OPEC-IEA GHG CCS WORKSHOP FOR SCIENTISTS AND PROFESSIONALS IN OPEC MEMBER COUNTRIES

Technical Study

Report Number: 2009/15

Date: December

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ACKNOWLEDGEMENTS AND CITATIONS

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IEA Greenhouse Gas R&D Programme (IEA GHG),OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries, 2009/15, December 2009".

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Summary Report of OPEC-IEA GHG CCS Workshop

for scientists and professionals in OPEC member countries

Date: 15 – 20 November 2009 Sonatrach, Hassi Messaoud, Algeria

Organised by IEA GHG, OPEC, Algerian Ministry of Energy and Mines, and Sonatrach

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Executive Summary

This workshop was proposed to the IEA GHG by OPEC, and the first plan was to hold the workshop in February 2009, in Algeria. Due to difficulties in preparing invitation letters and visas; the workshop was postponed to November 2009. The suggestion was that Carbon Capture and Storage (CCS) was an important topic not being adequately dealt with by OPEC member countries. Therefore, this workshop was planned to introduce scientists and professionals from OPEC member countries with a general overview of the complete CCS chain. In addition, this workshop was considered as a good opportunity for IEA GHG to interact with professionals from these countries, who are involved mainly in the oil and gas sector.

The Ministry of Energy and Mines together with Sonatrach, agreed to host the workshop in Hassi Messaoud, Algeria. An organizing committee was established, with members form IEA GHG, OPEC, the Ministry of Energy and Mines and Sonatrach. The workshop was held from the 16th to 20th of November, 2009 and attracted over 25 delegates from 7 countries.

The invitations to participate were sent to all OPEC member countries. Considering the different interest in CCS, 7 OPEC member countries participated in the workshop (Qatar, Algeria, Kuwait, Saudi Arabia, Iraq, Libya, and the United Arab Emirates). The delegates had different backgrounds, which varied from chemical engineering to petroleum engineering and geologists. The interest in CCS topics varied from one delegate to another.

The workshop included technical sessions to cover major CCS aspects, as well as breakout group discussions on three generic CCS topics. The presentations and breakout groups covered the main CCS themes over the course of 4 days: CO_2 capture technologies, transport, storage, CCS financial, legal and safety status, public acceptance, and four case studies.

The programme of the workshop was constructed by the IEA GHG team, to cover all topics related to CCS. Special focus was given to the major large scale case studies (In Salah, Sleipner, Weyburn and Abu Dhabi DF). The technical programme was followed by a visit to the In Salah location. This activity was a good opportunity for the participants to visit a real CCS large scale demonstration. In addition, it was an occasion for some technical and scientific discussions mainly on issues concerning CO_2 treatment, injectivity, and monitoring.

The group working activity was designed to increase the involvement and proactivity of the delegates in the programme and to encourage discussions, networking and social interactions. The group activity was well received and achieved the expected objectives. There was a suggestion for the future, to receive or even prepare the topics of the working groups' activity in advance before the workshop.

The programme of the workshop was fully achieved and well received from participants. The interest and interaction of the participants varied from topic to another. It was clear that the main interest of the participants were in CO_2 storage, EOR, injection and monitoring techniques and status. In addition, more general topics related to financial support, HSE, legal and political status

and public perception were of general interest to all participants. Due to different interests and backgrounds, there have been other topics suggested for future IEA GHG-OPEC's activities, among others, financial aspects, legislation, CDM, Carbon credit, trading and negotiating positions, CCS risk assessment and the capture technologies related specifically to oil and gas.

In general, it can be concluded that the workshop was a success. It achieved the objectives by introducing CCS concepts to the participants and gave the chance for the IEA GHG team and other speakers to interact with a group of professionals with different background and experience. The participants showed great satisfaction in the workshop sessions, content and programme, which met their expectations to a very good level.

For the future, it is important to actively maintain contact between IEA GHG and OPEC member countries. The nature, location and content of future activities should be decided and agreed with OPEC well in advance. The nature of the future OPEC-IEA GHG's activity could vary from a general CCS training workshop to more specific topics or knowledge and expertise exchange.

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1 Introduction

This workshop was previously proposed to the IEA Greenhouse Gas R&D Programme (IEA GHG) by OPEC, and following the approval of the workshop, the first plan was to hold the workshop in February 2009 in Algeria. Due to difficulties in preparing invitation letters and visas; the workshop was postponed to November 2009. The suggestion was that Carbon Capture and Storage (CCS) was an important topic not being adequately dealt with by OPEC member countries. Therefore, the workshop was planned to fulfil two major objectives:

- To introduce scientists and professionals in OPEC member countries with a general overview of the complete CCS chain.
- For IEA GHG to interact with professionals from these countries, who are involved mainly in the oil and gas sector. This interaction will provide IEA GHG with a different point of view and will help IEA GHG to set future plans for CCS activities related to oil and gas sector.

As the originators of the concept, OPEC suggested to host the workshop and other future activities in one of the OPEC member countries. The Ministry of Energy and Mines together with Sonatrach agreed to host the workshop in Hassi Messaoud, Algeria. An organizing committee was established, with members form IEA GHG, OPEC, Ministry of Energy and Mines and Sonatrach. The workshop was held from the 16th to 20th of November, 2009 and attracted over 25 delegates from 7 countries, most of who actively participated in the discussion and breakout sessions.

The workshop included invited speakers to cover major CCS topics, as well as breakout group discussions on three generic CCS topics. The presentations and breakout groups covered the main CCS themes over the course of 4 days: CO_2 capture technologies, transport, storage, CCS financial, legal and safety status, public acceptance and four case studies. The use of breakout groups was very beneficial for the delegates to contribute effectively, and to give their clear opinion of the different CCS aspects.

This workshop as a first dedicated activity to the OPEC member countries has established a very good starting point and a strong relation between IEA GHG and OPEC for future cooperation.

2 Participants

This workshop is dedicated to OPEC member countries. The invitations to participate were sent to all OPEC member countries. Considering the different interest in CCS, 7 OPEC member countries participated in the workshop (Qatar, Algeria, Kuwait, Saudi Arabia, Iraq, Libya, and the United Arab Emirates).

The participants had different backgrounds and interest, which varied from chemical engineering to petroleum engineering and geologists. The interest in CCS was not the same for all participants. The

majority were more interested in EOR, safety, financial, storage and monitoring techniques. The interest in the capture technologies related to power sector was found to be limited.

The list of participants including their backgrounds and interest can be found in Appendix 1.

Figure 1: Group photo of the participants in the workshop

3 Programme

The programme was constructed by the IEA GHG team. It was established in a way to cover all topics related to CCS. Special focus was given to the major large scale study cases (In Salah, Sleipner, Weyburn and Abu Dhabi DF).
The programme was divided into four days followed by site visit to In Salah CO_2 capture and injection facilities. The full programme and the list of invited speakers are attached in appendix 2.

3.1 The first day

The first day started with an official opening of the workshop by a welcome speech from Djelloul Bachi, Director of production at Sonatrach. He welcomed the delegates, thanked the organisers, and hoped that the workshop would achieve its objectives and would be full of success. In their speeches, Miloud Medjelled, Director at the Ministry of Energy and Mines, and Najah Taher, the OPEC representative, extended thanks to the delegates, hosts and organisers of the workshop.
They explained the important role of CCS in order to control atmospheric levels of CO_2 and the interest of both OPEC and Algerian government in CCS as one of the major tool to mitigate global warming. The interest of such technology goes beyond the workshop to a major interest in becoming more involved in the IEA GHG's and other international activities.

Mohammad Abu Zahra also welcomed the delegates on behalf of IEAGHG, and hoped that the workshop would be beneficial, and include meaningful discussions. Speaker expressed thanks to the organising committee, and the level of work and commitment willingly provided.

Figure 2: Official opening of the OPEC-IEA GHG CCS workshop

Mohammad followed with an introduction to the IEA GHG, explaining the background of the Programme, its activities and involvement in the CCS field and explained its funding structure. In addition, he explained the background and origination of the workshop, touching briefly on the objectives of the workshop, the technical sessions and the connected group visits and activities. The agenda was presented, and the topics to be covered over the three day workshop were listed as:

- CO_2 capture technologies
- CO_2 transport and storage
- CCS general topics (financial, safety, legal, public acceptance and global projects)
- Study cases
- Working groups.

A copy of the agenda can be found in Appendix 2.

The technical sessions in the first day started with a general overview of climate changes and CCS technologies by Mike Haines from IEA GHG and Monica Lupion from CIUDEN, respectively. Following that session, the three major capture technologies (Post, Pre, Oxy-fuel combustion) were introduced to the participants to a certain extend of details by Mohammad Abu Zahra and Monica Lupion. The technical sessions for the first day were concluded by a presentation of Mike Haines about CO_2 transport and infrastructure.

3.2 The second day

The second day of the workshop focused on CO_2 storage status, techniques and opportunities. It started with an introduction of CO_2 storage by Neil Wildgust from IEA GHG. Neil followed this introduction with more detailed presentations over the status of storage in aquifers and in depleted hydrocarbon reservoirs.

Jean-Pierre Deflandre from IFP presented the techniques for storage site characterisations and discussed different issues related to that topic. Discussing CO_2 storage opportunities, Ghaniya Al Yafei from ADCO discussed techniques, opportunities and status of EOR.

In the last technical session of the second day, Pascal Audigane from BRGM presented modelling as a tool to assess the long term storage of CO_2. Jon Lippard from Statoil discussed the monitoring techniques and status. This session was very interesting and got very high attention of the participants.

3.3 The third day

The technical sessions of the third day started with a description of the current costs of CCS and possible options for cost reductions presented by Mike Haines. After that, Heleen de Coninck from ECN discussed the political and legal status of CCS. These presentations opened a large debate on the feasibility of CCS from legal and financial prospective. In addition, the legal and political issues brought the participants to a discussion regarding the involvement of the developing countries in the development of CCS technologies and who should be responsible of these developments and the later deployment.

Later on, three case studies were presented. Neil Wildgust presented the Weyburn case, Jon Lippard presented the Sleipner case and Iain Wright presented the In Salah case. The interest in these cases was high, especially the In Salah case because it represents an actual application of CO_2 capture and injection in one of the OPEC member countries (Algeria) and since a visit was scheduled on the last day of the workshop to the In Salah location.

The case study from Abu Dhabi – DF was not presented because the speaker (Paul Bryant from Hydrogen Power International) was not able to join the workshop. The third day ended with an overview of the CCS project on global scale by Neil Wildgust. This presentation gave a good overview of the large scale activities related to CCS. The focus was clearly on the storage and CO_2 injection. This is due to the fact that CO_2 injection projects are the only available large scale projects to date. Most of the currently running capture projects are either R&D or small scale demonstration. Extending such an overview to the R&D projects might increase the value of the presentation and give the participants better idea of the running CCS activities.

3.4 The fourth day

Only one technical session was presented on the fourth day. The first presentation by Mike Haines discussed the health and safety issues in relation to CCS. Followed by a presentation about the barriers to the introduction of CCS, public perception and financing by Heleen de Coninck. This

session was well received by the participants. This type of generic presentations received major discussion and debate from the delegates.

In the last session of the day, the three groups presented their findings and conclusions on their own subject.

At the end of the workshop, the opportunity was given to all speakers and delegates to comment on the groups' presentations and the workshop. Delegates and speakers expressed their satisfaction with the outcomes of the workshop, and welcomed the strong involvement from everyone present. The workshop was ended with closing comments from Mohammad Abu Zahra, who again thanked the host and the organisers for their support and warm hospitality. He acknowledged all those who supported, developed and organised the workshop, with particular thanks to Taher Najah, Djelloul Bachi, Madjid Allak, Miloud Medjelled, Djellas Naceredine, Fuad Siala, Fouzia Zouani, Anne Rechbach and Monica Lupion.

Djellas Naceredine closed the workshop on behalf of Sonatrach and the Ministry of Energy and Mines. He acknowledged the effort of IEA GHG and OPEC to make this workshop a successful gathering of scientists and professionals from OPEC member countries. He expressed high satisfaction for the excellent quality of communication before and during the workshop. He extended his thanks to the technical team, invited speakers and all delegates.

The technical programme of the workshop was ended and the rest of the day spent in an outside trip to another Sonatrach location and to the Sahara desert.

3.5 The working groups

A major part of the workshop was oriented to the group working activities. The objectives of the working group were:

- To increase the involvement and pro-activity of the delegates in the programme
- To give the delegates a general overview of specific topic in relation to CCS
- To hear the opinion of the delegates of the CCS topics from their own experience and background

In addition, the groups' activity encouraged discussions, networking and social interactions between the participants. At the end of the first day, the groups' activity was introduced by Monica Lupion. The delegates were divided into three working groups and two or three speakers were involved in each group as mentors to facilitate the activity. Each group had one of the following topics to discuss during the workshop.

- Group1: Can CCS be part of an integrated, sustainable and secure energy system?
- Group2: Is CCS a viable option for developing countries?
- Group3: Is EOR a distraction to CCS development?

The working groups' activity involved three working sessions and on the last day each group presented their finding in a short presentation followed by questions from speakers and delegates. The major conclusions of each of the groups could be summarised as follow:

Conclusions of group 1:

- CCS could be a part of integrated, sustainable energy system
- Country specific – driven by political commitment based on local socio-economic and environment development path of each country
- Project specific and site specific
- Large scale deployment of CCS needs international agreement in terms of support in technology transfer, financial resources and Investment and capacity building.

Conclusions of group 2:

CCS is a viable option for developing countries provided that:

- Confirmation of success is required.
- Cost reduction.
- Technology improvement.
- Financial Incentives Provided

Conclusions of group 3:

- CO_2-EOR could effectively increase oil production as well powerful recovery methods in addition to CO_2 storage technique.
- CCS can store huge amount of CO_2 underground and can be accepted as part of CDM project.
- EOR is not going to distract CCS development in case of any future EOR need for CO_2 deployment.
- The case of In Salah: the CO_2 is stored in the reservoir which can be used in any future EOR inquires (Hassi Messaoud).

The group activity was well received and achieved the expected objectives. At the start of the activity it was not easy for some individuals to adapt the concept of working group and to deal with such generic topics. There were a few comments to that it might have been a more useful if the participants had received the topics in advance before the workshop or if they had to prepare the activity as a presented paper in advance. However, after the first day, the groups understood the topics and the aim of the activity far better and they worked out on their topics in an active and productive way.

Figure 3: Session of the working group activity

Final presentations of the working groups' topics provided a good overview and vision of the different groups on their subjects. These views are of utmost interest since they are coming from groups with different background and expertise than what we used to deal with in the CCS community. It must be pointed out that in the final evaluation of the workshop, most delegates evaluated the working groups' activity positively, and they agreed that it was useful and that they benefited from these groups' discussions.

3.6 The visit to In Salah

In Salah is one of the four largest CO_2 geological storage projects. The CO_2 storage started in August 2004 with an annual capacity of one million tonne CO_2 (www.insalah.com). This project is considered to be an industrial scale demonstration of CO_2 geological storage with conventional CO_2 capture form natural gas.

In the third day of the workshop, the In Salah project was introduced by Iain Wright from BP as one of the study cases. This introduction gave an overview of the projects objectives, status and future. The In Salah project is considered to be an important case study for this workshop due to the fact that it is a demonstration in on the OPEC member countries (Algeria). In addition, as mentioned earlier it is one of the largest CO_2 storage demonstration projects.

In the last day of the workshop (Friday 20/11/2009) 25 participants visited the In Salah gas treatment and CO_2 injection locations. The visit started with a welcome presentation and an introduction to the In Salah project given by Selama Faycal, the In Salah Gas operations manager. In his presentation, Mr. Selema explained the conventional capture process, the project basis, plans, the CO_2 compression and injection process and capacity.

After introducing the project, the participants were divided into two groups for the visit of the facilities. The first part of the visit covered the natural gas treatment plant, the CO_2 separation plant (using a MDEA conventional process), CO_2 dehydration process, and CO_2 compression plant. Then the visit was concluded by visiting the CO_2 injection and the storage field.

The In Salah visit was an excellent opportunity for the participants to visit a real CO_2 capture, transport and storage large scale demonstration. In addition, it was an occasion for some technical and scientific discussions mainly on issues concerning CO_2 treatment, injectivity, and monitoring.

At the end of the visit, which was evaluated to be both exciting and useful for the participants, Mohammad Abu Zahra thanked the host and the location mangers for their hospitality and for receiving the participants in the In Salah location.

Figure 4: Group photo during the visit to In Salah

4 Participants feed back

A questionnaire form was distributed to all participants (appendix 4) and the 14 responses were received at the end of the workshop. The table below summarises the number of responses for each categories of the evaluation.

	Poor	Average	Very good	Excellent
Session topics		2	12	
Content of the presentation		3	10	
Presenters		1	9	3
How well the workshop met your expectations		2	5	5
Standard of materials		3	8	2
Group work topics		3	9	2
Visit		1	6	7
Venue			6	8
Overall organisation		1	6	7

It can be seen clearly from the table that the majority of the participants evaluated the workshop sessions, content, presenters, material and group topics as very good. In addition, the visit to In Salah, the venue and the overall organisation exceeded the very good to excellent. It is clear that the workshop has met the participants' expectations to a very good or even excellent level.

In addition, the evaluation considered the opinion of the participants of the more useful and less useful sessions in the workshop. The evaluation concluded with suggestions for topics for a future workshop, options for improvement and general comments.

The responses to these questions varied from full satisfaction to more specific interest. Considering the more useful sessions, the responses varied between:

- All sessions
- Case studies
- Public perception
- Group discussions
- Political and legal status
- Monitoring
- Cost studies
- EOR
- Geological storage
- Visit to In Salah

Considering the less useful sessions, the responses varied from none to the following comments:

- Presentations with repeated basics and details
- Details in the CO_2 capture technologies, which are based on the power sector and mainly on coal
- Transport technologies
- The sessions were a bit difficult to follow and understand due to the number of the English native speakers

Asking for other topics those participants would like to see in a future CCS workshop, the following topics were suggested:

- Financial aspects and more into the possibilities to reduce CCS costs
- Legislation and legal issues
- CDM, Carbon credit, trading and negotiating positions, progress and impact on CCS development
- More details on monitoring techniques
- Other NGO's point of view (e.g. Greenpeace)
- CCS risk assessment and safety
- The current R&D status and projects in more details
- Capture technologies related to oil and gas (e.g. natural gas treatment and associated gases)
- Wells description and behaviour of the wells as a reaction to CO_2 injection

The following suggestions were provided to improve future OPEC IEA GHG workshops:

- To involve more countries!!
- Have a split between basic learning and advance sessions
- Include latest development and progress in CCS in the presentations
- Extra time for discussions
- Case studies more related to oil and gas upstream and downstream processes
- Inform the delegates of the working groups' topics in advance
- More country's specific topics (real case studies from OPEC member countries)
- Involve lawyer experts in the CCS
- The organised side activities (dinner, visit, travelling and timing) to be made more clear to the participants

At the end the following general comments and acknowledgments were received from the participants:

- The workshop and the visit to In Salah were very useful and successful
- Very well organised, well thought, smooth running and interesting event
- Very good choice of location to keep the focus on the workshop
- Invited speakers requested in the future to have more information on the background of the participants well in advance
- Keeping future communications and interactions between the participants are required

In general it can be concluded that there was a clear satisfaction and interest between the participants. Despite the trouble of the luggage and the delays in the airports, which have nothing to do with the organisers, the workshop met the participants' expectations.

5 Workshop evaluation

While evaluating this workshop, it is important to consider couple of issues:

- This is the first IEA GHG-OPEC's activity
- The information on the background, interest and experience of the participants were not clear or available for the organisers and speakers in advance
- The programme of the workshop was scheduled and operated to a certain extent in a similar way to the IEA GHG CCS summer school.

Considering the two main objectives of the workshop, it can be concluded that the workshop was successful. It achieved the objectives by introducing the CCS concepts to the participants and gave the chance for the IEA GHG team and other speakers to interact with different group of professional with different backgrounds and experience.

The programme of the workshop was fully achieved and well received from participants. The interest and interaction of the participants varied from topic to another. It was clear that the main interest of the participants were in the CO_2 storage, EOR, injection and monitoring techniques and status. In addition, more general topics related to financial support, HSE, legal and political status and public perception were of general interest of all participants. The capture technologies and options (post, pre and oxy-fuel combustion) were of the least interest of the participants due to the fact that these technologies are more connected to the power sector rather than to the oil and gas industry.

This different interest of the CCS topics is related to the participants' background and expertise. The majority of the participants were either geologists or petroleum engineers. Their involvement in the oil and gas sector directed their interest to topics more related to EOR, CO_2 storage and CCS generic subjects.

The communications with the organisers before and during the workshop were very good and achieved the required level of communication. However, it is important to improve the communication between OPEC and the participants. It might be useful on some stage to have direct contact between IEA GHG and the participants to speed up the procedure and to avoid delay or misunderstanding. Any future arrangements or communications need to be agreed between IEA GHG and OPEC.

5.1 Participants

The quality of the participants at the workshop was high. The participation in all activities was good.

Comments:

- Few of the participants were in senior positions with long term experience in oil and gas. This added extra value to their opinions and contribution. However, for future workshops or activities, it is good to encourage the participation of more young professionals
- More details on the background and interest of the participants need to be provided in advance.

5.2 Venue/Accommodation/Catering

The venue selected by the organisers was excellent and none of the associated facilities could be faulted. The venue certainly contributed to the success of the workshop. Having all facilities in the same location saved time and increased social interaction.

The accommodation and services during the workshop were excellent and to a very high standard.

Comments:

- Venue choice had a high impact on the success of the workshop. Venues should be easily accessible from an international airport for ease of transfer. The problems occurred during travelling caused a bit of problem at the start and the end of the workshop.

5.3 Workshop programme

The programme covered all CCS aspects. It did achieve the objectives of the workshop by giving the participants a good overview of all CCS technologies and aspects. The programme was well organised and well received by the participants.

Comments:

- The balance between lectures and working groups needs to be evaluated. Increasing time for working groups might be advantageous
- Content of the sessions and the programme could be improved if the background of the participants was provided to the organisers early enough.

5.4 Invited speakers

Speakers' participation was varied. Several presenters only stayed for part of the workshop. One only stayed for one day. Others stayed for all or several of the days and contributed to the student activities.

Comments:

- For future events we should encourage lecturers to stay for longer periods. Lecturers who cannot commit for such time periods should be replaced wherever possible
- While organising the workshop, there was a problem in encouraging speakers to participate in the workshop. This is mainly due to their availability and the location. For the future, it would be more convenient to rely on the IEA GHG's team to cover most topics of the workshop
- The content and length of the presentations should be evaluated by the organisers in advance.

5.5 Working groups

Despite the difficult start for one of the groups, this activity seemed to work extremely well, participants got very involved and the presentations were all good. The activity generated a degree of interaction. Participants appeared to enjoy the working group activity.

Comments:

- Keeping the working group as a major activity in the up coming workshops is important

- More time needed for the working groups, which will improve the content and the value of the groups' discussions
- Inform the participants of the topics and the working methodology of the groups' activity prior to the workshop might improve the expected outcome
- Include real case studies from OPEC countries, which could be provided by the participant as working project is a valuable suggestion from the participants

5.6 Supporting materials

Collecting the presentations and generating a USB memory stick of lectures was a good idea. Many lectures changed their presentations between then and the day of presentation or did not even provide them in advance. That is why the presentations were provided to the participants on the last day as a reference for the future. The hard copies of presentations were provided during the workshop and also well received, but again some of them were out of date. Providing a selection of IEA GHG's report on CD was useful but not effective in helping the participants work programmes.

Comments:

- Asking for presentations early is a good discipline
- Provide the presentations in advance to be able to prepare a book of presentations at the start of the workshop.

5.7 Social activities

Initially there were no plans for specific social activities rather than the daily interaction between the participants during the workshop breaks, lunch and dinner. A trip to another site of Sonatrach and to an out site location in the Sahara desert was organised on the 4th day of the workshop. This short trip was received in a good way by the participants and gave a different taste to the whole workshop. The soccer match between Algeria and Egypt was also an event for social interaction especially with Algerian participants. The outside dinner on the 2nd day of the workshop was also excellent.

Comments:

- Include social break for future events.

5.8 In Salah visit

The visit to In Salah served as both technical and social activity. The whole experience flying over the Sahara with a small group of people was a good chance for geology exploring and social interaction between the participants. The visit of the location was amazing. The participants acknowledge this visit very much in the evaluation.

Comments:

- Keep such a visit as part of future activities, once possible.

6 OPEC-IEA GHG future activities

Considering the successful workshop, it is recommended to carry on future activities for OPEC member countries on regular basis. However, the content and the nature of the future activities might vary.

Out of the discussion with the organisers and the participants during the workshop, many ideas of future activities and cooperation between OPEC member countries and IEA GHG were mentioned and discussed.

CCS workshop format: It is advised to consider the comments of the participants provided earlier in the report if another CCS workshop using the same general guidelines is carried out. In addition, it is suggested to make the technical sessions more dense and shorter. On the other hand, increase the available time for the groups' activities and discussions during the technical sessions. In addition, the working group activity could be improved by asking the participants to prepare and provide specific case studies from their fields and institutes in advance. These prepared case studies could be evaluated and discussed to a wider extend during the workshop. A suggestion of 3-4 day workshop including a social activity or site visit could be a good future approach.

Topic-specific workshop or meetings: these specific meetings could be organised between experts in the different CCS fields including the IEA GHG team together with groups from OPEC member countries who are interested in certain topics of CCS. These meetings could be very specific in topics and targeted group of participants. For example, to discuss issues related to CDM and carbon trading scheme. Another example is to discuss certain CCS application (e.g. associated gases, natural gas treatment), technology or country specific topics.

Direct cooperation and knowledge exchange with IEA GHG: this could be achieved by having IEA GHG's team involved in some of the OPEC's R&D teams meeting. This could be done either on the overall OPEC level or on the level of each country depending on their own interest. Doing this activity from the other direction could be an option, by having professionals from OPEC member countries as secondees within IEA GHG. This would help the professionals of OPEC member countries to gain more experience in the CCS field and to learn more about IEA GHG's activities and methodology.

In general, it is important to keep the contact between IEA GHG and OPEC member countries very active. The nature, location and content of future activities should be decided and agreed with OPEC well in advance.

7 Appendices

7.1 Appendix 1: List of participants

Name	Company/country	Expertise
Dr Taher Najah	OPEC/AUSTRIA	Downstream
Ms Farida Toufouti	Algerian Ministry- ARH / Algeria	HSE Engineer
Ms Faiza Hallal	Algerian Ministry- ARH / Algeria	HSE Engineer
Mr Slimane Benmansour	Algerian Ministry- Alnaft / Algeria	Geology Engineer
Ms Fadila ben abdeloumene	Sonatrach /Algeria	Deputy manager of environment management
Mr Hakim Derghmoum	Sonatrach /Algeria	CO_2 In salah sequestration
Mr Brahim Achi	Sonatrach /Algeria	Petroleum engineer
Mr Hacen Bouhadjar	Sonatrach /Algeria	Economic engineer
Dr. N. Djellas	Sonatrach /Algeria	Chemical engineering
Mr Ammar Hadim	Sonatrach /Algeria	Petroleum engineer
Mrs Nora Zouaoui	Ministry of energy and mines	Chemistry
Ms Zohra Bouhouche	Ministry of energy and mines	Geologist Engineer
Mrs Akila Azirou	Ministry of energy and mines	Geologist Engineer
Ms Wahiba Ladjouzi	Ministry of energy and mines	Geologist Engineer
Ms Karima Batouche	Ministry of energy and mines	Geologist Engineer
Ms Fouzia Zouani	Ministry of energy and mines	Oil refining engineer
Dr Ebenerzer Regkumar Abraha	Qatar petroleum	Clean development mechanism-HSE
Mrs Bin Dhaaer Ghania Salem	ADCO/UAE	Reservoir engineer-EOR
Mrs Majda A.Al Busairi	Ministry of oil/Kuwait	Petrochemical controller
Mr M.Al Qenaei	KPC/Kuwait	Reservoir engineering
Mr Hamad Al Marri	Qatar petroleum	Head of surface facilities development
Mr Abdulla Ahmed Al-Suwaidi	Qatar petroleum/ Qatar	Head of Oil field development
Ms Saba Yousif	Ministry of oil/Iraq	Head Environmental Section
Mr Nadhim Mutlag	Ministry of oil/Iraq	Manager, Gas Studies Department
Mr. Dhiyab Anazi	Saudi Aramco/ Saudi Arabia	Environmental Engineer

7.2 Appendix 2: Workshop agenda and invited speakers

Name	Institutes	Country	Expertise
Mohammad Abu Zahra	IEA GHG	UK	CO_2 Capture
Mike Haines	IEA GHG	UK	Capture/Transport
Monica Lupion	IEA GHG-CUIDEN	UK	CO_2 Capture
Neil Wildgust	IEA GHG	UK	Geological storage
Jean-Pierre Deflandre	CO2GeoNet-IFP	France	CO_2 storage-microsismic
Ghaniya Al-yafei	ADCO	UAE	EOR
Pascal Audigane	CO2GeoNet-BRGM	France	Reactive transport machine
Jon Lippard	Statoil	Norway	CO_2 monitoring
Heleen de Coninck	ECN	Netherlands	CCS General
Iain Wright	BP	UK	Storage and injection

OPEC-IEA GHG CCS workshop

for scientists and professionals in OPEC Member Countries

Agenda

	Day 1 (16/11/09)	Day 2 (17/11/09)	Day 3 (18/11/09)	Day 4 (19/11/09)	Day 5 (20/11/09)
08:30	Welcome Taher Najah Rabah Nadir Allouani Mohammad Abu Zahra	Introduction to CO_2 Storage	Current costs and cost reduction options	Health and Safety Issues	Visit to In Salah Location
08:45	Introduction and IEA GHG overview Mohammad Abu Zahra	Neil Wildgust	Mike Haines	Mike Haines	
09:00	Mitigating Climate change what are the options Mike Haines	Storage - Aquifers status Neil Wildgust	Political & legal status of CCS	Barriers to the introduction of CCS - public perception and financing	
09:30	CCS Overview and technical options Monica Lupion	Storage - Depleted hydrocarbon reservoirs Neil Wildgust	Heleen de Coninck	Heleen de Coninck	
10:00	Coffee	Coffee	Coffee	Coffee	
10:30	CO_2 post-combustion capture Mohammad Abu Zahra	Storage – Site characterization issues Jean-Pierre Deflandre	Case studies: Weyburn Neil Wildgust	CCS projects global Neil Wildgust	
11:15	CO_2 pre-combustion capture (IGCC) Monica Lupion	EOR opportunities and status Ghaniya Al-Yafei	Case studies: Sleipner Jon Lippard	Break-out Groups	
12:00	Lunch	Lunch	Lunch	Lunch	
13:30	CO_2 Oxy-fuel capture Monica Lupion	Modeling - Assessing the long term fate of CO_2 Pascal Audigane	Case studies: In Salah Iain Wright	Group 1 presentation	
14:15	Transport issues and infrastructure needs Mike Haines	Monitoring techniques and status Jon Lippard	Case studies: Abu Dhabi - DF 4 Paul Lyndon Bryant	Group 2 presentation Group 3 presentation	
15:00	Coffee	Coffee	Coffee	Presentations feed back and review	
15:30	Working Groups Introduction Monica Lupion	Break-out Groups	Break-out Groups	Review of workshop and close Taher Najah Rabah Nadir Allouani Mohammad Abu Zahra	
15:40	Break-out Groups			Close	
17:00	Close	Close	Close		

7.3 Appendix 3: Evaluation form

OPEC-IEA GHG CCS workshop

for scientists and professionals in OPEC Member Countries

CONFIDENTIAL FEEDBACK FORM

	Poor	Average	Very good	Excellent
Session topics				
Content of the presentation				
Presenters				
How well the workshop met your expectations				
Standard of materials				
Group work topics				
Visit				
Accommodation				
Meals				
Venue				
Overall organisation				

Which sessions did you find more useful?

Which sessions were less useful?

What other topics would you like to see in a CCS workshop?

How could future OPEC IEAGHG workshops be improved?

General comments

OPEC-IEA GHG CCS workshop

Hassi Messaoud, Algeria

16th – 19th November, 2009

Attendee List

Students

Farida Toufouti	Algeria	Fayza Hallal	Algeria
Slimane Benmansour	Algeria	Fadila Ben Abdelmoumene	Algeria
Hakim Deghmoum	Algeria	Nora Zouaoui	Algeria
Zohra Bouhouche	Algeria	Akila Azirou	Algeria
Fouzia Zouani	Algeria	Wahiba Ladjouzi	Algeria
Maryam Jahandideh	I.R. Iran	Mohammad Saboormaleki	I.R. Iran
Nadhim Abbas Mutlag	Iraq	Sara Abdulateef Yousuf	Iraq
Majida Abdulrahman Al-Busairi	Kuwait	Mohammed Abdulwahab Al-Qenaei	Kuwait
Almunir Mohamed Abdulmaula	S. P. Libyan A. J.	Mustafa Belgasem Abunowara	S. P. Libyan A. J.
Ebenezer Rajkumar Abraham	Qatar	Abdulla Al-Suwaidi	Qatar
Hamad Jaralla Al-Marri	Qatar	Dhiyab Anazi	Saudi Arabia
Ahmed Salem Al Hammadi	United Arab Emirates	Ghaniya Bin Dhaaer Al-Yafei	United Arab Emirates
Taher Najah	OPEC Secretariat	Karima Batouche	Algeria

Mentors

Neil Wildgust	IEA GHG	Monica Lupion	IEA GHG
Dr. Mohammad Abu Zahra	IEA GHG	Mike Haines	IEA GHG
Iain Wright	BP	Jon Lippard	Statoil
Jean-Pierre Deflandre	CO2GeoNet-IFP	Pascal Audigane	CO2GeoNet-BRGM
Ghaniya Al-Yafei	ADCO	Dr. Heleen de Coninck	ECN

IEA Greenhouse Gas R&D Programme

The IEA Greenhouse Gas R&D Programme
An Overview

Dr. Mohammad Abu Zahra

IEA Greenhouse Gas R&D Programme

OPEC-IEAGHG CCS Workshop

for Scientists and Professionals in OPEC Member Countries

Hassi Messaoud-Algeria November 2009

IEA Greenhouse Gas R&D Programme

- A collaborative research programme founded in 1991
- Aim: *Provide members with definitive information on the role that technology can play in reducing greenhouse gas emissions.*
- Producing information that is:
  - Objective, trustworthy, independent
  - Policy relevant but NOT policy prescriptive
  - Reviewed by external Expert Reviewers
  - Subject to review of policy implications by Members
- IEA GHG is an IEA Implementing Agreement in which the Participants contribute to a common fund to finance the activities. Funding approximately 1.8 million £/year (2 million €/year).

Contracting Parties and Sponsors

IEA GHG Activities

•Theme 1 – Technology Evaluations

- Techno – economic evaluations
- Technical assessments
- Expert meetings

•Theme 3 International Co-operation

- International Research networks
- Practical R,D&D
- JIPs
- Direct collaborations

•Theme 2 – Facilitating Implementation

- Technical assessments
- Provision of Evidence Based Info. In support of regulatory development
- IEA/CSLF/G8 Activities
- CCS Summer School

•Theme 4 - Dissemination

- Quarterly newsletter
- Web sites
- Public summary reports
- GHGT Conferences
- International Journal on Greenhouse Gas Control

IEA GHG Studies >120

Implementation Support

- Methodology for CCS projects under CDM
- Guidelines for CCS site characterisation
- CCS Project Financing
- Regional capacity for CO_2 storage in India

Regulatory Support

- Risk assessment and regulatory needs
- Environmental impact assessment for CCS
- Capture-ready power plant (IEA/G8)
- Monitoring Selection Tool

Technical Assessments

- Improved solvent scrubbing processes for CO_2 capture
- Capture of CO_2 from medium scale installations
- Improved Oxygen production processes
- Collection of CO_2 from distributed sources
- CO_2 Capture in the cement industry
- Co-production of hydrogen and electricity
- Remediation of leakage from geological storage
- Fuel Cells for CHP
- CO_2 Pipeline transmission costs

International Research Networks

•CO_2 Capture

- CO_2 Capture – post combustion capture
- Oxyfuel capture – now OCC-1
- Solid looping
- Environmental impacts

•Geological Storage

- Modelling
- Monitoring
- Risk Assessment
- Well bore integrity
- Environmental Impacts

•Public Communication

- New network under development

• Others

- Expert group on operational flexibility
- CCS and Sustainability

•Aim of networks are to: foster international co-operation, share data and learn from actual experiences and develop evidence based information on technology status and future research needs

•Networks contributing to international knowledge on “what we have learnt “

Facilitating Implementation

Working with other organizations to help promote CCS as a GHG mitigation option

1. Input to G8 Road mapping exercise
2. Co-organisers of IEA Regulators Network

1. Evidence based information
2. CCS/CDM Report

United Kingdom
Foreign & Commonwealth Office

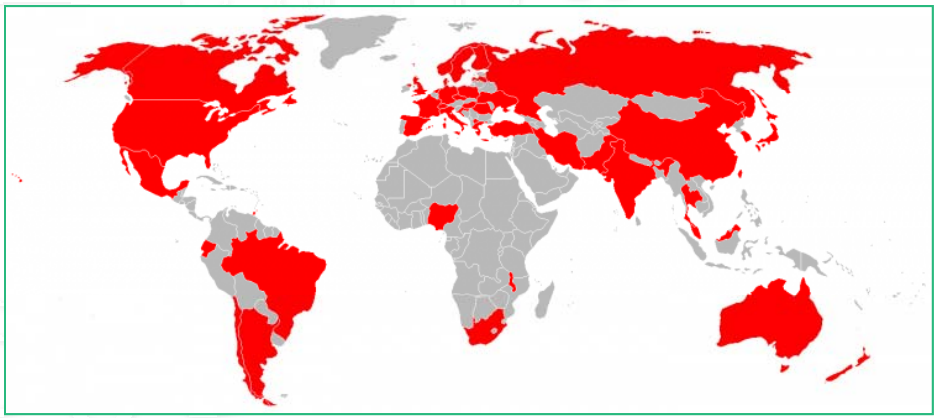
1. Capacity Building workshop in Indonesia

1. Policy and Regulation Task Force
2. Technical Task Force

1. Member of Technical Working Group
2. Risk Assessment Task Force

Summer School

- IEA GHG Summer School Series to date
  - 80 students applied for the 1st (2007), 120 for the 2nd (2008)
  - 115 students attended
  - 34 countries represented, 6 continents
- 3rd in Series held in Australia in August, 2009
  - 260+ students applied
  - 30 countries applied
- 44 countries in total



IEA Greenhouse Gas R&D Programme

Practical R&D Activities

Systems Studies/Capture

- DYNAMIS
- International Test Centre

Technical Reviews

- US REGIONAL PARTNERSHIPS
- US EPA VUNERABILITY ASSESSMENT FRAMEWORK
- OTWAY BASIN PILOT PROJECT
- WEYBURN
- RECOPOL

Storage Projects

- WEYBURN
- SACS/CO2STORE
- CO2REMOVE
- CO2SINK
- MOVECBM

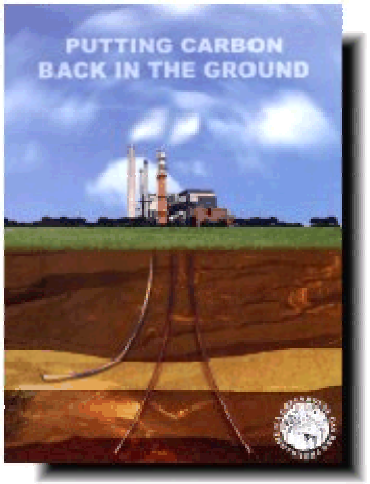
Greenhouse Gas Technologies Conference (GHGT)

- Premier International GHG conference
- Focused on CCS
- Held every two years
- GHGT-8, 2006 – Trondheim, Norway
  - 950 Delegates
- GHGT-9, 2008 – Washington, USA
  - 16th – 19th November
  - 850 abstracts submitted
  - ~1500 Delegates
  - http://mit.edu/ghgt9
- GHGT -10, 2010 – Amsterdam, Netherlands
- www.ieagreen.org.uk/ghgt.html

- Key Dates:
  - 15th September 2009 - Web site Open
  - 15th December 2010 - Abstract submission
  - 18th May 2010 - Notifications
  - 31st August 2010 - Paper submission date
  - 19th -23rd September - 2010 Conference

Communications

- Web sites
  - Two main web sites, receiving at lot of hits
  - Wikipedia site established
- Newsletter
  - 7500 paper copies, Increasing size
- Glossy Reports
  - Geologic Storage Safety, Natural Analogues, etc



www.co2captureandstorage.info

Support Tools

- Monitoring Selection Tool
- Transmission Calculator
- Storage Cost Estimator

Host Site

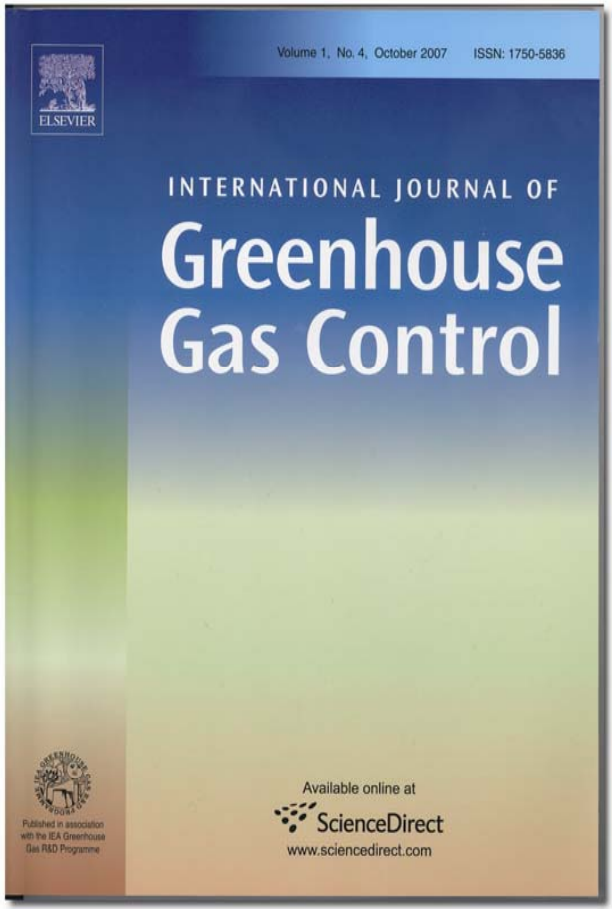
- Network Meetings
- Technical meeting reports

Databases

- CCS R,D&D Database
- CO_2 Emissions
- Risk Scenarios
- Best Practice Literature

International Journal of Greenhouse Gas Control (IJGGC)

- International Journal on Greenhouse Gas Control launched
  - Released Quarterly
  - Peer reviewed
  - Original research
  - 6 issues per year planned
- www.elsevier.com



Thank You

Any Questions?

Reference material on IEA GHG can be found at:

www.ieagreen.org.uk

Reference material on CCS can be found at:

www.co2captureandstorage.info

Mike Haines

- Chemical engineer – Cambridge University
- 1967-2002 – Shell International
- 2002 –present IEAGHG R&D programme

Mitigating Climate Change

What are the options

Mike Haines

- Chemical Engineer
- Career
  - Part 1 Heavy petrochemicals (13 yrs)

  - Part 2 Oil and Gas Exploration and Production (20 yrs)
  - Part 3 Retirement (3 months)

  - Part 4 Green House Gas abatement (7 yrs .?)

- Sessions in this OPEC-IEAGHG Workshop

  - Mitigating climate change - options
  - Transport issues and Infrastructure

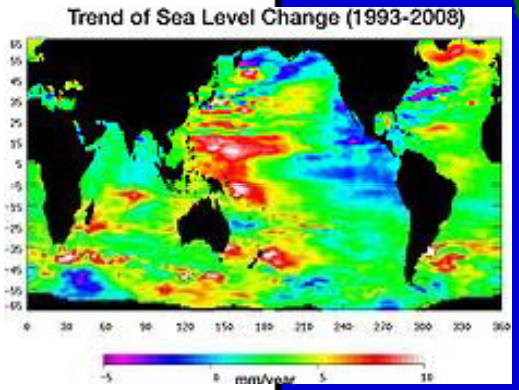
  - Costs and cost reduction options

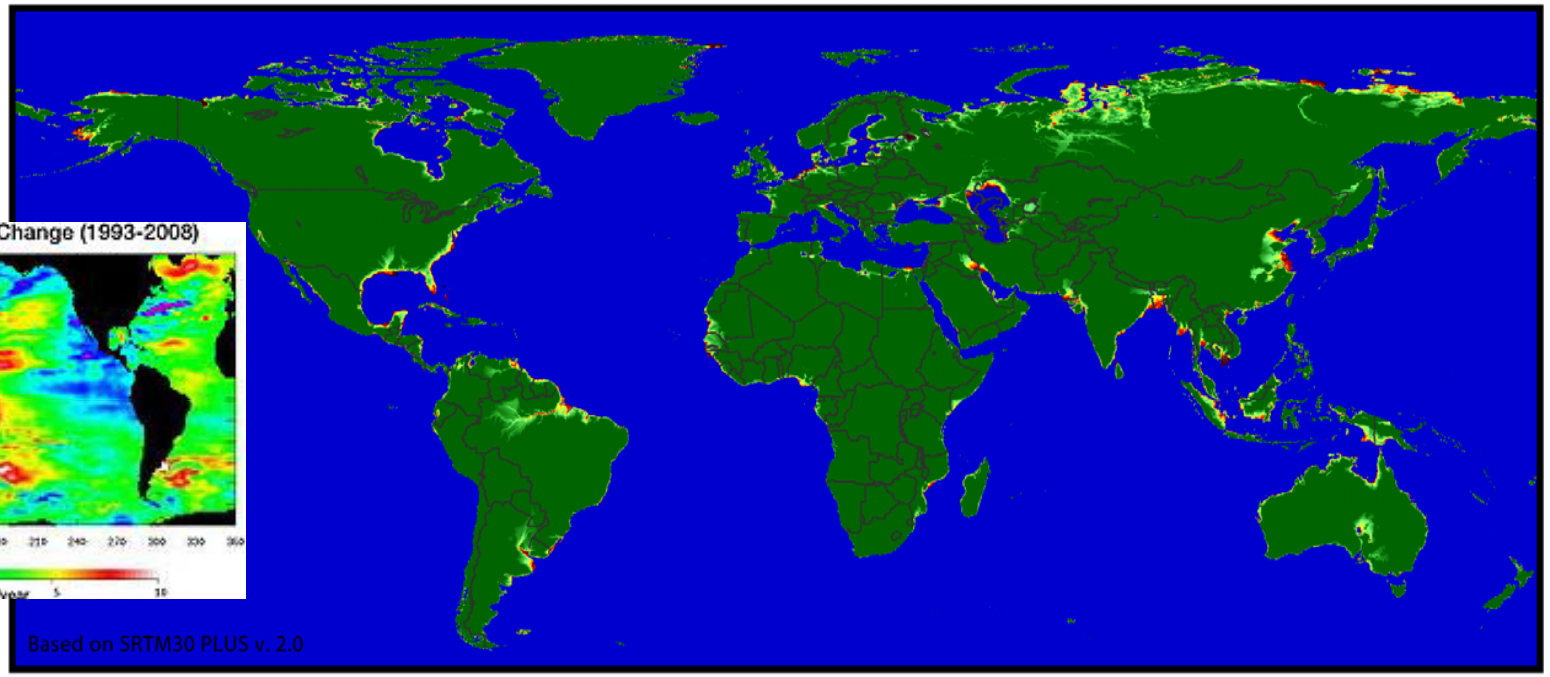
  - Health and Safety

Will climate change happen?

- Increasing and overwhelming evidence is building up to support predictions
- Early signs of effect are now apparent
  - Melting ice
  - Small increase in average temperature
  - Rate of sea level rise?
- Must be distinguished for cyclic climate variations
  - E.g. El Nino

Regions Vulnerable to Sea Level Rise



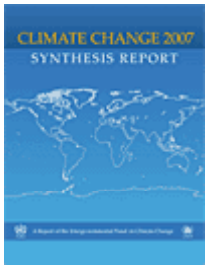


Height Above Sea Level (m)

0 1 2 3 5 8 12 20 35 60 80

Some sources of information

- UNFCCC is the international organisation at the centre of global actions on climate change
- IPCC is commissioned by UNFCC to report on climate change and related issues
- The last formal assessment was the 4th assessment published in 2007



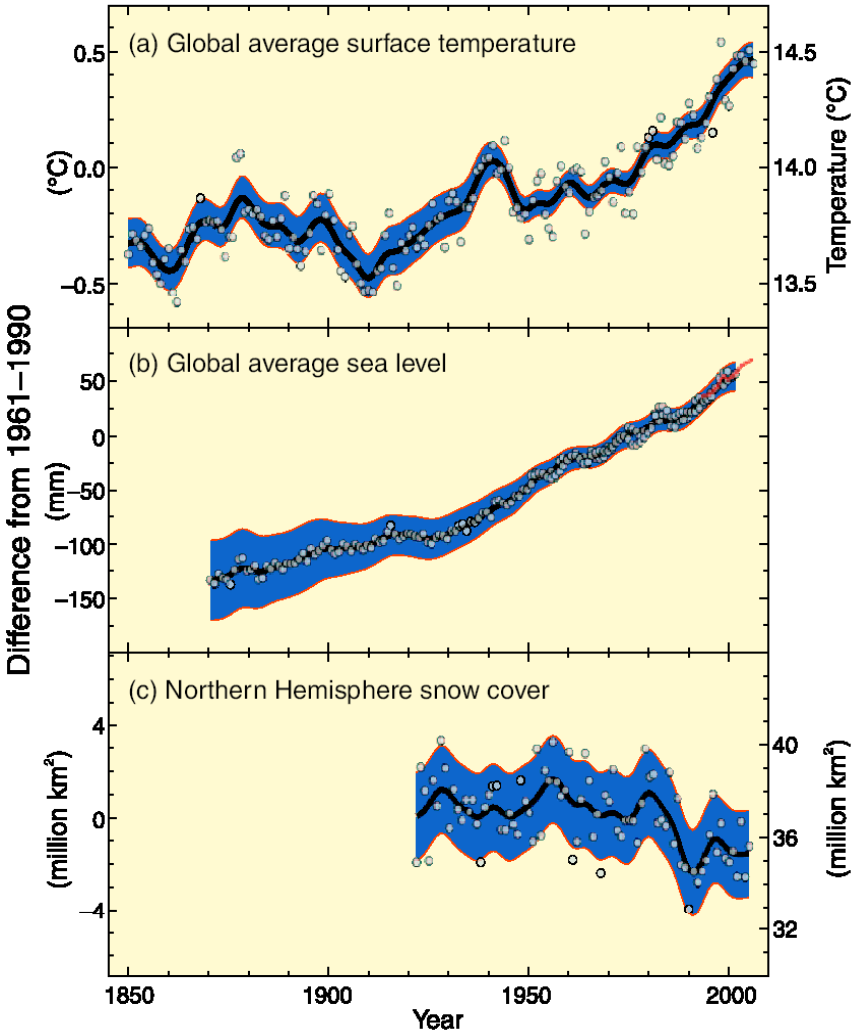
- The UK "Stern Report" is a further source of information with emphasis on economic effects
- Ecofys report "Factors Underpinning Future Action"

(Includes summaries of country positions in negotiation)

IPCC 4th assessment report 2007*

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level

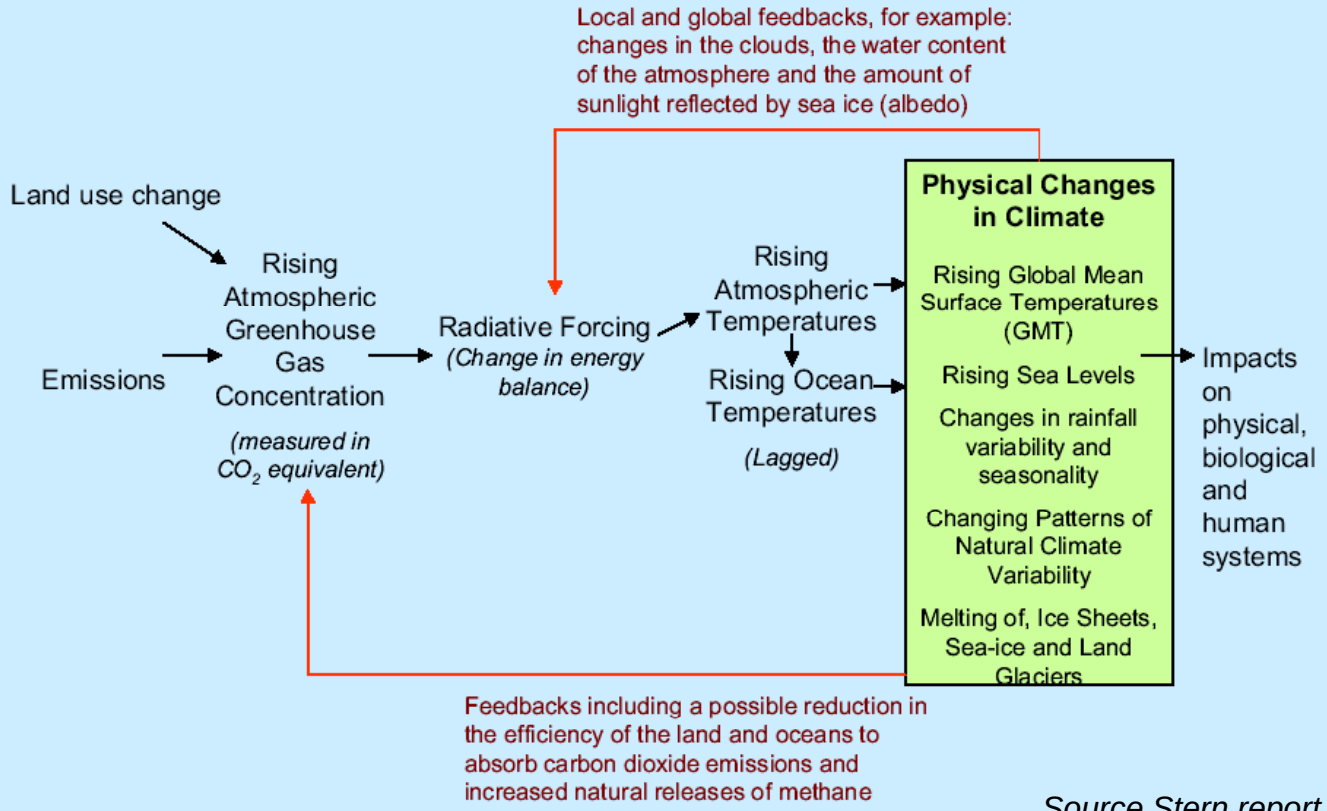
Changes in temperature, sea level and Northern Hemisphere snow cover



*http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

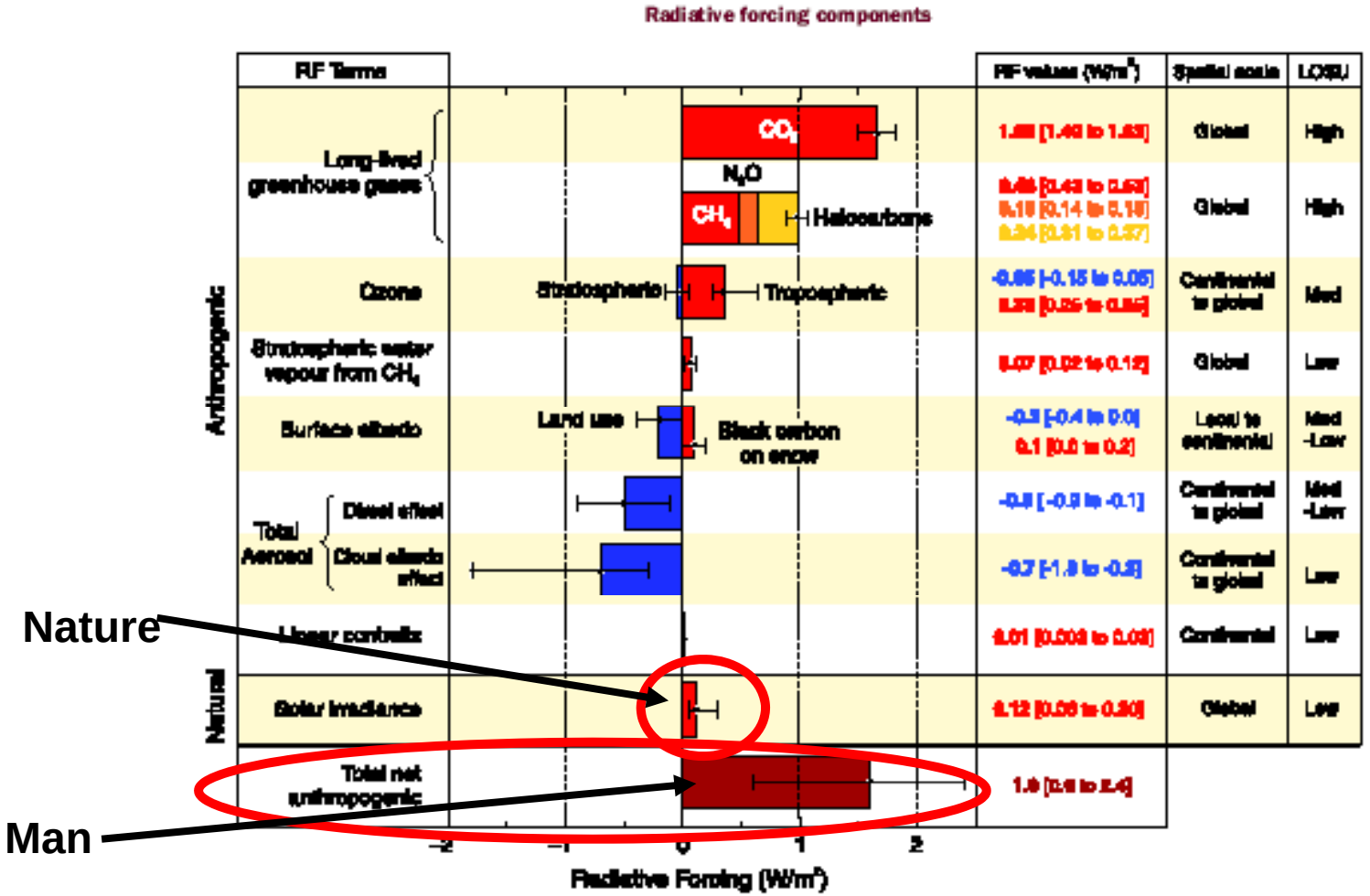
Stern report – GHG-climate links

Figure 1.4 The link between greenhouse gases and climate change.

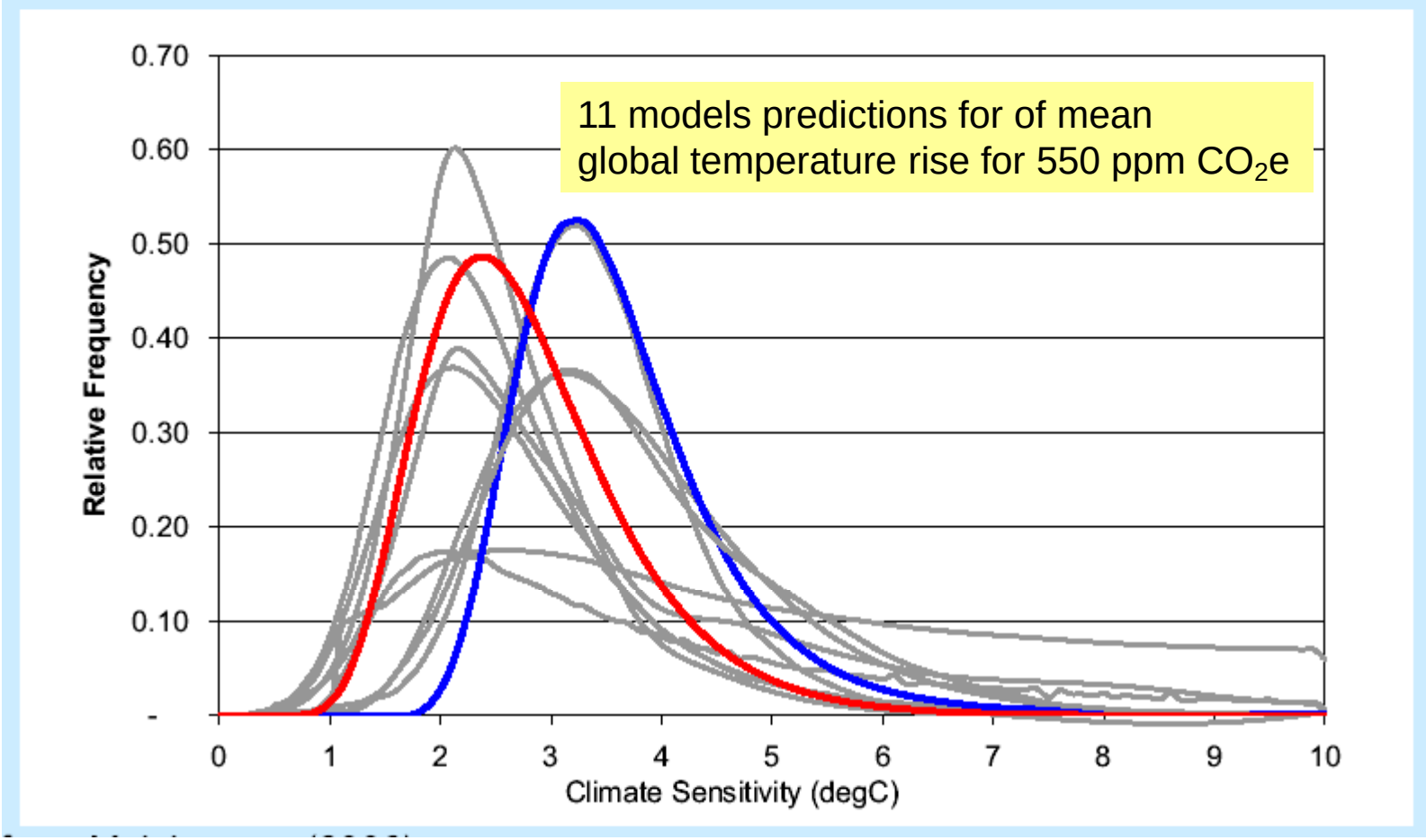


Source Stern report Part 1 page 8

IPCC conclusion – Very Likely

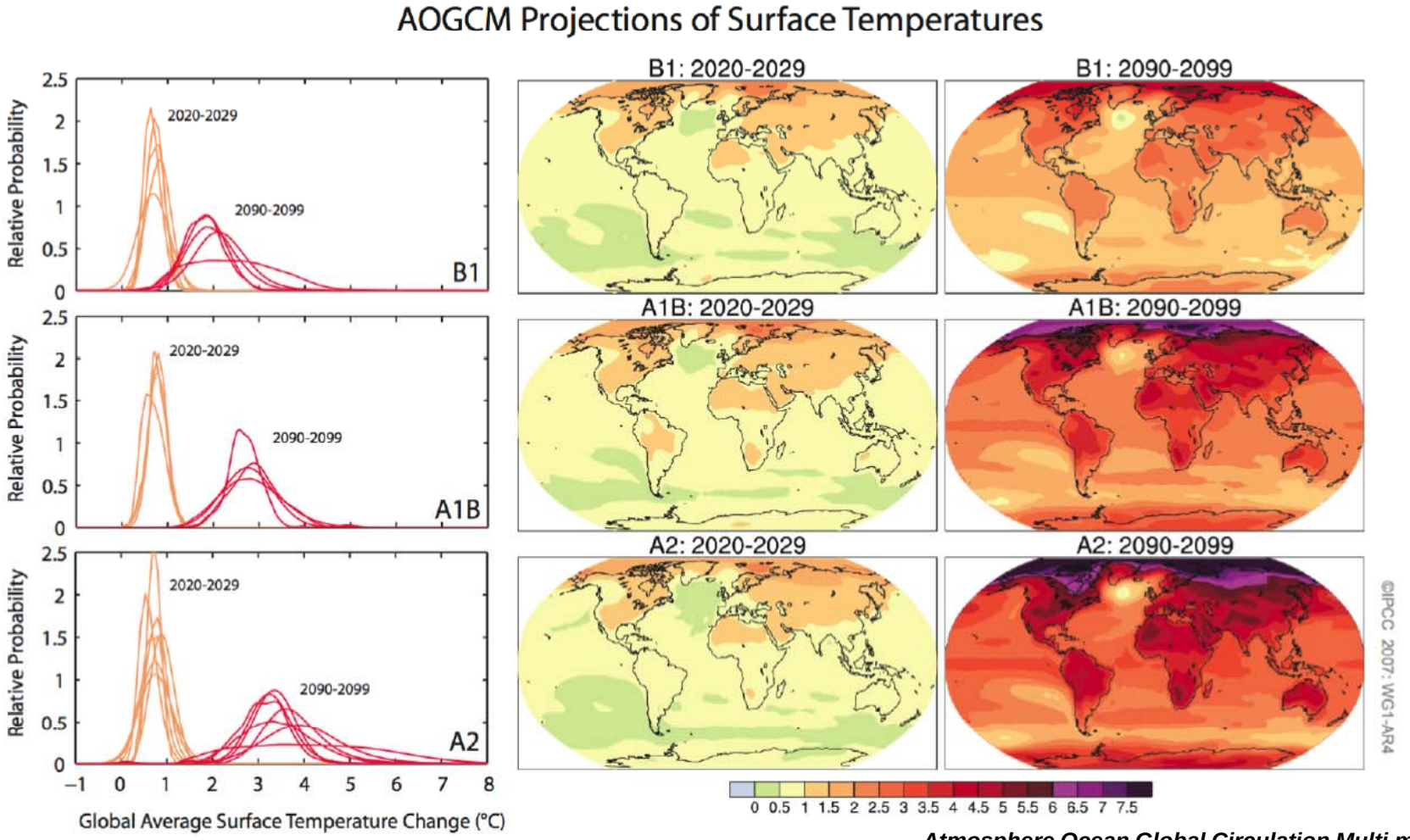


Temperature rise predictions



Source Meinhausen 2006

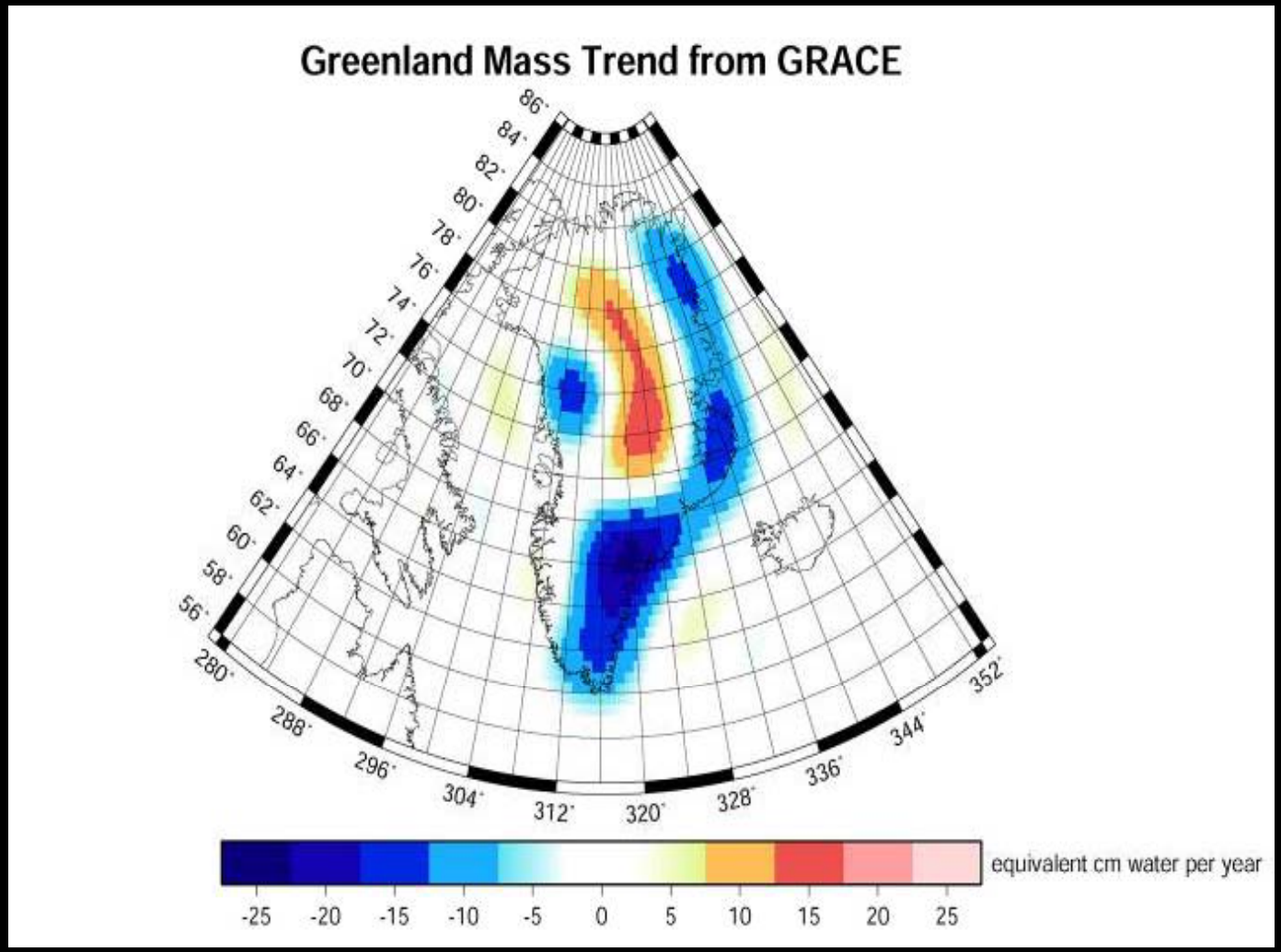
Local effects will be greater!



Atmosphere Ocean Global Circulation Multi model

Source - UNEP presentation on melting glaciers

Greenland Ice Sheet

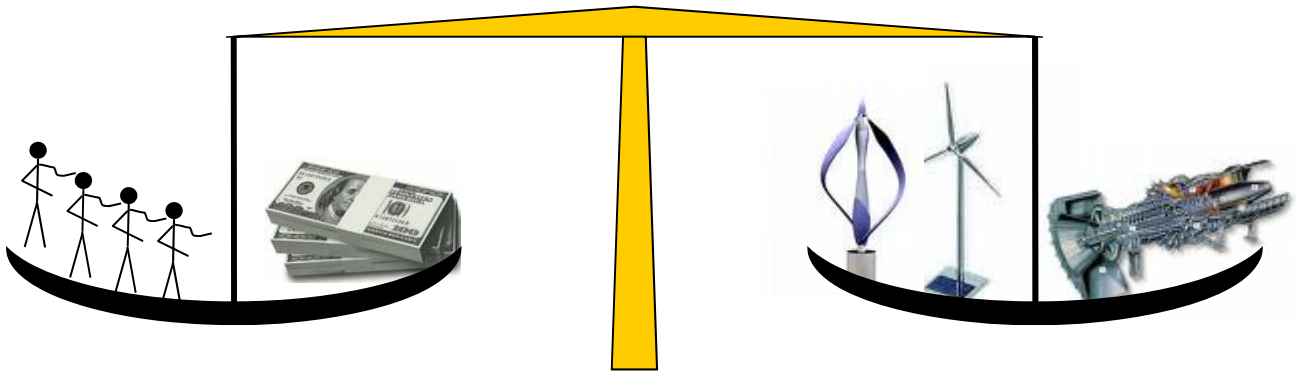


NASA Earth Observatory

Dramatic ice mass losses concentrated in the low-elevation coastal regions, with nearly half of the loss coming from southeast Greenland

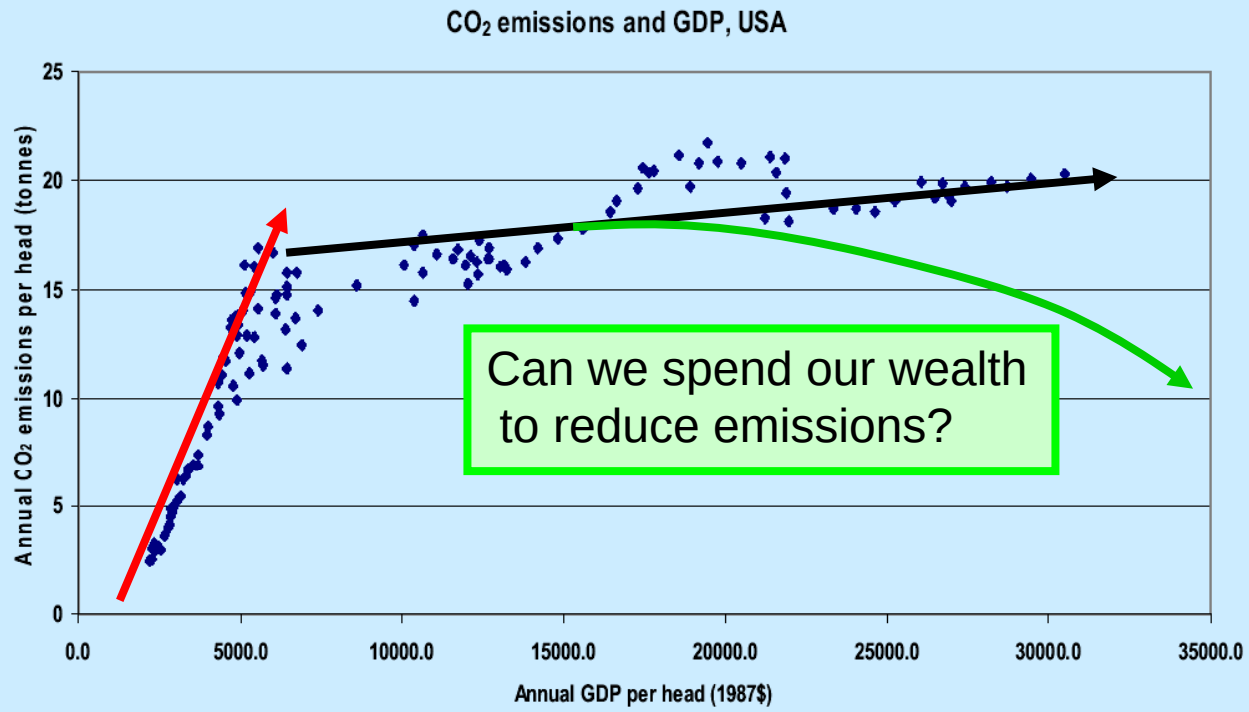
Technology v wealth & numbers

- Technology can cut GHG emissions
- Increased wealth tends to increase emissions – more heating, driving, flying etc.
- Increased numbers - increased emissions



Wealth increases emissions – up to a point

Figure 7.4 Annual emissions of CO_2 per head vs. GDP per head, USA



Source: Huntington (2005)

Technology can reduce emissions

- Some Big effects:-
  - LED light bulbs
  - Nuclear power
  - Hydropower, wind power, solar power ….
- Some Medium effects:-
  - Supercritical steam power plant
  - More efficient gas turbines
  - Home insulation, Hybrid cars …
- Some small effects
  - Blackle – for computer screens
  - Auto turn off of standby power to electronic devices …

Interim Conclusion

- We could spend some of our wealth on technology to reduce our GHG emissions

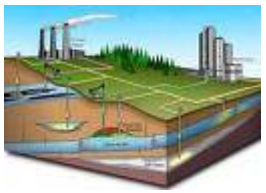
Renewable energy

Hybrid cars

Smart metering

Heat pumps

Energy efficiency



CCS

What are the options

Do nothing – but have to adapt to:-

- Sea level rise
- Temperature increase
- Rainfall change –drought/flood
- Storm severity
- Ice melt …….

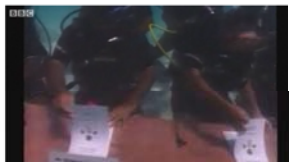
Take action

- Use less fossil fuel*
- Cut energy consumption
- More efficient energy use
- Carbon capture and storage

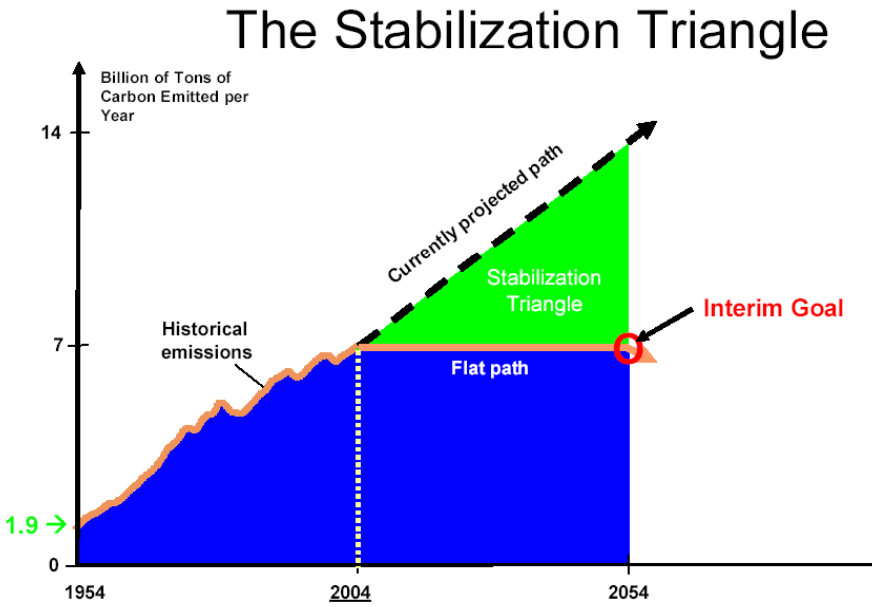
* By implication use more:-

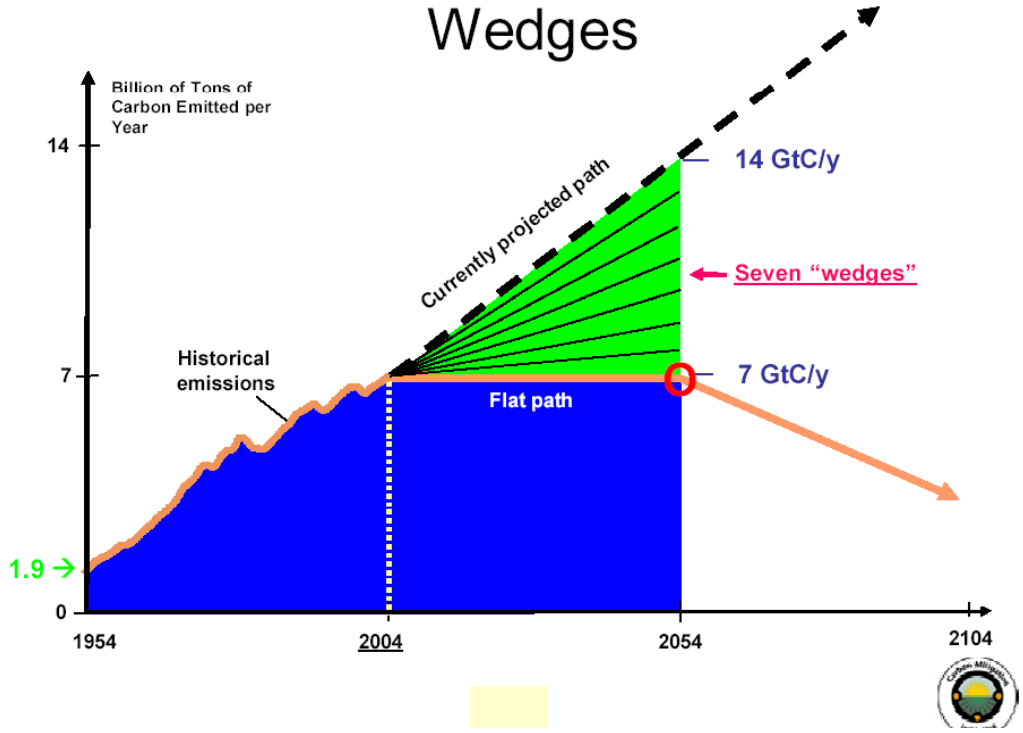
- Renewable energy
- Nuclear energy

Maldives cabinet makes a splash

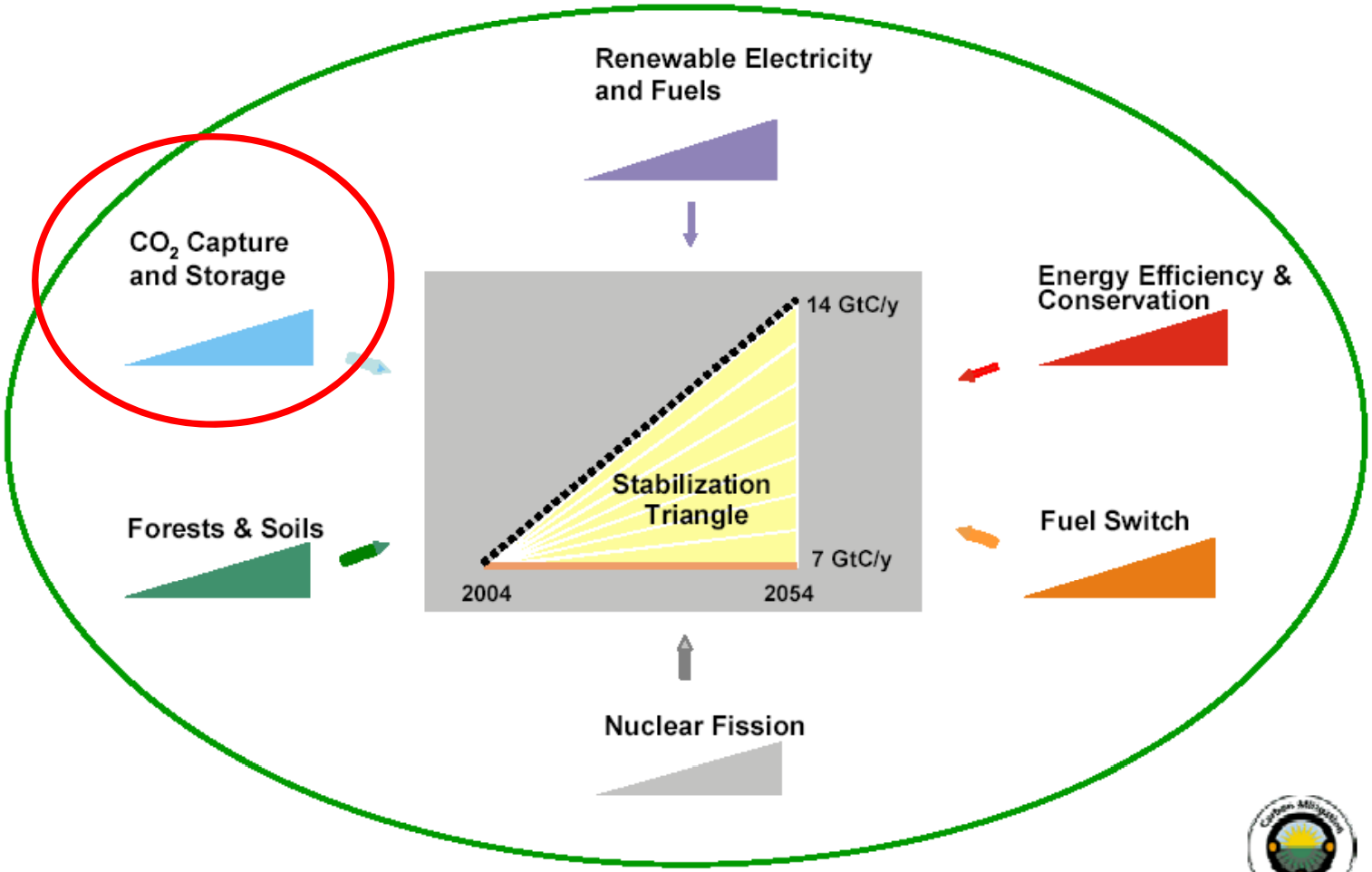


Stabilization wedges





Seven stabilization wedges – Socolow et al



CCS in context

- CCS is one of a number of initiatives which have to be implemented to prevent dangerous climate change
- Plans and road maps for its deployment are in development
- Organisations to foster its implementation have been set up

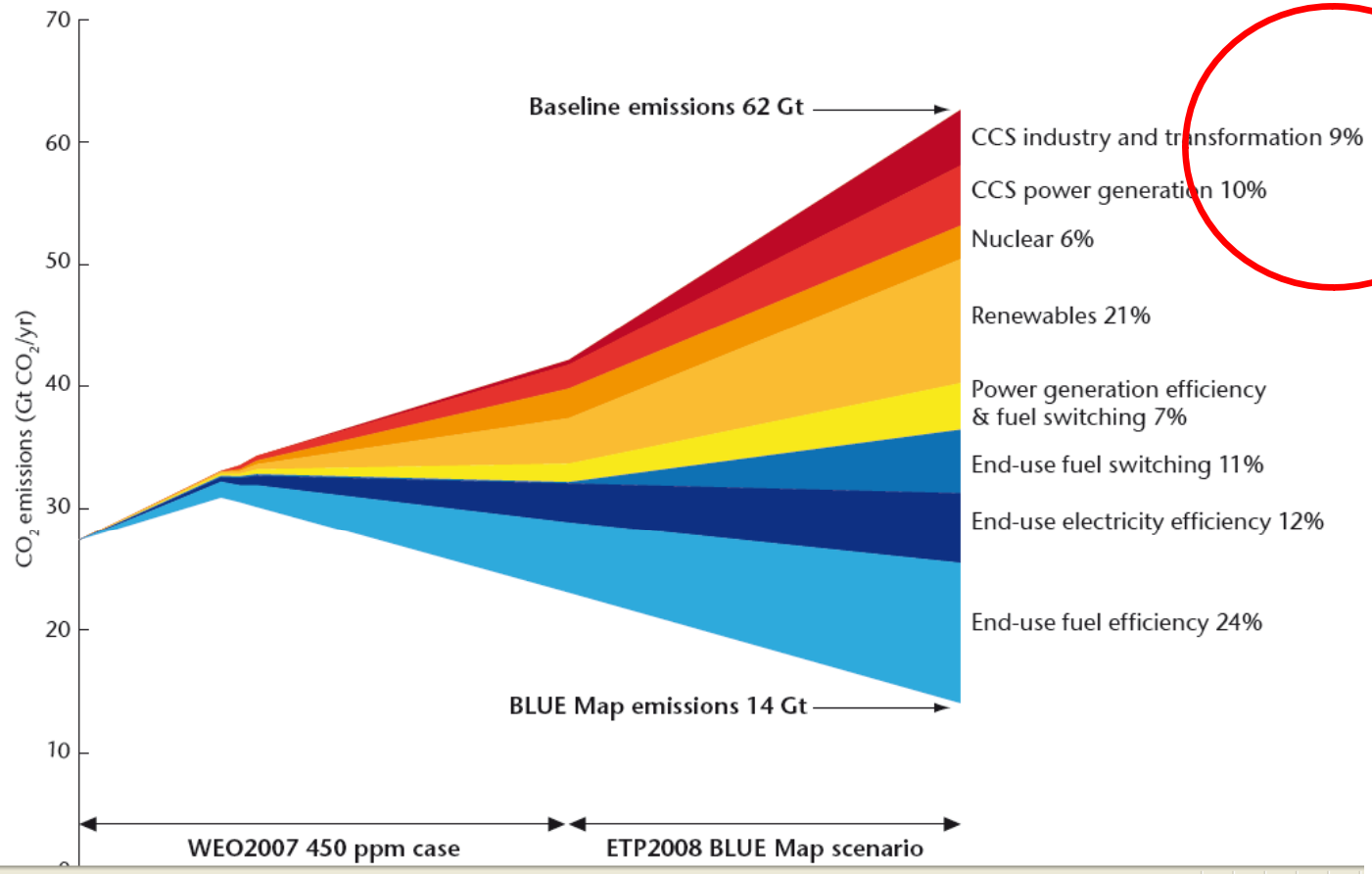
Plans

- EU call for 12 CCS technology demonstration projects
- US DOE $2.4 billion stimulus funds for energy of which $1.5 targets CCS
- IEA roadmap issued Oct 2009
  - 100 projects by 2020
  - 3000 projects by 2050

Latest IEA Roadmap 2009

Figure 1: CCS delivers one-fifth of the lowest-cost GHG reduction solution in 2050

CCS involved in 19%

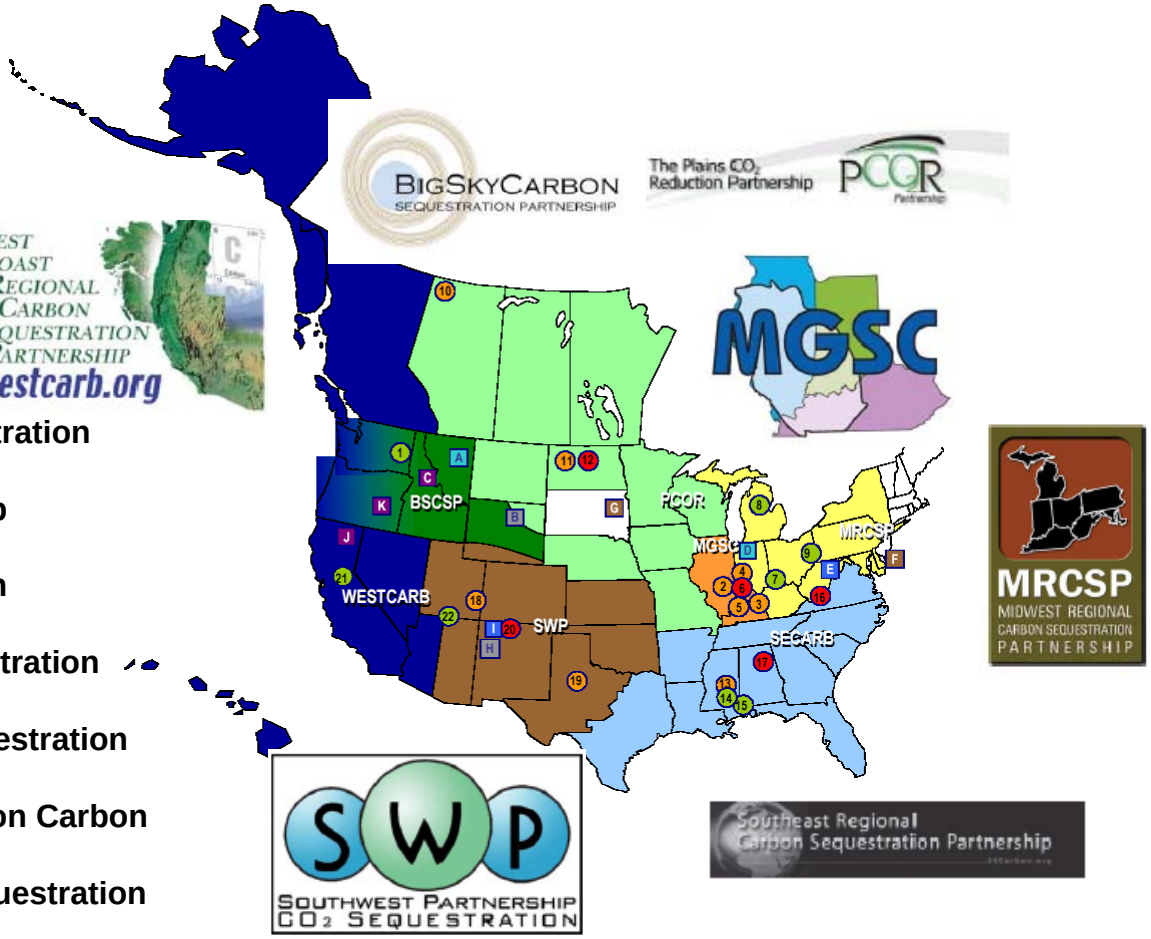


International Organisations

- IEAGHG R&D programme (1991)
- CSLF (2003)
- Asia-Pacific partnership on clean development and climate
- CCSA (2006) *UK based trade association*
- GCCSI (2009)

Organisations -continued

- US regional partnerships



- Big Sky Regional Carbon Sequestration Partnership (Big Sky)
- Plains CO2 Reduction Partnership (PCOR)
- Midwest Geological Sequestration Consortium (MGSC)
- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Southeast Regional Carbon Sequestration Partnership (SECARB)
- Southwest Regional Partnership on Carbon Sequestration (SWP)
- West Coast Regional Carbon Sequestration Partnership (WESTCARB)

Imperatives for CCS

- Global dependency on fossil fuel
- Low cost option compared with many others
- High capacity option (whilst storage resources last)
- Rapid implementation is technically feasible

Favourable for CCS

- Relatively safe
- Relatively low environmental impact
- Elimination virtually all gaseous emissions is possible
- Can be retrofitted (although expensive and inefficient to do so)
- Potential lead in to Hydrogen economy
- Skilled staff exist (but many more needed)

Barriers to CCS

- Proving security of storage sites
- Regulations not fully in place
- Not yet recognised under Kyoto CDM or JI mechanisms
- Public resistance at some land storage sites
- Increased consumption of fuel
- It is an interim measure, some do not support it as it rivals renewable energy

Potential show stoppers for CCS

- Lack of sufficient storage capacity
- Inability to demonstrate long term security of storage
- Incidents which result in severe adverse publicity

I wish you all a very enjoyable and interesting summer school

CARBON CAPTURE AND STORAGE OVERVIEW

by

Monica Lupion

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

16th November 2009. Hassi Messaoud (Algeria)

*Corresponding Author's Email: m.lupion@ciuden.es

CIUDEN: FUNDACION CIUDAD DE LA ENERGIA

An initiative of the Spanish Administration

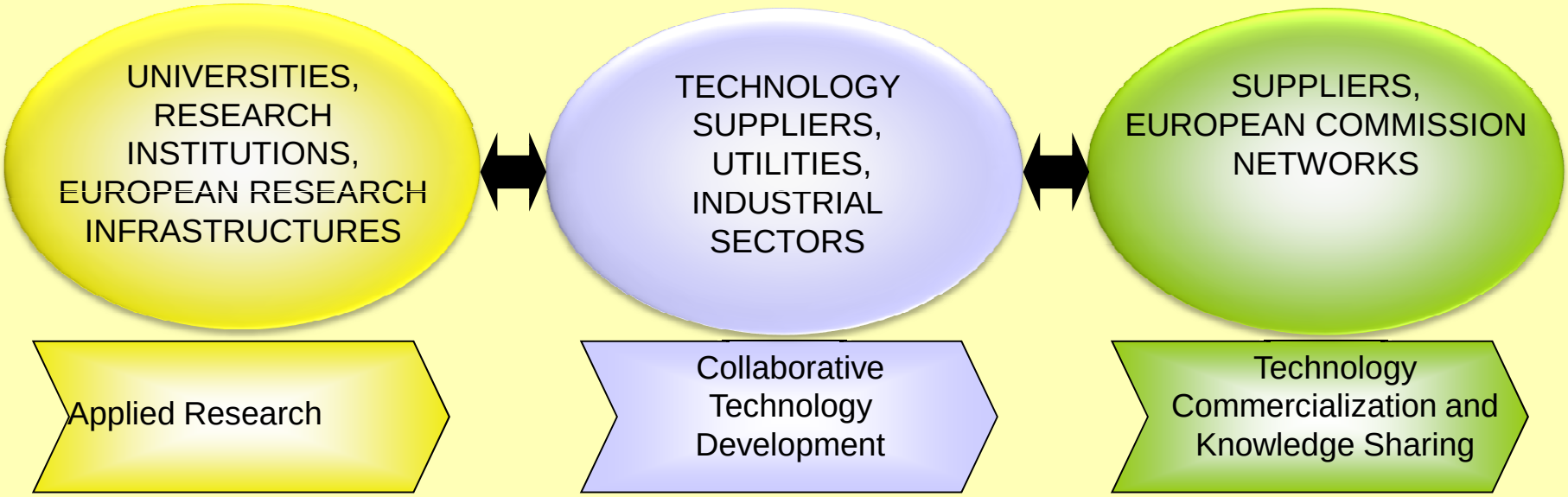
CIUDEN: FUNDACION CIUDAD DE LA ENERGIA

Promote and financially support R&D+D for CO_2 capture and storage technologies and abandoned mines restoration

PROGRAM A	PROGRAM B	PROGRAM C
TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES	CO_2 GEOLOGICAL STORAGE	ABANDONED LAND ACTION PLAN
ADDRESSING	ADDRESSING	ADDRESSING
OXYFUEL AND POST-COMBUSTION TECHNOLOGIES AT EL BIERZO	FULL SIZE INJECTION TESTS IN SUITABLE GEOLOGICAL FORMATIONS IN SPAIN	RESTORATION OF LAND RESOURCES THROUGH REVEGETATION FOR LANDSCAPE RECOVERY

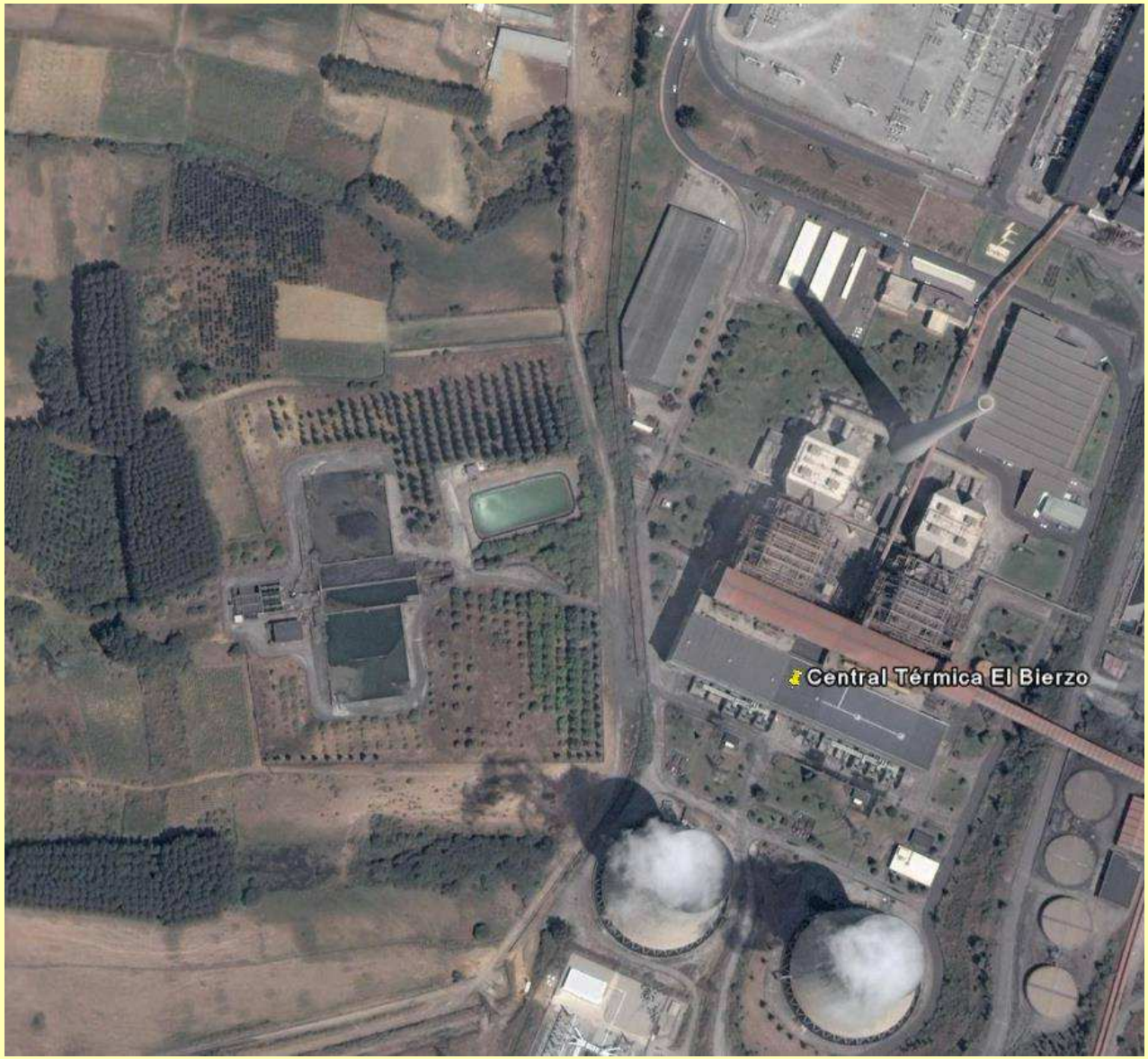
CIUDEN: FUNDACION CIUDAD DE LA ENERGIA

To create and manage a world-wide reference center for CCS & CCT development



A DEFINITIVE CO_2 CAPTURE, TRANSPORT AND STORAGE PROJECT FOR TECHNOLOGY DEVELOPMENT

CIUDEN: FUNDACION CIUDAD DE LA ENERGIA



CIUDEN: The Site

Scope

I. The importance of Fossil Fuels and CCS

II. What does Carbon Capture and Storage means?

III. Why Geological Storage of CO_2?

IV. Which are the challenges for CCS deployment?

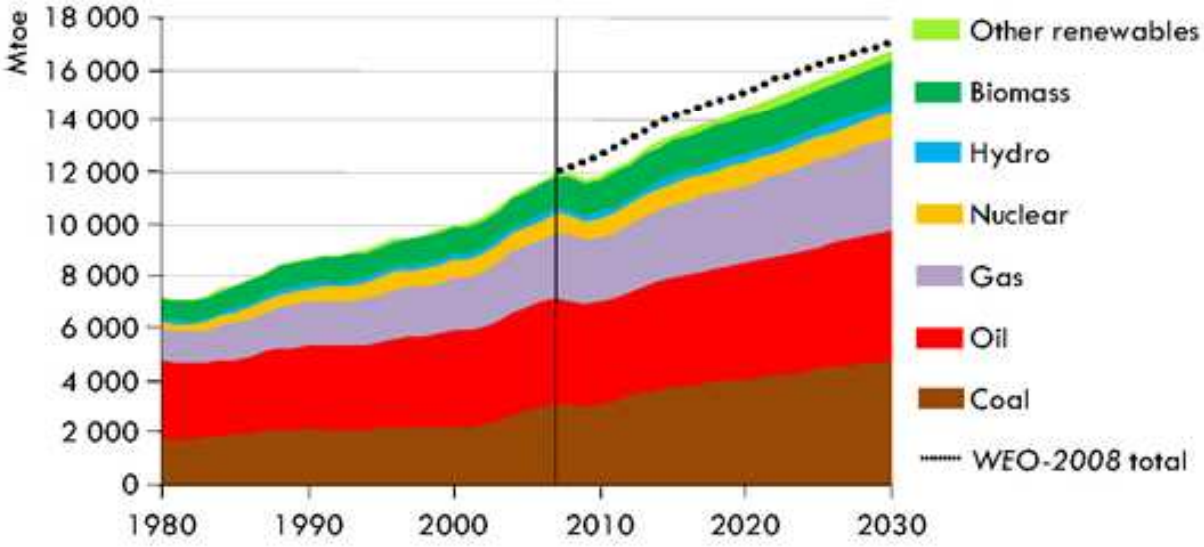
V. Concluding remarks

The importance of fossil fuels and CCS

Why fossil fuels are so important?

World Energy Outlook 2009

World primary energy demand by fuel in the Reference Scenario



Global demand grows by 40% between 2007 and 2030, with coal use rising most in absolute terms

© OECD/IEA - 2009

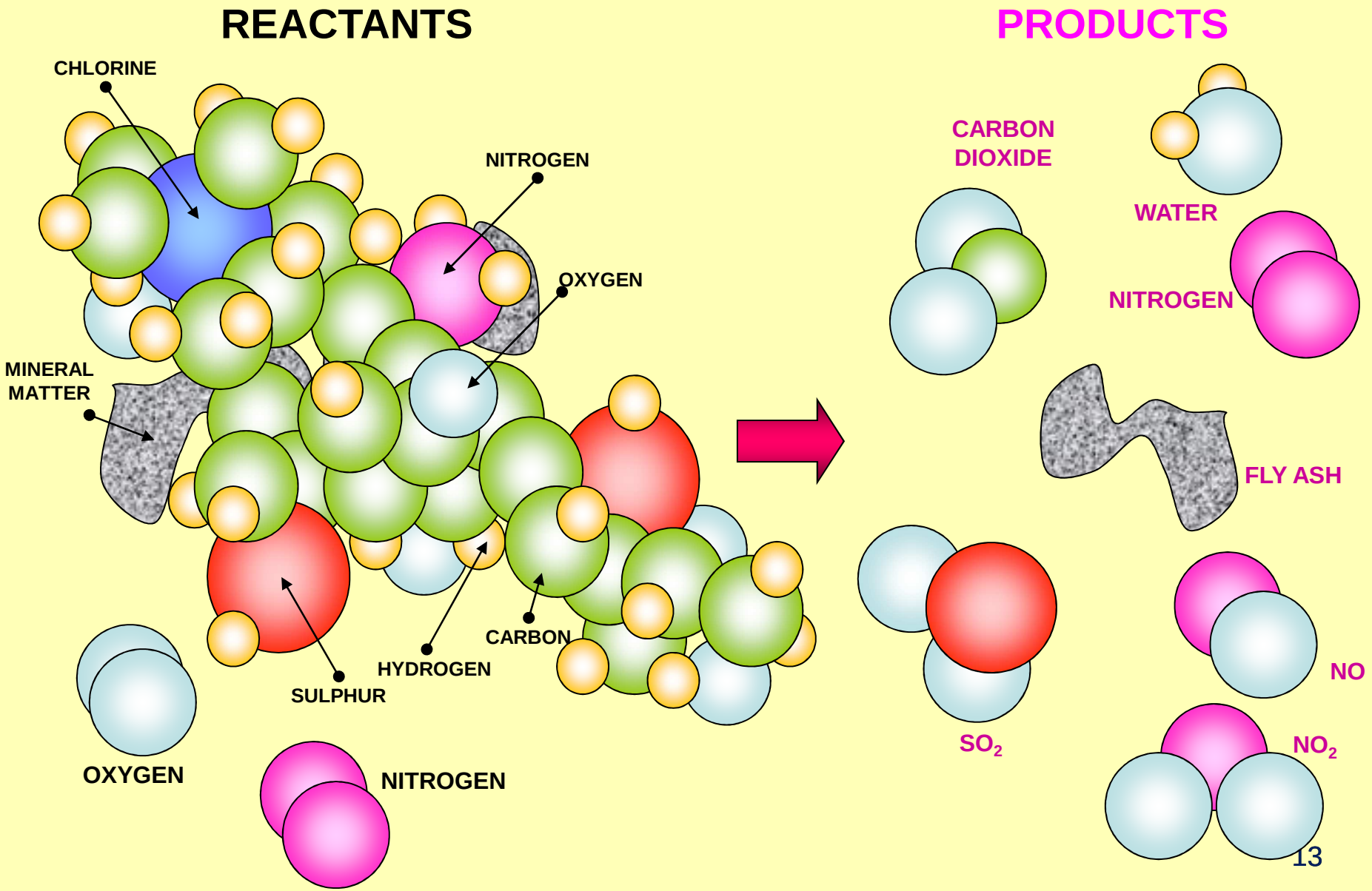
Comparison of primary energy sources for power generation

CRITERIA / PRIMARY ENERGY	SECURITY OF SUPPLY	ENVIRONMENTAL IMPACT	COMPETITIVE PRICES	SOCIAL ACCEPTANCE
RENEWABLES	★	★★★	★	★★★
NUCLEAR	★★★	★★	★★★	★
OIL	★★	★	★	★★★
GAS	★★	★★	★	★★★
COAL	★★★	★	★★	★

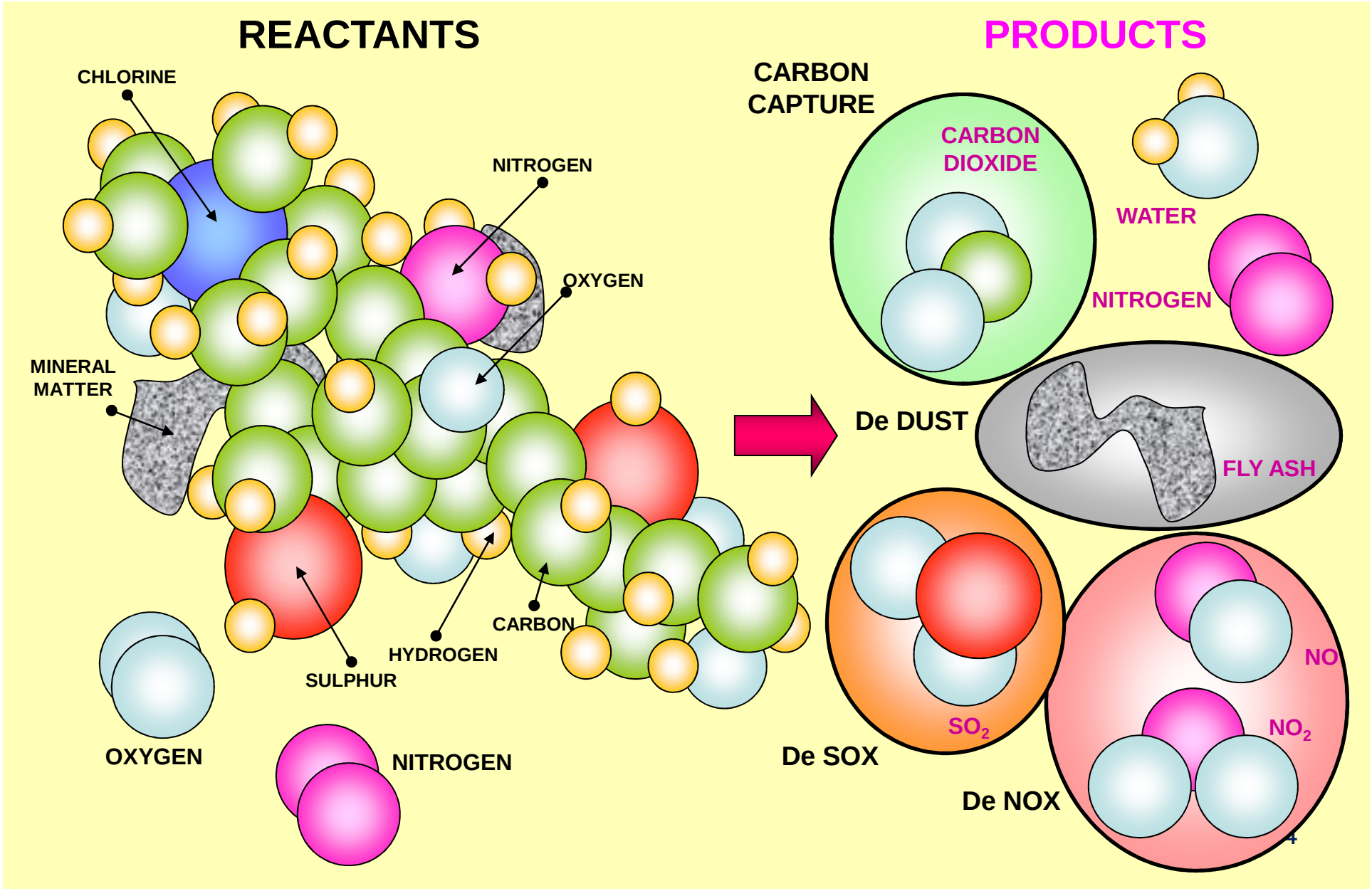
The early times of industry

How power generation is today

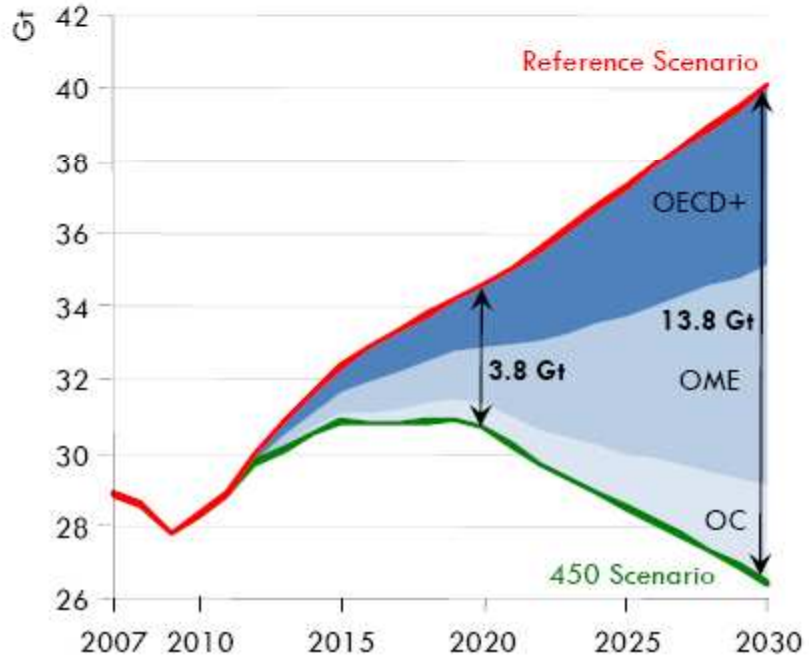
The process of coal combustion

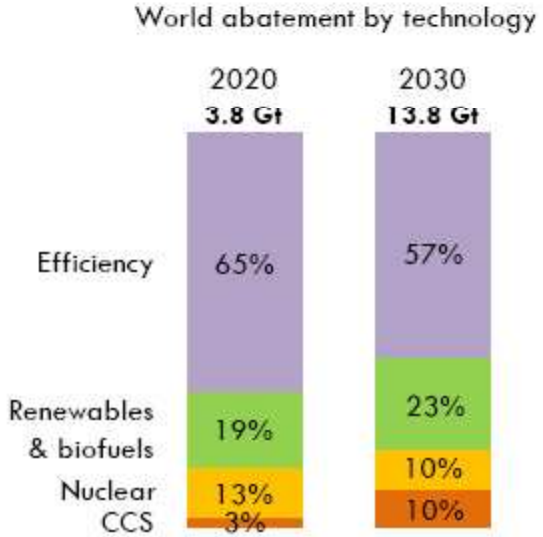


The cleaning of flue gases from coal combustion



CCS as part of the solution portfolio





The aim is a global CCS project Portfolio

- Gas Processing and EOR
  - ➢ Duplicating existing projects

- Coal Gasification for Chemicals or Liquids
  - ➢ Retrofit existing plants

- Coal and Gas Power Projects
  - ➢ New plants and retrofits

Adapted from Koppe. 2009 IEA GHG CCS Summer School

Carbon Capture and Storage
VALUE CHAIN

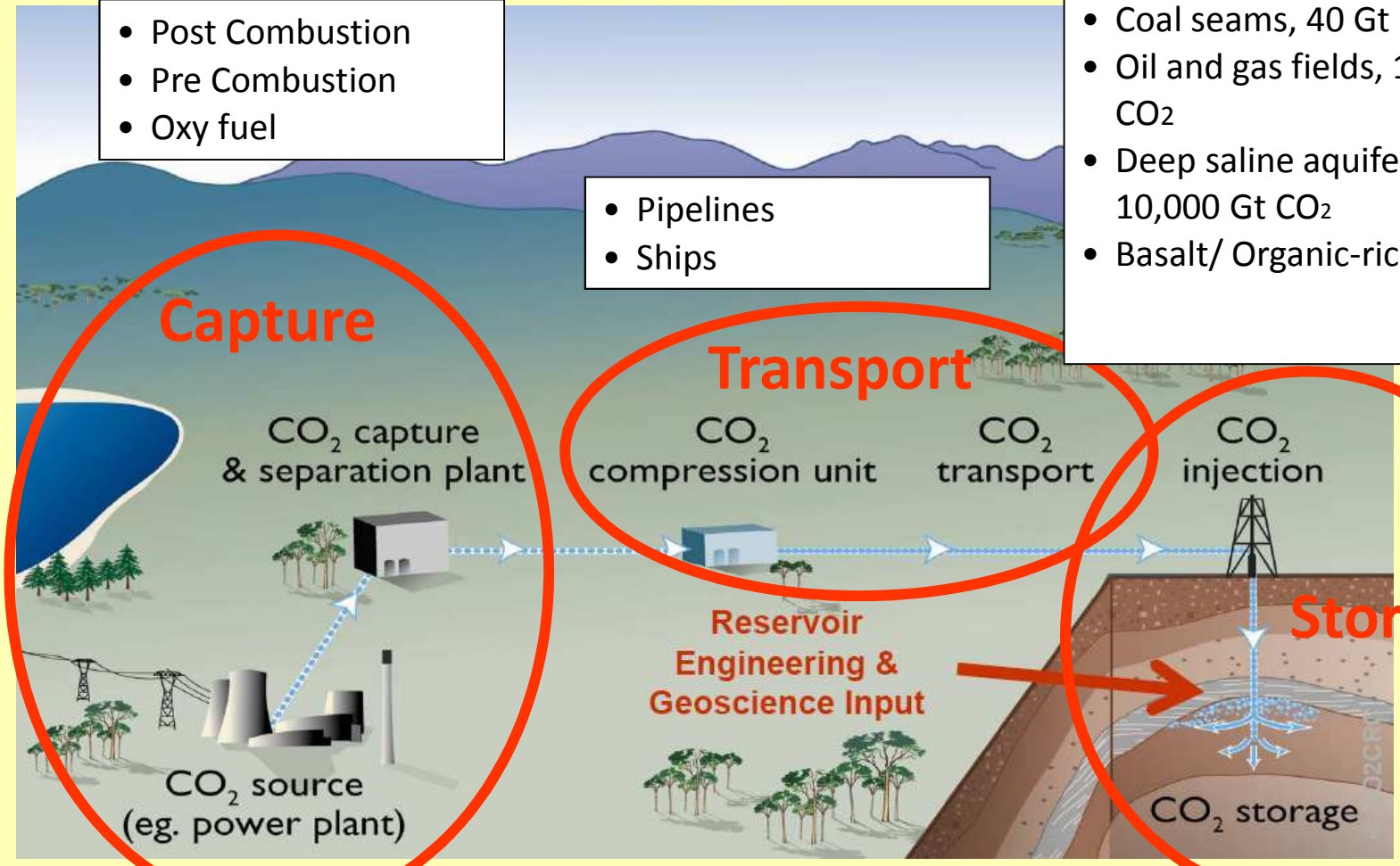
CO_2 separation

Compression

Transport

Injection

CO2 Capture and Storage



A sense of Scale

✓ **HOW MUCH CO_2 IS EMITTED?**

- **400 MW (net) NGCC -> 1.4 Mpta of CO_2**
- **500 MW (net) SC PC -> 3.5 Mtpa of CO_2**

✓ **HOW BIG ARE THE PIPELINES?**

- **For 3.6 Mtpa about 12 inch ID (30 cm aprox)**
- **For 50 Mtpa about 28 inch ID (70 cm aprox)**

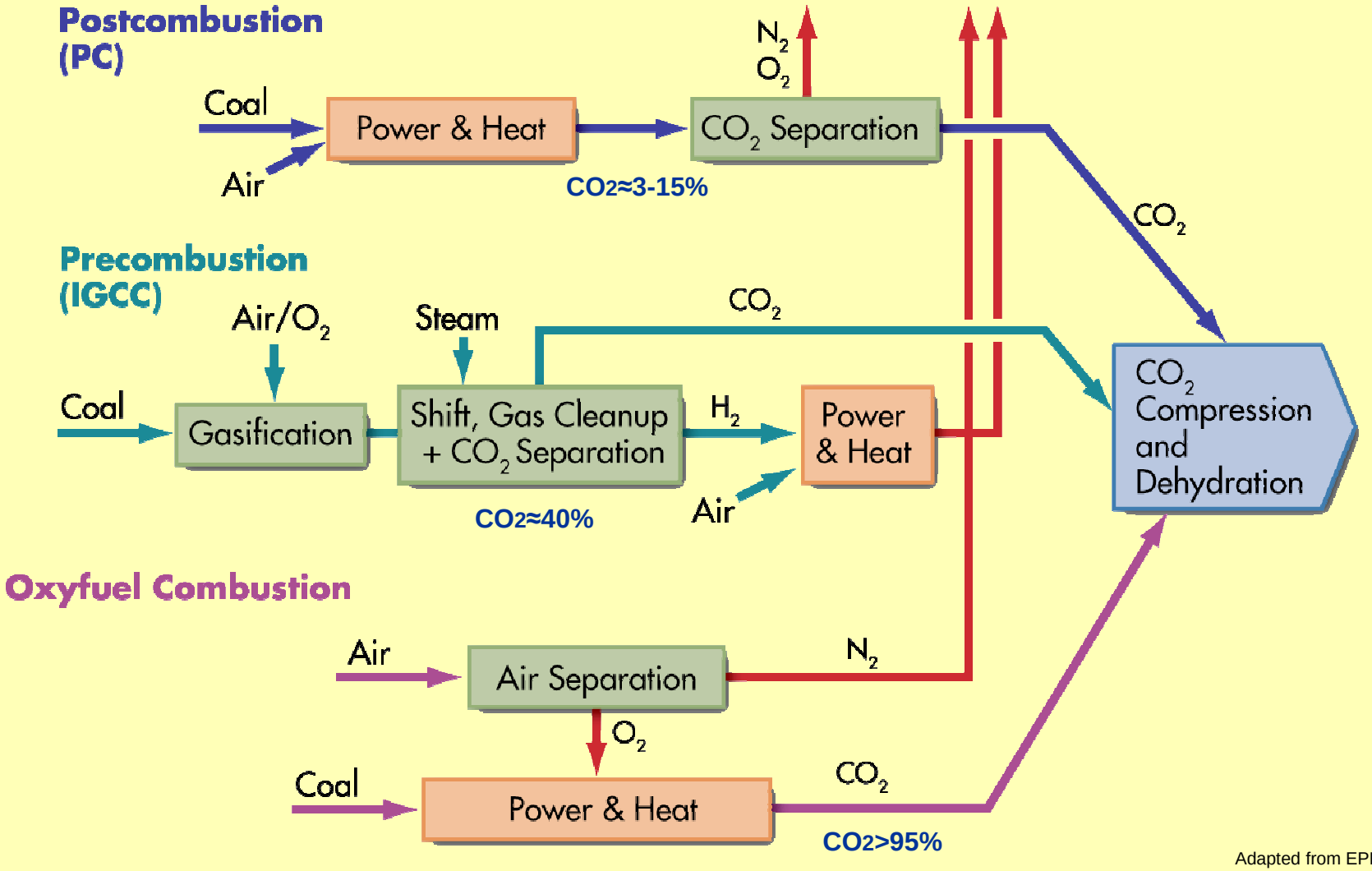
✓ **HOW LARGE IS A GIGA-TONNE?**

- **About 320 500MW PC plants**

Adapted from Gerdes. 2009 IEA GHG CCS Summer School

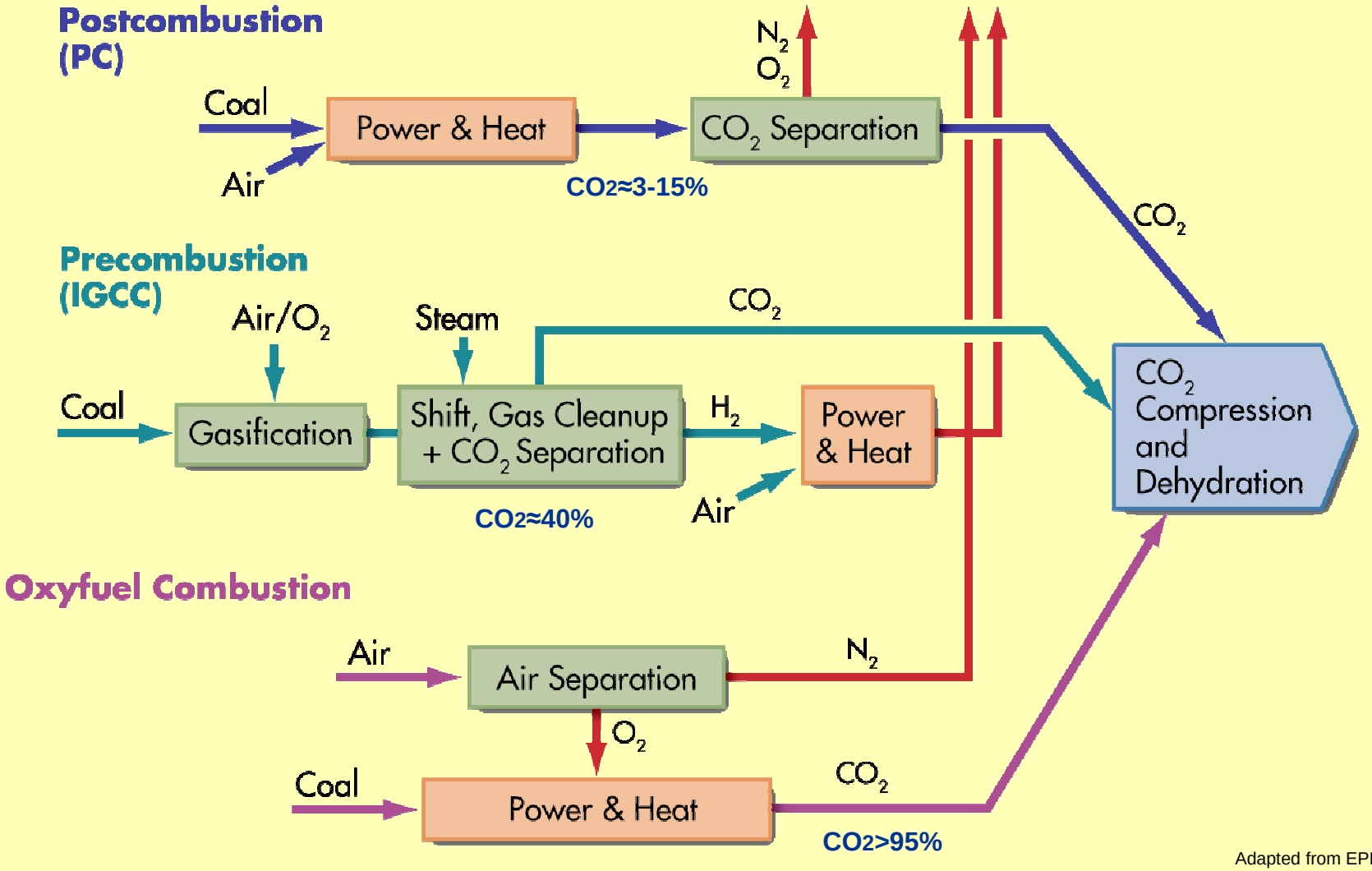
Capture technologies

General Overview of CCS technologies



Adapted from EPRI 2007

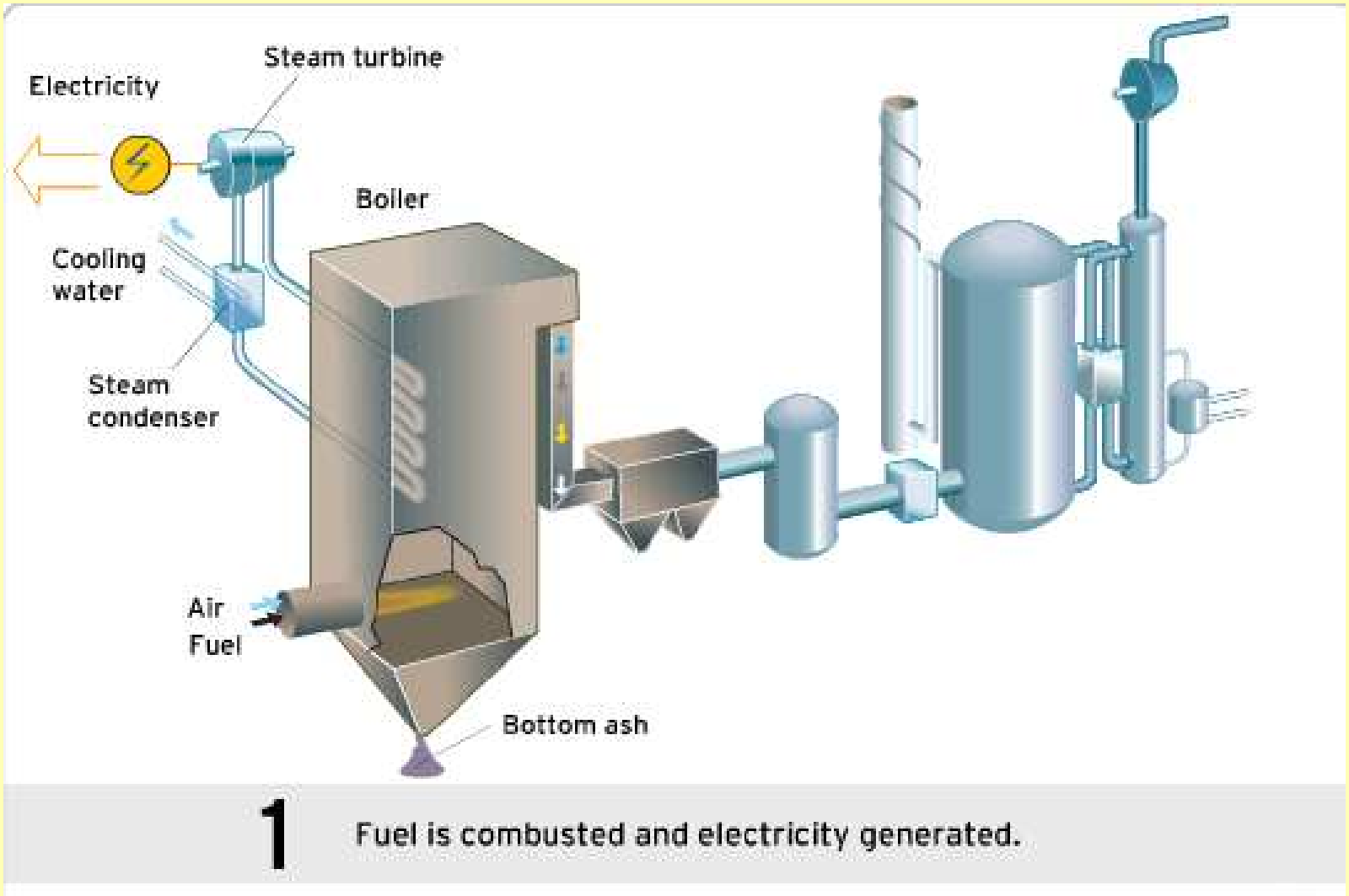
General Overview of CCS technologies



Adapted from EPRI 2007

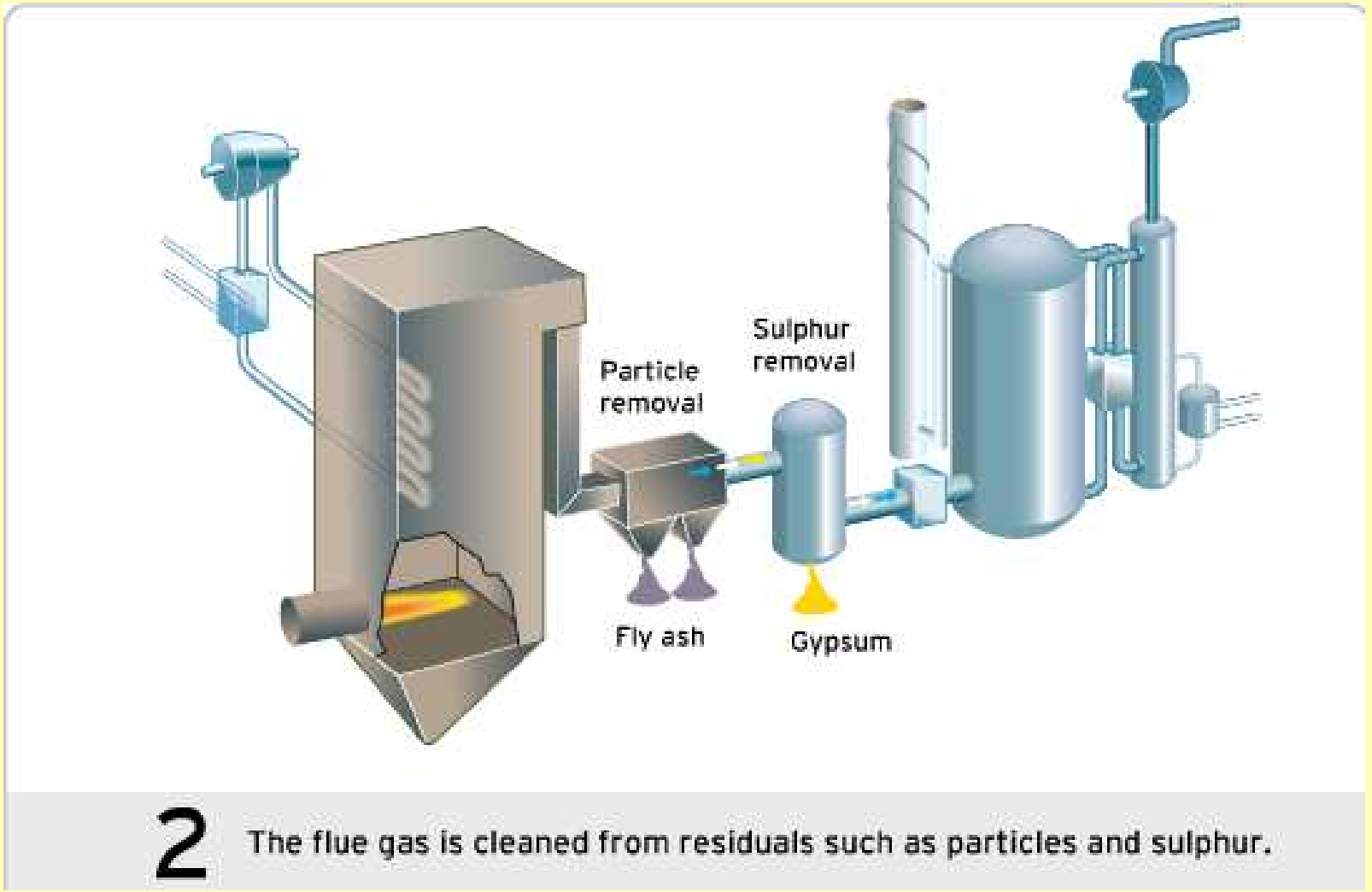
NO SILVER BULLETS!

A little bit of technology: POSTCOMBUSTION



Source: VATTENFALL

A little bit of technology: POSTCOMBUSTION



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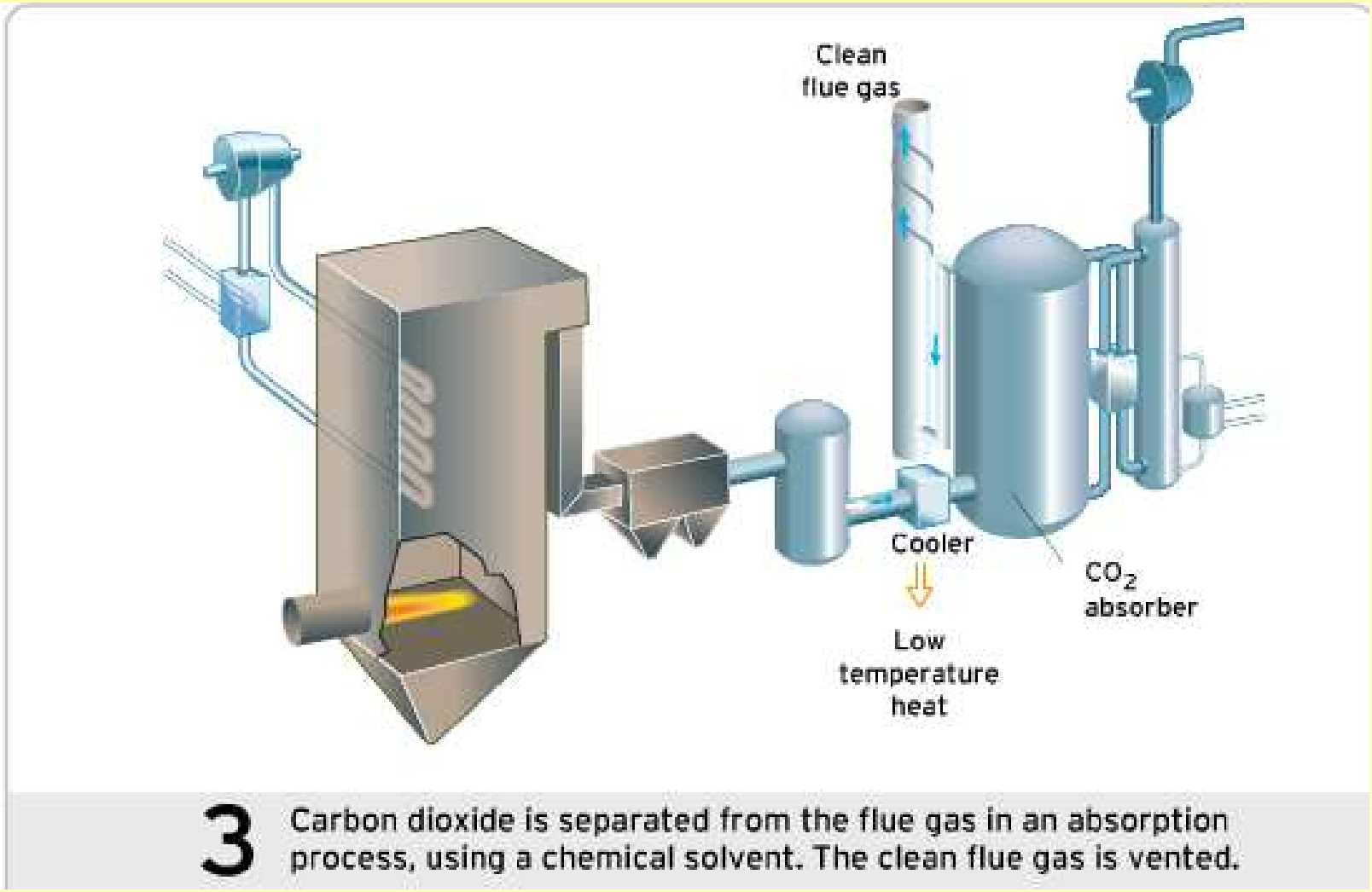

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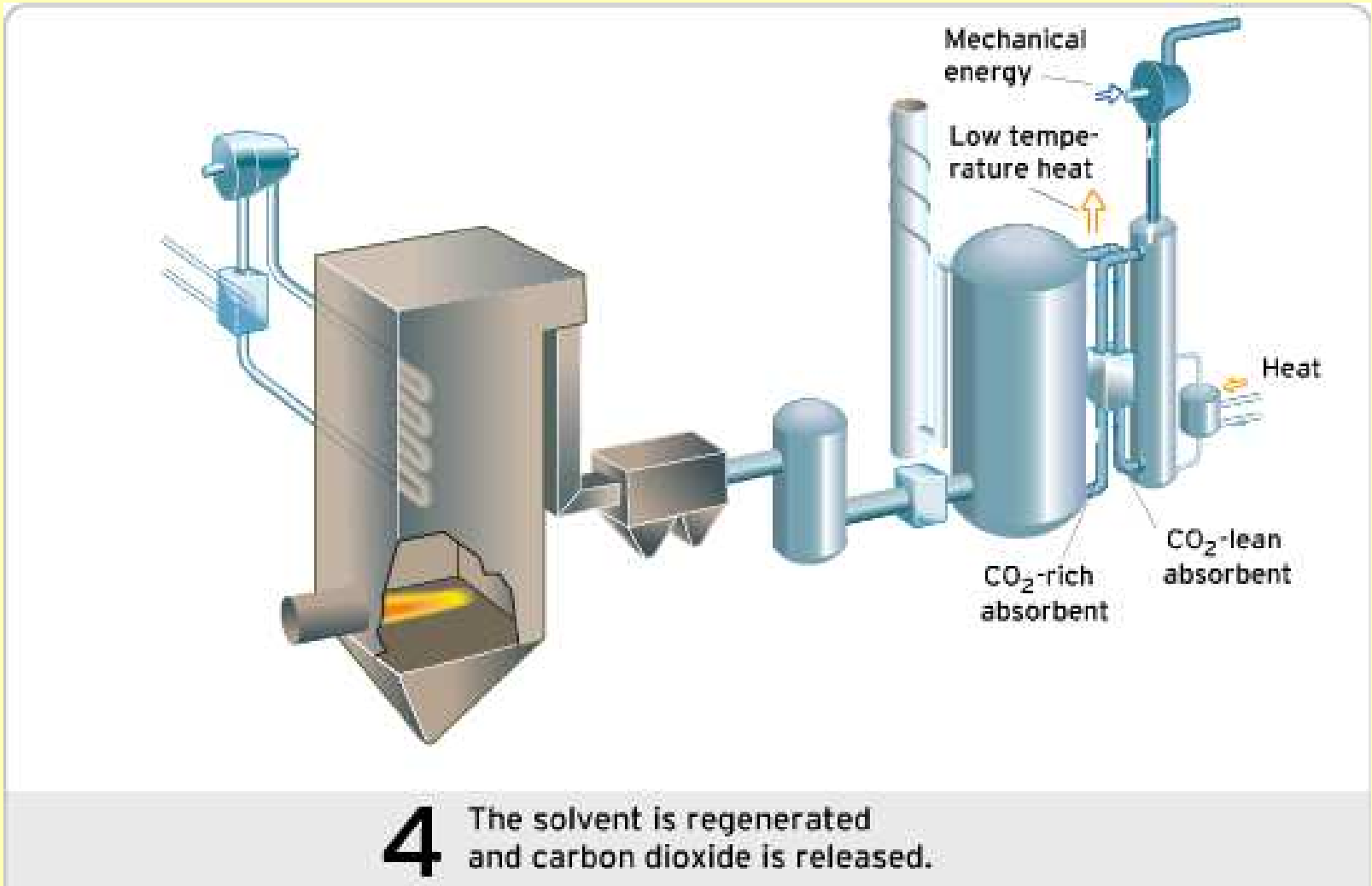
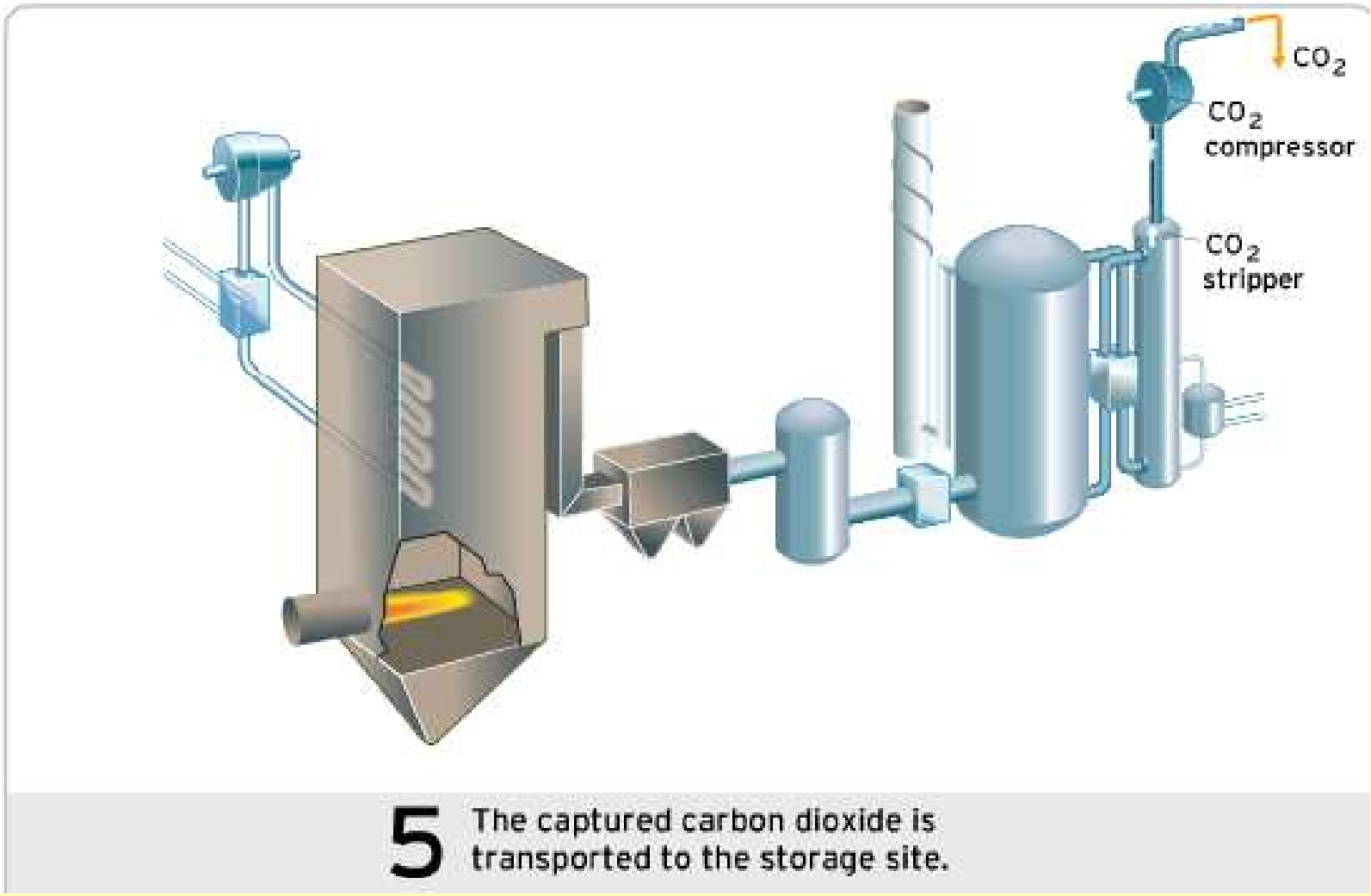


Source: VATTENFALL

A little bit of technology: POSTCOMBUSTION



Source: VATTENFALL

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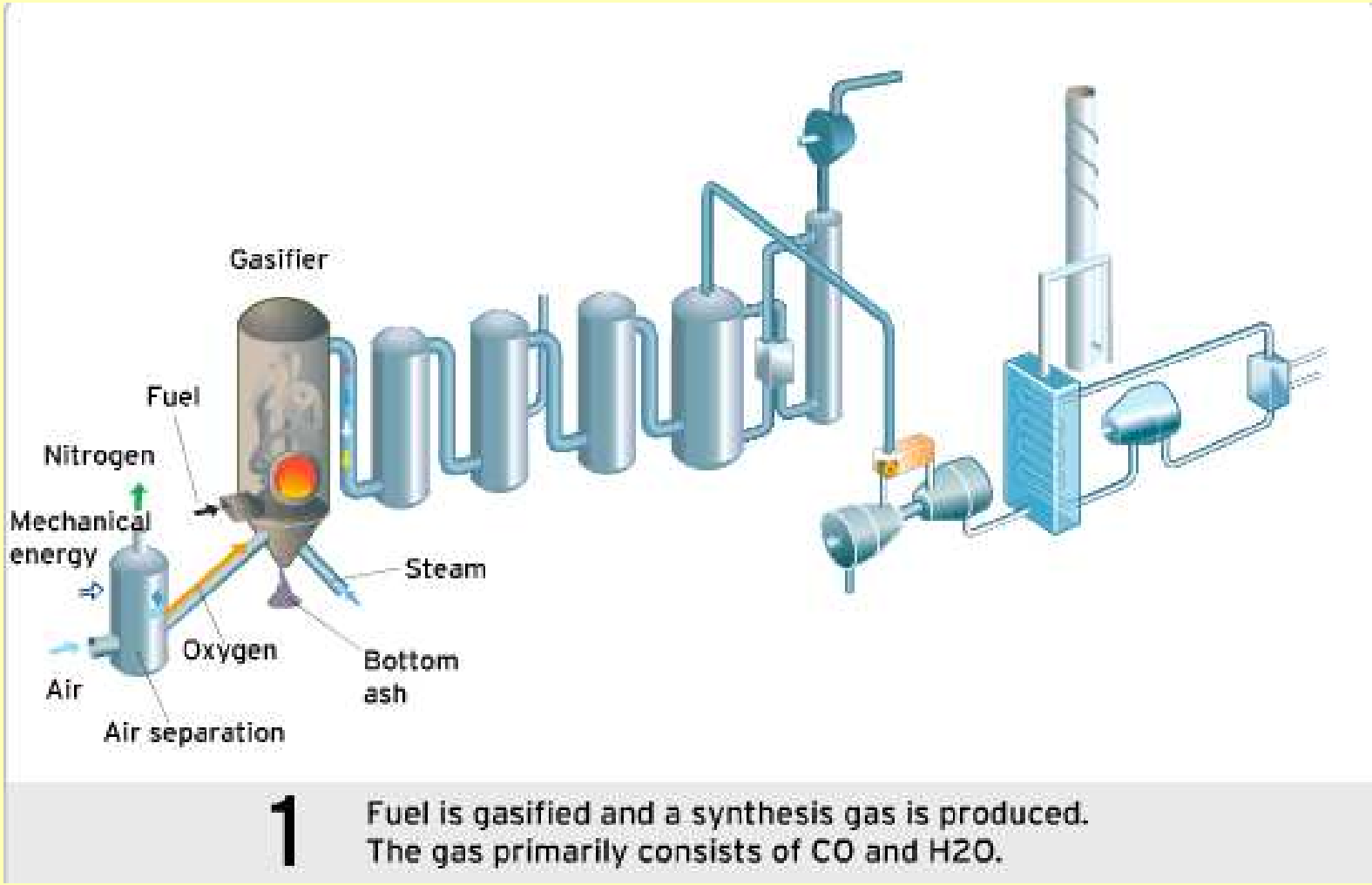
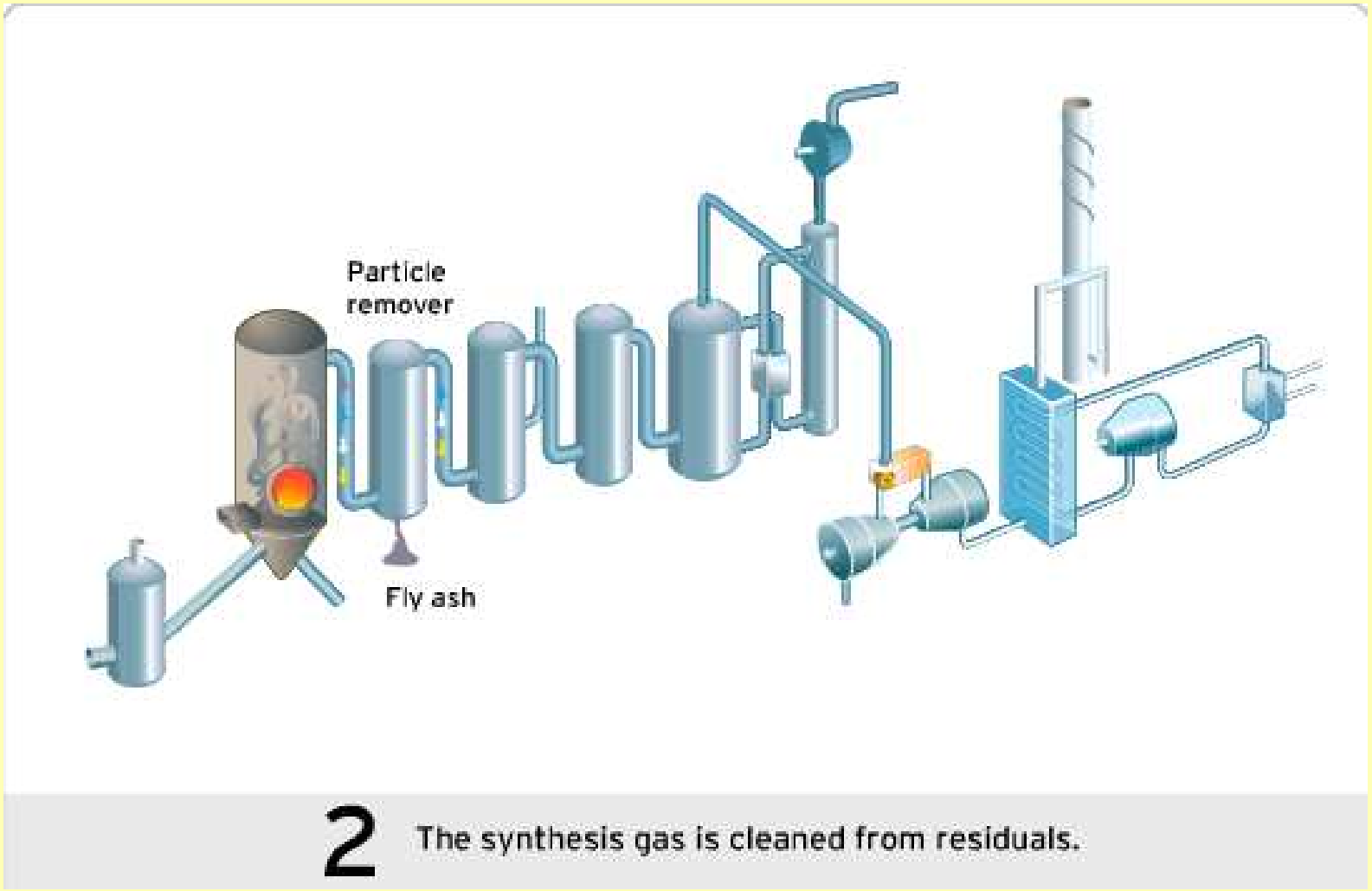


Source: VATTENFALL

A little bit of technology: PRECOMBUSTION



Source: VATTENFALL

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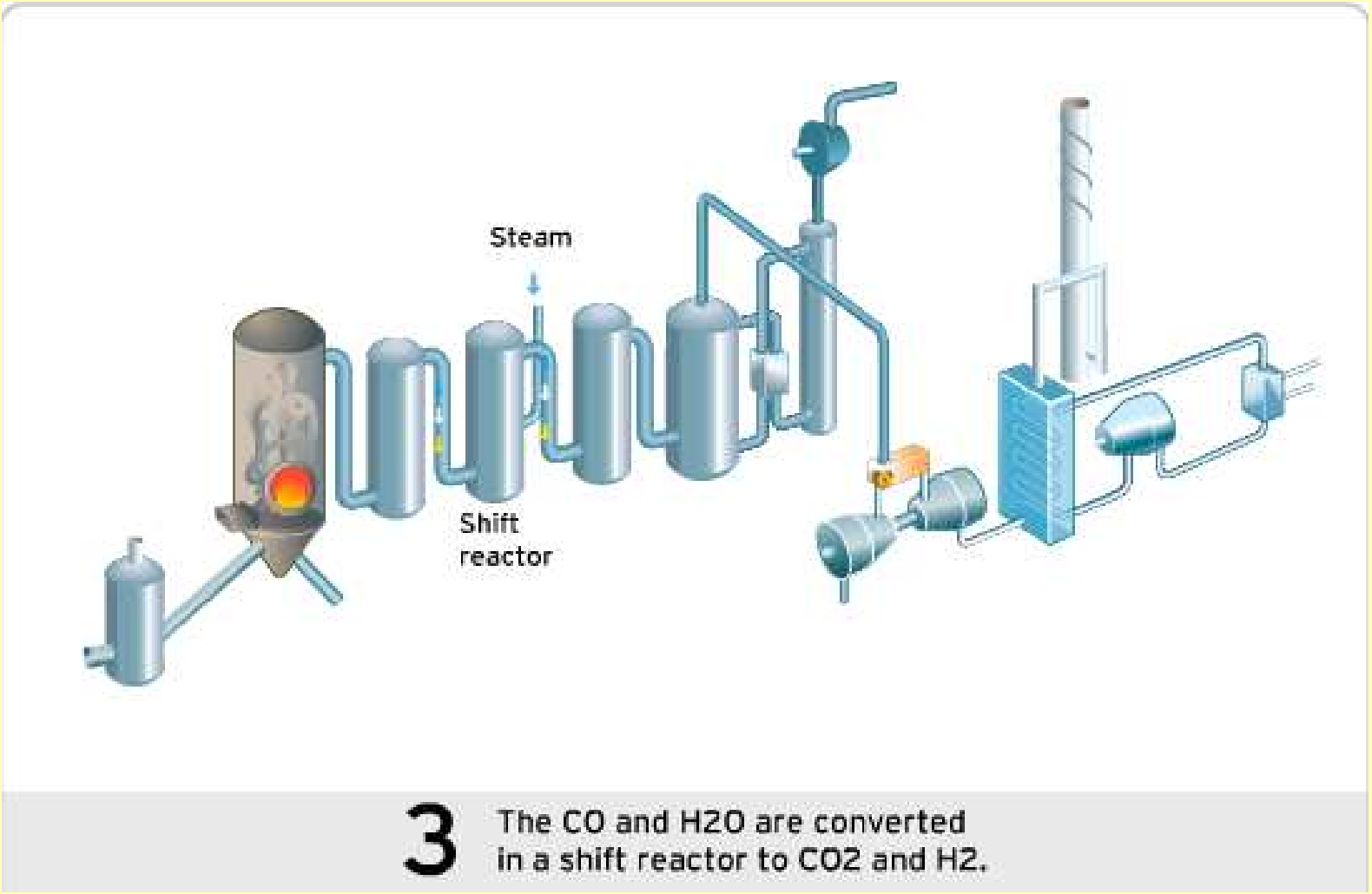

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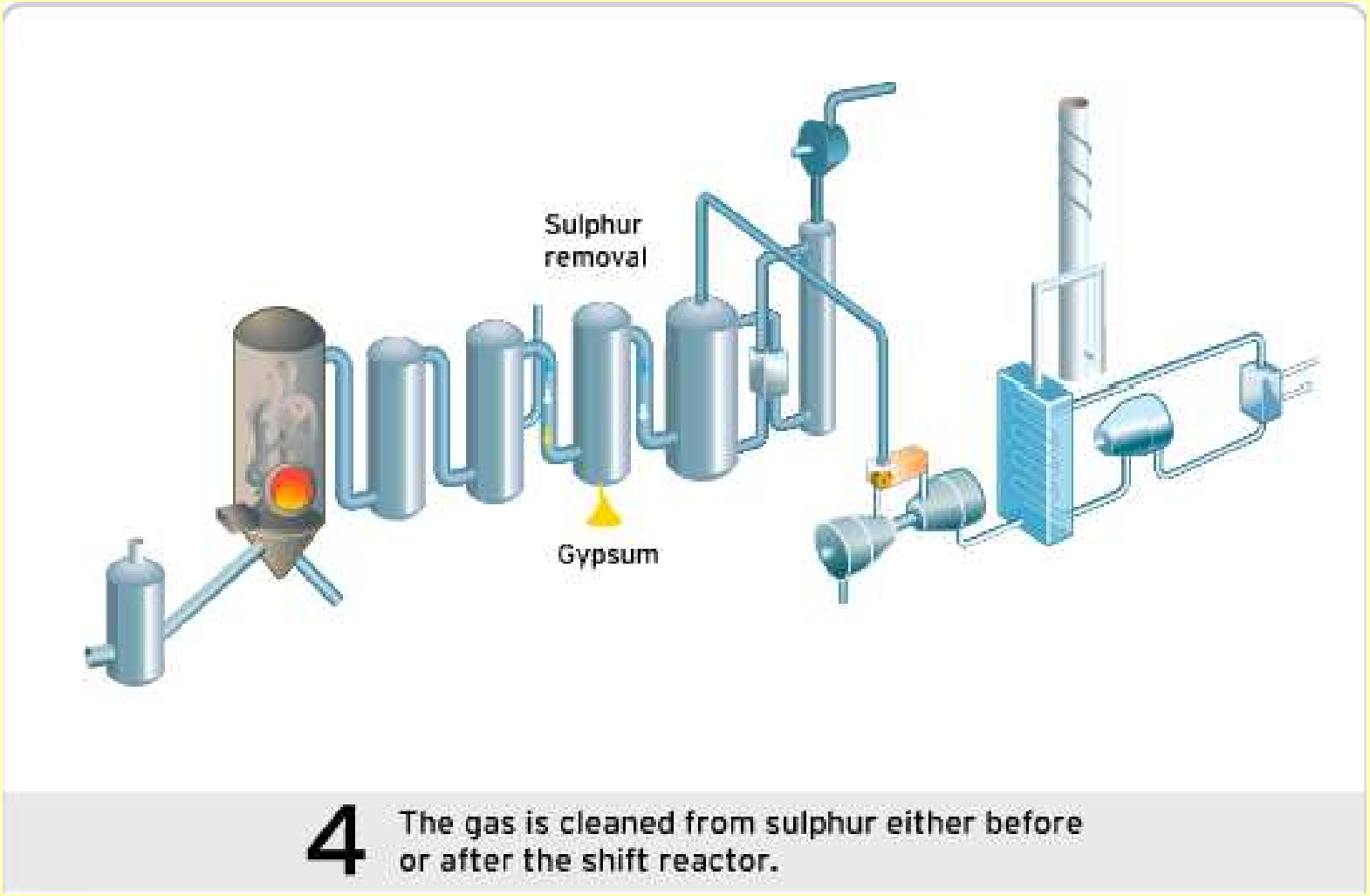

Source: VATTENFALL

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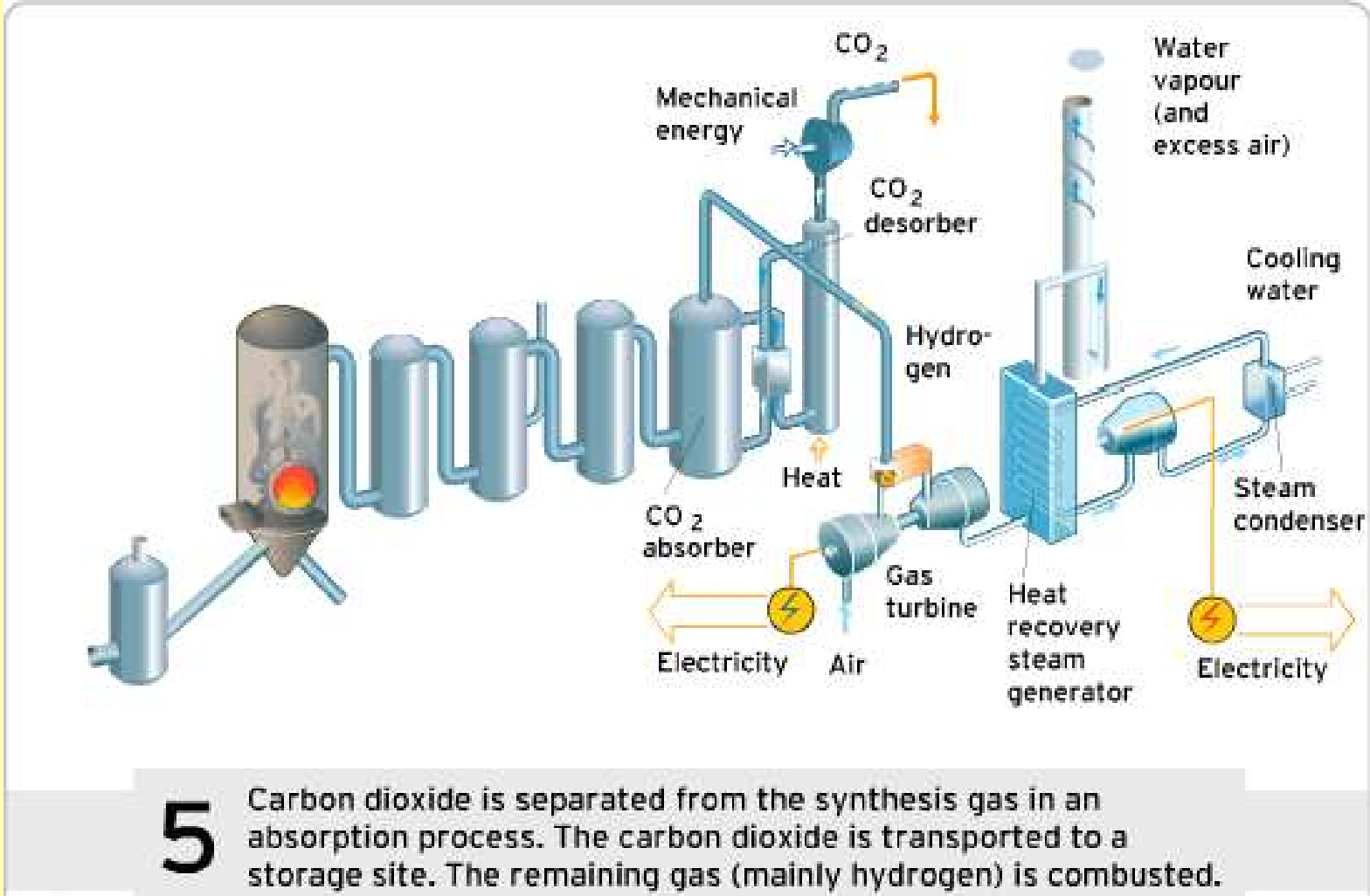
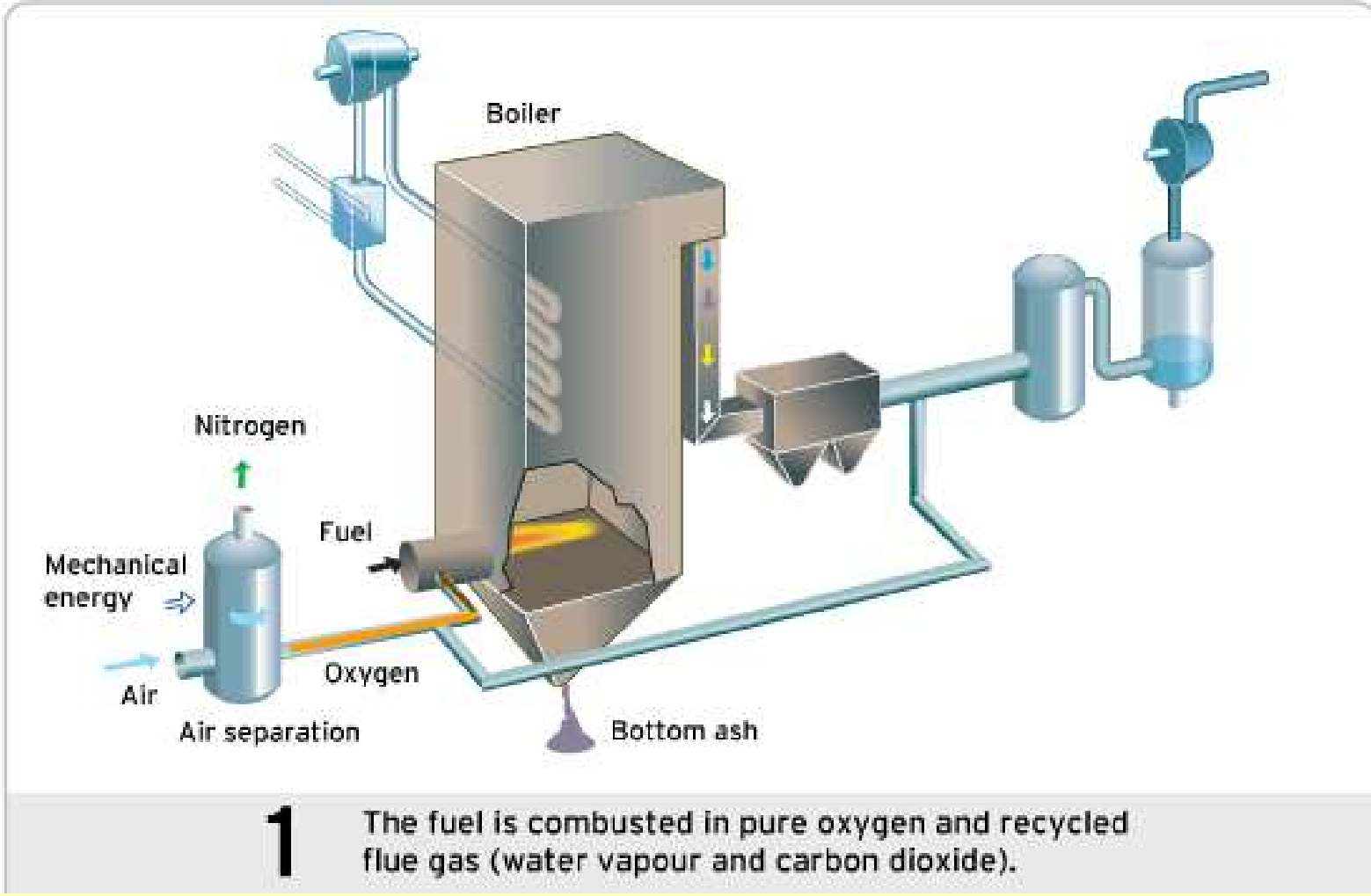


5 Carbon dioxide is separated from the synthesis gas in an absorption process. The carbon dioxide is transported to a storage site. The remaining gas (mainly hydrogen) is combusted.

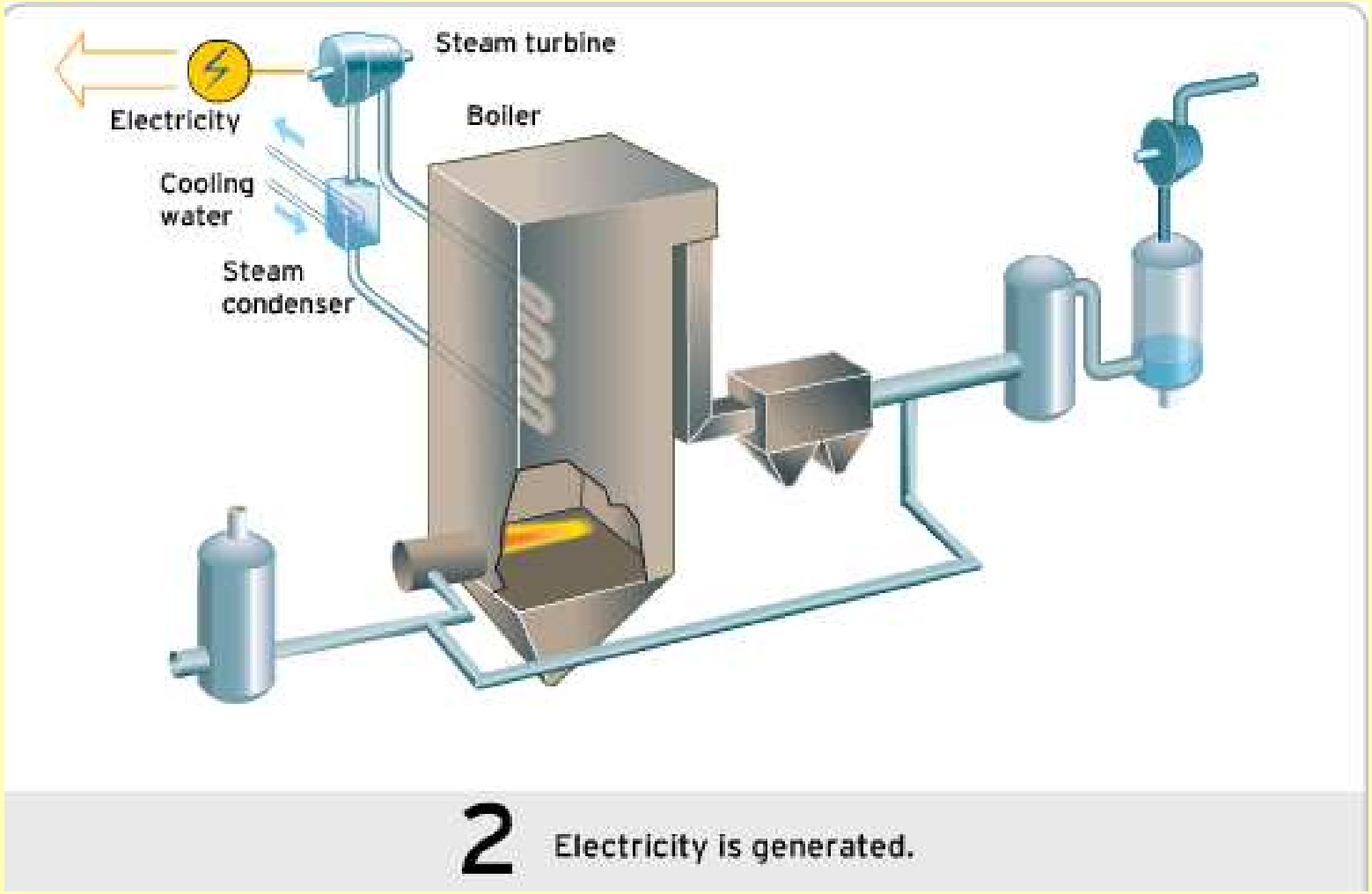
Source: VATTENFALL

A little bit of technology: OXYCOMBUSTION



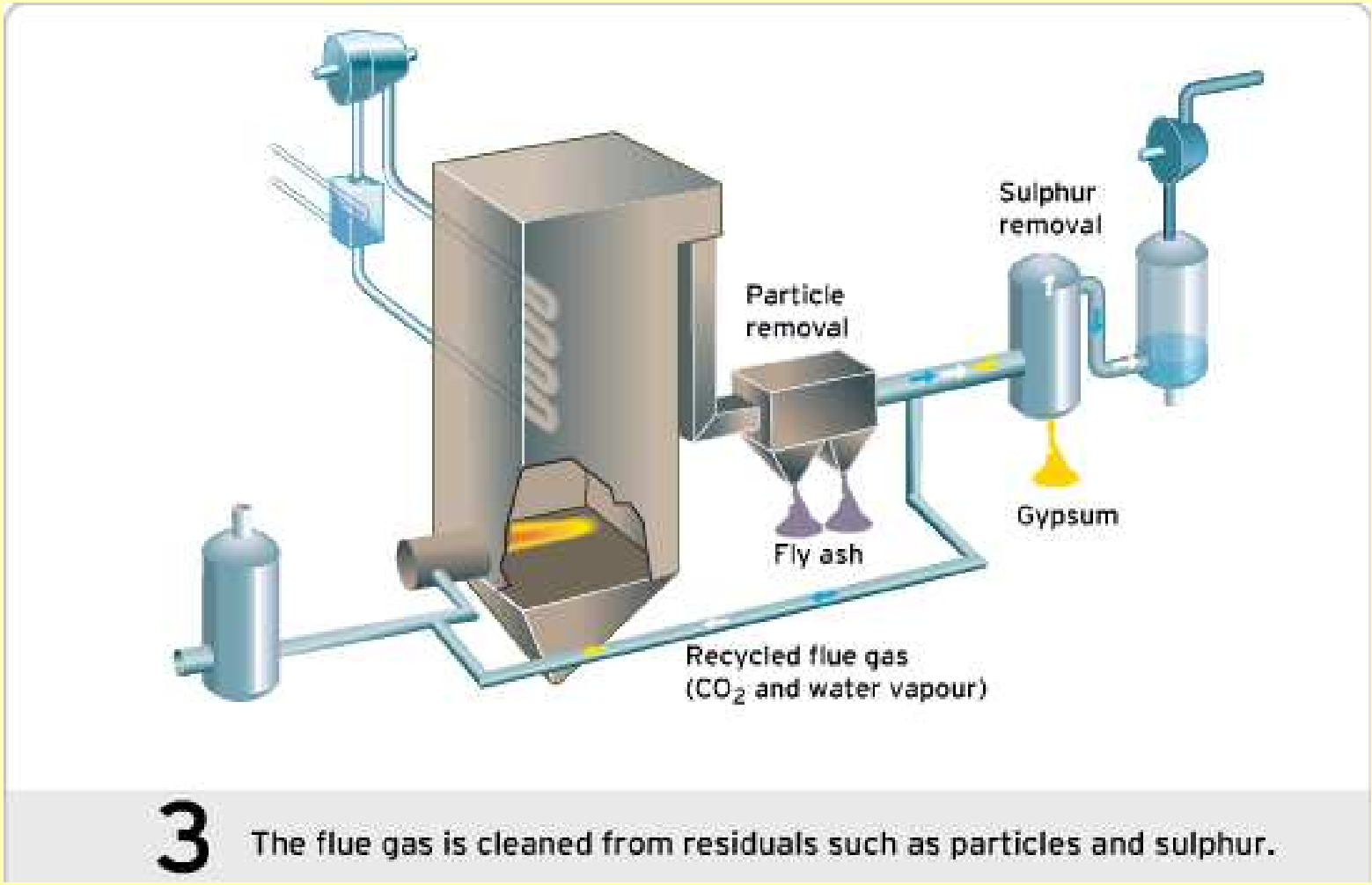
Source: VATTENFALL

A little bit of technology: OXYCOMBUSTION



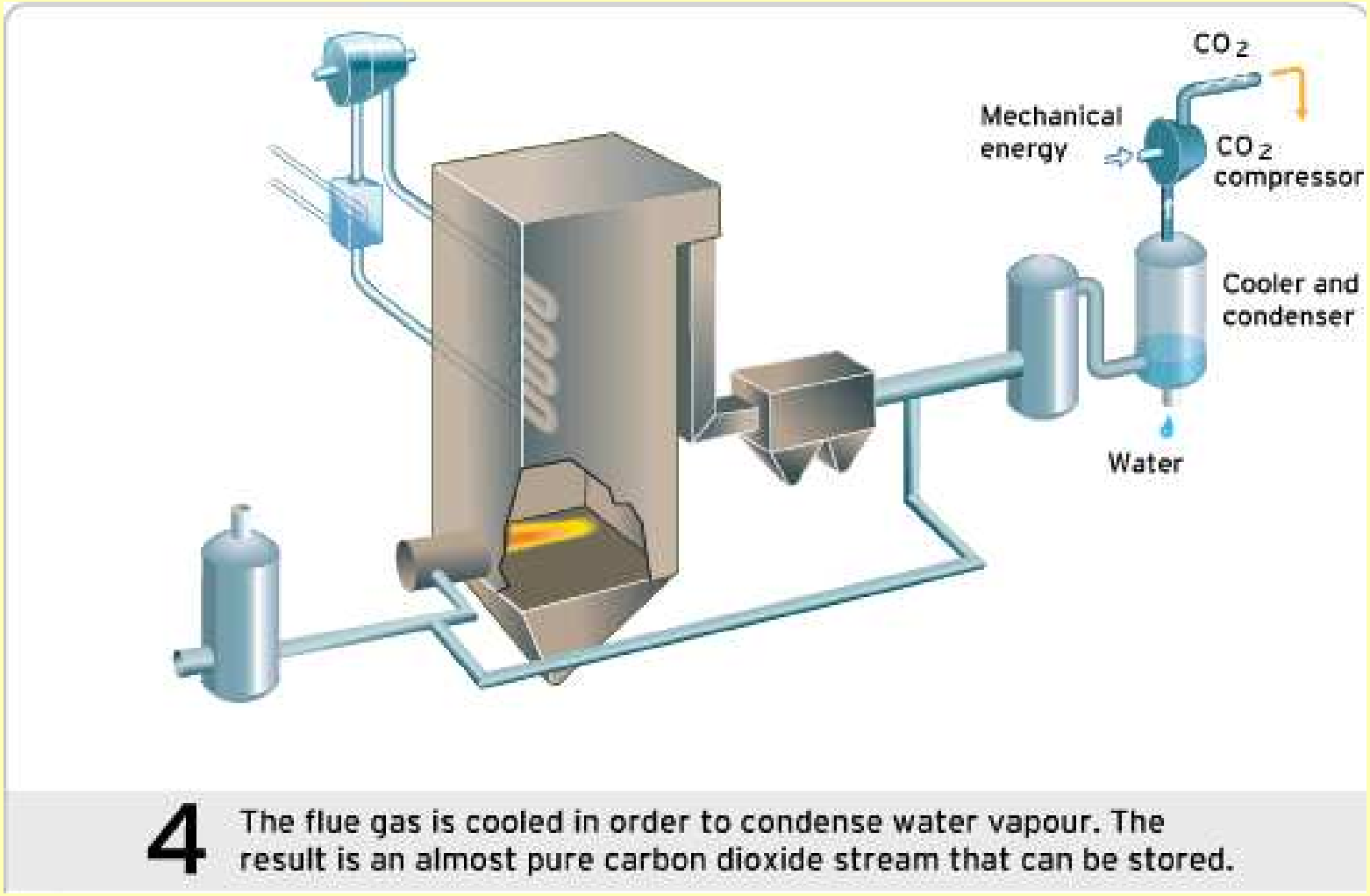
Source: VATTENFALL

A little bit of technology: OXYCOMBUSTION



Source: VATTENFALL

A little bit of technology: OXYCOMBUSTION



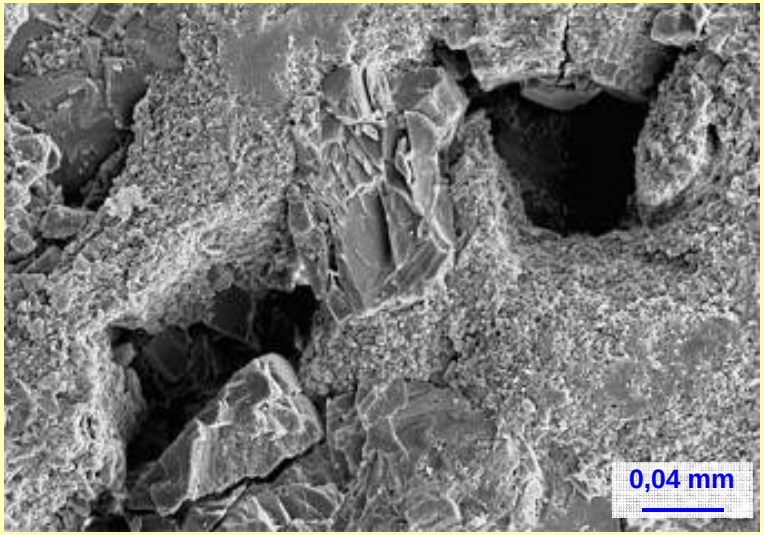
4 The flue gas is cooled in order to condense water vapour. The result is an almost pure carbon dioxide stream that can be stored.

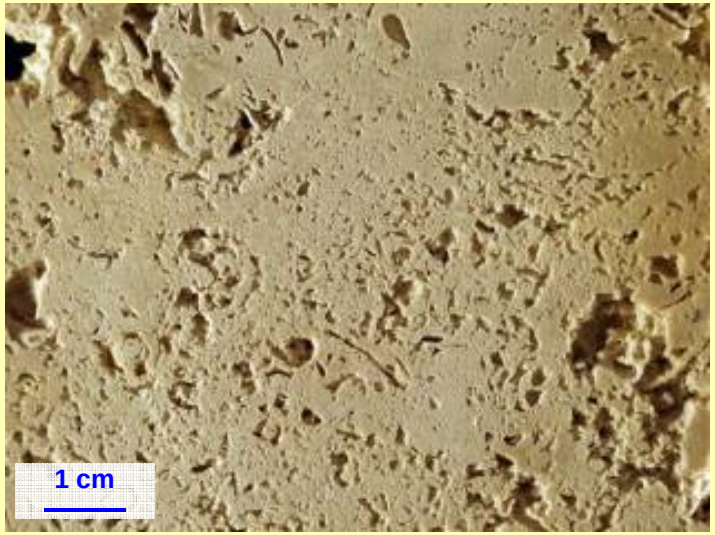
Source: VATTENFALL

Storage technologies

Why geological storage of CO_2?

