Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Carbon dioxide sequestration

1. Summary of the impact (indicative maximum 100 words)

Carbon dioxide sequestration is the process by which pressured CO_2 is injected into a storage space within the Earth rather than released into the atmosphere. It is one of the major ways that carbon dioxide emissions can be controlled.

Research since 2004 by applied mathematicians at the University of Cambridge into the many different effects that might be encountered during this process has had considerable impact on government and industry groups in determining how the field is viewed and how it should and might be industrially developed. The work played a major role in the CO2CRC conferences and was subsequently reported to the Australian Government by the CO2CRC chair and organisers.

2. Underpinning research (indicative maximum 500 words)

This research addressed the process and the consequences of carbon dioxide sequestration in porous rock and also possible leakage from the storage space.
The research was carried out by members of the Department of Applied Mathematics and Theoretical Physics (DAMTP): Professor Huppert (Professor from 1989-2011), Professor John Lister (Royal Society URF from 1992, University Lecturer from 1997, Reader from 2001, Professor from 2006 to present), Dr Jerome Neufeld (Research Associate from 2007-2009, now a Lecturer at the Department of Earth Sciences). There were collaborations with Professor Michael Bickle of the Department of Earth Sciences and Dr Andrew Chadwick, member of the British Geological Survey.

The research carried out in DAMTP began in 2004 and consisted of the development of mathematical models for the spread and leakage of carbon dioxide injected into a porous medium. Informed by novel laboratory experiments in the G.K. Batchelor Laboratory in DAMTP models were developed for rate of spread as a gravity current of a carbon dioxide plume directed towards a horizontal cap rock. It was found that, treated as a one-phase fluid, the axisymmetric current, fed at a constant flux, increases its area at a rate directly proportional to time This same result was found, somewhat surprisingly, if the intruding carbon dioxide is considered as a two-phase fluid that incorporates effects due to surface tension.

This increase in area with time was clearly seen in the seismic data obtained in 1999, 2001, 2002, 2004, 2006 and 2008 from the longest-living, large-scale field operation of carbon dioxide sequestration, at Sleipner in the North Sea. The data analysis also allowed the determination of the time at which the input carbon dioxide first encountered the upper horizons of the field, in some instances up to three years after initial injection. The Group also compared the data collected at the Otway Project in Australia in 2008/9 with its own model which allows for flow up a slope, as is the case for the Australia situation.

Research was also conducted into the leakage that might occur if there was either a point or line fracture through which the carbon dioxide could escape. Further, a series of models was developed to analyse the mechanisms by which carbon dioxide can dissolve in the surrounding brine and produce vigorous convection due to the fact that the mixture is heavier than either of the initial fluids. By this mechanism the carbon dioxide is gradually stored permanently at the base of the confining aquifer. Since the Sleipner project commenced in 1996, 1 million tonnes of carbon dioxide have been input annually with 100,000 tonnes permanently stored by this mechanism each year. Using linear extrapolation, then, to gain approximate timescales, these models show that if the supply was curtailed now (after 16 years of input), it would take 160 years for the carbon dioxide to be at such a relatively heavy state that it would lie at the bottom of the aquifer and so be stored safely and permanently.

3. References to the research (indicative maximum of six references)

1. *Lyle, S., Huppert, H.E., Hallworth, M.A., Bickle, M. and Chadwick, A. (2005) "Axysymmetric gravity currents in a porous medium", J. Fluid Mech. **543,** 293-302. DOI: 10.1017/S0022112005006713.
2. *Vella, D. and Huppert, H.E. (2006) "Gravity currents in a porous medium at an inclined plane", J. Fluid Mech. **555,** 353-362. DOI: 10.1017/S0022112006009578
3. Neufeld, J.A., Vella, D. and Huppert, H.E. (2009) "The effect of a fissure on storage in a porous medium", J. Fluid Mech. **639,** 239-259. DOI: 10.1017/S0022112009991030.
4. Golding, M.J. and Huppert, H.E. (2010) "The effect of confining impermeable boundaries on gravity currents in a porous medium", J. Fluid Mech. **649,** 1-17. DOI: 10.1017/S0022112009993223.
5. Vella, D., Neufeld, J.A., Huppert, H.E. and Lister, J.R. (2011) "Leakage from gravity currents in a porous medium. Part II. A line sink", J. Fluid Mech. **666,** 414-427. DOI: 10.1017/S002211201000491X
6. *Boait, F.C., White, N.J., Bickle, M.J., Chadwick, R.A., Neufeld, J.A. and Huppert, H.E. (2012) "Spatial and temporal evolution of injected CO2 at the Sleipner Field, North Sea", J. Geophys. Res. **117,** B03309. DOI: 10.1029/2011JB008603.

