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## CARBON CAPTURE AND STORAGE THE LACQ PILOT RESULTS & OUTLOOK



Exploration & Production – Paris  
2, place Jean Millier – La Défense 6  
92078 Paris-La Défense Cedex – France  
Tel.: +33 (0)1 47 44 45 46

Exploration & Production – Pau  
Avenue Larribau – 64018 Pau Cedex – France  
Tel.: +33 (0)5 59 83 40 00

TOTAL S.A.  
Share capital: 5 914 832 865 Euros  
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# CONTENTS



THREE YEARS OF INJECTION



ACTING FOR THE PLANET

QUALIFYING AN INTEGRATED CO<sub>2</sub> CAPTURE-TRANSPORT-STORAGE CHAIN



INNOVATING



ENSURING STORAGE INTEGRITY

TAKING RESEARCH FORWARD



EXPLAINING

DEVELOPING

11



21



23

# THREE YEARS OF INJECTION

On February 8, 2007, Total announced the launch of a CO<sub>2</sub> capture-transport-storage pilot at the Lacq basin, in keeping with its commitment to reduce greenhouse gas emissions. By January 8, 2010, the industrial chain was up and running. Over the ensuing three years, **more than 51,000 metric tons of CO<sub>2</sub>** were successfully injected into the Rousse reservoir.

The pilot, developed by the Research & Development teams of Total's Exploration & Production branch, is a European first. It has served to test a complete CO<sub>2</sub> capture-transport-storage chain based on a 30-thermal megawatt (MWth) oxycombustion gas boiler. It was deployed in connection with steam production for facilities at the Lacq industrial complex.

What is the outcome of this experiment unmatched in Europe?

- **The pilot has attained its objectives, namely:**
    - Proving the technical feasibility of an integrated CO<sub>2</sub> capture-transport-geological storage chain
    - Testing and validating oxycombustion on a 30-MWth boiler
    - Collecting the data needed to design the boiler of the future (200-MWth)
    - Developing a method for characterizing the storage reservoir
    - Defining a method for monitoring the integrity and environmental impact of a CO<sub>2</sub> storage site
    - Developing research programs with the academic world
  - **Safety performance was positive:** no accidents, with or without lost time, were recorded over the period.
  - **The installation's availability rates were satisfactory:** 83% for the pilot and 99% for the boiler (excluding scheduled shutdowns).
- According to the Intergovernmental Panel on Climate Change (IPCC), there are several hundred industrial sites worldwide that generate more than 100,000 metric tons of CO<sub>2</sub> per year and thus are potential candidates for geological storage.



Lacq basin  
Southwest France

*We invested over €60 million to build this demonstrator unit. In addition, Total has contributed to furthering university research on CO<sub>2</sub> capture-transport-storage technologies by allocating €€3 million to fund several French R&D programs since 2010.*

**TOTAL**  
Alain Goulois, Vice President  
Research & Development,  
Exploration & Production

## 60 million euros

The cost of building the pilot, entirely funded by Total.



## WHAT WILL HAPPEN AFTER INJECTION?

THE END OF INJECTION ON MARCH 15, 2013 DID NOT SPELL THE END OF THE PILOT INSTALLATION OR THE RESEARCH PROGRAMS. THE RESERVOIR WILL BE MONITORED FOR THE NEXT THREE YEARS (2013-2016), AND ACADEMIC AND SCIENTIFIC PARTNERSHIPS CONTINUE IN FRANCE AND ABROAD.

# ACTING FOR THE PLANET

*Experts agree that to control global warming, greenhouse gas emissions must be curbed. In recent years, geological storage has emerged as a promising route forward. The results of the Lacq pilot confirm the potential of this option.*

## Total, a responsible industrialist

Total strives to play an exemplary role in meeting this challenge. To reduce greenhouse gas emissions from our activities and thereby limit global warming, we have committed to:

- Reduce gas flaring related to our Exploration & Production activities
- Invest in renewable energies: solar and biomass
- Improve the energy efficiency of our installations and help drive energy performance gains by our customers
- Contribute to the emergence and mastery of CO<sub>2</sub> capture-transport-storage technology, which is essential for sustainable growth in our own activities as well as being applicable to many other industrial processes.

Carbon capture and storage is an innovative solution and an effective counterpart to reducing emissions at the source (by curbing energy consumption and developing the use of non-carbon energies).

### 14%

CO<sub>2</sub> capture-transport-storage could account for 14% of cumulative emissions reductions through 2050. This would amount to the capture and storage of 120 billion tons\* of CO<sub>2</sub> between 2015 and 2050.

Source: IEA (Energy Technology Perspectives, 2012 2°C Scenario)

\*meaning that by 2050, an annual 8 billion metric tons of CO<sub>2</sub> - more than twice the energy-related CO<sub>2</sub> emissions of the European Union in 2010 - would be captured and stored.

Capture and storage technologies could be decisive in the fight against climate change, to which France is deeply and actively committed. These technologies could ultimately cut CO<sub>2</sub> emissions in industries such as refining, steel and cement manufacture.