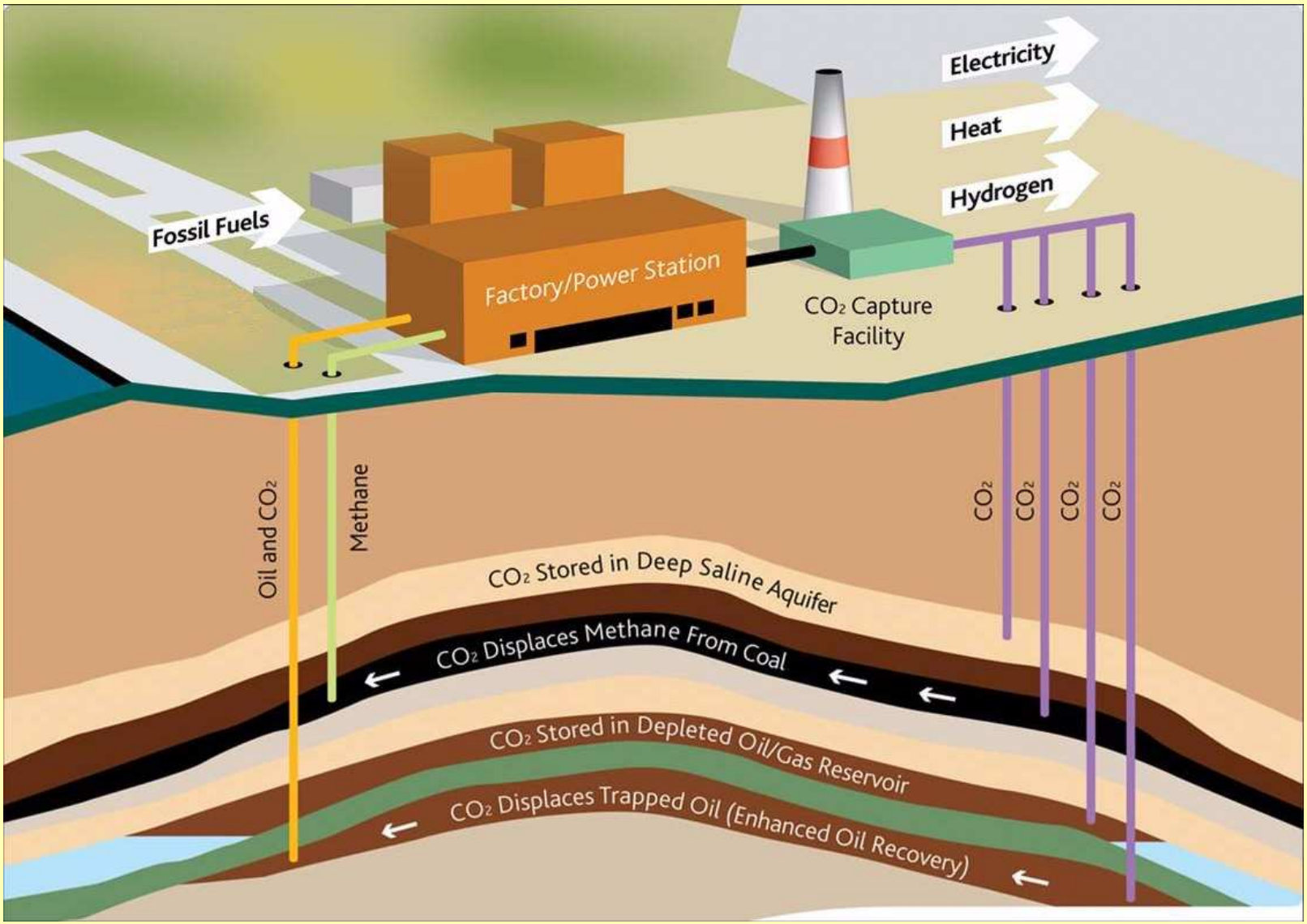
- ✓ **To store billions of tons annually**
- ✓ **Reservoirs of thousands of km^3 are required**
- ✓ **Only feasible option: suitable geological settings in sedimentary basins**



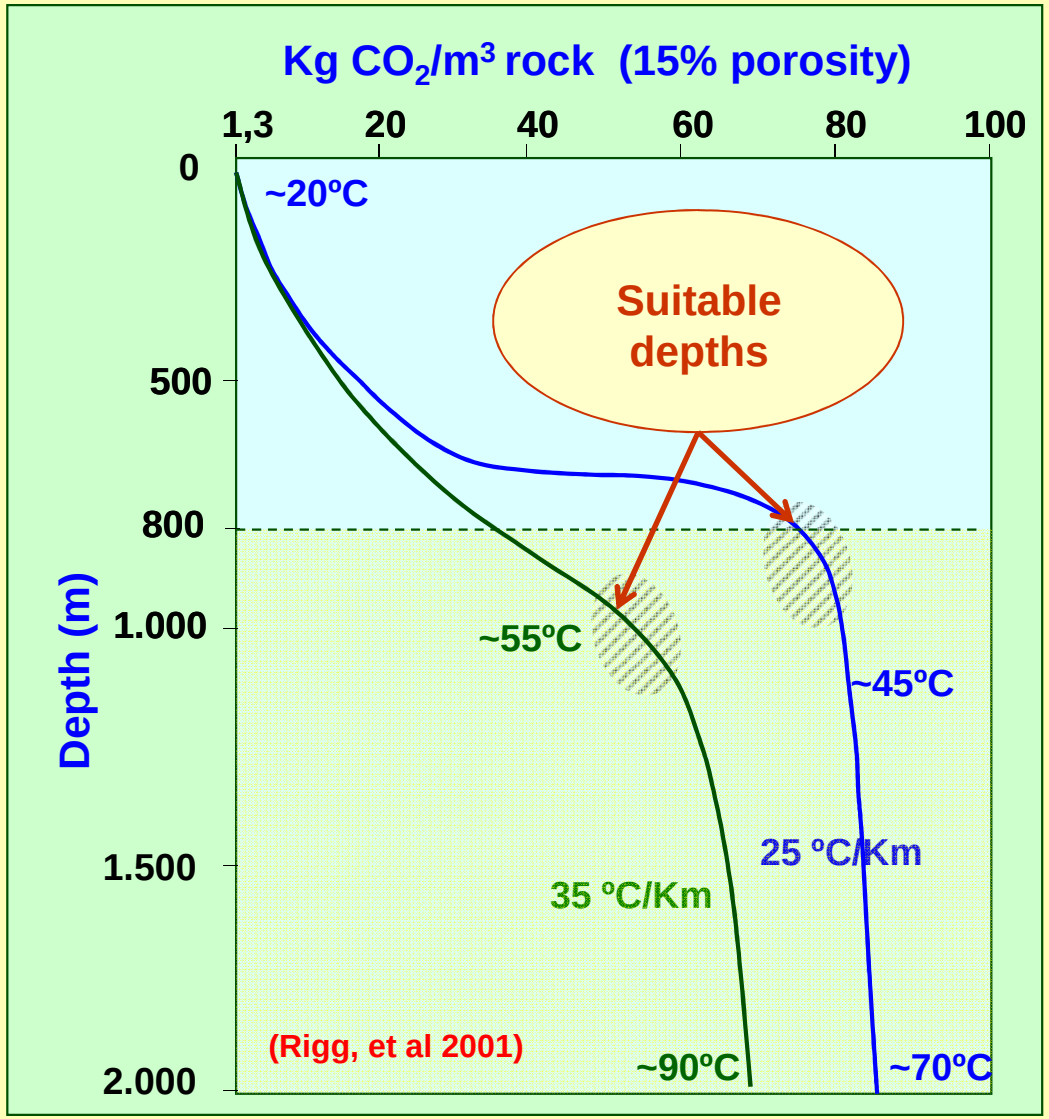


- ✓ **Suitable geological formations are found in layers of porous rock which have space available for the CO_2**
- ✓ **A solid, non-porous, layer of rock must lie on top of the porous layer, providing a 'cap' that does not allow CO_2 to permeate upwards**

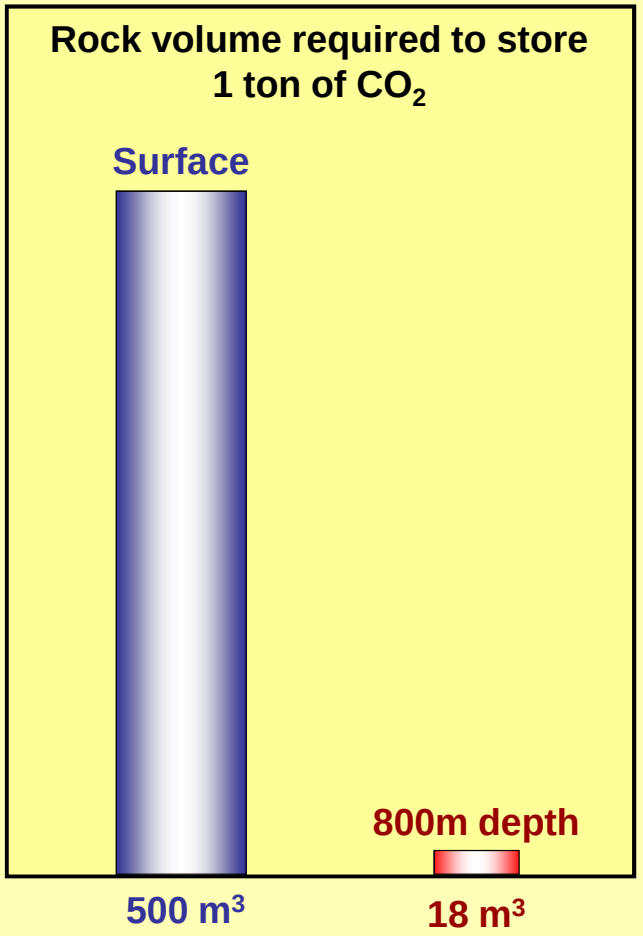
Alternatives to store CO_2 underground



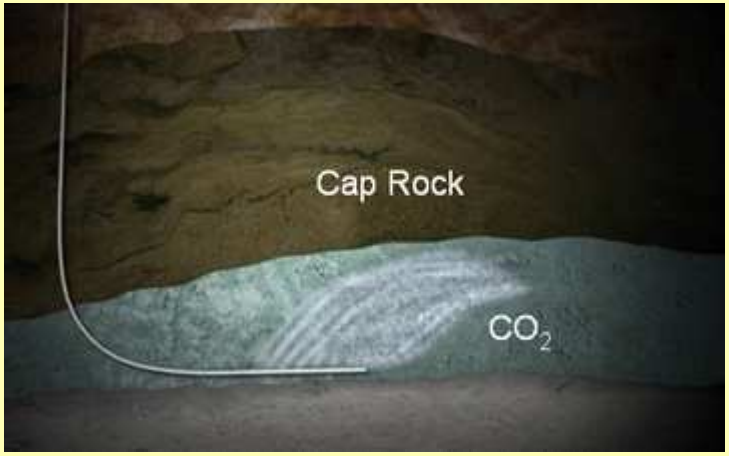
The main advantage of CO_2 geological underground



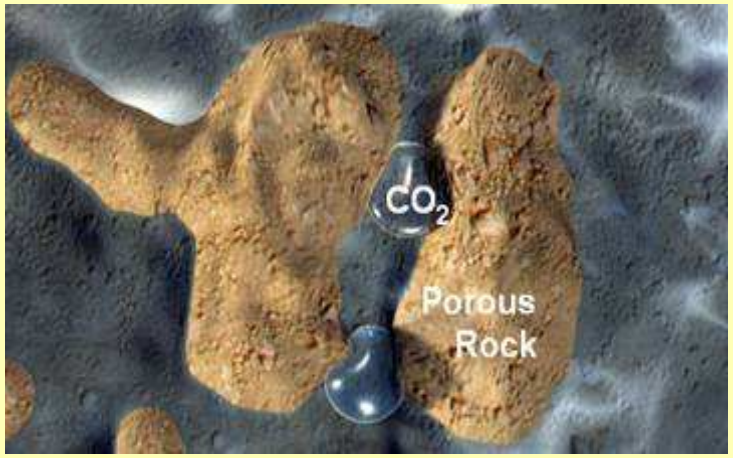
CO_2 density depends on depth and geothermal gradient



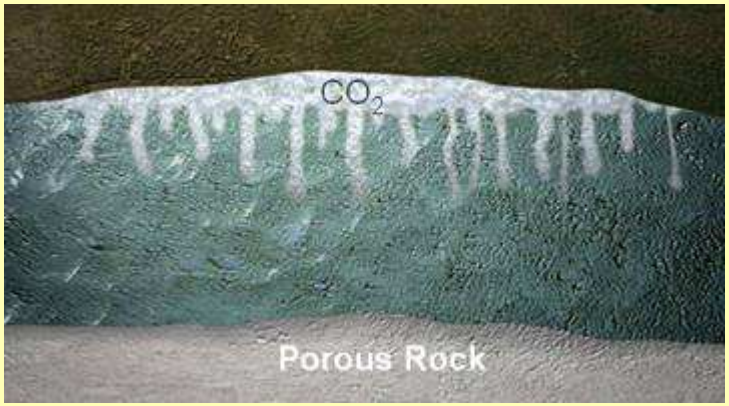
The four trapping mechanisms



Structural/stratigraphic trapping



Residual trapping



Solubility trapping

Mineral trapping

Challenges for CCS

Challenges for CCS

Technical/Industrial

- Uncertainties around CCS technologies (performances, operation, scale-up etc.)
- Potential bottleneck of CCS equipment for industrial ramp-up
- Costs and energy penalty
- Knowledge sharing in a (pre)-competitive environment

Regulatory

- Lack of regulation framework for permitting (especially storage)
- Need for long-term CO_2 regulation at national, regional and international level
- Lack of clarity on future role of coal

Financial

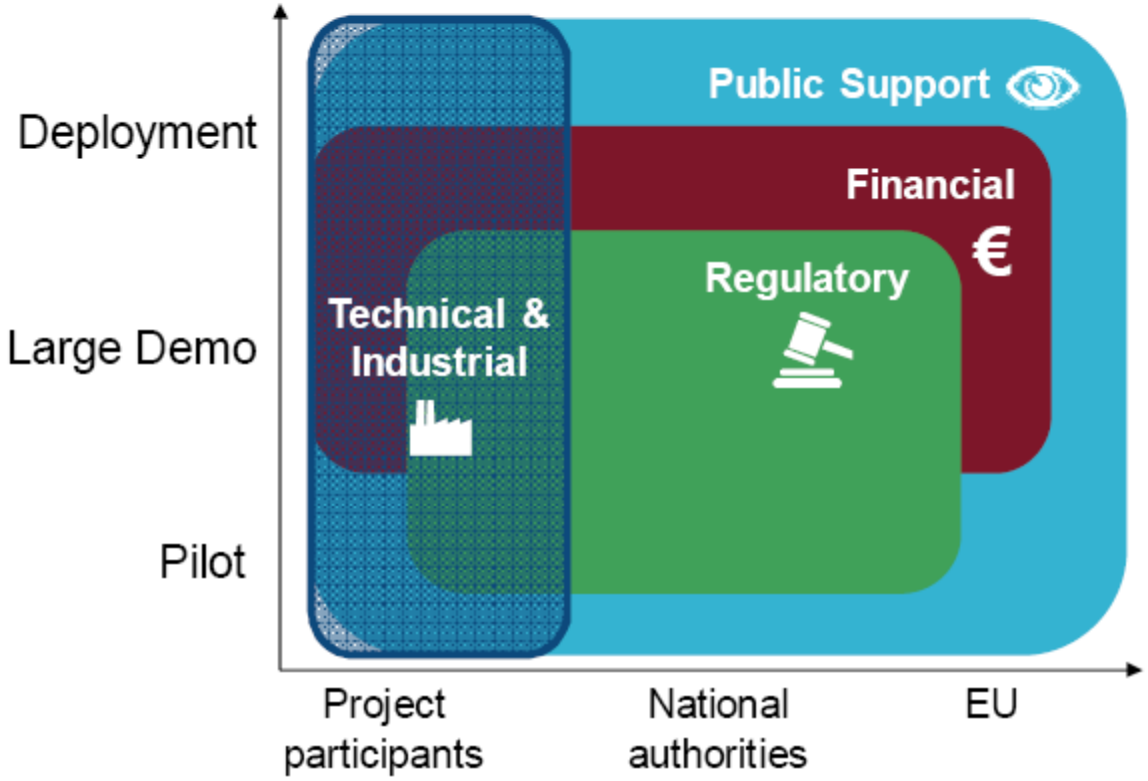
- Uncertainty/lack of funding (EU, Member States etc.)
- Uncertainties around cost of CCS technologies, revenues and incentives
- Funding streams not in line with cost spending for CCS
- Development of new insurance tools

Public support

- Lack of awareness of CCS among general public
- Risk of NIMBY response to any new industrial assets (including CCS)

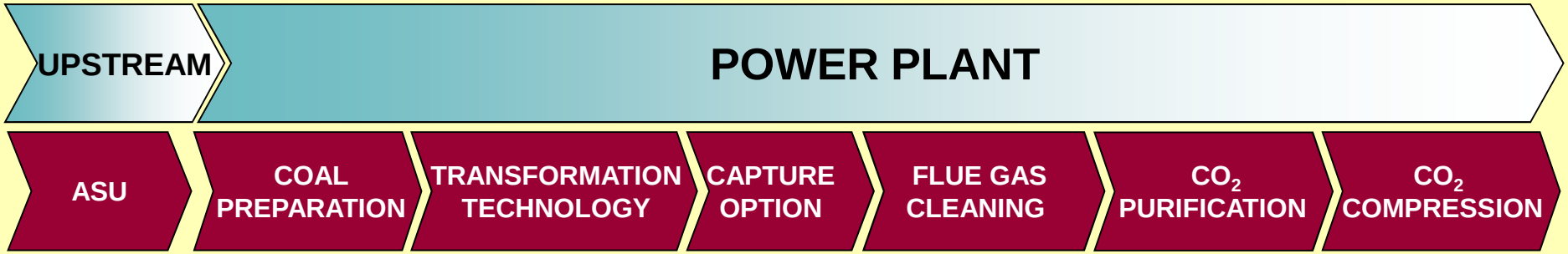
Source: J Heithoff . ZEP General Assembly. Oct 09

Urgent action is required to demonstrate and deploy CCS



Source: J Heithoff . ZEP General Assembly. Oct 09

The technological challenge



All major components of a carbon capture and sequestration system are commercially available

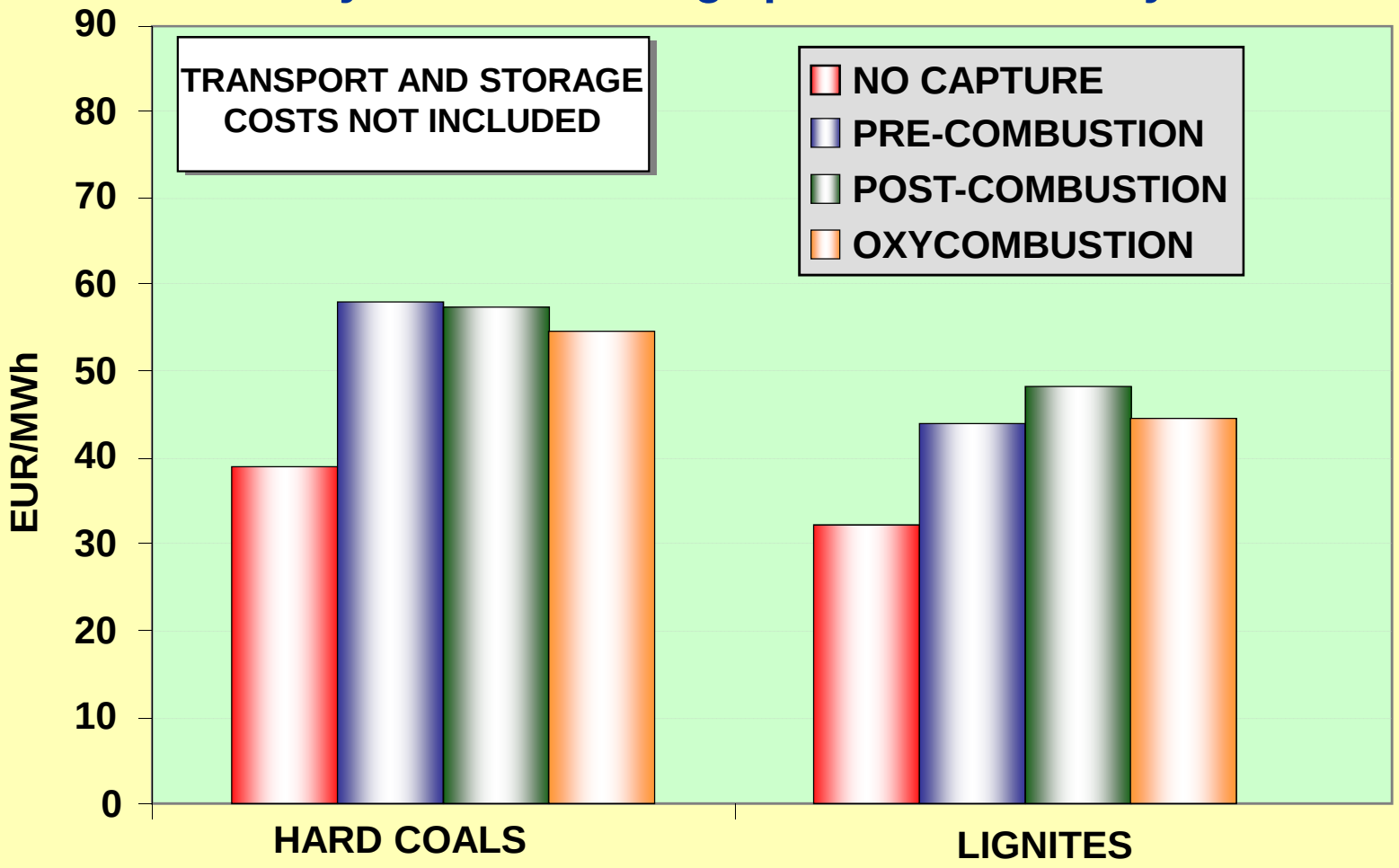
but

no capture power plant in is operation today

Adapted from "CO_2 Capture and Storage (CCS) – Matrix of Technologies ", ZEP

The Financial Challenge

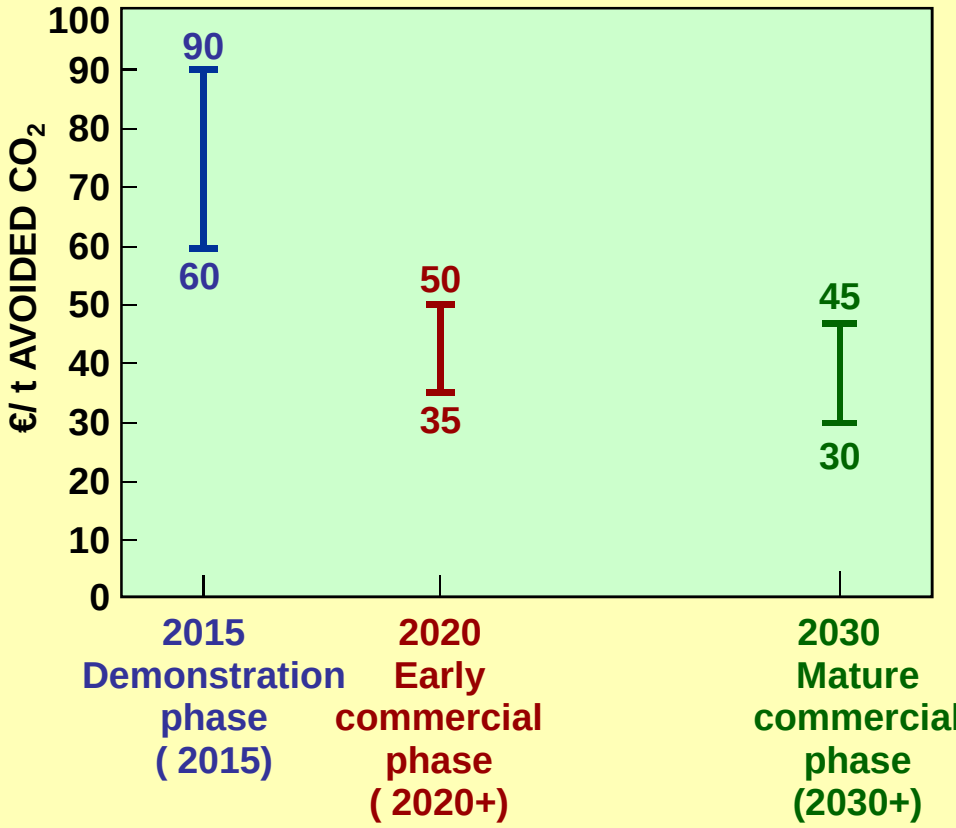
Electricity costs from large power stations by 2020



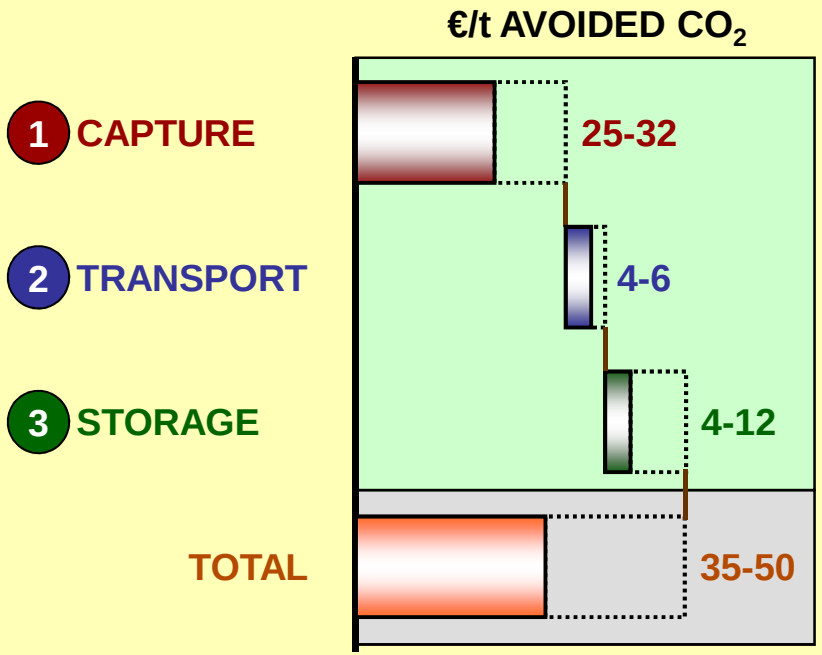
➢**Global process efficiency must be increased in order to reduce costs and improve competitiveness**

The Financial Challenge

CO_2 costs



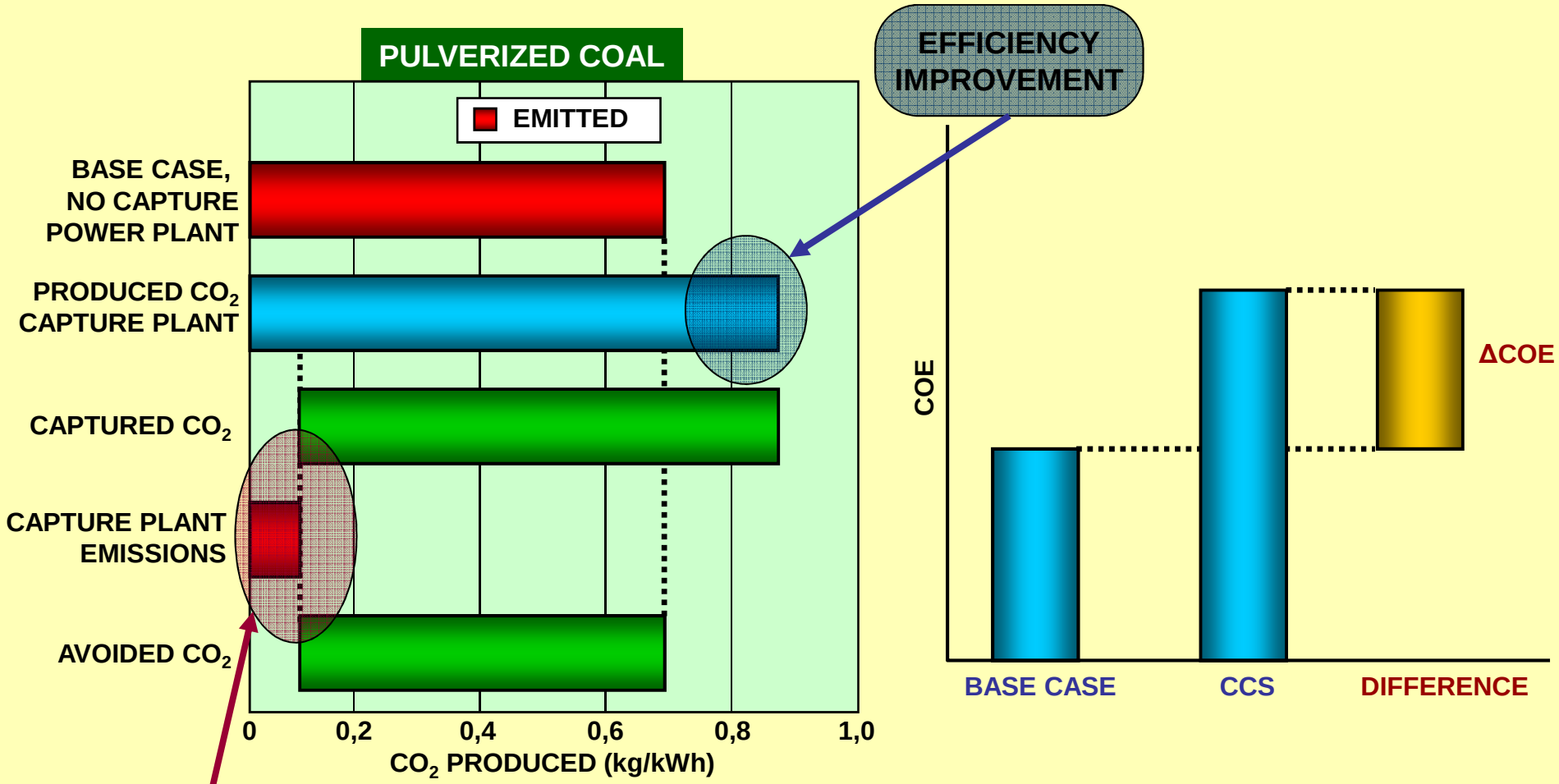
Avoided CO_2 cost



CO_2 cost breakdown of early commercial units

From Carbon Capture & Storage: Assessing the Economics. The McKinsey Company. September 2008

The Financial Challenge
Avoided CO_2 vs. captured CO_2



AVOIDED CO_2 COST:

$$\frac{\Delta CE}{\left(CO_{2,BASE} - CO_{2,CCS}\right)_{EMITTED}}$$

Financing Projects

✓ AUSTRALIA

- **AUS 2 bn (USD 1.65 bn) fundings: Large CCS projects**
- **AUD 100 mm/y: GCCSI**

✓ CANADA

- **CAN 1.3 bn (USD 1.2 bn): R&D, mapping and demo projects**
- **Providence of Alberta: CAN 2 bn (USD 1.8 bm) - large CCS projects**

✓ EUROPEAN UNION

- **Revenue from the auctioning of 300 mm credits with ETS: CCS / renewable**
- **EUR 1.05 bn (USD 1.5 bn): EEPR**

✓ JAPAN

- **JPY 10.8 bn (USD 116 m): Large CCS projects**

Financing Projects

✓ NORWAY

- **Tax NOK 230 (USD 40)/MtCO2**
- **1.2 bn (USD 205m): CCS projects**

✓ UNITED KINGDOM

- **Funding for up to 4 CCS projects via the CCS competition**

✓ UNITED STATES

- **USD 3.4 bn: Economic Recovery Act for clean coal and CCS**
- **USD 1.0 bn: new ways to produce energy from coal**
- **USD 800 m: Clean Power Initiative**
- **USD 1.52 bn: Industrial CCS projects**

Legal and regulatory frameworks

- ✓ **London protocol, 2006**
  - **Offshore CO_2 Storage**
- ✓ **Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)**
- ✓ **United Nations Framework Convention on Climate Change**
  - **2008 CCS Directive for Geological Storage of CO_2**
- ✓ **Interngovermental Panel on Climate Change**
  - **Guidelines for National Greenhouse Gas Inventories**
- ✓ **EUROPEAN COMMISSION**
  - **2008 CCS Directive for the Geological Storage of CO_2**
- ✓ **AUSTRALIA**
  - **State and National Regulatory Frameworks for CO_2 Storage**
- ✓ **United States, Canada, Norway and Japan**

The Public opinion challenge

- ✓ The Public is **poorly informed** about energy transformation and its environmental effects
- ✓ The Public **favours renewable** energies, but generally does not want to pay higher prices for them
- ✓ The Public is generally **unaware of CCS** and is against the idea of putting CO_2 underground
- ✓ The Public believes that CO_2 is **toxic**
- ✓ Most important concerns are related to **transportation and storage**
- ✓ There is a **long way** to reach public acceptance but it must be started **inmediately**
- ✓ The CCS large scale **demo projects** will greatly help if adequate Public Acceptance strategy

7th Annual Conference on CCS
Pittsburgh (PA, USA), May 5 - 8, 2008

Concluding remarks

CONCLUDING REMARKS

- ✓ **Scale**
- ✓ **Integration**
  - **Retrofits applications**
  - **Better manage emissions: combustion design and clean-up**
- ✓ **Energy penalty**
  - **Post: Desorption and CO_2 Compression**
  - **Pre: ASU, CO-Shift & CO_2 Desorption and CO_2 Compression**
  - **Oxy: ASU and CO_2 Compression**
- ✓ **Combustion stream composition for post- and oxy-**
- ✓ **Hydrogen combustion and upscaling gasifiers in pre-**
- ✓ **Novel capture process approaches**

NO "WINNER" TECHNOLOGY

CONCLUDING REMARKS

✓ Technological Challenge

- **Integrated, large-scale CCS power stations are not commercially available**

✓ Financial Challenge

- **CCS requires higher CAPEX and OPEX**
  - ➢ **REDUCTION OF COST OF INSTALLATION AND OPERATION**

✓ Regulatory Challenge

- **Regulations are currently under preparation for Capture and specially for Storage**

✓ Social Challenge

- **Public acceptance and not rejection is a requisite for CCS**
  - ➢ **EARLY COMMUNICATION**

LEARNINGS FROM DEMO PHASE REQUIRED

Relevant websites

International Energy Agency	www.iea.org
International Energy Agency – Greenhouse Gas Programme	www.ieagreen.org
Carbon Sequestration Leadership Forum	www.cslforum.org
Global CCS Institute	www.globalccsinstitute.com
International Performance Assessment Center for CCS	www.ipac-co2.com
Intergovernmental Panel on Climate Change	www.ipcc-nggip.iges.or.jp
CO2CRC	www.co2crc.com.au
Zero Emissions Platform	www.zeroemmissionplatform.eu
United States Department of Energy	www.energy.gov
World Resources Institute	www.wri.org
Bellona Foundation	www.bellona.org
US DOE – National Energy Technology Laboratory	www.netl.doe.gov
CO2GeoNet	www.co2geonet.com

CARBON CAPTURE AND STORAGE OVERVIEW

by

Monica Lupion

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

16th November 2009. Hassi Messaoud (Algeria)

*Corresponding Author's Email: m.lupion@ciuden.es

IEA Greenhouse Gas R&D Programme

CO_2 Post Combustion Capture

Dr. Mohammad Abu Zahra

IEA Greenhouse Gas R&D Programme

OPEC-IEAGHG CCS Workshop

for Scientists and Professionals in OPEC Member Countries

Hassi Messaoud-Algeria November 2009

Overview

- CO_2 Post Combustion Capture Process
- Post Combustion Capture Technological Options
- State-of-art technology: Status, Challenges and Focus!!
- Post Combustion Capture 2nd and 3rd Generation Processes
- Post Combustion Capture R&D Focus and Future
- Conclusions

CO_2 Post Combustion Process

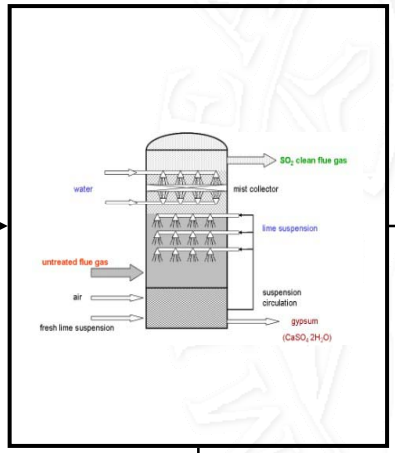
Power Plant - An Integrated Approach

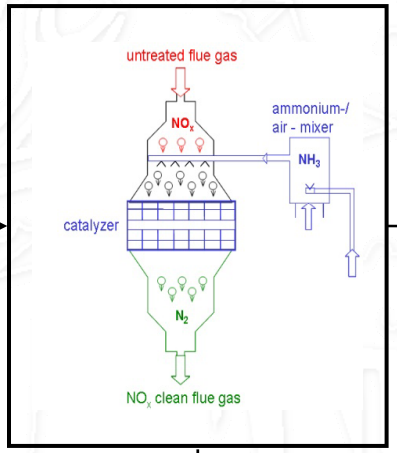
SO_2 Removal

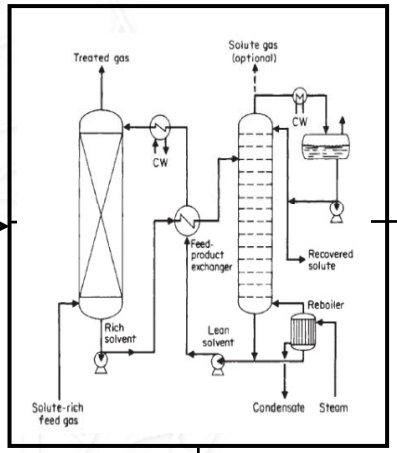
NO_X Removal

CO_2 Capture

Untreated flue gas







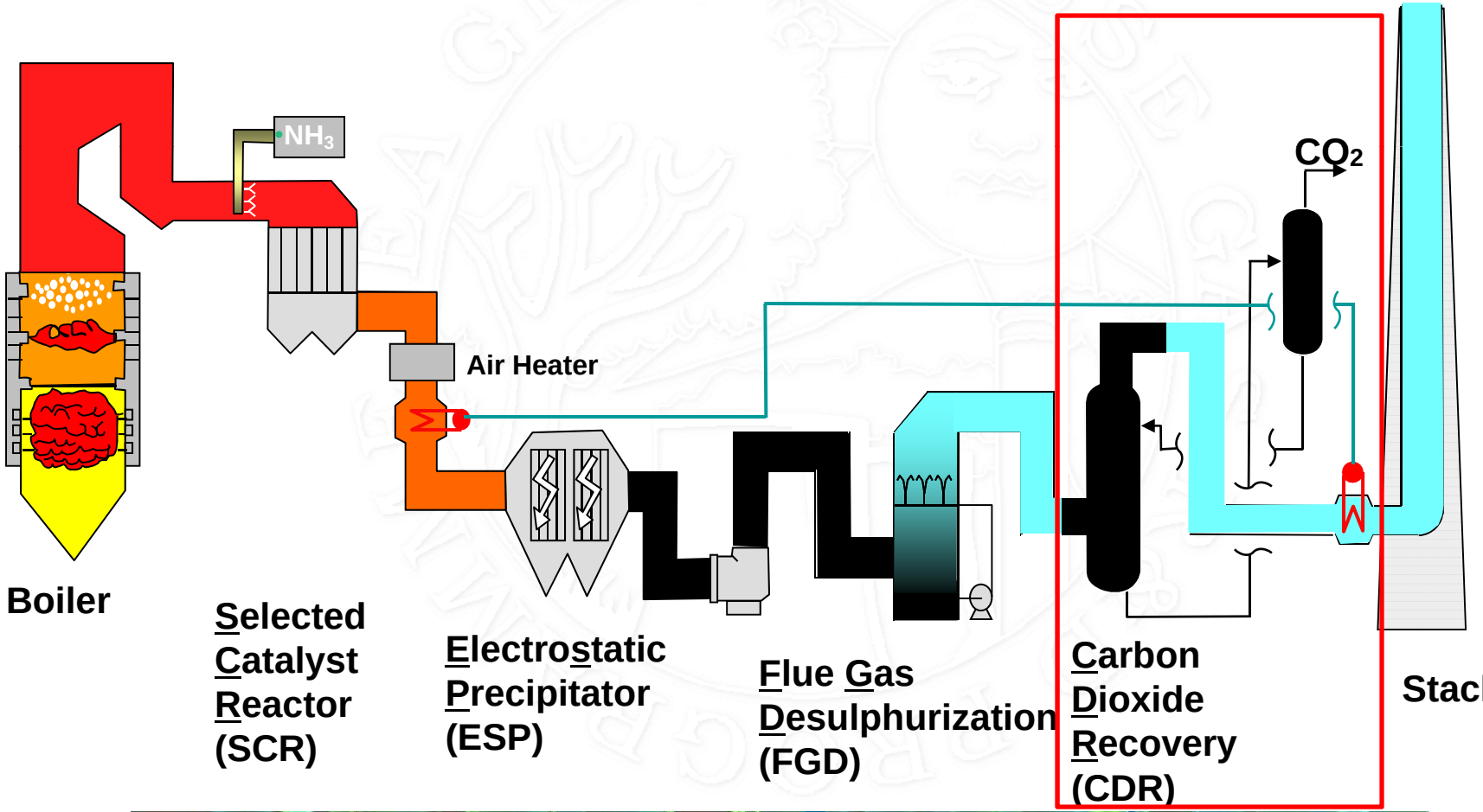
Clean flue gas

Gypsum

N_2

Captured CO_2

Coal Fired Power Plant An Integrated Approach



Source: Mitsubhishi Heavy Industries

Why post-combustion capture?

- The possibility of add-on to existing power plants (retrofit possibility).
- Capture technologies are considered available and the solvent technologies are proven on a smaller scale.
- Capture readiness makes the post-combustion capture relatively easy to incorporate into power plants.
- It has more operational flexibility in switching between capture – no capture operation mode.
- Learning by doing will lead to cost reductions similar to experience with SO_2 capture process development.
- Learning by searching will lead to better solvents and processes

What are challenges for CO_2 capture?

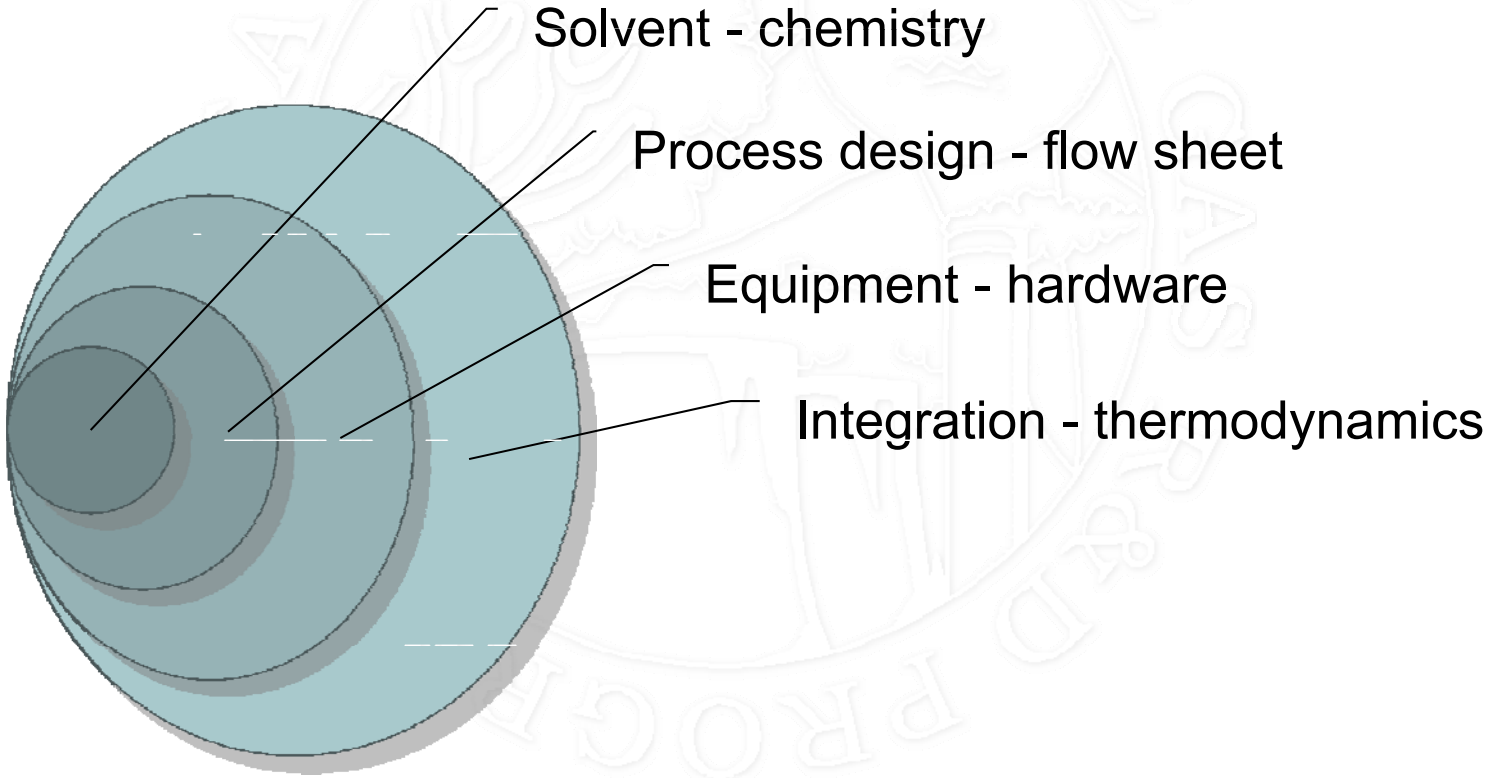
Capture of CO_2 can be done with technologies presently available but:

- Sizeable efficiency reduction
- Power generation costs will increase
- There is no experience with CO_2 capture at the power plant scale

Therefore the following questions need to be addressed:

- How to reduce the additional power consumption as a result of the capture process?
- How to reduce the costs of the capture?
- Can we make these processes reliable in power generation environment?

Integrated approach in solvent process development for post-combustion capture

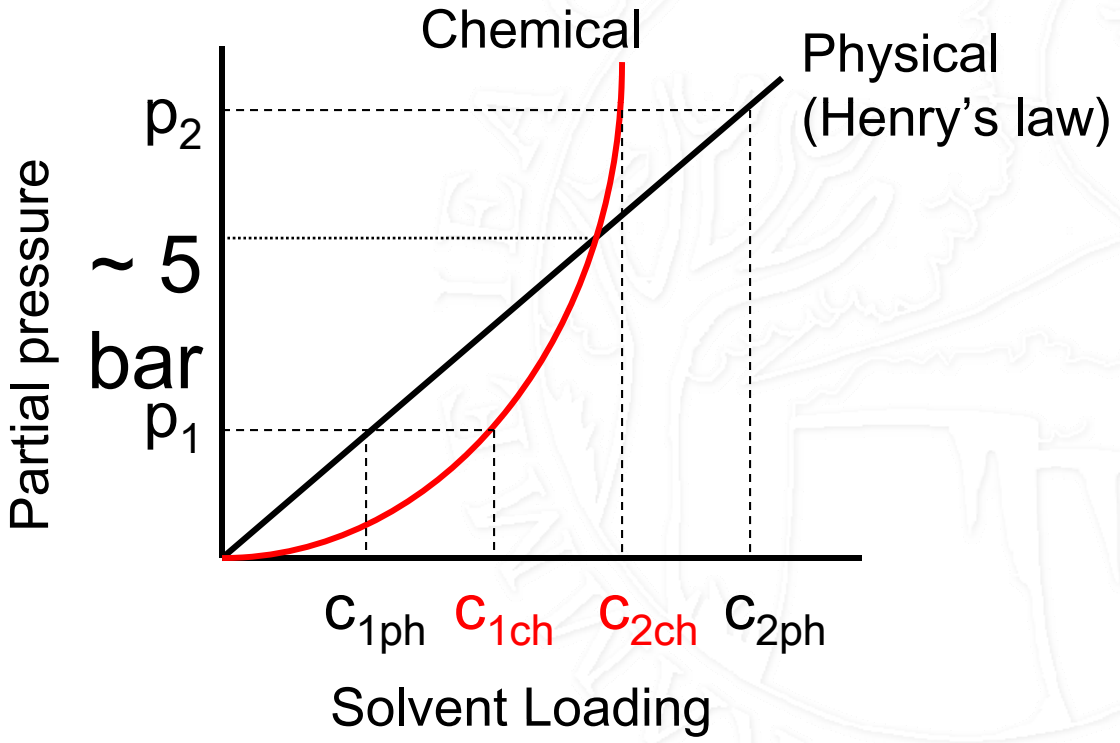


CO_2 capture routes: classification

- Post-combustion capture: separation **CO_2-N_2**
- Pre-combustion capture: separation CO_2-H_2
- Oxyfuel combustion (Denitrogenation): separation O_2-N_2

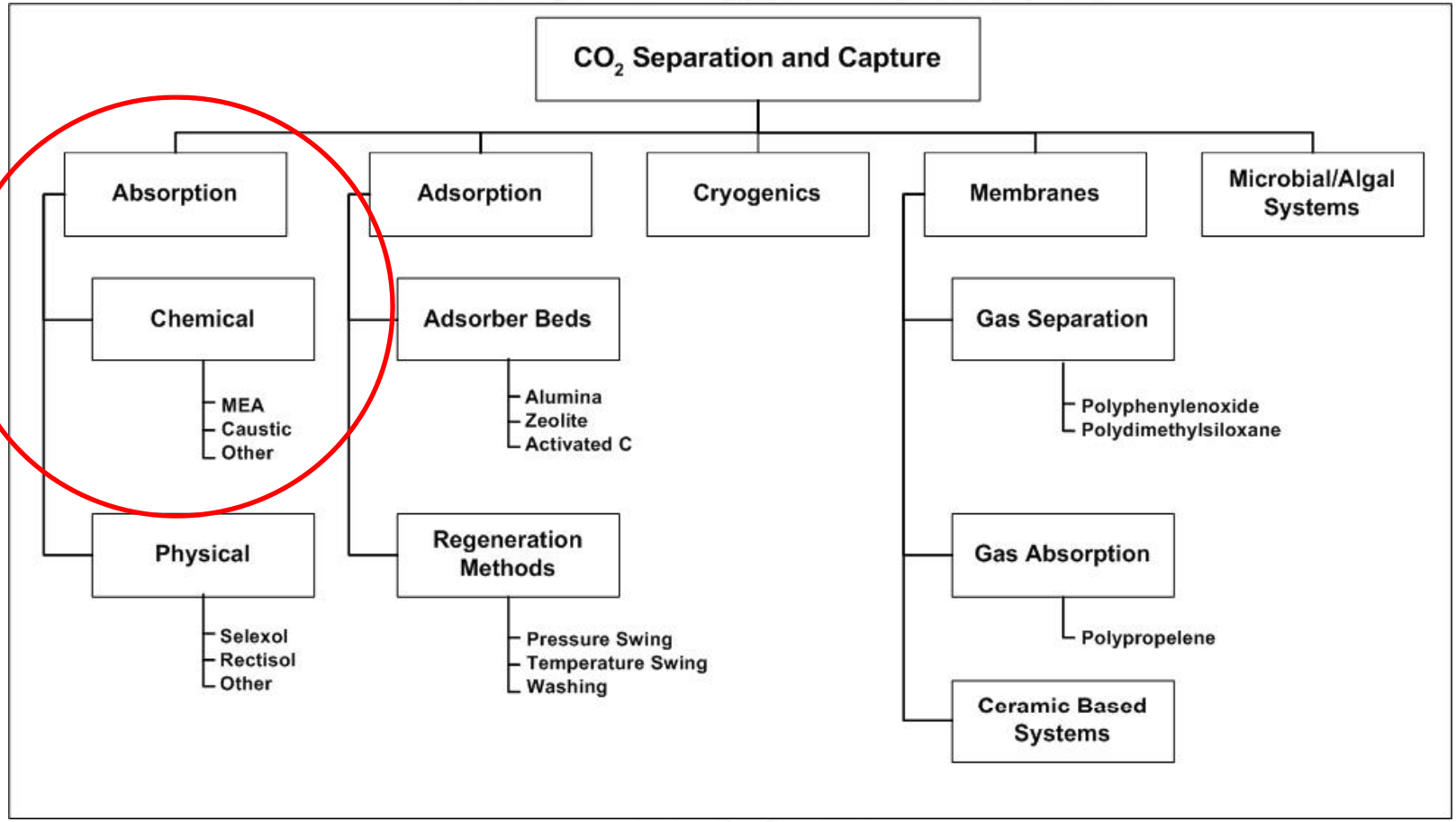
	Post-comb. (flue gas)	Pre-comb. (shifted syngas)	Oxyfuel comb. (exhaust)
p (bar)	~1 bar	10-80	~1 bar
[CO_2] (%)	3-15%	20-40%	75-95%

Chemical versus physical absorption



- Low partial pressure (p_1):
- $C_{1ph} < C_{1ch}$
- Chemical absorption deserves preference
- p_2: reverse

Technology options for CO_2 capture



State-of-Art Technology!?

Solvent Chemical Absorption

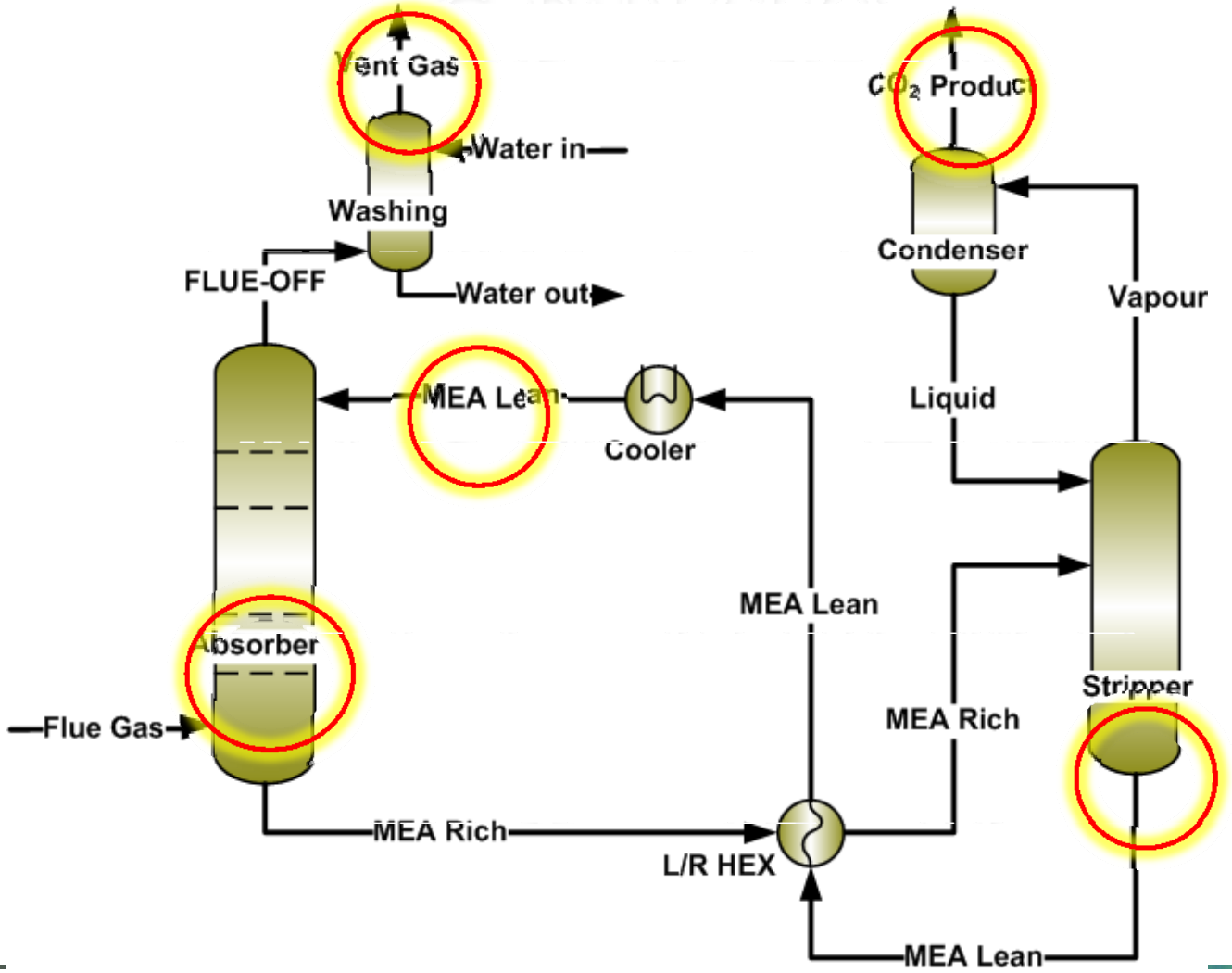
Step 1: A gas mixture is contacted with a liquid to preferentially dissolve component(s) from the gas to form a solution in the liquid;

Step 2: The 'loaded' solvent is exposed to alternate pressures and/or temperatures in order to re-release the absorbed gas. This operation is known as 'Stripping' and allows the solvent to be recovered for re-use.

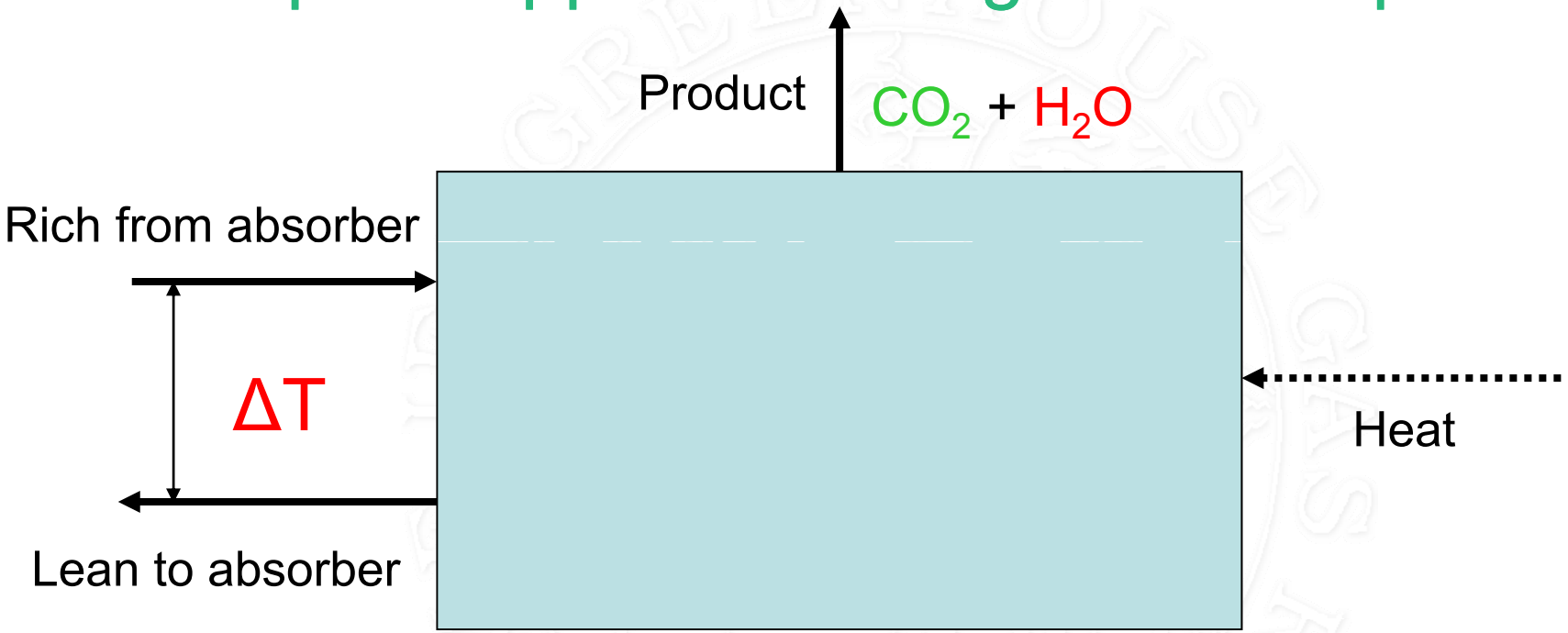
State of the art post-combustion CO_2-capture

- Fluor Daniel Econamine FG^{SM}
  - 30% MEA solution incorporating additives to control corrosion
  - > 20 commercial plants in sizes between 0.2 and 15 tonnes CO_2/h
- ABB-Lummus
  - 15-20% MEA solution
  - 4 commercial plants in size between 6 and 32 tonnes CO_2/h
- Mitsubishi Heavy Industries
  - KS-1 – sterically hindered amines
  - 2 commercial plants: 9 tonne CO_2/h
- More to come…..

CO_2 capture conventional flow sheet



Conceptual approach to regeneration process



Crucial solvent properties:

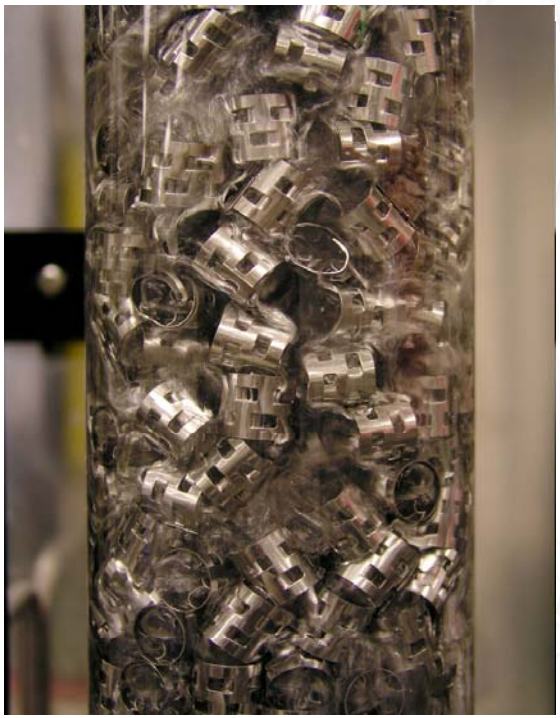
- Binding energy [kJ/mole CO_2]
- Specific loading [m^3/tonne CO_2]
- Heat capacity [MJ/m^3K]

Energy impacts for post-combustion CO_2 capture using solvent processes

- Thermal energy
  - Regeneration of solvents; Extracted from steam cycle in power plant:
    - Sum of solvent heating, desorption enthalpy and reflux ratio
    - Energy impact determined by solvent properties, process design and integration into power plant
- Electricity
  - Flue gas fans:
    - Higher CO_2-content in flue gas reduces specific power consumption
  - Solvent pumps, cooling water pumps:
    - Higher CO_2-loading of solvent reduces specific power consumption
  - CO_2 compressor:
    - Specific power consumption determined by pressure ratio

Solvent Absorption

- Counter current flow through a packed column is most common



- Plate towers are also used, mainly in the stripping step*.

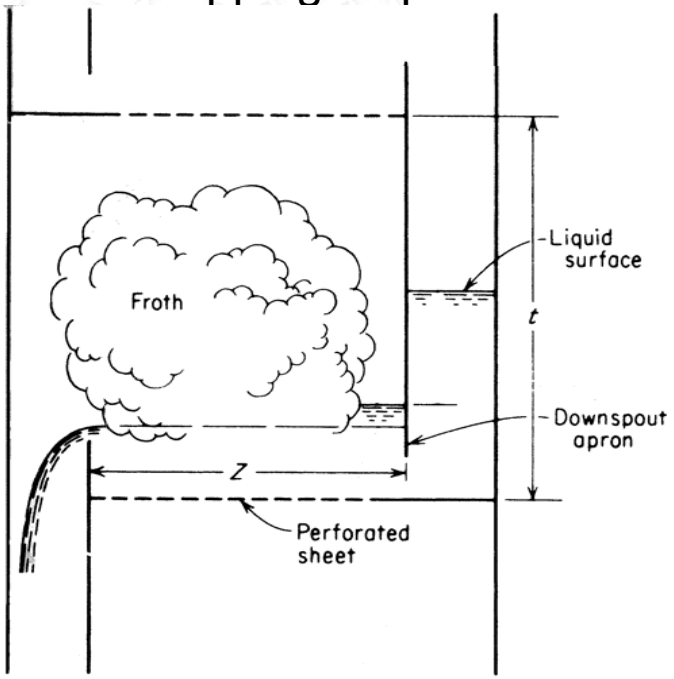


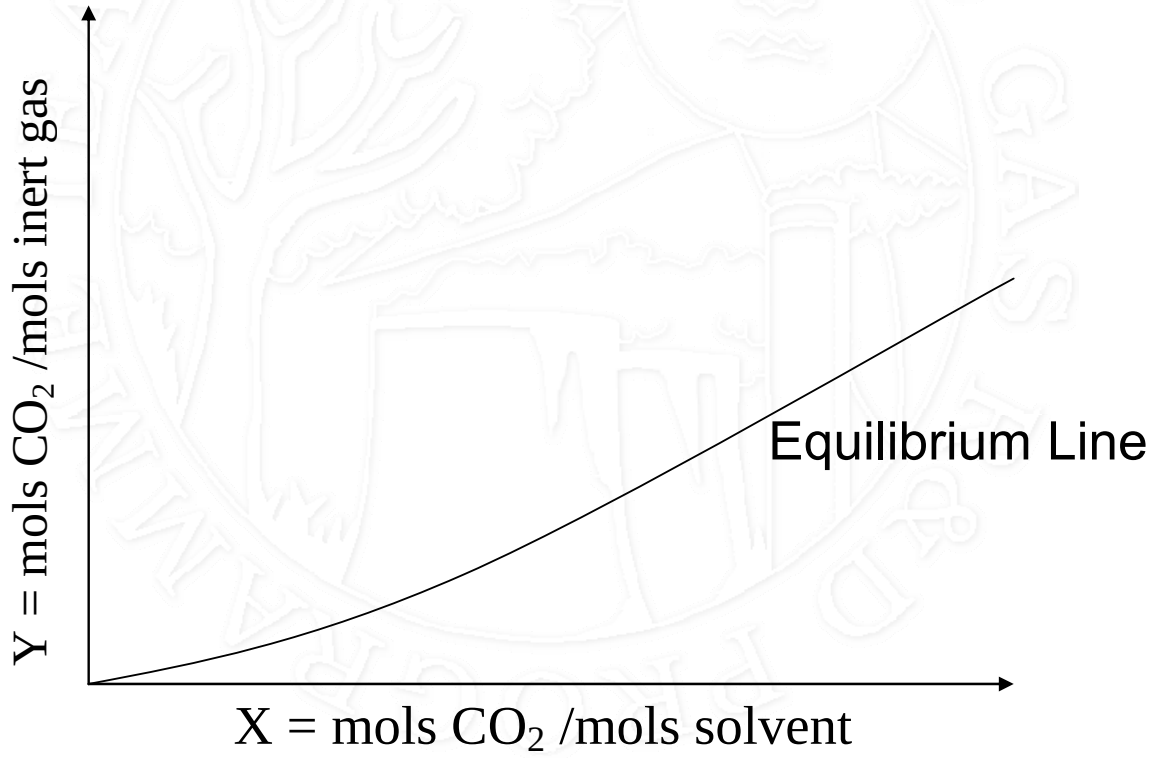
*Image source: Mass Transfer Operations, R.E. Treybal, (1980) McGraw-Hill

Understanding Solvent Absorption

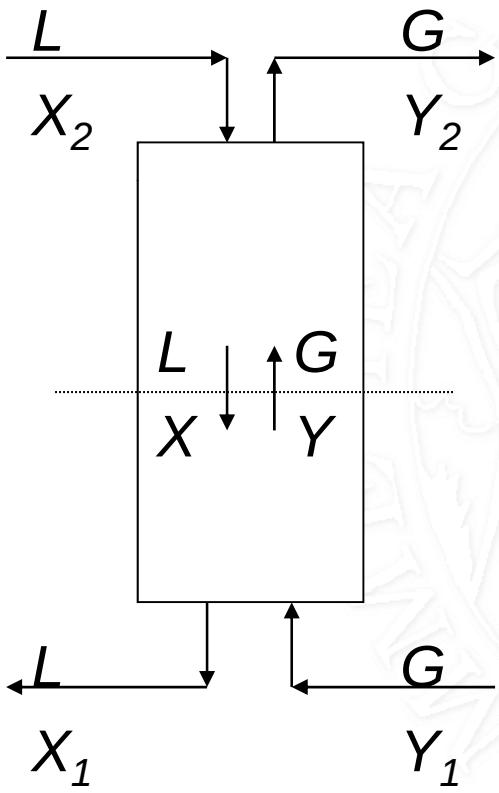
- Calculations in Solvent Absorption require 3 types of equations:
  - Equilibrium relationship
  - Mass and Energy Balances
  - Mass transfer or efficiency equations (kinetics)

Equilibrium

The capacity of a solvent to take up CO_2 is given by an equilibrium relationship (loading vs. partial pressure):



Mass Balances

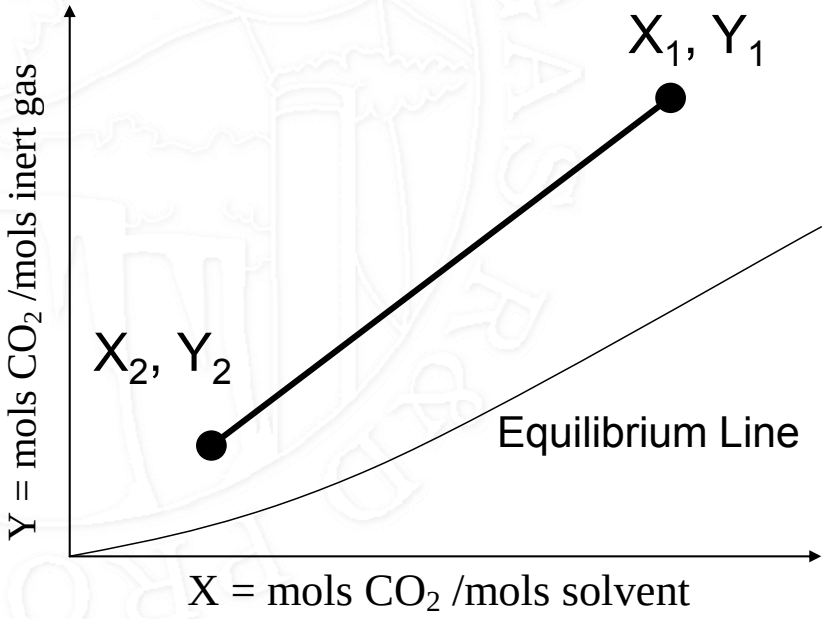


L – flow rate of solvent

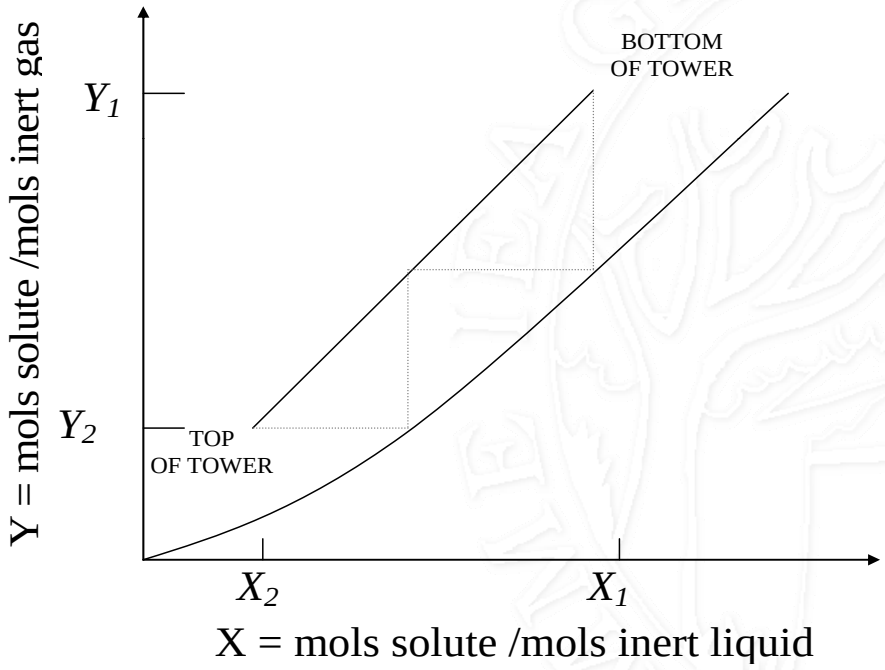
G – flow rate of inert gas

$$G(Y_1 - Y) = L(X_1 - X)$$

Operating Line on an *X-Y* diagram has a slope of *L/G* and passes through (X_1, Y_1) and (X_2, Y_2).



Tower Height

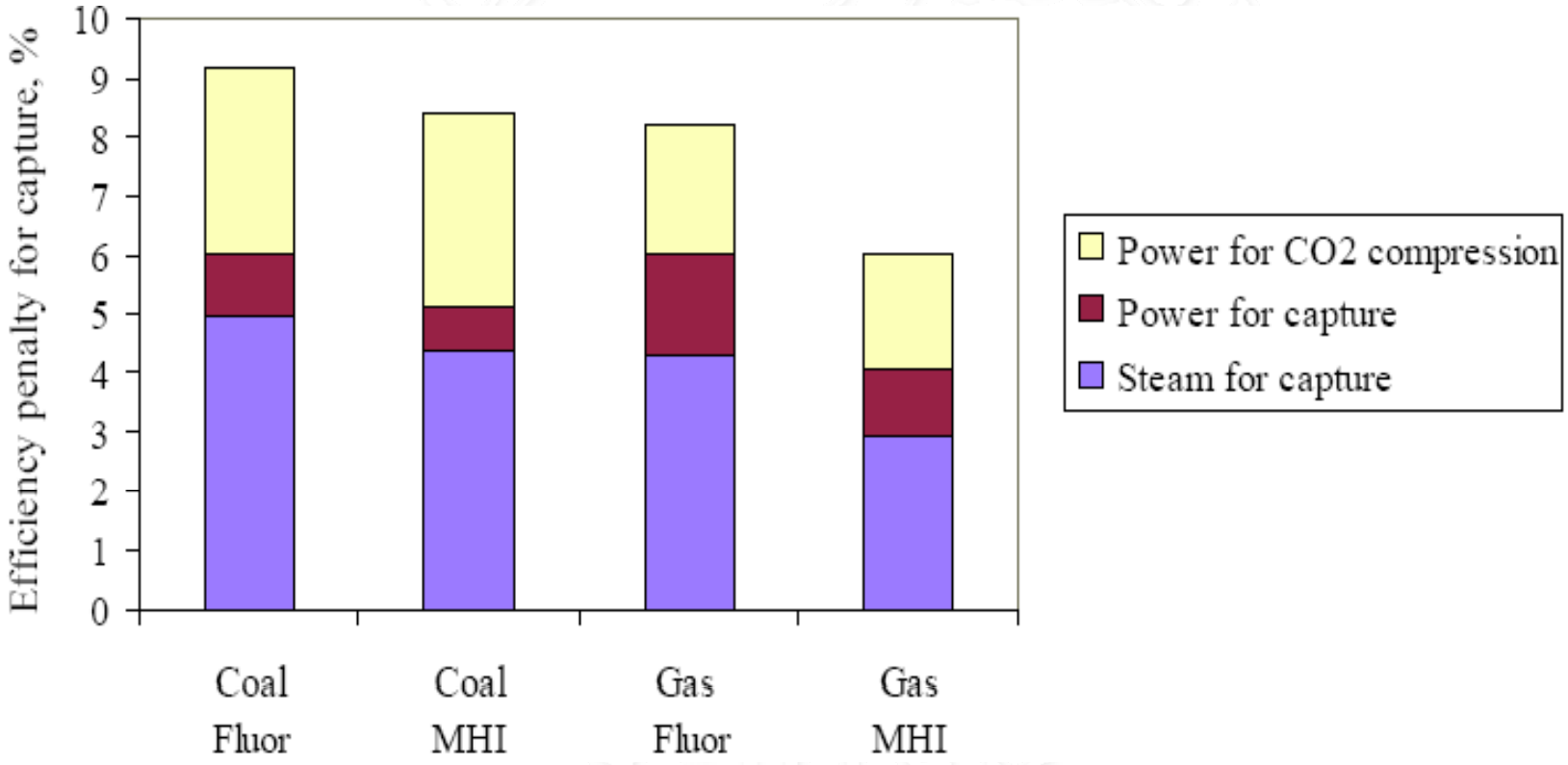


- For a plate tower, the number of ‘steps’ in the staircase indicates the number of ‘theoretical’ plates
- An efficiency factor converts theoretical plates to real plates
- Plates are typically 1-2 m apart
- For a packed column, the height of packing can be found by multiplying the number of ‘steps’ by the height of packing required for each step
- The height of packing required is a function of the mass transfer rate

Conventional Capture Process Challenges!!

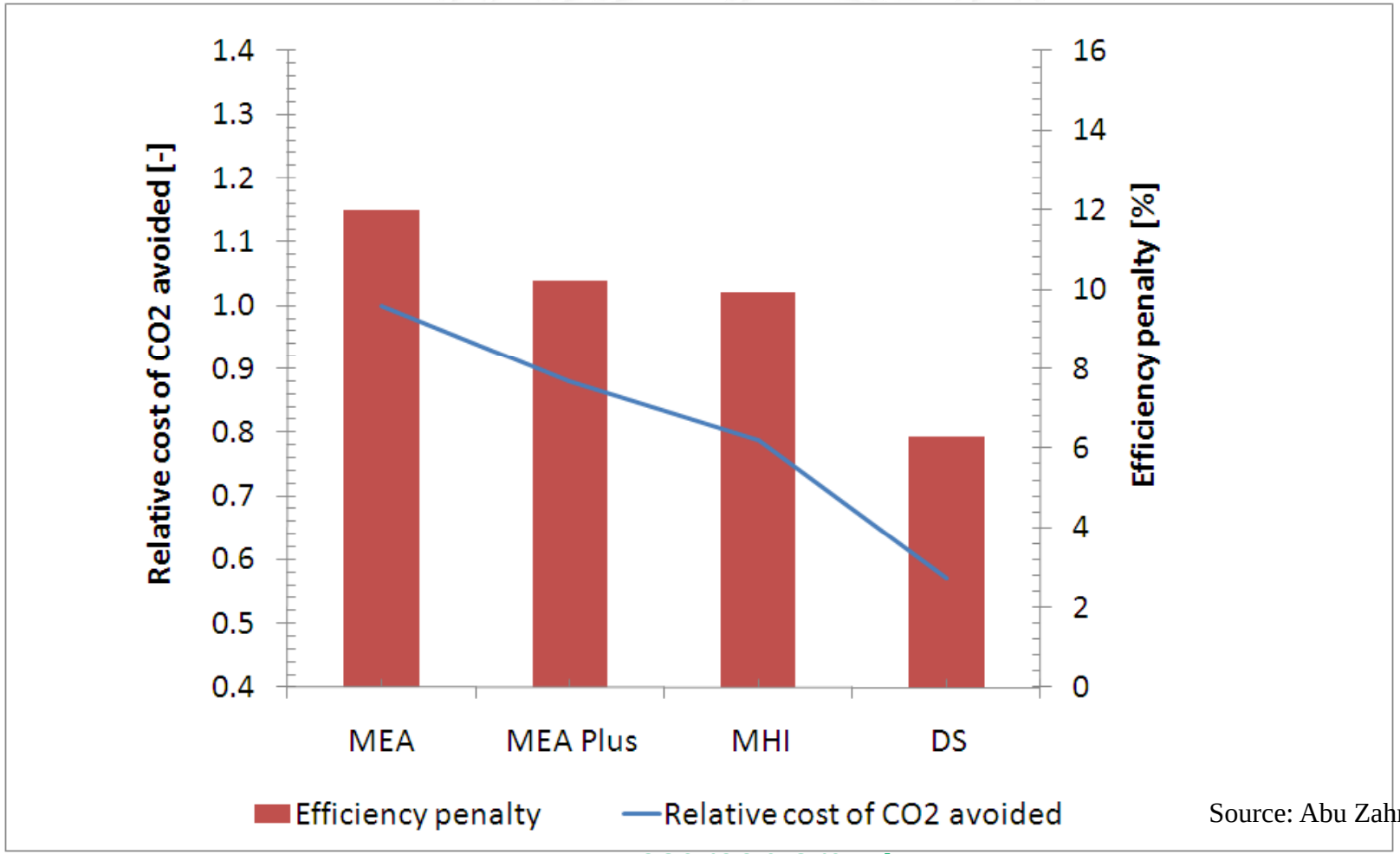
- Low total flue gas pressure
- Low CO_2 concentrations
- Very high flow rates (big columns)
- High energy demand in the reboiler (25-35% of power plant output)
- Impurities cause solvent degradation, loss of performance and equipment corrosion
- Solvent can be lost from the top of the absorber

Post-combustion capture: Impact on net power plant efficiency



Source: CO2Net lectures 2006

Improved solvent systems



Source: Abu Zahra 2009

Post-Combustion Capture 2nd/3rd Generation Solvent/Processes

Amine Solvents

Primary and Secondary Amines

$2(R\text{-}NH_2) + CO_2 \leftrightarrow R\text{-}NH\text{-}COO^- + R\text{-}NH_3^+$

Two solvent molecules required for each CO2 molecule sorbed.

Carbamates form.

Examples:

MEA

Ammonia

Tertiary and Hindered Amines

$R_3\text{-}N + CO_2 + H_2O \leftrightarrow R_3NH^+ + HCO_3^-$

One solvent molecule required for each CO_2 molecule sorbed, but slower rate.

Carbonates form.

Examples:

AMP

MDEA

Increasing reaction rate

Increasing capacity

Primary and Secondary amines

Ammonia

$2NH_3 + CO_2 \leftrightarrow NH_2COO^- + NH_4^+$

Alstom/EPRI, Powerspan/NETL; UK CAER/E-ON, CSIRO

Advantage –less degradation and so can handle more O_2, SO_X and NO_X

Disadvantage – solvent volatility means losses are high unless low temperatures are used.

Example:

Chilled Ammonia

Tertiary and Hindered Amines

a) Hindered amines

- Mitsubishi KS-1, Exxon Flexsorb PS
- Less solvent required.
- Slightly lower energy consumption.
- Lower rates of solvent degradation

b) Methyldiethanolamine (MDEA)- tertiary amine

- DOW, Huntsman, BASF
- Used industrially for H_2S removal in particular
- Slower kinetics which leads to greater tower height
- Improved through the use of promoters

Amino Acid Salts

$^{-}OOC\text{-}R\text{-}NRH + CO_2 + H_2O \leftrightarrow {}^{-}OOC\text{-}R\text{-}NRH_2^{+} + HCO_3^{-}$

Advantages – non- volatile

- Non – toxic and biodegradable
- Resistant to degradation by O_2, SO_X and NO_X

Examples:

BASF Puratreat

Siemens/TNO

Potassium Carbonate

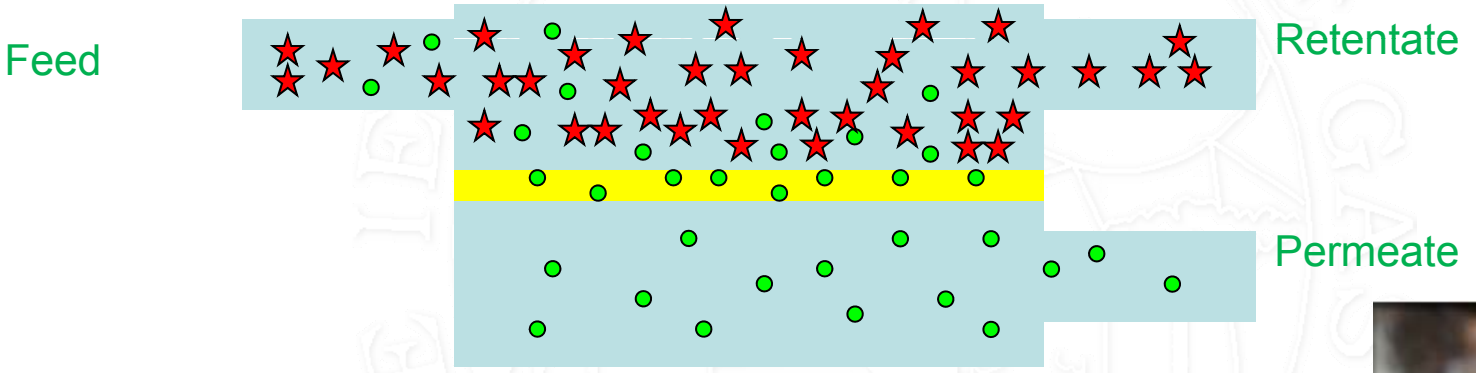
- $CO_3^{2-} + CO_2 + H_2O \leftrightarrow 2\ HCO_3^-$
- Non-volatile
- Non – toxic and biodegradable
- Resistant to degradation by O_2, SO_X and NO_X
- Slower kinetics which gives greater tower height. Improved through the use of promoters
- DOE/University of Illinois, CO2CRC

Comparison of Solvent Properties

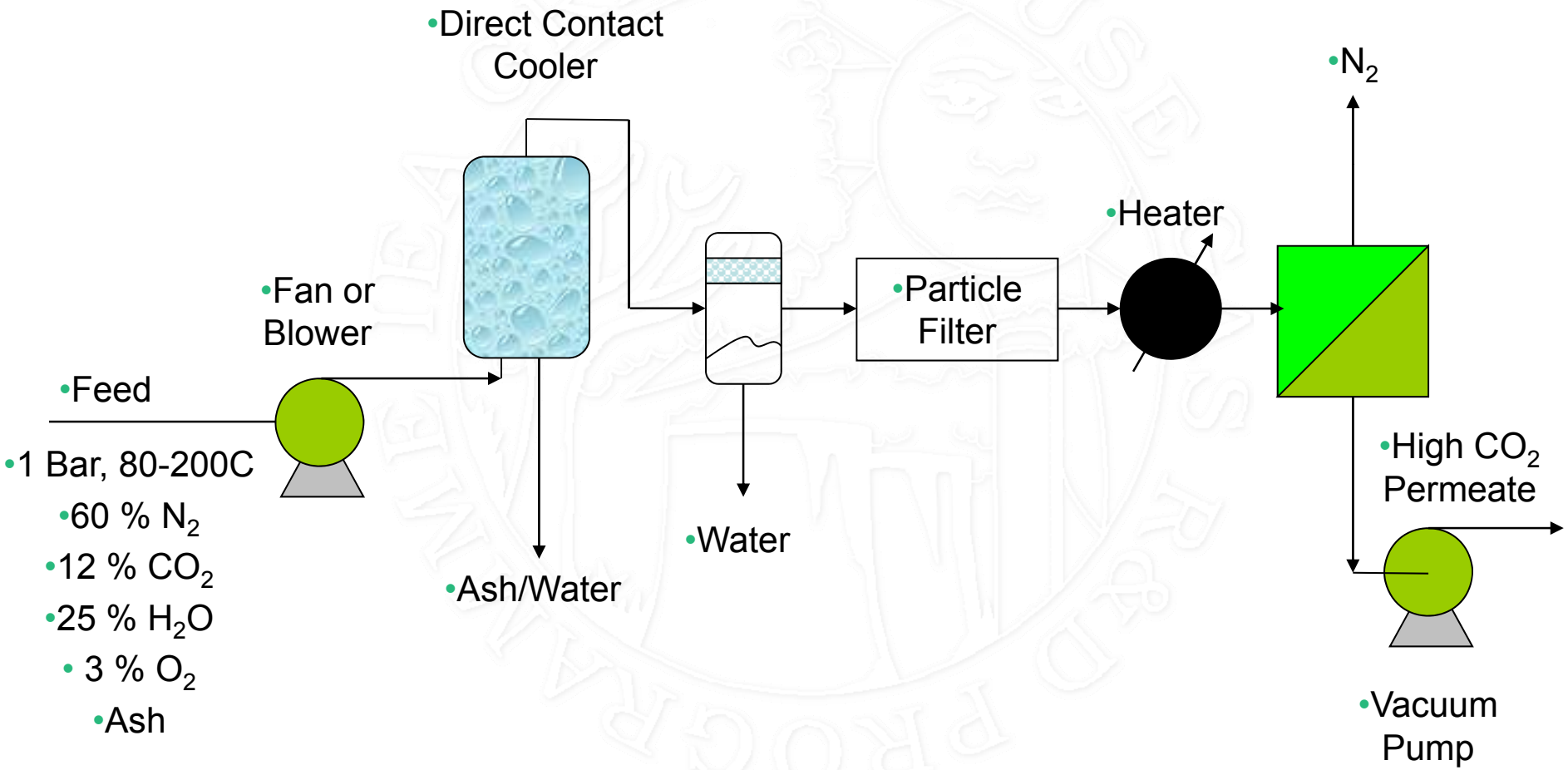
	Cost (US$/lb)	Volatility (atm x 10^3 at 40C)	Degradation	Corrosion	Stripper Steam Requirement
MEA	40	0.1	High	High	4.2
MDEA	300	0.003	Moderate	Moderate	3.3
Ammonia	5	200	None	High	
Potassium Carbonate	40	0	None	High	3.5

Membrane Technology

Selective membranes concept



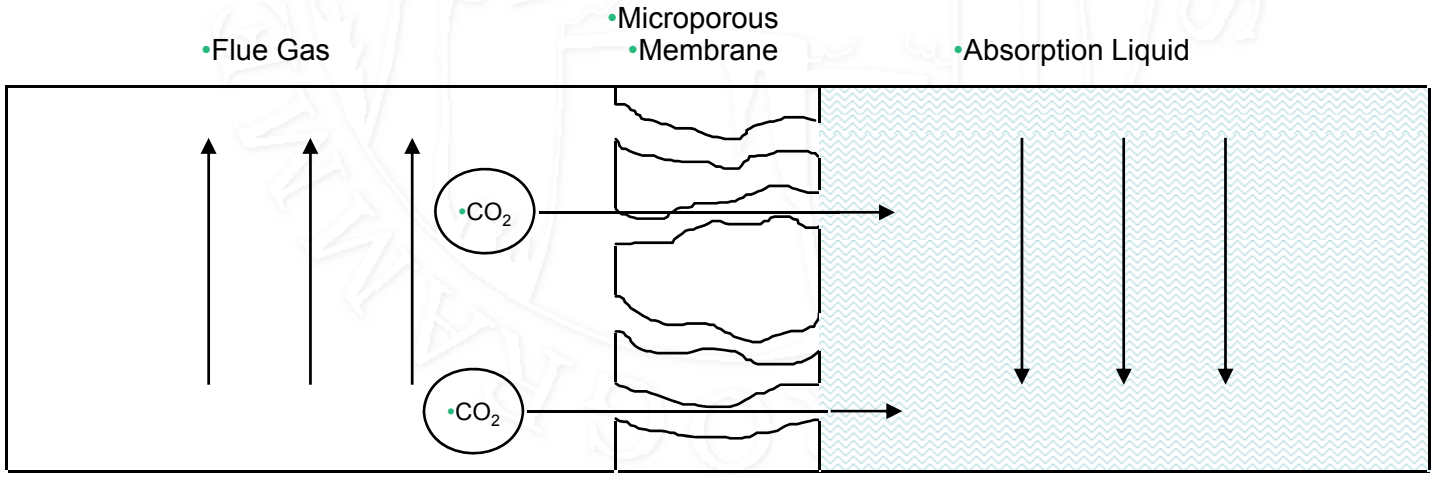
Coal Fired Post-Combustion Capture



Membrane Gas Absorption

Absorption liquid on one side of the membrane and the gas stream on the other side of the membrane

- The membrane must not be wetted by the absorption liquid
  - Size of the pores:
    - Large enough so that the CO_2 can easily pass through the membrane
    - Small enough so that the liquid will not wet the pores



Comparison to Conventional Absorption

Advantages

a) Higher Interfacial Area (1400-2200 m^2/m^3)
b) Independence of Phases
c) Operation in Any Orientation
d) Smaller footprint

Disadvantages

a) Membrane Resistance
b) Laminar Phase Flows
c) Transmembrane Pressure
d) Difficulties in Scale-Up
e) Compatible Membrane-Solvent System

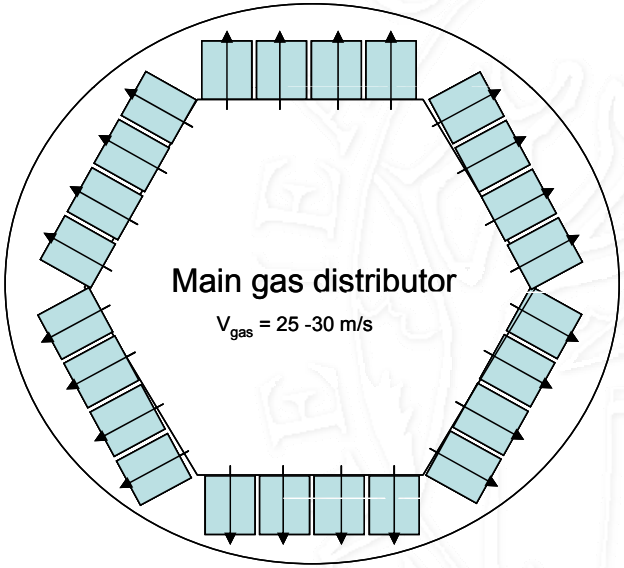
CASTOR base case – conventional absorber

Power plant			**Bituminous coal fired power plant [600 MW_e]**	**Gas fired combined cycle [393 MW_e]**
CO_2 product capacity	ton CO_2/hr		410	131
Equipment	**Parameter**	**Unit**		
Absorber column	Columns		2	2
	Dimension	m	Φ 10.9m x 28.1m	Φ 10.7m x 29.5m
	Volume of Packing	m^3	1448	1605

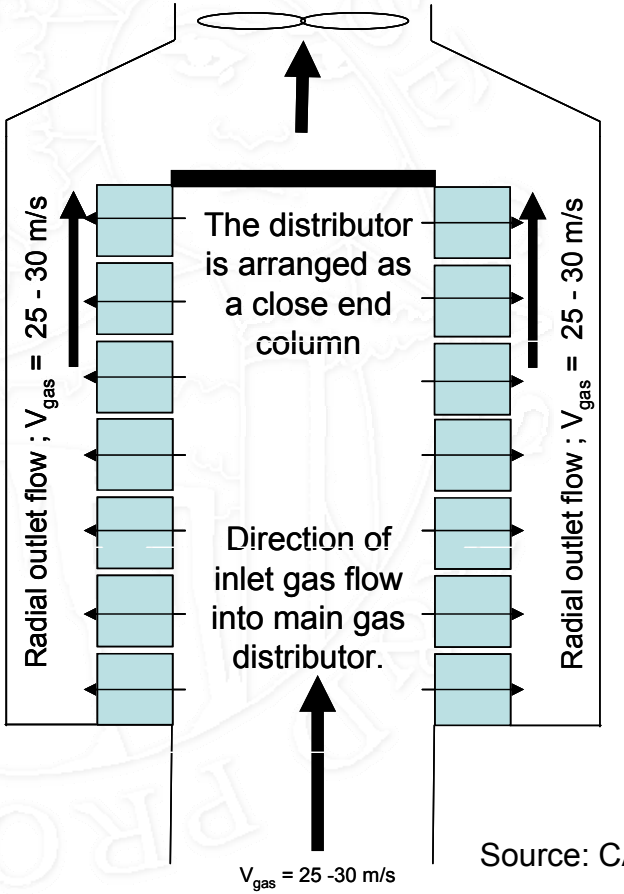
Source: CASTOR Project-TNO

Design of large scale membrane absorber

TOP VIEW



SIDE VIEW



= Membrane module gas channel
Vgas = 2 m/s

Source: CASTOR Project-TNO

Results coal-fired case

	Straight through	Radial flow
Total number of modules	481	481
Module length (m)	3.0	3.0
Gas speed in module (m/s)	2.0	2.0
Gas speed in distributor (m/s)	1.3	30.0
Total installed membr. area (m^2)	9.31E+05	9.31E+05
Min. height of contactor housing (m)	3	16
Number of contactor housings	1	1
Diameter of housing (m) (square)	22.0	11.2

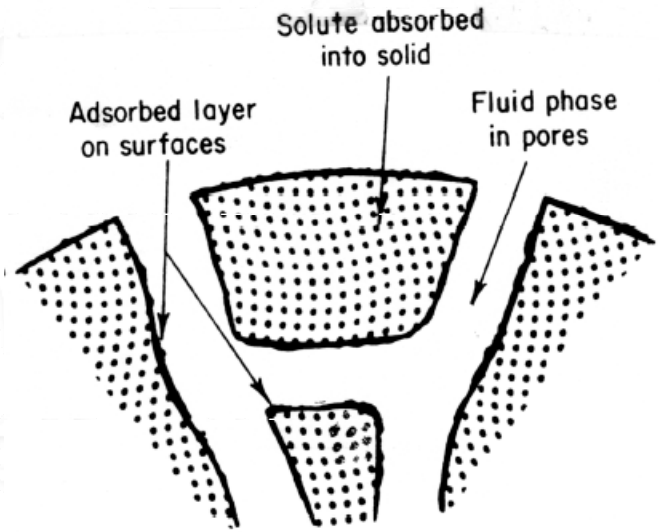
Source: CASTOR Project-TNO

Adsorption

Adsorption Theory

Adsorption utilizes a solid (usually granular, beads, pellets) material which is selective for one or more components in the gas phase.

Adsorption is proportional to the amount of surface. Therefore very porous solids are used (up to 3000m_2/gram)



Adsorbent Features

To be attractive commercially, an adsorbent should:

- have a large internal surface area.
- the area should be accessible through pores big enough to admit the molecules to be adsorbed. It is a bonus if the pores are also small enough to exclude molecules which it is desired not to adsorb.
- the adsorbent should be capable of being easily regenerated.
- the adsorbent should not age rapidly, that is lose its adsorptive capacity through continual recycling.
- the adsorbent should be mechanically strong enough to withstand the bulk handling and vibration that are a feature of any industrial unit.

Adsorption Processes

- PSA – pressure swing adsorption – pressure is varied
- VSA – vacuum swing adsorption – pressure is varied from a vacuum to some value above atmospheric pressure.
- TSA – temperature swing adsorption – temperature is varied.
- ESA – electrical swing adsorption – a current is applied cyclically to a conducting adsorbent such as a carbon.

Issues for post-combustion CO_2-capture

- Solvent technologies are leading option but currently:
  - Power cost increases >50%
  - Generation efficiency decreases by 15 – 35%
- Solvent process break-throughs required
  - Energy requirements
  - Reaction rates
  - Contactor improvements
  - Liquid capacities
  - Chemical stability/corrosion
  - Desorption process improvements
  - Hence cost reductions
- Integration with power plant
  - Heat integration with other process plant
  - Concepts for “capture readiness”

Post Combustion Where to Focus!!?

- Perfect solvent: Higher capacity, lower regeneration energy, stable and cheaper ….
- Heat integration with the power plant
- Heat recovery (top of stripper, heat exchangers..)
- Cheaper equipments (absorber > 45% of CAPEX)

Summary: Post-combustion capture

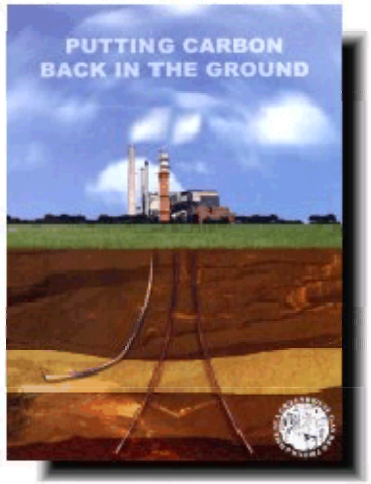
- Chemical absorption is currently most feasible technology
- Technology is commercially available, although on a smaller scale than envisioned for power plants with CO_2 capture (>500 MW_e)
- Energy penalty and additional costs are high with current solvents. R&D focus on process integration and solvent improvement.
- CO_2 capture between 80-90%
- Power cycle itself is not strongly affected (heat integration, CO_2 recycling)
- Retrofit possibility

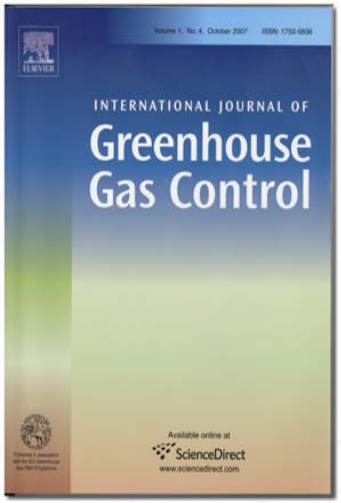
Conclusions

- Solvent Absorption with MEA is the minimum risk approach to carbon dioxide capture
- Costs can be reduced (but risk increases) by use of alternate solvents
- Membranes, adsorbents and others have potential as Gen II/III solutions.

IEA Greenhouse Gas R&D Programme

- General - www.ieagreen.org.uk
- CCS - www.co2captureandstorage.info





GHGT-10

19th – 23rd September 2010

Amsterdam

www.ghgt.info/ghgt10.hmtl

PRECOMBUSTION TECHNOLOGY

for Coal Fired Power Plant

by

Monica Lupion

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

16th November 2009. Hassi Messaoud (Algeria)

*Corresponding Author's Email: m.lupion@ciuden.es

Presentation Outline

- Introduction
  - General overview of the Pre-Combustion Technology
- Gasification
  - Technology Overview
  - Basic Chemistry
  - Types of Gasifiers
  - Combustion versus Gasification
- IGCC
  - IGCC Overview
  - IGCC Comparison
  - Large Scale IGCC Projects
  - Key IGCC Market Barriers
- IGCC with CO_2 Capture
  - General Overview
  - Economics of IGCC with CO_2 capture

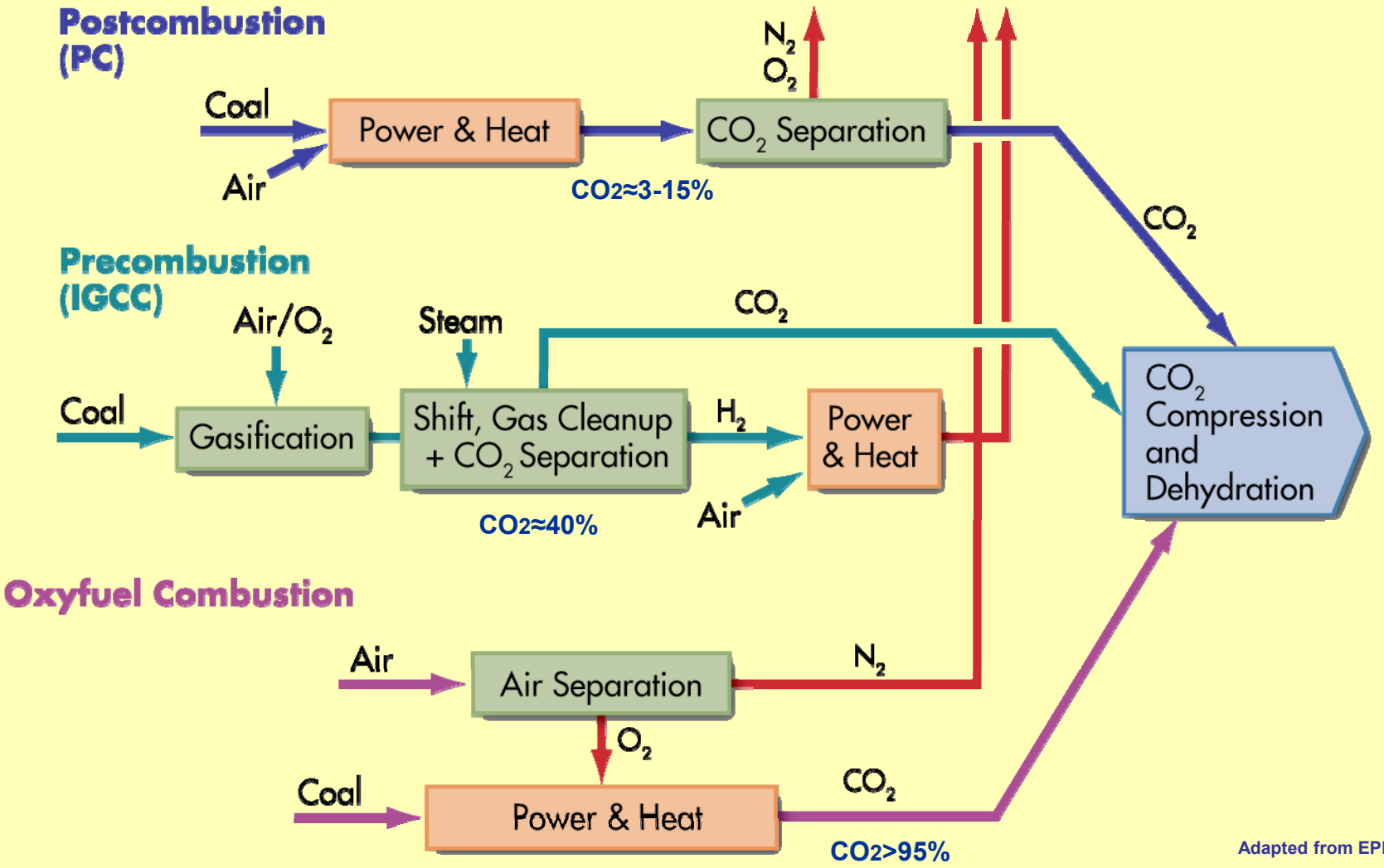
Introduction

General overview of the Pre-Combustion Technology

General Overview of Pre-Combustion Technology

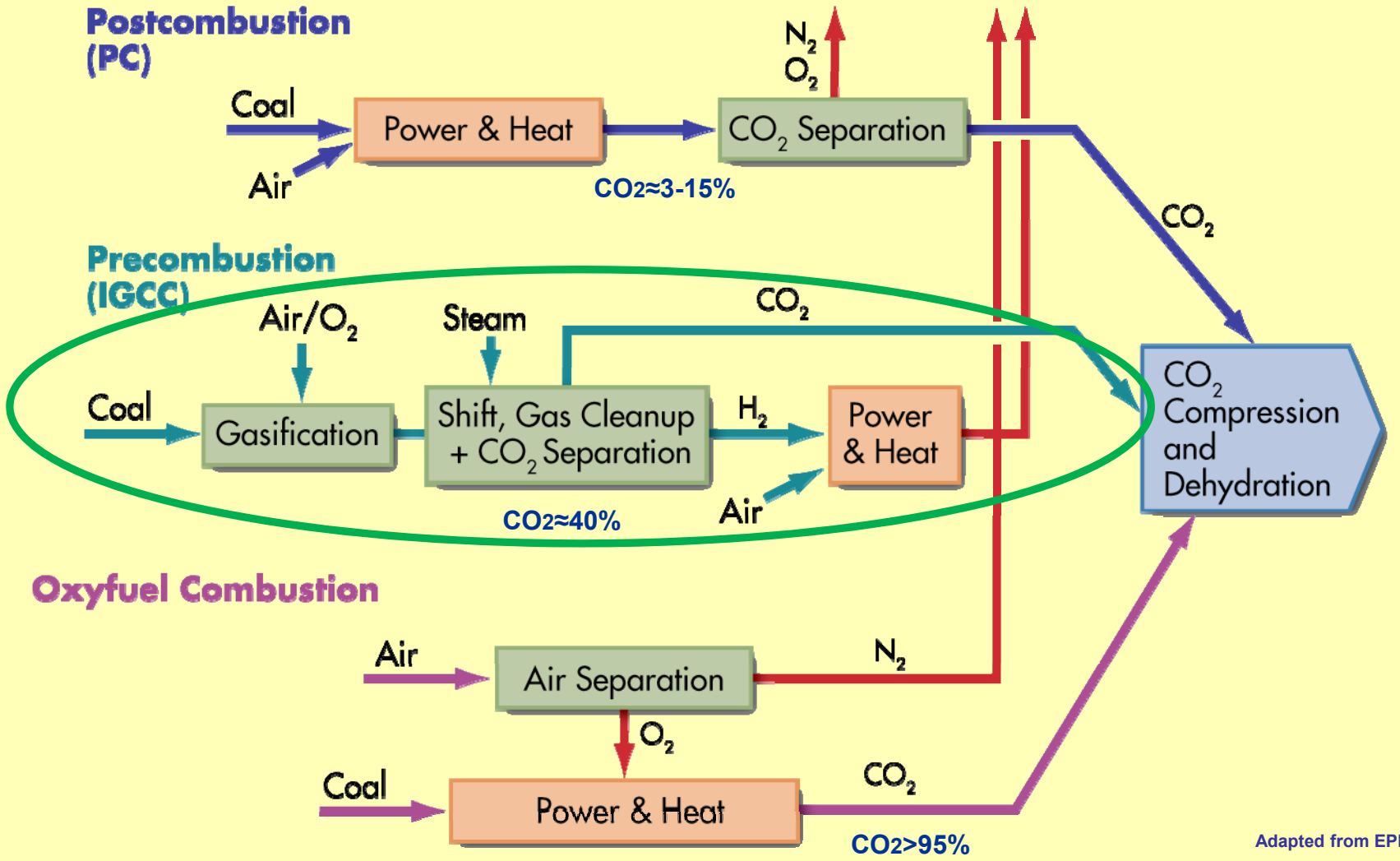
- Pre-combustion capture process is not a new concept
  - Primarily based on production of synthetic gas, separating the CO_2 and using the decarbonised gaseous fuel for the gas turbine
- One of the main elements is the gasification of the fuel feedstock to produce syngas
- Gasification technologies could produce a waste gas stream, which has high concentration of CO_2
  - This offers an opportunity to capture CO_2 at low cost
- It should be noted that CO_2 capture is not a process requirement, but could be easily implemented if warranted

General Overview of Pre-Combustion Technology



Adapted from EPRI 2007

General Overview of Pre-Combustion Technology



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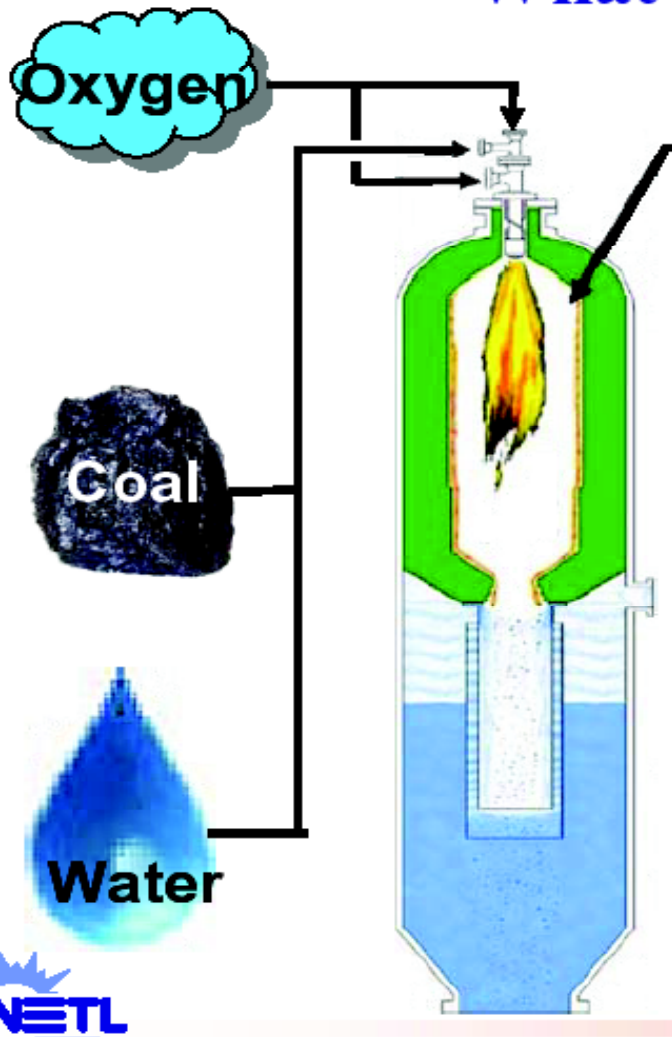
Gasification

Technology Overview

What is Gasification?



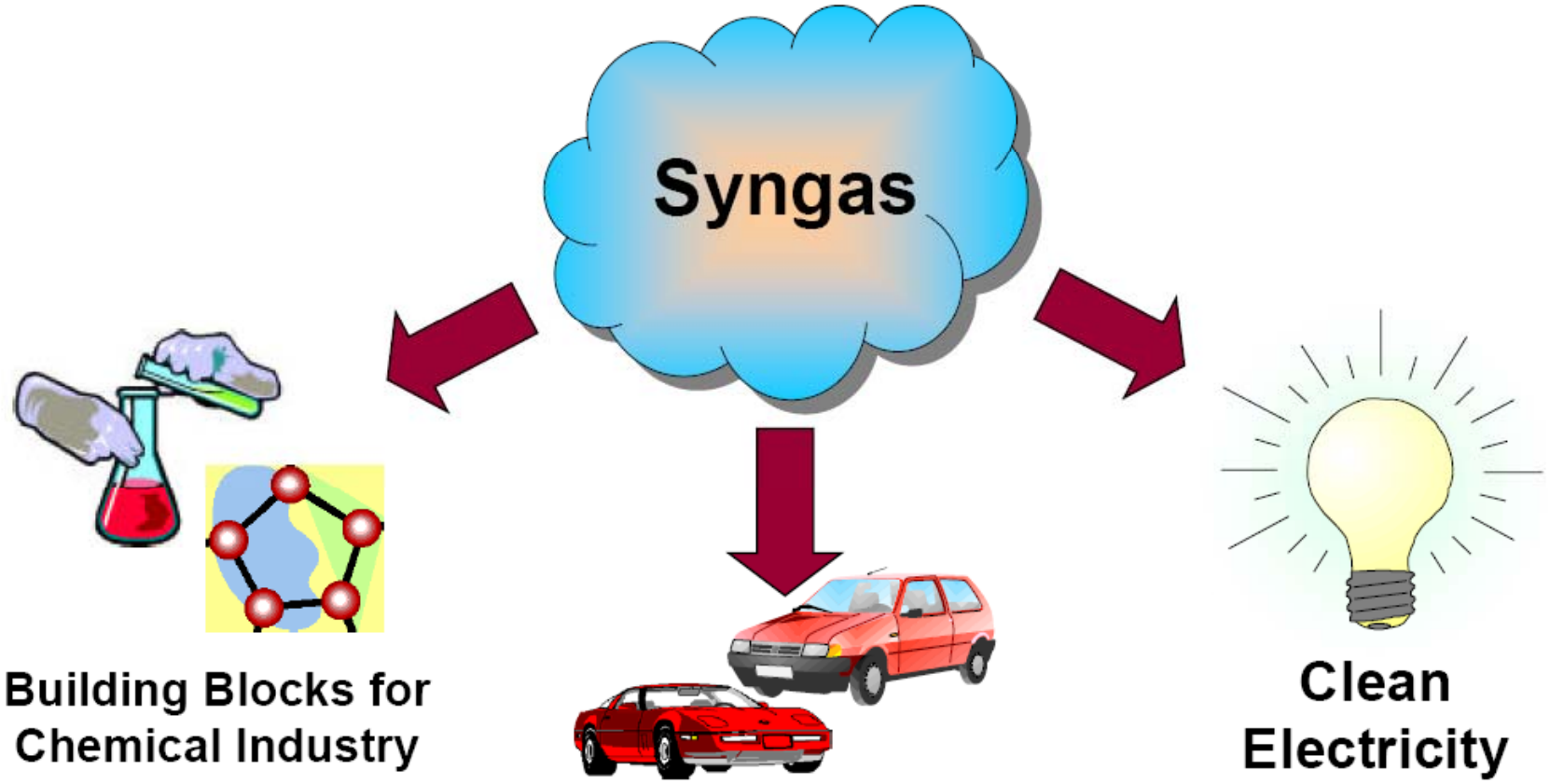
Extreme Conditions:
- 500 psig or more
- 2,600 Deg F
- Corrosive slag and H_2S gas

Products (syngas)
CO (Carbon Monoxide)
H_2 (Hydrogen)
[CO/H_2 ratio can be adjusted]

By-products
H_2S (Hydrogen Sulfide)
CO_2 (Carbon Dioxide)
Slag (Minerals from Coal)

Gas Clean-Up **Before** Product Use

So what can you do with CO and H_2 ?



Gasification

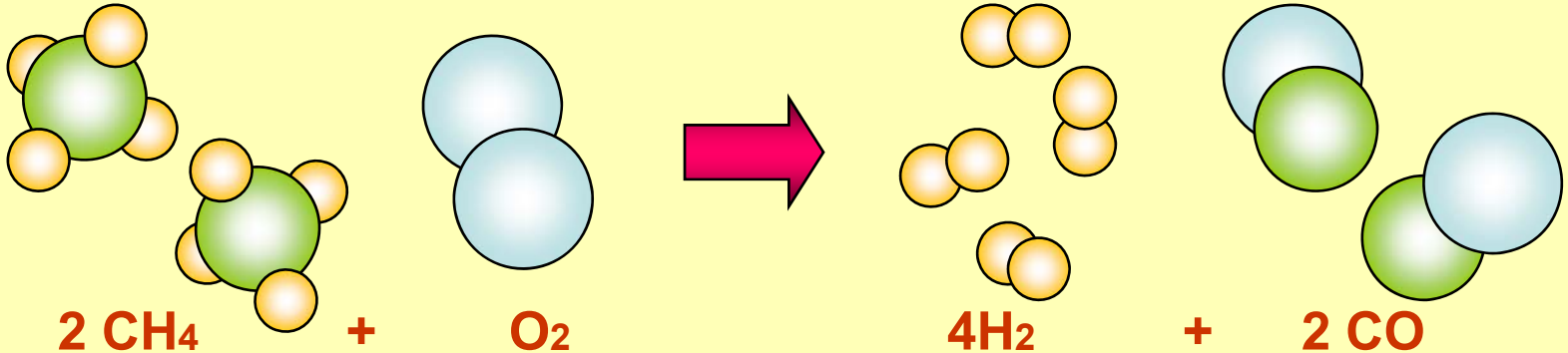
Basic Chemistry

Technology Overview: Basic Chemistry

A *partial* oxidation process that can convert any hydrocarbon into hydrogen and carbon monoxide (synthesis gas or syngas)

$$(CH)_n + O_2 \longrightarrow H_2 + CO$$

For example:



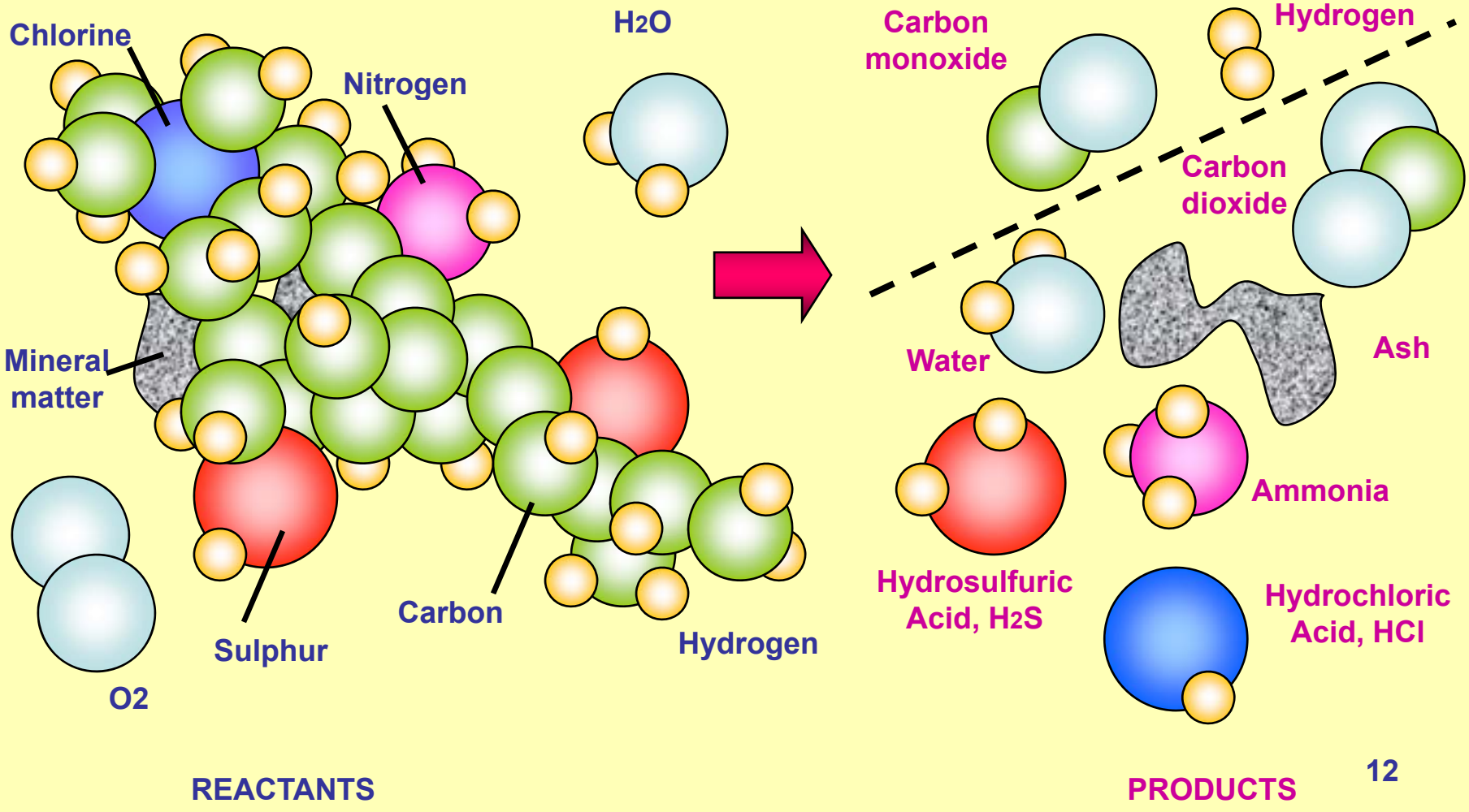
$2\ CH_4$ + O_2 $4H_2$ + $2\ CO$

[Methane] [Oxygen] [Hydrogen] [Carbon Monoxide]

Process Conditions: ≈ 950-1550 C, 25-70 bar

Technology Overview: Basic Chemistry

Severe thermo-chemical operating conditions



Technology Overview: Basic Chemistry

CONCEPT

Partial oxidation process to produce syngas

GASIFICATION AGENTS

- Elemental OXYGEN: AIR → POOR SYNGAS ($CO + H_2 + N_2$)
- Elemental OXYGEN: O_2
- Combined OXYGEN: H_2O → WATER SYNGAS ($CO + H_2$)
- Mixtures OXYGEN/WATER

IDEAL GASIFICATION

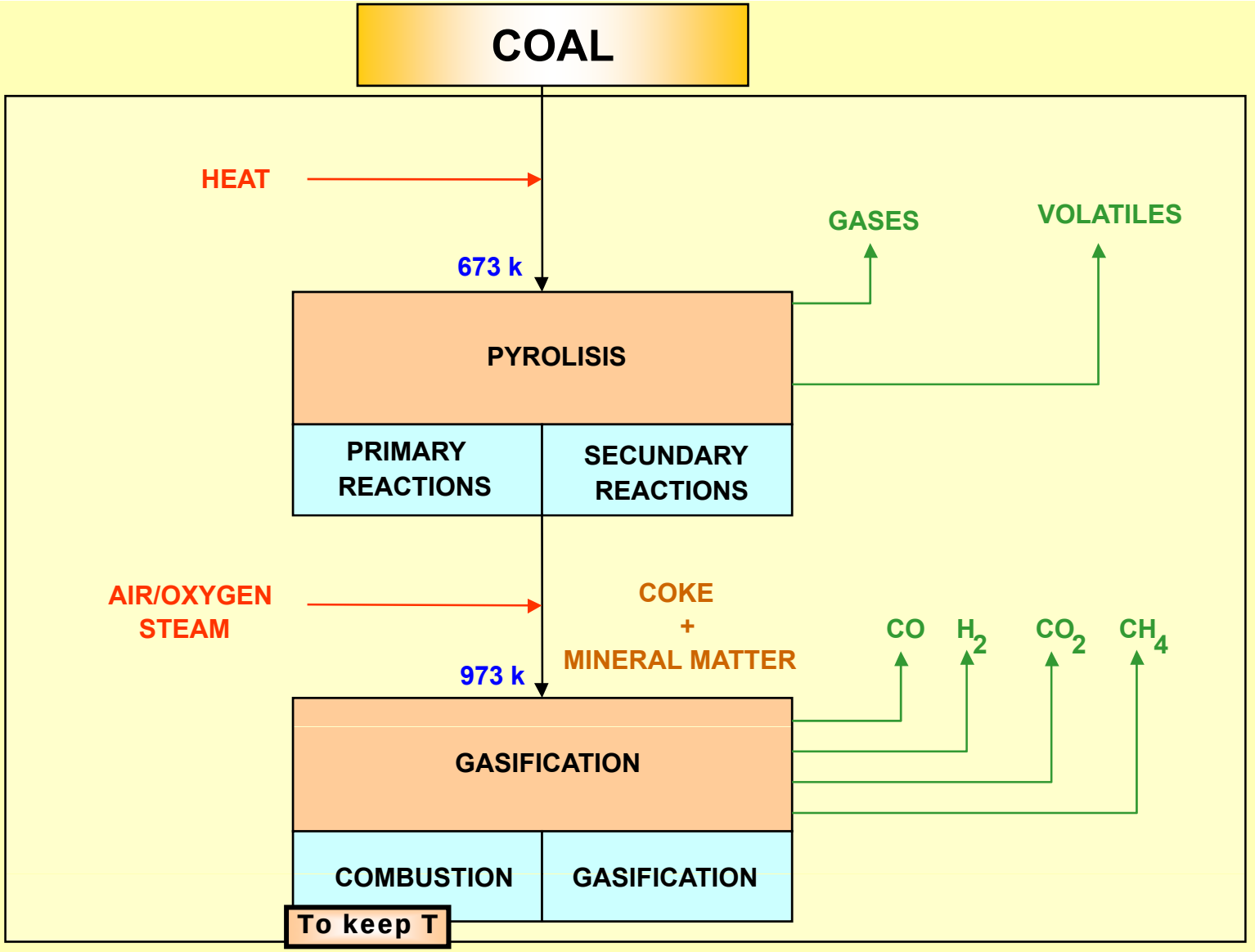
- CARBON → CARBON MONOXIDE
- INEFFICIENCIES:
  - PARTIAL FORMATION CO_2
  - INCOMPLETE CARBON OXIDATION
- COLLATERAL REACTIONS:
  - PYROLISIS
  - HYDROGENATION ($C + 2\,H_2 \longrightarrow CH_4$)

Chemistry & Reactions

The following reactions are important in coal gasification:

Coal Devolatilization = CH_4 + CO + CO_2 + Oils + Tars + C (Char)	
$C + O_2 = CO_2$	(exothermic – rapid)
$C + 1/2O_2 = CO$	(exothermic – rapid)
$C + H_2O = CO + H_2$	(endothermic – slower than oxidation)
$C + CO_2 = 2CO$	(endothermic – slower than oxidation)
$CO + H_2O = CO_2 + H_2$	Shift Reaction (slightly exothermic– rapid)
$CO + 3H_2 = CH_4 + H_2O$	Methanation (exothermic)
$C + 2H_2 = CH_4$	Direct Methanation (exothermic)

Technology Overview: Basic Chemistry



Gasification

Types of Gasifiers

Technology Overview: Gasifiers

3 MAYOR TYPES OF GASIFIERS

- Moving Bed
- Fluidized Bed
- Entrained Flow

GASIFIERS CHARACTERISATION

- Reactants and products inlet
- Particle size
- Resident time
- Operating Temperature
- Operating Pressure

BASIC GASIFICATION CHEMISTRY

- Gasifier Vessel: $C_xH_y + O_2 \rightarrow CO + H_2$
- Water/Gas Shift: $CO + H_2O \rightarrow H_2 + CO_2$

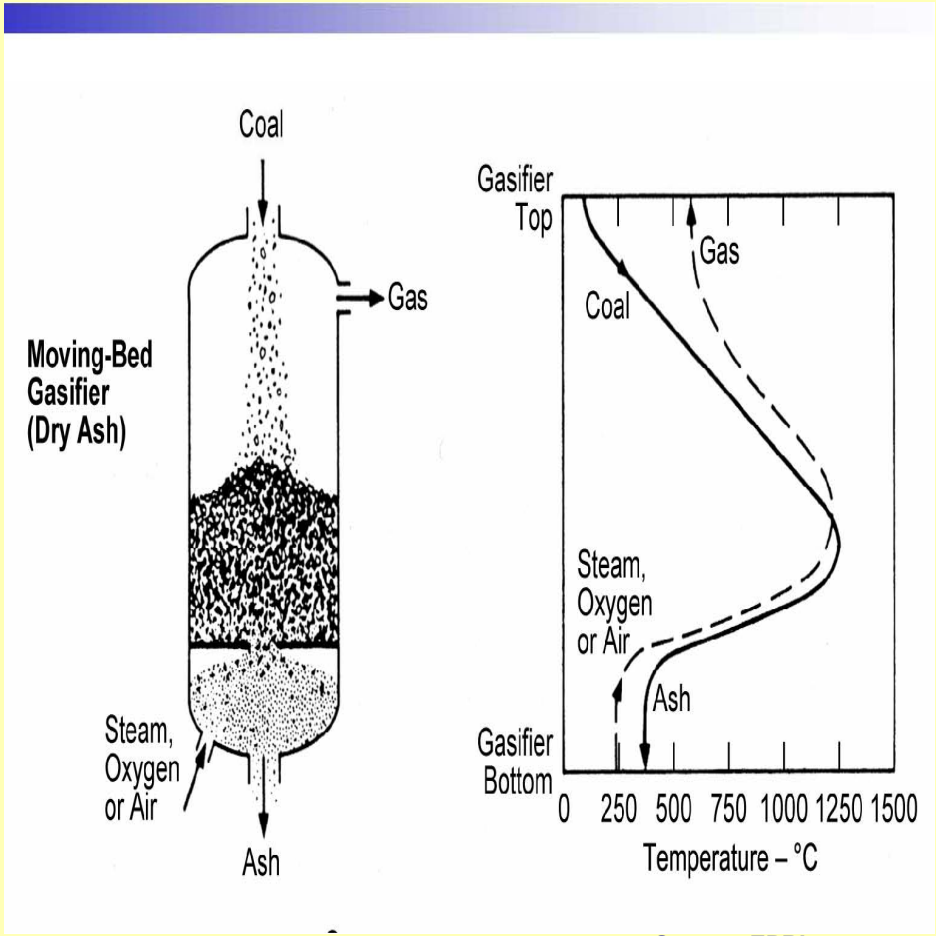
Technology Overview: Gasifiers

First Generation Gasifiers

	C %	Resident time	Pressure (bar)	Temperature (°C)	Particle Size
Moving Bed (LURGI)	99	1-1/2 h	30	1100	>10 mm
Fluidized Bed (WINKLER)	70	3/4 h	1	900	0-10 mm
Entrained Flow (KOPPERS-TOTZEK)	88-98	Few seconds	1	1500	70% 200 mesh x down (dry)

Moving Bed Gasifiers

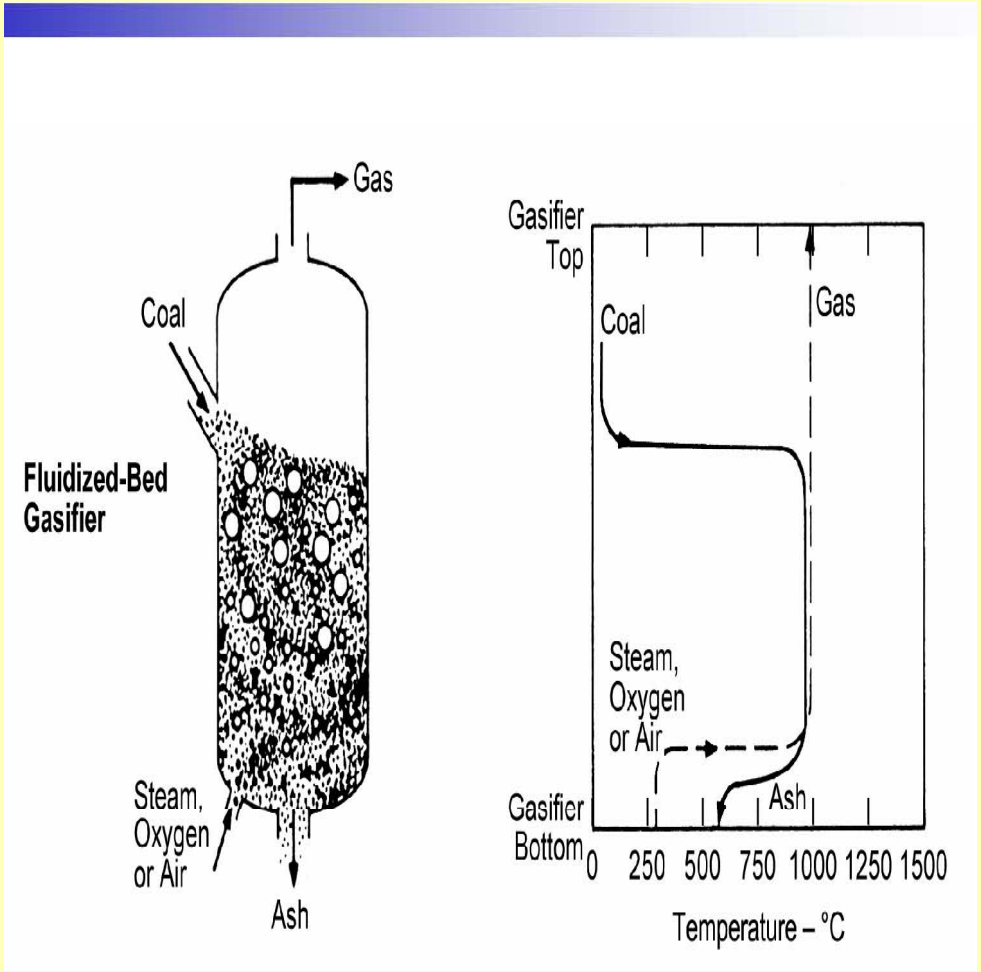
Dry carbon fuel is fed through the top of the gasifier. As it slowly drops through the vessel, it reacts with steam and oxygen as they flow in opposite in directions over the bed. The fuel goes through the process until it is completely spent leaving behind low temperature syngas and dry ash. Trace contaminants are later scrubbed from the syngas



Source: EPRI

Fluidized Bed Gasifiers

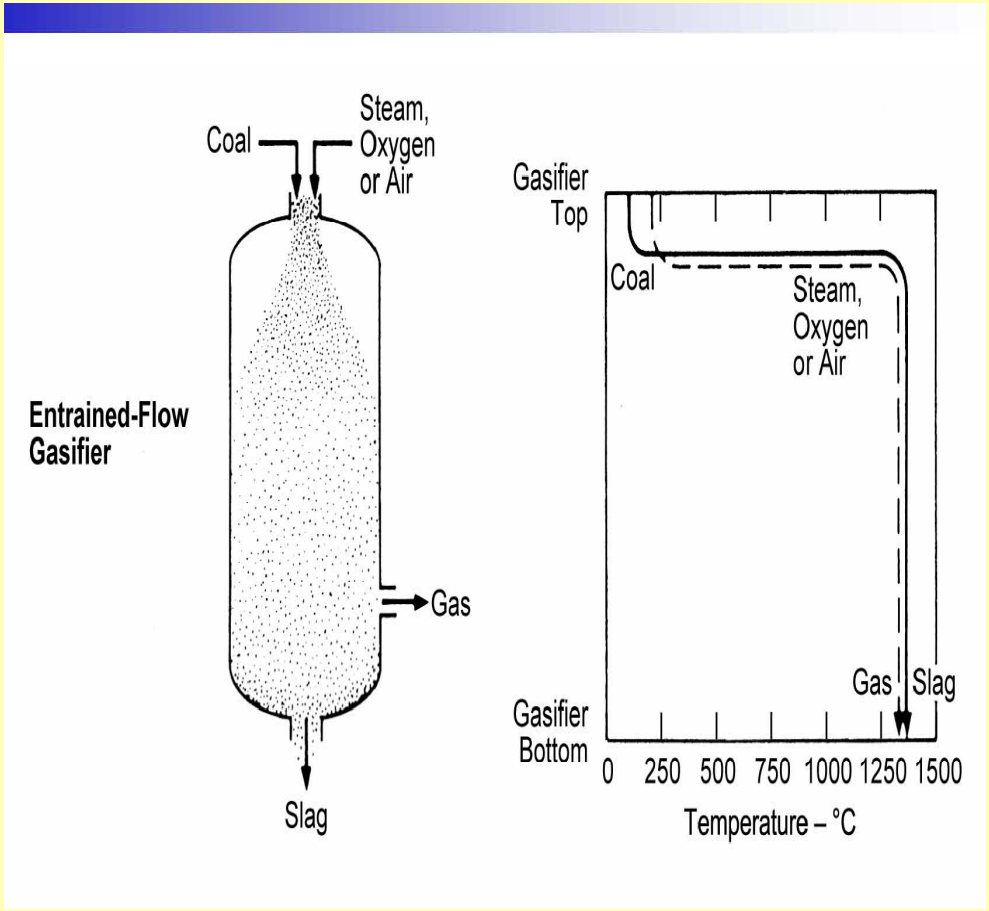
Steam and oxygen flow upwards through the reactor tower while fuel is injected into, and remains suspended in, this stream while gasification takes place. Moderate temperature syngas exits the while dry (unmelted) ash is evacuated at the bottom



Source: EPRI

Entrained Flow Gasifiers

Fuel can be fed dry or wet (mixed with water) into the gasifier. The reactants (steam and oxygen) flow uni-directionally through the gasifier, as the stages of gasification take place, until high temperature syngas exits the reactor. Molten slag drops out at the bottom



Source: EPRI

Gasification

Combustion vs Gasification

Combustion vs Gasificacion

Combustion

- SO_2 & SO_3 is scrubbed out of stack gas – reacted with limestone to form gypsum
- NO_X controlled with low NO_X burners and catalytic conversion (SCR)
- Flyash removed via ESP or bag filters
- Hg can be removed by contacting flue gas with activated carbon

Gasification

- H_2S & COS are easily removed from syngas and converted to solid sulfur or sulfuric acid
- NH_3 washes out of gas with water, thermal NO_X controlled by diluent injection, optional SCR for deeper NO_X removal
- Ash is converted to glassy slag which is inert and usable
- >90% of Hg removed by passing high pressure syngas thru activated carbon bed

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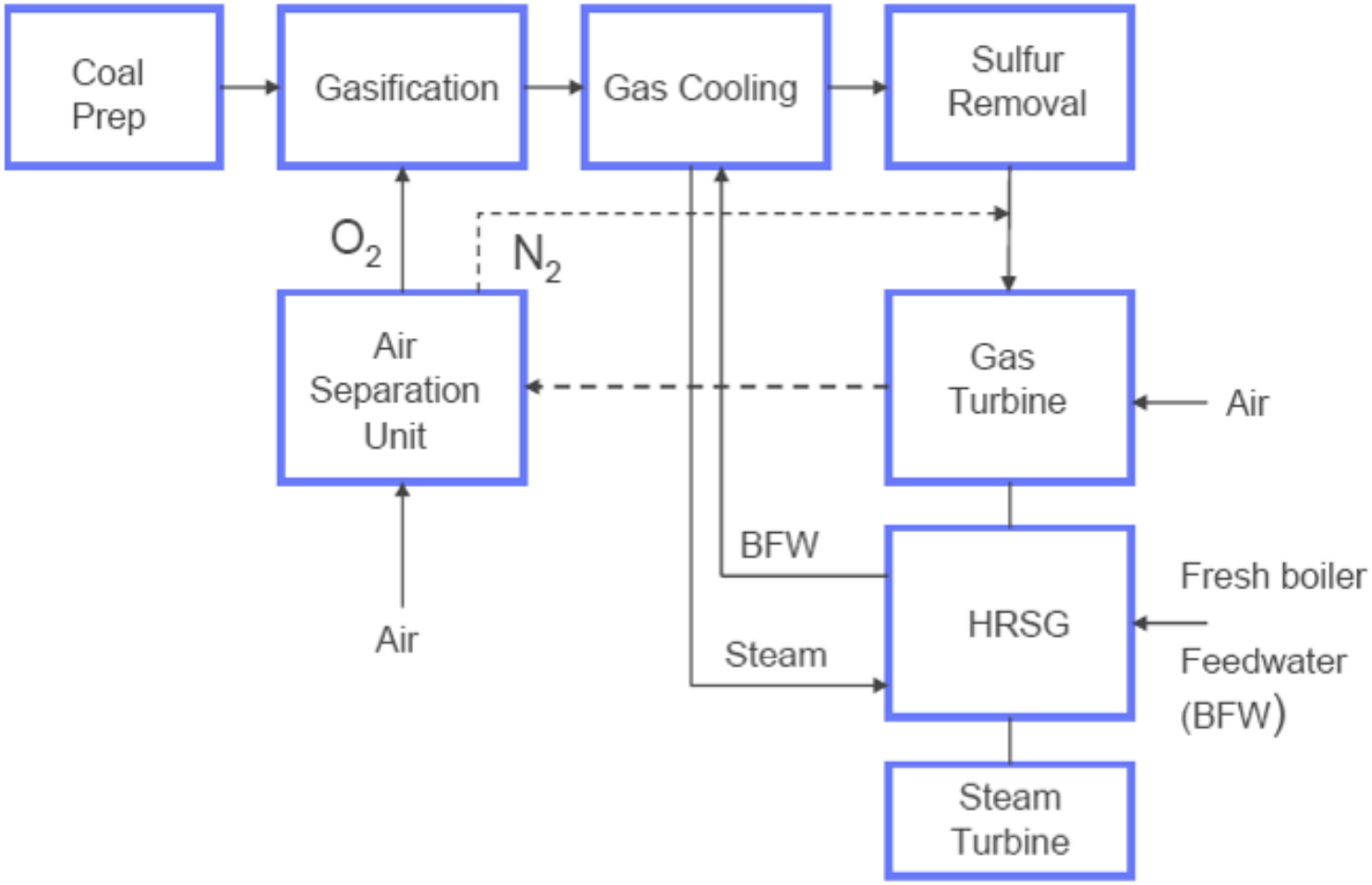
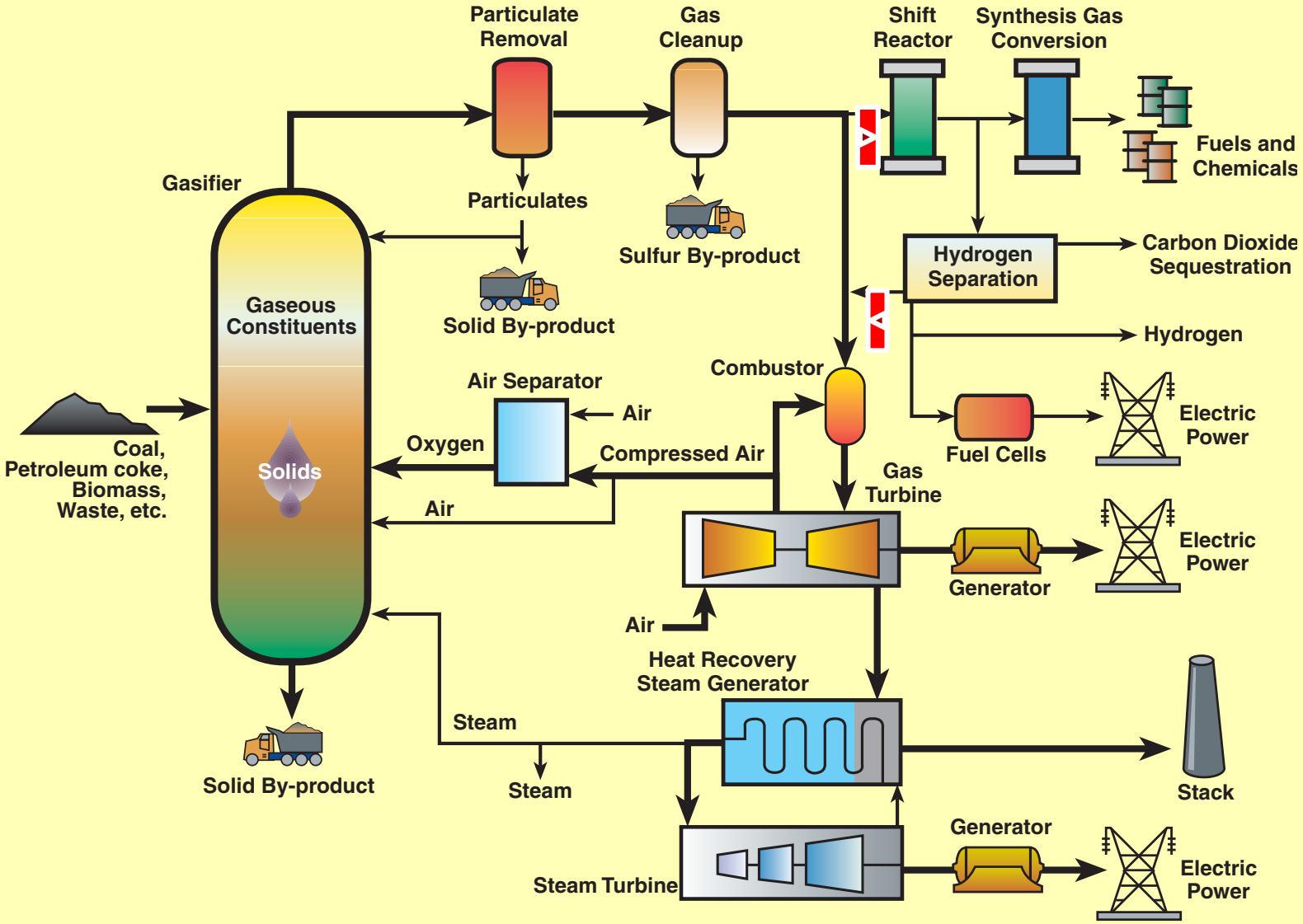
IGCC

IGCC overview

IGCC Overview



IGCC Overview



IGCC

IGCC Comparison

IGCC vs Conventional Coal PS

- Pre-combustion clean-up of fuel prior to power generation
- Environmental Technology => Greatest potential for future
  - ✓ Proven lowest NO_X, SO_X, particulate matter and lower hazardous air pollutants
  - ✓ Proven mercury and carbon dioxide removal
  - ✓ Lower water usage, lower solids production
  - ✓ Sulfur and non-leachable slag by-products
  - ✓ CO_2 under pressure takes less energy to remove than from PC flue gas at atmospheric pressure (Gas volume is <1% of flue gas from same MW size PC)
- Proven polygeneration flexibility, now and in future
  - ✓ Power, hydrogen, steam, chemicals, zero-sulfur diesel
- Practical opportunity to retrofit carbon capture equipment

Solid Wastes

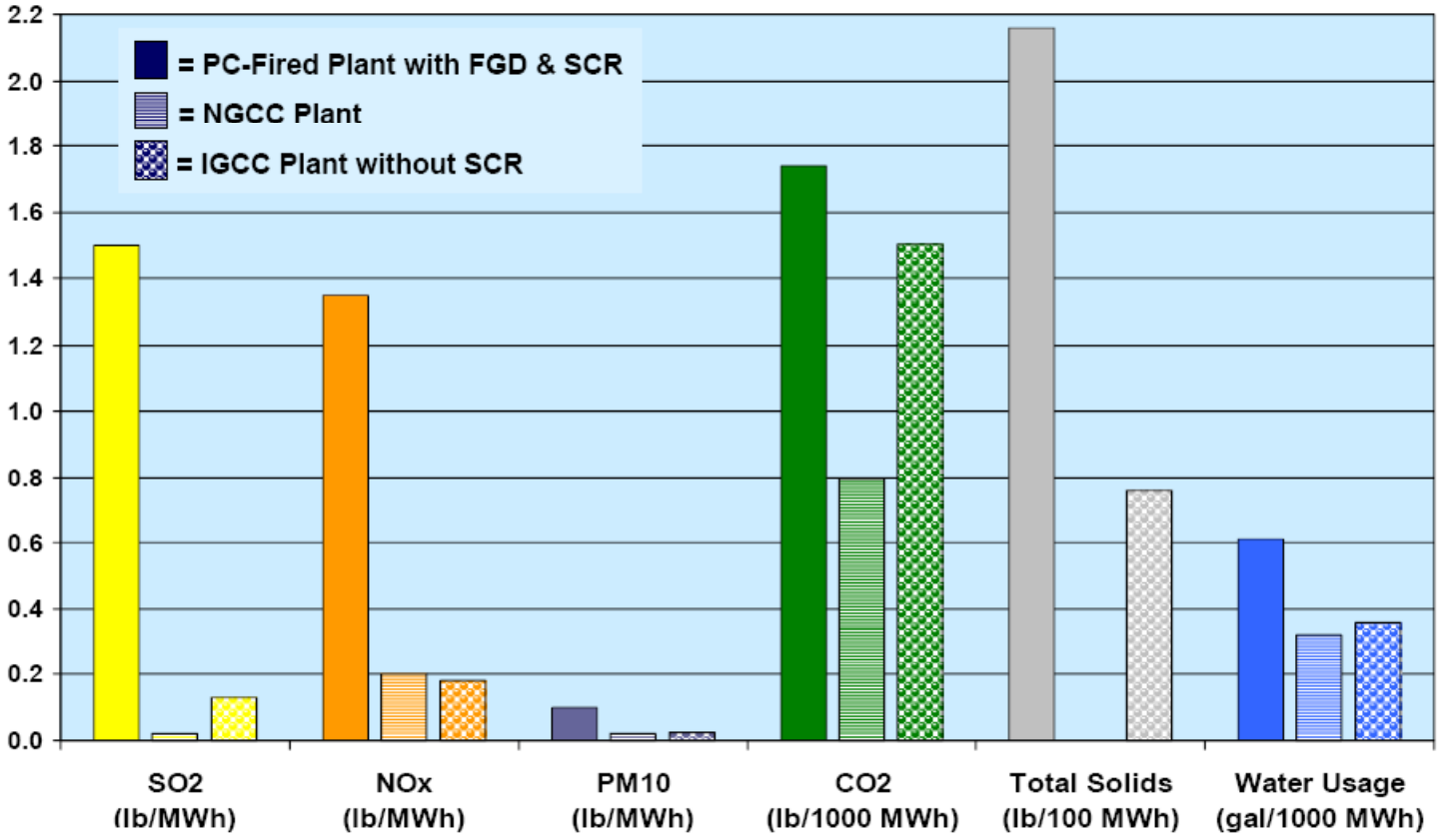
- ✓ Less Volume: IGCC produce about half the solid wastes of conventional coal plants
- ✓ Better Form: IGCC solid wastes are less likely to leach toxic metals than fly ash from conventional coal plants because IGCC ash melts and is vitrified (encased in a glass-like substance)

Water Use

- ✓ Less Water: IGCC units use 20%-50% less water than conventional coal plants and can utilize dry cooling to minimize water use

IGCC vs Conventional Coal PS

Comparison of Environmental Factors
Pulverized Coal-Fired, NGCC, and IGCC Plants



* Based on 1998 Parson study for DOE : "Market-Based Advanced Coal Power Systems"

IGCC

Large Scale IGCC Projects

Coal IGCC in Operation Worldwide

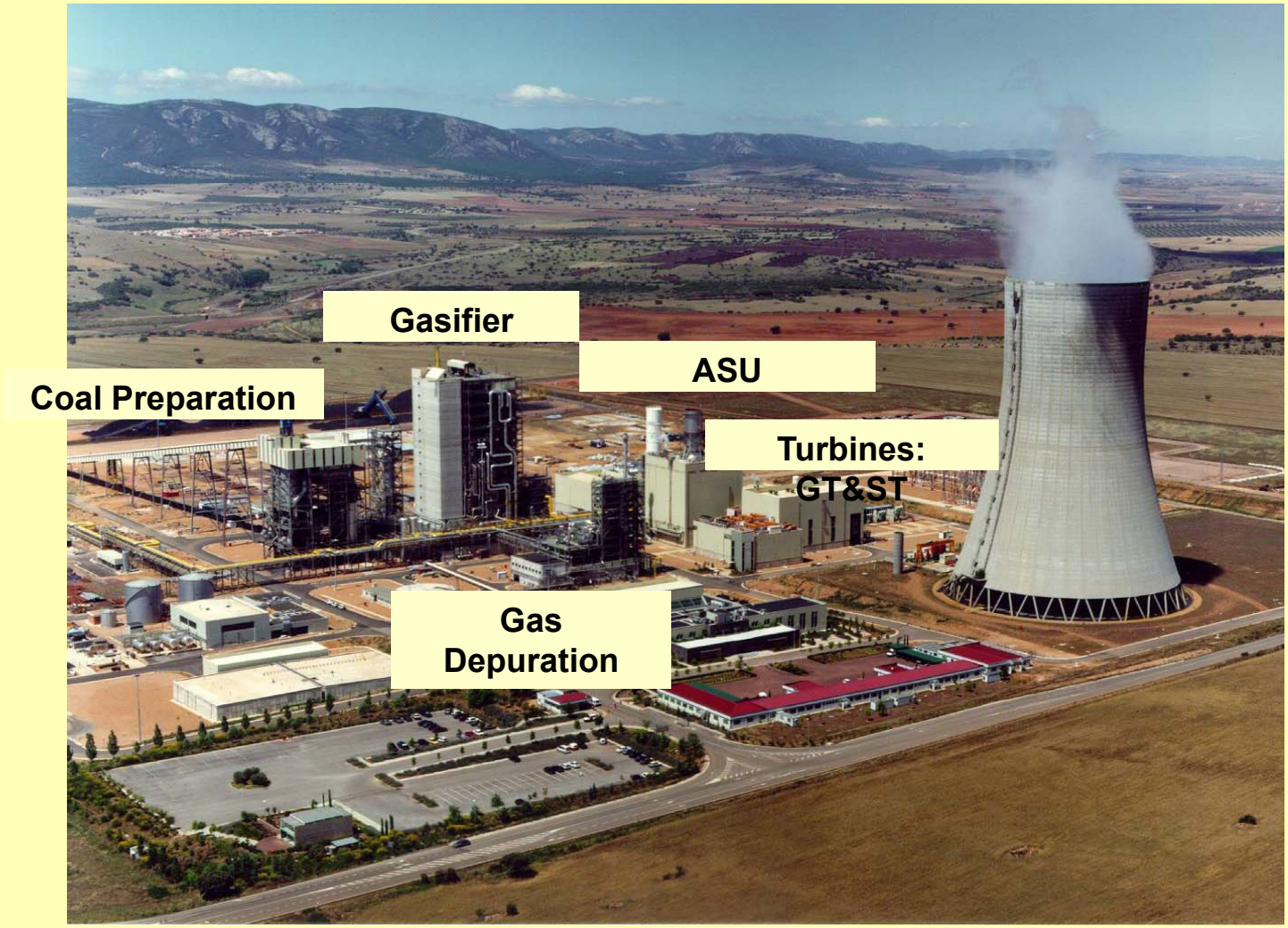
Projects Site	Buggenum Netherland	Puertollano Spain	Wabash River USA	Tampa USA	Nakoso Japan
Gasifier type	O_2-blown Dry-feed Shell	O_2-blown Dry-feed Plenflo	O_2-blown Slurry-feed E-Gas™	O_2-blown Slurry-feed GE	Air-blown Dry-feed MHI
Coal consumption (metric t/d)	2,000 t/d	2,600 t/d	2,500 t/d	2,500 t/d	1,700 t/d
Gross output (GT)	284 MW 1,100˚C-class	335 MW 1,300˚C-class	297 MW 1,300˚C-class	315 MW 1,300˚C-class	250MW 1,200˚C-class
Demonstration test start	Jan. 1994	Dec. 1997	Oct. 1995	Sep. 1996	Sep. 2007

Nuon- Buggenum, Netherlands 250 MW IGCC

Wabash 260 MW IGCC Repowering

Tampa Electric - Polk 250 MW IGCC

300 MWe ELCOGAS IGCC (Puertollano, Spain)



250MWe Air Blown IGCC (Fukushima, Japan)

IGCC

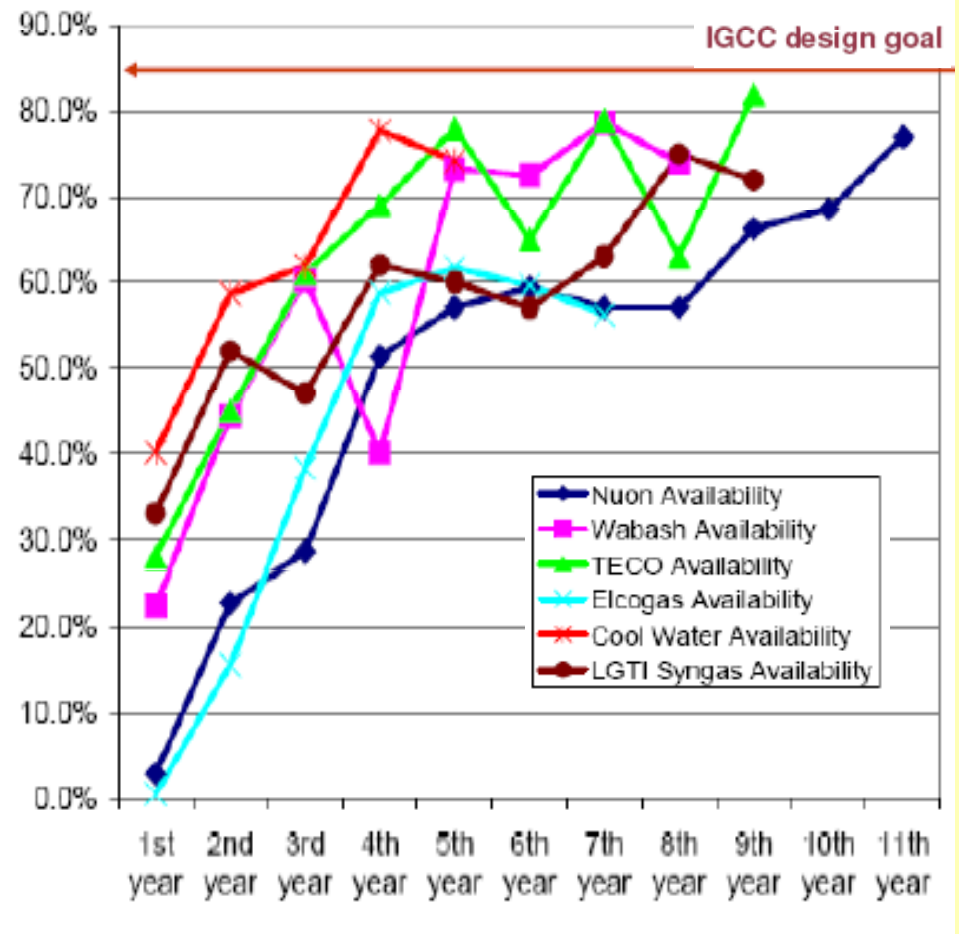
Key IGCC Market Barriers

Key IGCC Market Barriers

- Unfamiliar and uncomfortable technology to power industry: “chemical plant” not combustion boiler
- Currently higher capital and operating costs relative to supercritical boilers
- Standard designs and guarantee packages not yet fully developed
- Reluctance of customers to be “early adopters”, and assume technology application risk
- Environmental benefits threaten existing coal power fleet
- Questions about feasibility and cost using low-rank coals, particularly lignite
- IGCC is an emerging industry, vs. established boiler industry
- Real interest in coal gasification to SNG, zero sulfur diesel, ammonia and other chemicals will assist IGCC development

Key IGCC Market Barriers

- Will reliability hinder the deployment of IGCC?
- Record for IGCC's availability has been poor but improving.
- Complexity of the plant could be a turn off to prospective investors or power generation company
- Cost is another issue

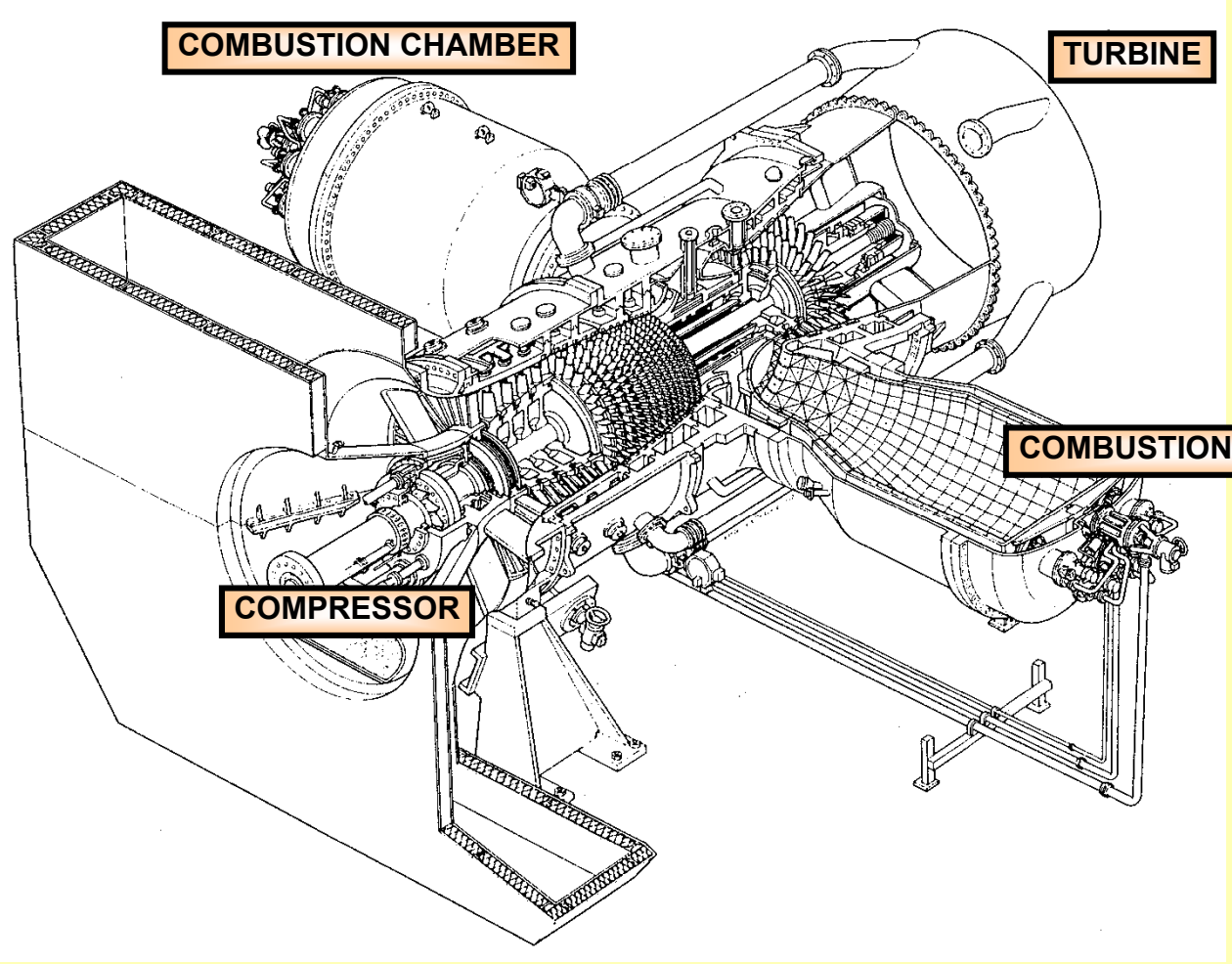


Source: EPRI

IGCC Improvement Opportunities

- Gas Turbines redesign to recover the derating, lost performance and efficiency with syngas and hydrogen firing
- Reduce ASU consumption: Ion Transfer Membrane, ITM (?)
- Gas separation membranes and processes (such as dedusting systems for particles depuration) that can operate at warmer temperatures
- Longer term possiblities such as Solid Oxide FC would eliminate the need for shift and CO_2 removal

Development in Gas Turbine Technology: Horizontal Silo



Development in Gas Turbine Technology: Annular Combustor

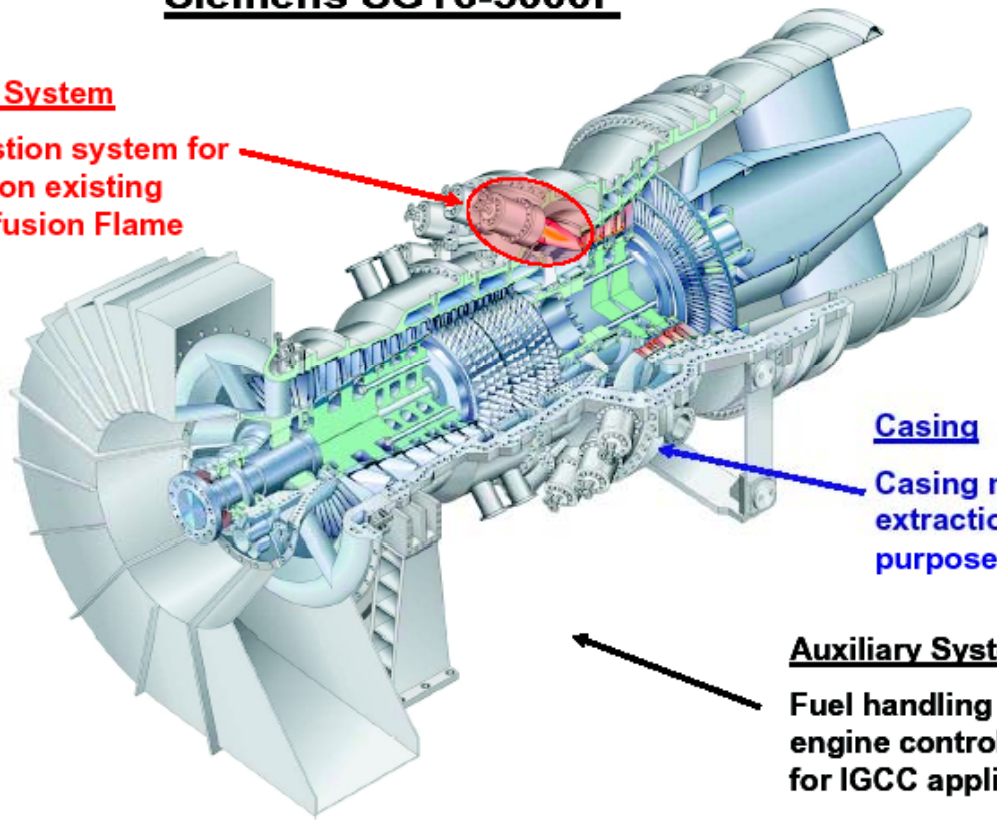
IGCC Gas Turbines
Typical Gas Turbine Changes for IGCC Applications

SIEMENS

Siemens SGT6-5000F

Combustion System

New combustion system for IGCC based on existing Siemens Diffusion Flame technology



Casing

Casing modified for air extraction / integration purposes

Auxiliary Systems

Fuel handling auxiliaries and engine control system modified for IGCC application

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Key IGCC Market Barriers

Oxygen Production (I)

Why Oxygen Separation Membrane Technology is Important

- **In an IGCC plant, the air separation unit**
  - Accounts for ~15% of the plant capital cost
  - Consumes ~ 10% of the gross power output
- **Reducing capital cost and increasing efficiency of ASU**
  - Improve economic viability of IGCC,
  - Stimulate commercial deployment.
- **Systems studies of membrane technologies have shown significant potential**
  - Increased net MWe
  - IGCC plant efficiency
  - Major decreased cost of oxygen production,
  - Overall decrease in Cost of Electricity (COE)

Source: NETL

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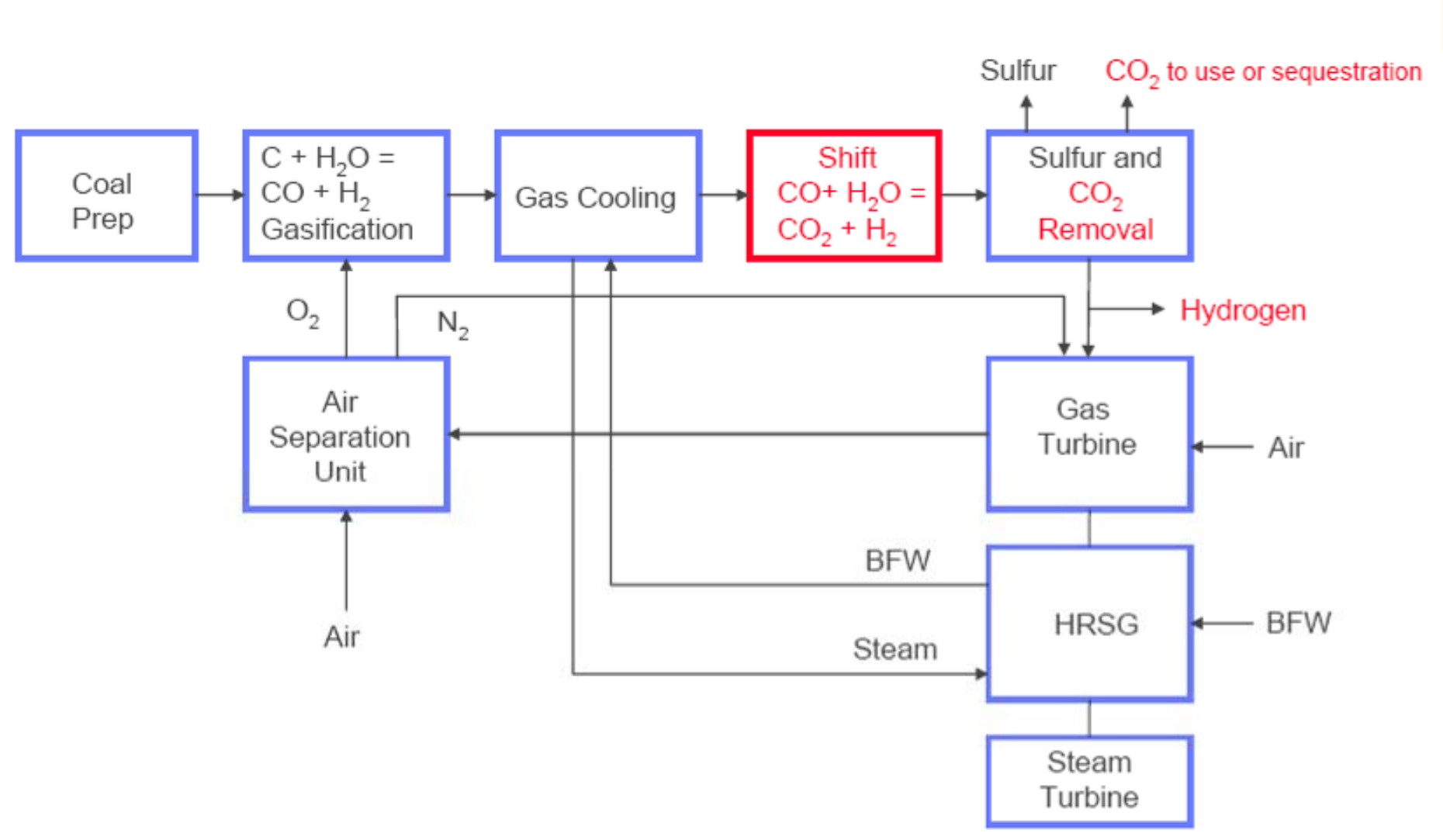
IGCC with CO_2 capture

General Overview

IGCC with CO_2 capture: General Overview

IGCC with CO_2 capture and Hydrogen coproduction



IGCC with CO_2 capture: General Overview

- Advantages
  - High CO_2 concentration and high overall pressure
    - Lower energy consumption for CO_2 separation as compared to post-combustion capture
    - Compact equipment
  - Proven CO_2 separation technology
  - Possibility of co-production of hydrogen
- Disadvantages
  - IGCC is unfamiliar technology for power generators
  - Existing coal fired plants have low availability
  - IGCC without CO_2 capture has generally higher costs than pulverised coal combustion

Coal Gasification Plants w/CO_2 Capture (Today)

- IGCC and CO_2 removal offered commercially:
  - Have not operated in an integrated manner
- Three U.S. non-power facilities and many plants in China recover CO_2
  - Coffeyville
  - Eastman
  - Great Plains
- Great Plains recovered CO_2 used for EOR:
  - 2.7 million tons CO_2 per year
  - ~340 MWe if it were an IGCC

No Coal IGCC Currently Recovers CO_2

The Great Plains Synfuels Plant

http://www.dakotagas.com/Companyinfo/index.html

Weyburn Pipeline

http://www.ptrc.ca/access/DesktopDefault.asp

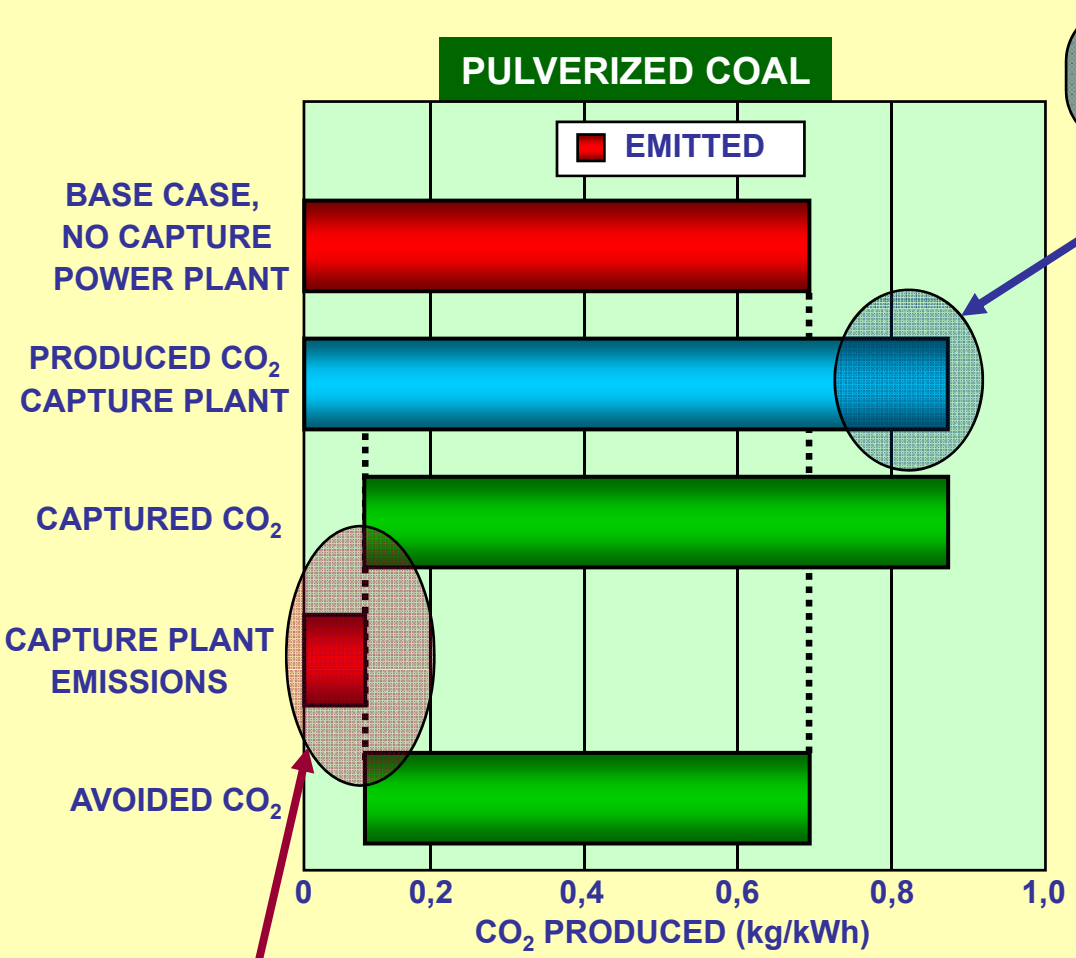
x Source: EPRI

IGCC with CO_2 capture

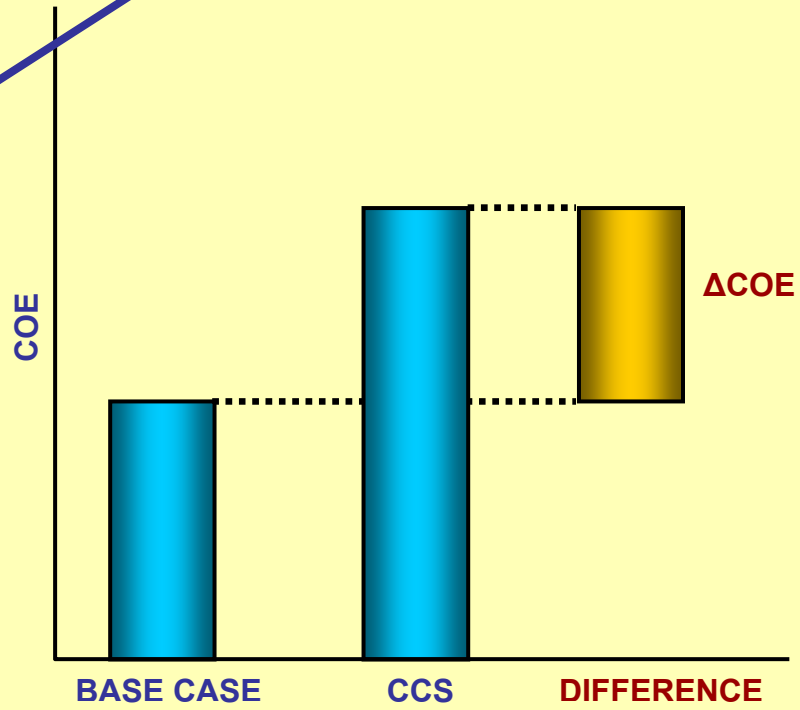
Economics of IGCC with CO_2 capture

Economics of IGCC with CO_2 capture

Avoided CO_2 vs. captured CO_2



EFFICIENCY IMPROVEMENT

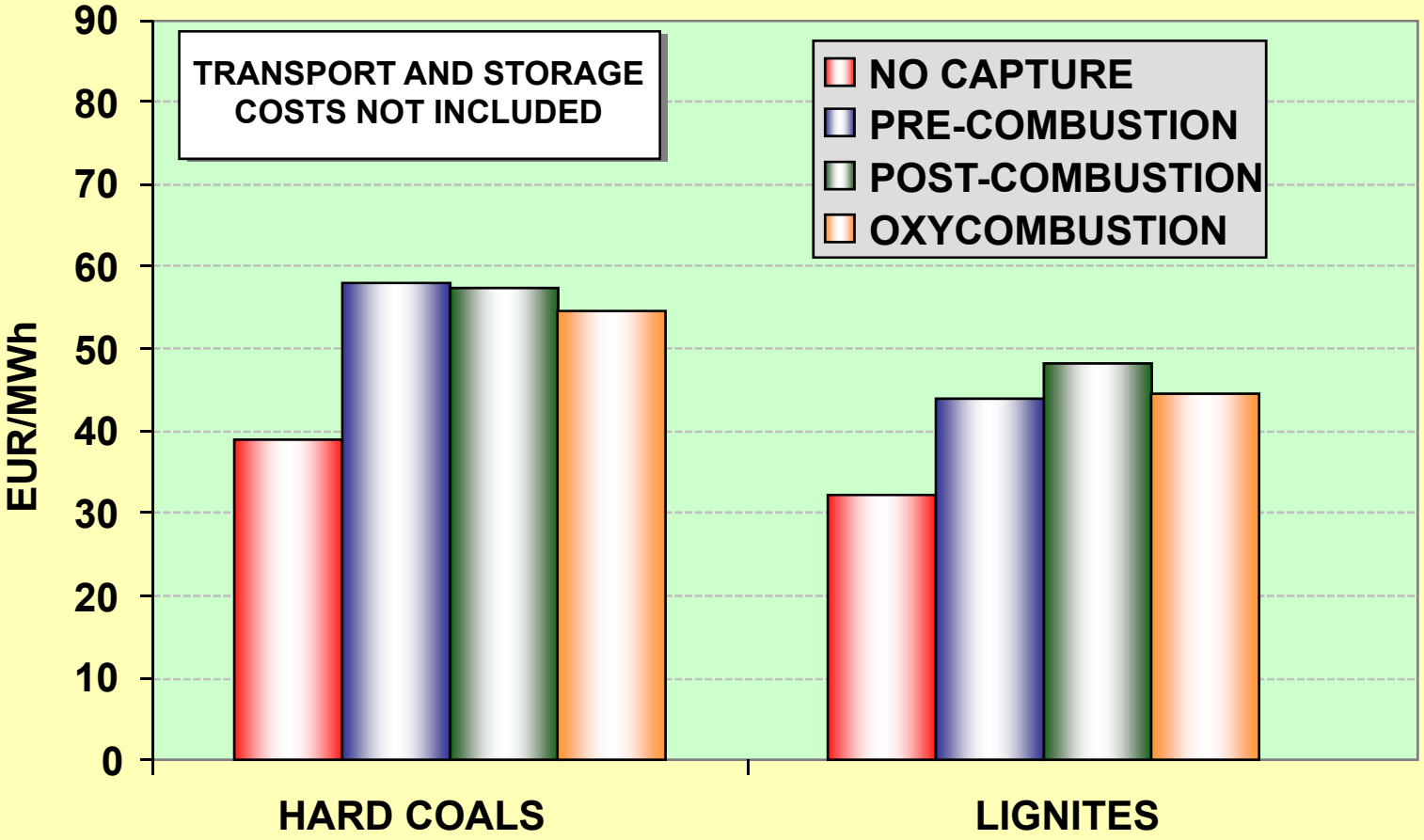


CAPTURE EFFICIENCY IMPROVEMENT

AVOIDED CO_2 COST:

$$\frac{\Delta CE}{(CO_{2,BASE} - CO_{2,CCS})_{EMITTED}}$$

Electricity costs from large power stations by 2020



Global process efficiency must be increased in order to reduce costs and improve competitiveness

Coal Characteristics Drive Technology Selection

	IGCC w/ CCS	PC w/ CCS
Bituminous Coal	Usually Favored	
Sub-Bituminous Coal	Water use limits Lower elevation Lower moisture Lower ash	Higher elevation Higher moisture Higher ash Higher ambient temp.
Lignite Coal		Usually Favored

Source: EPRI

CO_2 Capture & H_2 Production Pilot Plant. Facts

August 2009 update

Company	ELCOGAS, S.A (Spanish utility)
Location	Puertollano (Spain). Integrated in the Puertollano IGCC plant
Feed gas	Coal gas at 20-24 bar
Size	14 MWt (2% of total coal gas produced in the IGCC plant)
Technology	Pre-combustion Carbon Capture (90%). No Storage foreseen
Budget	Construction & Commissioning: 12 M€
Frame	National Research Project, granted by *Spanish Science and Innovation Ministry* and *Regional Government (JCCM)*
Start date	2005
End date	Commissioning by March 2010

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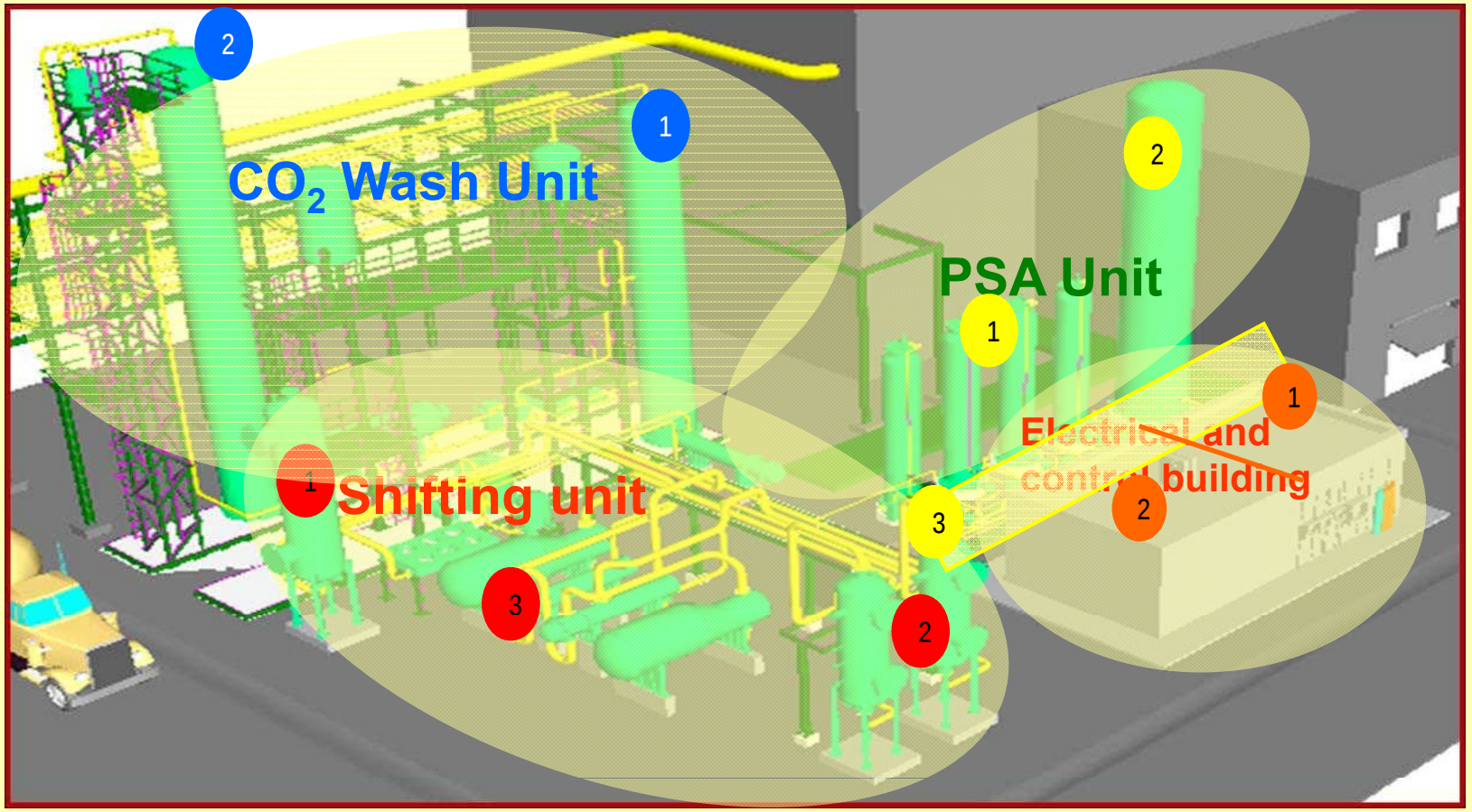
MINISTERIO DE CIENCIA E INNOVACIÓN
Junta de Comunidades de Castilla-La Mancha

CO_2 Capture Pilot Plant. Preliminary 3D view



Shifting Unit (several suppliers):

1. Desulphurization reactor
2. Shifting reactors
3. Heat exchangers: kettles and shell&tube

CO_2 Wash Unit (supplied by Linde Caloric):

1. Syngas absober – 12 m
2. CO_2 stripper – 16,5 m

Electrical and control building:

1. Control room
2. Electrical room

PSA Unit (supplied by Linde):

1. Adsobers – 6,5 m
2. Tail gas drum – 12,5 m
3. Valve skid

CO_2 Capture Pilot Plant. Status Aug 2009

Done:

- ✓ 93 % engineering work
- ✓ 92% equipments bought
- ✓ 9% construction

Mechanical Erection: to be started by 17th August 2009

End commissioning: March 2010

End of programmed tests (under PSE): March 2011

KEY CONTRACTORS

Engineering	**Empresarios Agrupados**
CO_2 Unit	**Linde-Caloric**
PSA Unit	**Linde**
Civil work	**Local company (Construcciones Ocaña-Cañas)**
Control	**Zeus Control**
Reactors	**Tecnical**
Heat exchangers	**Tecnical and Boreal-Vila**
Catalysts	**Johnson Matthey**
Piping and fitting	**Local suppliers (Sidsa and Cuñado)**
Control valves	**SAMSON**
Safety and relief valves	**Tyco Valves and Controls**
Manual valves	**Local supplier (SAIDI)**
Electrical components	**GE Power**
On-line analysis system	**ABB Process Automation Division**

Selected location for Pilot Plant

Thank you!!!

Monica Lupion

Fundacion Ciudad de la Energia **CIUDEN**

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OPEC-IEA GHG CCS workshop for scientists and professionals

OXYFUEL COMBUSTION

for Power Generation

by

Monica Lupion

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

16th November 2009. Hassi Messaoud (Algeria)

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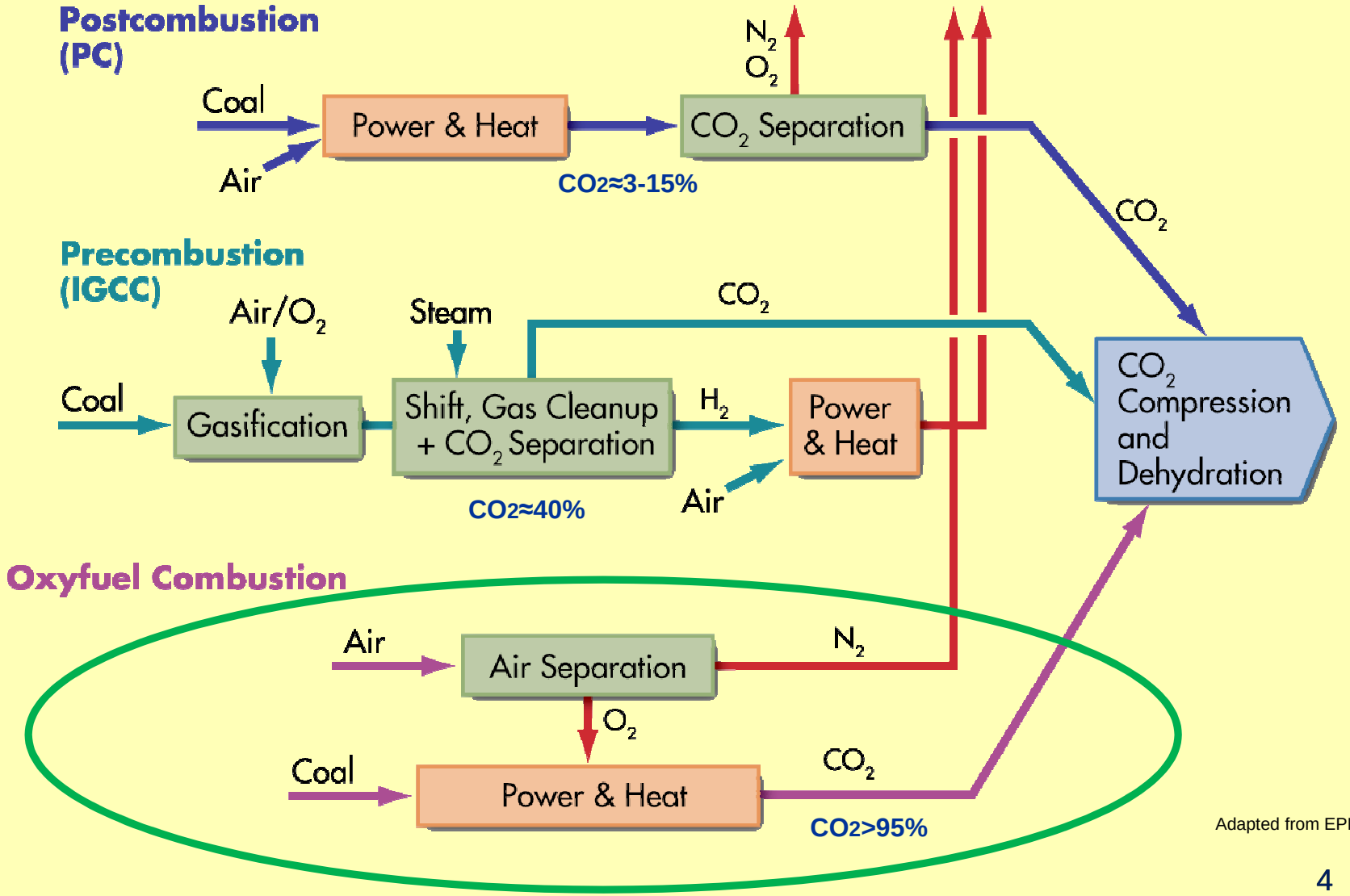
Presentation Outline

- Introduction
  - General overview of the Oxyfuel Combustion
  - Oxyfuel Combustion Application in the Industry: Historical Perspective
- Technical considerations
  - General principles
  - Oxy-firing versus air-firing
  - Recycled Flue Gas (RFG)
  - Technical options: PC / CFB
  - Air Separation Unit
  - NO_x, SO_x and particles
  - CO_2 Processing
- Large Scale and Demo projects
- Summary and Concluding Remarks

Introduction

General Overview of the Oxyfuel Combustion

General Overview of Oxyfuel Combustion



Adapted from EPRI 2007

General Overview of Oxyfuel Combustion

- **"Oxy-Combustion" – is the use of oxygen instead of air for burning of fuel**
  - The least mature among the 3 mostly considered capture technology options for the power generation
  - For boiler application, part of the flue gas is recycled to reduce flame temperature

- **Three main development issues**
  - Boiler and burner development - "Design issues"
  - Air Separation Unit – "Cost of oxygen production"
  - CO_2 processing – "Removal of impurities"

General Overview of Oxyfuel Combustion

- **Advantages**
  - Over IGCC is reliability, availability and familiarity → boiler and burners could be fairly conventional
  - Possibility of compact boilers with lower quantities of flue gas recycle
  - Possibility of avoiding FGD
- **Disadvantages**
  - Testing for the large scale burners are still on-going. Oxyfuel fired boiler for power generation is not yet commercially available
    - Deployment of demonstration plant is needed to gain confidence
  - High cost of oxygen production
    - Advanced oxygen separation membranes with lower energy consumptions at pilot plant scale

Introduction

Oxyfuel Combustion Application in the Industry: Historical Perspective

Development of Oxy-Fuel Combustion Application in Industry

1940 – 1950

High Temperature Applications
- Welding
- Metal cutting
- Flame Polishing

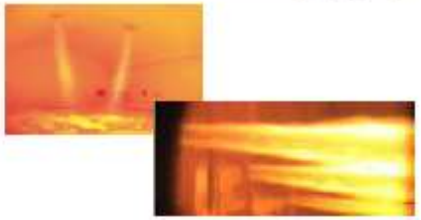
1960 – 1970

Productivity Enhancement via O2 Enrich Combustion (OEC)
- Glass, Aluminium & Cement industries

1980 – 1990

Fuel Savings – Emergence of full Oxy-Fuel Combustion Application
- waste incineration
- steel and copper industries

Idea of using Oxy-Coal Combustion with RFG for Enhanced Oil Recovery (1982)



1990 – 2000

NOx Reduction
- glass melting furnaces
- OEC coal fired boilers

2000 – 2010?

CO2 Reduction
- Power Generation industry
  - IGCC & OxyFuel boiler applications

Adapted from slide of Sho Kobayashi, Praxair

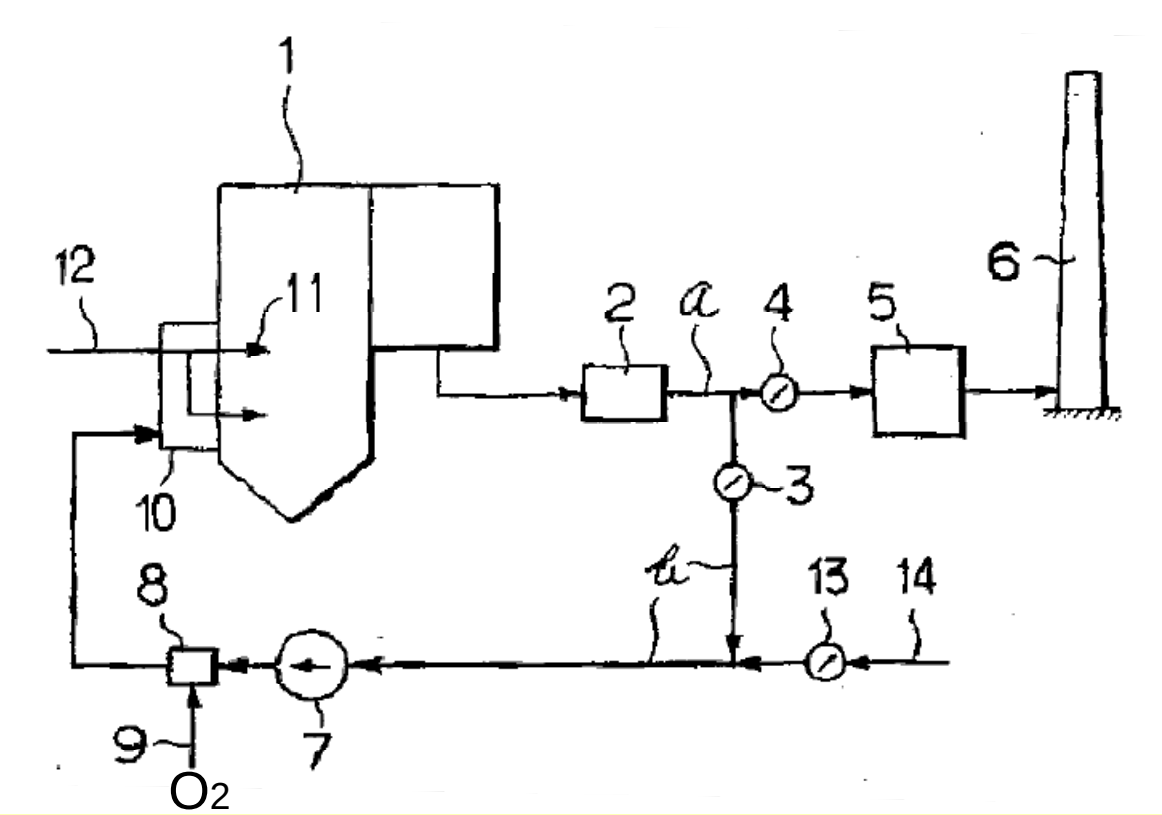
Pictures from IFRF, Air Liquide, Asahi Glass, Linde Gas

Historical Perspective – The Early Days

- 1982: Initial suggestion by Abraham et. al. (OGJ) of using Oxy-Coal Combustion to produce CO_2 for EOR
  - 1st public document looking at capturing CO_2 from flue gas using Oxy-Combustion

- However ... as early as 1970's work has started in the development of Oxy-Coal Combustion with Recycled Flue Gas
  - 1974: Japan initial conception of using oxy-coal combustion for power generation
  - 1978: Economic feasibility of oxy-coal combustion was investigated for EOR application (*H. Farzan, Babcock & Wilcox / A. Wolsky, Argonne National Laboratory*)

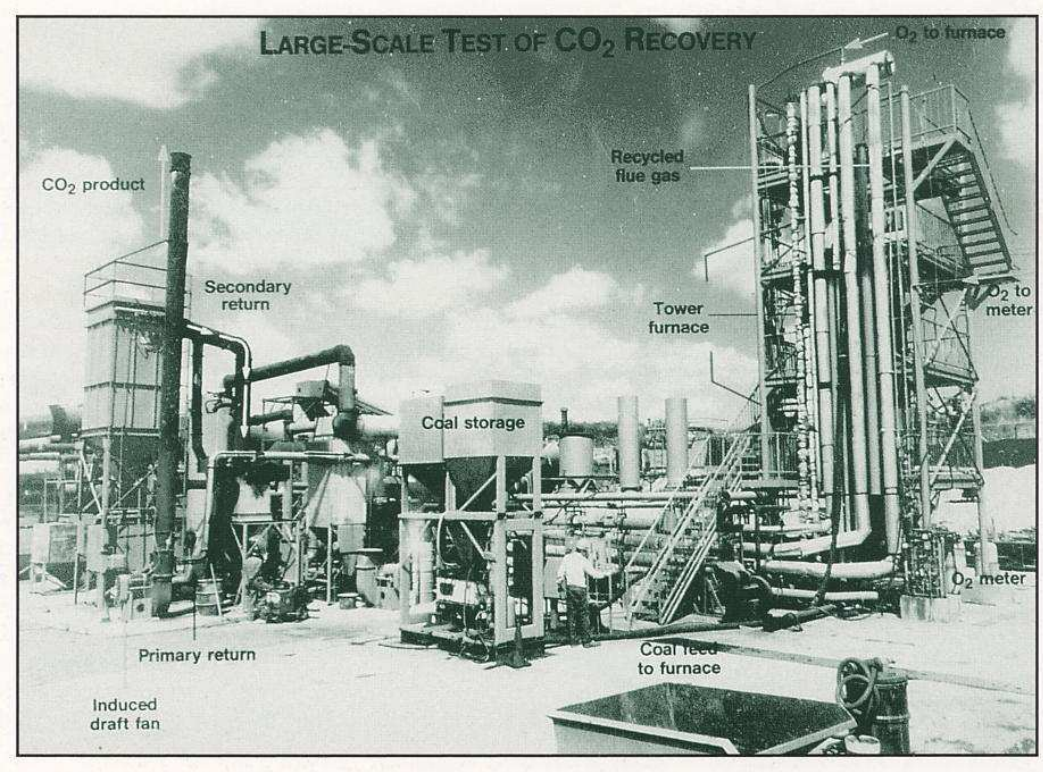
Japan's initial conception of Oxyfuel Combustion application for Power Generation (1974)



Work Done between 1980-2000

- ✓ 5 Major pilot scale studies between 1980 - 2000
  - ANL Research Programme (1983-1988)
    - Battelle (115 kWth)
    - EERC (3 MWth)
  - EC Thermie Project – International Flame Research Foundation (1993-1995)
    - IFRF (2.5 MWth)
    - MBEL (Doosan Babcock) – Air Products – Naples & Ulster Univ (150 kWth)
    - International Combustion – Imperial College – EDP – IST (150kWth & 35MWth)
  - NEDO – IHI (1.2 MWth) (together with Tokyo Institute of Tech.)
  - CANMET (300 kWth)
  - US DOE – B&W / Air Liquide (1.2 MWth)

ANL - EERC Study
World's 1st Oxy-Coal Industrial Pilot Scale Study
Tower Furnace (~ 3MWth)



Vattenfall - Janschwalde (PC -250MWe)
KEPCO/KOSEP - Yongdong (PC - 100MWe)
Black Hills Power - Wyoming (PC - 100MWe)
FW/Praxair - Jamestown (CFB - 50MWe)
Endesa/CIUDEN - El Bierzo (CFB - 300MWe)

Alstom	Schwarze Pumpe	2008	30MWth	Lignite
Hitachi Babcock	Schwarze Pumpe	2010	30MWth	Lignite
IHI	Callide	2010	30MWe	Coal
Alstom / AL	Lacq	2009	30MWth	Gas/Oil?
CIUDEN	El Bierzo Facitity	2010	30MWth	Coal
CIUDEN	El Bierzo Facility	2010	20MWth	Coal
ENEL HP Oxyfuel	Brindisi Test Facility	2012	48MWth	Coal

Target :
"Commercialised by 2020"

By 2014-2018

Demonstration of 50– 300MWe full scale power plant.

2008

World's <u>FIRST</u> 30 MWth
<u>full chain demonstration</u>
at Schwarze Pumpe Pilot Plant

2007

B&W CEDF (30MWth)
large scale burner testing started

2003 - 2005

Vattenfall (ENCAP ++)
CS Energy / IHI Callide Project

1998 – 2001

CANMET
US DOE Project / B&W / Air Liquide

1990 - 1995

EC Joule Thermie Project
- IFRF / Doosan Babcock / Int'l Combustion
NEDO / IHI / Jcoal Project

1980's

ANL/Battelle/EERC completed the first industrial scale pilot plant

By the end of 2010/2011,
Users (i.e. Power Plant Operators) will have 6 burners manufacturers fully demonstrating "Utility Size Large Scale Burners" which should give a high level of confidence in going to the next step

First large scale 35MWth Oxy-Coal Burner Retrofit Test done by International Combustion

B&W	CEDF	2008	30MWth	Coal
Alstom	Alstom CE	2010	15MWth	Coal
Doosan Babcock	DBEL - MBTF	2009	40MWth	Coal

Updated by S. Santos (03/08/09)

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Technical considerations

General principles

General principles

- Conventional Combustion (Coal, Natural Gas, Fuel Oil) with AIR

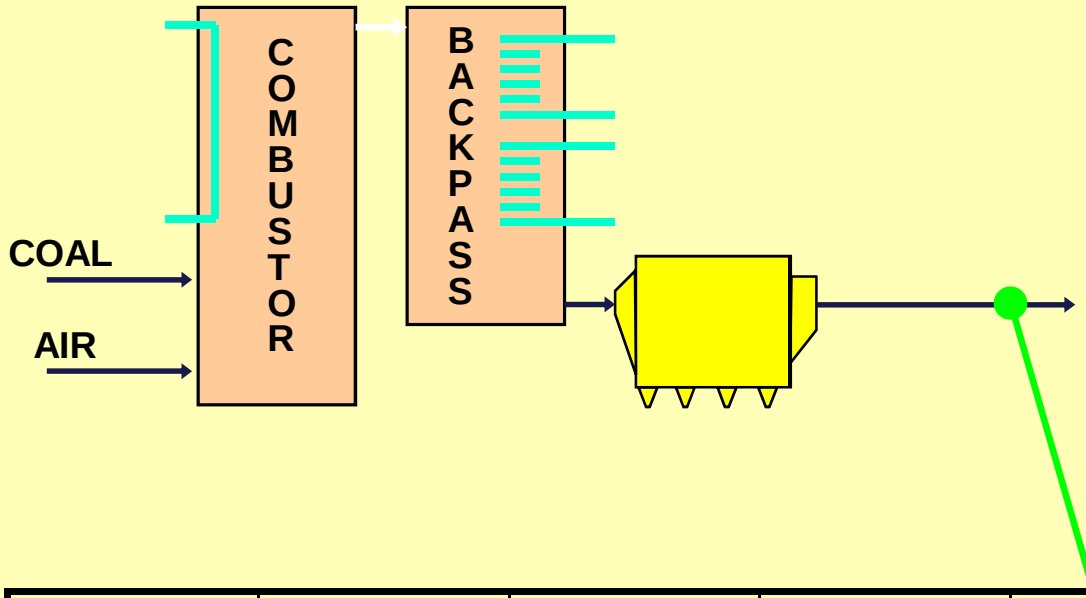
$CO_2 \approx$ 3 to 20%v d.b.

