveness of injecting

nitrogen as the fundamental mechanism to increase oil production. The rapid decline of the oil volumes produced at Cantarell should serve as a wakeup call for the management of other fields, such as KMZ.

APPENDIX 1

Appendix 1. Relevance of the Akal Field in Mexico

Item	*2000-2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
Oil production (mbd)	1 741	934	541	366	314	235	203
Natural gas production (mmcfd)	688	1 559	1 397	1 191	1 014	926	921
Water production (mbd)	4	56	62	68	103	99	115
Wells operating (#)	191	171	162	152	161	164	149
Oil production/well (mbd)	9.1	5.5	3.3	2.4	2.0	1.4	1.4
1P oil reserves, liquid and condensate (mmbd)	n.d	n.d	2 151	1 839	1 733	1 629	1 467
1P natural gas reserves, (mmcfd)	n.d	n.d	1 216	1 469	1 148	1 092	1 038
1P reserve/prod.-oil (years)	n.d	n.d	10.9	13.8	15.1	19.0	19.8
Ratio gas/oil (cf/bl)	421	2 977	5 216	6 364	5 013	4 889	6 274
Ratio of Akal oil production to total Cantarell production	94.8%	89.8%	78.9%	65.6%	62.7%	51.7%	53.4%
Ratio of Akal natural gas production to total Cantarell production	93.2%	96.8%	99.7%	97.3%	94.4%	92.3%	91.9%
Ratio of total 1P oil reserves at Akal to total Cantarell reserves	n.d	n.d	72.7%	72.4%	74.0%	69.1%	75.2%
Ratio of total 1P natural gas reserves at Akal to total Cantarell reserves	n.d	n.d	61.1%	89.3%	88.2%	82.3%	83.4%

n.d.: no data available; mbd: thousands of barrels per day; mmcfd: millions of cubic feet per day; cf/bl: ratio of Gas to Oil, the quantity of dissolved gas in oil in cubic feet per barrel (cf/bl).

Source: Created by the author based on data from Pemex and CNH.

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[2] In September 1974, drilling reached a depth of 3,400 meters, identifying oil-saturated sediments, with porosity and permeability. In 1975, drilling continued to 3,535 meters, finding oil impregnations, which led to the drilling of a second well in 1976, to a depth of 4,934 meters.

[3] After initiating production with 3.7 mbd, the Balam field achieved a platform of 55 mbd in December 1994, although the next year it averaged a mere 20.3 mbd, a trend that persisted until 1996, to later reach a low of 6.9 mbd in May 1997. [4] In 1997, Bechtel was hired to provide services and take part in managing the project. New forms of hiring and methods to procure materials and equipment were developed, pursuant to "international practices."

[5] Between 1997 and 1998, the strategies included increasing Cantarell production to 1.4 million barrels per day, reducing the amount of gas released into the atmosphere, injecting gas into the well, and more.

[6] Other important projects that year included Burgos and Delta del Grijalva, as well as the reconfiguration of the

Cadereyta Refinery.

[7] Between 1997 and 2002, 26 offshore drilling, production, and gas compression platforms were constructed. Pemex, Press Release 17/05/2002.

[8] As of December 2003, 218 wells were operating, representing nearly 50% more wells than Pemex operated in 1996.

[9] Even in 2004, 221 companies were participating in operations at the Cantarell complex, of which more than 90% were foreign (Pérez, 2004).

[10] Some of the notable measures adopted include: testing new production timelines; developing adjacent fields, such as Sihil, Kutz, Ixtoc, and Kambesah, to take advantage of the already-existing infrastructure; establishing differentiated exploitation strategies depending on the geological conditions of the reserves; adding new infrastructure to handle salt in exploitation activities; building and installing additional drilling platforms; using new drilling technologies (non-conventional wells); and finishing wells to produce in less thick zones (SENER, 2011: 103).

[11] For example, Pemex forecast oil production levels for the Cantarell complex at 1.9, 1.68, and 1.43 mmbd, for the years 2006, 2007, and 2008, which contrasted with the observed values of 1.8, 1.4, and 1 mmbd, respectively (Pemex, 2005).

[12] Up until the energy reform, all operations to procure works, materials, and services had to adhere to a unique legal scheme defined for the entire government, which delayed Pemex's purchasing operations.

[13] Cantarell was one of the first areas on which the CNH honed in to deal with the problem facing Pemex.

[14] The name Cantarell was initially used to refer to the Akal and Nohoch fields. Years later, the Cantarell Complex was defined to include the Kutz, Chac, and Sihil fields, and later, the Ixtoc and Takín fields were added, and the name became the Cantarell Project. Even later on, the Ek and Balam fields were added to the so-called Comprehensive Cantarell Asset. Finally, the Kambesah andUtán fields were added.