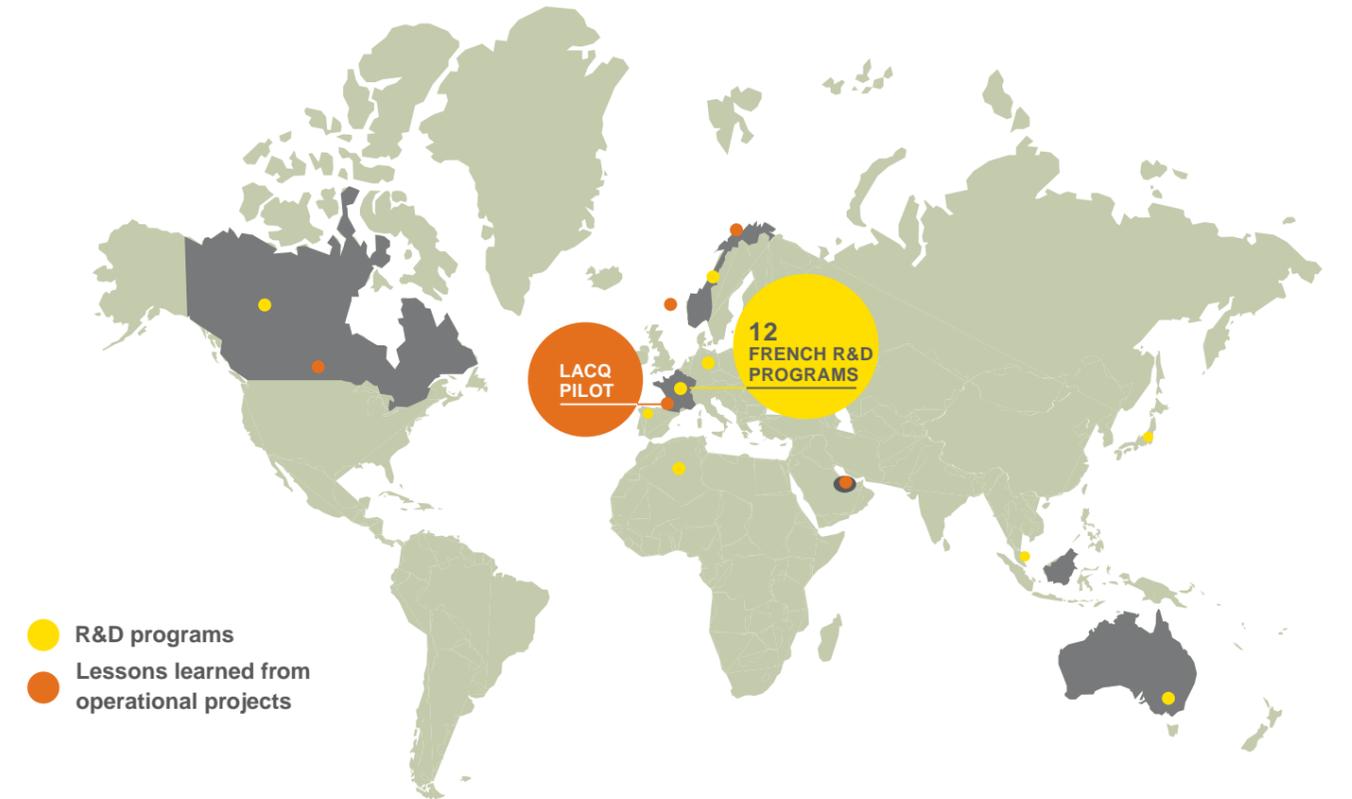
**FRENCH MINISTRY FOR ECOLOGY, SUSTAINABLE DEVELOPMENT AND ENERGY**  
Lionel Perrette, Advisor for CO<sub>2</sub> capture and storage technologies

Carbon capture and storage is particularly well suited to industrial sites that release large quantities of CO<sub>2</sub> (over 100,000 tons) such as coal- and gas-fired power plants, steelworks, refineries and petrochemical complexes.

**TOTAL**  
Manoelle Lepoutre, Executive Vice President, Sustainable Development and Environment

### TOTAL, A PARTNER IN SEVERAL PROJECTS WORLDWIDE

Total has been actively involved in both operational projects and R&D programs devoted to CO<sub>2</sub> injection and storage for more than 16 years.



## CHALLENGE

UNDER ONE OF THE INTERNATIONAL ENERGY AGENCY (IEA) SCENARIOS, ATMOSPHERIC CONCENTRATIONS OF CO<sub>2</sub> MUST REMAIN BELOW 450 PPM TO PREVENT GLOBAL AVERAGE TEMPERATURES FROM RISING BY MORE THAN 2°C BY 2050. THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) HAS INDICATED THAT A TEMPERATURE INCREASE OF MORE THAN 2°C WOULD CAUSE SEA LEVELS TO RISE AND TRIGGER MORE FREQUENT EXTREME WEATHER EVENTS SUCH AS FLOODS, DROUGHTS AND STORMS. IN THIS CONTEXT, CO<sub>2</sub> CAPTURE-TRANSPORT-STORAGE HAS A CRUCIAL ROLE TO PLAY.