- Dilution with Nitrogen makes the CO_2 Separation more expensive
  - OPTION: Combustion with OXYGEN (~95%v)
  - BUT: Air Separation required (O_2-N_2 and other gases)

Flue Gas with CO_2 (>80%v d.b.)
+
H_2O, N_2, O_2, Ar, Particles, SO_X, NO_X

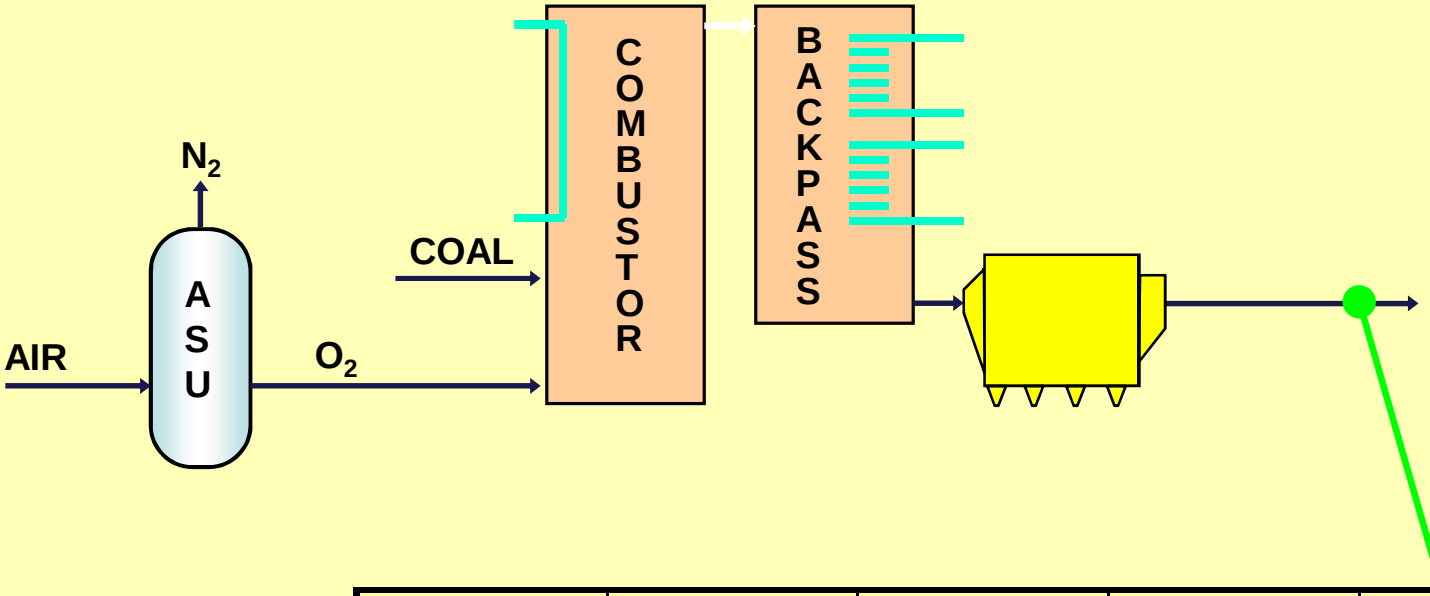
- Flue Gas Recycled to control Temperature in the boiler
- Additional effect: Gas Flow to extract and transfer entalphy from the boiler
- Not yet commercially available, but applicable to new and existing PS
- With a great potential to have a better efficiencies than conventional PS + post - CO_2 Capture

Gases Flow and Composition: CONVENTIONAL COMBUSTION



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100

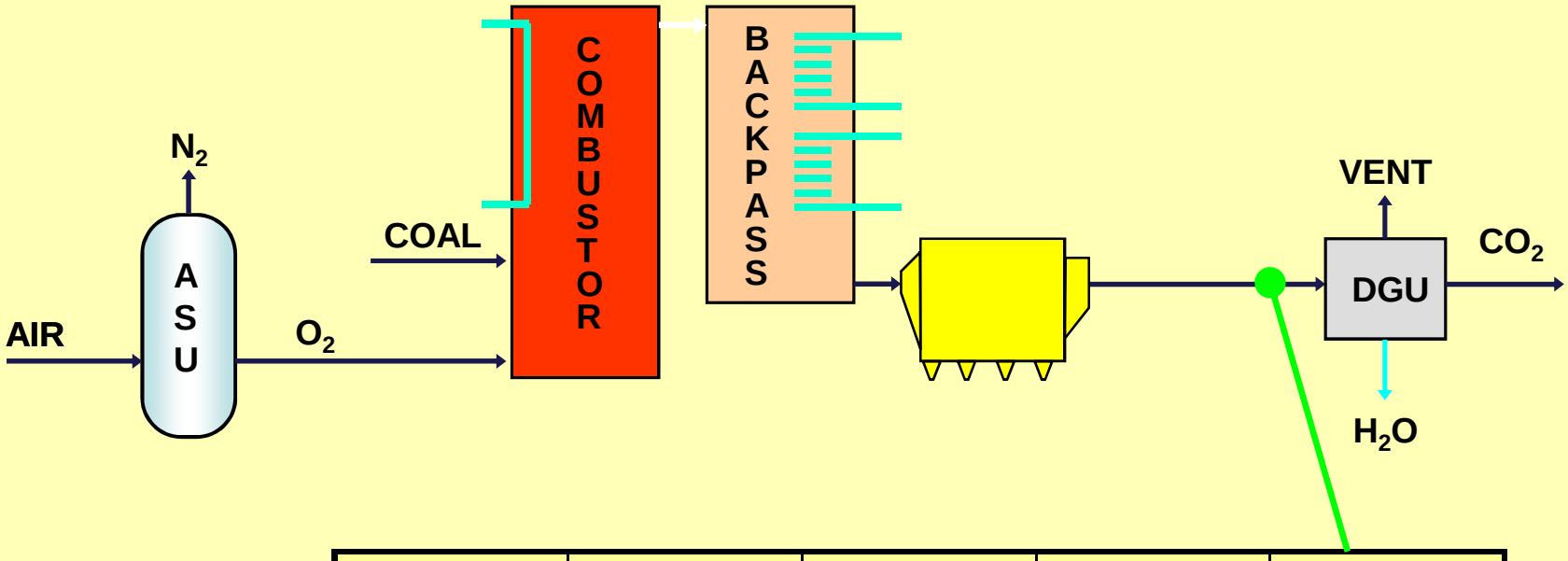
Gases Flow and Composition: COMBUSTION with OXYGEN



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100
O_2	5	67	25	3	22

General principles

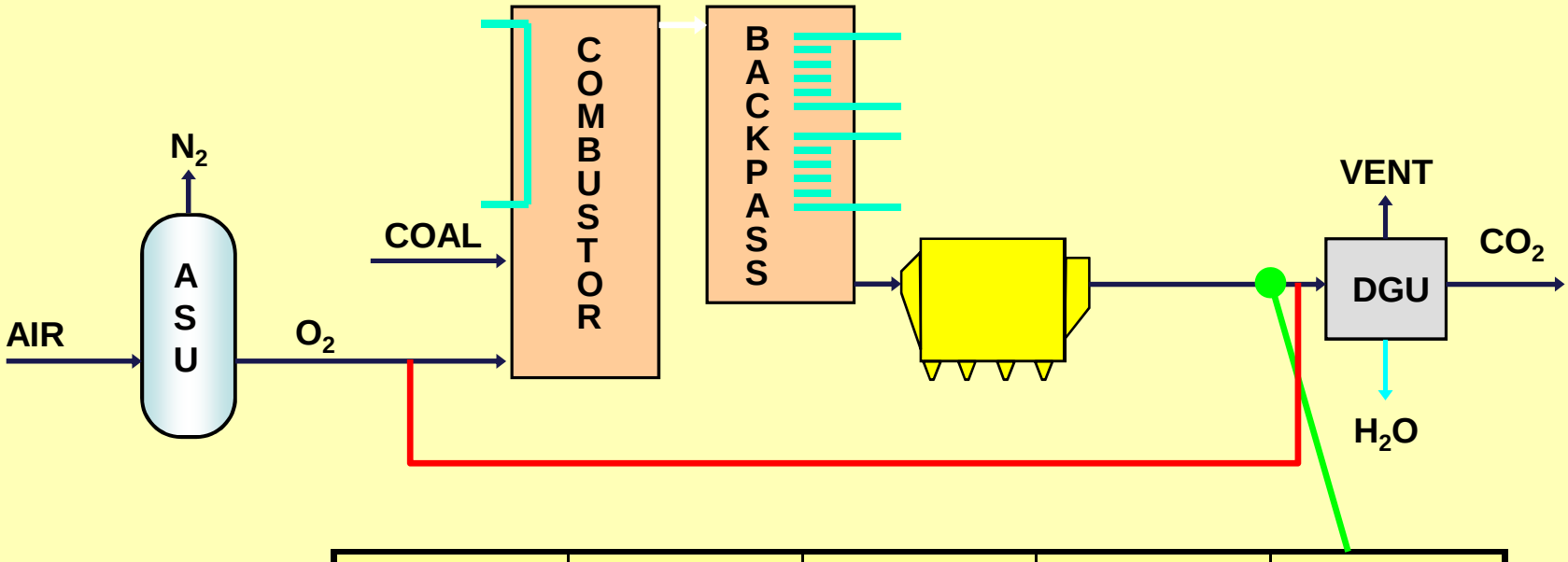
Combustion with Oxygen will produce VERY HIGH TEMPERATURES in the furnace



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100
O_2	5	67	25	3	22

General principles

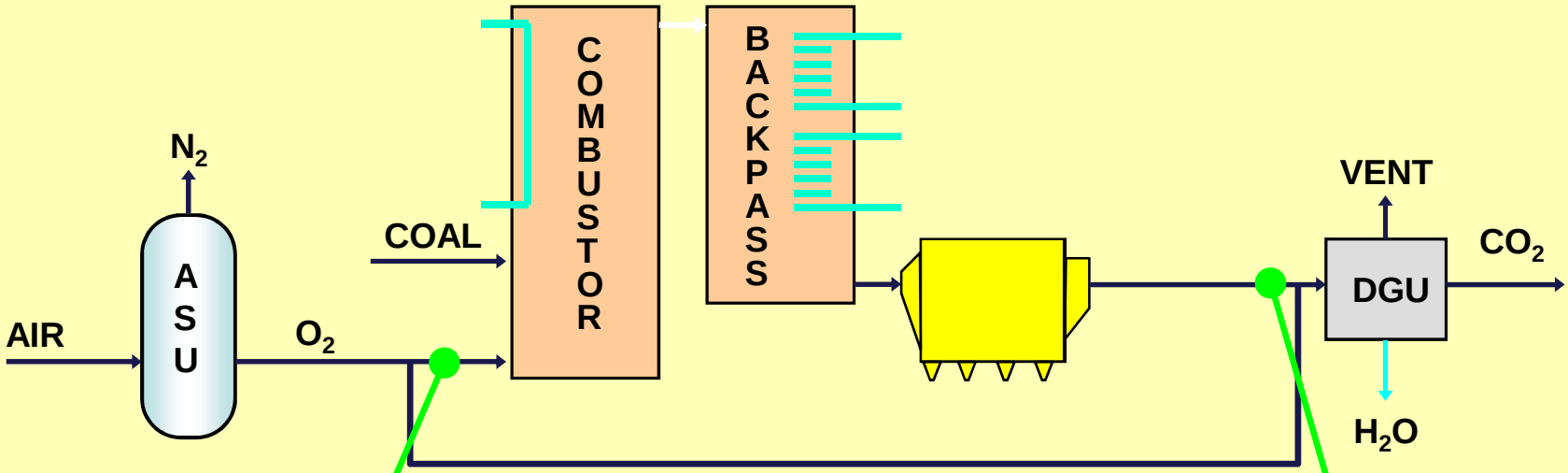
Temperature reduction: RECIRCULATION of FLUE GAS



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100
O_2	5	67	25	3	22

General principles

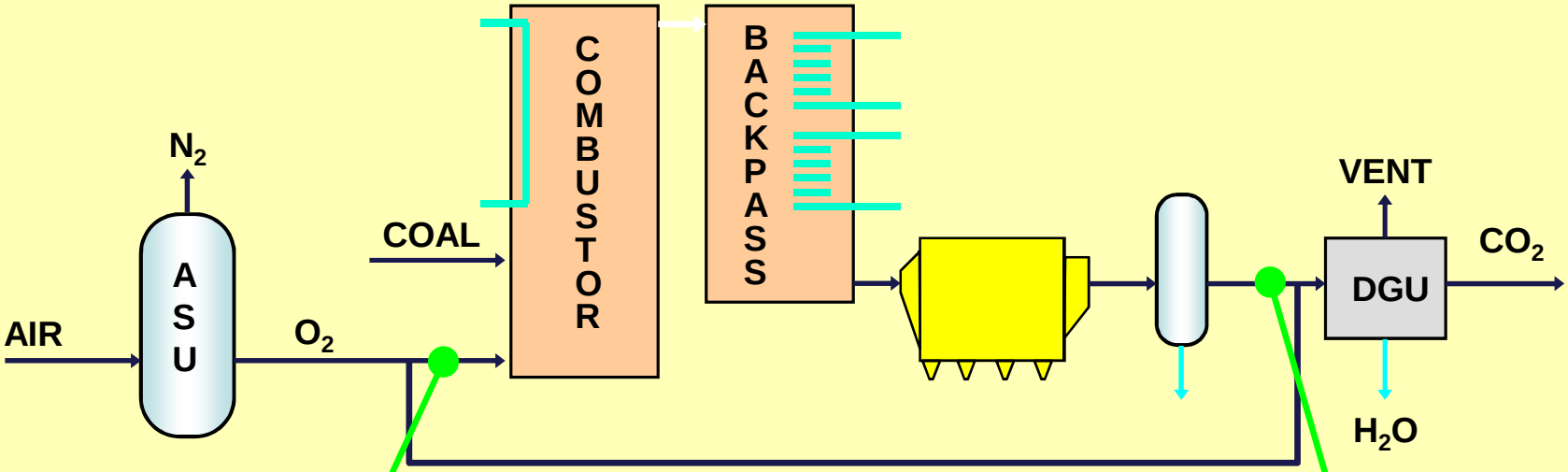
WET RECIRCULATION: O_2 30% → 36% Flue Gas Reduction



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100
O_2	5	67	25	3	22
30% O_2	5	67	25	3	64

General principles

DRY RECIRCULATION: O_2 30% → 35% Flue Gas Reduction
CO_2 83.5 %



	N_2	CO_2	H_2O	O_2	REL VOL
AIR	75	15	7	3	100
O_2	5	67	25	3	22
30% O_2	6	83.5	7	3.5	65

Technical considerations

Oxy-firing versus Air-firing

Differences of Combustion in O_2/CO_2 compared to Air-firing

Flows and Concentrations

- ✓ To obtain a similar Adiabatic Flame Temperature (AFT) the O_2 concentration in the gas that pass through the burner is ≈ 30%
- ✓ The high concentration of CO_2 and H_2O in the furnace gases results to a higher gas emissivities
- ✓ The volume of gases through the furnace is reduced
- ✓ The volume of flue gas (after recycling) is reduced by about 80%

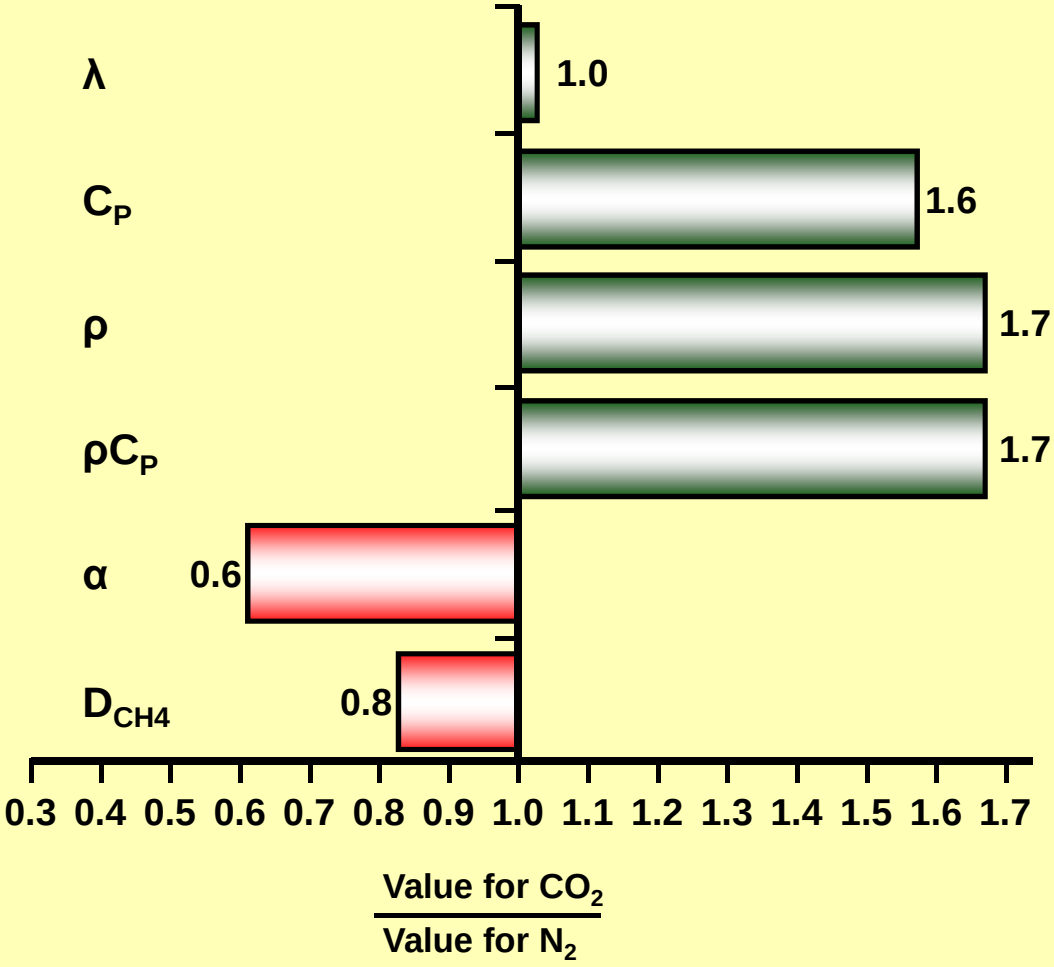
Differences of Combustion in O_2/CO_2 compared to Air-firing

Gases Properties

- ✓ Physical and Thermal Gases Properties
- ✓ Radiant Heat Transfer in the Steam Generator
- ✓ Convective Heat Transfer in the Steam Generator
- ✓ Flame Stability, Ignition and Combustion
- ✓ Evolution of the Mineral Matter
- ✓ Formation and Reduction of Pollutants: NO_X, SO_X

Gas Properties Differences

Gas Properties Ratios for CO_2 and N_2 at 1200K



COMPARISON OXY/AIR

→ **HIGHER O_2 THRU BURNER**

→ **LOWER BURNER VELOCITY, HIGHER COAL RESIDENCE TIME IN FURNACE**

→ **SLOWER FLAME PROPAGATION VELOCITY**

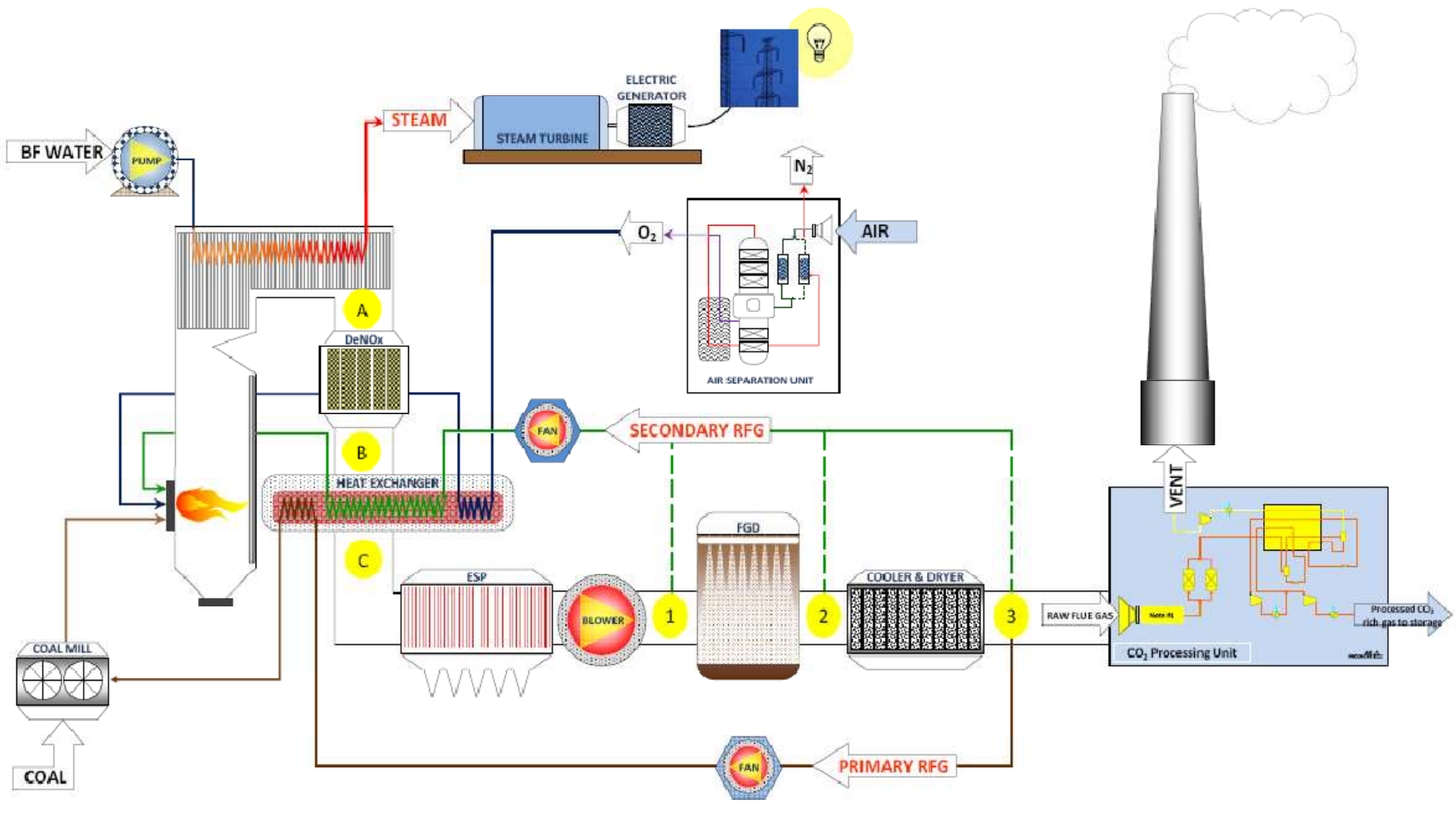
λ	THERMAL CONDUCTIVITY
C_P	MOLAR HEAT CAPACITY
α	THERMAL DIFFUSIVITY
D_{CH4}	MASS DIFFUSIVITY

Technical considerations

Recycled Flue Gas (RFG)

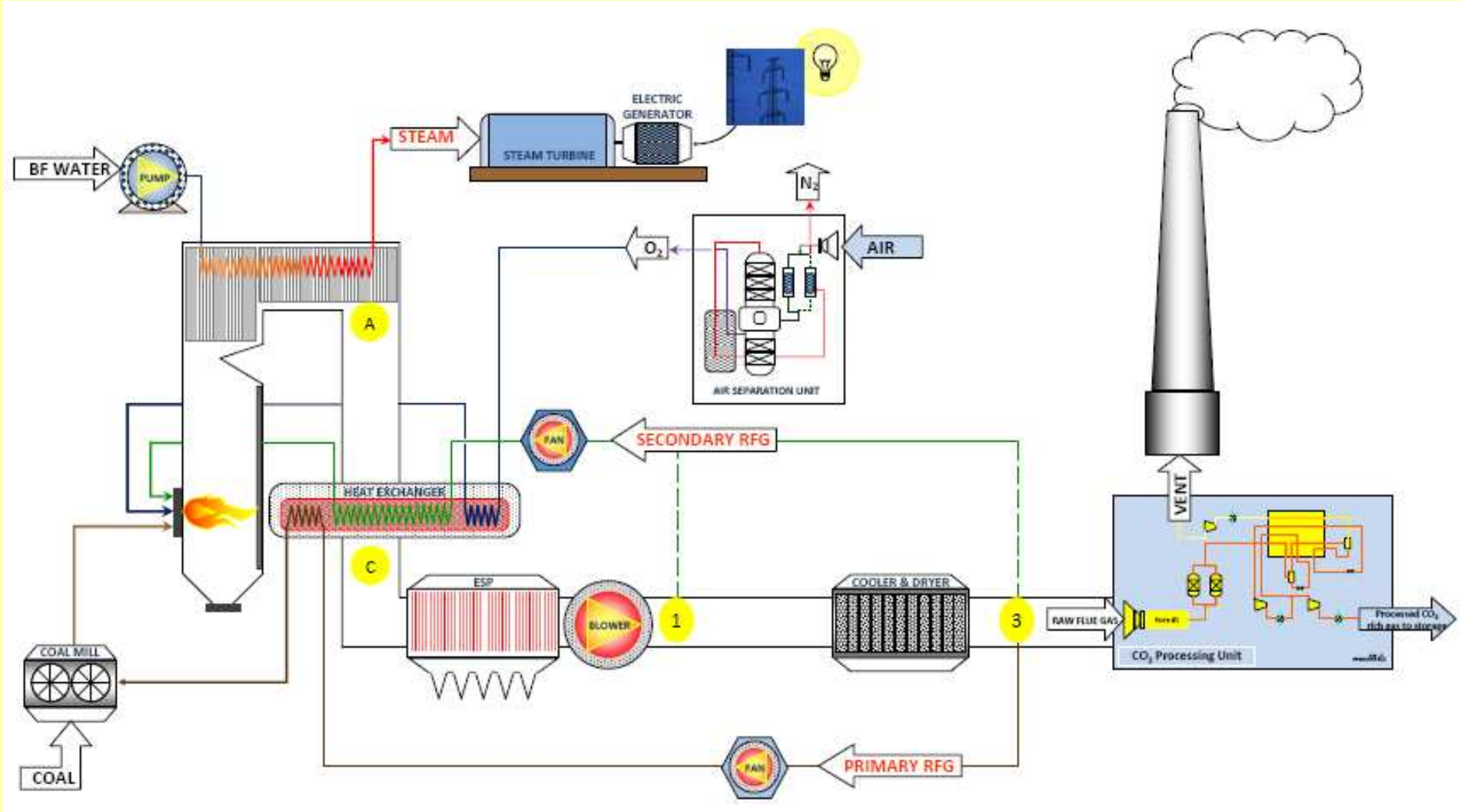
$$R = \frac{m_{RFG}}{m_{PFG} + m_{RFG}}$$

Where can you extract the Recycled Flue Gas?



Recycled Flue Gas

Where can you extract the Recycled Flue Gas? (For practical application using low S coal)



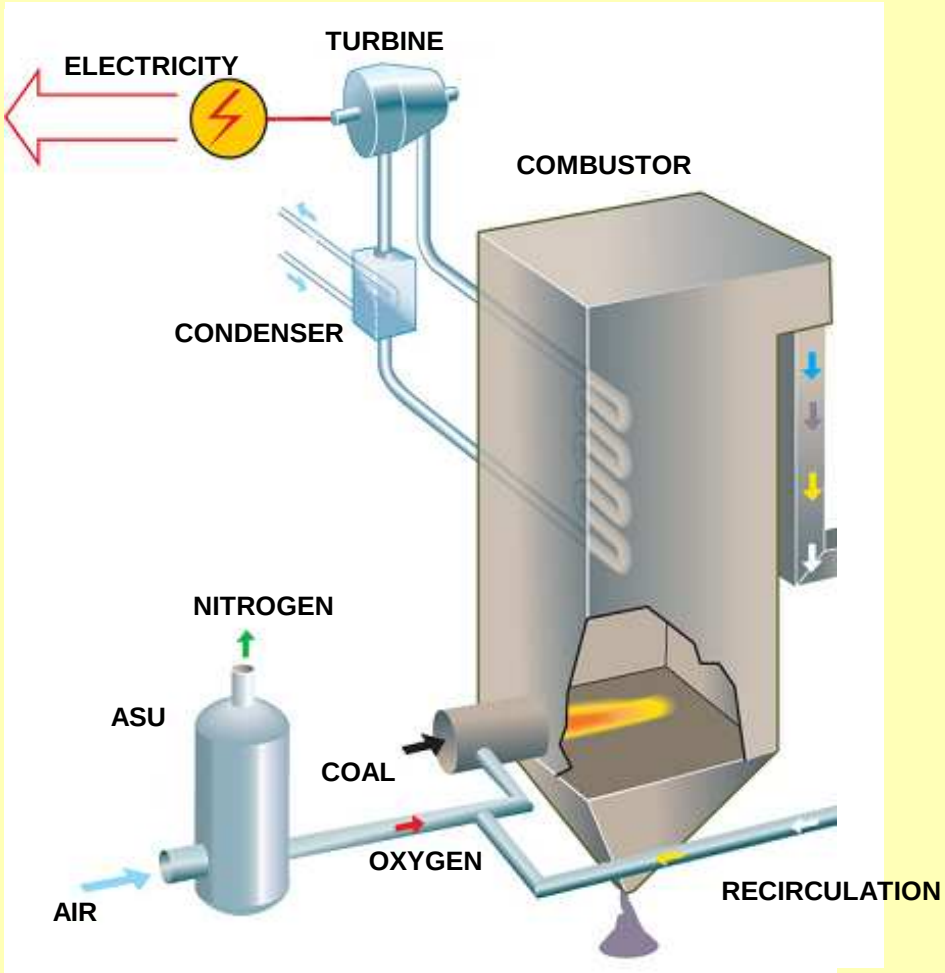
Factors affecting the Recycle Ratio

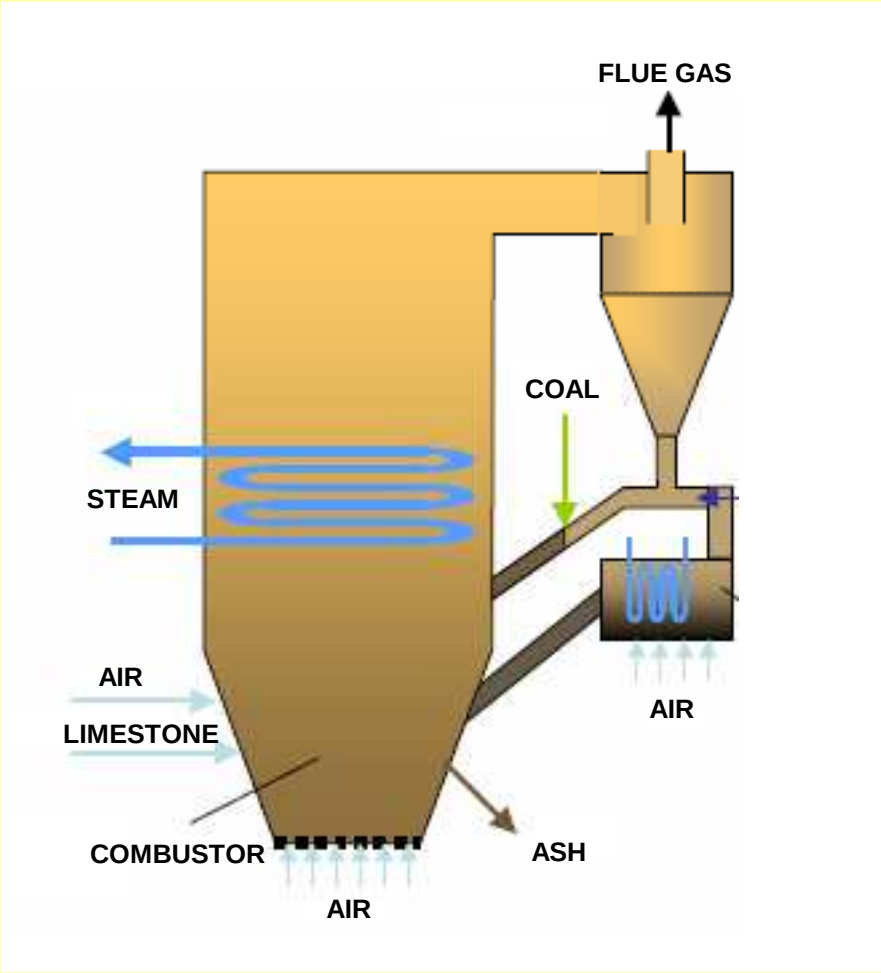
- Critical factors affecting the optimum amount of recycled flue gas
  - Burner and boiler design (heat transfer and flame stability oxygen distribution through burner)
  - Air ingress
  - Purity of oxygen from the ASU
  - Coal type
  - Level of moisture content in comburent
  - Comburent (oxidant) temperature

Technical considerations

Technical options: PC / CFB

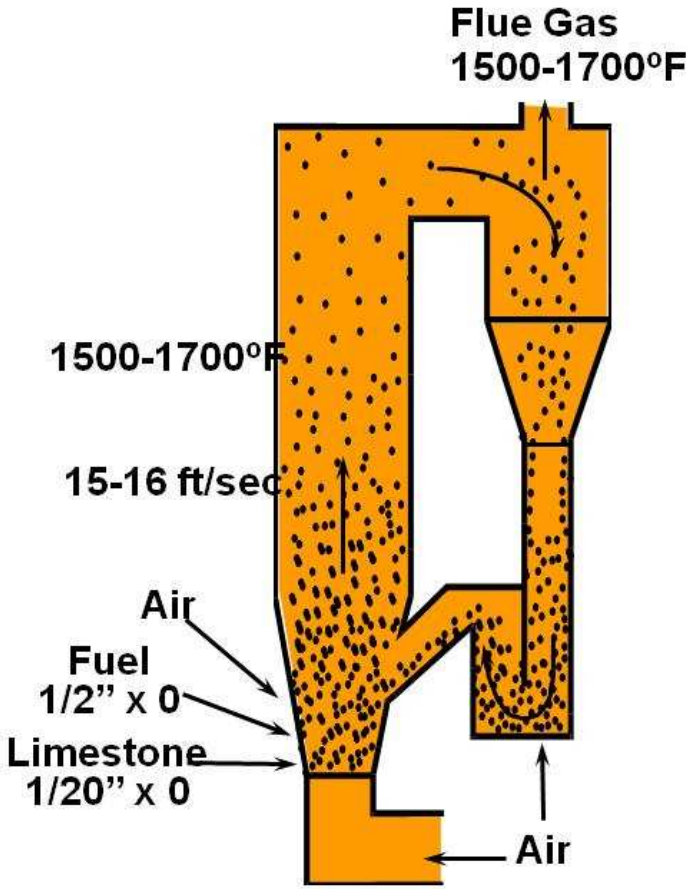
Pulverised Coal and Circulating Fluidized Bed Combustors



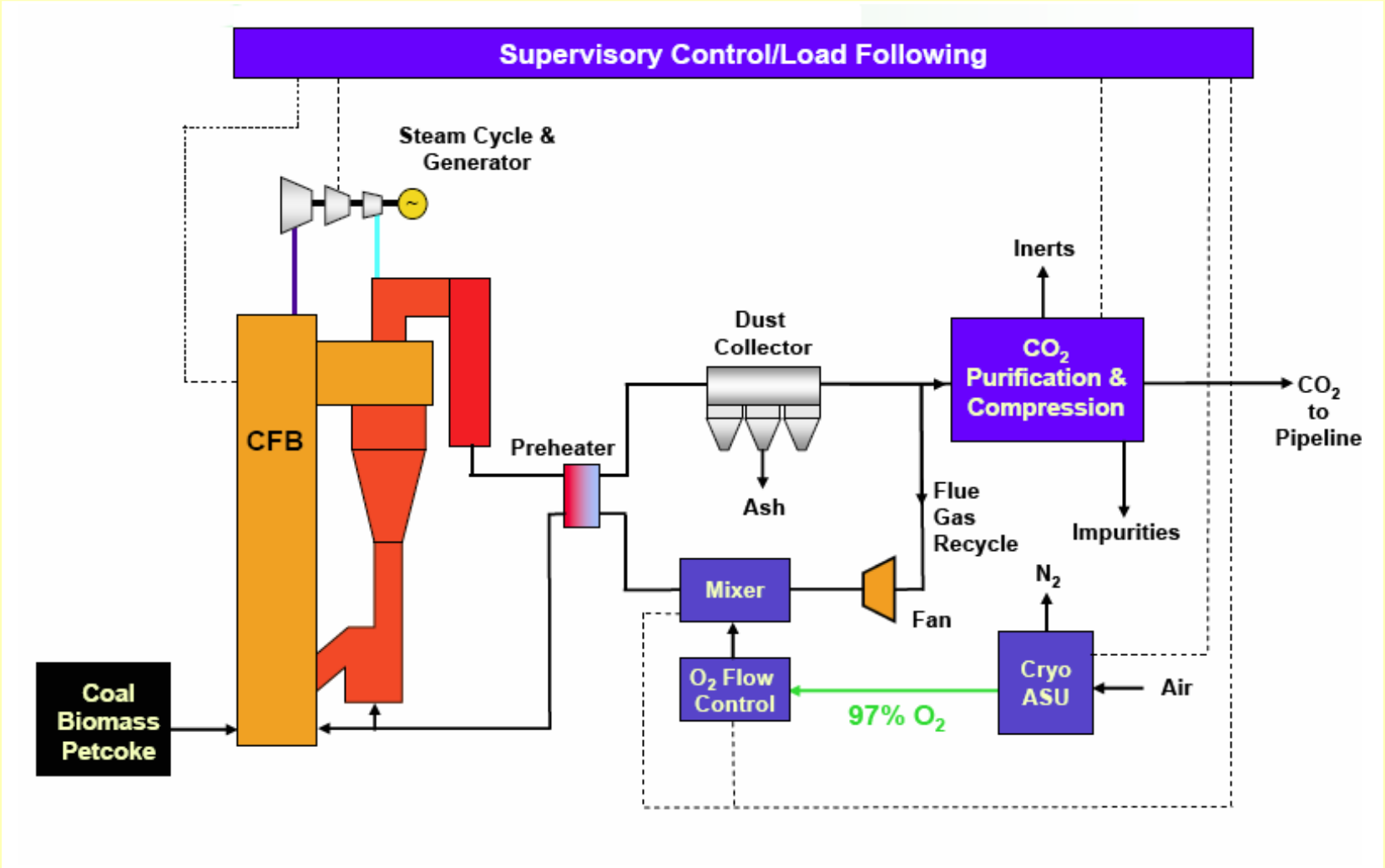


Circulating Fluidized Bed Process Advantages

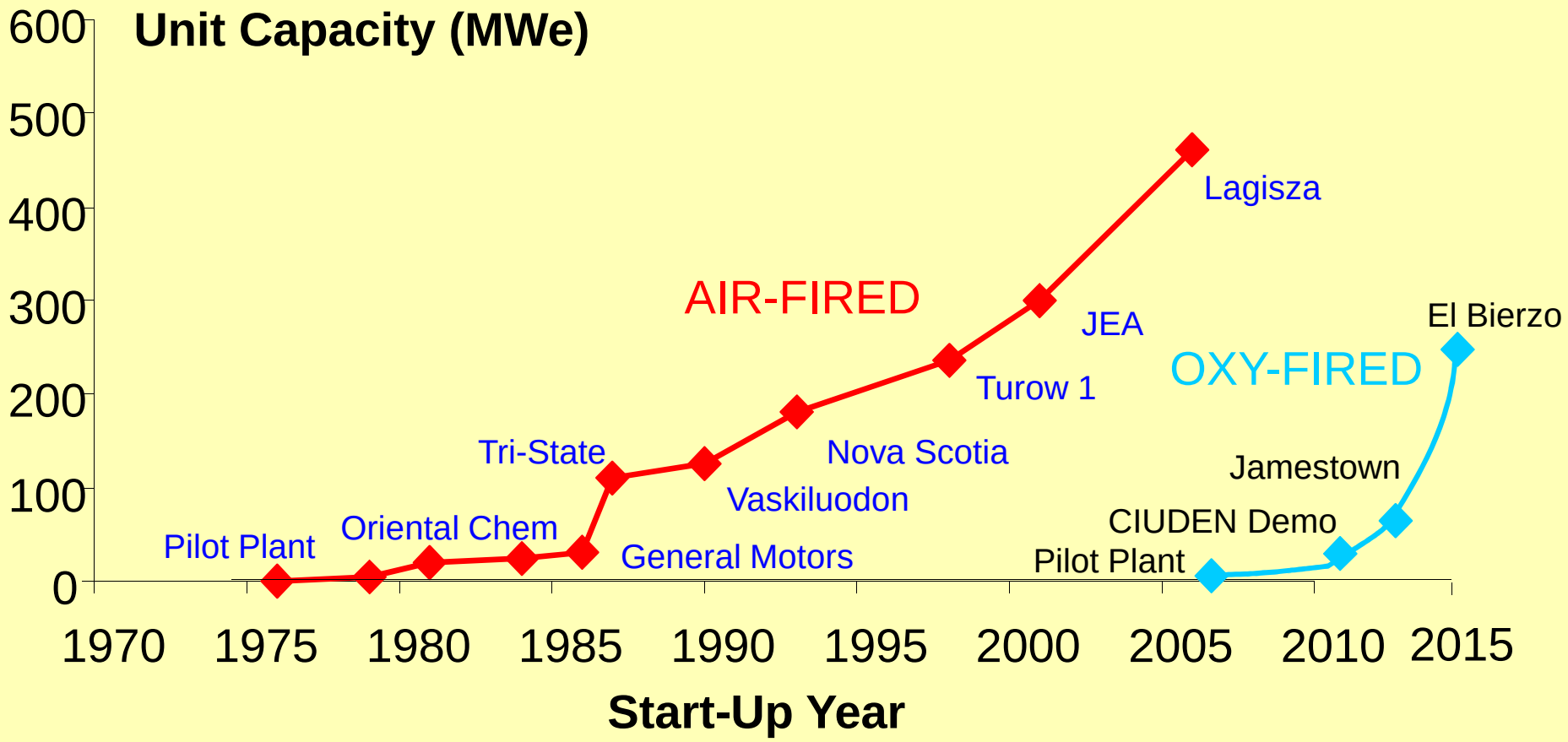
Feature	Benefit
Low furnace temperatures	- Low NO_x - In-bed SO_2 capture -Fuel flexibility (Biomass) - Ideal for Oxy-coal CCS
Hot circulating solids	- Tolerant to fuel variations - Efficient heat transfer - Simple feed systems - Uniform heat flux - Ideal for SNCR
Long solid residence time	- Good fuel burnout - Good sorbent utilization



Oxy-Coal CFB Power Plant



Evolution of CFB Unit Capacities



Technical considerations

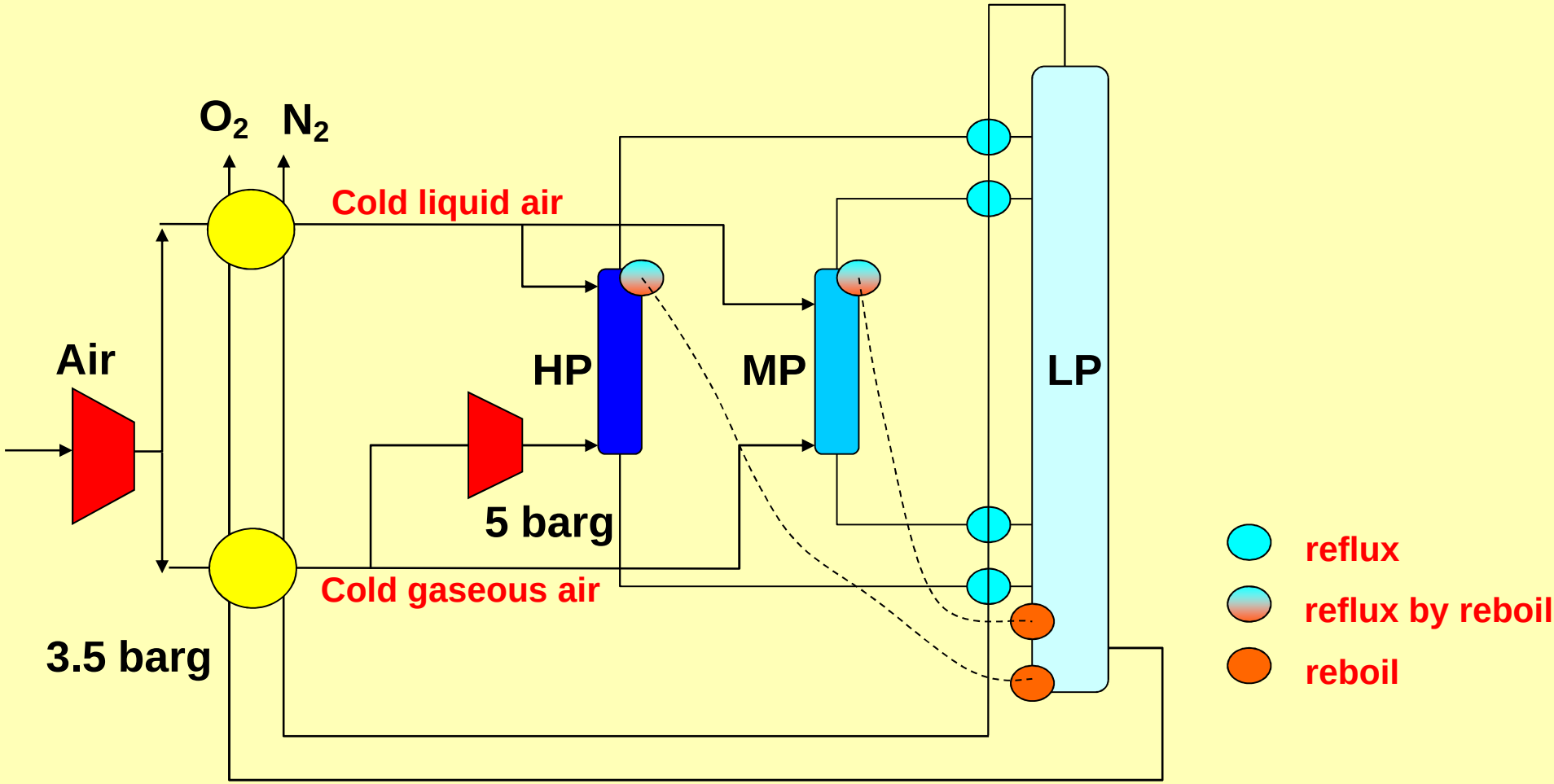
Air Separation Unit, ASU
(Oxygen production)

Current status

- As of today, the **only** available technology for oxygen production in large quantities is **cryogenic** separation
- Industrial gas companies could offers cryogenic ASUs where a single train can produce **5000 metric tons per day of oxygen** with no duplication of equipment
- In a multiple trains configuration, our largest reference (operated by Air Liquide) is totaling **40000 t/d**

Air Separation Unit

For 500 MWe (Net Output) ~10,000 t/d of oxygen required!



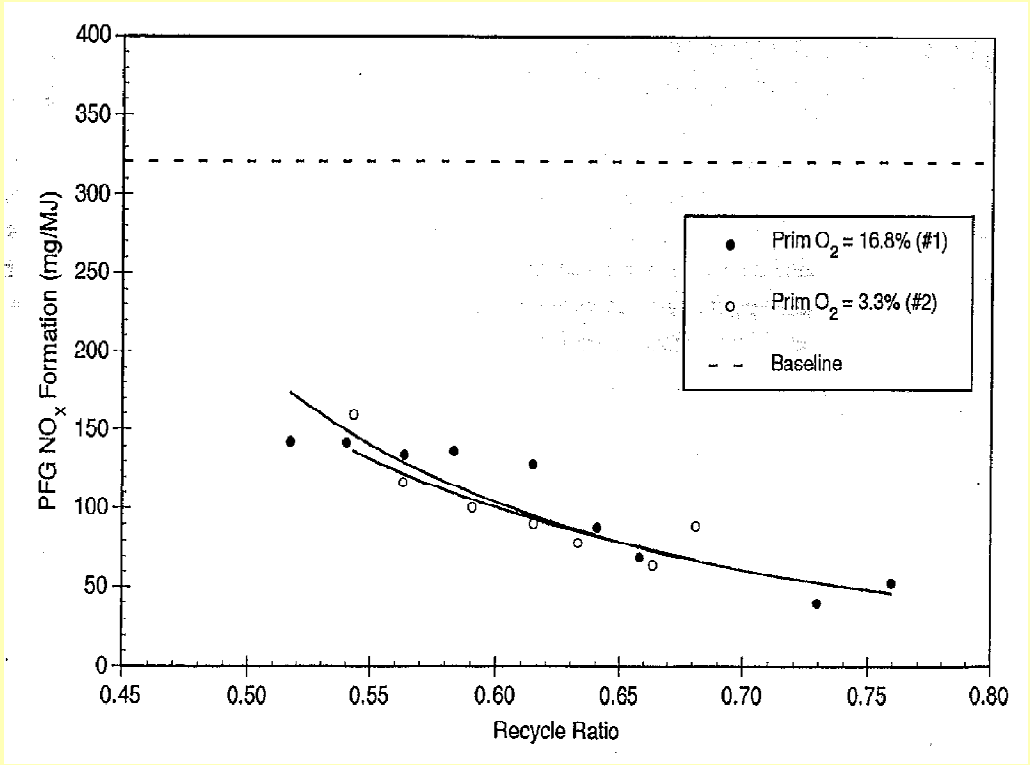
ASU General Operation

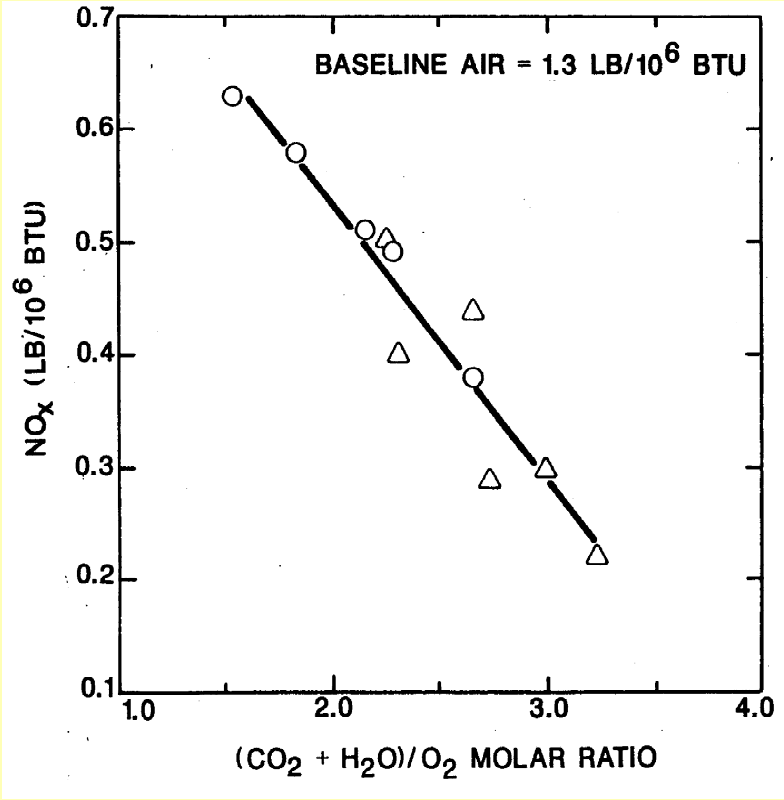
- Two levels of air compression (saves power)
- Oxygen production in HP/MP/LP 3 column system
  - Power consumption reduced to ~200 kWh/t (~150-170 kWh/t by 2010-2012)
- Optimum oxygen purity suggested:
  - 95% - 97%
  - Higher purity not worthwhile due to:
    - ✓ Excess O_2 requirement (19%)
    - ✓ Boiler air in leakage (1%)
    - ✓ ESP air in leakage (2%)

Technical considerations

NO_x and SO_x

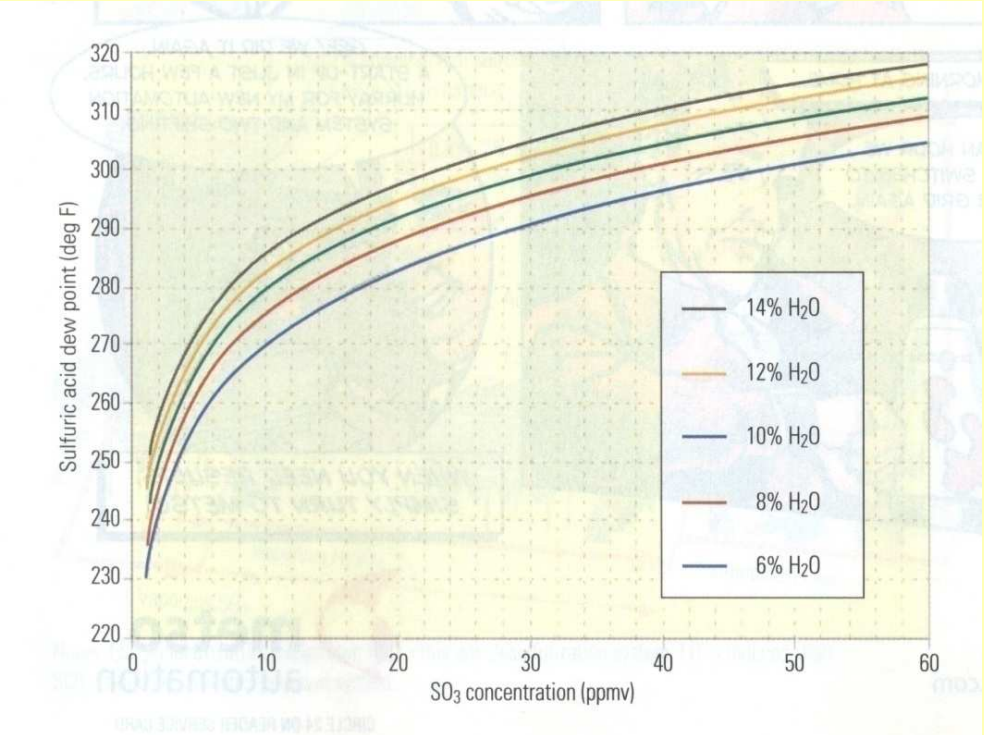
NO_x Emissions
(Results from ANL-EERC and IFRF)





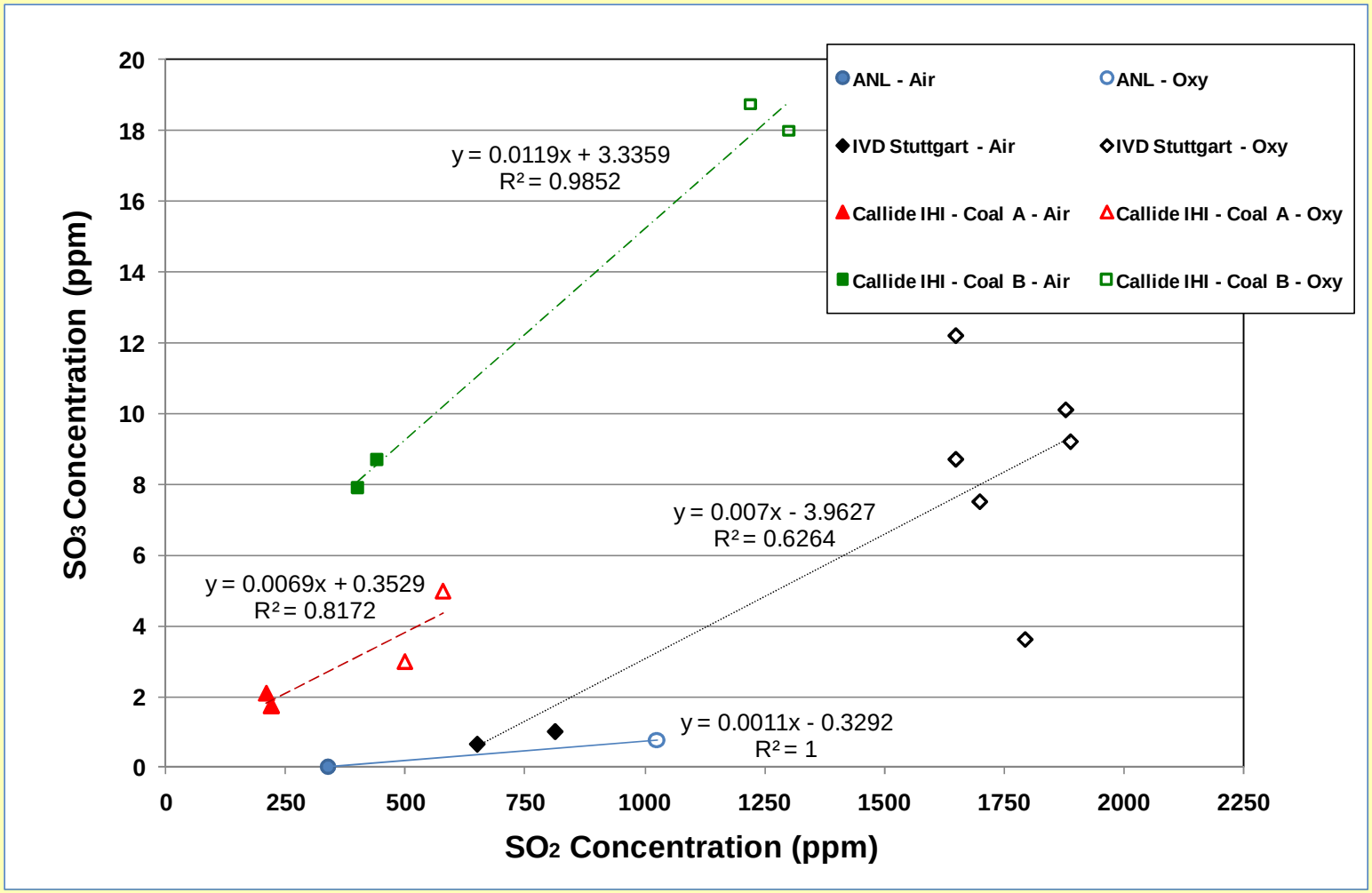
SO_3 Emissions

- ANL study (1985) have indicated that SO_3 formation is 3 to 5 times greater as compared to conventional air – firing mode
- We need to know more about the potential operational issue



From Chemical Engineering Progress (Vol. 70)

Measured SO_3 concentrations from Experimental Work of ANL/EERC, IVD-Stuttgart, Callide-IHI



Technical considerations

CO_2 processing

CO_2 processing

- CO_2 produced from oxyfuel requires purification
  - Cooling to remove water
  - Inert removal
  - Compression

- Current design has limitations
  - SO_x/NO_x removal
  - Oxygen removal
  - Recovery limited by phase separation

➢ **Necessary to define CO_2 quality requirement!!!**

CO_2 Concentration and Impurities

	TOLERANCE	
COMPONENT	LOW	HIGH
CO_2 (%)	>90	>95
H_2 (%)	<4	<4
N_2 (%)	<4	<4
Ar (%)	<4	<4
CH_y (%)	<10	<5
O_2 (ppm)	<10	<1000
H_2O (ppm)	<10	<600
CO (ppm)	<100	<40000
NO_X (ppm)	<100	<1500
SO_X (ppm)	<100	<1500
H_2S (ppm)	<100	<15000
PARTICLES (mg/Nm^3)	<0.1	<10

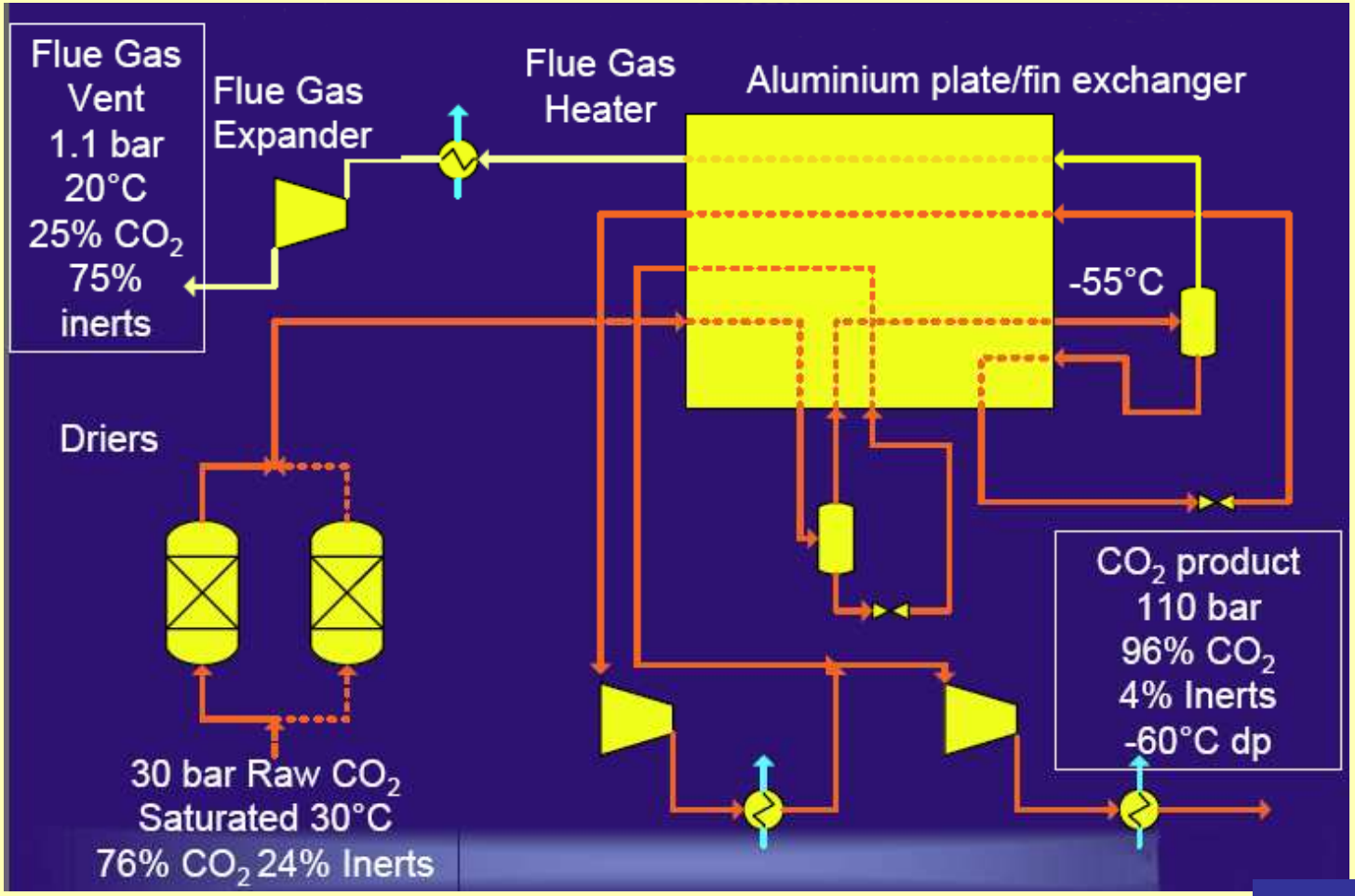
LIMITING FACTOR

EOR H&S CORROSION UNCLEAR STORAGE

Source: ALSTOM

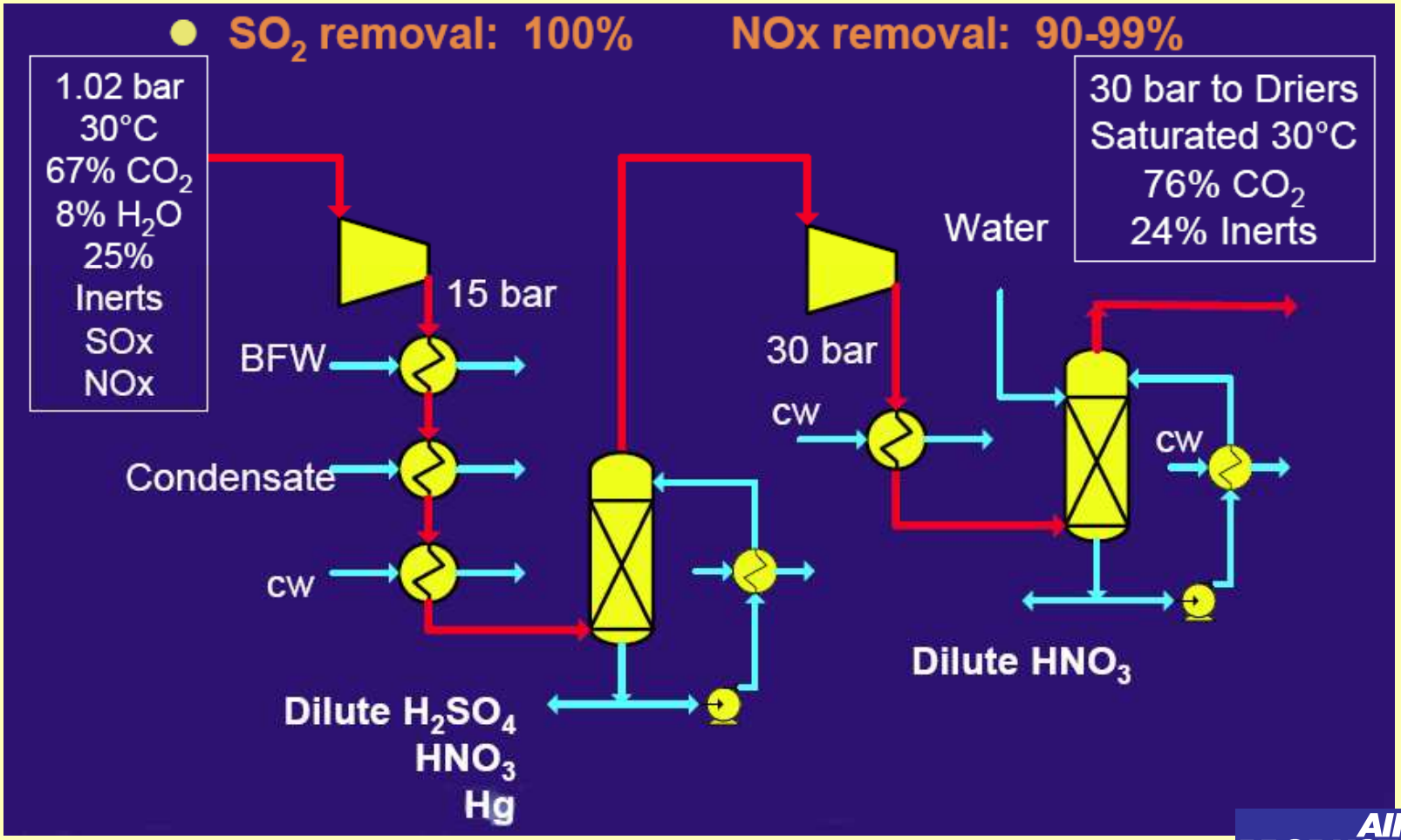
CO_2 Compression: Current Status (I)

Compression and Inerts Elimination at 110 bar



CO_2 Compression: Current Status (II)

AIR PRODUCT's Sour Compression Process



CO_2 Compression: Current Status (III)

NO_x, SO_2 Reactions in the CO_2 Compression System

- SO_2, NO_x and Hg can be removed in presence of H_2O and O_2
- SO_2 converted to Sulphuric Acid, NO_2 converted to Nitric Acid:
  - $NO + ½\ O_2 = NO_2$ (1) Slow
  - $2\ NO_2 = N_2O_4$ (2) Fast
  - $2\ NO_2 + H_2O = HNO_2 + HNO_3$ (3) Slow
  - $3\ HNO_2 = HNO_3 + 2\ NO + H_2O$ (4) Fast
  - $NO_2 + SO_2 = NO + SO_3$ (5) Fast
  - $SO_3 + H_2O = H_2SO_4$ (6) Fast
- Rate increases with Pressure to the 3rd power
  - only feasible at elevated pressure
- No Nitric Acid is formed until all the SO_2 is converted
- Pressure, reactor design and residence times are important

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Large Scale and Demo projects

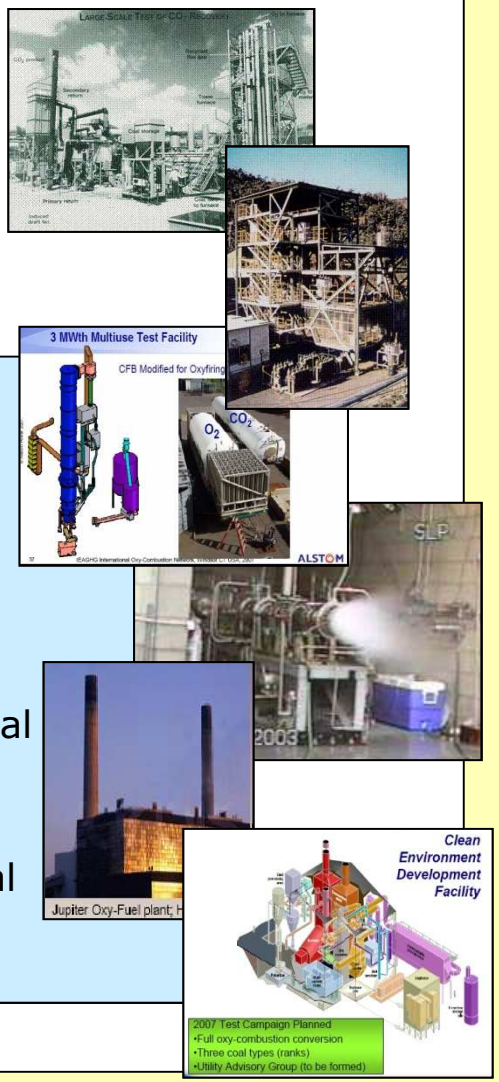
Oxyfuel Combustion

Current State of the Technology – Past, Present to Future

Industrial Scale Experiments

2008

❑ **ANL/EERC (USA):**	1982-1987	3.0 MW_t	Coal
❑ **Joule Thermie (EU):**	1992-1996	3.0 & 35 MW_t	Coal
❑ **IHI (Japan):**	1992-2000	1.2 MW_t	Coal
❑ **B&W /AL (USA):**	2000-2005	1.2 MW_t	Coal
❑ **Alstom (USA):**	2004-2005	3.0 MW_t	CFB/Coal
❑ **Kimberlina (USA):**	2002-2006	15.0 MW_t	NG
❑ **Jupiter (USA):**	2007-2009	15.0 MW_t	NG/Coal
❑ **B&W CEDF (USA):**	2006-2008	30.0 MW_t	Coal

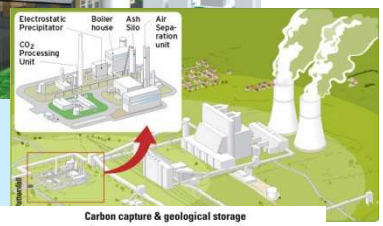


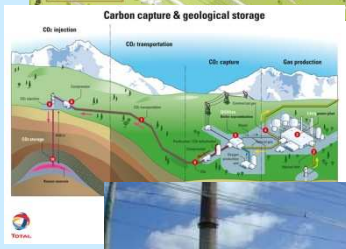
Oxyfuel Combustion

Current State of the Technology – Past, Present to Future

Industrial Scale Experiments → **Pilot Plants and Industrial Scale Experiments**

2008 2012





PILOT PLANTS with CO_2 Capture and Storage

❑ **Vattenfall (Germany): Schwarze Pumpe**	2008	30 MW_t	Lignite/Coal
❑ **Total (France):**	2008	30 MW_t	NG
❑ **CS Energy (Australia): Callide Project**	2010	90 MW_t	Coal
❑ **CIUDEN (Spain):**	2010	20/30 MW_t	Anthracite/Coal/ Coke

Industrial Large Scale Burner Testing

❑ **Doosan Babcock (UK)**	2009	40 MW_t	Coal
❑ **Alstom (USA)**	2010	15 MW_t	Coal
❑ **Hitachi Babcock (DE)**	2011	30 MW_t	Coal

Oxyfuel Combustion

Current State of the Technology – Past, Present to Future

Industrial Scale Experiments → **Pilot Plants and Industrial Scale Experiments** → **Demonstration Power Plant**

2008 2012 2020

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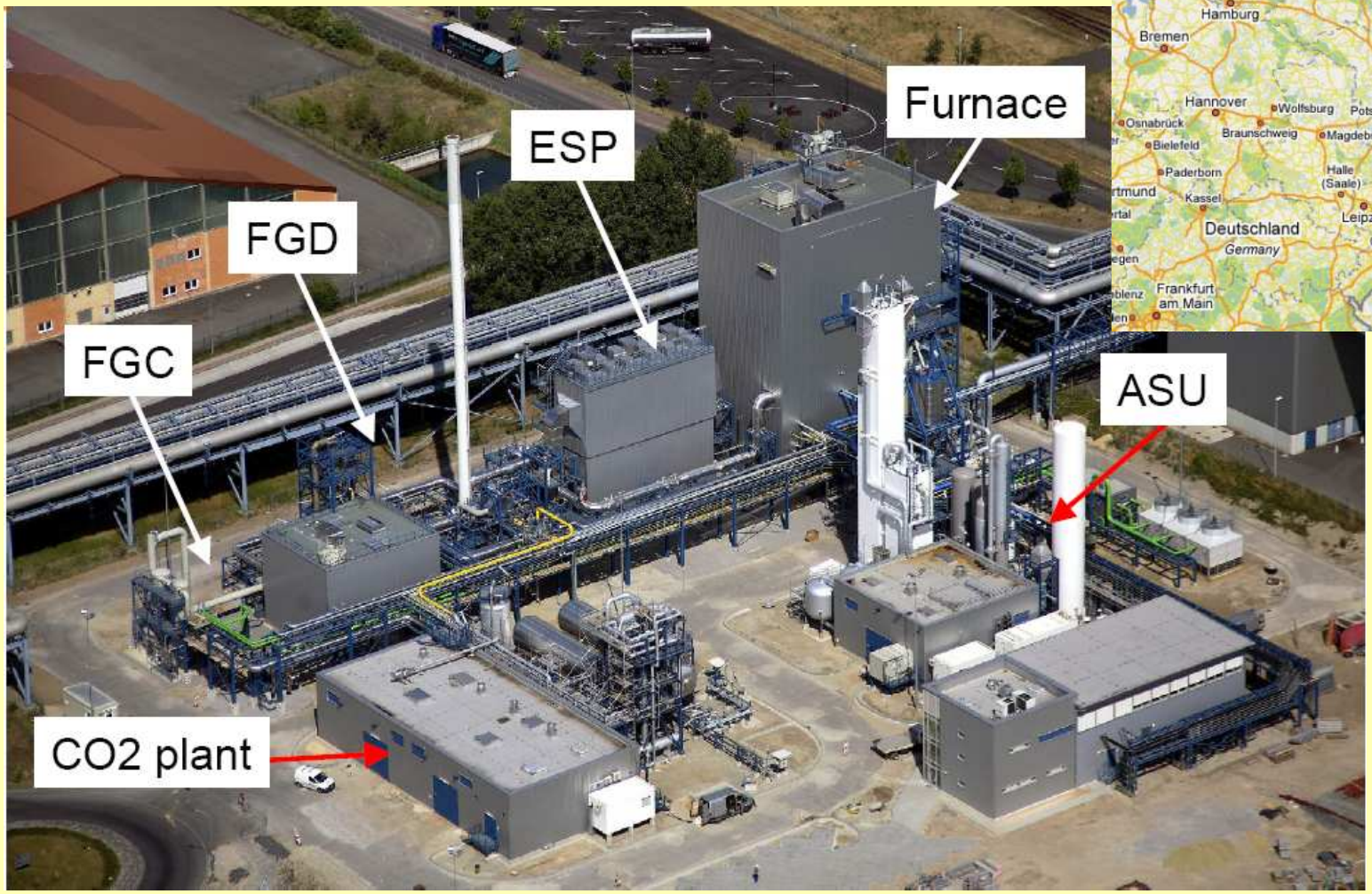
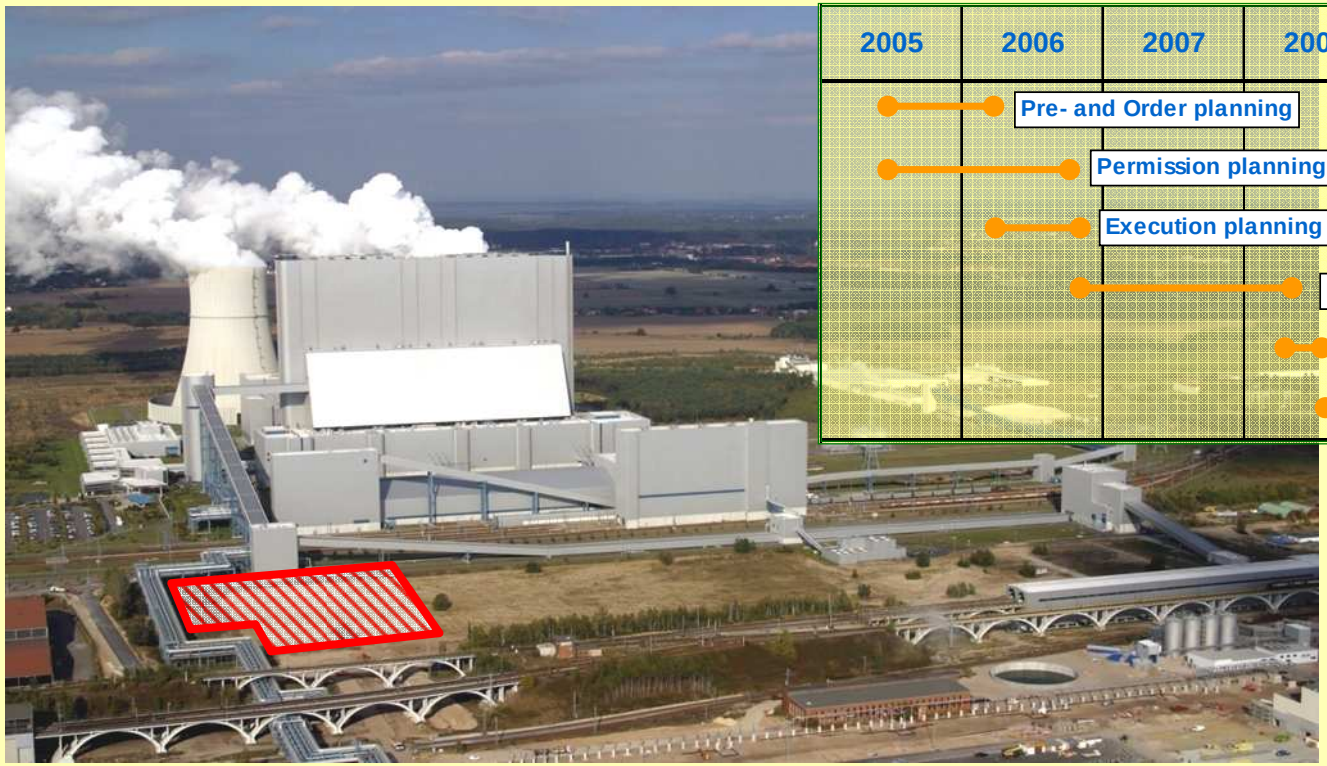
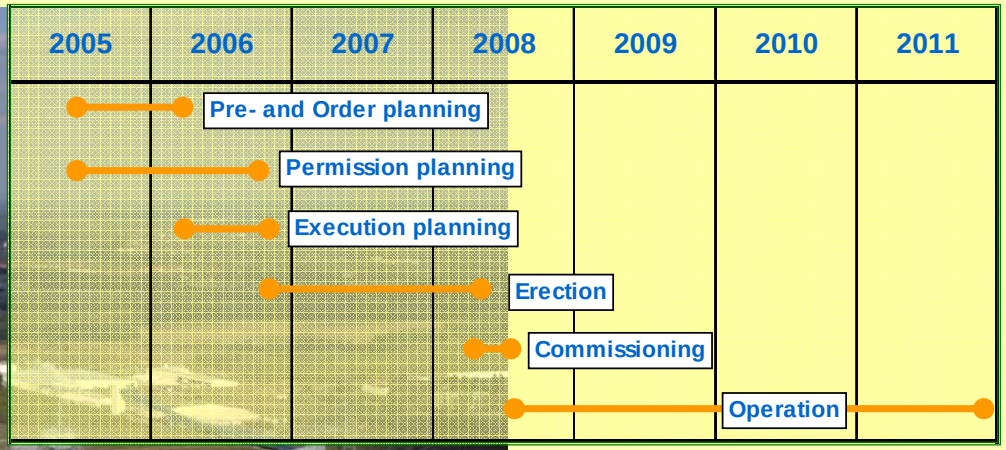
Schwarze Pumpe Oxy-Combustion Pilot Plant



Schwarze Pumpe Oxy-Combustion Pilot Plant

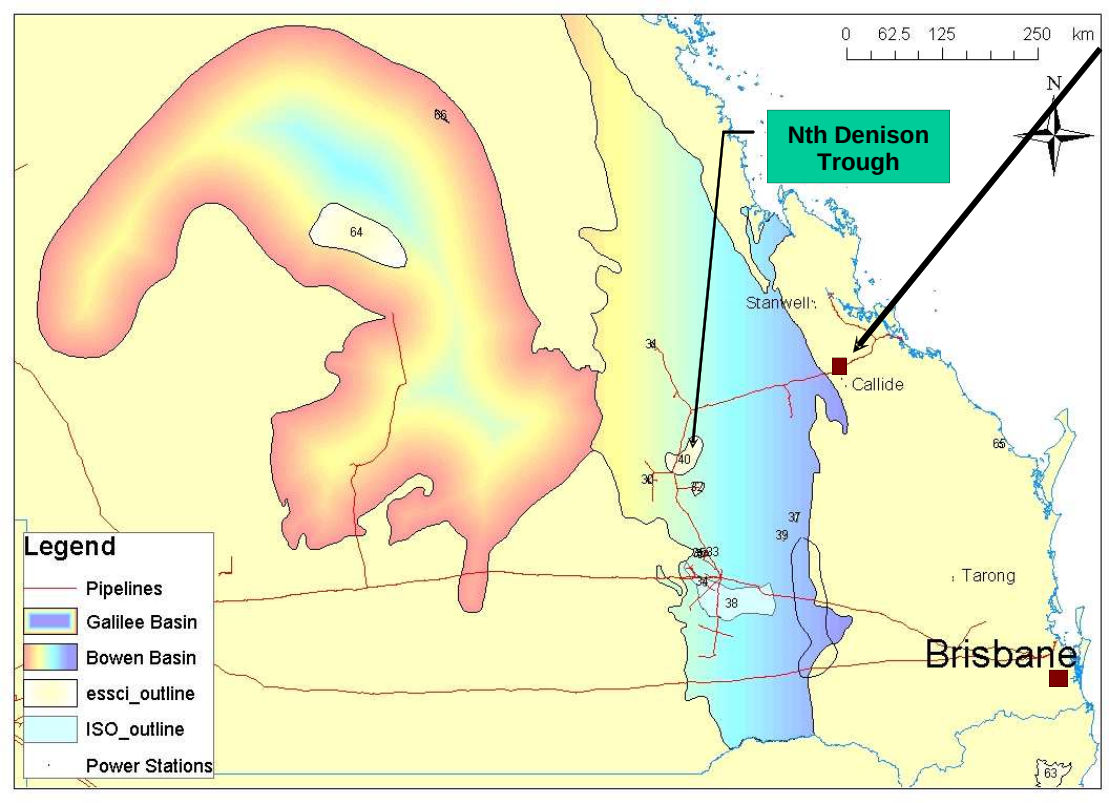


Time Table for Implementation of Oxy-Fuel Project



Schwarze Pumpe Oxy-Combustion Pilot Plant

Callide A Project: Japanese-Australian Collaboration



Callide-A Power Station

Capacity: 4 x 30 MW_e
Commissioned: 1965 – 1969
Refurbished: 1997/98

Steam Parameters: 4.1 MPa, 460°C
Steam Flowrate: 123 t/h steam

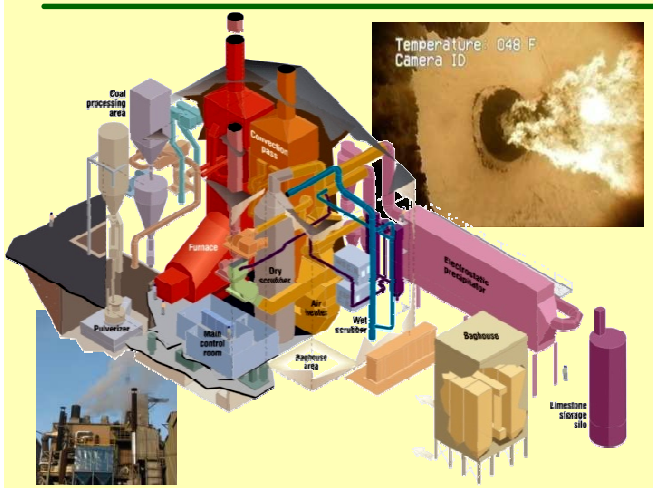
Callide A Project: Retrofit to a coal fired power plant with an oxycombustion boiler

Callide A Project: Japanese-Australian Collaboration

- Callide-A Oxy-Combustion Retrofit Project
- IHI (Japan) and CS Energy (Australia)
- Project is also supported by the Australia Coal Association, JCoal, JPower (EPDC), Mitsui
- Commissioning would start by end of 2010 / early part of 2011

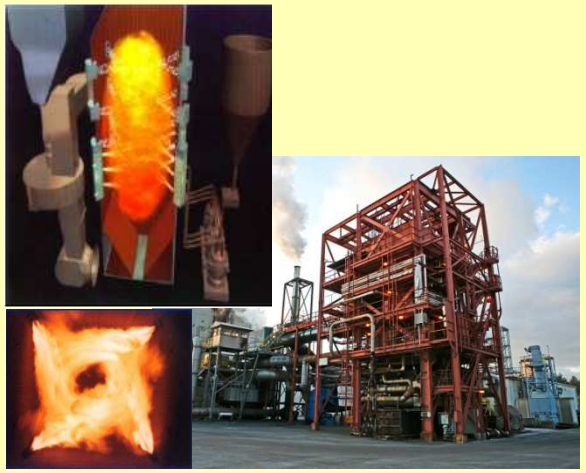
Large Scale and Demo projects

Today... There are 3 Major Full Scale PC Burner Testing Facilities Worldwide Retrofitted for Oxyfuel



- B&W – 30MW$_{th}$ CEDF
- Barberton, Ohio, USA
- Start of Operation: Oct. 2008
- Wall Fired Burner Development

- Doosan Babcock – 40MW$_{th}$/90MW$_{th}$ MBTF
- Renfrew, Scotland, UK
- Start of Operation: Jun. 2009
- Wall Fired Burner Development



- Alstom Power Plant Lab. – 15MW$_{th}$/30MW$_{th}$ BSF
- Windsor, Connecticut, USA
- Start of Operation: Nov. 2009
- T-Fired Burner Development

Courtesy of Alstom, B&W and Doosan Babcock

CIUDEN TDPs

CIUDEN is designing, constructing and will operate technology development plants (TDPs)

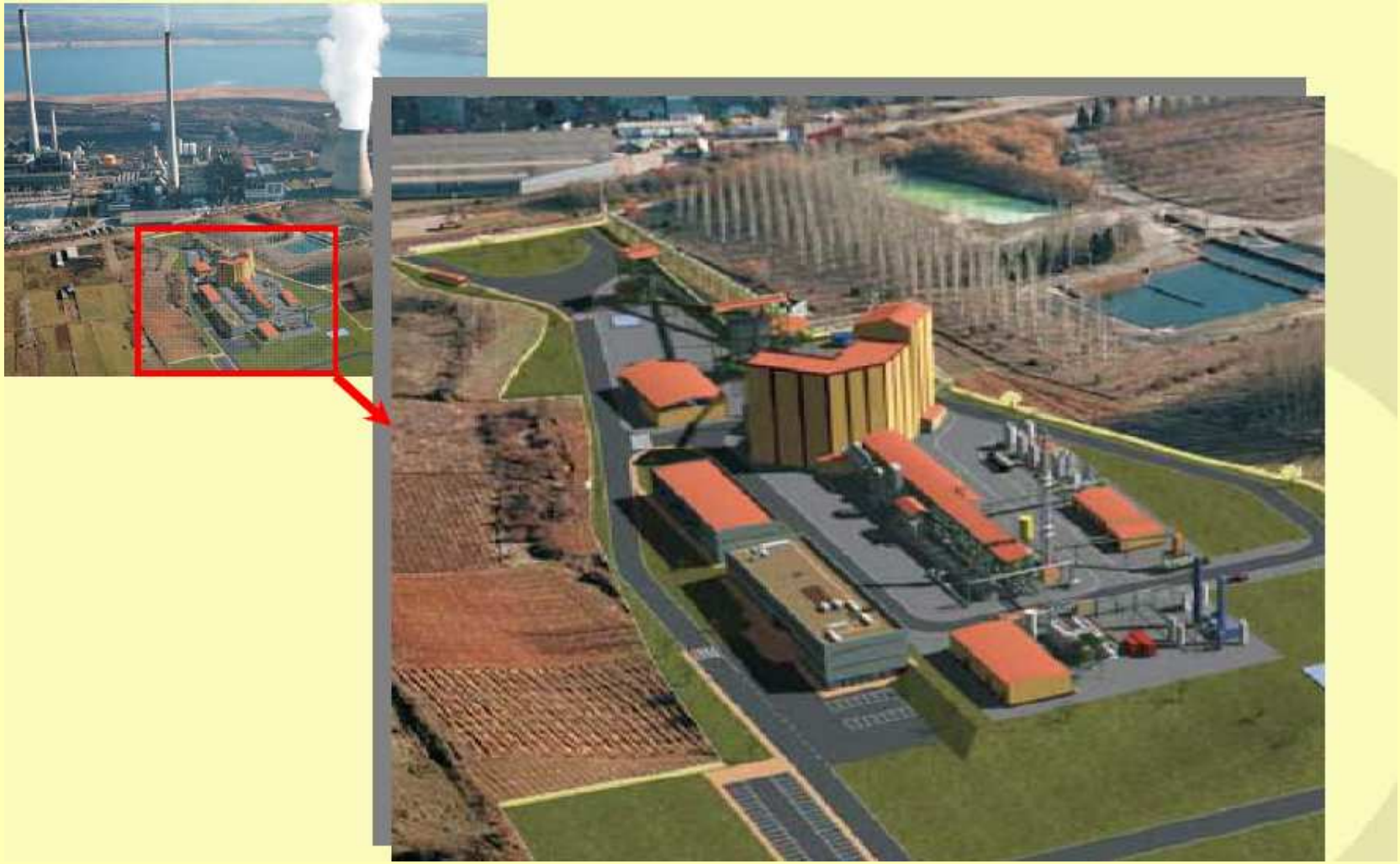
- Capture : To validate close-to-market and emerging technologies for application at commercial scale
- Transport : To obtain technical criteria for design, management and safe operation of CO_2 pipeline through long-term runs
- Geological Storage : To develop technologies and processes for injection and monitoring in saline aquifers providing support to industrial-scale activities

CIUDEN CAPTURE TDP characteristics

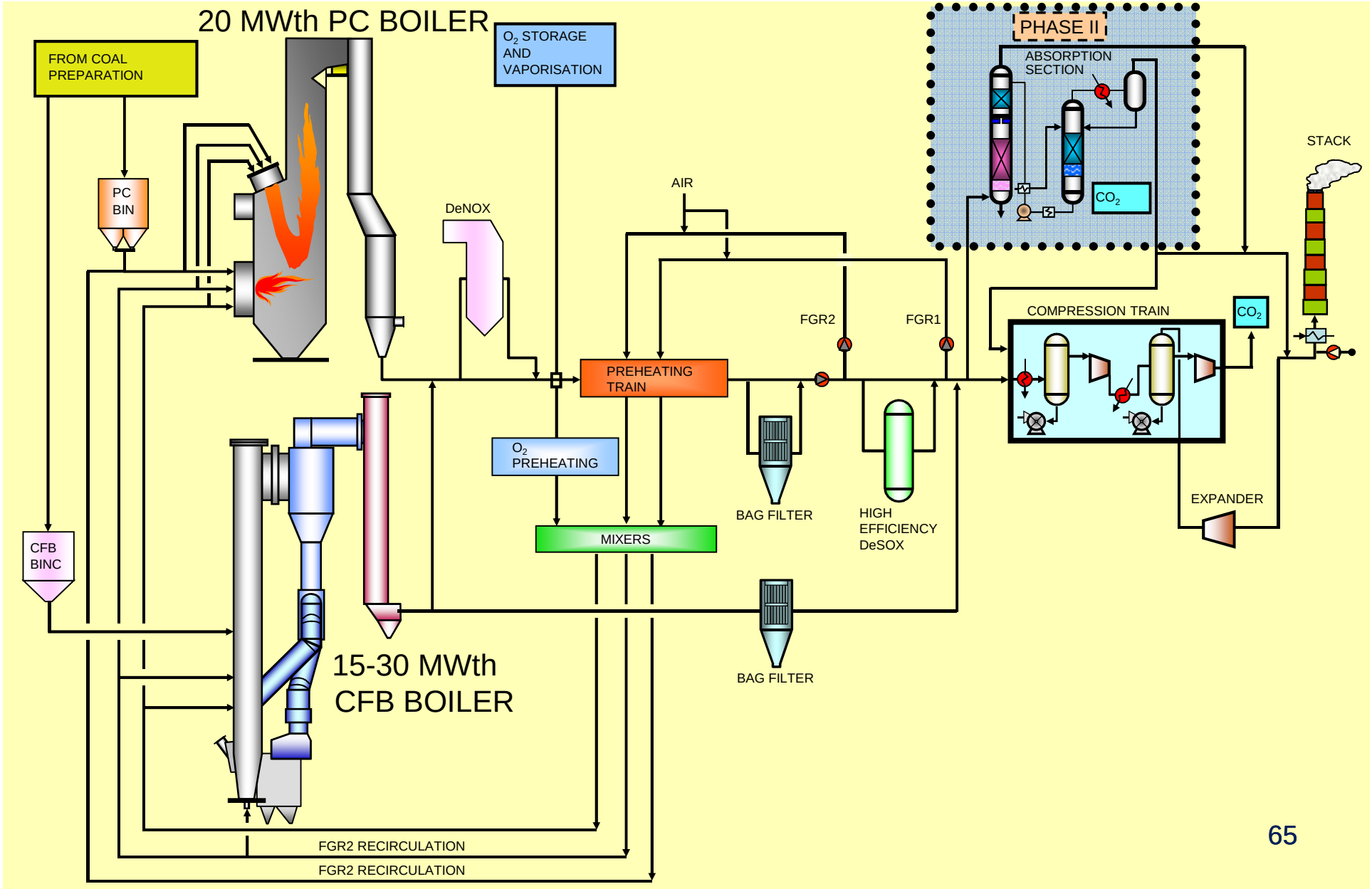
- ✓ Main process: Oxycombustion
- ✓ Technologies: 2 boilers, PC and CFB (20+30 MWth)
- ✓ Fuels: anthracites, bituminous, subbituminous coals, pet coke, biomass
- ✓ Complete gas cleaning train
- ✓ CO_2 purification and compression unit

CIUDEN CAPTURE TDP site

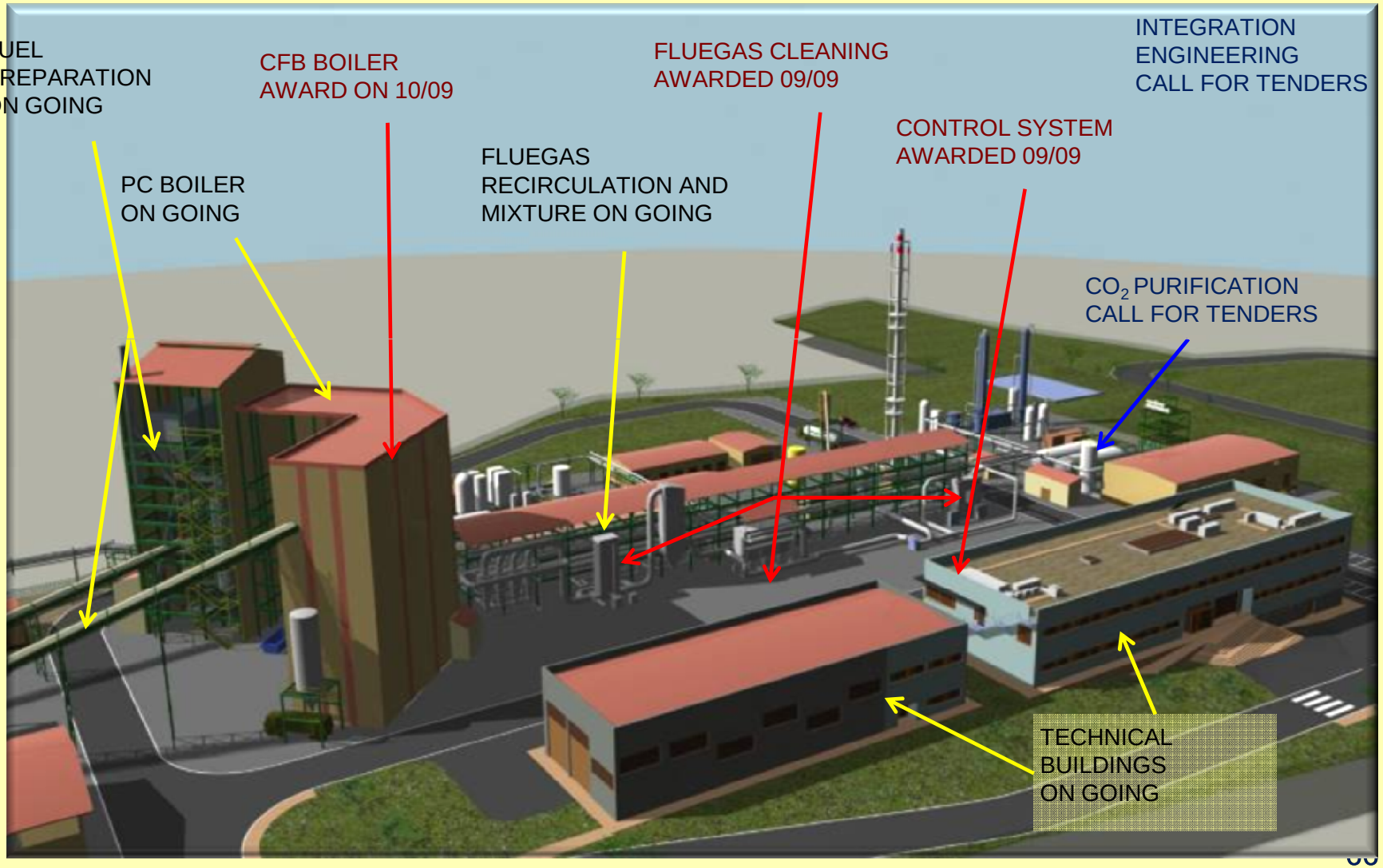
CIUDEN CAPTURE TDP site



CIUDEN CAPTURE TDP diagram



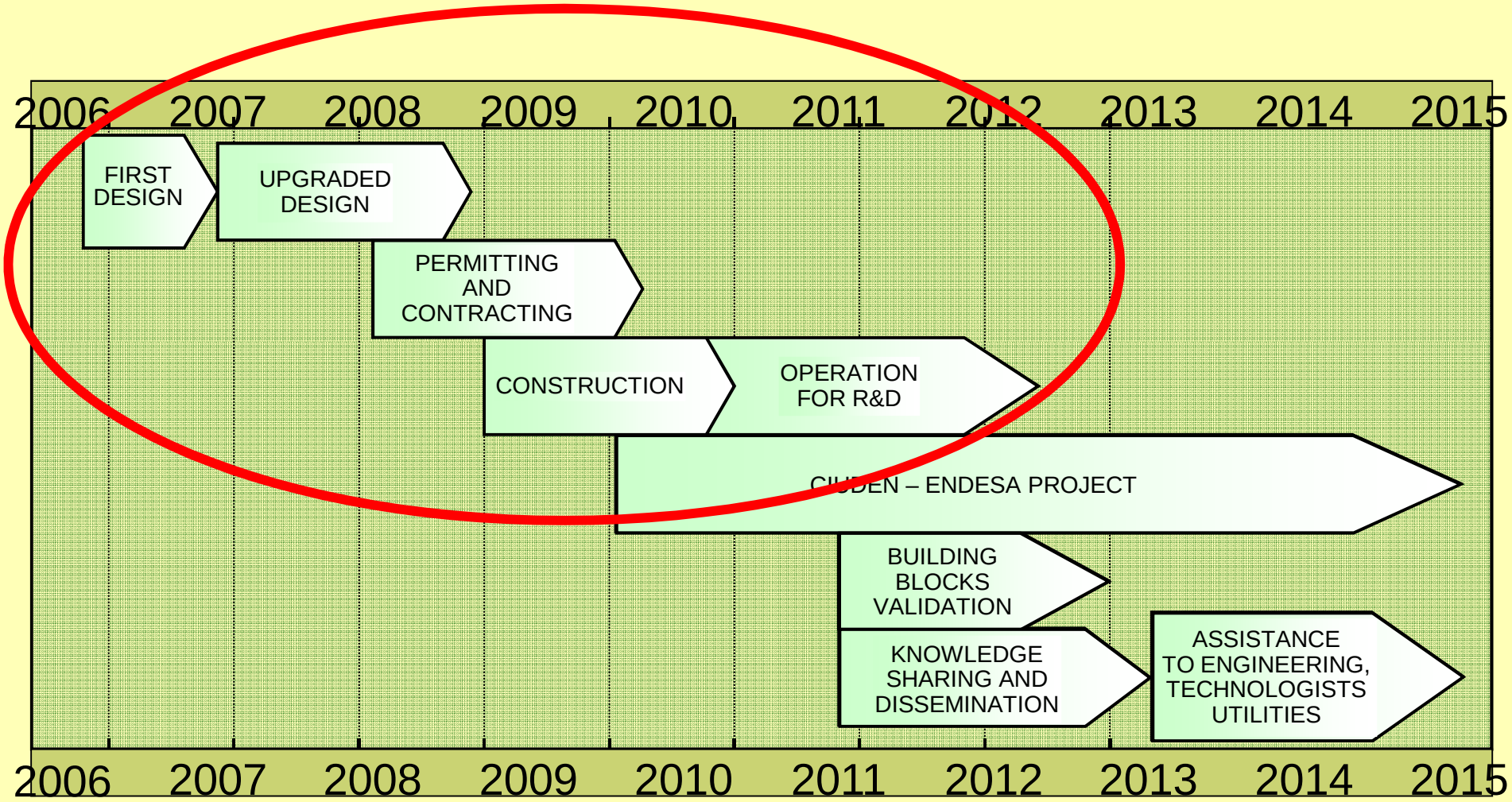
CIUDEN CAPTURE TDP
Contractors current status



CIUDEN Oxy-Combustion Pilot Plant

Current Status Sept/09

CIUDEN CAPTURE: Time schedule



Oxyfuel Combustion

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Oxyfuel Combustion

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The 6 EEPR Demo projects

CIUDEN: OXYCFB 300 Demo Plant

Construction and operation of the 30 MW_{th} TDP

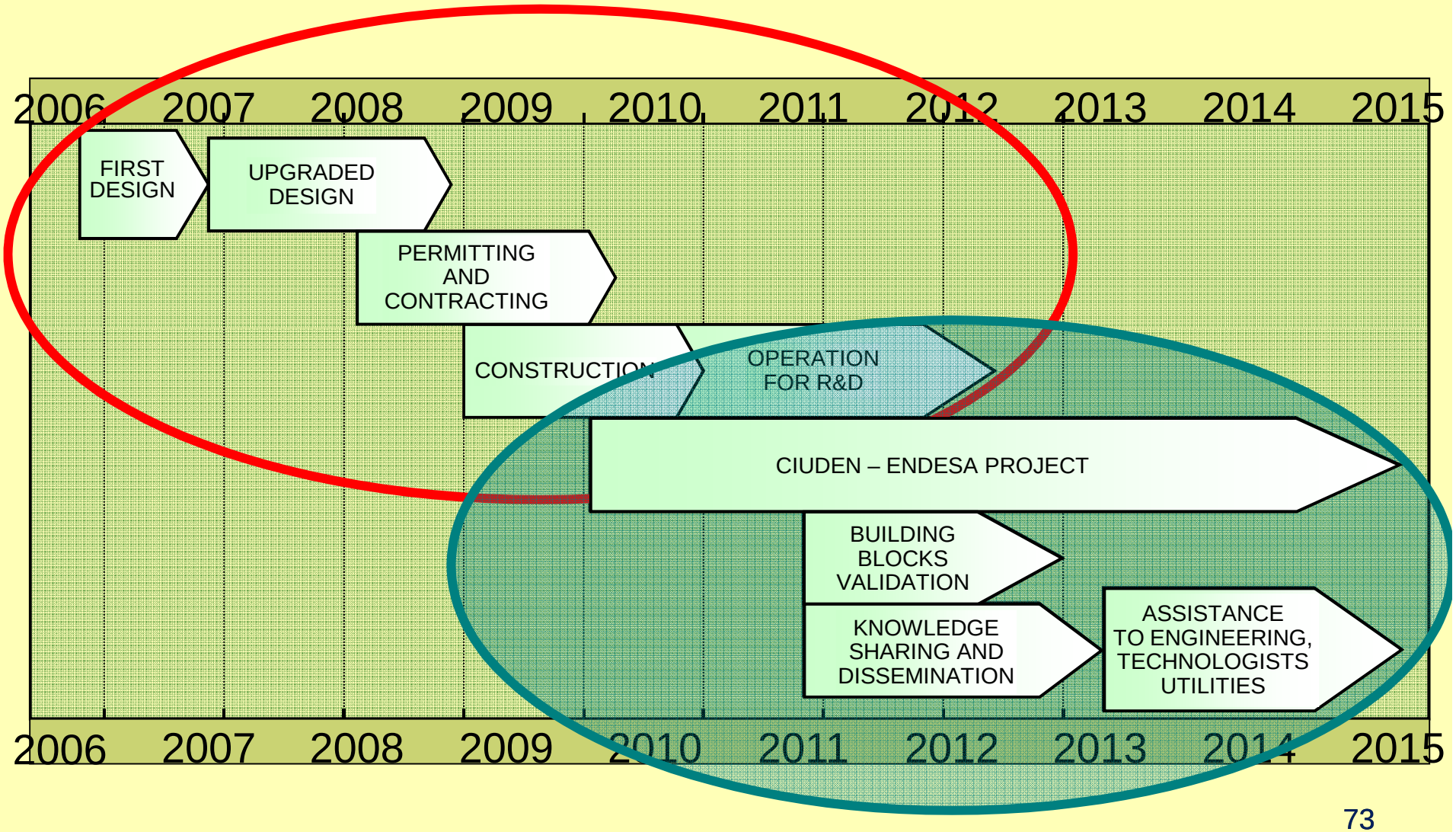
Selection and development of the industrial storage

Construction and operation of a TDP for storage and monitoring technologies

Construction and operation of the 300 MW_e Demo Plant: OXY CFB 300

Development and management of the industrial storage installation : CO_2 captured 1 Mt/a

CIUDEN CAPTURE: Time schedule



Summary and Concluding Remarks

Boiler & Burner development

- Demonstration at Large Scale required
- Coal Properties
  - Heat transfer and flame properties
  - Devolatilisation and ignition properties
  - Char burnout (reactivity)
  - Slagging, fouling and ash deposition
  - Pollutant emission (especially Hg, trace element and SO_3)
- How to deal with Air In-Leakage
- Boiler materials in relation to corrosion
- Safety issue particularly in handling Oxygen
- Development in CFD modeling is an essential tools to help design of future burners and boilers

Air Separation Unit

~10,000 t/d of O_2 is required for a 500MWe (net) oxy-coal power plant with CCS.

- 2 single trains of 5000 TPD ASU required

- Remaining Issues
  - How can we advance the development in distillation column
  - What could be the maximum capacity of oxygen production per train?
  - Operation flexibility (i.e. load following, etc…)
  - What will you do about the large volume of Nitrogen produced from this ASU?

➢ Novel oxygen production (membranes, chemical looping)

CO_2 Processing

- We need to establish what is appropriate and acceptable level of impurities in our CO_2 based on aspects of:
  - Health, Safety and Environment considerations
    - Regulations to be established without disadvantaging any capture technology
  - Quality specifications defined by transportation/delivery of CO_2 to the storage sites
    - Also to consider the changes to the CO_2 properties by the impurities and its possible reactions
  - Quality specifications defined by the storage CO_2 for different storage options

➢ The quality of CO_2 should be openly discussed

CO_2 Processing

- Depending on the requirement of the oxygen content, processes are now available to produce CO_2 purity from 95% - 99.999%
- Removal of SO_x and NO_x depends on the “lead chamber reaction” to occur
- Integration of ASU and CO_2 processing in the overall oxyfuel combustion plant are key to achieve high efficiency and low capital expenditure

CONCLUDING REMARKS

- Fundamental understanding of the principles of Oxy-Coal Combustion well established during the past 20 years
  - Still some gaps in knowledge – but already ready for large scale demonstration of the technology
- Integration of the different processes: oxycombustion, production of oxygen and CO_2 processing
- Large scale demonstration of Oxy-Coal Combustion necessary for rapid deployment
  - Oxy-combustion will be a competing option vs post-combustion for coal fired power plant retrofit
  - Oxy-combustion will be a competing option vs IGCC for new built coal fired power plant

Special thanks to **Stanley Santos**

from

IEA Greenhouse Gas R&D

Programme

Thank you!!!

Monica Lupion

Fundacion Ciudad de la Energia **CIUDEN**

m.lupion@ciuden.es

OPEC-IEA GHG CCS workshop for scientists and professionals

Pipelines and infrastructure

Key issues

CCS – the transport element

Middle – the pipeline system

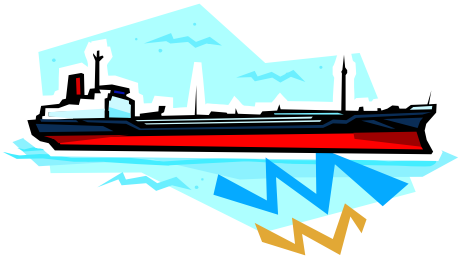
Beginning:-

Compression drying and purification

Booster station

End:-

Pressure and temperature adjustment Flow control



CO2 shipping
Possible but very costly

Overview

- Pipeline systems
  - The beginning – Compression and purification
  - The middle – the pipeline
    - Design considerations and issues
      - Sizing
      - Routing
      - Phasing
      - Mechanical design
      - Process specifications
      - Metering
      - Monitoring – pigging, surveillance, corrosion, integrity
  - The end – the injection system

Overview cont

- Other infrastructure
  - Hydrogen distribution
  - Capture site infrastructure
    - Land take
    - Location
    - Utilities – water, power connections
  - Injection site infrastructure
    - Onshore – land take
    - Offshore – subsea or via platform

Compression and purification

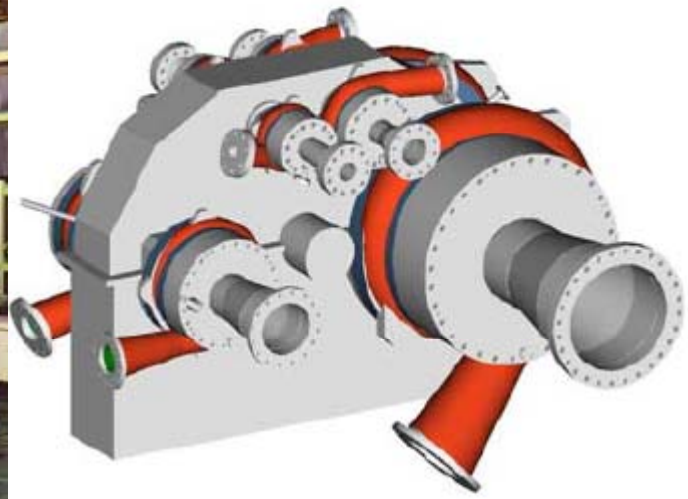
- Compression when in gas phase
- Pumping when in liquid or dense phase

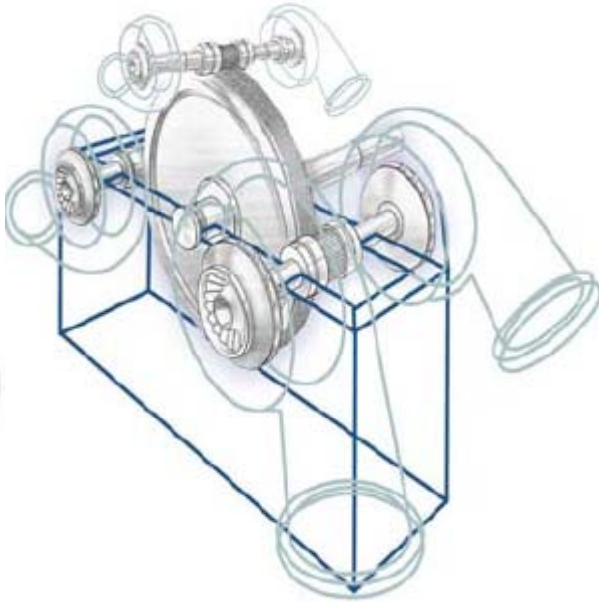
- Highly specialised equipment – MAN-turbo
- Integral gear – centrifugal machines

MAN TURBO AG

ASME TURBO EXPO 2007
CO2 Compression

- Integral-gear centrifugal compressor

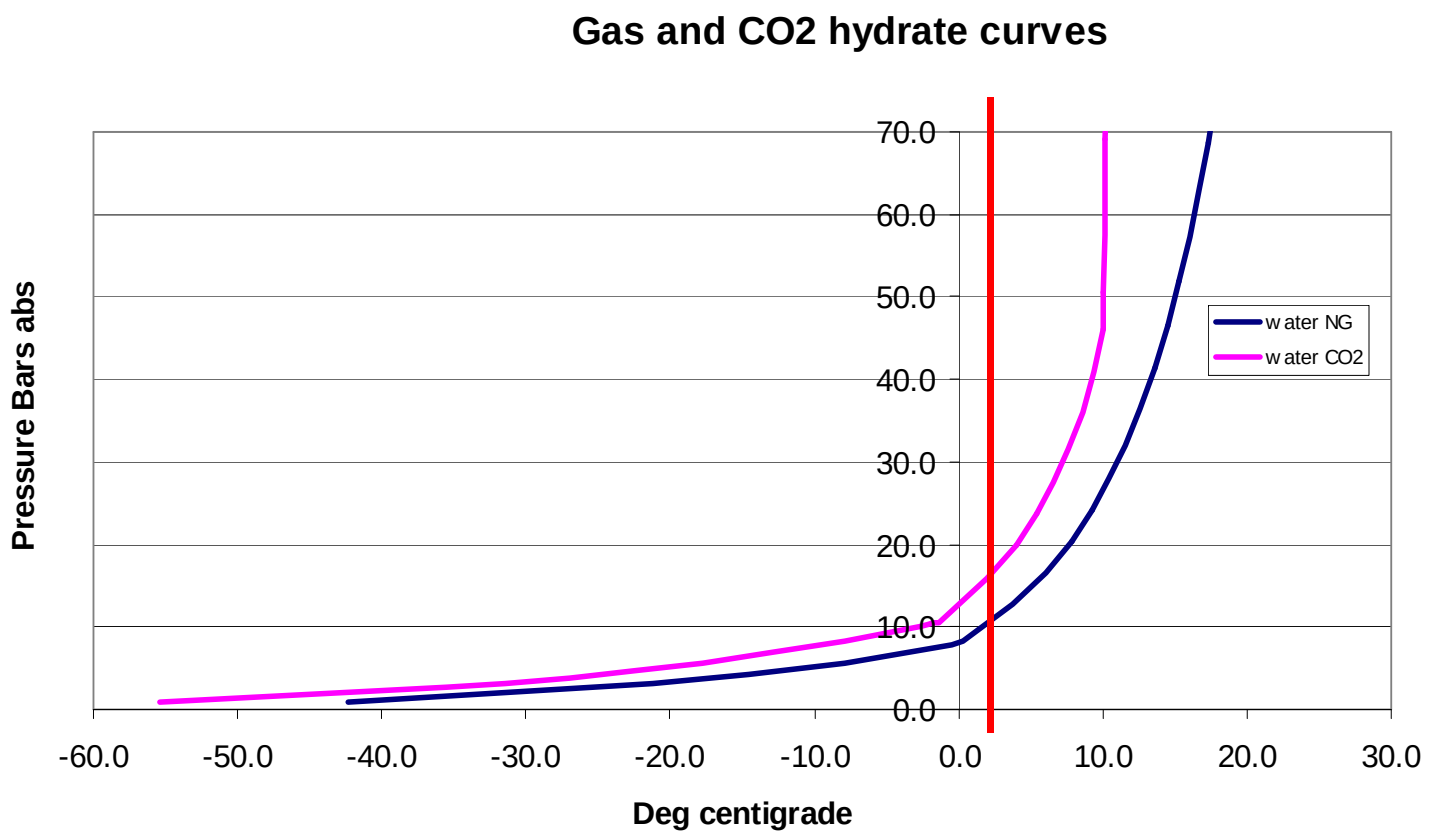




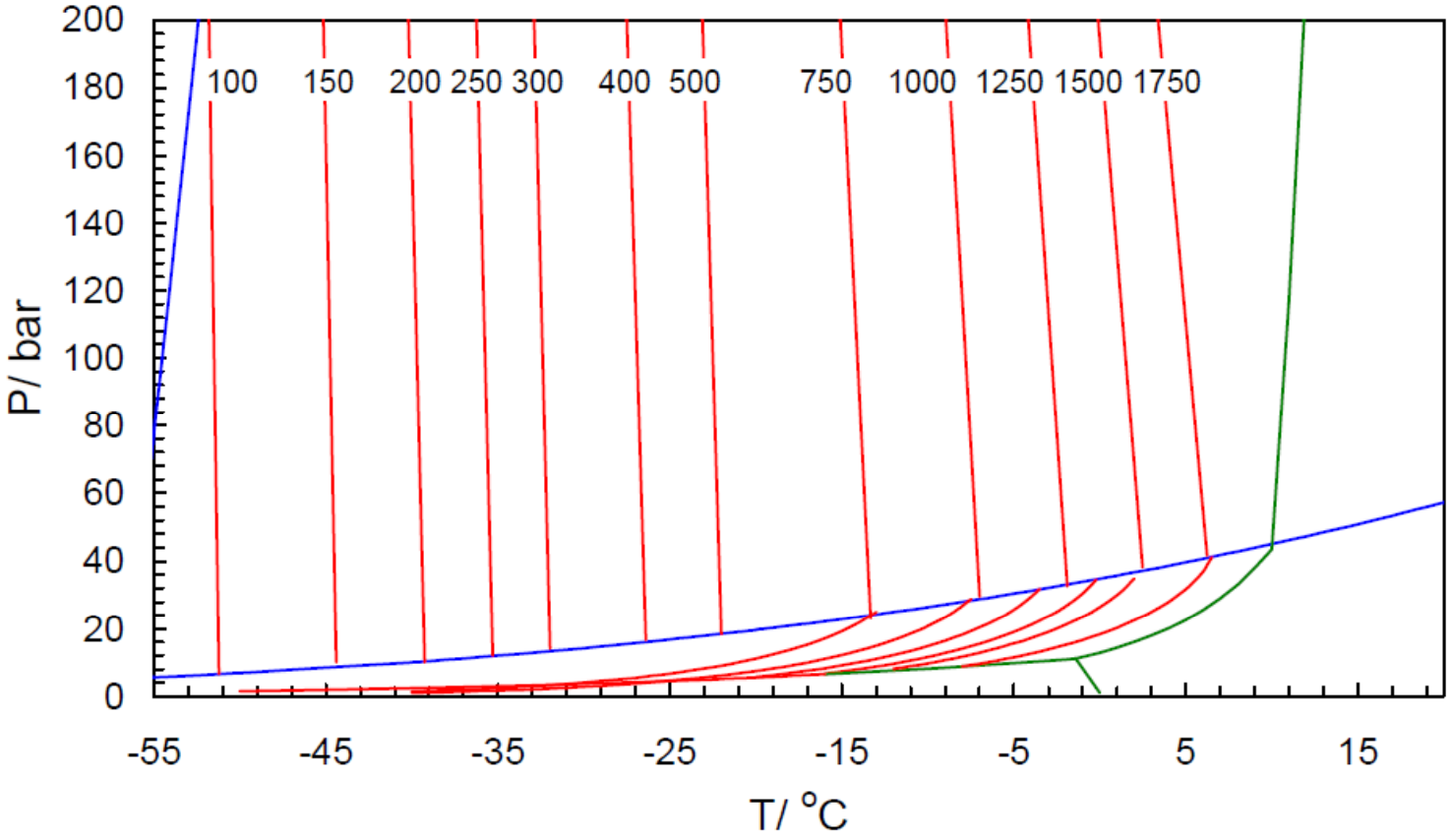
Purification

- Drying
  - To prevent corrosion
  - To avoid hydrate formation
- Methods
  - Compress and condense - e.g. Sleipner
  - Glycol absorption – enough for pipeline spec
  - Molecular sieves – For oxy-combustion cryogenic clean up

CO_2 hydrate formation



Hydrate stability/water solubility



Green lines: Hydrate stability of CO_2 in the presence distilled water or ice; Blue lines: VLE and SLE lines of pure CO_2; Red lines: Hydrate stability of CO_2 at fixed water content (Note in the vapour region, the water contents are (from left to right): 100, 150, 200, 250, 300 and 400 ppm)

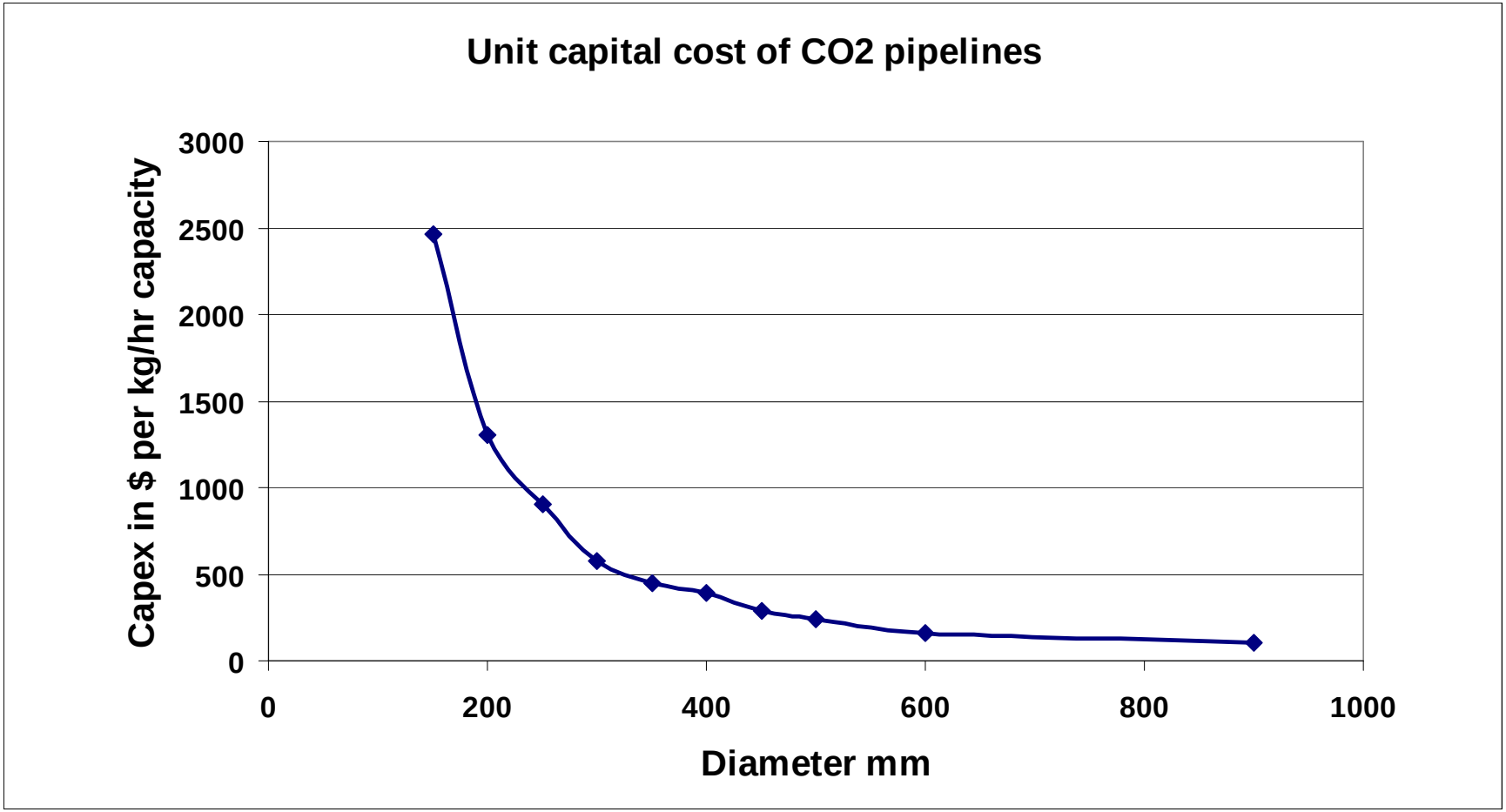
Purification

- Other components
  - H_2S, SO_2, NOx, Hg, Ash, HCl, HF
  - N_2, O_2, Ar, H_2, CO
- Presence and amount depends on process
- Removal
  - H2S – amine scrubbing
  - SOx/NOx – Reaction with O2 + cryogenic
  - Other gases – Cryogenics to -50C
  - Hg - Guard bed
  - Acidic gases – water or alkaline wash

Pipelines – sizing issues

- Unit transport costs are lower for:
  - Larger diameter lines
  - Operation at supercritical conditions
- Pressure boost by pumping is cheaper than by compression
- Two phase region has to be avoided

Basis – Inlet 120bar, outlet 80bar, pure CO2 at 10C, supercritical state

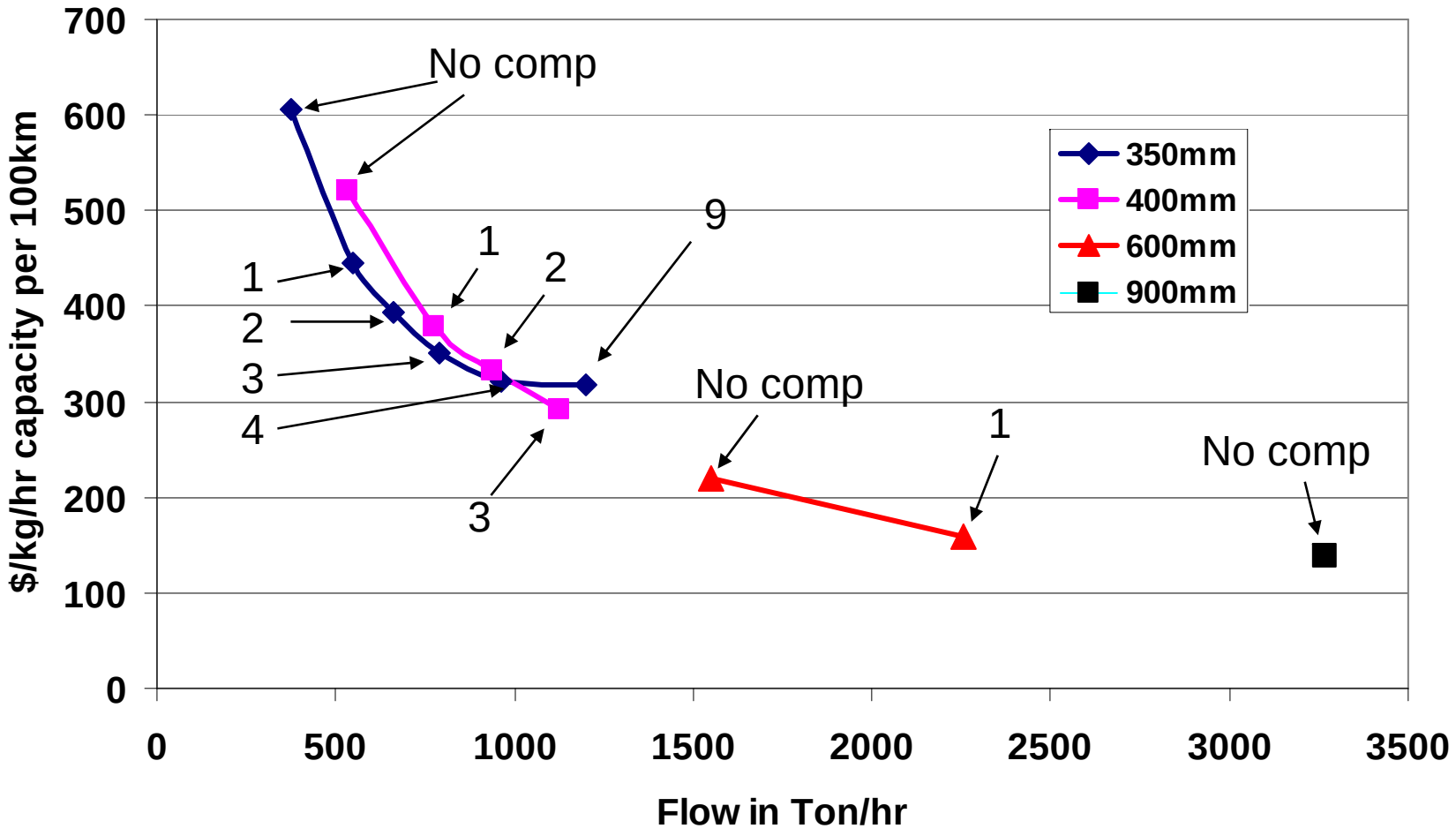


Sizing issues – pressure boosting

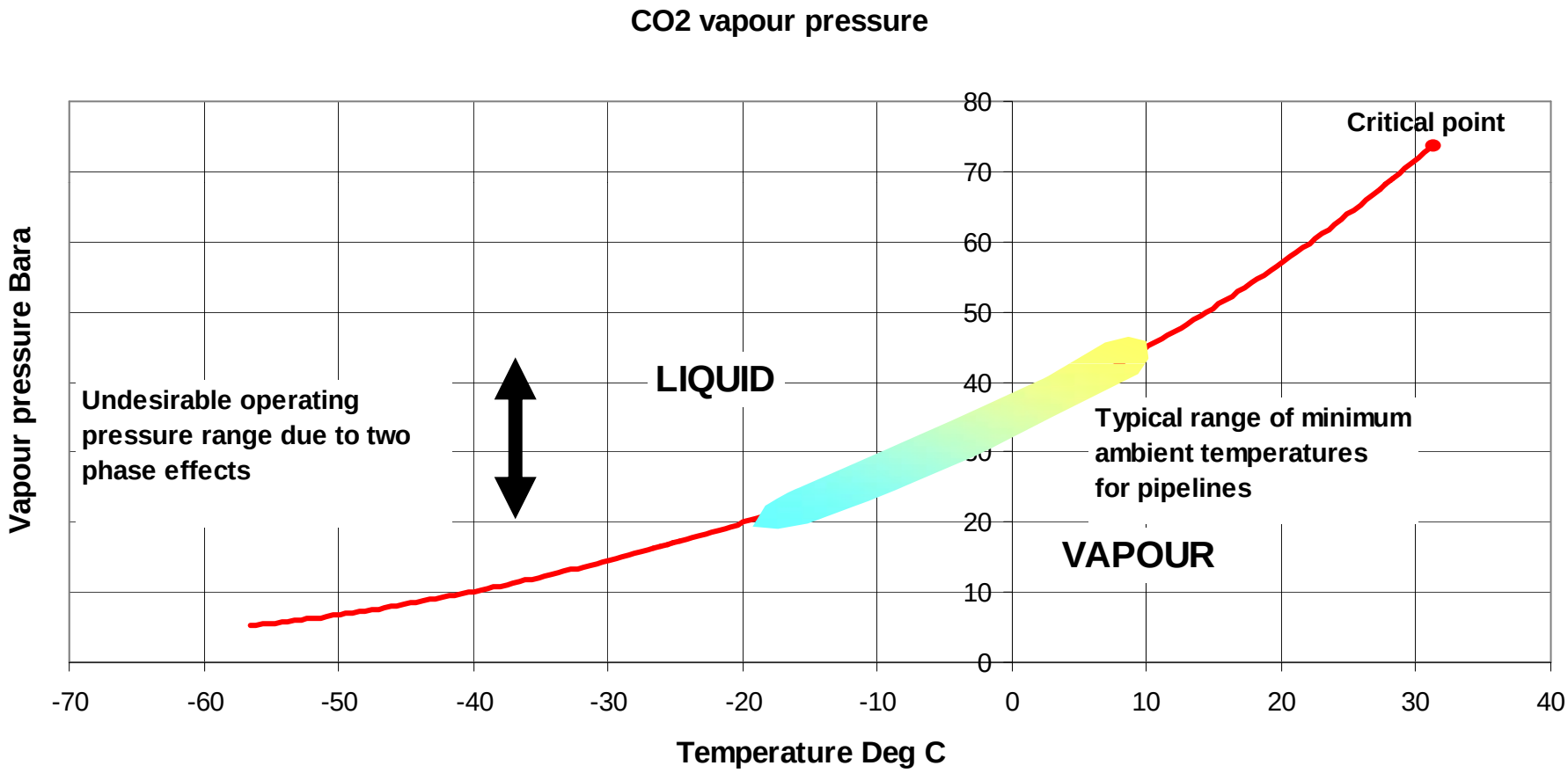
- Economic balance between cheaper smaller diameter lines and cost of additional compression or booster stations
- Higher pressure thicker walled lines are less prone to external damage.
- Booster stations are additional source of leakage
- Booster stations complicate pigging arrangements

Unit costs for pipeline transport

Sizing and costs based on IEAGHG CO2 pipeline calculator



Avoiding the two phase region

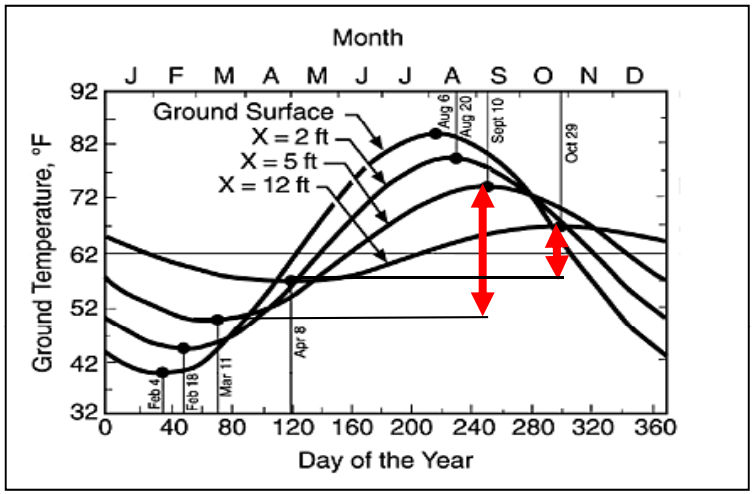


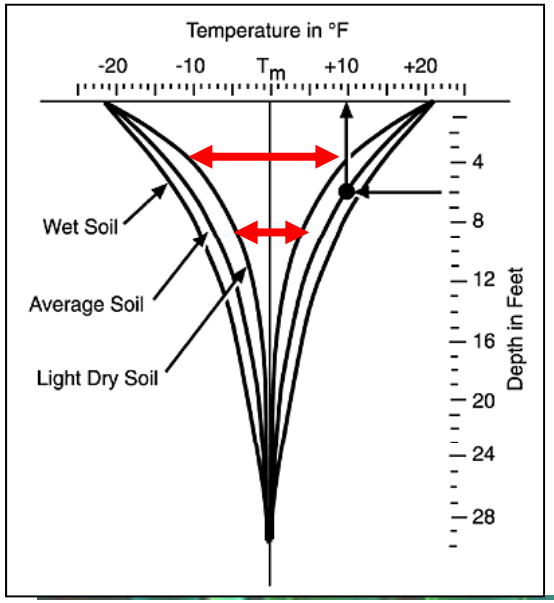
Pipelines routing

- Most standard routing considerations apply
- Points to consider
  - High density hence height changes will influence design
  - CO2 is a heavy asphyxiant gas hence location low areas need to be considered especially in populated areas
  - Safety distances to population based on dispersion calculations could be quite large

Pipelines – Mechanical design

- Basic considerations of steel strength apply
- Low temperature performance must be specified in line with minimum temperatures due to leaks or depressurization
  - DBTT (Ductile to brittle transition temperature)
  - Hardness
    - NB welds as well as base material must be covered
- Requirements expected to be slightly tighter than for natural gas



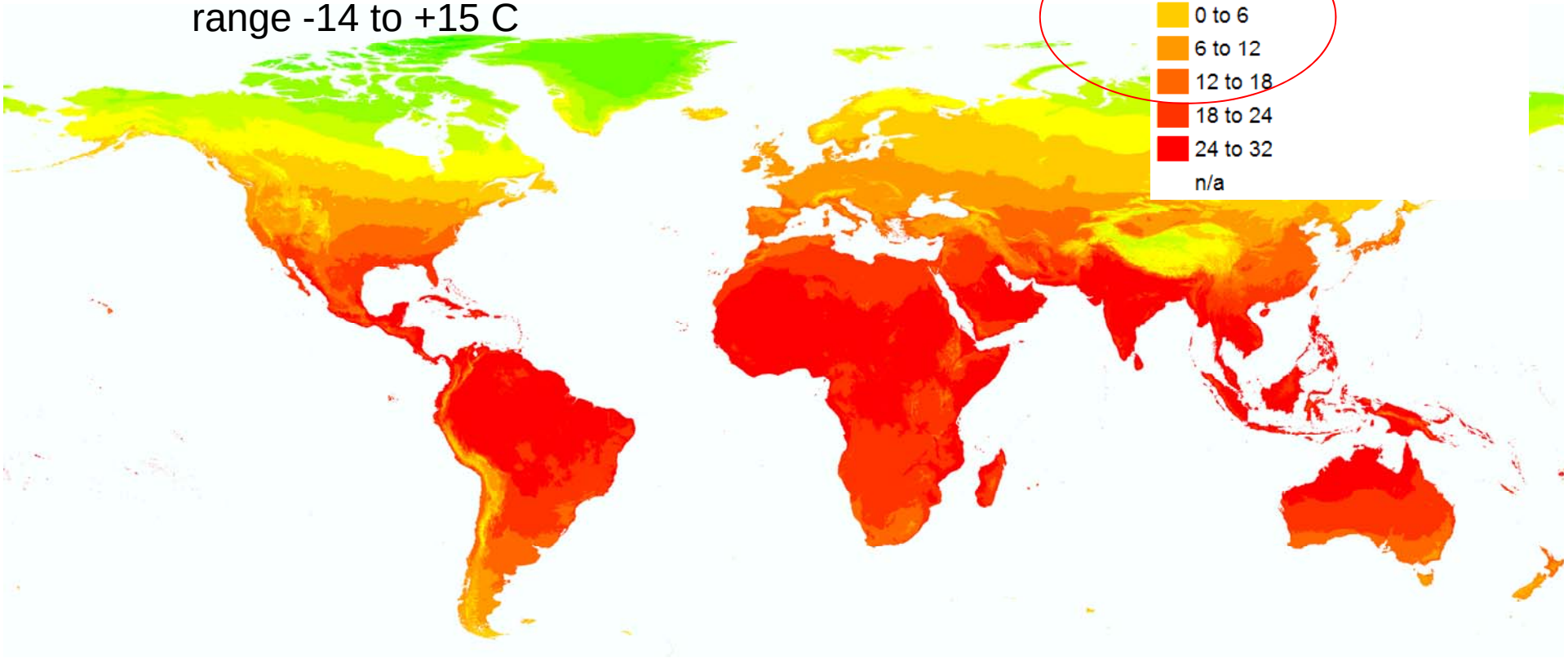


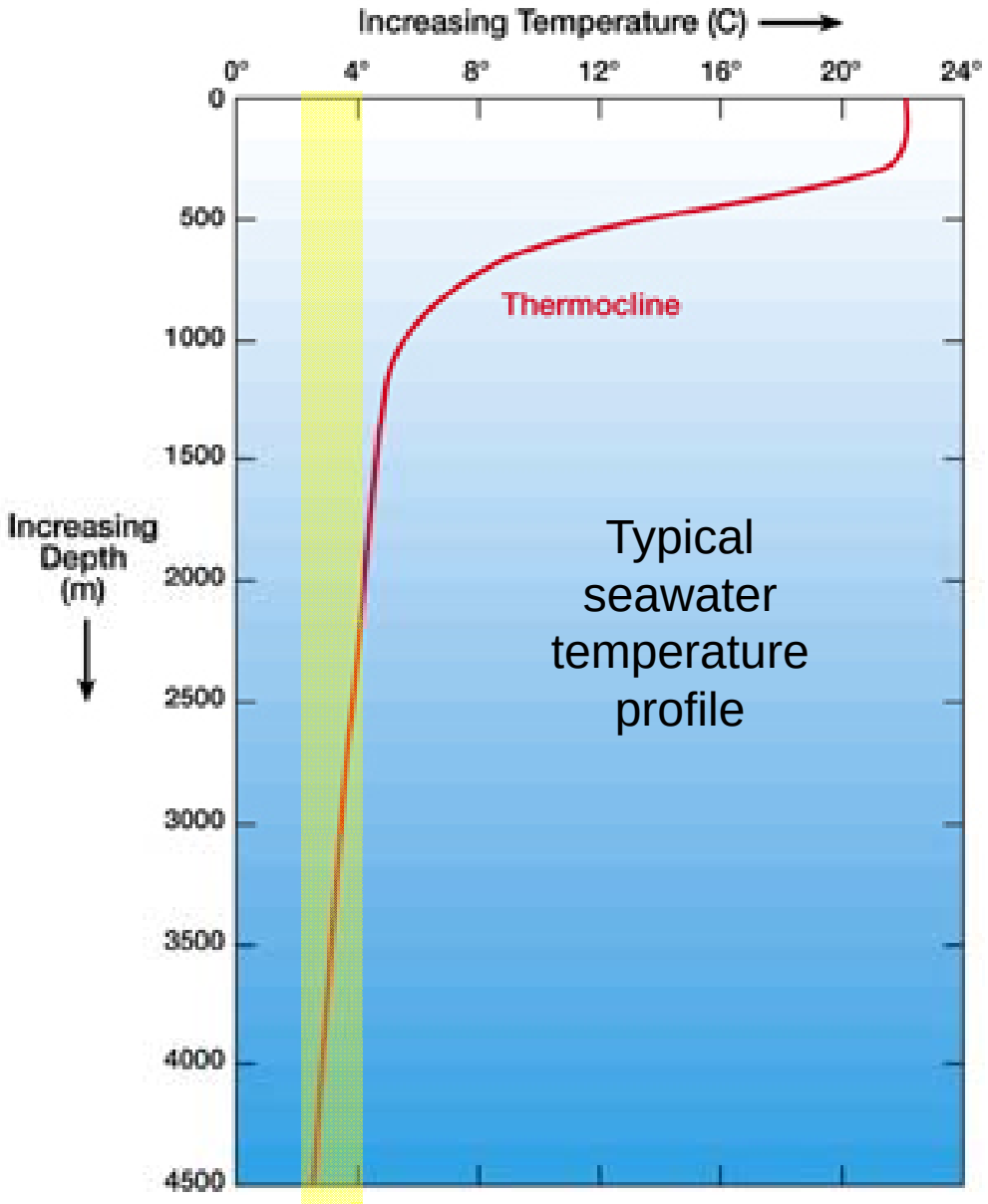
Typical burial depth 1-3 metres
Min T 3-8 C below mean T

What are global mean temperatures?

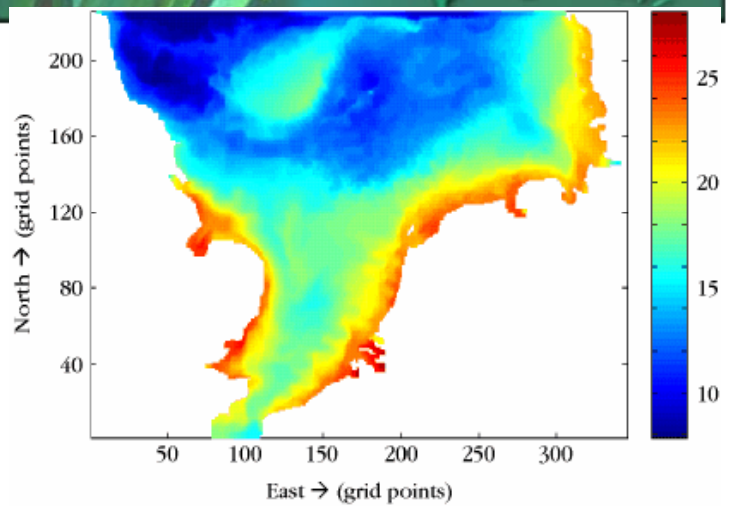
Typical onshore averages range from -6 to + 18 C

Hence minimums likely to be in range -14 to +15 C





Typical seawater temperature profile



Contents of pipelines laid on the sea bed will cool to about 2-4 C except in shallower waters

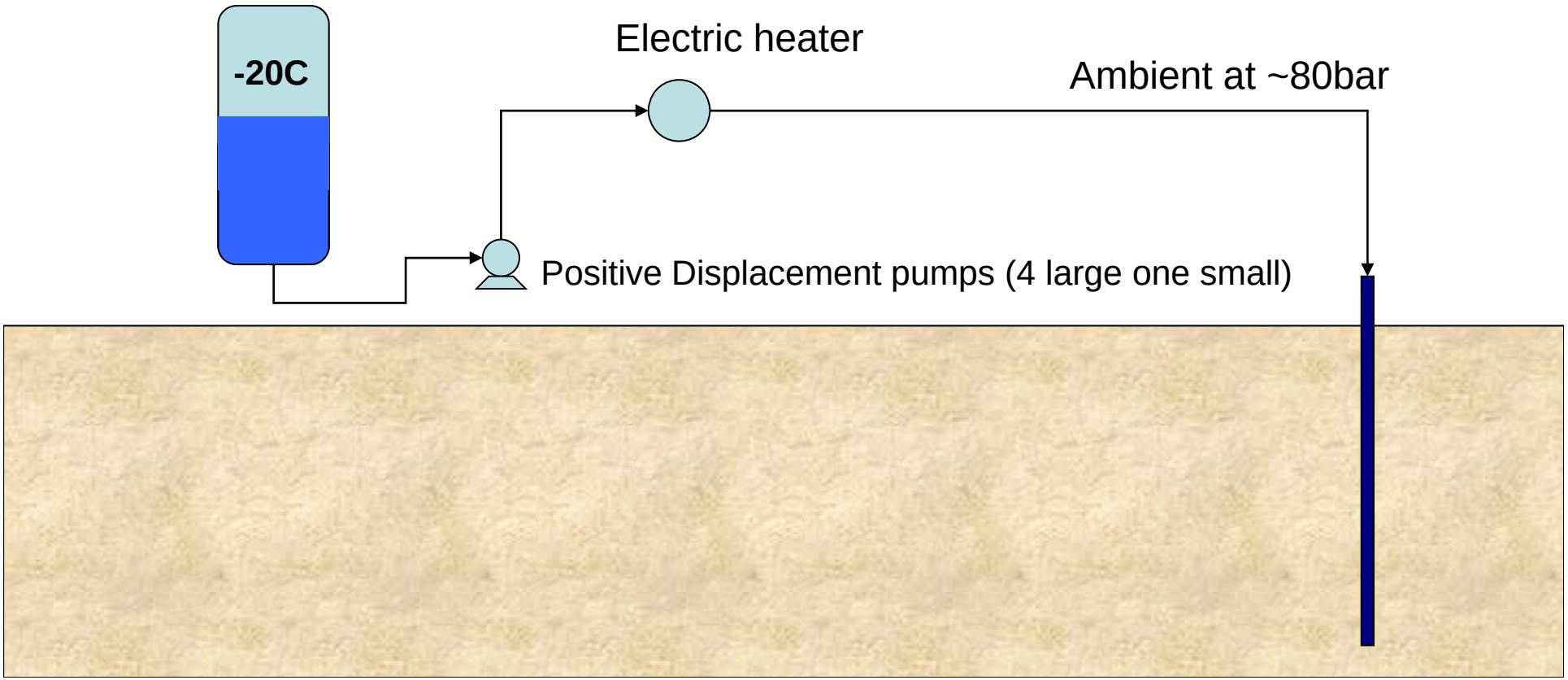
Process issues

- Composition range of transported CO2
  - Effects on phase envelope
  - Effects on corrosion
- Injection regime
  - Well head and down hole conditions
    - Static head due to density of CO2
    - Temperature drop if flow is throttled
    - Adjustments to temperature and pressure at well head

Process issues illustrated

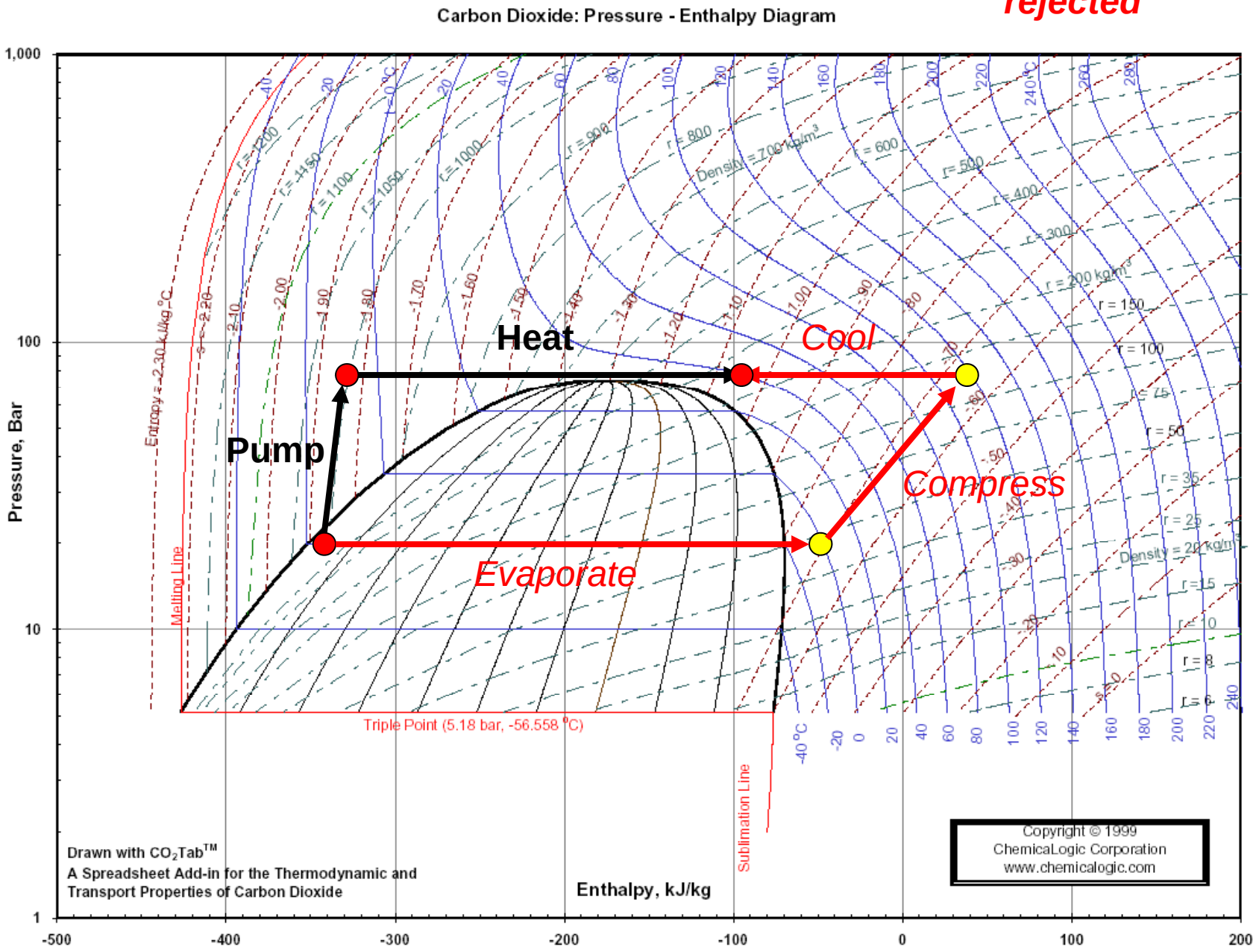
Ketzin project CO2 conditioning

Refrigerated pressurized liquid CO2 storage (2)



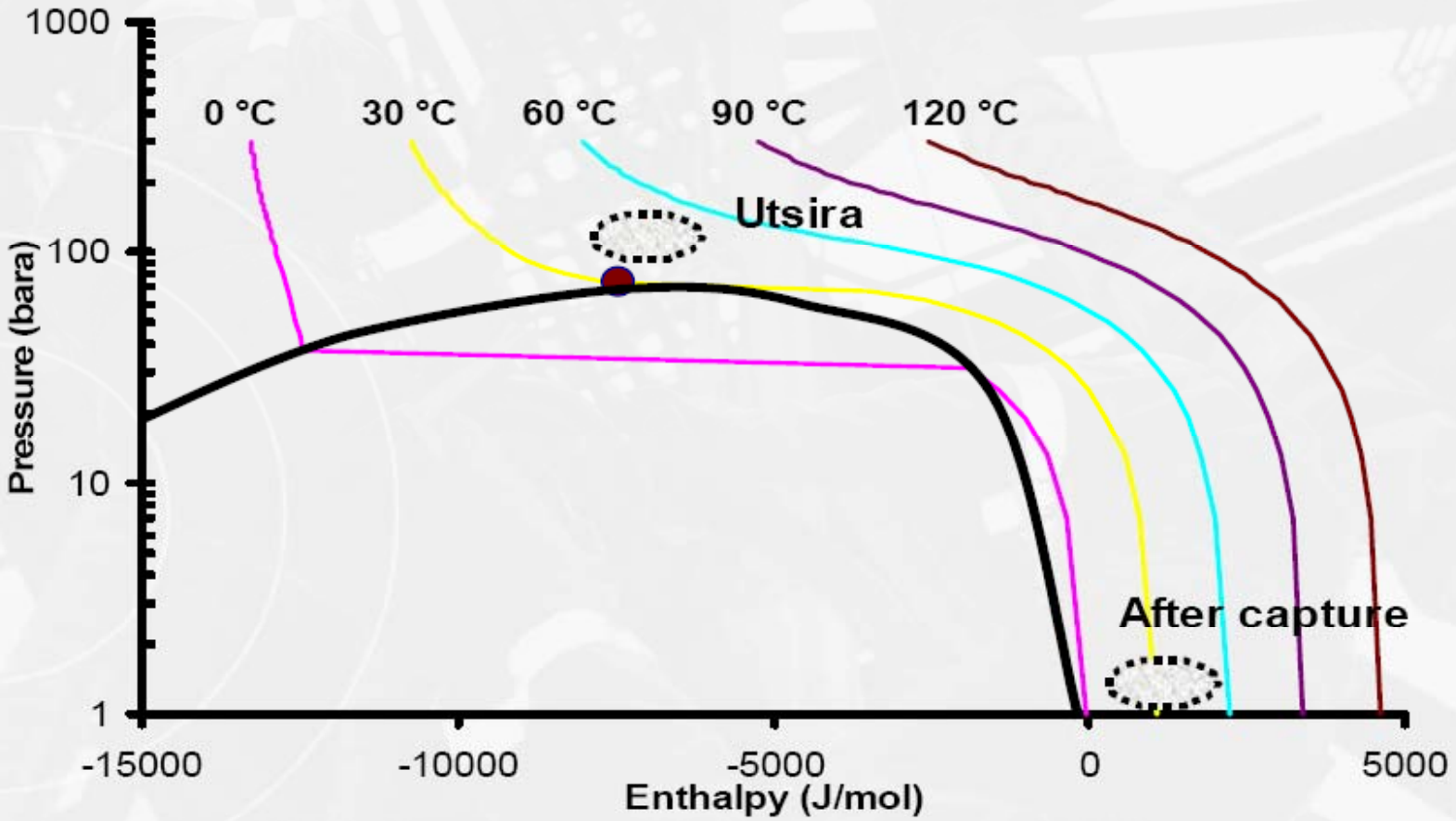
→ **Chosen for Ketzin**

→ ***Considered but rejected***



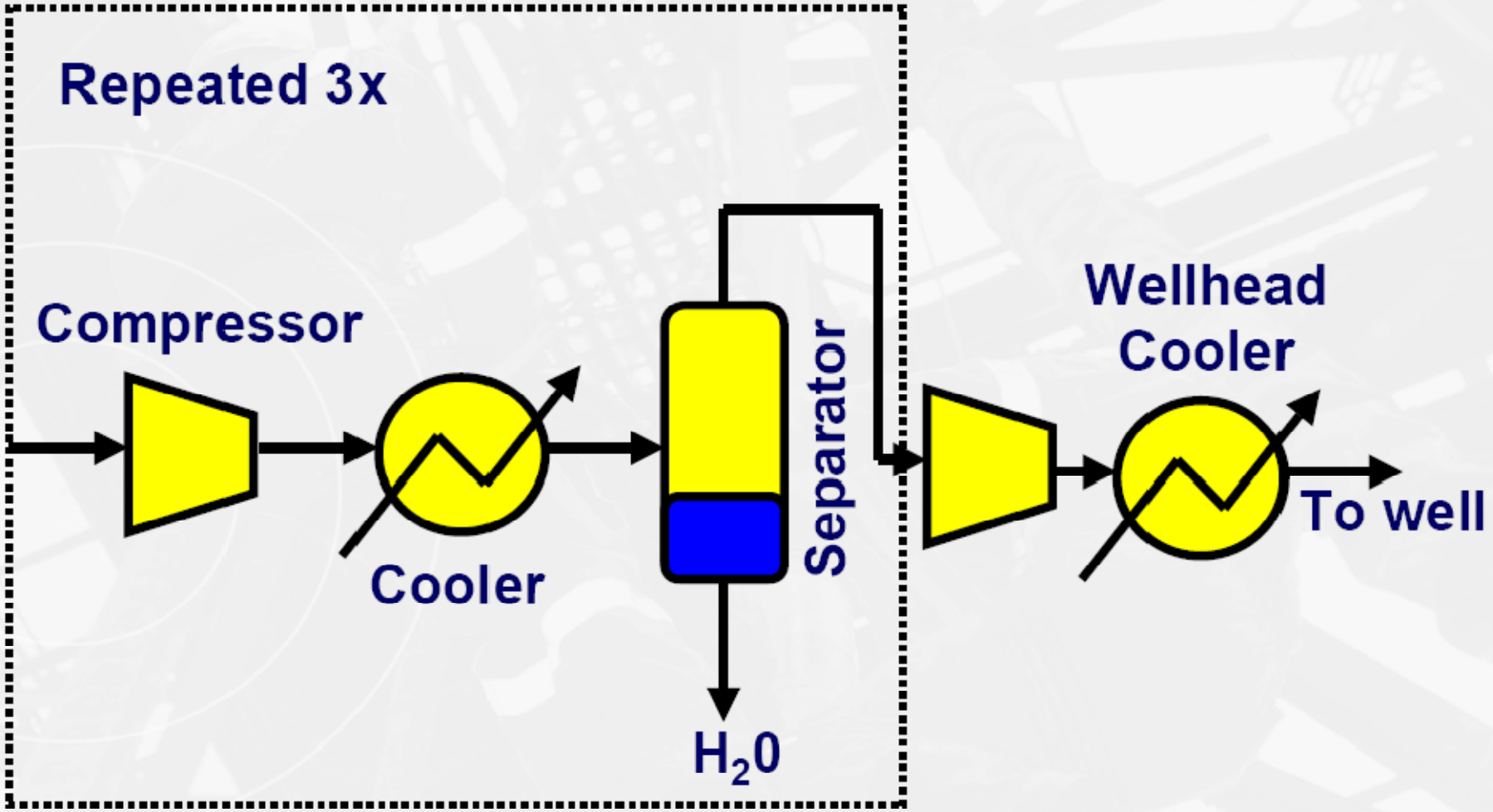
Thermodynamics

STATOIL



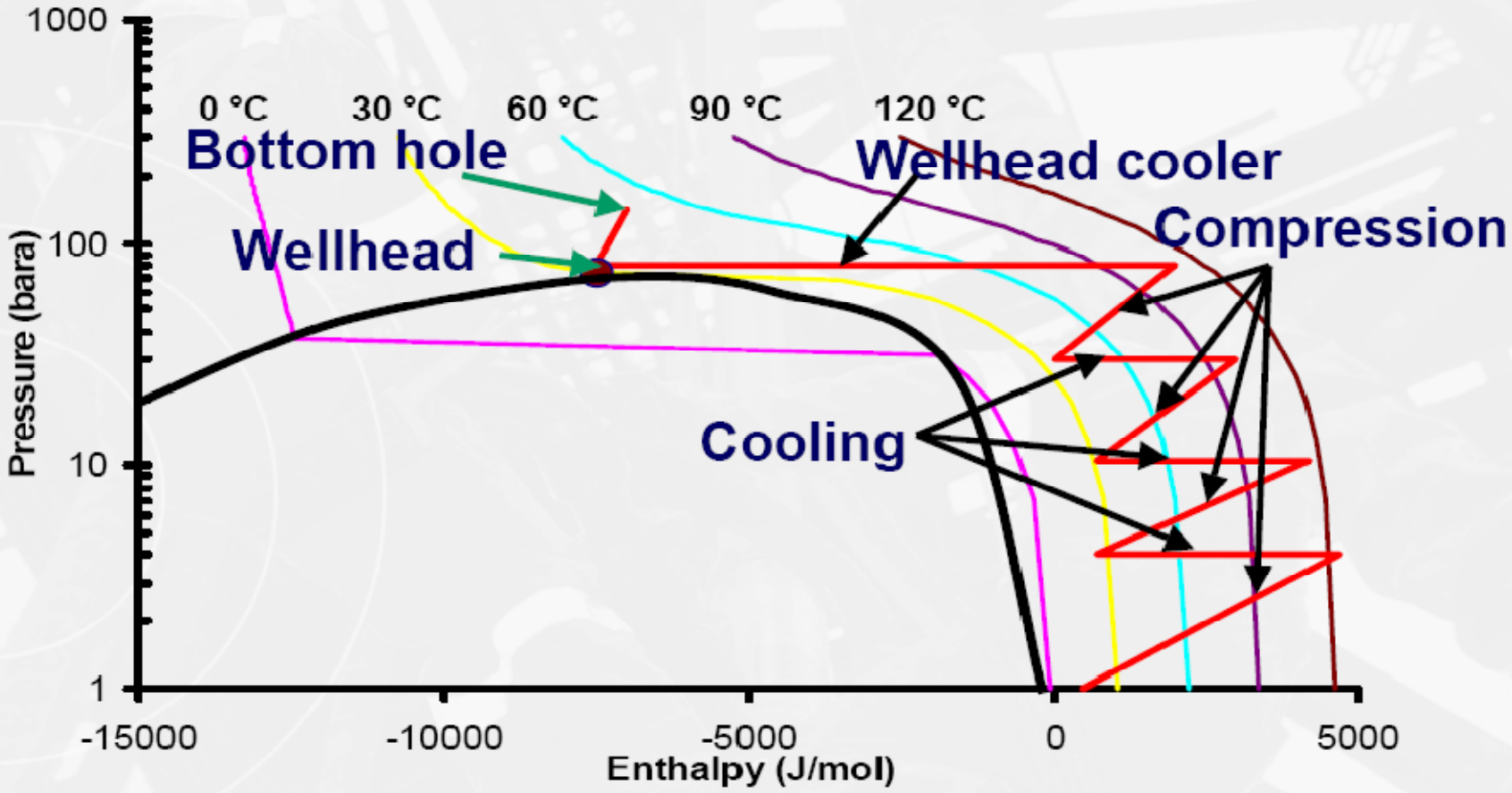
Process Flow Diagram of CO_2 Injection

STATOIL

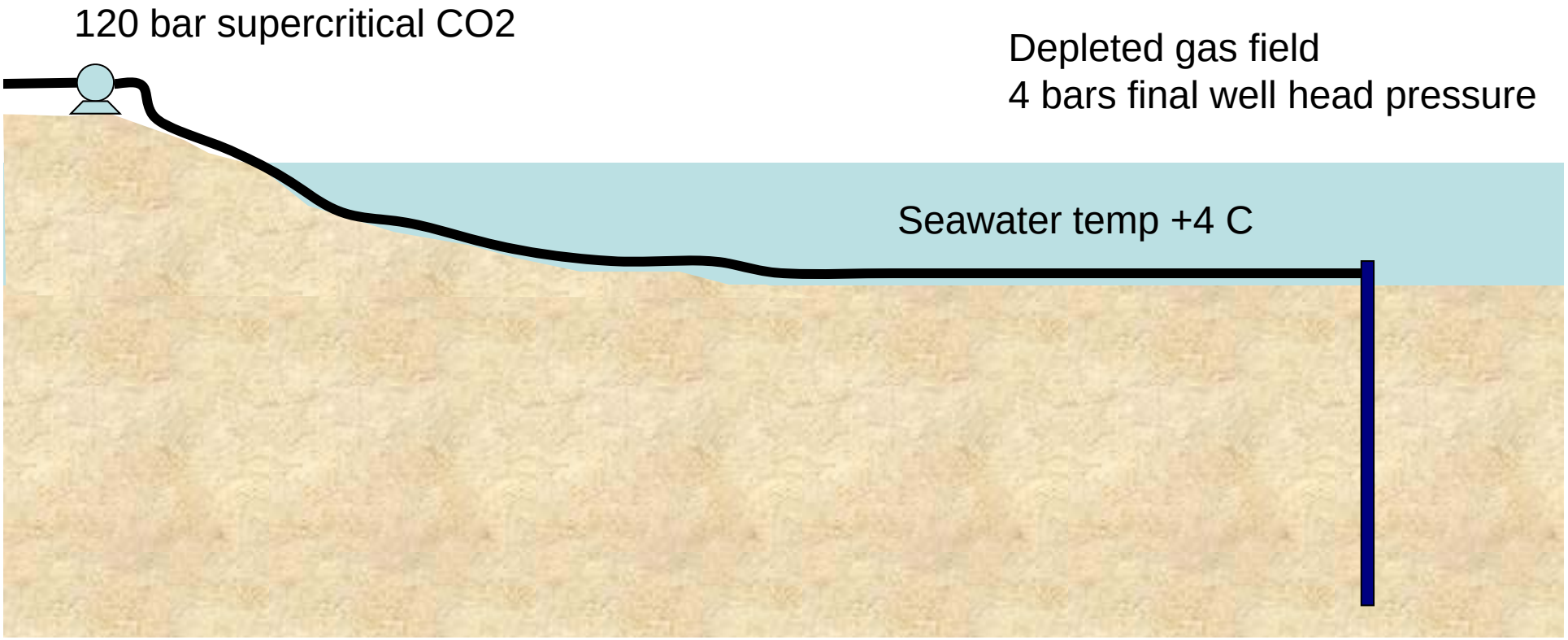


Thermodynamics

STATOIL

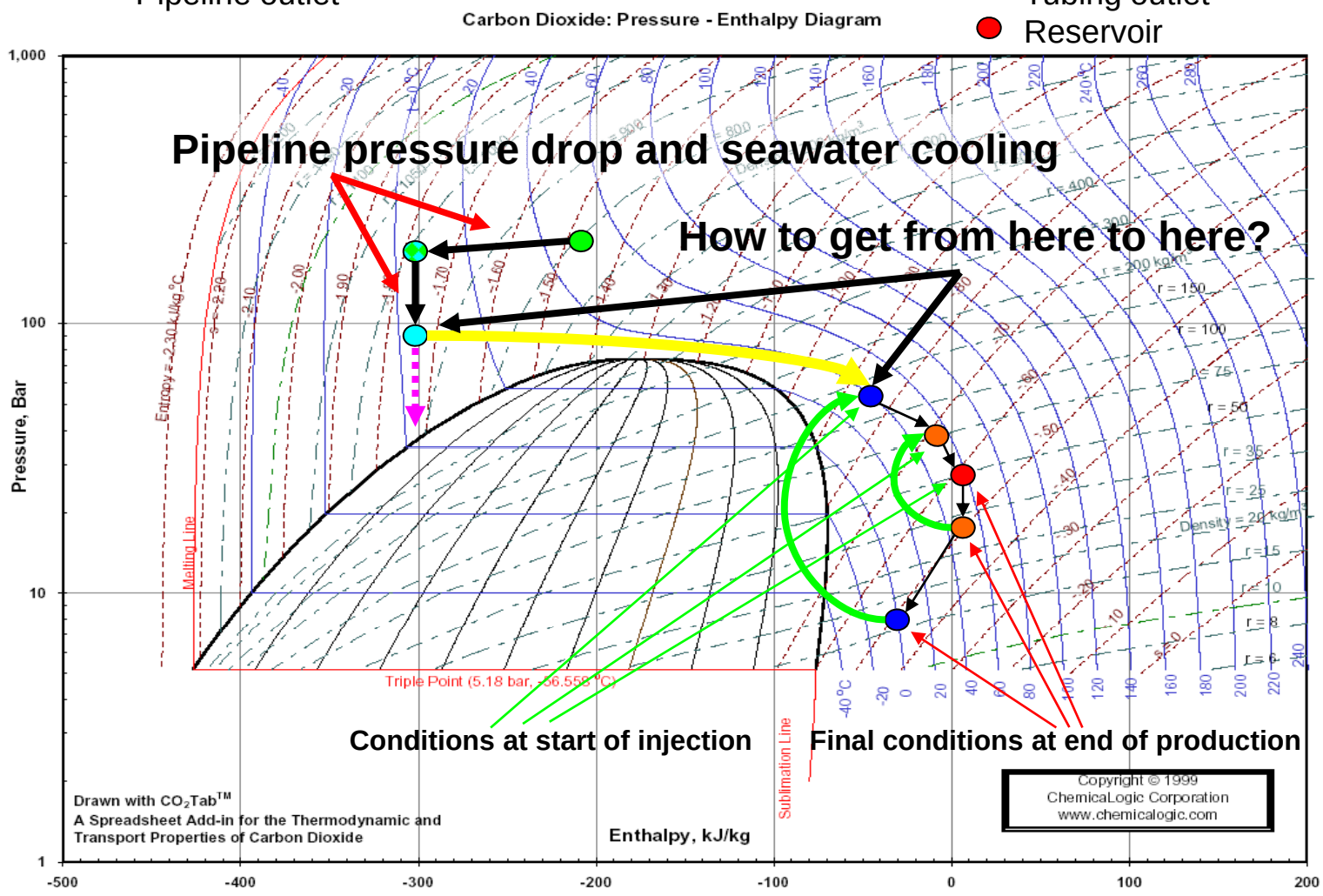


Process issues illustrated



Pipeline inlet
Pipeline outlet

Wellhead
Tubing outlet
Reservoir



Integration of pipeline systems

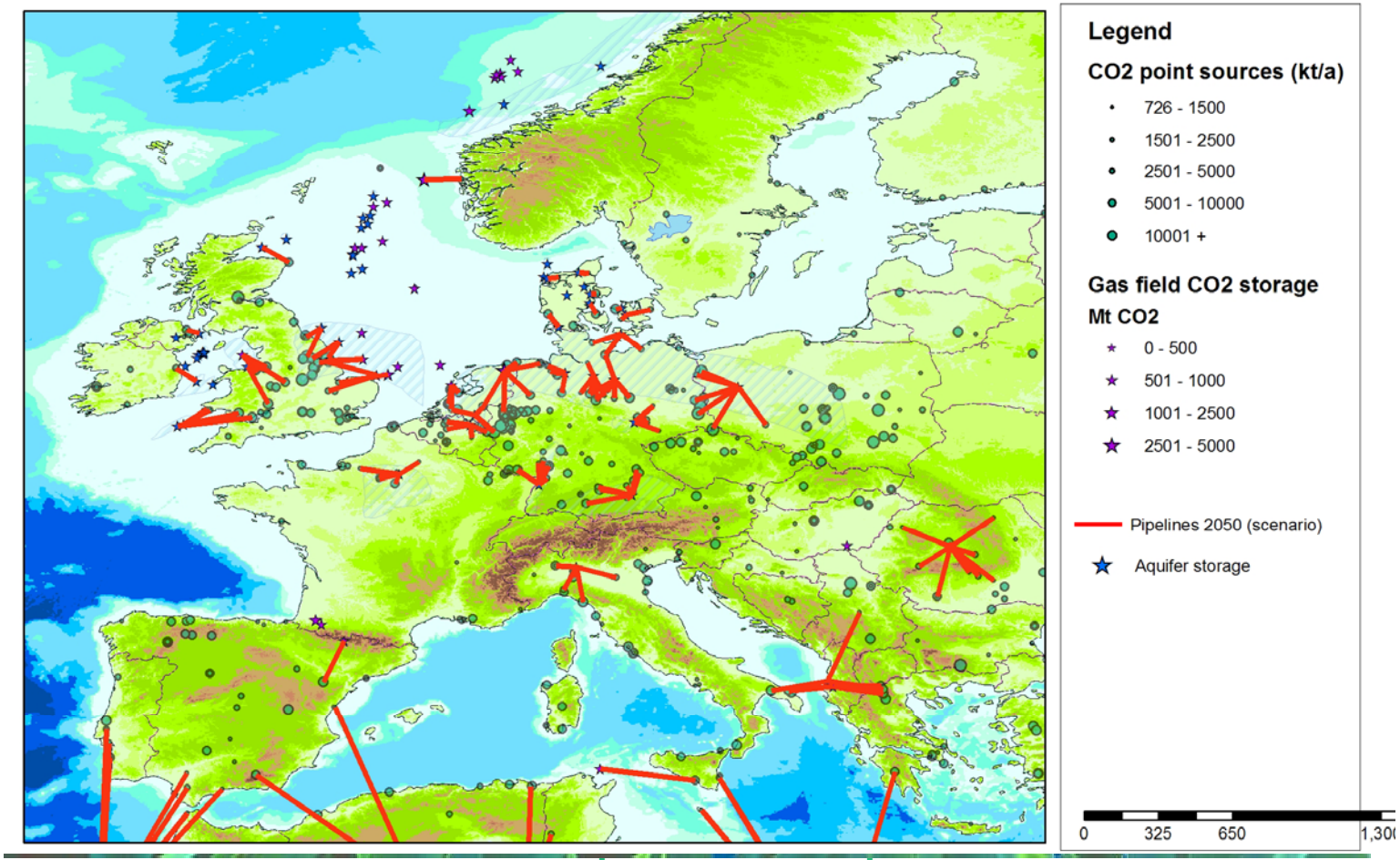
- IEA roadmap – 3000 capture plants by 2050
- Would shared pipelines be more appropriate?
- Issues are:-
  - Cost benefits of sharing transport lines
  - Effect of phasing on economics
- IEAGHG has study on implications ongoing

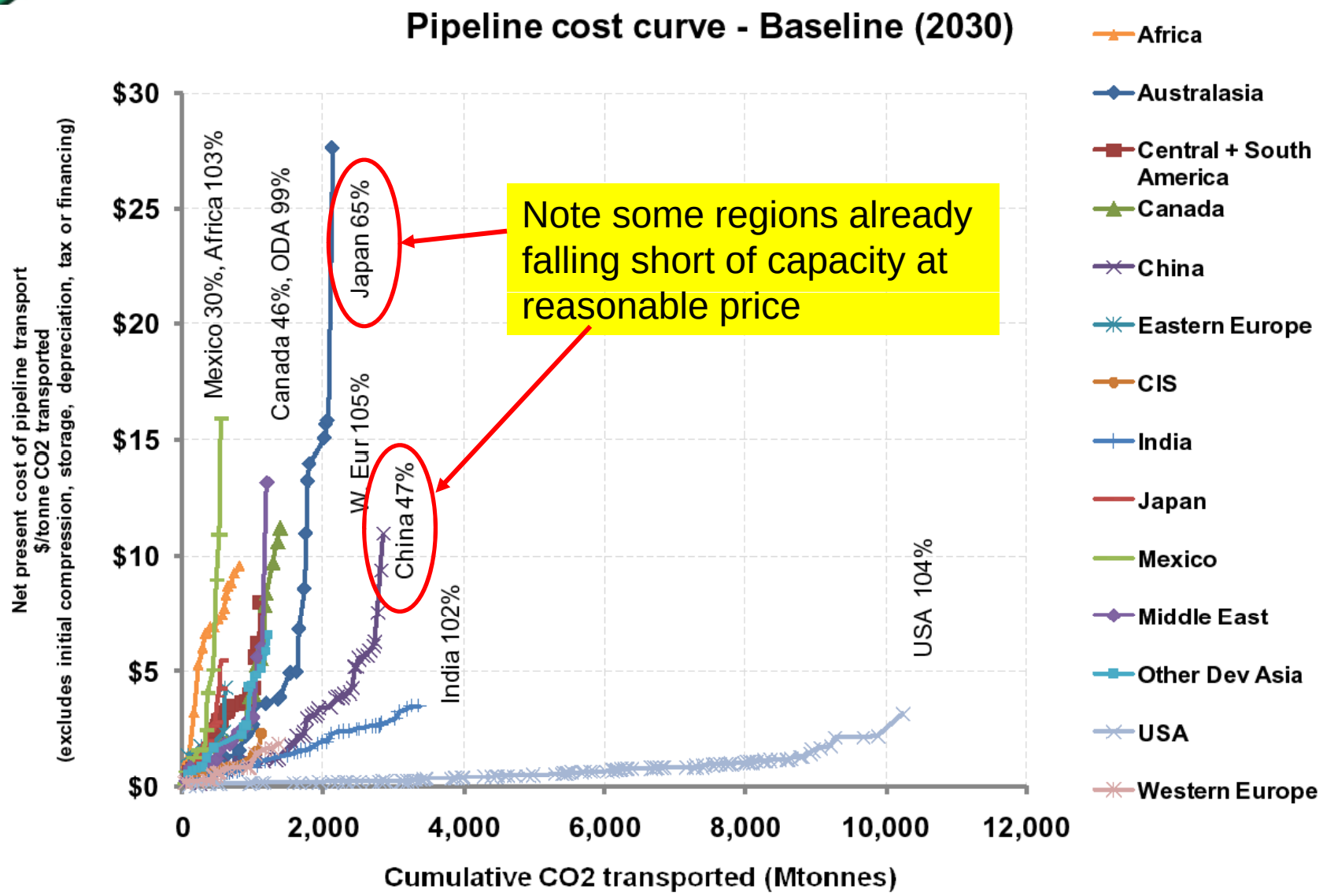
Initial findings

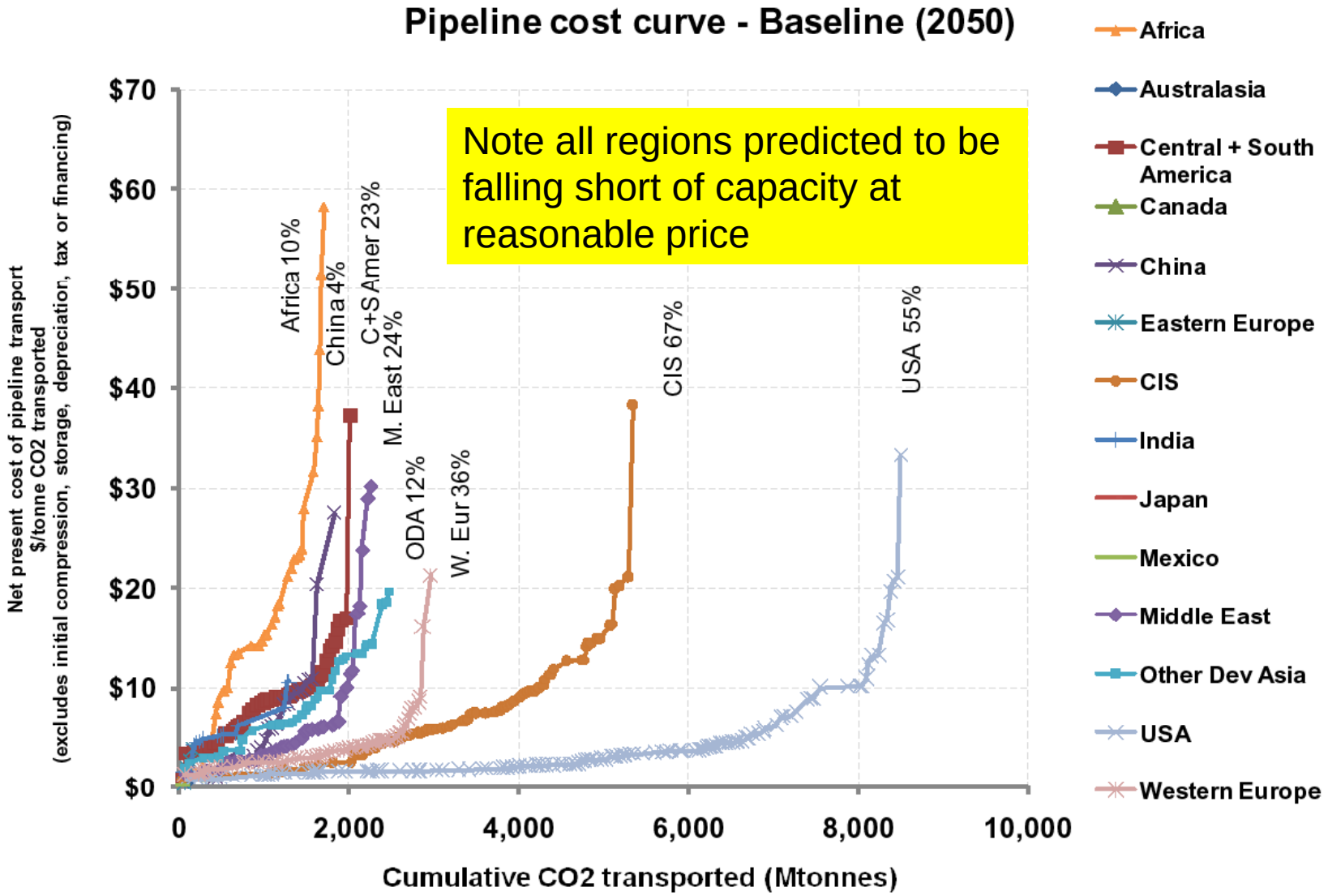
- Large regional variations in transport cost to meet IEA “bluemap scenario” targets
- Most regions short of proven storage capacity particularly by 2050 (based on storage capacity estimates used)
- Integrating pipelines could save approx 27% of overall length globally and 46% in cluster amenable locations
- Costs saving possible but phasing considerations may greatly reduce them.

Typical GIS sink source matching results

A map of networks to meet blue map CCS demand in 2050




Pipeline cost curve - Baseline (2030)
Net present cost of pipeline transport $/tonne CO2 transported (excludes initial compression, storage, depreciation, tax or financing)
$30
$25
$20
$15
$10
$5
$0
0
2,000
4,000
6,000
8,000
10,000
12,000
Cumulative CO2 transported (Mtonnes)
Mexico 30%, Africa 103%
Canada 46%, ODA 99%
Japan 65%
W. Eur 105%
China 47%
India 102%
USA 104%
Note some regions already falling short of capacity at reasonable price
Africa
Australasia
Central + South America
Canada
China
Eastern Europe
CIS
India
Japan
Mexico
Middle East
Other Dev Asia
USA
Western Europe


Pipeline cost curve - Baseline (2050)
Net present cost of pipeline transport $/tonne CO2 transported (excludes initial compression, storage, depreciation, tax or financing)
$70
$60
$50
$40
$30
$20
$10
$0
0
2,000
4,000
6,000
8,000
10,000
Cumulative CO2 transported (Mtonnes)
Note all regions predicted to be falling short of capacity at reasonable price
Africa 10%
China 4%
C+S Amer 23%
M. East 24%
ODA 12%
W. Eur 36%
CIS 67%
USA 55%
Africa
Australasia
Central + South America
Canada
China
Eastern Europe
CIS
India
Japan
Mexico
Middle East
Other Dev Asia
USA
Western Europe

Other infrastructure

- Hydrogen distribution
- Capture site infrastructure
  - Land take
  - Location
  - Utilities – water, power connections
- Injection site infrastructure
  - Onshore – land take
  - Offshore – subsea or via platform

Hydrogen

- Hydrogen can be an alternative product of pre-combustion capture
- Can be used to:-
  - Replace natural gas
  - Blend into natural gas
- Key considerations are:-
  - Change in Wobbe index and flame speed
  - Line capacities are slightly lower
  - Hydrogen storage to replace gas storage
  - Line integrity requires enhanced inspection

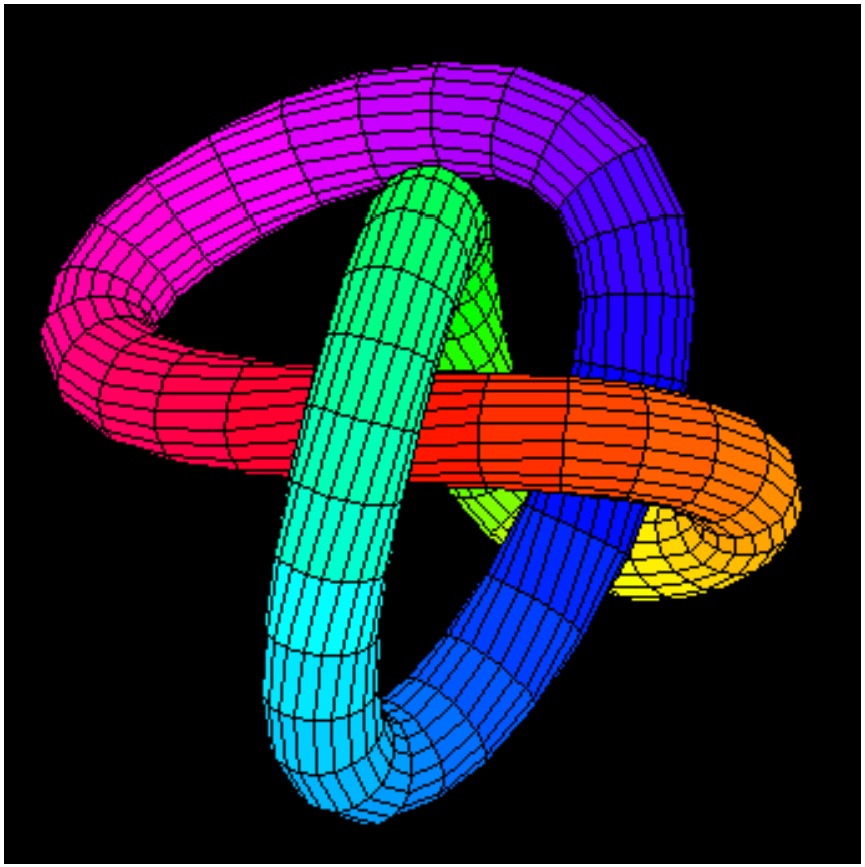
Capture site infrastructure

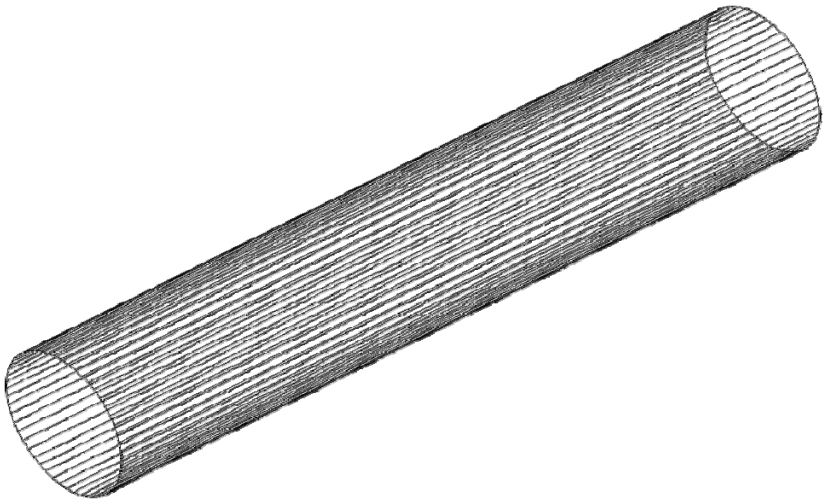
- Land take
  - Capture plants have significantly more equipment and could require up to double the land area.
- Location
  - Existing sites may be less ideal
    - Routes and distance to storage
    - Changes in fuel source – coal imports, use of biomass
    - Utilities – existing water and power connections

Injection site infrastructure

- Onshore
  - Well sites and flow lines
    - Centralise and use deviated wells?
    - Horizontal wells needed anyway for injectivity?
- Offshore
  - Seabed or platform based facility
    - What is available
    - Maintenance of former oil/gas platforms expensive
    - Is any well head processing needed. (Snovit!!)

Straightening out infrastructure





IEA Greenhouse Gas R&D Programme

Introduction to Geological Storage

Neil Wildgust, Ludmilla Basava-Reddi

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

Hassi Messaoud, Algeria

16th – 19th November, 2009

Sources of CO_2

Power production from fossil fuels

Industries, e.g. Steel, cement and ammonia production

Residential Sector

Transport Sector

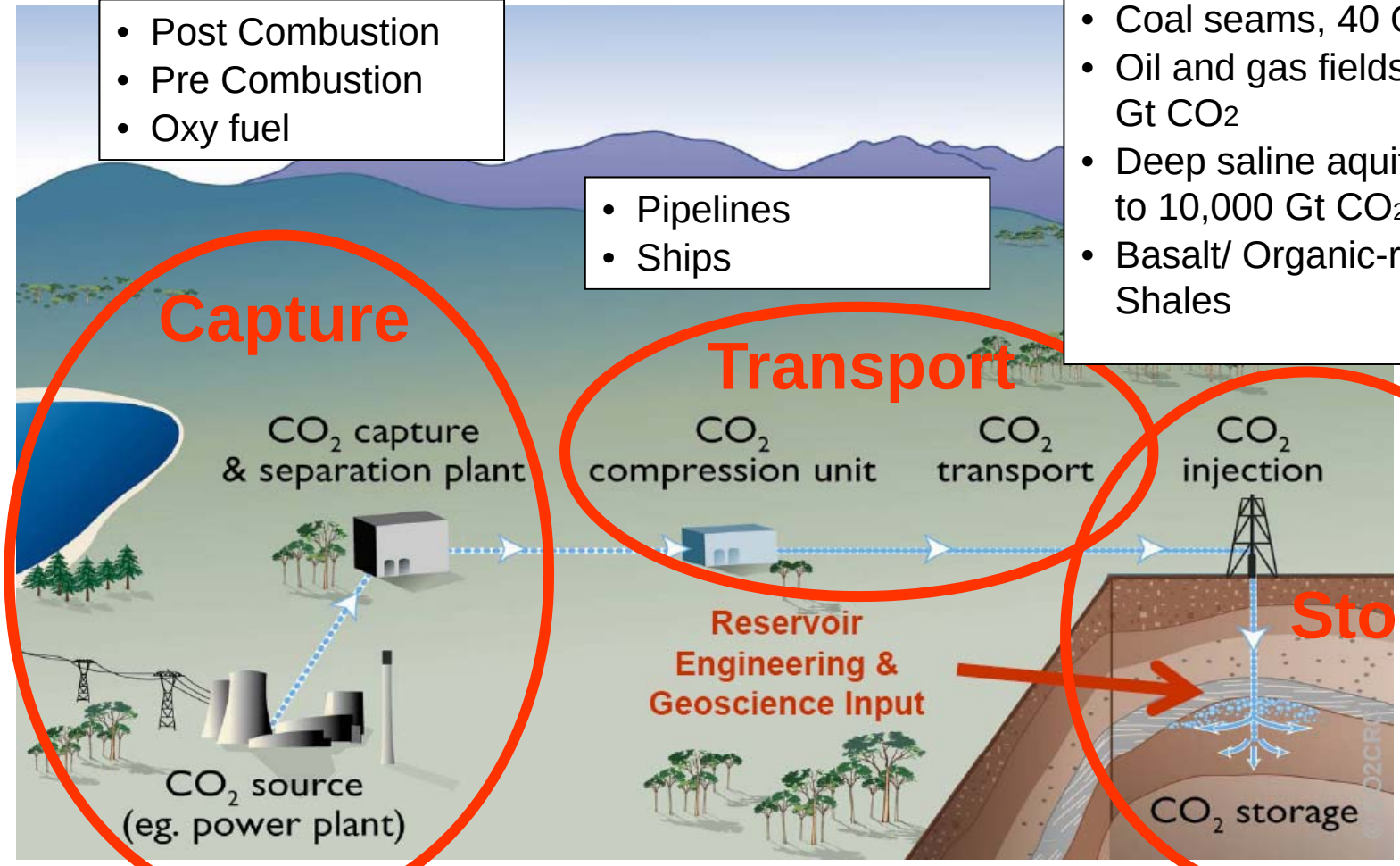
Stationary Sources
- CO_2 Capture possible

CO_2 Capture and Storage

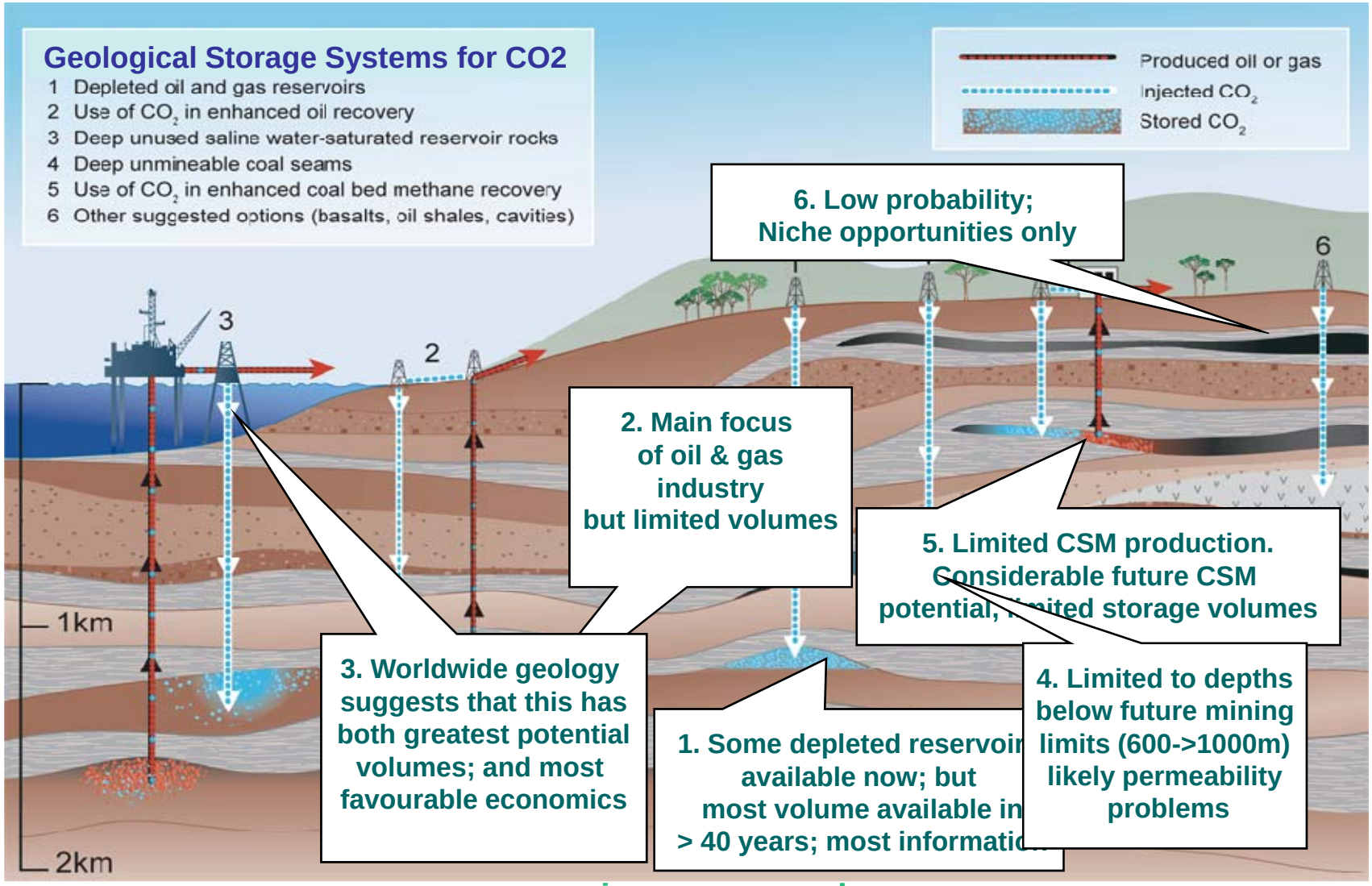
- Post Combustion
- Pre Combustion
- Oxy fuel

- Pipelines
- Ships

- Coal seams, 40 Gt CO_2
- Oil and gas fields, 1,000 Gt CO_2
- Deep saline aquifers – up to 10,000 Gt CO_2
- Basalt/ Organic-rich Shales



IEA Greenhouse Gas R&D Programme



www.ieagreen.org.uk

IPCC 2005

Geological CO_2 Storage "Systems"

Oil & Gas Reservoirs

- Depleted fields
- EOR / EGR

Saline Formations

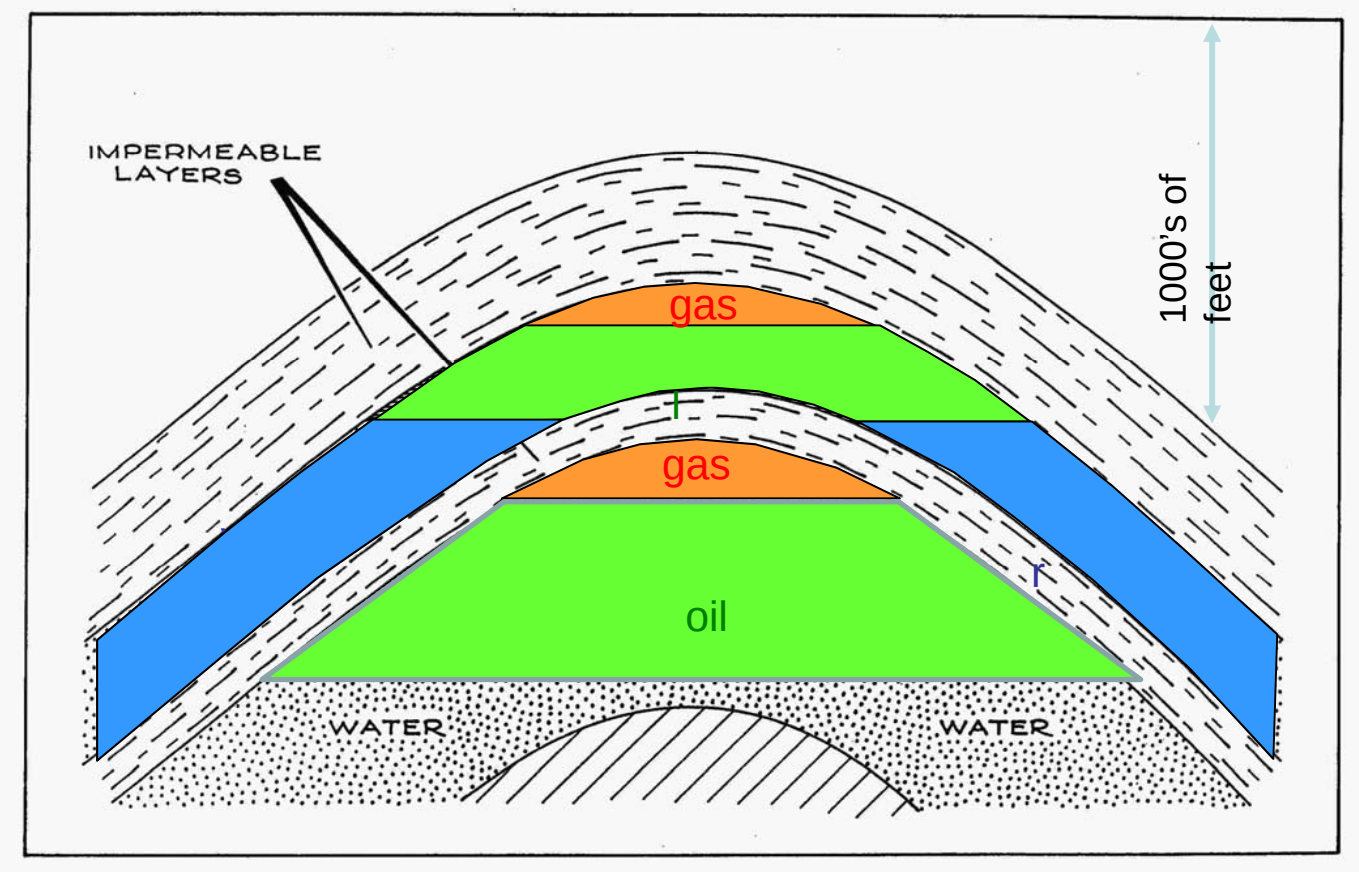
- Structural / Stratigraphic trapping
- Residual saturation
- Solubility trapping
- Mineral trapping

Coal Systems

- Inter / intra seam sediments
- Coal seams (adsorption)
- ECBM

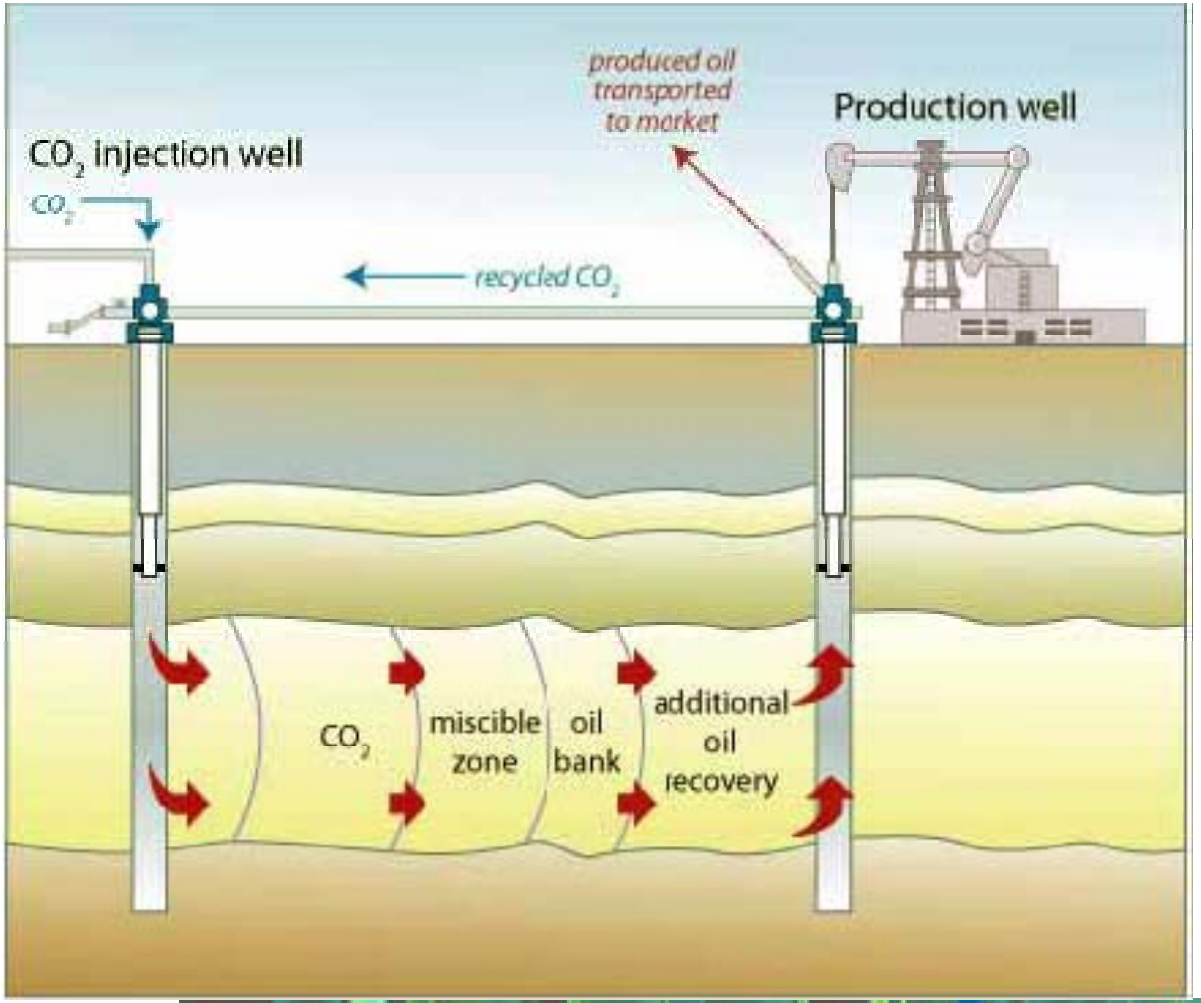
Oil & Gas Reservoirs: Depleted Fields

- Usually in simple anticlinal trap
- Proven Capacity (porosity for oil & gas)
- Proven containment (seal held oil & gas)
- Data rich (lots of wells, seismic)



Courtesy Kaldi, 2009

Oil & Gas Reservoirs: EOR with CO_2 Storage



- Proven containment (seal held oil & gas)
- Data rich (lots of wells, seismic)
- Objective: produce more oil (CO_2 storage secondary!)