References which best represent the 2+ quality of the underpinning research

4. Details of the impact (indicative maximum 750 words)

This research has been the basis of calculations made to assess the viability of CCS as a technology to ameliorate the effects of carbon emissions and their impacts on climate change. The mathematical models and their successful comparisons with field data have provided policy makers with the information needed to estimate the quantities of CO2 that can be stored and to evaluate the risks associated with leakages from underground reservoirs.

This research has impacted European policy makers through the European Academies Science Advisory Council (EASAC). As a result of his research, Huppert was invited in 2011 by the president of EASAC to be the Chair of the Working Group on Carbon Capture and Storage (CCS). The President of EASAC [11] writes "Professor Huppert was nominated by the Royal Society to chair the working group that carried out the study on the basis of his research on the fluid dynamics of carbon dioxide stored in geological formations, and his extensive efforts to lecture to a wide range of audiences on this important and topical issue". The CCS Working Group has published the report, *Carbon storage and capture in Europe, (2013, pp95)* [8] for the European Parliament. The report, which makes explicit reference to the research outlined in section 3, was distributed to all politicians, scientists and policy makers on energy in Europe in May 2013 and will inform political debate and international strategies on climate change. The report was released at a press conference on 21 May 2013 and at the Royal Society in London on 12 June 2013 [13]. This report is highlighted on its website by the CCS Association which has industrial members representing a wide sector of UK industry [10].

Huppert's research has also had a significant impact on the policy of the Australian Government on CCS. According to the Chief Executive of CO2CRC [9],
"This work in turn provides confidence to Government and the community at large that underground storage of CO2 is understood, that it can be monitored and that it works. The impact of this on public policy in Australia is that CCS has become recognised as an important mitigation option for Australia and the Government has provided significant funding (in excess of $1 billion) to support CCS. Obviously this has been the consequence of the work of many people in CO2cRC and other organisations, but the work by Herbert and his collaborators has certainly contributed. It is also appropriate to mention the various public presentations that Herbert has given in Australia which have been picked up by the media and which have provided a factual and positive account of what the relevance of CCS is to the whole issue of climate change and mitigation".

On the basis of the research outlined above, Huppert was asked to present this work to the All-Party Parliamentary Group for Earth and Environmental Sciences, to an audience of around 100 people, including both MPs and Peers, on 16 October 2012.

Huppert was awarded the Bakerian Lectureship of the Royal Society for 2011 [7]. This is the major lecture in the physical sciences delivered each year at the Royal Society. The title was 'Carbon storage: caught between a rock and climate change' and was based on the whole gamut of Huppert's research, explaining the concepts of carbon dioxide sequestration and the possible consequences to an audience of over 250. The Royal Society [12] states that "The total viewing figure for "Carbon storage: caught between a rock and climate change" from it being given on 24 March 2011 to today (1 May 2013), is 1618, according to our Google Analytics record. The webcast has been accessed from 59 countries, with the ten most popular being the United Kingdom, United States, Australia, Canada, Germany, France, Switzerland, Netherlands, Spain and China". This accessible presentation of this research encouraged the audience to engage with current scientific and political debates on solution to climate change.

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. Royal Society, 2011. *2011 Bakerian Lecture: Professor Herbert Huppert FRS* [online] Available at http://royalsociety.org/events/2011/carbon-storage/ [Accessed 17 May 2013].

8. EASAC CCS report, 23 May 2013 Carbon capture and storage in Europe [online] Available at http://www.easac.eu/home/reports-and-statements/detail-view/article/easac-report.html [Accessed 14 June 2013].

9. Statement from Chief Executive of CO2CRC, CBE, CEO, CO2CRC, Canberra, Australia, corroborating of the impact of the group's work in CO2CRC conferences

10. Scientific Adviser to the European Parliament who attended the launch of the EASAC CCS report and is carrying the matter forward to the European President and MEPs.

11. Statement from the President of EASAC corroborating Huppert's invitation and contribution to EASAC

12. Statement from Manager, Science Communication, Royal Society corroborating viewing figures for "Carbon storage: caught between a rock and climate change"

13. Royal Society press release on Carbon storage and capture in Europe report: http://blogs.royalsociety.org/in-verba/2013/06/24/capturing-an-opportunity-or-storing-up-trouble-ccs-in-the-uk-and-europe/