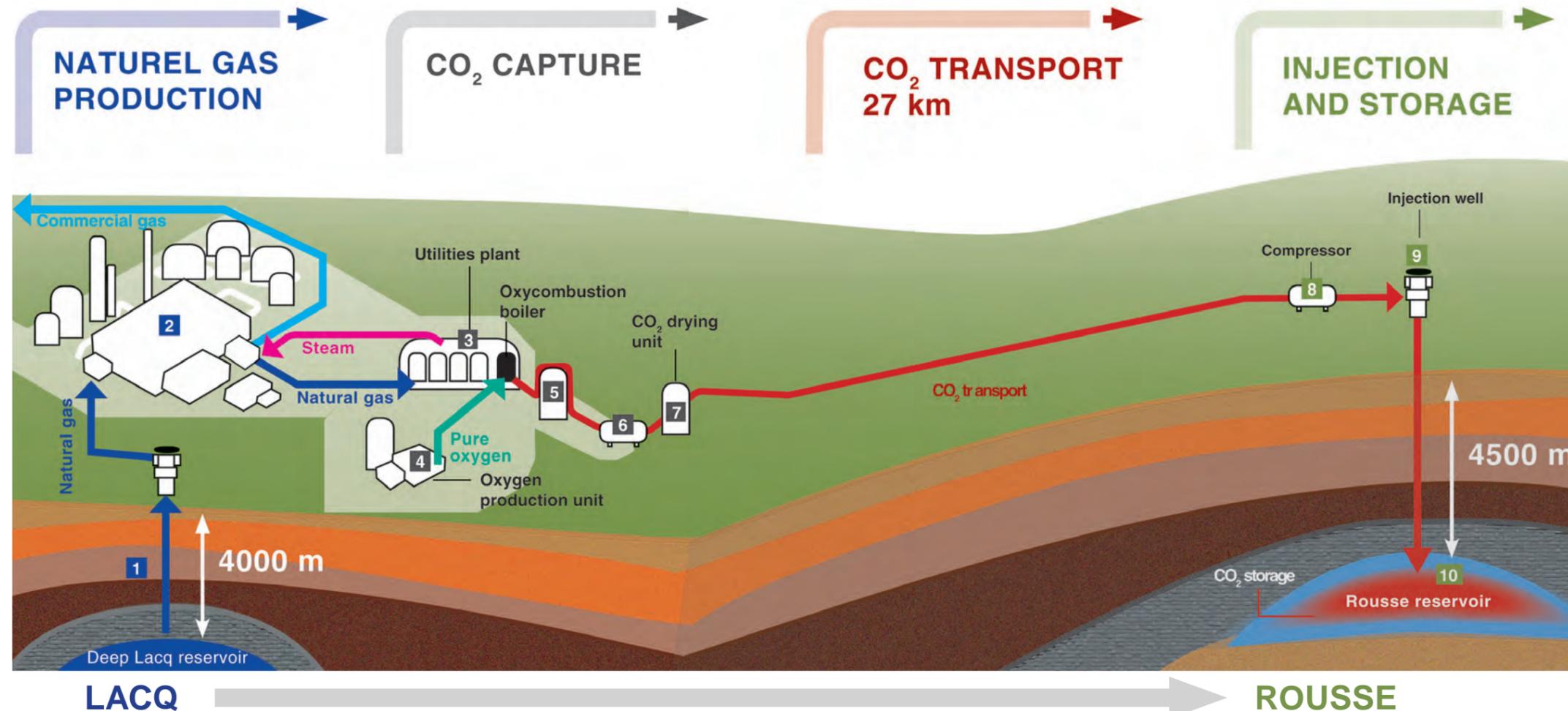
## INTEGRATED CAPTURE-STORAGE, A SOLUTION WITH A FUTURE

THE ENVIRONMENTALLY-RESPONSIBLE SOLUTION OF INTEGRATED CO<sub>2</sub> CAPTURE, TRANSPORT, AND STORAGE OCCUPIES A KEY POSITION IN CONNECTION WITH FUTURE ENERGY SYSTEMS. THE EUROPEAN UNION WOULD LIKE TO SEE OTHER INDUSTRIAL DEMONSTRATORS DEVELOPED BY 2020, IN ORDER TO CHARACTERIZE A NUMBER OF DEEP AQUIFERS POTENTIALLY SUITABLE FOR LONG-TERM STORAGE OF CO<sub>2</sub>.



# QUALIFYING AN INTEGRATED CO<sub>2</sub> CAPTURE-TRANSPORT-STORAGE CHAIN

The Lacq pilot is the first in Europe to implement an end-to-end CO<sub>2</sub> capture-transport-storage chain integrated within an industrial complex to test oxycombustion on a 30-MWth gas boiler.



- 1 Natural gas production
- 2 Lacq gas treatment plant
- 3 Utilities plant including the oxycombustion boiler
- 4 Oxygen production unit
- 5 Flue gas purification/dehydration
- 6 Compression of wet CO<sub>2</sub>
- 7 CO<sub>2</sub> drying unit
- 8 CO<sub>2</sub> compression
- 9 CO<sub>2</sub> injection
- 10 CO<sub>2</sub> storage

## A NATURAL GAS PRODUCTION UNIT AND A UTILITIES PLANT

- Upstream of the chain: a utilities plant equipped with five boilers provides steam to Lacq's industrial complex.
- Steam generation releases flue gas containing CO<sub>2</sub>.

## CO<sub>2</sub> CAPTURE BY OXYCOMBUSTION

- For the CO<sub>2</sub> capture and storage pilot, one of the five gas boilers installed in 1957 – initially using air combustion – was retrofitted for oxycombustion to capture the CO<sub>2</sub>.
- Combustion using pure oxygen releases flue gas with a high concentration of CO<sub>2</sub> and water vapor.
- The flue gas is purified and dehydrated. The wet CO<sub>2</sub> (concentration of 90 to 93%) is compressed at 27 bar then dried for transport.

## TRANSPORT

- The distance between the capture-compression unit and the Rousse injection site is 27 km.
- The CO<sub>2</sub> is transported via pipelines formerly used to carry gas extracted from the Rousse field to the Lacq plant.

## INJECTION AND STORAGE

- The CO<sub>2</sub> is compressed at a pressure of over 40 bar before being injected to a depth of 4,500 meters, into the Rouse reservoir.
- Protected by a 2000-m layer of clay and marl formed more than 35 million years ago, the now-depleted Rouse reservoir produced gas for 36 years, from 1972 to 2008. Its properties are optimal for safe, long-term storage of CO<sub>2</sub>.

# INNOVATING

*The Lacq pilot has provided an opportunity to develop several innovations to industrialize the capture-transport-storage process.*



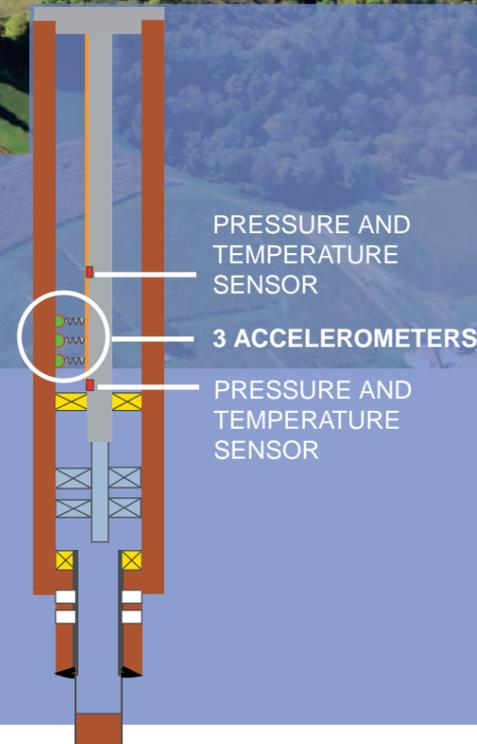
## A FULLY INTEGRATED CHAIN

The fully integrated chain developed by Total is the first experiment of its kind in Europe. It includes all the steps involved in capturing, transporting and storing industry-generated CO<sub>2</sub> from the unit emitting the greenhouse gas (steam production) to its permanent storage in a depleted reservoir, 4,500 meters below the surface.



## HIGHLY SENSITIVE MICROSEISMIC SENSORS

Three accelerometers have been installed at the bottom of the injector well. These new-generation sensors record low-magnitude tremors (down to -3 on the Richter scale) and can detect seismic events corresponding to displacements as small as 0.015 mm along a 30-cm long fault.



## RETROFITTING AN AIR BOILER

For the very first time, an industrial air boiler dating to 1957 has been converted into a 30-MWth oxycombustion gas boiler. This technology generates a CO<sub>2</sub>-rich flue gas. Gas/oxygen burners (8-MWth) were developed for the purpose by Air Liquide.

## STCA TECHNOLOGY

Cementing is a key component of well integrity and safety. In developing a cell to analyze the mechanical properties of cements (Slurry To Cement Analyzer, STCA), Total has achieved an important innovation.

The STCA cell is the only device that allows reliable measurements of a cement's mechanical properties in downhole conditions. The test sample can be maintained at downhole pressure and temperature conditions for the duration of the analysis. Formerly, preparing and instrumenting the sample for testing necessarily meant returning it to atmospheric conditions after it had set – a step liable to damage the cement and a source of considerable inaccuracies in subsequent measurements.

With this major breakthrough, Total's cementing laboratory (at the Scientific and Technical Center in Pau) is now at the forefront of well integrity, a strategic issue for reliable CO<sub>2</sub> storage and for all of Total's drilling activities.



## Reservoir

The Lacq pilot validated a method for selecting and qualifying a CO<sub>2</sub> storage site. Various monitoring tools were tested on the Rousse site.