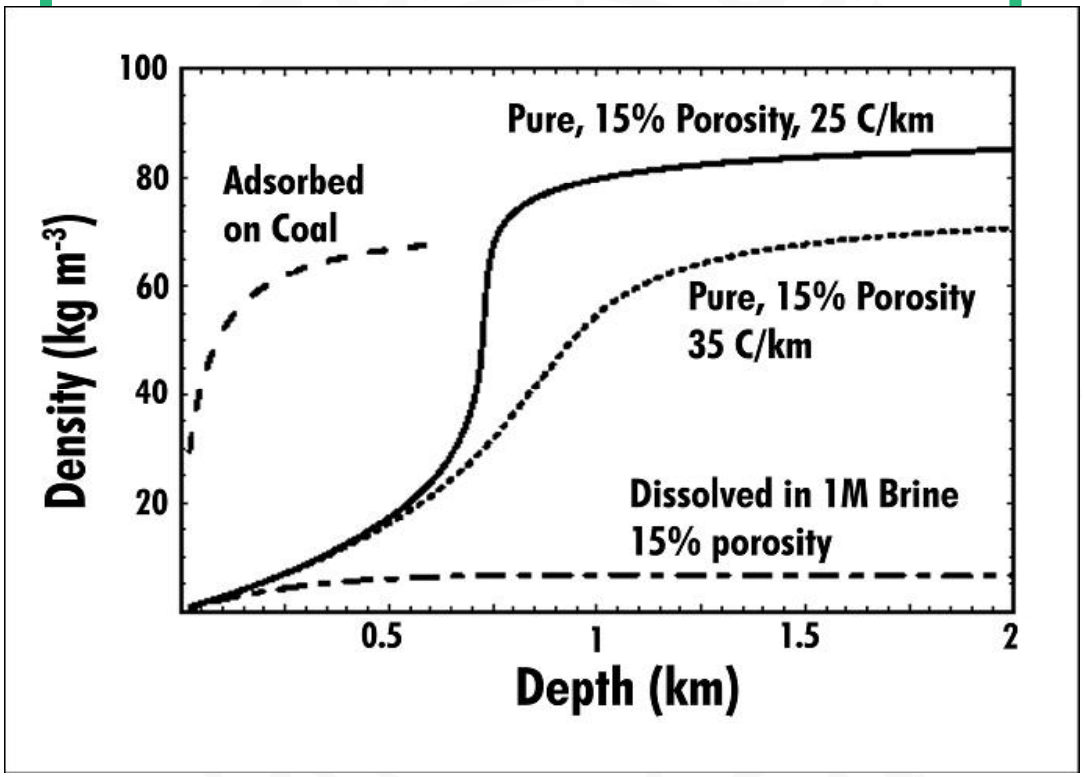
Courtesy Kaldi, 2009

CO_2 Storage in Coals Systems

CO_2 storage potential may include coal systems (coal seams and associated sediments) as well as the storage potential arising from using CO_2 for Enhanced Coal Bed Methane Recovery

Courtesy Kaldi, 2009

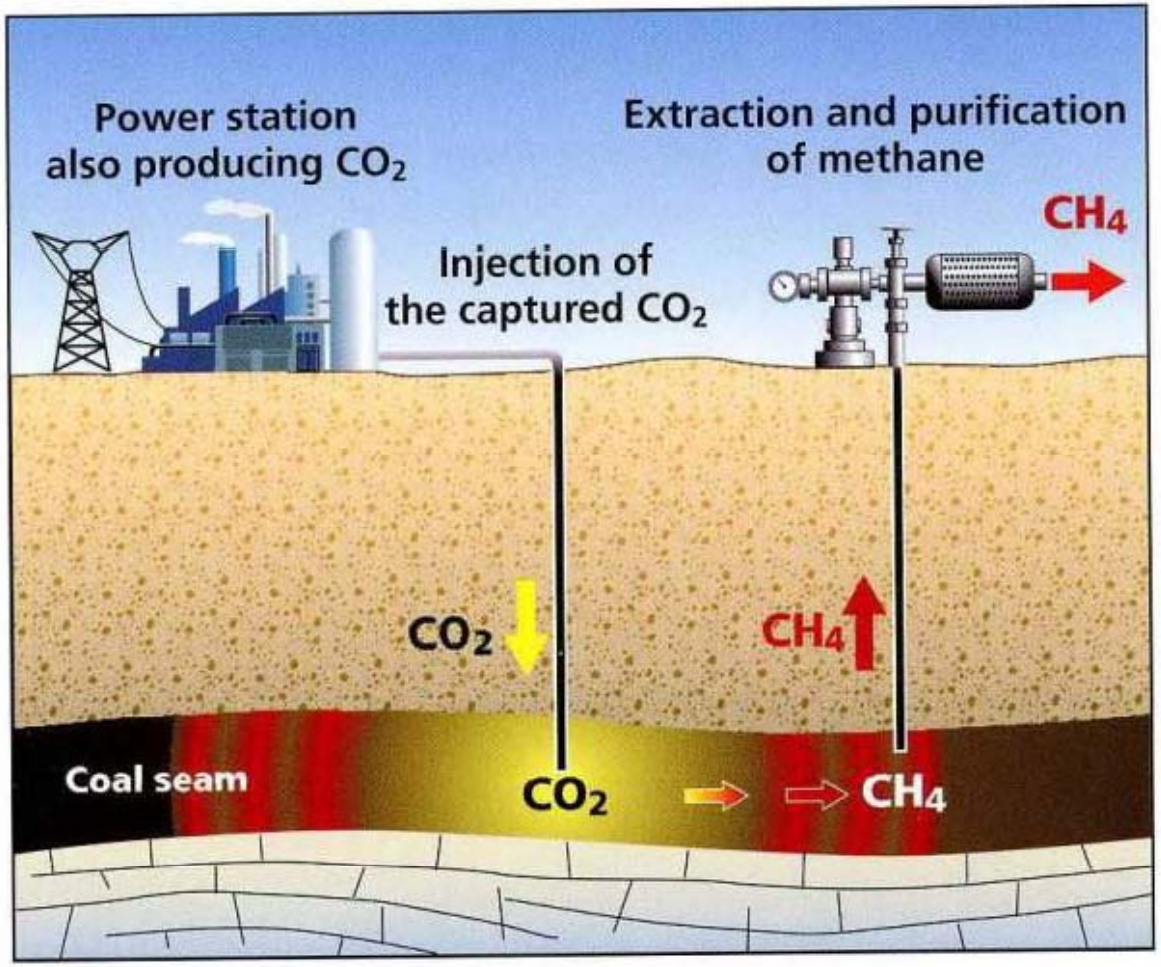
Storage density of CO_2 in coal & pore space as a function of depth



Highlights how storage density of CO2 adsorbed onto coal at subcritical depths is comparable to storage density of CO2 stored in pore space at supercritical P/T (depth). (***From Ennis-King & Paterson, 2001)***

Courtesy Kaldi, 2009

Storage in coal seams



The principle of Enhanced Coal Bed Methane (ECBM) recovery, which allows the natural methane gas trapped in coal to be tapped.

Courtesy Kaldi, 2009

Other types of Storage

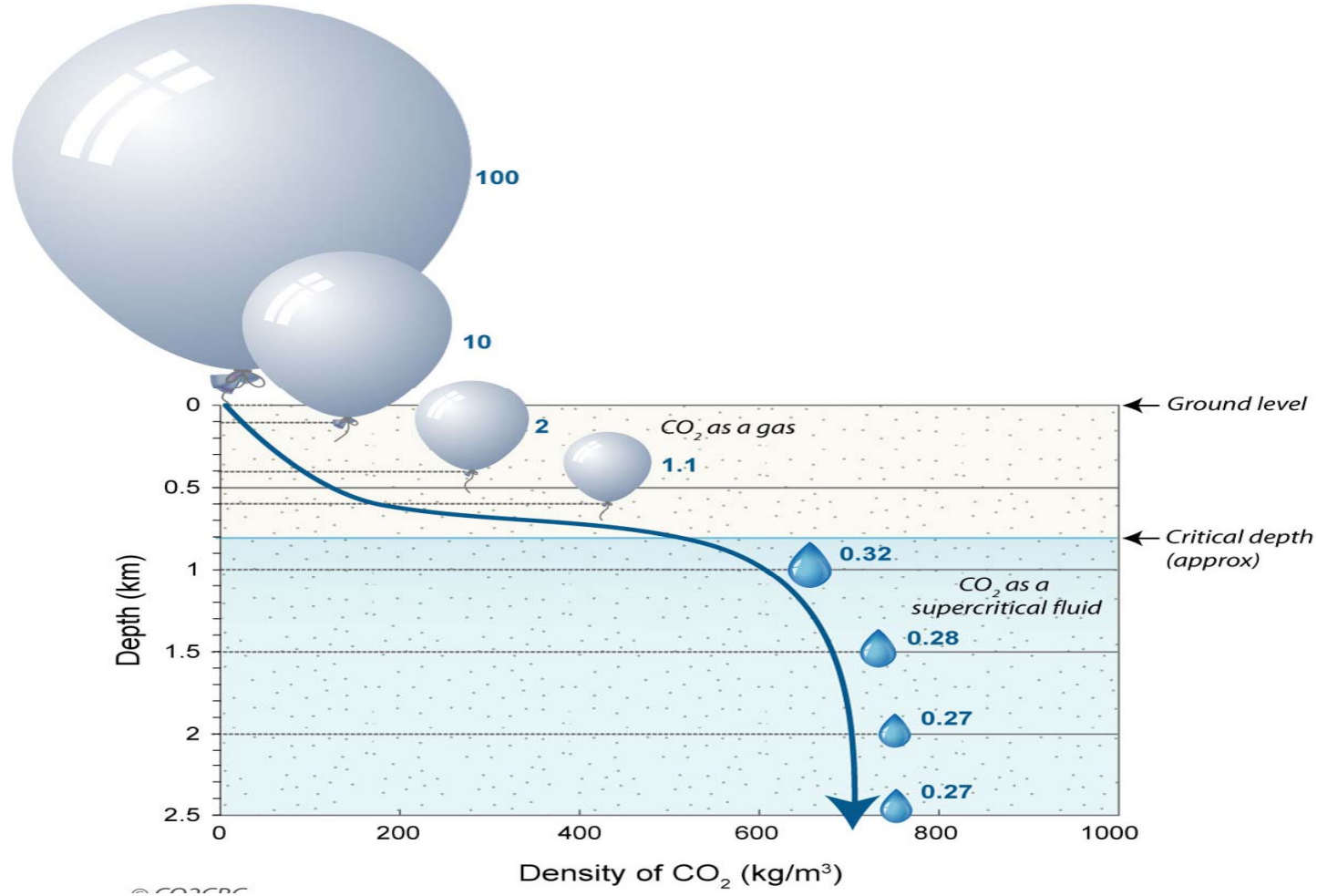
Basalt Formations

- Unique chemical makeup, potentially convert all injected CO_2 to a solid mineral form
- Research focused on enhancing mineralisation reactions and increasing CO_2 flow

Organic Shales

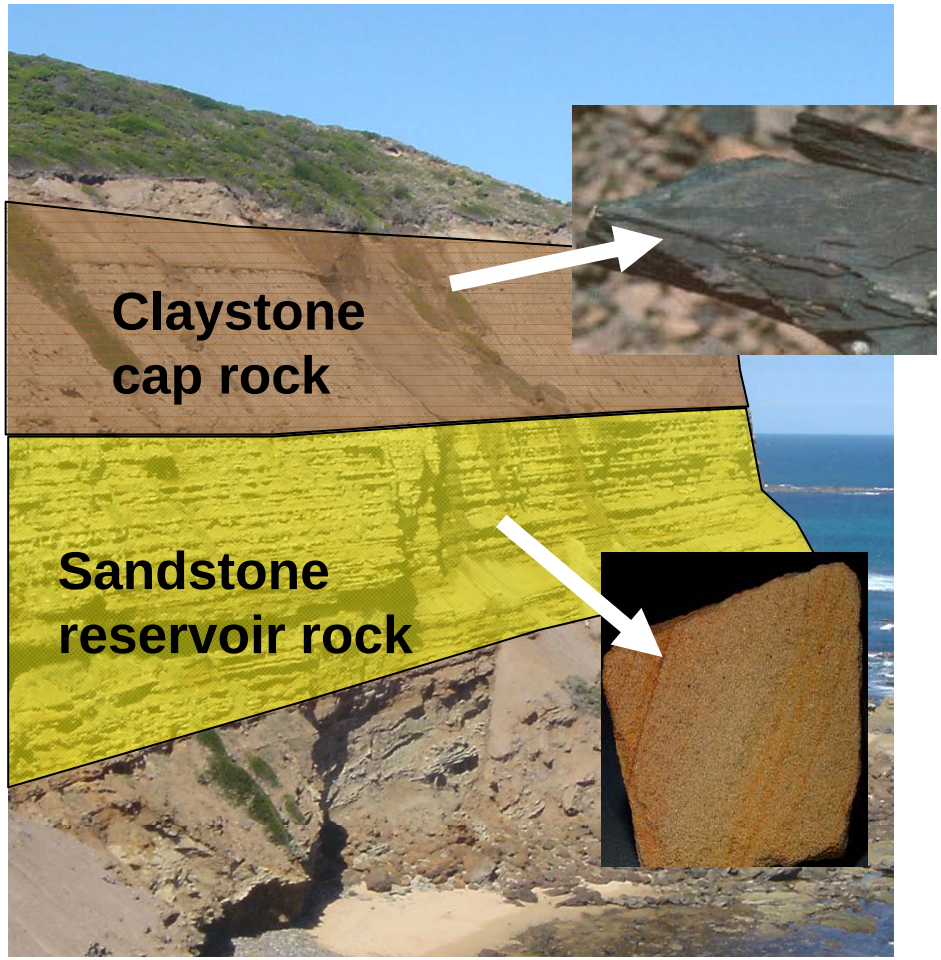
- CO_2 adsorbs on to surface
- Low permeability
- Research focused on achieving economically viable injection rates

CO_2 Properties change with Depth



Courtesy Kaldi, 2009

Geological Storage of CO_2



What do we need?

RESERVOIR ROCK – porous, e.g. sandstone

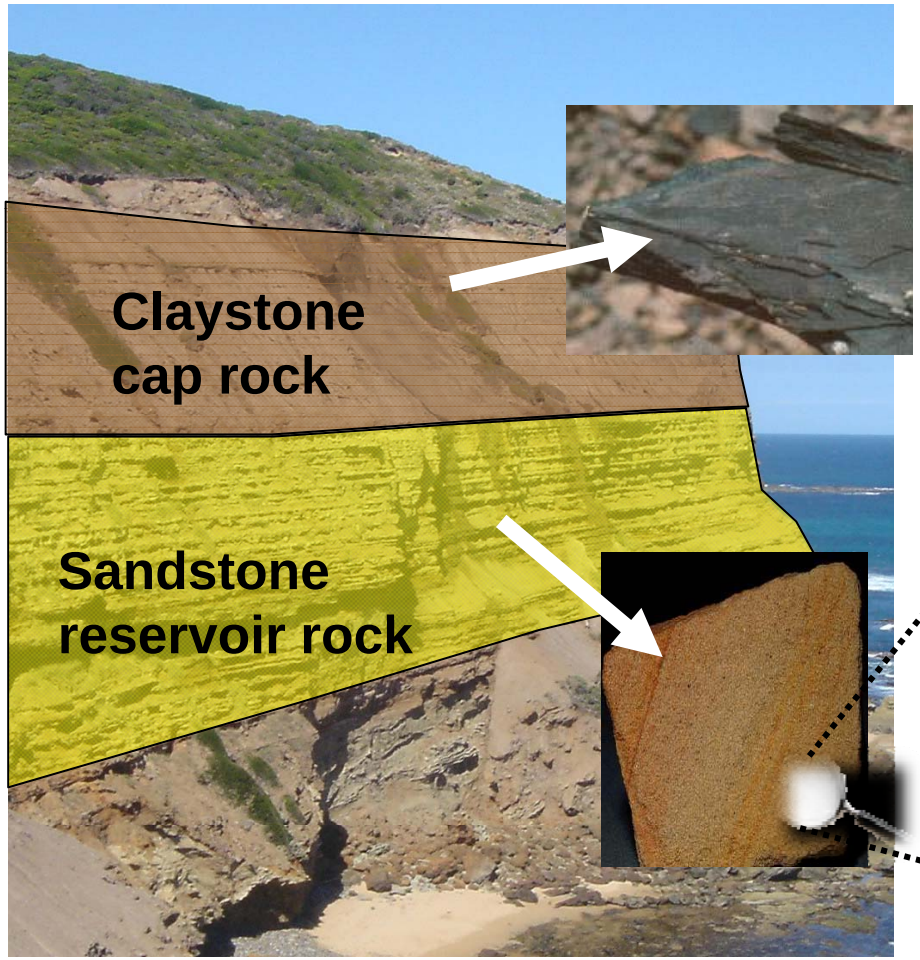
SEAL ROCK – non-porous, e.g. claystone

How does it work?

- **CO_2 injected into porous reservoir rock**
- **CO_2 held in place by overlying non-porous seal rock**

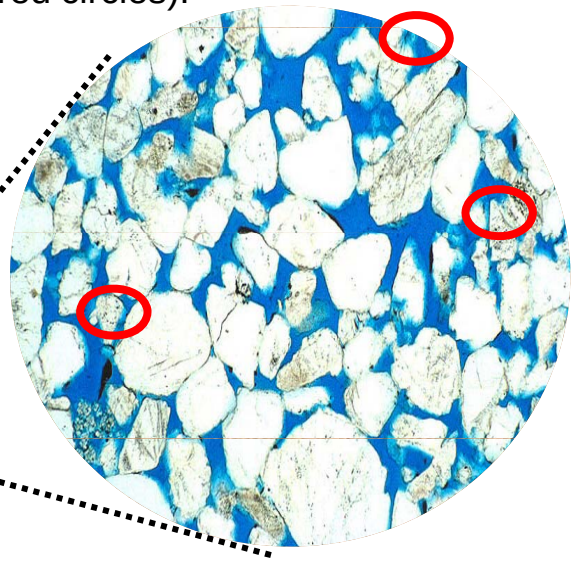
Courtesy Kaldi, 2009

Geological Storage of CO_2



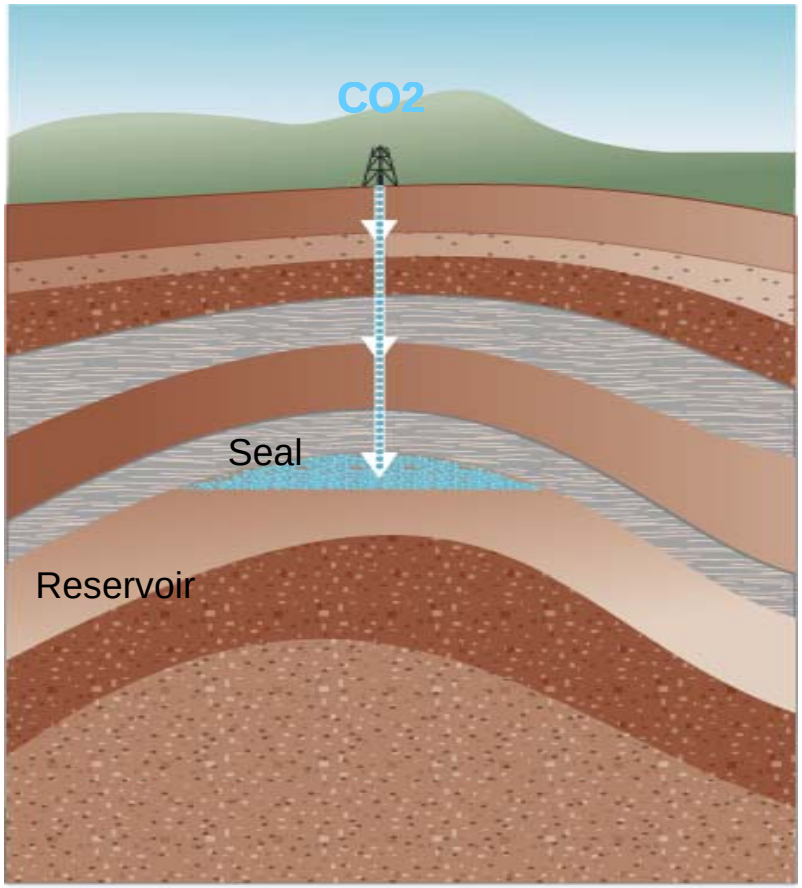
Porosity is the storage space in the rock for fluids and is shown by the blue spaces in this photomicrograph of a thin slice through a reservoir sandstone.

Permeability is a measure of the ability of the rock to allow fluid flow. Permeability is strongly affected by the geometry of the porosity – in particular the size of the spaces connecting the pores in the rock (red circles).



Courtesy Kaldi, 2009

Structural trap for CO_2

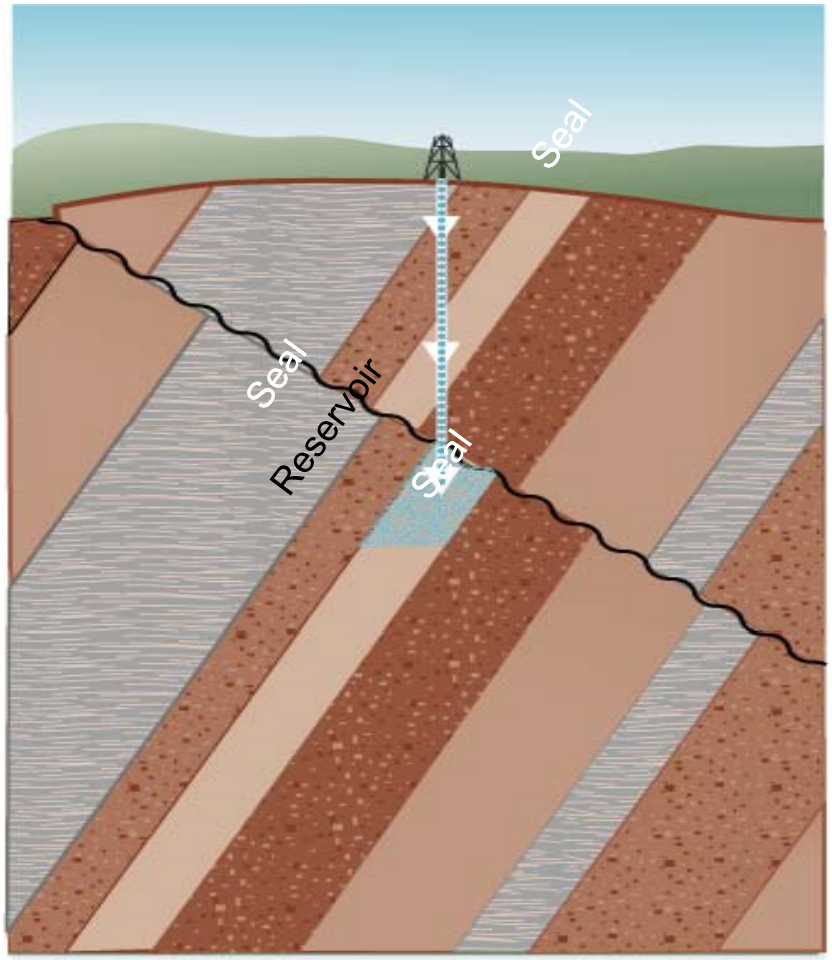


Anticline

- Injection into reservoir rock
- Buoyancy drives CO_2 upwards
- Top seal prevents escape
- Such features have safely held oil, gas & natural accumulations of CO_2 for millions of years

Courtesy Kaldi, 2009

Structural trap for CO_2



Fault Trap

- Injection into reservoir rock
- Buoyancy drives CO_2 upwards
- Either fault-juxtaposed seal

or

- shale gouge on fault plane

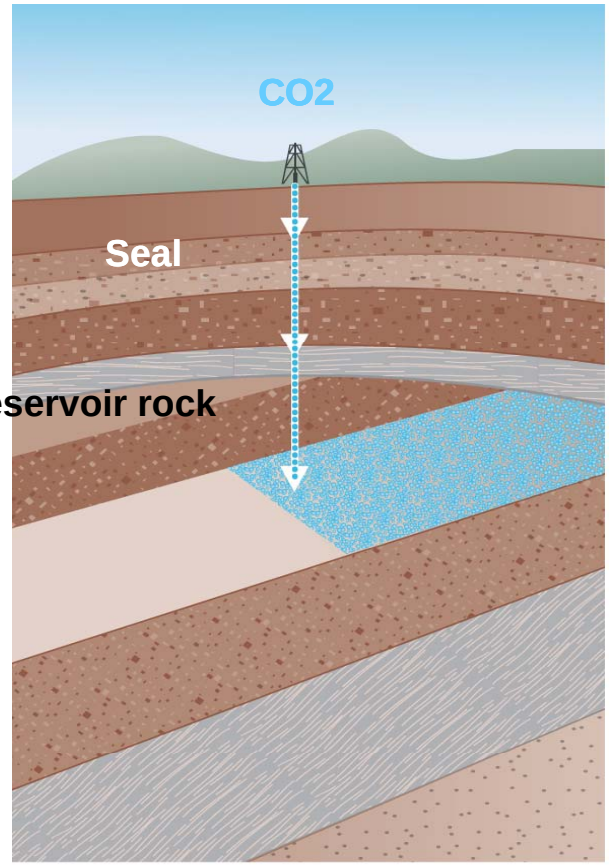
prevents escape

- Such features have safely held oil, gas & natural accumulations of CO_2 for millions of years
- **Need to determine risk of fault movement subsequent to injection!!**

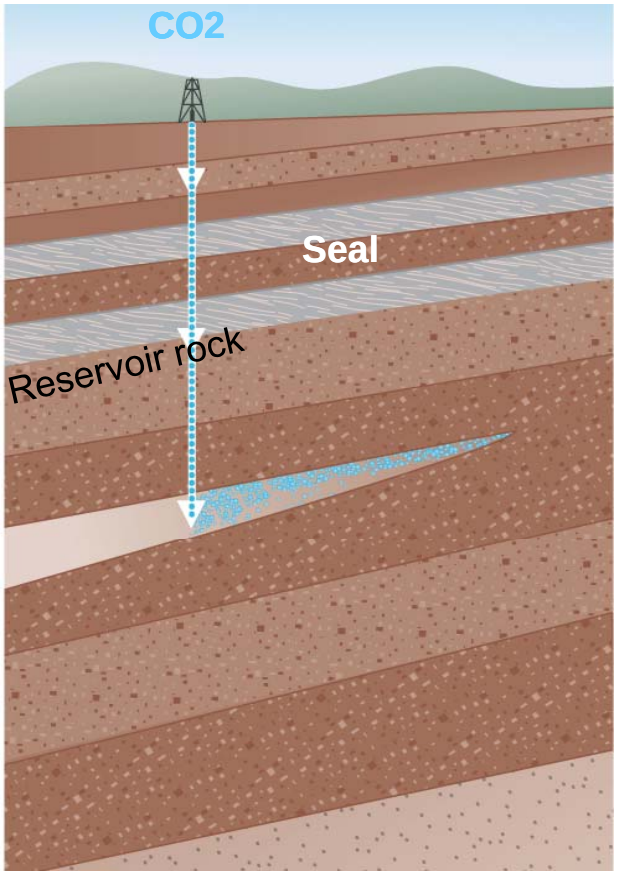
Courtesy Kaldi, 2009

Stratigraphic Traps

Unconformity

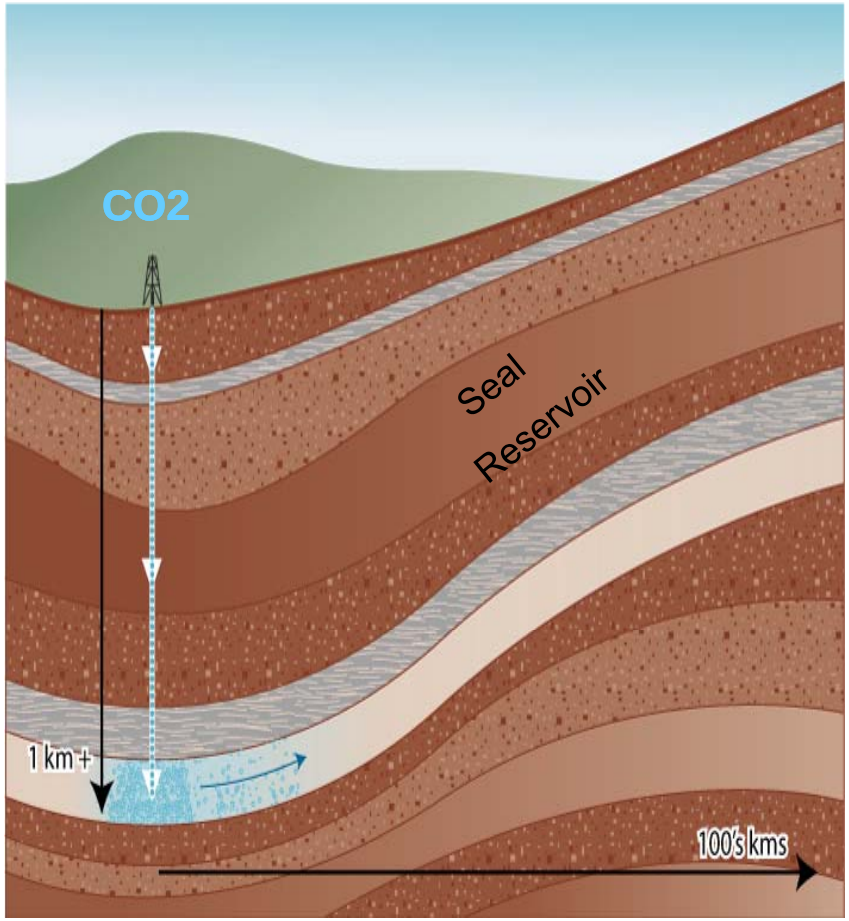


"Pinch-out"



Courtesy Kaldi, 2009

Geological traps for CO_2



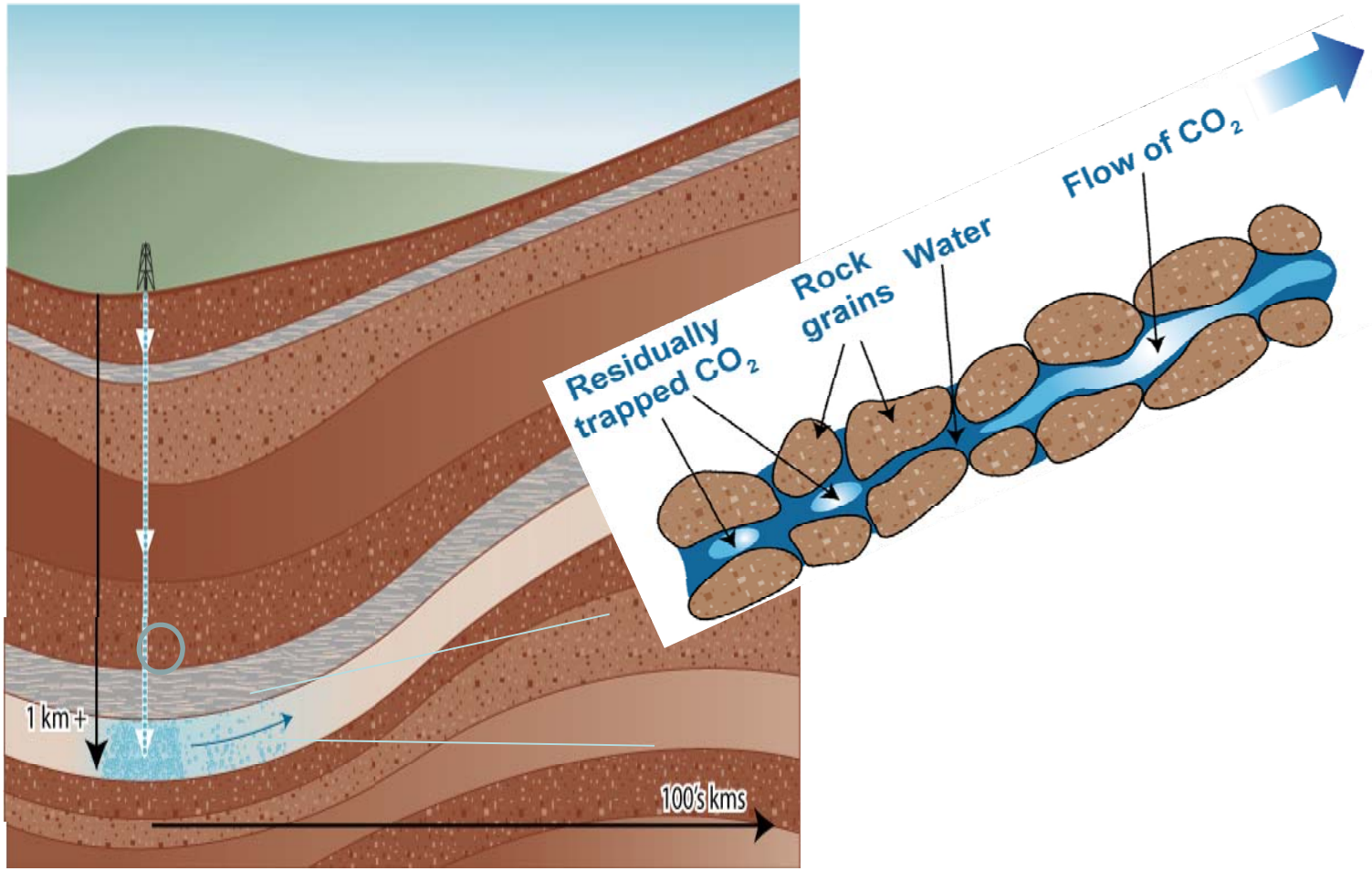
Saline Formations

Mechanisms:

- **Residual Trapping**
- **Solution Trapping**
- **Mineral Trapping**

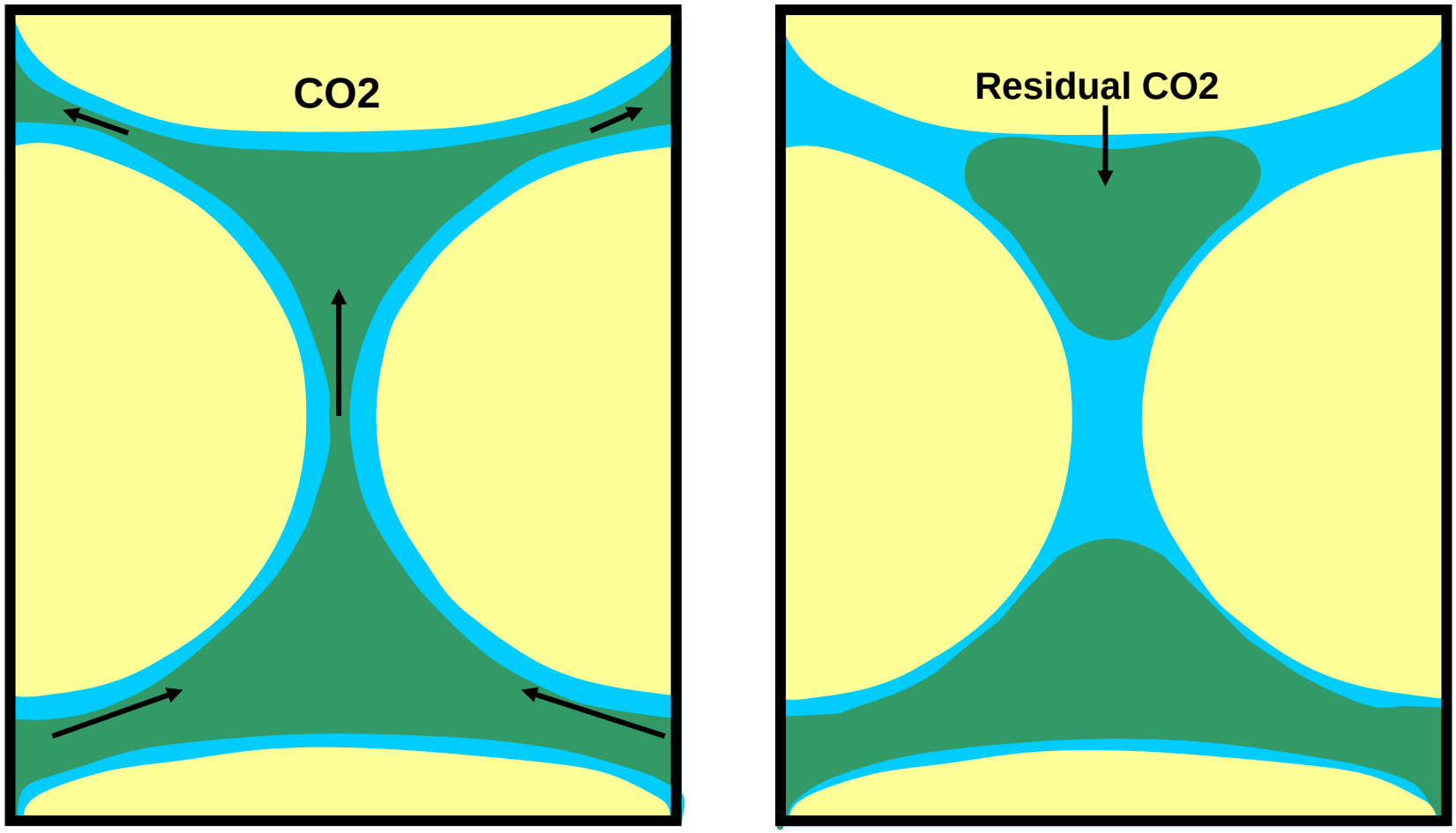
Courtesy Kaldi, 2009

Residual Trapping



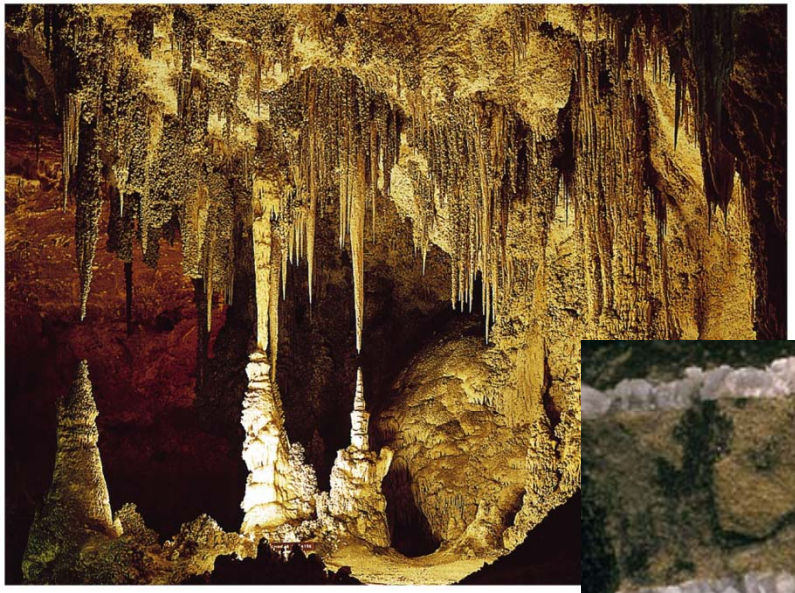
Courtesy Kaldi, 2009

Residual Saturation



Courtesy Kaldi, 2009

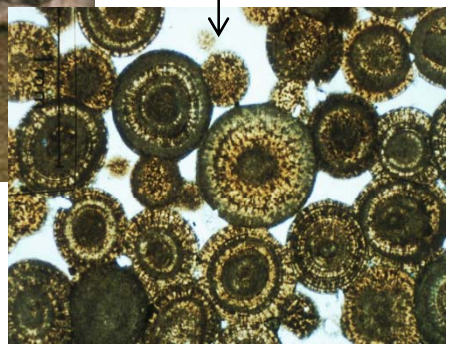
Mineral Trapping



1 m

$CaCO_3$ (Calcite) precipitation occurs at all scales

1 cm

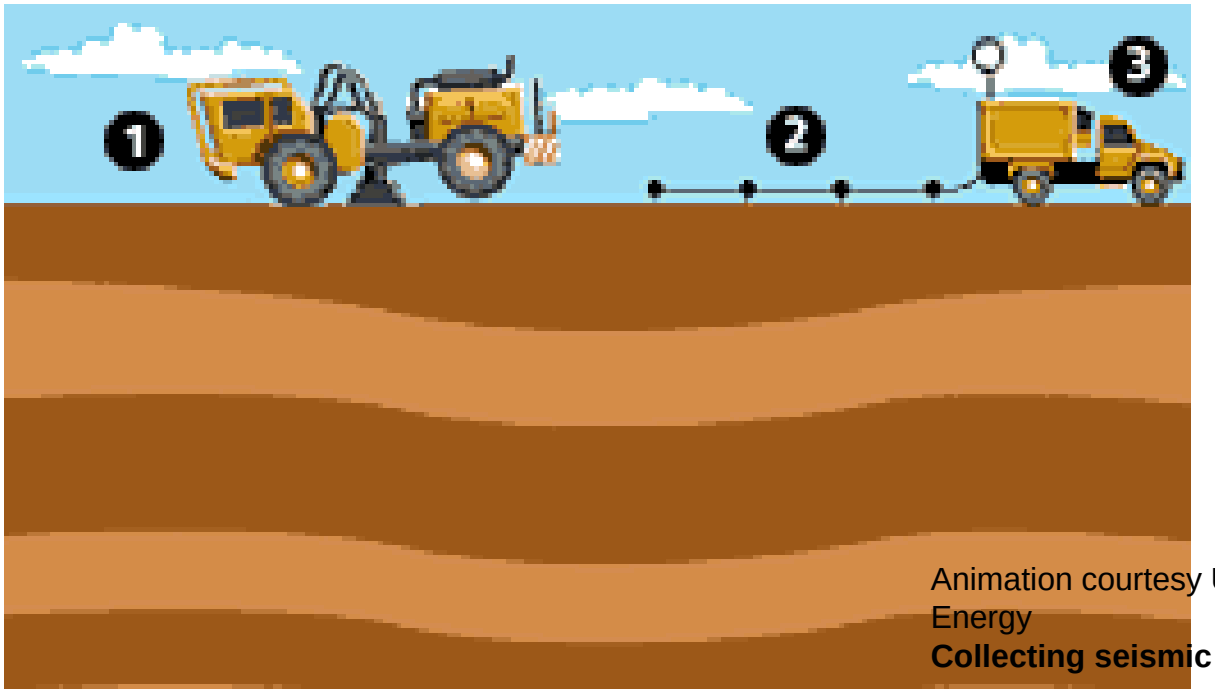


Courtesy Kaldi, 2009

How do we know what's down there?

- Geophysics
  - Seismic; gravity; magnetics
- Drilled wells
  - Rock
    - Core; sidewall core; drill cuttings
  - Wireline logs
- Analogs
  - Outcrops
  - Modern depositional environments
- Integrated models

What is Seismic?



Animation courtesy US Department of Energy
Collecting seismic data on land

Seismic imaging uses reflected sound waves to create a picture of underground rock formations. It can show potential CO_2 reservoirs and seal rocks and other geologic features such as faults. After injection begins, it can show the location of the CO_2.

Courtesy Kaldi, 2009

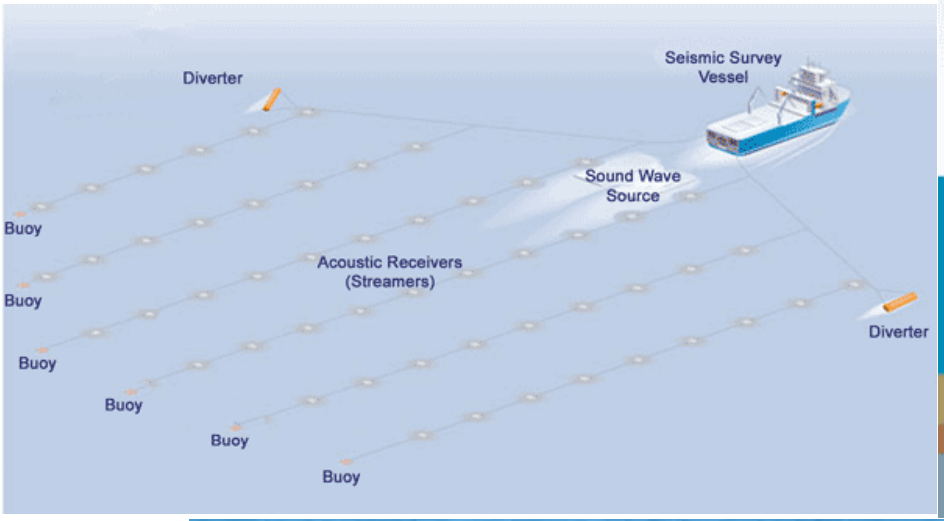
Onshore Seismic

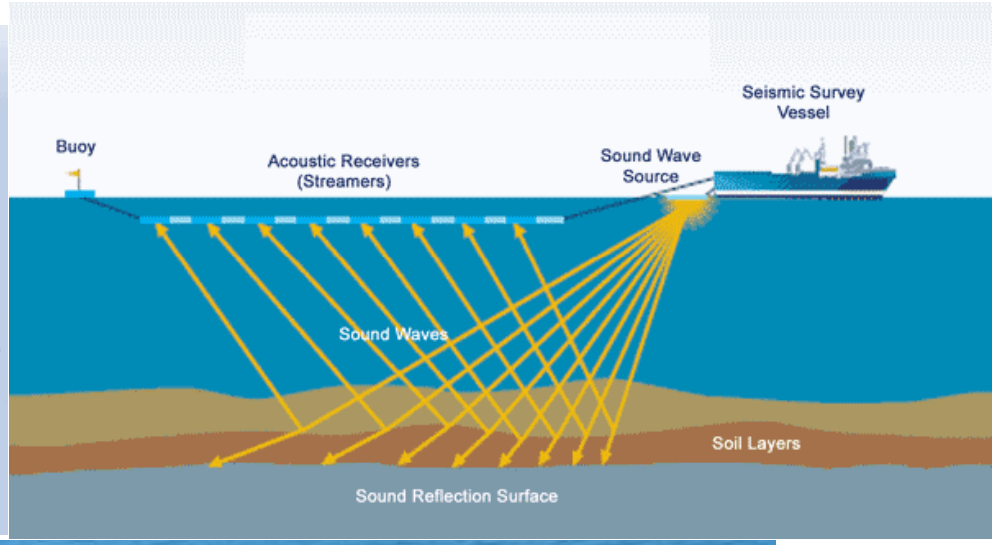
Truck-mounted Vibroseis
("Thumper")

BobCat-mounted
weight drop

Courtesy Kaldi, 2009

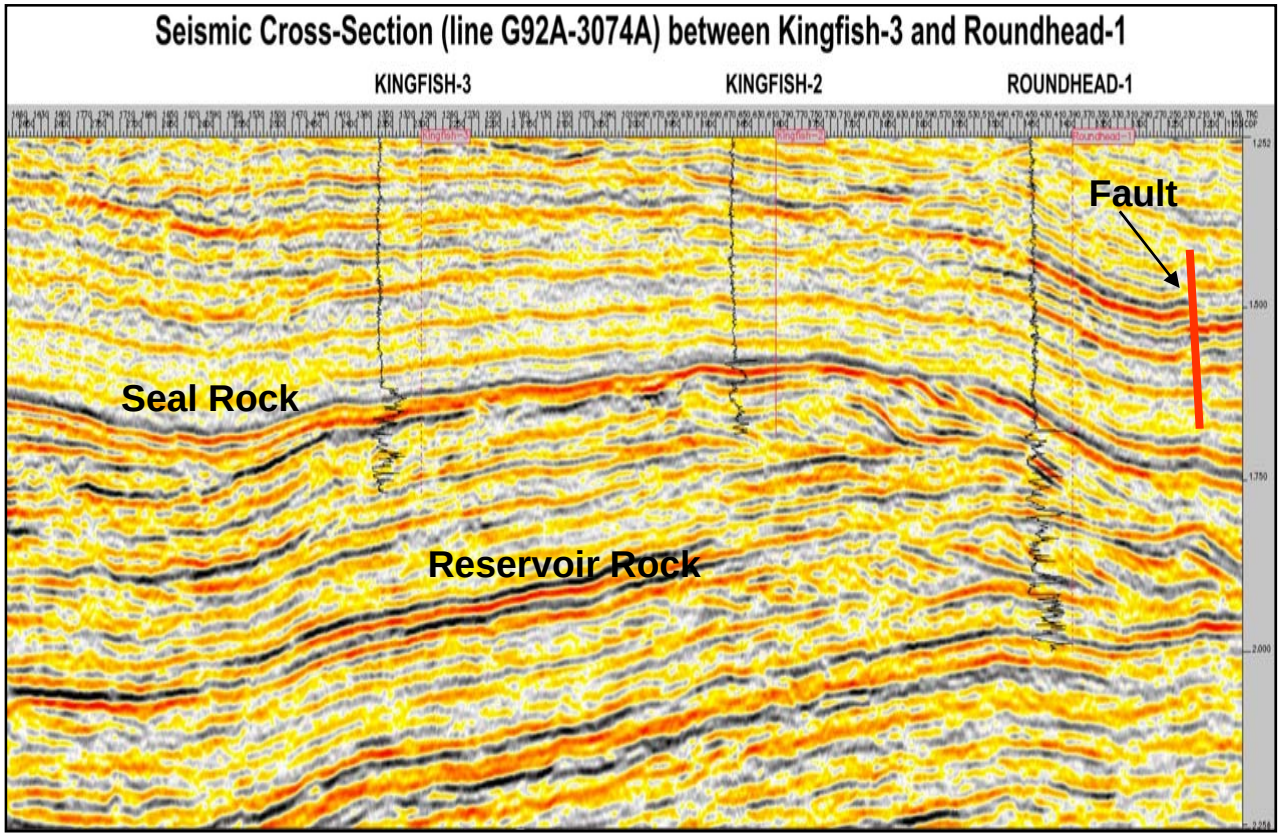
Offshore Seismic





Courtesy Kaldi, 2009

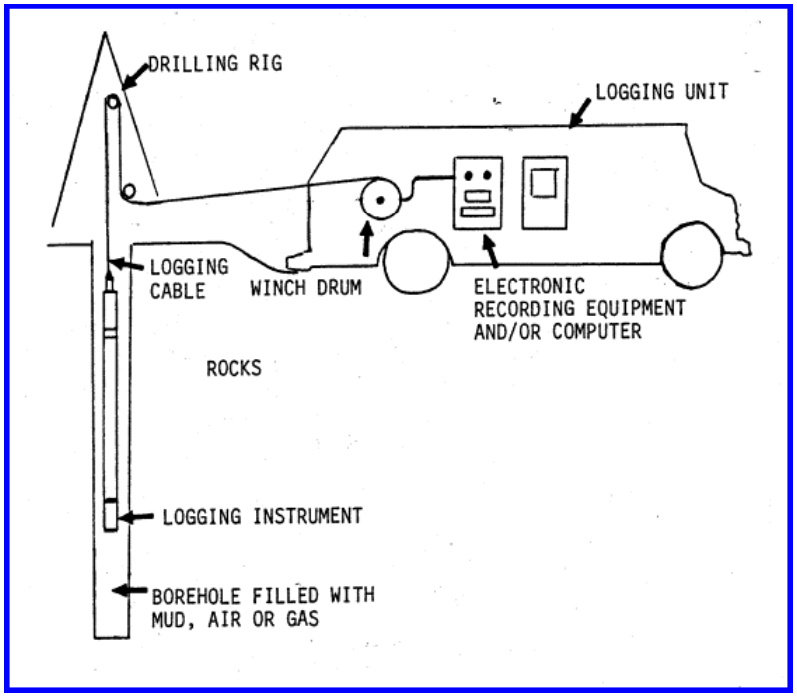
Seismic cross-section: Gippsland Basin

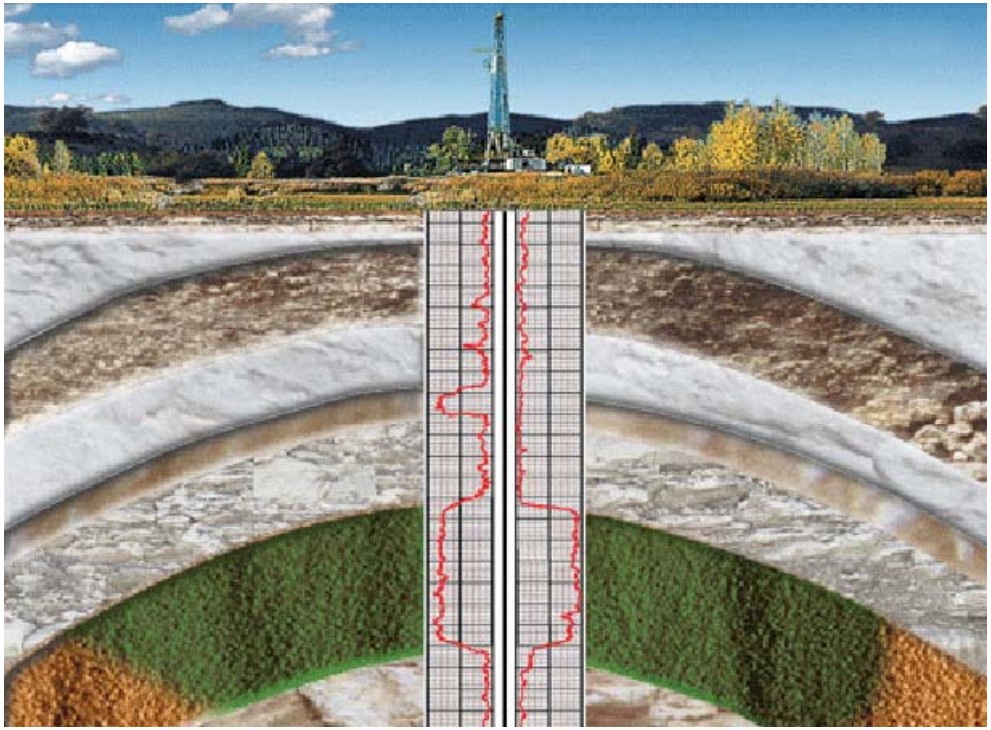


Seismic imaging uses reflected sound waves to create a picture of underground rock formations. It can show potential CO_2 reservoirs and seal rocks and other geologic features such as faults. After injection begins, it can show the location of the CO_2.

Courtesy Kaldi, 2009

Wireline Well Logging





Courtesy Kaldi, 2009

Injectivity

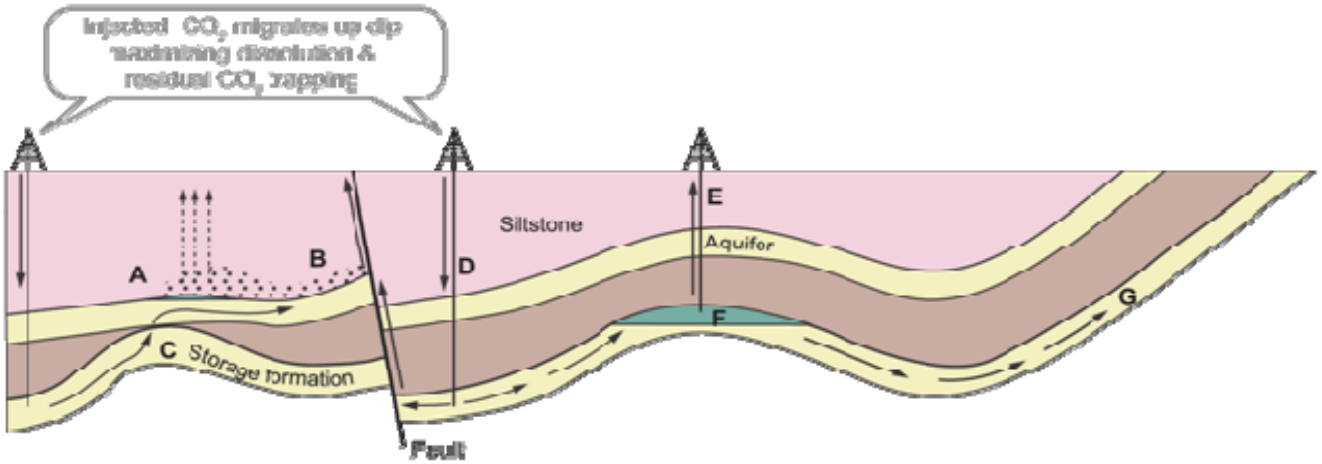
$$I_{v/t} = A * P_i * k$$

$I_{v/t}$ = Injection rate
A = Area (of wellbore in contact with formation)
P_i = injection pressure (below frac)
k = permeability

($I_{v/t}$ is proportional to number of wells)

Courtesy Kaldi, 2009

Leakage Scenarios



Potential Escape Mechanisms

A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone	**B.** Free CO_2 leaks from A into upper aquifer up fault	**C.** CO_2 escapes through 'gap' in cap rock into higher aquifer	**D.** Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault	**E.** CO_2 escapes via poorly plugged old abandoned well	**F.** Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure	**G.** Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

A. Extract & purify ground-water	*B. Extract & purify ground-water*	*C. Remove CO_2 & reinject elsewhere*	*D. Lower injection rates or pressures*	*E. Re-plug well with cement*	*F. Intercept & reinject CO_2*	*G. Intercept & reinject CO_2*

Source: IPCC, 2005

Monitoring

Why monitor?

- Worker & public safety
- Local environmental to groundwater and ecosystems
- Green house gas mitigation effectiveness

Methods

- Soil Gas
- Seismic (4D)
- Geobotanical
- E-M/ Magnetic Surveys

Commercial-scale CCS Projects

Sleipner

Snøhvit

In-Salah

Weyburn/Midale

Images Courtesy of BP, Statoil, and PTRC

Public Perceptions

Why is Public Perception Important?

- Need local agreement at pilot demonstration sites (depending on policy of local government)
- Government funding of CCS projects / Research

How do we determine their perceptions?

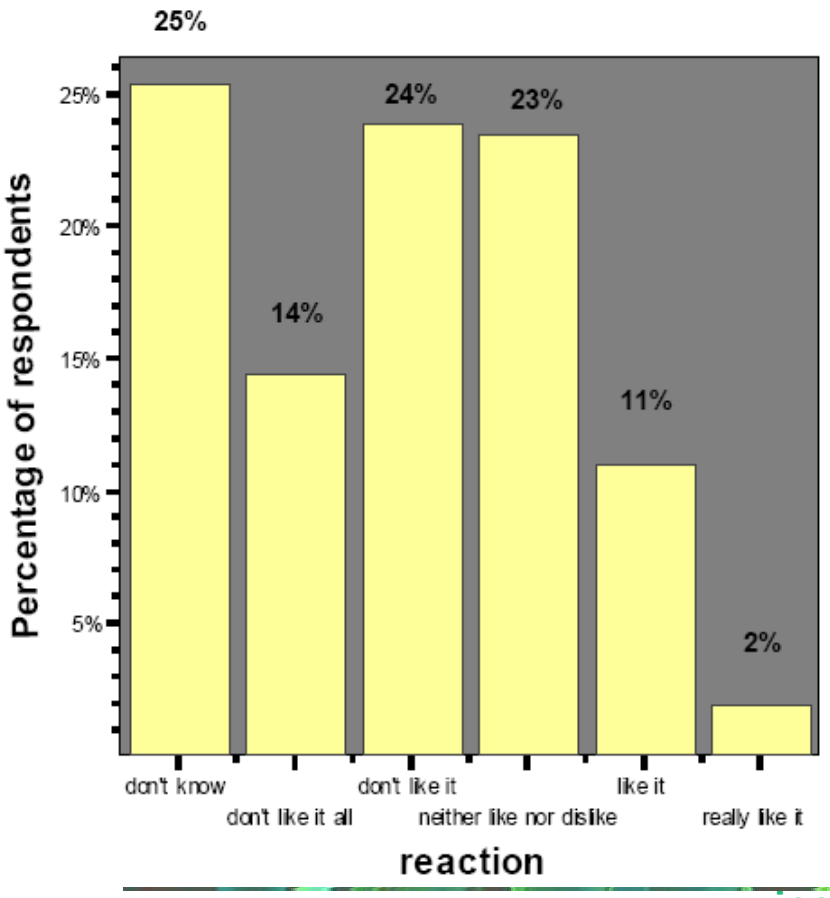
- Surveys (combined with information)
- Focus groups

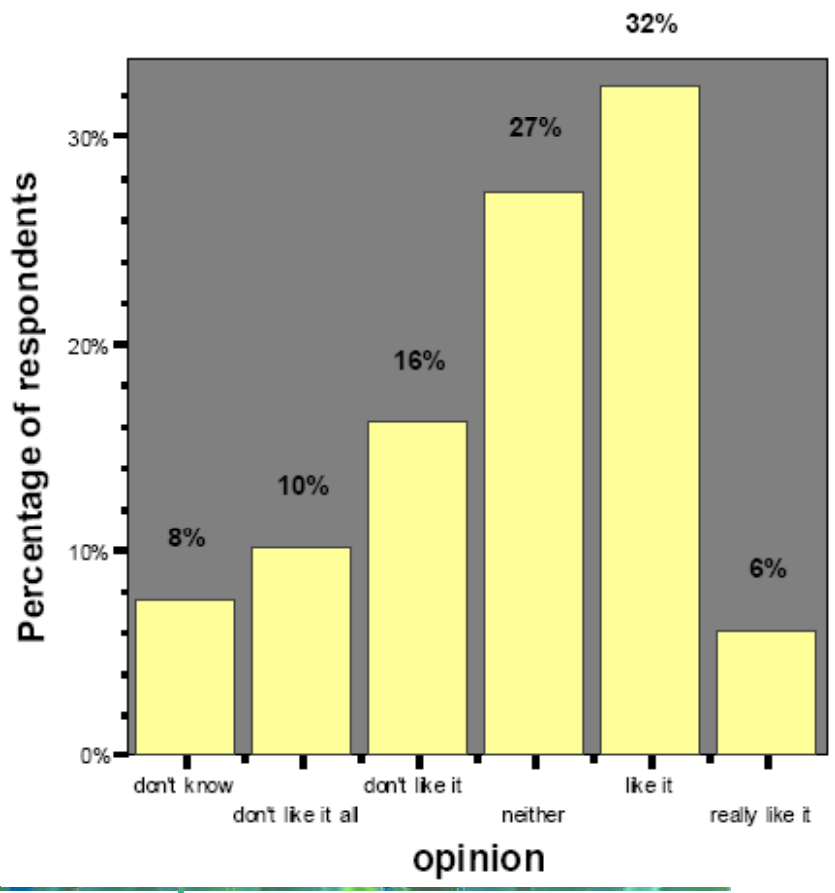
Surveys of lay public show:

- Low level of knowledge of CCS
- Dislike CCS when compared to renewable energy
- Though it is slightly preferred to nuclear

- Become more positive when given more information

Reaction to CCS with/ without Information





Shackley et al, 2004

Public Perceptions

Main Concerns

- Leakage and risk to local population and ecosystems
- Effects on drinking water
- Efficiency
- What emissions will be produced
- Compensation (for local communities)

Factors to consider when communicating to a local community

- Previous awareness of climate change
- Level of education
- CCS more popular if presented as a bridging technology
- Trust of the risk messenger (communication will be easier)
- Previous environmental damage to area and how it was dealt with
- 2-way communication exchange has been proven more effective

IEA Greenhouse Gas R&D Programme

Aquifer Storage / Deep Saline Formations

Neil Wildgust, Ludmilla Basava-Reddi

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

Hassi Messaoud, Algeria

16th – 19th November, 2009

Structure of Talk

- Introduction
- Development Issues (2008 IEAGHG Study)
- Storage Capacity (2009 IEAGHG Study)
- IEAGHG Modelling Network
- Case Studies

What is Aquifer Storage?

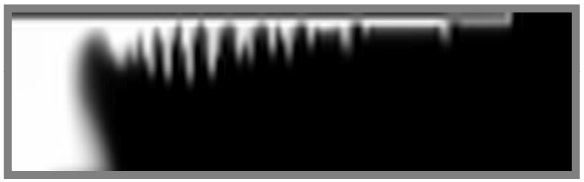
- Deep sedimentary rocks saturated with formation waters / brine
- Widespread
- Hold the largest potential storage capacity
- Range of capacity estimates
- Simulations carried out through modelling
- Need more exploration

Picking a Site

- Statement of Storage Aims
- Site Screening, ranking and selection
- Site Characterisation
  - Geological Characterisation
  - Predictive Flow Modelling
  - Geochemical and Geomechanical Assessment
  - Risk Assessment
  - Monitoring Program design and support
- Site Design and Planning Consent
- Site Construction
- Site Operations
- Site Closure

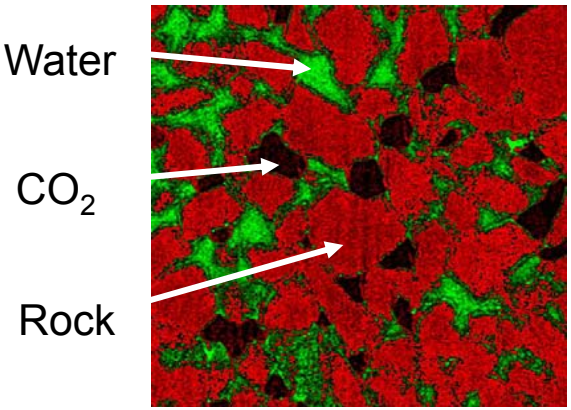
What Keeps the CO_2 Underground?

- Physically trapped beneath seals
- CO_2 dissolves in water

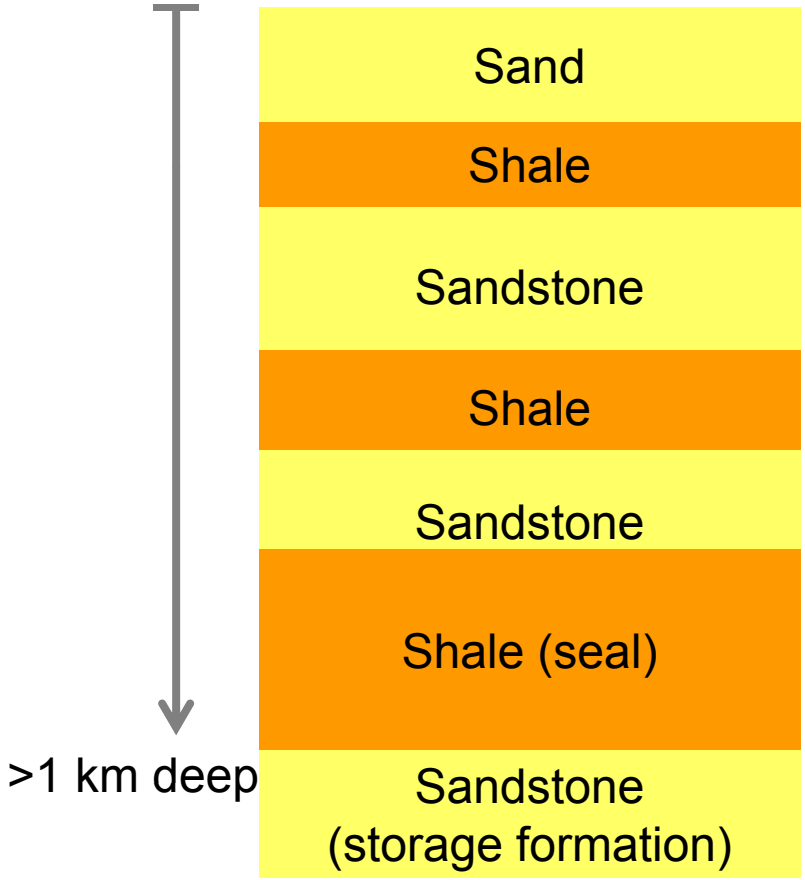


X-ray of CO_2 in sandstone

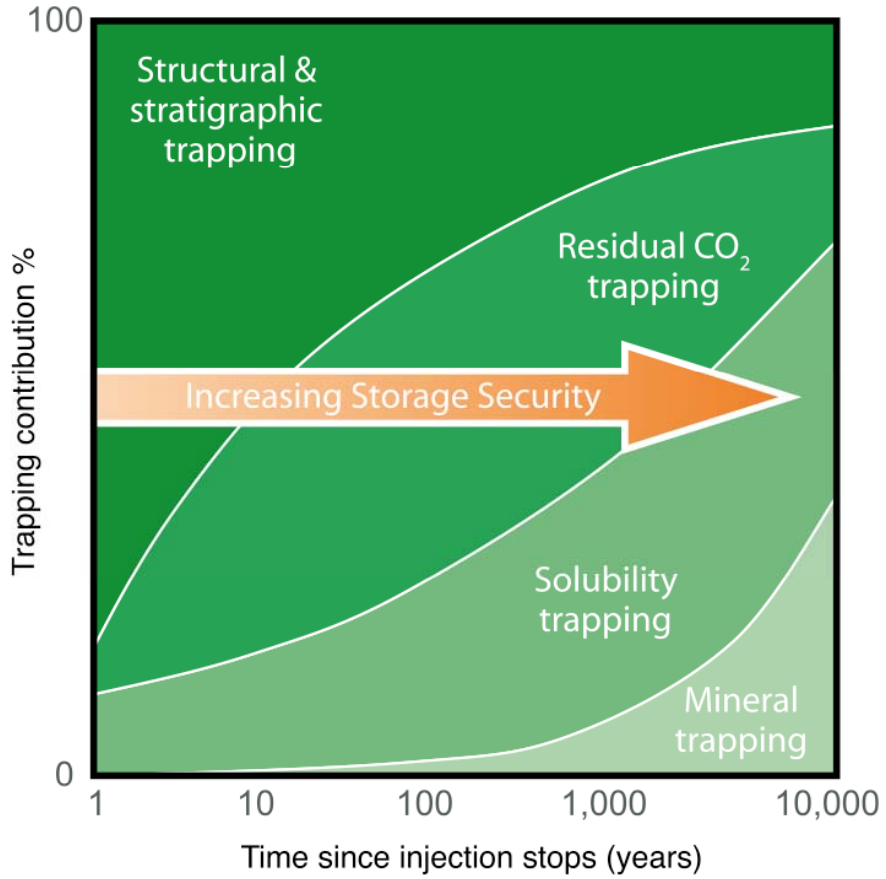
- CO_2 is trapped by capillary forces



- CO_2 converts to solid minerals



CO_2 Containment Mechanisms



IPPC Report 2005

Aquifer Storage – Development Issues

- Project undertaken by CO2CRC of Australia
- Focus on science research and injection projects
- Aims:
  - Review research from around the world since the publication of the IPCC SRCCS,
  - Identify knowledge gaps and priority areas for further research,
  - Provide a comprehensive summary of research, data sources, storage reservoir properties and injectivity data.

Storage Science

- Report describes in detail, progress made in understanding geochemistry of storage processes and advances in numerical models
- Key remaining gaps:
  - Better understanding of long term geochemistry
  - Improvement of coupled simulation models
  - Quantification of leakage scenarios
  - Potential wellbore leakage due to cement degradation

Geochemistry and Trapping

- Recent advances made through experimental and natural analogue studies plus modelling
- Simulation and experimental data on solubility has been matched, but more representative P/T experimental work needed
- More field and lab data is required to further incorporate kinetics and calibrate modelling
- Poor understanding of geochemical processes could lead to storage risk over-estimation

Geochemical Trapping

- CO_2 Solubility
  - Depends on Pressure, Temperature and composition of formation waters.

- Ionic and Mineral Trapping
  - Consumption of hydrogen ions through mineral dissolution reactions
  - Adsorption on mineral surfaces
  - Ion exchange

This can be predicted through modelling, then natural analogues can be used to evaluate the predictive capabilities of geochemical models.

Reactive Transport Modelling

- Predicts short and long-term spatial changes in mineral and fluid chemistry
- Distribution of CO_2 into various trapping mechanisms – risk of leakage.
- Shows mineral trapping over large timescales (100's to 100,000's years)
- Solubility and ionic trapping – shorter timescales
- Changes in porosity predicted
- CO_2 sequestration high in certain formations (e.g. Calcite)

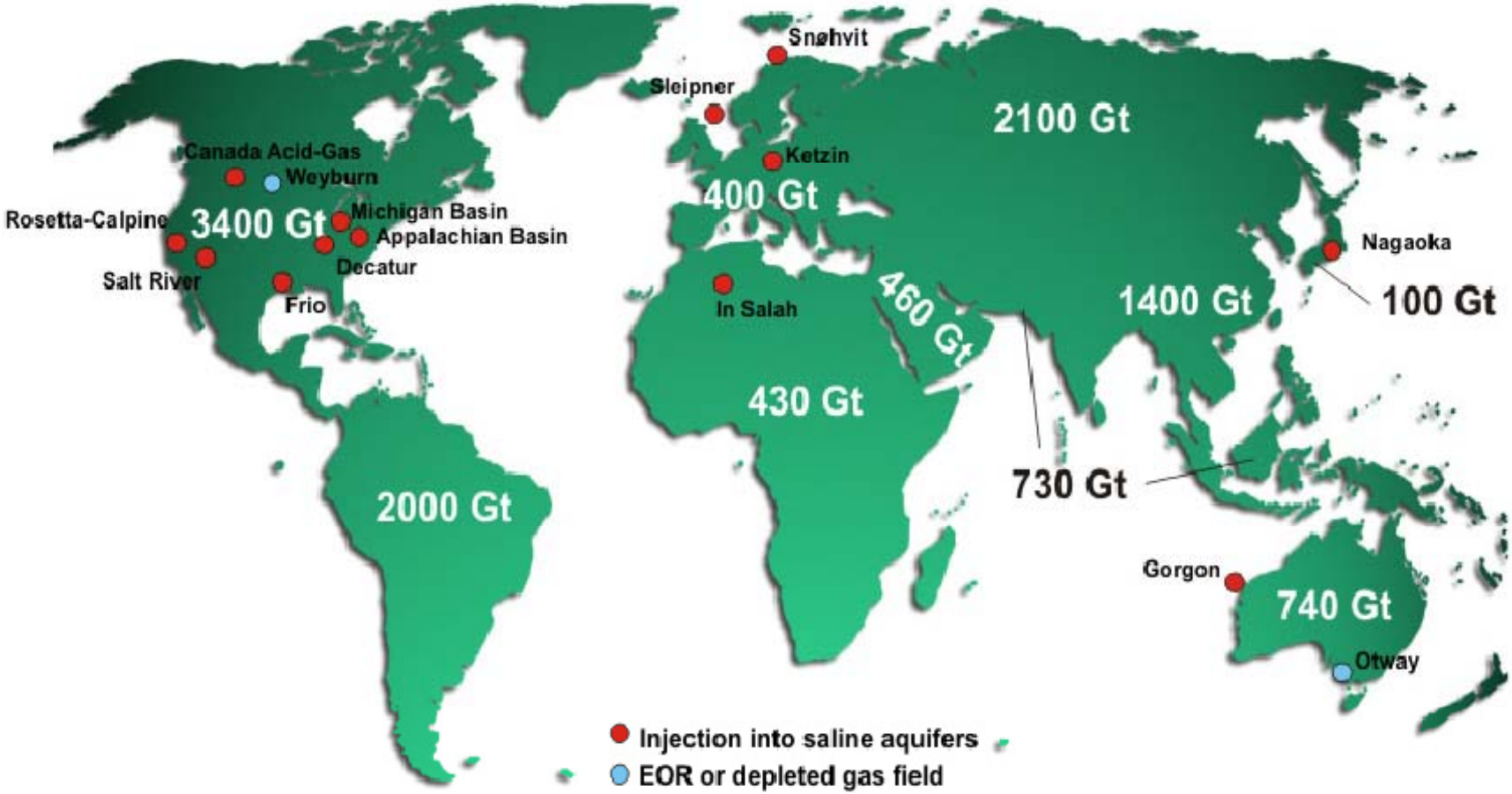
Numerical Simulation Modelling

- Report provides an overview of significant factors affecting current ‘state of the art’
- Effects of heterogeneity, relative permeability hysteresis and convective mixing all researched
- Coupled models now include hydrodynamics, geochemistry and geomechanics
- Planned IEA GHG workshop in February 2009

Storage Capacity

- Report highlights continued discrepancies in methodology e.g. CSLF versus US DOE;
  - Structural traps or whole formation?
  - Free phase or solubility trapping?
- Gaps:
  - Consistent methodology
  - Further regional work
- Note IEA GHG storage capacity study (EERC)

Regional Storage Capacity



Storage Capacity Estimation

Total Pore Volume

Total physical limit of what the storage system can accept. Assumes entire volume is accessible to store CO_2 in the pore space or dissolved in formation fluids or adsorbed at 100% of total coal volume.

Operational Capacity

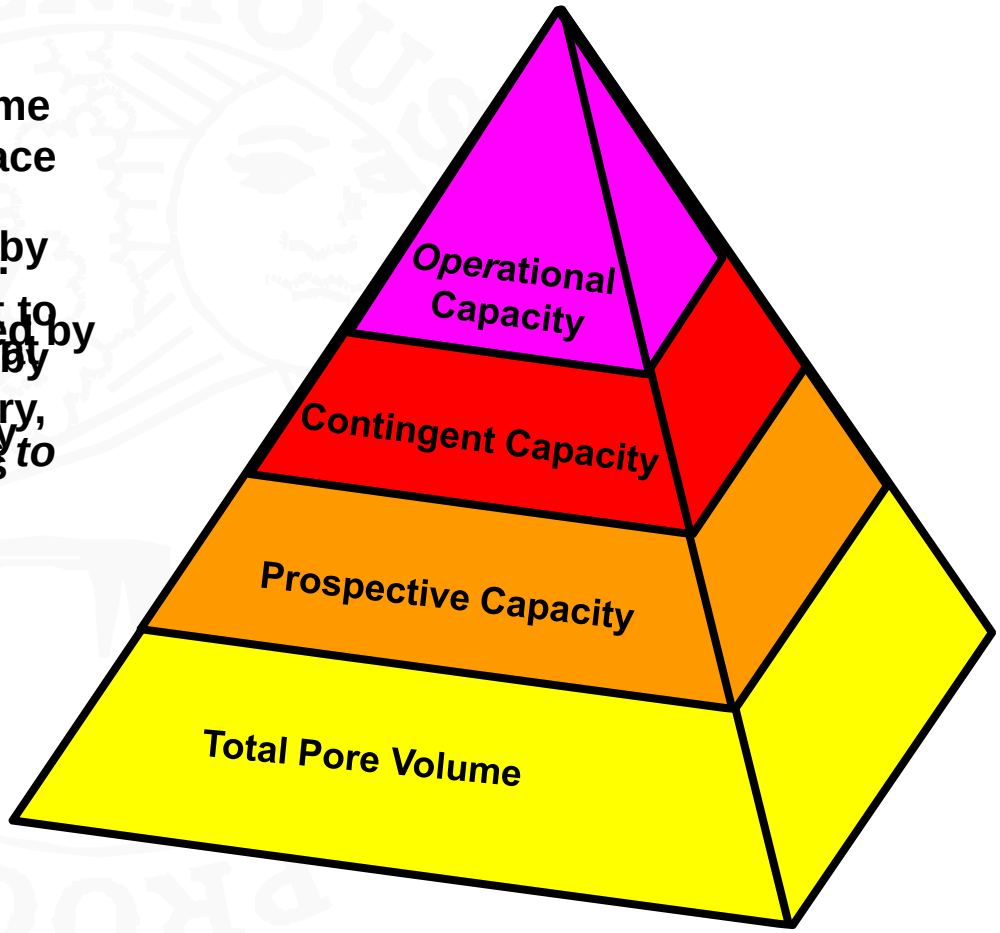
Subset of contingent capacity obtained by detailed matching of specific stationary CO_2 sources with specific storage sites that are adequate technically, legally and regulatory, and economically. Corresponds to "Proved, marketable reserves" used by industry

Prospective Capacity

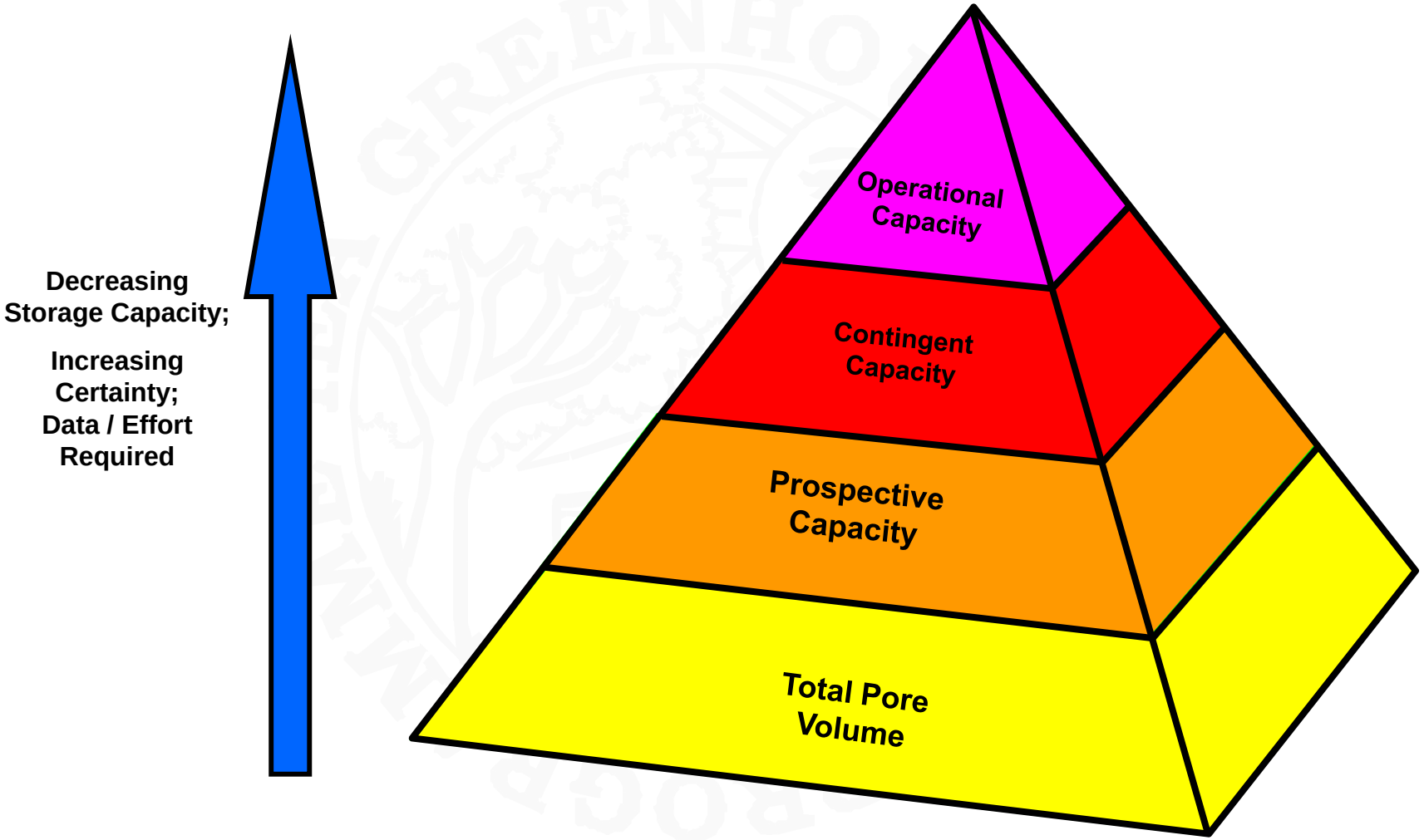
Subset of Total Pore Volume obtained by applying technical, geological & engineering limits. This estimate usually changes with acquisition of new data, or knowledge

Contingent Capacity

Subset of Prospective Capacity obtained by considering technical, legal and regulatory, infrastructure and economic limits. This is an estimate of what can currently be produced, always be physical, technical, regulatory and economic limitations. Value prone to changes as technology, policy, regulations and/or economics change. *Corresponds to "Reserves" as used in energy and mining industries*



Storage Capacity Estimation



Site Characterisation

- Recent documents reviewed include 2007 Best Practice Manual from SACS/CO2STORE, and separate 2008 CO2CRC report
- Study report recommends further development of best practice from broader project range
- IEA GHG has 2 studies on site characterisation, with DNV and ARC respectively

Risk Assessment

- No consistent RA methodology has yet been proposed for CO_2 storage projects
- Quantitative RA process for CO_2 storage is widely thought to be unrealistic due to present limitations of knowledge
- RA continues to be debated by the risk assessment network

Monitoring

- Report briefly discusses results from Frio, Nagaoka and Sleipner projects
- Monitoring techniques for shallow groundwater, soil and atmosphere require demonstration (natural analogues)
- Improvements in monitoring and verification require further injection projects
- IEA GHG monitoring network

Monitoring

- Pressure and Temperature measurements (Frio and Nagaoka)
- Direct Measurements for CO_2 Detection
  - Geochemistry (Sleipner, Frio and Nagaoka)
  - Soil-Gas CO_2 fluxes (Frio and Nagaoka)
  - Tracers (Frio and Otway)
- Remote Sensing
- 4-D Seismic (Sleipner and Nagaoka)
- 4-D VSP (Frio)
- Cross-well Seismic (Frio and Nagaoka)
- 4-D Gravimetry (Sleipner and In-Salah)
- Cross-well Electromagnetics (Frio and In-Salah)
- Well-logging (Frio and Nagaoka)

Monitoring

Onshore only | Offshore only | Onshore & Offshore | Primary use | Secondary use

				Deep	Shallow	Plume location/migration	Fine-scale processes	Leakage	Quantification
Seismic			3D/4D surface seismic	■	■	■	■	■	■
			Time lapse 2D surface seismic	■		■	■		
			Multicomponent seismic	■		■	■		
	Acoustic imaging		Boomer/Sparker		■	■		■	
			High resolution acoutstic imaging		■	■		■	
			Microseismic monitoring			■			
	Well-based		4D Cross-hole seismic	■		■	■		■
			4D VSP	■		■	■		
Sonar Bathymetry			Sidescan sonar		■			■	
			Multi beam echo sounding		■			■	
Gravimetry			Time lapse surface gravimetry	■		■			■
			Time lapse well gravimetry	■			■		
Electrical/Electro-magnetic			Surface EM	■	■	■		■	
			Sea bottom BM	■	■	■			
			Cross-hole EM	■			■		
			Permanenent borehole EM	■			■		
			Cross-hole ERT	■			■		
			ESP	■	■	■		■	
Geochemical	*Fluids*	Down-hole / springs	Downhole fluid chemistry	■	■		■	■	■
			PH measurements	■	■		■	■	■
			Tracers	■	■		■	■	■
		Marine	Seawater chemistry		■			■	■
			Bubble stream chemistry		■			■	■
	Gases	Atmosphere	Short closed path (NDIRs & IR lasers)		■			■	■
			Short open path (IR diode lasers)		■			■	■
			Long open path (IR diode lasers)		■			■	■
			Eddy covariance		■			■	■
		Soil gas	Gas flux		■			■	■
			Gas concentratrations		■			■	■
Ecosystems			Ecosystems studies		■			■	
Remote sensing			Airborne hyperspectral imaging		■			■	■
			Satellite interferometry	■		■			
			Airborne EM		■			■	
Others			Geophysical logs	■			■		■
			Pressure/temperature	■				■	■
			Tiltmeters	■	■	■	■		

Storage Costs

- Normalisation of cost data to create a predictive model is problematic
- Available data is sparse and from disparate sources
- Regulatory regimes will help to determine major cost elements
- Report findings consistent with IEA GHG decision to delay study on storage costs

Regulatory Aspects

- Key issues
  - Long term liability
  - Monitoring and verification requirements
  - Emission trading scheme implications
- Regulatory frameworks are being urgently prepared in several regions
- IEA Regulators Network contributing to this area

Issues and Knowledge Gaps 1

	Issue	2008 Progress	Gaps	Comments
Storage capacity	Capacity estimates	US DOE Atlas Japan (Europe, Australia)*	Africa Asia Latin America	*Work in progress
	Methodology	US DOE CSLF CO2CRC	Universal document	Should be consistent application
Storage science	Geochemistry	Solution composition, surface processes	Reactive surface area; experiments on some aspects of trapping	Field-relevant experimental data needed
	Numerical models	Modelling of natural analogue and experimental data; well leakage	Data for calibration, upscaling	Need demonstration projects

Issues and Knowledge Gaps 2

	Issue	2008 Progress	Gaps	Comments
Storage engineering	Capacity		Portfolio of environments	Need more demo projects
	Injectivity			
Monitoring	Testing and improvement	Results e.g. from Frio, Nagaoka and Sleipner	Long term monitoring and verification data	
	Leak detection		Cost-effective strategies	
	Verification			

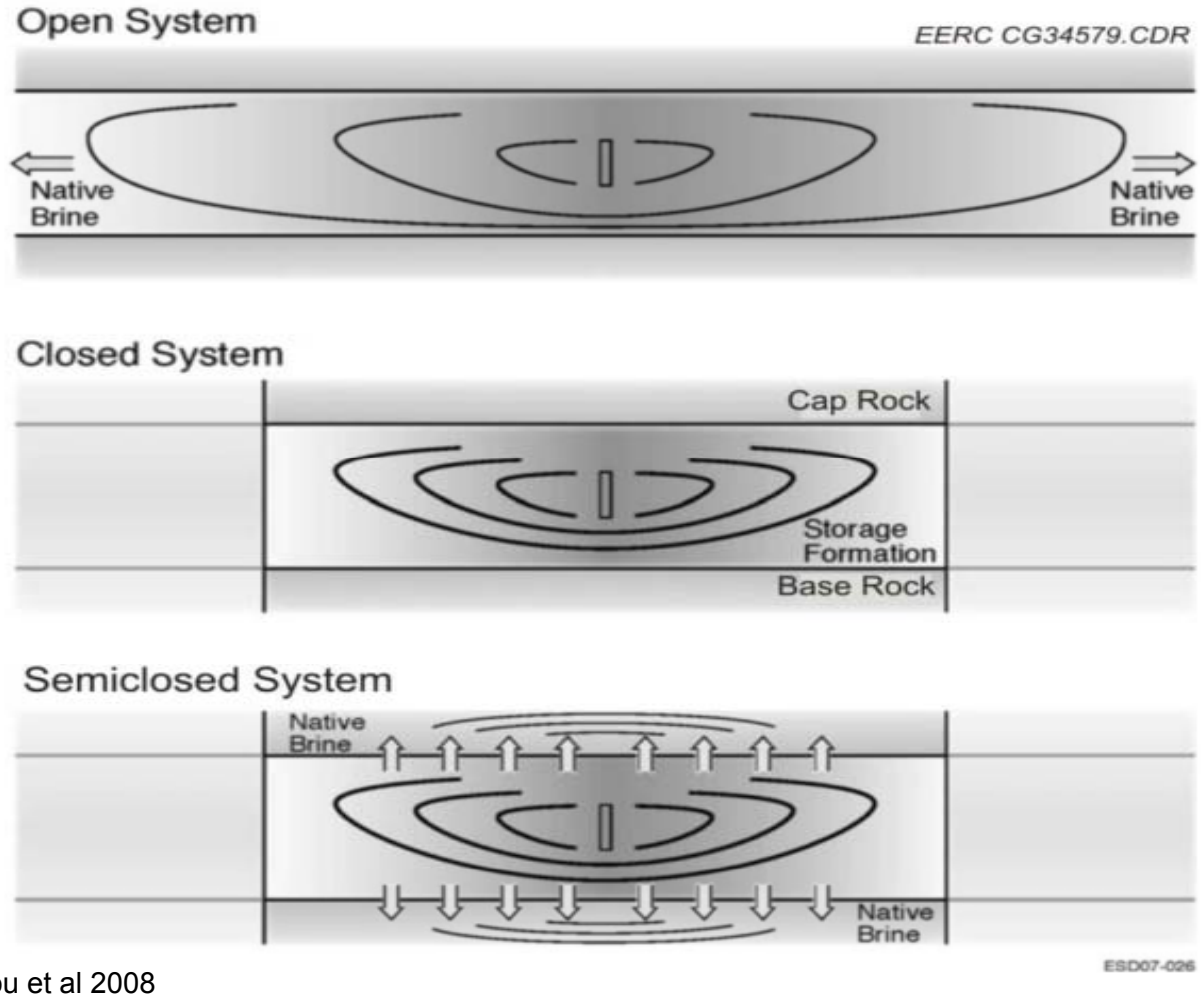
Issues and Knowledge Gaps 3

	Issue	2008 Progress	Gaps	Comments
Regulations	Lack of framework	Draft legislation in USA, Europe, Australia	**Finalised legislation and trading schemes**	
Economics	Costs not well known		**Comparability of cost estimates**	Location and legislative factors
Risk and operational safety	Lack of quantitative methods			
	Need for safety protocols	Best practice manual(s)		

Storage Coefficients

- CSLF and US DOE storage resource estimation methodologies require development of coefficients
- Study undertaken by Energy and Environment Research Centre, University of North Dakota
- Co-sponsored by US DOE
- Main aims of the study:
  - Review storage resource estimation methodologies and associated resource classification schemes;
  - Compile database of key parameters from injection projects and associated modelling studies;
  - Develop a series of storage coefficients that can be applied to regional resource surveys;
  - Consider hydrocarbon fields and saline formations

Open / Closed Systems



Zhou et al 2008

Open system

- Majority of systems
- Fluid and Pressure commumication across the formation

Closed System

-Lateral flow boundaries restrict movements (e.g. faults)
- Injection causes pressure increase
- Limits effective storage capacity

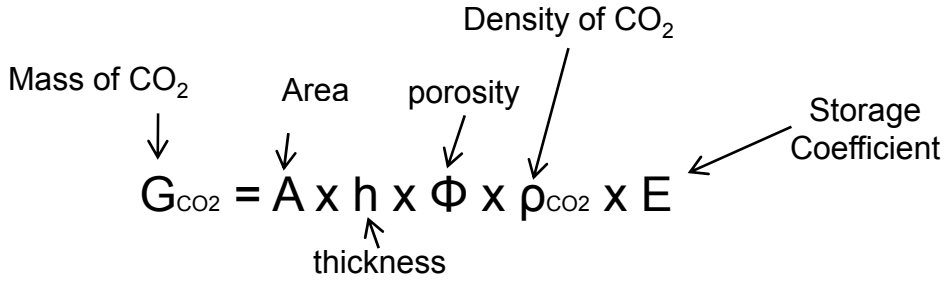
Storage Capacity Estimation

Use modelling to estimate capacity. 2 main factors to consider:

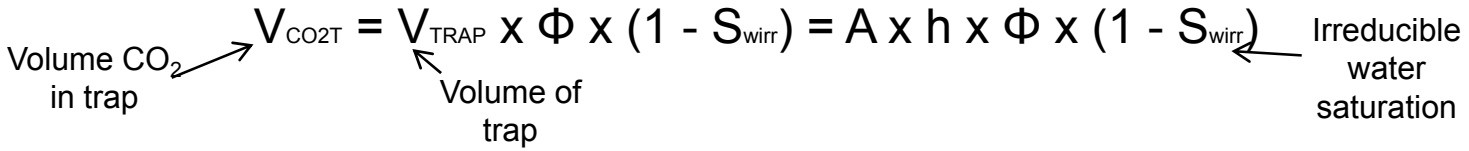
- Limit capacity estimates to structural traps or consider the entire formation
- How capacity is considered in terms of storage as free-phase or dissolved phase CO_2

2 Approaches

US DoE:



CSLF:



The storage coefficients can be related by:

$$E_E = C_c \times (1 - S_{wirr})$$

Methodology

- Paucity of ‘real-world’ projects and data
- Approach employed: modelling from database of likely DSF characteristics developed from HC field databases and literature search
- Provided statistical datasets for modelling
- Uniform injection and evaluation scheme developed for modelling runs
- Coefficients for ***Effective Resource*** derived at site scale and extrapolated to formation scale

Modelling Assumptions

- Coefficients derived for time at cessation of injection
- Trapping dominated by physical containment, but solution and residual trapping also included
- Plumes defined by the extent of free-phase CO_2
- Homogeneous models initially run with averaged properties to assess parameter sensitivity

Modelling

- Approximately 200 simulations run with statistically-derived heterogeneous models
- Coefficients derived for separately for 3 lithologies
- Structural setting found to exert biggest influence on storage efficiency at site scale
- Site scale modelling results extrapolated to formations scale, assuming open system

Formation Level Coefficients for Effective Resource

Lithology	Storage Coefficients (%) by probability percentile		
	P10	P50	P90
Clastics	1.9	2.7	6.0
Dolomite	2.6	3.3	5.5
Limestone	1.4	2.0	3.3
All	1.7	2.6	5.1

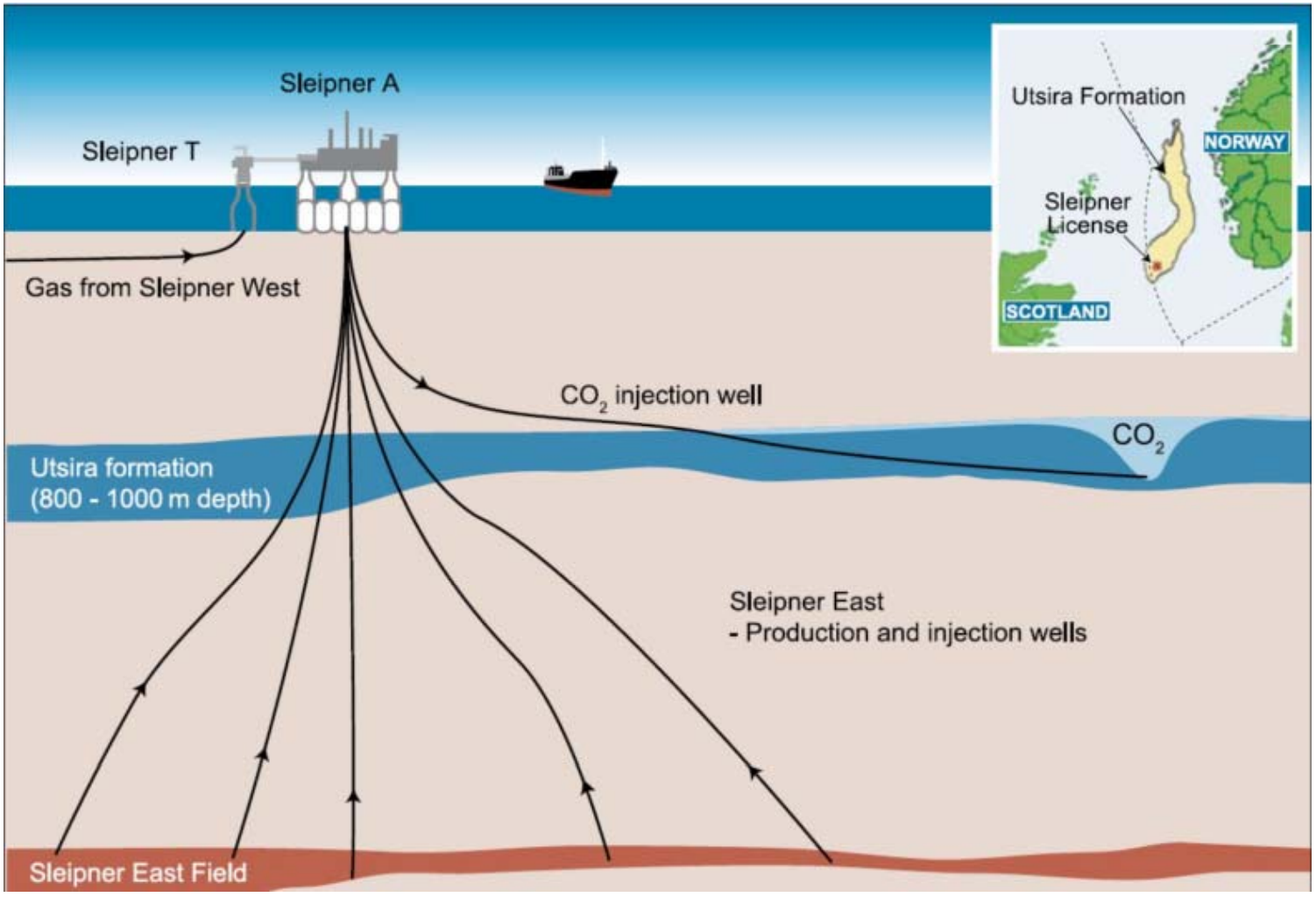
IEA GHG Modelling Network

- Created 2009
- Gap identified in other Storage Networks
- Intricately linked with other storage research networks (monitoring, risk assessment and wellbore integrity)
- Modelling:
  - Pre-injection site assessment
  - During and post-injection processes
  - Monitoring and risk assessment

Aims of Modelling Network

- Create online reference databases and discussion forums
- Guidance documents – practitioners and non-specialists
- Sharing of approaches and data
- Model and code comparison info/ links to benchmark studies
- Updates on lessons learnt and knowledge gaps
- Provide storage performance assessment input to the risk assessment network
- ID critical processes requiring modelling for storage
- Model performance standards
- Online modelling exercises for comparison of methods
- Comparison of numerical and analytical approaches

Case Study - Sleipner



IPCC, 2005

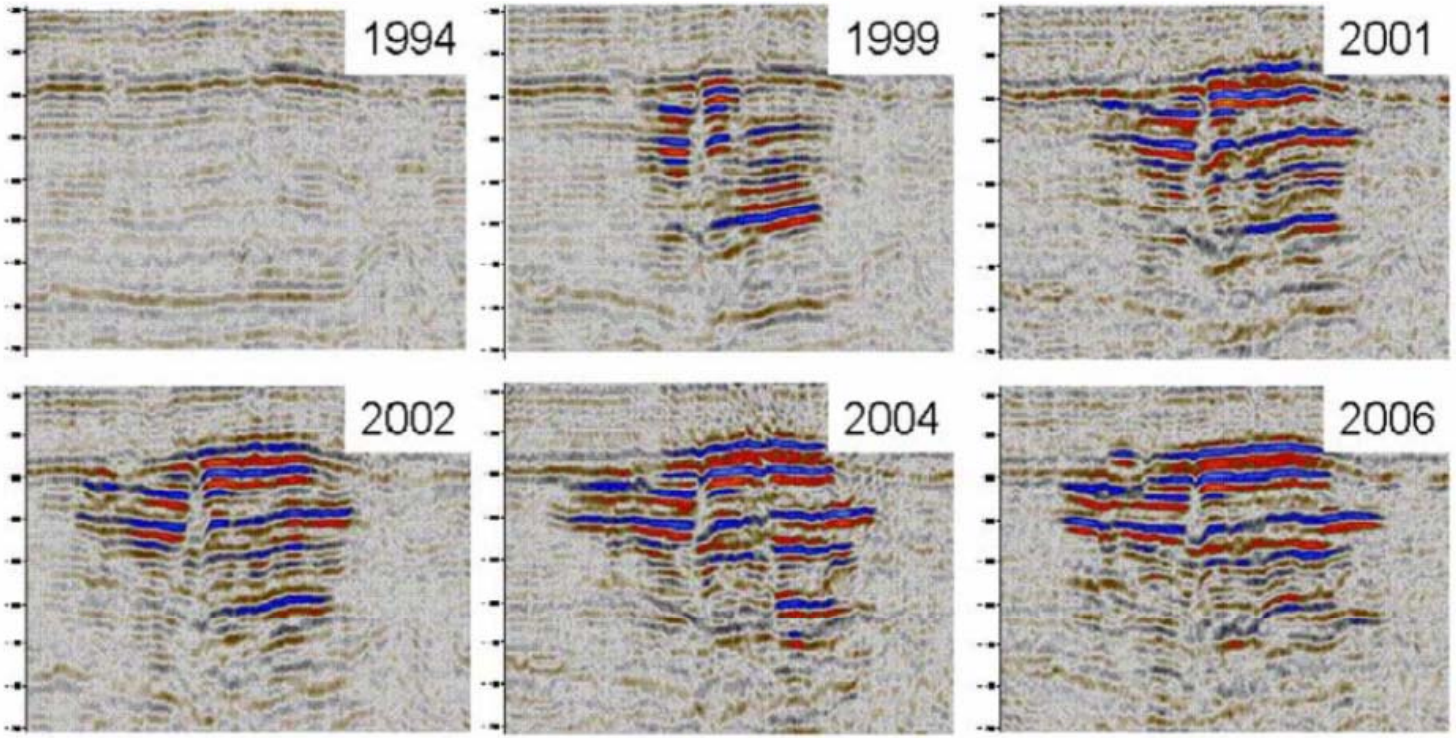
Case Study - Sleipner

- 1st commercial CO_2 storage project
- Stored in Utsira sandstone formation 50-250m thick
- Capacity predicted at 600Gt
- >10Mt CO_2 stored in Utsira formation since 1996
- Planned injection of 25 Mt

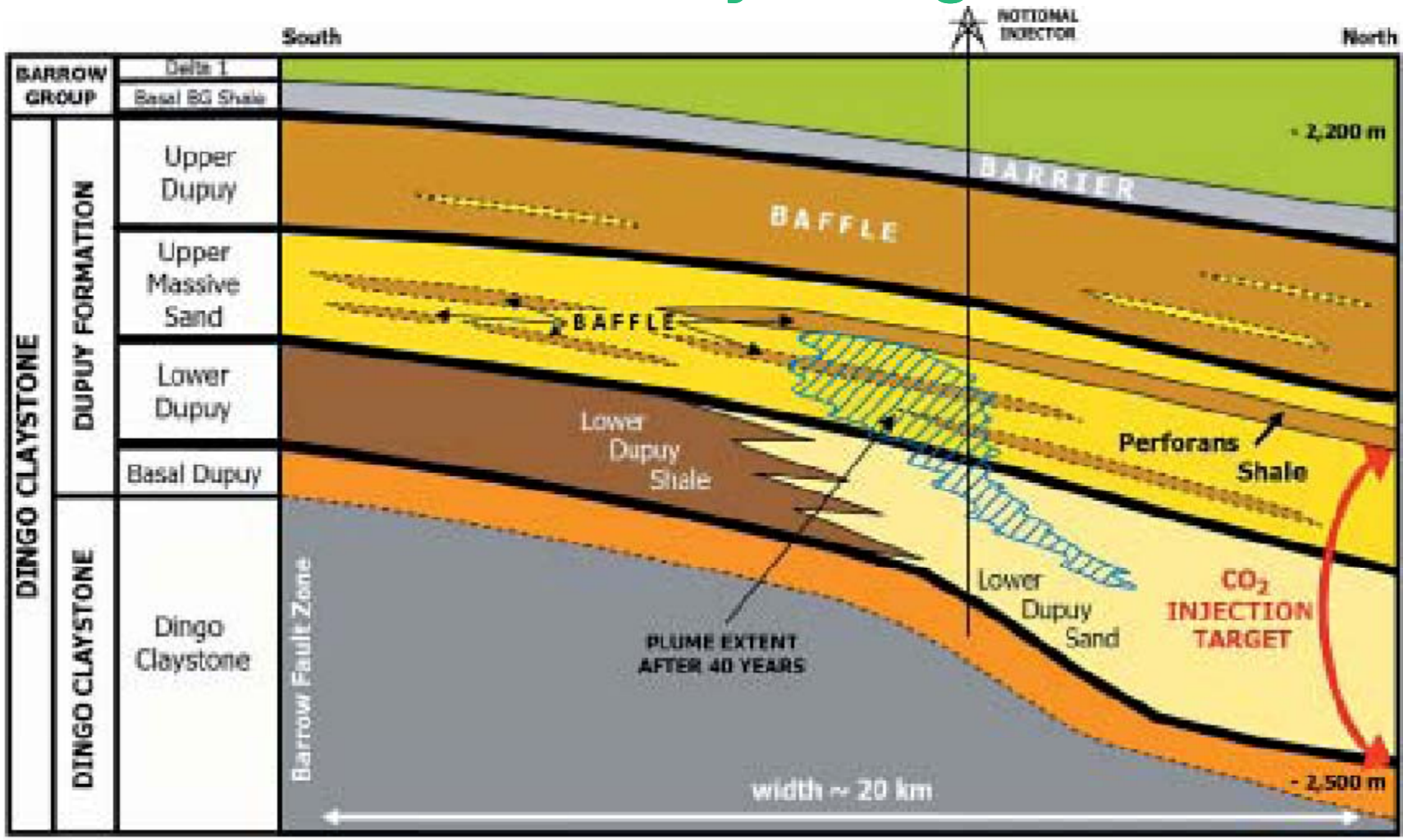
- Site charcterised by 3-D Seismics, well-logs and core samples (1993-1994)
- Monitored with 4-D Seismics and 4-D Gravity surveys (from 2002)
- By 2005, plume 5km^2 around injection point
- CO2 expected to completely dissolve in formation water over time

Case Study - Sleipner

4-D Seismic Survey
Shows plume migration



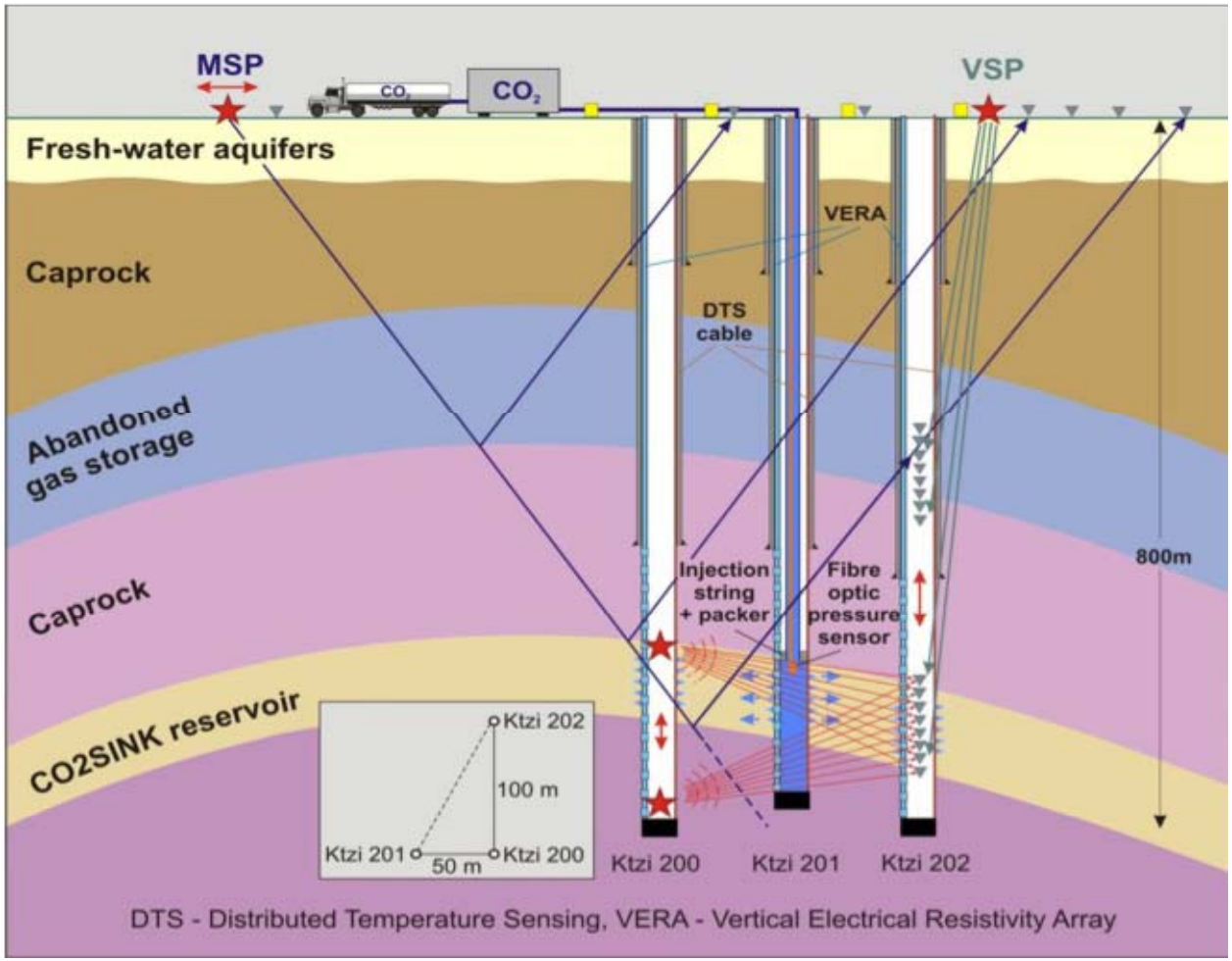
Case Study: Gorgon



Case Study: Gorgon

- Exploiting large natural gas resources of greater Gorgon area, offshore Western Australia
- Natural gas is 14% CO_2
- Planned to inject 2.7 - 3.2 Mt/yr
- Total 125Mt CO_2
- 7 Injection wells planned

Case Study: Ketzin (pilot)



CO2SINK project website

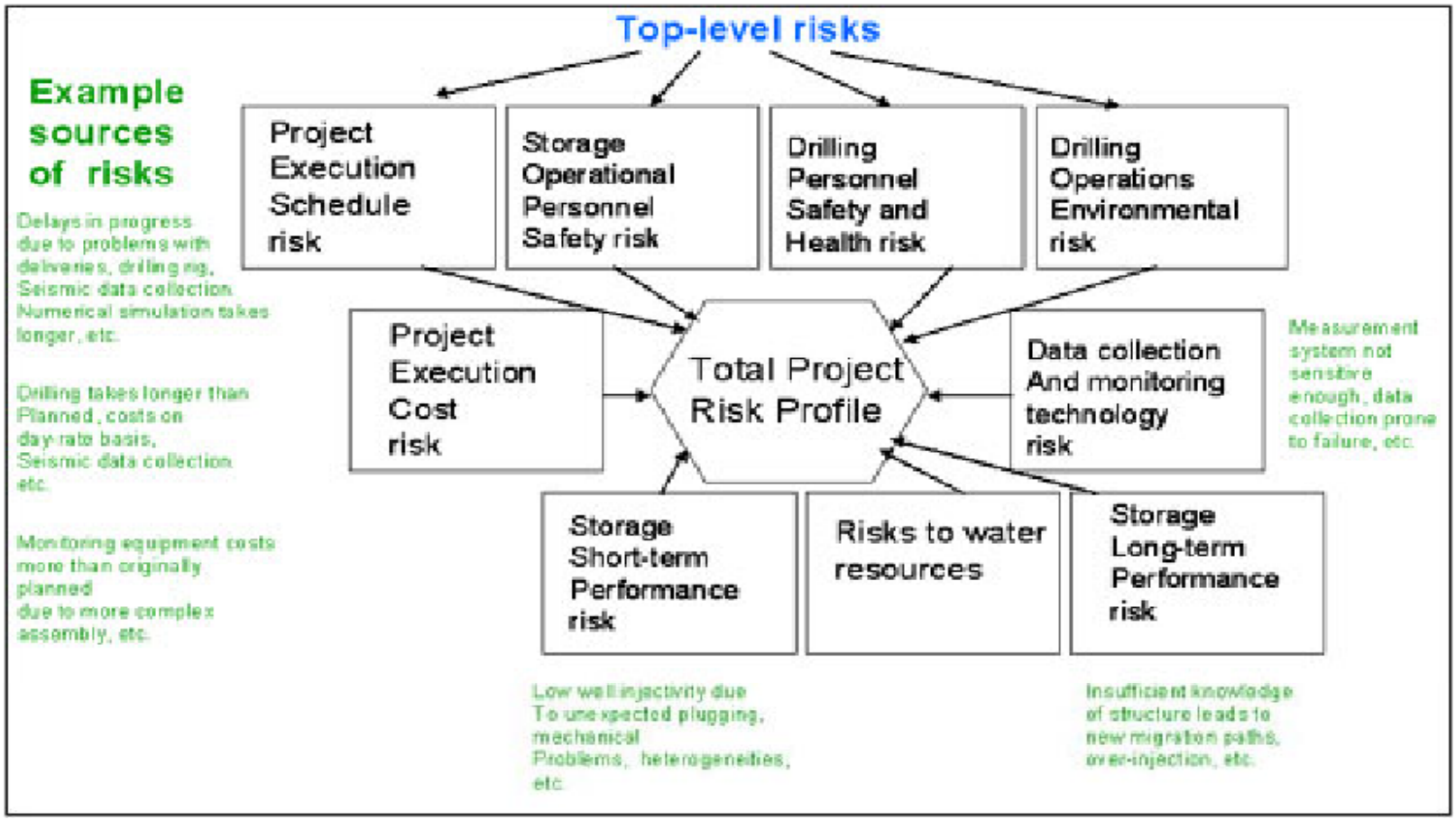
Case Study: Ketzin (pilot)

- Research project started April 2004
- Aims to develop in-situ lab to investigate on-shore CO_2 storage
- Injection started 2008
- Sandstone aquifer, Upper Triassic Stuttgart formation in Ketzin anticline
- 30,000t/yr anticipated over 3 years
- Injection target 500-700m depth, so CO_2 partly in gaseous state
- Clay and gypsum caprock
- 1 injection well

- 2 observation wells
- Monitoring by borehole based seismics and electrical measurements
- Cross-well seismics, VSP, MSP, 2D and 3D time lapse
- 4-D seismics (baseline survey in 2005)

Case Study: Ketzin (pilot)

Risk Assessment



CO2SINK project website

IEA Greenhouse Gas R&D Programme

Global CO_2 Geological Storage Potential in Hydrocarbon Fields

Neil Wildgust

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

Hassi Messaoud, Algeria

16th – 19th November, 2009

Content of Presentation

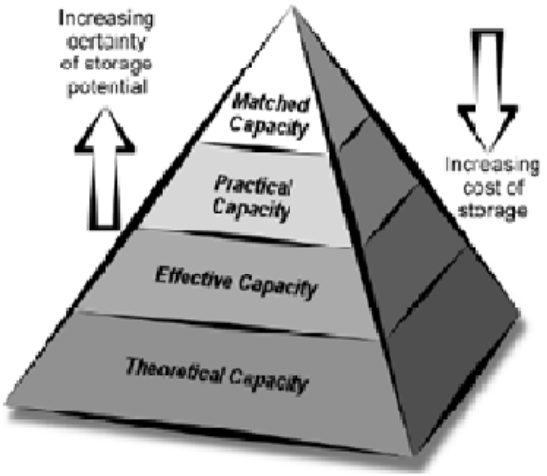
- Global geological storage capacity for CO_2
- Storage in depleted gas fields
- Storage associated with CO2-EOR

Global CO_2 Storage Capacity

IPCC 2005 estimates

- 1,000 to 10,000Gt in saline aquifers
- 675 to 900Gt in depleted oil and gas fields
- 3 to 200Gt in coal beds

CSLF Resource Pyramid



Depleted Gas Fields Study

- IEA GHG study undertaken in 2008 by Poyry Consulting, Element Energy and BGS
- Regional theoretical, effective and practical capacities calculated using USGS petroleum assessments
- Regional matched capacities calculated using AAPG Giant Fields database and GIS based source-sink matching

Limitations of Study

- High level data sources due to global context:
  - USGS 1995 world and US petroleum assessments
  - 2008 AAPG Giant Fields Atlas
  - IEA GHG point source emission database
- Study necessitated use of many generic factors and simplifying assumptions
- Regional results must be treated with caution

Simplifying Assumptions

- Many made, due to nature of study, e.g.
  - Total recoverable gas reserves converted to equivalent CO_2 capacities (0.7t/m^3, GEF 200)
  - Reservoirs re-filled to original pre-production pressure
  - Minimum depth 800m
  - Minimum economic storage capacity of 50Mt onshore/100Mt offshore
  - Estimated dates for close of gas production

Global Gas Field Capacities from USGS Dataset

- **Theoretical** – *assuming all available pore space through gas production utilised* – **900Gt**
- **Effective** – *assumed 75% of theoretical to allow for geological & technical factors* – **680Gt**
- **Practical** – *discounting effective capacity by 40% to allow for sub-economic field size, and 1% of sites to be rejected due to risk assessment (leakage)* – **390Gt**

Regional Capacities from USGS Data (Gt)

Region	Theoretical	Effective	Practical
N America	**75**	**56**	**33**
Asia-Pacific	100	75	45
South America	60	45	27
Europe	83	62	37
Former Soviet Union	340	260	150
Middle East & Africa	240	180	110
TOTAL	**900**	**680**	**390**

Matched Storage Capacities

- Source data: IEA GHG point source emissions and AAPG Giant Fields Atlas
- Source-sink matching exercise using a GIS-based network connection algorithm
- Assessment made on decade-by-decade basis with estimated close of production (CoP)
- Fields closing after 2050 or shallower than 800m discounted

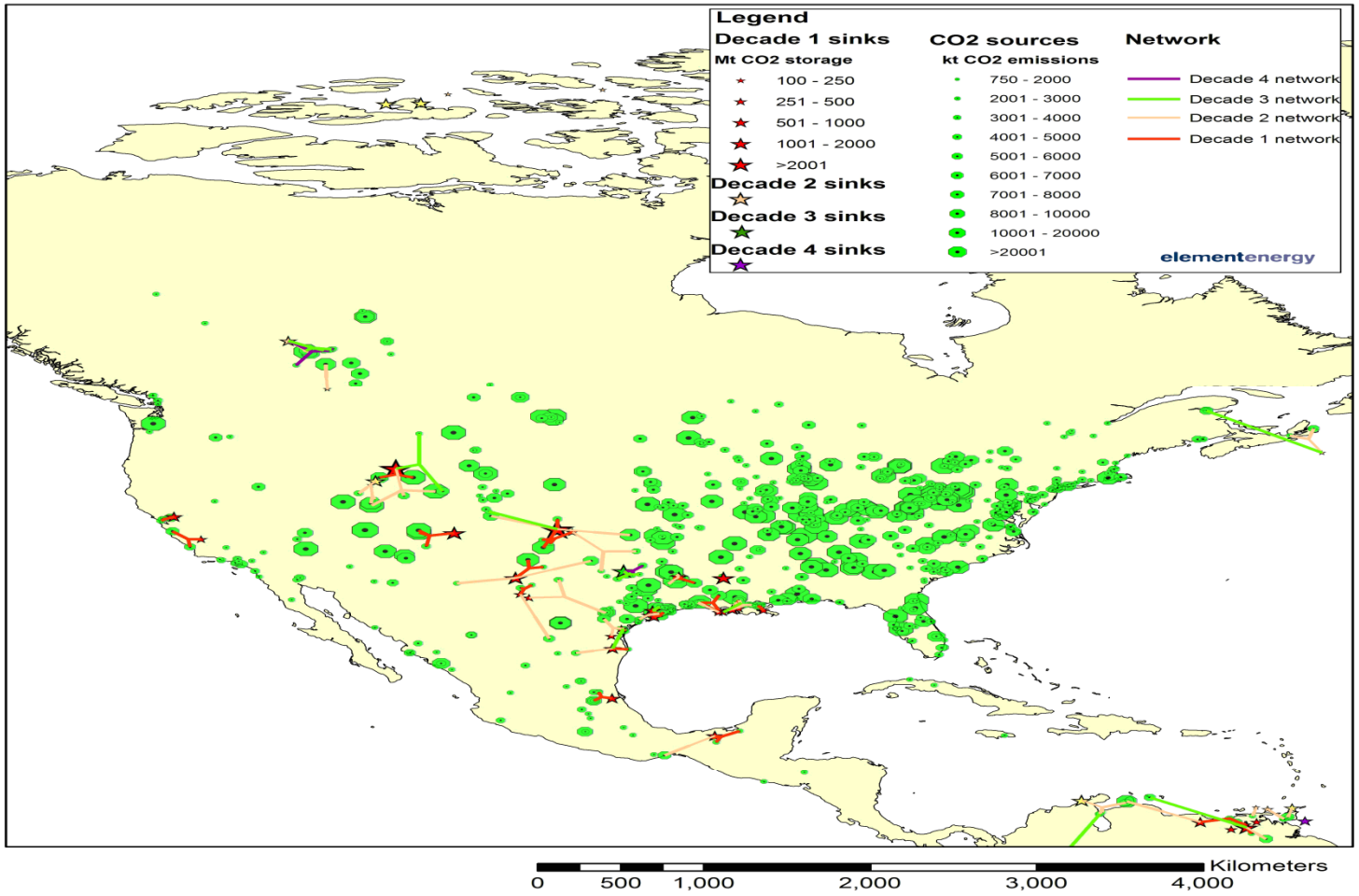
Source-sink matching

- GIS-based algorithm used to undertake source-sink matching exercise
- Sinks allocated by decade according to estimated CoP
- Up to 3 sources allowed to connect to each sink per decade, provided capacity sufficient
- Matching based on technical/economic factors, not geopolitical

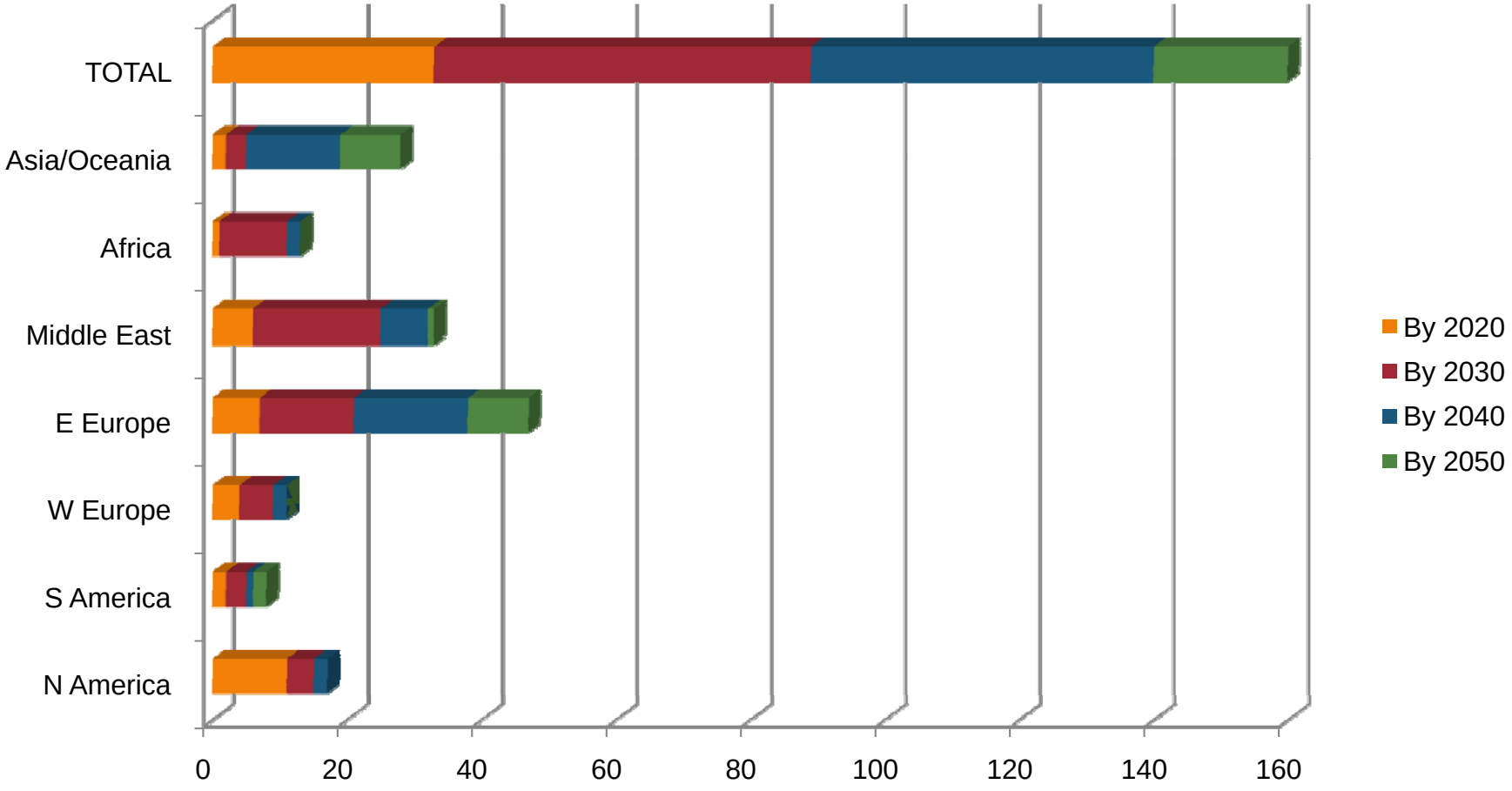
Matched Regional Capacities (Gt)

Region	By 2020	By 2030	By 2040	By 2050
N America	**11**	**15**	**17**	**17**
S America	2	5	6	8
W Europe	4	9	11	11
E Europe	7	21	38	47
Middle East	6	25	32	33
Africa	1	11	13	13
Asia/Oceania	2	5	19	28
TOTAL	**33**	**89**	**140**	**160**

North American Source-Sink Matching



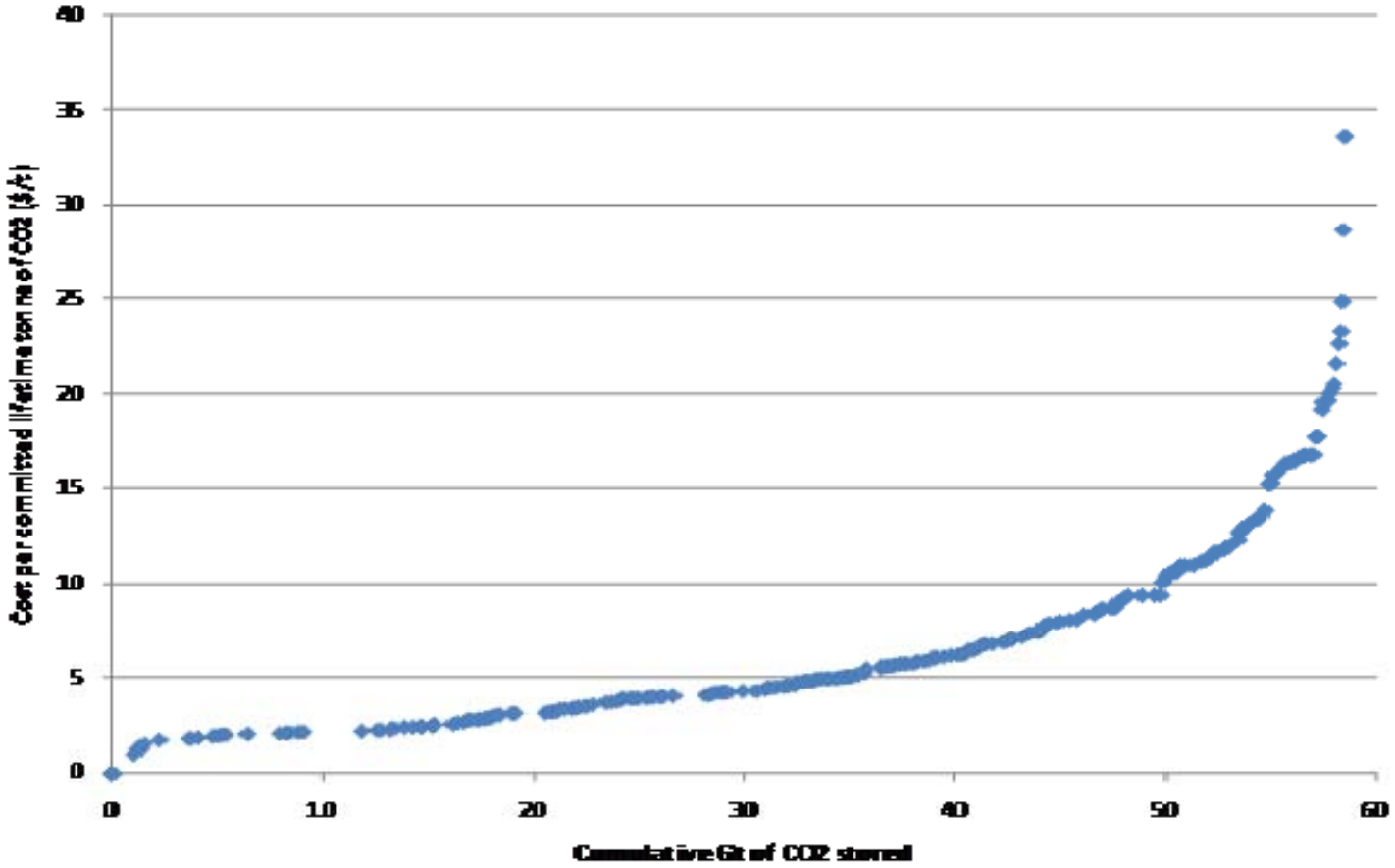
Matched Capacities (Gt) for Gas Fields



Storage Costs

- Matched source-sink connections used to estimate transport and storage costs
- New infrastructure assumed
- Pipelines mapped as straight lines but costs estimated on 1.25x route length
- Geopolitical factors not considered
- North America: 8Gt capacity <$5/t by 2050

Cost Abatement Curve

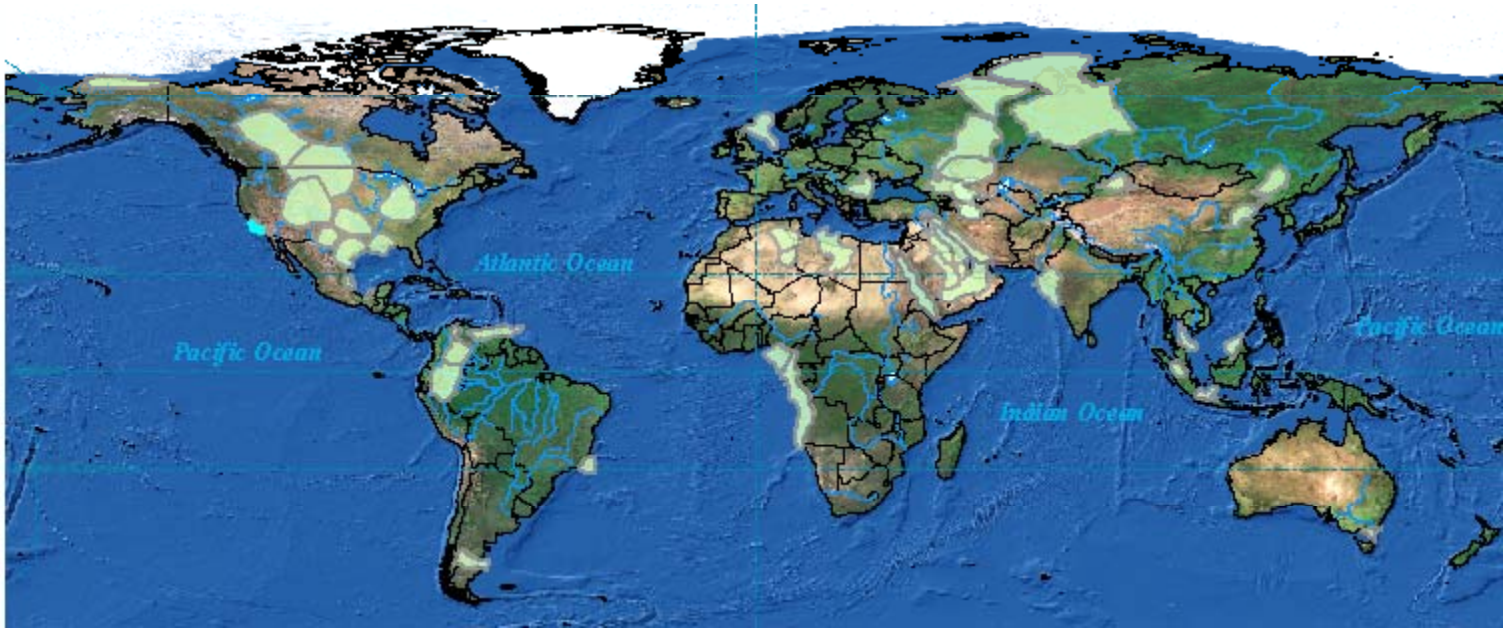


CO2-EOR Study

- Undertaken by Advanced Resources International, based in the USA
- Global study involving:
  - Characterisation of hydrocarbon basins
  - Estimation of OOIP
  - Judgement of CO2-EOR potential
  - Estimation of CO_2 storage potential

Identification of World Basins

- **The top 40 basins from the USGS assessment were selected, as ranked by volume of oil produced and booked as reserves, for further study.**
  - **Contain 96% of the "Known Oil" identified**
  - **Spread over every continent, but concentrated in the Middle East and Eastern Europe/Russia**
- **Also included 12 U.S basins with large volumes of "Known Oil"**



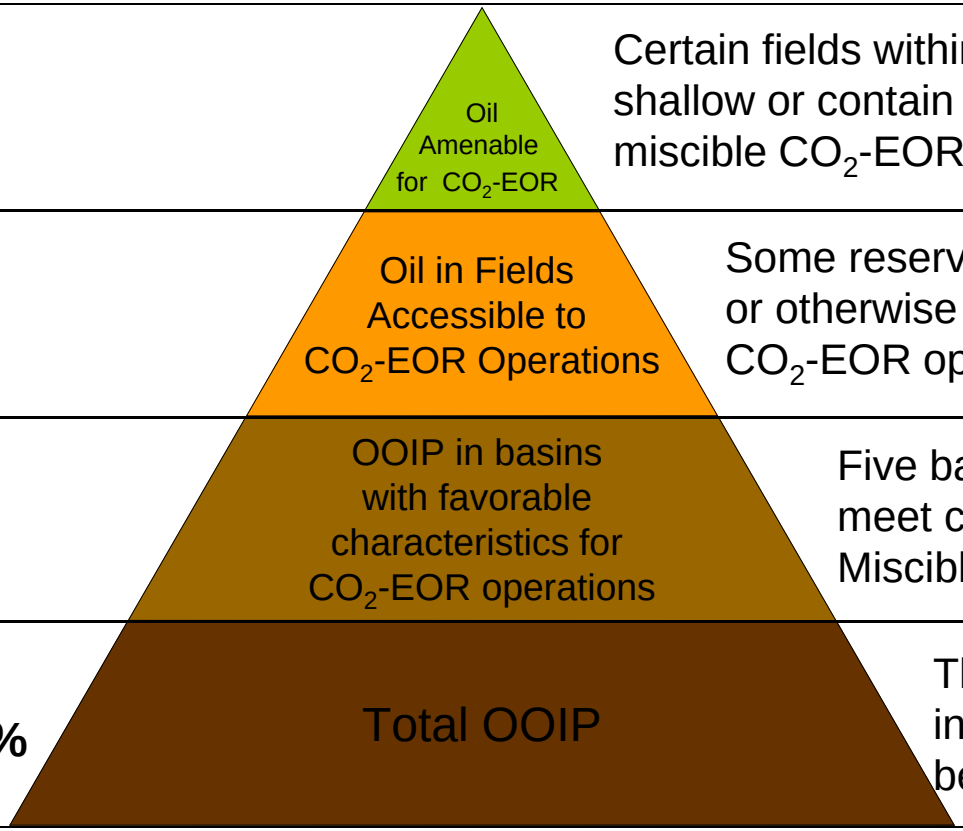
Asia & Pacific	**9**
Central and S America	**7**
Europe	**2**
Former Soviet Union	**6**
Middle East and Africa	**13**
North America	**15**

Establishing the CO_2-EOR Target

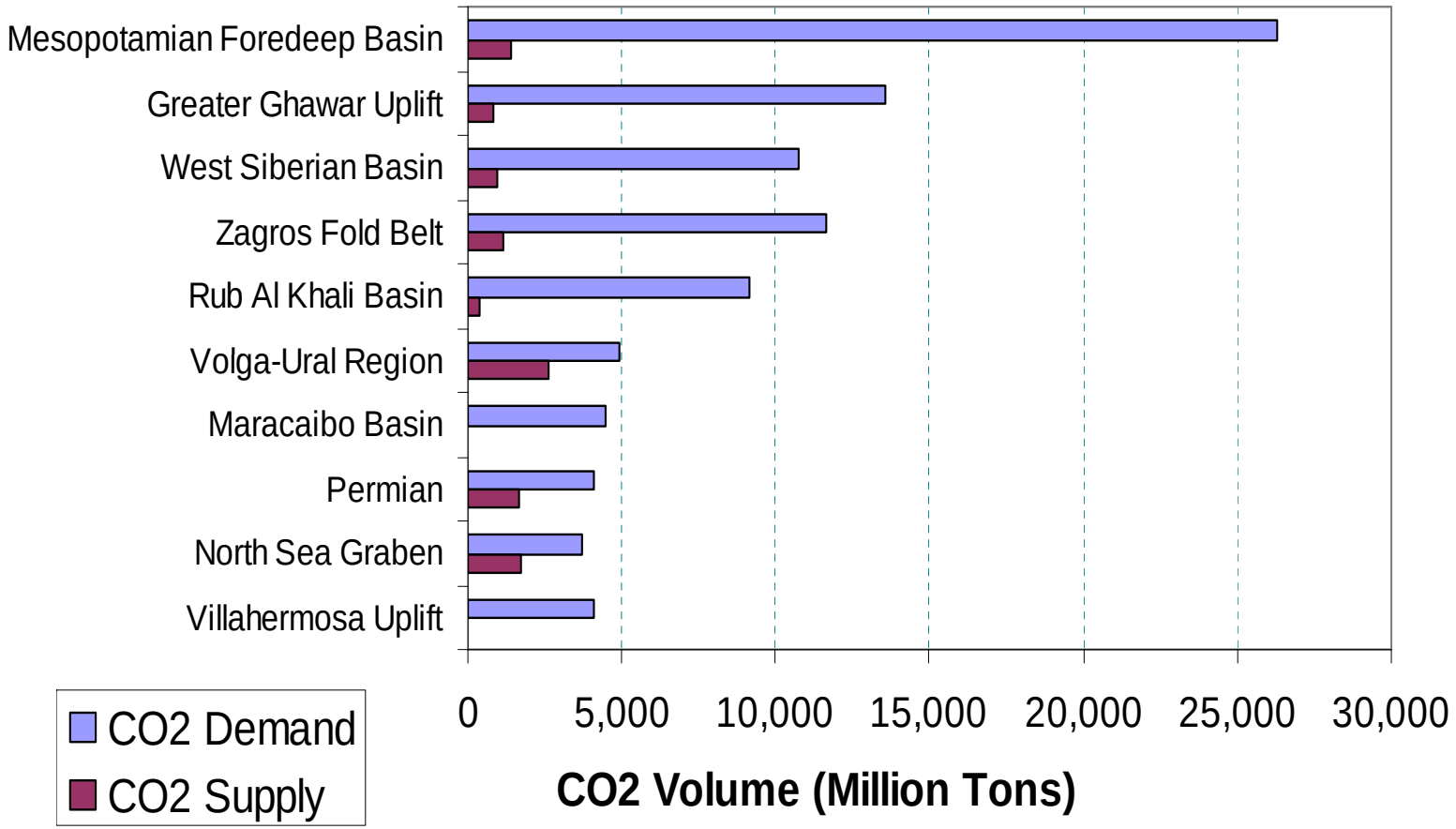
EOR Target

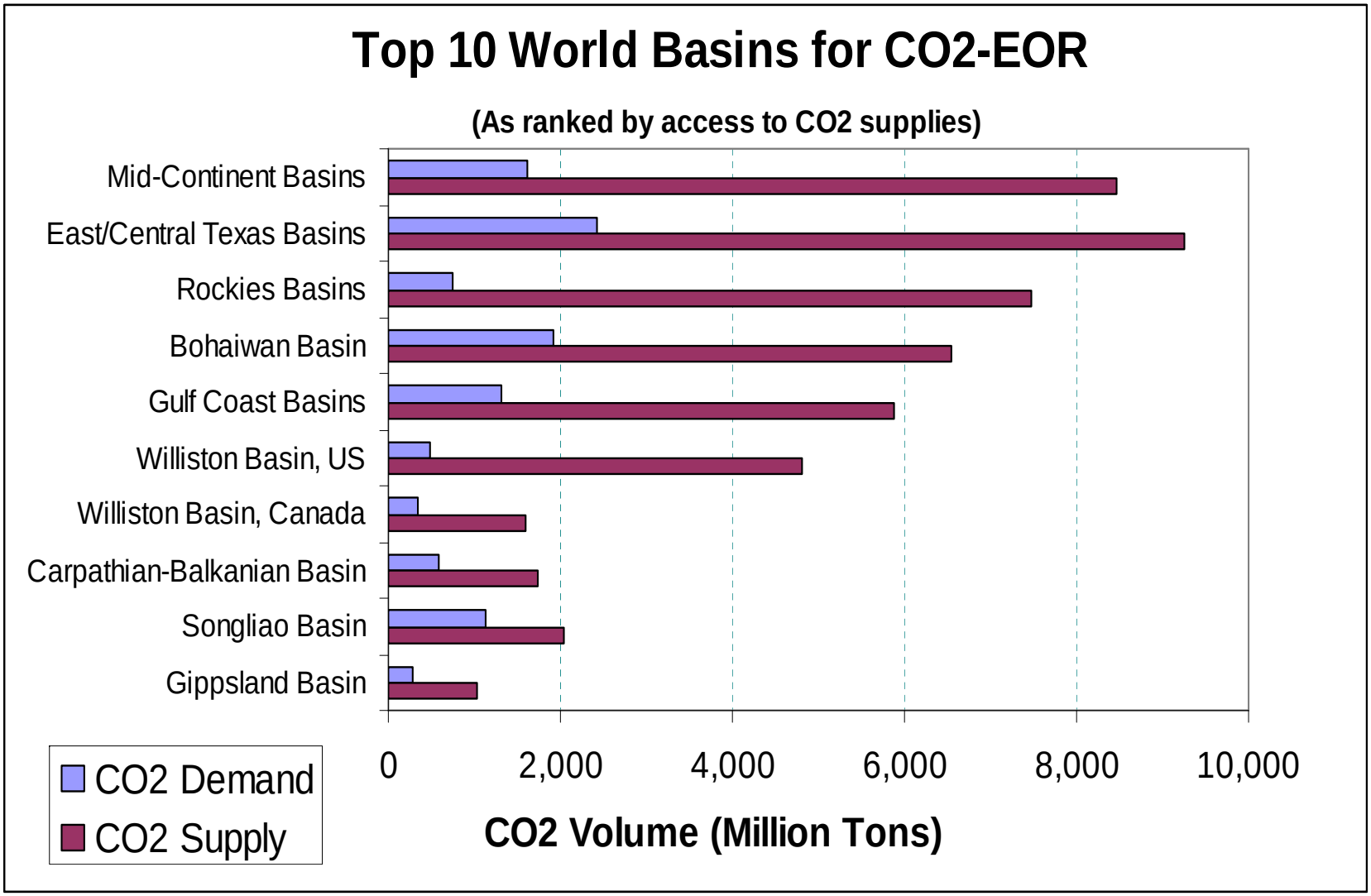
Rationale

Volume (Billion Barrels of oil)	% of OOIP	
2,156	**48%**	Certain fields within a basin may be too shallow or contain oil too heavy for miscible CO_2-EOR operations
3,213	**72%**	Some reservoirs are too small, or otherwise inaccessible to CO_2-EOR operations
4,368	**98%**	Five basins did not meet criteria for Miscible CO_2-EOR
4,465	**100%**	The total volume of OOIP in the 54 basins will not be available for CO_2-EOR



Top 10 World Basins for CO2-EOR




Top 10 World Basins for CO2-EOR
(As ranked by access to CO2 supplies)
Mid-Continent Basins
East/Central Texas Basins
Rockies Basins
Bohaiwan Basin
Gulf Coast Basins
Williston Basin, US
Williston Basin, Canada
Carpathian-Balkanian Basin
Songliao Basin
Gippsland Basin
0
2,000
4,000
6,000
8,000
10,000
CO2 Demand
CO2 Supply
CO2 Volume (Million Tons)

Options to Increase CO2-EOR Capacity

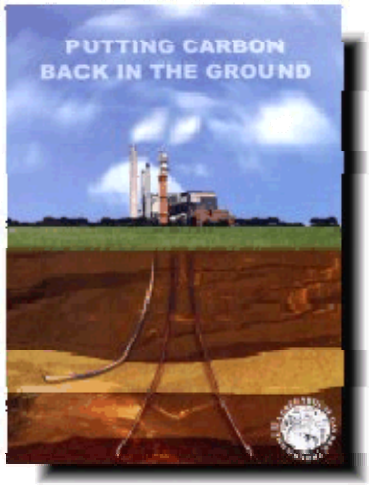
- Earlier application of CO2-EOR in the oil field production
- Development and use of ‘next generation’ CO2-EOR technology
- Application of CO2-EOR to residual oil zones beneath ‘traditional’ reservoir accumulations

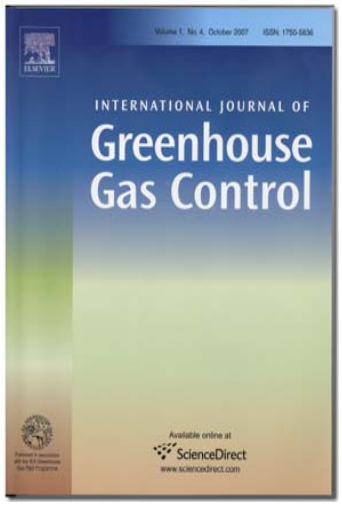
Revised CO_2 Storage Capacities

Storage Type	IPCC Estimated Global Capacity (Gt)	IEA GHG Estimated Global Capacity (Gt)
Saline Formations	1,000 to 10,000	
Depleted Gas Fields	675 to 900	160 to 390
CO2-EOR		65 to 130
Coal Beds	3 to 200	

IEA Greenhouse Gas R&D Programme

- General - www.ieagreen.org.uk
- CCS - www.co2captureandstorage.info





OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries
Hassi Messaoud, Algeria
16th – 19th November, 2009

Storage: site characterization issues

Jean-Pierre Deflandre
Olivier Vincké

© IFP

Outlines

- Introduction to CO_2 storage
  - What do we need?
  - Present options
  - A multi-scale problem
- Site characterization issues
  - Reservoir capacity
  - Injectivity
  - Storage complex integrity
  - Risk of leakages
- Modelling to predict
- Conclusions

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Introduction to CO_2 storage: what do we need?

- Reliability of the storage site
  - long term trapping and confinement of the CO_2
  - no leakage (remediation possible)
- Efficiency of the storage reservoir
  - accessibility
  - storage capacity
  - injectivity
- Public acceptance: a key parameter

SAFE & Efficient & Probant

Based on a good initial characterization of the site and an adapted short and long term monitoring programme

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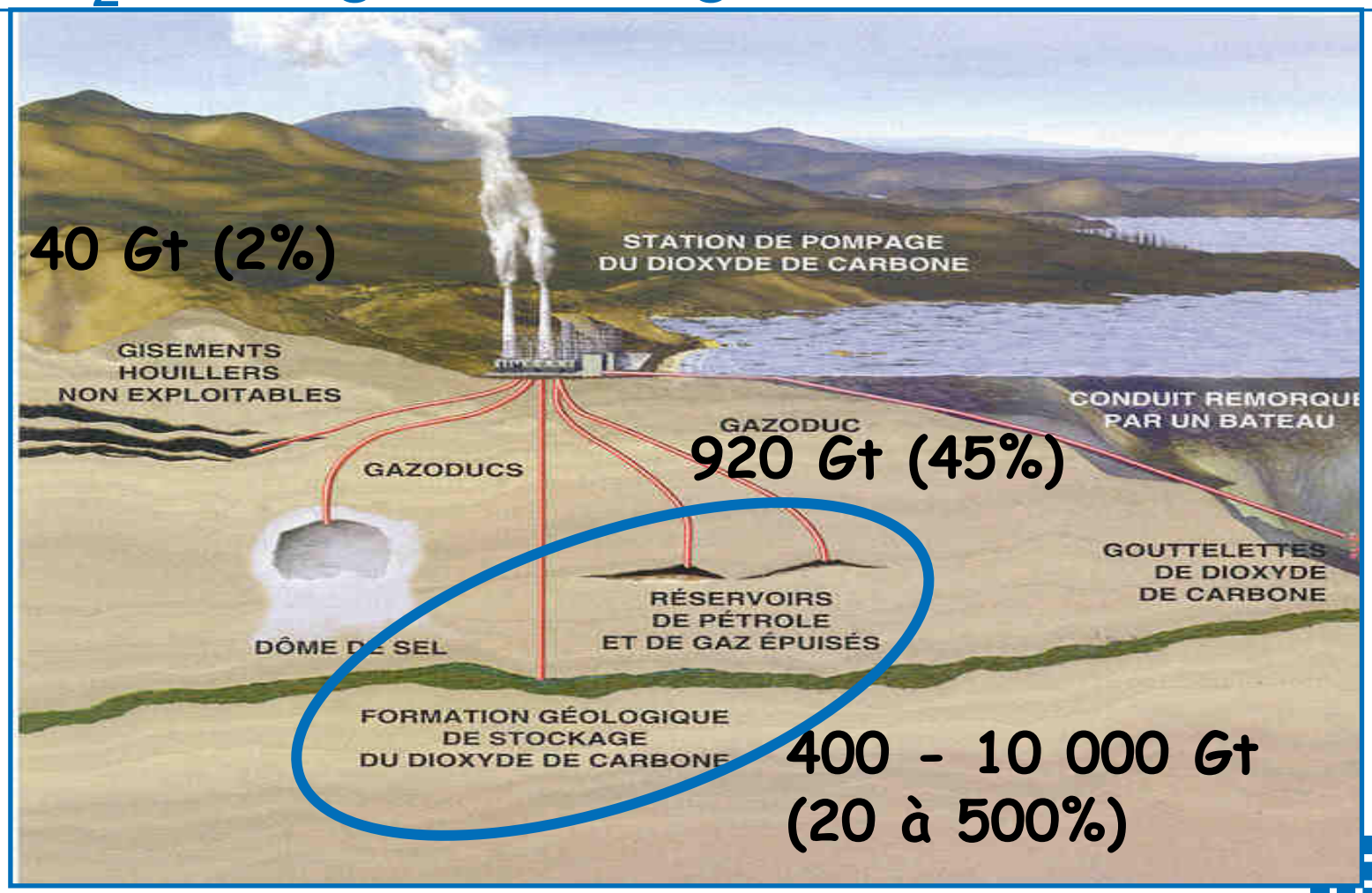
CO_2 Geological Storage



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CO_2 geological storage

- Hydrocarbon Reservoirs (oil and gas)
  - ↗ proven to be tight (to non reactive gas)
  - ↗ geological traps
  - ↗ well-known objects
  - ↗ possible benefit through EOR / EGR
- Deep Saline formations
  - ↗ huge porous volume: the biggest place for storage
  - ↗ no drinkable water
  - ↘ generally poorly investigated

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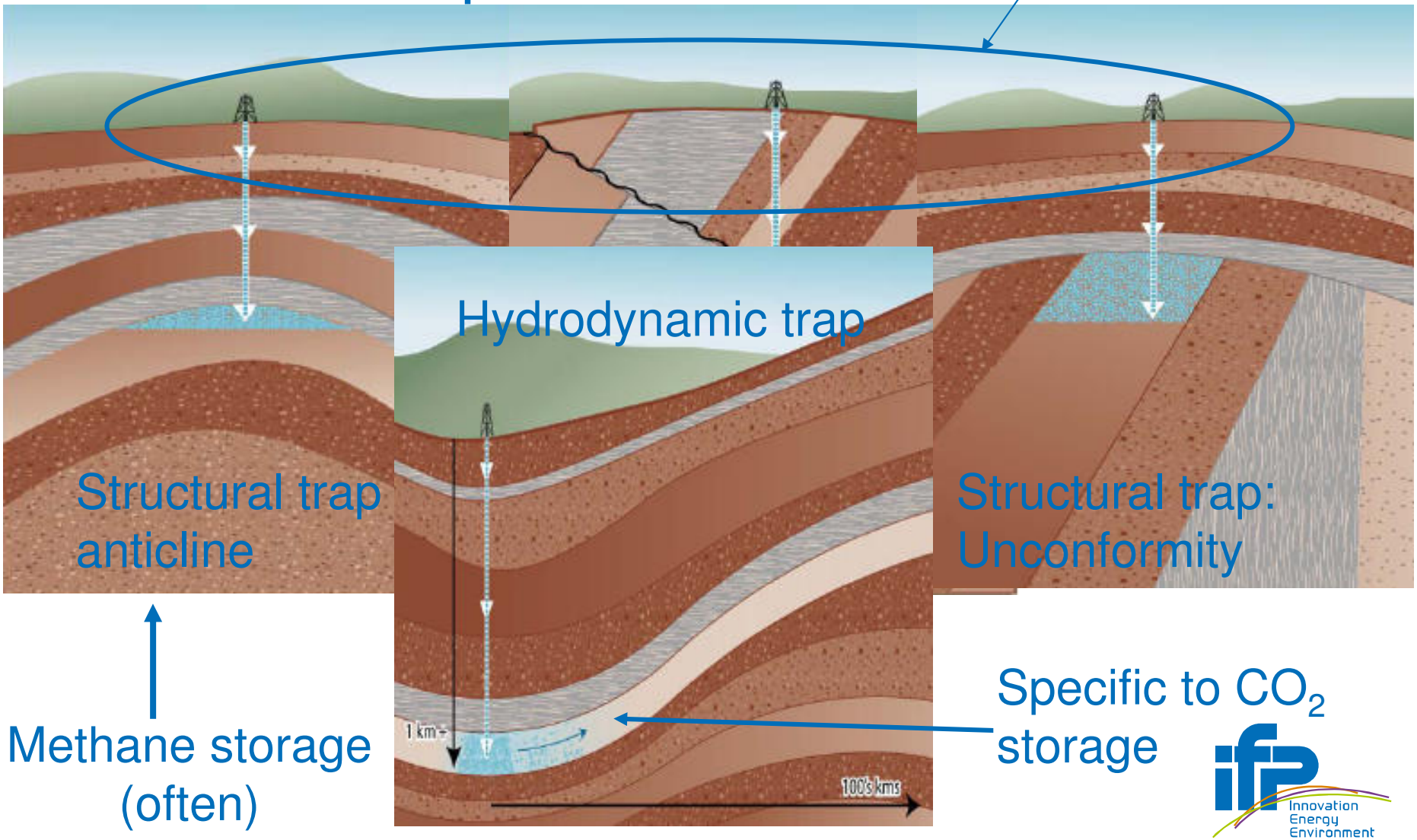
Differents Traps



Methane storage (often)

Specific to CO_2 storage

© IFP

Confined underground aquifers

- Considered as *a priori* sealed
- No or not a lot of existing wells

- Nevertheless:
  - No (or only a few) information on their properties
  - No (or only a few) information on overburden formation
  - Limited storage capacity

→ **Lots of characterisation work to achieve**
Economical efficiency
Some similarities with CH_4 storage

© IFP

Hydrodynamic traps

- Storage capacities
  - Fluid trapping at geological time scale
  - Very large volume capacities
- Nevertheless:
  - Quite unknown
  - Possible connections and communications with other aquifers
  - May have already been drilled for different purposes (leakage risk)

© IFP

Depleted oil & gas reservoirs

- Considered as *a priori* sealed and known
  - They have trapped hydrocarbons during geological times
  - Caprock reliability was achieved
  - Lots of data
- Nevertheless:
  - Importance of the quality of applied well abandon protocols
  - Geomechanical integrity may have been compromised during production history in association with effective stress redistribution (compaction / fracturation for example)
  - Not enough documented out of reservoir layers

→ **Nowadays, lots of works are on going in that domain within R&D projects or demonstration ones**

CASTOR
CO2SINK
CO2ReMoVe
...

→ **The training and short term option**

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On-going CO_2 pilot project: a few examples

- Sleipner (North-Sea - Norway): Re-injection of produced CO_2 in an upper aquifer
- Snøhvit (Offshore Norway): Re-injection of produced CO_2 in a lower aquifer
- In Salah (Algeria): Re-injection of produced CO_2 from different fields in the Krechba reservoir (below the GWC level)
- K12b (Offshore The Netherlands): Re-injection of produced CO_2
- Ketzin (Germany): Demonstration pilot project for CO_2 storage
- Weyburn (Canada): Enhanced oil recovery based on CO_2 injection
- Frio (Texas – USA): Demonstration pilot project for CO_2 storage in brine aquifer
- Lacq (France): CCS demonstration pilot project in the Rousse depleted reservoir

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Risk analysis: caprocks, faults & fracture networks, structural saddle

Risk level depending on site

- Caprocks (and overburden)
  - Nature and lateral continuity
  - Mechanical history
- Faults and fracture networks
  - Transmissivity
  - Mechanical properties / reactivation risk
- Geological structure
  - Existing faults (always!)
  - Seismic risk: earthquakes

→ **Long term risk mainly**

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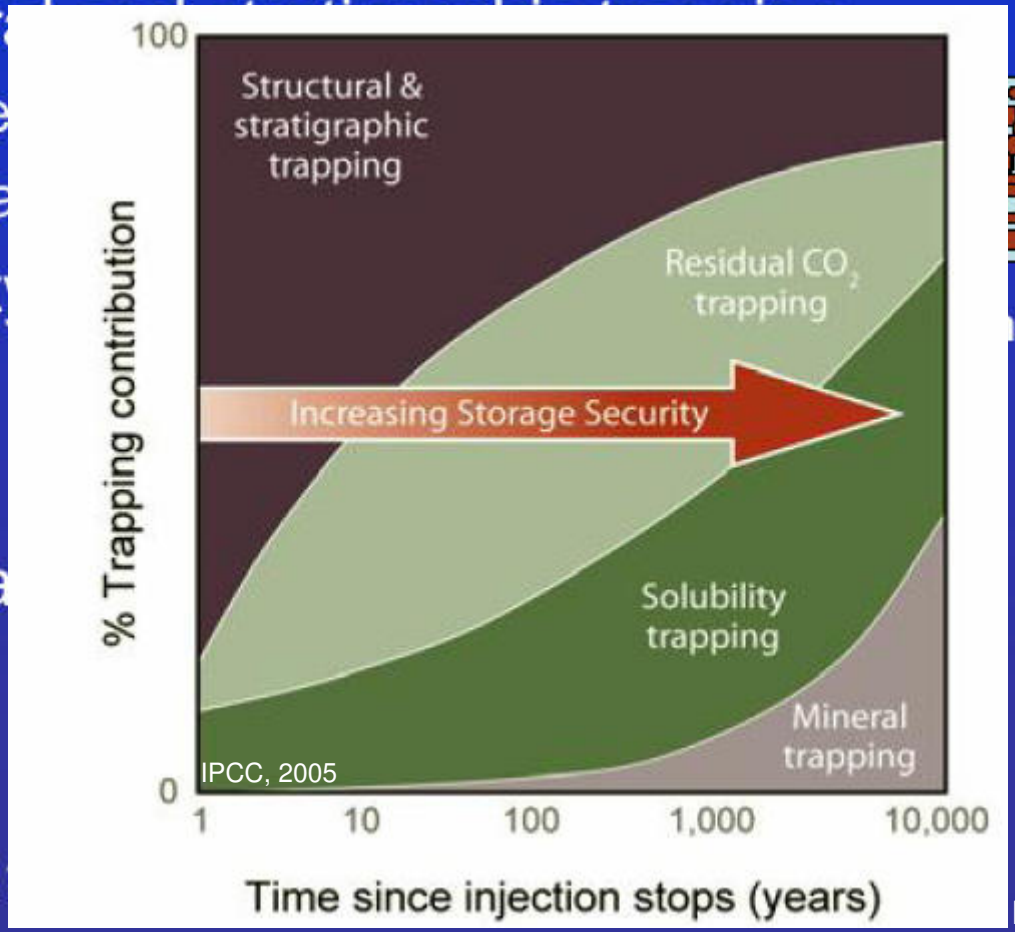
Different trapping mechanisms… Different time scales

- Structura
  - Perme
  - Capilla
- Solubilit
- Residua
- Mineral



ale

Benson, 2005

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The site life cycle (deep saline aquifer)

- Site selection (a few years)
  - identification
  - characterization
  - test injection phase

  → Different options

  → Go / No go
- Site exploitation (a few decades of years)
  - site development: developing infrastructures
  - reservoir fill-up (injection phase)
- Site closure and abandonment (at least 1000 years)
  - closure phase
  - post-closure phase (20 years or more depending on case)
  - abandonment phase (very long term)

→ Responsibility (liability) transfer

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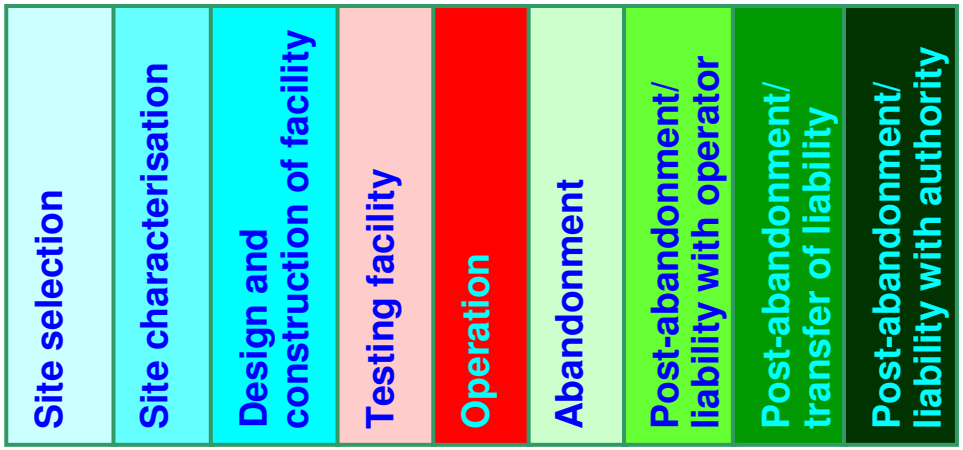
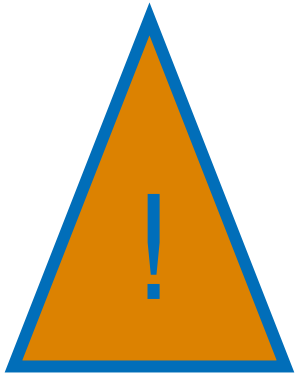
The CO_2 storage workflow

Life cycle of a CO_2 storage facility





Risk management

Baseline surveying & risk assessment

Monitoring & verification

Remediation planning & actions

To Demonstrate Safety and to remediate if necessary

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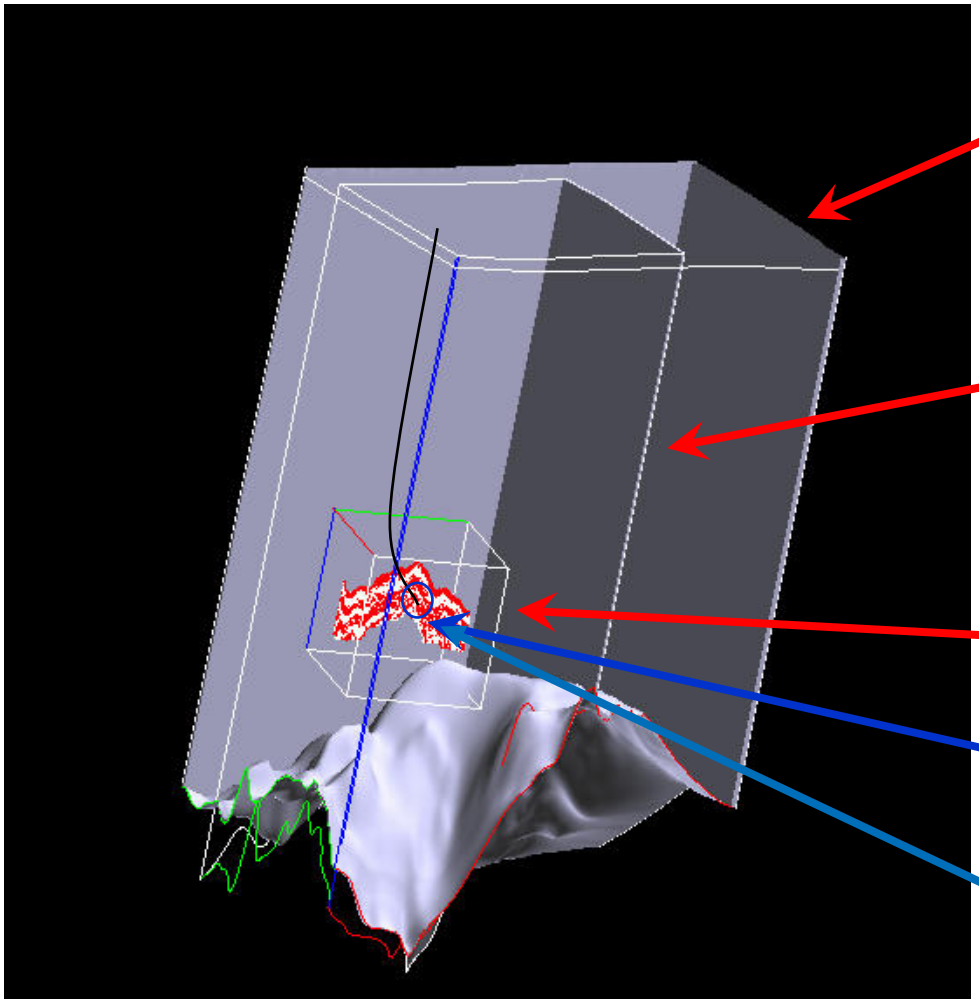
CO_2 storage: a multi-scale study



Basin scale

Storage Complex scale

Storage scale

Near wellbore scale

Pore scale

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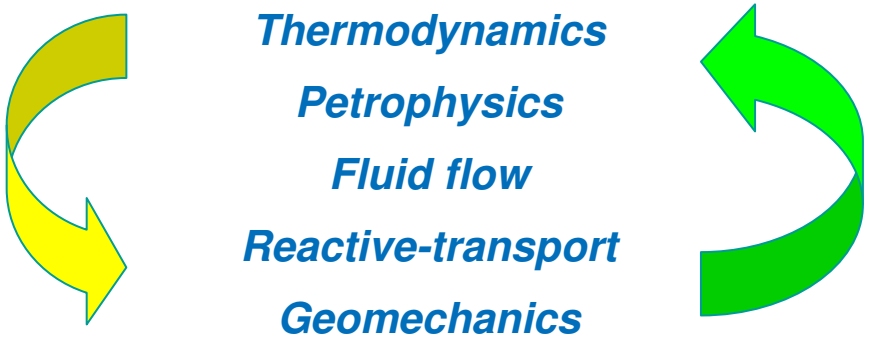
Adapting upscaling needs integrating multi physico-chemical coupled phenomena

Analysis of the storage mechanisms

Adapted experimental program

Lab. studies



Thermodynamics

Petrophysics

Fluid flow

Reactive-transport

Geomechanics

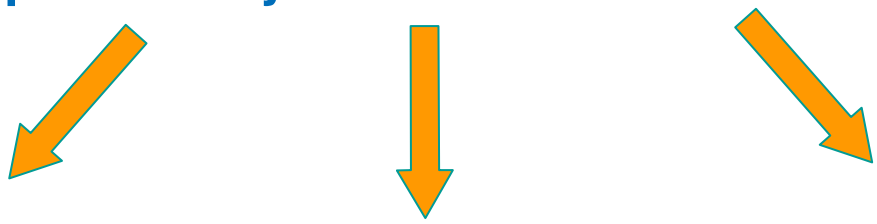
Measurement procedures

Constitutive laws

Simulator parameterisation

predictivity level at the core scale

Large scale studies



Well

Storage

Basin

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Outlines

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- Conclusions

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Site characterization issues

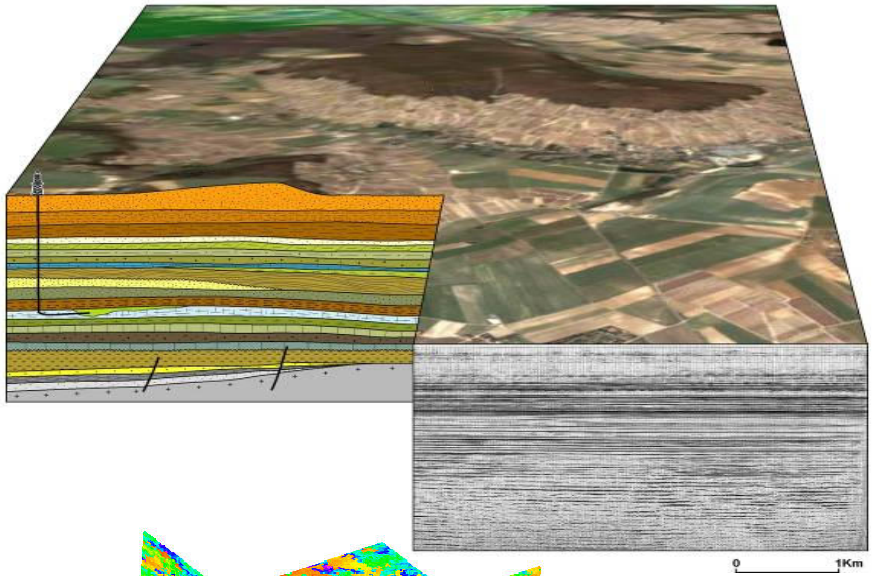
- A multi-scale problem
- Laboratory scale (from well cores and outcrops)
- Loggings (old oil & gas wells, new ones devoted to CO_2 storage)
- Seismic imaging, seismicity monitoring, gravimetry... surface gas monitoring, aquifer control

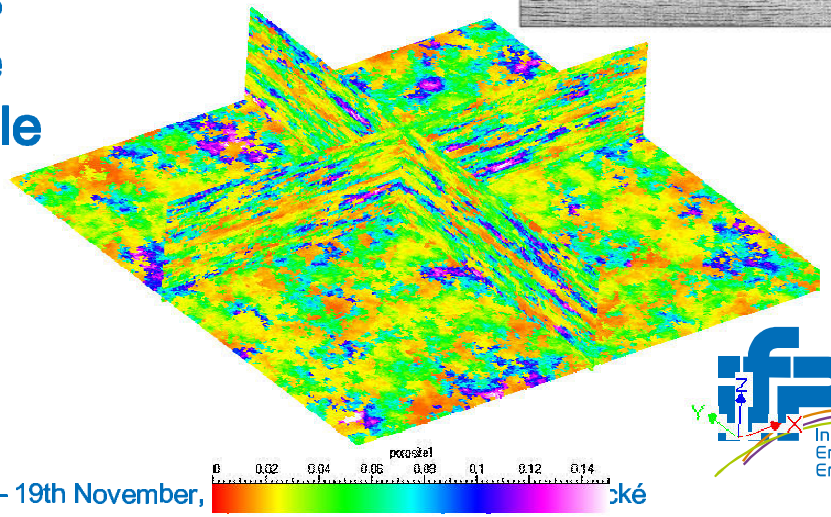
→ **Characterizing the site**
To be able to predict
Constituting a monitoring baseline

© IFP

Selection and evaluation of CO_2 storage locations

- Structure determination and internal organization
- Depth to have CO_2 at supercritical state (ok under 7 MPa @31°C)
- Properties determination (porosity, permeability) of permeable zones (sandstones) and less permeable (shales) from logging and available measurements





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Necessary information for capacity estimation and interaction prediction

- Mineralogy of both reservoir and caprock
- Petrophysical properties of both reservoir and caprock (ϕ, K, pore throat, capillary pressure, particle size...)
- In situ fluid compositions of reservoir(s) and upper aquifers, density and pH
- In situ pressure and temperature (P, T)
- Hydrogeology

&

- Composition of the injected CO_2 stream (O_2, NO_x, SO_x, CH_4...) / impact on fluid thermodynamics
- Pressure and temperature of the stream at injection

→ **This leads evaluating: capacity, injectivity and reactive transport**

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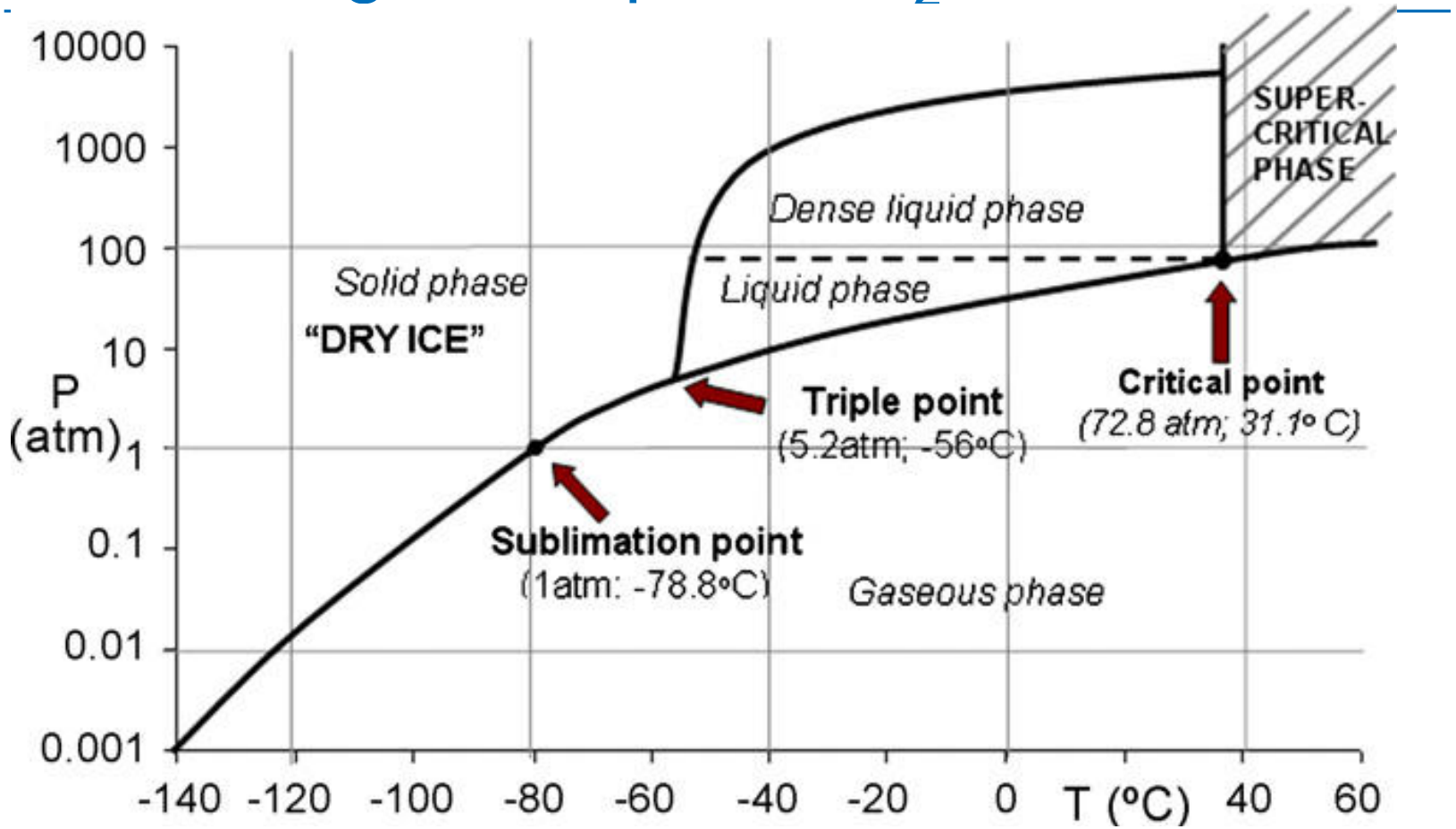
Phase diagram of pure CO_2



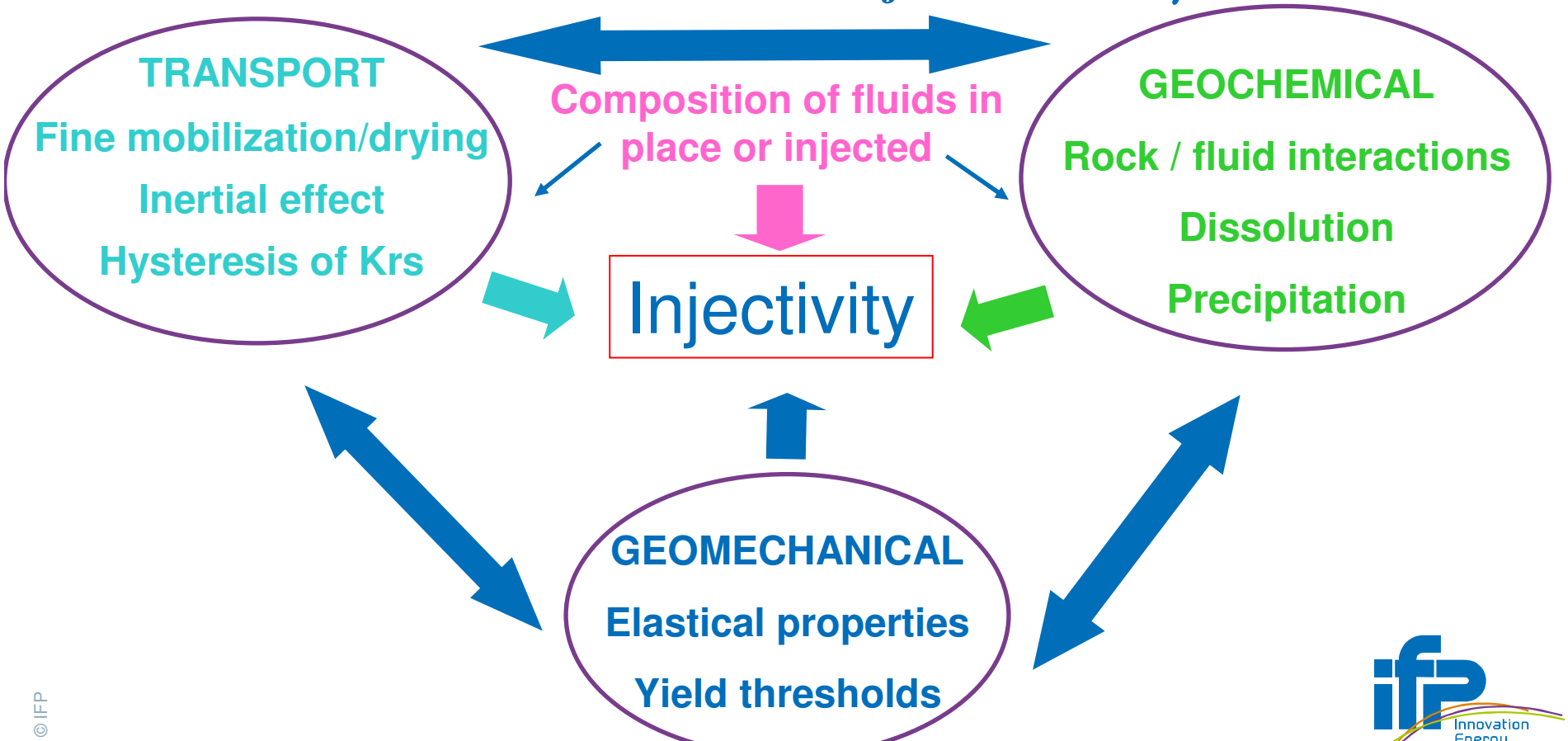
Different when not pure!

Mazzoldi *et al.*, 2008

© IFP

Injectivity study: influent mechanisms

$$II = Injectivity\ Index = \frac{Flow\ rate}{P\,inj - P\,res} \propto \frac{K\,K_r}{\mu}$$



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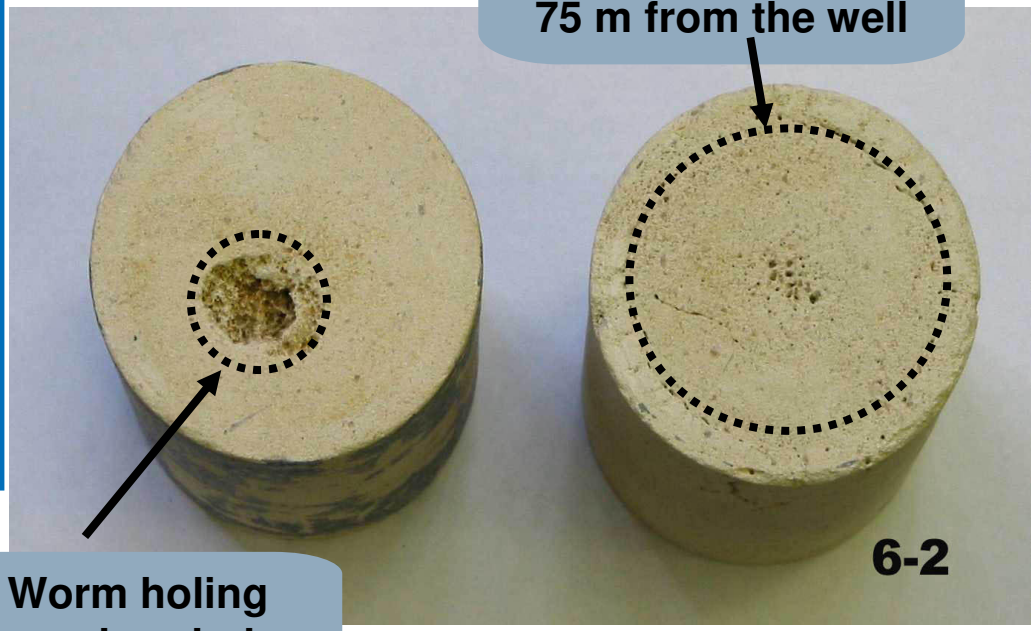
CO_2 geological storage

- Injectivity evaluation



Egermann et al., 2005

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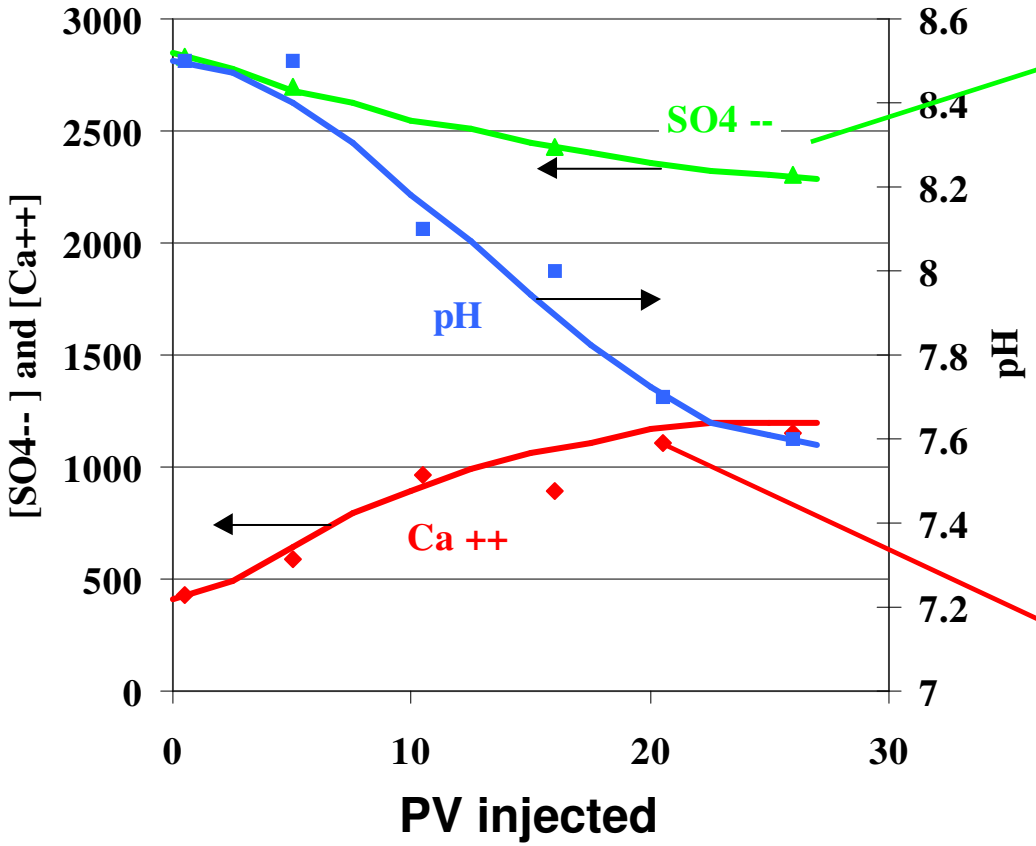
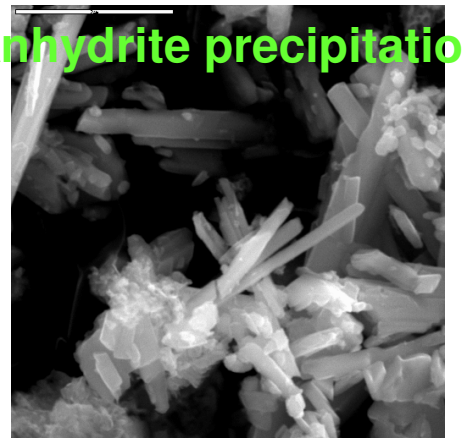
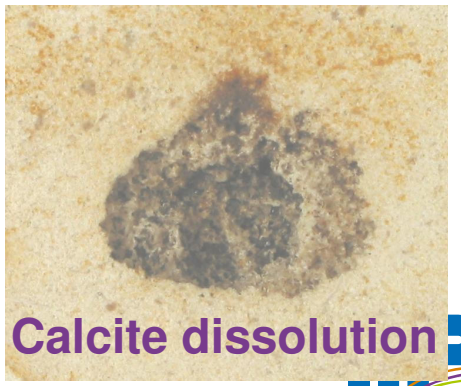
From laboratory to near wellbore upscaling







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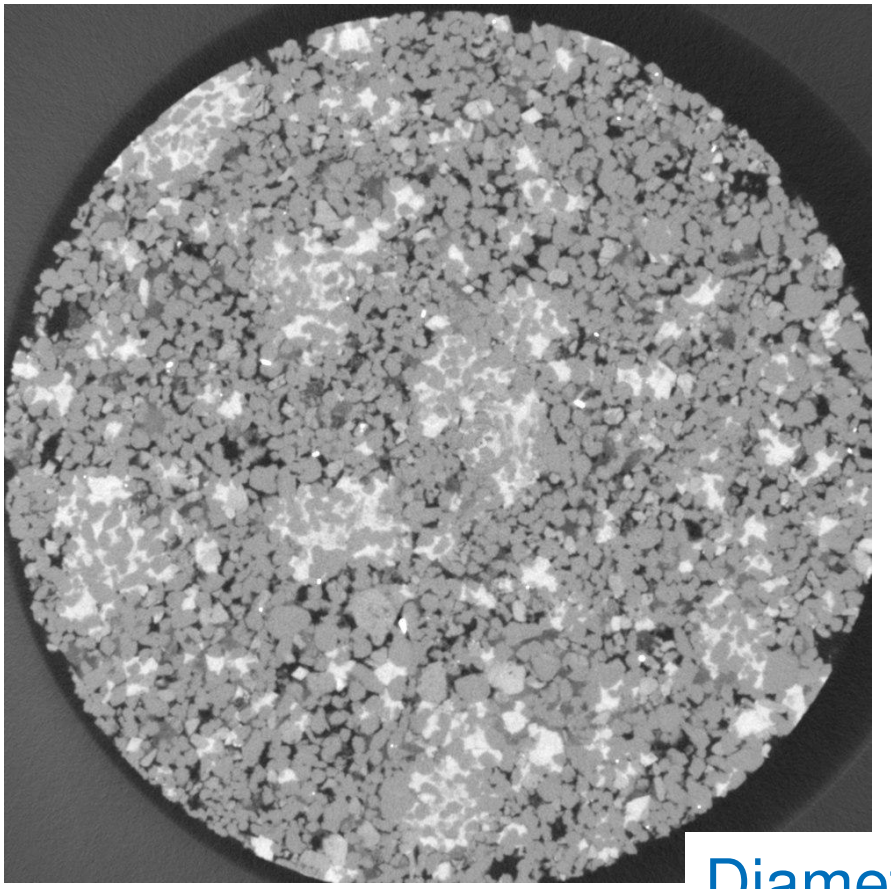
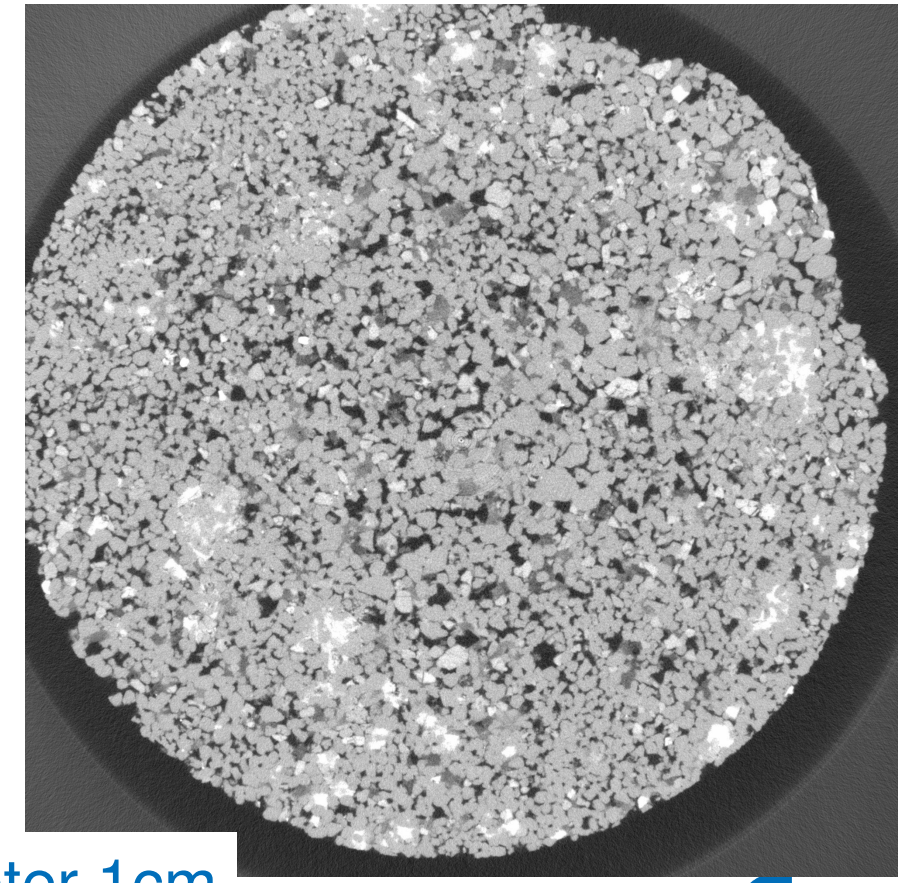
Micro-CT : investigations
A tool for capturing complexity in reservoirs and cap-rocks
Pore structure evolution under reactive flow



Diameter 1cm



Before

After reactive flow

© IFP

Micro-CT : investigations
A tool for capturing complexity in reservoirs and cap-rocks

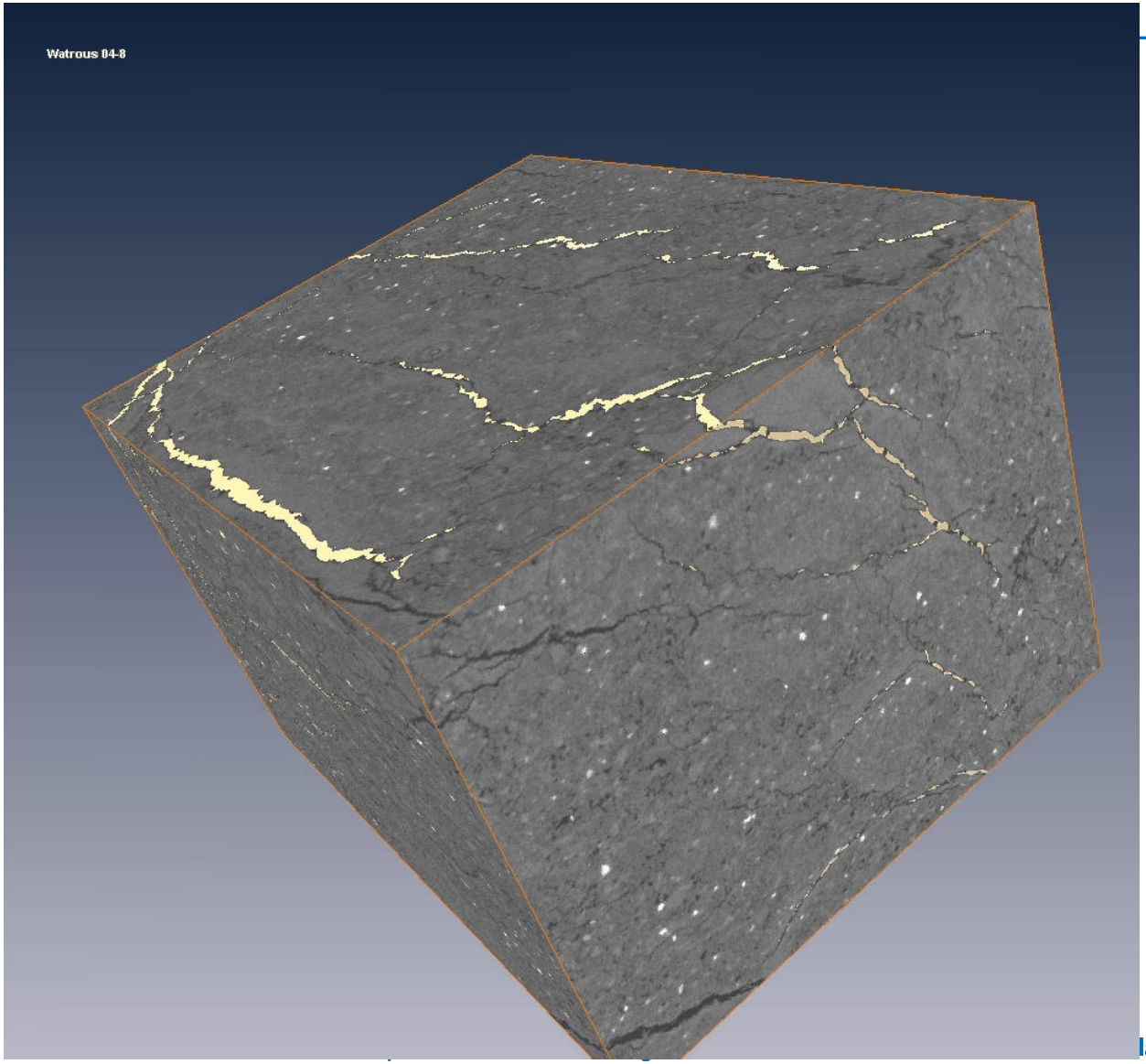


Image of 3D network of fissures with size under CT-scanner resolution

block size 1x1x1cm

© IFP

Characterization of caprocks

Accessible data on overlaying rocks is limited

Cuttings, cores

k, Phi, NMR, Mercury porosimetry, thin sections, ..