[15] Cantarell recorded a reduction in 1P oil reserves between 2004 and 2013 of 1.823 billion barrels of oil, which meant a total of two years of national production equivalent to the production platform in 2013.

[16] One of the fields that contributed to oil production was Sihil-24, which was drilled to 3,400 meters of depth at a cost of nearly 40 million dollars, as it contributed 11,500 barrels per day in an area of greater depth (Newspaper *El Economista,* 2012).

[17] The number of producing wells rose between January 2009 and December 2012 from 7 to 15 in the case of the Ek field and from 5 to 20 in the case of the Sihil field. National Hydrocarbons Commission, www.cnh.gob.mx, 12/3/2012.

[18] Other calculations produced different estimates; Cambridge Energy Research Associates estimated 4.5%, Exxon-Mobil between 4% and 6%, and the International Energy Agency 6.7% (Höök *et al.,* 2009: 2262).

[19] Between 2011 and 2012, an average volume of 101 mbd was produced, after averaging 62 mbd between 2008 and 2010 (Comisión Nacional de Hydrocarburos, 2013).

[20] By 2008, Akal had the second-highest oil recovery factor in the country at 35.3%, below the Abkatún-Pol-Chuc field, which recorded the highest percentage in the country at 37.5%. These two were followed by Nohoch with 29.7%, and the rest of the fields at Cantarell lagged far behind (Comisión Nacional de Hydrocarburos, 2010).

[21] In 2004, the announcement was made that the plant would begin operating in December 2006, but it actually opened at the end of 2008.

[22] The plant cost a little more than 150 million dollars, and the objective was to treat gas with nitrogen concentration

of up to 19.1%, reducing it to 1.2%, to comply with the Official Mexican Standard 001-SECRE-2003.

[23] Since 2001, Pemex recorded exploitation indices of 92.3%, as compared to the 98% stipulated in international standards.

[24] Pursuant to a document drafted by the President of the Grupo Constitución de 1917, the volume of gas burned has been higher, reaching the following figures: 2001: 85 thousand; 2002: 63,600; 2003: 52 thousand; 2004: 36 thousand; 2005: 38,400; 2006: 57,200; 2007: 112 thousand; 2008: 266 thousand; 209: 206 thousand; and 2010: 120 thousand barrels of crude oil equivalent (Garaicoechea, 2013: 1-5).

[25] According to the National Hydrocarbons Commission (CNH), Pemex endangered the optimal exploitation of crude oil in Cantarell derived from the overexploitation between 2010 and 2011, especially as a result of the amount of gas released into the atmosphere through flares. The commission estimated that the state enterprise failed to extract nearly 106 thousand barrels of oil per day, due to the fact that its method of gas exploitation wasted oil (Comisión Nacional de Hydrocarburos, 2011).

[26] The standard to reduce gas released into the atmosphere through flares—particularly in Cantarell—was published in the Mexican *Official Federal Gazette* by the National Hydrocarbons Commission on December 4, 2009. Between 2010 and 2011, the goals for gas exploitation were not met. By 2012, the goal for average gas exploitation was to reach 97.5%, pursuant to Resolution CNH.E.07.001/11 from the CNH.

[27] Estimated with public information from Pemex Exploración y Producción, Northeast Offshore Region, Cost-Benefit Analysis Document, Cantarell Project, Change in Amount and Scope, Mexico, October 2012.

[28] According to information from the Ministry of Energy, the domestic rate of return on the project has exceeded 900% (Comisión Económica para América Latina, 2001: 16).

[29] This corresponds to the average production cost at the Cantarell field reported by Pemex to the Security Exchange Commission.

[30] There were more wells, major and minor repairs, additional platforms, equipment to produce with an artificial jacking system (continuous pneumatic pump) in many of the wells and the laying of kilometers of pipeline, among other factors, as well as expenditures on operations and research.

[31] This was calculated based on a decline rate of 6%, which is the upper threshold of the range stipulated as international practice. This was compared with the real production value of hydrocarbons. All since 2004, which is when Cantarell hit peak oil production. Moreover, this took into account real gas production and its value at market prices.

[32] In fact, studies from the International Energy Agency indicate that by 2030, 20% of global oil production will be derived from secondary or tertiary recovery methods, including at Cantarell (Comisión Nacional de Hydrocarburos, 2012: 10).

[33] Includes the drilling of 130 development wells, one injector well, the construction of seven offshore structures and 31 pipelines, major and minor repairs, and the maintenance of the infrastructure (Pemex PEP, 2012a: 54).