Many subsurface modeling studies were conducted between 2007 and 2010, before the start of injection:

- **Flow studies** showed that pressures would remain well below the reservoir's initial pressure (i.e., before gas production began).
- **Geomechanical studies** demonstrated that pressures as low as these will not cause damage to the formation.
- **Geochemical studies** confirmed that the CO<sub>2</sub> causes no chemical reactions that would compromise the reservoir rocks and/or caprock.

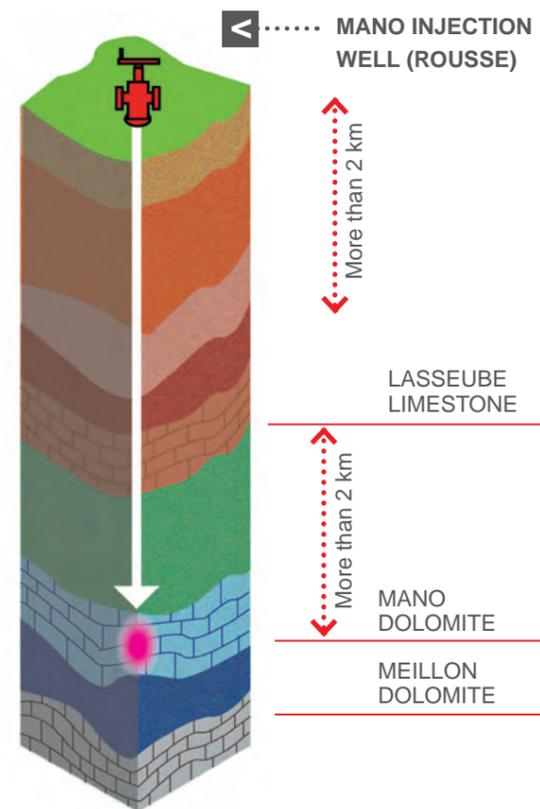
### ENSURING LONG-TERM INTEGRITY

WHAT WILL BECOME OF THE CO<sub>2</sub> INJECTED INTO THE ROUSSE RESERVOIR AFTER 100, 200, 500, 10,000 YEARS? HOW WILL IT EVOLVE?

To answer these fundamental questions, we modeled the long-term behavior of the CO<sub>2</sub> in the reservoir. Simulations show:

- Gradual **migration** of the injected CO<sub>2</sub>: it is denser than the reservoir's natural gas (CH<sub>4</sub>) and migrates to the bottom.
- **No change of phase in the CO<sub>2</sub>**: estimates indicate that most of the CO<sub>2</sub> will lastingly remain in its gaseous state and that only a small fraction will be dissolved or converted into carbonate rock.
- **Stabilization of the reservoir's long-term pressure**, at a level well below the initial pressure of 485 bar (before the Rousse reservoir was brought on stream).

CHALLENGE



## The well

The main lesson learned from the pilot is that CO<sub>2</sub> enhances the mechanical properties of the cement, the main integrity barrier in the injection well.

The former natural gas producer well on the Mano reservoir (Rousse gas field) was selected for the injection process. It is the reservoir's only well. In 2009, the integrity of the well was verified by analyzing the cement before the new completion (well equipment) was installed. In 2011, the completion was removed to install new microseismic sensors at the bottom of the well. No corrosion was detected on the 4,500 m of metal tubing during this operation.

### R&D INNOVATION

#### Evaluating the impacts of CO<sub>2</sub> on a cement sheath

The studies carried out as part of the ReGaSeq (Residual Gas Sequestration) project were aimed at understanding the interaction mechanisms between acid gases and petroleum cements; they showed that the mechanical properties of a cement actually improve on contact with CO<sub>2</sub>. The research teams worked on this project with the LML (Lille Mechanics Laboratory) and the LERM (a consulting company specializing in materials based in Arles, southern France).

#### What chemical mechanism was found to be at play?

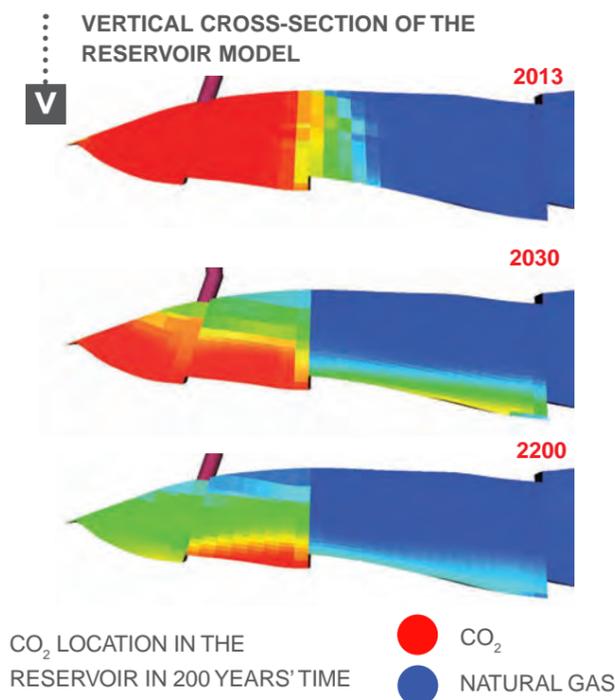
The CO<sub>2</sub> initially extracts the calcium from the cement. The dissolution of the calcium increases the material's porosity. Subsequently, the extracted calcium recombines with the CO<sub>2</sub> and precipitates as calcite. The pores are plugged, the material's permeability is reduced and its mechanical properties are improved. In other words, the CO<sub>2</sub> strengthens cements that ensured integrity at the outset.

> Meanwhile, Total and its industrial partners (Schlumberger, Halliburton, Baker...) are qualifying a list of remediation products to be used in the event a leak occurs on an injector well containing carbon dioxide or hydrogen sulfide.

### R&D INNOVATION

For the first time, a risk analysis included expertise in every discipline, from surface to subsurface. After all potential "integrity loss" scenarios had been addressed, additional studies and laboratory measurements were performed. We carried out this work with specialized institutes, such as IFPEN (the French institute of petroleum and new energies), BRGM (the French geological survey), the IPGP (Institute of Earth Physics of Paris) and the UPPA (University of Pau). The objectives were to confirm and reinforce storage safety by identifying the parameters to be monitored during injection (downhole pressure and temperature, microseismic events) and subsequently, to ensure that the reservoir had not lost its integrity.

> Throughout the three-year injection program, monitoring confirmed that the reservoir was evolving as expected. The reservoir, geochemical and geomechanical models developed by Total and its research partners are therefore reliable.



By analyzing the data collected, Total's Geoscience teams (geomodeling, geomechanics and geochemistry) were able to qualify the Rouse site as an ideal location for storing the CO<sub>2</sub> captured from Lacq's industrial installations.