Diagraphies

Phi, NMR, FF

Analogs

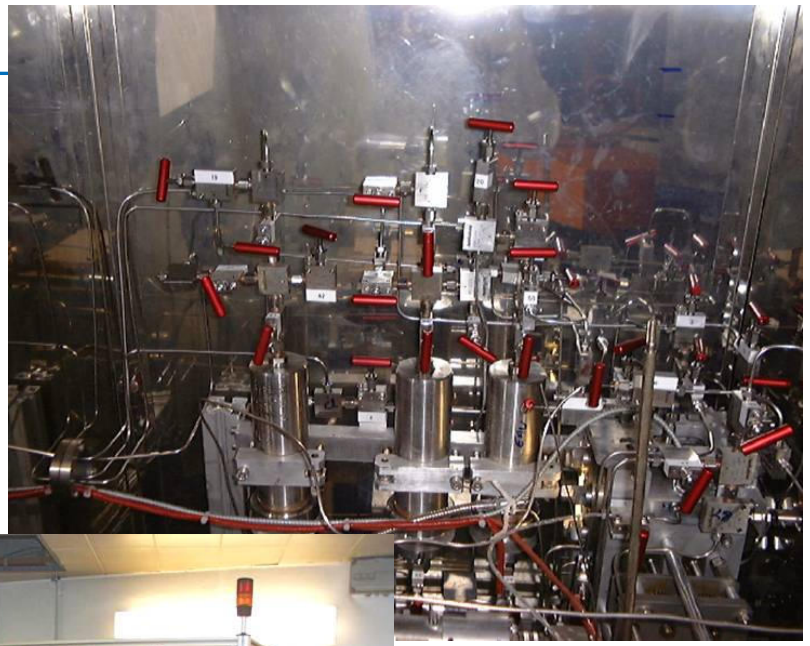
Complete rock structure characterization

Development and validation of methodologies and tools to derive representative petrophysical parameters for CO_2 migration

© IFP

Caprock study: devices

Low K - Darcylog



IFT

Reactive flows: SDM

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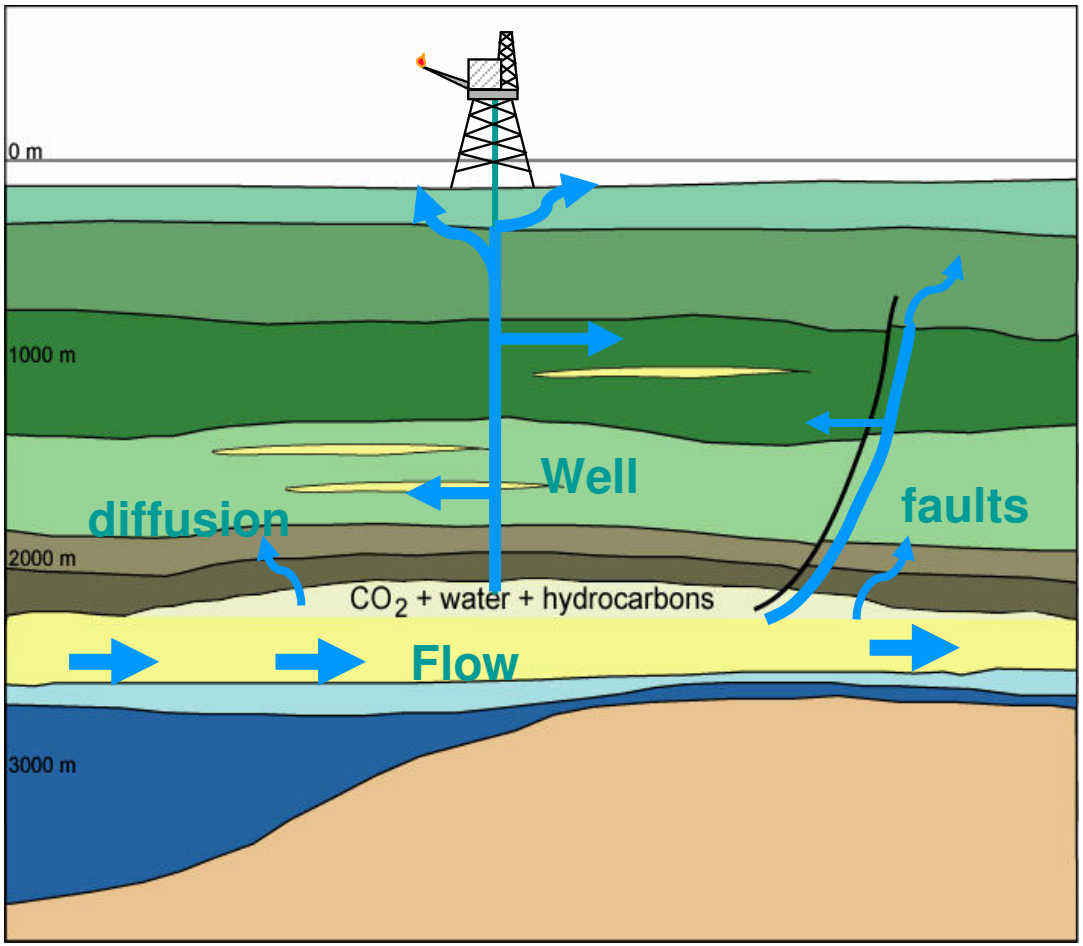
Storage integrity

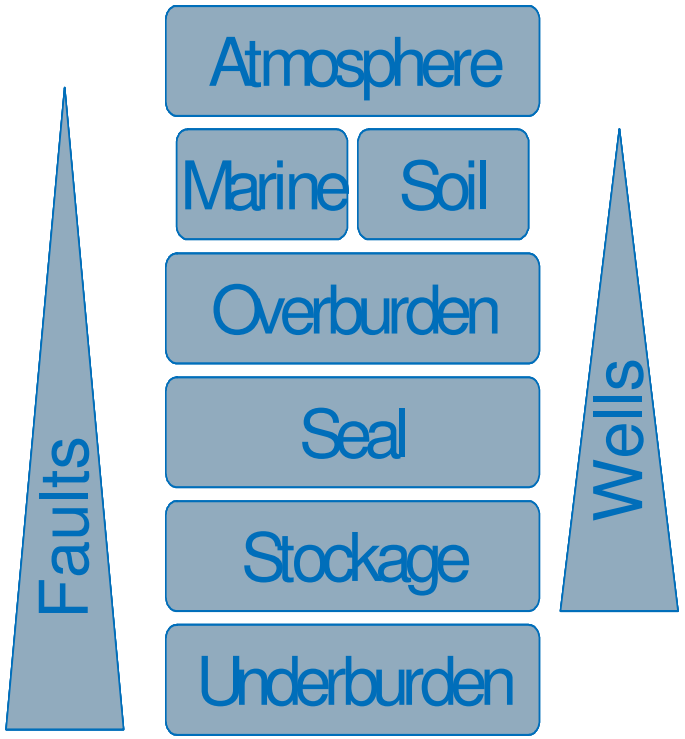
- When characterizing a site, the problem of integrity is the most important one. It deals with leakage:
  - existing wells (remediation possible but quite costly)
  - caprock discontinuities (lateral leakage), caprock integrity (maximum admissible injected pressure in relationship with injectivity)
  - fracture networks (propagation in case of hydraulic fracturing due to high pressure level)
  - structural fault: risk of reactivation due to stress changes induced by reservoir pressure variations

→ Laboratory tests and Modelling studies to predict

© IFP

CO_2 potential leakage risks





→ Monitoring to detect

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Leakages and events

Type	Leakage occurence time	Lost volume	Risk location
Near wellbore	while injection	small to medium	localised
Abandoned Wells	months to100 years ...	>>> with time	localised
CO_2 leakage through seals	1000 years and more with k <<<	very small but continuous	not localised
Leakage due to geochemical / geomechanical effects	from injection start .... 1000 years	high ...	localised or not
Leakage due to external events	earthquake volcanoes	rapid and important	not localised

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Innovation Energy Environment

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Modelling to predict

The characterization step helps building the initial reservoir model and the complex storage or basin geomodel.

- Fluid flow modelling
- Geochemical modelling
- Geomechanical modelling

} Reactive transport modelling

- Short term performance assessment (CO_2 migration and risk)
- Long term performance assessment (CO_2 migration, trapping and risk)

Permanent monitoring will help to verify prediction and to update the geomodel over time.

© IFP

From reservoir to site modelling

- For previous pilot cases, initial models were limited to the reservoir: people focussing on gas injection and associated reservoir pressure variations.
  - The first objectives were to check injectivity (good enough to inject sufficient amount of CO_2 without the risk of fracturing the caprock) and to estimate the plume extension.
- Soon a complete modelling of the structure appears necessary to take into account geomechanical effects and long term geochemical ones.

  This is a real challenge as it was not common to work at this scale in the oil industry for reservoir modelling (same for gas storage too).

© IFP

No history matching possible

- Performance assessment studies based on different scenarios
  - Permeability of matrix, fracture networks and faults are modified such as lateral difference to simulate leakages
- Uncertainty analysis
- Constraining with monitored data

© IFP

Sleipner:
an example of multiphase flow simulation

- supercritical CO_2 injection in the Utsira formation (above the gas field)
- depth=1012m
- 1 million tons/year
- K=1-3 darcy
- 7 minerals
- 8 chemical elements
- 16 aqueous species
- 2 phases: supercritical gas and water

Mineral	Formula	Sand composition (%)	Shale composition (%)
anorthite	$CaAl_2Si_2O_8$	0	10
calcite	$CaCO_3$	1	10
dolomite	$MgCa(CO_3)_2$	1	10
illite	$Si_{3.43}Al_{2.24}Mg_{0.38}O_{10}(OH)_2K_{0.8}$	3	10
k-feldspar	$KAlSi_3O_8$	2	25
kaolinite	$Al_2Si_2O_5(OH)_4$	2	25
quartz	SiO_2	90	10

→ A first challenge:
having a representative 3D earth model

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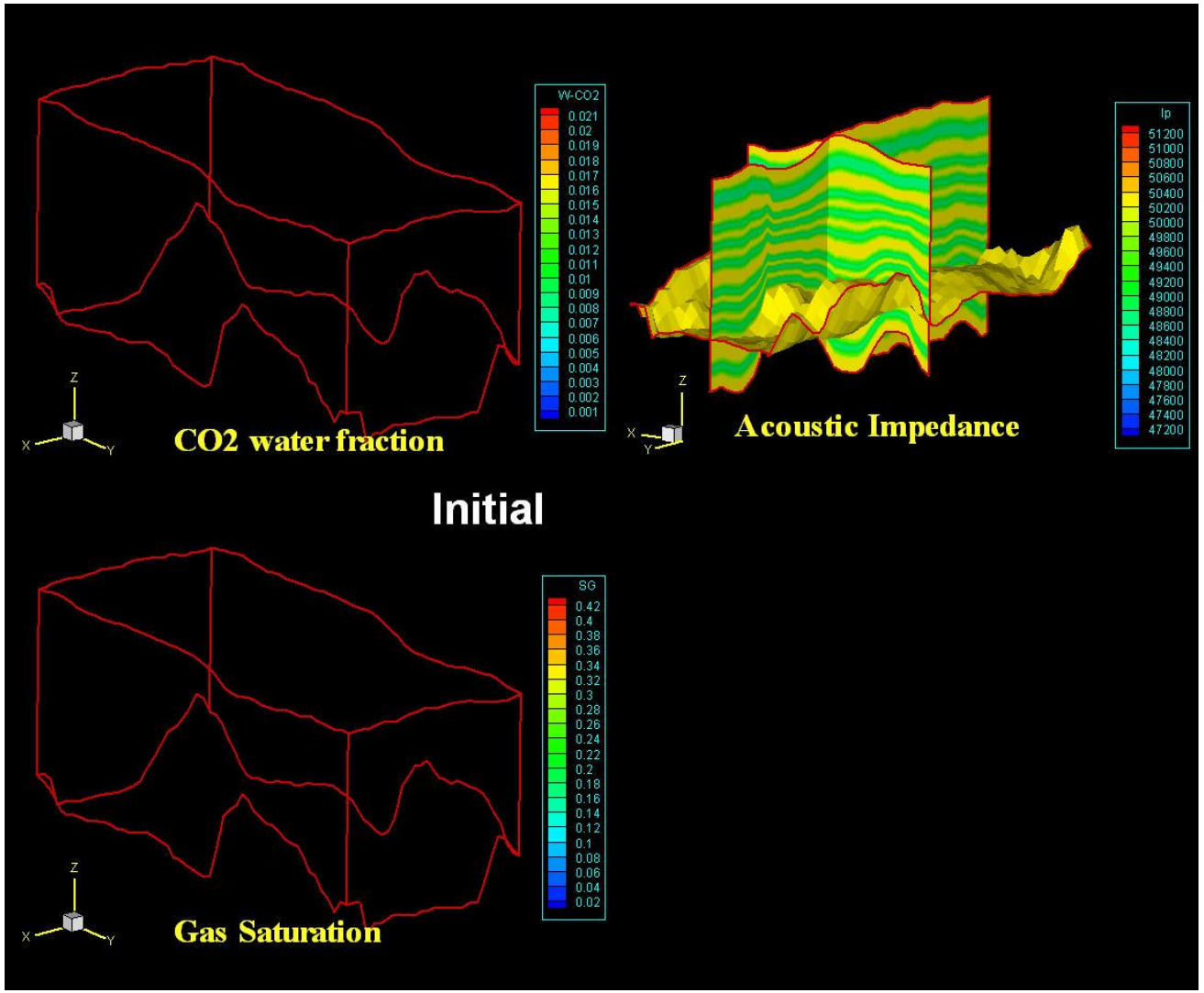
COORES (IFP) - Sleipner



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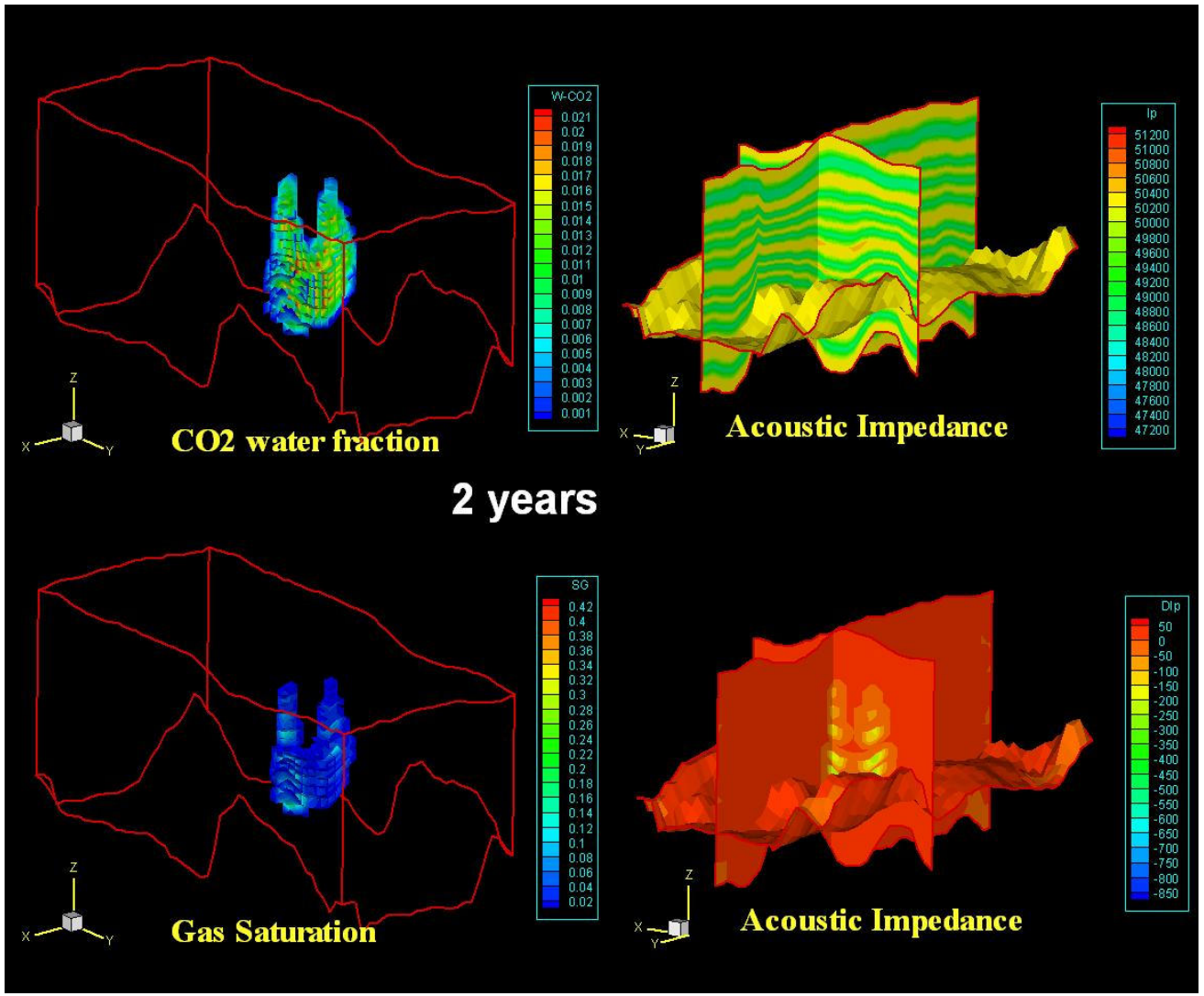

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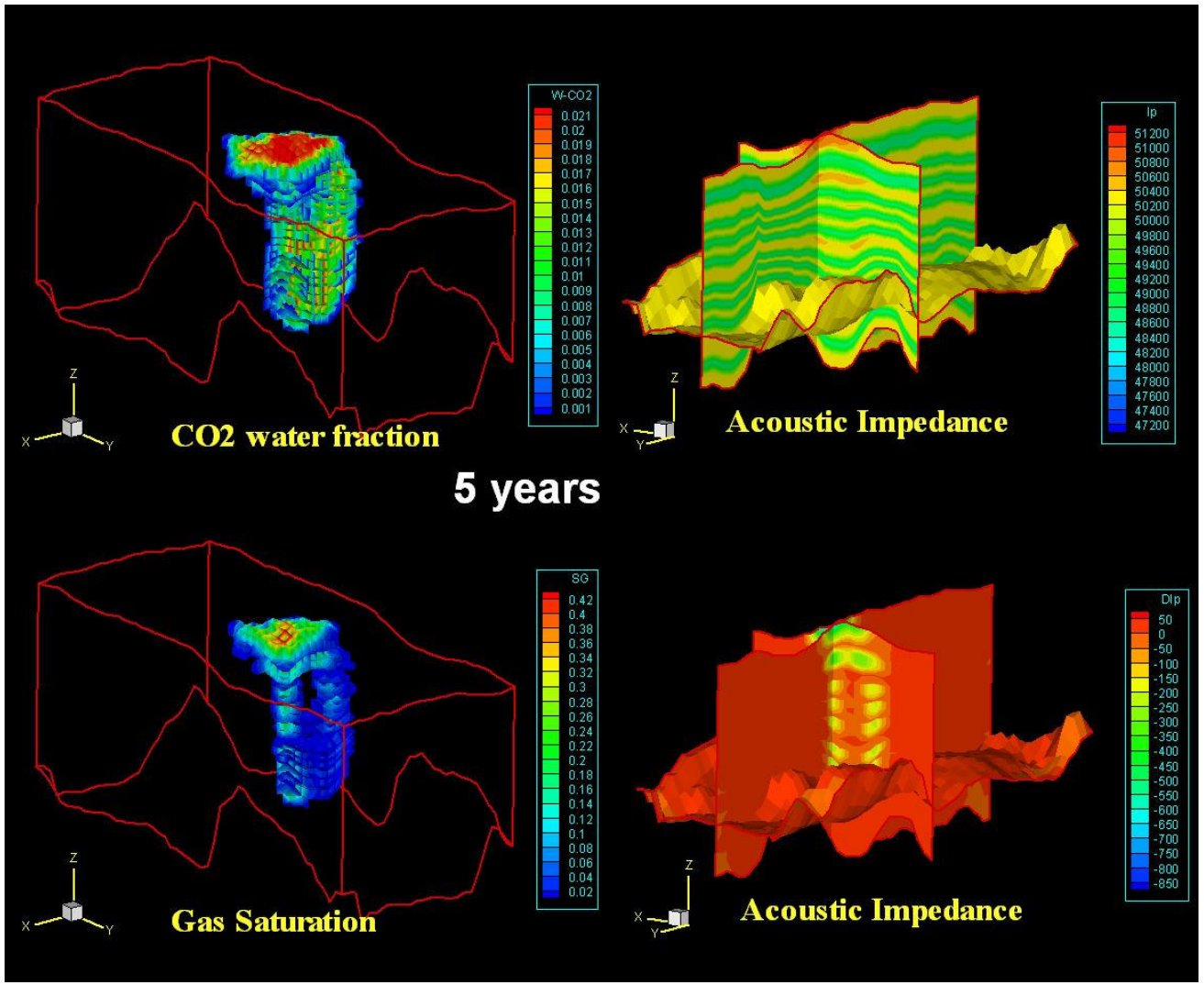

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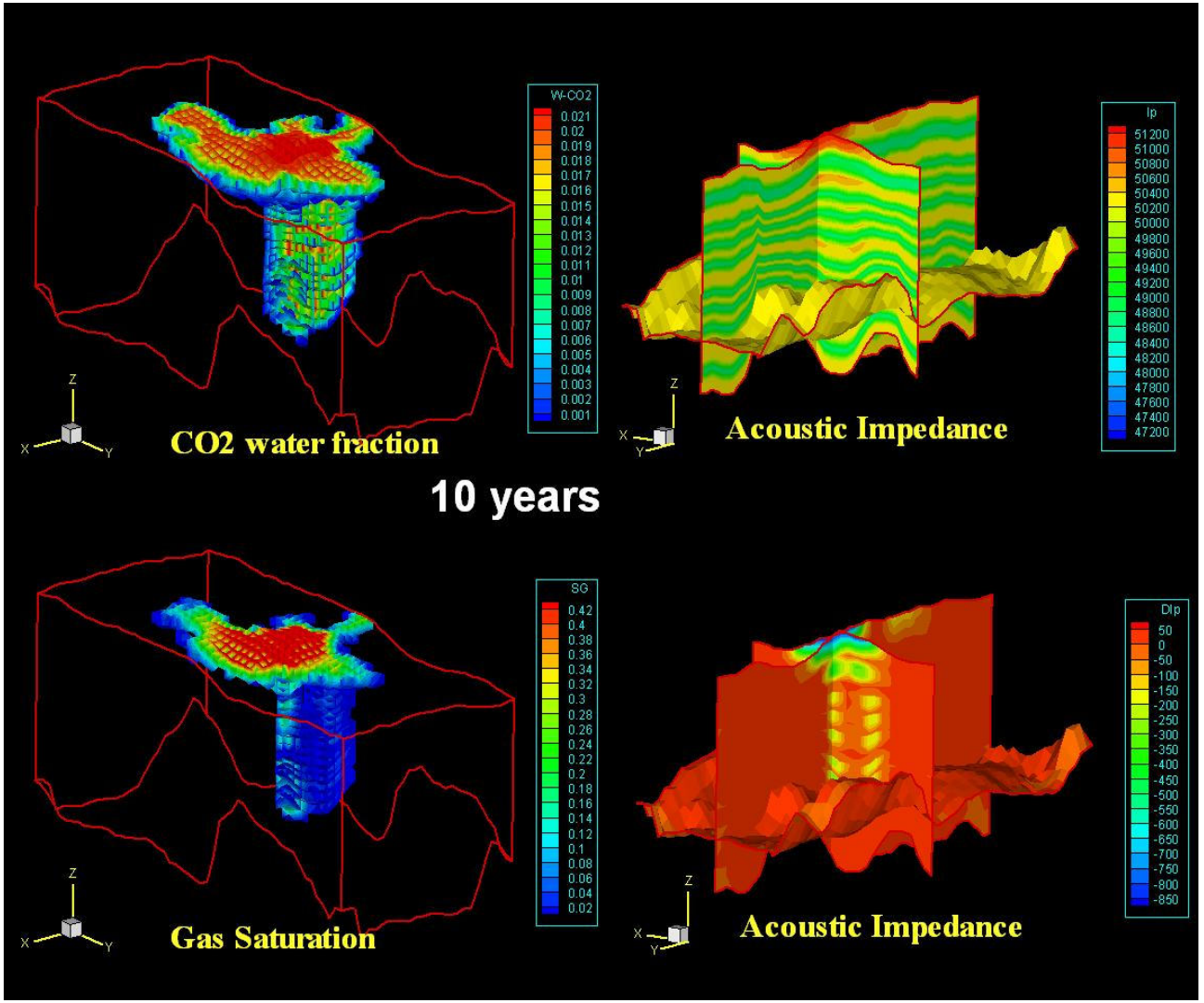

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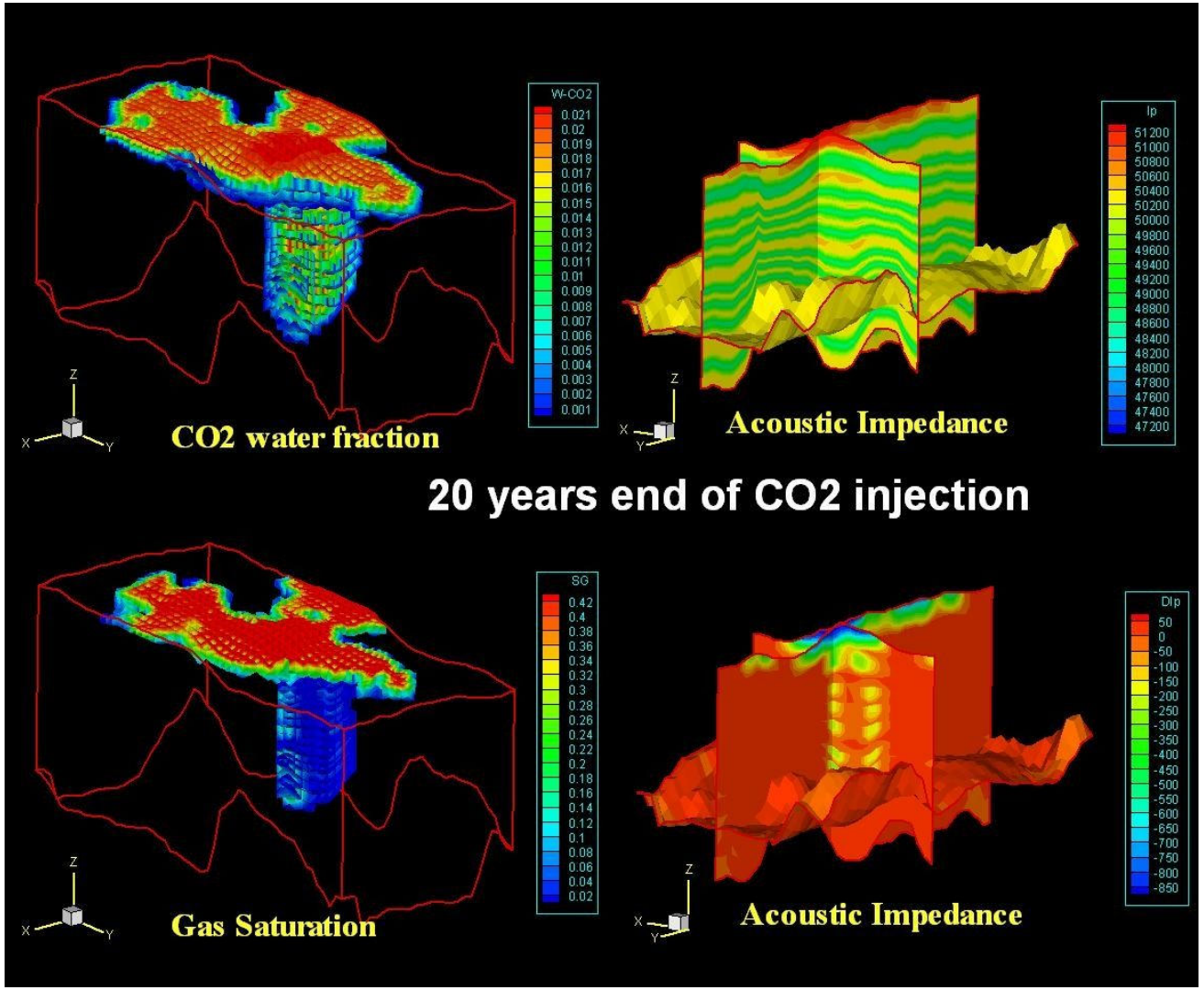

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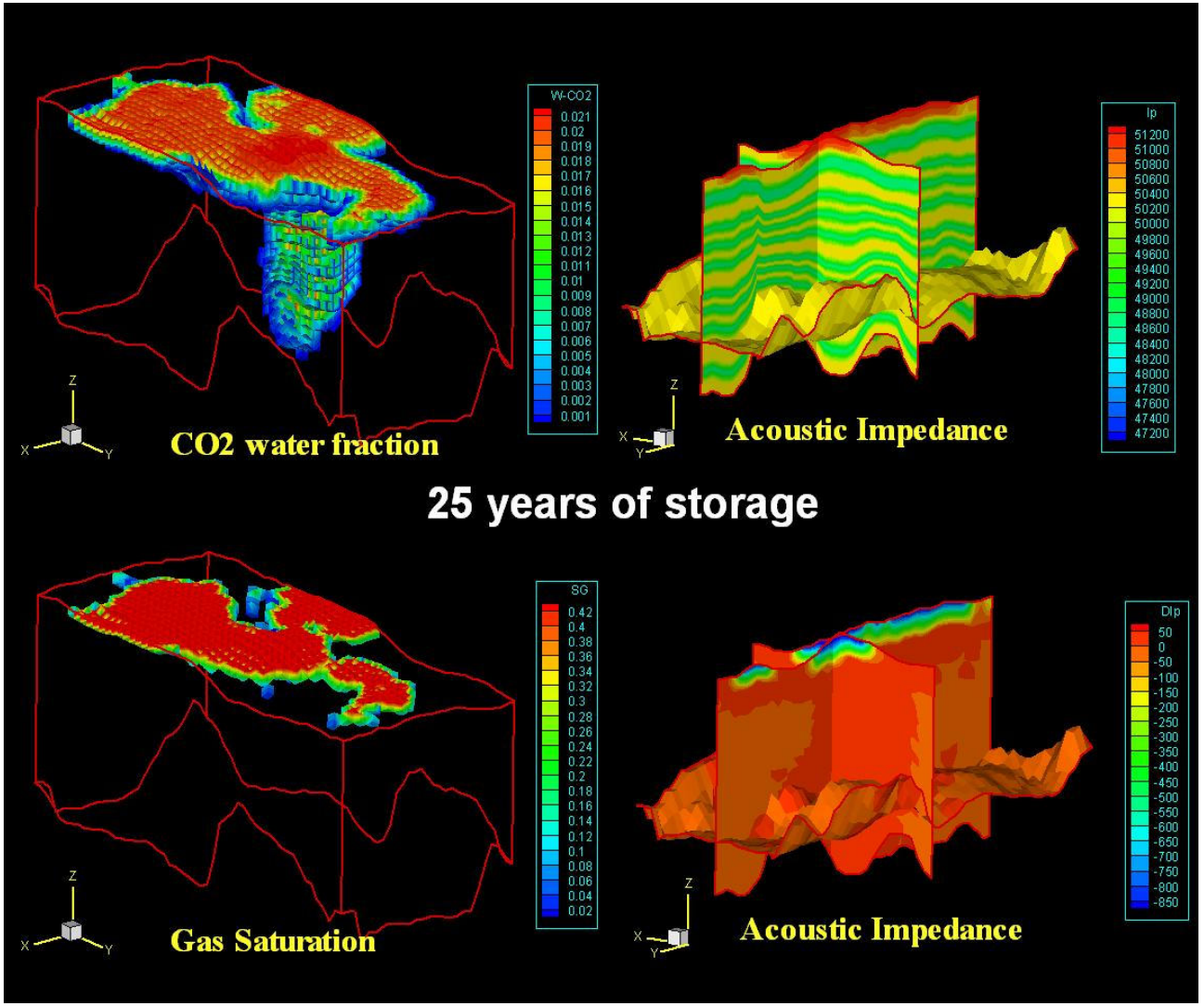

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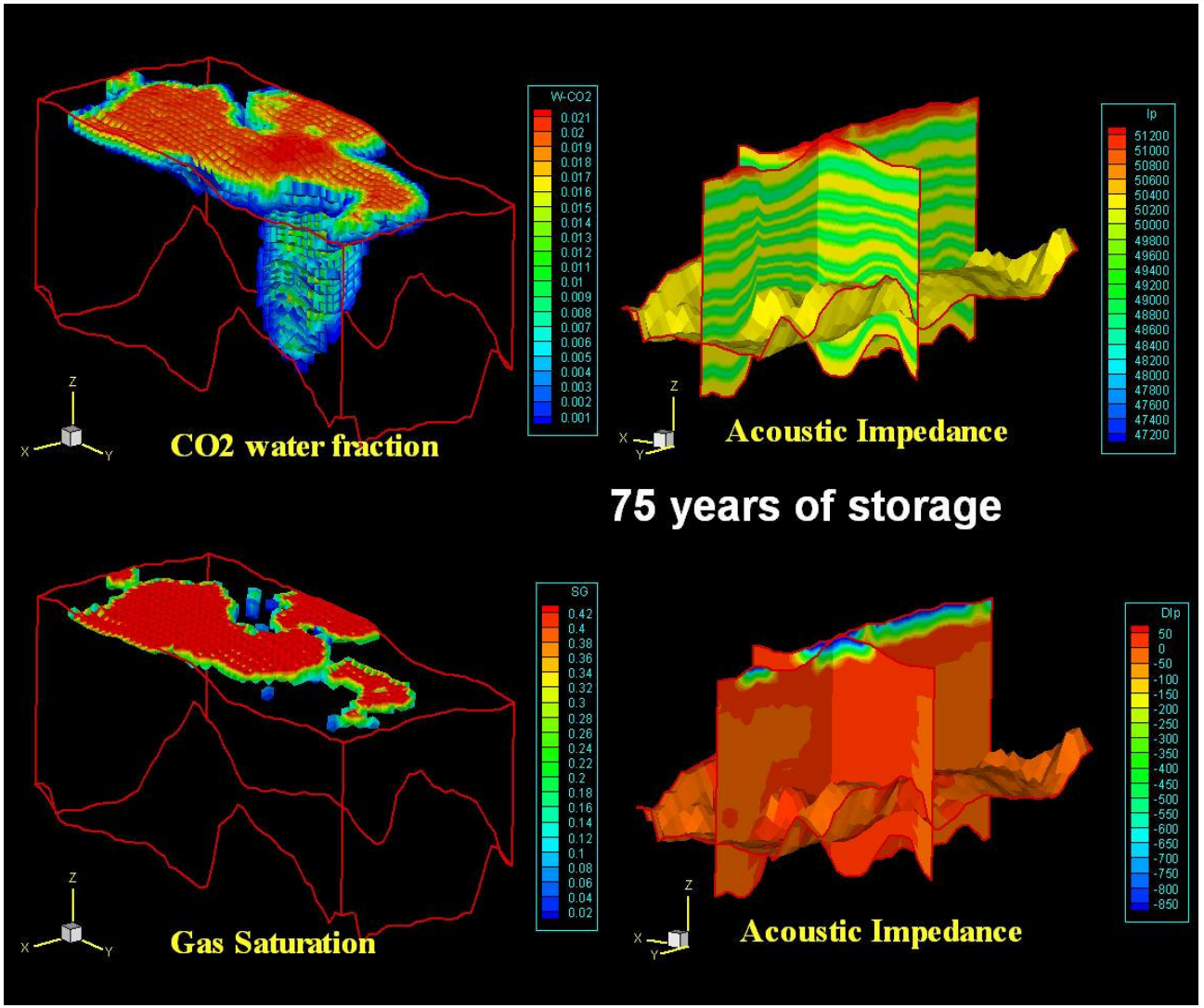

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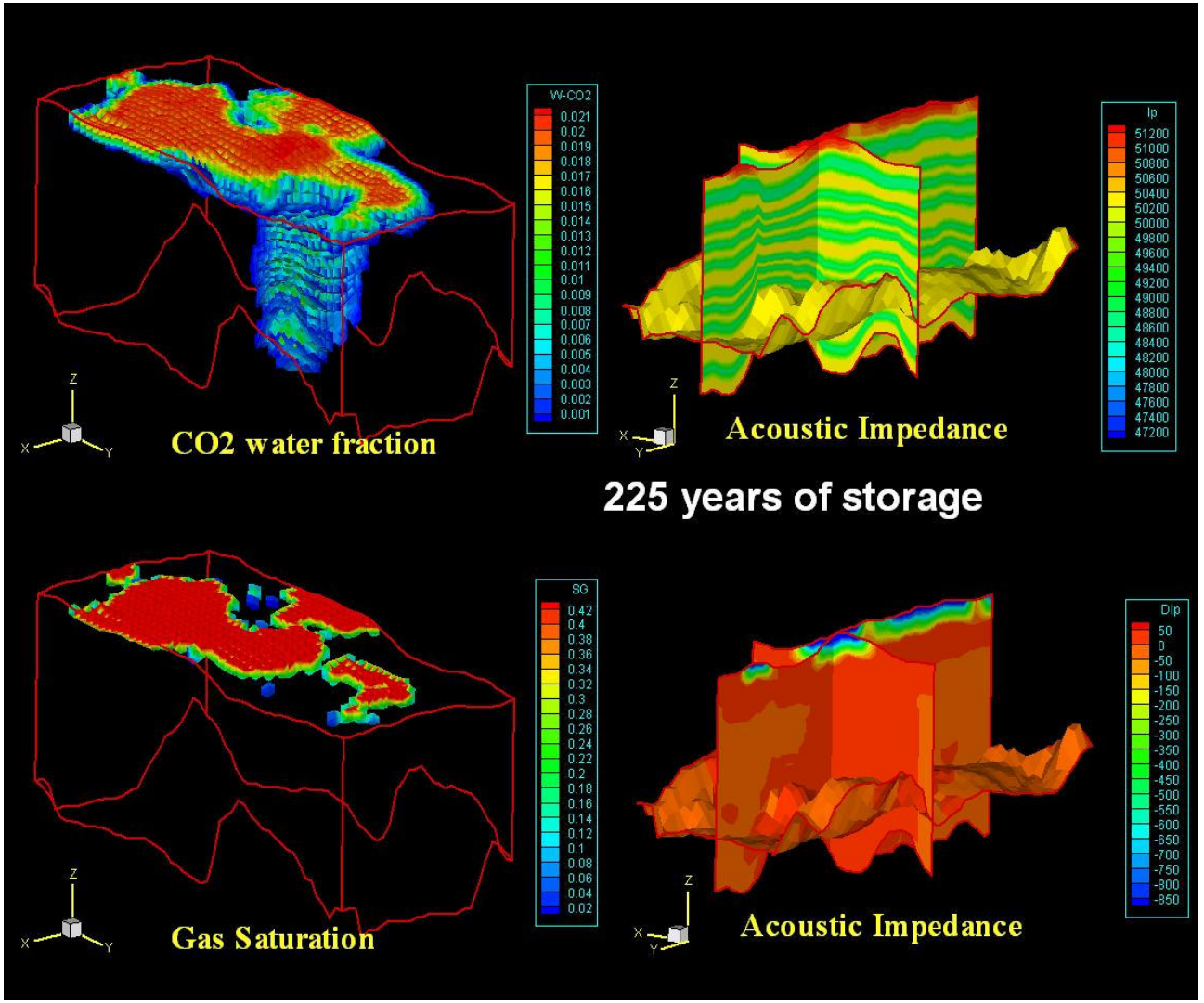

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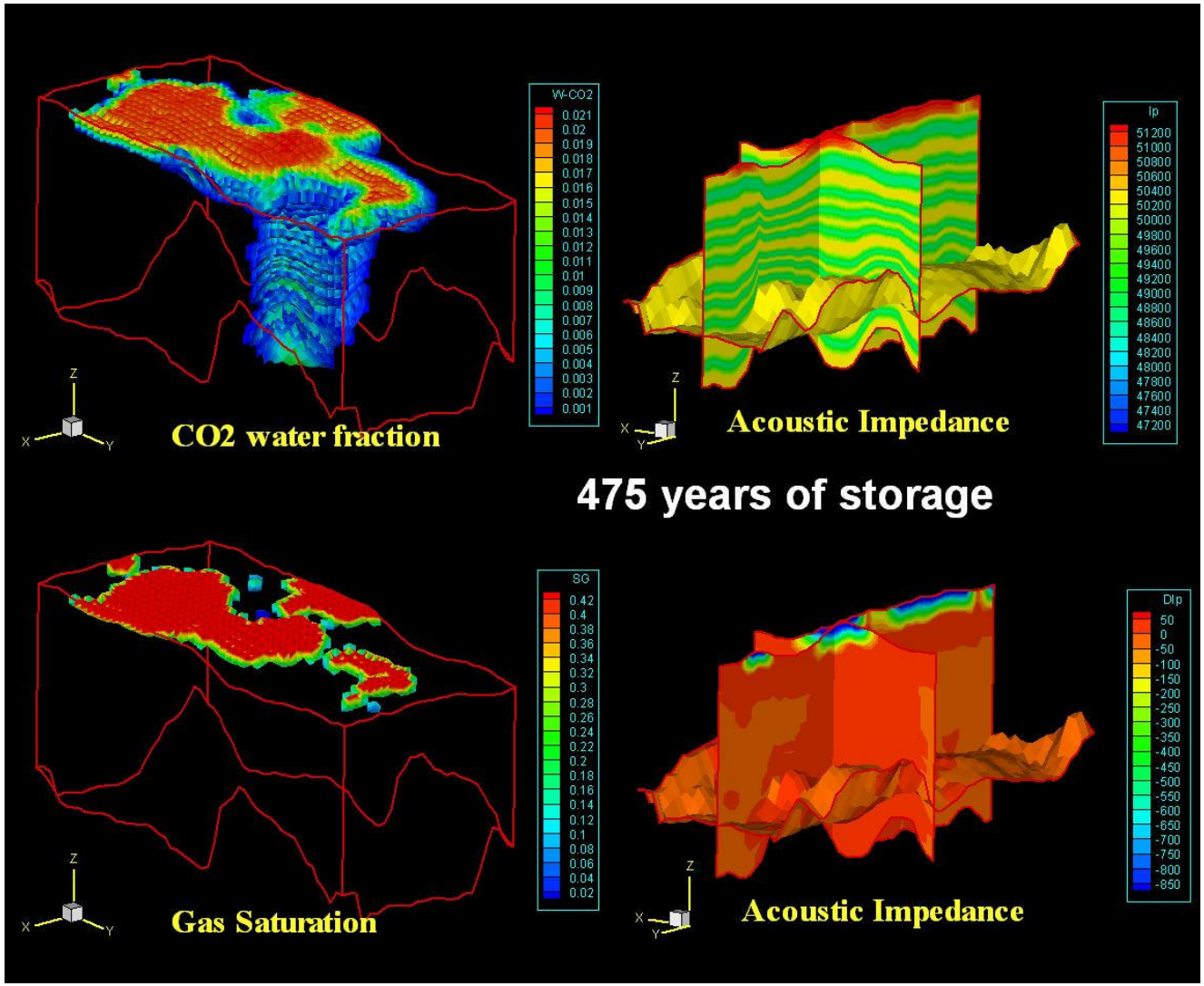

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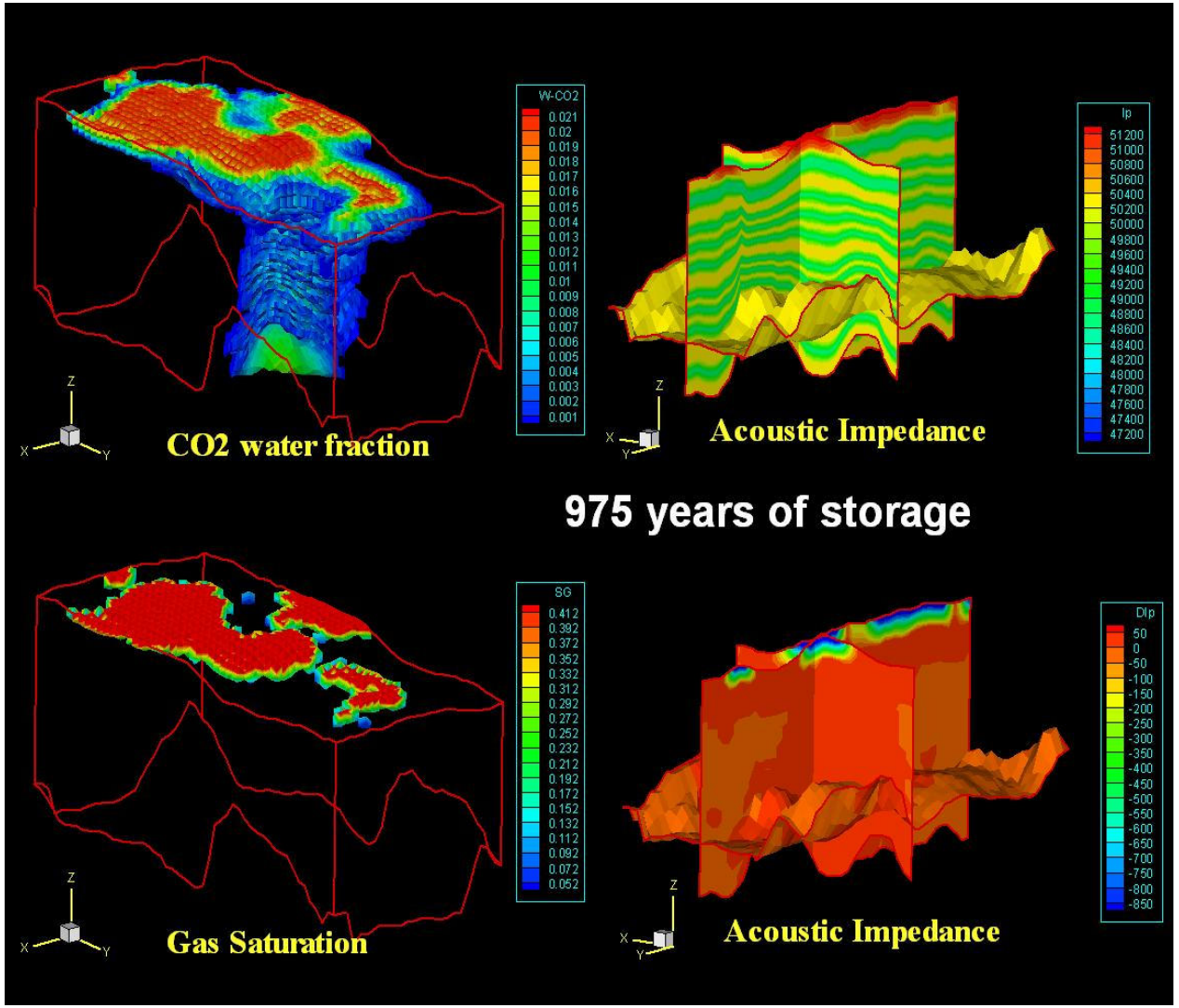

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CO_2 migration

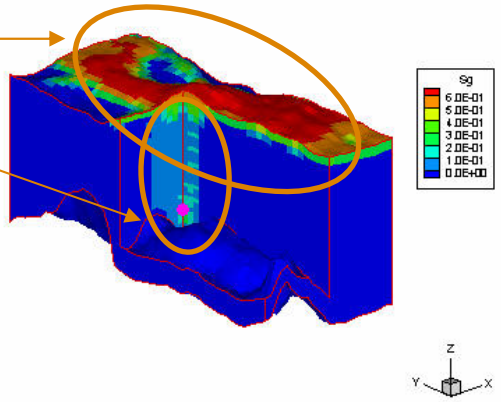
Supercritical CO_2 saturation

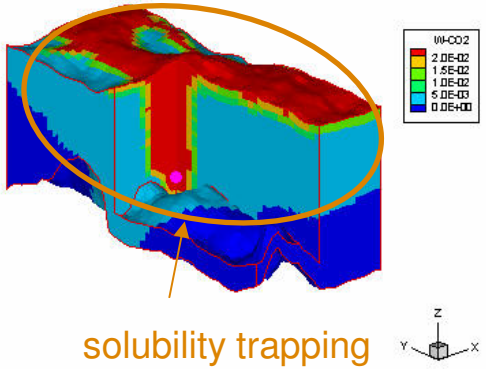
Dissolved CO_2 fraction in water

structural trapping

residual trapping

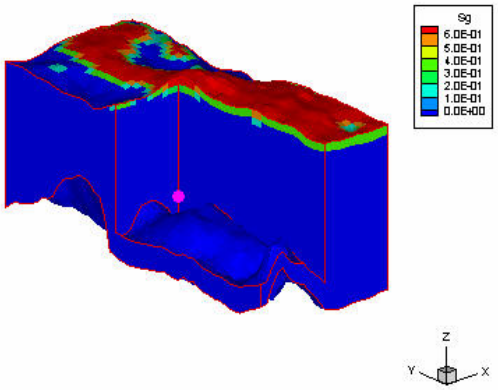
End of injection (40 years)

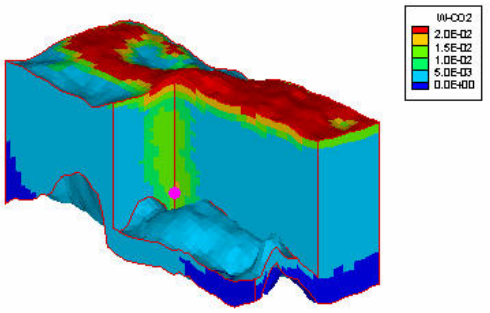




solubility trapping

End of storage (1000 years)





Le Gallo et al, IEA-GHGT8, 2006

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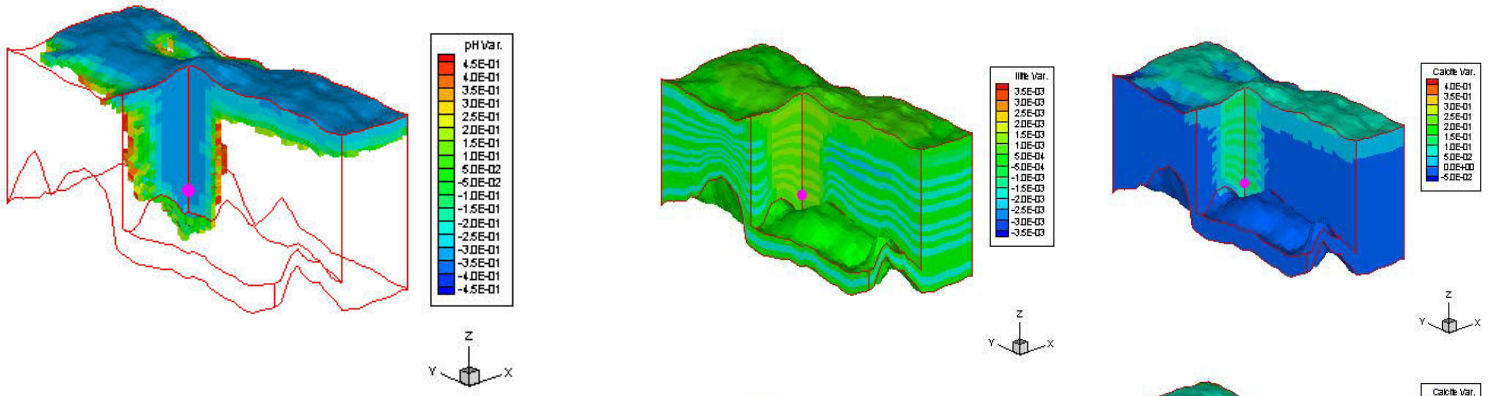
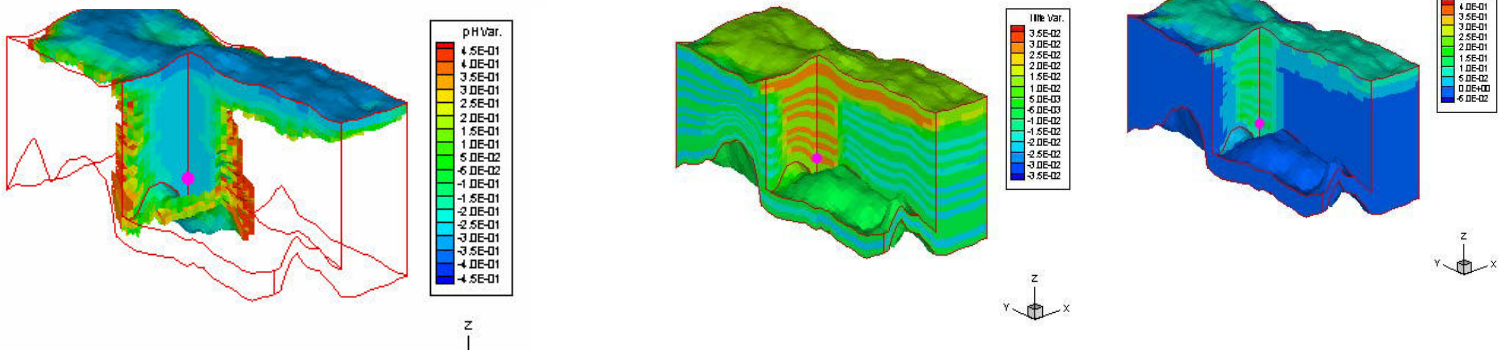
Chemical evolutions (mineral trapping)

pH | illite | calcite

End of injection (40 years)



End of storage (1000 years)



- **Most of the geochemical changes occur within the CO2-rich water region**
- **With different reaction rates, calcite mainly dissolves fairly rapidly in the reservoir while illite mostly precipitates over long storage time**

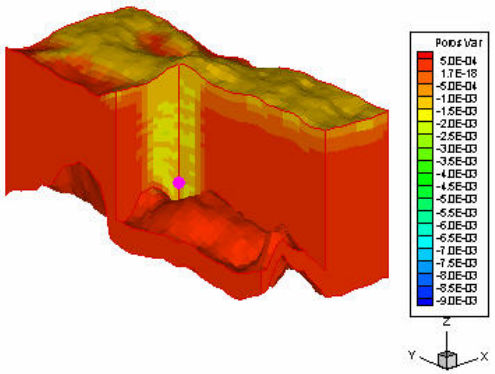
© IF

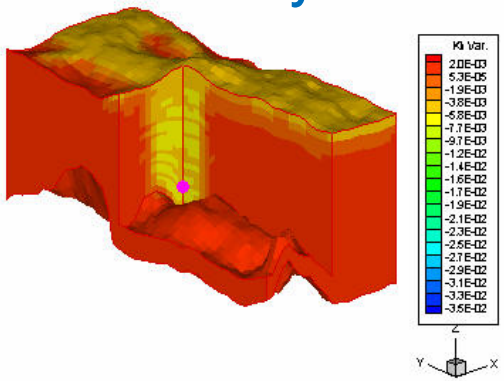
Petrophysical evolutions

Porosity

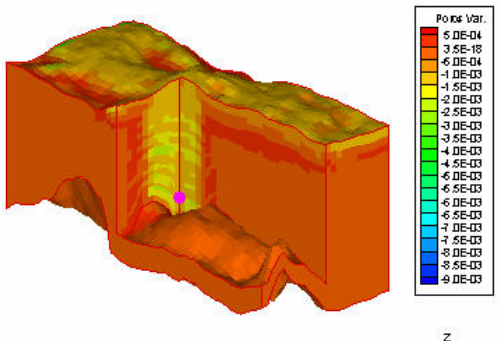
Horizontal permeability

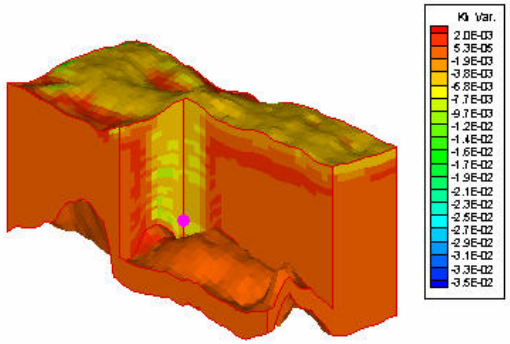
End of injection (40 years)





End of storage (1000 years)





The influence of geochemistry is quite minor as well since there is no significant porosity and consequently permeability variation

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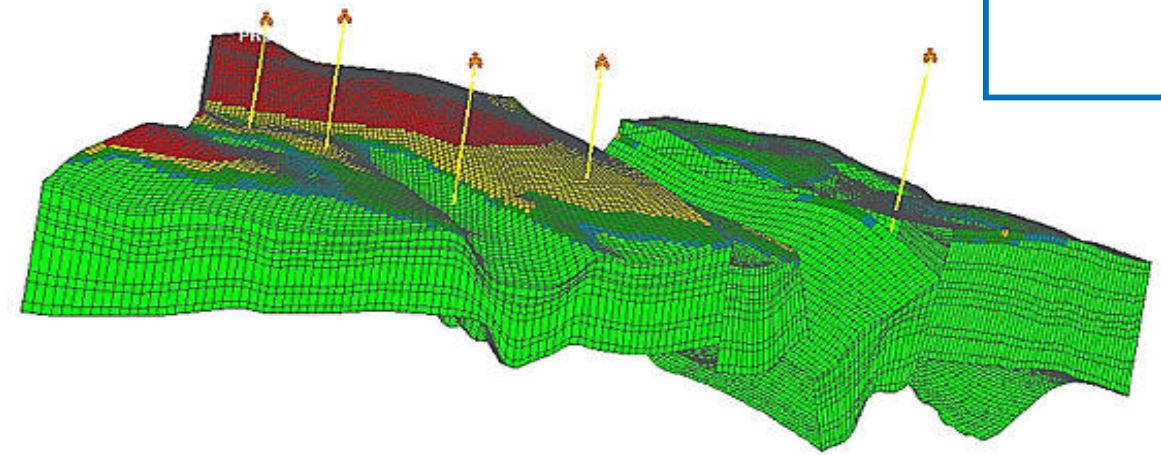
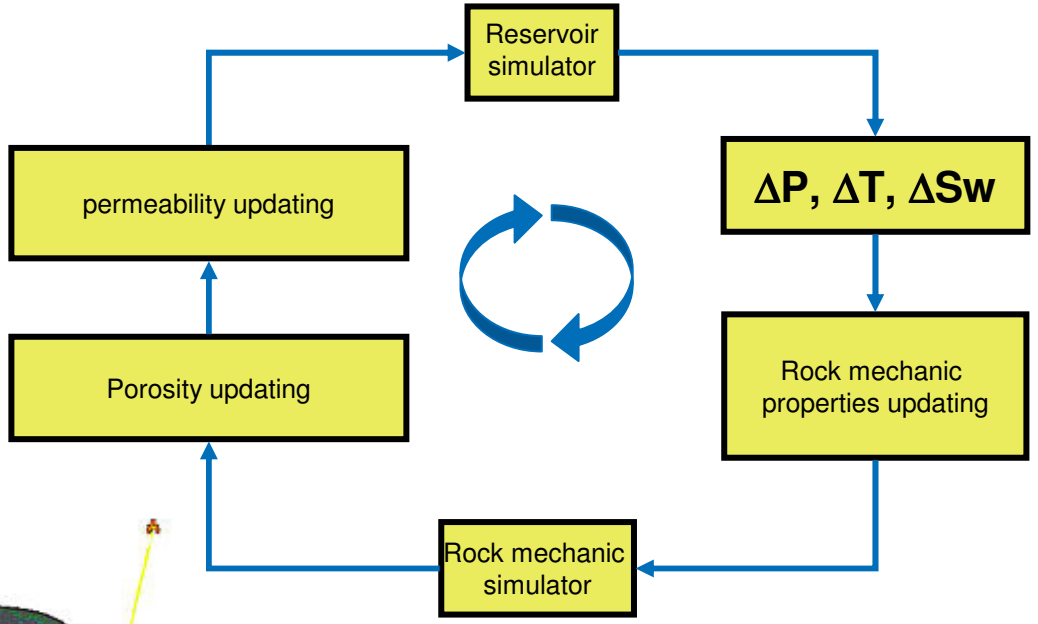
Geomechanics and flow modelling





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Main problem

Reactivation of existing faults (CO_2 storage)

- associated to non-natural mechanical solicitations
  - **stress path due to the depletion of oil and/or the injection of gas**
- goal : be able to predict the evolution of the permeability of the fault, when the geological structure is destabilized by the process of injection

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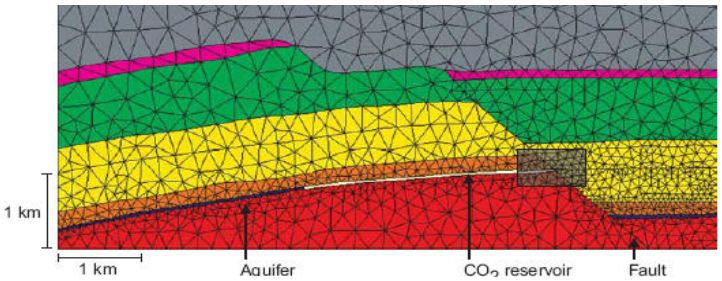
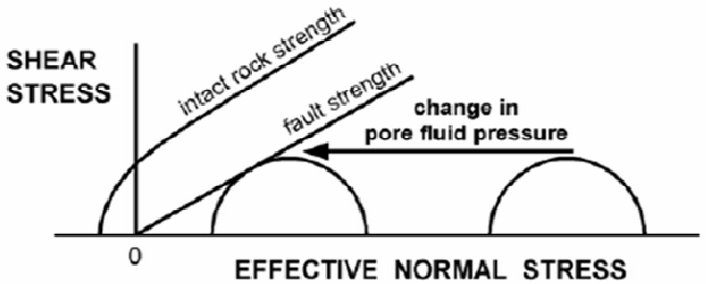
Reactivation of faults

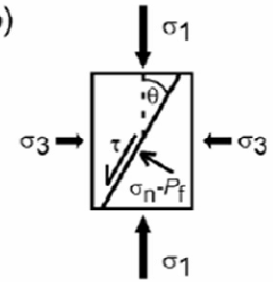
- Modeling of faults at the macroscopic scale
  - reservoir + cap rock + underburden + overburden

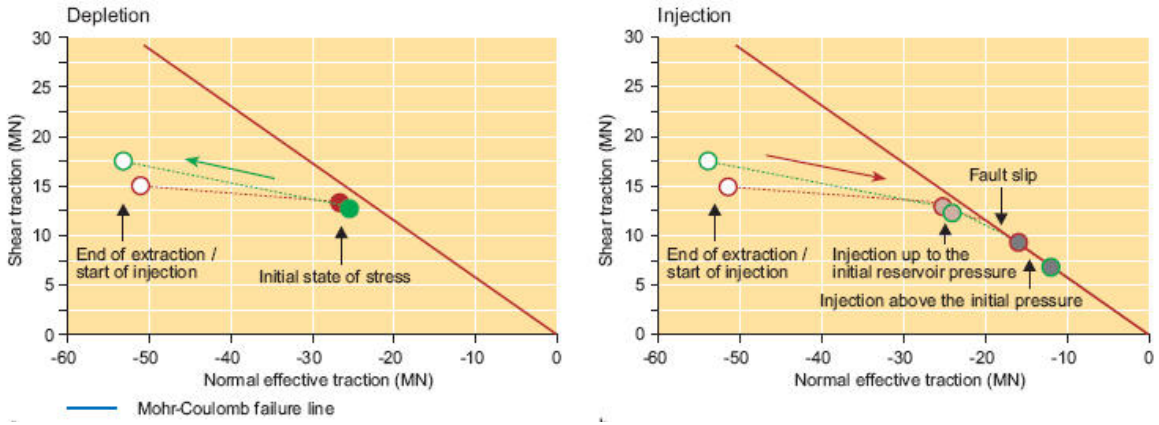
➡ **Simple discontinuity + Mohr-Coulomb: most general case**

Montmirail (B. Orlic & B. Schroot , 2005)









➡ Prediction of the reactivation, but no piece of information concerning the permeability and the post-yield evolution...

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At this stage, these are only predictions

Monitoring is operated to verify / detect / control predictions or remediation operations.

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Monitoring to verify / detect and learn

- Site characterization → **Geomodel initial "filling"**
- Reference measurements
- Production monitoring

} **4D monitoring**
Time lapse monitoring
Repetitive monitoring

- Permanent or discreet measurements
- Measurements on request
- Direct or indirect measurements

Optimization
Flexibility
Efficiency

→ **Geomodel updating**

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Outlines

- Introduction to CO_2 storage
  - What do we need?
  - Present options
  - A multi-scale problem
- Site characterization issues
  - Reservoir capacity
  - Injectivity
  - Storage complex integrity
  - Risk of leakages
- Modelling to predict
- Conclusions

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Conclusions (1/3)

- Site characterization is the key and decisive step in selecting a site for CO_2 to be stored.

- It helps to state on storage:
  - Integrity
  - Capacity
  - Performance

  by making prediction based on both laboratory measurements and numerical modelling performed using an initial 3D-earth model that has to be developed.

- It deals with a complex multi-scale problem considering time, space and physical phenomena.

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Conclusions (2/3)

- After initial characterization, site description will benefit from a continuous and evolving adapted monitoring programme starting prior to CO_2 injection and continuing until after closure.
- A continuous update of the earth model can then be achieved allowing to improve description and understanding of phenomena.

  (This allows to perform more reliable prediction and to improve history matching results on monitored pressure and any other parameter measured.)

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Conclusions (3/3)
Storing CO_2 in oil & gas structure

- A series of major differences
  - the reservoir is quite well characterized (more cores, wells and acquired data)
  - caprocks were not well characterized (it is evolving now)
  - the reservoir is depleted; CO_2 is injected below the initial reservoir pressure (this is an important difference with saline aquifers when considering geomechanical behaviour)
  - Production allows history matching and then to better understand fluid displacement and pressure changes into the reservoir (not possible with CO_2 storage in saline aquifers)
  - Existing wells represent a high risk of leakages but well located in comparisons with the structural one (leakage on a fault, through caprocks...)

→ **A good way for rejuvenating some brown fields**

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Than you for your attention

and many thanks to the Exploration and Production IFP R&D teams

thanks to the EU for financial support in the CCS domain through a series of projects.

j-pierre.deflandre@ifp.fr
olivier.vincke@ifp.fr

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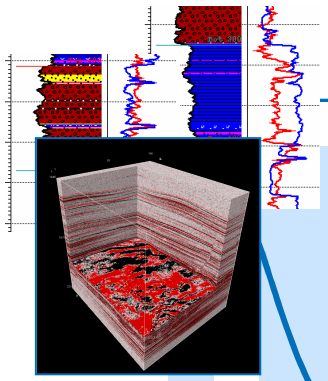
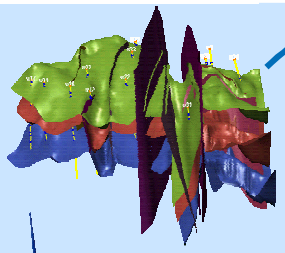
Integrated study reservoir workflow

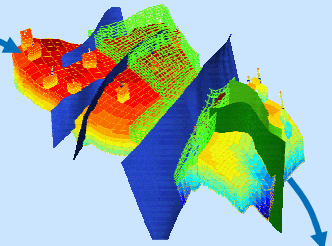


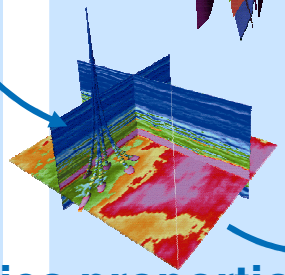
Well and seismic data

Structural model

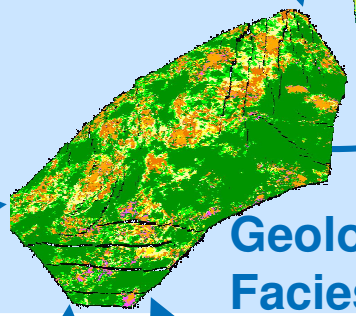
Stratigraphic model





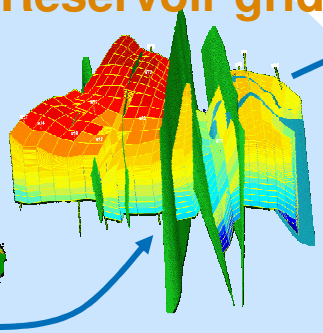


Facies proportions model

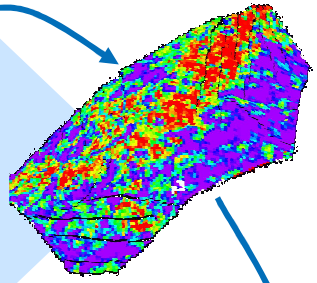


Geological model: Facies, porosity, permeability

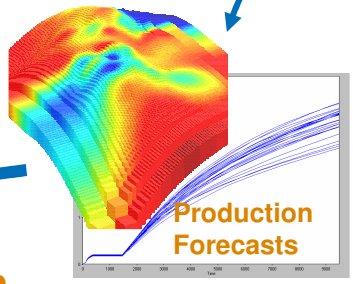
Reservoir grid



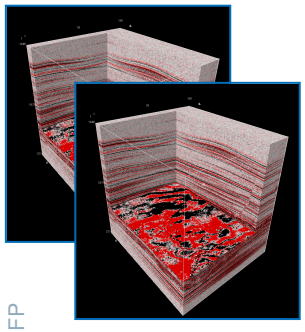
Upscaling



Flow simulation

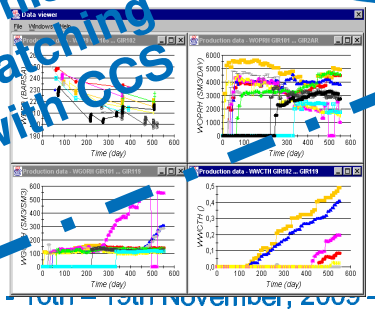


Geomodel updating



Integration of 4D seismic data

no history matching with CCS !



Integration of production data

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OPEC-IEA GHG-CCS

Workshop 2009

EOR

STATUS AND OPPORTUNITIES

Mrs. Ghaniya S. Bin-Dhaaer Al-Yafei

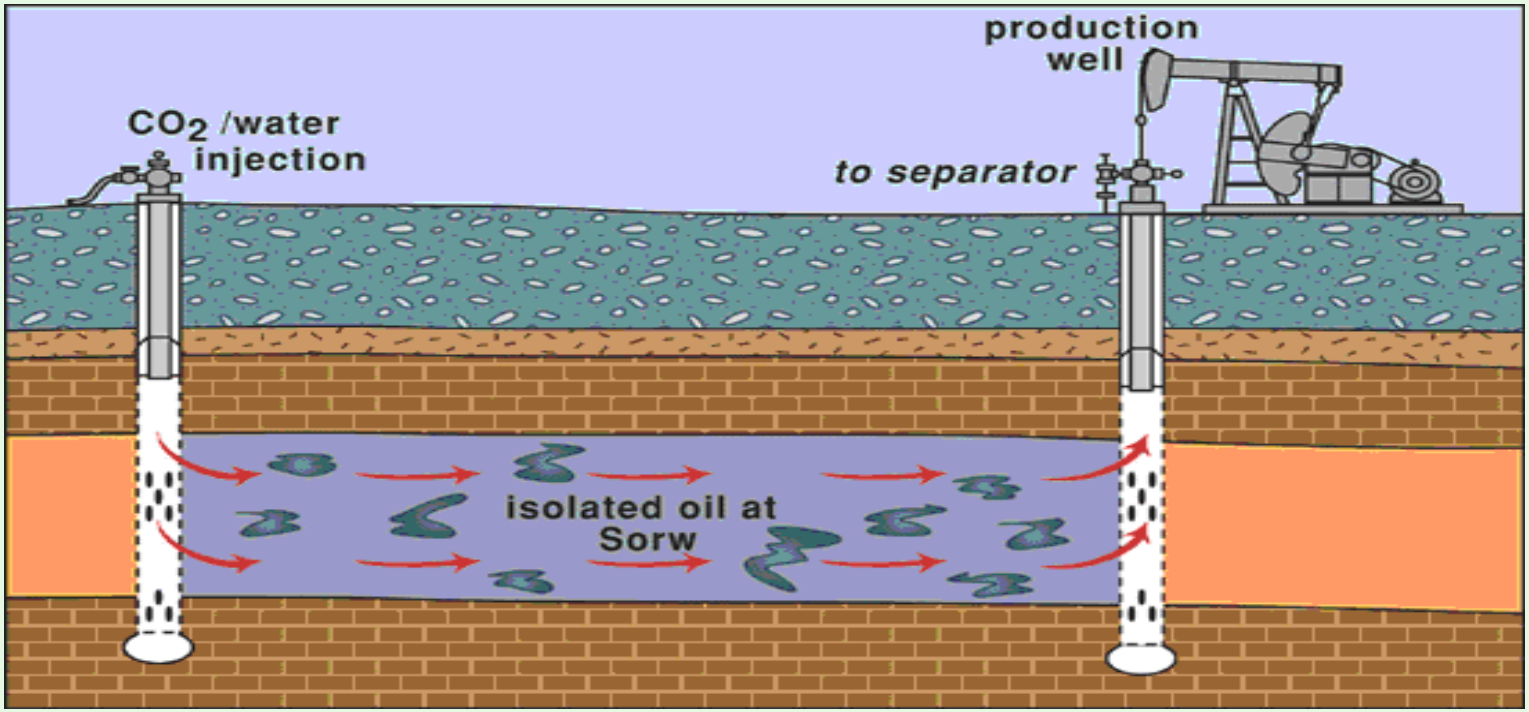
Abu Dhabi-UAE

Outline

- EOR Concept
- Status of EOR Production
- EOR Potential
- Cost of EOR Oil
- EOR Methods
- Abu Dhabi CO2-EOR Pilot

What is Enhanced Oil Recovery?

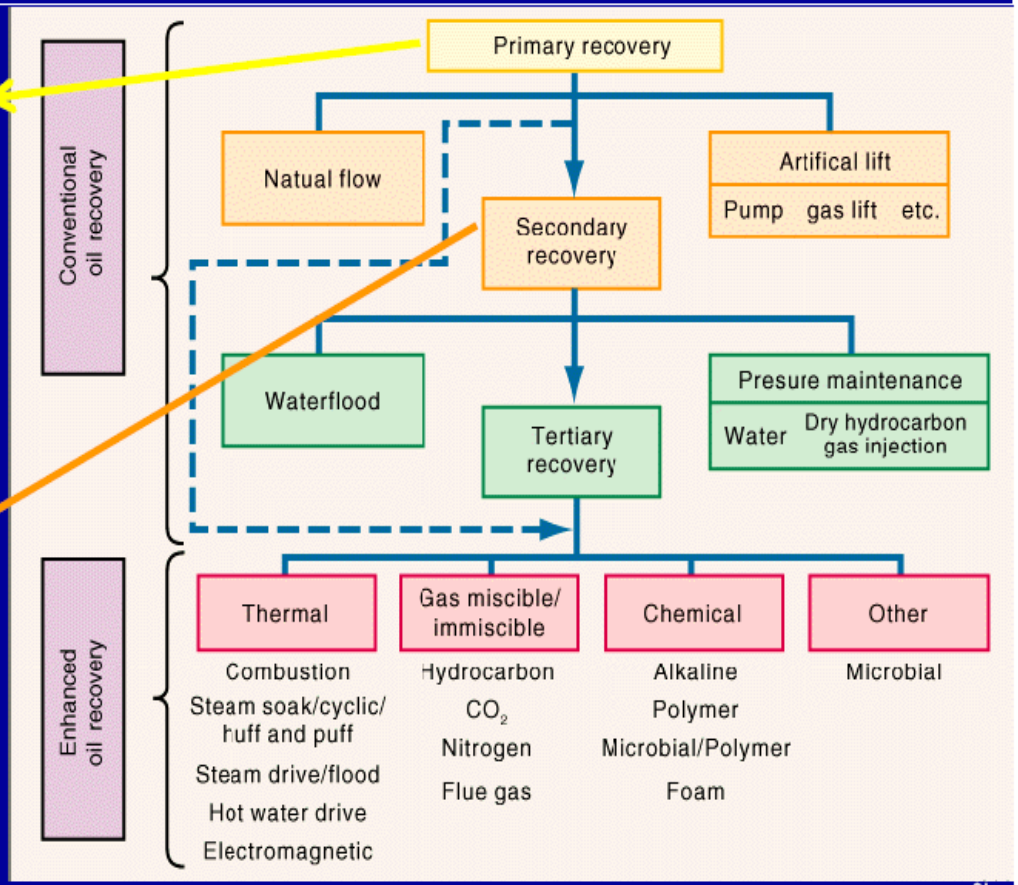
Enhanced Oil Recovery (EOR) is recovery of oil using means other than primary (natural depletion) or secondary (e.g., water-flooding, etc.). Using EOR, 30-70 % or more, of the reservoir original oil can be extracted compared to 20-40% using primary and secondary recovery.



« EOR » is applied to methods used for recovering oil from a petroleum reservoir beyond that recoverable by primary and secondary methods

Refers to production using the energy inherent in the reservoir from gas under pressure or a natural water drive

Refers to injection of water (waterflooding)



OAPEC - IFP Joint Seminar 28 & 29/06/2005

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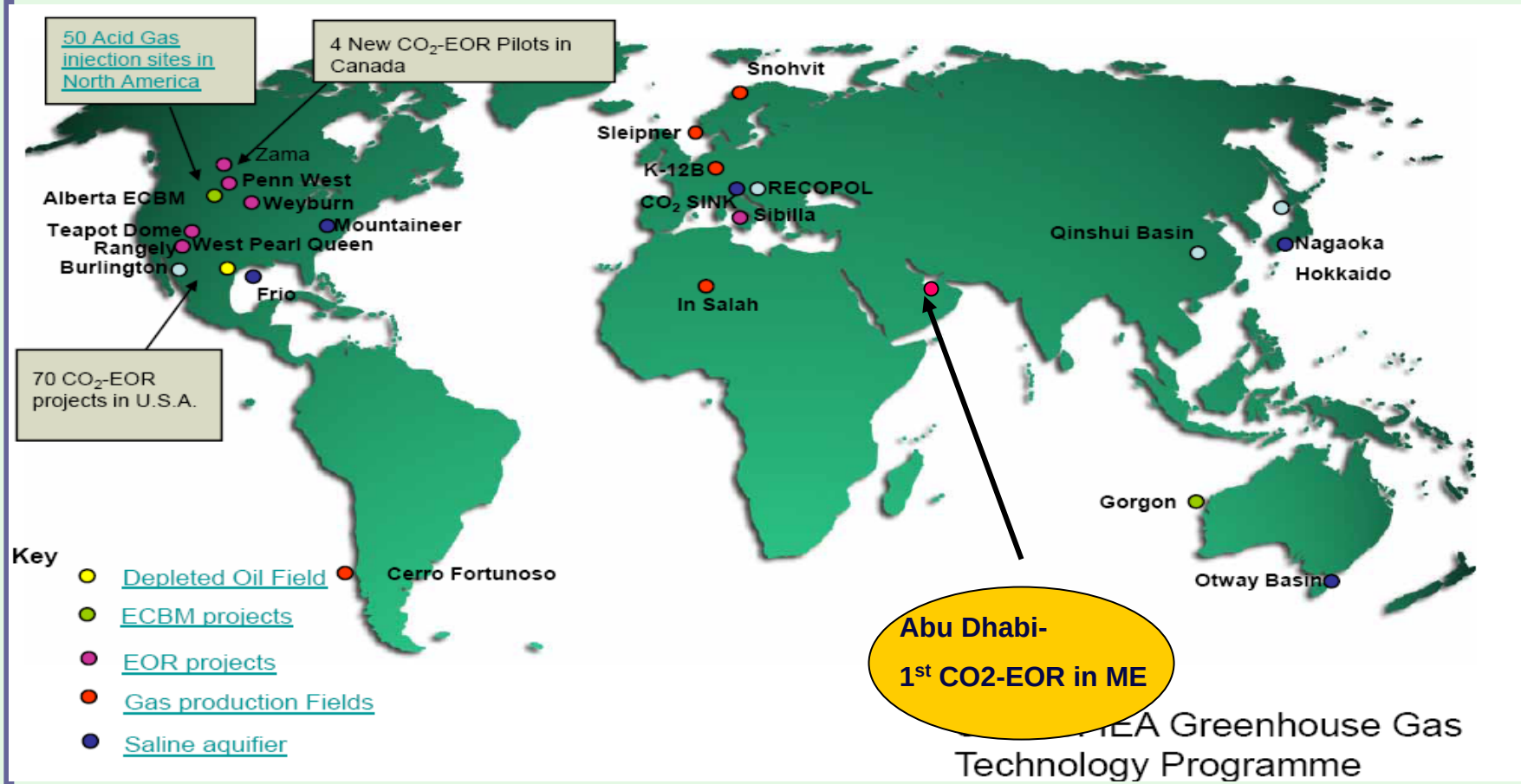
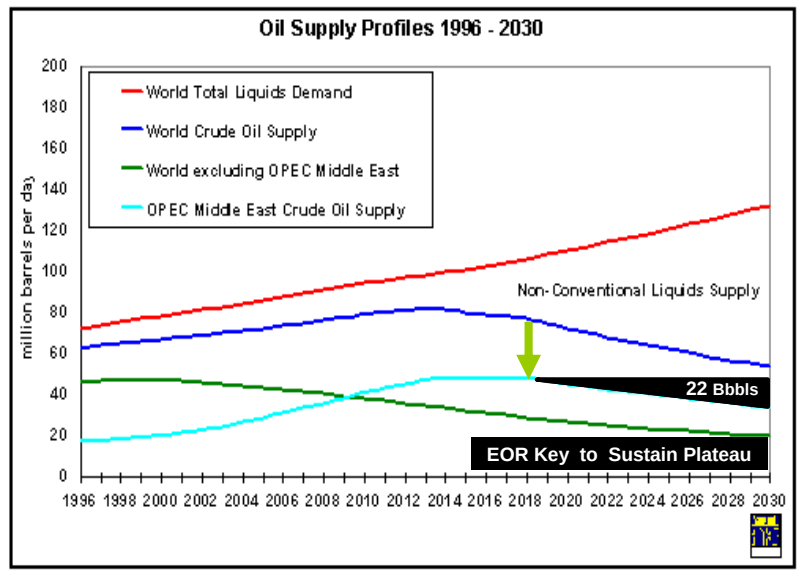
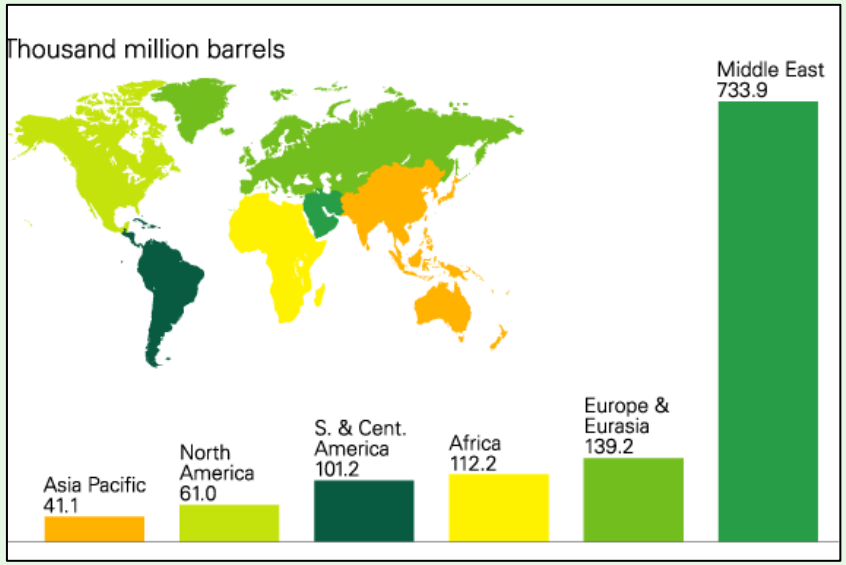
EOR & CCS PROJECTS WORLDWIDE

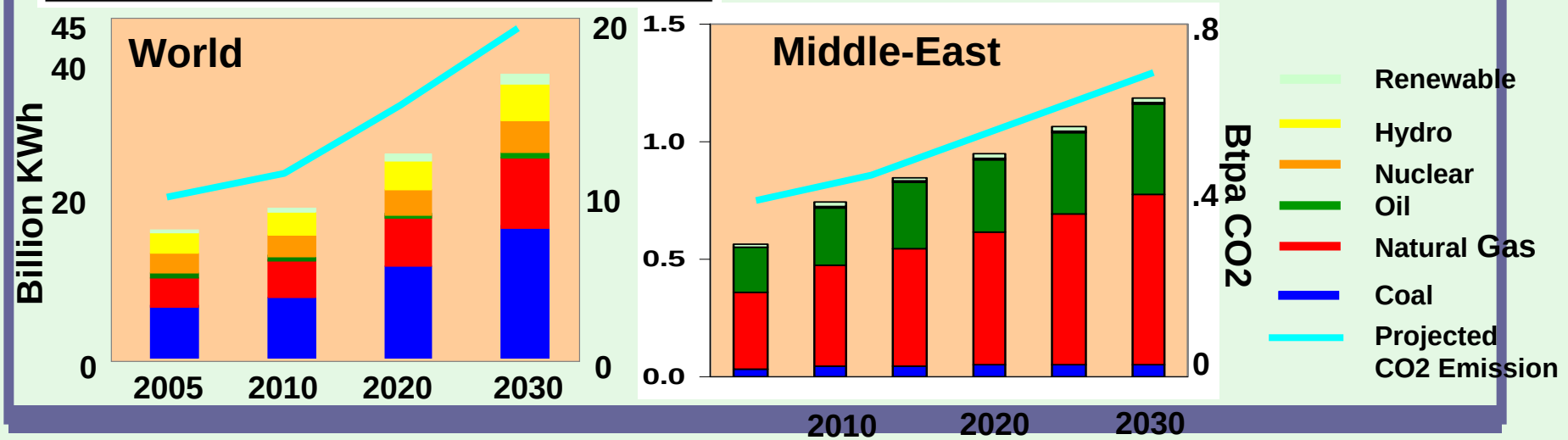


First CO2-EOR in the Region

Predicted Global Oil Demand, Global and Middle-East Power Generation Demand and CO2 Emission







Reserves and Resources, Conventional Oil worldwide

- **Current oil cumulative production = 1.07 10^{12}bbls**
- **Remaining conventional oil reserves = 1.1 10^{12}bbls (ca. 40 years production at today's rate)**
- **Reserves expected to be found = 1.3 10^{12}bbls (ca. 40 years production)**
- **Increasing the average recovery factor from**
- **35% to 45 % = 0.1 10^{12}bbls**

This is the target for technology

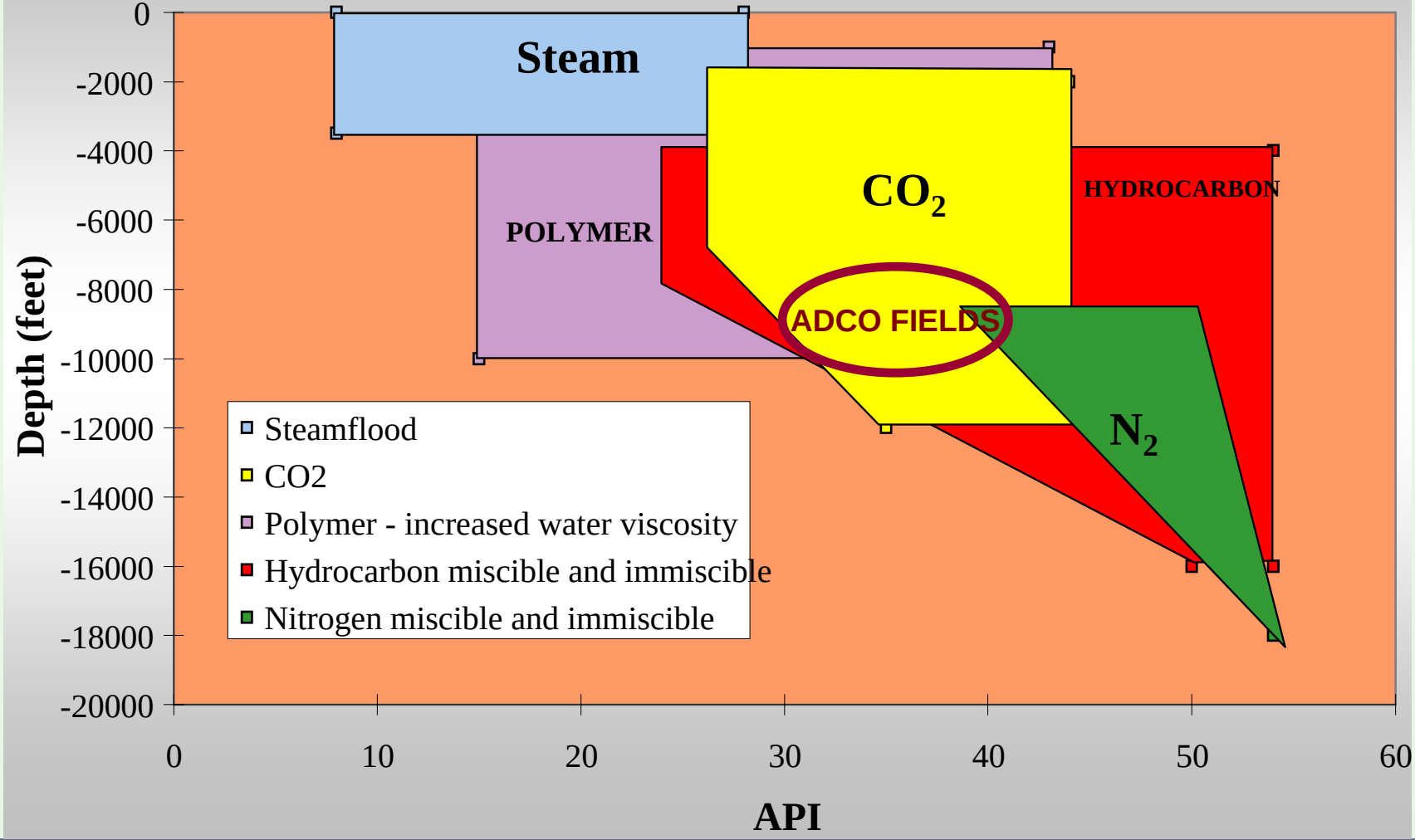
Fluid Properties Affect Recovery Factor

RECOVERY EFFICIENCY = **Areal Sweep Efficiency** * **Vertical Sweep Efficiency** * **Microscopic Displacement Efficiency**

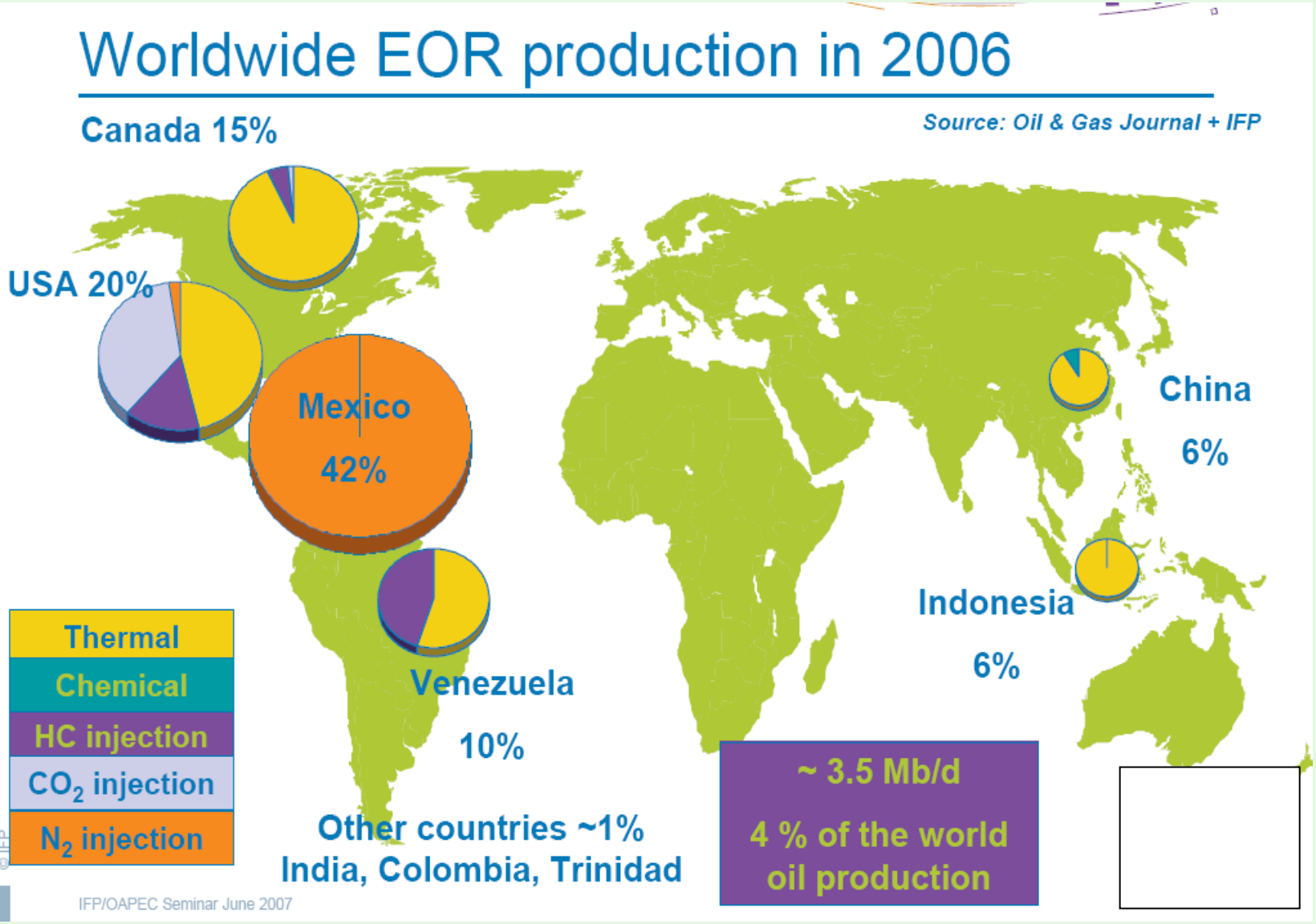
FLUID PROPERTIES AFFECT ALL THREE FACTORS

- VISCOSITIES found in definition of mobility ratio which affects areal and vertical sweep efficiency
- DENSITIES define degree of gravity segregation and therefore affects vertical sweep efficiency
- IFT, MASS TRANSFER and MISCIBILITY affect Residual Oil Saturation which defines microscopic displacement efficiency

Depth and API Range of Major EOR Methods (Current Worldwide Projects)



Worldwide EOR production in 2006



Reported US EOR Production

ACTIVE US EOR PROJECTS

Table 2

	1988	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008
Thermal											
Steam	133	137	119	109	105	92	86	55	46	40	45
Cumbustion in situ	9	8	8	5	8	7	5	6	7	12	12
Hot water	10	9	6	2	2	1	1	4	3	3	3
Total thermal	**152**	**154**	**133**	**116**	**115**	**100**	**92**	**65**	**56**	**55**	**60**
Chemical											
Micellar-polymer	9	5	3	2							
Polymer	111	42	44	27	11	10	10	4	4	0	1
Caustic/alkaline	4	2	2	1	1	1					
Surfactant		1									1
Total chemical	**124**	**50**	**49**	**30**	**12**	**11**	**10**	**4**	**4**	**0**	**2**
Gas											
Hydrocarbon miscible/ immiscible	22	23	25	15	14	11	6	7	8	13	13
CO_2 miscible	49	52	52	54	60	66	63	66	70	79	100
CO_2 immiscible	8	4	2	1	1		1	1	1	2	5
Nitrogen	9	9	7	8	9	10	4	4	4	3	4
Flue gas (miscible and immiscible)	2	3	2								
Other			1	1							
Total gas	**90**	**91**	**89**	**79**	**84**	**87**	**74**	**78**	**83**	**97**	**122**
Other											
Microbial			2	1	1	1					
Total other	**0**	**0**	**2**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**
Grand total	**366**	**295**	**273**	**226**	**212**	**199**	**176**	**147**	**143**	**152**	**184**

Oil & Gas Journal April 21, 2008

Reported US EOR Projects

US EOR PRODUCTION

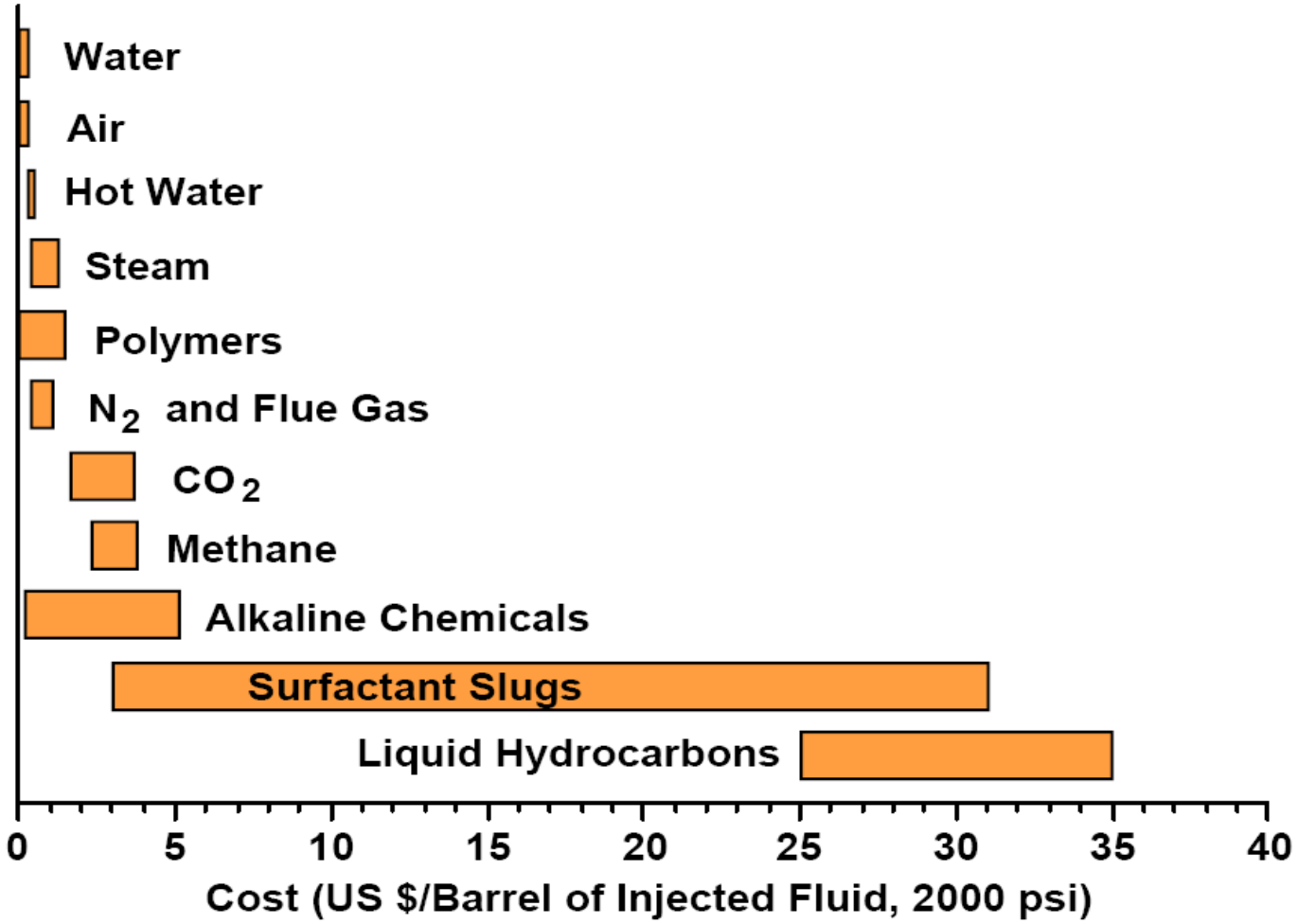
Table 1

	1986	1988	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008
Thermal												
Steam	468,692	455,484	444,137	454,009	415,801	419,349	439,010	417,675	365,717	340,253	286,668	273,947
Cumbustion in situ	10,272	6,525	6,090	4,702	2,520	4,485	4,760	2,781	2,384	1,901	13,260	17,025
Hot water	705	2,896	3,985	1,980	250	250	2,200	306	3,360	3,360	4,370	1,776
Total thermal	**479,669**	**464,905**	**454,212**	**460,691**	**418,571**	**424,084**	**445,970**	**417,675**	**371,461**	**345,514**	**304,298**	**292,748**
Chemical												
Micellar-polymer	1,403	1,509	617	254	64	0	0	0				
Polymer	15,313	20,992	11,219	1,940	1,828	139	139	1,598				
Caustic/alkaline	185											
Surfactant			20					60	60	60		
Total chemical	**16,901**	**22,501**	**11,856**	**2,194**	**1,892**	**139**	**139**	**1,658**	**60**	**60**	**0**	**0**
Gas												
Hydrocarbon miscible/ immiscible	33,767	25,935	55,386	113,072	99,693	96,263	102,053	124,500	95,300	97,300	95,800	81,000
CO_2 miscible	28,440	64,192	95,591	144,973	161,486	170,715	179,024	189,493	187,410	205,775	235,344	240,313
CO_2 immiscible	1,349	420	95	95				66	66	102	2,698	9,350
Nitrogen	18,510	19,050	22,260	22,580	23,050	28,017	28,117	14,700	14,700	14,700	14,700	19,700
Flue gas (miscible and immiscible)	26,150	21,400	17,300	11,000	—	—	—	—				
Other				6,300	4,400	4,350	4,350	—				
Total gas	**108,216**	**130,997**	**190,632**	**298,020**	**288,629**	**299,345**	**313,544**	**328,759**	**297,476**	**317,877**	**348,542**	**350,363**
Other												
Carbonated waterflood												
Microbial				2	2							
Total other			**2**	**2**								
Grand total	**604,786**	**618,403**	**656,700**	**760,907**	**709,094**	**723,568**	**759,653**	**748,092**	**668,997**	**663,451**	**652,840**	**643,111**

Oil & Gas Journal April 21, 2008

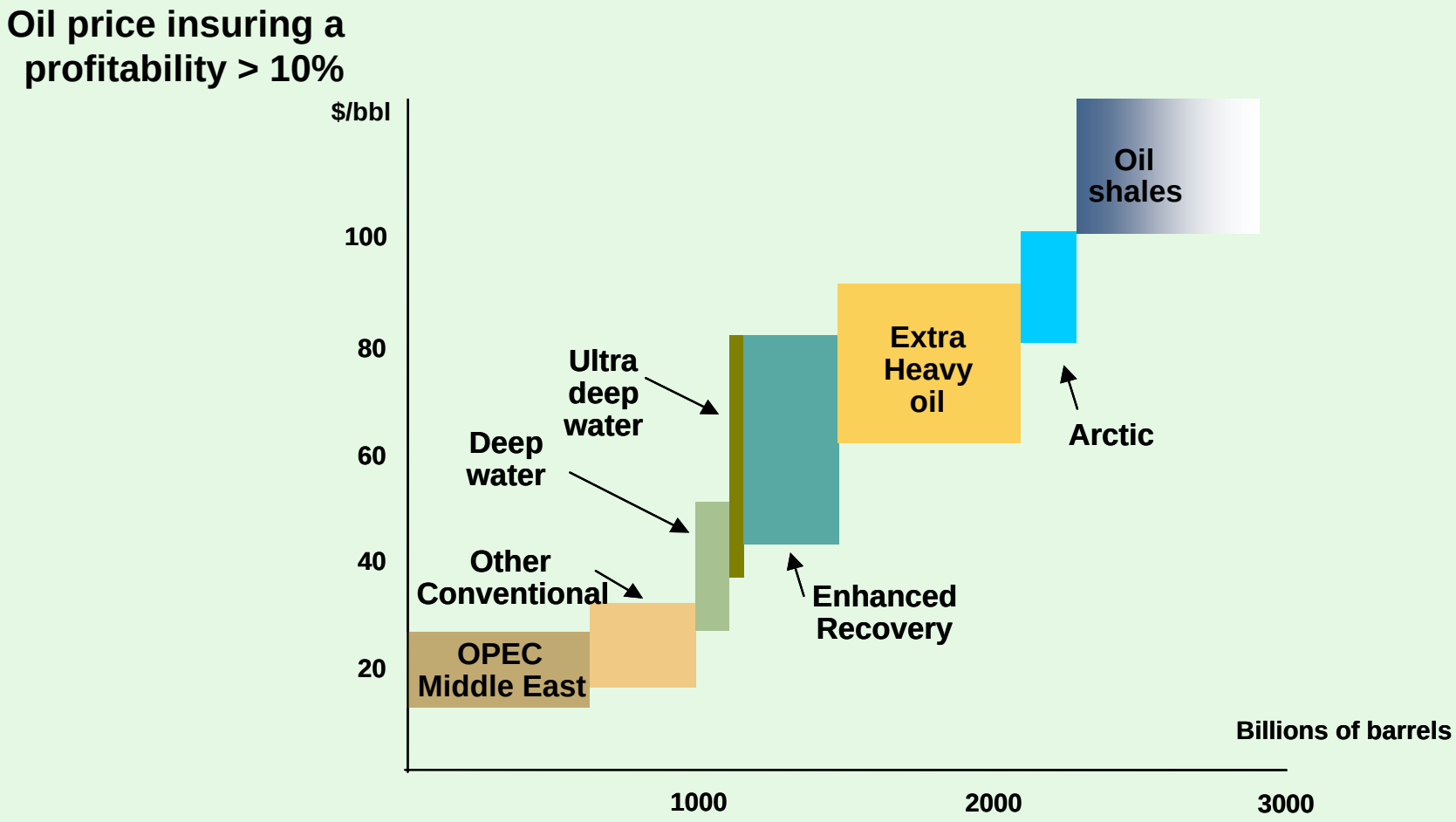
U.S. Oil Production in 2007 – 6.88 x10^6 stb/d

Estimated Cost of a Barrel of EOR Injectant...



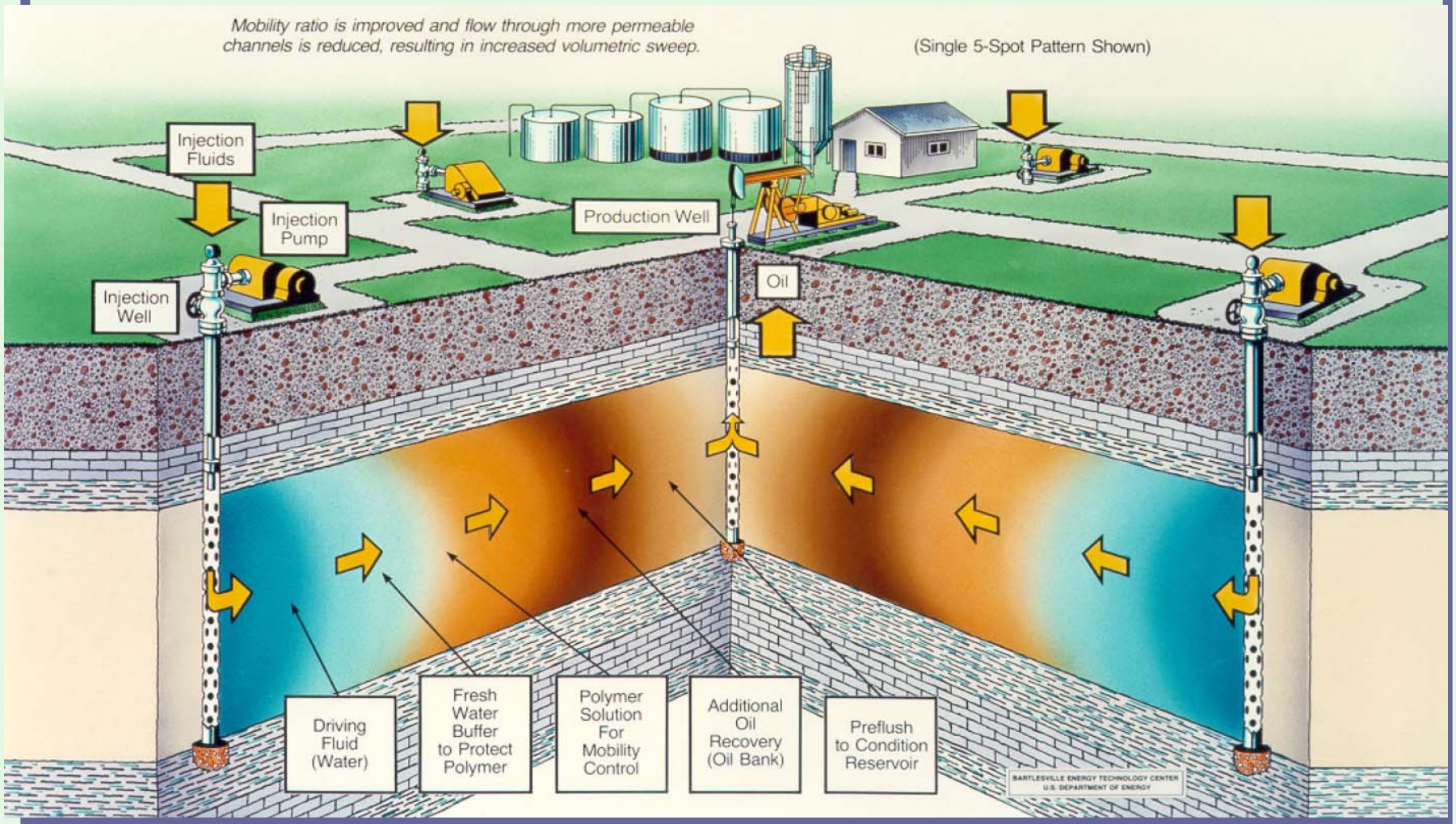
From Taber (1990)

Long term oil supply cost curve

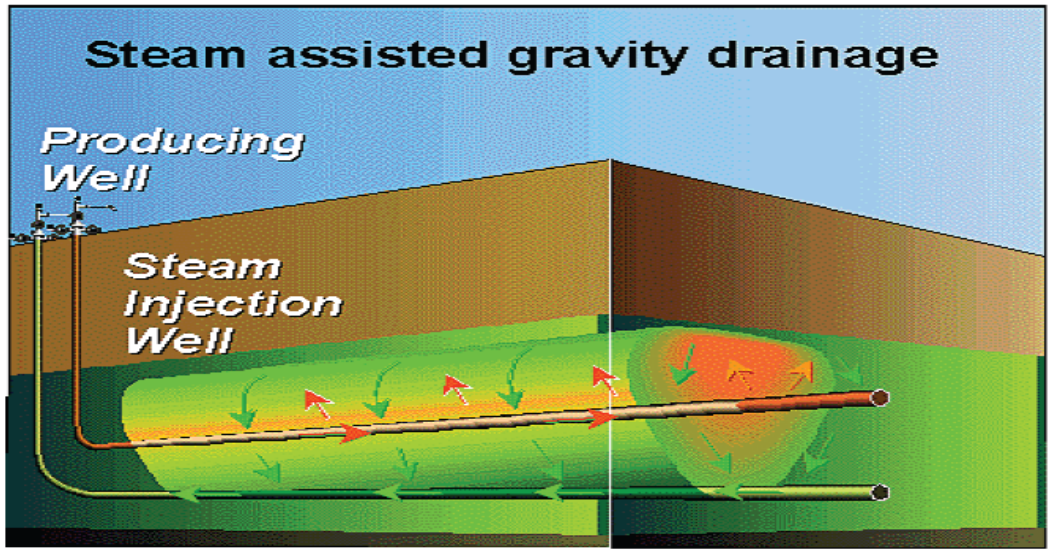


Sources : AIE, Total

Polymer Flooding



SAGD , the technology used in Athabasca



High recovery if reservoir suitable

- Reservoir depth > 80 m
- Minimum Pay zone > XX m
- Horizontal wells
  - 500 – 1000 m long
  - 5 m between injector & producer

BUT…..

- Very large energy needs and large CO_2 emissions
- Requires equipment compatible with high temperature : pumps, sensors, multiphase meters,..

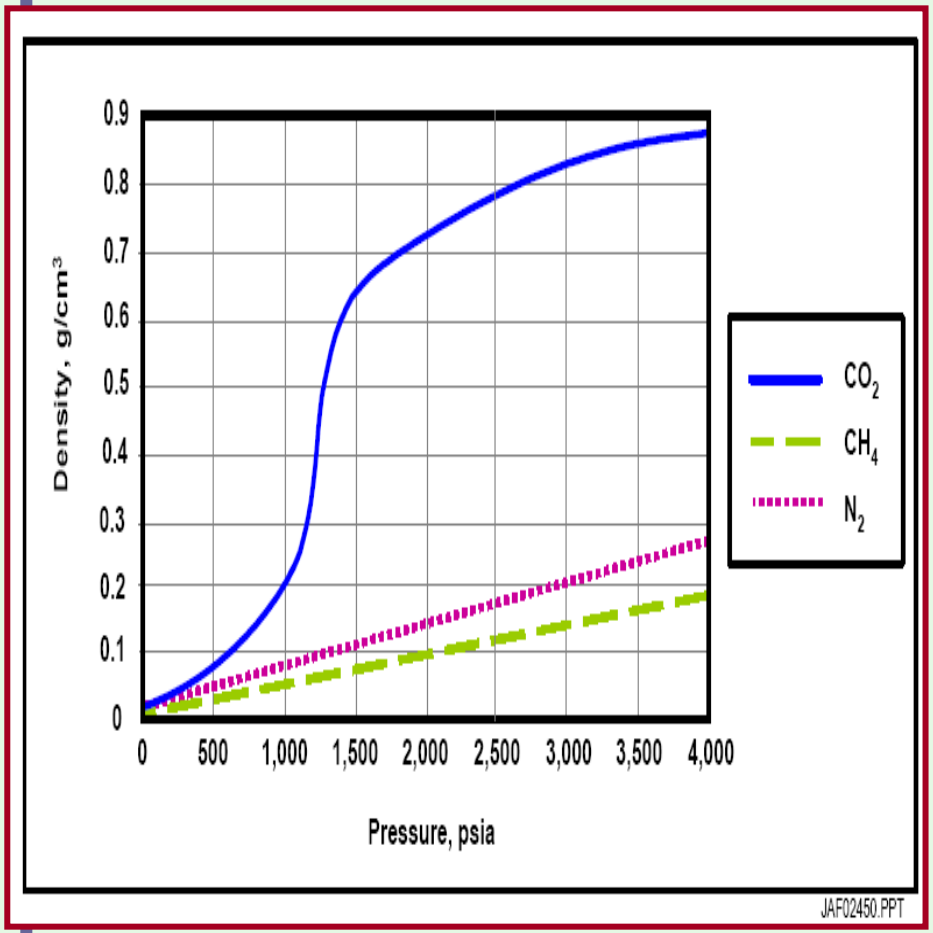
Typical 100 kbopd SAGD Project

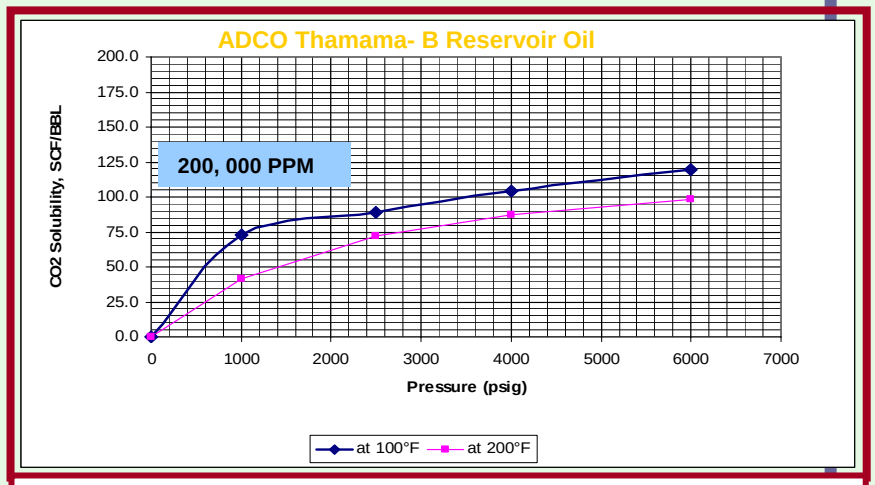
- Steam requirement: 250 kbspd (1650 t/h)
- Energy requirement: 1100 MWth
- Equivalent auto consumption: ~ 20%
- CO_2 emission: 60 kg/b (12 000 t/d) – If gas is used as fuel

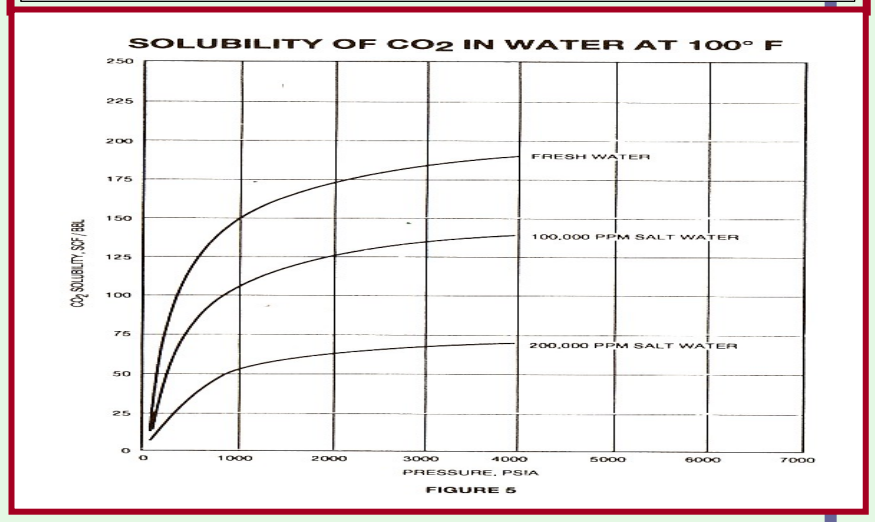
CO_2 and its challenges

- Complex Phase Behavior with Reservoir Oils
- May result in Asphaltene flocculation and deposition
- Corrosion (solubility in Brine)
- CO_2/Brine Carbonate Rock Dissolution
- Accurate Compositional Simulator with Correct Physics is needed to model the CO2-EOR process

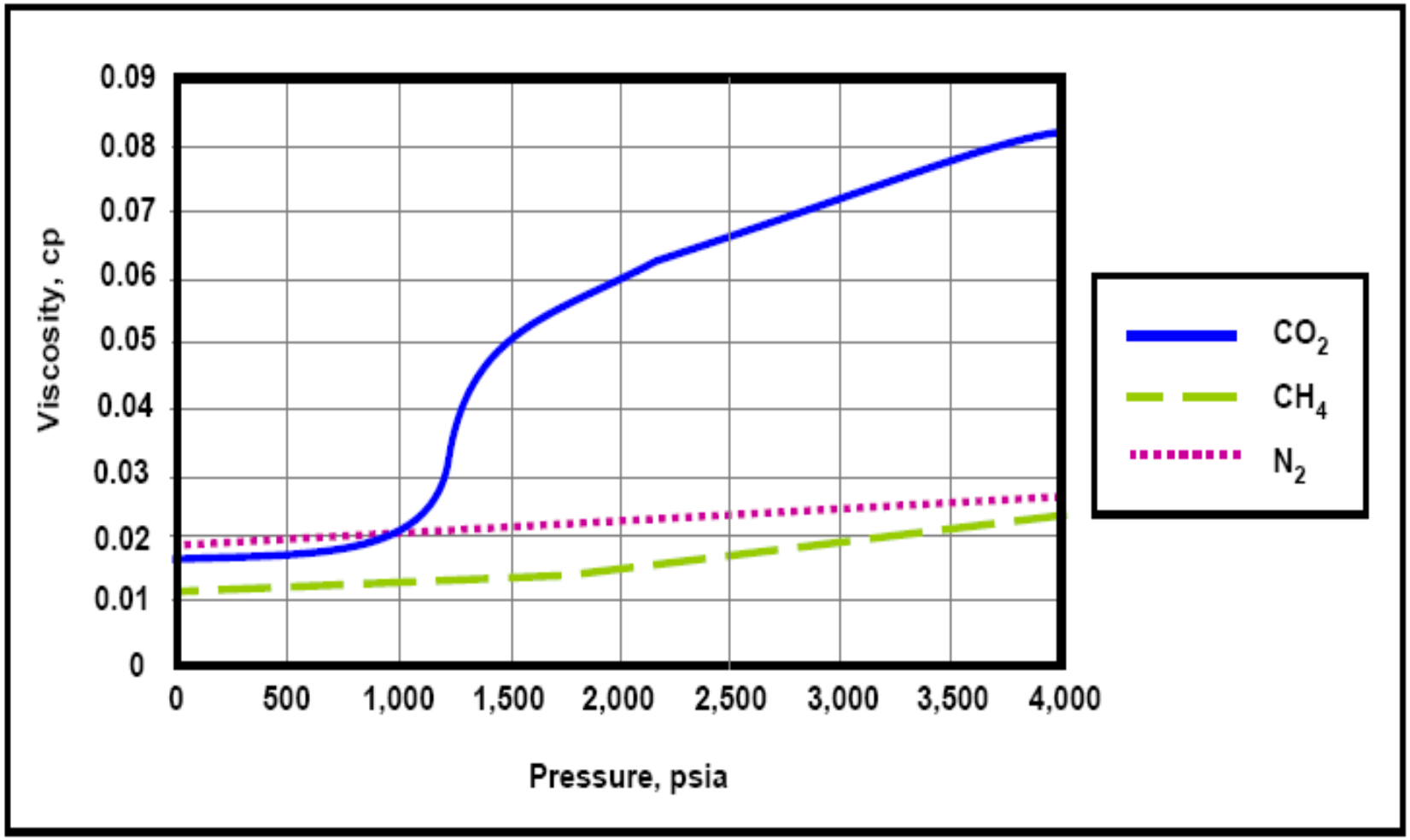
CO2 Properties – Density
Much higher compared to CH4 and N2







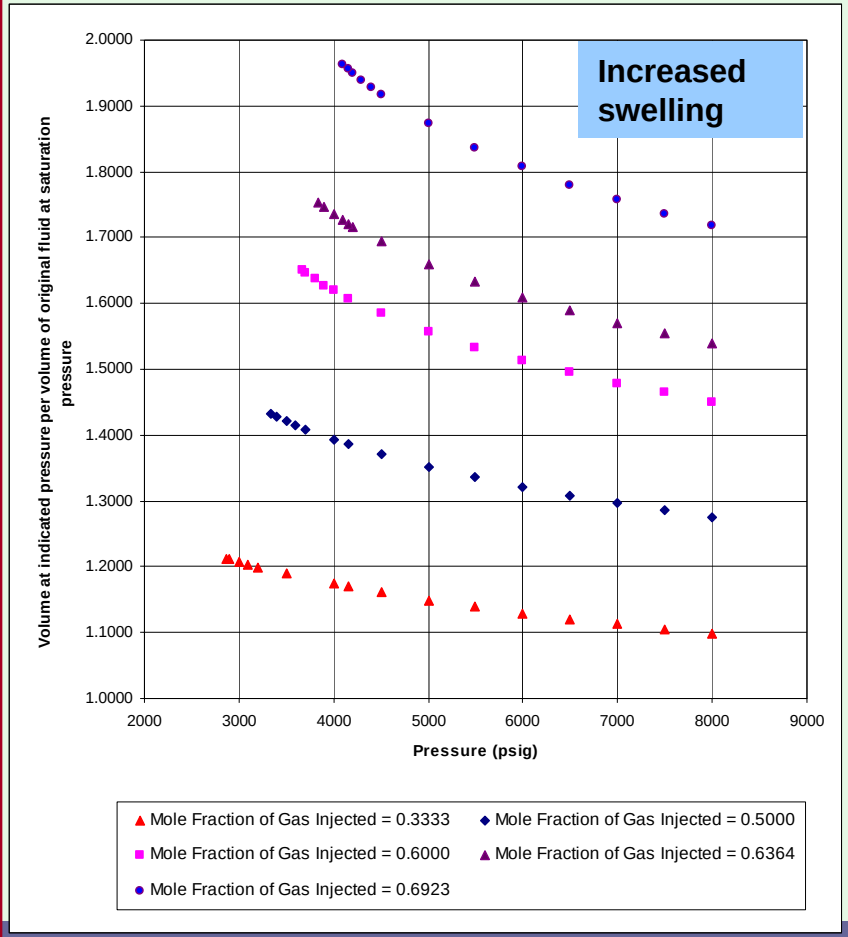
Carbon Dioxide, CH_4 and N_2 viscosities at 105^0F. At high pressures, the viscosity of CO_2 is also greater then that of methane or nitrogen, although it remains low in comparison to that of liquids. Viscosities were calculated with an EOS.

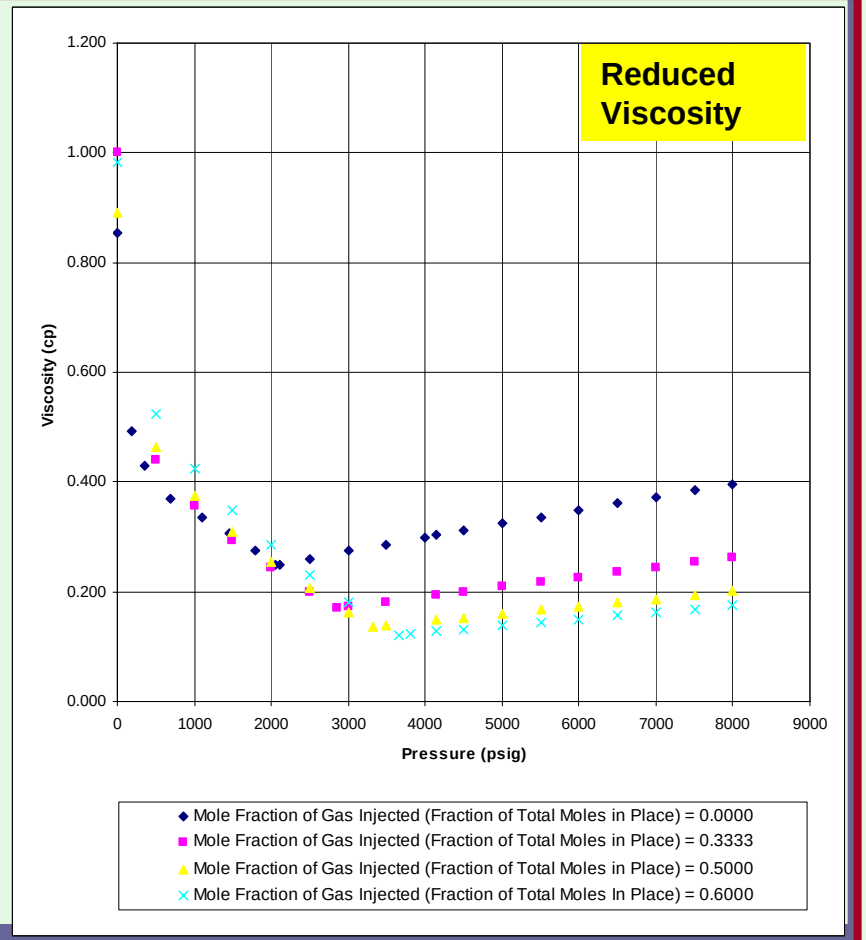


CO2 – Reservoir Oil Properties

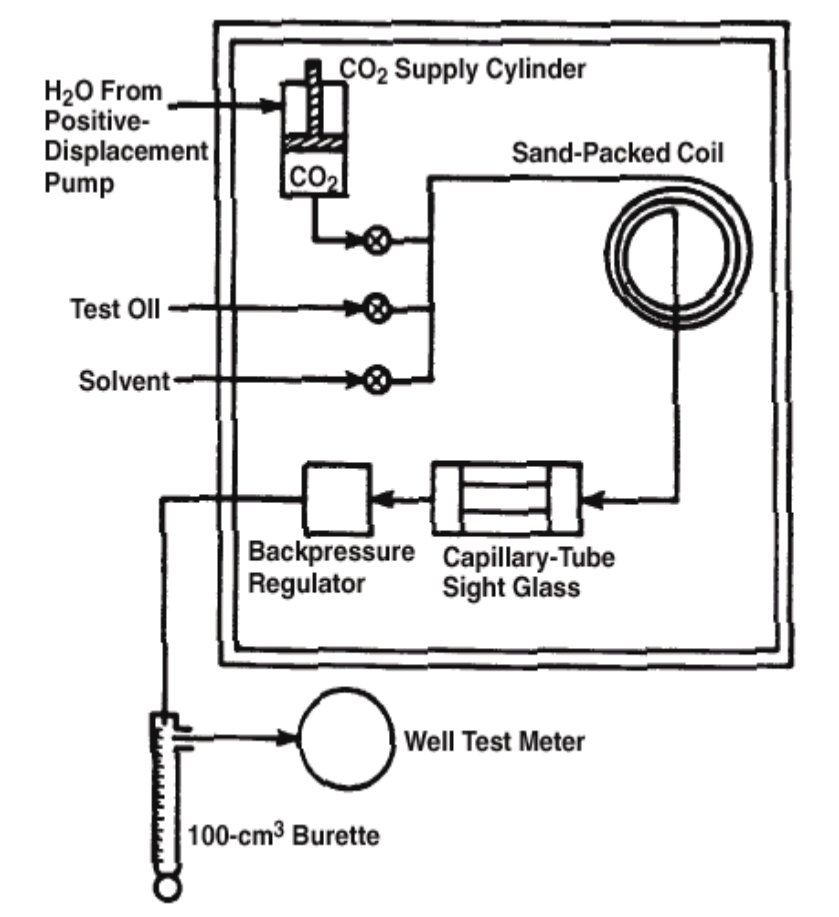
Oil with dissolved CO2 –Increased swelling , Reduced Viscosity

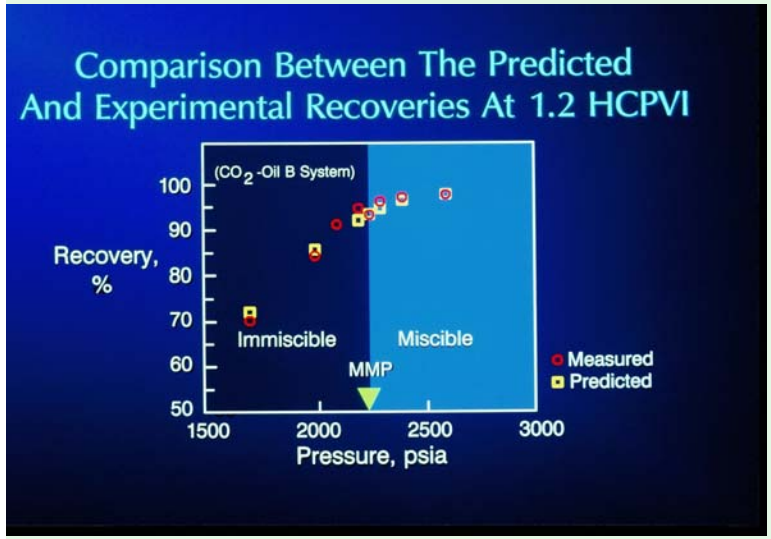
ADCO Advanced PVT Results

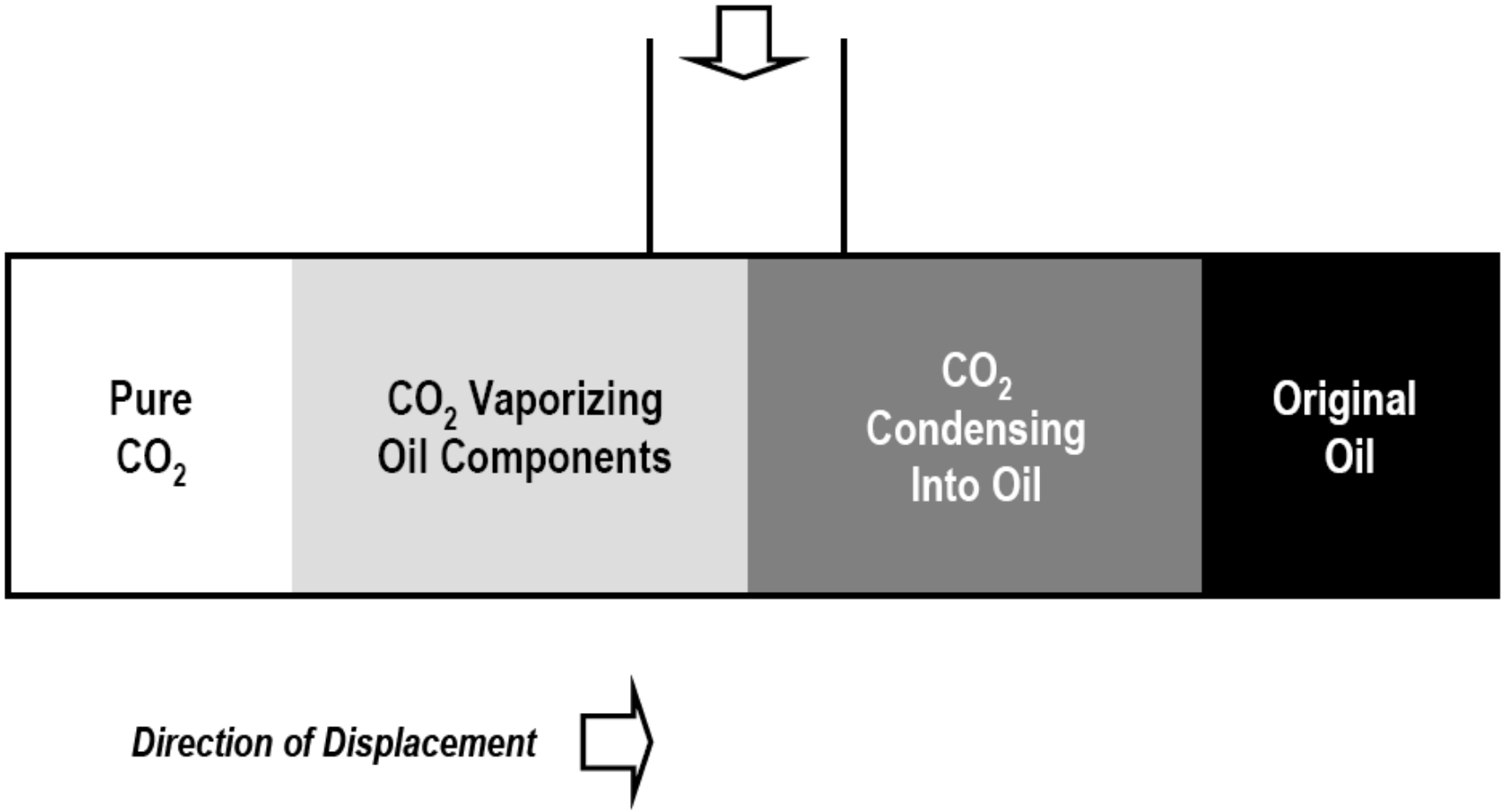




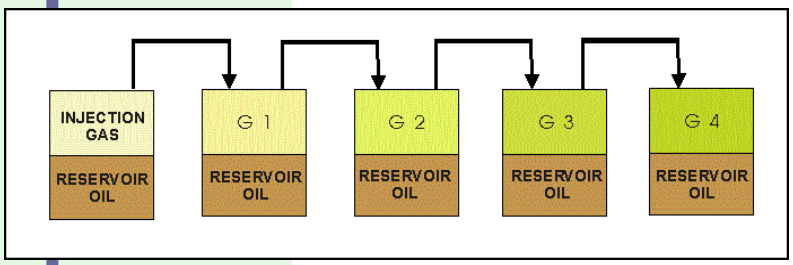
CO2 – Reservoir Oil Properties
Slim Tube Displacements (Determine MMP)

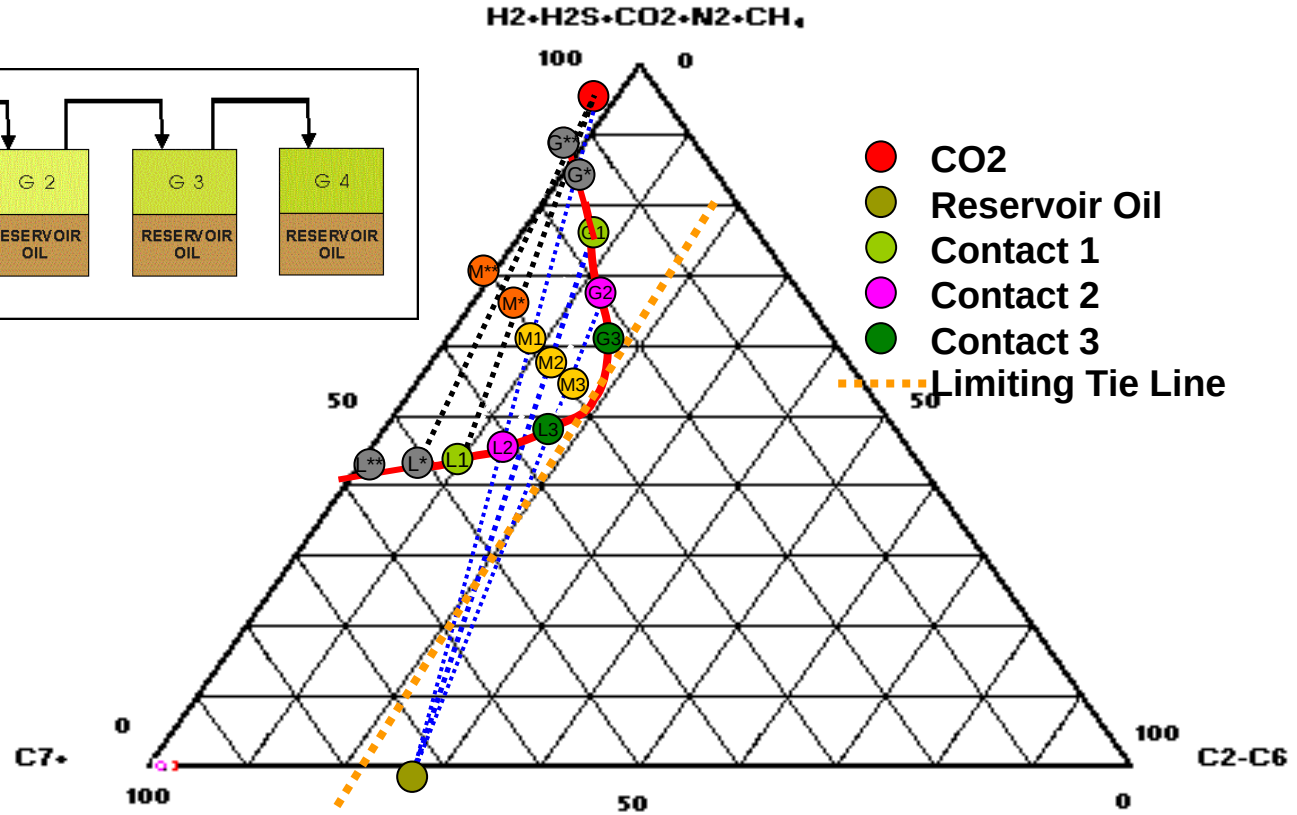




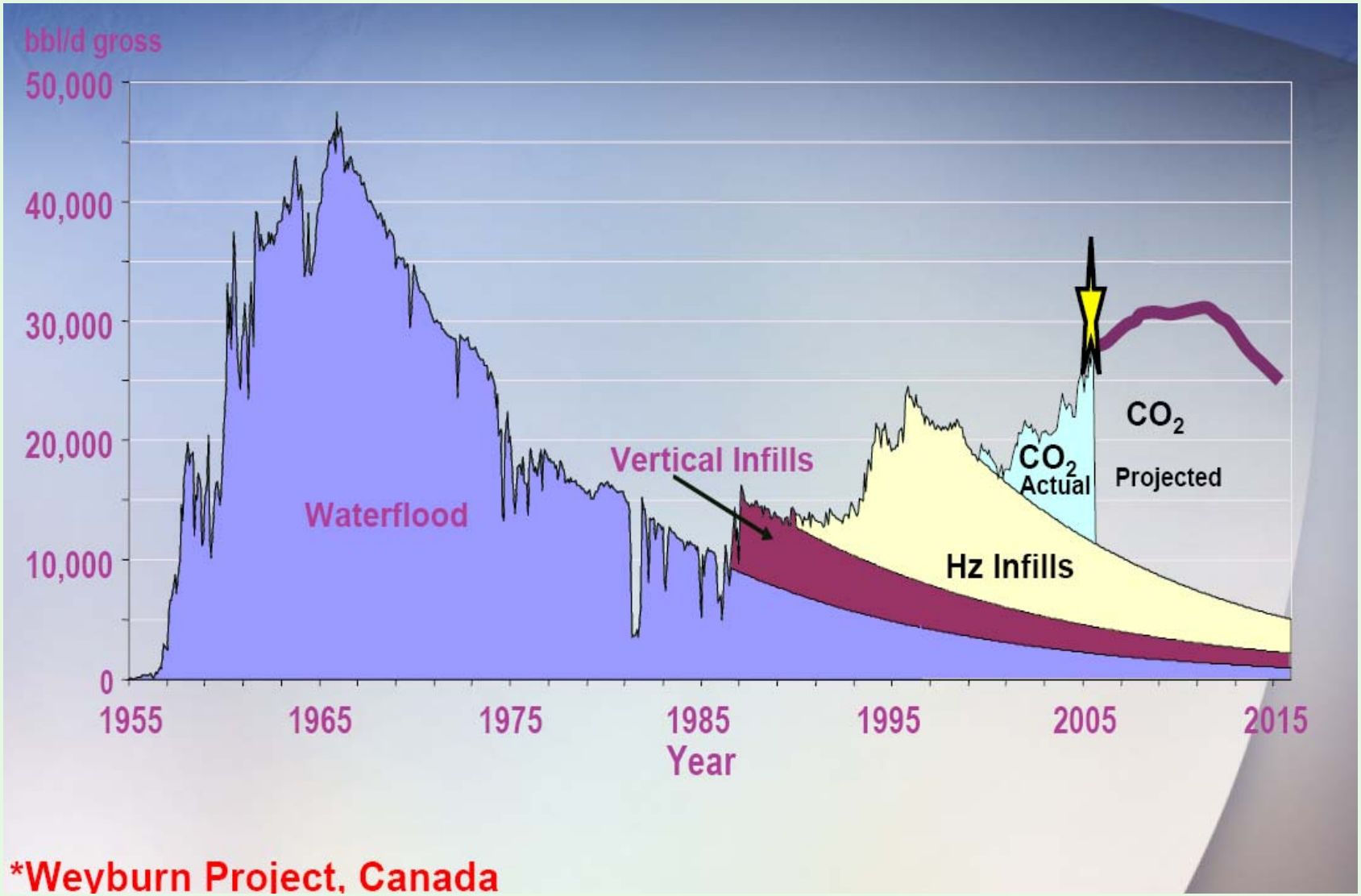

Miscibility is Developed in This Region
(CO_2 and Oil Form Single Phase)
Pure CO_2
CO_2 Vaporizing Oil Components
CO_2 Condensing Into Oil
Original Oil
Direction of Displacement

CO_2 – Reservoir Oil Properties
Multi-contact vaporization experiments





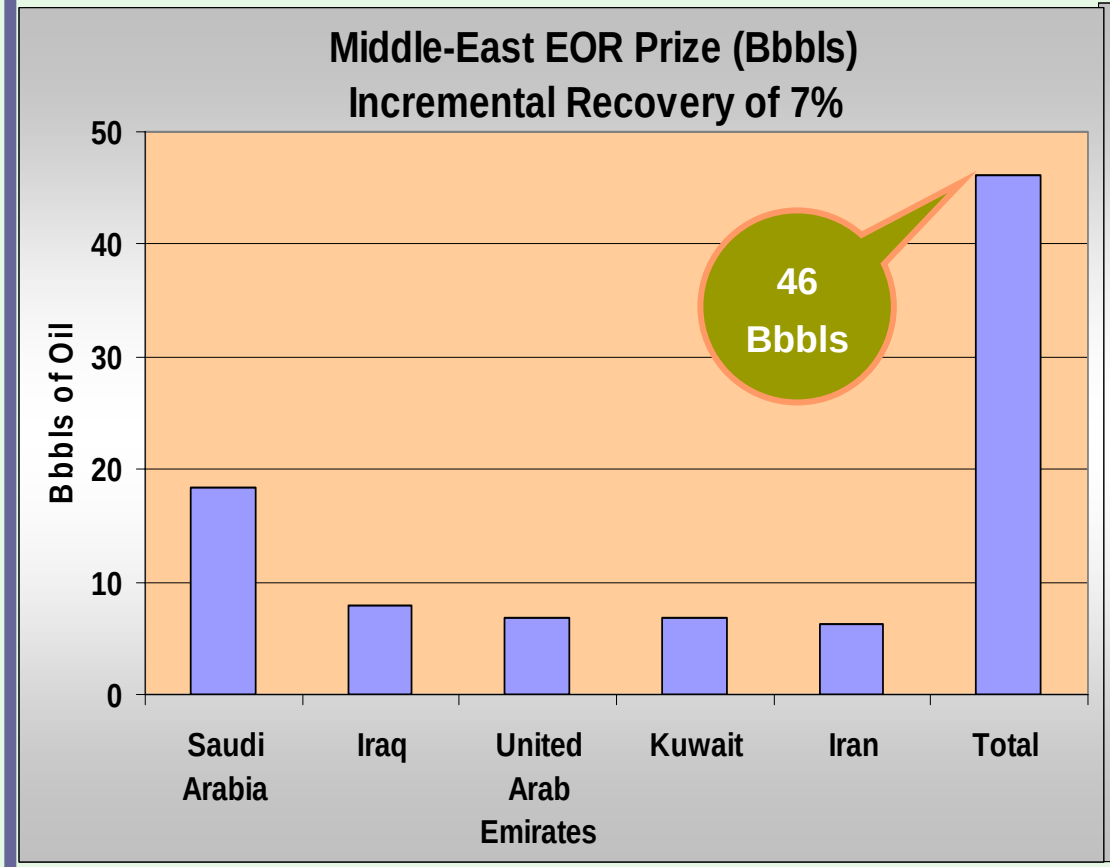
Example of CO_2 project

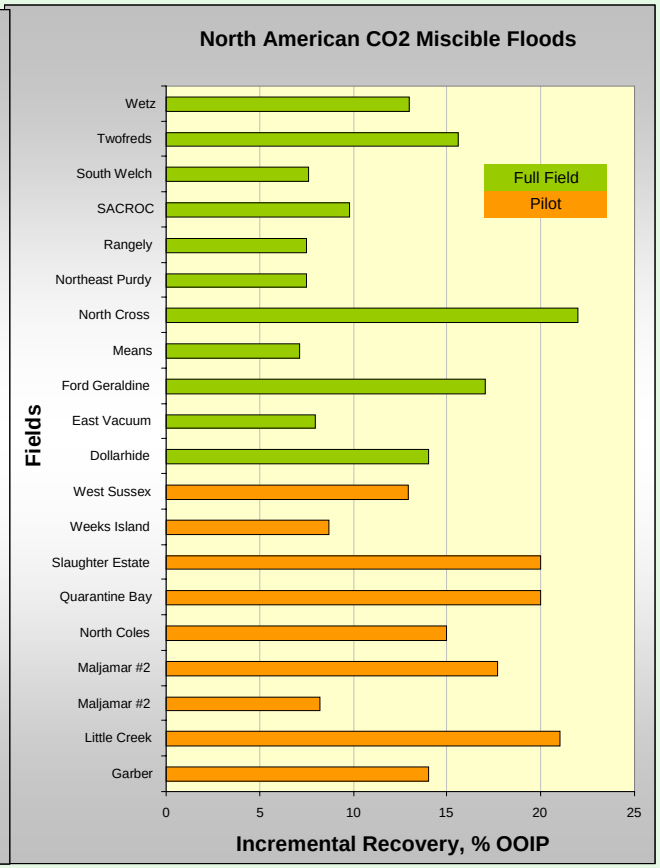


INCREMENTAL RESERVES POTENTIAL

CO_2 EOR has potential to add significant reserves in the middle-east

US Department of Energy 2004





BP Statistical Review of World Energy June 2003, *OGJ Dec 2002

Objectives for current Abu Dhabi CO2 pilot (started 9 Nov. 2009)

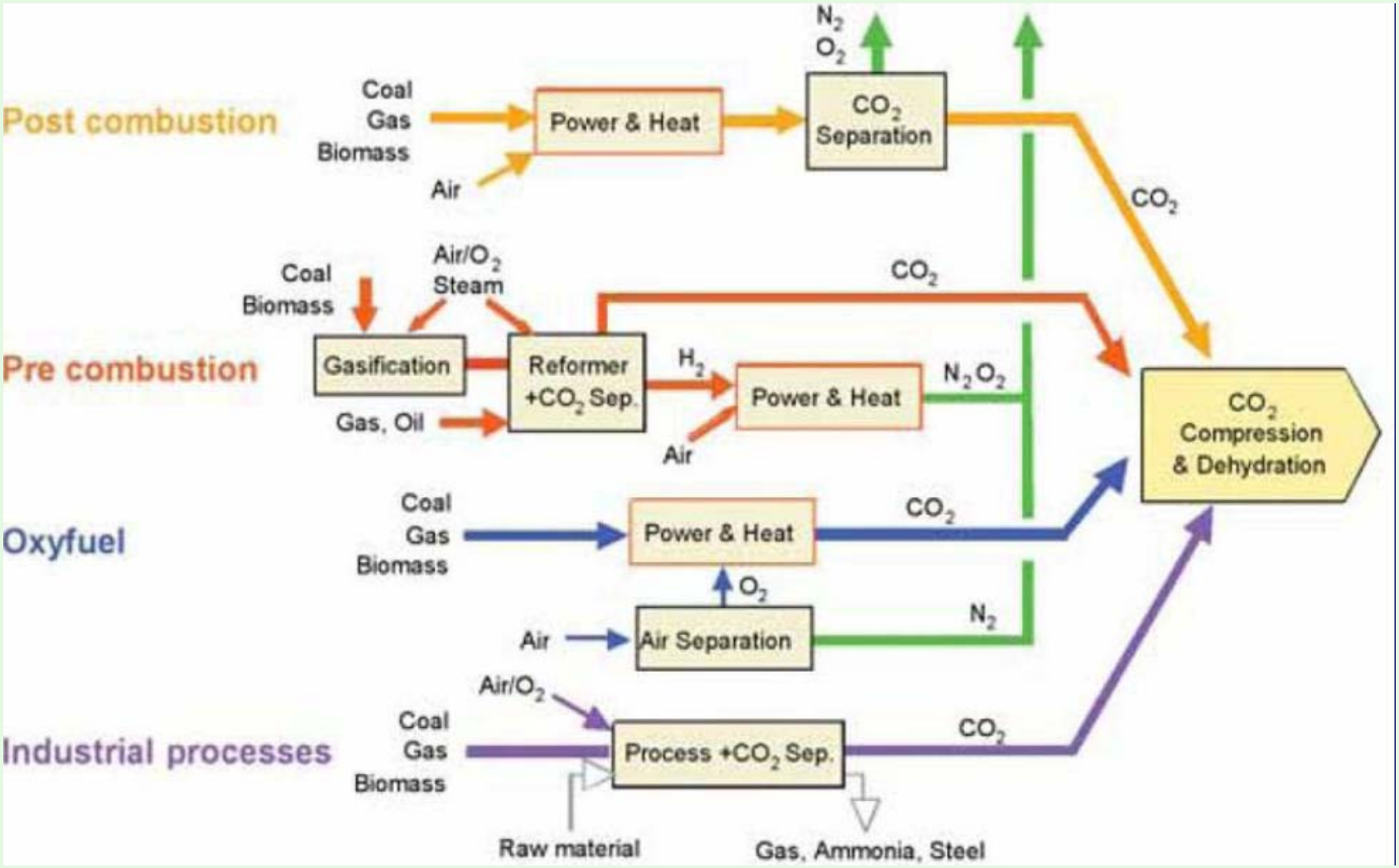
Initial Scheme: CONTINUOUS CO2 INJECTION

- Determine occurrence of asphaltene deposition if any
  - And therefore impact on CO2 on injectivity
  - Rock fluid interaction being studied extensively in the lab. Also possible to convert to WAG after one year of continuous injection.
- Determine issues related to well designs especially for mitigation of corrosion , facilities handling & injection capabilities
- Obtain field data to calibrate reservoir models and laboratory results
- Appraise CO2 enhanced oil recovery potential in a tight reservoir
- Verify the CO2 injection requirements for full field development

Laboratory studies

- **CO_2 PVT/Advanced PVT studies**
  - **Slim Tube-MMP determination**
  - **CO2-Swelling**
  - **EOS modeling**
  - **CO2 solubility in Brine (Variable salinity/P/T)**
- **CO_2 core flooding (SCAL)**
  - **Secondary/WAG/Tertiary CO_2 Flooding**
  - **Rock fluid interaction studies**
  - **Ultimate Recovery**
- **Asphaltene**
  - **CO2-Asphaltene flocculation studies**
  - **Asphaltene envelope**

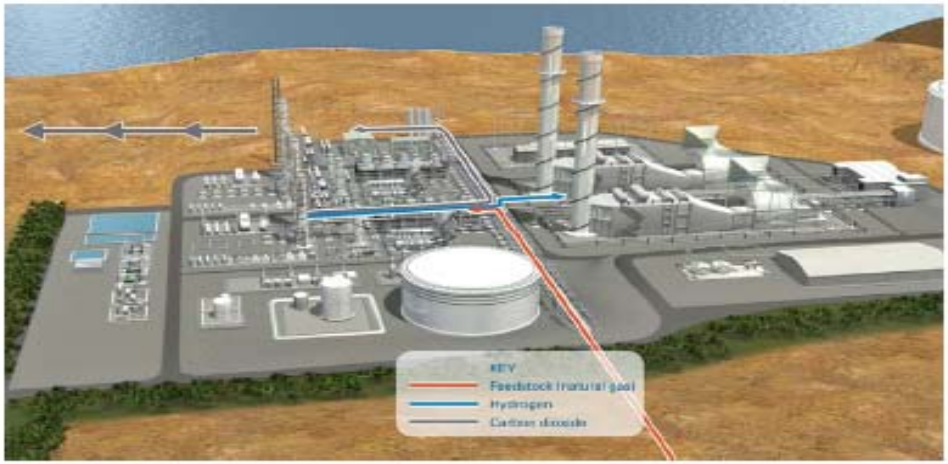
CO2 capture Process



Pre-Combustion Capture -MASDAR

Hydrogen Power Project, Abu Dhabi

MASDAR مصدر bp hydrogen energy



Project Milestones

Could be:

- World's first power plant powered by hydrogen derived from natural gas
- Delivered CO_2 could replace natural gas for Enhanced Oil Recovery
- On-stream by 2012

Climate Change Milestones

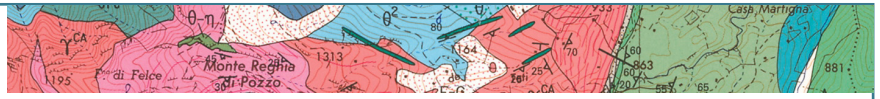
- **420 MW** of low-carbon electricity = 5% of Abu Dhabi's capacity
- **1.7 mmtpa CO_2** avoided = decarbonizing Abu Dhabi's transport sector
- Secure geological storage of CO_2

alternativenergy

CONCLUSIONS

- EOR is a well established concept in the industry and necessary to optimize production and utilize remaining Hydrocarbon resources.
- EOR is required to delay impending Hydrocarbon supply decline
- CO2-EOR for incremental recovery and mitigation of GHG
- Abu Dhabi implementing CO2-EOR. First pilot drilled in Nov. 2009. Expect pilot results and evaluation by end-2010
- Success will sequester most of the produced CO2 in Abu Dhabi

Thank you



MODELING – ASSESSING THE LONG TERM FATE OF CO2

PASCAL AUDIGANE ,

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

Hassi Messaoud, Algeria

16th – 19th November, 2009

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Summary

> Motivation for modelling CCS

- Geological targets
- Physical processes to simulate

> Case study:

- Storage efficiency
- Cap rock Integrity
- Near well effect
- Enhanced Gas Recovery
- Leakage through abandoned well

> Actual limitations of numerical tools, future works…

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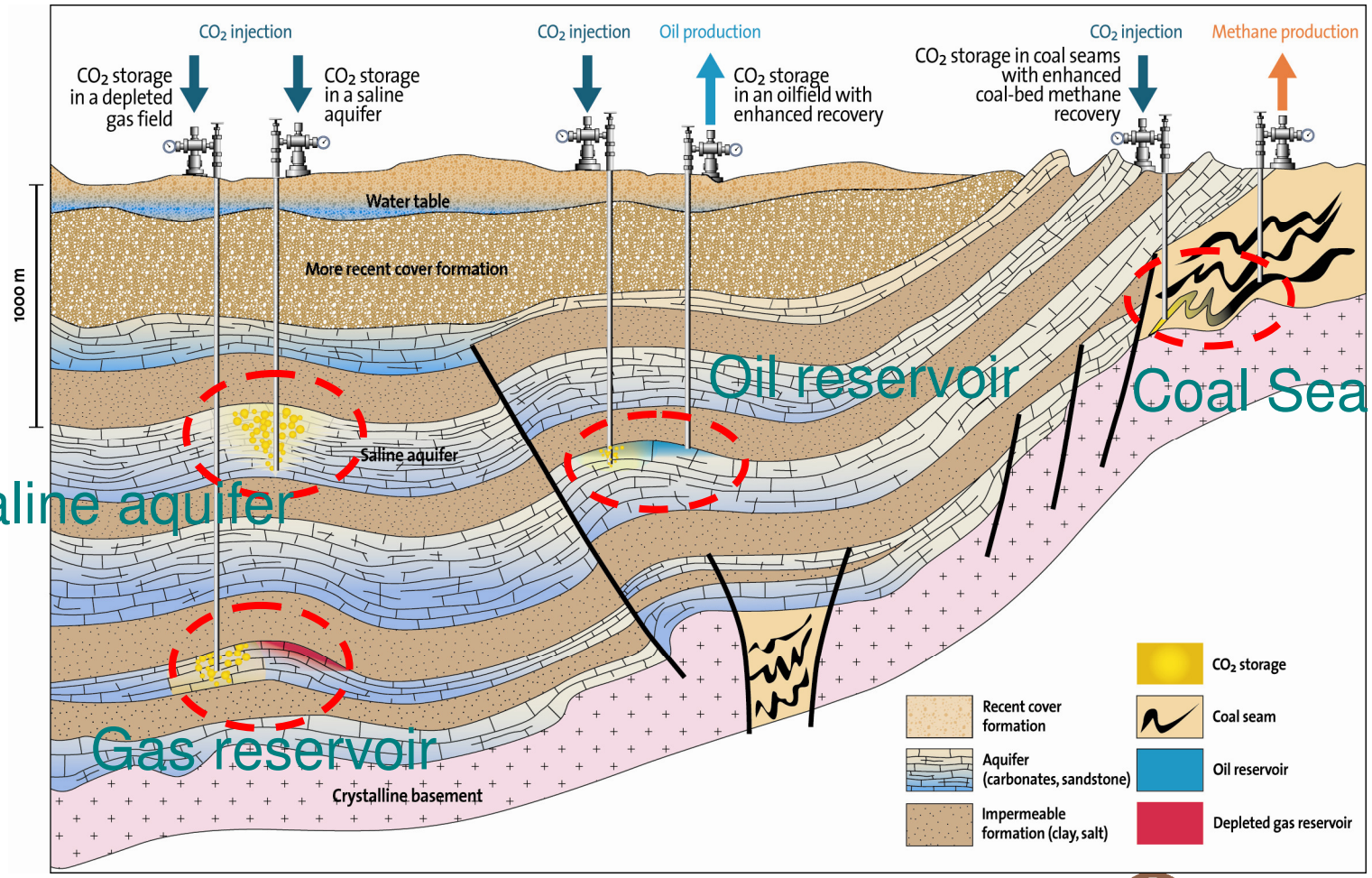
Geological Storage Targets



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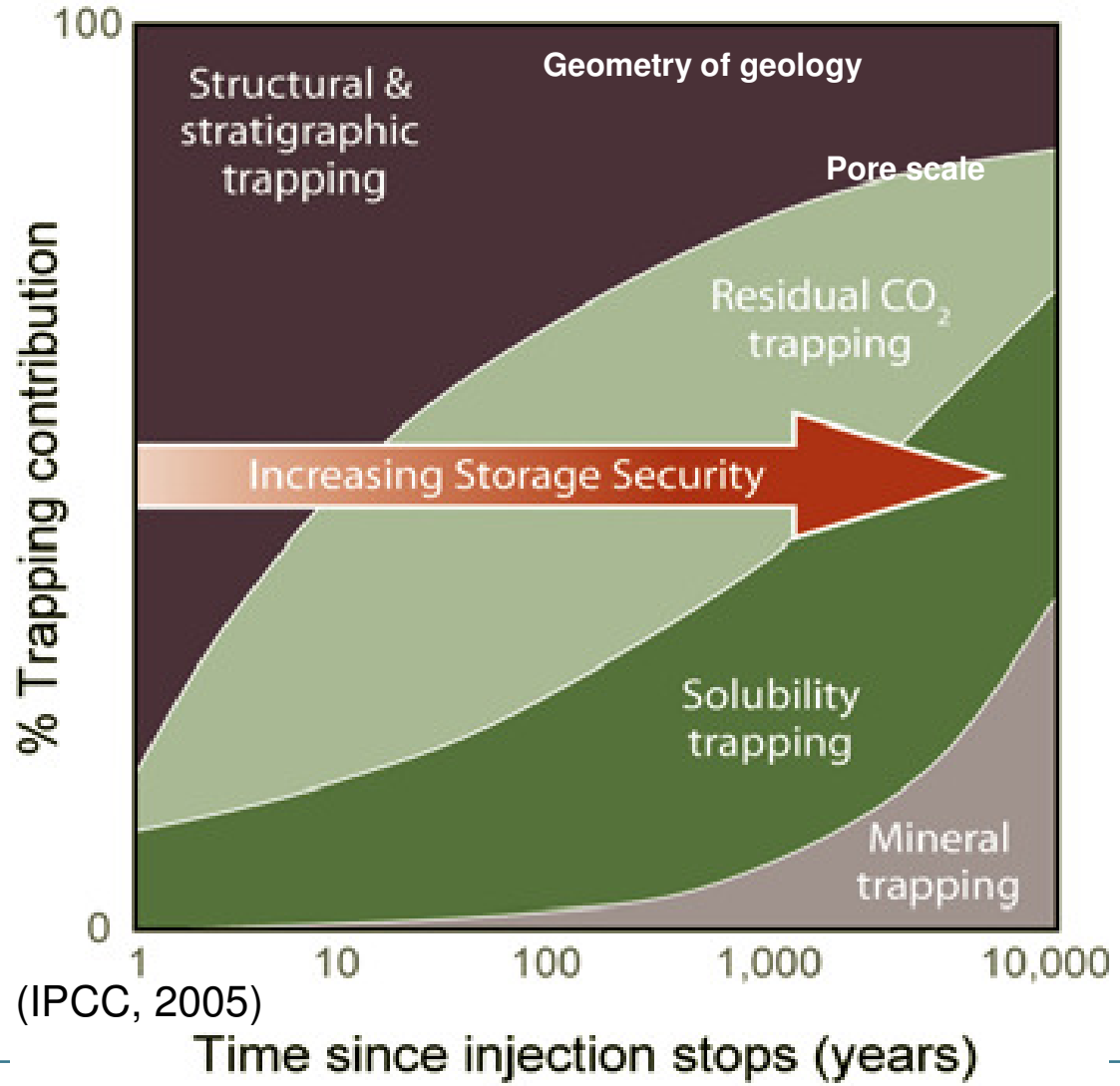
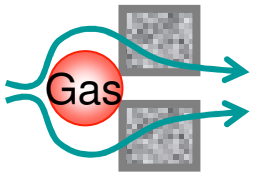
Trapping mechanisms versus characteristic time



(IPCC, 2005)

Residual trapping



Solubility trapping

Liquid

Mineral trapping

Solid

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Physical processes

- **Multiphase flow**
- **Dissolution**
- **Fluid rock interactions**
- **Capillary forces**
- **Many other important processes are not presented here (geomechanic, geophysics, thermal…)**

- **Why:**
  - **Efficiancy estimate**: how much CO2 can we store?
  - **Storage security**: Pressurization, sealing integrity, gas bubble extension, leakage path
  - **Time scale issue**: Short and long term evaluation
  - **Lenght scale issue**: near well effect, hydrological impact at the basin scale, water quality…

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Scenario 1:

- **Storage efficiency**
- **Long term fate of CO2**
- **Multiphase fluid flow**
- **Heterogeneity**
- **Fluid rock interactions**
- **Kinetics**
- **Mineral, solubility, structural, residual trapping**

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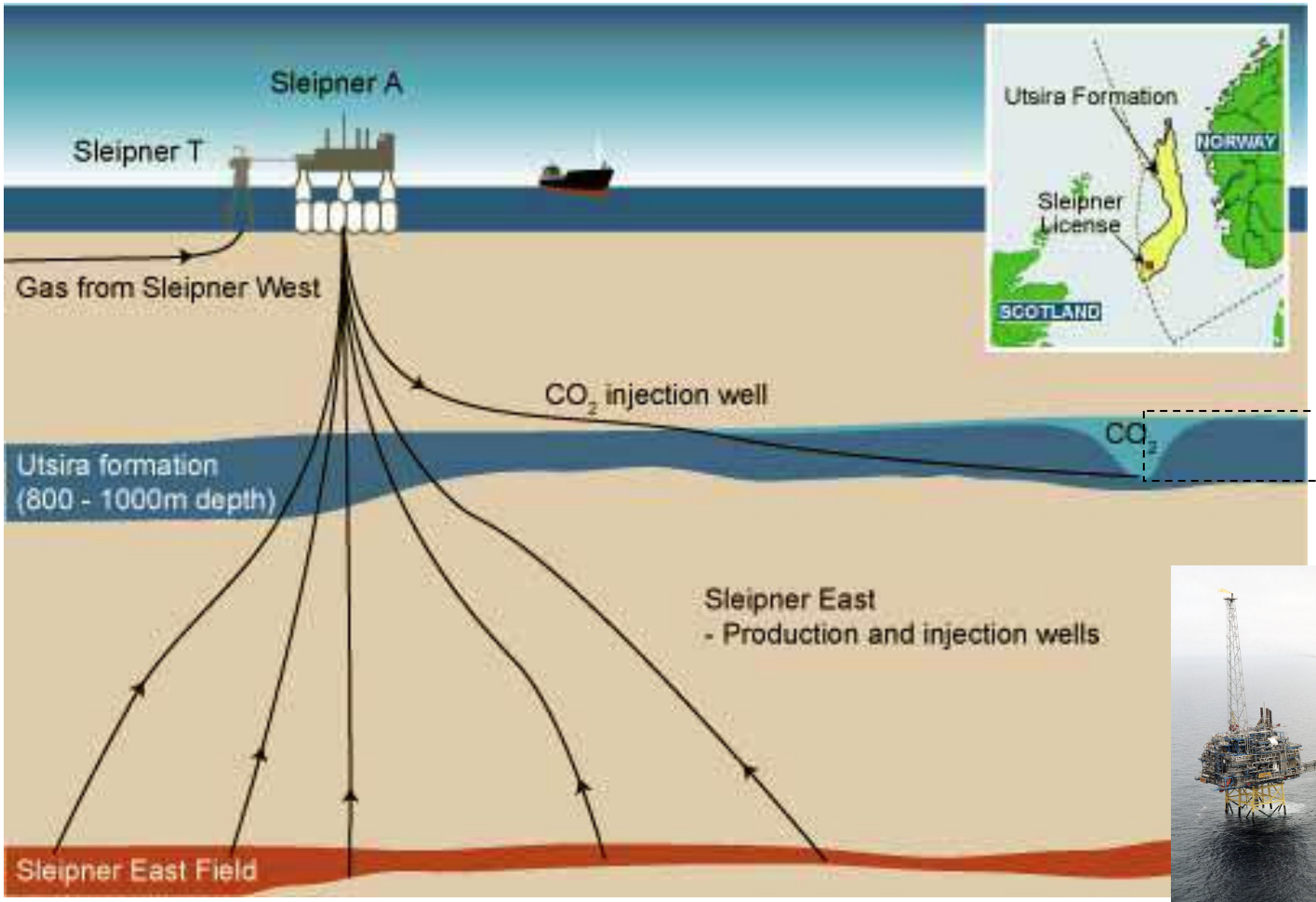
The Sleipner CO_2 storage project



▸ 2D radial geometry

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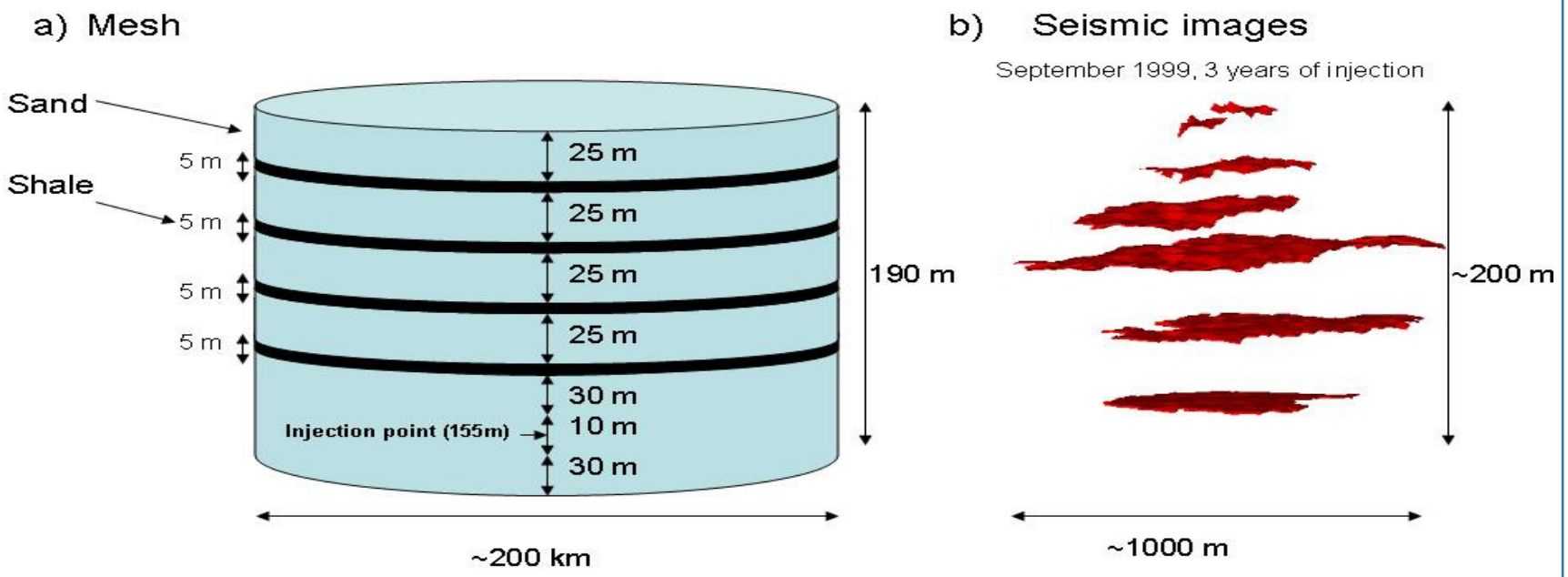
2D model of CO_2 injection at Sleipner

(Audigane et al., 2007a, Am. J. of Sc., In Press)



- 184 m thick reservoir formation with alternance of sand layers and shale layers
- Vertical 2D mesh with a cylindrical geometrical configuration, centered around an injection point located 155 m beneath the top
- Mesh: 22 layers in the vertical and 52 cells in the radial direction with logarithmic progression

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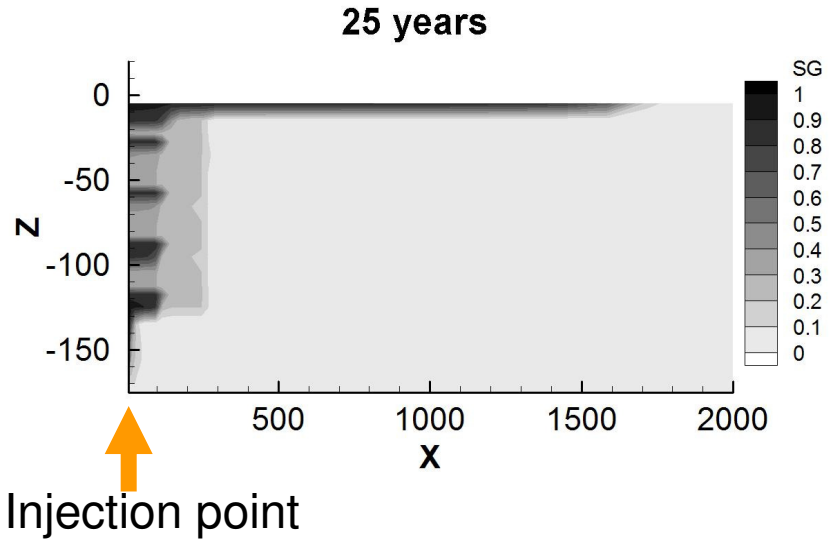
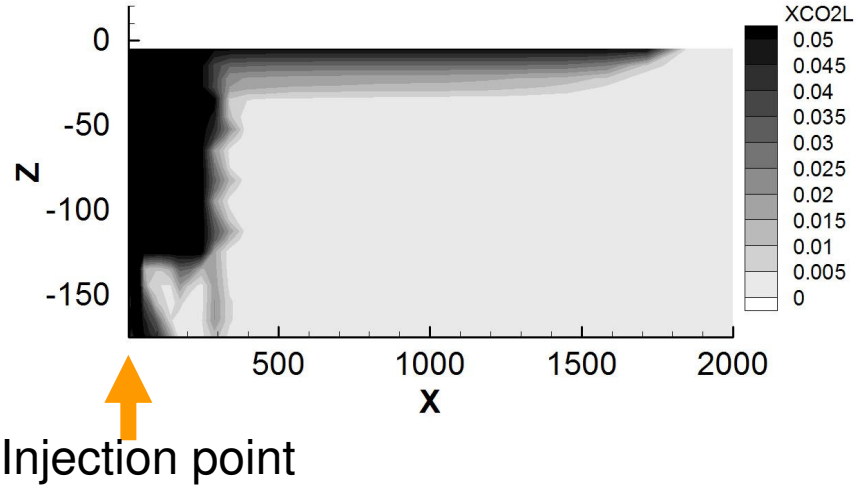
CO_2 migration after 25 years of injection



Concentration of supercritical CO_2 in the reservoir

Note the accumulations under the Shale layers



Amount of dissolved CO_2 in the water (mass fraction)

- Above the injection point maximum saturation is reached
- At the edges we see lower saturation ranges

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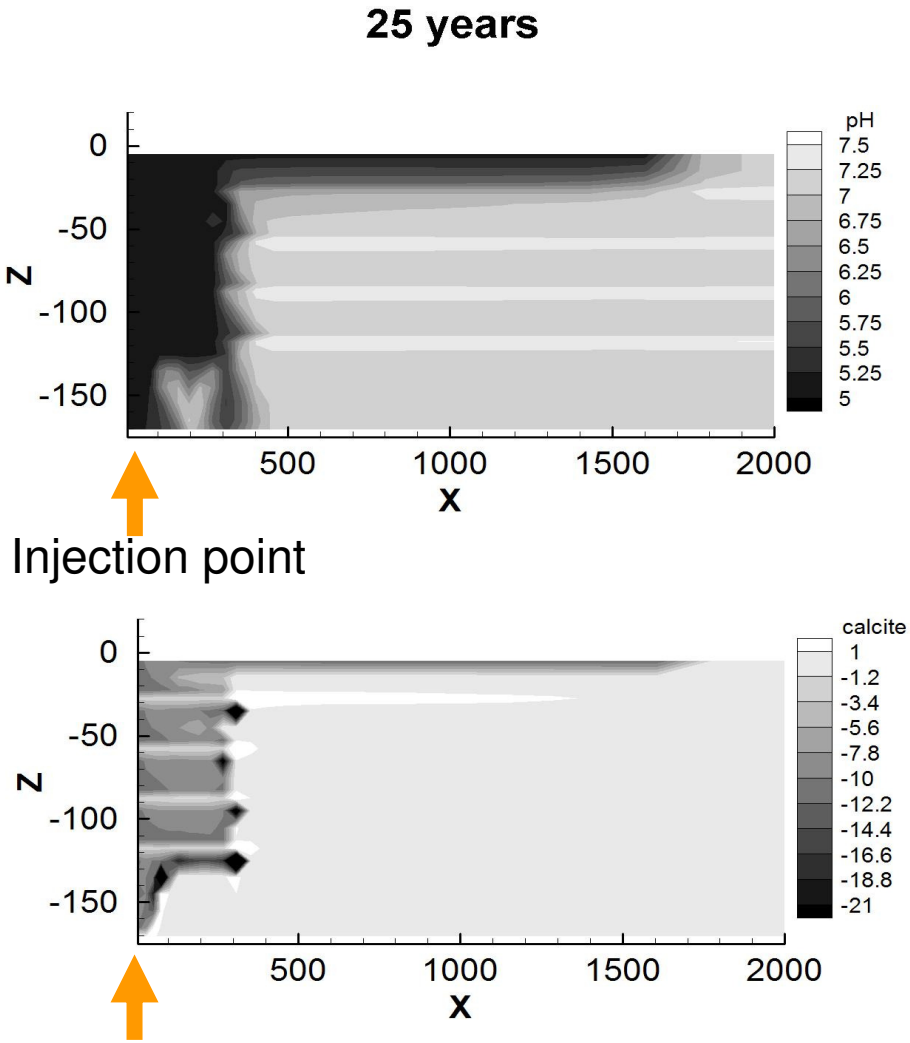
Effects of CO_2 dissolution after 25 years of injection



The negative sign corresponds to mineral dissolution

pH change of the water due to CO_2 dissolution.

However pH doesn't decrease below 5.13, due to buffering by calcite dissolution.

Calcite dissolution (mol/kg^3) in the acid water.

The dissolution of calcite is less pronounced in the shales than in the sands. However *some calcite precipitates below each shale layer* at the interface between the CO_2 saturated brine and the initial brine, due to mixing of different waters in these regions.

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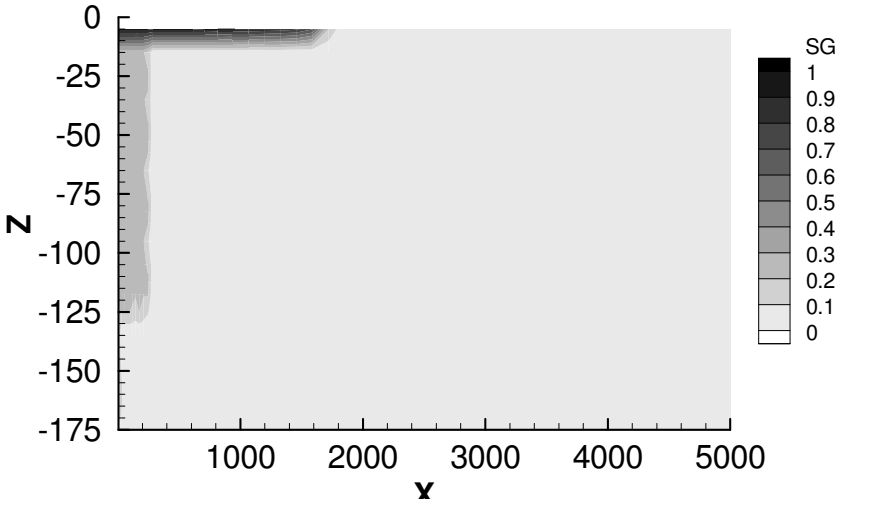
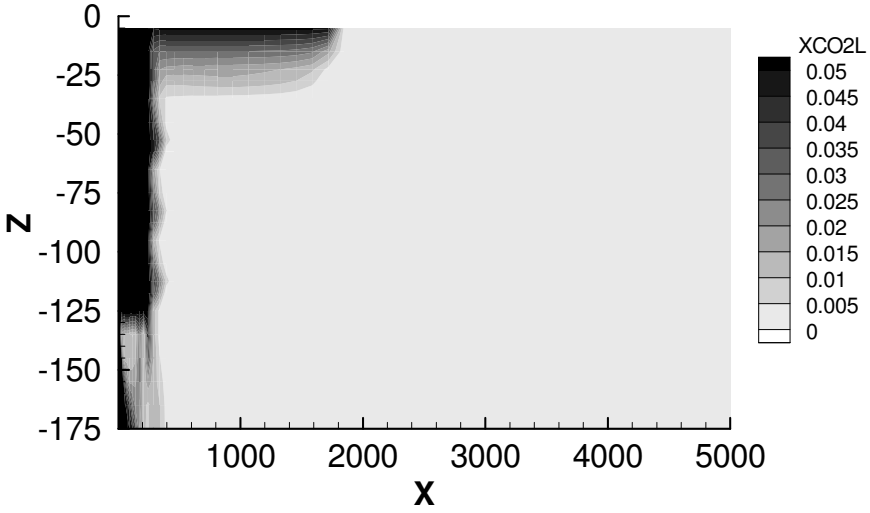
CO_2 migration after 50 years with injection only in the first 25 years



Concentration of supercritical CO_2 in the reservoir

Note how almost all CO_2 has moved to the top of the reservoir



Amount of dissolved CO_2 in the water (mass fraction)

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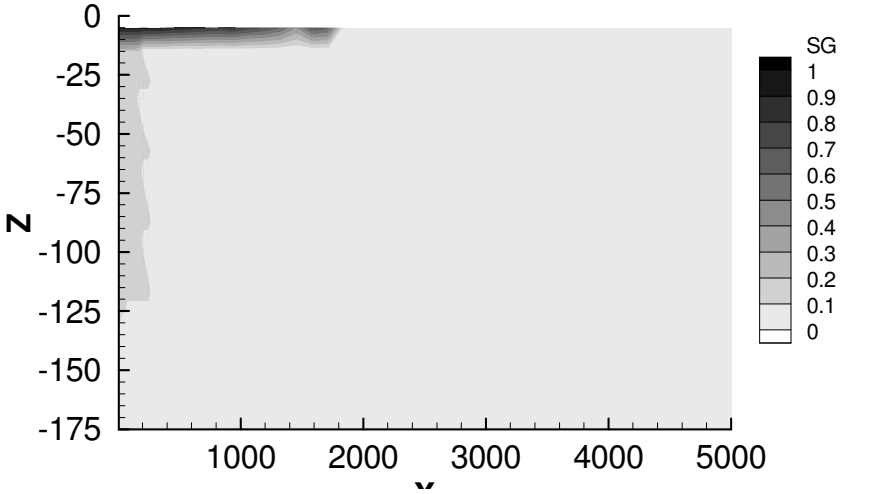
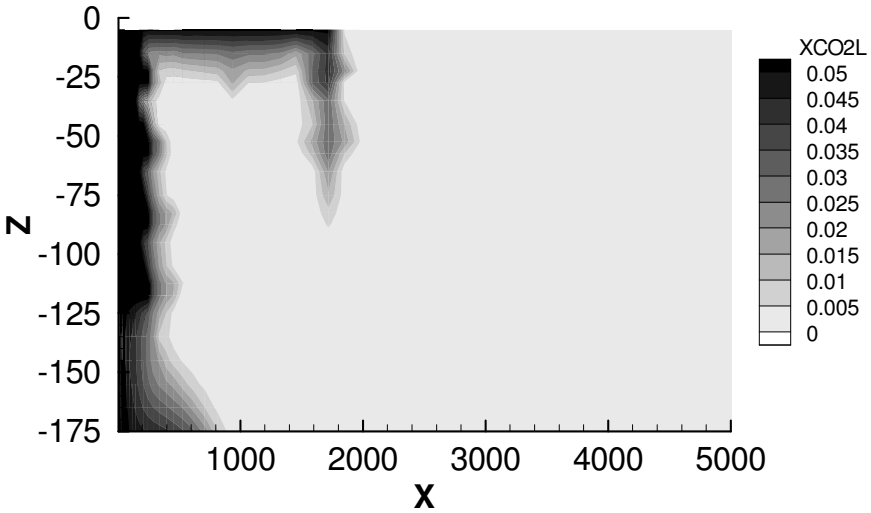
Similar, but after 1000 years …



Concentration of supercritical CO_2 in the reservoir



Amount of dissolved CO_2 in the water (mass fraction)

Note that brine with dissolved CO_2 migrates downward as it is approximately 10 kg/m3 denser than brine without CO_2.

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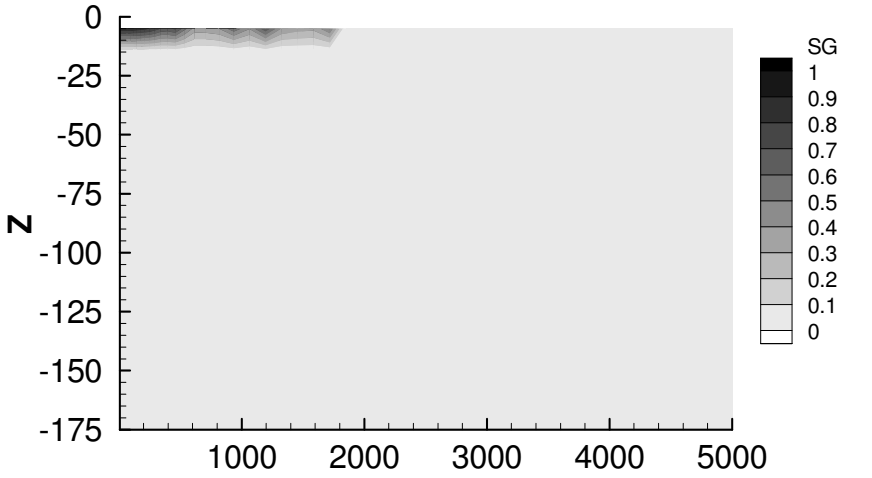
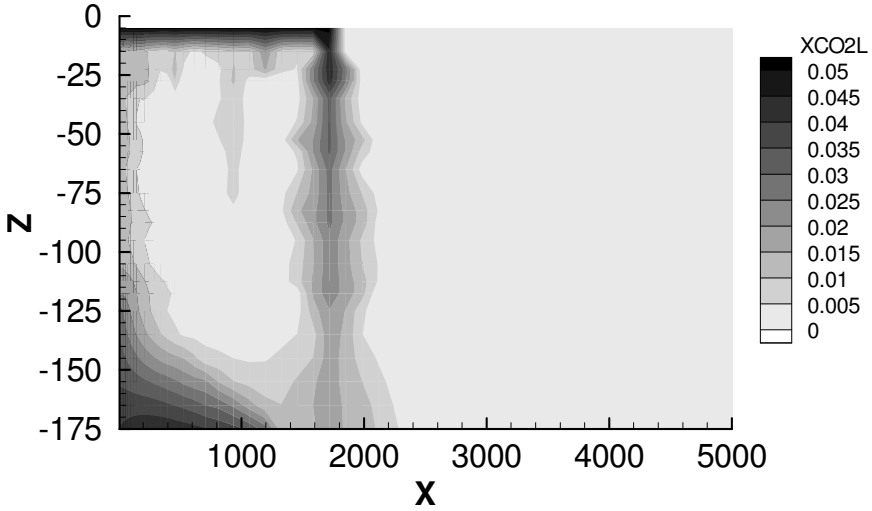
… After 2000 years …



Concentration of supercritical CO_2 in the reservoir

Note how almost all CO_2 has dissolved already.

The CO_2 plume extends to a maximum radius of 2,000 m around the injection well.



Amount of dissolved CO_2 in the water (mass fraction)

Note convection induced by density gradients

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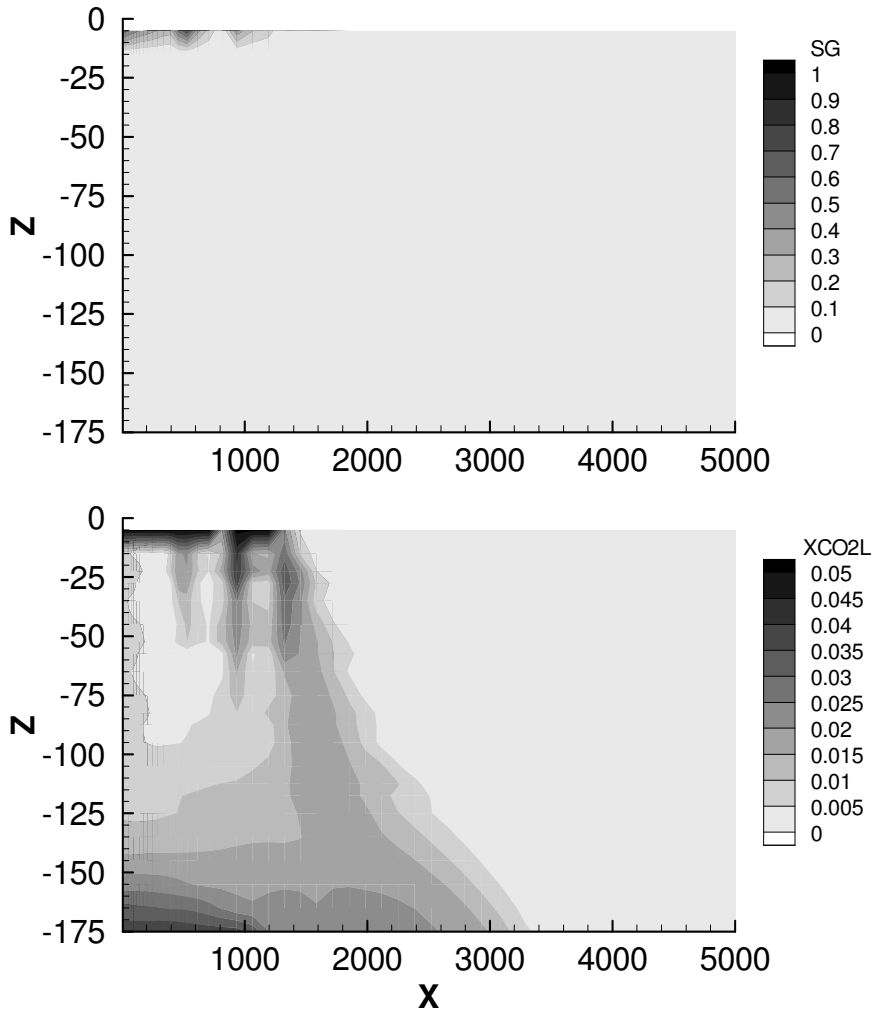
… After 5000 years …



Concentration of supercritical CO_2 in the reservoir

Note how almost all CO_2 has dissolved already.

Amount of dissolved CO_2 in the water (mass fraction)

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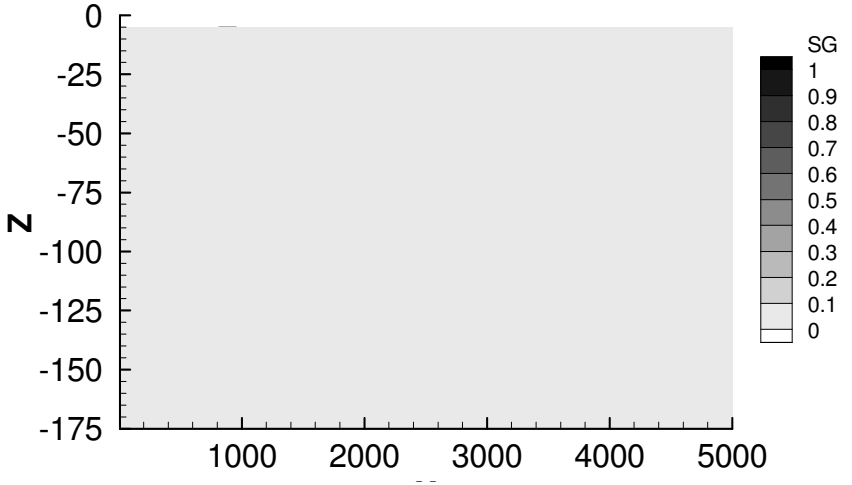
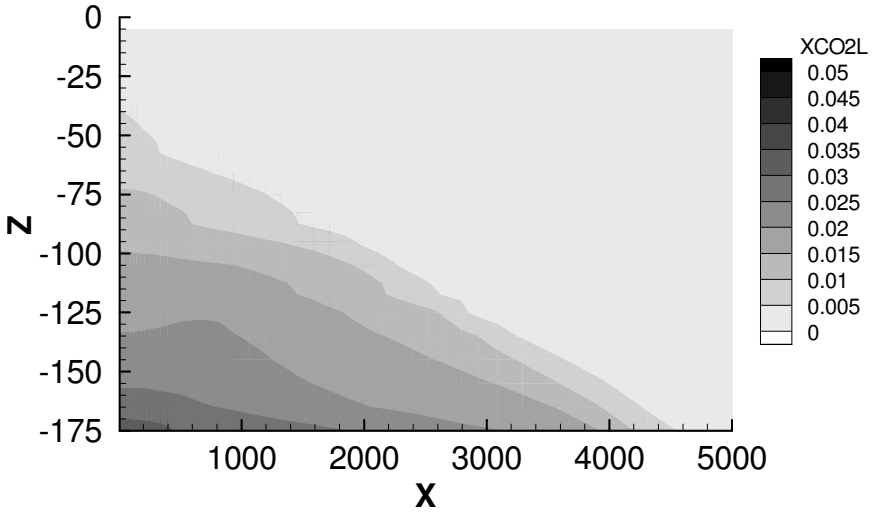
And finally after 10000 years



All supercritical CO_2 has dissolved, there is no more free CO_2 in the reservoir



Amount of dissolved CO_2 in the water (mass fraction)

Dissolved CO_2 accumulates at the bottom of the reservoir with a lateral extent of 4.5 km around the injection well

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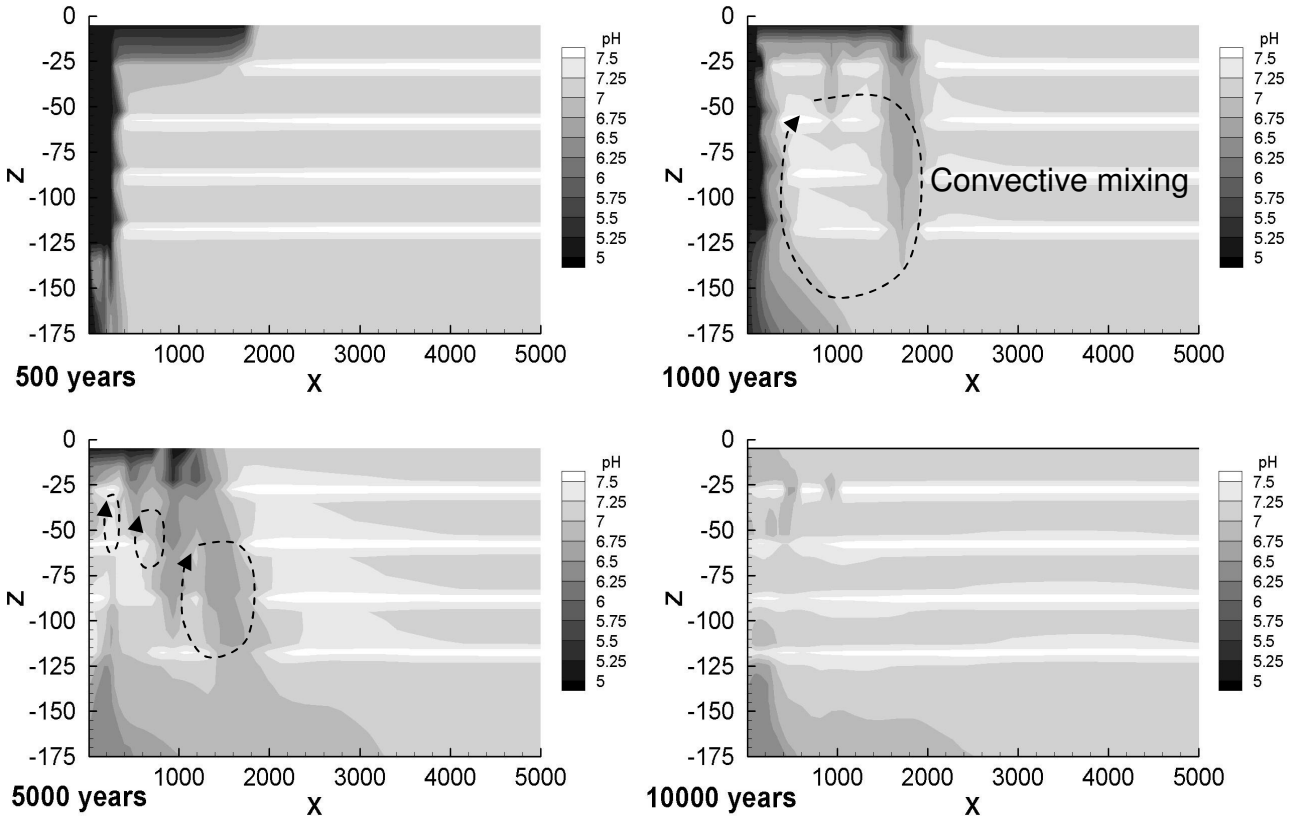
Towards a stabilization?



Dissolution of CO_2 increases the acidity of the brine, but is buffered by carbonate dissolution
Maximum decrease of pH is 5.13.

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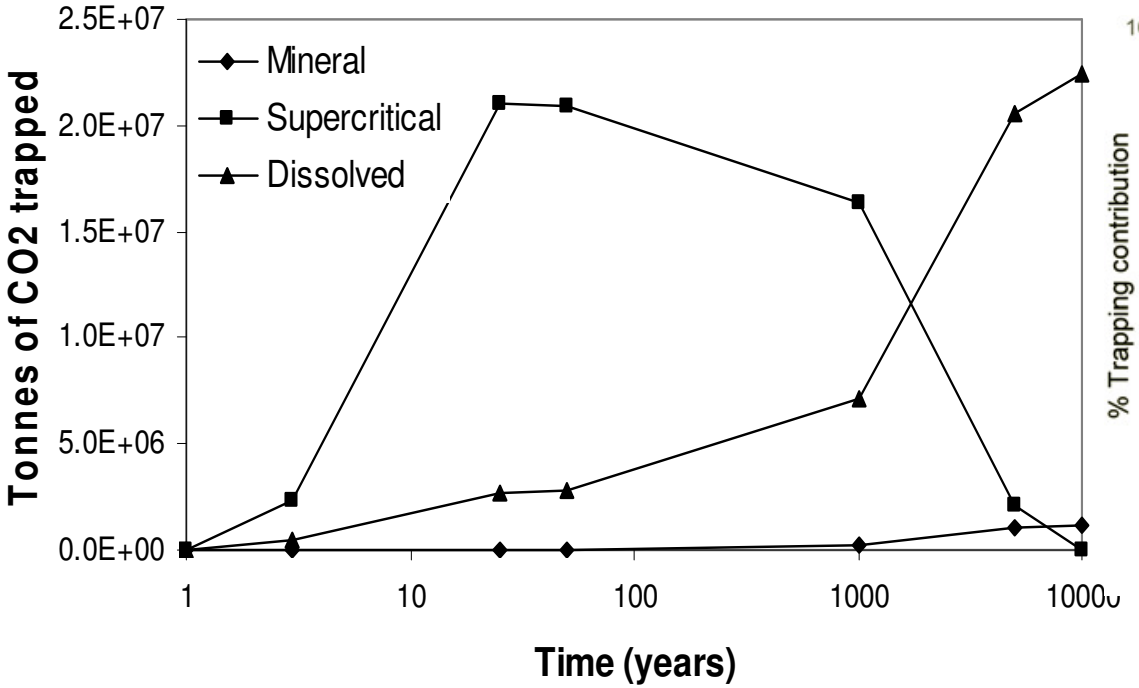
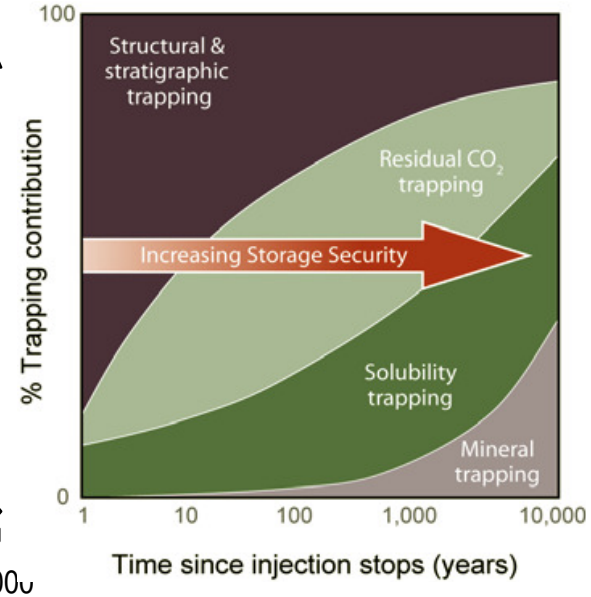
Amount of CO_2 stored





Total amounts of carbon dioxide present as a free (supercritical) gas phase, dissolved in the aqueous phase, and trapped in carbonated minerals (dawsonite mainly).