**TOTAL**  
Sylvain Thibeau, Expert in the geological storage of CO<sub>2</sub>

### TWO ADVANTAGES TO STORING CO<sub>2</sub> IN DEPLETED HYDROCARBON RESERVOIRS:

- THE RESERVOIRS HAVE ALREADY DEMONSTRATED THEIR INTEGRITY FOR SEVERAL MILLION YEARS.
- THE INDUSTRY HAD AN OPPORTUNITY TO STUDY THEM THROUGHOUT THE PRODUCTION PHASE; THEIR GEOLOGICAL, GEOCHEMICAL AND GEOMECHANICAL CHARACTERISTICS ARE WELL-DOCUMENTED.

# Environmental monitoring

As part of the ANR Sentinelle program, Total and several French universities have developed a method for monitoring CO<sub>2</sub> concentrations in the geosphere (0 to 80 m below the surface of the Earth), the biosphere (0 to 10 meters above the surface) and the atmosphere (0 to 2,000 meters above the surface of the Earth).

The aim of this program is to validate surveillance tools.

Total has deployed an environmental monitoring program as required by the Aquitaine regional authority for the environment, planning and housing (DREAL). It encompasses water quality (surface water and groundwater), ecosystems (fauna and flora) and soil gases and includes regular tracking of physico-chemical and biological indicators sensitive to changes caused by increased levels of CO<sub>2</sub>.

## R&D INNOVATION

### AIR

An aerial installed on the Rouse site records changes in the weather and the CO<sub>2</sub> concentration in the air. This is part of a program developed with France's national agronomic research institute, INRA, to highlight correlations between climate conditions and greenhouse gas concentrations. An infrared camera developed with the University of Lorraine was used on site to view and quantify the volumetric concentration of CO<sub>2</sub>.

### SOIL

Soil gas concentrations are measured at 35 points around the Rouse site, one meter below the surface. Twice a year, BRGM takes a reading of methane and CO<sub>2</sub> concentrations emanating from the soil using an infrared analyzer. To supplement this data, INERIS measures gas flows using an accumulation and external recirculation chamber (CARE). These bi-annual readings are compared with the baseline figures (measurements taken from September 2008 to December 2009).



MEASUREMENT OF GAS FLOWS IN THE SUBSOIL BY INERIS

### AQUIFERS

**Surface water** – Seven physico-chemical indicators – oxidizable organic matter, nitrates, phosphates, pH and alkalinity (risk of acidification), conductivity and sulfates (for mineralization) – and two biological indicators (for benthic macro-invertebrates and diatom communities) are measured twice a year in five locations.

**Groundwater** – Four indicators: pH, conductivity, bicarbonates and carbonates are measured twice a year in 12 locations.

The Platform for Experimental Research in Lacq (PERL) is conducting a research program on the impact of CO<sub>2</sub> on aquatic ecosystems.

### FAUNA AND FLORA

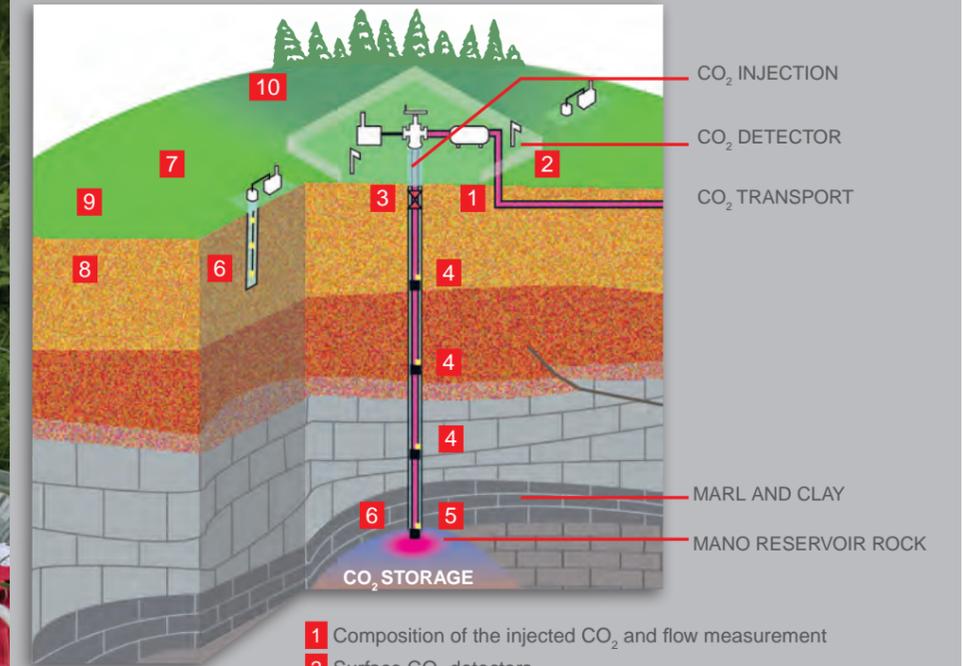
Once a year, 65 different habitats around the Rouse site are inventoried (insects, amphibians and plants).

### RESULTS

- No deviation from the baseline results
- No CO<sub>2</sub> leaks detected
- Changes in CO<sub>2</sub> concentration consistent with climate variations (heat, humidity, etc.)
- No impact of CO<sub>2</sub> on ecosystems.

Total has worked hand in hand with the French authorities to define a regulatory framework for environmental monitoring.

## RESERVOIR INTEGRITY MONITORING SYSTEM



- 1 Composition of the injected CO<sub>2</sub> and flow measurement
- 2 Surface CO<sub>2</sub> detectors
- 3 Well annulus pressure
- 4 Pressure and temperature in the injector
- 5 Pressure and temperature in the reservoir
- 6 Microseismic equipment
- 7 Soil gas measurement
- 8 Groundwater quality
- 9 Surface water quality
- 10 Biodiversity – fauna and flora



ANALYSIS OF SURFACE WATER AROUND THE ROUSSE SITE

# TAKING RESEARCH FORWARD



To advance knowledge in the area of CO<sub>2</sub> capture-transport-storage, the doors of the Rouse site were opened wide to the scientific community. Several innovative technologies have been qualified, enabling the actors of the scientific world to gain greater understanding of CO<sub>2</sub> storage.

## Our partners

Since the beginning of the project, our R&D teams have been working with industrialists, scientists, laboratories and public and private research bodies on four different themes:

- > **Qualifying a reliable and economically acceptable capture technology on a gas boiler**
  - Oxycombustion: AIR LIQUIDE
- > **Validating a method for selecting and qualifying a geological storage site and testing various monitoring tools**
  - ANR/SENTINELLE project
  - Scientific partners: IFPEN, BRGM, INERIS, INRA, NPL
- > **Developing methodologies pertaining to well integrity and abandonment**
  - ANR/SENTINELLE project: ReGaSeq (Residual Gas Sequestration)
  - Scientific partners: LCPC, ENPC, LERM, BRGM, LML and others
  - Industrial partners: CEA (LETI), Oxand, Lafarge, Schlumberger, Vallourec
- > **Developing methods relating to acid gas reservoir integrity, including caprock degradation, fault reactivation, and gas diffusion**
  - ANR projects: associated gases, Coliner project
  - Scientific partners: École des Mines in Paris, UPPA, BRGM, University of Orsay, CNRS of Montpellier
  - Industrial partners: EDF, CEA, Lafarge, IRSN, Air Liquide.

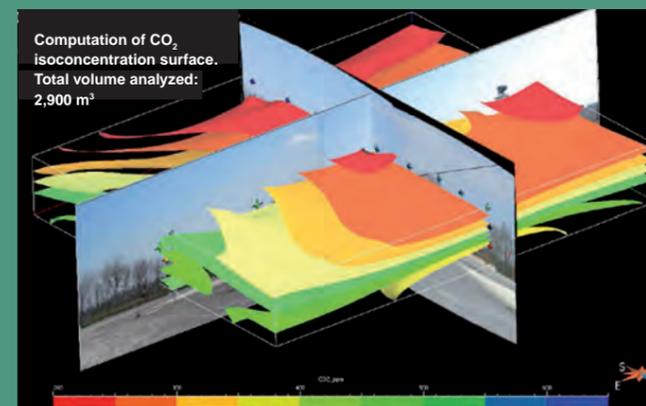
Acronyms: see Glossary, page 24



## SENTINELLE

THE SENTINELLE PROGRAM IS PARTLY FUNDED BY THE ANR AND CONCERNS "SURFACE GEOCHEMICAL MONITORING OF CO<sub>2</sub> STORAGE SITES: FLOWS/ COMPOSITION AND TRACING OF SOURCES IN THE GEOSPHERE, BIOSPHERE AND ATMOSPHERE."

LAUNCHED IN 2007, THE PROGRAM BRINGS TOGETHER THE FOLLOWING PARTNERS: TOTAL; THE UNIVERSITY OF LORRAINE (UMR 7359, GEORESOURCES); IFPEN; KAISER OPTICAL SYSTEMS; INERIS (DIVISION OF GROUND AND SUBSURFACE RISKS); CNRS DR05 (PIERRE AND SIMON LAPLACE INSTITUTE, UMR 8539 DYNAMIC METROLOGY LABORATORY); INRA (UMR 1091 ENVIRONMENT AND MAJOR CROPS LABORATORY); BRGM-MMA/MSE (METROLOGY, MONITORING AND ANALYSIS DEPT.).



3D MODEL OF CO<sub>2</sub> CONCENTRATION IN AIR – VOLUME ANALYZED: 2,900 m<sup>3</sup>

Taking part in a pilot project is always a terrific opportunity for an academic team. On the Lacq-Rousse site, our researchers were able to conduct programs solidly grounded in reality, far from laboratory idealism, based on realistic databases with samples taken from the actual reservoir and caprock, and not just from outcrops. In addition, they learned to come to terms with the real constraints of an industrial site (e.g., safety, restricted access, local residents).

### UNIVERSITY OF LORRAINE

Jacques Pironon, Director of mixed research unit (UMR) no. 7359, GeoResources

The ANR supported this project based on its scientific and technical merits, its potential to advance the state of the art, and the high caliber of its methodology and coordination.

The first research programs on carbon capture and storage are now over 20 years old. The scientific community needs pilot units like the Rouse one to move forward, particularly on the storage aspect, which is highly dependent on local geology. Thanks to this pilot, the ANR SENTINELLE teams have had access to actual field data.

### FRENCH NATIONAL RESEARCH AGENCY (ANR) / SUSTAINABLE ENERGY AND ENVIRONMENT DEPARTMENT

Isabelle Czernichowski-Lauriol, CO<sub>2</sub> Capture and Storage Program Director

The Lacq platform was a chance for the Group to manage the technologies and costs involved in a carbon capture and storage chain, but also to acquire in-depth knowledge of the methods for characterizing and monitoring a geological storage site, and gain experience in the realities of stakeholder relations.

Cooperation with the scientific partners of the academic world was highly successful: giving them access to facilities and data so as to enable them to carry out experiments unlocked crucial progress.

### TOTAL

Jean-François Minster, Senior Vice President, Scientific Development



# The technologies qualified



## TOTAL VALIDATES A CAPTURE-TRANSPORT-STORAGE CHAIN INTEGRATED WITHIN AN INDUSTRIAL SITE

The steam-generating unit that emits CO<sub>2</sub> at the Lacq industrial complex is 27 kilometers away from the depleted reservoir on the Rouse field into which the CO<sub>2</sub> is injected for storage.

The three years of injection have demonstrated the feasibility of the entire chain. The pilot's performance has met expectations:

- The boiler achieved an availability rate of 99% in oxycombustion mode, and the availability rate of the injection chain was 83% (excluding scheduled shutdowns).
- No corrosion was observed on the pipeline transporting the CO<sub>2</sub> between Lacq and the Rouse reservoir.
- The downhole pressure, currently about 80 bar, has evolved in line with predictions.

## THE COMPRESSOR Defining the most suitable technology

DURING THE INJECTION PHASE, CORROSION CAUSED BY THE FORMATION OF NITRIC ACID WAS ENCOUNTERED IN THE THIRD STAGE OF THE RECIPROCATING COMPRESSOR AT LACQ. WE ADJUSTED THE OPERATING PARAMETERS OF THE PILOT AND IMPROVED THE EFFICIENCY OF INTER-STAGE SEPARATION. THIS ENABLED THE COMPRESSOR TO FUNCTION PROPERLY. FOR AN INDUSTRIAL-SCALE PROJECT, A CENTRIFUGAL COMPRESSOR WOULD BE THE PREFERRED OPTION.



## OXYCOMBUSTION, A PROMISING TECHNOLOGY

By validating oxycombustion technology at the scale of a 30-MWth boiler, we achieved a major step forward for CO<sub>2</sub> capture-transport and geological storage.