Dissolution trapping plays a major role in the long term, while mineral trapping is minor at Sleipner.

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Scenario 2: Caprock integrity

- **Fluid rock interactions**
- **Diffusion**
- **Monophasic**
- **kinetics**

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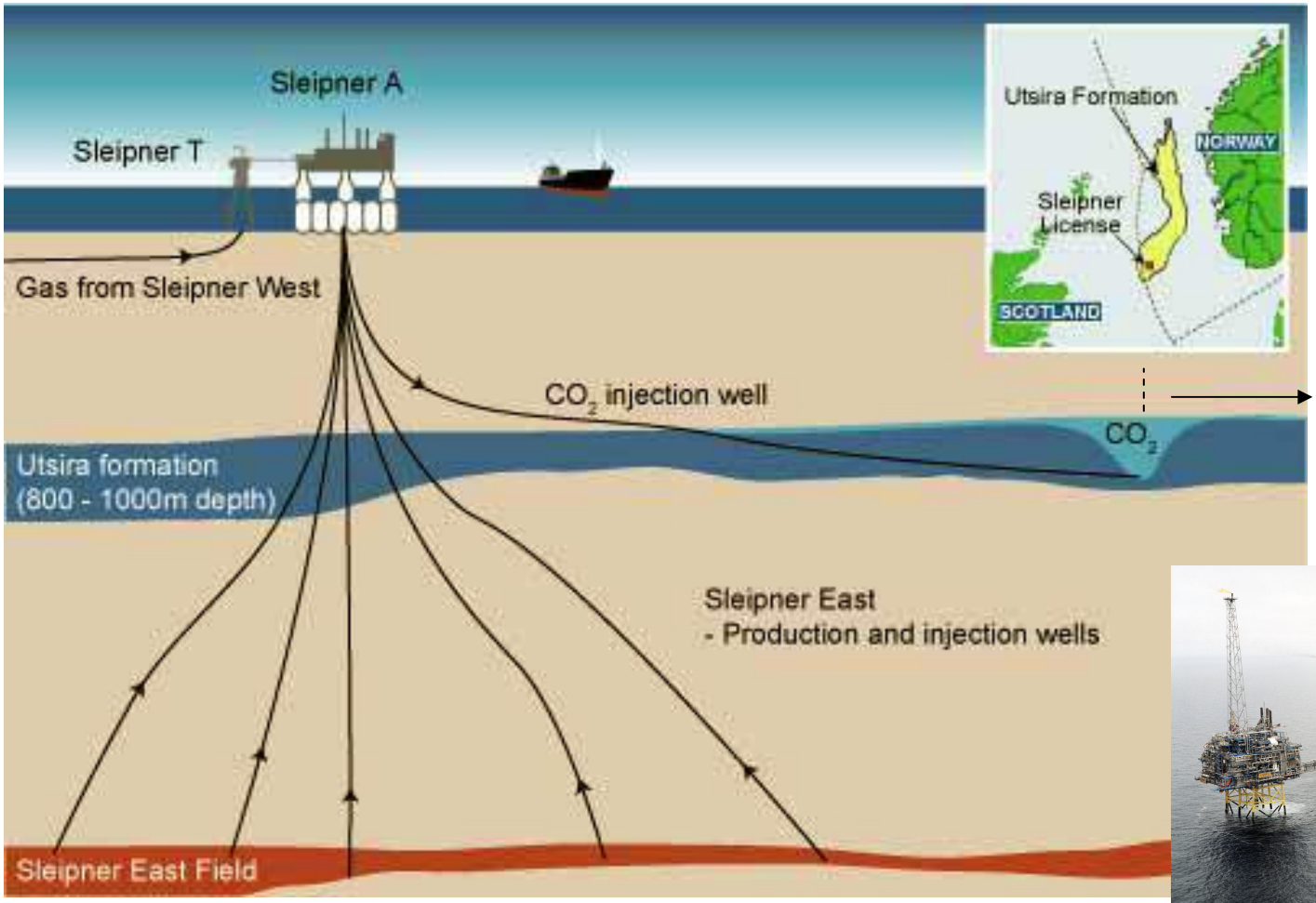
The Sleipner CO_2 storage project



1D geometry: security

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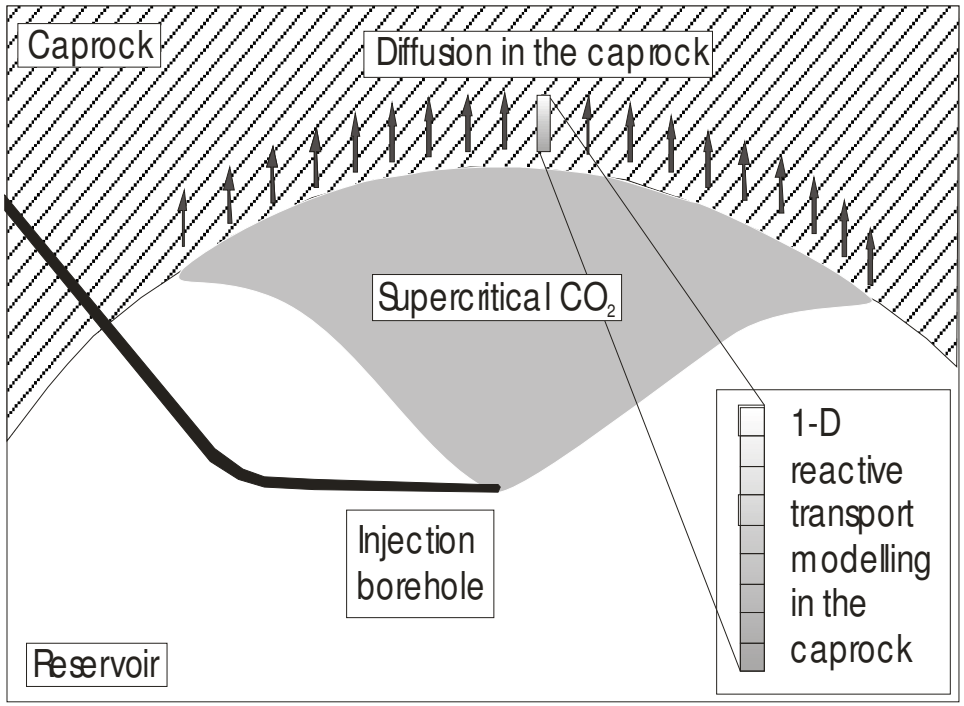
Sleipner, 1D diffusion in cap rock

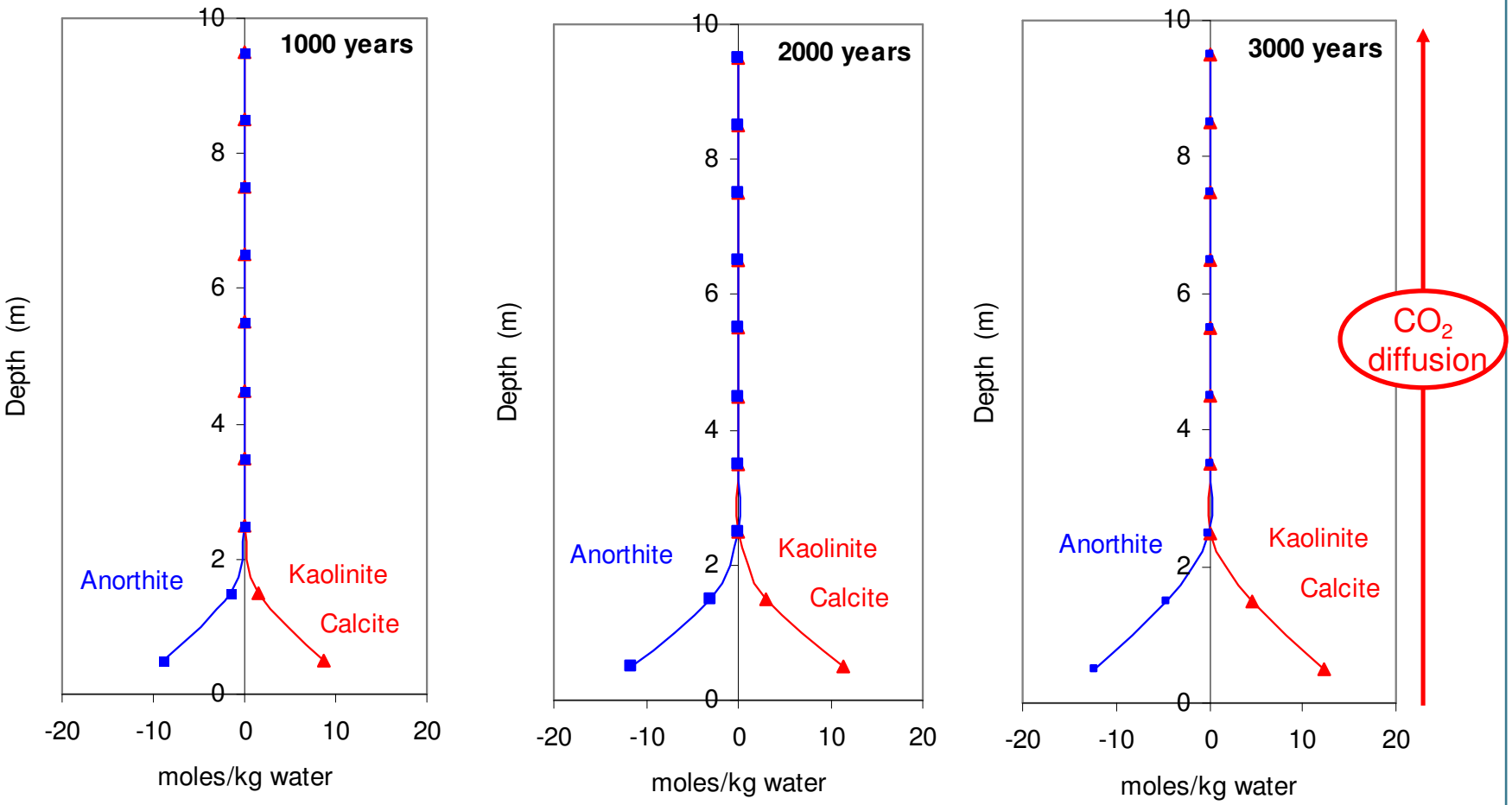
(Gaus et al. 2005, Chem. Geol, 217, 319-337)

At Sleipner (North Sea), the CO_2 (extracted from a gas plateform emission) is injected in the Utsira sand formation underlying the Nordland shale caprock from one horizontal well.
This work focuses on the geochemical aspect of the CO_2 injection with special attention to the long term integrity of the cap rock preventing upward migration of CO_2.

Geochemical reactions between dissolved CO_2 and the minerals present in the cap rock can lead to porosity and permeability changes compromising cap rock integrity.
The case of diffusion of dissolved CO_2 through the base of the cap rock after injection is treated using **PHREEQC**.



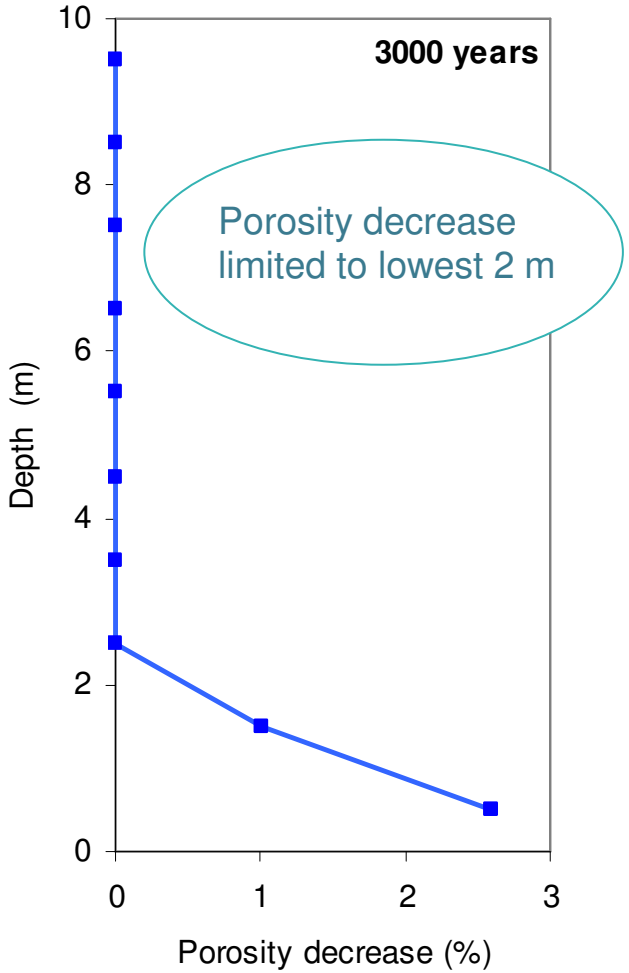
Reaction profiles: 50/50 albite/anorthite



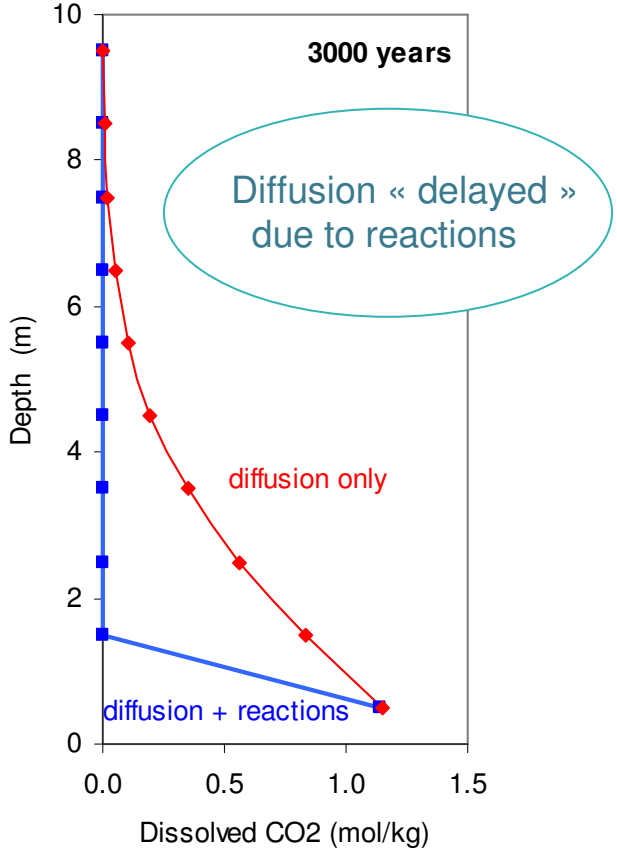
Dominant reaction only

Porosity and diffusion profiles - after 3000 years

Porosity change profile



Diffusion profile



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Long term predictions of caprock reactivity at Sleipner

> Results

- Diffusion of CO_2 in the cap rock is a slow process, can be further retarded due to geochemical reactions.
- Only the lower meters of the caprock are affected by geochemical reactions over the 3000 year modelling period (10m out of 250m)
- Plagioclase alteration is identified as the most important reaction
- Porosity reduction due to geochemical reactions is at maximum 3% for the most reactive cap rock composition, which might locally improve the cap rock integrity
- At the very bottom of the cap rock some carbonate dissolution is expected to occur leading to a minor porosity increase, that will however not migrate further into the cap rock.

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Scenario 3: Near well effect

- **Dry out zone**
- **Salt precipitation**
- **Limitations of geochemical models**

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1D radial dissecation, Dogger, France

(André et al., 2007, En. Conv. Mgmt., Volume 48, Issue 6, 1782-1797)

- **Assessment of the physical and chemical impact of CO_2 injection on the properties of the carbonated Dogger aquifer**

- **1D radial injection model is proposed to evaluate the evolution of the geochemical reactivity induced by injection of CO_2**
  - TOUGHREACT

- **Near well dry out and dissecation phenomenum with high salinity**
  - SCALE2000

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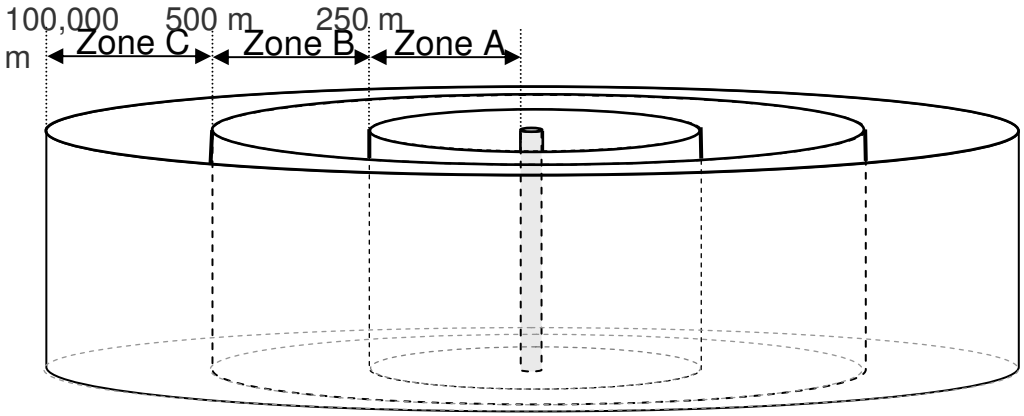
The Dogger aquifer

- carbonated reservoir
- represented by a cylindrical geometry centered around a vertical injection well
- one layer (no gravitational effect) with a thickness of 20 m
- maximal radial extension of 100 km
- 1610 co-centered cell elements
- first cell radius containing the injection well is equal to 0.3 m
- next 500 cells radius is also constant and equal to 0.5 m
- hydrostatic pressure is imposed in the outermost column of the mesh



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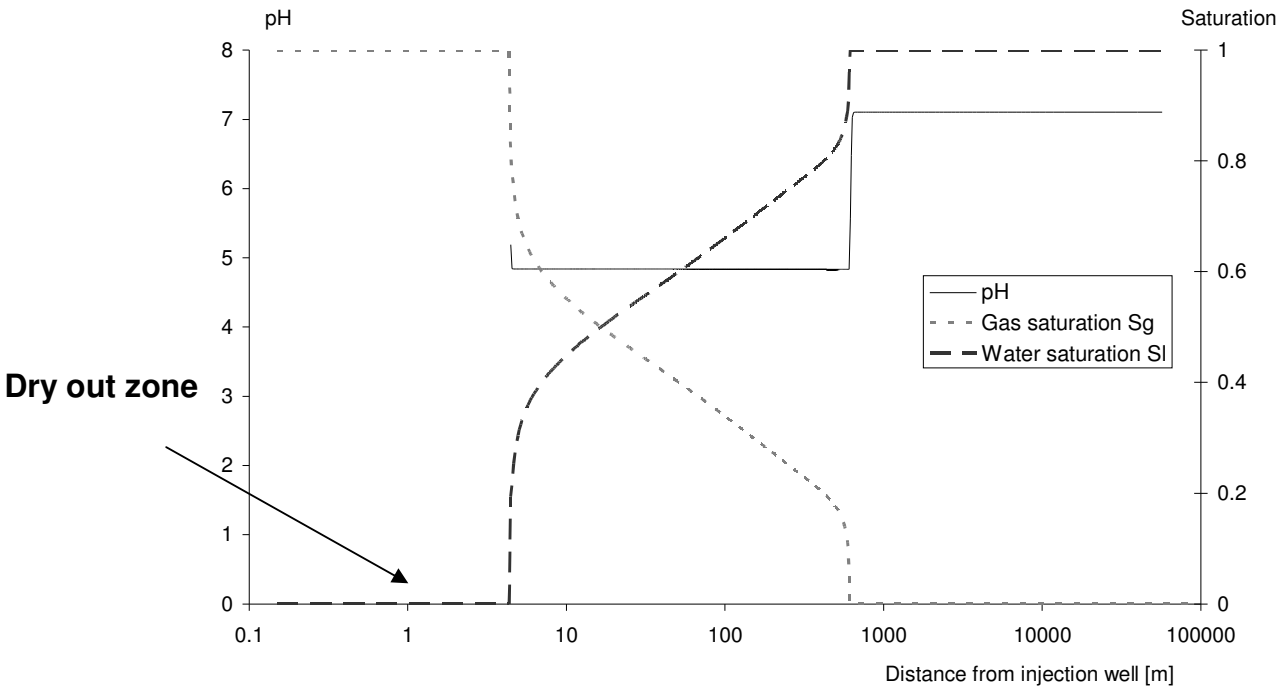
Results Case B

> **CO2 supercritical and brine flow**

> **Buckley-Leverett profile**



At the end of 10 years injection at 10 kg/s

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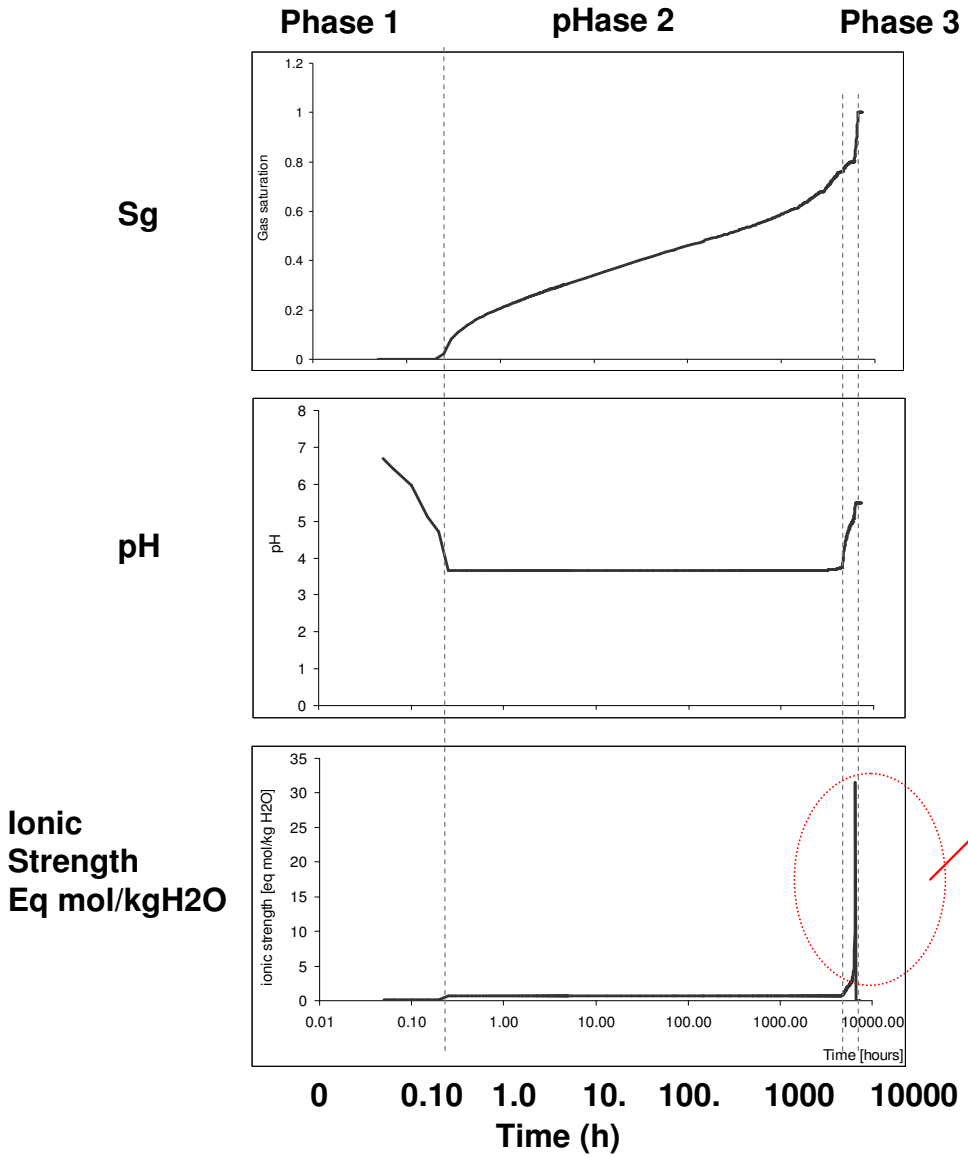
Dry out zone at 1 m from the well



- **History chemical evolution for a point located 1 meter away from the well**
- **Three phases identified:**
  - Mono phase liquid
  - Two phases
  - Mono phase supercritical (dry out)

Out of the Dubye Hückel Formalism: Ionic Strength <0.5

USE OF SCALE2000 To define correct Index of Saturation for precipitated minerals

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Scenario 4: Enhanced Gas recovery

- **CO_2 + CH_4 + H_2O fluid flow**
- **Close system (reservoir)**
- **Over pressure**
- **Heterogeneity**

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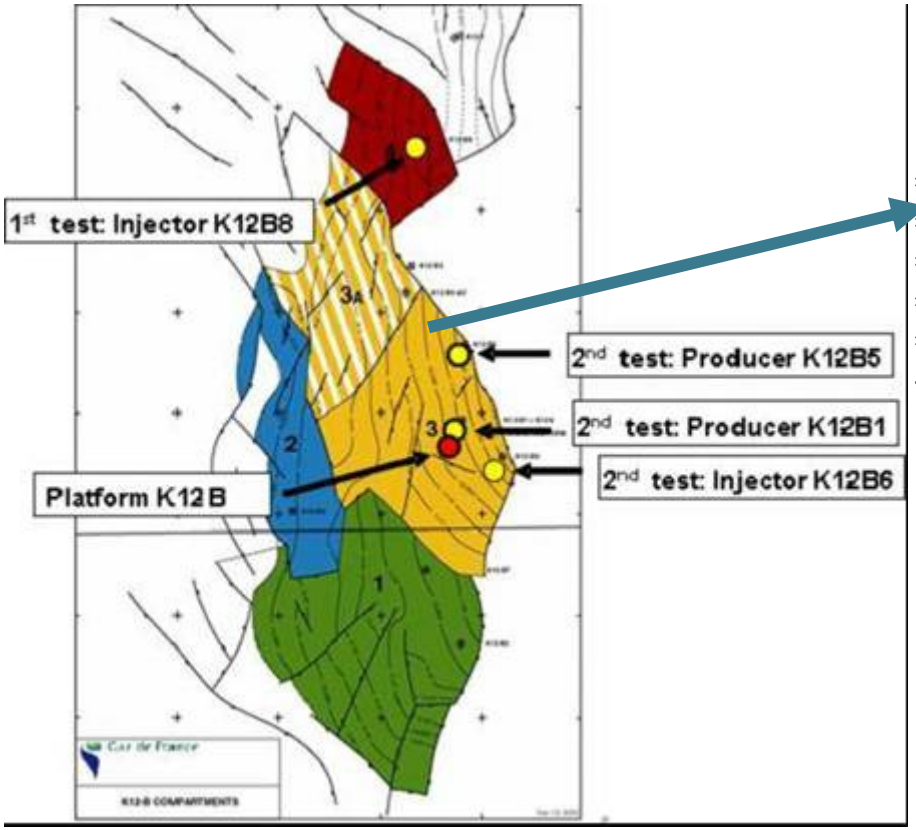
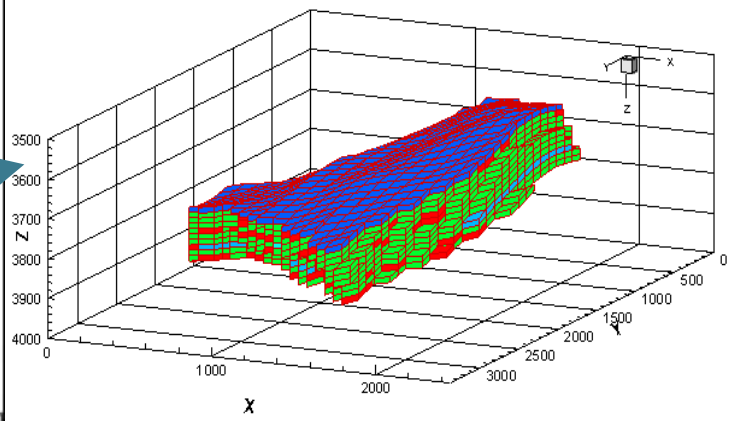
3D model of CO_2 injection in K12-B

(Audigane et al. 2007, AAPG special publication)

> Injection scenario and reservoir model geometry

- Simulation of the phase 3 of the project: full scale injection ~310-475 kton/yr
- Up gridded reservoir mesh (30,000 cells) from TNO (Geel and Duin, 2005).





3,000 cells

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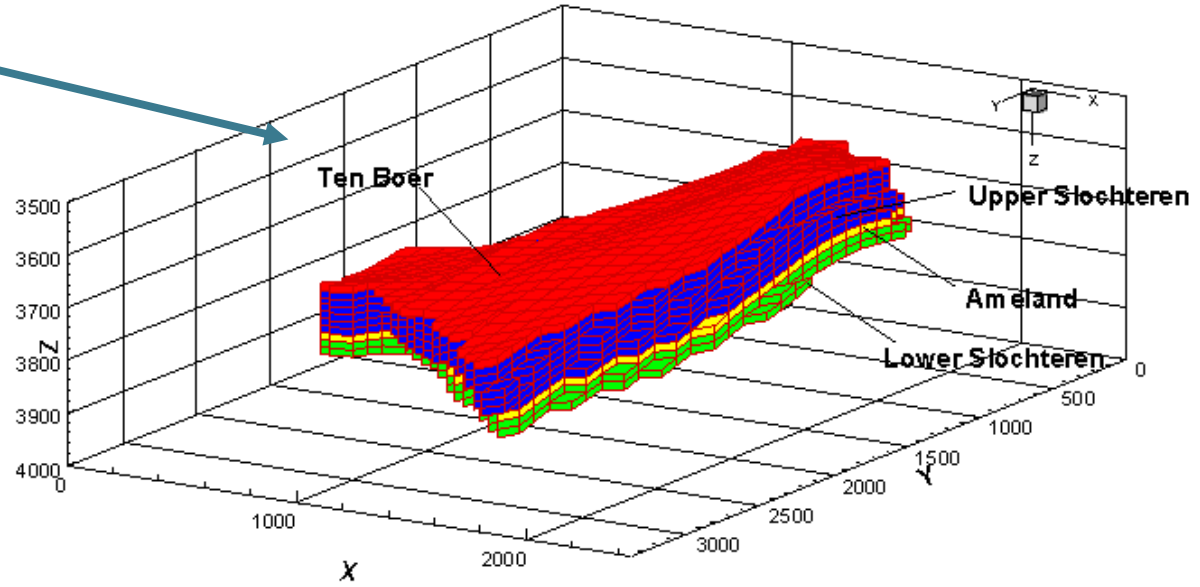
Stratigraphic Units identified

One analogue sample



Literature review

1- **Ten Boer** Claystone, a 10-15 m (33-49 ft) playa lake deposit with some silt stringers

2- **Upper Slochteren** Formation, a 140 m (459 ft) thick sandstone of mixed fluvial/aeolian origin with good reservoir properties

3- **Ameland Claystone**, a 35 m (115 ft) thick shale package

4- **Lower Slochteren** Formation, a 80 m (262 ft) thick sandstone of mixed fluvial/aeolian origin with fair reservoir properties.

(Geel and Duin, 2005)

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Numerical tools and injection scenario

> Reactive transport and geochemical batch modeling

- TOUGHREACT Lawrence Berkeley National Laboratory, (Tianfu Xu and Karsetn Pruess)
  - Kinetics rate, porosity changes due to mineral precipitation/dissolution..
  - No methane

> Hydrodynamics

- TOUGH2/EOS7C LBNL, (Curt oldenburg and Karsten Pruess)
  - Methane and CO_2 mixtures,
  - no chemical reactivity

> Injection scenario

- 10 years at a 10 kg/s rate well K12-B6.
- Production of 1 kg/s from wells K12-B5 and B1
  - **Case A**: CO_2 only with geochemistry TOUGHREACT
  - **Case B**: CO_2 and CH_4 with CH_4 production, no chemistry TOUGH2/EOS7C

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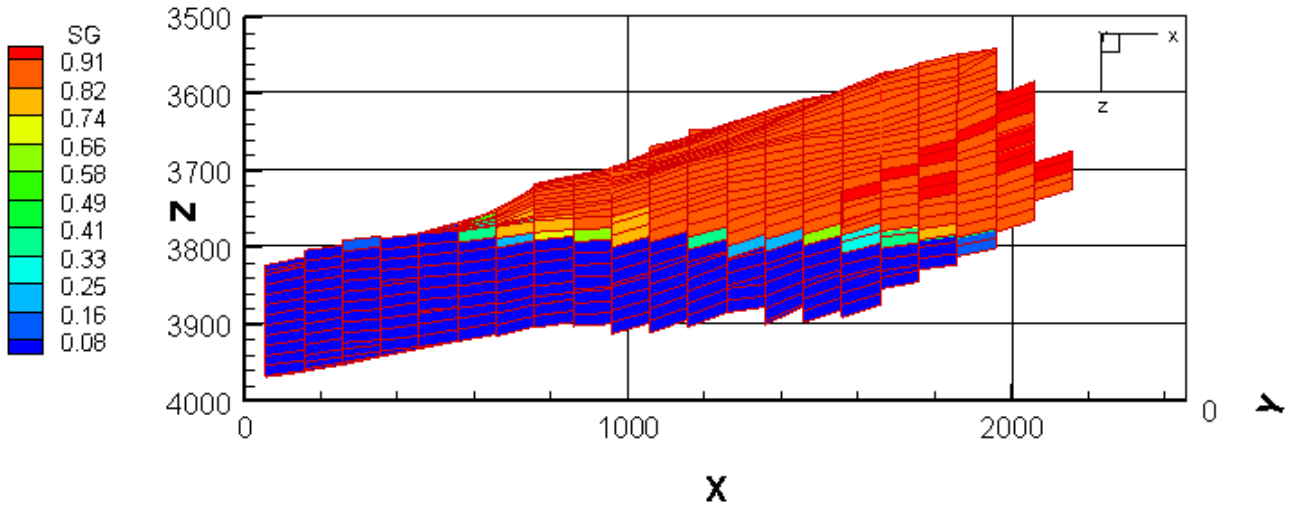
Initial Gas saturation field



South view of the initial gas saturation field on the grid mesh considered for the case A simulation.
The gas water contact is about 3800 m (12468 ft) depth.

Reservoir contains 13% of CO_2 initially

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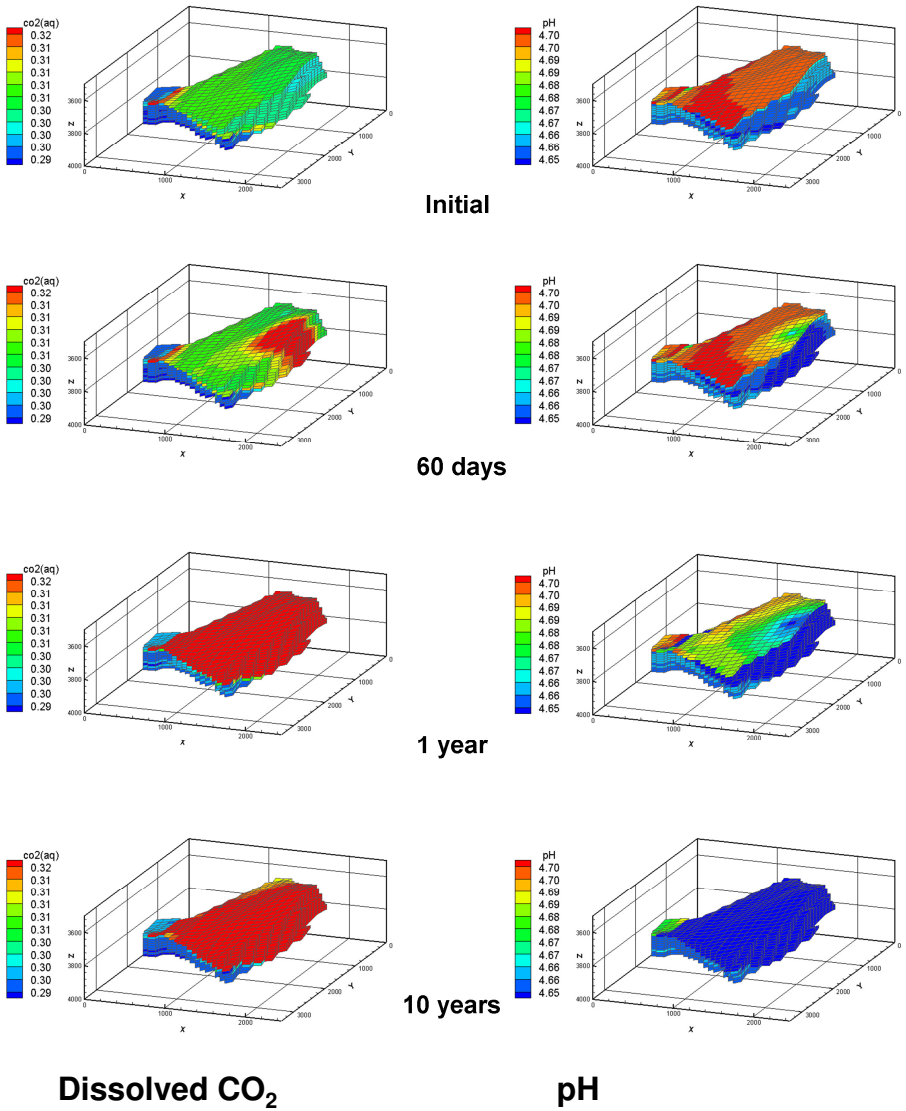
Case A simulation results



No methane, CO_2 only.

Initially 13% of CO_2 in the reservoir
-> Fitted Initial geochemical equilibrium

pH variation follows the migration of the dissolved CO_2 and at the end of the injection the simulated pH decrease is observed on the entire grid mesh.

However minor pH modifications are identified inside the reservoir.

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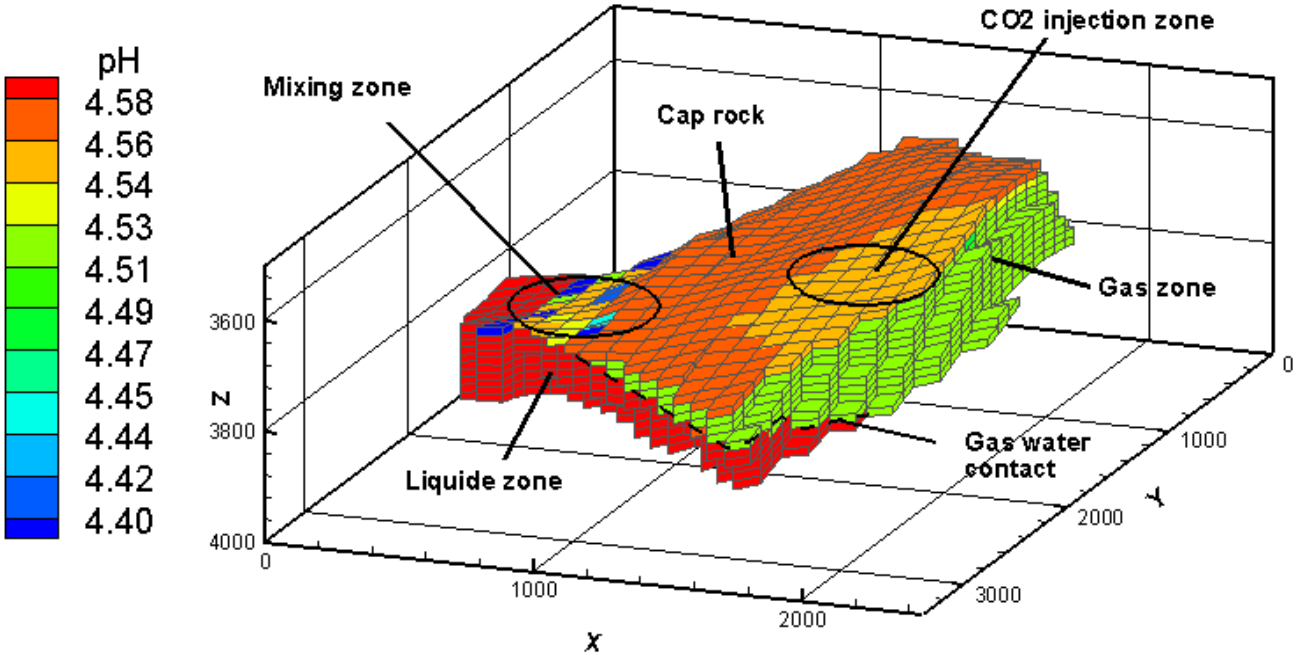
pH variations



The mixing zone is the most reactive zone of the simulation because it corresponds to the zone with the most important gas saturation and mineralogy variations

Still, geochemical reactivity remains at a low level

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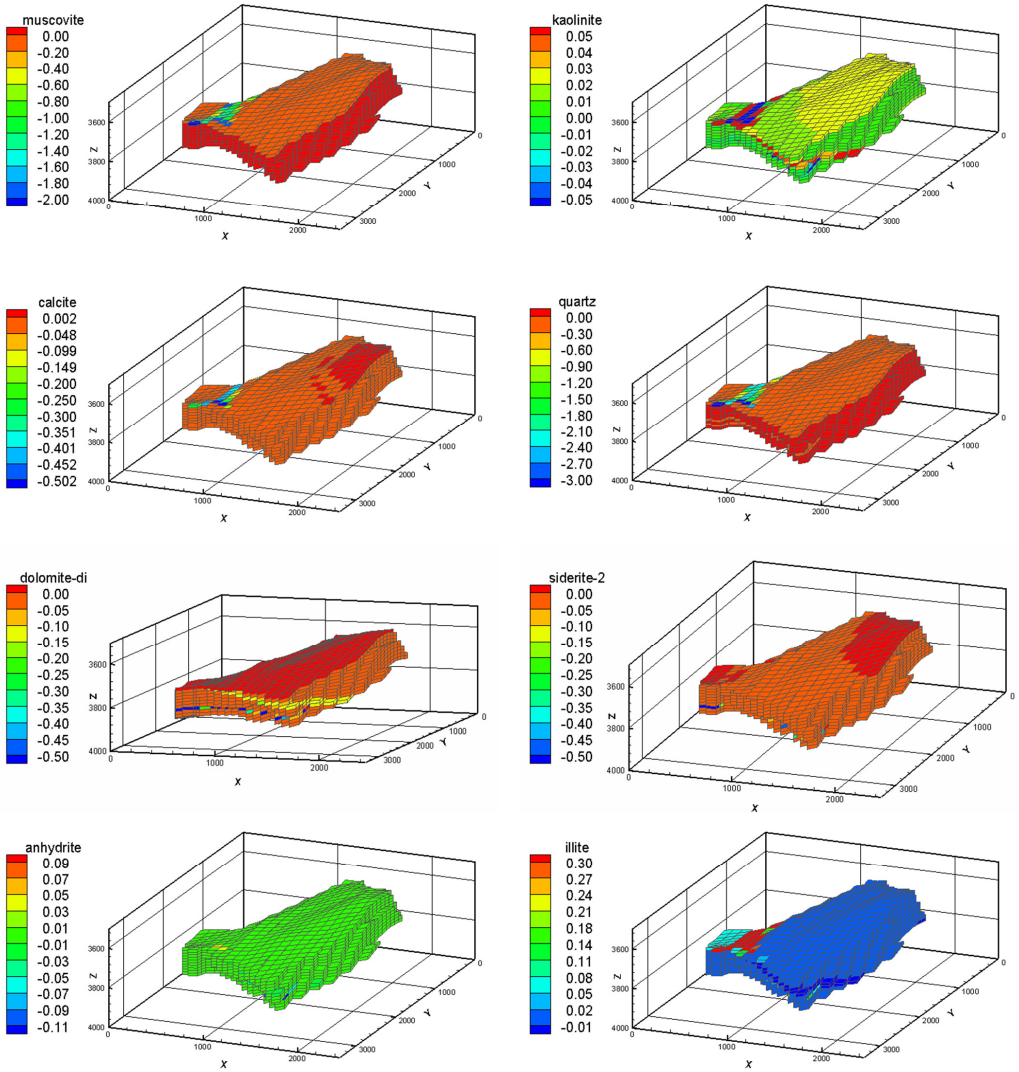
Minerals alteration

- Mineral precipitation and dissolution is low
- The most important changes occur in the mixing zone
- Muscovite and quartz dissolve leading to the precipitation of illite
- Kaolinite dissolution leading to calcite and kaolinite precipitation
- Calcite and kaolinite dissolution
- Dolomite and siderite dissolves due to acidification



Conclusion for Case A

- **An overall very low geochemical reactivity, porosity change less than 0.1%.**
- **This is explained by the fact that the original reservoir contained already 13% of CO_2, and therefore, geochemical system is already equilibrated with CO_2**
- **Mineral trapping plays a minor role in terms of geological sequestration process (less than 0.001 kg/m^3 of medium estimated)**
- **This is a good aspect in terms of reservoir and cap rock integrity for the K12-B field**

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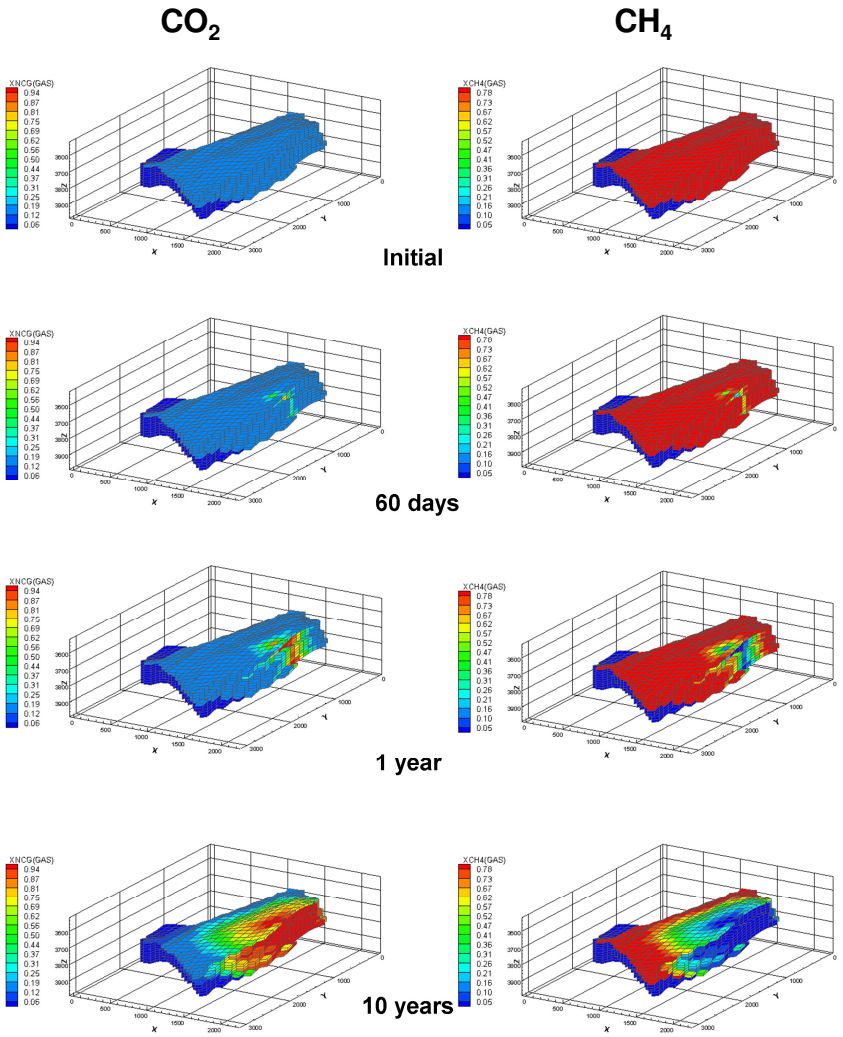
Case B simulation results

- **Enhanced gas recovery scenario envisaged**
- **CO_2 can flush CH_4 through permeable regions of the reservoir**
- **10 kg/s injection**
- **2 x 1 kg/s production**



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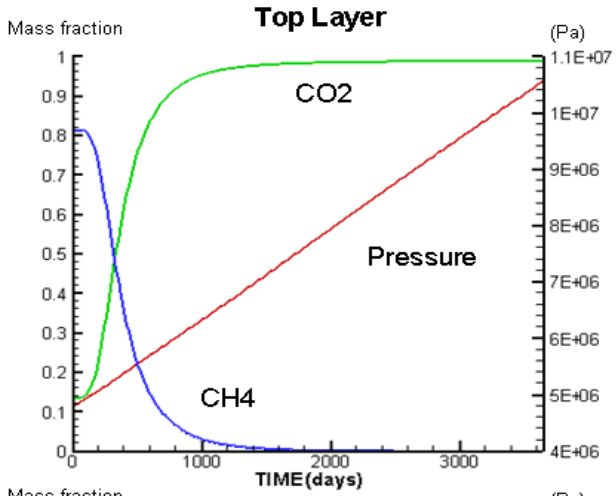
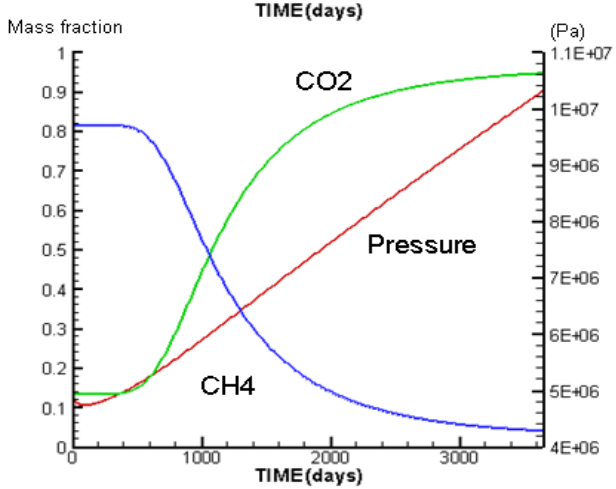
Breakthrough curves

- **Breakthrough**
  - K12B1: 60 days (450 m away from B6)
  - K12B5: 1 year (850 m from B6)
- **50% of CO_2**
  - K12B1: 1 year
  - K12B5: 3 years
- **End of injection**
  - K12B1: 100% CO_2
  - K12B5: 95% CO_2
- **Linear pressure increase**
  - Closed system

K12B1



K12B5



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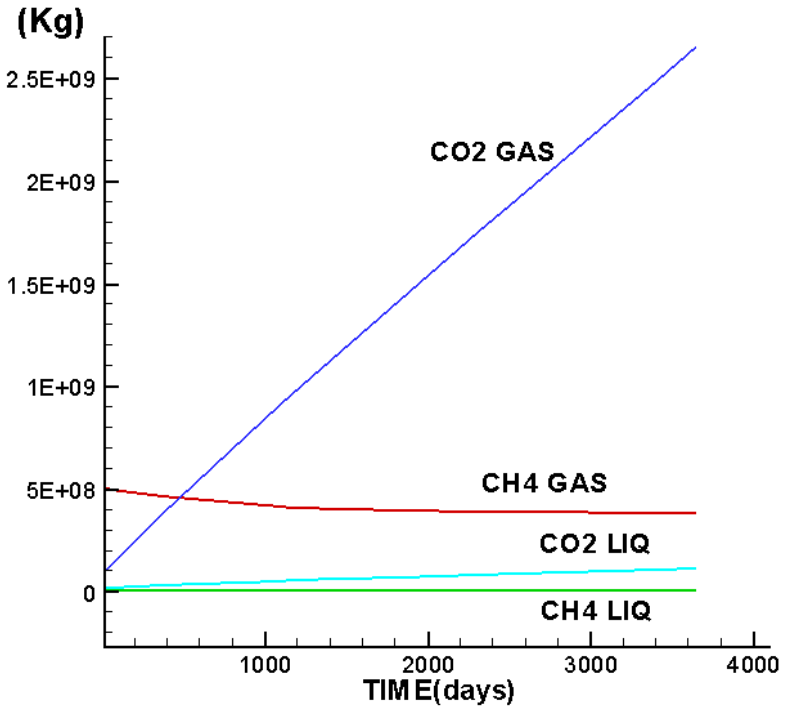
Conclusion for Case B

- **At the end of injection, structural trapping is the main process for CO_2 trapping.**
- **After 10 years of injection at 10 kg/s 2.67 10^9kg remains as gas phase while 1.16 10^8kg has been dissolved in the liquid phase**



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Conclusion for the K12B study

- **Low recovery factor for the case of EGR efficiency**
- **Breakthrough of 60 days and one year for the producers**
- **Low geochemical reactivity explained by the fact that the original reservoir contained already 13% of CO_2**
- **Mineral trapping plays a minor role in terms of geological sequestration process**
- **Excellent reservoir and cap rock integrity**

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Scenario 5: Leakage through abandoned well

- **Multiphase fluid flow**
- **Fluid rock interactions**
- **Impact on water quality**
- **Risks assessments**

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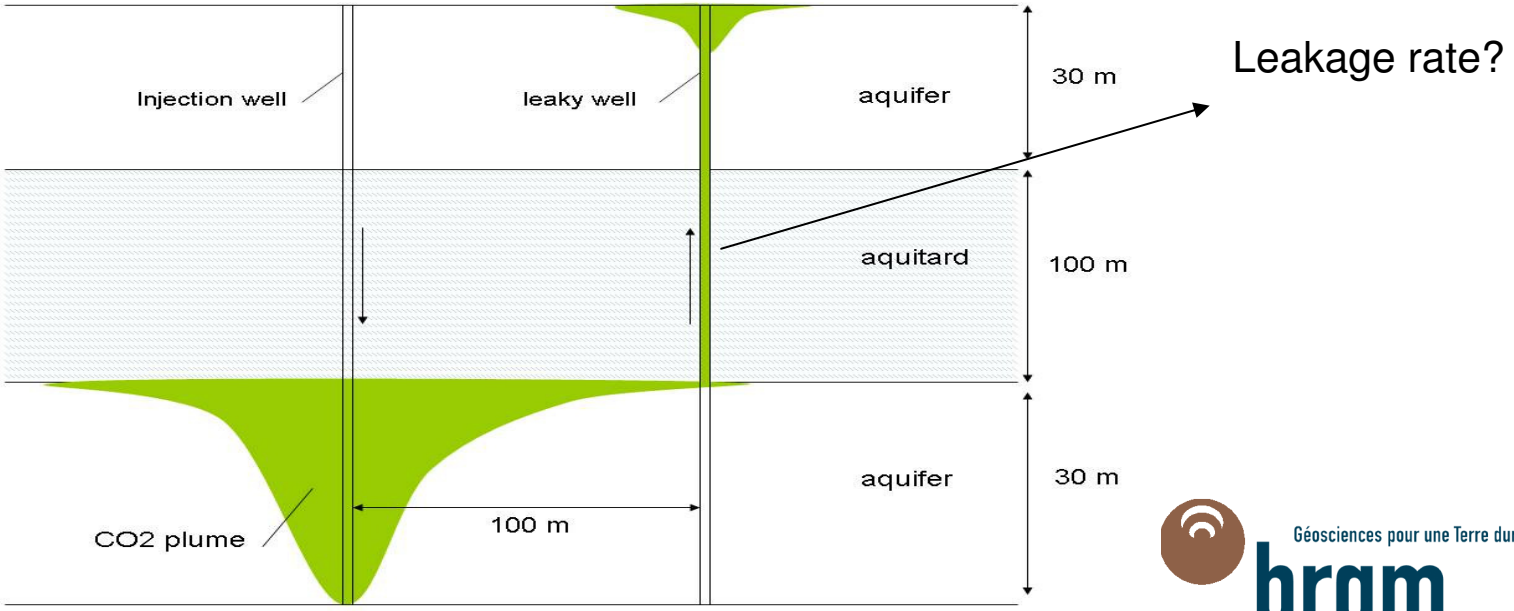
Benchmark Stuttgart Problem 1.1

- **University of Stuttgart recently submitted a problem-oriented benchmark assessing code performance for CCS modeling (Class et al., 2009)**



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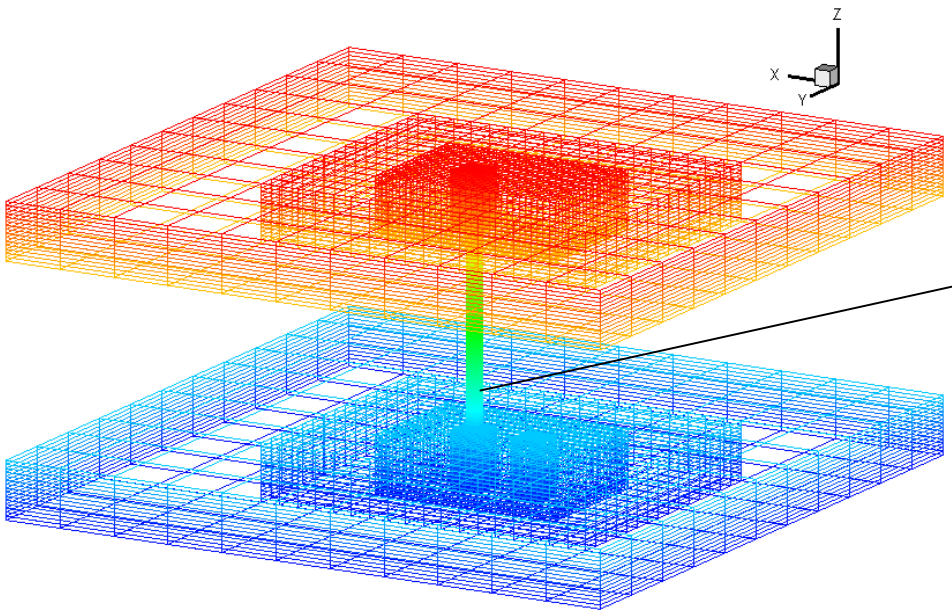
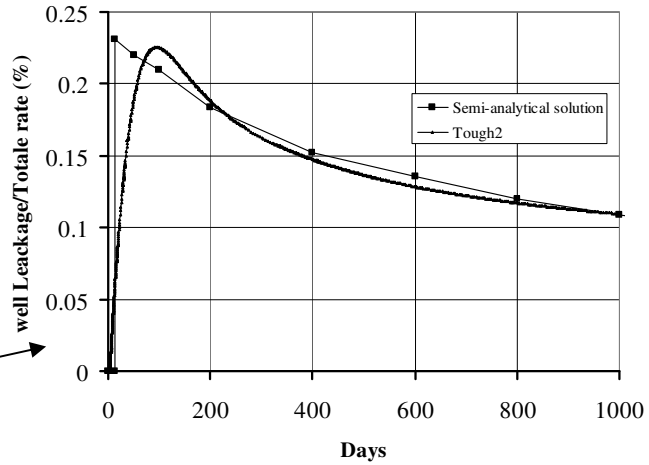
Complex geometry

> **To handle properly geometrical configuration corresponding to leakage through one well we needed to develop**
  - Local Grid Refinement option
  - Grid block deletion
  - 3D vizualisation…





For all participants contribution see

Class et al., 2009 Computational Geosciences

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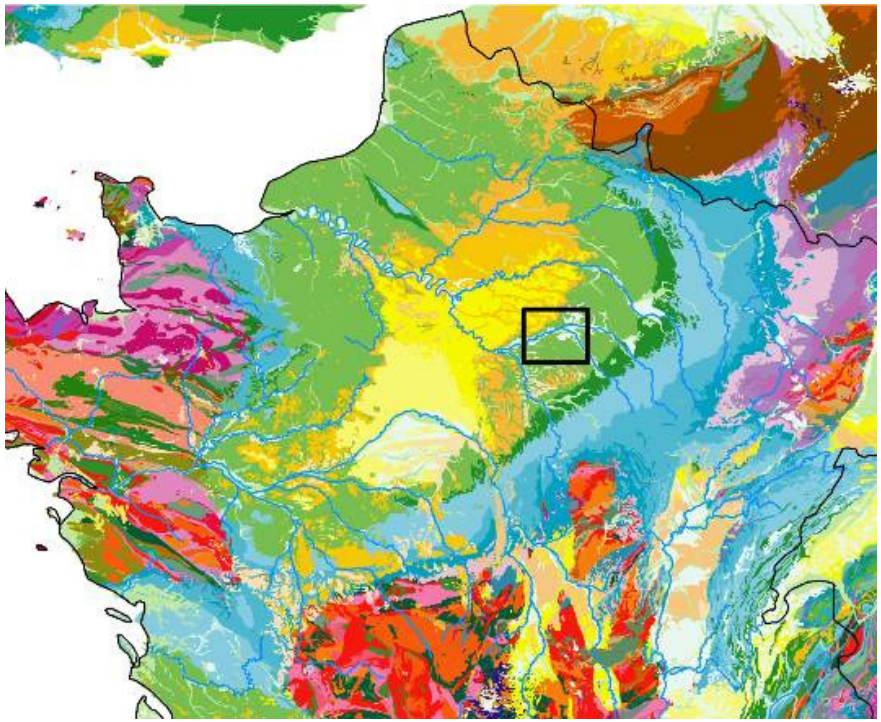
Application to Paris Basin

(Humez et al., 2010, in Prep.)



- **This complex, multilayered aquifer system provides two suitable aquifers (Triassic and Dogger) for large-scale CO_2 storage in a deep saline aquifer**
- **In this study, we consider CO_2 injection into the Dogger Aquifer and observe the impact of leakage on the Albian fresh groundwater (exploited for water supply)**

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Hydrogeochemistry

> Aquifer investigated for CCS: Dogger

- Middle Jurassic (Dogger) aquifer mainly composed of carbonates
- Exploited for geothermal and petroleum resources,
- Sedimentary studies of this aquifer (Rojas et al., 1989) show that the most permeable facies, the oolitic limestone, retains or even increases its initial porosity by fracturing and dissolution
- We consider only the oolithic limestone to be the productive layer of the Dogger aquifer

> Impacted aquifer: Albian

- The Albian confined aquifer, a sandy multilayered aquifer
- Mainly composed of quartz, glauconite, kaolinite, muscovite, carbonates (siderite, calcite, dolomite), phosphates, barite, and pyrite (Mégnien 1980)
- Waters present several chemical compositions according to their recharge origins, with some constant characteristics
  - Albian waters are anoxic with high Fe concentrations
  - pH around 7
  - low mineralized (0.3 to 0.6 g/L)
- The present study is based on average chemical composition measured in the study area

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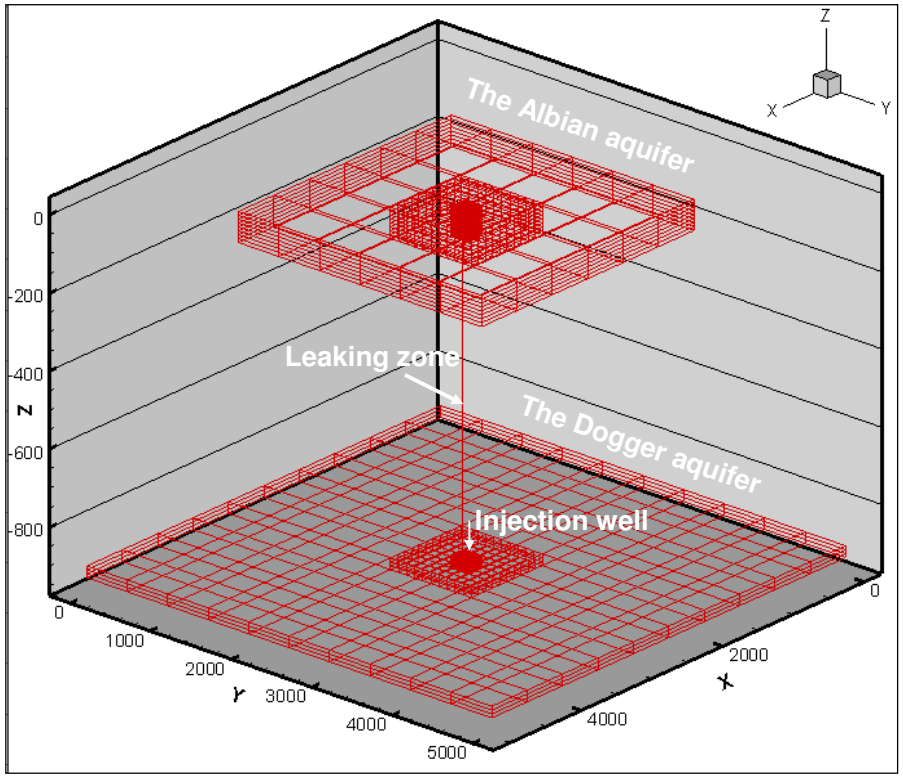
Flow modeling

> **Injection into the Dogger Aquifer:**
- horizontal formation
- thickness of 30 m and
- 5 by 5 km
- Depth = 1525 m

> **Albian Aquifer:**
- horizontal formation
- 80 m thick,
- 3 by 3 km
- 625 m deep

> **Abandoned well:**
- 1D porous media connecting the two aquifers
- located 100 m away from the injection well,
- with a horizontal area of 5 by 5 m and a length of 820

> **Mesh refinement has been applied with inactivation of the cap-rock gridblocks to build up a 3D model of the scenario with 5326 mesh elements**



	Dogger	Albian	Leak
Pressure (bar)	147	65	Gradient
porosity	0.12	0.2	0.15
K (m²)	6.67E-13	1E-9	1E-8

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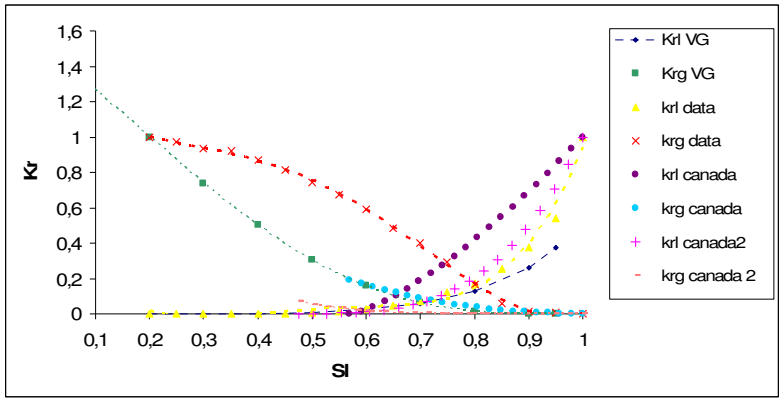
Multiphase flow

> Multiphase hydrodynamics parameters

Numerical models for predicting the fate of the injected CO_2 also need information about two important parameters:the relative permeability of CO_2 and brine capillarity pressure character



Variations of relative permeability according to water saturation (Sl).Points represent experimental data from Lavoux limestones(kr data) and from the carbonate Wabamun Group,Alberta basin,Canada (kr canada;kr canada 2) (Bennion and al. 2005)and then from Lavoux limestones parameters run in Van Genuchten model (kr VG)

	Albian	**Dogger**
Relative permeability (Van Genuchten)	**From Sleipner field parameters (Utsira sandstones)**	**From Lavoux limestones parameters**
λ=1 -1/n	**0.63**	**0.6**
Residual liquid phase saturation (Slr)	**0.05**	**0.2**
Liquid phase saturation (Sls)	**1.0**	**1.0**
Irreductible gas saturation (Sgr)	**0.2**	**0.05**
Capillarity pressure (Van Genuchten)	**From Sleipner field parameters (Utsira sandstones)**	**From Lavoux limestones parameters**
λ=1 -1/n	**0.63**	**0.6**
Residual liquid phase saturation (Slr)	**0.05**	**0.199**
Po (Pa)	**1400**	**54000**
Initial liquid phase saturation (Sls)	**1.0**	**1.0**

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Geochemical assumptions

- **Since the Dogger fm. is mainly composed of calcite (until 99%), other minerals are neglected as a first stage in the study.**
- **Water analysis from Rojas et al. (1989) is used for constraining the composition of the brine**
- **The equivalent mineralogy of the Albian formation was determined using Phreeqc. These calculations were made using analysis of water from several wells located in the study area, to simulate a water composition similar to the mean of the observed chemical compositions**
- **The leaky abandoned well defined as a 1D porous column is composed of a similar chemical composition to the Albian for the aqueous phase without any solid-phase minerals**
- **Calcite and siderite dissolution and precipitation at equilibrium, while for the other minerals kinetic constrain is applied according Palandri and Kharaka, (2004)**

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Chemical composition

	Dogger	Albien	Leak
T°C	160	60	gradient
pH	6.7	7.36	7.36
pCO2 (bar)	0.183	0.0141	0.0141
Salinity ($g.kgw^{-1}$)	5	1	1
Minerals	Calcite	Glauconite, Quartz, Siderite, Calcite Kaolinite, Pyrite	
Chemical elements (mol/kgw unit)			
[Ca2+]	2.265e-3	1.545e-3	1.545e-3
[Na+]	7.747e-2	8.65e-5	8.65e-5
[fe2+]	1.604e-5	3.013e-5	3.013e-5
[CO2aq]	7.482e-3	3.113e-3	3.113e-3
[Cl-]	6.965e-2	8.58e-5	8.58e-5
[mg2+]		1.016e-4	1.016e-4
[k+]		5.934e-5	5.934e-5
[SiO2aq]		9.405e-5	9.405e-5
[Al3+]		8.747e-9	8.747e-9
[SO42-]		3.02e-4	3.02e-4

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Scenario conditions

- **Injection is conducted at 9 kg/s (0.3 Mt/y) over the entire thickness of the Dogger fm. divided into three cells (3 kg/s by cell)**

- **System open by imposing constant pressure at the lateral boundary of both aquifers**

- **No regional flow since the lateral extension is limited to 2.5 km away from the injection point, the impact of a close boundary condition may play a role in the flow system therefore, we limit the scenario to a 5-years injection period**

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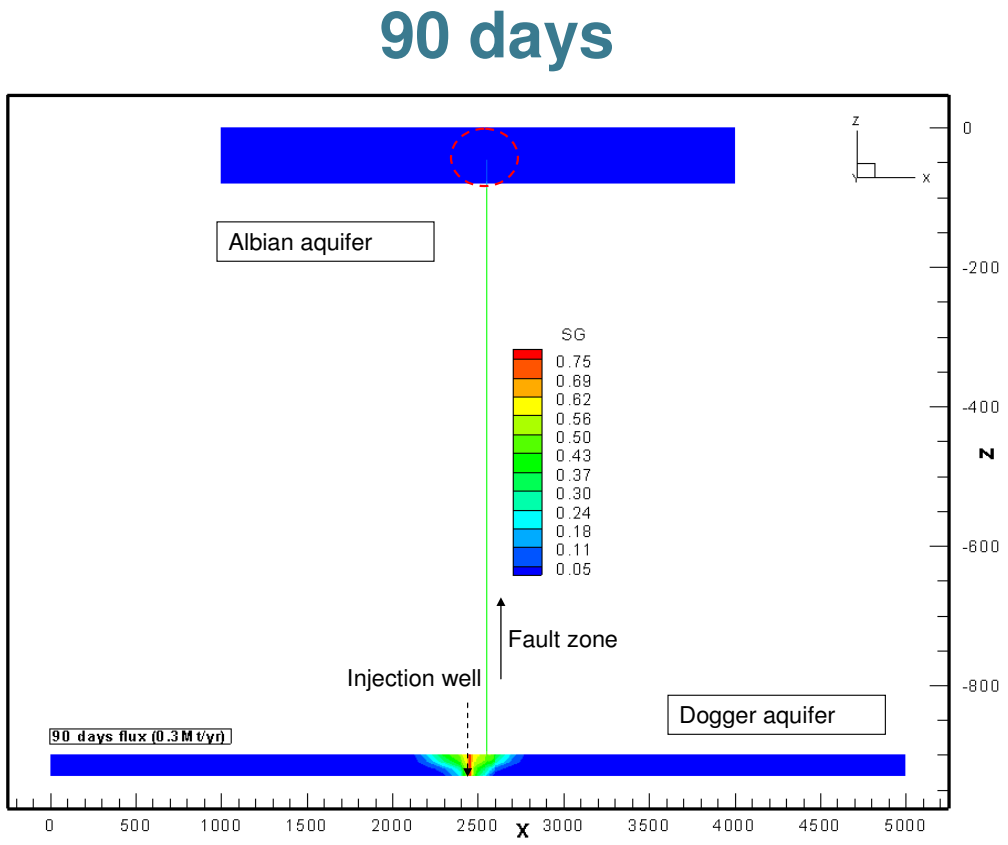
Simulation results

- Supercritical CO_2 reaches the Albian formation after 90 days at a flow rate of 0.2 kg/s, which rises to 1.1 kg/s after 5 yrs
- CO_2 intrusion is accompanied by water with a flow rate decreasing from 0.019 kg/s after 90 days to 0.003 kg/s after 5 years
- After 5 years, the lateral extension of the gas bubble in the Dogger fm. reaches ~1,500 m around the injection point, in which a few tens of meters are completely flushed by dried supercritical CO_2



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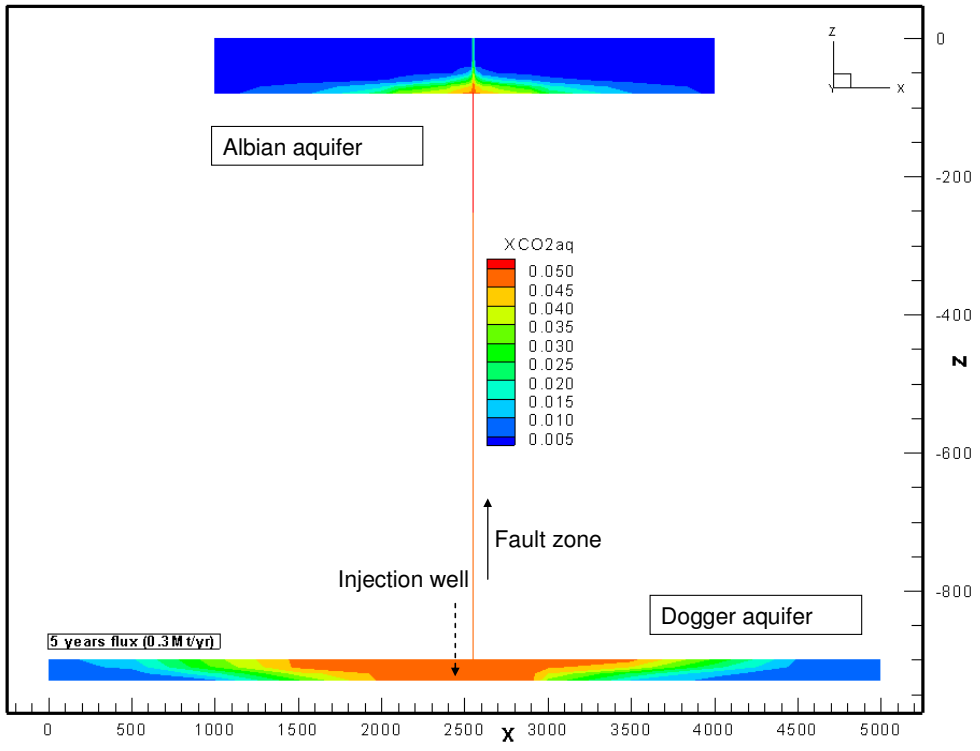
Gravity effects

- **Gravity effect and the impact of vertical permeability are clearly visible in both aquifers on dissolved CO_2**
  - In the Dogger fm., the CO2 injection rate is high enough so that the gas phase lighter than the brine reaches the top of the formation, forming a reverse bell shape envelope of gas where CO2 dissolves
- **On the opposite, when the gas phase slowly migrates through the leaky zone and enters the Albian aquifer, only the 1D vertical column is invaded by the gas**
- **Because the permeability is much higher in the Albian formation, the enriched CO_2 liquid phase, heavier than the brine, drops down to the bottom of the Albian aquifer faster than the upward migration of the gas**

5 years



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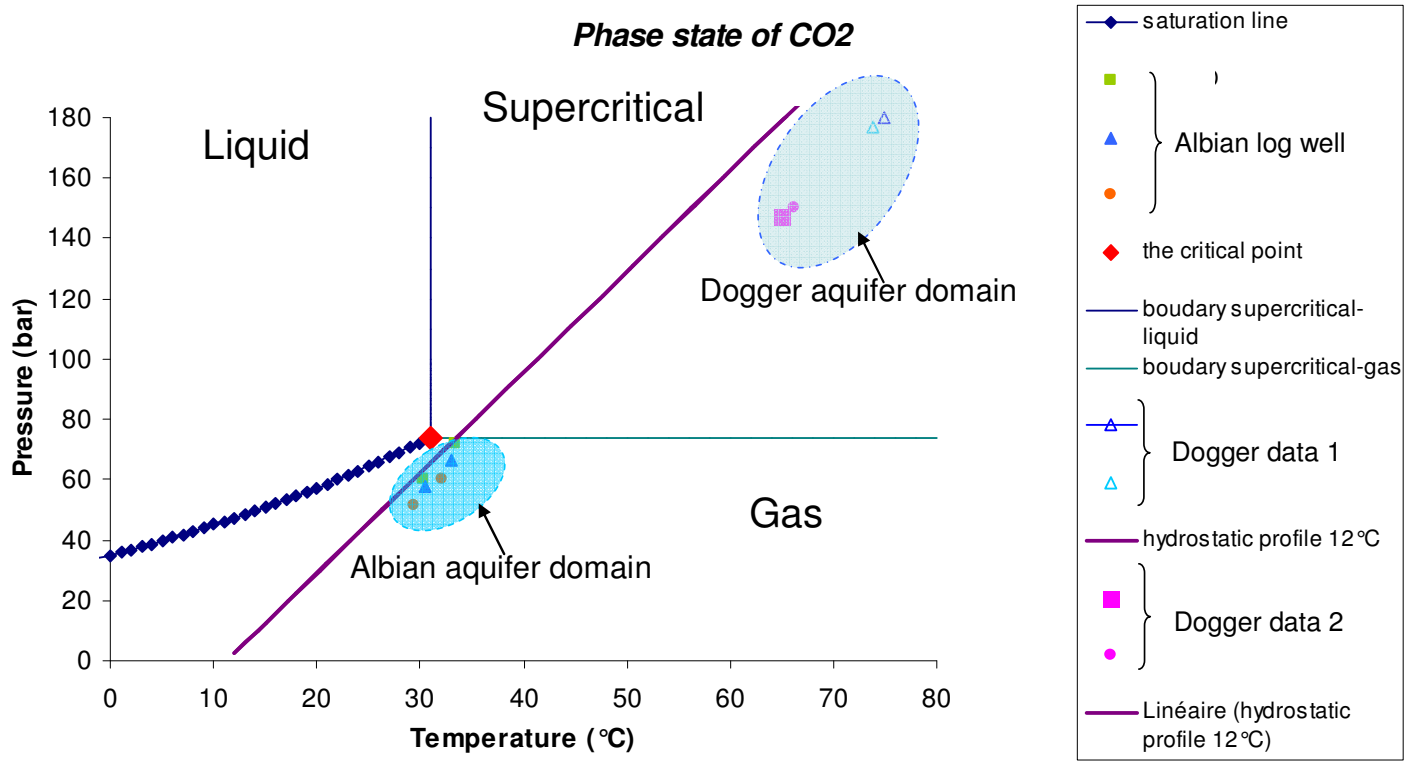
Temperature Pressure path



> **During its upward migration, CO_2 density is modified as pressure and temperature of the system is correlated to depth. From these calculations, CO_2 is injected under supercritical conditions into the Dogger before turning progressively to gas state at the Albian depth**

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Results

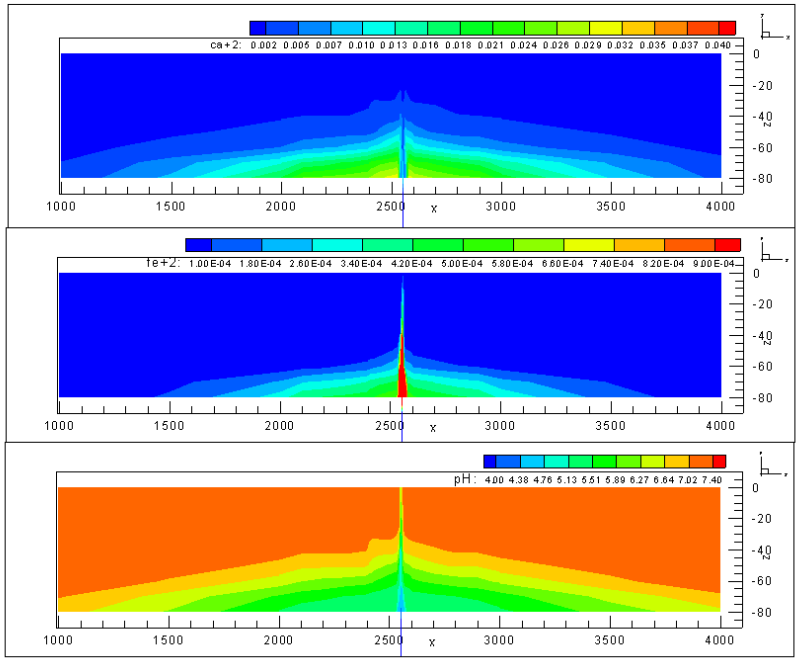
- **pH decrease precisely follows the dissolved CO_2 pathway**
- **After 5 years of injection, the extension of pH in the lowering zone reaches about 1 km around the leaky well in the Albian formation**
- **pH decreases (from 7.3 to 4.9), along with dissolution of CO_2 in the aqueous phase (from 3 mmol/kgw to 1.3 mol/kgw)**
- **calcium concentration increases from 1.3 to 31.6 mmol/kgw and iron concentration increases from 1.3 10^{-5} to 2.5 10^{-3} mol/kgw, which is significant**
- **Iron is not a health concern at concentrations normally observed in drinking water, but the taste and appearance of water are affected below the health-based value (WHO). In France, quality guidelines for iron are set to 3.6 µmol/L**

Albian aquifer

Ca

Fe

pH



5 years flux(0.3 Mt/yr)

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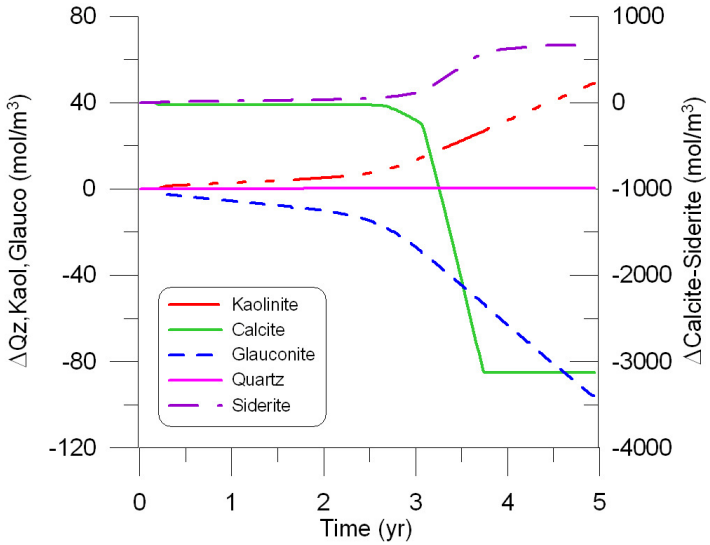
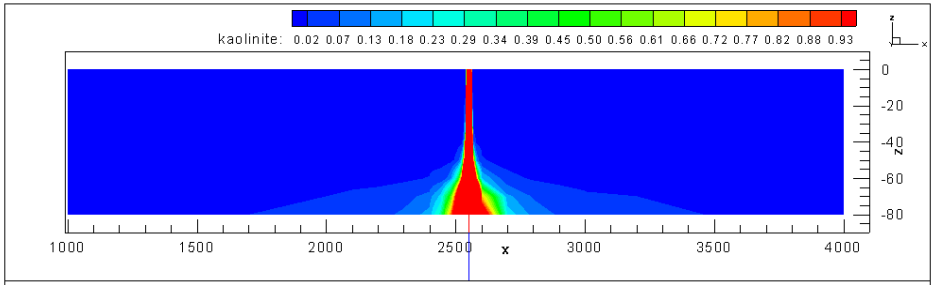
Albian minerals composition

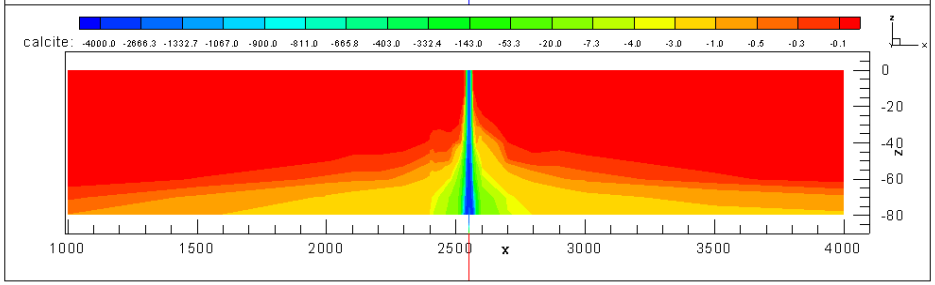
- **The solution becomes under-saturated with regard to most of the minerals**
- **Calcite and glauconite start to dissolve at the CO_2 intrusion point, releasing Ca (part of carbonate dissolution) and Fe, Mg, K, Si (due to silicate dissolution)**
- **Calcite dissolution is mainly localized above the intrusion point, with small impact around it until its total disappearance provoking a decrease in pH because of buffering capacity impact**
- **Siderite precipitates over time around the intrusion point, with little impact on iron concentration variation.**
- **Glauconite dissolution also entails an increase of Si and Al in solution touching off the precipitation of kaolinite and quartz around the intrusion point**
- **K and Mg elements do not involve any mineral phases precipitation**



kaolinite



calcite



Some comments…

- **Whereas carbonate chemistry and formation of an acid plume due to leakage of CO_2 is well understood, glauconite (phyllosilicate group) dissolution mechanisms are not**

- **They could play a prominent part in the Albian chemical impact:**
  - Dissolution rates for the glauconite were evaluated in Palandri and Kharaka (2004); this entailed a mineral dissolution assumed fast enough to be rapidly in equilibrium with a fast release of iron and silica, touching off the precipitation of kaolinite and quartz around the intrusion point

- **A change in redox conditions causes pyrite dissolution, which releases iron and sulphate elements:**
  - Arsenic could be associated with pyrite, and this dissolution of pyrite could impact water quality by releasing the associated arsenic

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Conclusion

- **By combining in house and commercial codes BRGM is being able to provide modeling studies on geological storage of CO_2 focusing on different physical processes: trapping processes, injectivity efficiency and site integrity for short and long term predictions at different scales.**

- **Numerical modeling is a simplification of very complex systems. Interpretations of such modeling have to be supported by on site measurements for calibration.**

- **Limitations remain for specific cases:**
  - Oil or gas field reservoir,
  - High saline aquifers
  - Desiccation
  - Coupling
  - CPU time and memory

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Listing of numerical codes

Models at a Glance

Study performed by Geogreen

Name	Affiliation	Developers[1]	Status[2]	Phase transition	Geo-chemistry	Thermal	Solid matrix Deformation	Discretization method (space)	Discretization method (time)	Wells & fractures
Athena	U. of Bergen	Heimsund	○	○	○	○	✗	MPFA (FV)	Implicit	No special treatment
CSLS	Stanford U.	Gerritsen Jessen	○	✓	✗	✗	✗	Pressure: MPFA Flow: Streamline	MMOC along streamlines	No special treatment
Spectral	Stanford U.	(Gerritsen)	✓	✓	✗	✗	✗	Spectral Galerkin	Explicit 4th order	Homogeneous medium
EOS7C	LBNL	Oldenburg	○	✓	✗	✓	✗	FD	Implicit	No special treatment
Dynaflow	Princeton U.	Prevost	✓	✓	○	○	✓	MFEM, VCFV, CCFV	Implicit	No special treatment
Elsa	Princeton U. U of Bergen	Nordbotten Kavetski	○	○	✗	✗	✗	Semi-Analytical	IMPES and fully implicit	1D wells with Darcy flow
FEHM	LANL	Pawar Viswanathan	○	✓	✓	✓	✓	Integrated FV	Implicit	Coupled wellbore flow; Dual porosity
GEM-GHG	Comp. Mod. Grp. U. of Texas	(Bryant)	✓	✓	✓	✓	✗	Adaptive grid, FD	Implicit	Line source/sink wells
MUFTE_UG	U. of Stuttgart U. of Heidelberg	Bielinski Ebigbo	✓	✓	○	✓	✗	Box method (FV)	Implicit or high order schemes	Lower dim. wells/ fractures planned
NUFT/LDEC/ GEMBOCHS	LLNL	Johnson	✓	✓	✓	✓	✓	FD, FE	Transport implicit Deform explicit	Dual porosity
PFLOTRAN	LANL	(Carey)	○	✓	✓	✓	✗	Integrated FV	Implicit	No special modes
STOMP	PNNL Battelle	White	✓	✓	✓	✓	✗	Integral FV	1st or 2nd order backward Euler	Separate subdomains
TOUGH2 ECO2N/EOSM	LBNL	Pruess	✓/○	✓	✓	✓	✗	Integrated FD	Implicit	Multi-continua models
TOUGHREACT	LBNL	(Pruess)	✓	✓	✓	✓	✗	Integrated FD	Implicit	Multi-continua
CO2-PENS	LANL	Viswanathan	○	A systems level code used to integrate the process models into comprehensive systems model						
T2CA	LBNL	Oldenburg	○	A TOUGH2 module for coupled subsurface-atmosphere transport of water, brine, CO2, 1 tracer, air						

[1] Developers present at workshop. For complete lists, see the questionnaires at the end of this document. Non-developer presenters are indicated with brackets.
[2] Green checks (✓) indicate 'yes' (or 'publicly accessible' for the status column), grey circles (○) 'still in development', and red crosses (✗) 'no'.

PHREEQC	USGS	_	free	no	yes	_	no
COORES	IFP	_	not free	yes	yes	yes	no
ECLIPSE	SLB	_	not free	yes	no	yes	?
SIMED	TNO	_	not free	yes	no	yes	no
MARTHE	BRGM	-	not free	no	yes	yes	no
CODE_ASTER	EDF	-	free	no	no	yes	yes

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Conclusion 1/2

- **Numerical modeling is a simplification of very complex systems: Interpretations of such modeling have to be supported by on site measurements for calibration**
- **The main limitations are the CPU time and memory and data**
- **Some predictions are provided to assess:**
  - Storage efficiency (injectivity and large scale CO2 migration)
  - Storage security (long term fluid rock interaction, over pressure)
  - Trapping efficiency (structural, residual, solubility, mineral)
  - Coupling some processes (geochemical, geomechanical)

Conclusion 2/2

> **New physico-chemical processes to focus on:**

- Near well effect (dry out zone, salt precipitation, cement alteration)
- Impact of storage to other aquifers
- Leakage through abandoned well
- Geochemical kinetic rates of mineral solubility
- Presence of other gaz (SOx, NOx)

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Actual limitations

> Compromise

- Detailed multiphase fluid flow description (3D reservoir grid models) incorporating geometry and heterogeneity of the geology
- Long term simulation
- Scaling effect of all physical and geochemical processes

> Today solution

- Use of a combination of different softwares to perform separate simulations for one specific purpose rather than coupling every processes

> Tomorrow solution

- Platform
- Parallelism of coupling between geochemistry and hydrodynamics

BRGM modelling team:

- Laurent André
- Isabelle Czernichowski-Lauriol
- Mohamed Azaroual
- Pierre Durst
- Irina Gaus
- Christophe Chiaberge
- Julie Lions
- Pauline Humez
- …

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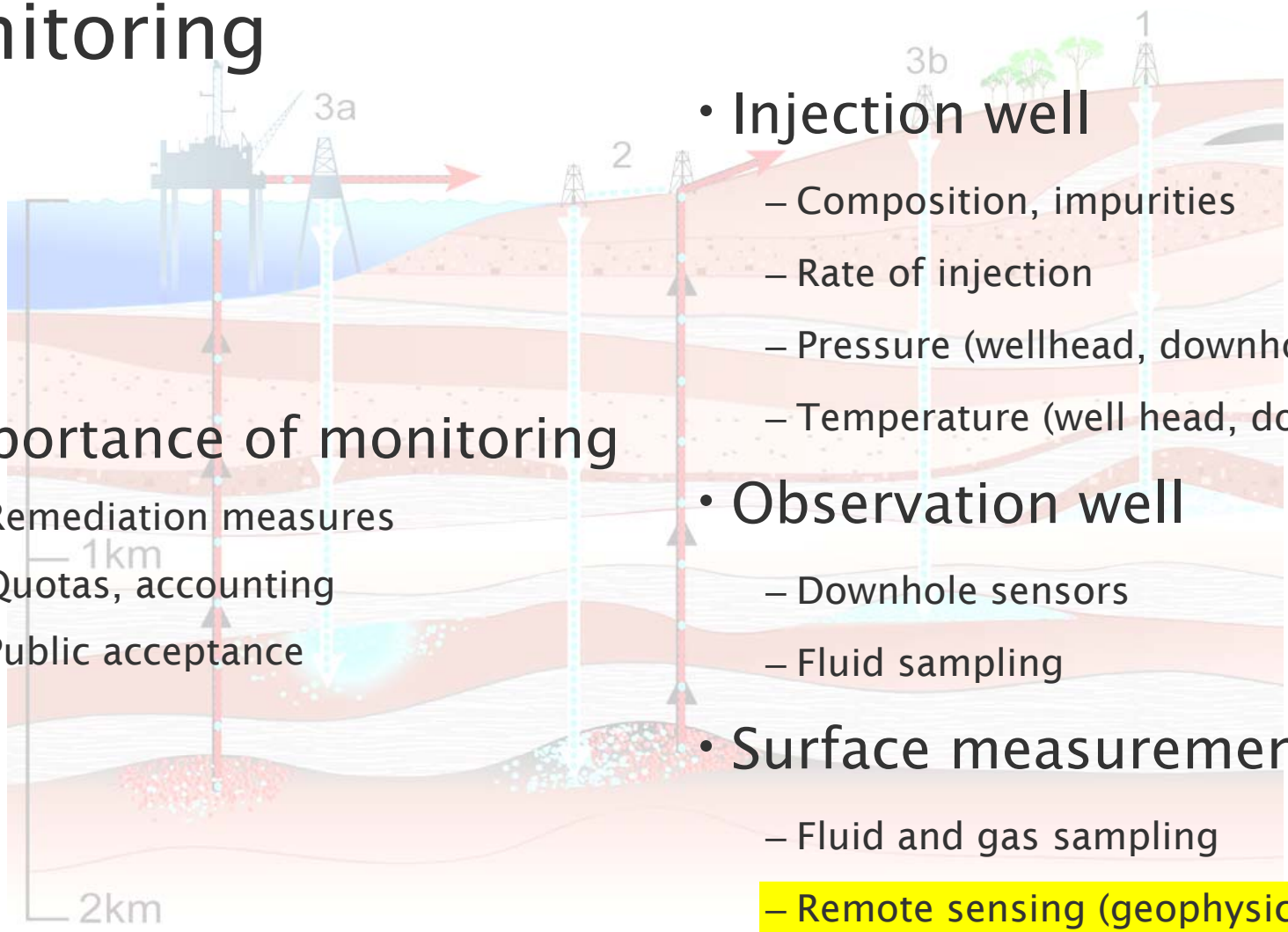
CO_2 monitoring and status

Jon Lippard Ola Eiken and Svend Østmo
Statoil

OPEC - IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries
Hassi Messaoud, Algeria
16th – 19th November, 2009

Classification: Internal Status: Draft

Monitoring

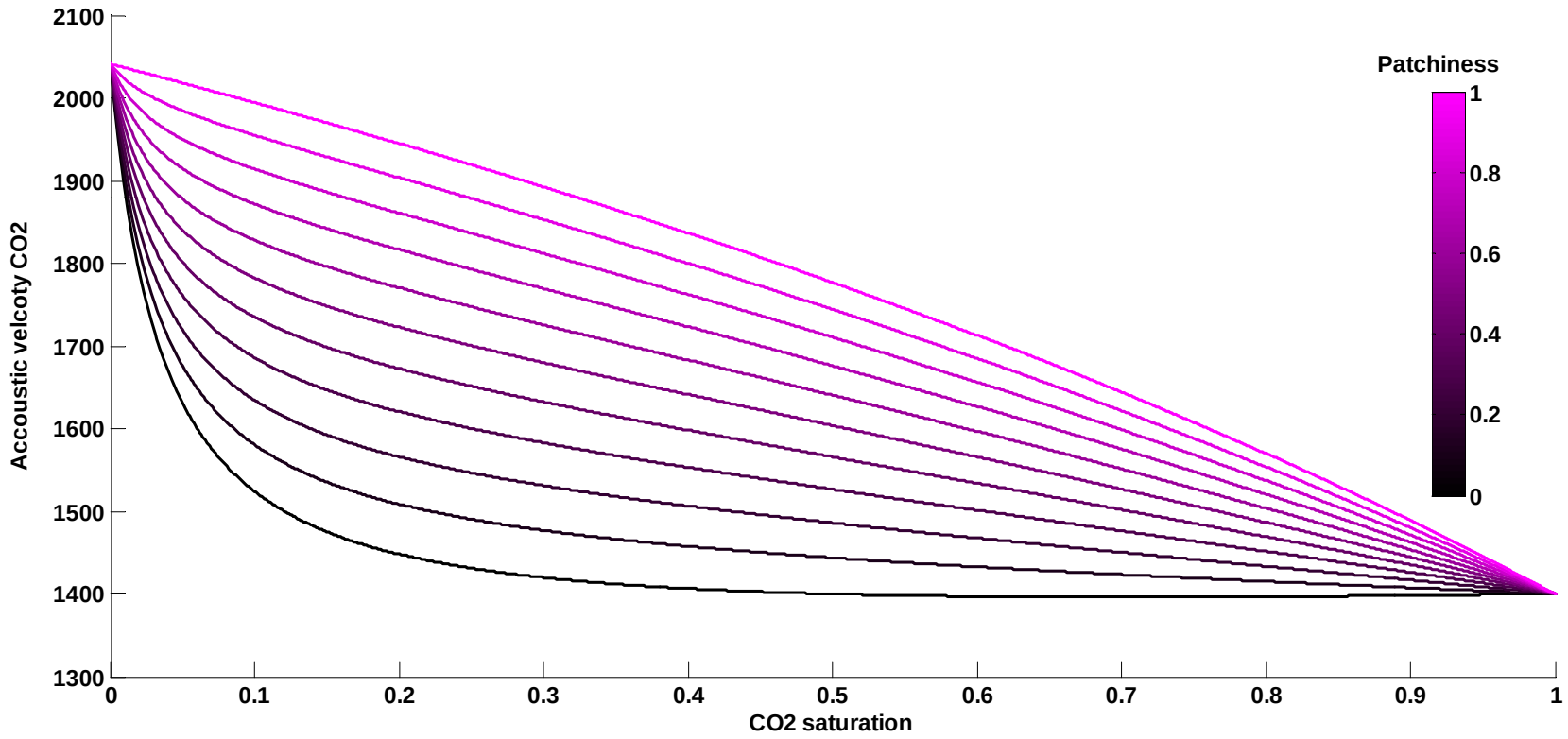


- Importance of monitoring
  - Remediation measures
  - Quotas, accounting
  - Public acceptance
- Injection well
  - Composition, impurities
  - Rate of injection
  - Pressure (wellhead, downhole)
  - Temperature (well head, downhole)
- Observation well
  - Downhole sensors
  - Fluid sampling
- Surface measurements
  - Fluid and gas sampling
  - Remote sensing (geophysics)

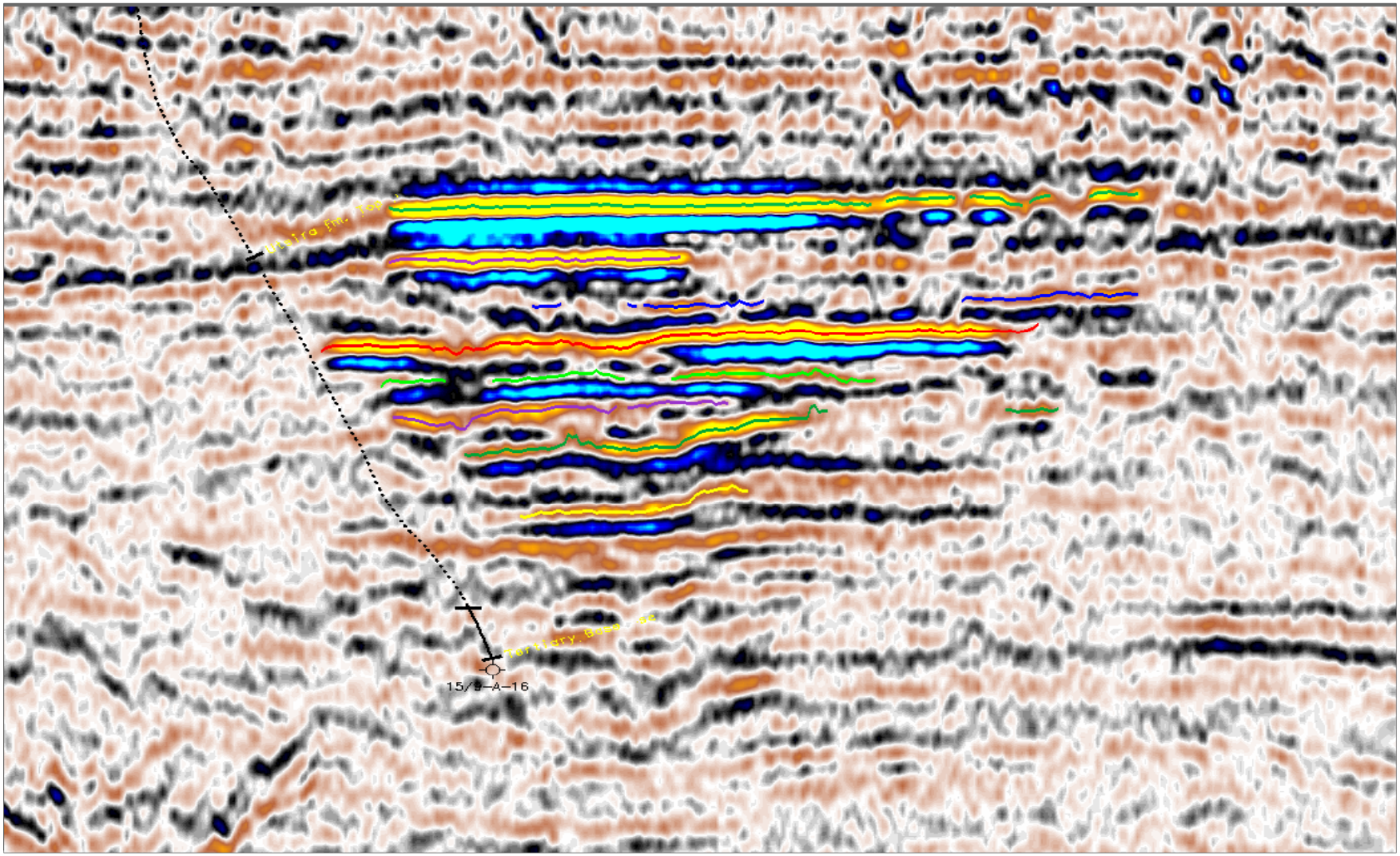
Surface geophysical monitoring tools

Technique	Measurement parameters	Example applications
Time-lapse (4D) seismic	P and S wave velocity Reflection horizon Seismic amplitude attenuation	Tracking CO_2 movement in and above storage formation
Passive seismic	Location, magnitude and source characteristics of seismic events	Development of microfractures in formation or caprock CO_2 migration pathways
Electrical and electromagnetic	Formation conductivity Electromagnetic induction	Tracking movement of CO_2 in and above the storage formation Detecting migration of brine into shallow aquifers
Time-lapse gravimetry	Density changes caused by fluid displacement	Detect CO_2 movement in or above storage formation CO_2 mass balance in the subsurface
Land or seafloor surface deformation	Tilt Vertical and horizontal displacement using interferometry and GPS Echo sounding, side scan sonar	Detect geomechanical effects on storage formation and caprock Locate CO_2 migration pathways

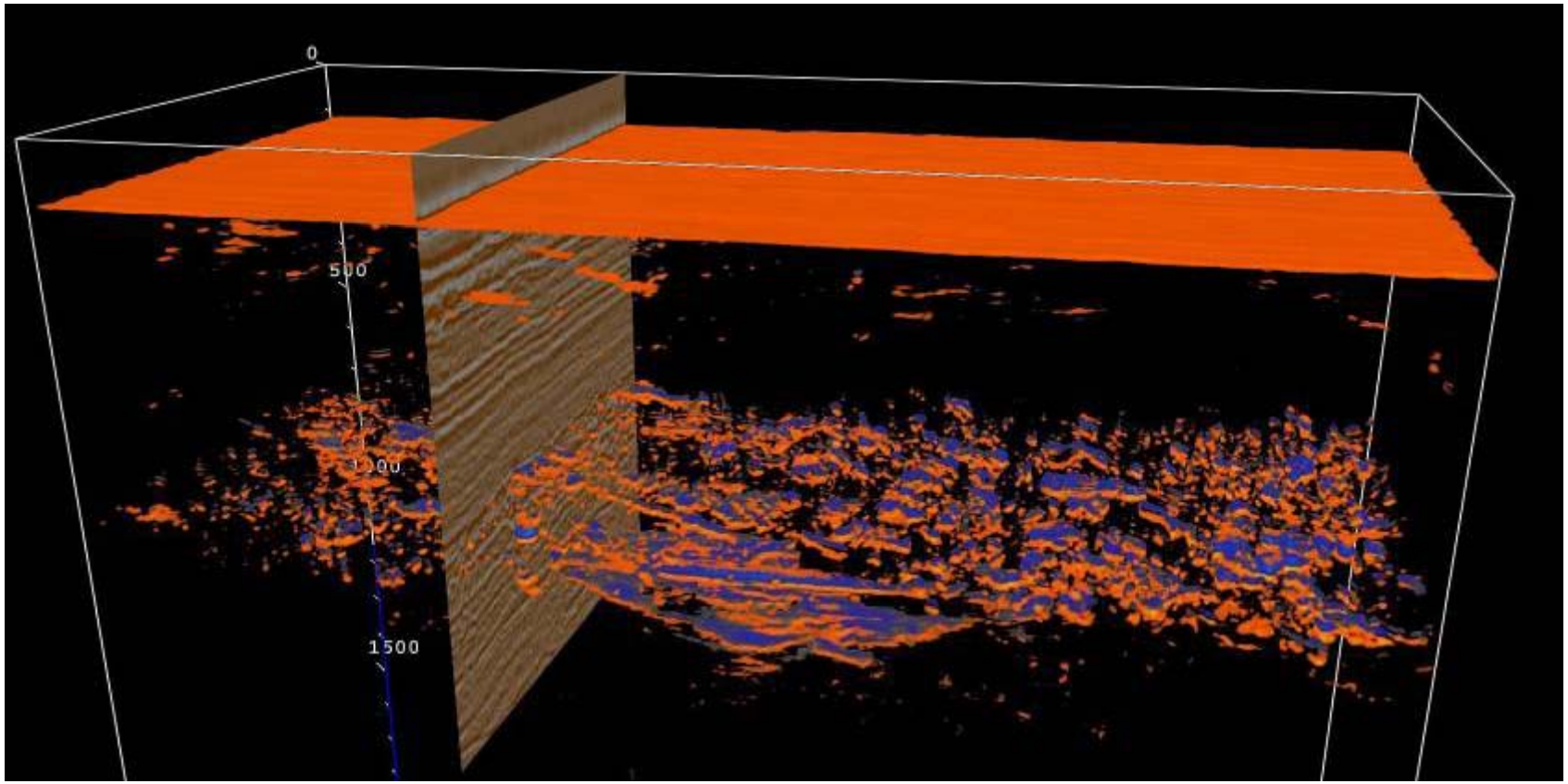
Accoustic velocity of CO2 as a function of saturation (Sleipner)



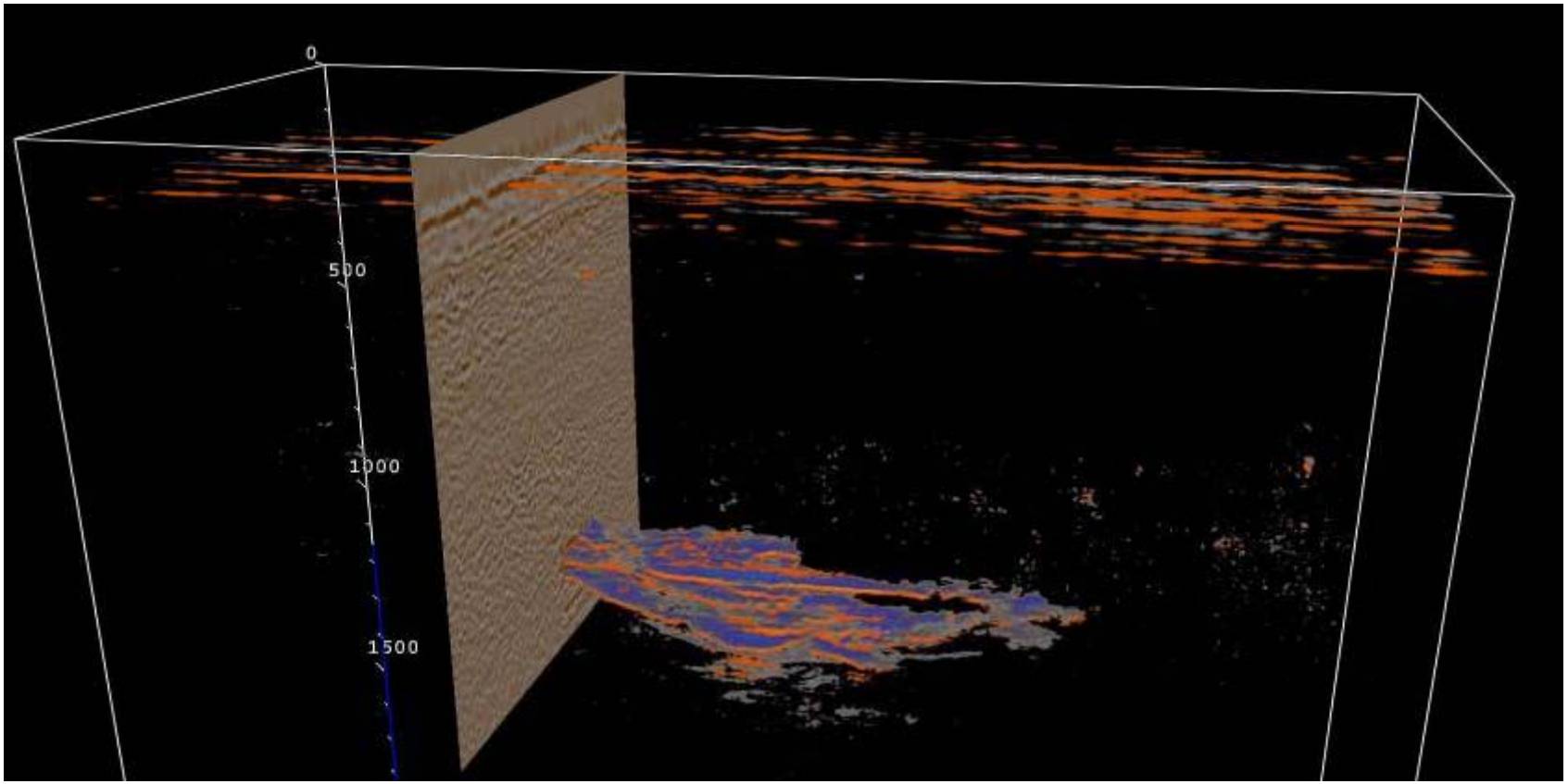
The CO2 distributes into 9 mappable layers



Seismic data in 2008 (3D)

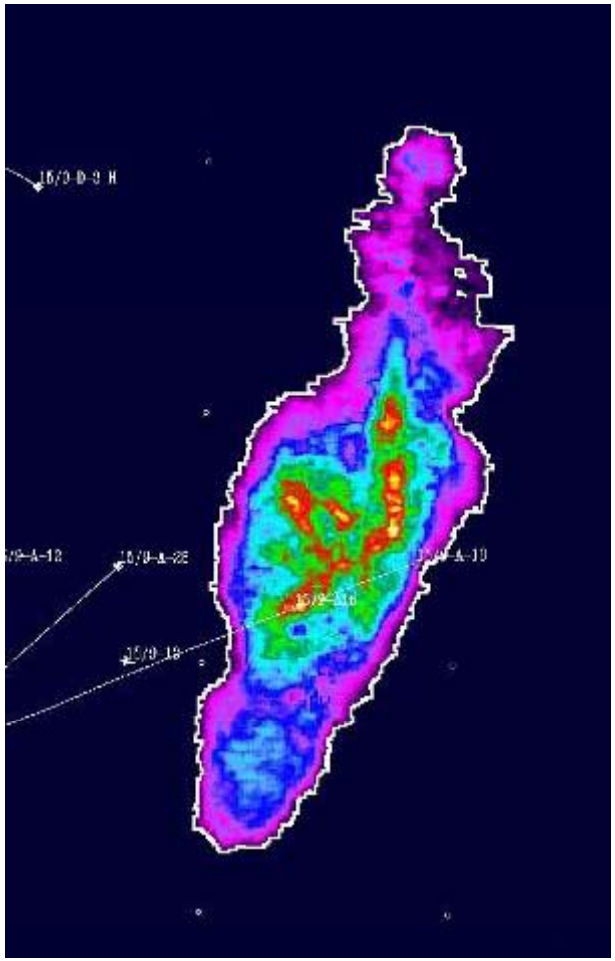


Seismic data in 2008 (4D)

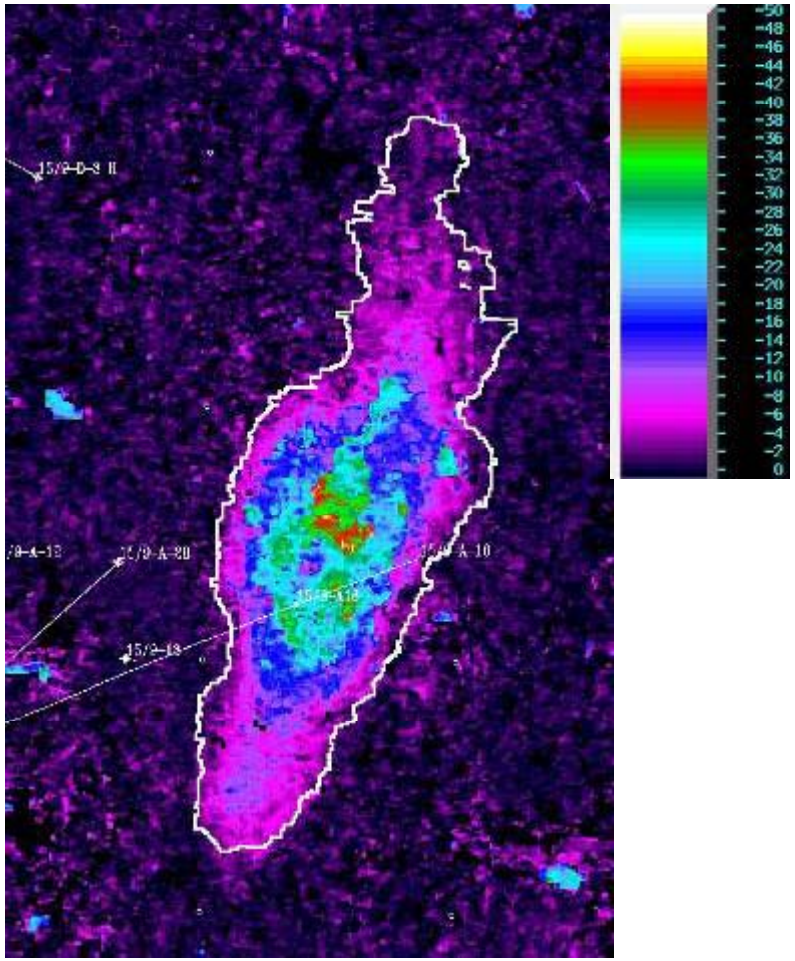


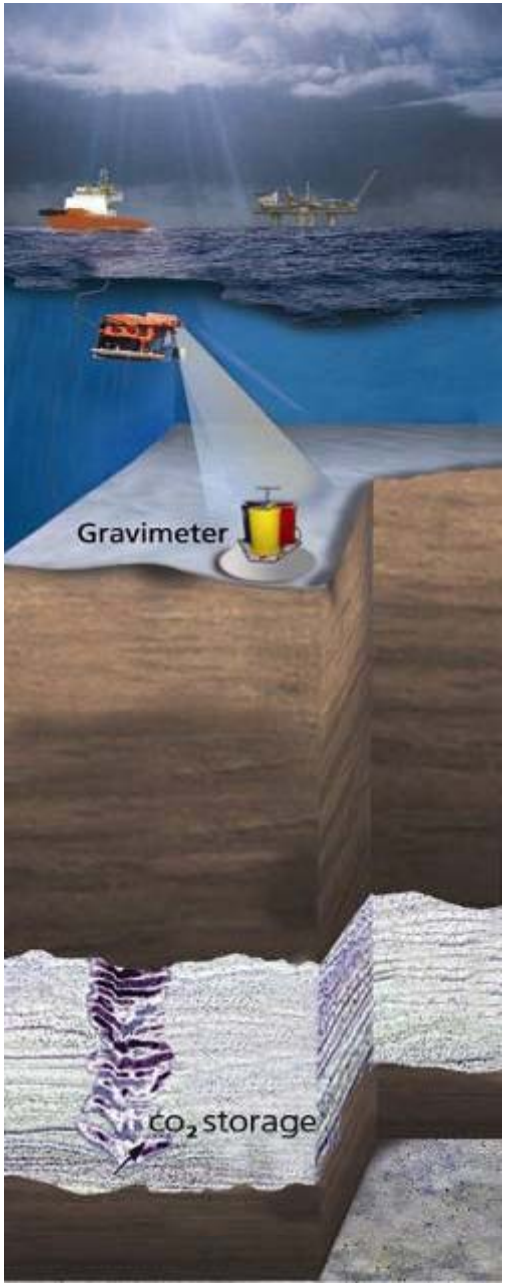
Pushdown beneath the CO_2 plume

amplitude



pushdown

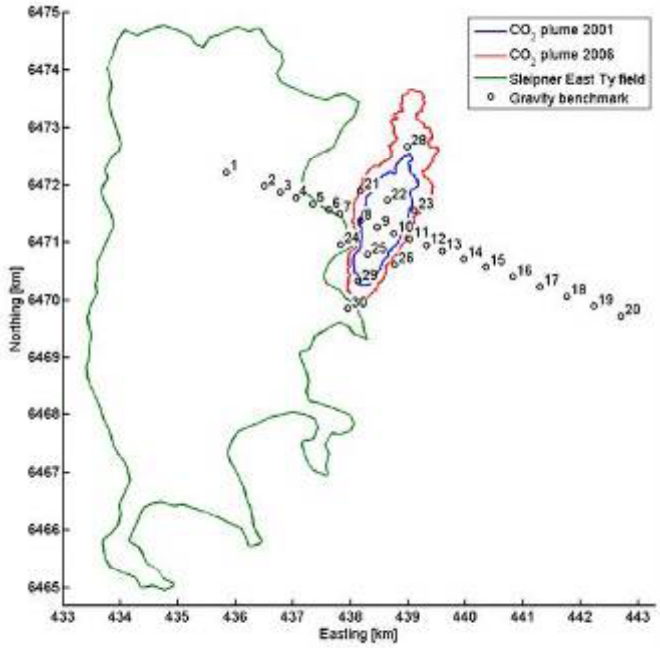


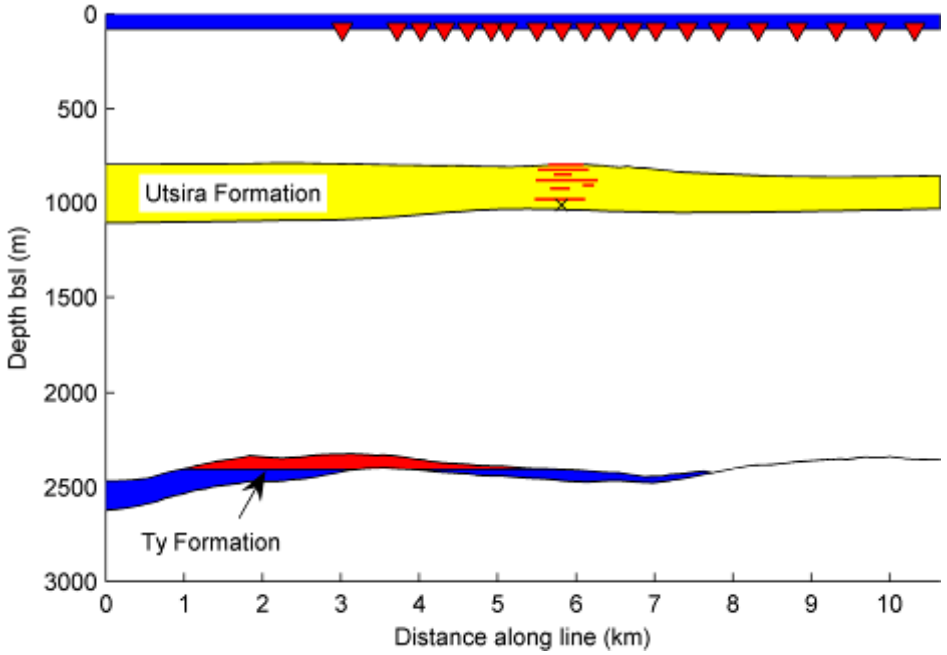


Time lapse gravimetry and surface deformation

- Time lapse gravimetric survey designed to monitor CO_2 injected into Utsira fm.
- 3 gravimeters and 1 pressure sensor placed on fixed concrete benchmarks deployed on the seafloor.
- Surveys 2002, 2005 and 2009 (planned).
  - Cost covered by research consortia (CO2STORE, NORSTORE, CO2ReMoVe) and USDoE

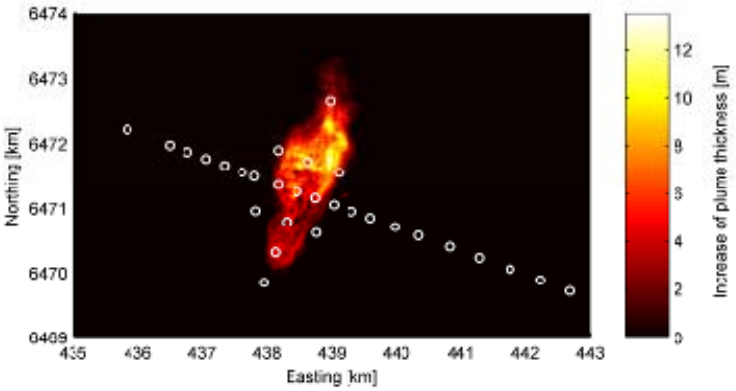
Gravimetry measures in-situ CO_2 density

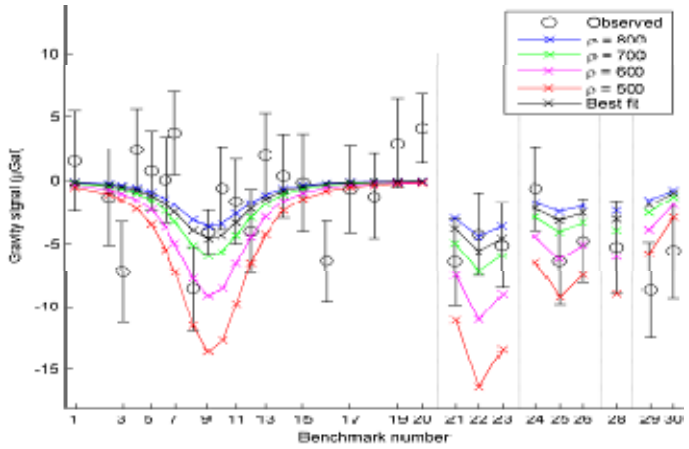




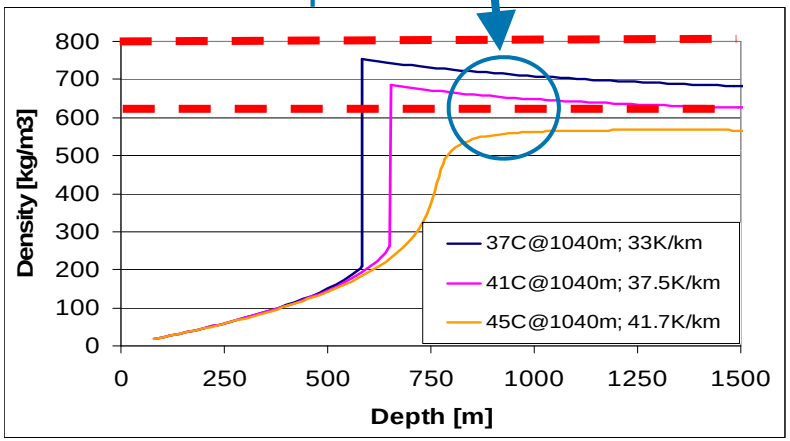
- 30 benchmarks in two lines across CO_2 injection point.
- Additional contribution from Ty Formation due to gas/condensate production.

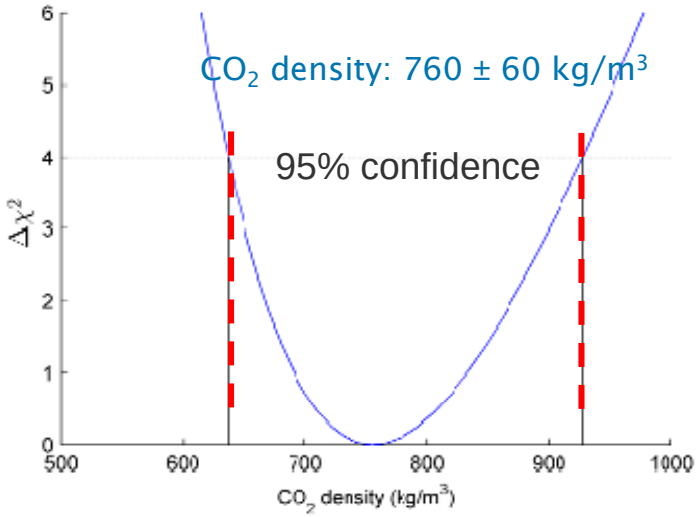
Inversion results





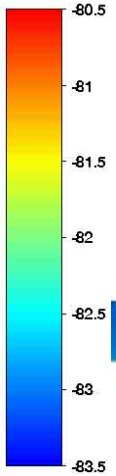
Sleipner/Utsira conditions

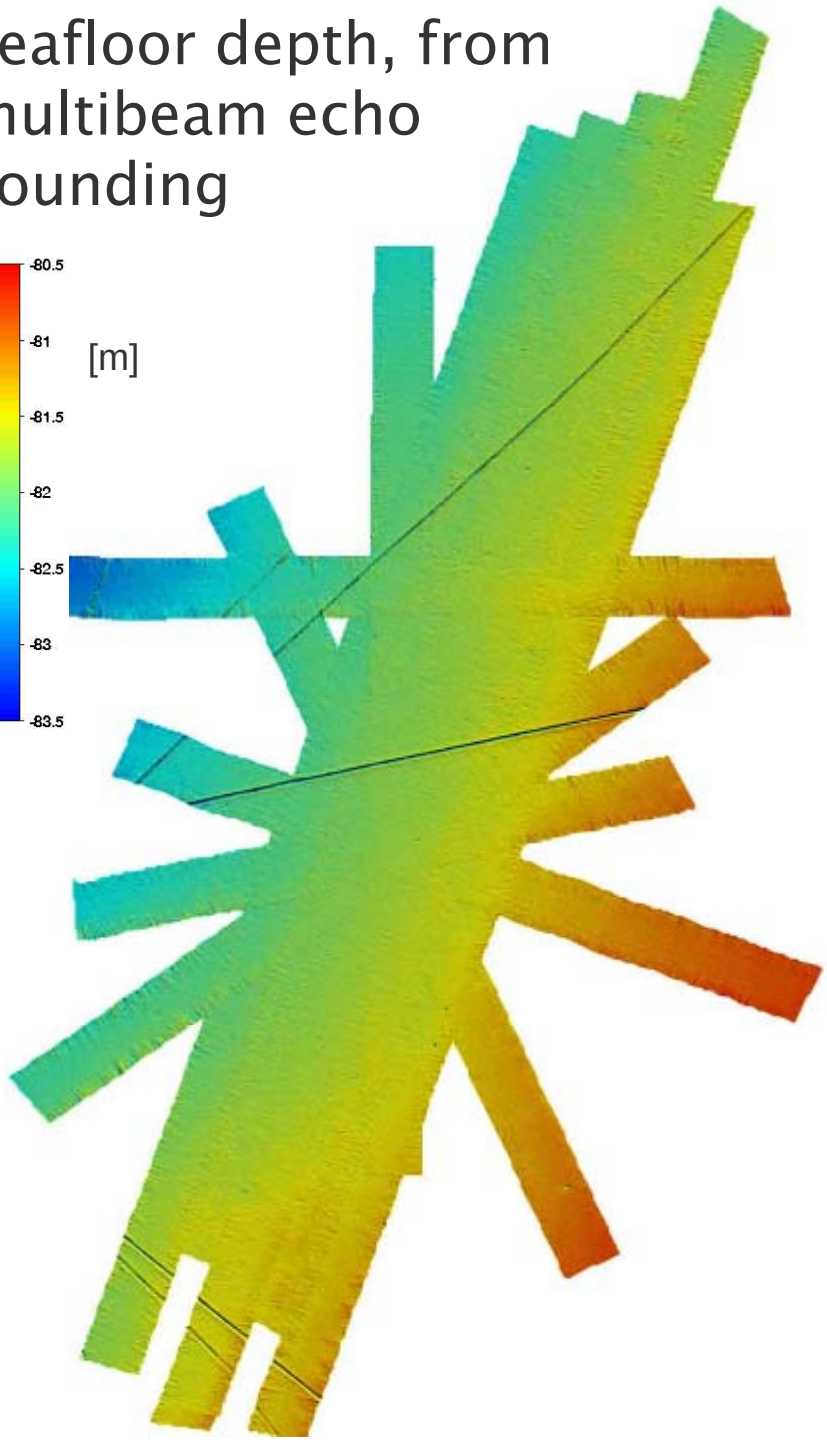




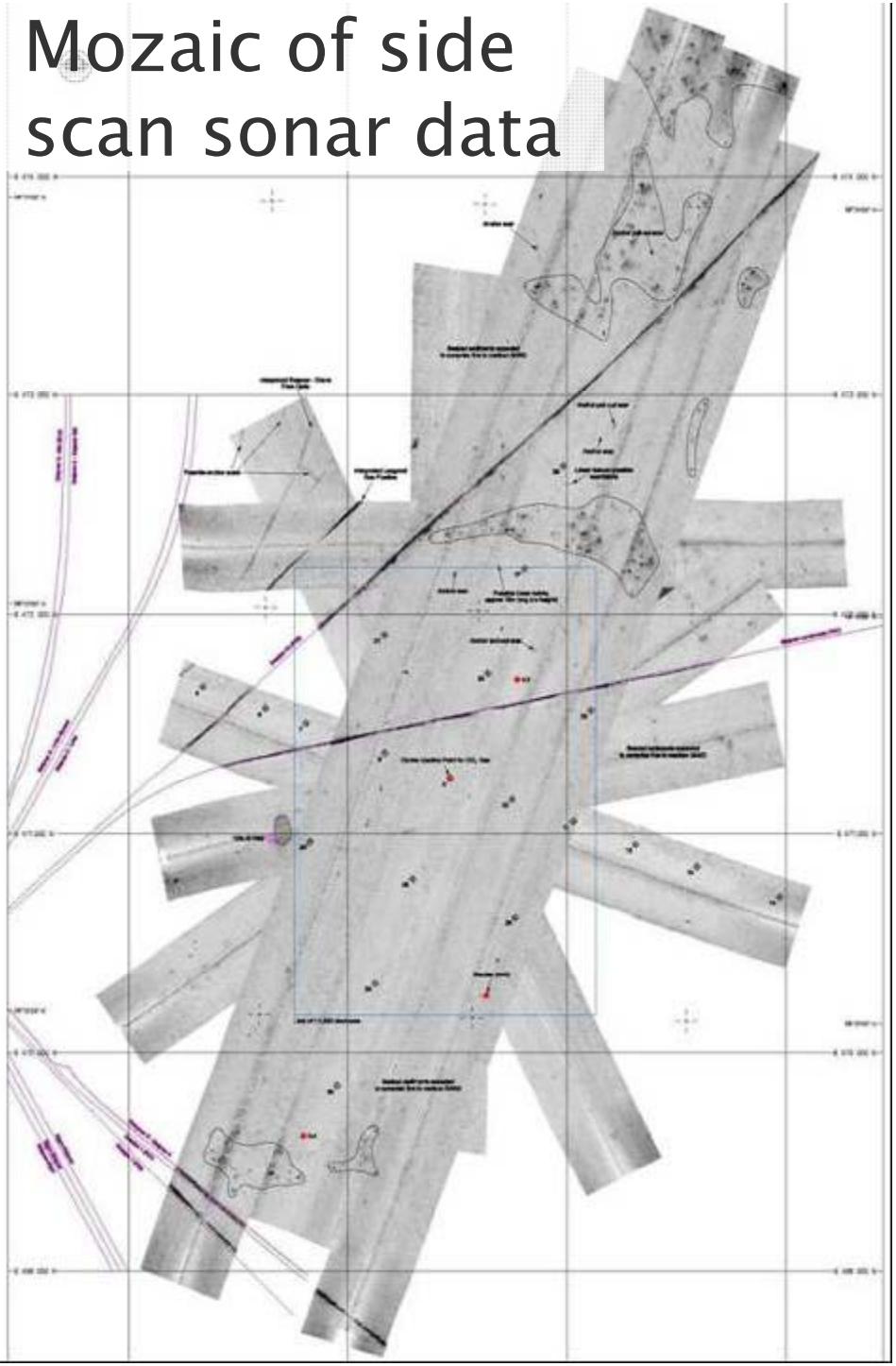
PVT analysis together with gravimetric result give an upper bound of 770 kg/m3 and a lower bound of 640 kg/m3 with 95% confidence.

Seafloor depth, from multibeam echo sounding

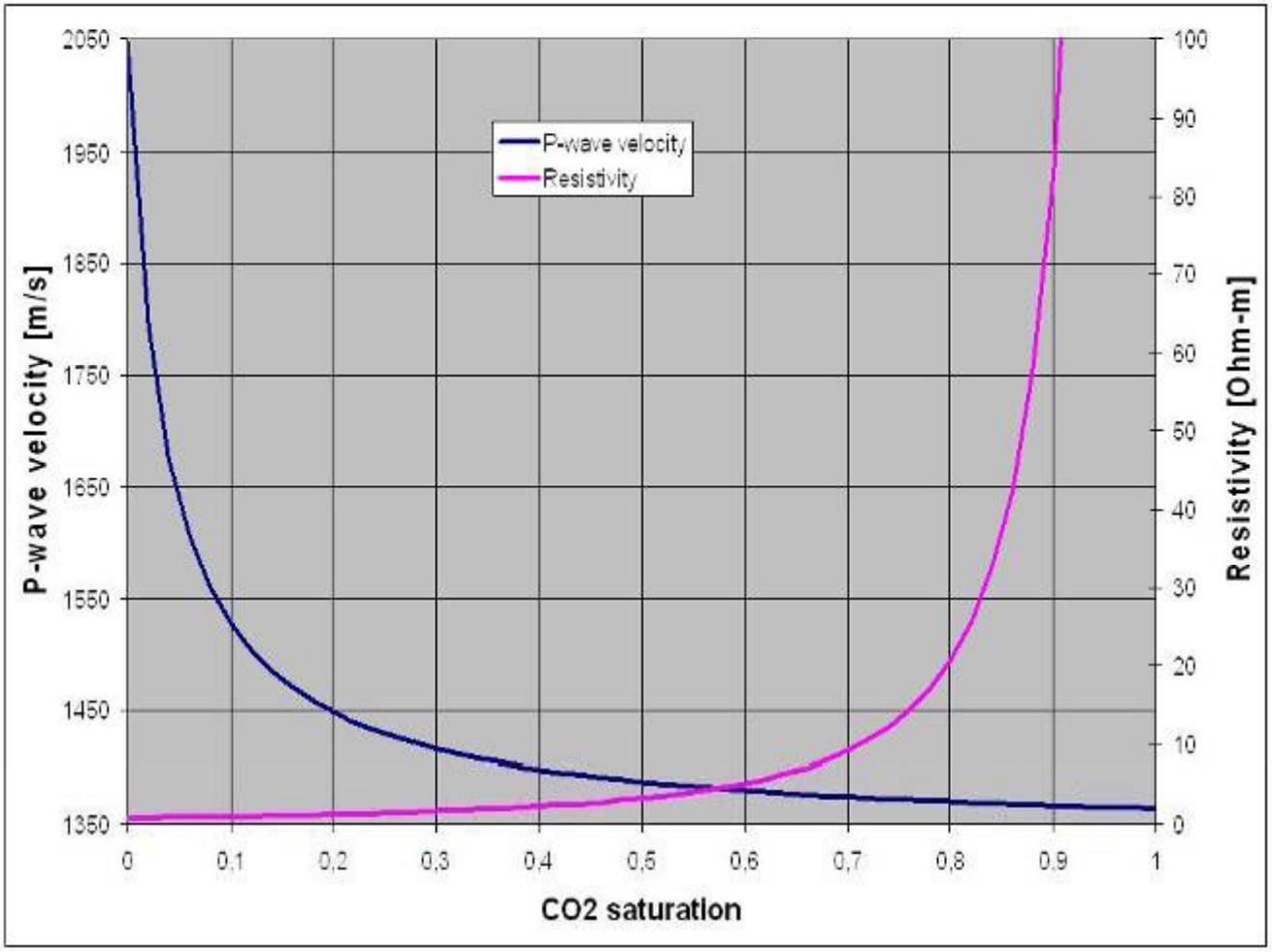




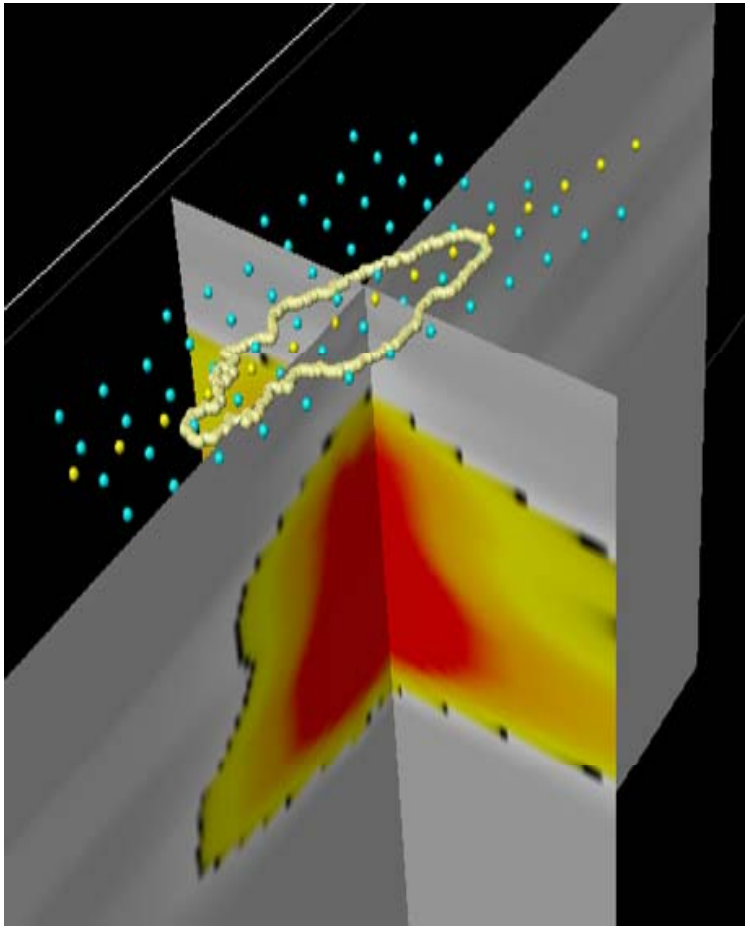
Mozaic of side scan sonar data

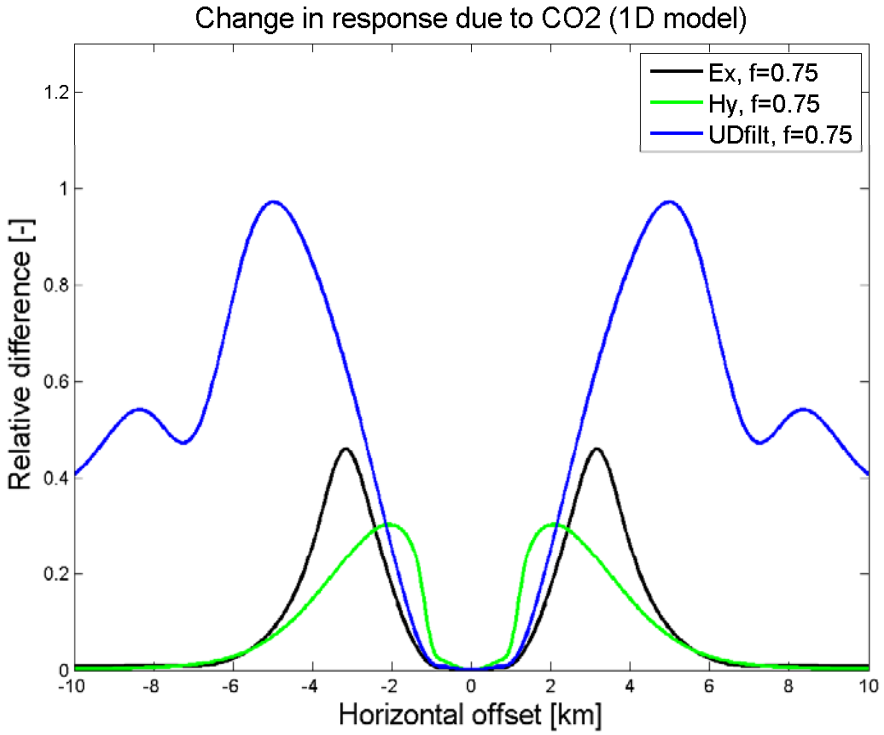


Controlled Source ElectroMagnetic monitoring



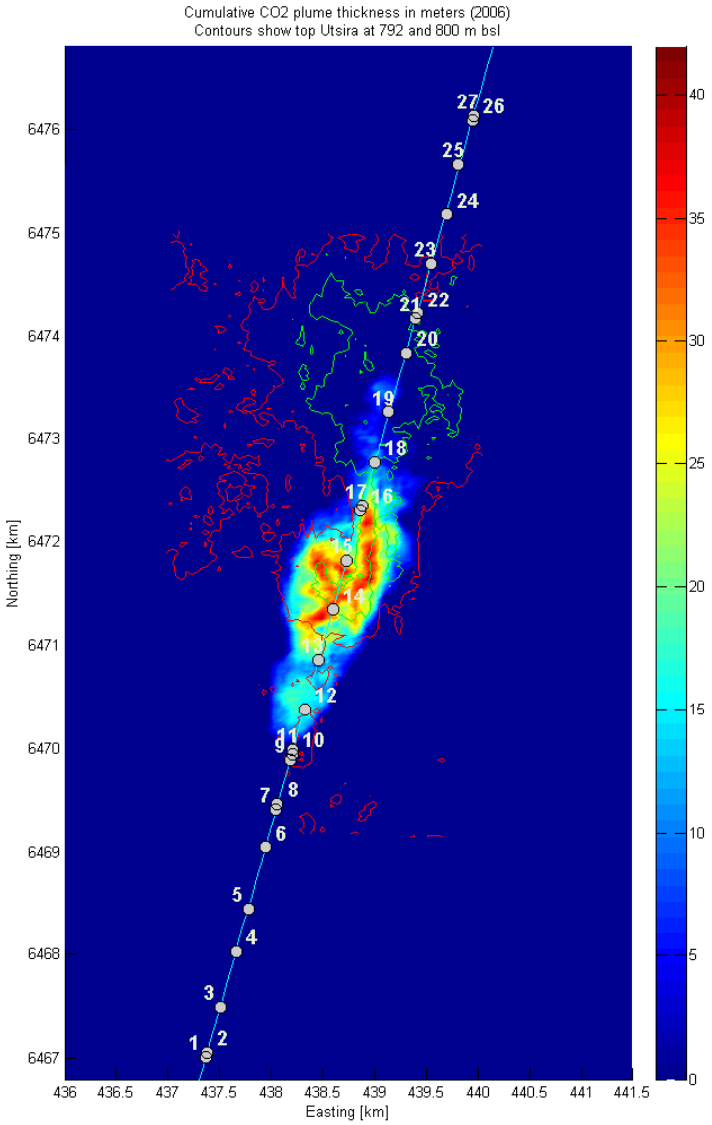
Controlled Source ElectroMagnetic monitoring





Sleipner Controlled Source Electromagnetic survey 2008

- Successfully acquired one line of CSEM data across CO_2 plume
- 27 receivers at 20 locations –
  - 500m between receiver locations
  - 50m between "doubled" receivers
  - Data quality is good, no indication of interference from pipelines etc.
  - Data processing is not good enough, reprocessing is ongoing
  - Too early to conclude on whether the CO_2 plume is visible

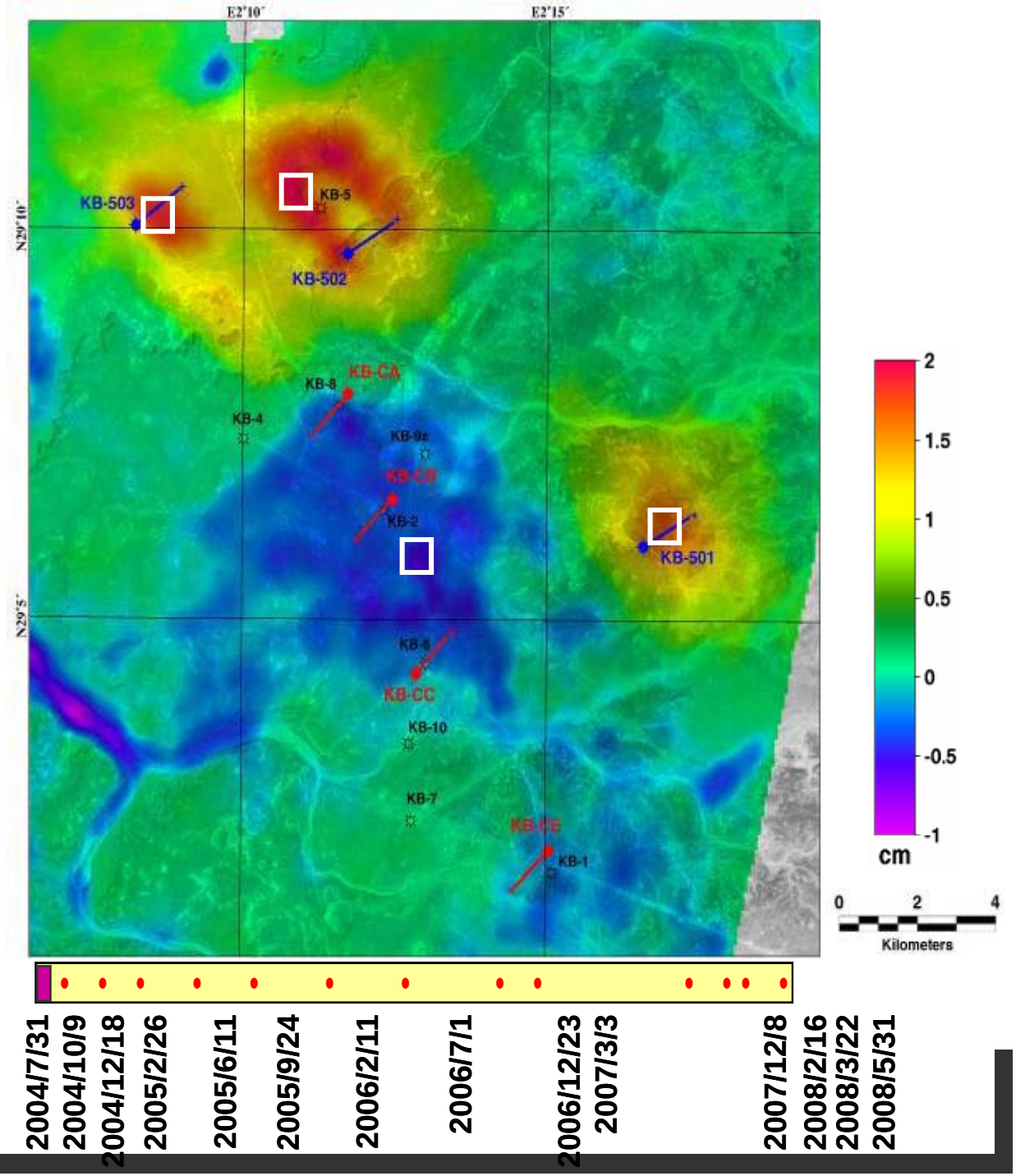


Technique	Measurement parameters	Example applications
Time-lapse (4D) seismic ✓	P and S wave velocity Reflection horizon Seismic amplitude attenuation	Tracking CO_2 movement in and above storage formation
Passive seismic	Location, magnitude and source characteristics of seismic events	Development of microfractures in formation or caprock CO_2 migration pathways
Electrical and electromagnetic ✓	Formation conductivity Electromagnetic induction	Tracking movement of CO_2 in and above the storage formation Detecting migration of brine into shallow aquifers
Time-lapse gravimetry ✓	Density changes caused by fluid displacement	Detect CO_2 movement in or above storage formation CO_2 mass balance in the subsurface
Land or seafloor surface deformation ✓	Tilt Vertical and horizontal displacement using interferometry and GPS Echo sounding, side scan sonar	Detect geomechanical effects on storage formation and caprock Locate CO_2 migration pathways

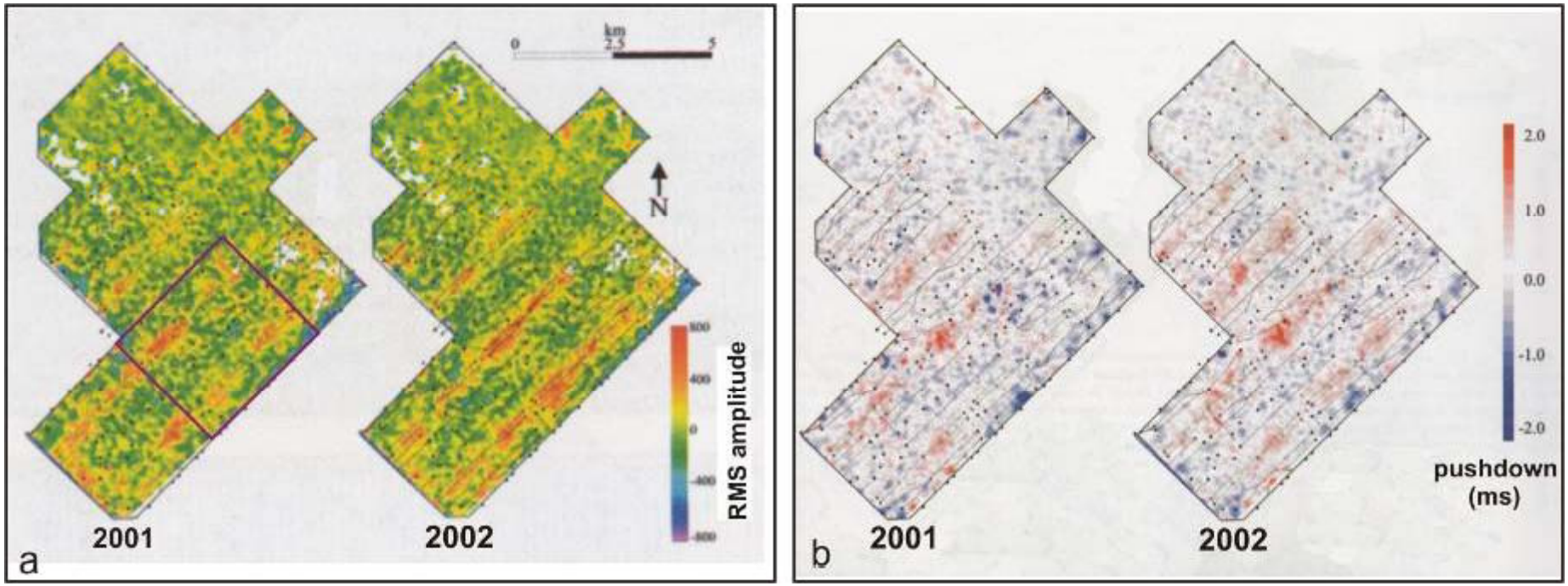
In Salah Surface Deformation Japex/JGI Study

Comments:

- Period 2004 to 2008
- Japan Geophysics Institute; Onuma & Ohkawa (2008)
- Based on Differential (DInSAR) method
- Subsidence seems to follow subsurface fault pattern
- Uplift pattern is clearly centered on injection wells with elongation in NW-SE stress direction
- No explanation of calibration or reference point given



Weyburn (Canada)



Weyburn: time-lapse seismic images from 2001 and 2002. a) Amplitude difference maps from the reservoir interval relative to the baseline survey b) velocity pushdown beneath the reservoir. *(from Wilson & Monea 2004)**.***

Thank you

CO2 monitoring and status

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Title: Geophycisist
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www.statoil.com

Current costs and cost reduction options

Introduction

- Capital cost estimating methods
- Operating costs of CCS systems
- Other costs
- Economic analysis of CCS systems
- Prospects for cost reduction

Cost estimating methods

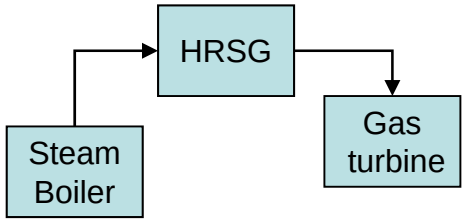
- Approach depends on maturity of project

- Concept
- Detailed design
- Execution

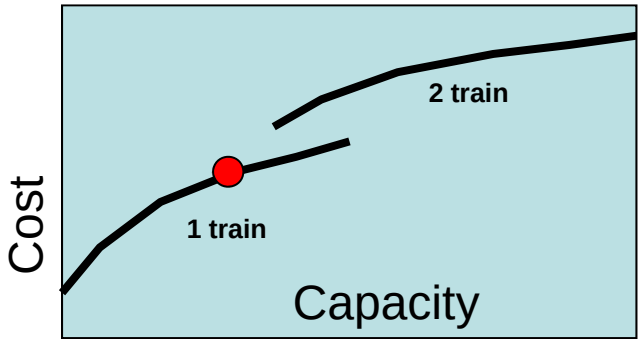
Available methods

- Functional systems
- Major equipment
- Detailed material and task takeoff

Functional systems approach



- Divide facilities into major blocks
- Estimate costs of each block
- Scale according to functional capacity
- Data sources – Costs for functional modules
- Scaling – graphical or exponent

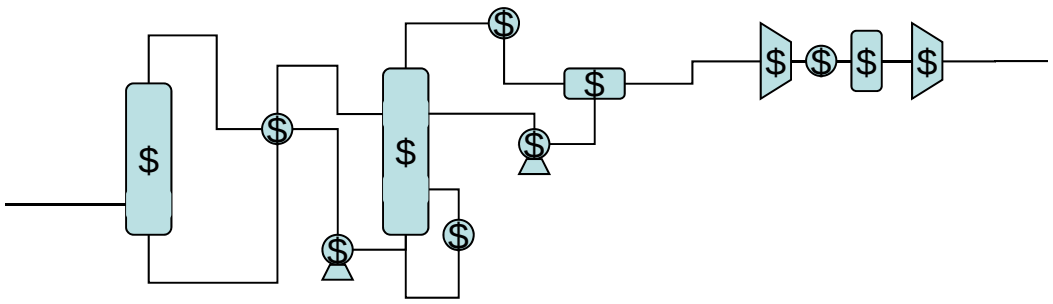


$$\frac{Cost_1}{Cost_{base}} = Cost_{base} \times \left(\frac{Cap_1}{Cap_{base}}\right)^{exponent}$$

Exponent typically in range .65 to .95

Major equipment based approach

- Identify all “major” items of equipment
  - i.e compressors, columns, pumps etc
- Estimate base cost for each item
- Apply factors to convert to fully installed cost
  - Subfactors for instrumentation, electrical, construction etc. can be used



Material and activity take-off approach

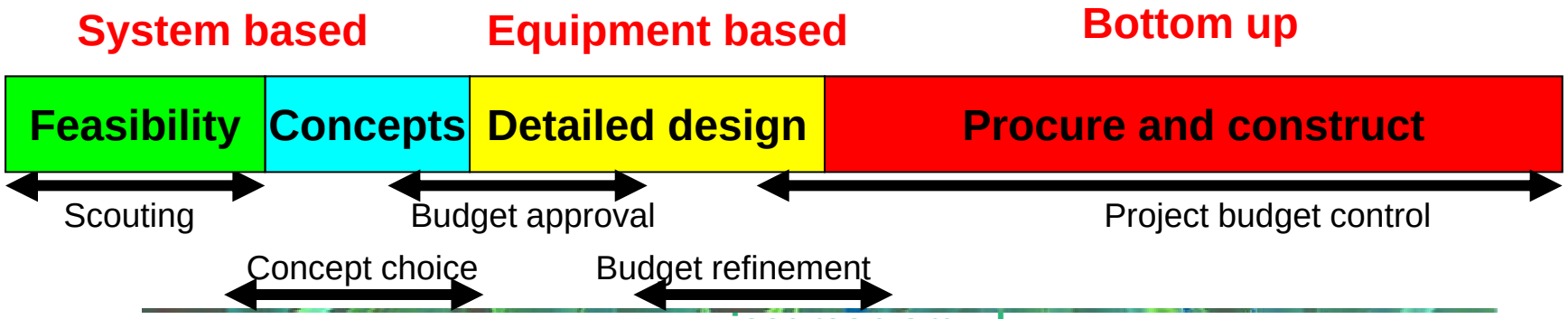
- All items to be purchased are identified and counted
  - Including instruments, pipelengths, fittings, cables, switchgear ….
- All manpower is identified
  - Design, management, construction hours…
- Every element is costed and summed

Calibration

- Calibration with feedback from completed projects greatly improves estimate accuracy
- Feedback easier to apply at high rather than detailed level

Relative merits

- Detailed bottom up approaches not necessarily any more accurate
- Functional approach preferred at early stage
- Bottom up approach preferred later
  - Actual costs will be increasingly available for check estimates during execution phase



Completeness and accuracy

- All items which attract cost should be included in estimate
- Large inaccuracies in single elements tend to cancel out
- Accuracy is normally stated for 90% certainty interval
  - i.e 5%- 95%
- Contingency typically added so that there is 50 % chance of exceeding budget.

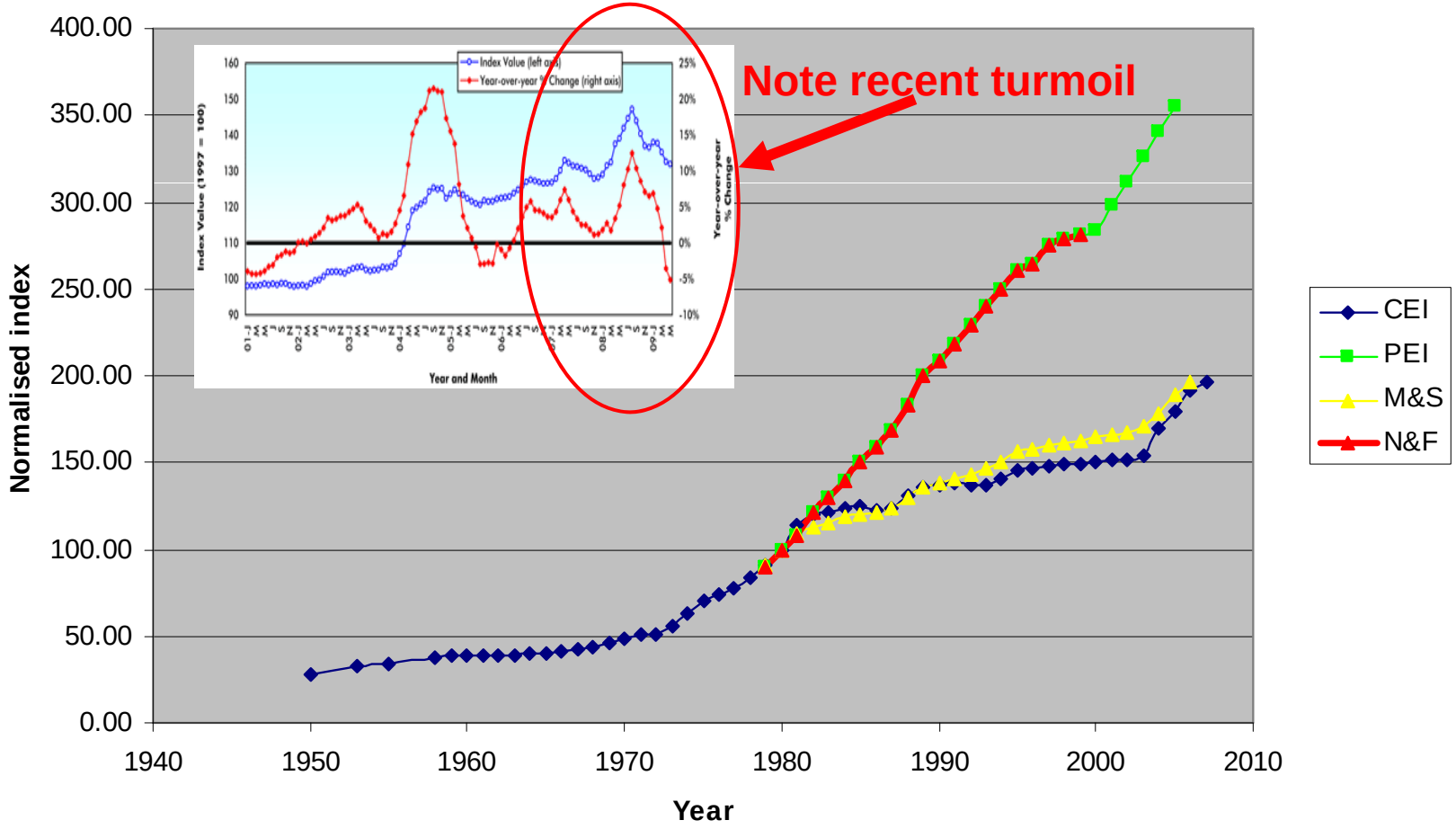
Other elements

- Site acquisition
- Site preparation
- General facilities – any buildings, offices, warehouses, maintenance workshops etc.
- Utilities – Cooling water, air, fuel, electrical supply systems
- Owners costs – administration, project management, licences, access roads, external links to rail and power etc (Some of these may be partly covered by the others) IEAGHG uses a standard 7% of installed plant for owners costs in the absence of other information.
- Insurance
- Initial inventories – working capital
- Temporary facilities – if required and not covered in construction costs
- Spares
- Contingency – cannot be ignored, some is always needed. IEAGHG uses 10% as a default

Escalation and currency

- Estimates made in one currency
  - Local
  - Major reserve $ or €
- Variations in exchange rate affect estimates
- Estimates made for a particular date
  - Prices change over time
  - Reflected in industry cost indices
    - CEI Chemical Engineering index, PEI Process Engineering index
    - Marshall and Swift, Nelson Farrar

Various cost indices normalised to 1980 =100



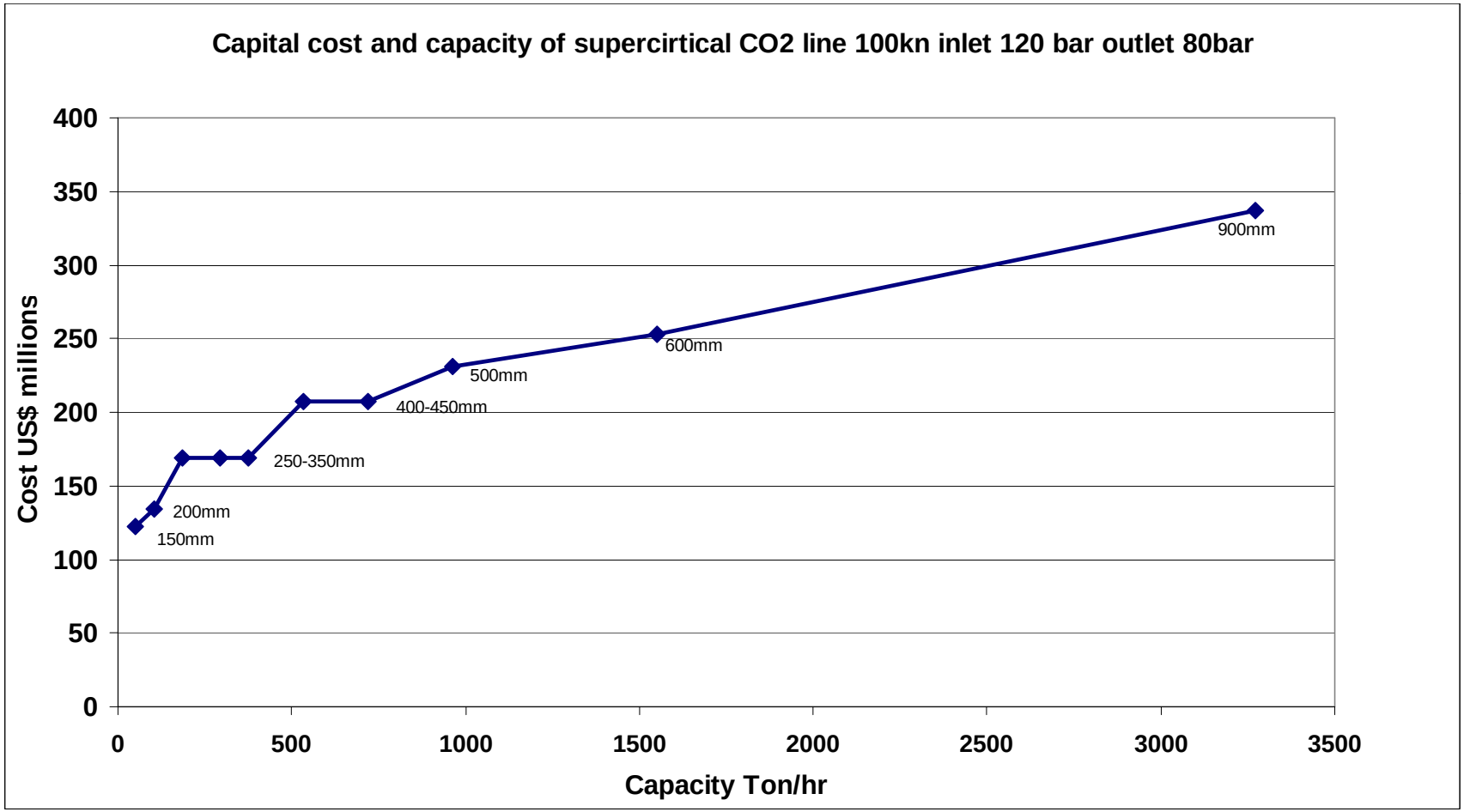
Operating costs

- Manpower for operation
- Manpower for maintenance
- Consumption of spare parts
- Inspection services
- Fuel
- Externally supplied utilities
- Auxiliary chemicals and other feedstocks
- Waste disposal.
- Insurance and special taxes (CO2 emission taxes?)
- Major overhaul costs

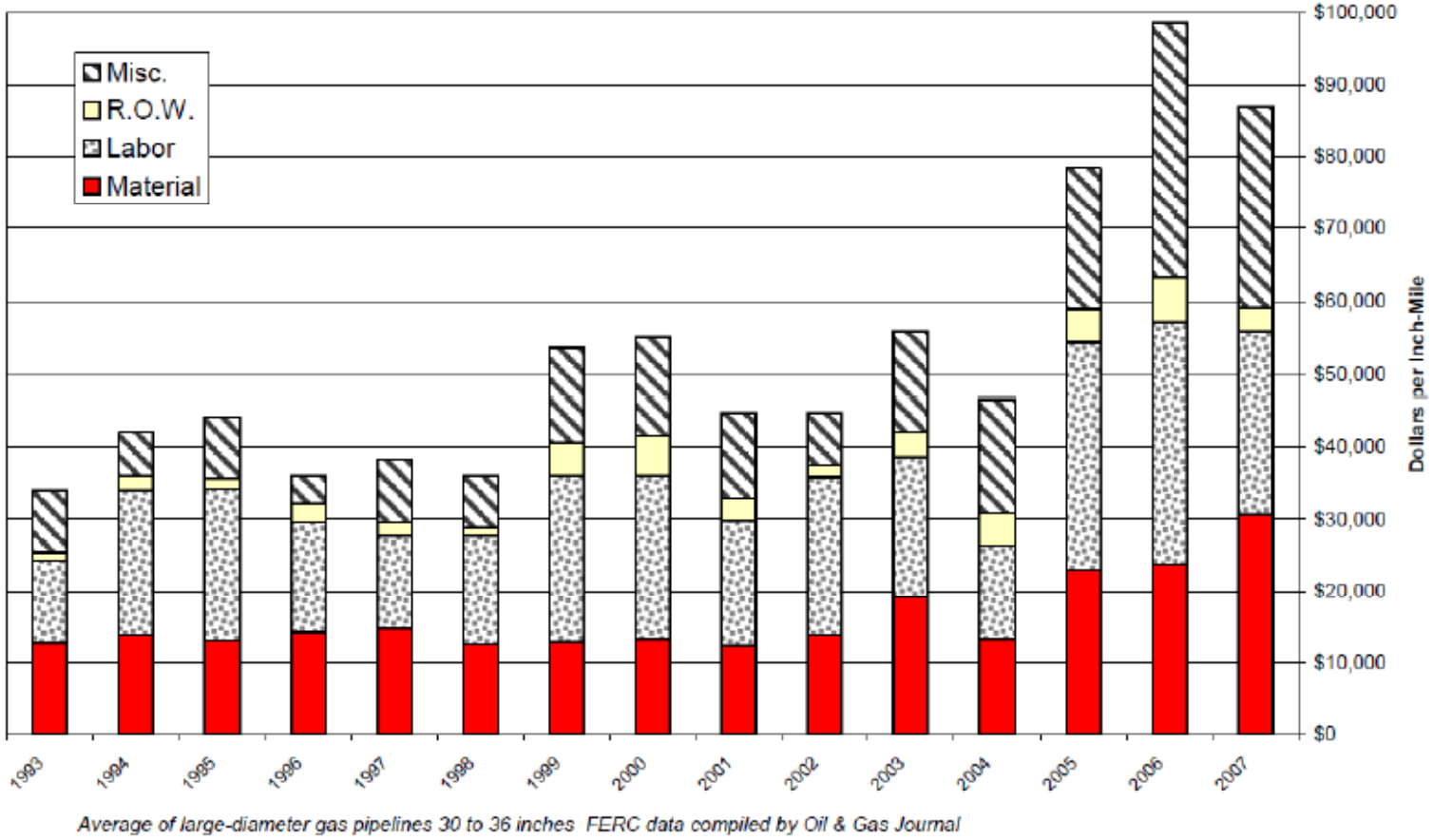
Transport and storage costs

- The hardware and its operation
  - Pipelines
  - Compression stations
  - Wells
  - Distribution piping
  - Platform (if off shore and not subsea)

Pipeline costs - calculated



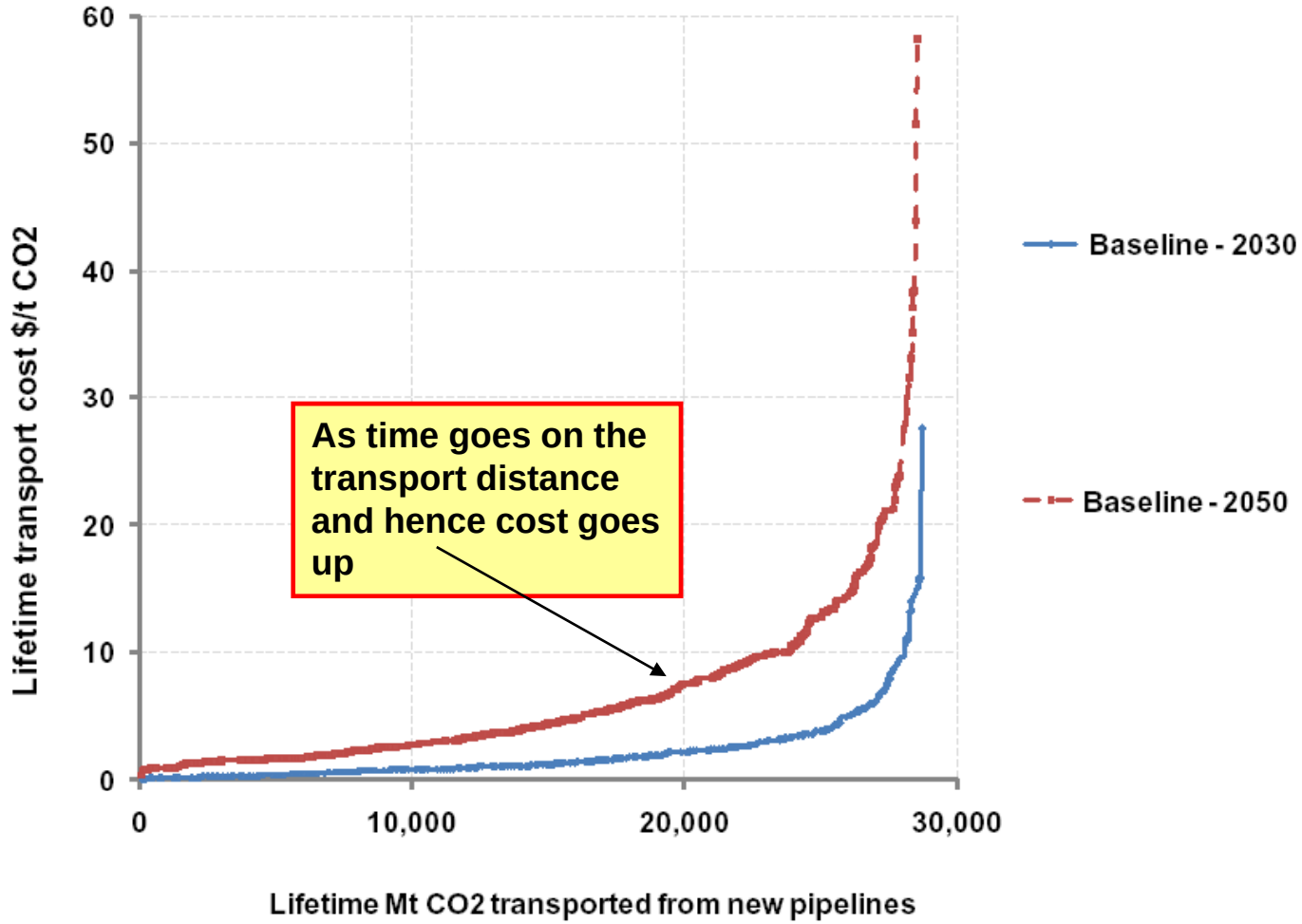
Pipeline costs - historical



Average of large-diameter gas pipelines 30 to 36 inches FERC data compiled by Oil & Gas Journal

Figure 26 Prices for large diameter pipelines in North America. FERC data compiled by the Oil and Gas Journal.

Global transport cost outlook



Well costs

- Main determinants
  - Injection rates
  - Depth

- 2005 study found wide variations ranging from $1-2.5 per ton CO_2 in Europe to $12-15 per ton in North America. Variation is due to differences in assumed injectivity

Special costs in CCS

- Finding costs
- Appraisal costs
- Monitoring costs
- Abandonment costs
- Special liability
  - i.e of leakage and loss of certificates

Financing Costs

- These depend on the source and arrangements for capital
- Usually dealt with in the economic analysis

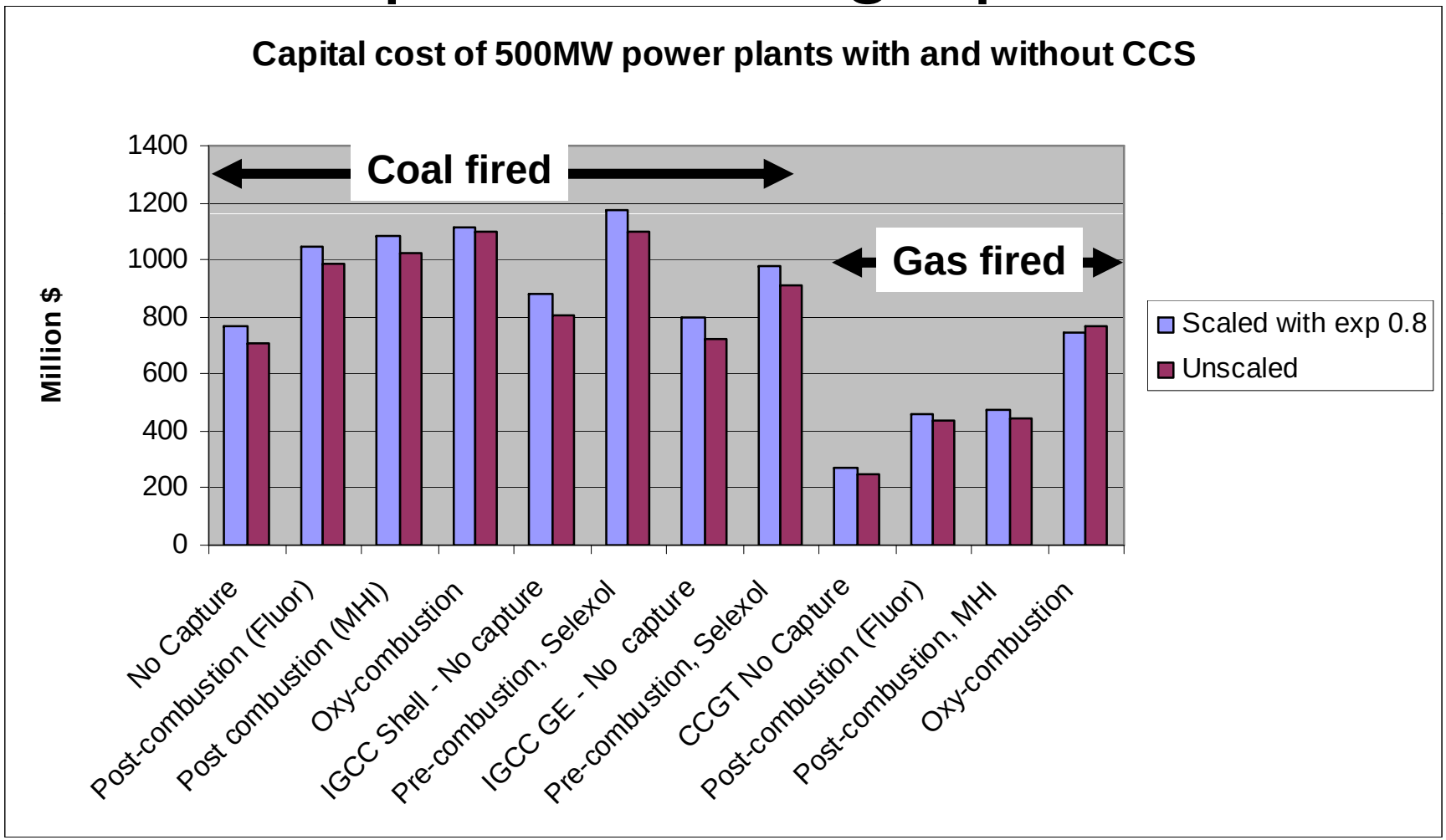
What are the costs?

Fuel	Power generation technology	CO_2 capture technology	Net power output MW	Capital cost $/kW
Coal	Pulverised fuel	None	758	1408
		Post-combustion (Fluor)	666	1979
		Post combustion (MHI)	676	2043
		Oxy-combustion	532	2205
	IGCC (Shell)	None	776	1613
		Pre-combustion, Selexol	676	2204
	IGCC (GE)	None	826	1439
		Pre-combustion, Selexol	730	1815
Gas	Gas turbine combined cycle	None	776	499
		Post-combustion (Fluor)	662	869
		Post-combustion, MHI	692	887
		Oxy-combustion	440	1532

Normalisation

- The costs are for plants with different net output
- Cost per Kw are comparable
- Example Cost of 500 MW plant
  - Method 1 simple multiply 500MW by unit cost
  - Method 2 Calculate total plant cost then scale using exponent to capacity of 500MW

Capture costs graphical



Economic analysis

- How much will it cost to capture CO_2?
- How much extra will it cost to generate electricity?

- Economic analysis looks at all costs and revenues and the cost of financing. A discount rate is used to account for the slow devaluation of modern money with time.

Key parameters

- Capital phasing
  - Money is spent before there is any income
  - Typical power plant 3 years to build phased 20/45/35
- Income phasing and stream factor
  - Full capacity not reached immediately
  - Typical assumption year 1 - 60% subsequent years - 85%

COE or cost of CO_2

- Results for power plant can be expressed in two ways;
  - The cost of electricity (with and without capture)
  - The cost of capturing CO2 (has to be done by comparison to no capture baseline)
- For real projects companies will need to input assumed power and CO2 credit values
  - Result then indicates whether investment will be profitable.

Economic analysis issues

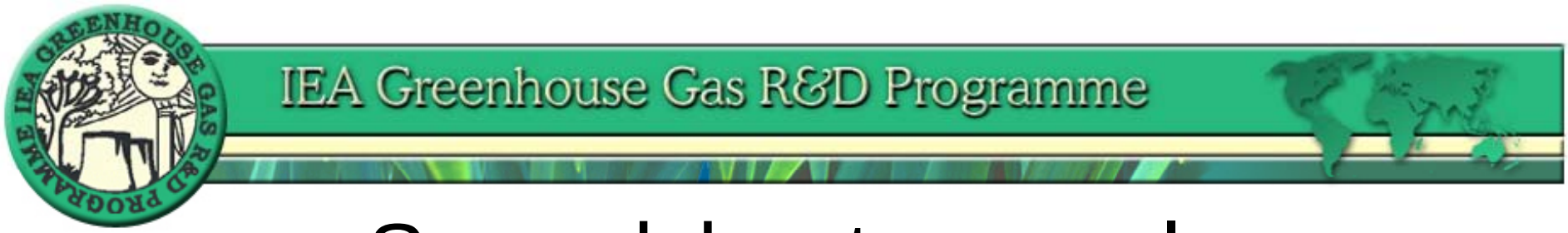
- Easy to calculate cost of electricty and cost of capture
- Difficult to project electricity prices and CO2 prices.
  - Electricity undergoes massive day to day fluctuations – important to know how much can be sold at peak load prices
  - CO2 is subject to trading with annual targets, Long term price is dependent on policy.

Risk and discount rate

- Discount rate covers inflationary effects and level of risk. Lenders ask more the bigger the risk
- Typical rates are:-
  - A small private company 25%
  - A large international company 15%
  - A large “utility” company 10%
  - Jointly owned infrastructure 7%
  - Government owned infrastructure 5%
- IEAGHG uses 10% for evaluations

Performing economic calculations

- Simple to do using a spreadsheet
- IEAGHG has simple spreadsheet set up for typical CCS capture plant.



Spreadsheet example

IEA GREENHOUSE GAS R&D PROGRAMME

Cost Evaluation - Example sheet

Version 1

Date : February 20

Production			**Capital Cost**		**Million $**	**Operating Costs**	**Million $/year**	**Economic parameters**		
Fuel feedrate	1913.0	MW	Installed costs		998.0	**at 85% load factor**		Discount rate	10.0	%
Net power output	666.0	MW	Average contingencies	10.0%	99.8	Fuel	76.9	Load factor (years 2-25)	85.0	%
By-product output	14.08	t/h	Owners costs	7.0%	69.9	Maintenance	32.9	Fuel price	1.50	$/GJ
Solid waste output	34.20	t/h	Total capital cost		1167.7	Chemicals + consumables	17.4	By-product price	0.0	$/t
CO_2 emissions	117	g/kWh				Insurance and local taxes	20.0	Waste disposal cost	0.0	$/t
CO_2 to storage	822	g/kWh	**Working Capital**			Waste disposal	0.0	Insurance and local taxes	2.0%	of installed cost/y
			Chemicals storage		1.7	Operating labour	8.5	Maintenance	3.3%	of installed cost/y
Reference plant data			Fuel storage		7.4	CO_2 storage	0.0	Number of operators	4.0	
For calculation of cost of emission avoidance			Total working capital		9.1			Cost per operator	50.0	$k/y
CO_2 emissions	743	g/kWh						Administration	30%	of operators cost
Electricity cost	4.39	c/kWh	**Decommissioning cost**		0	CO_2 storage cost, $/t stored	0	Fuel storage	30	days
								Chemicals storage	30	days
								Start up time	3	months
								Load factor, remainder year 1	60	%

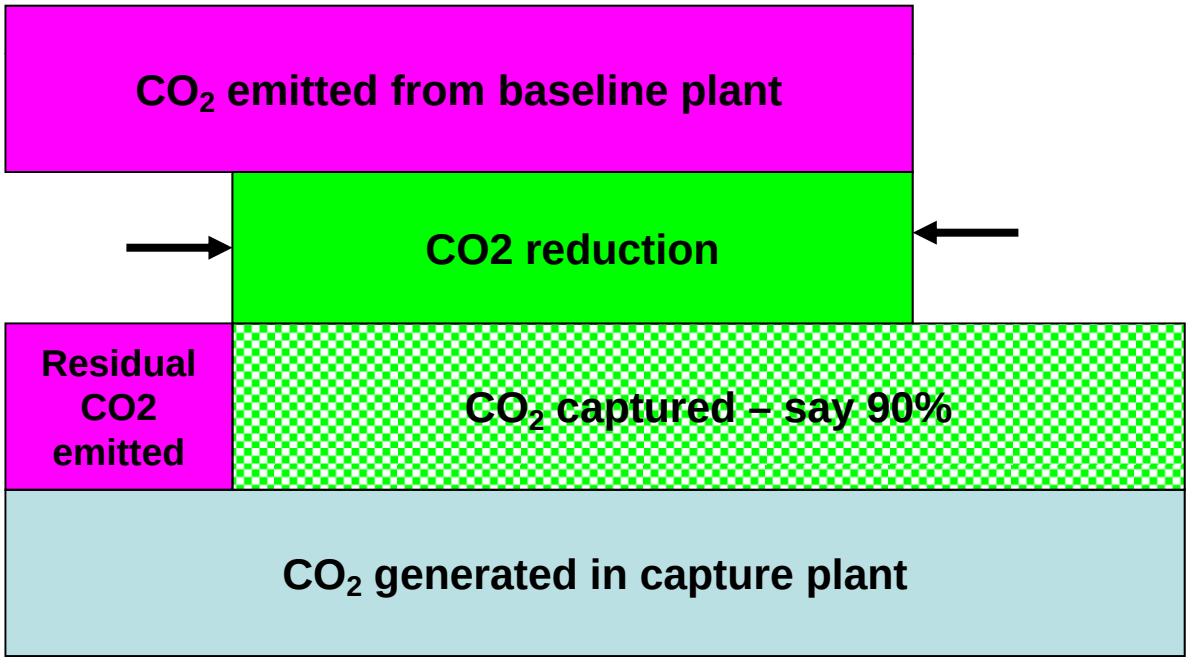
Results summary		
Electricity production cost	6.160	c/kWh
(Note: Type 'Tools' Solver' 'Solve' to calculate the electricity cost that gives a zero NPV)		
NPV	0.00	M$
IRR	10.00%	
Emission avoidance cost	28.3	$/t CO_2

Breakdown of c/kWh cost	
Fuel	25.18%
Capital	48.32%
Other costs	26.50%
CO2 storage	0.00%

CASH FLOW ANALYSIS

Million $	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	20
Year	**000**	**00**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	2
Load Factor				45%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	
Equivalent yearly hours				3942	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	7446	
Expediture Factor	20%	45%	35%																										
Revenues																													
Electricity	0.0	0.0	0.0	161.7	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	305.5	
By-product	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Operating Costs																													
Fuel	0.0	0.0	0.0	-40.7	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	-76.9	
Maintenance	0.0	0.0	0.0	-24.7	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	
Labour	0.0	0.0	0.0	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5	
Chemicals & consumables	0.0	0.0	0.0	-9.2	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	-17.4	
Waste disposal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Insurance and local taxes	0.0	0.0	0.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	
CO_2 storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Fixed Capital Expenditures	-233.5	-525.4	-408.7																										
Working Capital	0.0	0.0	0.0	-9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Decommissioning Cost																													
Total Cash Flow (yearly)	-233.5	-525.4	-408.7	49.5	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	
Total Cash Flow (cumulated)	-233.5	-759.0	-1167.7	-1118.1	-968.3	-818.5	-668.8	-519.0	-369.2	-219.4	-69.6	80.2	230.0	379.7	529.5	679.3	829.1	978.9	1128.7	1278.5	1428.2	1578.0	1727.8	1877.6	2027.4	2177.2	2327.0	2476.7	

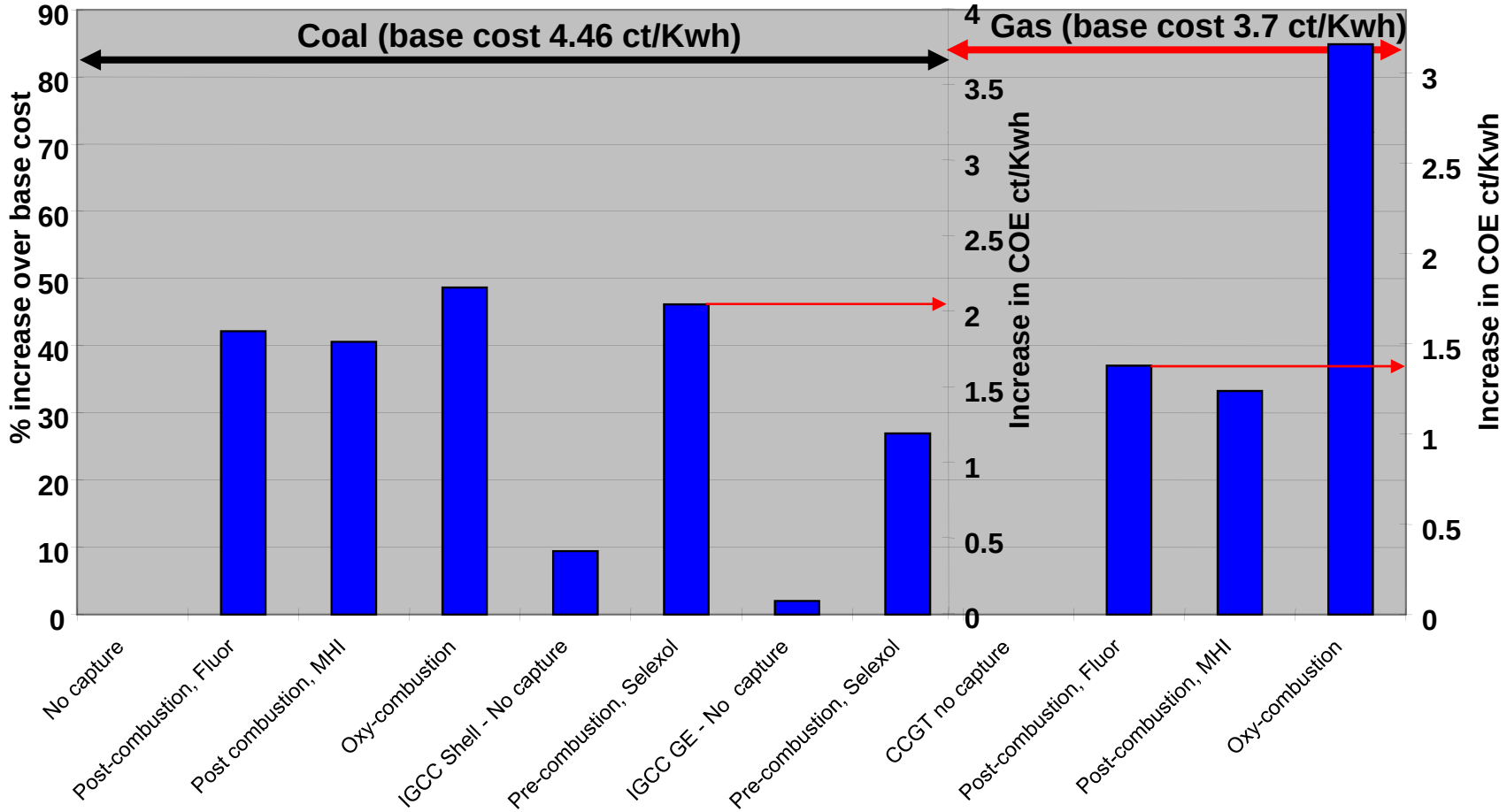
Calculation of CO_2 avoided



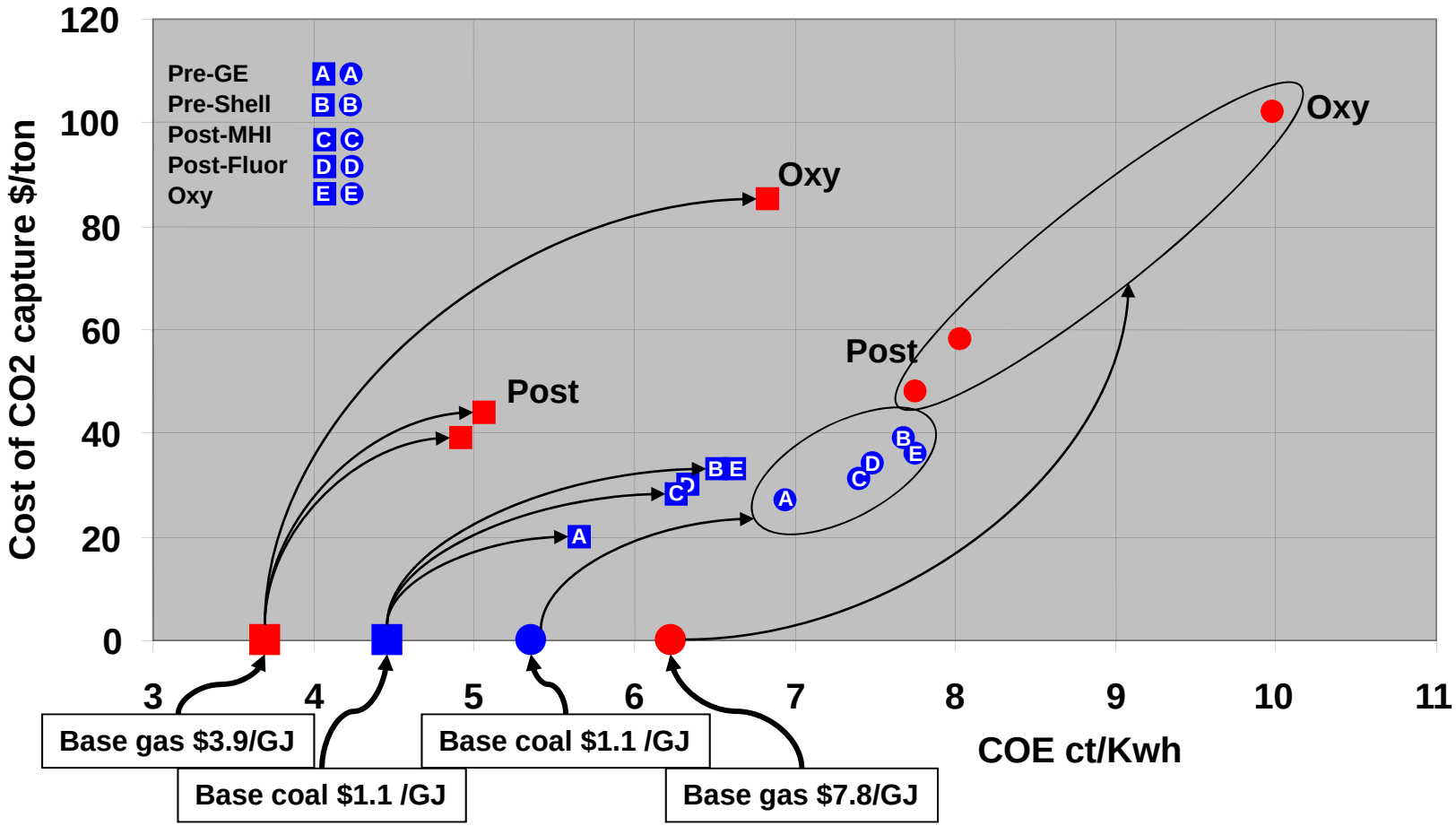
Costs converted by economics

Fuel	Power generation technology	CO_2 capture technology	$1.1/GJ coal, $3.9/GJ		$2.2/GJ coal, $7.8/GJ	
			c/kWh	$/t CO_2 avoided	c/kWh	$/t CO_2 avoided
Coal	Pulverised fuel	None	4.46		5.36	0
		Post-combustion, Fluor	6.34	30	7.49	34
		Post combustion, MHI	6.27	28	7.4	31
		Oxy-combustion	6.63	33	7.76	36
	IGCC (Shell)	None	4.88		5.81	0
		Pre-combustion, Selexol	6.52	33	7.68	39
	IGCC (GE)	None	4.55		5.6	0
		Pre-combustion, Selexol	5.66	20	6.94	27
Gas	Combined cycle	None	3.7		6.23	0
		Post-combustion, Fluor	5.07	44	8.03	58
		Post-combustion, MHI	4.93	39	7.76	48
		Oxy-combustion	6.84	85	9.98	102

Extra cost of electricity compared to coal or gas fired base plant



Relation between COE increase and CO2 capture cost



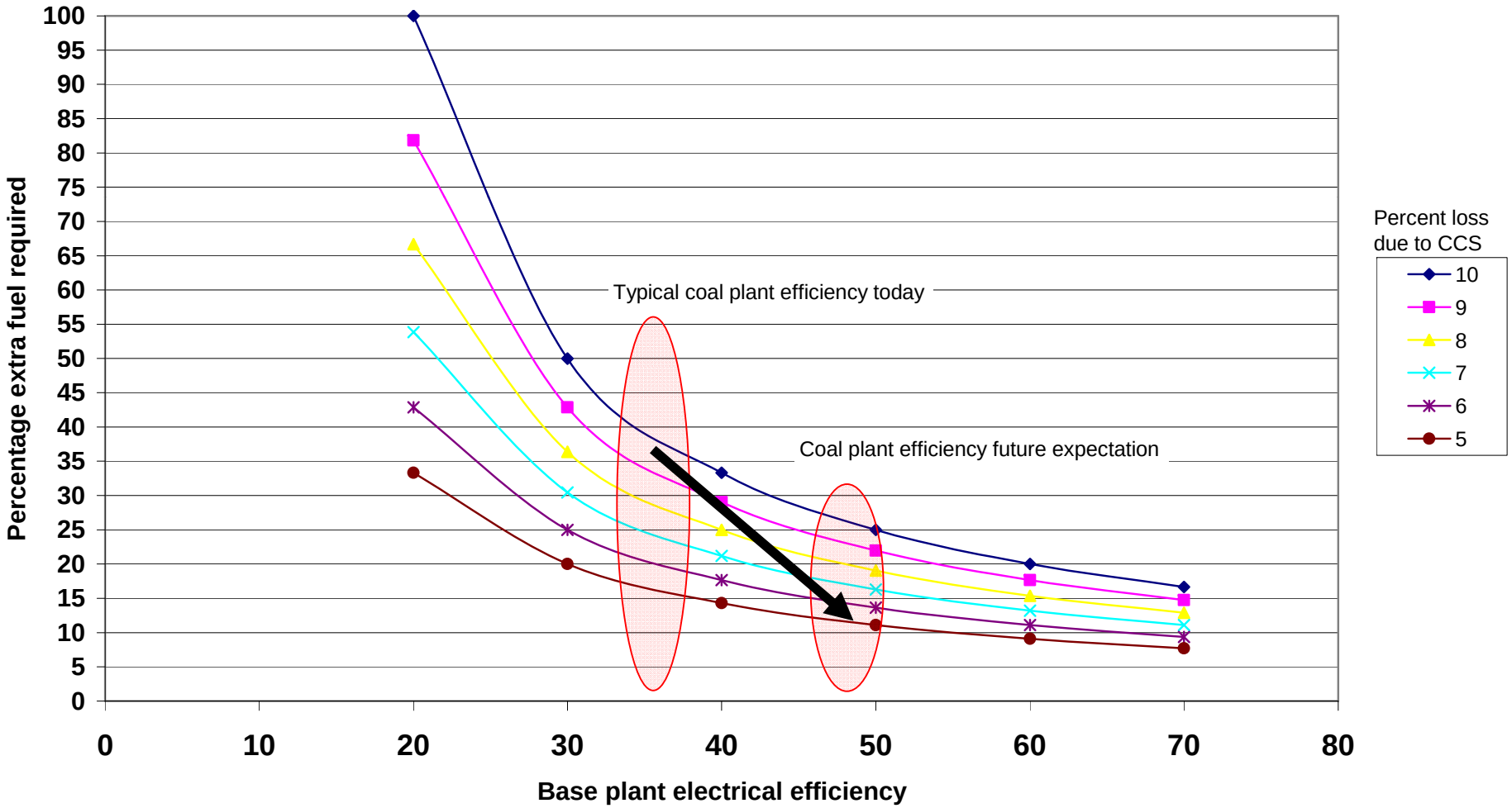
In conclusion

- Cost of CCS includes 3 main elements
  - Capture cost ($20-$100/ton CO_2)
  - Transport cost (rising towards $10/ton CO_2 and beyond as nearby sinks are used up – ballpark 1$/100km)
  - Storage costs (mainly well costs $2-$15/ton CO_2 highly dependent on depth and injectivity)
- Bulk power costs likely to be up to 50% more expensive

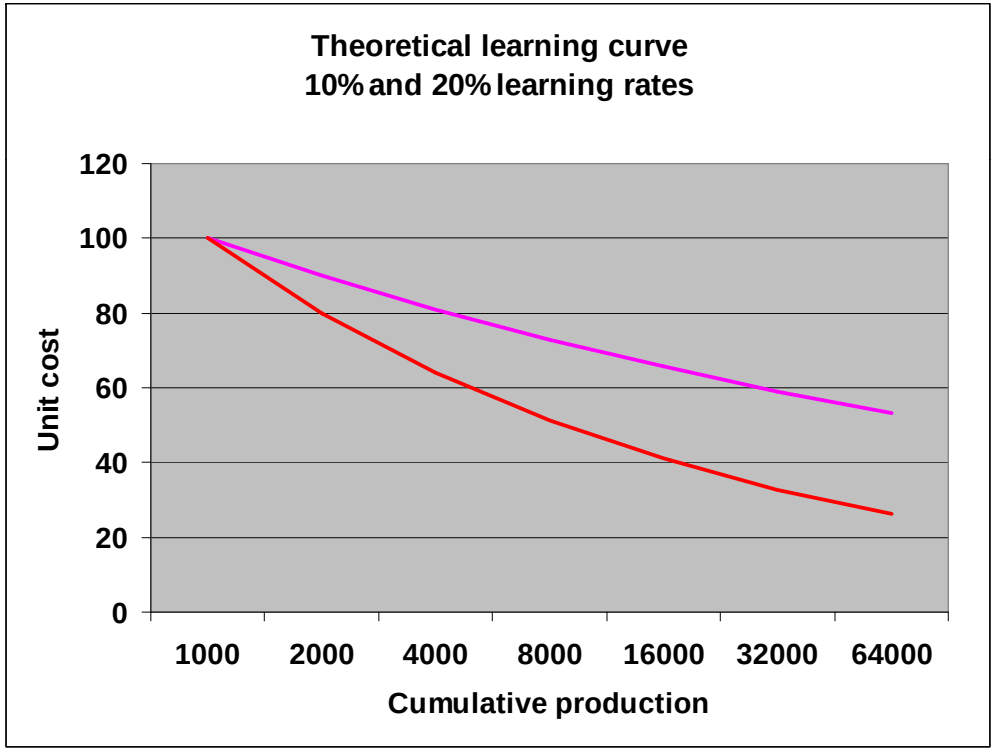
Prospects for cost reduction

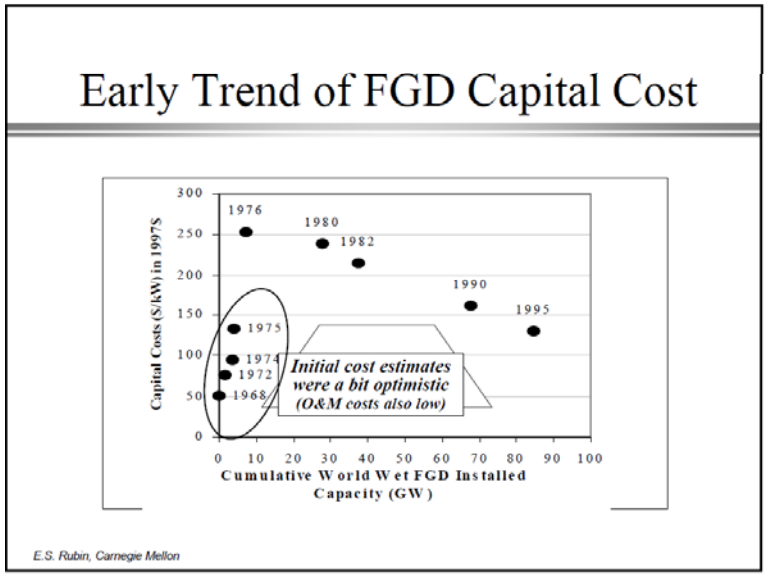
- Efficiency improvements ✓
- Learning effect ✓
- System integration
  - Matching unit capacity, H2 storage
- Technology advances ?
  - New sorbants, new O2 production
- Simplification/modularisation ???

Percentage extra fuel for CCS



Classic learning curve for new technology





Resources

- J Davison paper summarising capture costs
- Pipeline and CCS system cost calculator (Excel)
- Economic spreadsheet (Excel)

ECN

Energy research Centre of the Netherlands

CCS: making it legal and attractive

Heleen de Coninck

CCS workshop, November 18th, 2009, Algeria

www.ecn.nl

Energy research Centre of the Netherlands ECN

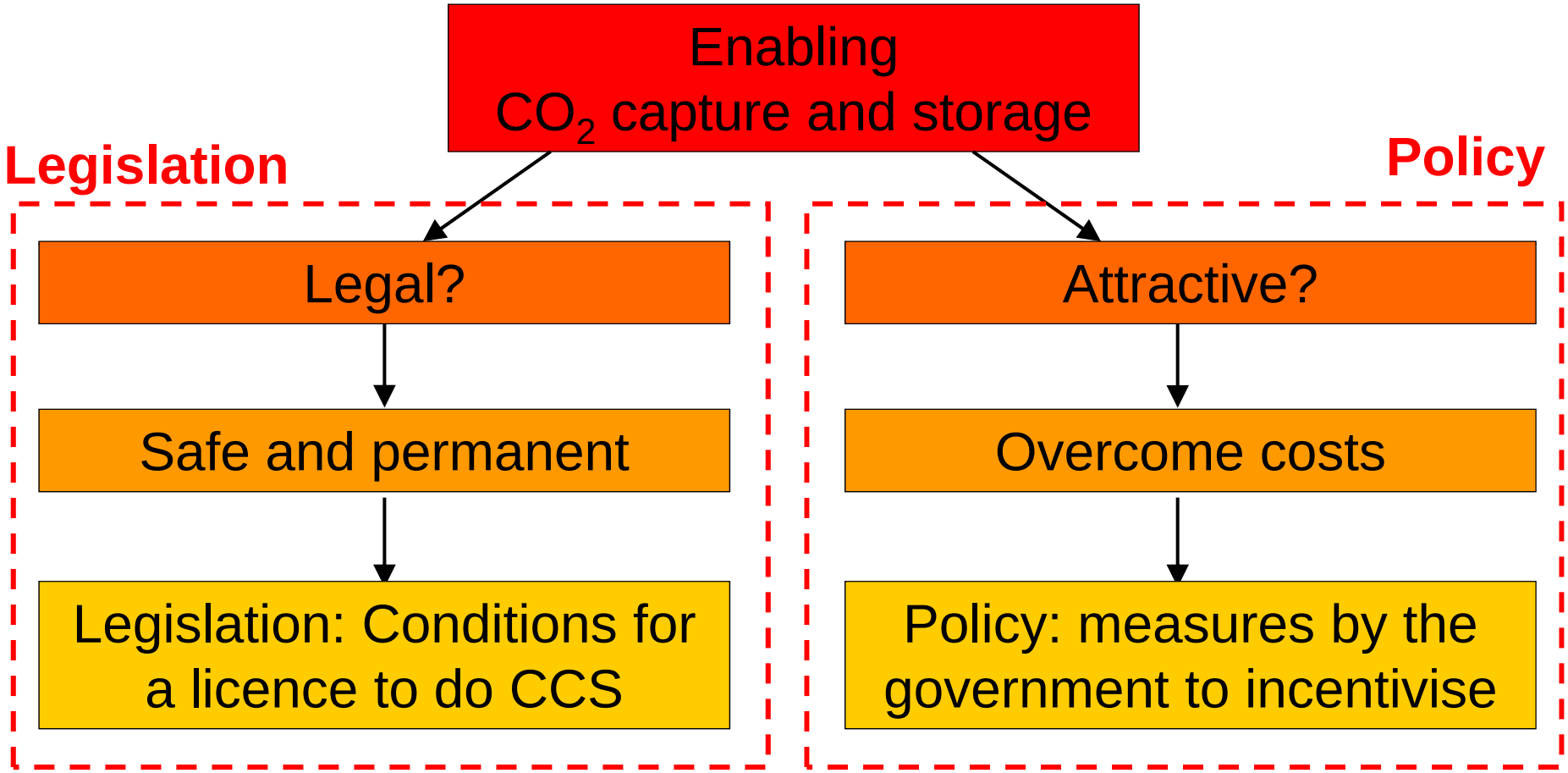
- Develop technologies for a sustainable energy system, and bring them to the market
- Ca. 700 scientific staff, in Petten and Amsterdam
- Technological research but also Policy Studies
- International Energy and Climate issues:

- International climate: technology for post-2012 climate policy
- Policies for energy and development
- Clean Development Mechanism
- EU ETS market impact
- Technology transfer

Presentation outline

- Introduction
- Risks of CCS
- Making CCS legal (and safe)
- Costs of CCS
- Policy options
- Conclusions

Introduction



ECN

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Legislation

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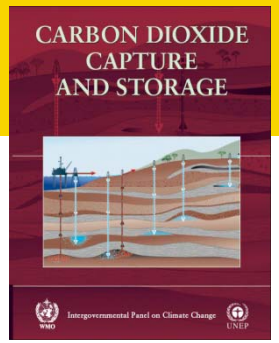
IPCC: legislation essential

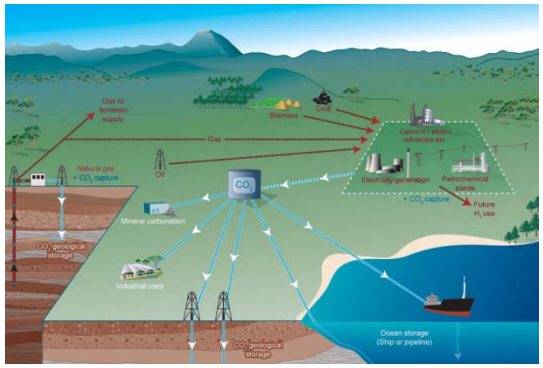


- Fraction retained in appropriately selected and managed geological reservoirs is
  - very likely to exceed 99% over 100 years, and
  - is likely to exceed 99% over 1,000 years.

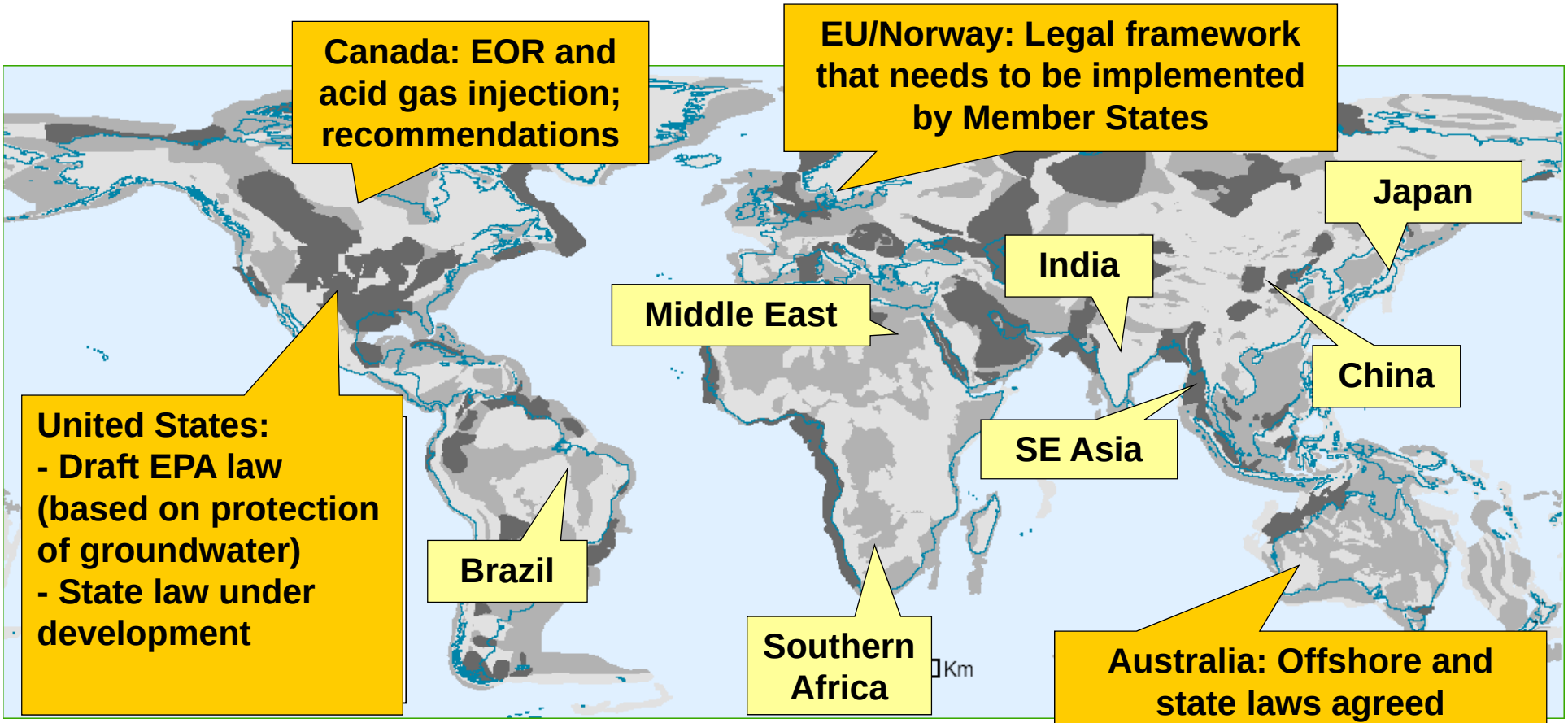
  ("Likely" is a probability between 66 and 90%, "very likely" of 90 to 99%)
- But only if: appropriate site selection, a monitoring program to detect problems, a regulatory system, remediation methods [..], risks are comparable to risks of current activities (natural gas storage, EOR, disposal of acid gas)

How do we ensure all that?

- Through laws that arrange under which conditions a license is extended
- Differs greatly per country, depending on the legal regime in the jurisdiction
  - Who owns the pore space?
  - Who is the competent authority?
- International accounting
- Existing legislation



CCS legislation around the world



How is CCS made legal?

European Union (2008):

- Passed a set of laws that removed legal obstacles in other legislation (IPPC, Water, Waste, others)
- Passed the CO_2 Geological Storage directive
  - Storage permit only if there is “no significant risk of leakage”
  - Liability transfer to Member State when evidence indicates that the CO_2 is completely and permanently contained”.
  - Prescribes to some degree site selection, characterisation, risk assessment and monitoring plan
- Member States need to implement the CCS-Directive by mid-2011

International: IPCC guidelines for inventories

Site characterisation: Identify geology of storage site, local and regional hydrogeology and seepage pathways

Risk of seepage: Evaluate potential for seepage based on site characterisation and realistic models that predict CO_2 movement

Monitoring plan: Adequate measurement based on seepage pathways identified. Validate update models if necessary

Report CO_2 injected and emissions from storage site

International: marine conventions

London Convention (1972) and Protocol (1996)

- Regulating dumping of waste offshore
- Seemed to prohibit CCS
- Amendment made to London Protocol about CCS

CO_2 transport across borders

- Basel Convention; London Protocol?
- Unresolved as of yet

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Policy

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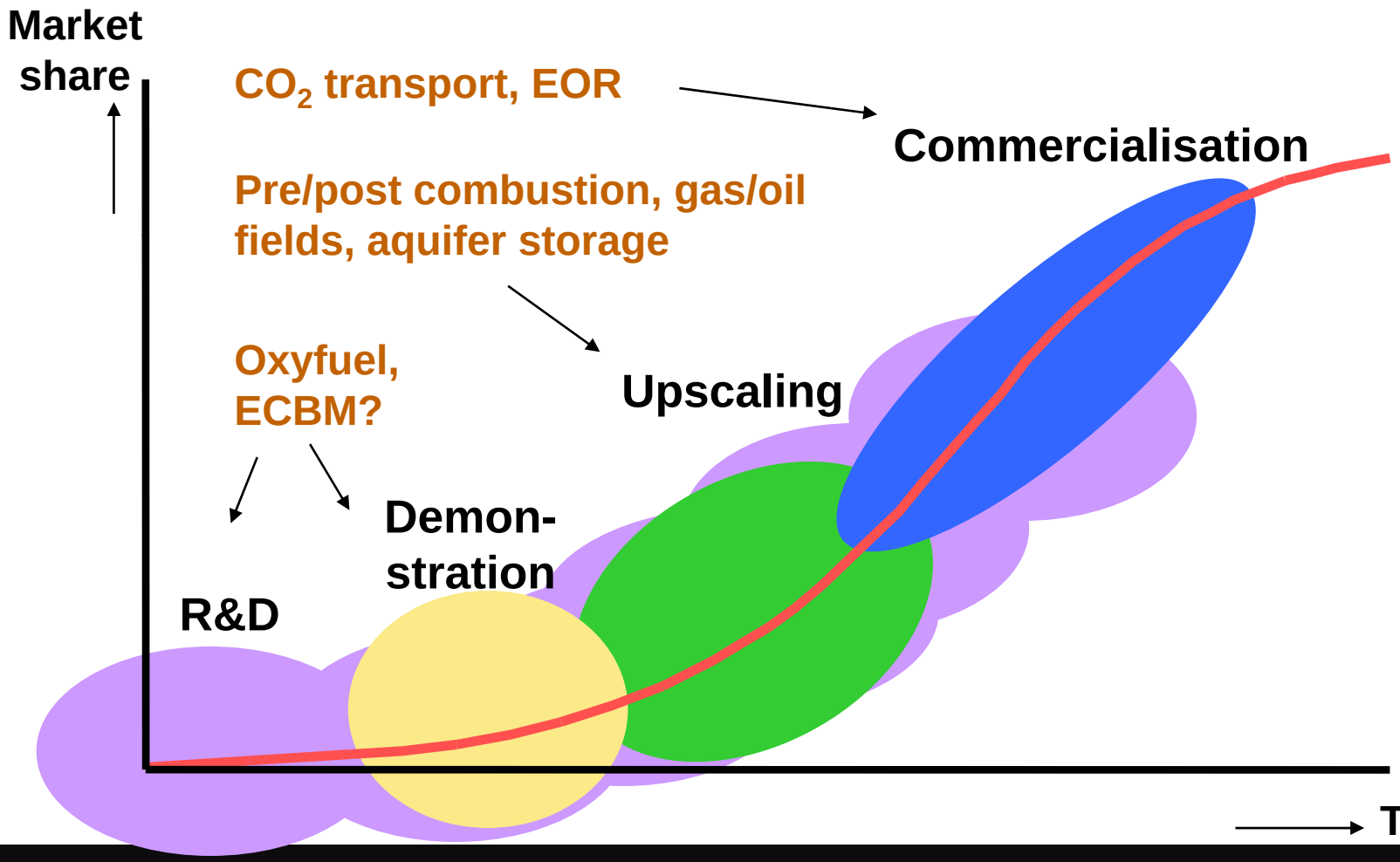
Appropriate policy for innovation phase?



EU Emissions Trading Scheme

Cap-and-trade of allowances; “constructed market”

Ca. 15,000 installations in EU (power, industry)

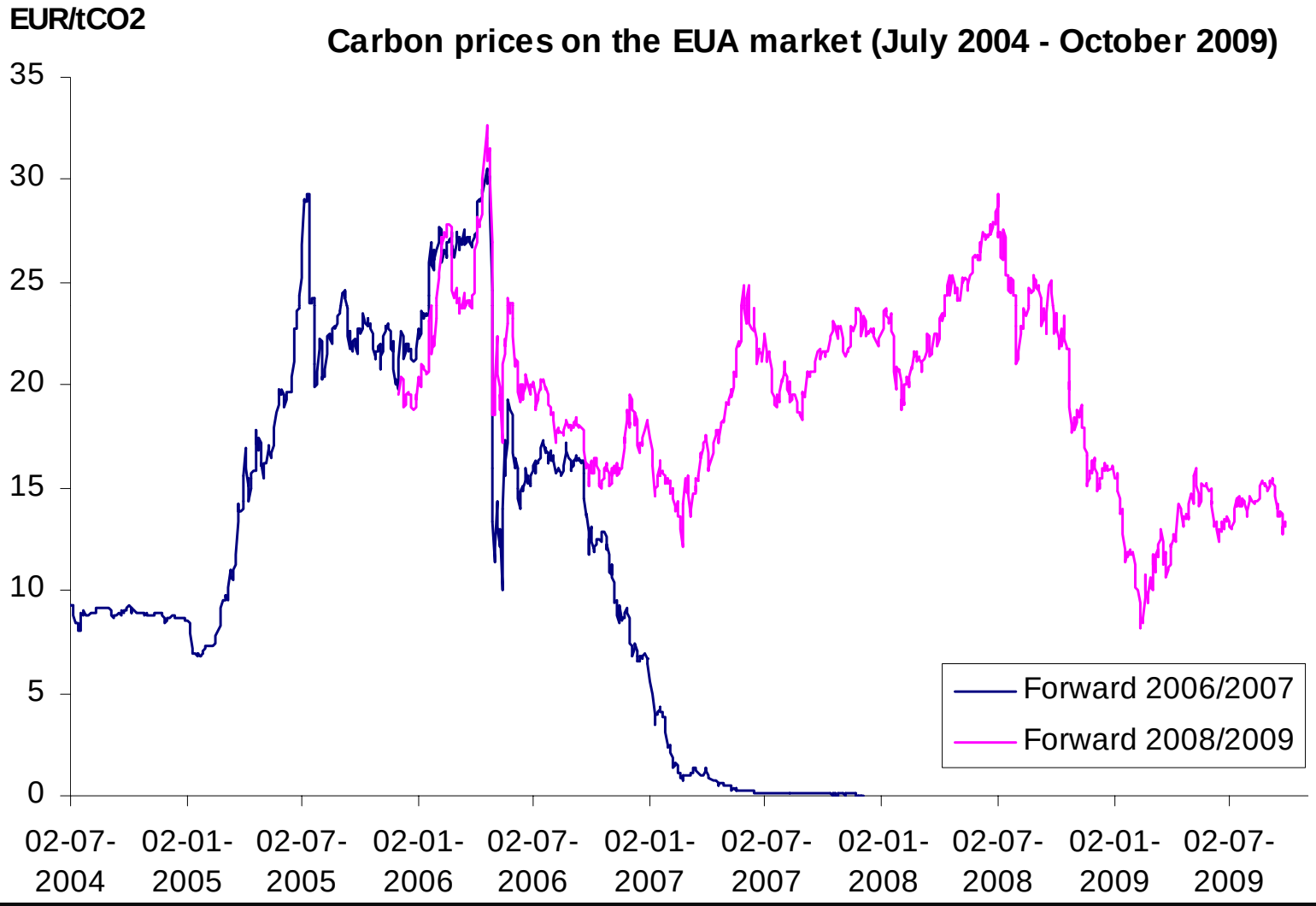
Cost- and environmentally effective instrument, if cap is low, enforcement is strong and leakage minimal

However, if EUA prices remain low:

- Preference for low-cost abatement options
- Innovation market failure
- ETS unlikely to lead to CCS deployment

→ Need for complementary policies

EU Emissions Trading Scheme



Complementary policies

- Public financial support (most likely MS level)
  - Investment support
  - Feed-in subsidies
  - CO_2 price guarantee
- Low-carbon portfolio standard with tradable certificates (most likely EU level)
- CCS obligation (EU level)

Investment support

- Early demonstrations, pipeline network
- All CCS-applications
- Environmentally effective
- Reduction of financial uncertainty for operator
- Government has influence on investment decisions
- Possibly high costs
- Poor incentive for further innovation or cost reduction

Feed-in subsidies

- Widely applied to promote renewables towards commercialisation
- Most likely Member State level, usually power sector
- Environmentally effective
- Reduction of financial uncertainty for operator
- Poor incentive for further innovation or cost reduction
- Risk of overshooting target and high costs

CO_2 price guarantee

- Guarantee a carbon price that is high enough to for CCS
- Most likely MS level, any sector
- Environmentally effective
- Reduction of financial and CO_2 market uncertainty for operator
- Poor incentive for further innovation or cost reduction

Low-carbon portfolio standard

- Source minimum % of power from specified sources
- May be combined with tradable certificates
- Applied for renewables in some MS and US States
- EU level, power sector
- Environmentally effective if target is strong
- Incentive for further innovation and cost reduction
- Risk for operator (technological, financial, and availability of storage)
- Complex and administratively challenging

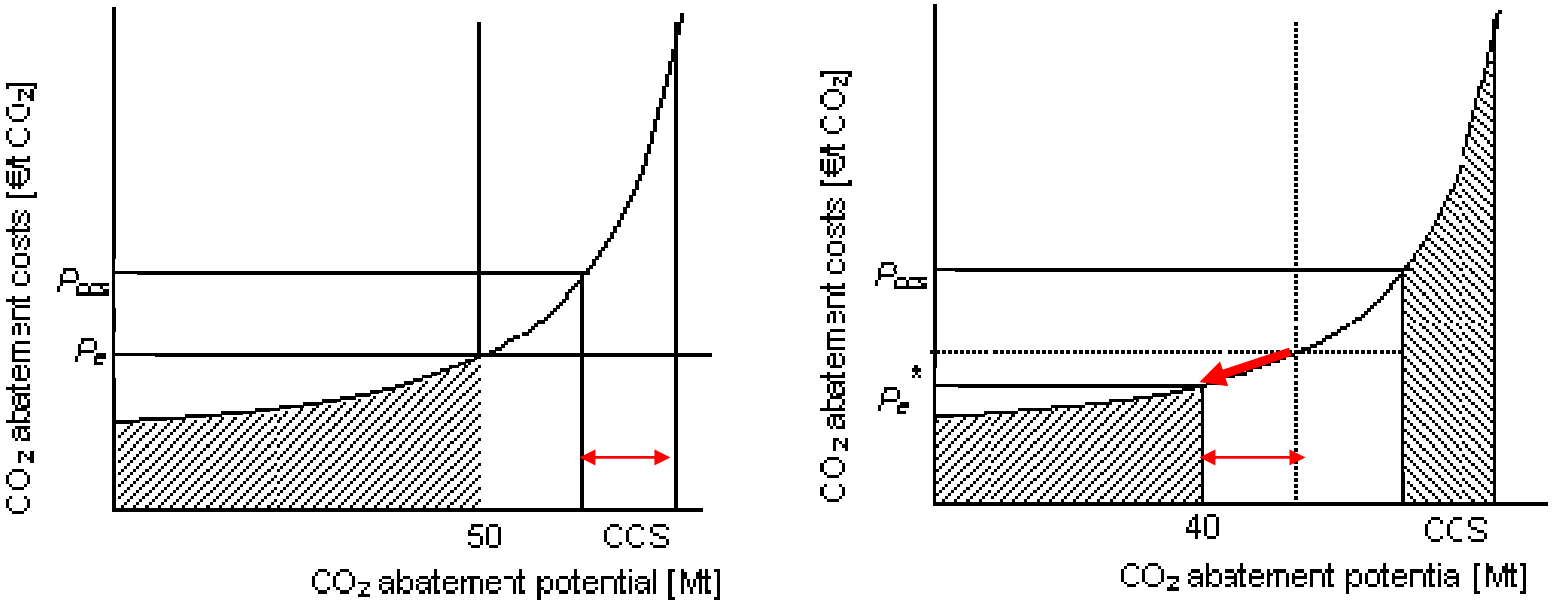
CCS obligation (2020 →)

- Also e.g. retrofit (2020-2040), CCS-ready (2012→)
- Targeted sector: power and/or other point sources
- EU or Member State level
- Environmentally effective
- Strong incentive for further innovation and cost reduction
- Easy to monitor and determine compliance
- Risk for operator (technological, financial availability of storage)

Multi-criteria analysis

	Effectiveness	Risk + cost burden	Consistency	Feasibility (NGO view)
ETS (weak)	-	0	+	+
ETS (strong)	+	+	+	+/-
Investment support	+	-	0	-
Feed-in subsidy	+	-	0	-
CO_2 price guarantee	+	-	0	-
Portfolio + certificates	+	+	0/-	+/-
Obligation	+	+	0/-	+

Interaction additional incentives ↔ ETS



Any additional instrument will reduce demand for EUAs and lower CO_2 market price *unless* cap is lowered accordingly

Other interactions

Renewable energy:

Diversion of resources + attention

→ *% renewables contingent on CCS implemented?*

Innovation:

Cost reduction discouraged

→ *Portfolio standard, obligation*

Electricity market:

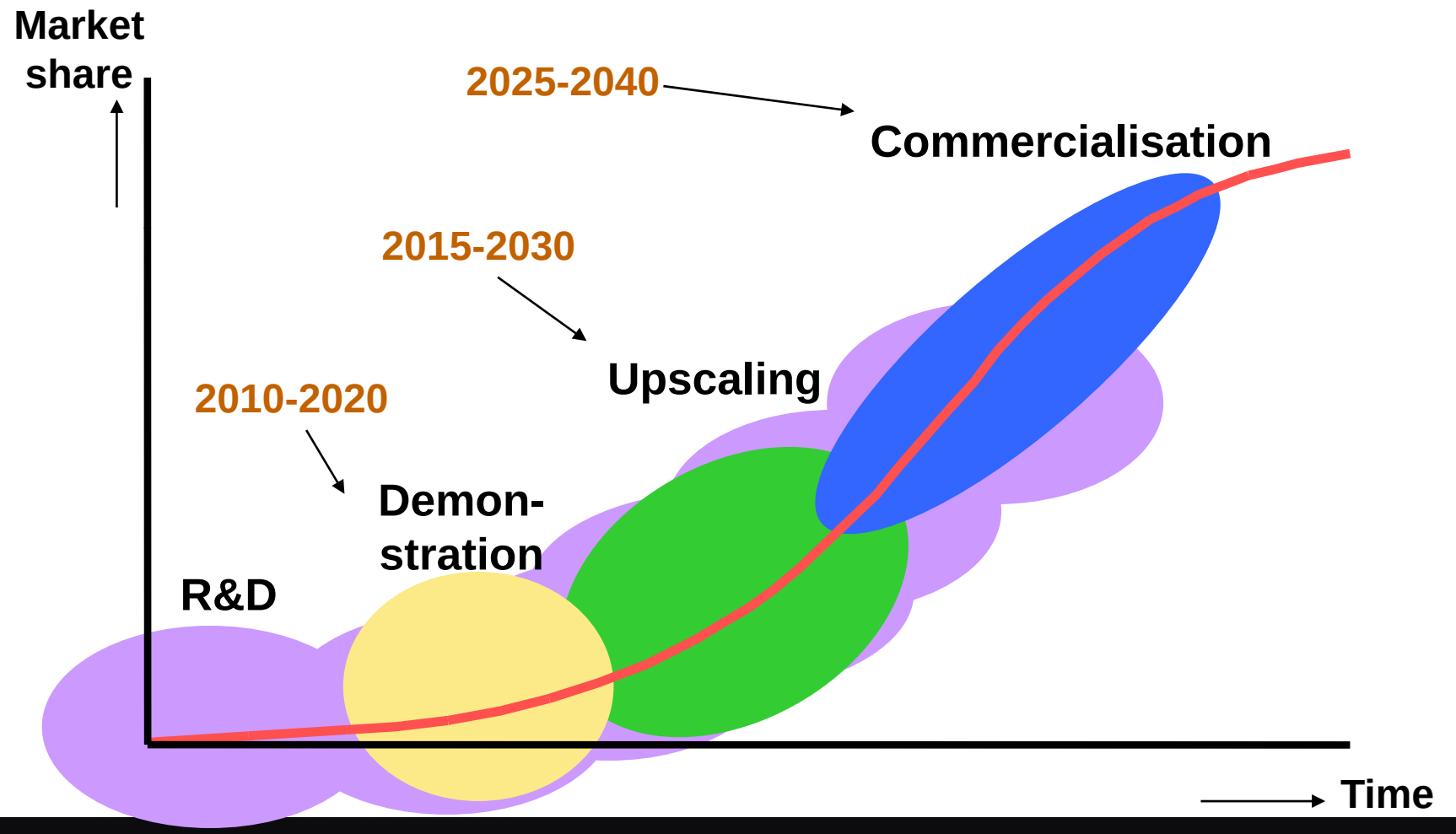
Technical reasons for placing CCS as baseload option,

however O&M cost lead to higher electricity price

Security of energy supply:

CCS only contributes if gas prices spur a shift to coal, and CO_2 prices are high enough for CCS

Timing of policies



International processes: Fragmentation!

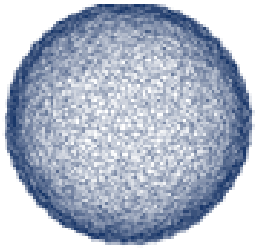
- IPCC: Special Report and Guidelines for Inventories (closed)
- UNFCCC/Kyoto Protocol: Clean Development Mechanism
- Carbon Sequestration Leadership Forum: Knowledge exchange and coordination
- IEA, IEA GHG R&D Programme: information provision, roadmaps
- Global CCS Institute (Australia): facilitate demonstration

International processes: functions

	Information exchange	New information	Knowledge coordination	Outreach	Capacity building	Funding demonstration	Structural incentive
UNFCCC/Kyoto	x			x	x		x
CSLF	x		x	x			
IEA etc	x	x	x	x	x		
G8	x						
Global CCS Institute	x	x	x	x	x		

Current status

- Mostly CCS provisions under EU ETS (but not CDM) and Australian/US proposals for emissions trading
- Funding for demonstrations, difficult but coming up
  - EU: stimulus package, 300 million allowances
  - Canada: tender for demonstration packages
  - United States: stimulus package, new bill?
  - Australia:
- Discussions in Copenhagen: possible progress?



Conclusions

- CCS legal: in some areas well underway, in others still to be done
- Accounting for GHG inventories
- CCS incentives for demonstration
- Structural incentive

Thank you

Heleen de Coninck: deconinck@ecn.nl

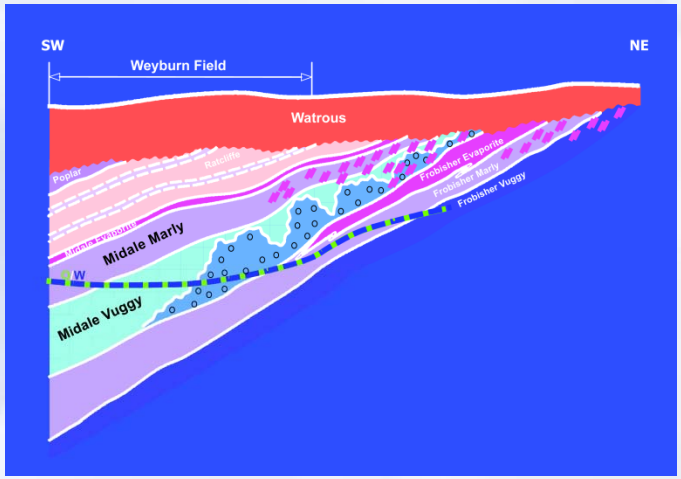
CO_2 Storage Monitoring Efforts at the Weyburn-Midale Fields, Canada.

B. Rostron, University of Alberta
R. Chalaturnyk, University of Alberta
C. Gardner, Chevron Energy Technology Company
C. Hawkes, University of Saskatchewan
J. Johnson, Schlumberger-Doll Research
D. White, Geological Survey of Canada
S. Whittaker, Petroleum Technology Research Centre

IEA GHG
WEYBURN-MIDALE
CO_2 MONITORING
AND STORAGE PROJECT

Weyburn Unit Reservoir

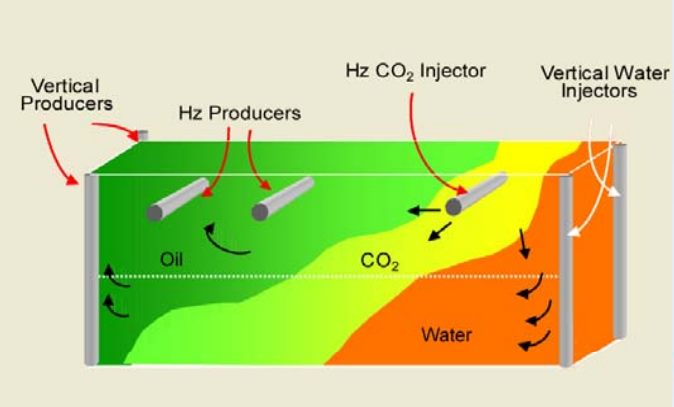
- Discovered 1954
- OOIP ~1.4 Billion BBLs
- Production: 25-34 API sour oil
- Mississippian-aged carbonates of the Midale Member (Charles Fm):
  upper “Marly” and lower “Vuggy”
- Reservoir is ~ 20 m thick, fractured
  ~ 1500 m depth, ~ 1000 wells
- Waterflood 1964; Vert+Hz infills 80/90’s
- Pre CO_2-EOR recovery:
  ~366 Million BBLs

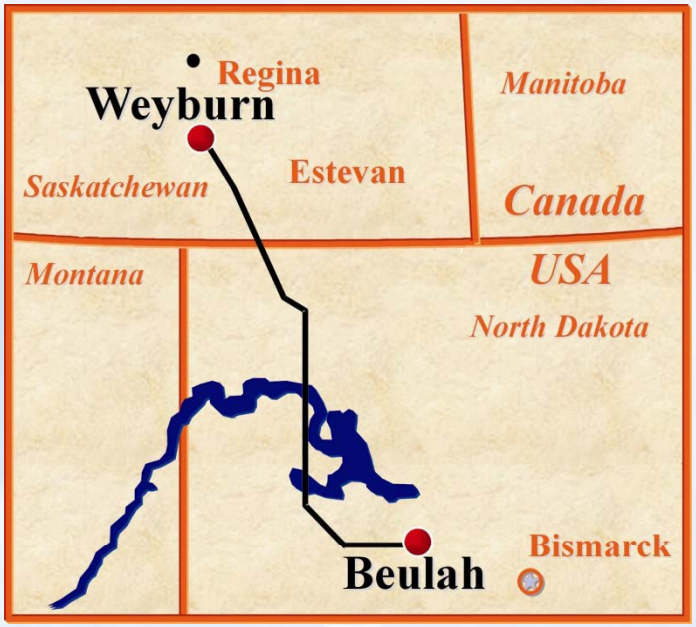


CO_2 EOR Project

- miscible/near miscible CO_2 injection
- Phase 1A: 19 inverted 9-spot patterns
- remaining 75 patterns over 15 yrs
- combination Horiz/Vert & Prod/Inj
- expected 130 million BBLs incr. oil

- CO_2 supplied by Dakota Gassification company(Great Plains Synfuels Plant), Beulah, ND, USA



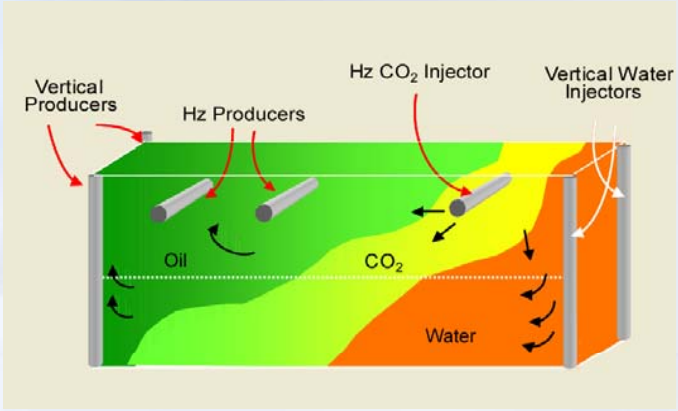


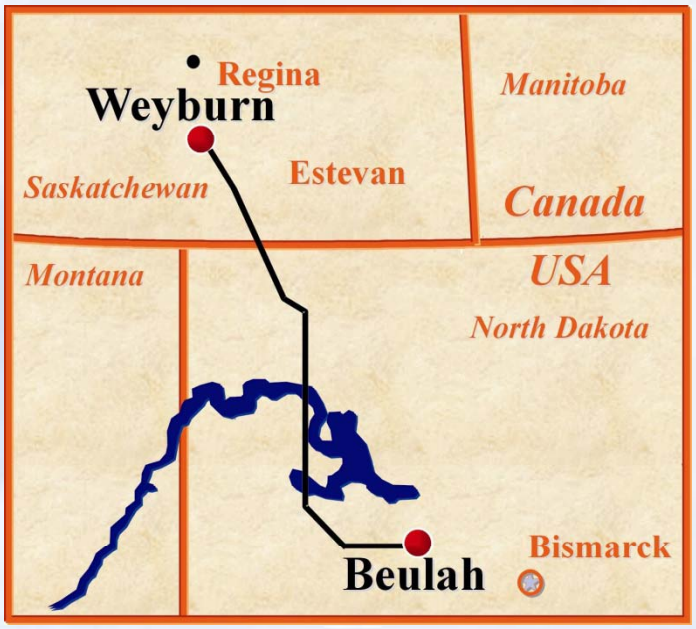
CO_2 EOR Project

- initial CO_2 injection Sept. 2000:
  (~5,000 tonnes/day or 95 MMSCF)

- Dec 2008: (6,550 + 5,500 tonnes/day)

- anticipated 30+ Million tonnes CO_2 sequestered





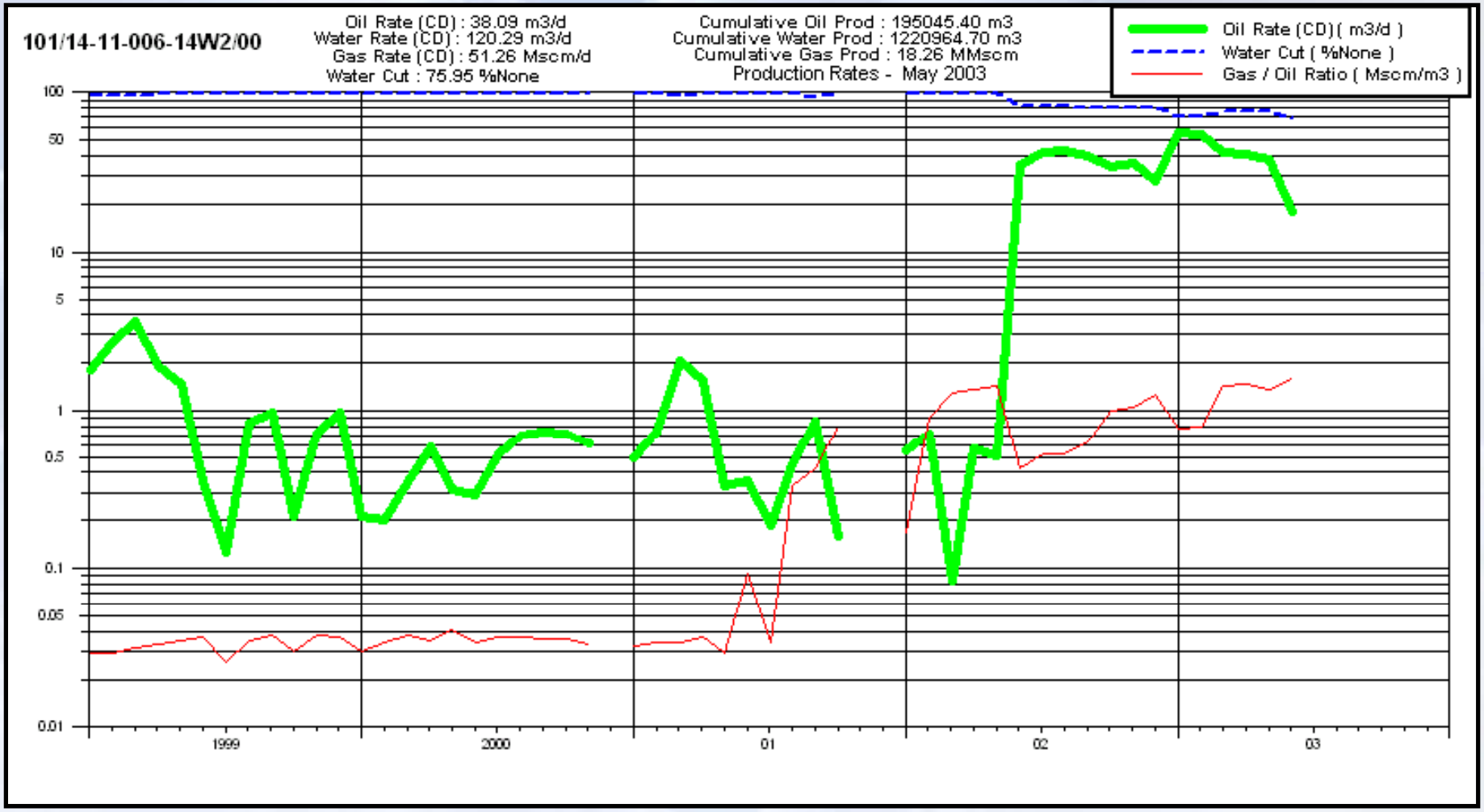
Weyburn:

- Dec 2008: (**13MT stored**)

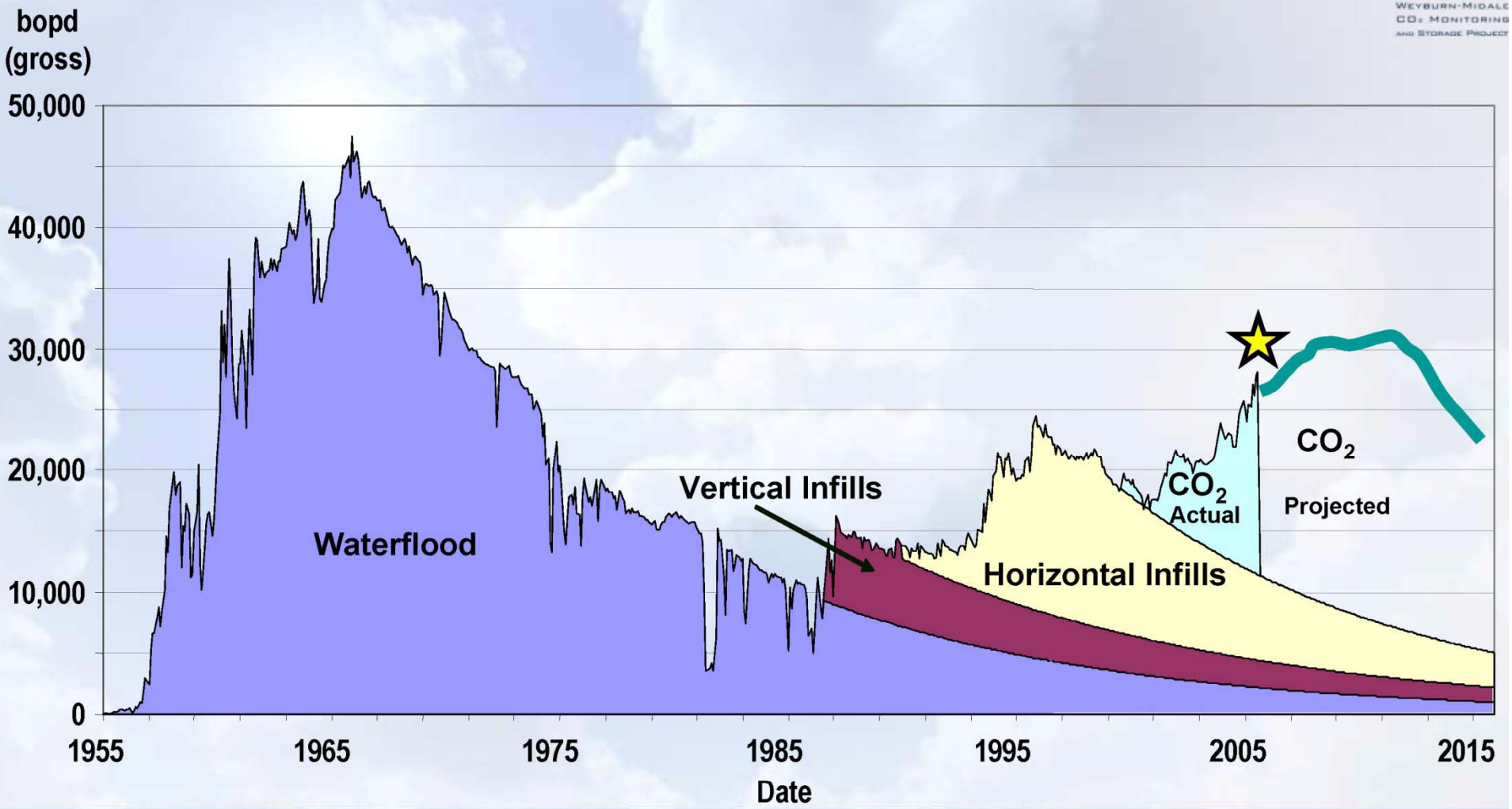
Midale:

- Dec 2008: (**1.6MT stored**)

Example well response



EnCana's Weyburn Unit Production Data



IEA-GHG Project Overview

Launched in July 2000 by PTRC in collaboration with EnCana

Assess technical and economic feasibility of CO_2 geological storage

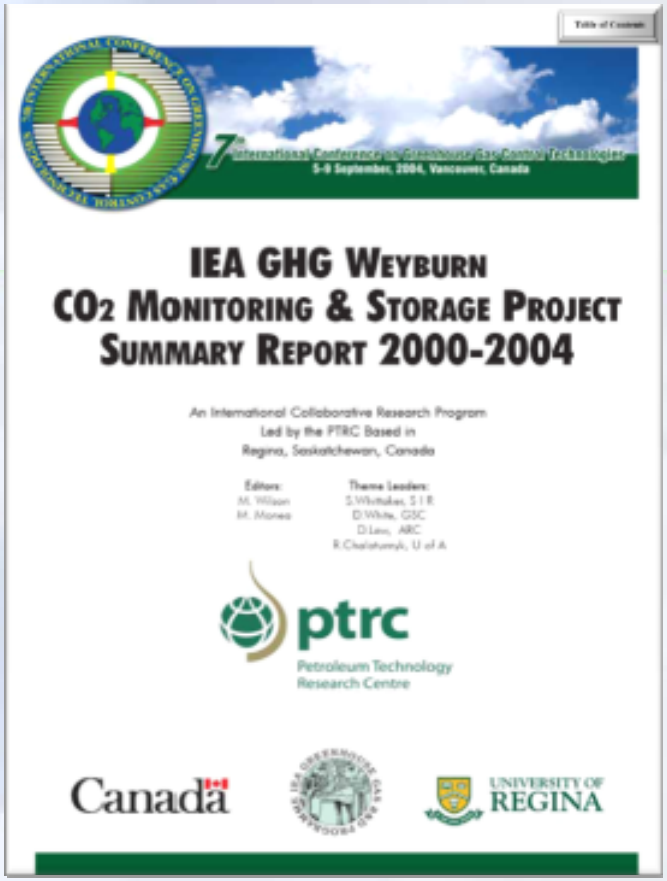
Funded by 15 industry and government sponsors (Canada, USA, Japan, European Union)

Employed 24 technology organizations and some eighty specialists in six countries

Phase I completed September 2004

Final Phase: initiated 2005

planned 2008-2011



download: www.ptrc.ca

Phase I Project Organization

Organized into 4 themes:

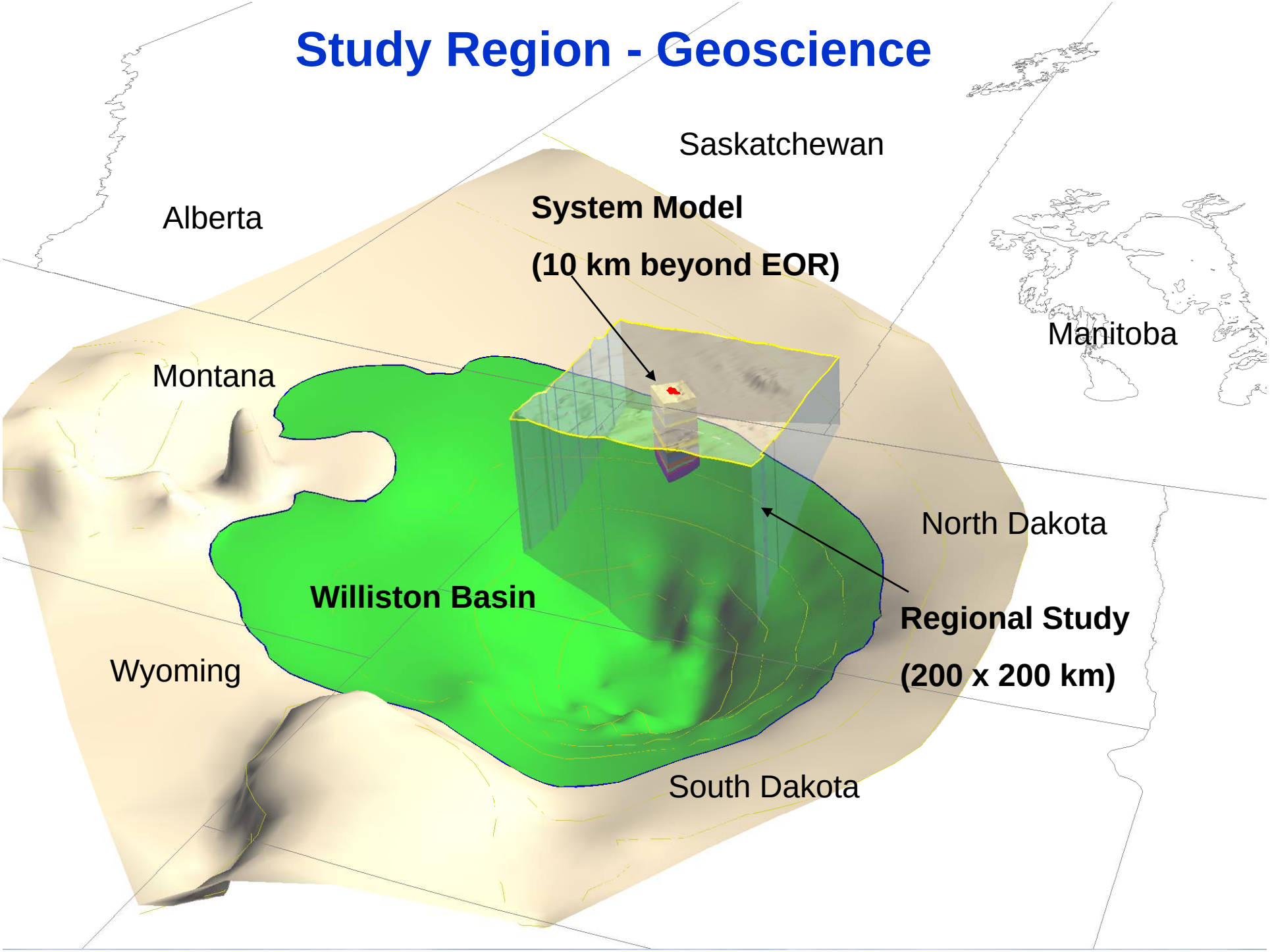
Theme 1: Geological Characterization of the Geosphere and Biosphere

Theme 2: Prediction, Monitoring, and Verification of CO_2 movements

Theme 3: CO_2 Storage Capacity and Distribution Predictions and the Application of Economic Limits

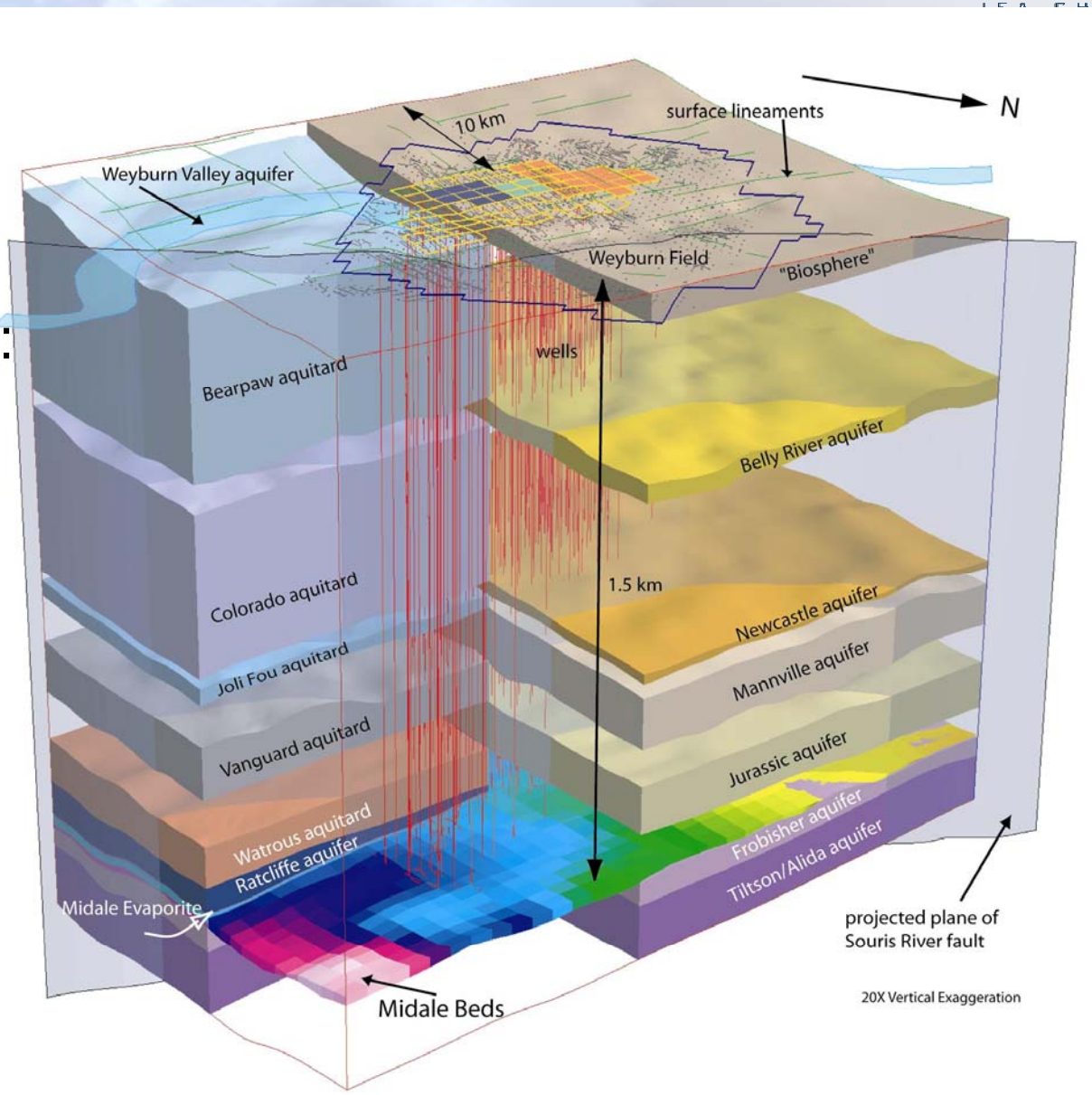
Theme 4: Long Term Risk Assessments of the Storage Site

Study Region - Geoscience



Geological/Hydrogeological Model

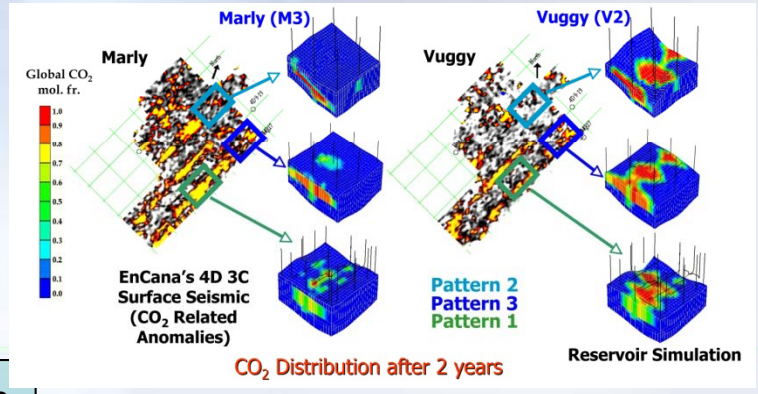
- 10 km beyond CO_2 flood limits
- Geological architecture of system
- Properties of system:
  - lithology
  - hydrogeological characteristics
  - hydrochemistry
  - poro/perm
  - faults

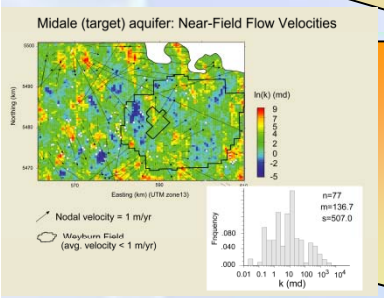


GEOSCIENCE FRAMEWORK

200 x 200 km

- **Stratigraphic framework**
- **Hydrostratigraphic framework**
- **Tectonic framework**





Geological Model

10 km beyond CO_2 flood

Theme 1

CO_2 Storage capacity and distribution

History matching

Theme 3

System Model

Risk Assessment

Prediction & Monitoring

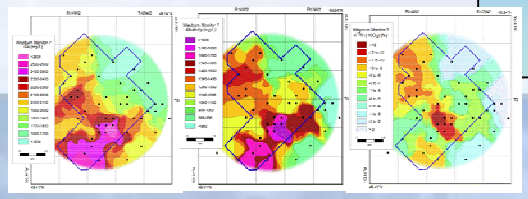
4D Seismic
Geochemical

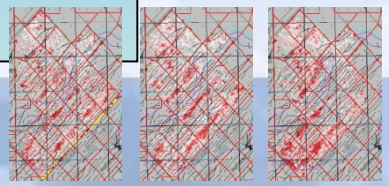
Theme 2

Features, Events, Processes

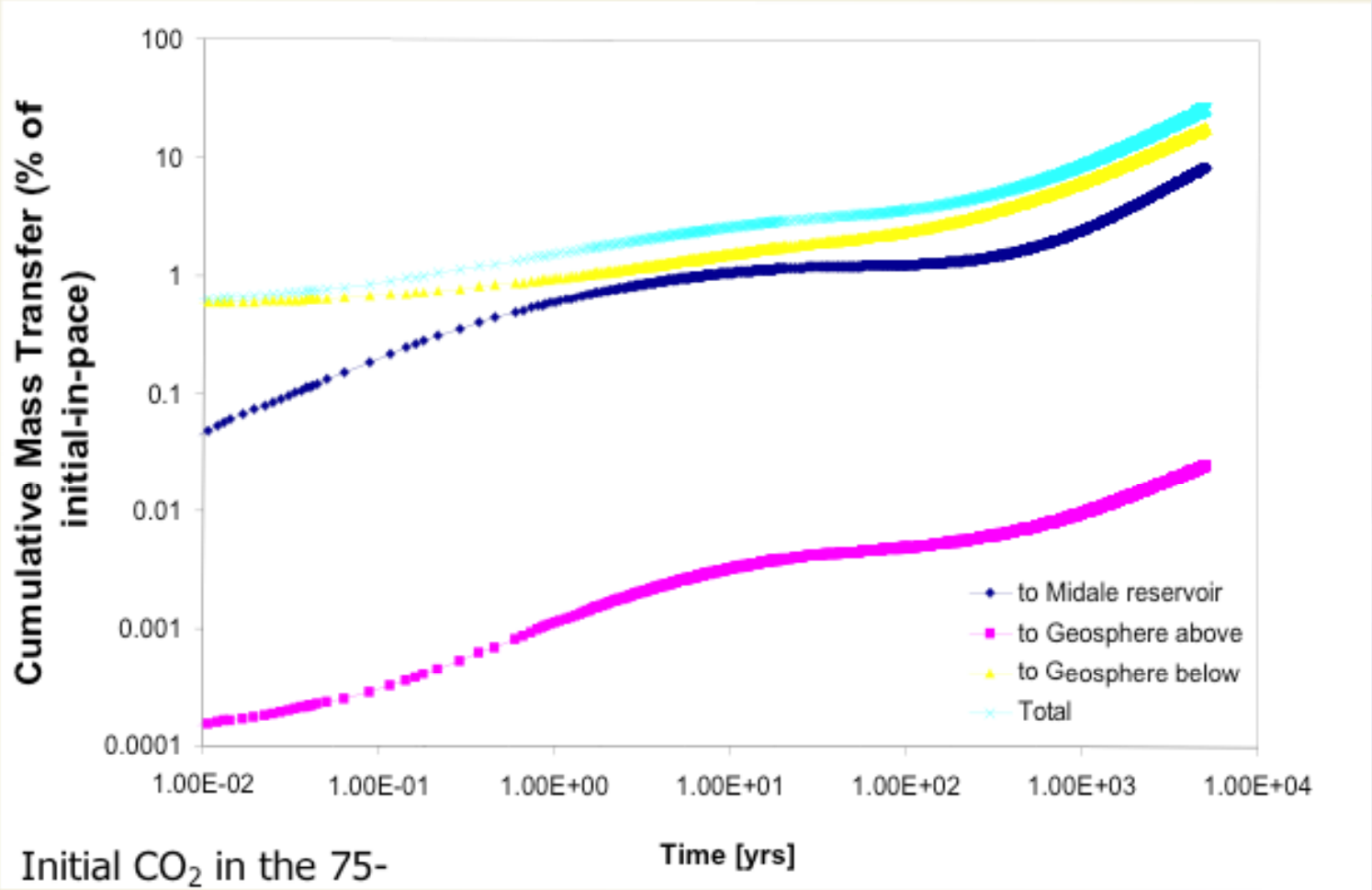
Numerical modeling

Theme 4





Cumulative Mass Transfer



Initial CO_2 in the 75-pattern area: 21 MT

Final Phase of IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project

Non-Technical Component

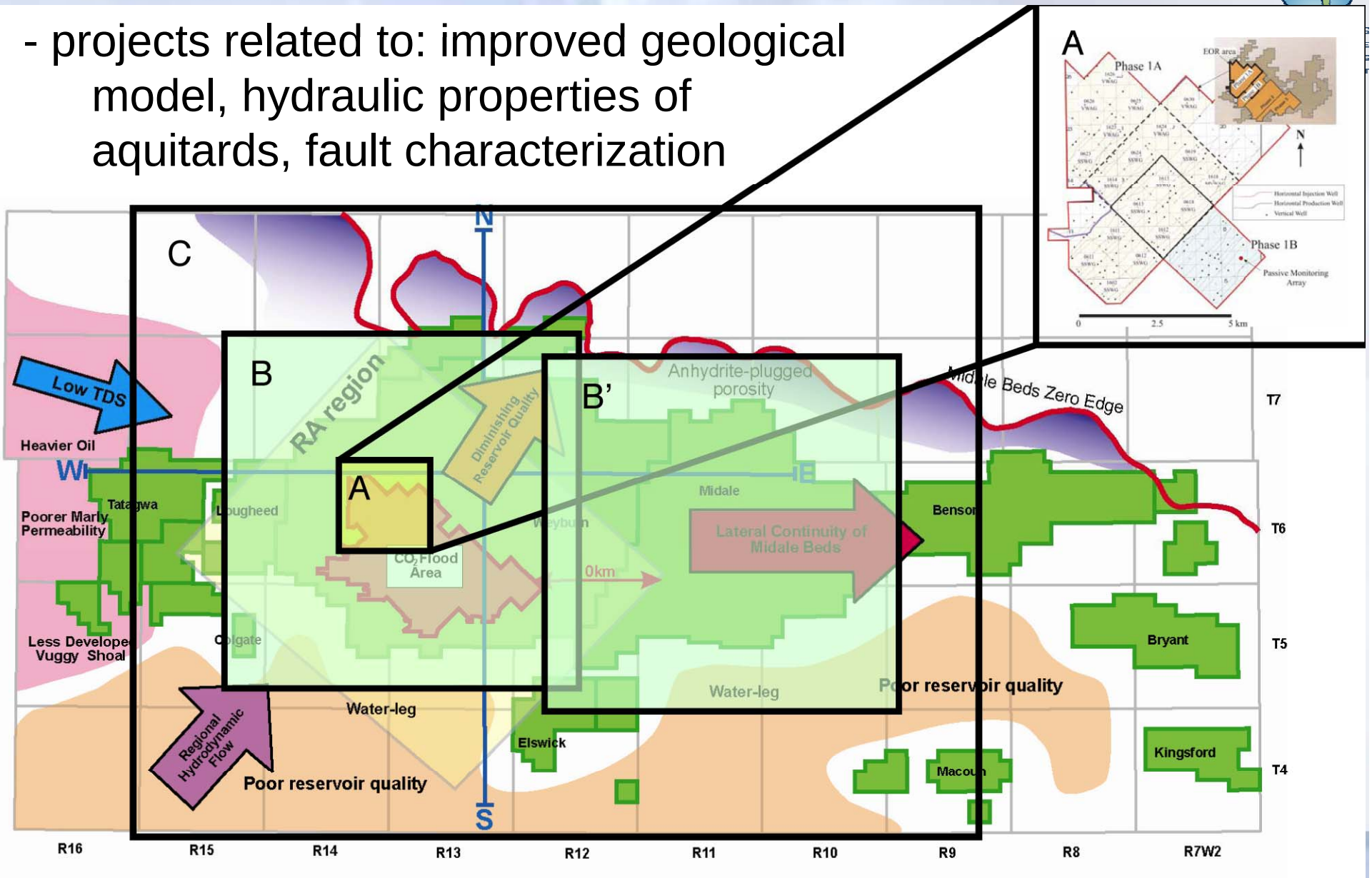
- REGULATORY
- PUBLIC COMMUNICATIONS
- FISCAL POLICY

Technical Components

- GEOLOGICAL INTEGRITY
- WELLBORE INTEGRITY
- STORAGE MONITORING METHODS (Geophysics & Geochemistry)
- RISK ASSESSMENT

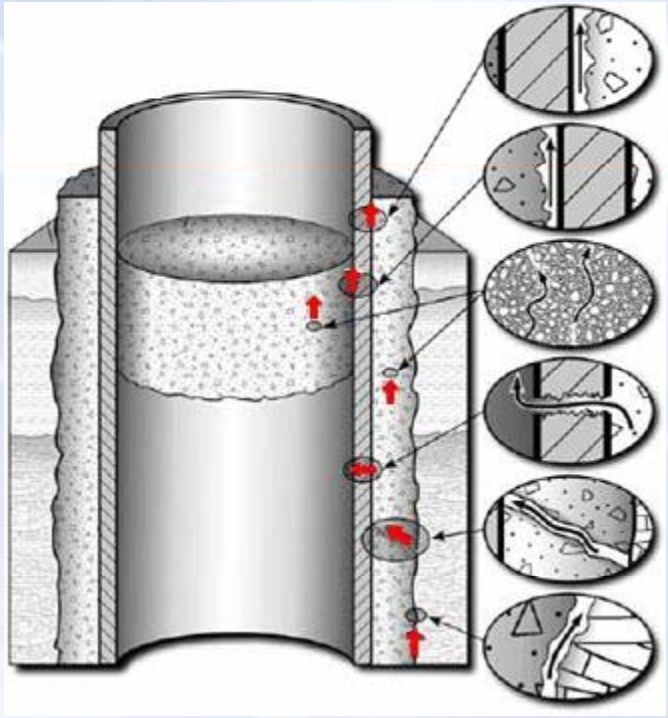
Theme 1: Final Phase Study Area(s)

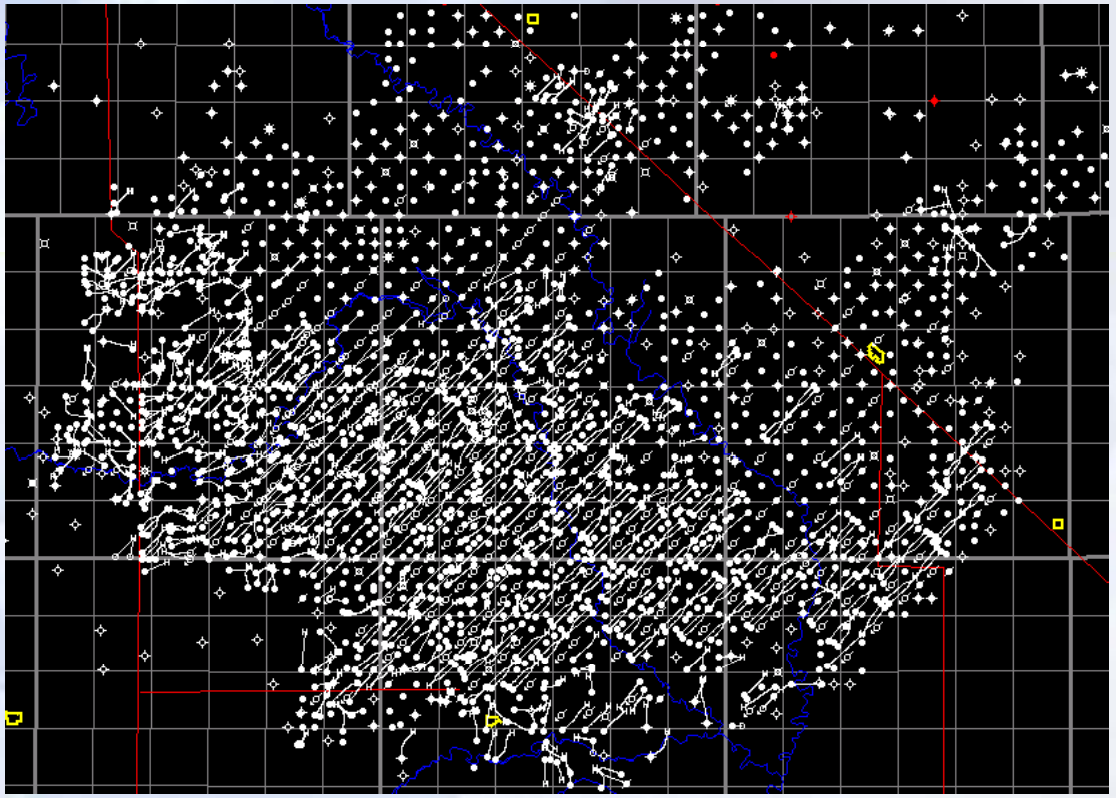
- projects related to: improved geological model, hydraulic properties of aquitards, fault characterization



Theme 2: Wellbore Integrity

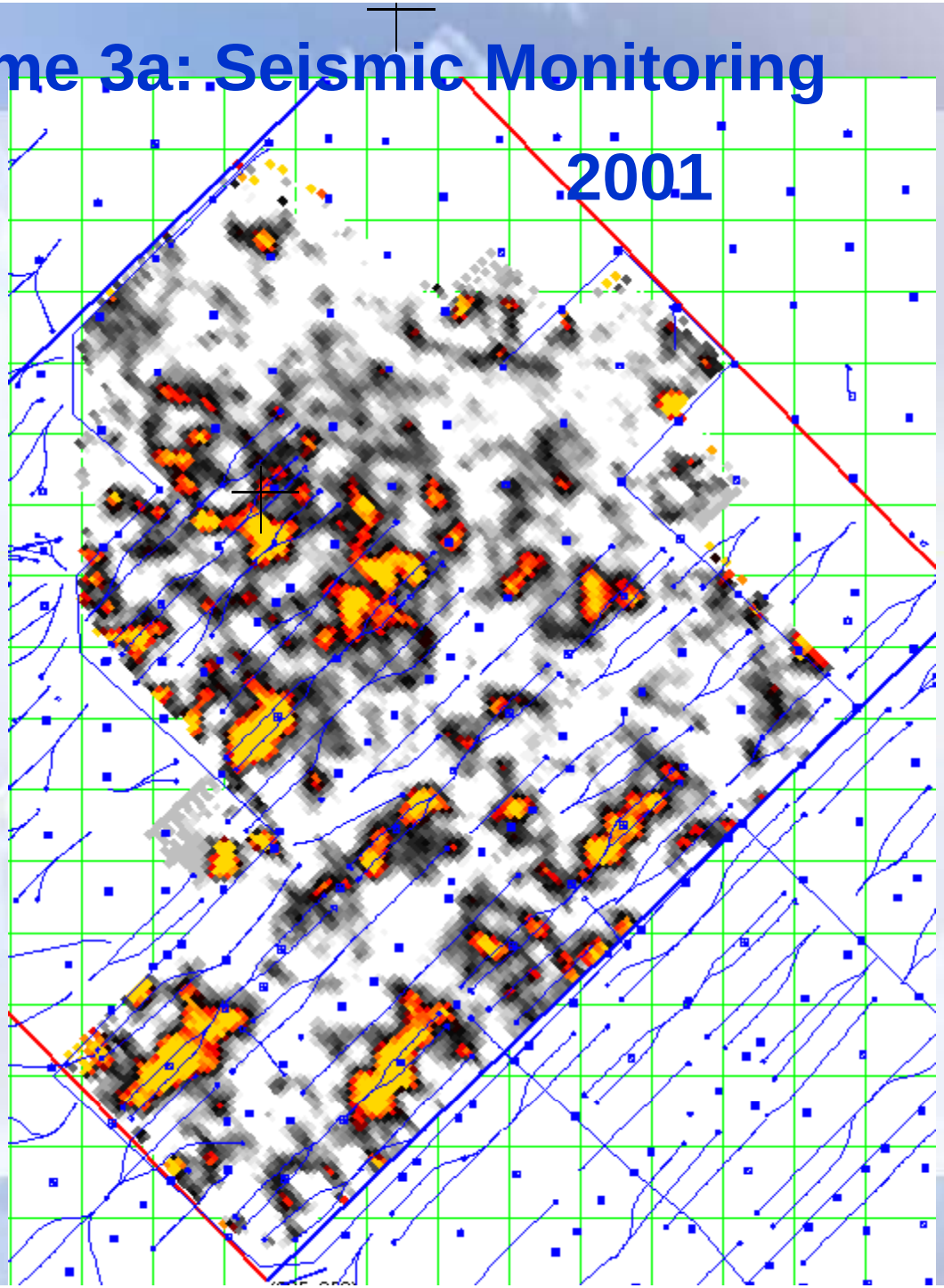
- projects related to: wellbore databases, knowledge synthesis, wellbore modelling





- Proposed “big ticket” item: in-situ cement/casing testing

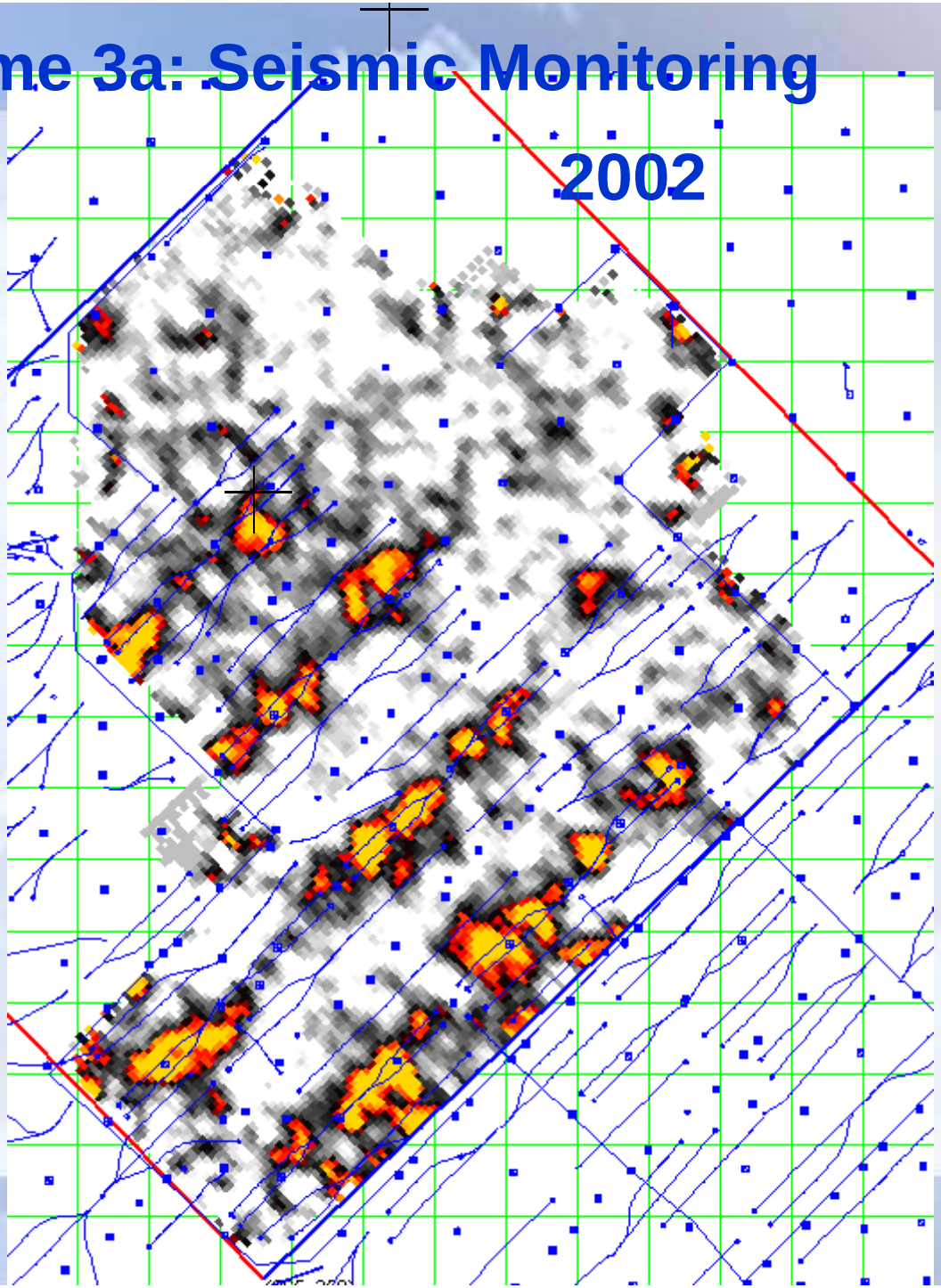
Theme 3a: Seismic Monitoring



Marly Amplitude Difference

1.2 MT CO_2 Injected

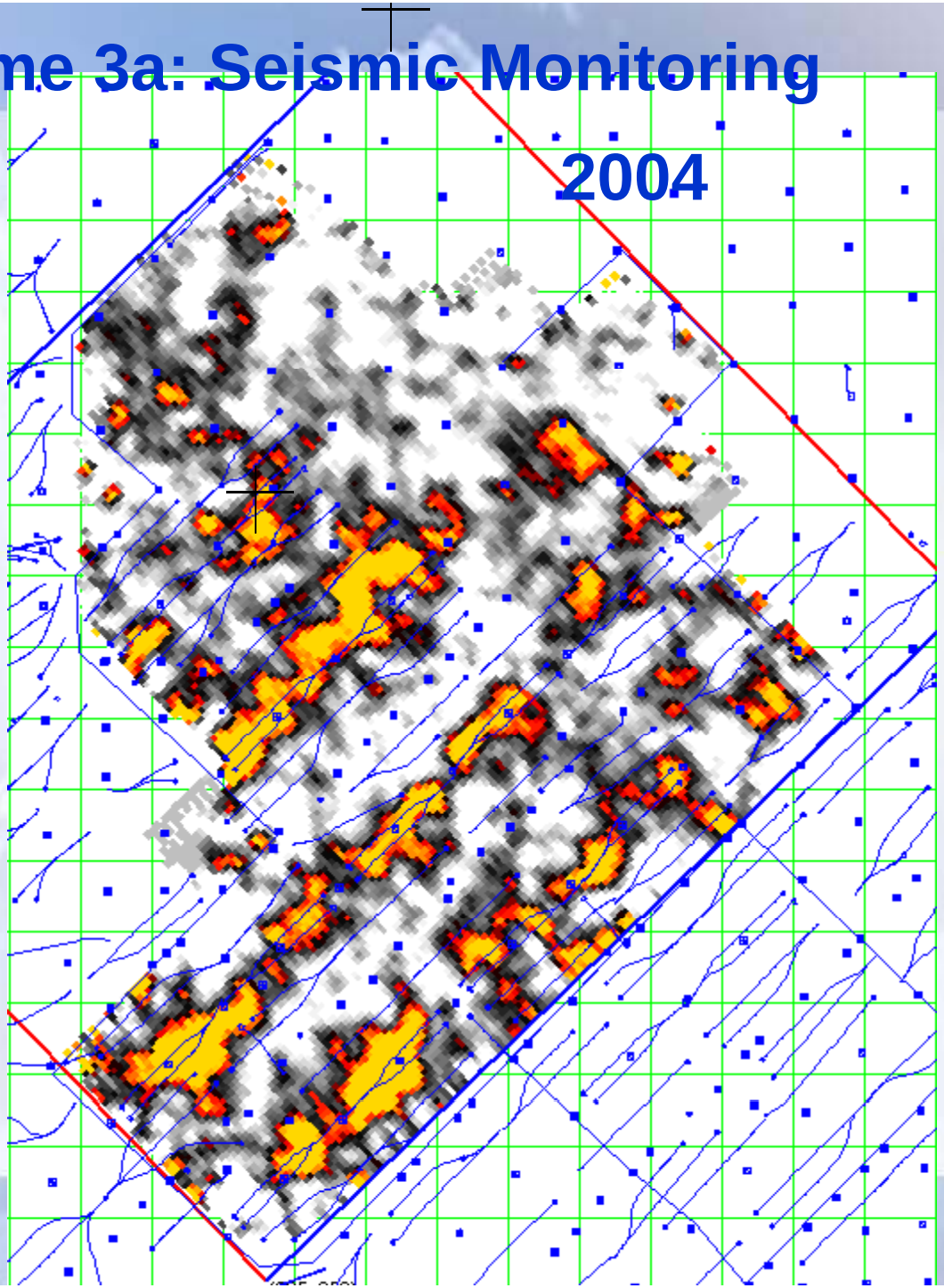
Theme 3a: Seismic Monitoring



Marly Amplitude Difference

2.6 MT CO_2 Injected

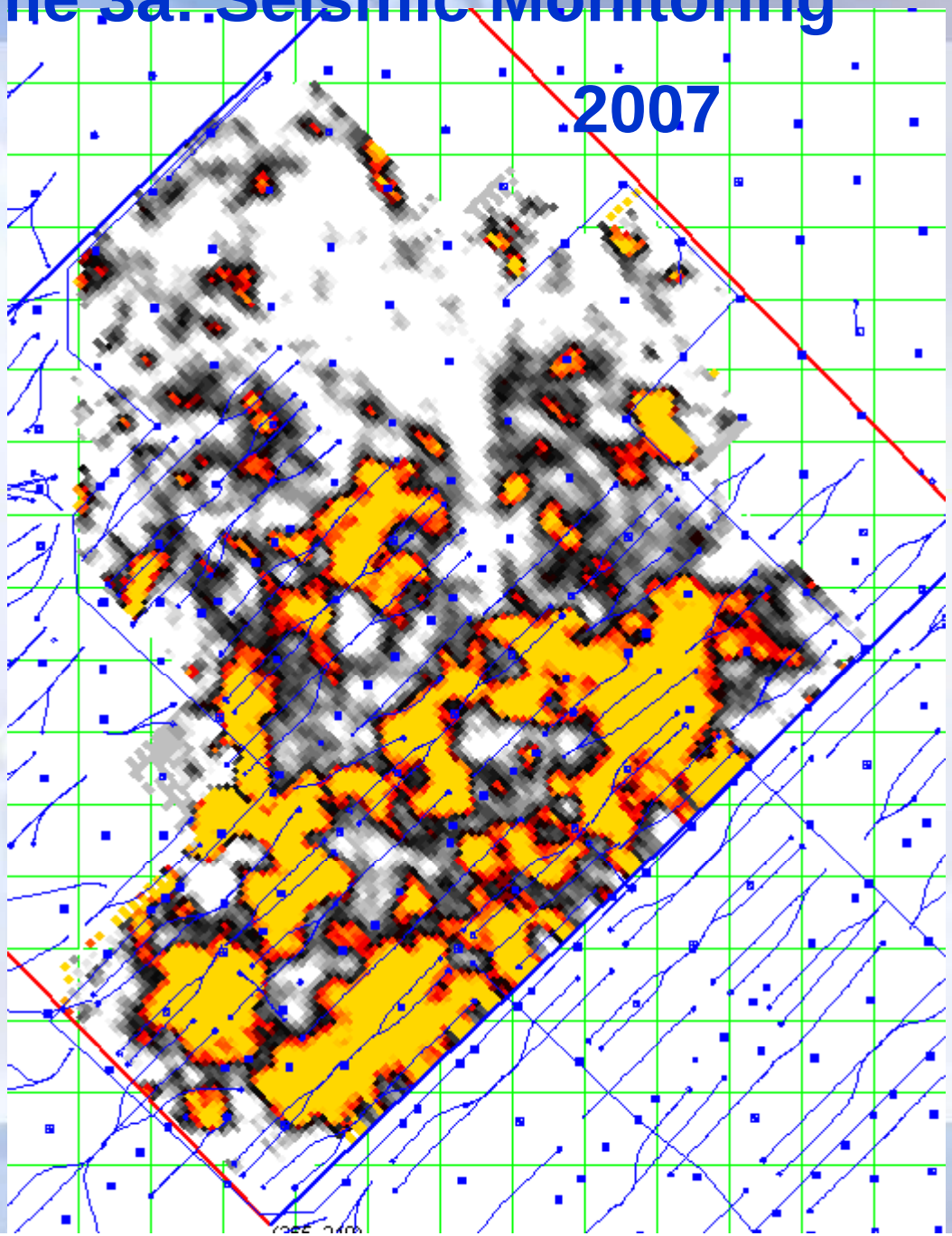
Theme 3a: Seismic Monitoring



Marly Amplitude Difference

~6 MT (?) CO_2 Injected (total field)

Theme 3a: Seismic Monitoring



Marly Amplitude Difference

14 MT CO_2 Injected (total field)

Microseismicity Summary (03-08)

Microseismicity is low: 175 microseisms near the reservoir; 148 locatable.

M=–3 to –1 (energy-equivalent of **30 mg-30gm of TNT**).

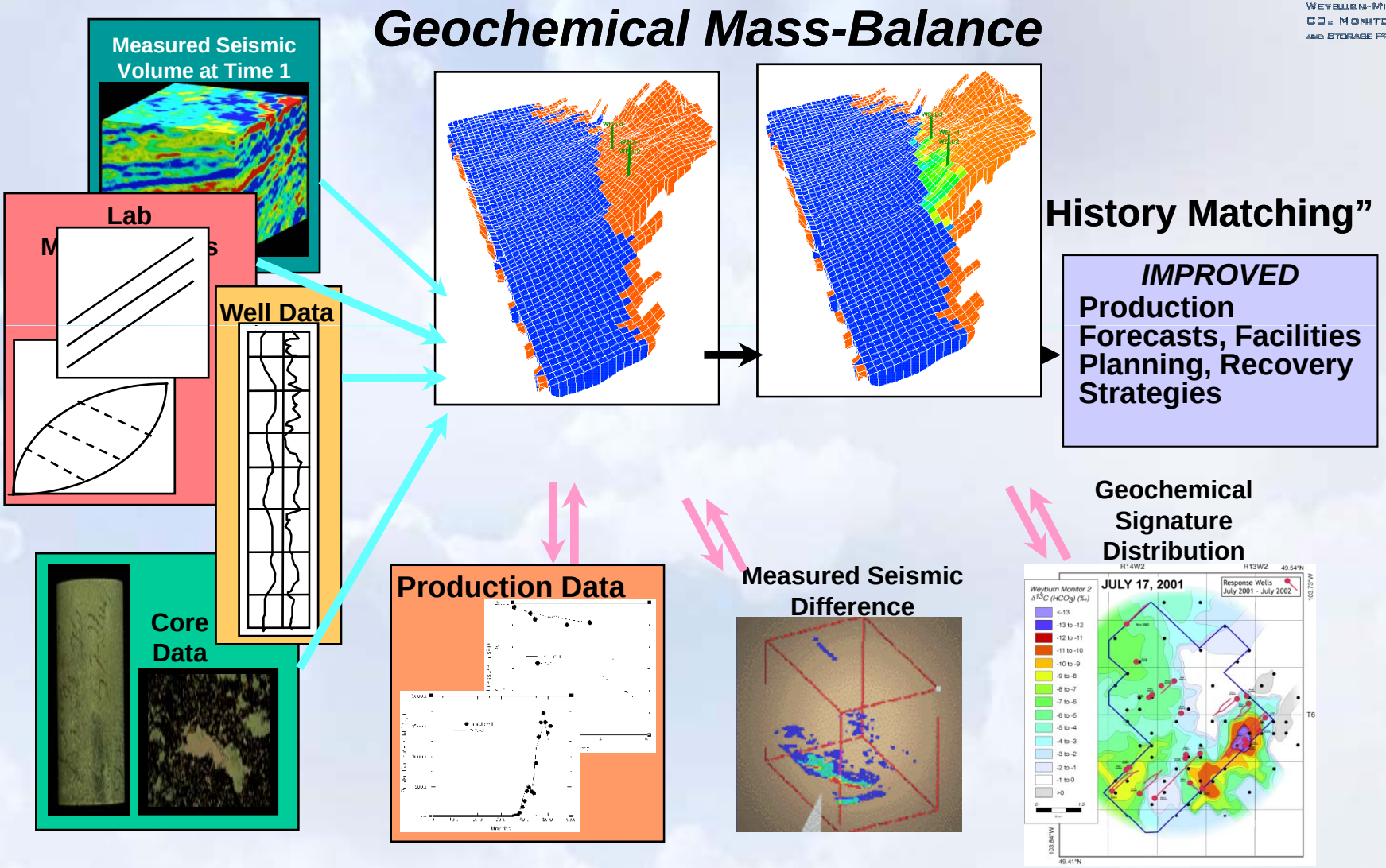
Very **sporadic**; clustered temporally and spatially.

Associated with changes in **injection rates** or temporary **well shut-downs**.

Tentative correlation of locations with CO_2 distribution from time-lapse seismic.

Theme 3b: Reservoir Modeling and Flow Simulation

Including Time Lapse Seismic & Geochemical Mass-Balance

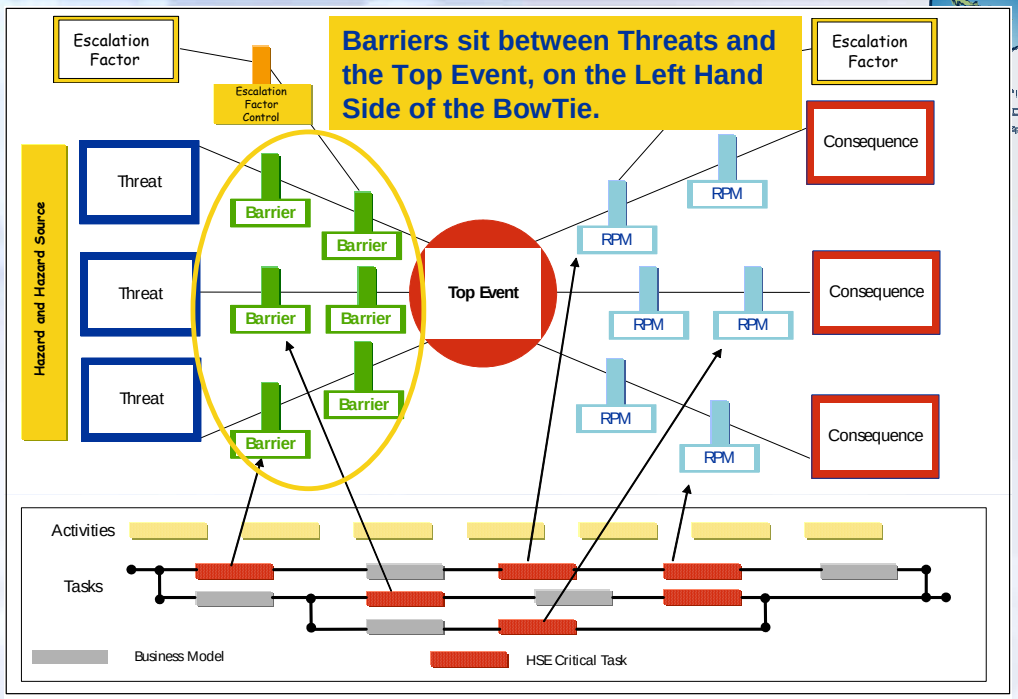


Reservoir Modeling and Flow Simulation

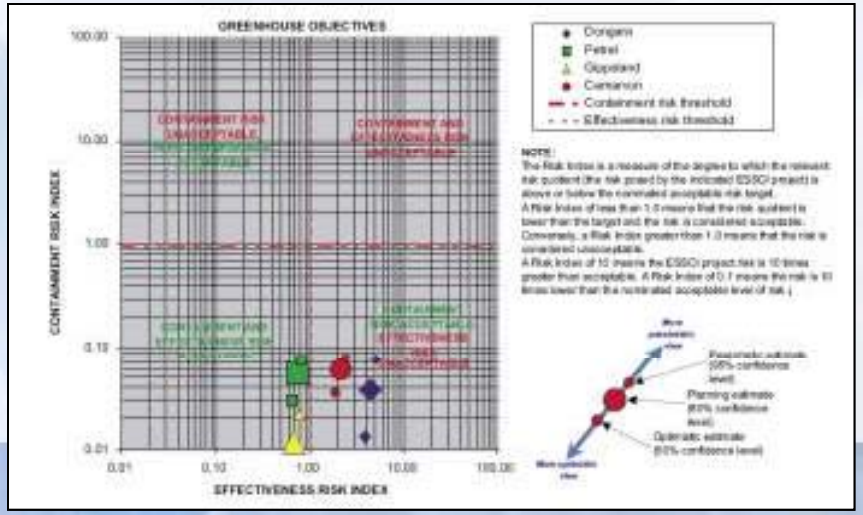
Theme 4: Risk Assessment

Application and comparison of different quantitative RA methods:

- Bow-Tie Method
- RISQUE (URS) Method
- Percolation-Invasion Methods (Permedia)

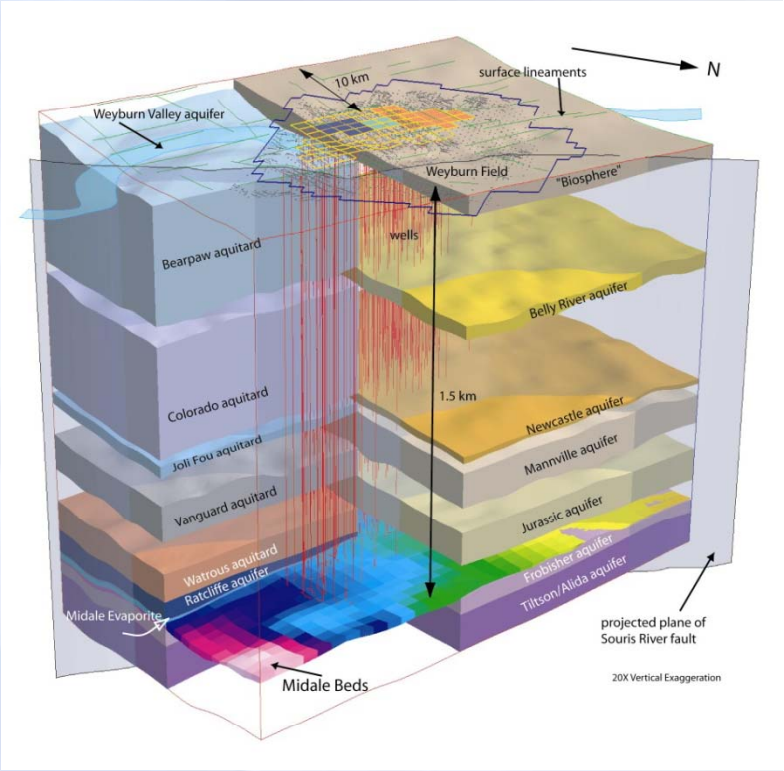


Qualitative Description	Order of Magnitude Likelihood (Annual Frequency or Probability Over a Set Period)	Basis
A. Certain	1 (or 0.999, 99.9%)	Certain, or as near to as makes no difference
B. Almost certain	0.2-0.9	One or more incidents of a similar nature has occurred here
C. Highly probable	0.1	A previous incident of a similar nature has occurred here
D. Possible	0.01	Could have occurred already without intervention
E. Unlikely	0.001	Recorded recently elsewhere
F. Very unlikely	1×10^{-4}	It has happened elsewhere
G. Highly improbable	1×10^{-5}	Published information exists, but in a slightly different context
H. Almost impossible	1×10^{-6}	No published information on a similar case



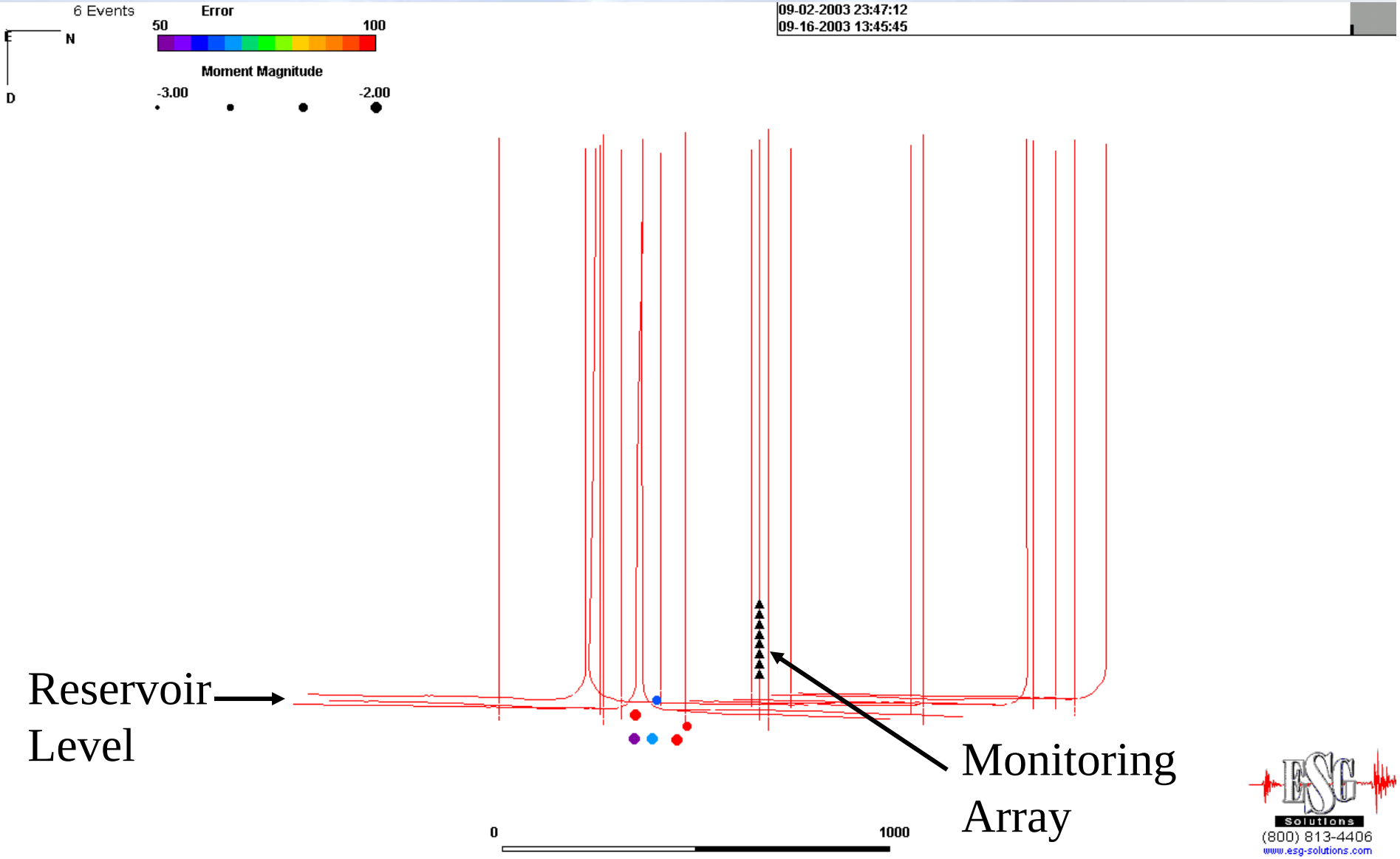
Conclusions

- Geological container at Weyburn is suitable for long-term storage of CO_2
- Effective trapping setting:
  primary seals are highly competent & thick shales above the reservoir serve as secondary barriers
- Risk Assessment using Geological Model indicates no seepage to surface over 5000 years
- Dec 2008: ~ 13 Mtonnes stored…
- Final Phase (2008-2011) work in progress



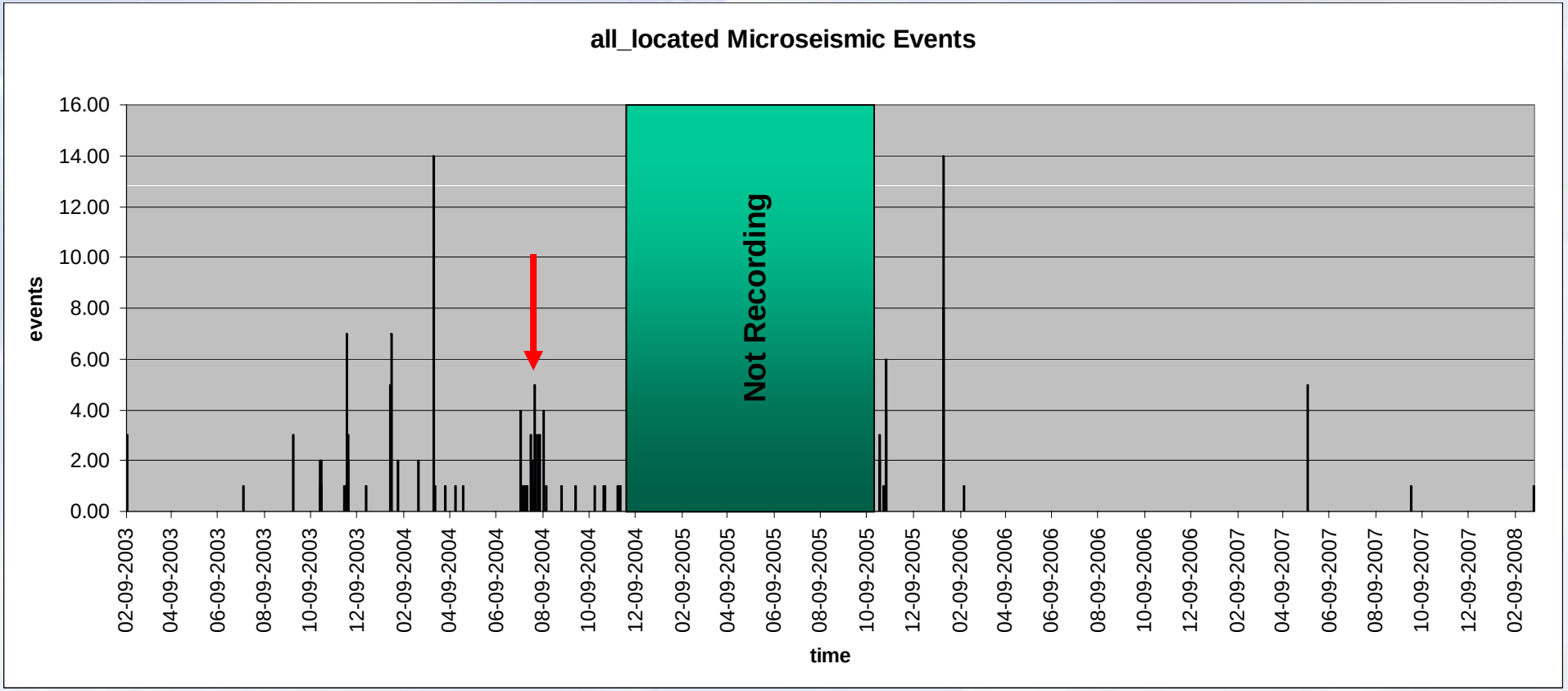
IEA GHG
Weyburn-Midale
CO2 Monitoring
and Storage Project

Section View

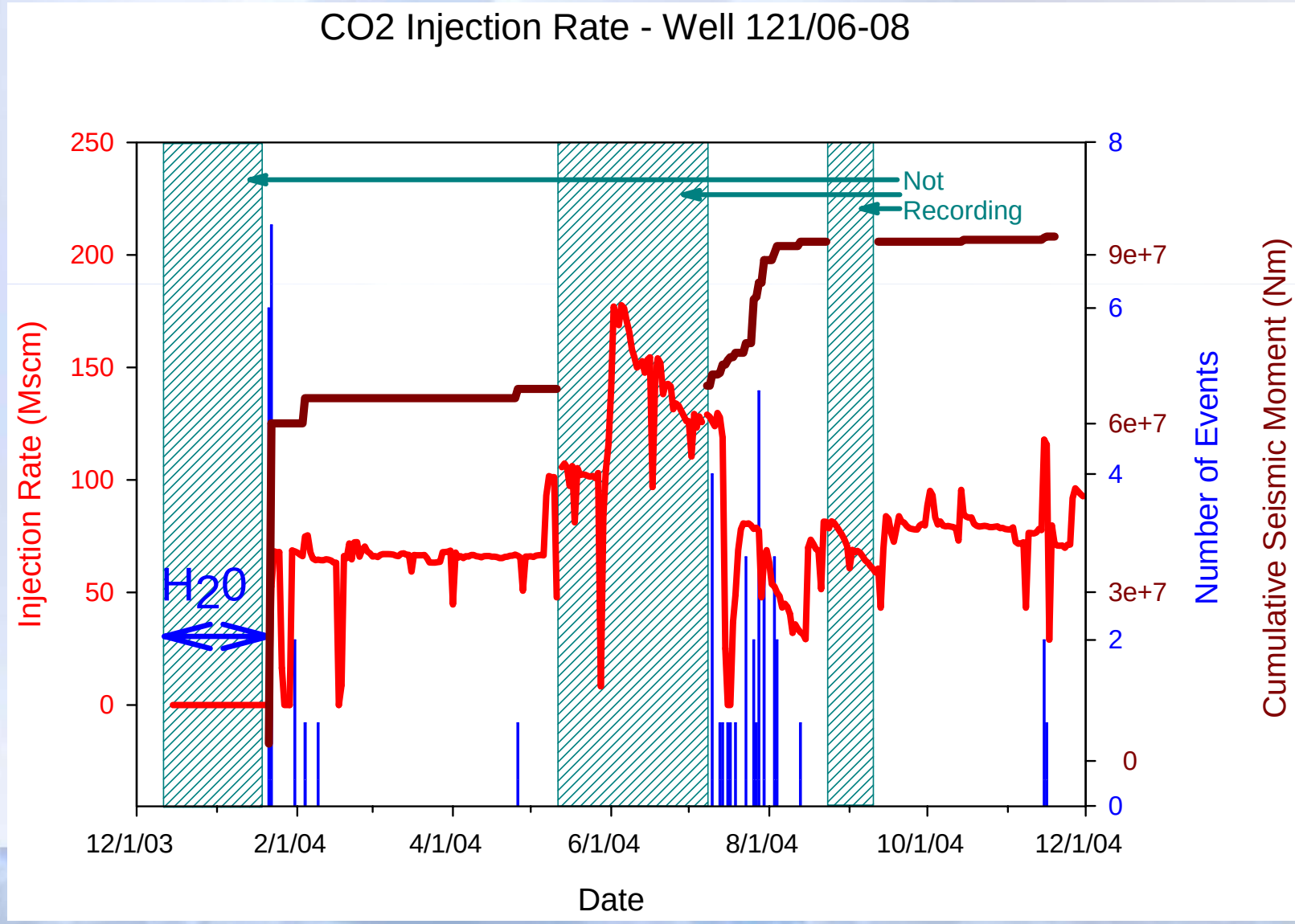


ESG Solutions
(800) 813-4406
www.esg-solutions.com

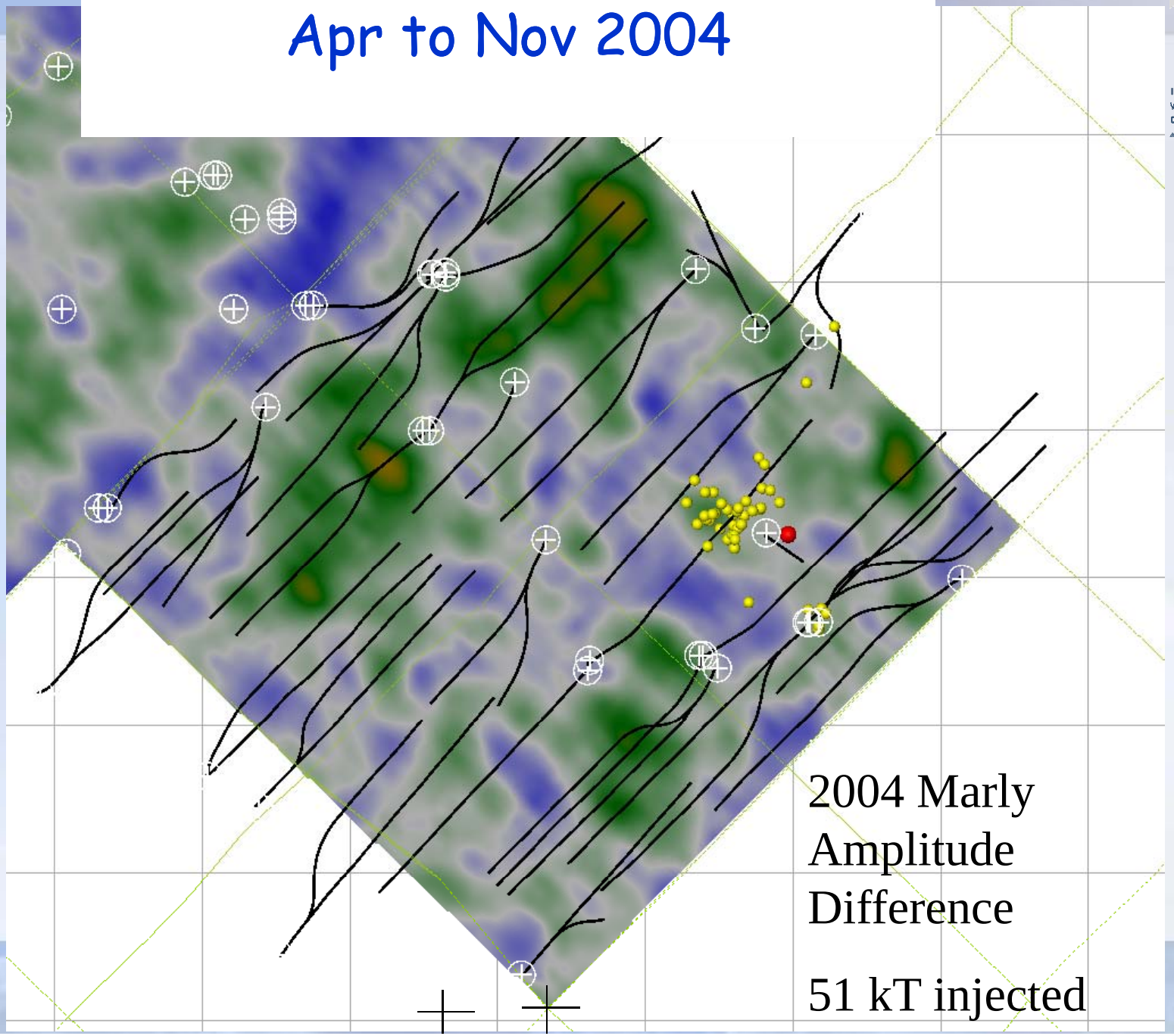
Located Events (2003-2008)



121/06-08 Cluster: Injection



Apr to Nov 2004



2004 Marly Amplitude Difference

51 kT injected

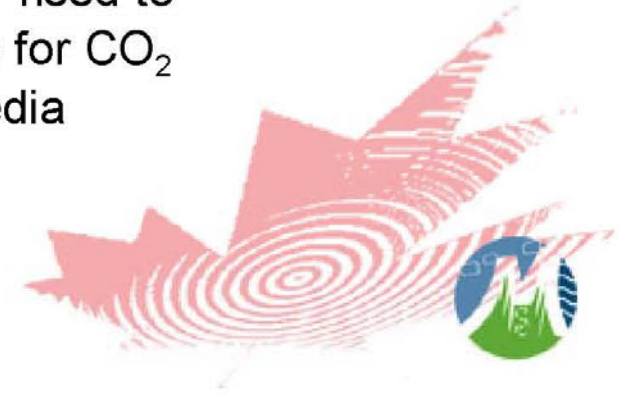
IEA GHG Weyburn-Midale CO2 Monitoring and Storage Project

IPCC Special Report on CO_2 Capture and Storage

CCS may contribute 15 to 55% (220 to 2,200 $GtCO_2$) to the cumulative mitigation effort worldwide this century

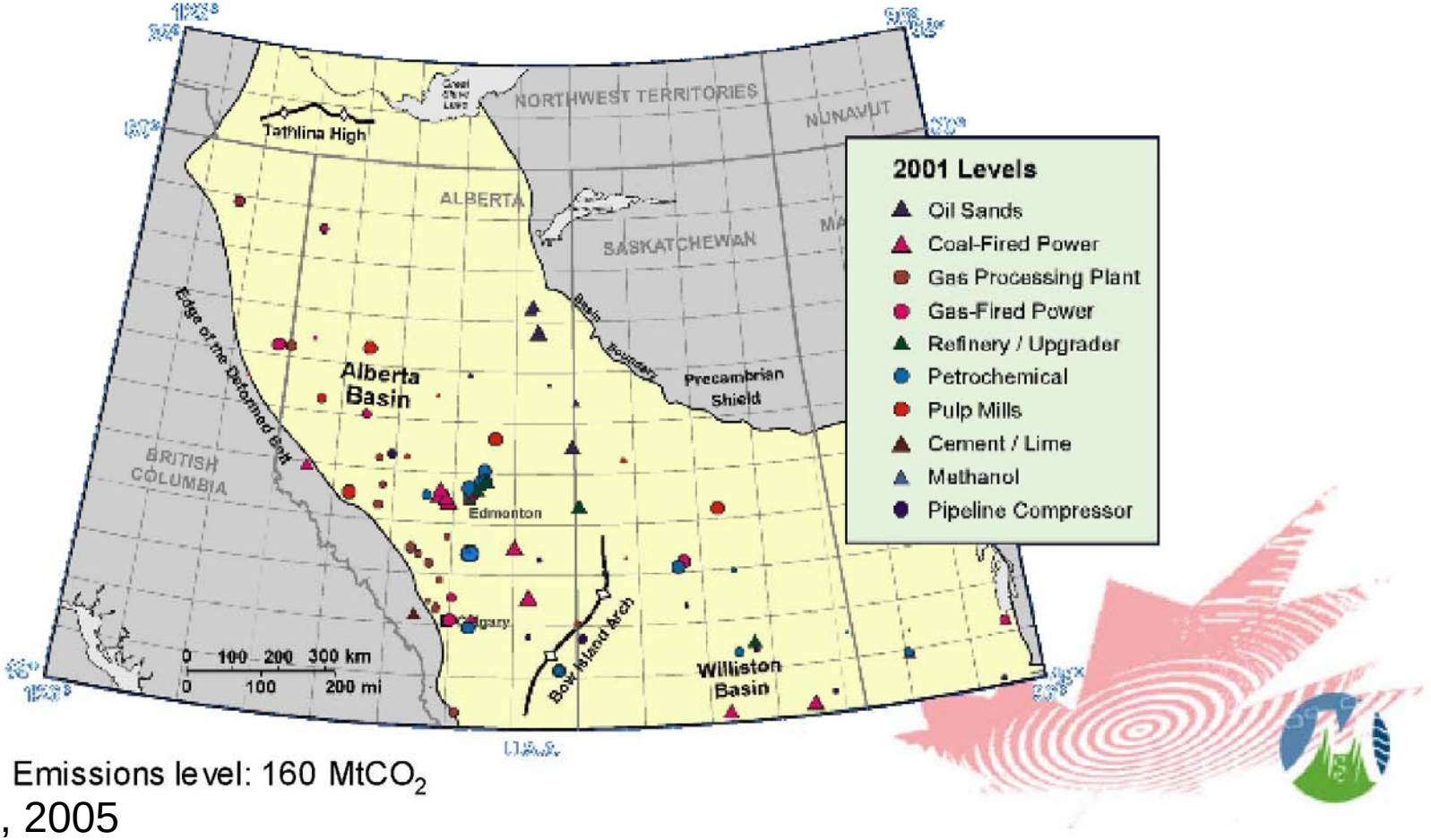
Available evidence suggests that worldwide it is likely that there is at least about 2,000 $GtCO_2$ of storage capacity in geological media

Hence the importance of and need to identify the capacity available for CO_2 storage in geological media



Bachu, 2005

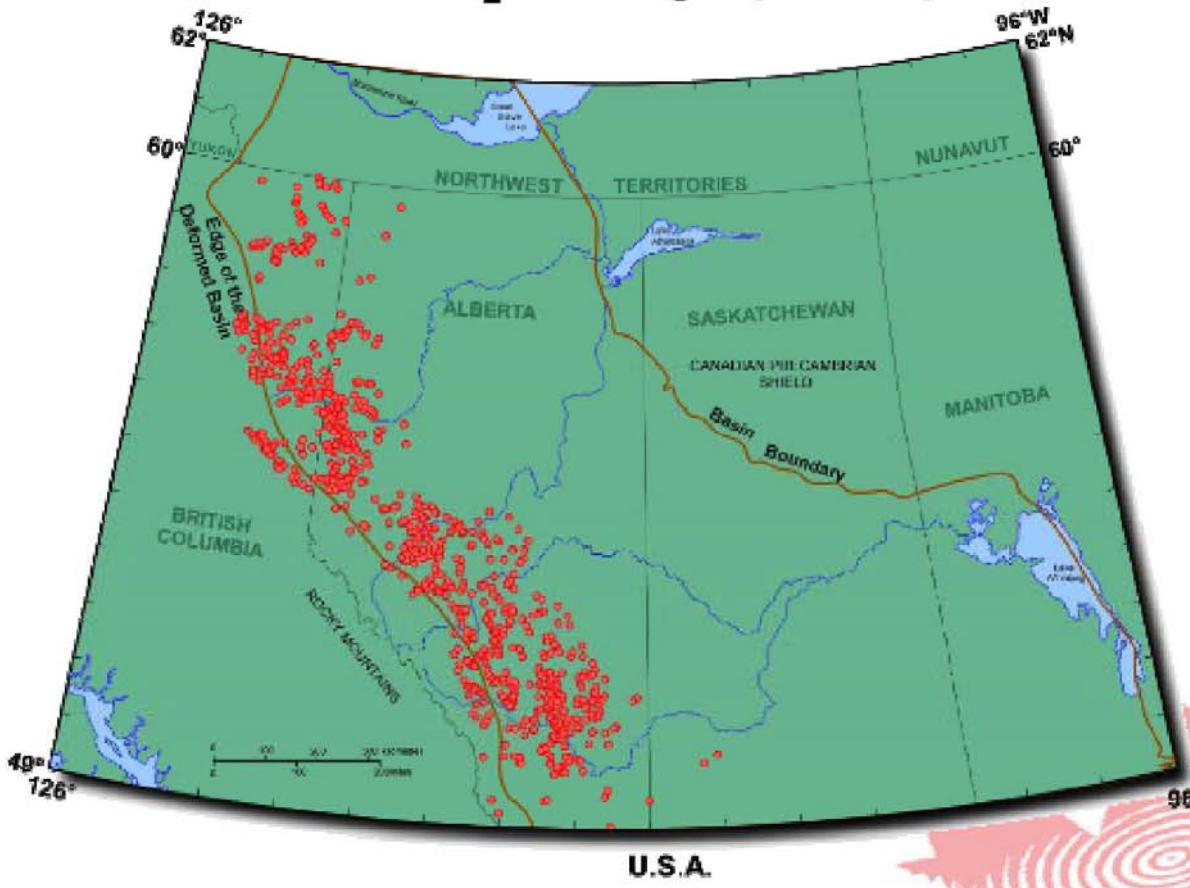
Location and Type of Large Stationary CO_2 Sources in the Western Canada Sedimentary Basin



Emissions level: 160 $MtCO_2$

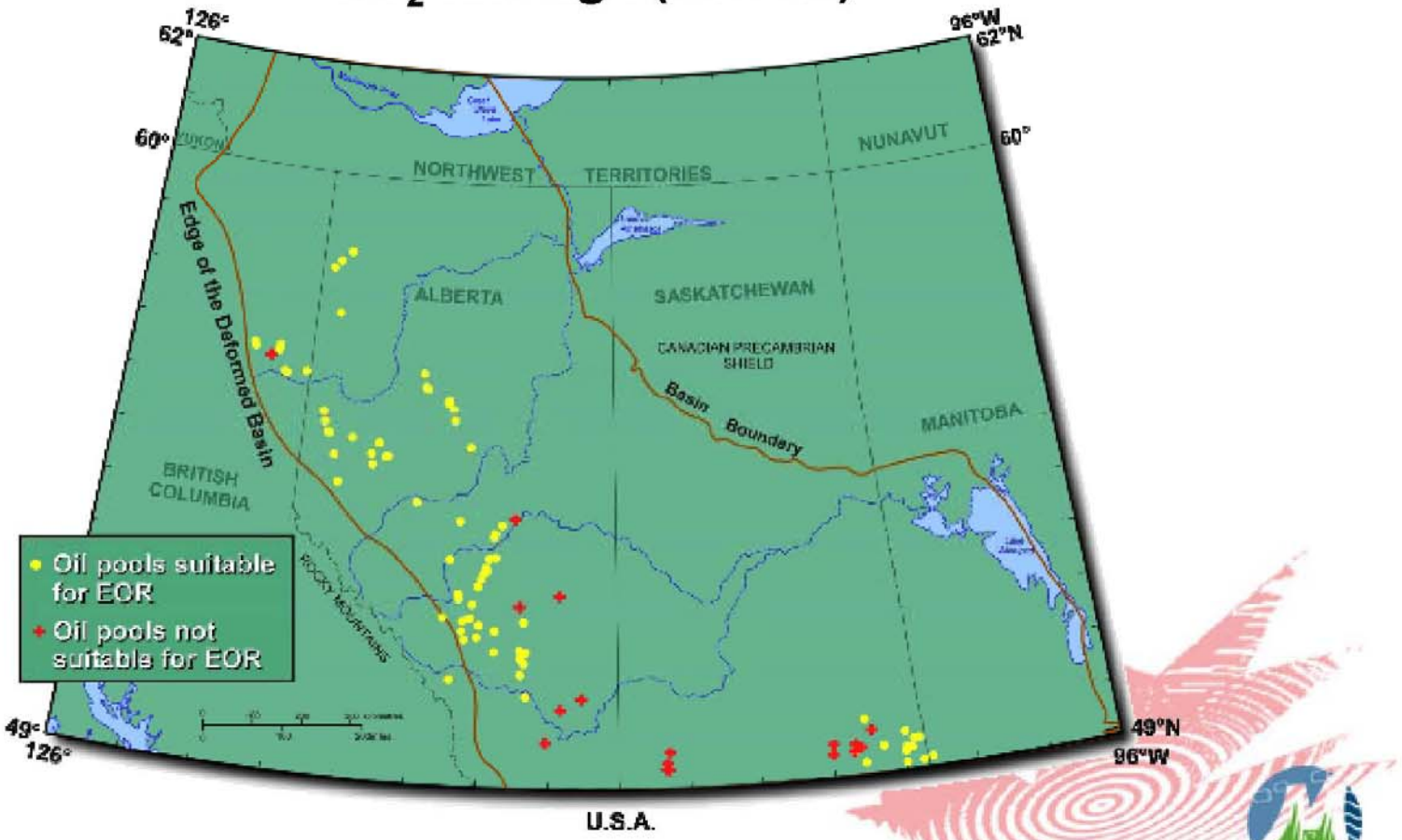
Bachu, 2005

Gas Reservoirs in Western Canada with High Capacity for CO_2 Storage (2.8 Gt)



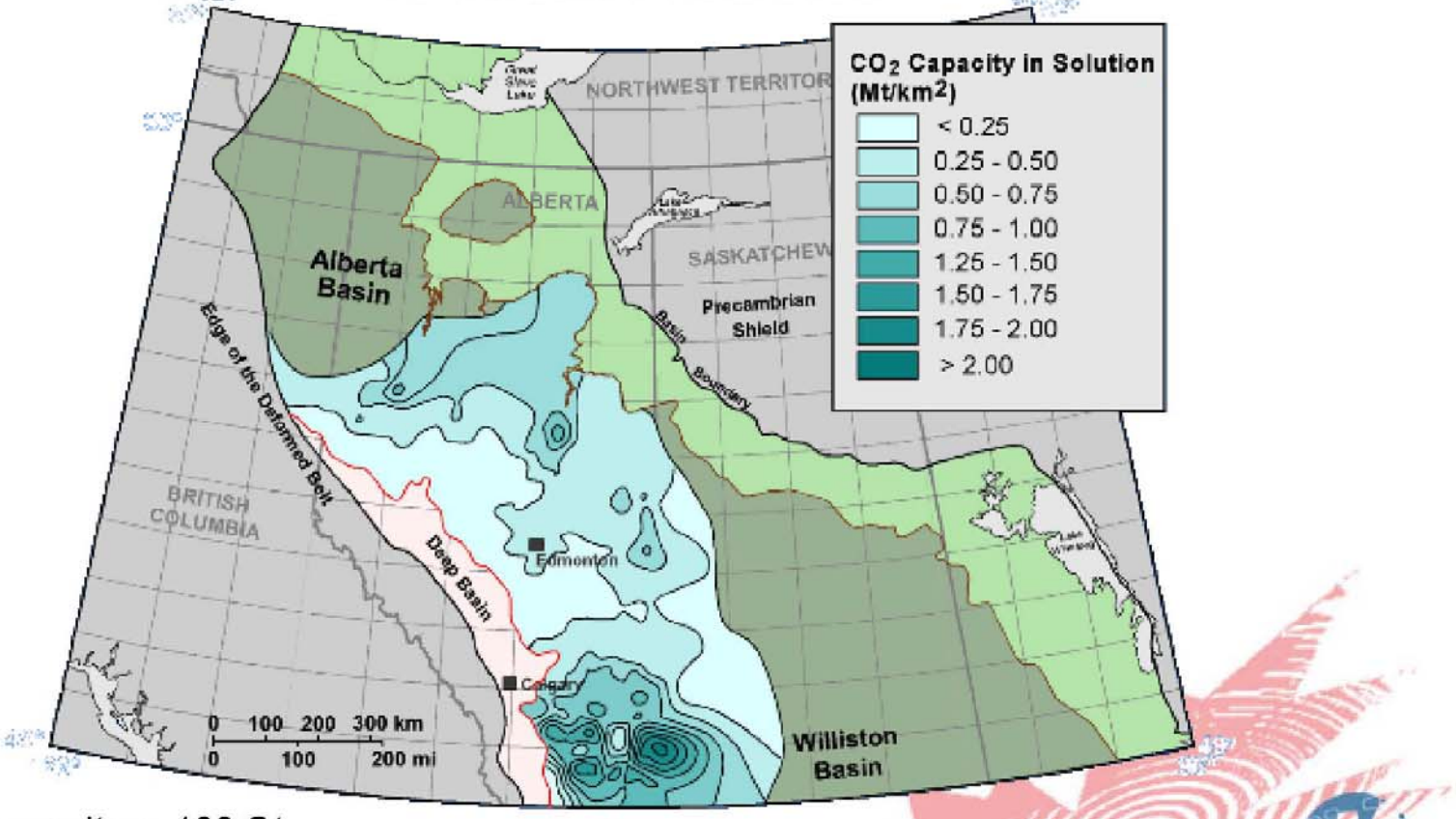
Bachu, 2005

Oil Reservoirs in Western Canada with High Capacity for CO_2 Storage (650 Mt)



Bachu, 2005

CO_2 Storage Capacity in Solution in the Viking Formation in Western Canada



Total capacity: > 100 Gt

Bachu, 2005

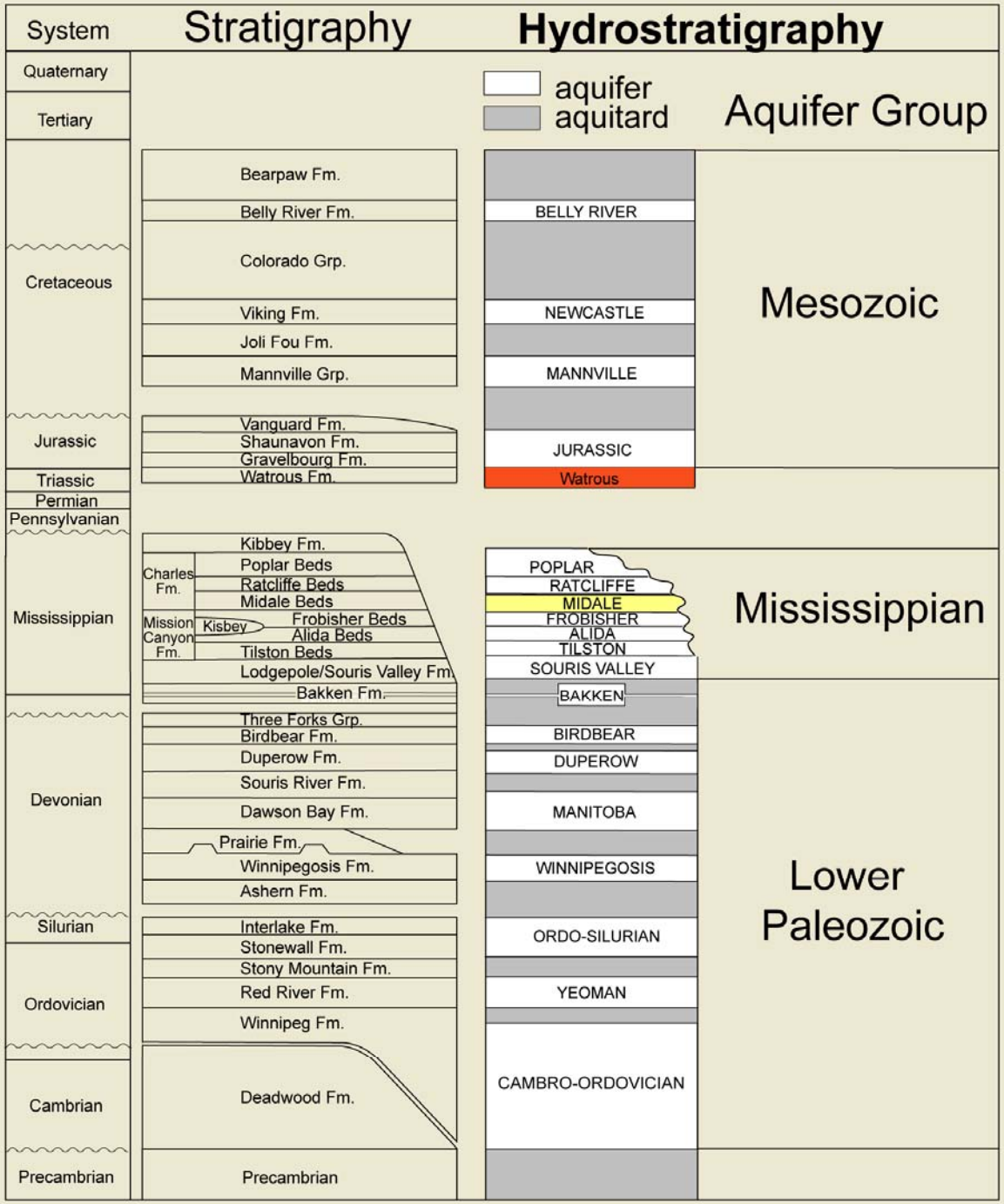
CO_2 Storage Capacity in Geological Media in the Western Canada Sedimentary Basin

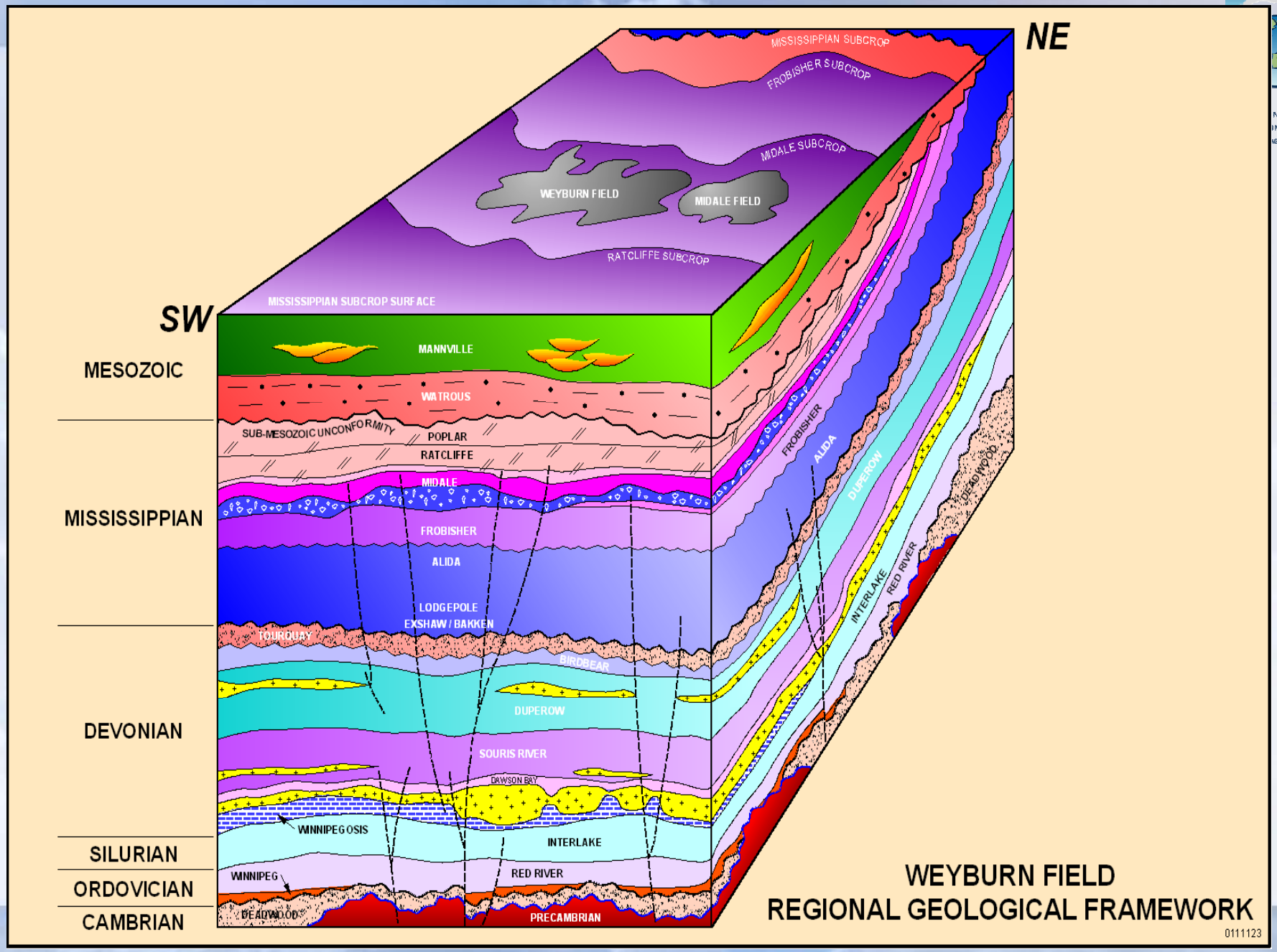
- 15 Gt in oil and gas reservoirs
- 1 Gt in uneconomic coal beds
- 100s – 1000s Gt in deep saline formations

160 Mt from large stationary sources in 2001

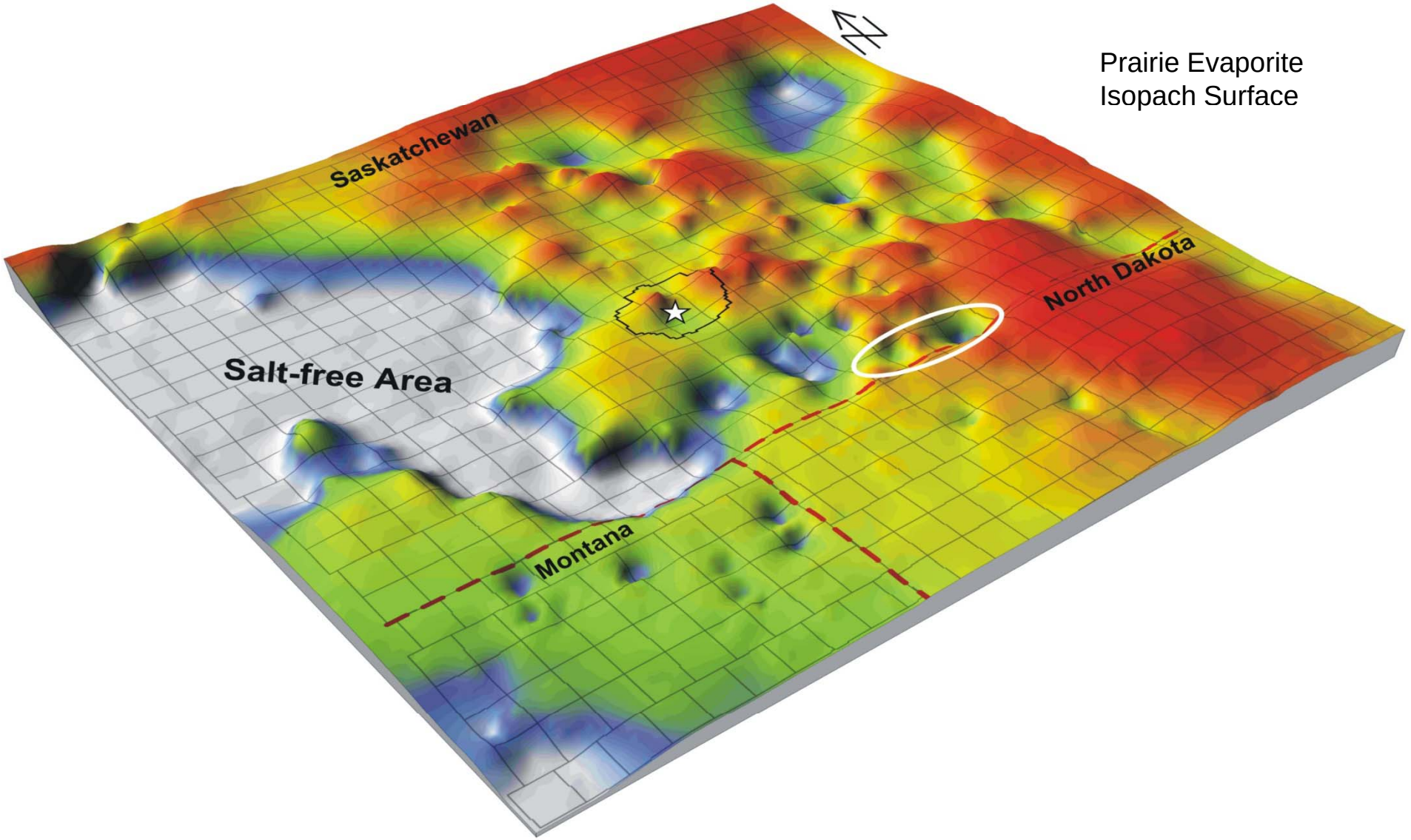
→ All CO_2 emissions from large stationary sources this century in the Prairie region of Canada could be stored in geological media

Bachu, 2005


System
Stratigraphy
Hydrostratigraphy
aquifer
aquitard
Aquifer Group
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Bearpaw Fm.
Belly River Fm.
Colorado Grp.
Viking Fm.
Joli Fou Fm.
Mannville Grp.
Vanguard Fm.
Shaunavon Fm.
Gravelbourg Fm.
Watrous Fm.
Kibbey Fm.
Charles Fm.
Poplar Beds
Ratcliffe Beds
Midale Beds
Mission Canyon Fm.
Kisbey
Frobisher Beds
Alida Beds
Tilston Beds
Lodgepole/Souris Valley Fm.
Bakken Fm.
Three Forks Grp.
Birdbear Fm.
Duperow Fm.
Souris River Fm.
Dawson Bay Fm.
Prairie Fm.
Winnipegosis Fm.
Ashern Fm.
Interlake Fm.
Stonewall Fm.
Stony Mountain Fm.
Red River Fm.
Winnipeg Fm.
Deadwood Fm.
Precambrian
BELLY RIVER
NEWCASTLE
MANNVILLE
JURASSIC
Watrous
POPLAR
RATCLIFFE
MIDALE
FROBISHER
ALIDA
TILSTON
SOURIS VALLEY
BAKKEN
BIRDBEAR
DUPEROW
MANITOBA
WINNIPEGOSIS
ORDO-SILURIAN
YEOMAN
CAMBRO-ORDOVICIAN
Mesozoic
Mississippian
Lower Paleozoic

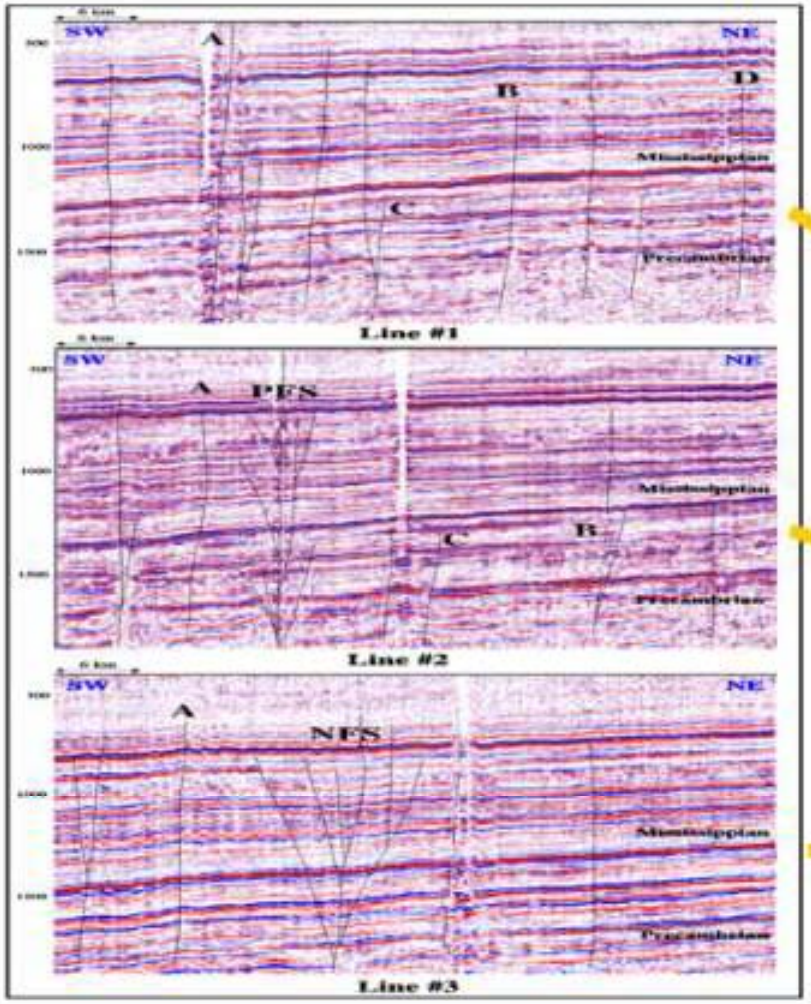

NE
SW
MISSISSIPPIAN SUBCROP
FROBISHER SUBCROP
MIDALE SUBCROP
WEYBURN FIELD
MIDALE FIELD
RATCLIFFE SUBCROP
MISSISSIPPIAN SUBCROP SURFACE
MESOZOIC
MANNVILLE
WATROUS
SUB-MESOZOIC UNCONFORMITY
POPLAR
RATCLIFFE
MIDALE
MISSISSIPPIAN
FROBISHER
ALIDA
LODGEPOLE
EXSHAW / BAKKEN
TOURDAN
BIRDBEAR
DUPEROW
SOURIS RIVER
DAWSON BAY
DEVONIAN
WINNIPEGOSIS
INTERLAKE
SILURIAN
RED RIVER
WINNIPEG
ORDOVICIAN
DEADWOOD
CAMBRIAN
PRECAMBRIAN
WEYBURN FIELD
REGIONAL GEOLOGICAL FRAMEWORK
0111123

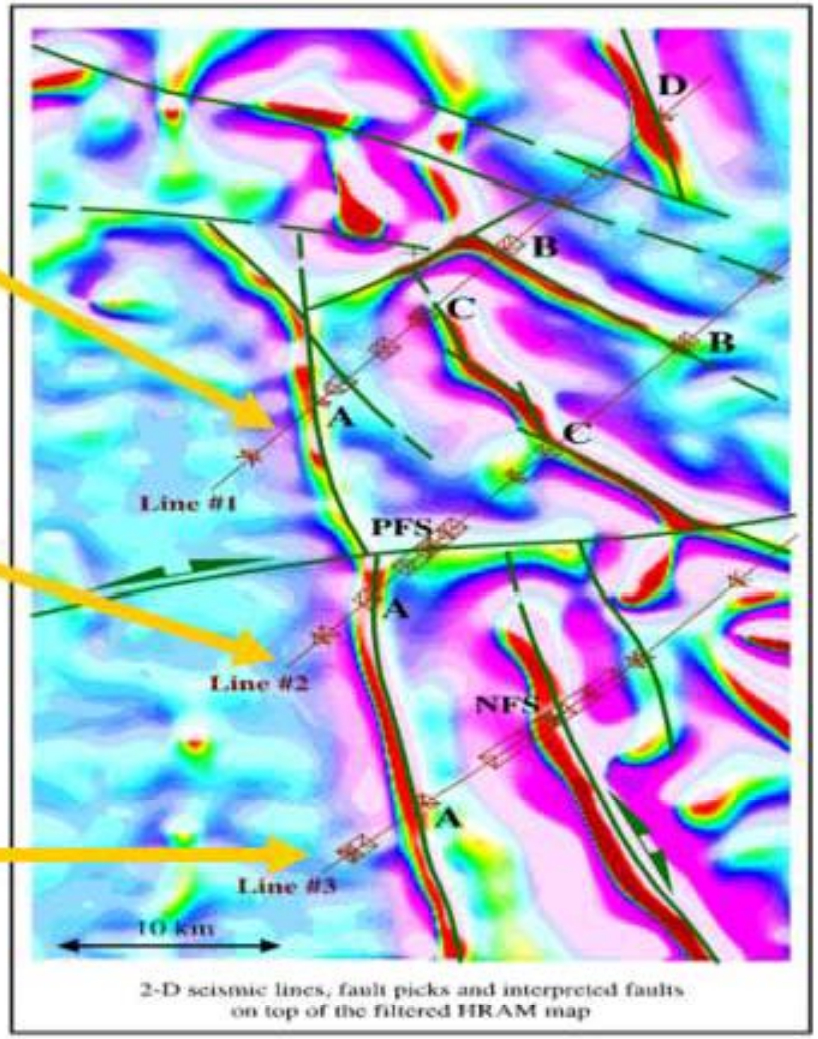
Geological Mapping: example isopach



Prairie Evaporite
Isopach Surface

Seismic and Aeromagnetic Integration

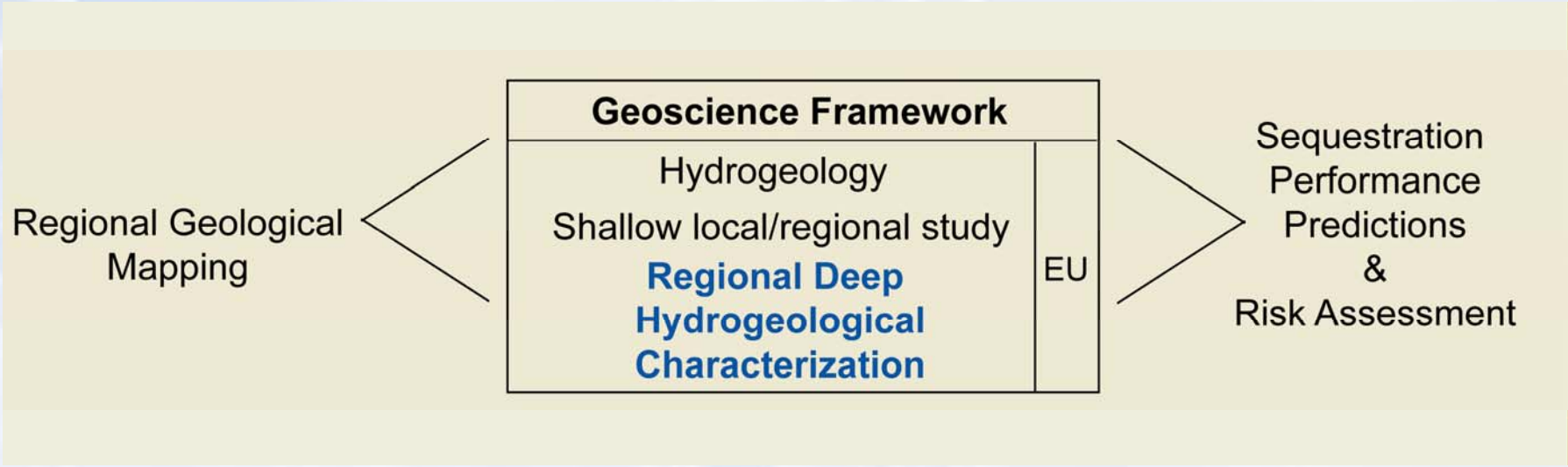




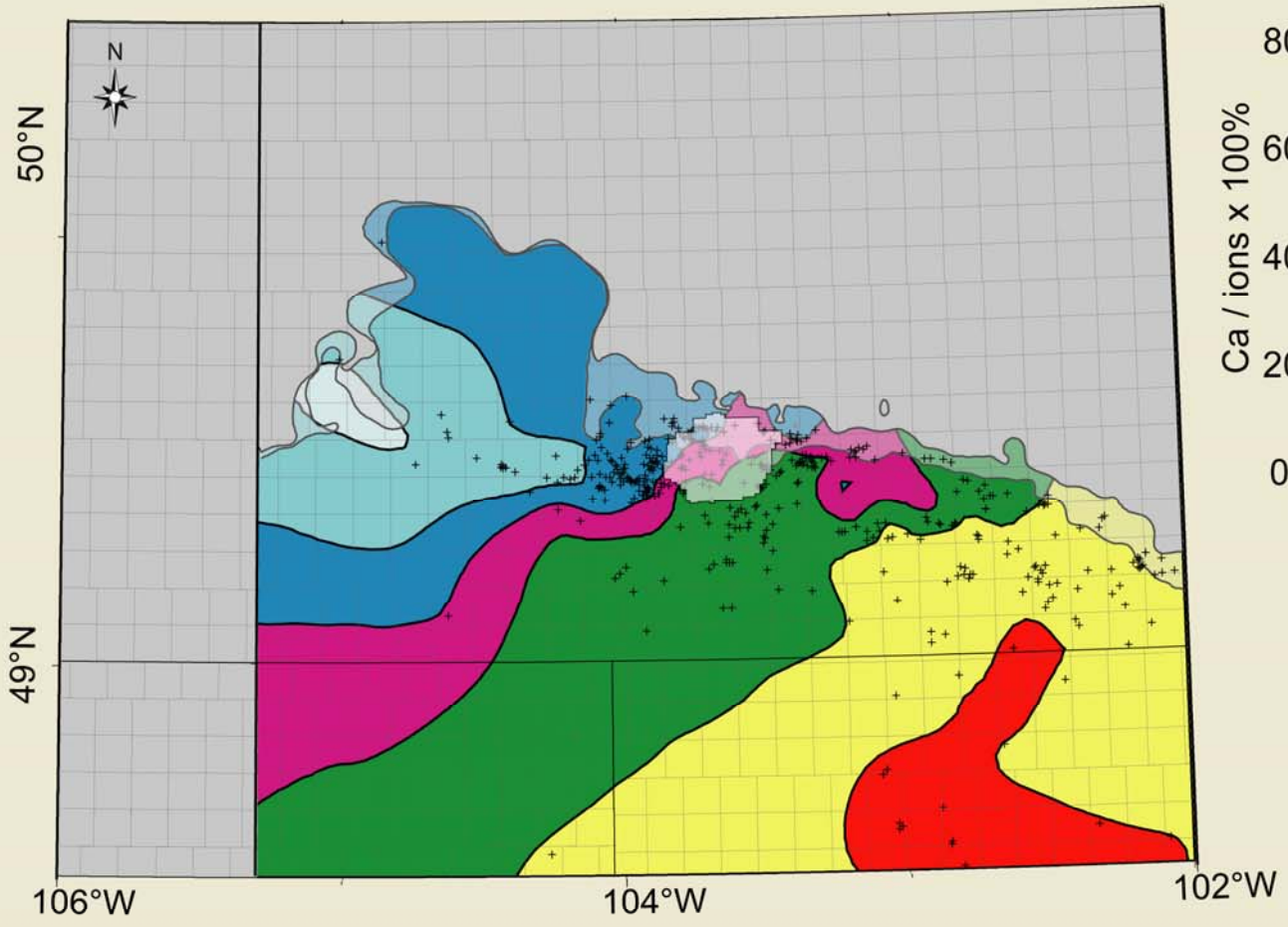
2-D seismic lines, fault picks and interpreted faults on top of the filtered HRAM map

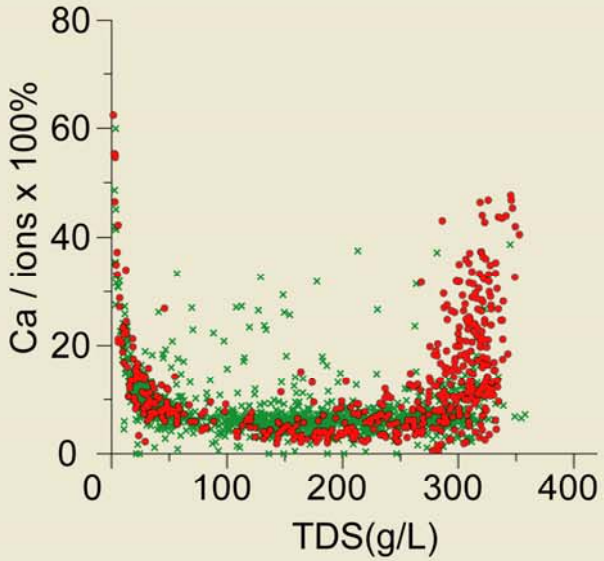
Hydrogeology

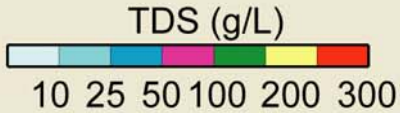
- Characterize basin hydrodynamics
- Assess Impact of fluid flow on CO_2 storage
- Quantify flow directions and rates



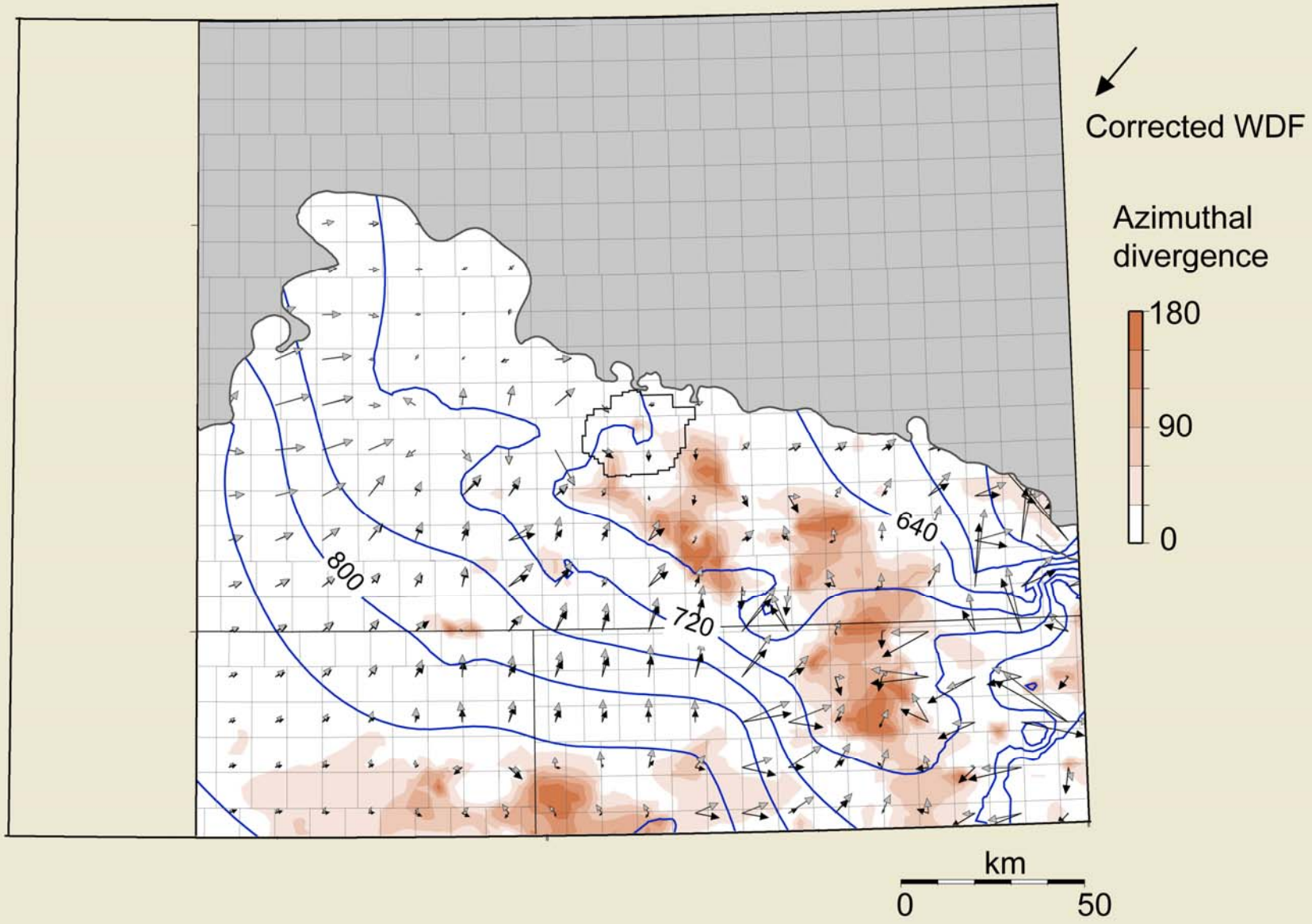
Typical Mississippian Aquifer: Midale (target aquifer)



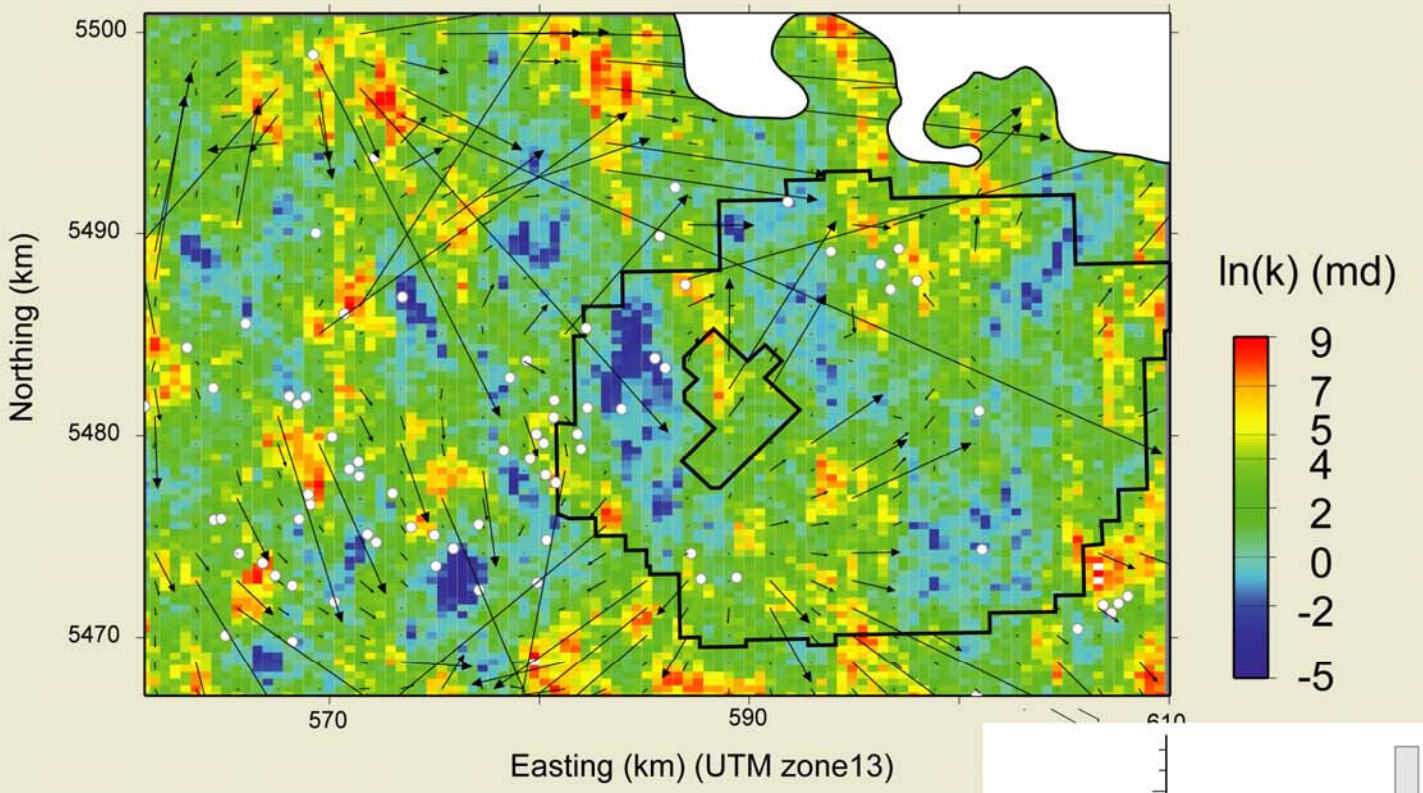




Typical Mississippian Aquifer: Midale (target aquifer)

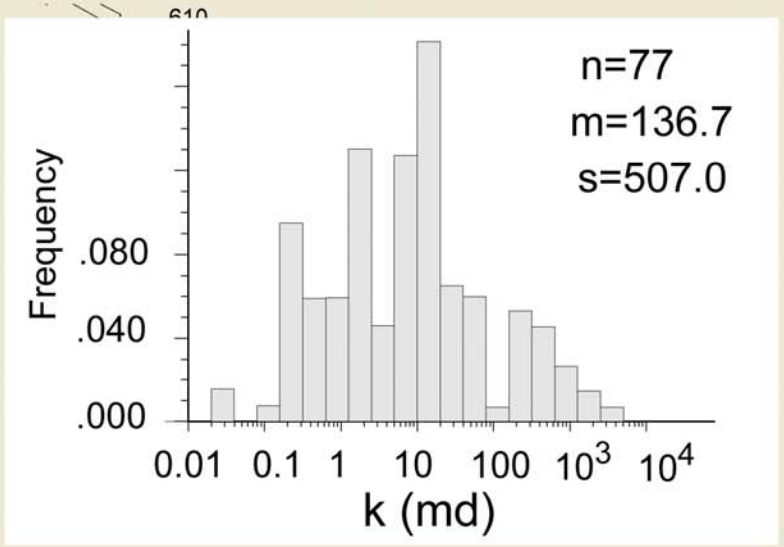


Midale (target) aquifer: Near-Field Flow Velocities



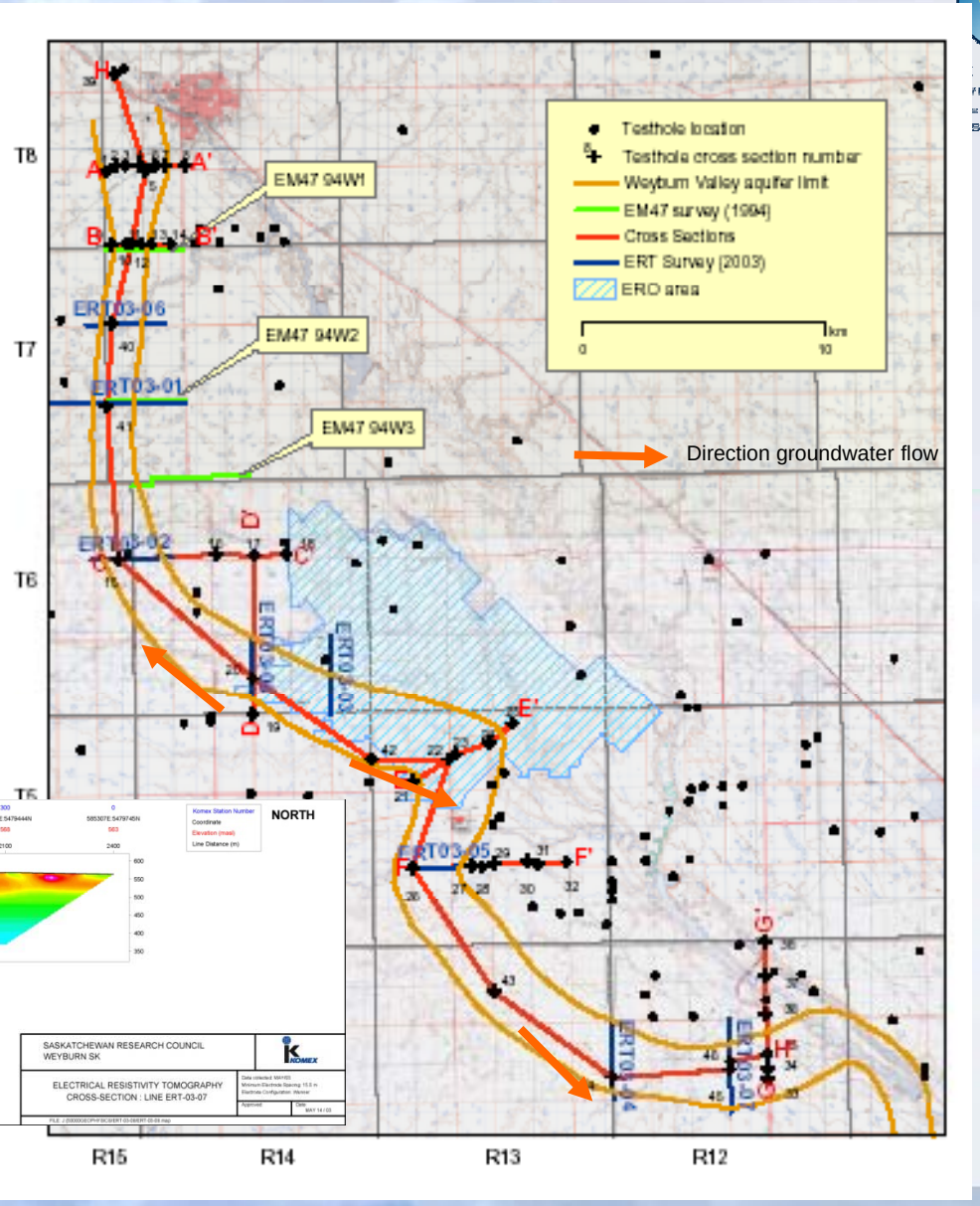
Nodal velocity = 1 m/yr

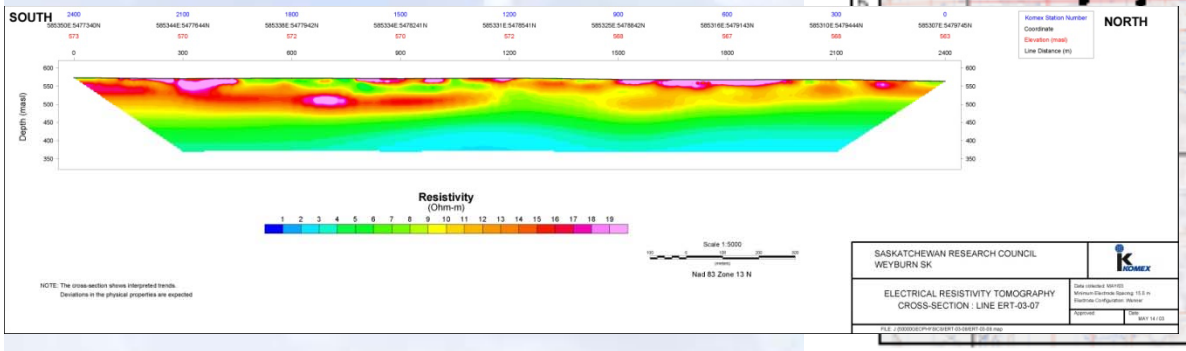
Weyburn Field
(avg. velocity < 1 m/yr)



Shallow Hydrogeology

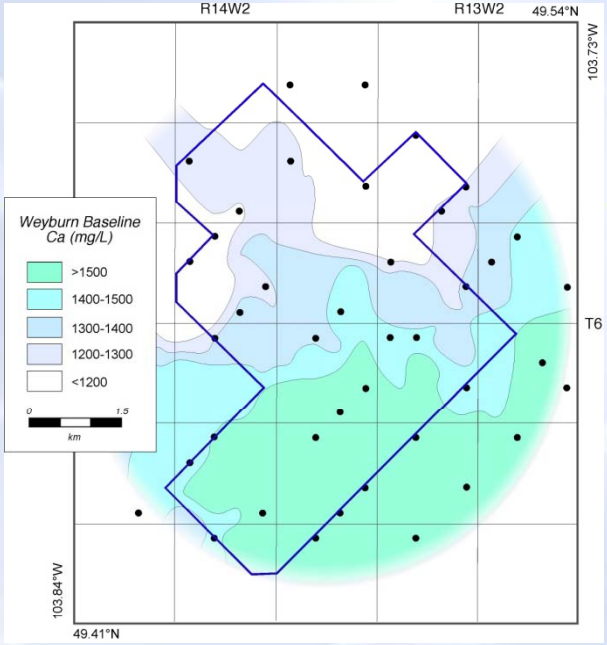
- 12 test holes
- 8 ERT surveys run to establish extent of Weyburn Valley Aquifer



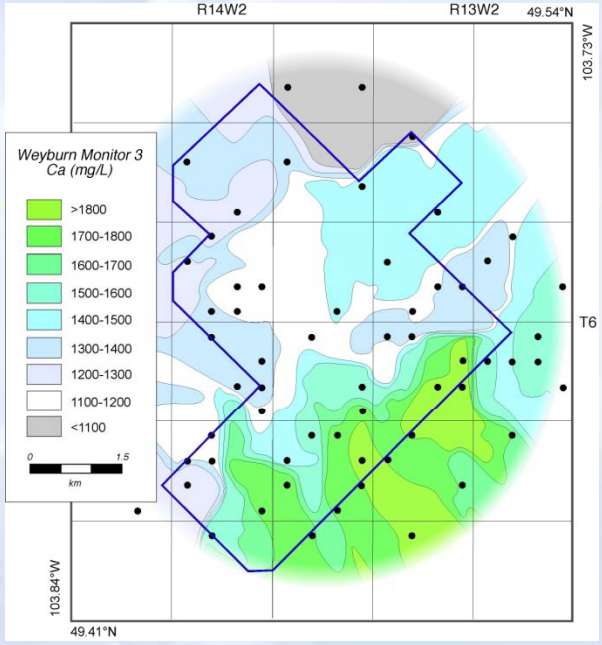


Reservoir Mineral Dissolution
Ca^{2+} in produced fluids

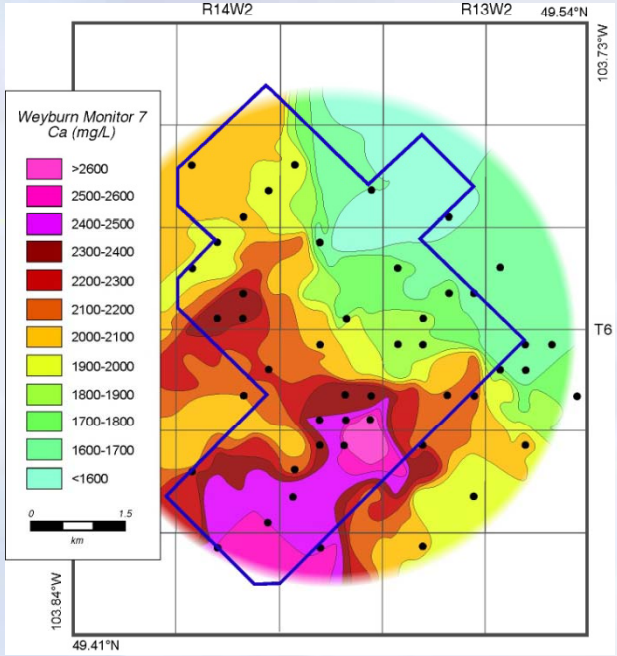
Pre-injection



12 months



31 months



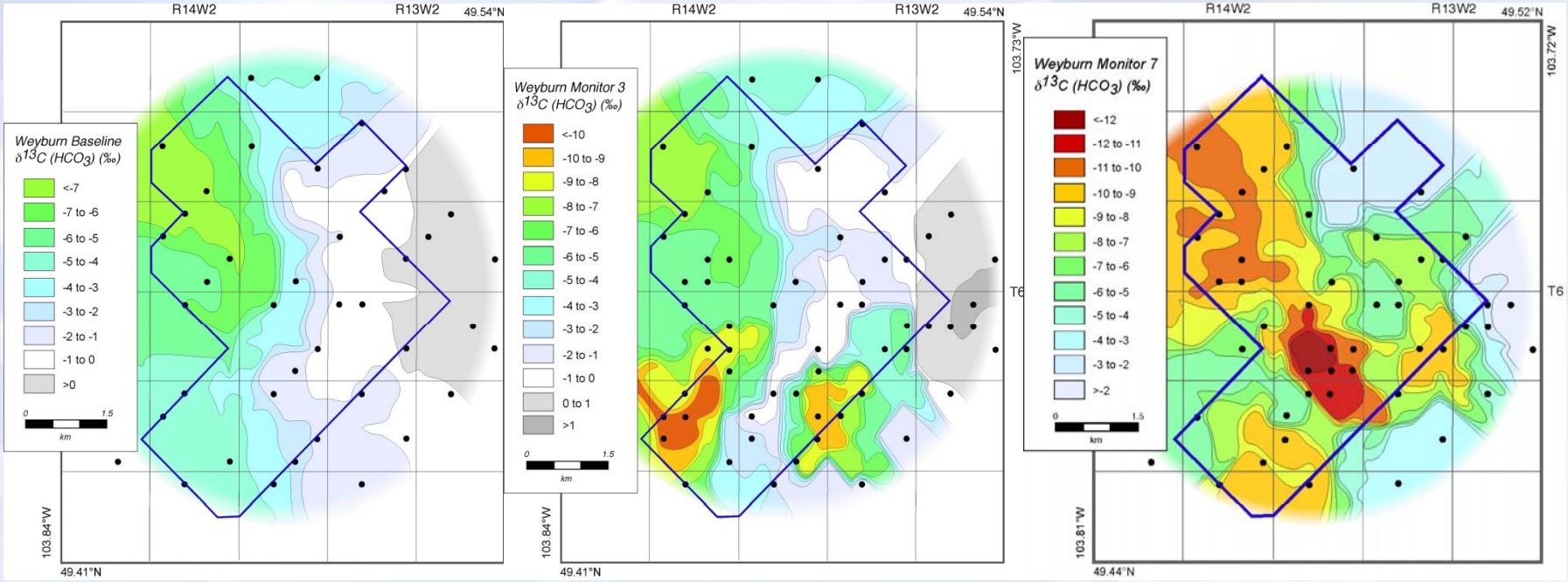
Calcite and dolomite dissolution increases the Ca^{2+} and Mg^{2+} concentrations in produced fluids.

$$CaCO_3 + H_2O + CO_2 \longrightarrow \mathbf{Ca^{2+}} + 2HCO_3^-$$

Geochemical Monitoring – Injected CO_2 Dissolution

$\delta^{13}C_{HCO3}$ in produced fluids

Pre-injection | 12 months | 31 months

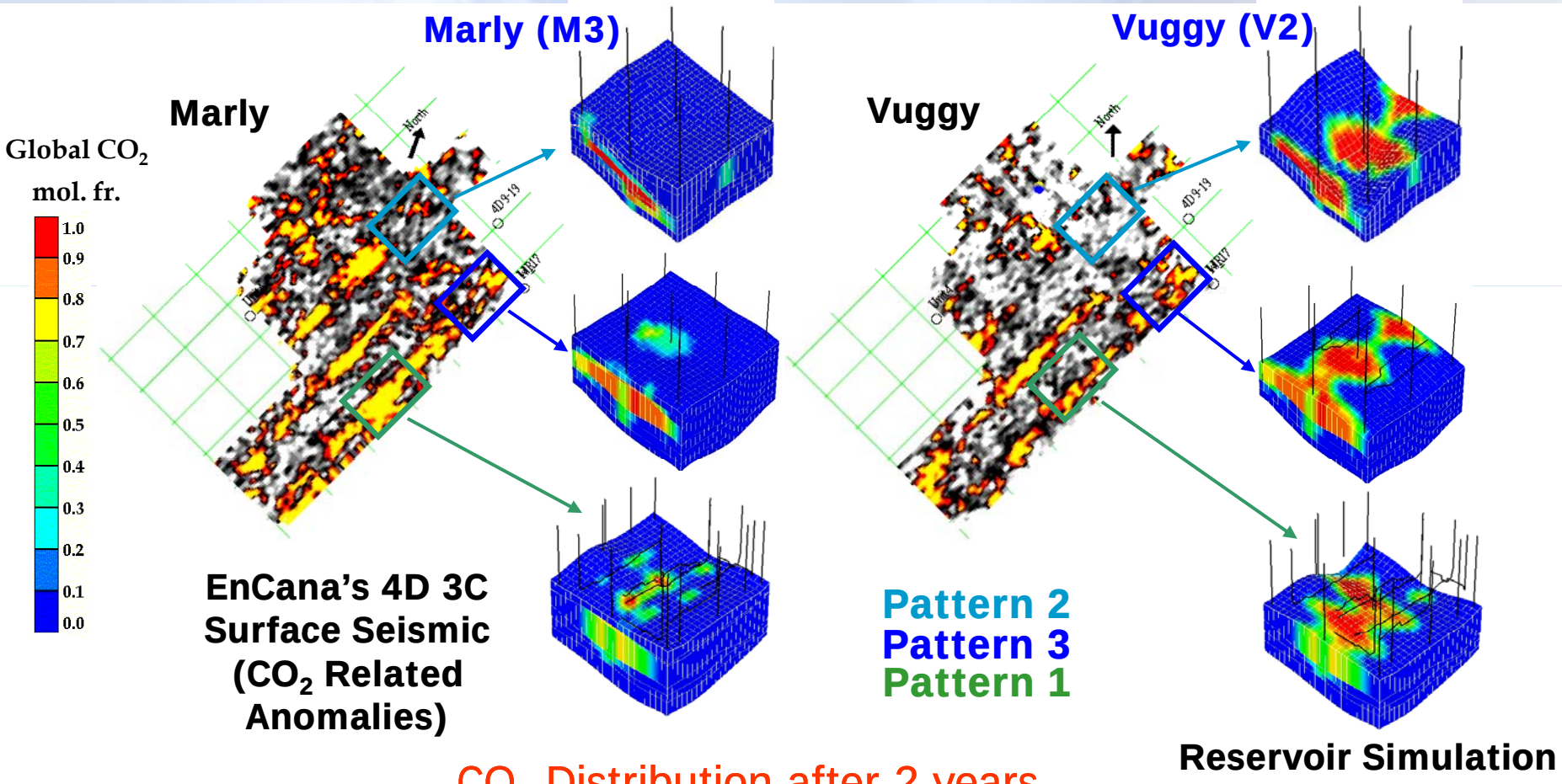


Injected CO_2 dissolution (decreasing $\delta^{13}C$ in produced fluid)

Injected CO_2: $\delta\ ^{13}C$=-20‰

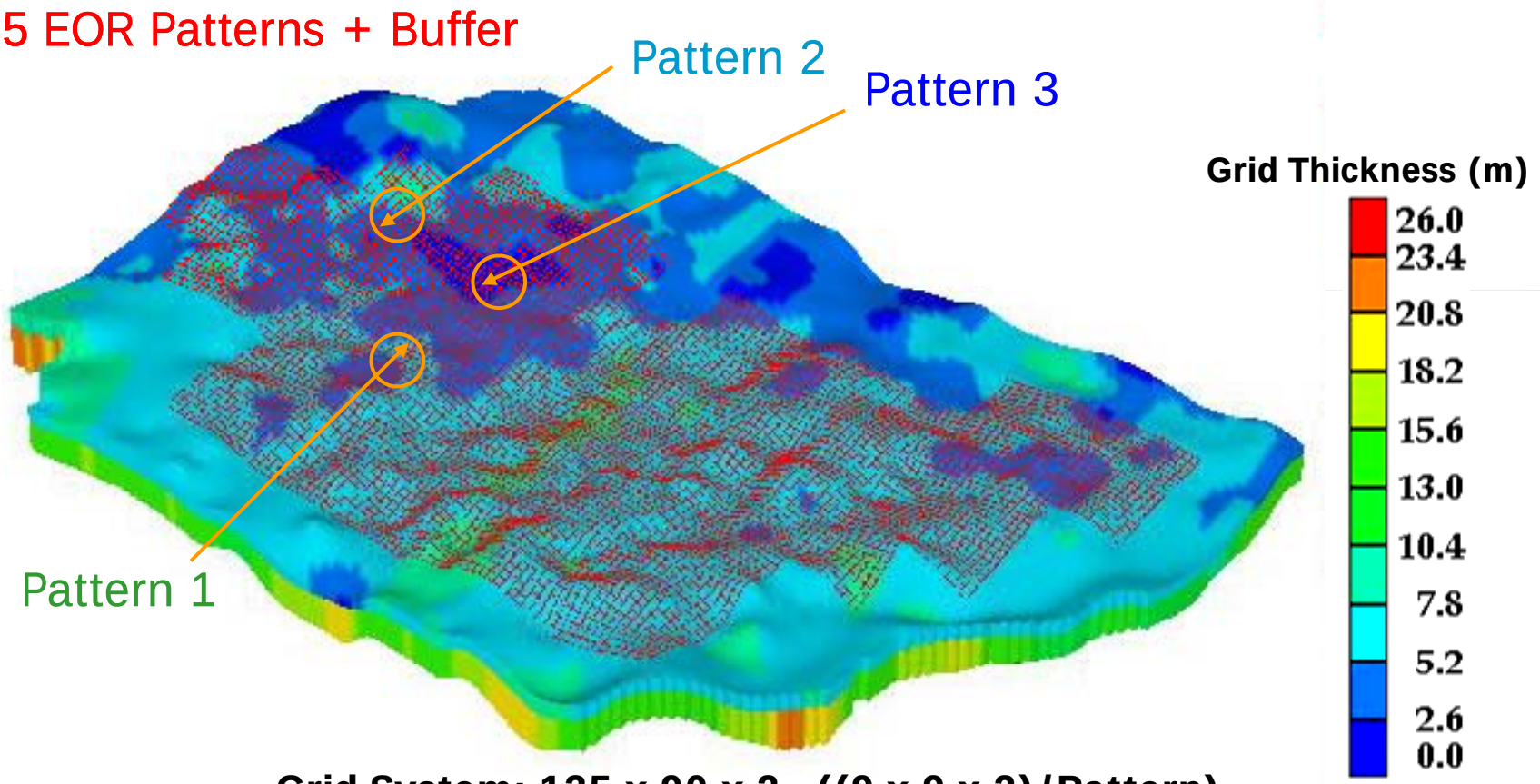
$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$

Single-Pattern Simulation history matching



CO_2 Distribution after 2 years

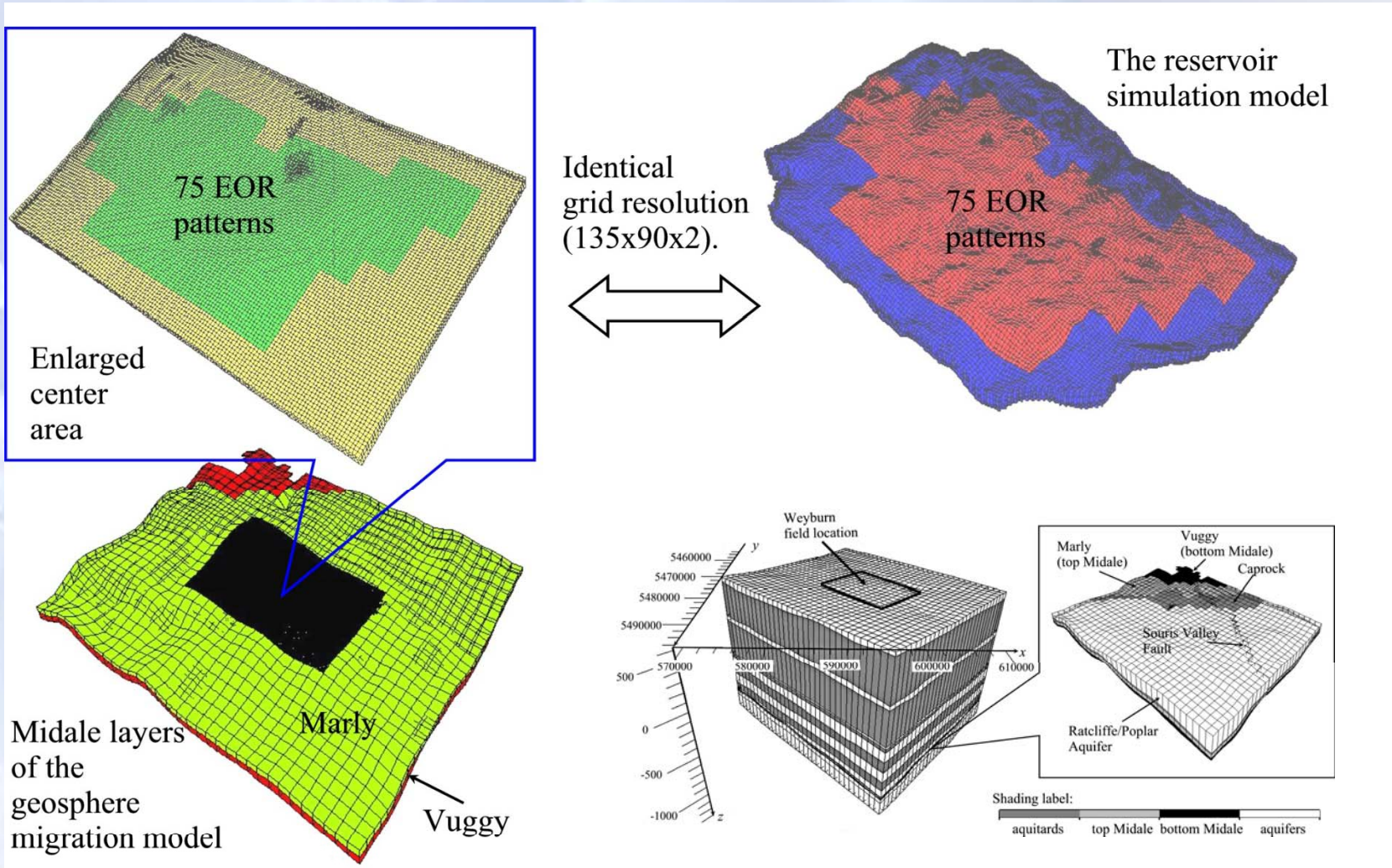
75-Pattern Simulation



Grid System: 135 x 90 x 2 ((9 x 9 x 2)/Pattern)

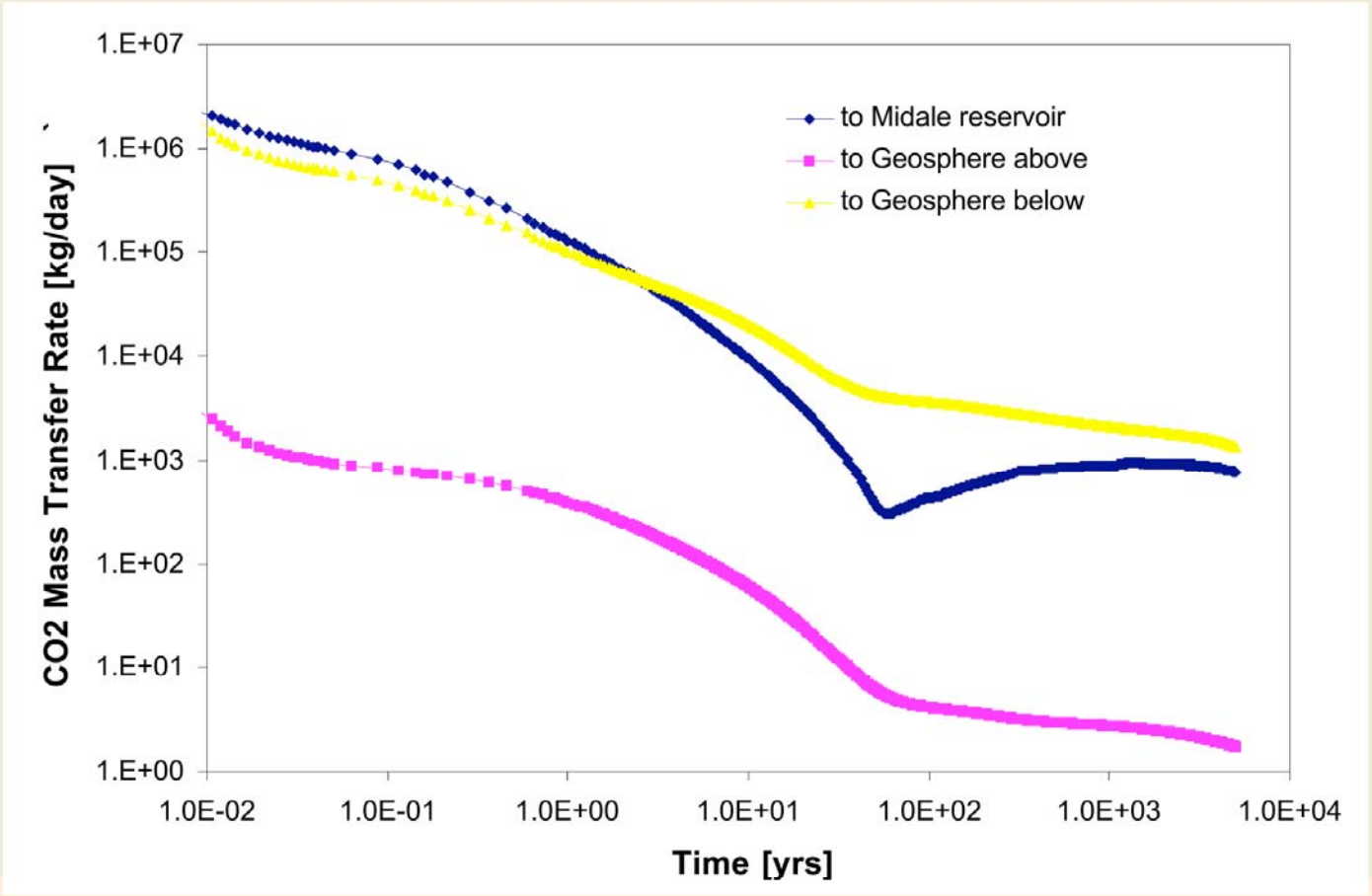
Vertical/Horizontal Scale = 30/1

Geosphere – Reservoir Modeling Integration



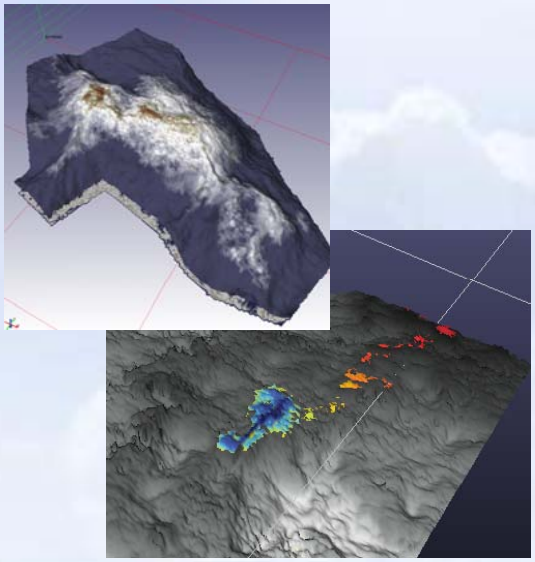
Results of Performance Assessment

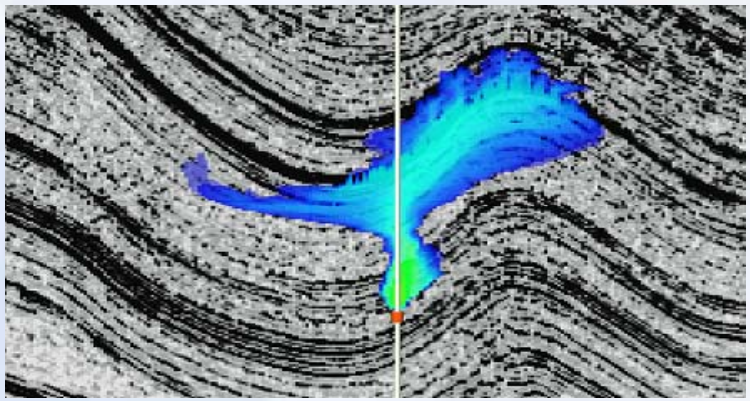
Rate of CO_2 Mass Leaving the 75 Patterns



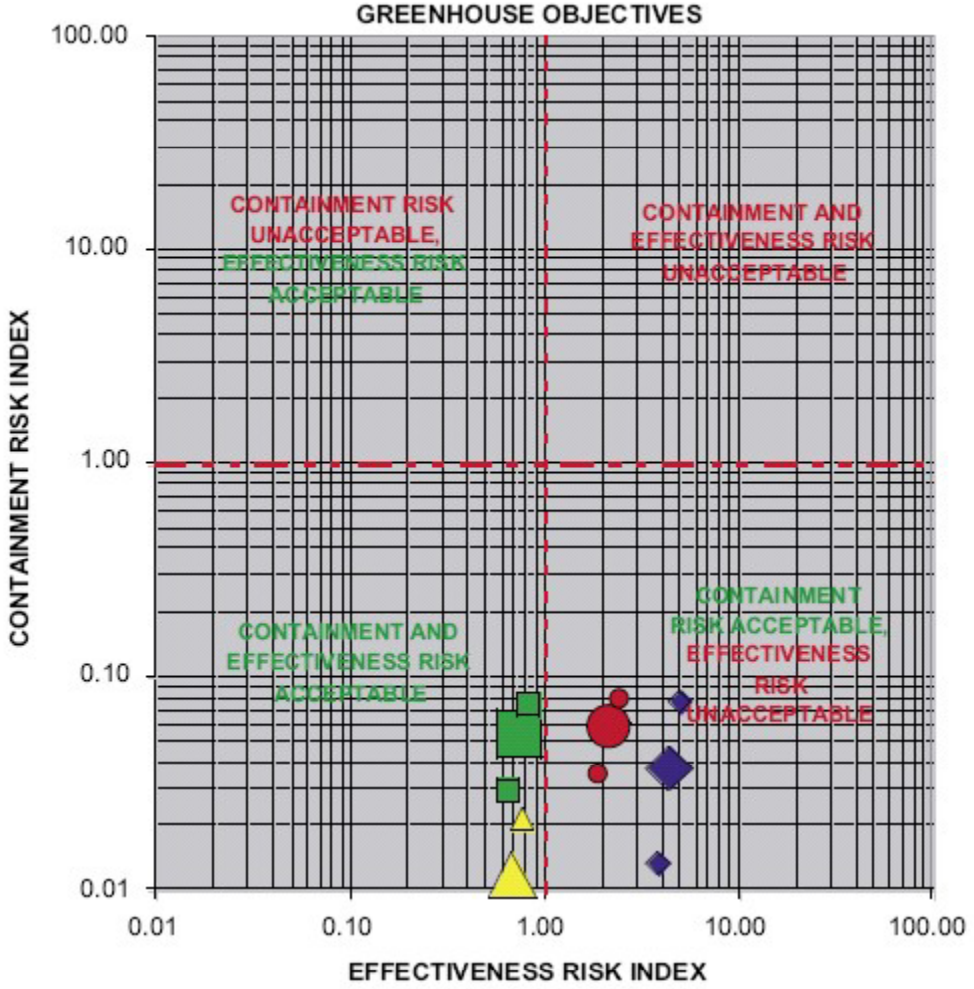
Permedia CO_2 Toolkit

- Regional – Basin – Prospect – Reservoir
  - Prospector, Basin-scale prospect mapping
  - Basin, Basin-scale simulator and prospect identification
  - Migration, Prospect calibration and risk assessment
  - Mixing, full physics mixing/reaction reservoir simulation





Assessing Risk in CO_2 Storage Projects: URS RISQUE Method



NOTE:
The Risk Index is a measure of the degree to which the relevant risk quotient (the risk posed by the indicated ESSCI project) is above or below the nominated acceptable risk target.
A Risk Index of less than 1.0 means that the risk quotient is lower than the target and the risk is considered acceptable. Conversely, a Risk Index greater than 1.0 means that the risk is considered unacceptable.
A Risk Index of 10 means the ESSCI project risk is 10 times greater than acceptable. A Risk Index of 0.1 means the risk is 10 times lower than the nominated acceptable level of risk.