- At the Lacq site, one of the five utility boilers producing steam and energy for the industrial complex was converted into an oxycombustion boiler. The burners no longer function with air, as in a conventional boiler, but with pure oxygen (except during start-up and heat-up).
- The success of the test at a scale of 30-MWth paved the way for designing the oxycombustion boiler of the future, with an output of 200-MWth. The technical characteristics of the new equipment were defined by Total, Air Liquide and Babcock & Wilcox using the data (thermal flows, temperature measurements, etc.) collected from the pilot unit.
- Oxycombustion offers the advantages of greater gas combustion efficiency for the production of steam and energy and the direct capture of the CO<sub>2</sub> emitted, at a concentration of 90 to 93%. However, further research is needed to lower costs and bring the technology within a profitable economic model.
- Oxycombustion can also be retrofitted on existing installations and applied to different fuels. Operation of an oxycombustion boiler is quite simple, much the same as for an air boiler.



*The Lacq pilot offered a chance to qualify a new oxycombustion concept. We developed new-generation oxygen/natural gas burners, that were successfully installed on a retrofitted boiler. This scientific and commercial partnership with Total also enabled us to validate our mathematical models based on an output of 8-MWth per burner.*

*From a scientific viewpoint, we have reached a new milestone as regards flue gas dehydration. Air Liquide was able to model totally new adsorption scenarios involving high CO<sub>2</sub> concentrations and extremely complex reactions of water and CO<sub>2</sub> with impurities. The pilot dehydration unit designed by Air Liquide to bring water concentration down to 30 ppm actually achieved values of around 10 ppm.*

**AIR LIQUIDE**  
Claude Heller, Program Director,  
Energy and Basic Industries



**MICROSEISMIC SURVEILLANCE: PROBES 4,500 M BELOW THE SURFACE**

An ambitious system has been put in place to record any seismic events that might affect the clay and marl caprock overlying the reservoir, thus causing a CO<sub>2</sub> leak.

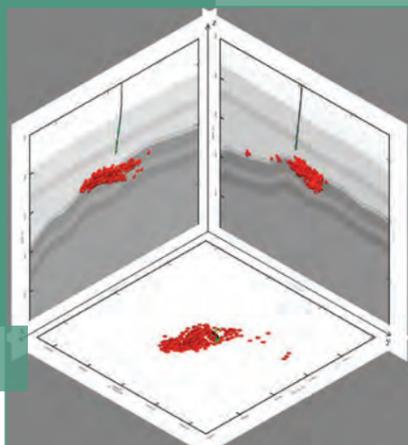
- The “innovative aspect” consists of the three accelerometers or seismic sensors installed at the bottom of the well, at a depth of 4,500 m, in March 2011. They are R&D prototypes that record low-magnitude earthquakes (down to -3) and can detect a shift of just 0.015 mm in a 30-cm fault.
- The “conventional aspect” comprises a system of seven wells 200 m deep, each fitted with four seismic sensors that record tremors of a magnitude as low as -1 on the Richter scale. They can detect a movement of 0.15 mm in a 3-m fault. No significant events were recorded during the three-year injection phase.
- A surface seismometer monitors natural seismic activity in the region.



TRANSMITTER CONNECTED BY OPTICAL FIBER TO THE DOWNHOLE SEISMIC PROBES

1,528

The number of microseismic events with magnitude ranging from -2.3 to -1.5 recorded downhole between March 2011 and March 2013. These events are 27,000 times less powerful than the lowest threshold of human perception, and have no impact on reservoir integrity.



LOCATION OF MICROSEISMIC EVENTS

**THE DEPLETED ROUSSE RESERVOIR: AN IDEAL SITE FOR CO<sub>2</sub> INJECTION**

Of the four sites considered in 2006, Rouse – a former natural gas field, in production from 1972 to 2008 – was ultimately selected. The pilot served to validate a method for qualifying potential CO<sub>2</sub> storage reservoirs.

- In geological terms, the depleted Rouse reservoir is completely isolated. For more than 35 million years, the reservoir rock formed a natural trap for gas at a pressure of 485 bar. The reservoir is capped by a layer of clay and marl 2,000 m thick, and withstood the powerful seismic tremors that occurred in the Tertiary period before the Pyrenees were formed.
- To assess the quality of the reservoir and determine precisely how much CO<sub>2</sub> it could contain, the R&D teams studied all the parameters offering insight into the initial field and its behavior during production: caprock properties (such as thickness and composition), fault stability, pressure, quantity of gas extracted, impact of production on the seal (settlement and compaction of the rock, etc.).
- The rock mechanics studies carried out on Rouse have yielded greater knowledge of depleted reservoirs and their suitability for gas storage.

**WATER, AIR, SOIL: RELEVANT MEASUREMENT TOOLS**

Thanks to the Lacq pilot, Total and its scientific partners have devised an efficient methodology for monitoring CO<sub>2</sub> in the geosphere, biosphere and atmosphere and invented numerous monitoring tools for the surveillance of the storage location.



ROCK SAMPLE FROM THE ROUSSE RESERVOIR

The Lacq pilot validated a geochemical monitoring method for CO<sub>2</sub> storage sites.

**FRENCH NATIONAL RESEARCH AGENCY (ANR) / SUSTAINABLE ENERGY AND ENVIRONMENT DEPARTMENT**  
**Isabelle Czernichowski-Lauriol,**  
 CO<sub>2</sub> Capture and Storage Program Manager

Surveillance of the CO<sub>2</sub>'s evolution after injection is crucial. The aim of this passive phase is to gather all the data necessary to demonstrate that the injected CO<sub>2</sub> will remain permanently and safely confined within the deep geological layers.

**FRENCH MINISTRY FOR ECOLOGY, SUSTAINABLE DEVELOPMENT AND ENERGY**  
**Lionel Perrette,** Advisor for CO<sub>2</sub> capture and storage technologies

# EXPLAINING

**Total developed and implemented a method to foster clear understanding of the stakes of the CO<sub>2</sub> pilot among local residents, elected representatives, citizens' groups, government officials and local economic actors. It consists of:**

> **Launching a stakeholder consultation** – In 2007, well before the administrative authorization and public inquiry procedures, Total held meetings with the local population to provide information and answer their questions on the future CO<sub>2</sub> capture-transport-storage pilot. At the same time, an exhibition, a website and an opinion register for comments were made available to the general public.

> **Creating a local information and monitoring commission (CLIS)** to keep associations, elected representatives, government officials and neighboring populations informed of the project's progress. Since 2007, the minutes of meetings have been published on the website of the regional planning authority (DREAL).

> **Forming a scientific committee** – Its members (French Ministry for Ecology, Sustainable Development and Energy, IPGP, BRGM, ADEME, the French Academy of Sciences, CNRS, IFPEN and ANR) do not belong to the company and have an independent expert view. The scientific committee has met seven times since the pilot came on stream in January 2010.

> **Informing local inhabitants** – A newsletter entitled "CO<sub>2</sub> capture and geological storage in the Lacq basin" has been created. It has been published quarterly by Total E&P France since the start of injection and is sent by name to the people living in proximity to the installations.

Beyond the pilot's scientific importance, we are also very interested in the acceptability process that Total has introduced. It is a key organizational innovation and easily replicable. Total has managed to involve local residents, elected representatives and citizens' groups to make them active stakeholders in the project rather than feel it is being forced upon them. No project can go forward today without going through this acceptability process.

**FRENCH ENVIRONMENT AND ENERGY MANAGEMENT AGENCY (ADEME)**  
**Daniel Clément, Deputy Director for Research**



## CHALLENGE

SINCE 2007, MORE THAN 300 DELEGATIONS OF ALL NATIONALITIES HAVE VISITED THE LACQ PILOT. PARTICIPANTS, INCLUDING INDUSTRIALISTS, EXPERTS, ELECTED REPRESENTATIVES, STUDENTS AND LOCAL RESIDENTS, FOLLOW A WELL-OILED ITINERARY: CONFERENCE ROOM INTRODUCTION TO THE PILOT, TOUR OF THE LACQ PLANT AND THE ROUSSE SITE. THE PILOT HAS ALSO BEEN PRESENTED AT MORE THAN 30 INTERNATIONAL CONFERENCES.

When the Ministry of Ecology gave the go-ahead for the Lacq CO<sub>2</sub> pilot, there was no regulatory context for oversight. European experts on the subject devised a framework directive for the whole of Europe, and BRGM then worked to transpose it into French law. Here again, the pilot was a great opportunity to define a framework and thresholds based on real measurements.

**FRENCH GEOLOGICAL SURVEY (BRGM)**  
**Catherine Truffert, Research Director**



# DEVELOPING

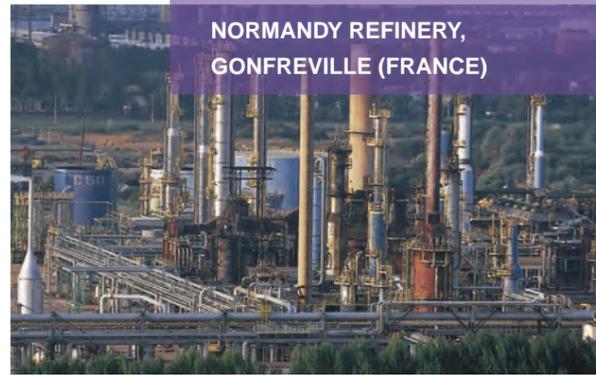
*The pilot has kept its promises. After three years of injection, there are no doubts about the technical feasibility of the CO<sub>2</sub> capture-transport-storage chain.*

There are two prerequisites for developing this technology on an industrial scale:

- **Demonstration of the chain's technical and economic viability** – Industrial-scale, integrated projects will drive improvements at every link in the chain and optimize the overall integration of the system. The countries and regions intent on developing CO<sub>2</sub> capture and storage (e.g., Europe, North America, Australia, China) are encouraging investments in this type of project.
- **Social acceptability** – Despite being well aware of the need to protect the planet, the people living next to the installations are worried about incidents liable to occur around the CO<sub>2</sub> storage sites. Upstream communication is essential to secure local residents' acceptance of future projects.



The industrial CO<sub>2</sub> capture-transport-storage chain could help industries that depend on fossil fuels – thermal and coal power plants, metallurgical factories, refineries and petrochemical plants – reduce their greenhouse gas emissions.



**NORMANDY REFINERY,  
GONFREVILLE (FRANCE)**

*This industrial pilot has proven Total's capacity to develop innovative projects, from both a methodological and technological point of view. The experiment would not have been as successful without the strong cooperation between the scientific partners and the R&D and operational teams of Total's Exploration & Production branch.*

**TOTAL**  
**Jacques Monne**, Manager of the Residual Gas Management R&D project, Exploration & Production

*The Lacq CO<sub>2</sub> pilot gave us a chance to work on themes that had never been addressed before: how the impurities injected along with the CO<sub>2</sub> affect the rock; the chemical reactivity mechanisms of the Rouse rock if a toxic gas is injected; the effect of oxygen on hydrocarbon residues in a depleted reservoir.*

**UNIVERSITY OF LORRAINE**  
**Jacques Pironon**, Director of mixed research unit (UMR) no. 7359, GeoResources

*CO<sub>2</sub> capture and storage is a highly topical issue, the more so in the current context of energy transition. For the decades to come, there is in effect no industrial alternative for keeping atmospheric CO<sub>2</sub> concentrations within the limits mentioned in international agreements. ADEME supports the idea of a European research platform in order to anticipate and consider capture-storage as an asset for territorial development. In the future, sites that can offer CO<sub>2</sub> storage will have a good head start.*

**FRENCH ENVIRONMENT AND ENERGY MANAGEMENT AGENCY (ADEME)**  
**Daniel Clément**, Deputy Director for Research



**LAFFAN REFINERY,  
QATAR**



**YEMEN LNG**

*With this pilot – the only one of its kind in Europe – our research program on acid gas injection has reached a major milestone. The knowledge acquired in terms of geological characterization of the host rock, reactivity to injection and surveillance is fundamental and will also benefit other future sectors such as geothermal systems, energy storage and enhanced recovery.*

**FRENCH GEOLOGICAL SURVEY (BRGM)**  
**Catherine Truffert**, Research Director



# GLOSSARY

**ADEME:** *French environment and energy management agency*

**ANR:** *French national research agency*

**BRGM:** *French geological survey*

**CEA (LETI):** *French Alternative Energies and Atomic Energy Commission – Laboratory for electronics and information technologies*

**CLIS:** *Local information and monitoring commission*

**CNRS:** *French National Center for Scientific Research*

**DREAL:** *Regional authority for the environment, planning and housing*

**EDF:** *French power company*

**ENPC:** *Ecole Nationale des Ponts et Chaussées (National civil engineering school)*

**E&P:** *Exploration & Production*

**IEA:** *International Energy Agency*

**IPCC:** *Intergovernmental Panel on Climate Change*

**IFPEN:** *French institute of petroleum and new energies*

**INERIS:** *French national institute for the industrial environment and risks*

**INRA:** *French national institute for agronomic research*

**IPGP:** *Institute of Earth Physics of Paris*

**IRSN:** *Institute for Radiological Protection and Nuclear Safety*

**LCPC:** *Central laboratory of Ecole Nationale des Ponts et Chaussées*

**LERM:** *a consulting company specializing in materials, based in southern France, with its own materials testing laboratory*

**LML:** *Lille Mechanics Laboratory*

**NPL:** *National Physical Laboratory*

**R&D:** *Research & Development*

**ReGaSeq:** *Residual Gas Sequestration (R&D project)*

**UPPA:** *University of Pau*