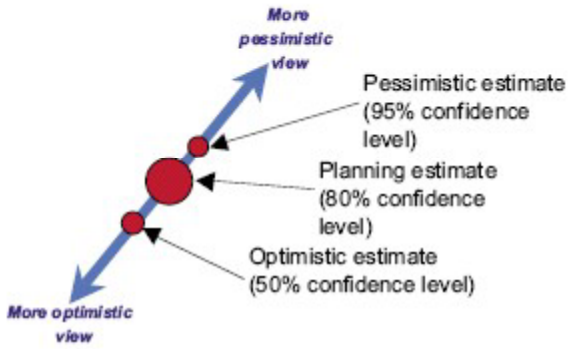
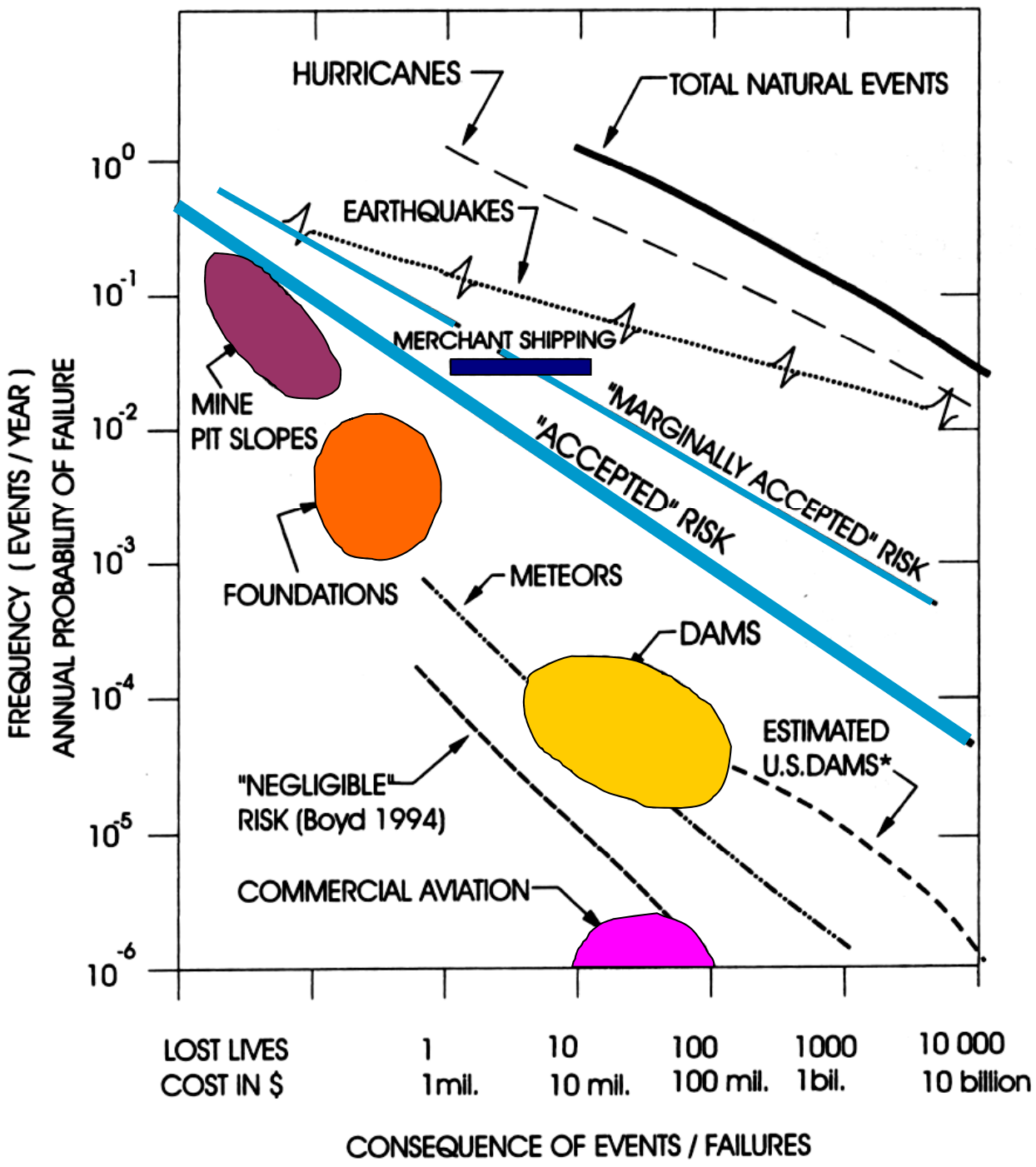


Figure 14. Relationships between containment and effectiveness for all storage projects.

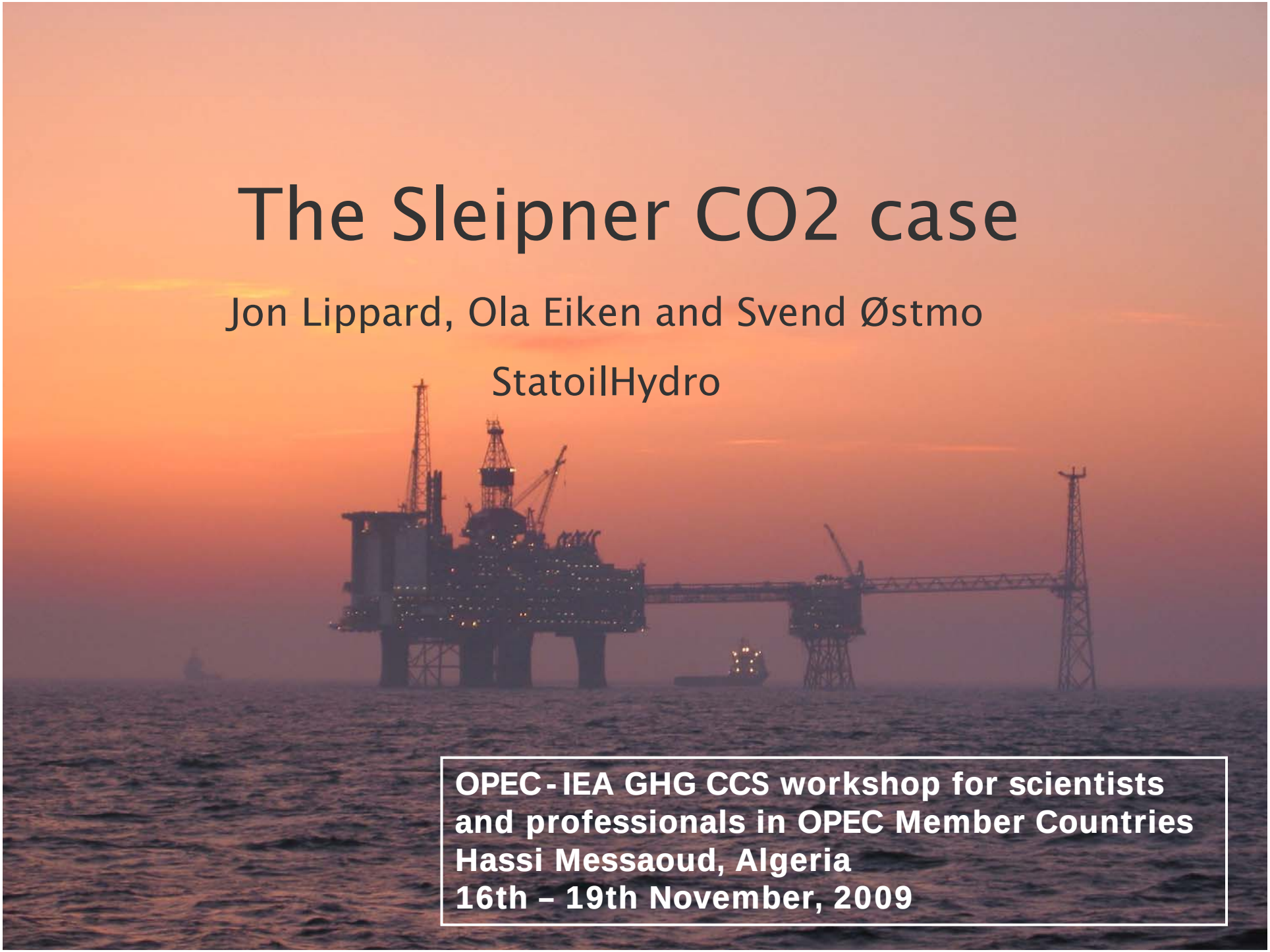
(Bowden and Riggs, APPEA Journal, 2004)


HURRICANES
TOTAL NATURAL EVENTS
EARTHQUAKES
MERCHANT SHIPPING
"MARGINALLY ACCEPTED" RISK
"ACCEPTED" RISK
MINE
PIT SLOPES
FOUNDATIONS
METEORS
DAMS
ESTIMATED
U.S.DAMS*
"NEGLIGIBLE"
RISK (Boyd 1994)
COMMERCIAL AVIATION
FREQUENCY (EVENTS / YEAR)
ANNUAL PROBABILITY OF FAILURE
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
LOST LIVES
COST IN $
1
1mil.
10
10 mil.
100
100 mil.
1000
1bil.
10 000
10 billion
CONSEQUENCE OF EVENTS / FAILURES

The Sleipner CO2 case

Jon Lippard, Ola Eiken and Svend Østmo

StatoilHydro



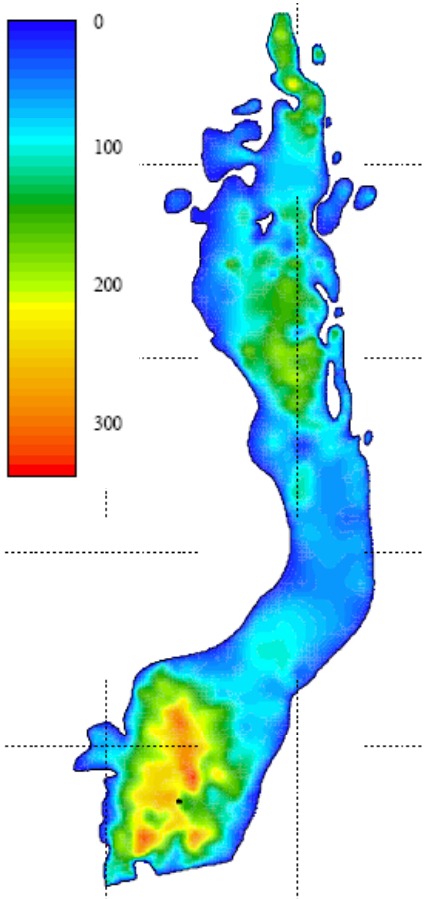
OPEC - IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries
Hassi Messaoud, Algeria
16th – 19th November, 2009

CO_2 capture

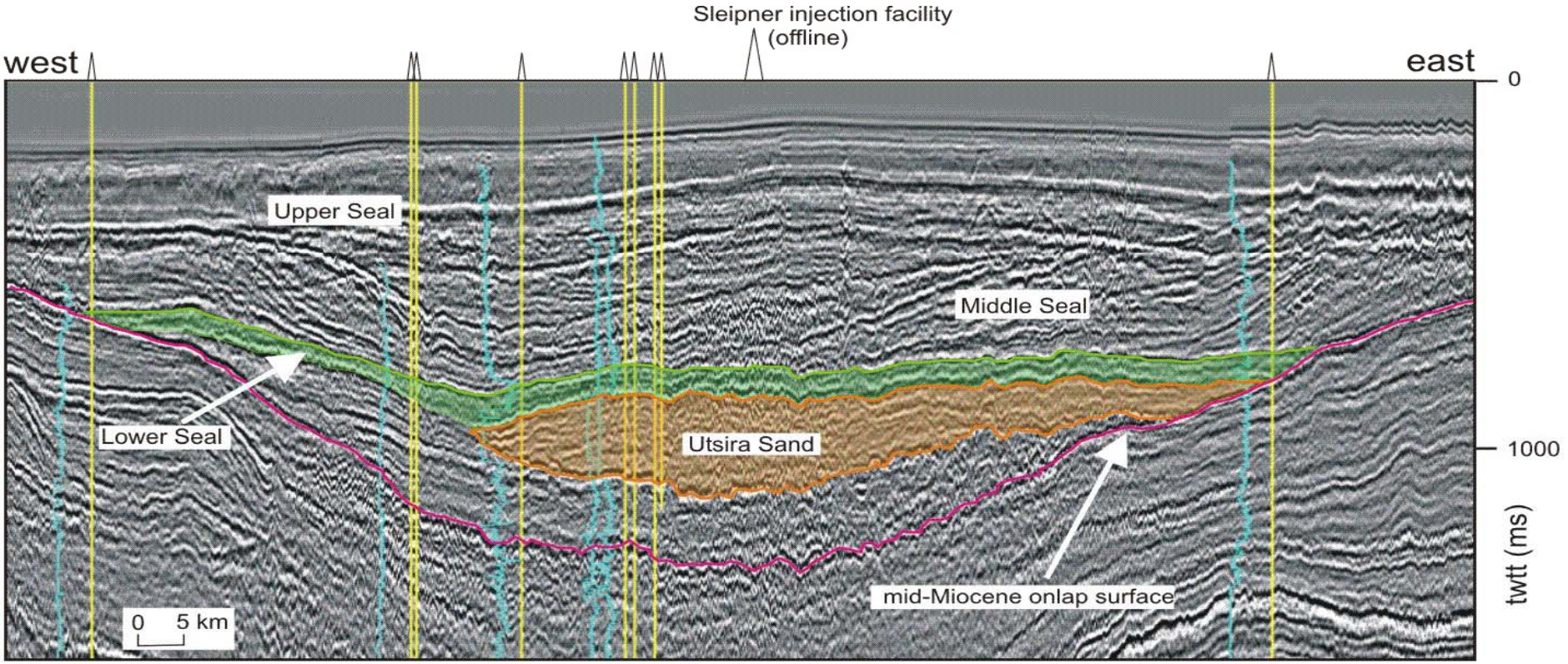
- Reduce CO_2 content of natural gas from Sleipner Vest from 4-9% to less than 2.5%
- Supply gas directly to market
- After capture, CO_2 is injected underground into the Utsira formation for storage only
- 50 MNOK ~ 9 MUSD saved in CO_2 taxes each year

The Utsira formation

- Saline aquifer
- Coverage: 26000 km^2
- Around injection site
  - Highly porous and permeable
  - 200 m thick
  - 800 m below sea level

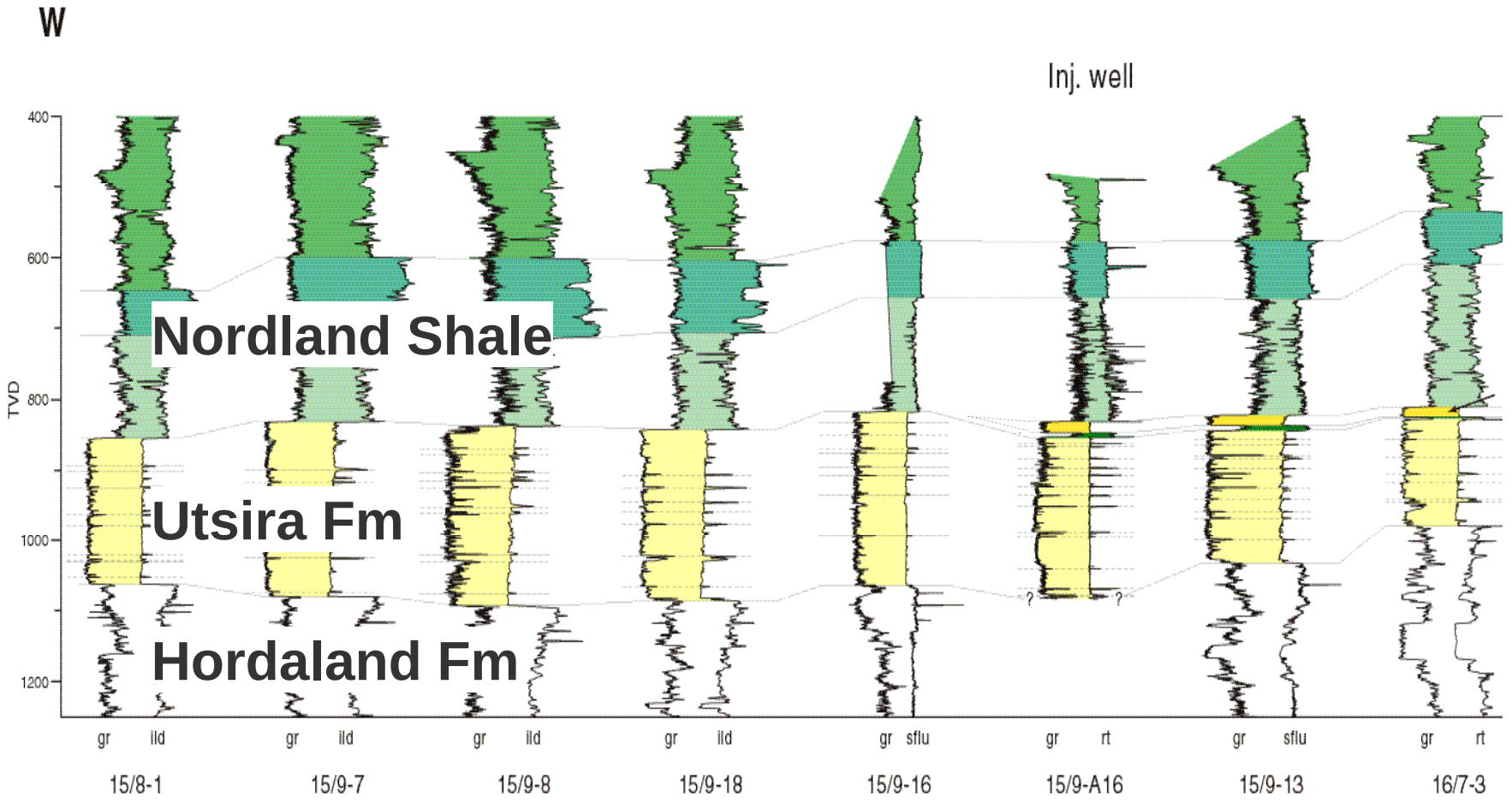


Thickness map (m)

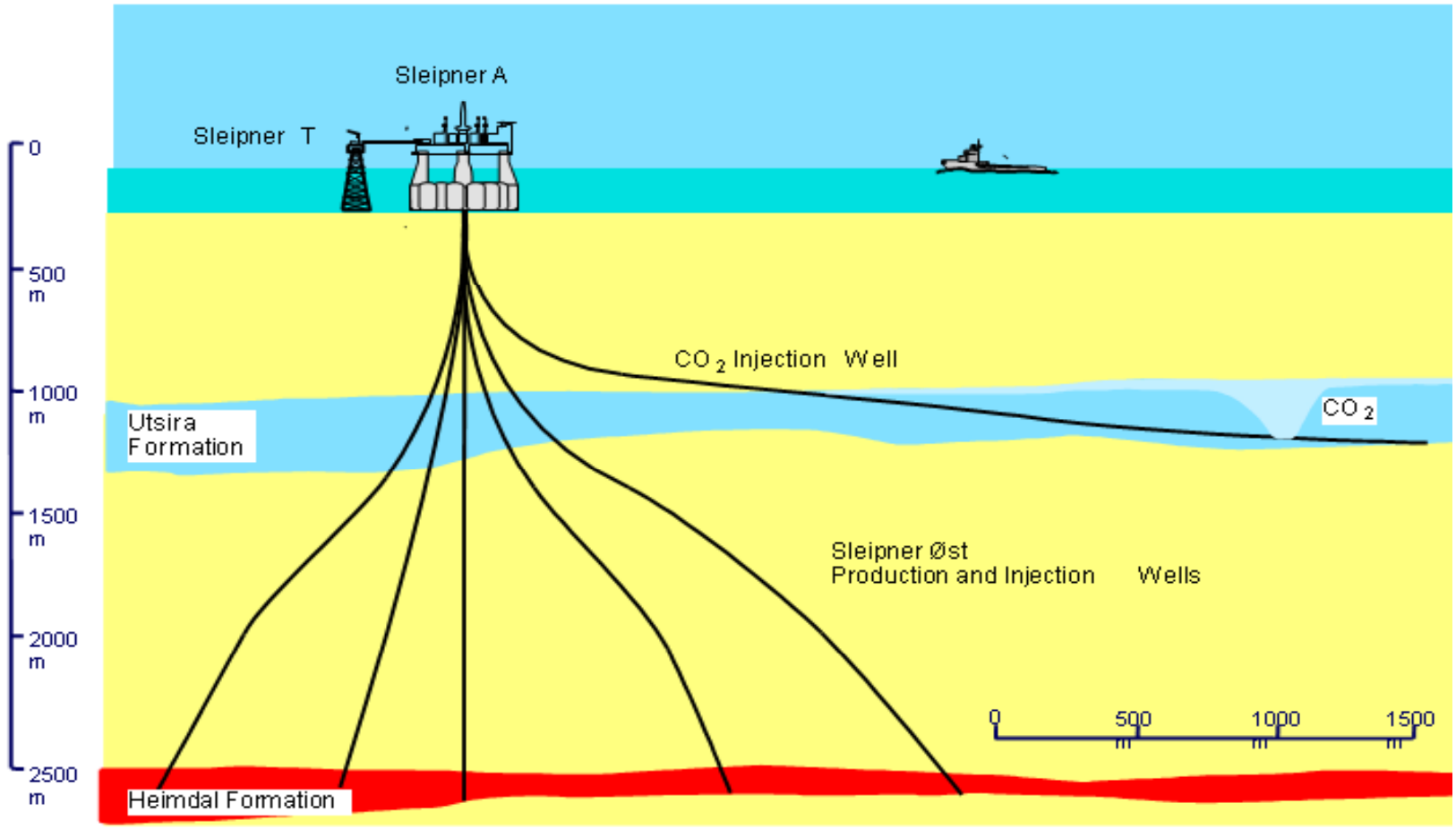


Net Sand (%)	Porosity (%)	Horizontal permeability
90 – 98	~ 38	1-8 D

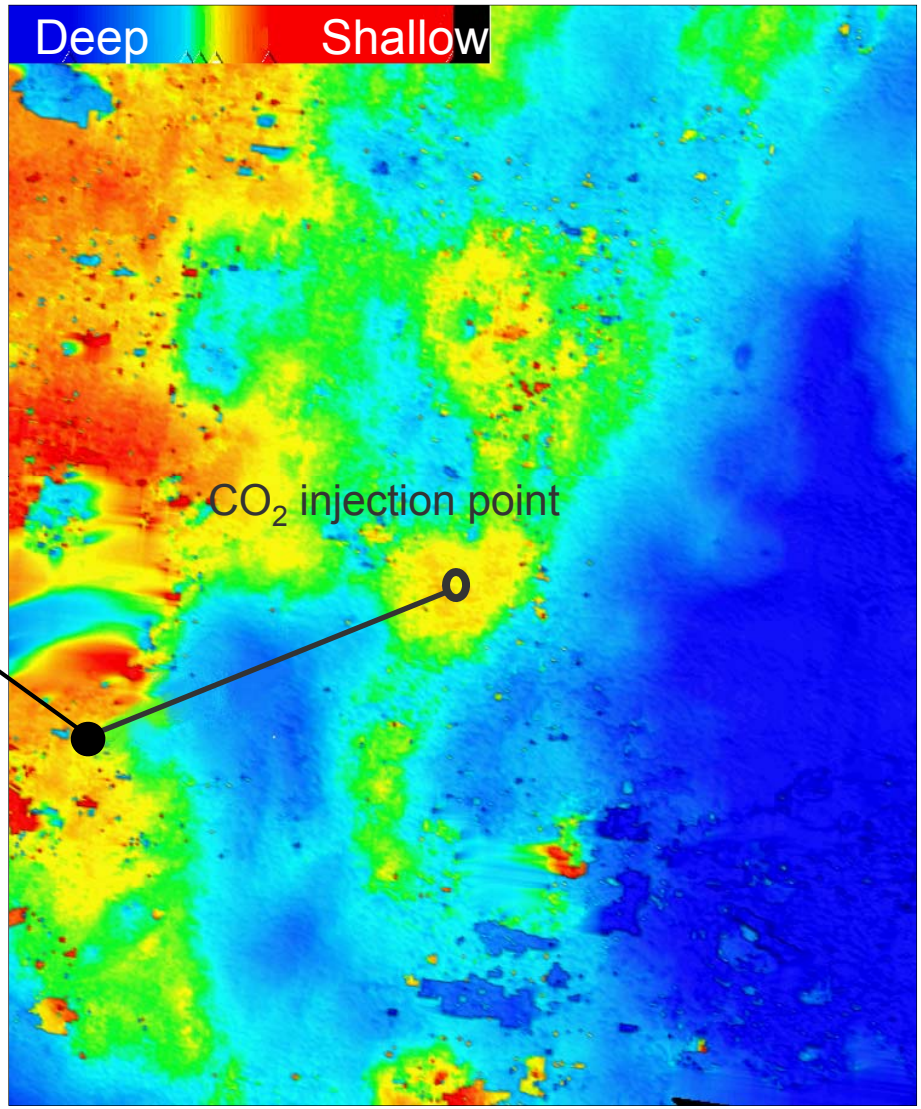
Utsira formation logs



Schematic view of CO2 Injection Well in Utsira



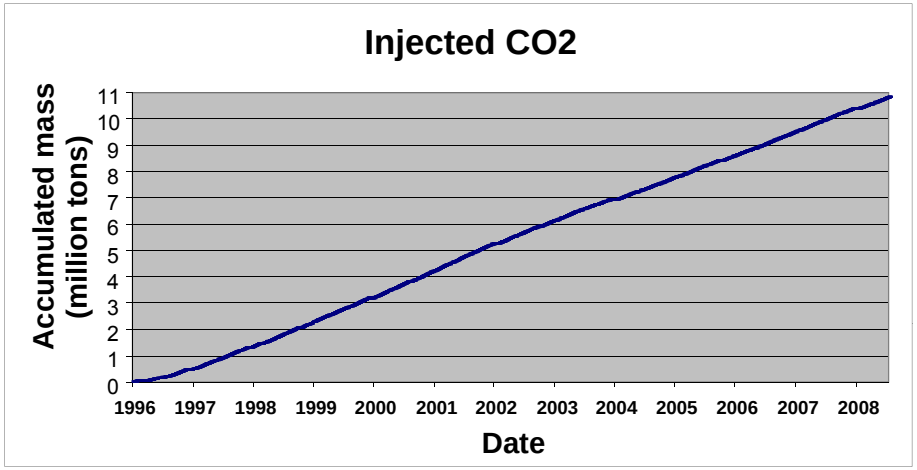
Top Utsira Fm. time map

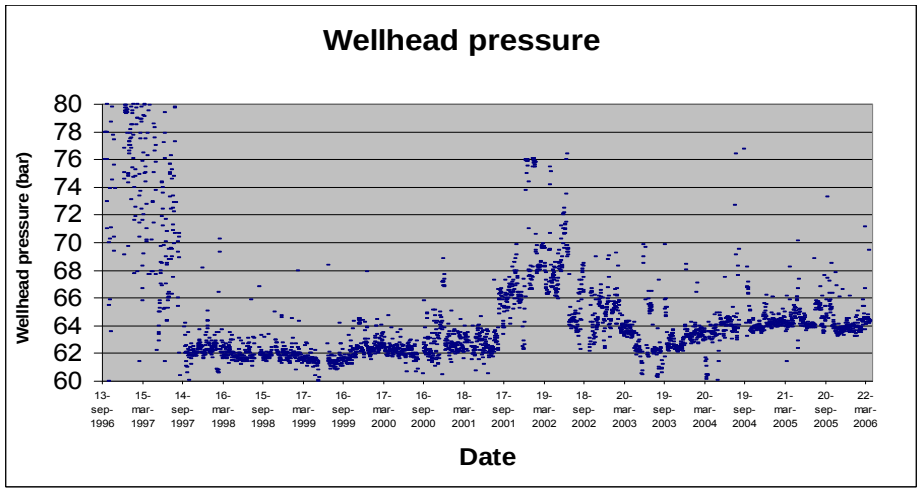


- Domal trap.
- Low relief.
- Sleipner A protected.

Injection data

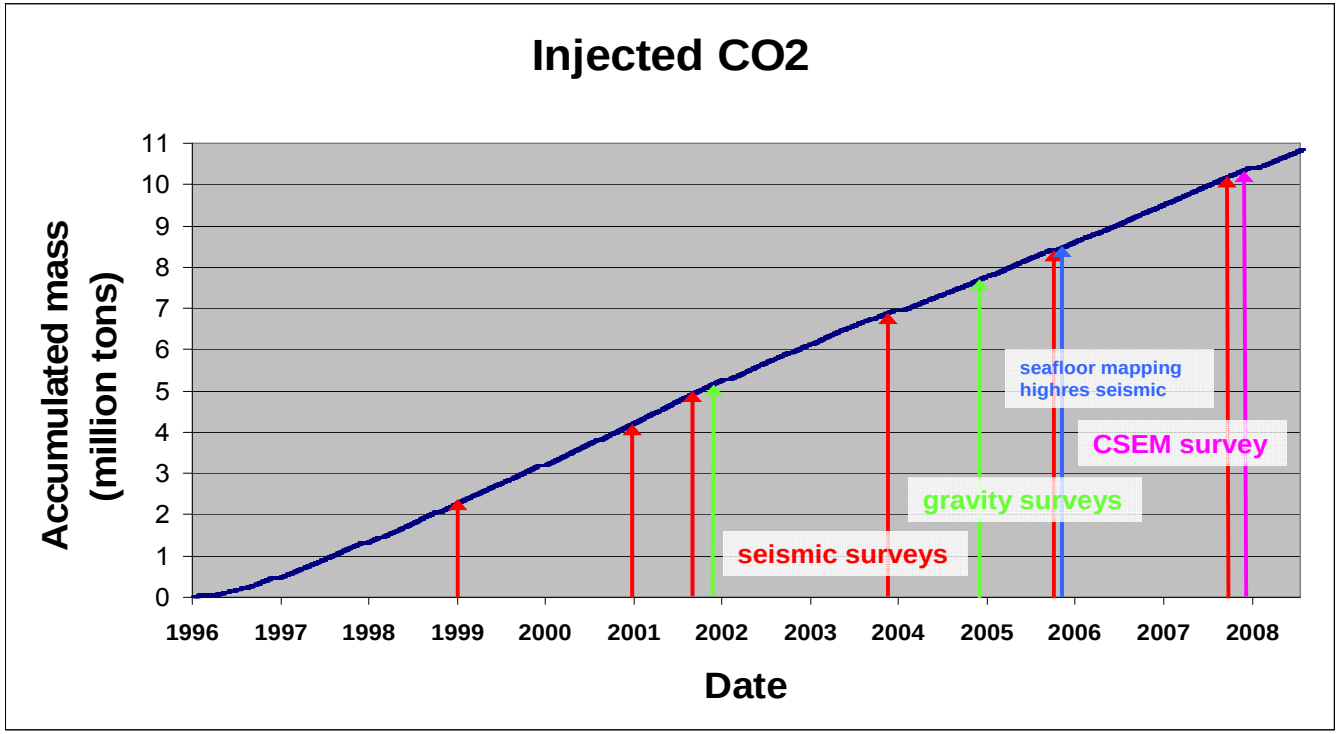
- 11,2 mill. tons injected over 13 years, since 1996
- Wellhead pressure stable at ~ 62 – 66 bar
- Wellhead pressure and flow rate is monitored continuously.
- Gas composition samples are taken intermittently.
- No downhole measurements
- About 98% CO_2 content



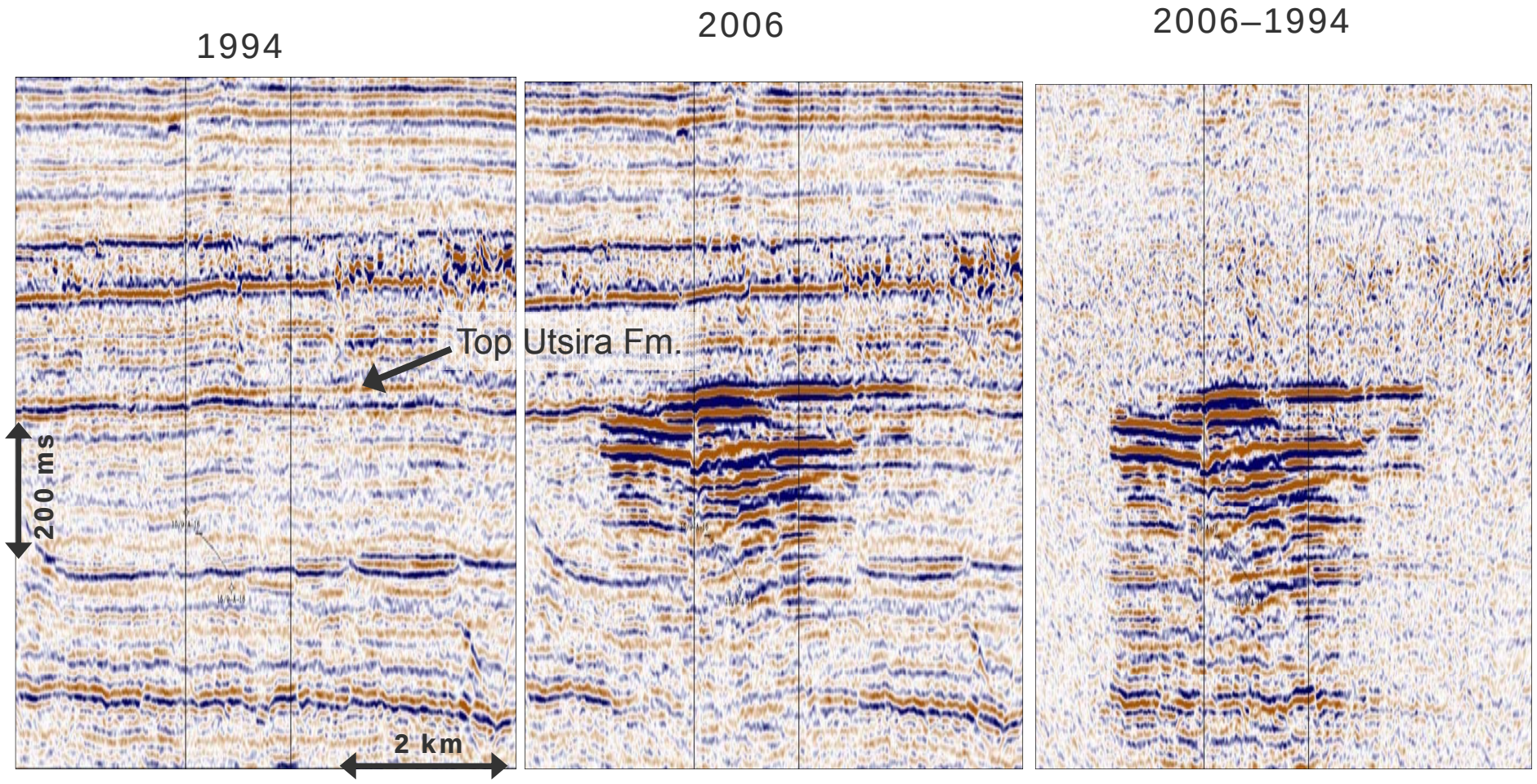


CO_2 Monitoring

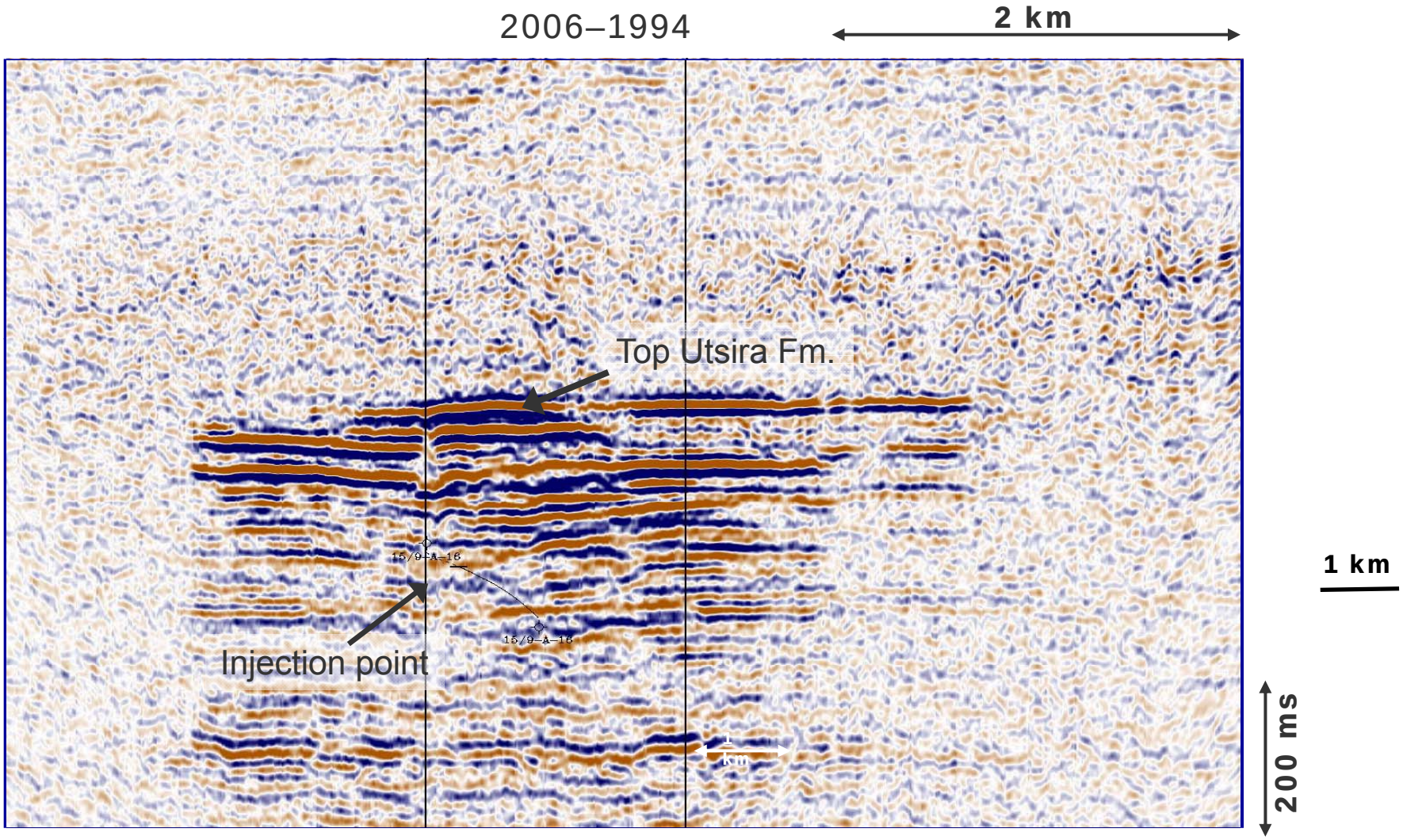
- 6 repeated 3D seismic surveys (1 high resolution 2D)
- 2 gravimetric surveys
- 1 CSEM survey
- 1 Sea floor mapping



Seismic monitoring



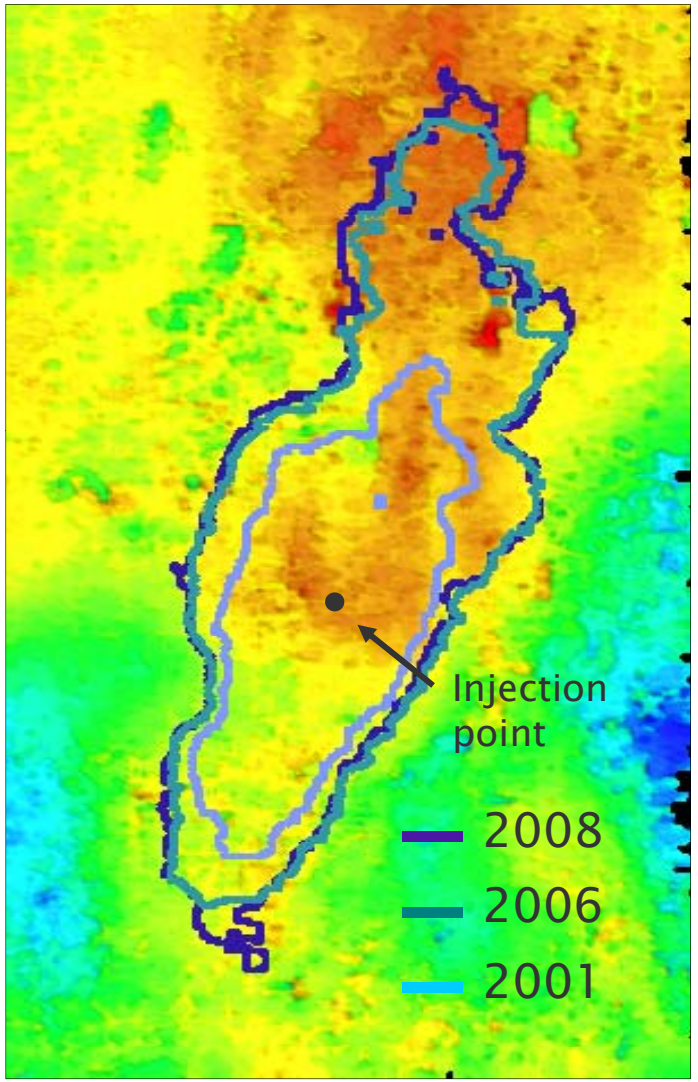
Seismic monitoring – difference sections



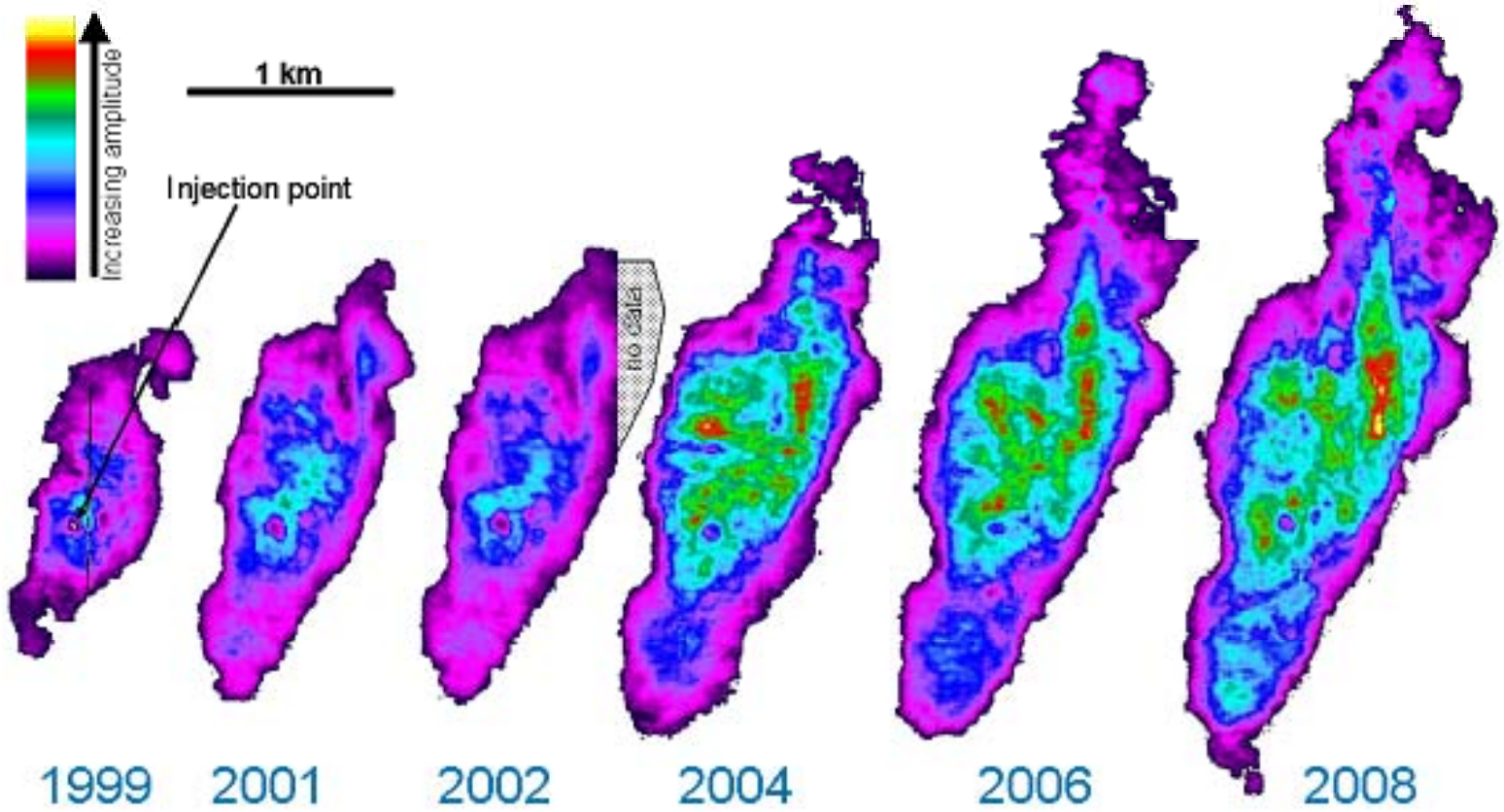
CO_2 distribution June 2008

- 10,2 million tonnes injected over 12 years
- Plume area: *2,8 km²* (*1,3 km²* in 2001)
- Plume long axis: *4039 m*
- Maximum distance from injection point: *2704m*
- Distance from CO_2 to wells:
  - Exploration well 15/9-13: *402m*, decreasing about 12 m/year
  - D-template: about 2 km straight west of northern plume
  - 15/9-19 wells: about 4,5 km north of plume

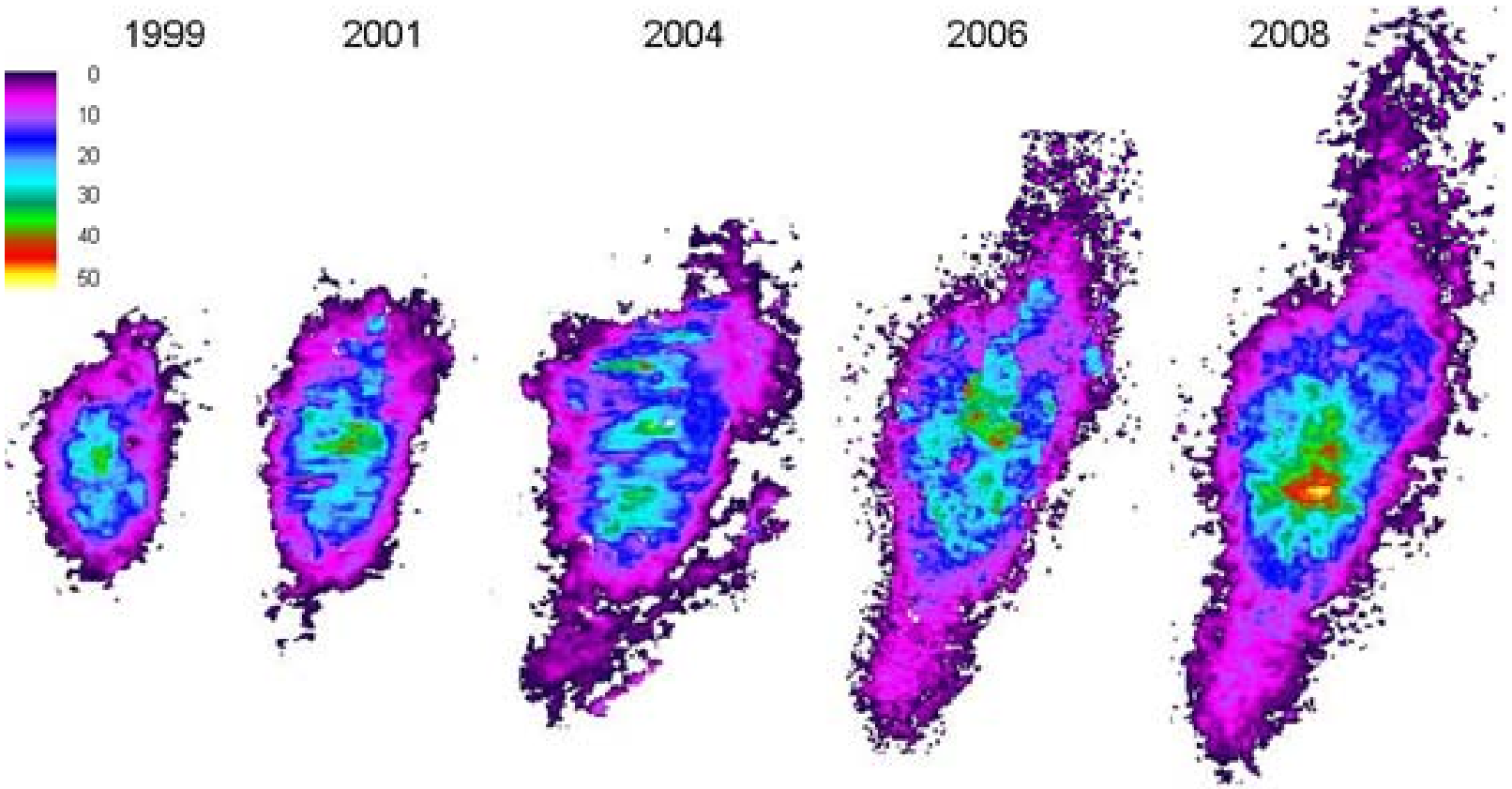
Plume extension & top Utsira time map



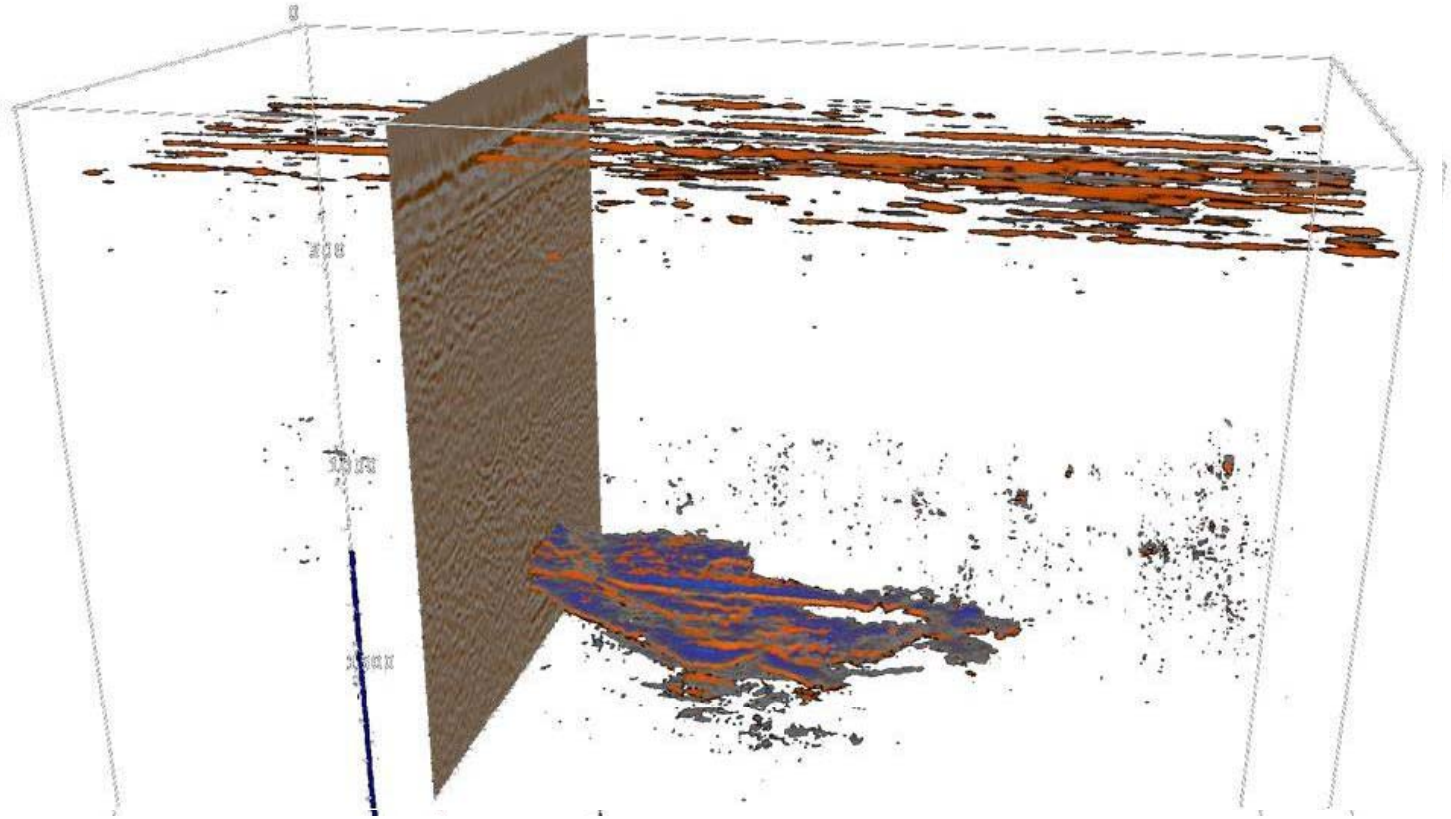
Cumulative amplitudes



Cumulative pushdown

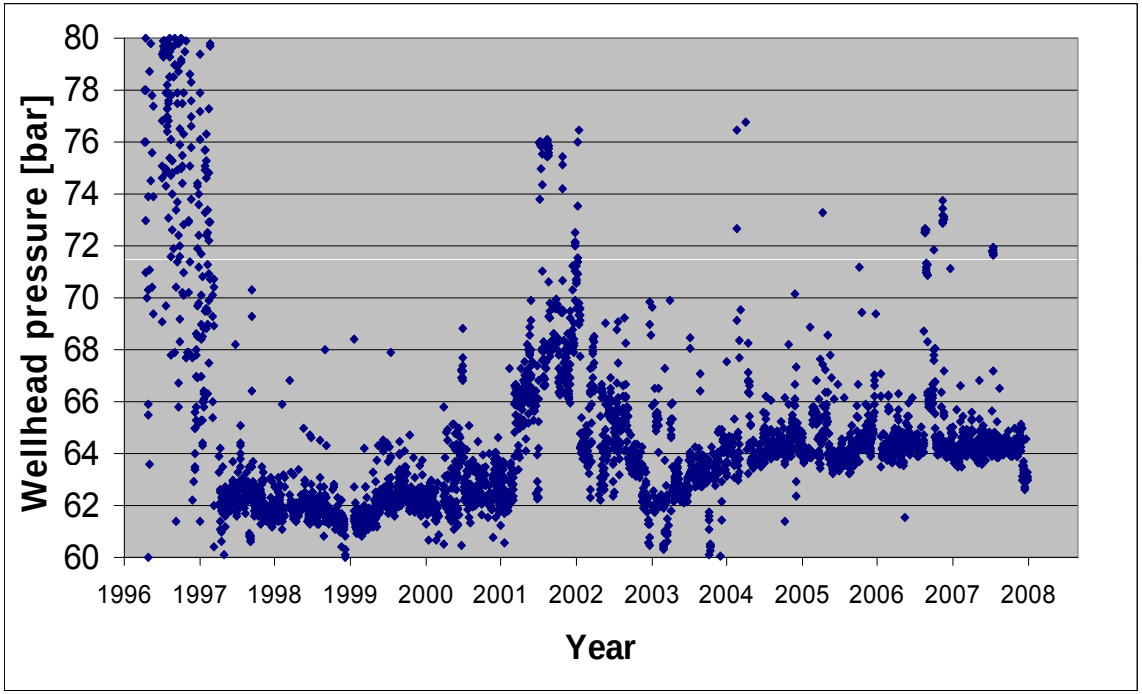


4D image of overburden

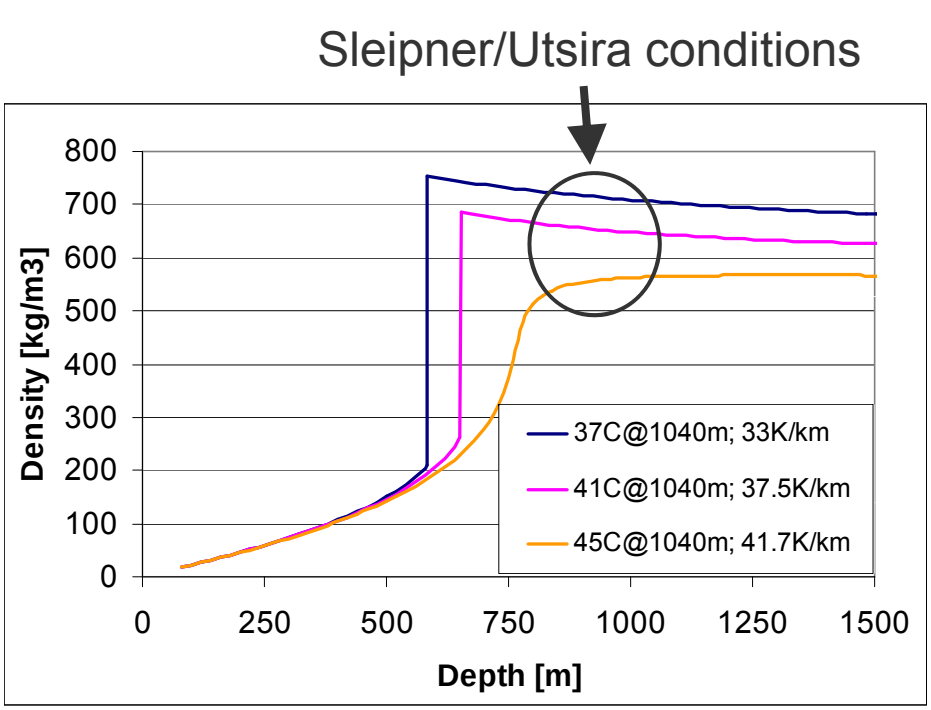


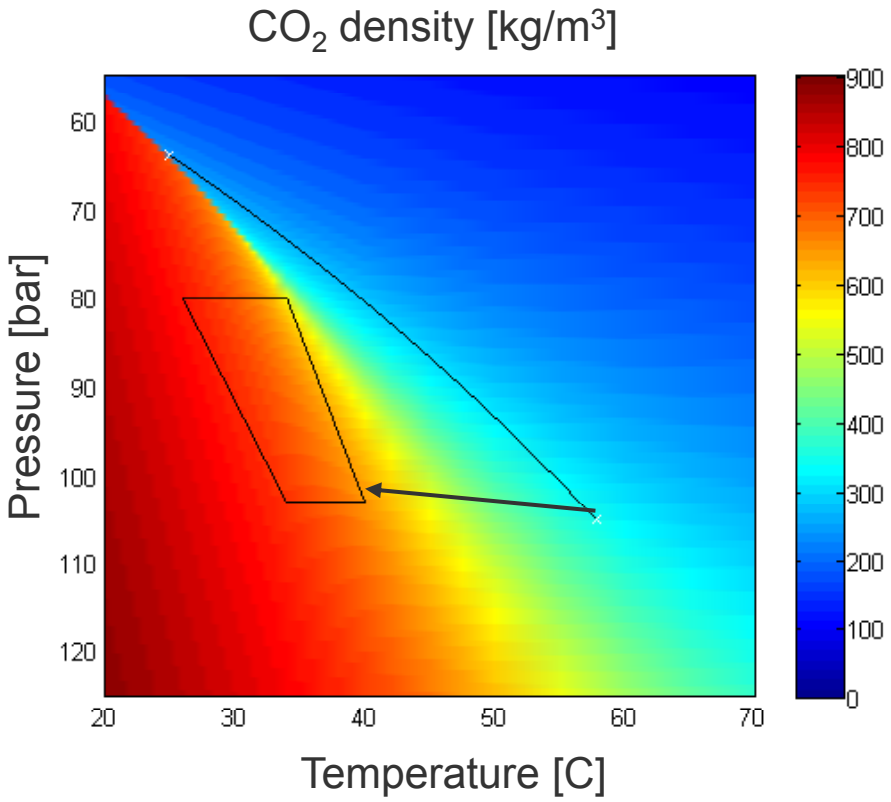
Wellhead and downwell PVT properties

- Wellhead temperature set at 25 ^{o}C
- Bottomhole pressure assumed to be close to hydrostatic (102 bar)
- Assuming adiabatic compression we get a bottomhole temperature of 57^{o}C

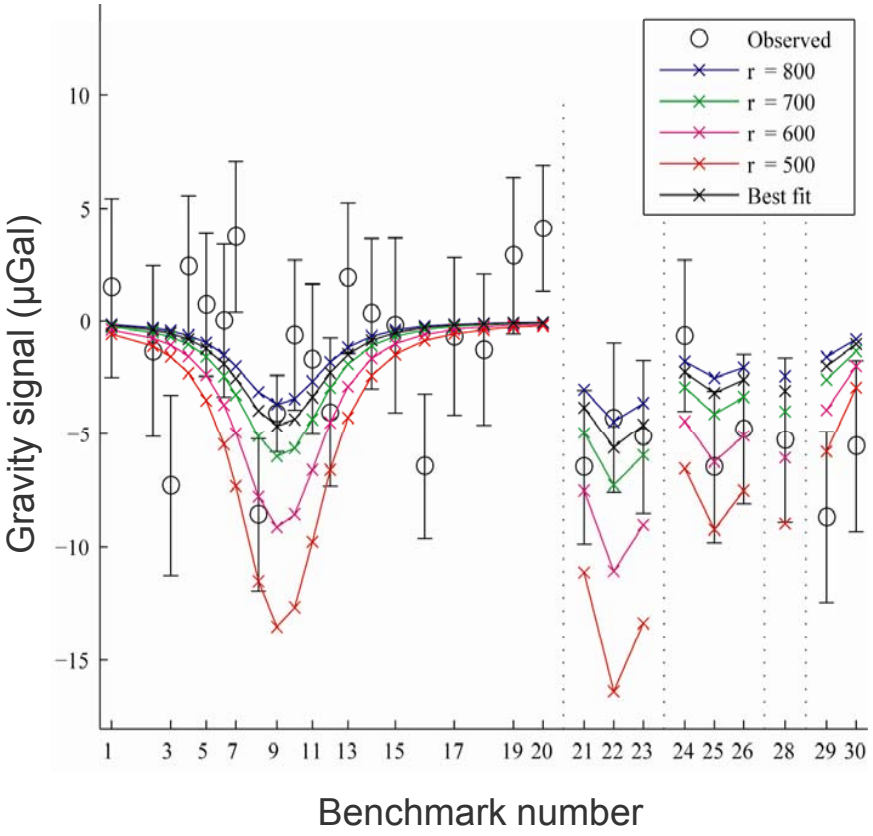


CO_2 in-situ density

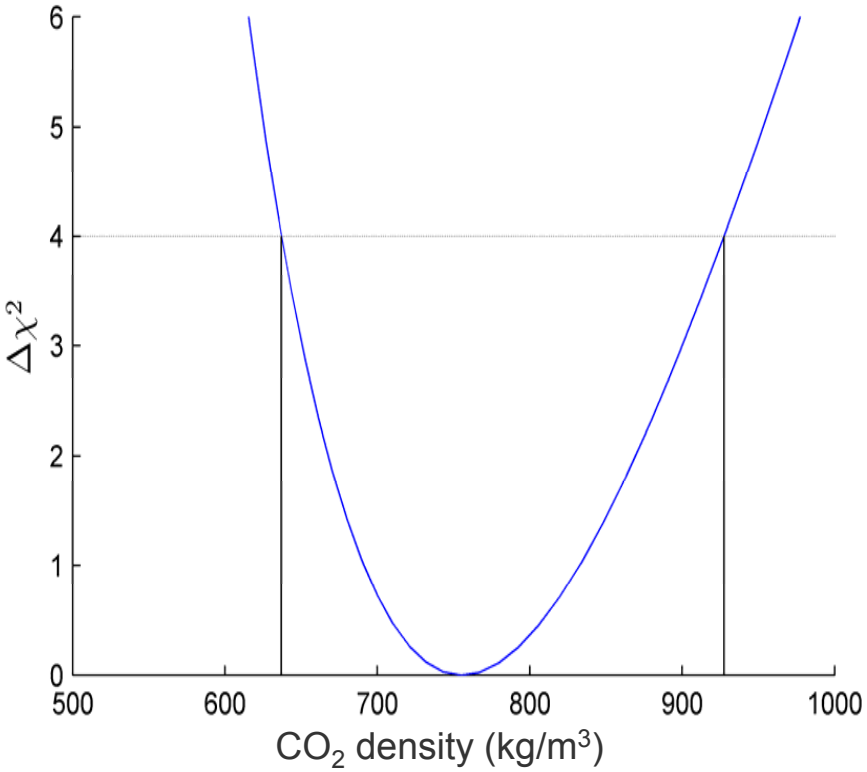




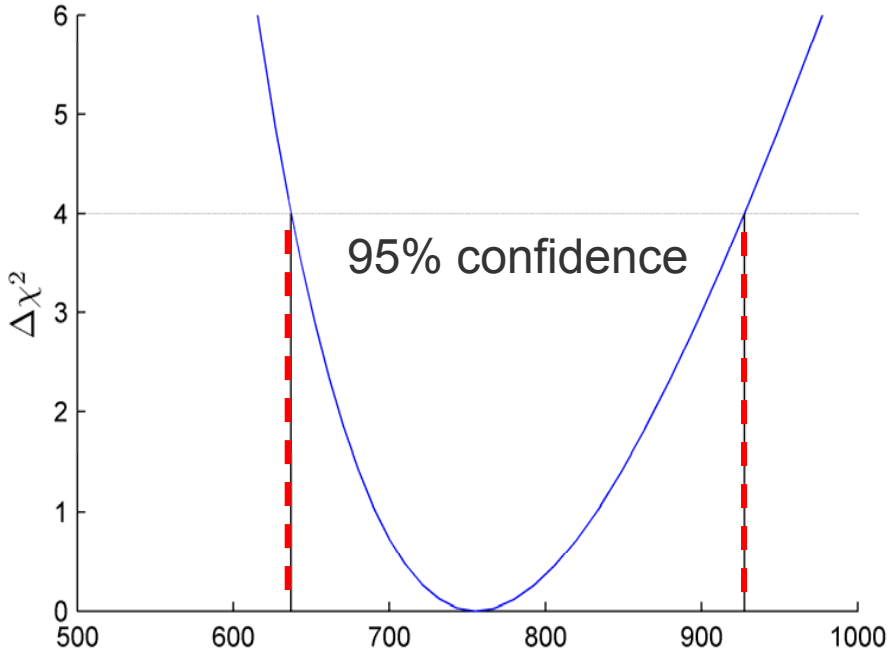
Analysis of gravity data gives a best fit estimate of the density

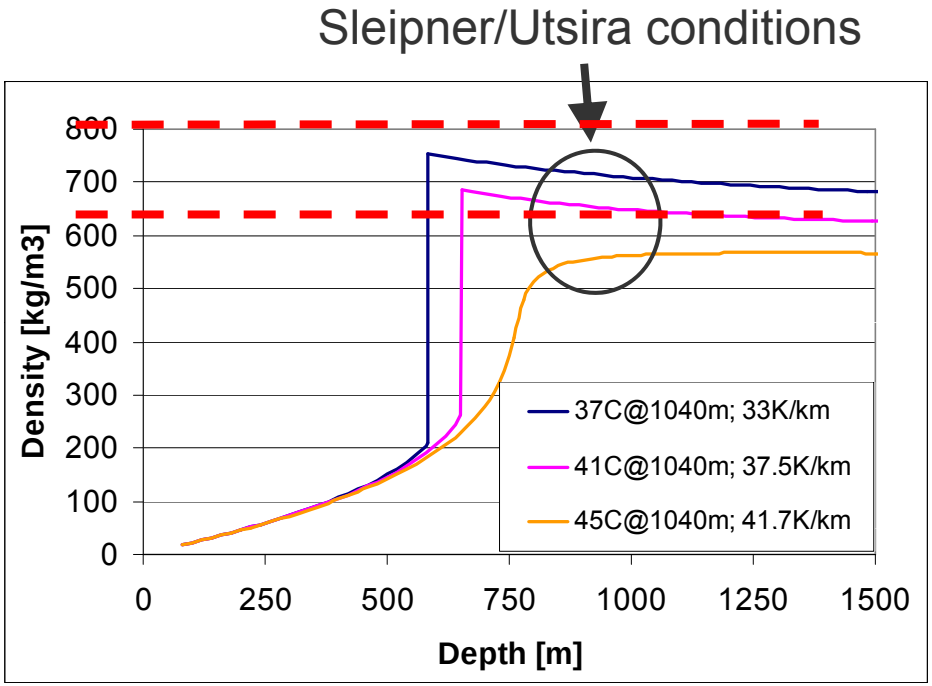


CO_2 density model fit of gravity data



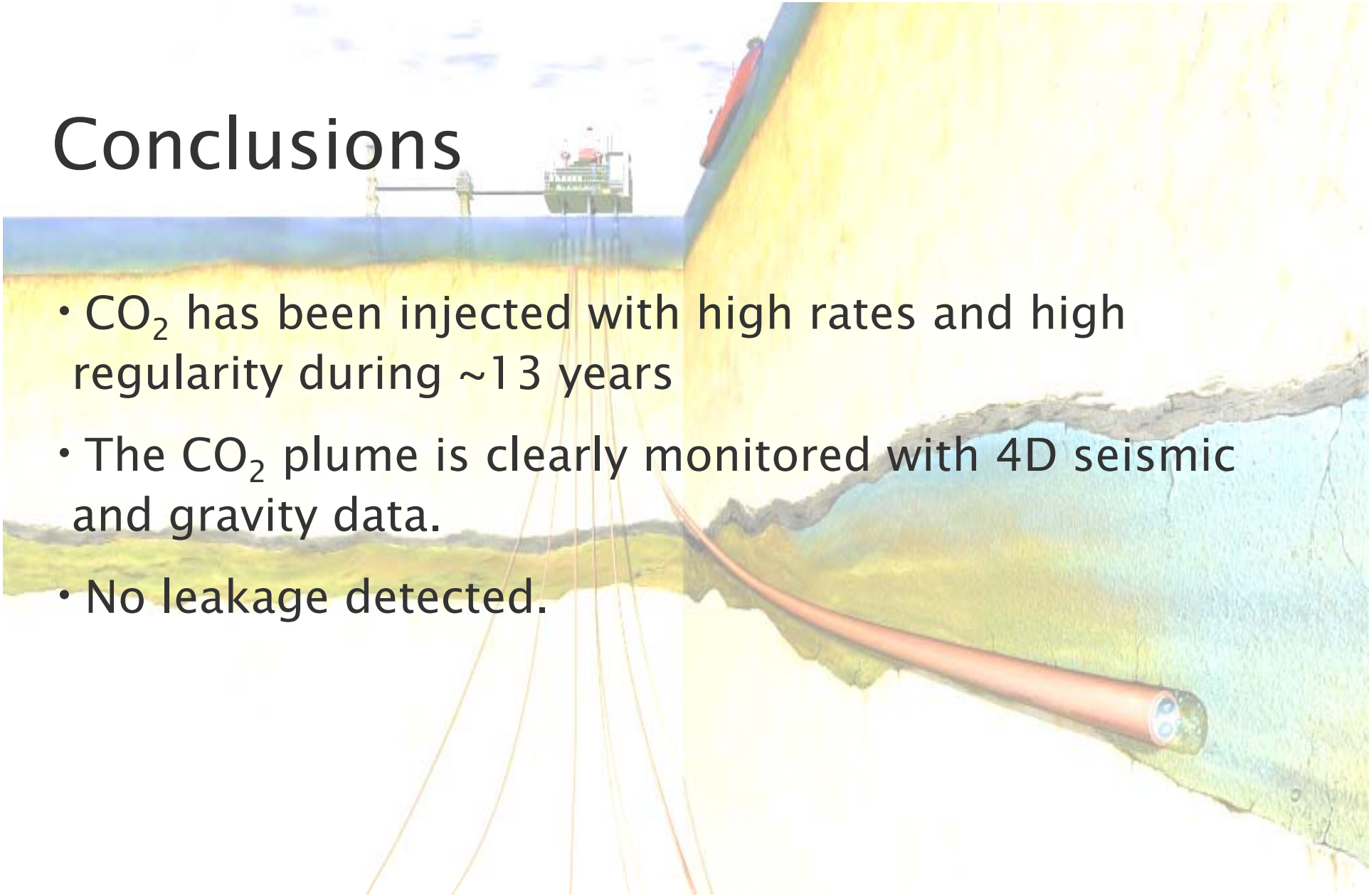
Combining gravimetry and PVT





PVT analysis together with gravimetric result give an upper bound of 770 kg/m3 and a lower bound of 640 kg/m3 with 95% confidence.

Conclusions



- CO_2 has been injected with high rates and high regularity during ~13 years
- The CO_2 plume is clearly monitored with 4D seismic and gravity data.
- No leakage detected.

Lessons Learned: Five Years Industrial-scale CO_2 Storage

Iain W. Wright BP (JIP Program Manager)

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European
Commission RTD

US Department
of Energy

Agenda: Iain's Overview Paper

In Salah Gas
Stockage de CO_2

- Project Context
- Investment
- Subsurface (CO_2 JIP): Progress to Date
- Focus on Satellite Imagery

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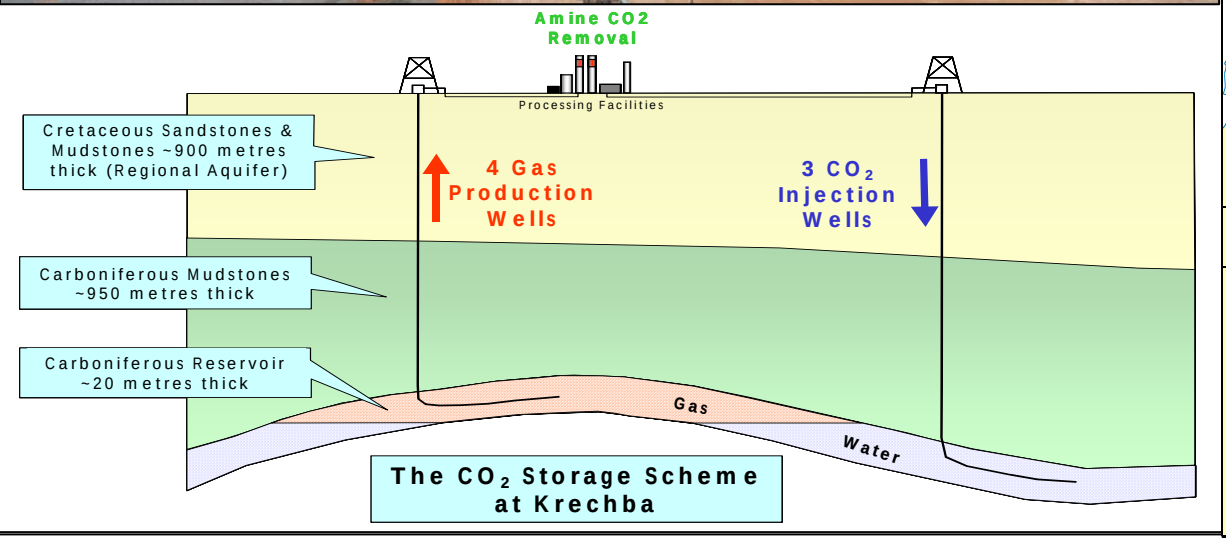
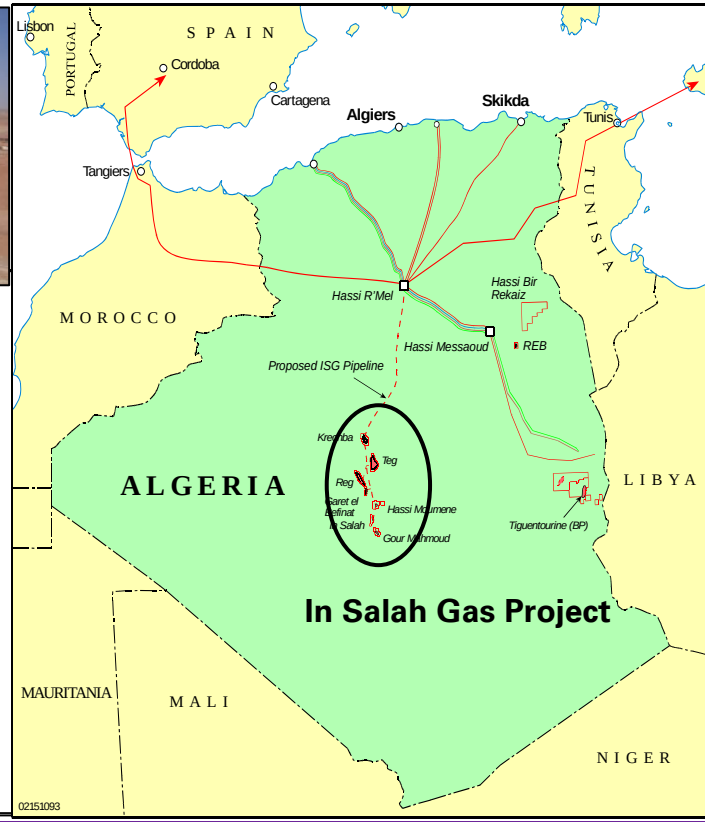
Project Overview

In Salah Gas
Stockage de CO_2



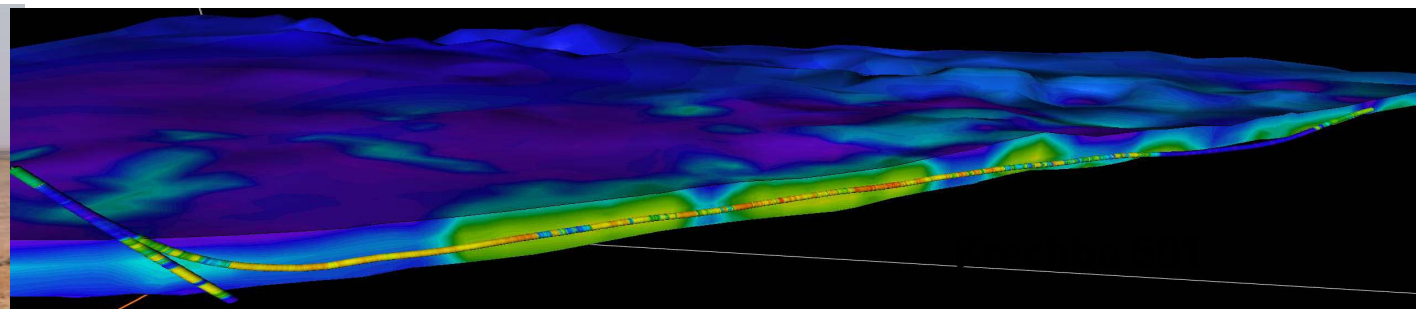


Project Fun Facts

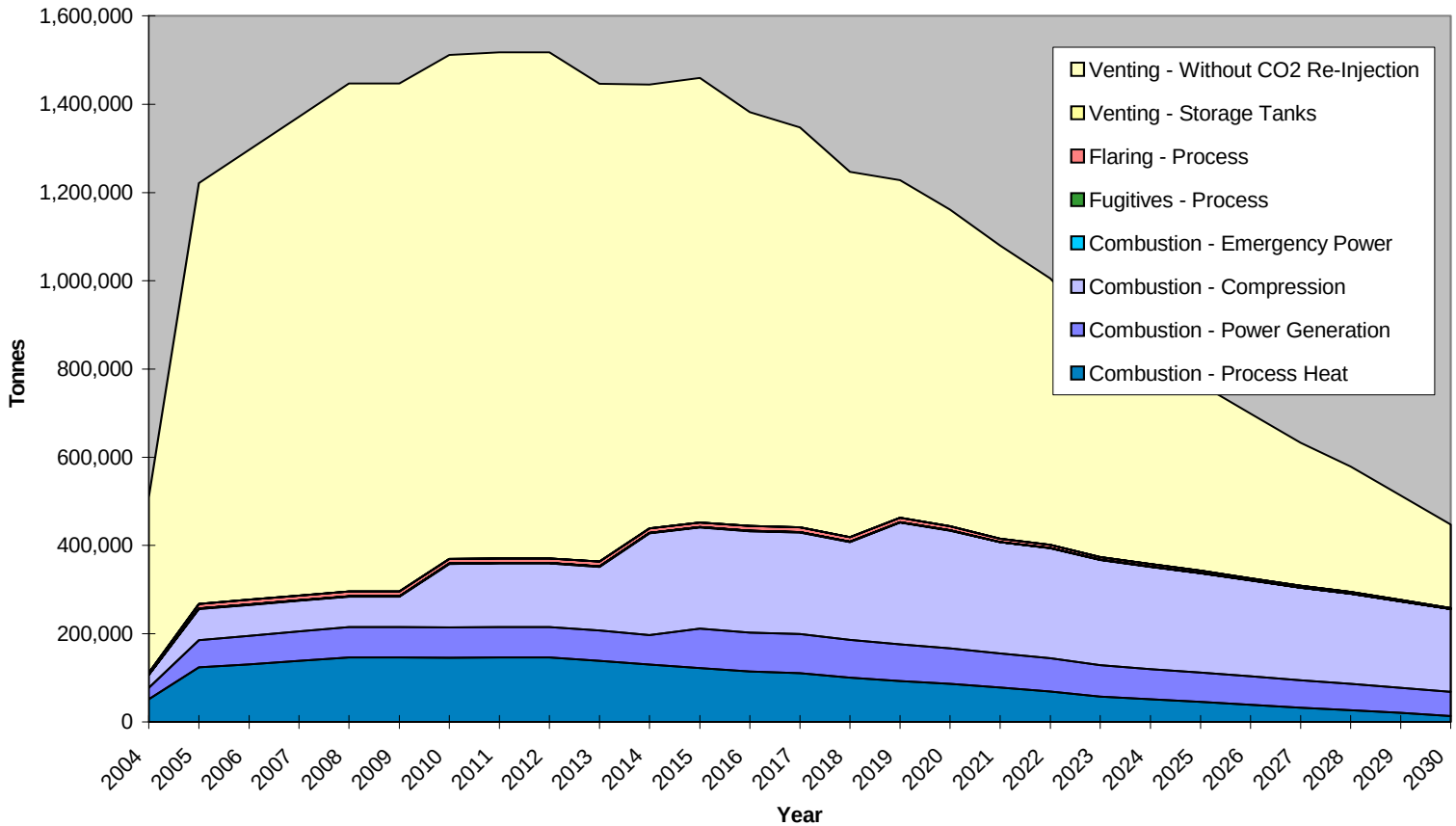
- Industrial Scale Demonstration of CO_2 Geological Storage (Conventional Capture)
- Storage Formation is common in Europe, USA & China
- Started Storage in August 2004
- 1mmtpa CO_2 Stored (17mm tonnes total)
- $100mm Incremental Cost for Storage No commercial benefit
- Test-bed for CO_2 Monitoring Technologies $30mm Research Project

Three Projects at In Salah

- **In Salah Gas Development (1bcf/d $2,000 million)**
- **In Salah CO_2 Storage (1mmtpa $ 100 million)**
  - **Lessons Learned: Surface CO_2 Capture**
- **In Salah CO_2 Assurance R&D (CSLF & EU $30 million)**
  - **Lessons Learned: Sub-surface CO_2 Storage**



In Salah: 25-Year CO_2 Footprint



Only the separated (yellow) CO_2 is being stored – the combustion CO_2 (blue) is vented

European Commission RTD

CO_2 Compression and Storage

In Salah Gas
Stockage de CO_2

50mmscf/d CO_2

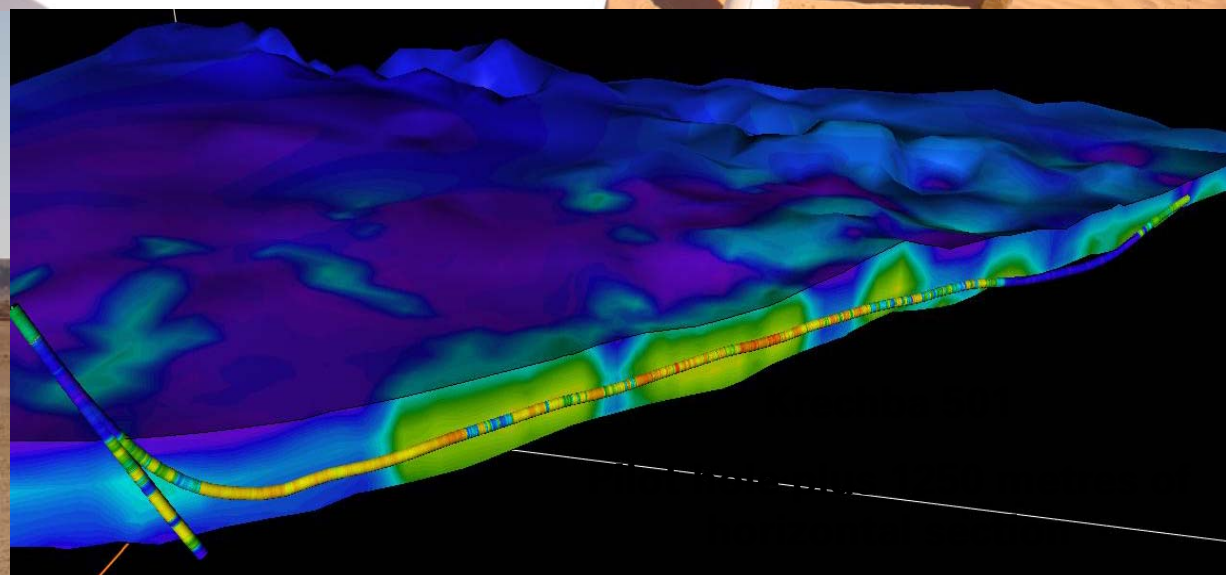
(1mmtpa)

Compression

Transportation

Injection

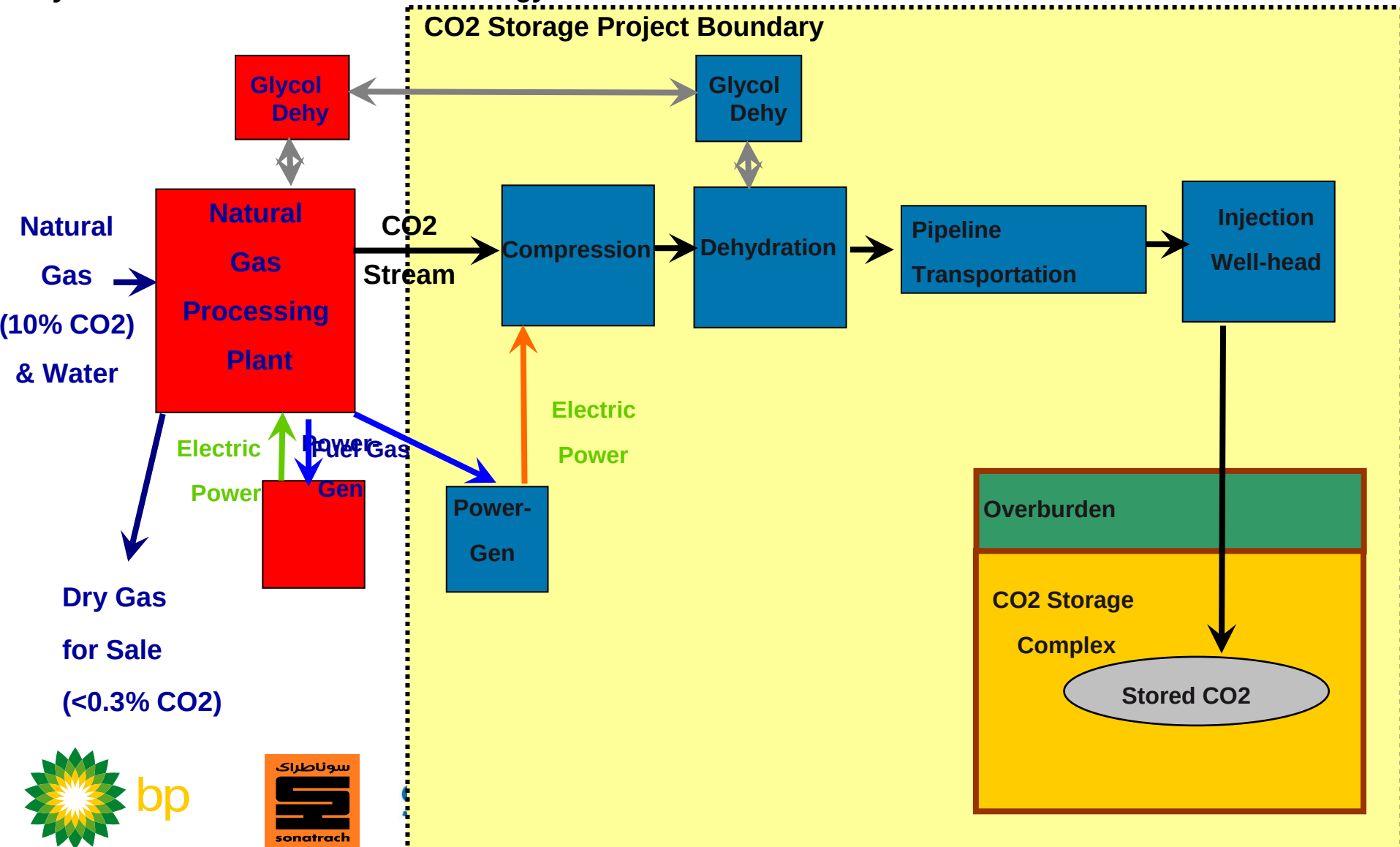
Storage



CO_2 Separation and Storage

In Salah Gas
Stockage de CO_2

Kyoto Protocol CDM: New Methodology for CCS



CO2 Storage: Joint Industry Project (JIP)

In Salah Gas
Stockage de CO_2

Objectives (2005-10)

1. Provide assurance that secure geological storage of CO_2 can be cost-effectively verified and that long-term assurance can be provided by short-term monitoring.

2. Demonstrate to stakeholders that industrial-scale geological storage of CO_2 is a viable GHG mitigation option.

3. Set precedents for the regulation and verification of the geological storage of CO_2, allowing eligibility for GHG credits

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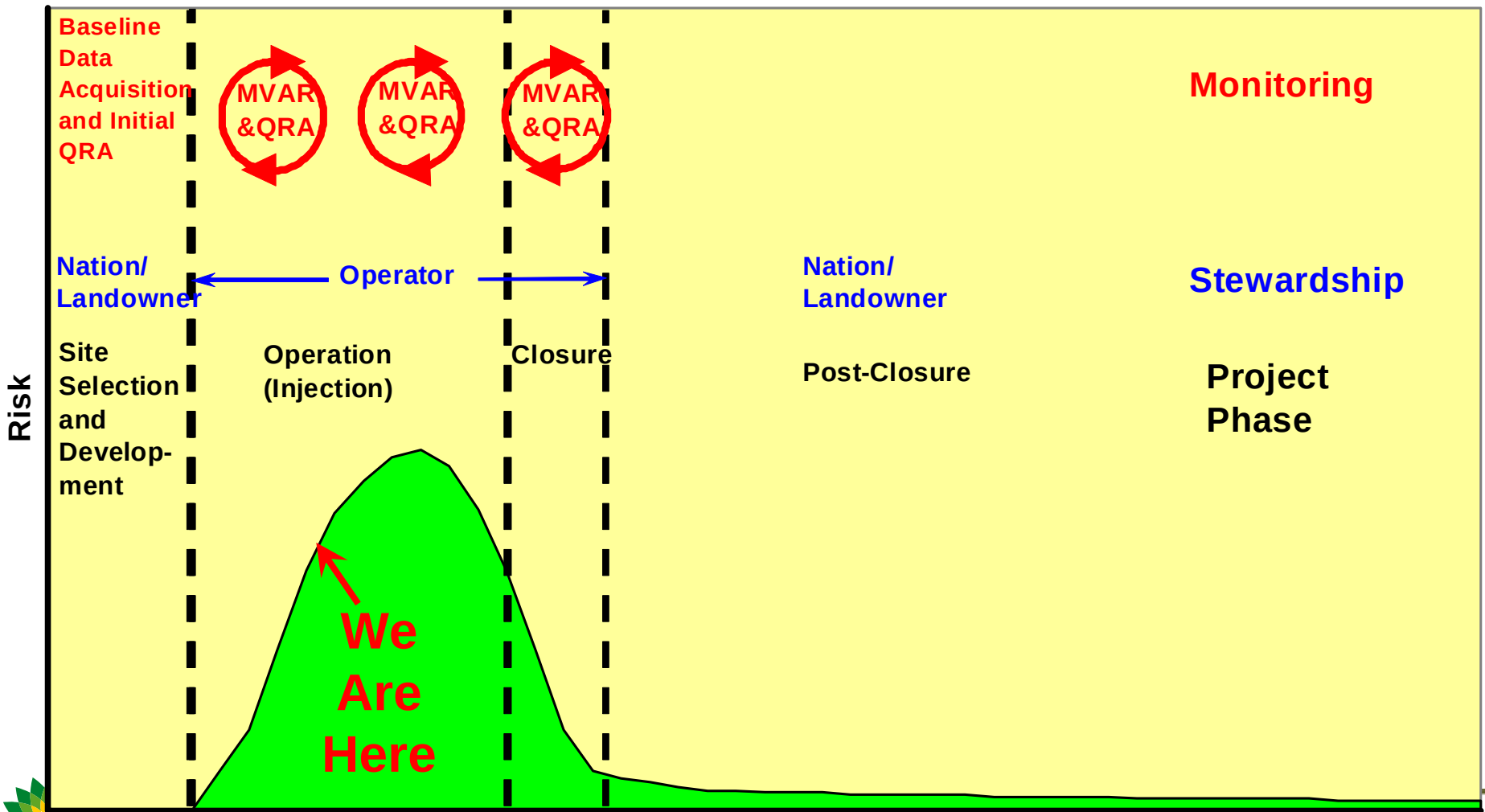
CGS Risk Profile

In Salah Gas
Stockage de CO_2

Risk Profile of a CGS Project



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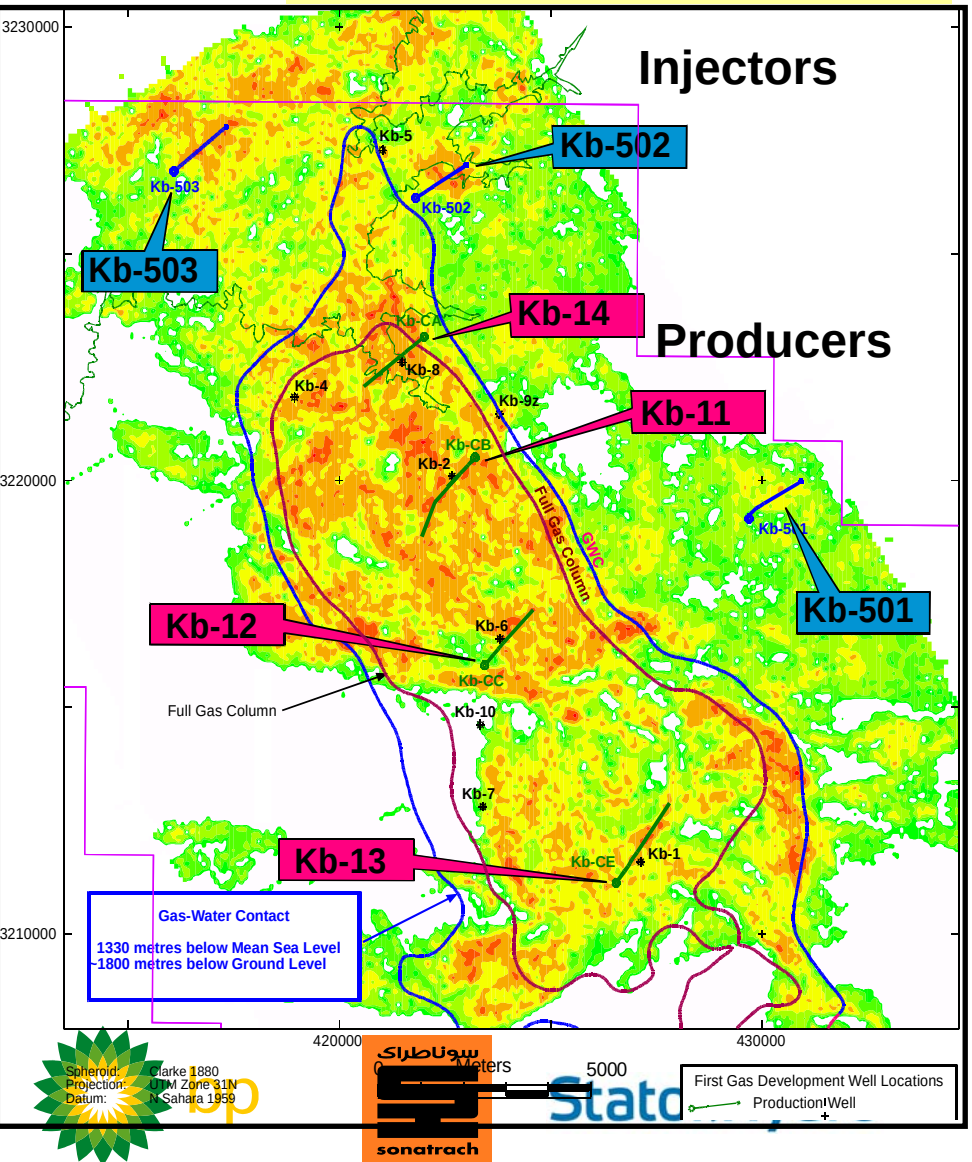
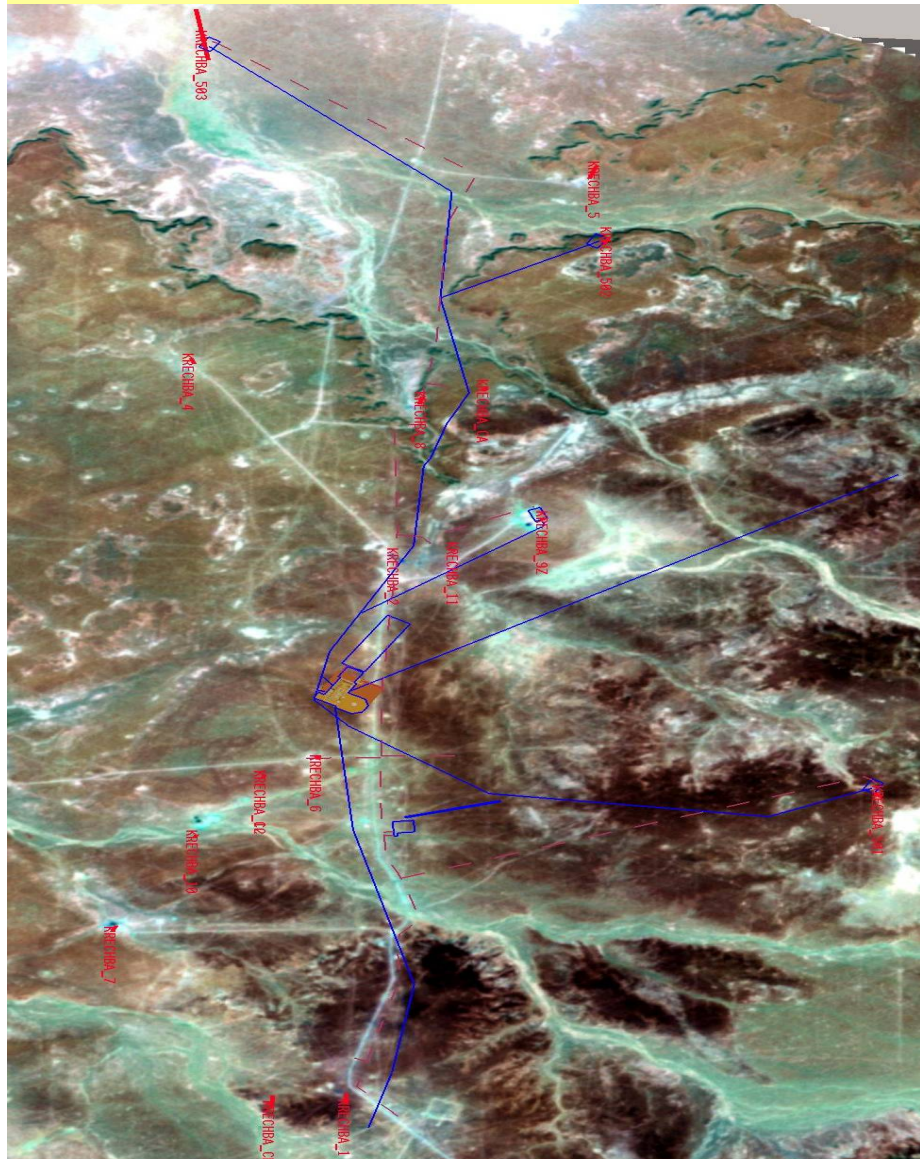
Krechba Field Layout

In Salah Gas
Stockage de CO_2

Reservoir

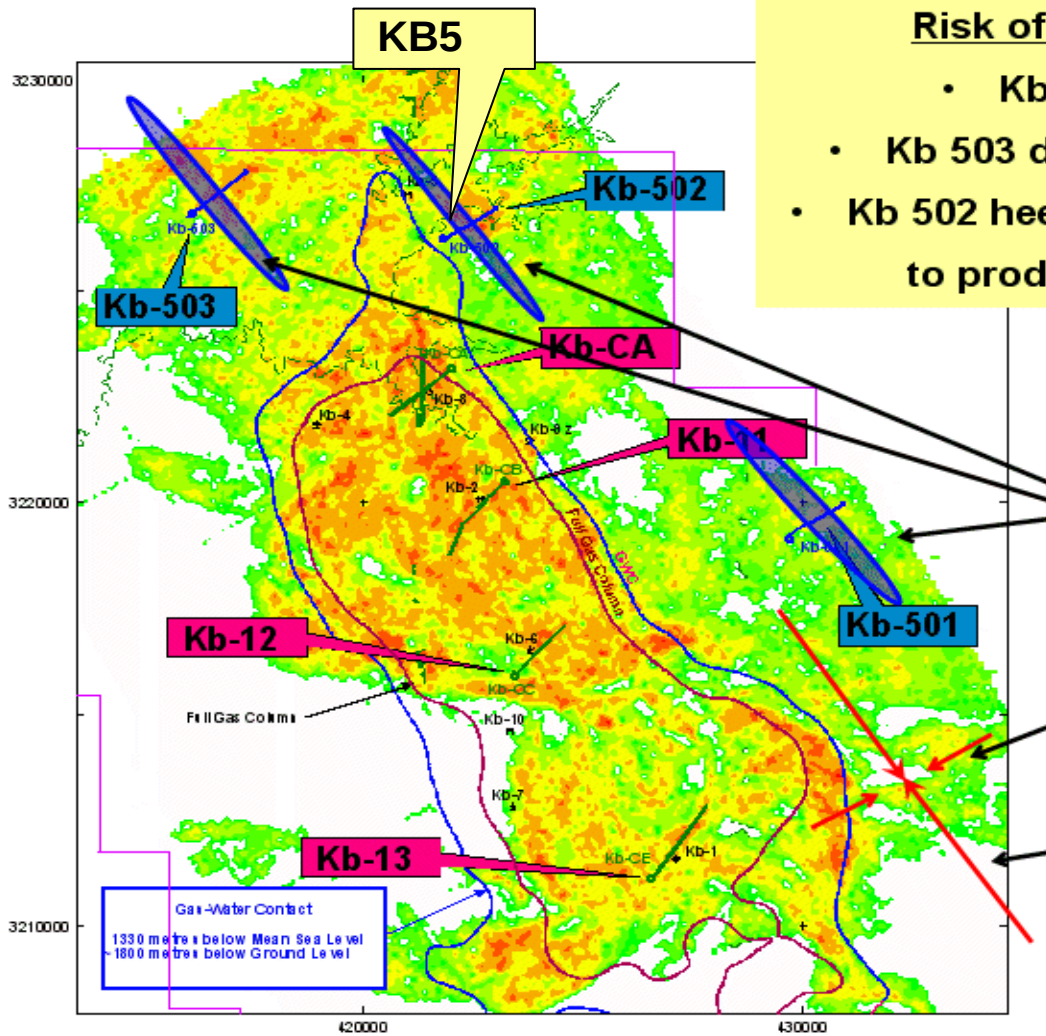
Surface





Expected CO_2 Migration

In Salah Gas
Stockage de CO_2



Risk of premature CO2 breakthrough

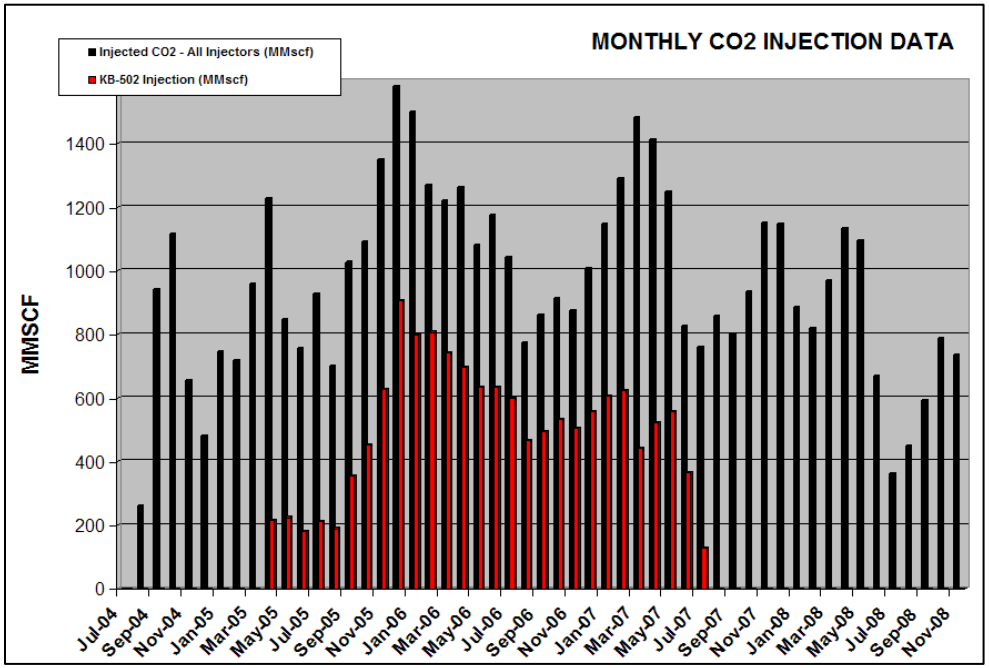
- Kb 501 location minimises risk
- Kb 503 distant from GWC at increased risk
- Kb 502 heel location close to GWC and closest to production pressure sink at most risk

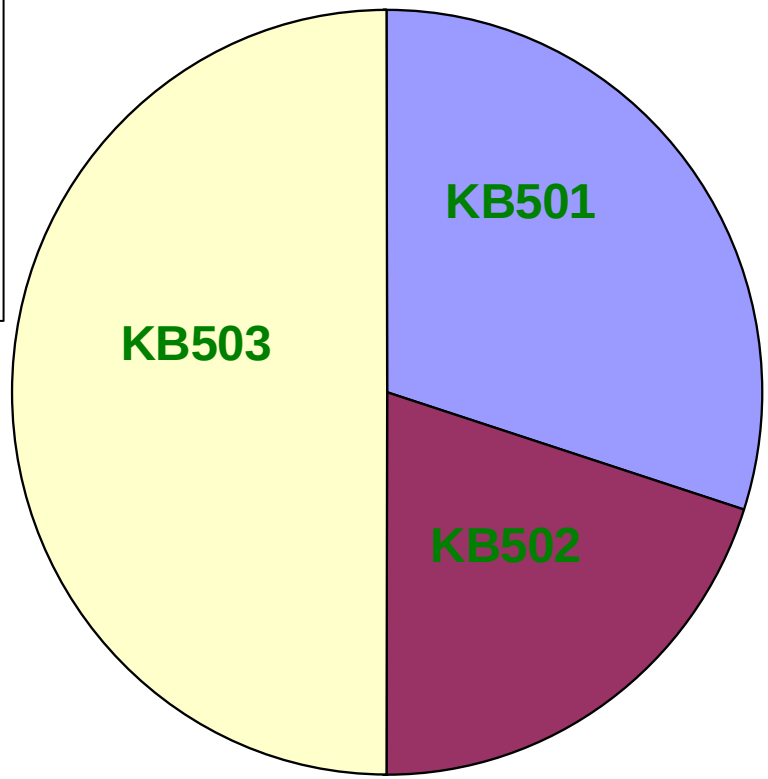
Preferential orientation of injector fractures

Minimum horizontal stress

Maximum horizontal stress

Injection Since Start-up

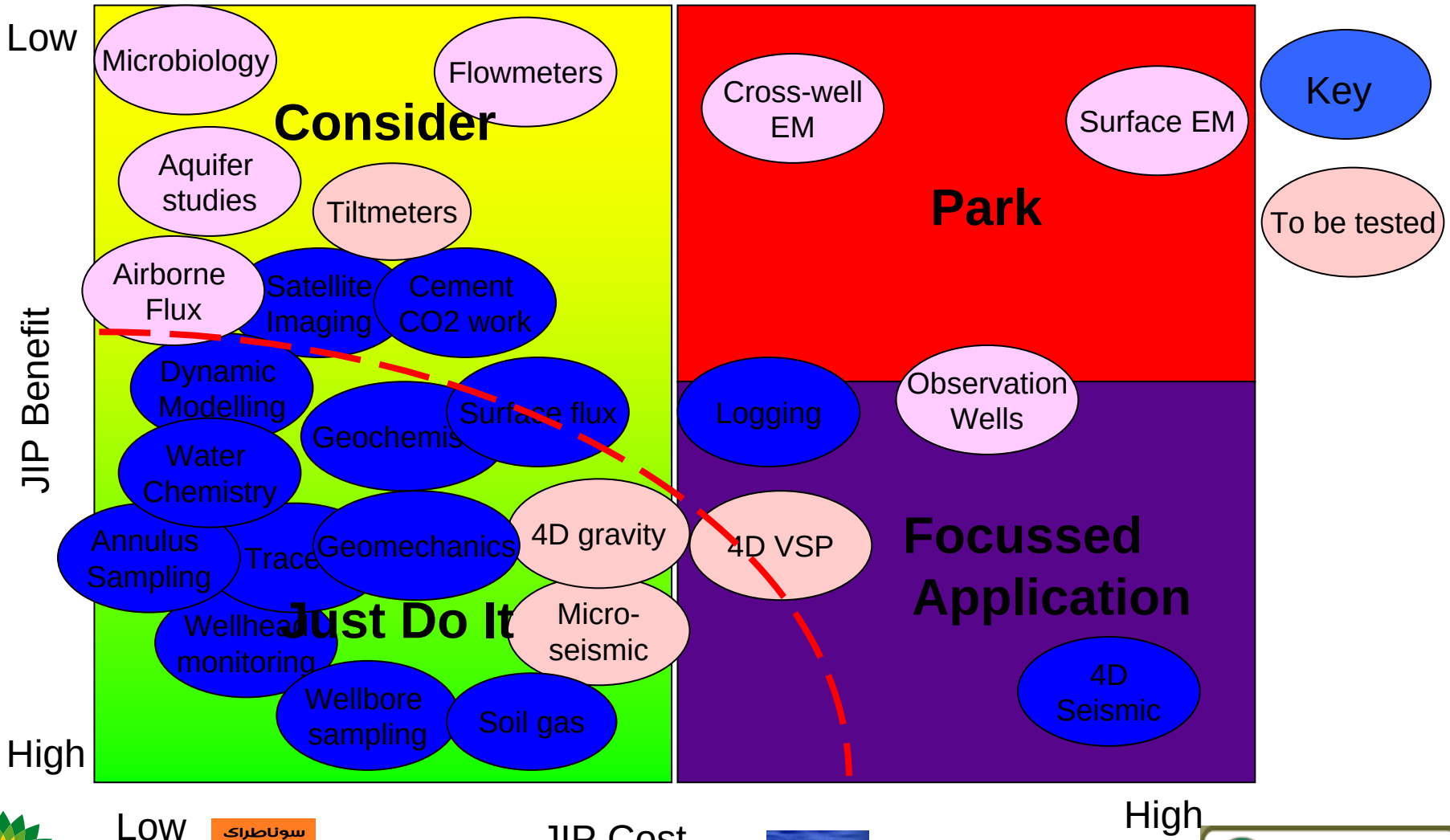




European Commission RTD

Selection of Monitoring Technology

In Salah Gas
Stockage de CO_2



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Monitoring Highlights: 2009

In Salah Gas
Stockage de CO_2

- Satellite Images (Pinnacle/MDA, Japex/JGI, TRE)
- Geomechanics (Livermore NL)
- Monitoring Wells (Sonatrach & ISG JV)
- Structural Geology (Midland Valley)
- Seismic (BGP)
- Modelling (Berkeley NL)
- Micro-Seismic (Berkeley NL)
- Tiltmeters/GPS (Pinnacle)

} Under Deployment

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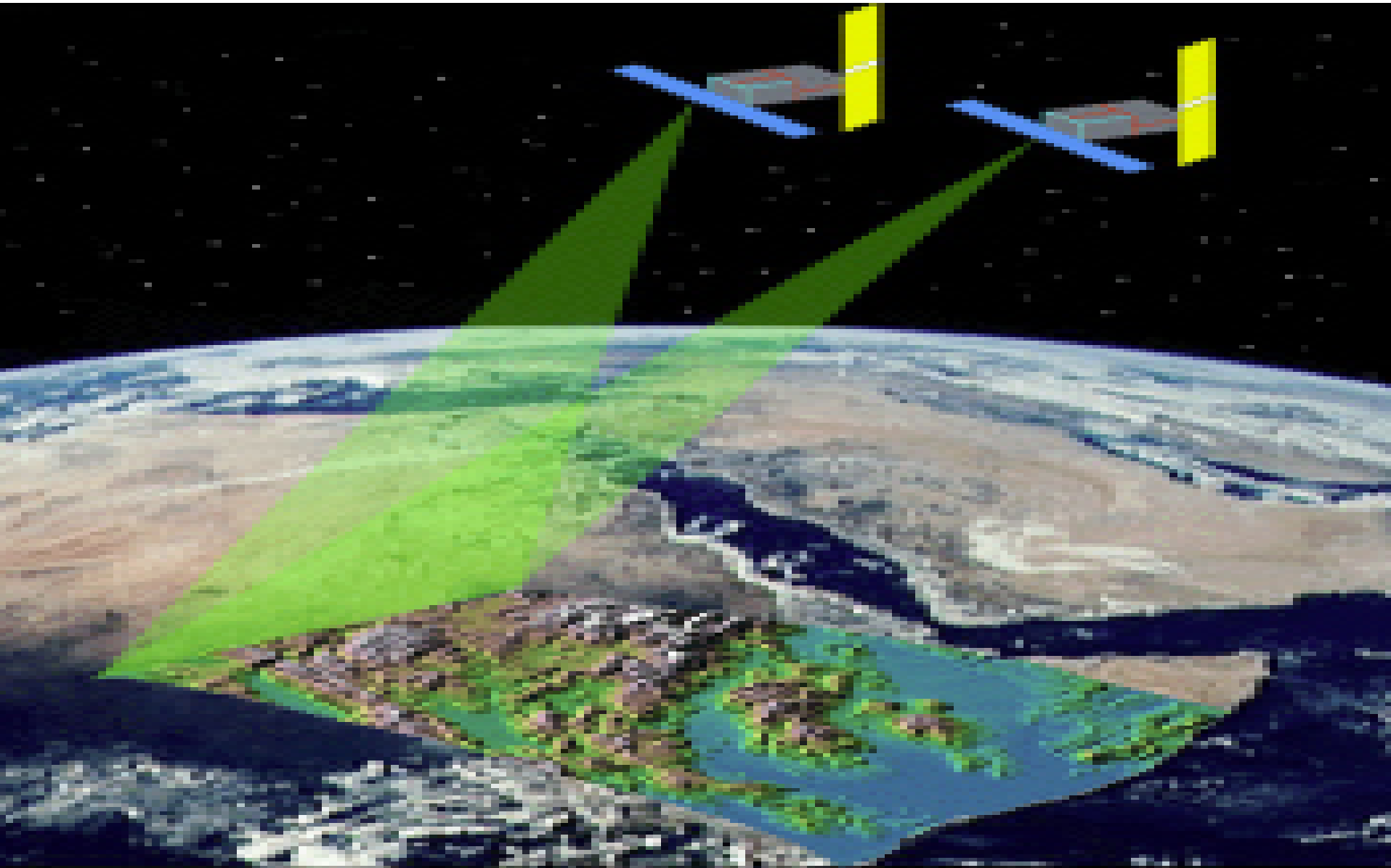
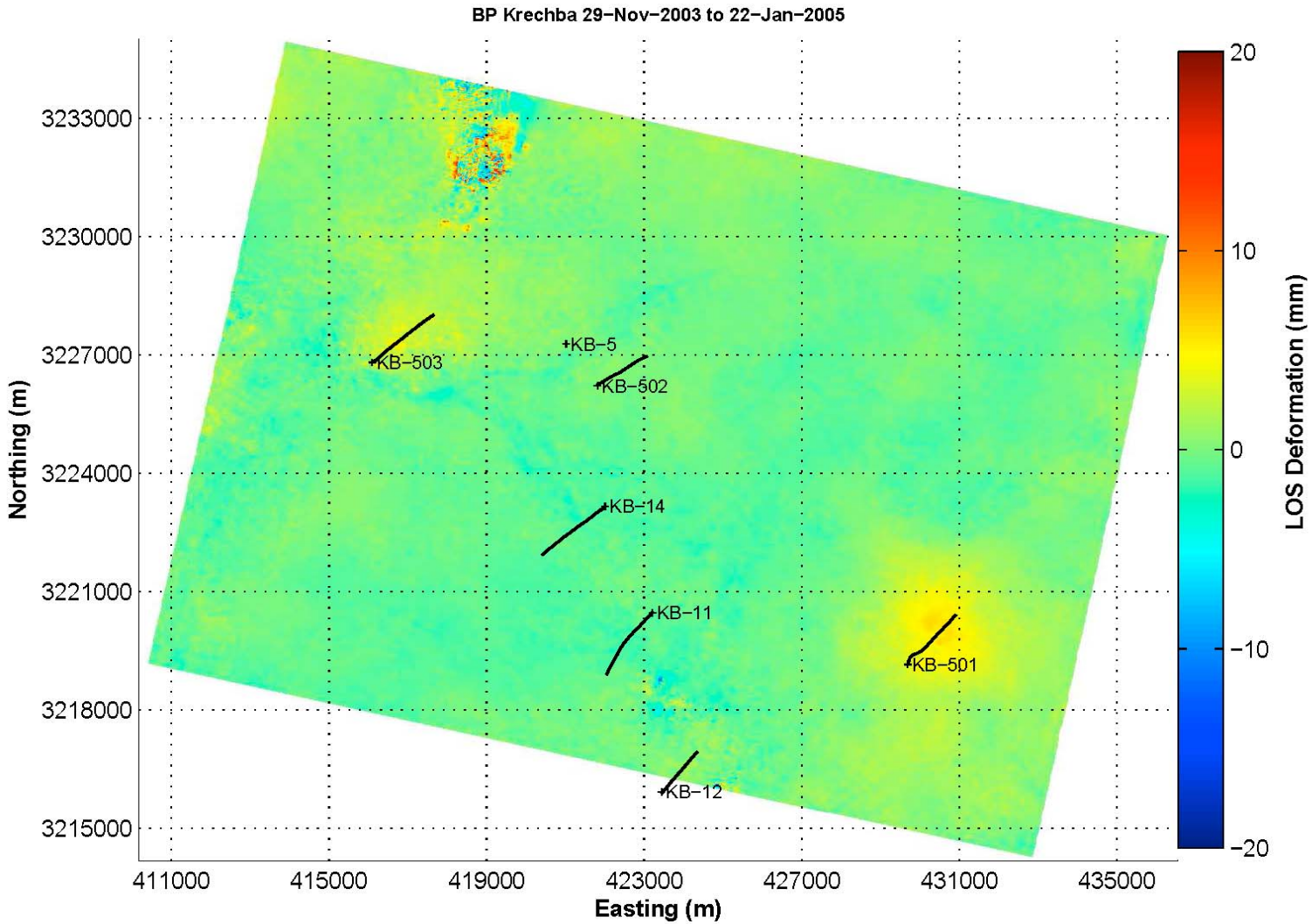
Interferometric Synthetic Aperture Radar (InSAR)

In Salah Gas
Stockage de CO_2



Satellite Images (Pinnacle/MDA)

In Salah Gas
Stockage de CO_2



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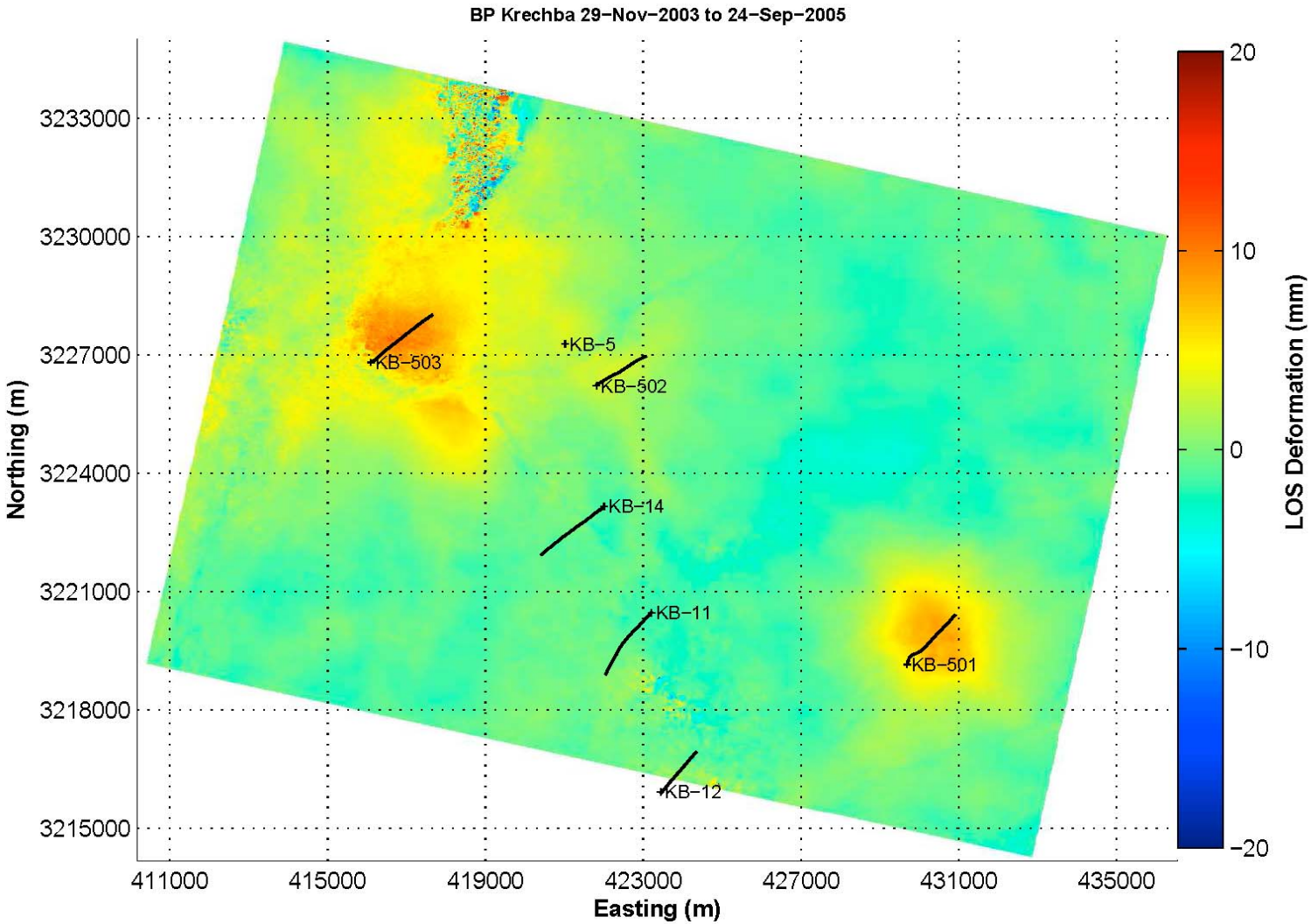
sonatrach

StatoilHydro

European Commission RTD

US Department of Energy

Satellite Images (Pinnacle/MDA)



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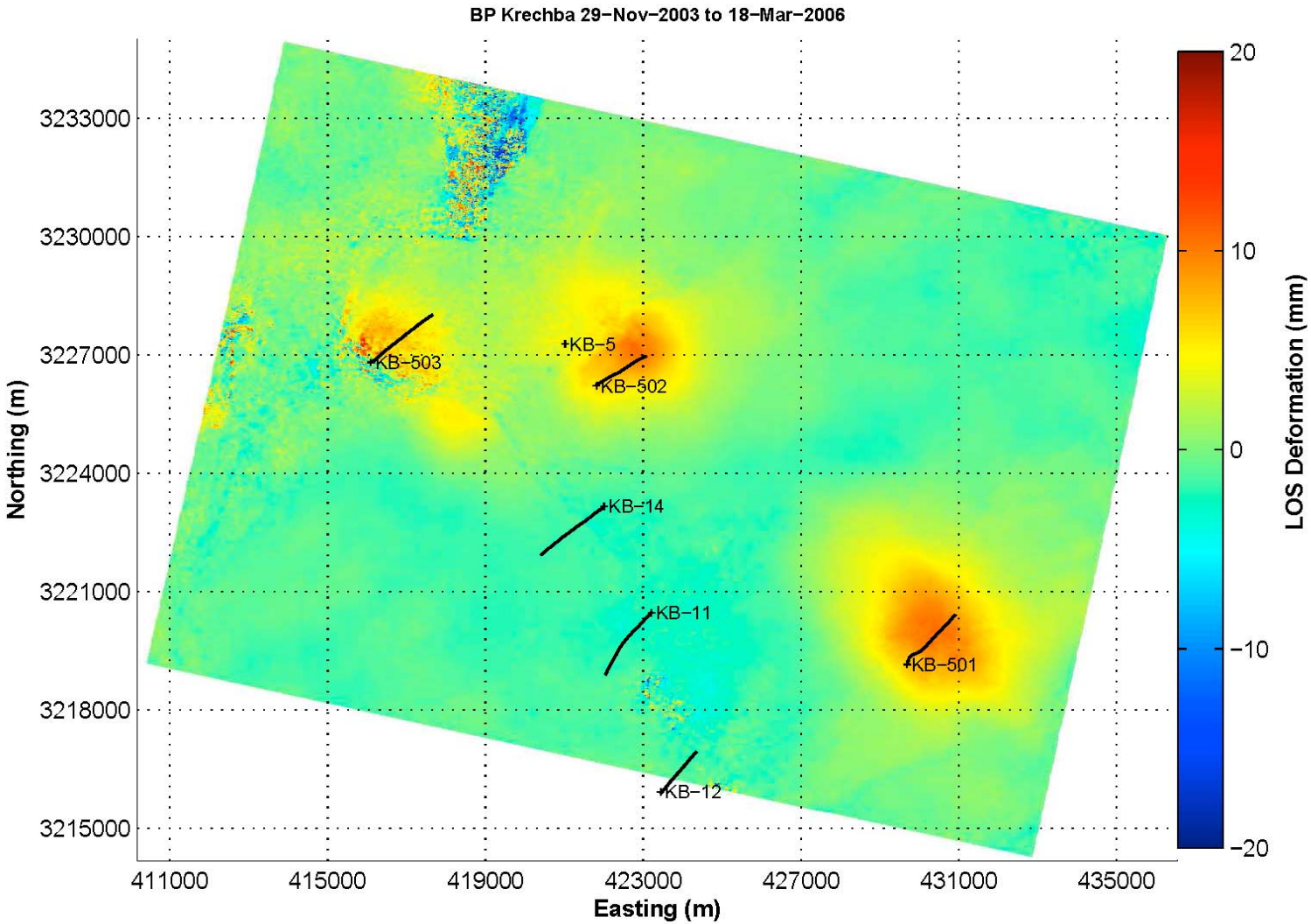

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US Department of Energy

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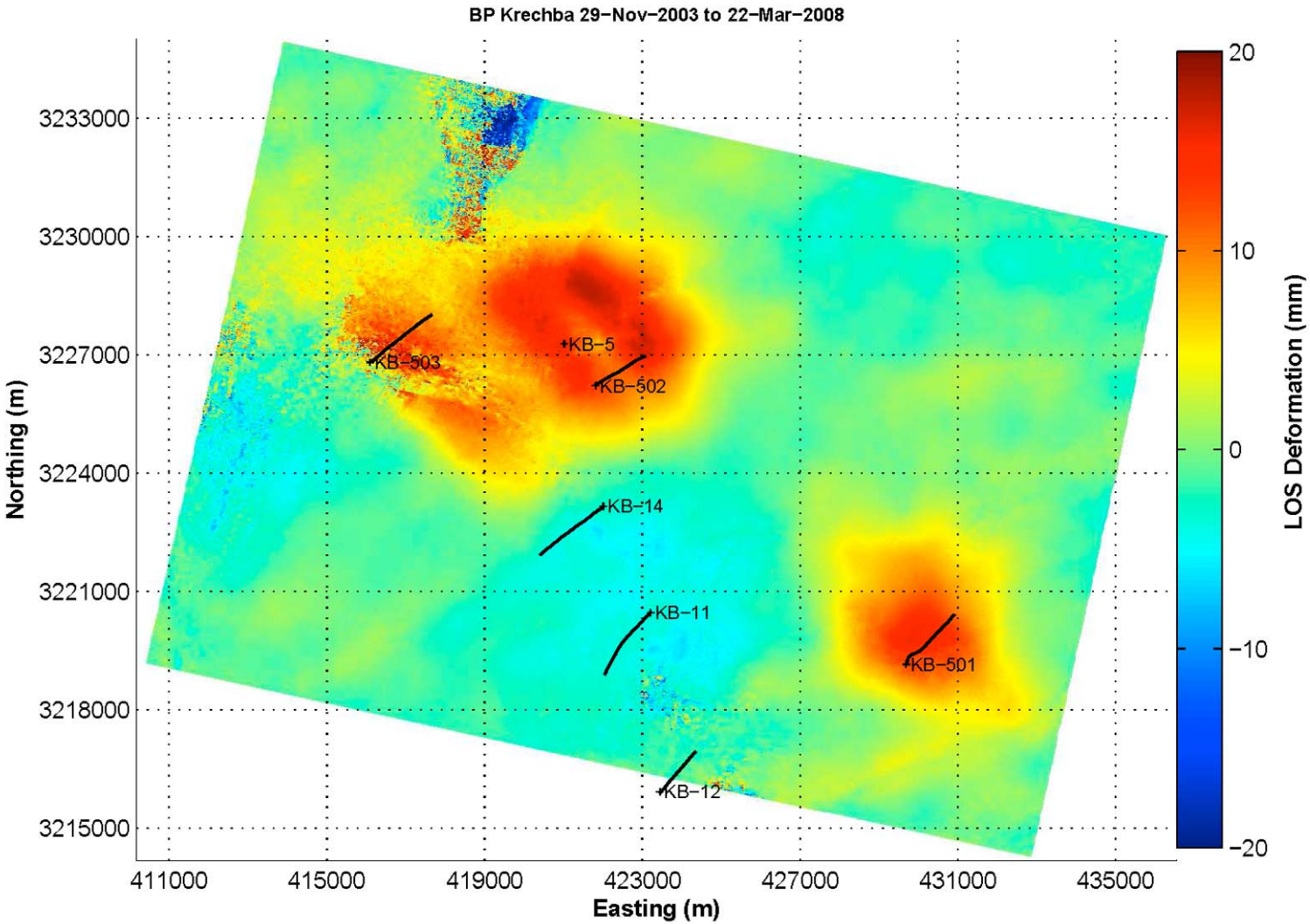

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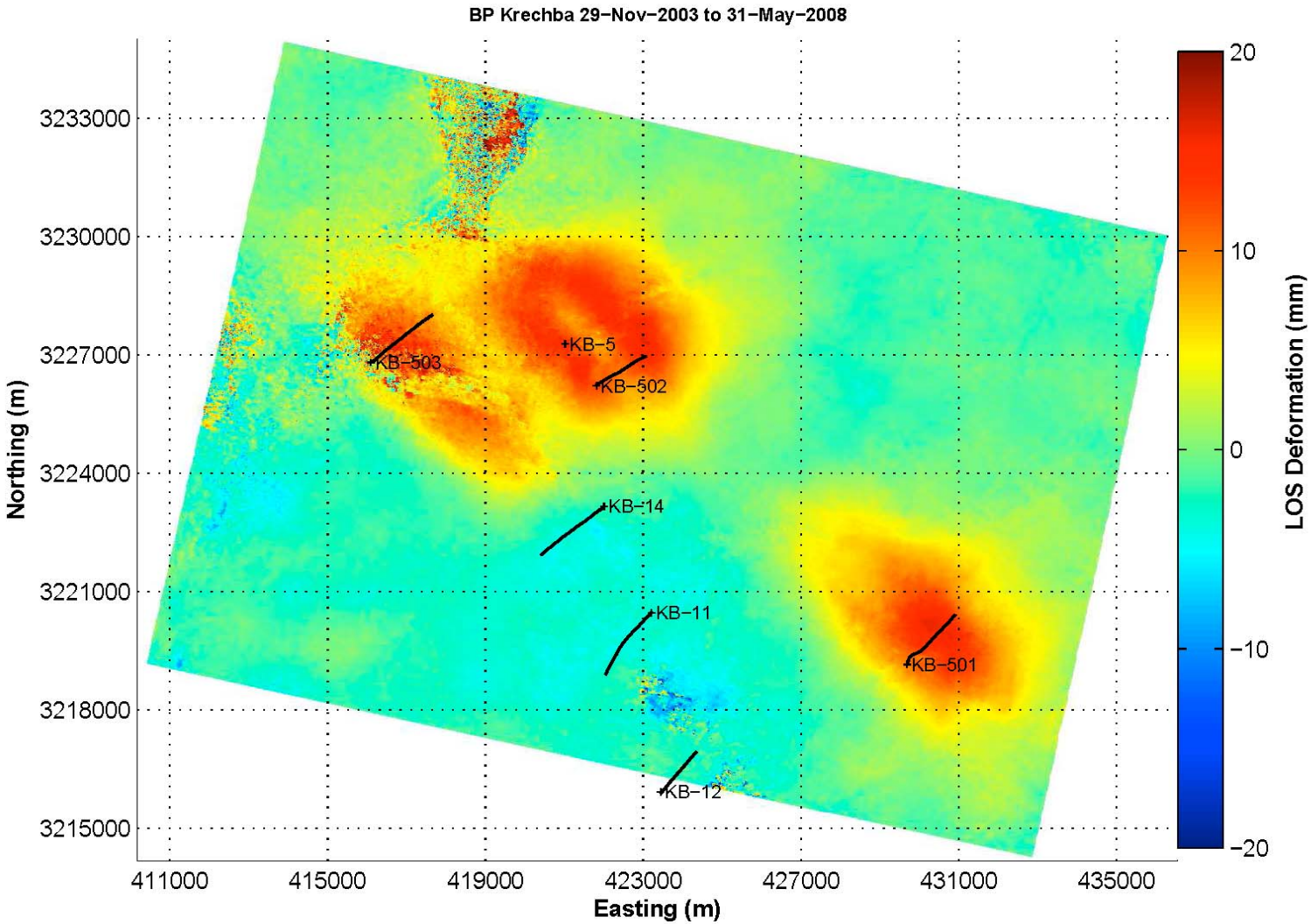
Stockage de CO_2



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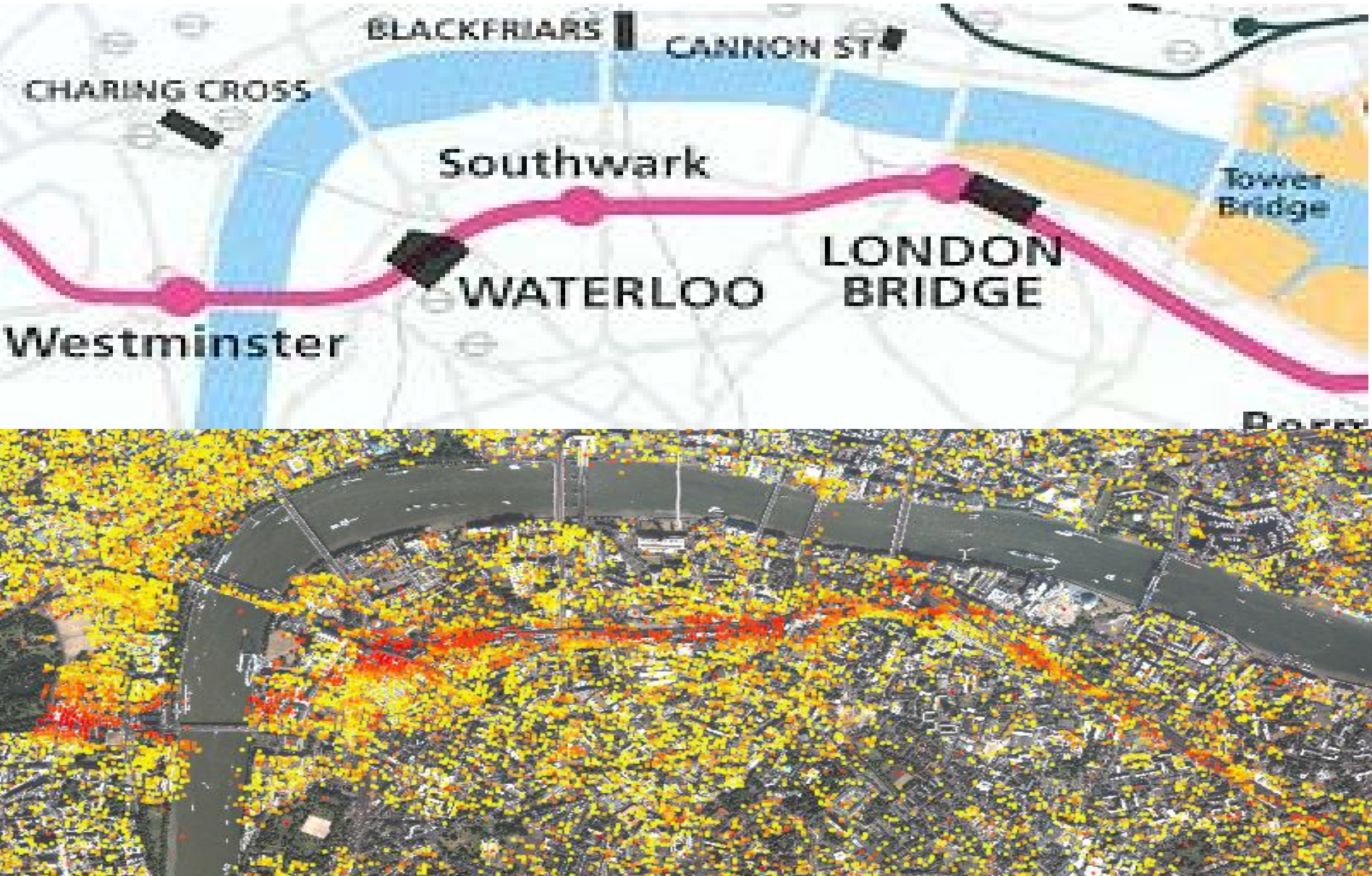
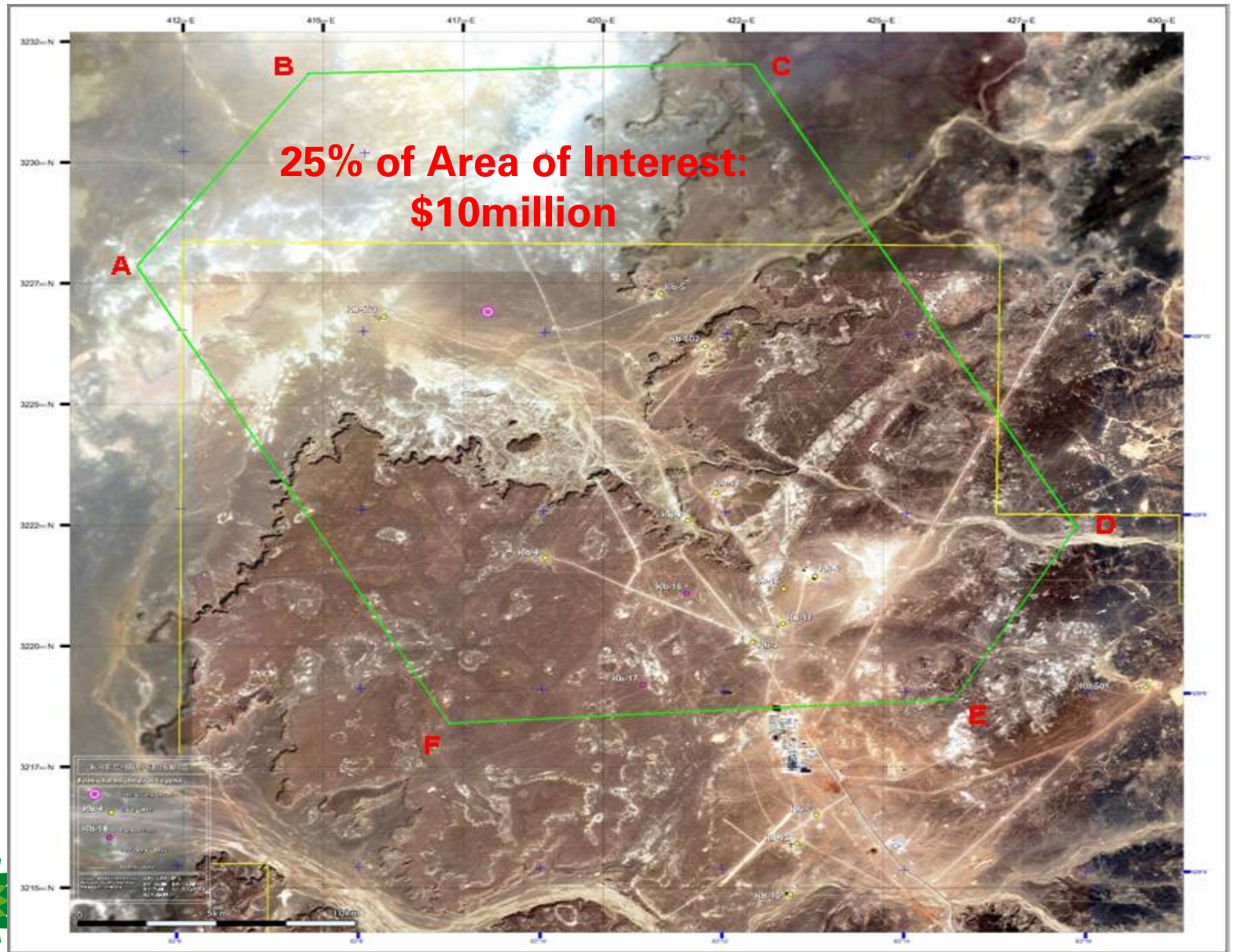
INSAR: London Jubilee Line Construction

In Salah Gas
Stockage de CO_2



Seismic Coverage

In Salah Gas
Stockage de CO_2



S Department
Energy

Summary

- **Demonstrates the technical viability of CCS** to capture and securely store industrial scale volumes of CO2 in a deep saline formation
- **Invaluable in informing and influencing developing regulations** for CCS; JIP's experience continues to be actively sought out by major governments.
  - **Site Selection and Management**
- **Storage monitoring technologies need to be defined on a site specific basis**
  - **Seismic is not a panacea**
- **Well integrity has been confirmed as a top risk to be managed**
- **Compressor selection is key to ensure reliable operations**; lessons learned transferred to other Projects

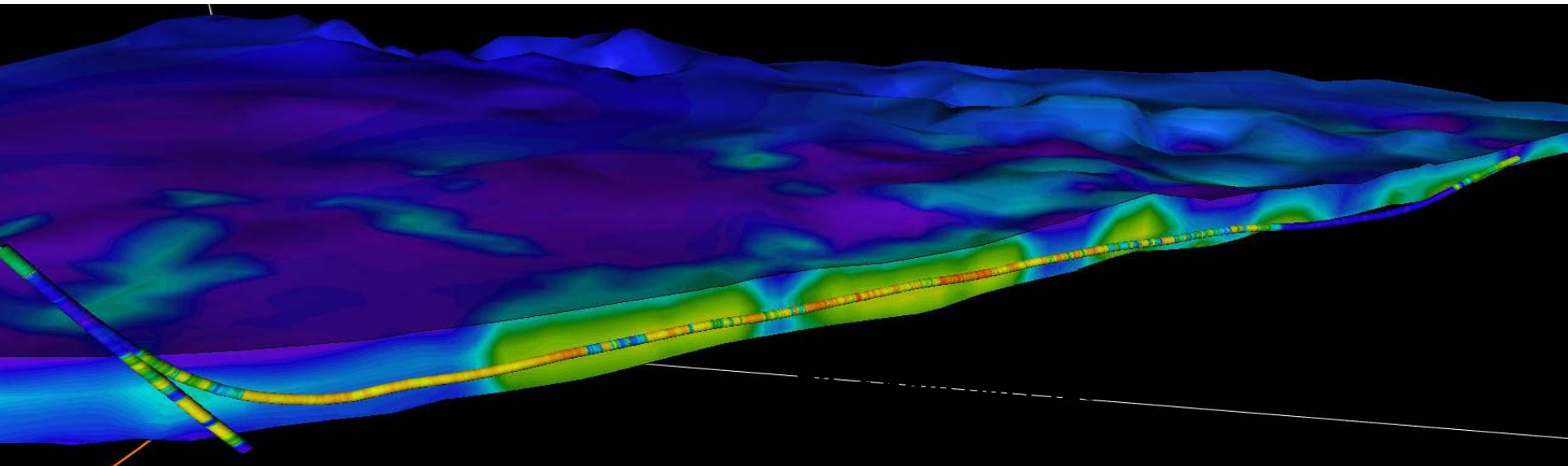
bp sonatrach StatoilHydro European Commission RTD US Department of Energy

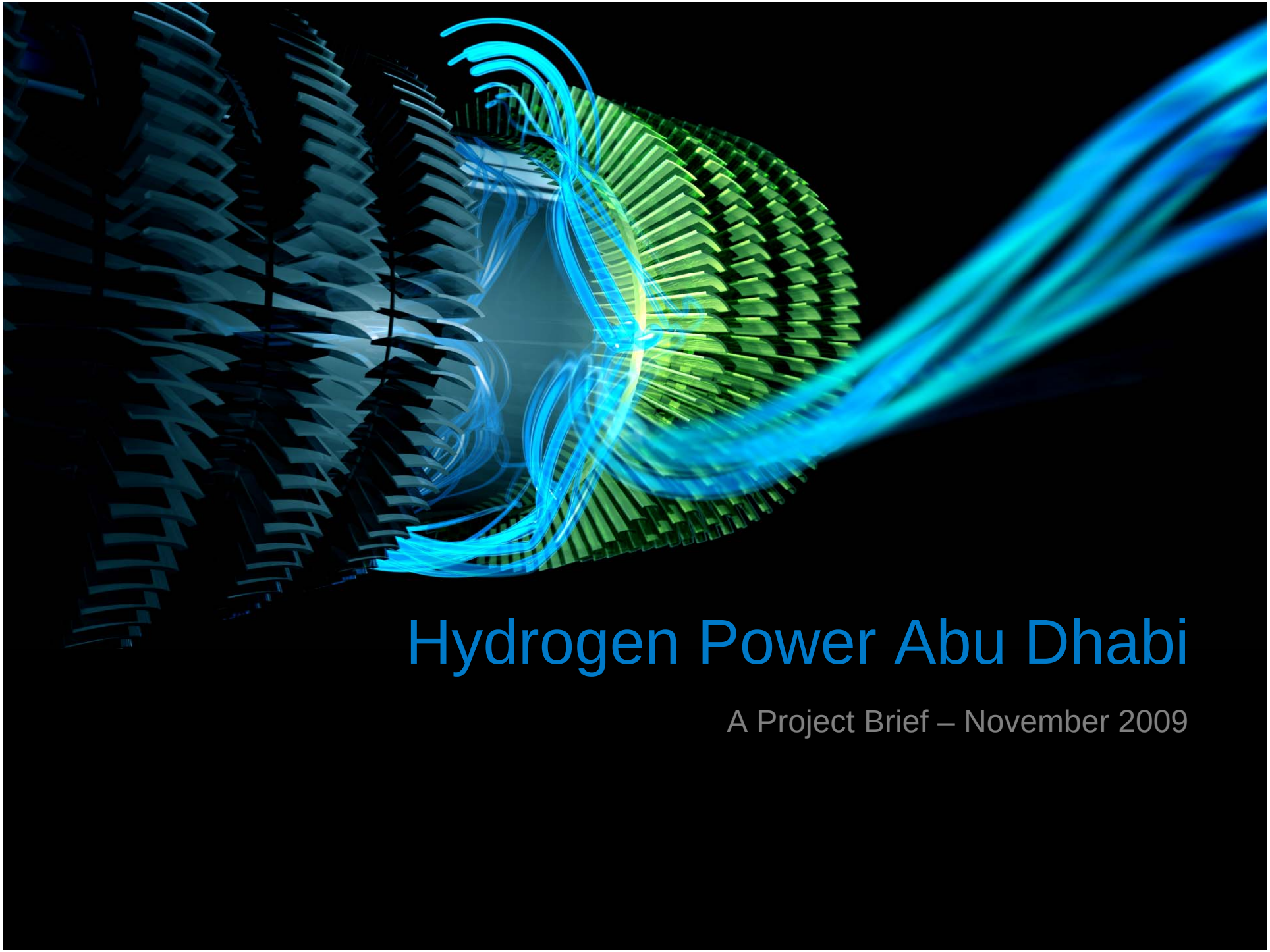
Thank You - Questions?

In Salah Gas
Stockage de CO_2

Useful Links:

In Salah JIP:	www.insalah.com
Check your carbon footprint at:	www.bp.com
Princeton Wedges:	www.princeton.edu/cmi
CCS Technology:	www.co2captureproject.org
EU CCS Roadmap:	www.zero-emissionplatform.org
Hydrogen Power JV:	www.hydrogenenergy.com
Iain's email:	wrightiw@bp.com





Hydrogen Power Abu Dhabi

A Project Brief – November 2009

The key facts…

Hydrogen Power Abu Dhabi

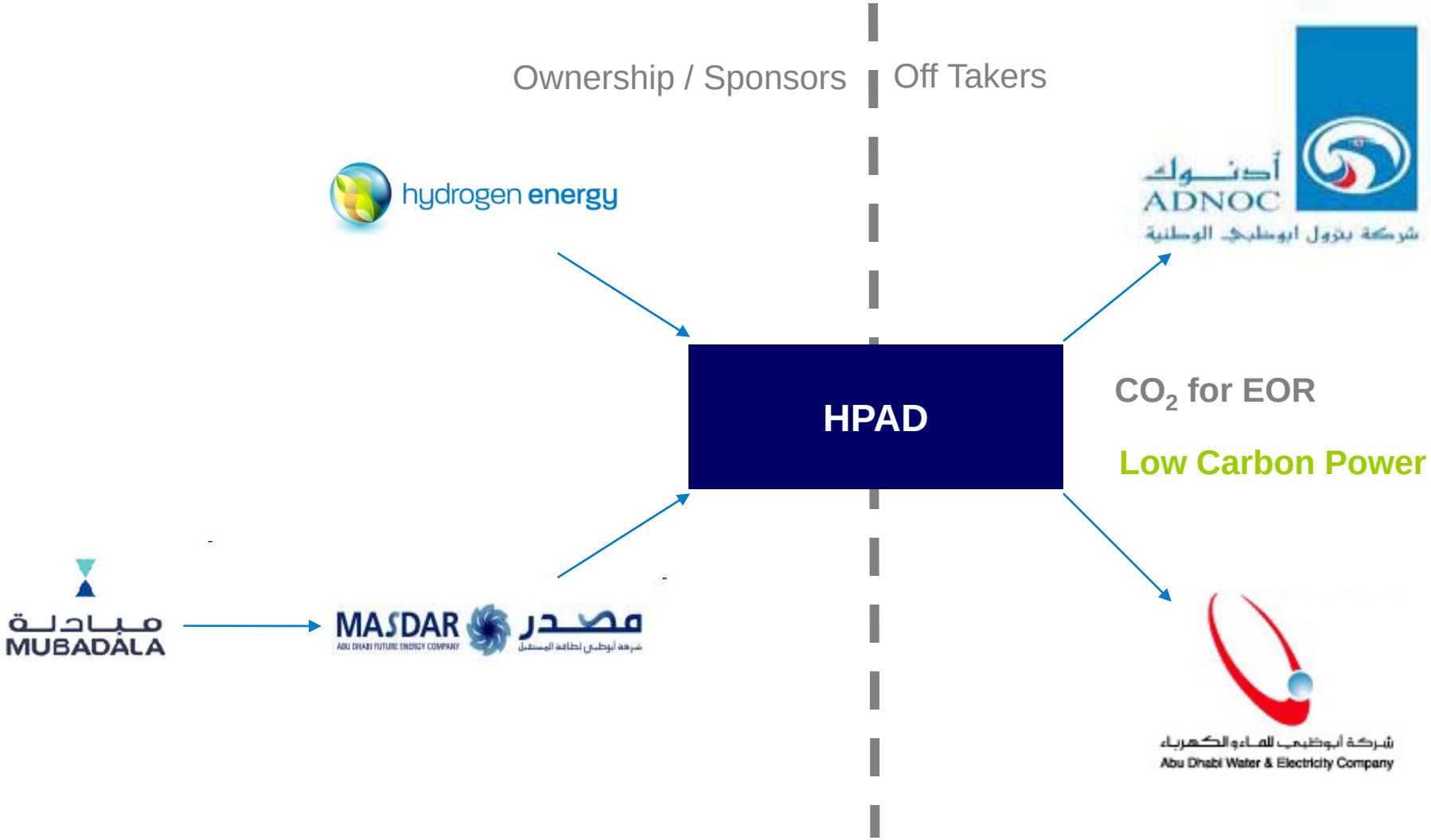
MASDAR ABU DHABI FUTURE ENERGY COMPANY مصدر شركة أبوظبي لطاقة المستقبل hydrogen energy

World Largest Hydrogen Power Plant (Gross)	**:**	**500**	**MW**
World Largest Hydrogen Power Plant (Net)	**:**	**400**	**MW**
Estimated CO2 Captured For EOR	**:**	**1.7**	**M ton/Year**
Expected Target for Commissioning	**:**	**2013**	

Pre-combustion Carbon Capture Technology

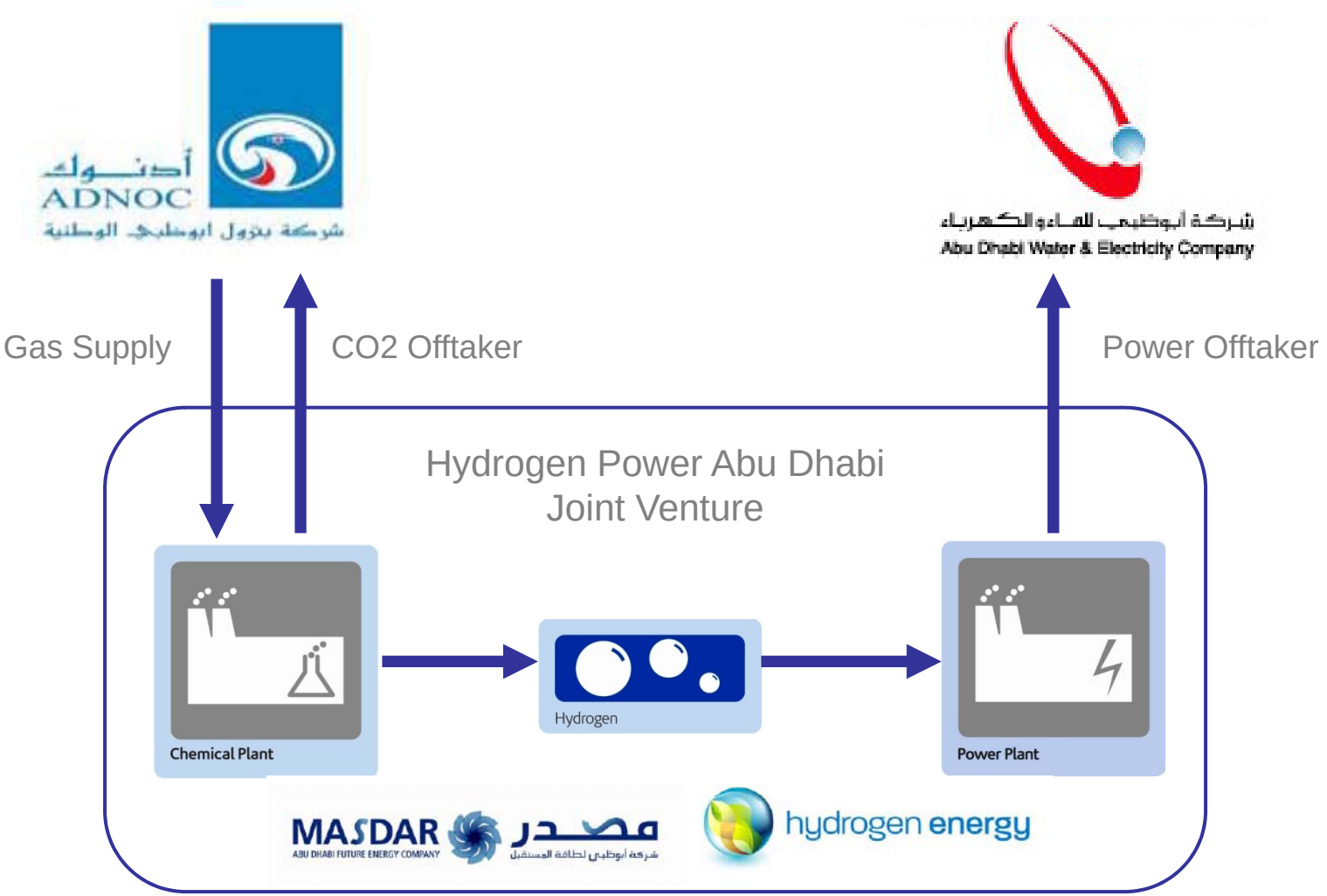
Who is HPAD?

Hydrogen Power Abu Dhabi



What is HPAD?

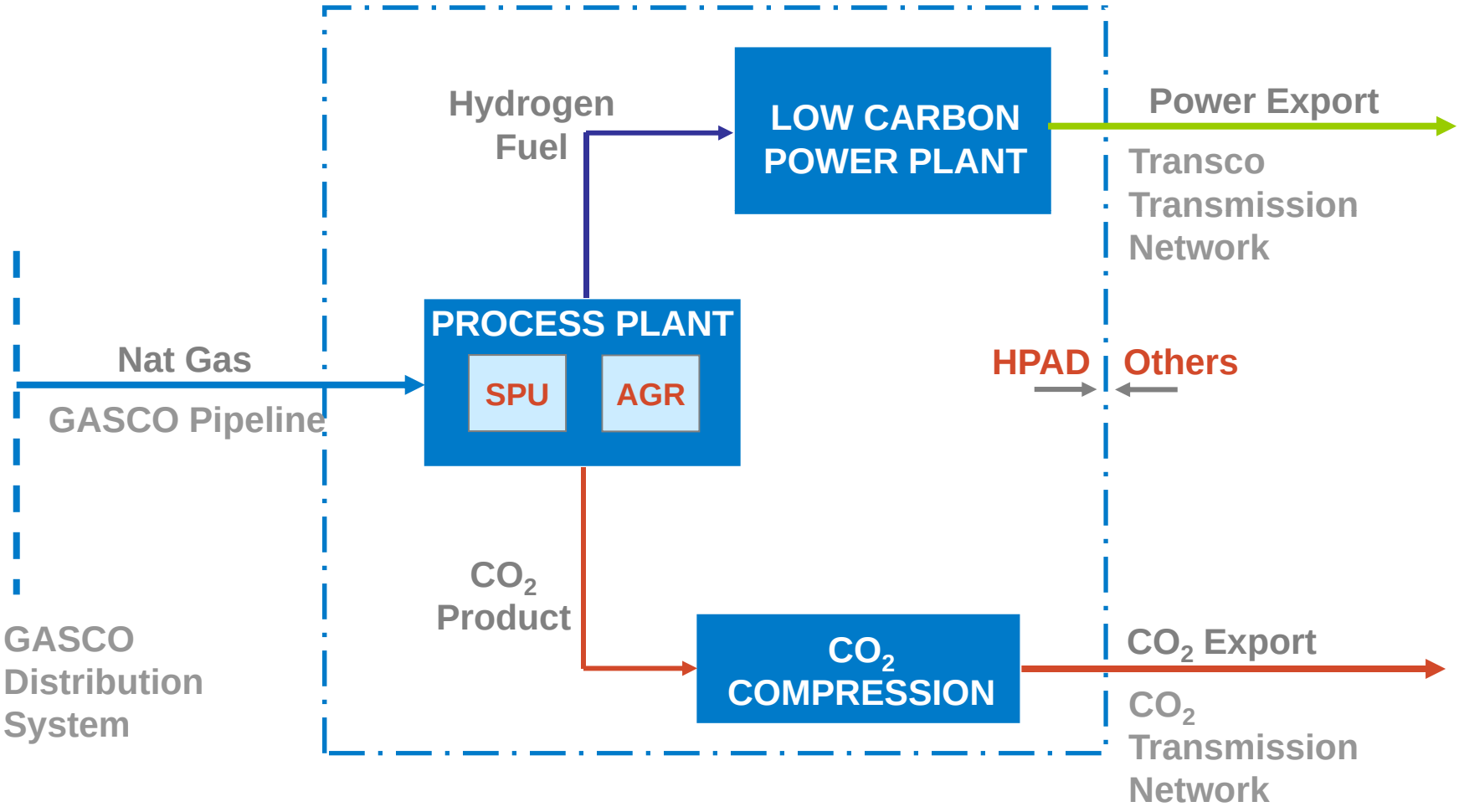
Hydrogen Power Abu Dhabi



The HPAD scope

Hydrogen Power Abu Dhabi

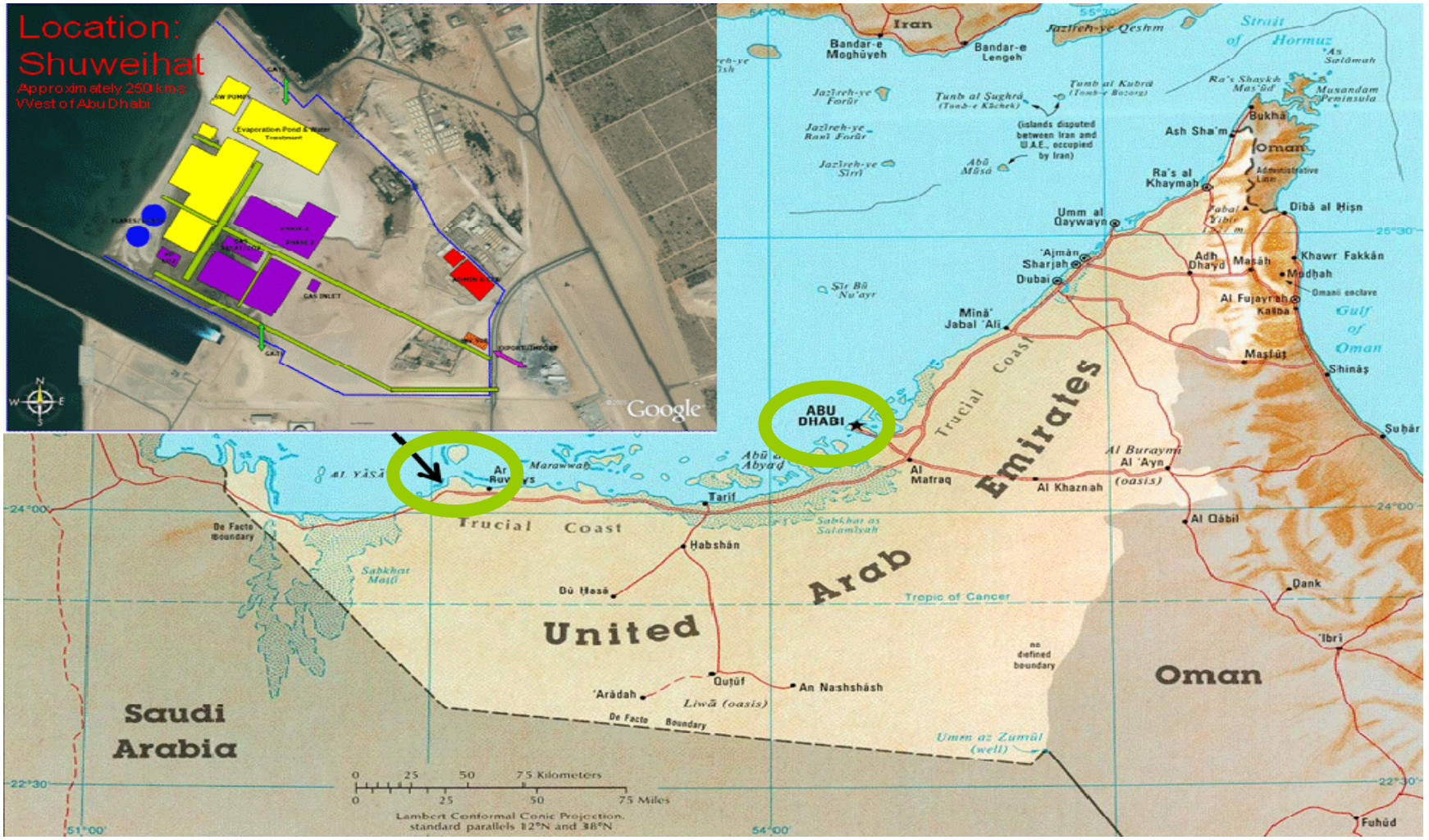
MASDAR مصدر hydrogen energy



Where is HPAD?

Hydrogen Power Abu Dhabi

MASDAR مصدر hydrogen energy



HPAD and Masdar's CO_2 transport network

Hydrogen Power Abu Dhabi

MASDAR مصدر ABU DHABI FUTURE ENERGY COMPANY شركة أبوظبي لطاقة المستقبل hydrogen energy

The plant location

Hydrogen Power Abu Dhabi

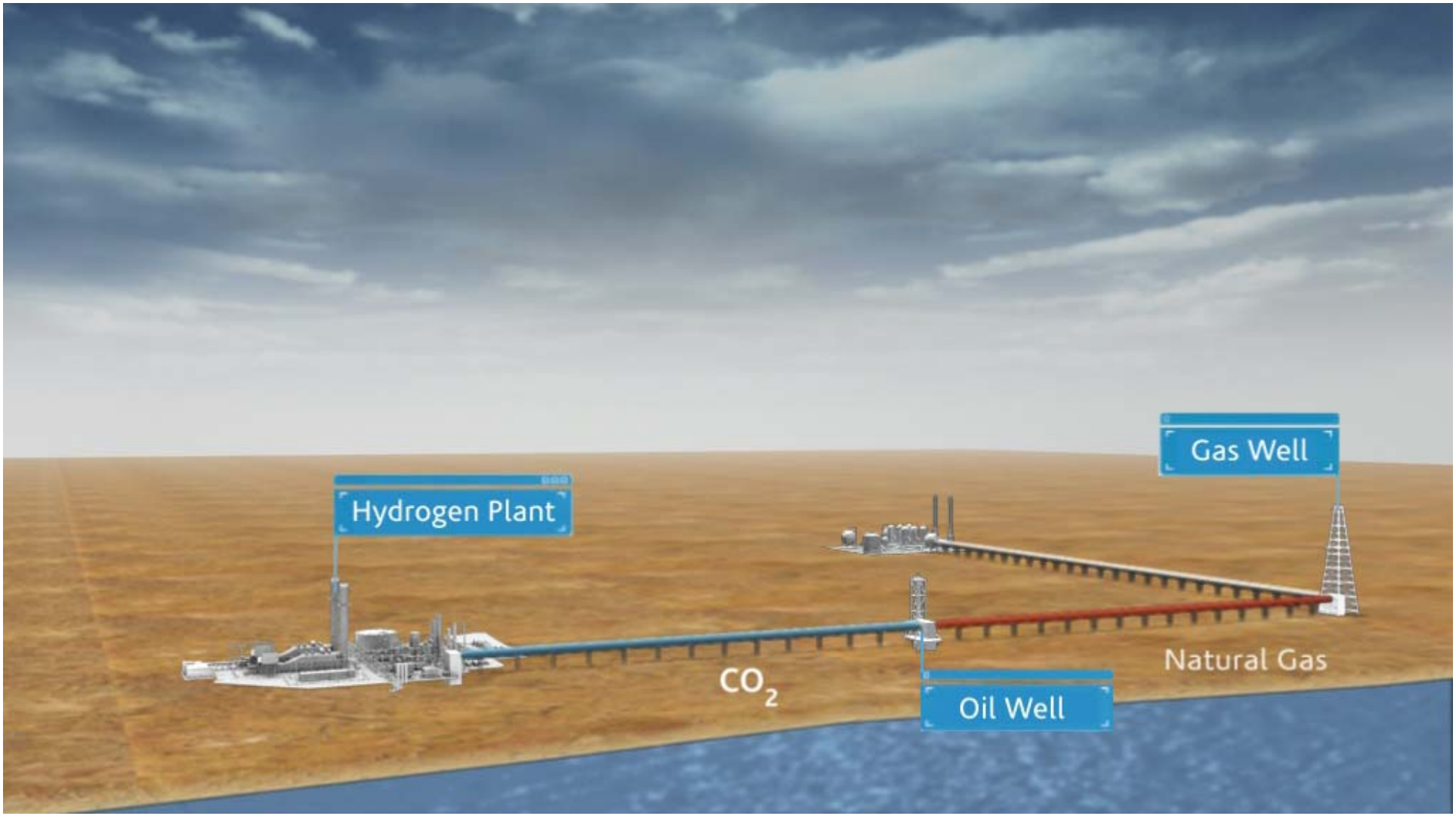
MASDAR ABU DHABI FUTURE ENERGY COMPANY مصدر شركة أبوظبي لطاقة المستقبل hydrogen energy

1. natural gas
2. CO_2
3. hydrogen
4. low-carbon electricity
5. CO_2 for storage

EOR drives the value proposition in Abu Dhabi

Hydrogen Power Abu Dhabi

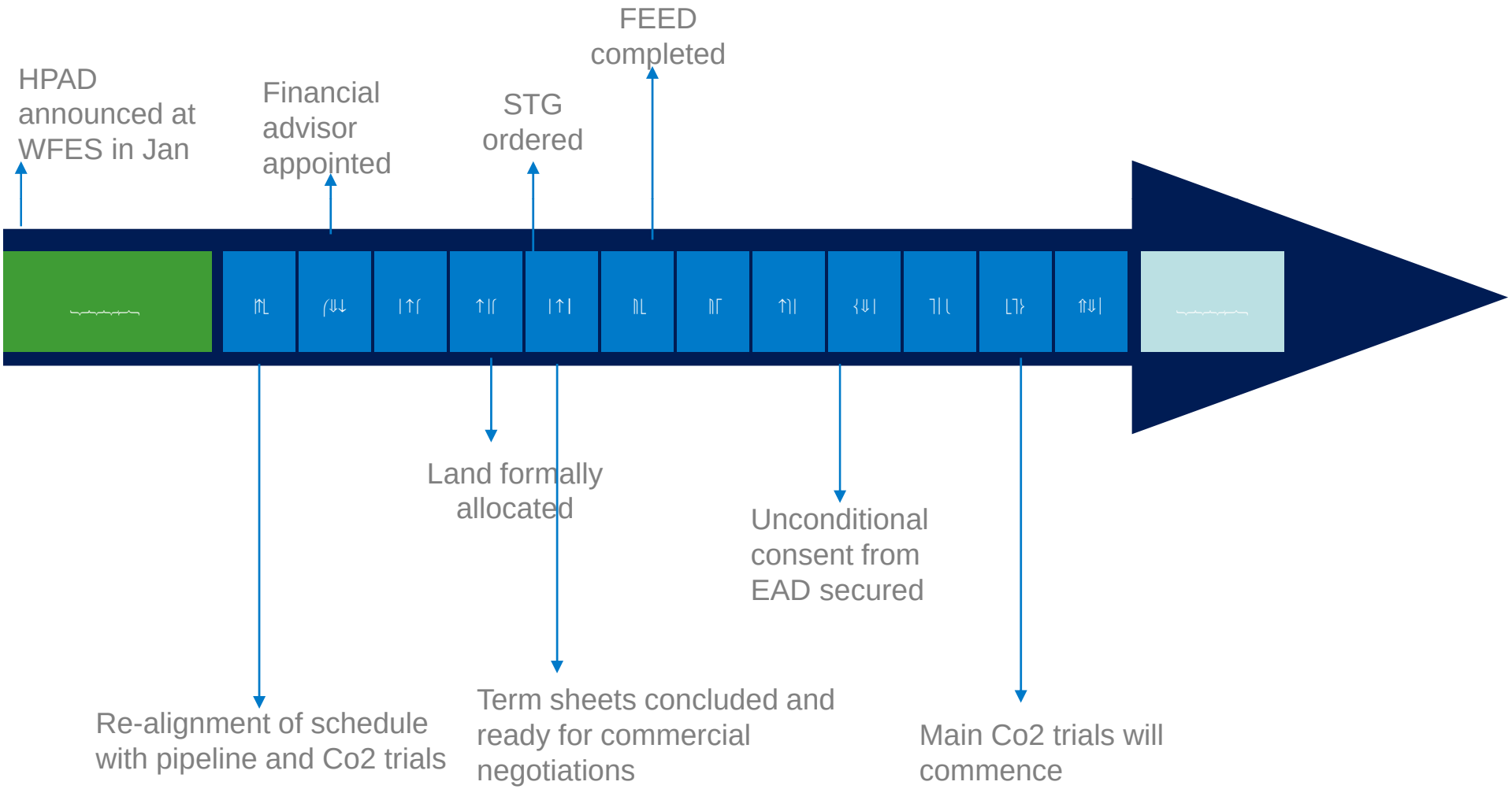
MASDAR مصدر hydrogen energy



Achievements to date

Hydrogen Power Abu Dhabi

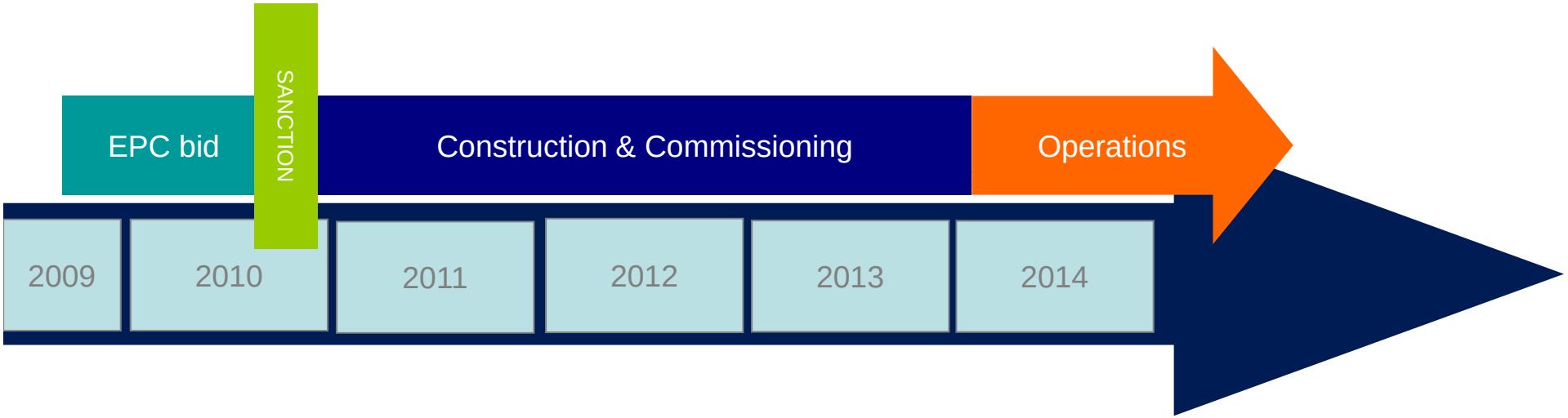
MASDAR مصدر hydrogen energy

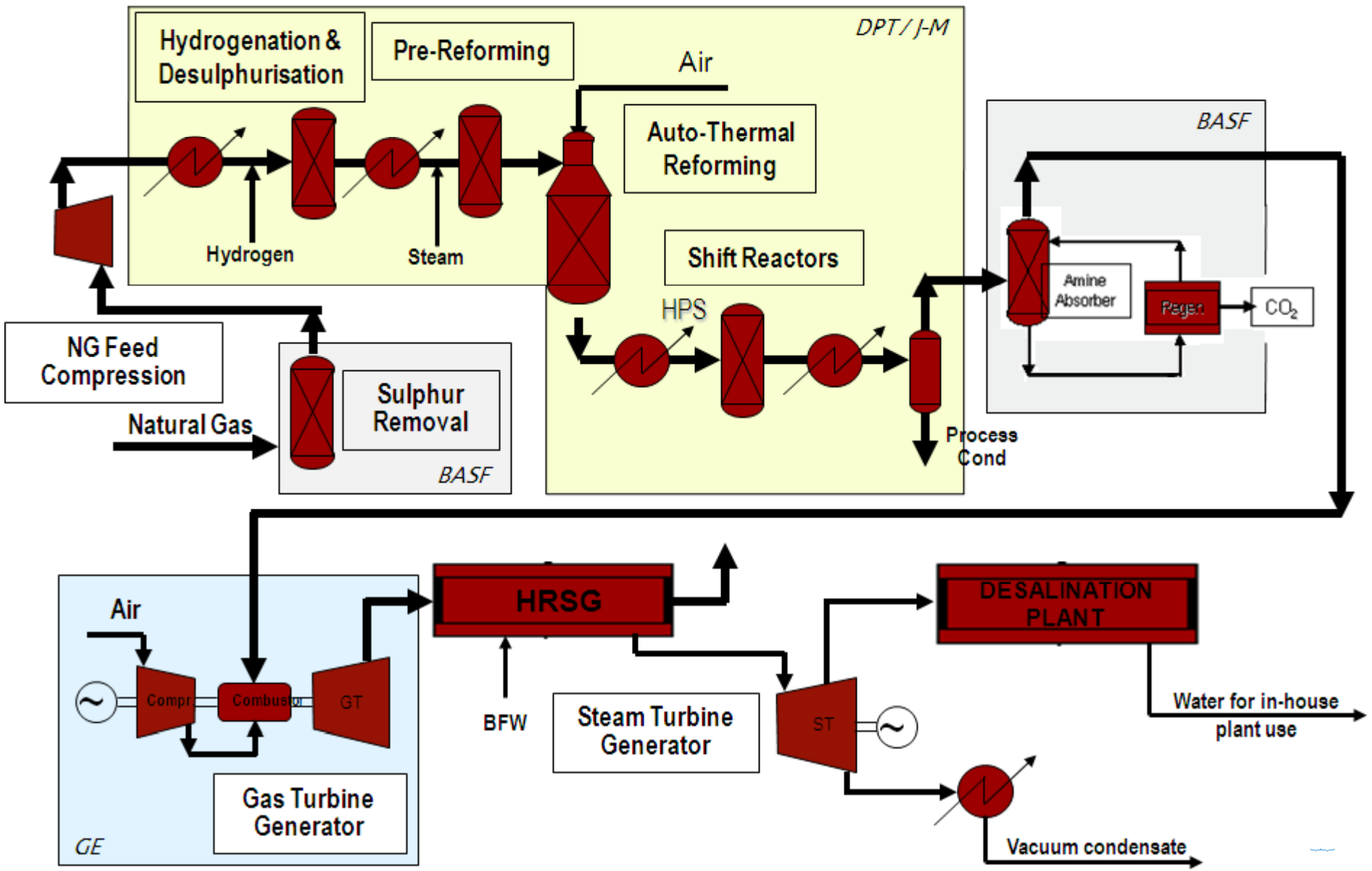


HPAD schedule

Hydrogen Power Abu Dhabi

MASDAR ABU DHABI FUTURE ENERGY COMPANY مصدر شركة أبوظبي لطاقة المستقبل hydrogen energy




Hydrogen Power Abu Dhabi
MASDAR
hydrogen energy
DPT / J-M
Hydrogenation & Desulphurisation
Pre-Reforming
Air
Auto-Thermal Reforming
Hydrogen
Steam
Shift Reactors
HPS
BASF
Amine Absorber
Pegen
CO_2
NG Feed Compression
Natural Gas
Sulphur Removal
BASF
Process Cond
Air
Compr
Combustor
GT
Gas Turbine Generator
GE
HRSG
BFW
Steam Turbine Generator
ST
DESALINATION PLANT
Water for in-house plant use
Vacuum condensate

Plant performance expectations

Hydrogen Power Abu Dhabi

MASDAR ABU DHABI FUTURE ENERGY COMPANY مصدر شركة أبوظبي لطاقة المستقبل hydrogen energy

Natural Gas Feed	~95 mmSCFD (83.5 t/h)
Power output	~500MWe gross, ~380MWe net (RSC)
Target Nox emissions	≤ 70mg/Nm³ on 'Low Carbon' Power (RSC)
Thermal Efficiency	~46% ('Low Carbon' Power) (RSC) ~50% (CCGT plant)
Co_2 Production	~1.7 mmtpa (~210 t/h)
Co_2 Purity	99% (sales spec)
Desal Plant Output:	110m³/h desalinated water for process consumption and domestic use

Proven Technologies

Hydrogen Power Abu Dhabi

MASDAR مصدر hydrogen energy

- SPU (ATR): Ammonia 4 secondary reformer, J-M Teeside
- SPU (ATR): Atlas Methanol, Trinidad
- SPU (Shift): SAFCo Fertiliser plant, Saudi Arabia
- AGR: Qatar Gas LNG2, Qatar
- AGR: In Salah, BP Algeria
- Power Generation (IGCC): Sarlux, Italy

Krebcha – Insalaha, Algeria

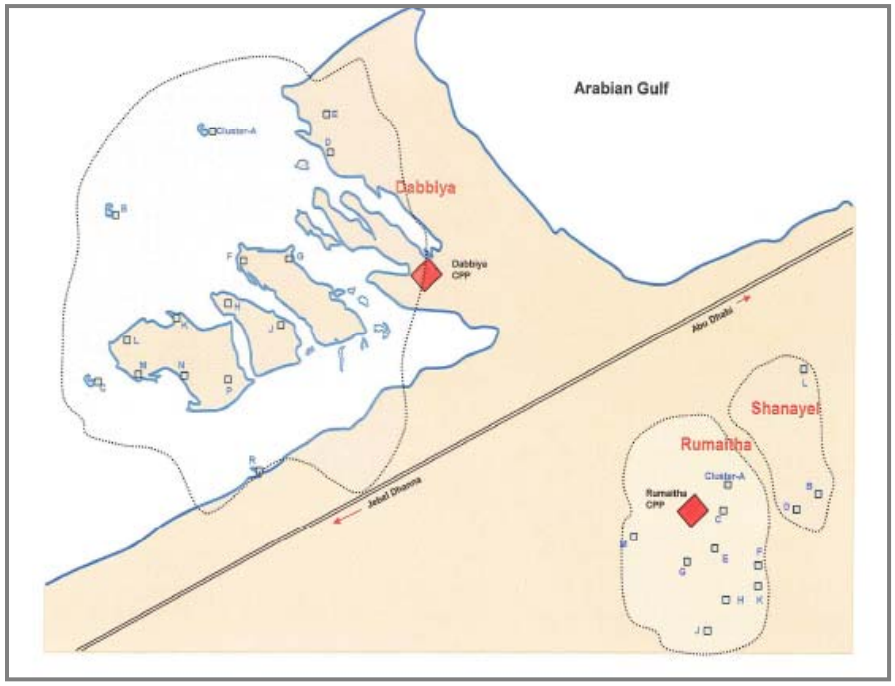
ADCO – CO_2 Pilot

Hydrogen Power Abu Dhabi

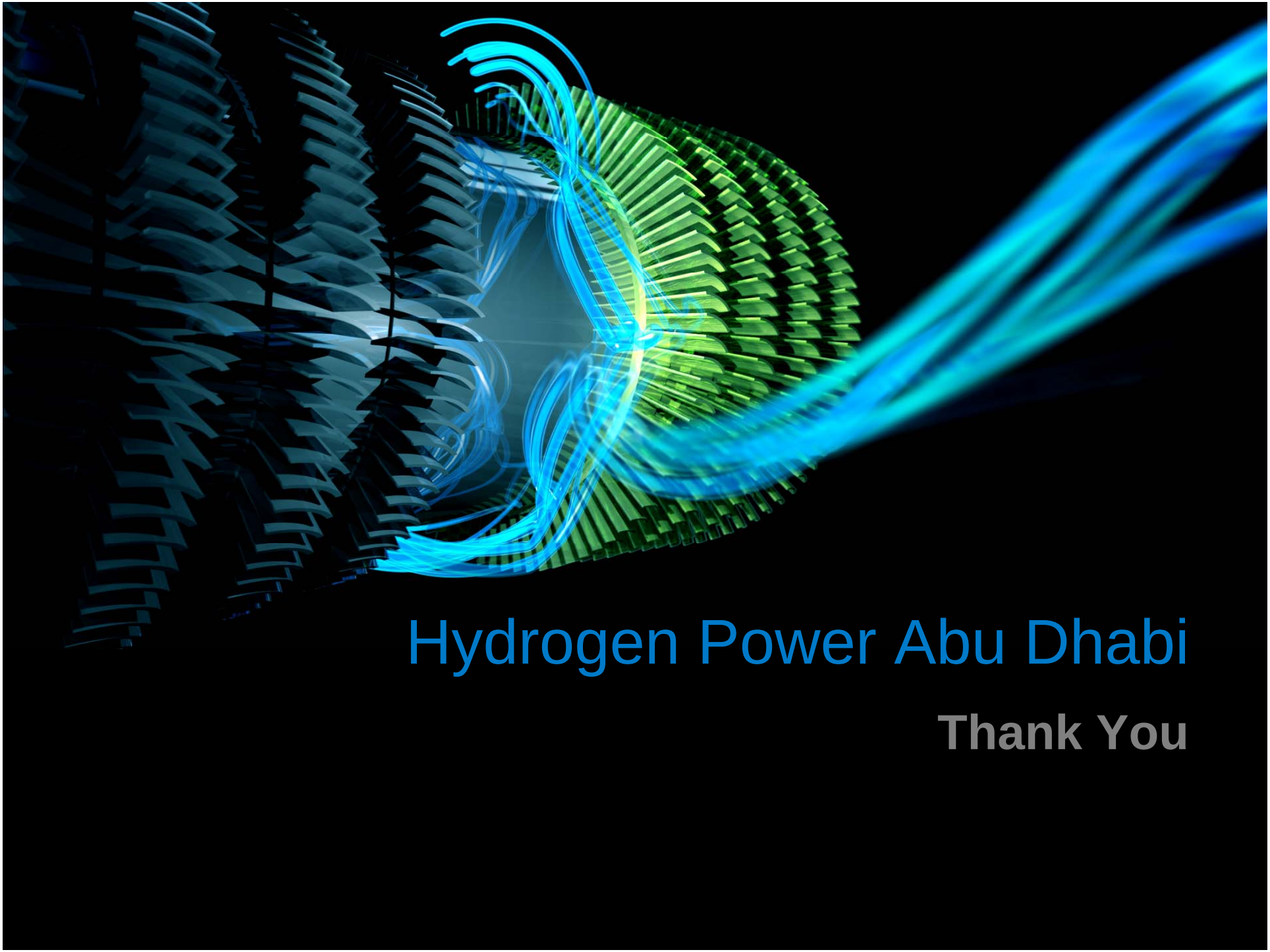
MASDAR مصدر hydrogen energy

CO2 Testing

- Priority is for Masdar to mobilise early CO2 supply chain to service ADCO pilot from Oct 2009
- HEI support of Masdar's early CO2 supply to ADCO (ongoing)
- Praxair under contract for 60t/day CO2 supply
- Design and procurement of equipment is progressing
- Drilling Ra 68 has completed the injection well



Test site located on Rumaitha field



Hydrogen Power Abu Dhabi

Thank You

Health and safety issues

Hazards in CCS operations

Overview

- Safety & Health
  - Hazards associated with CO_2 in CCS
    - Toxicity
    - Low temperature
    - Dry ice erosion
    - High Pressure and corrosion
    - High density
    - Detection
    - Other substances and contaminants

Overview Cont.

- Environment
  - EIA
  - Effects on Flora and Fauna
    - Onshore
    - Offshore

MSDS classifications

CO_2

Label 2.2 : Non flammable, non toxic gas.

SO_2

H_2S

Label 2.3 : Toxic gas.

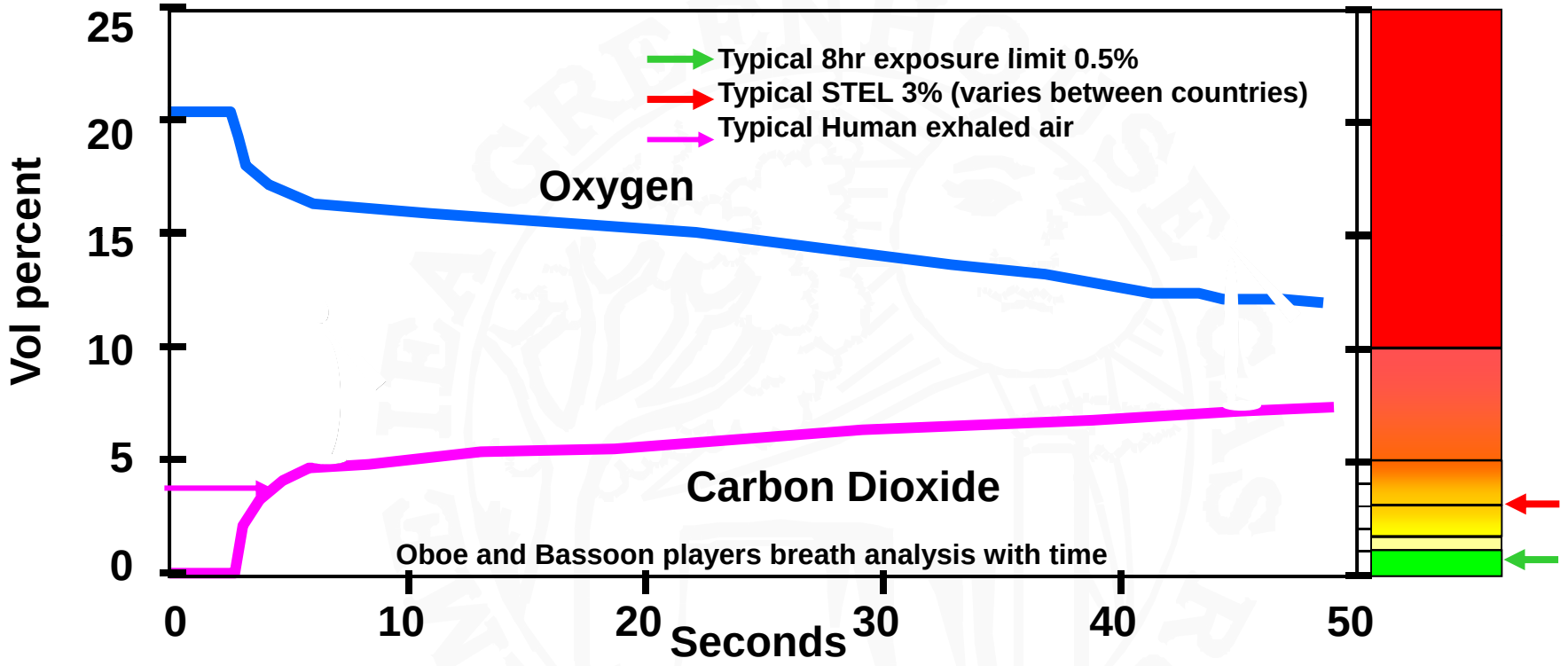
Label 2.1 : flammab gas.

N : Dangerous for the environment

T+ : Very toxic

F+ : Extremely flammable

Health effects of Carbon Dioxide



<1	No effects
1-1.5	Slight effect on chemical metabolism after exposures of several hours
3	Weakly narcotic,deeper breathing, reduced Hearing, headache, increased blood pressure and pulse rate.
4-5	Deeper, more rapid breathing. Signs of intoxication after 30 minutes
5-10	Breathing more laborious, headache and loss of judgement
>10	Unconsciousness in under one minute, further exposure to high levels eventually results in death.

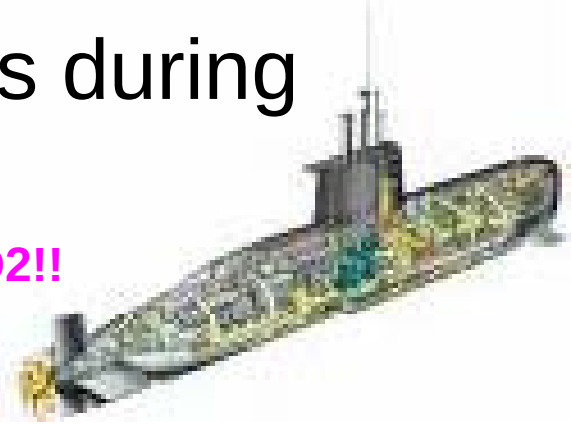
Toxicity of key contaminants

- H2S
  - TLV 10 ppm STEL 15 ppm
- SO2
  - TLV 2ppm STEL 5 ppm
- Hence if H2S> 0.1-0.2% or SO2 > 400ppm these contaminants are potentially more toxic than the CO2

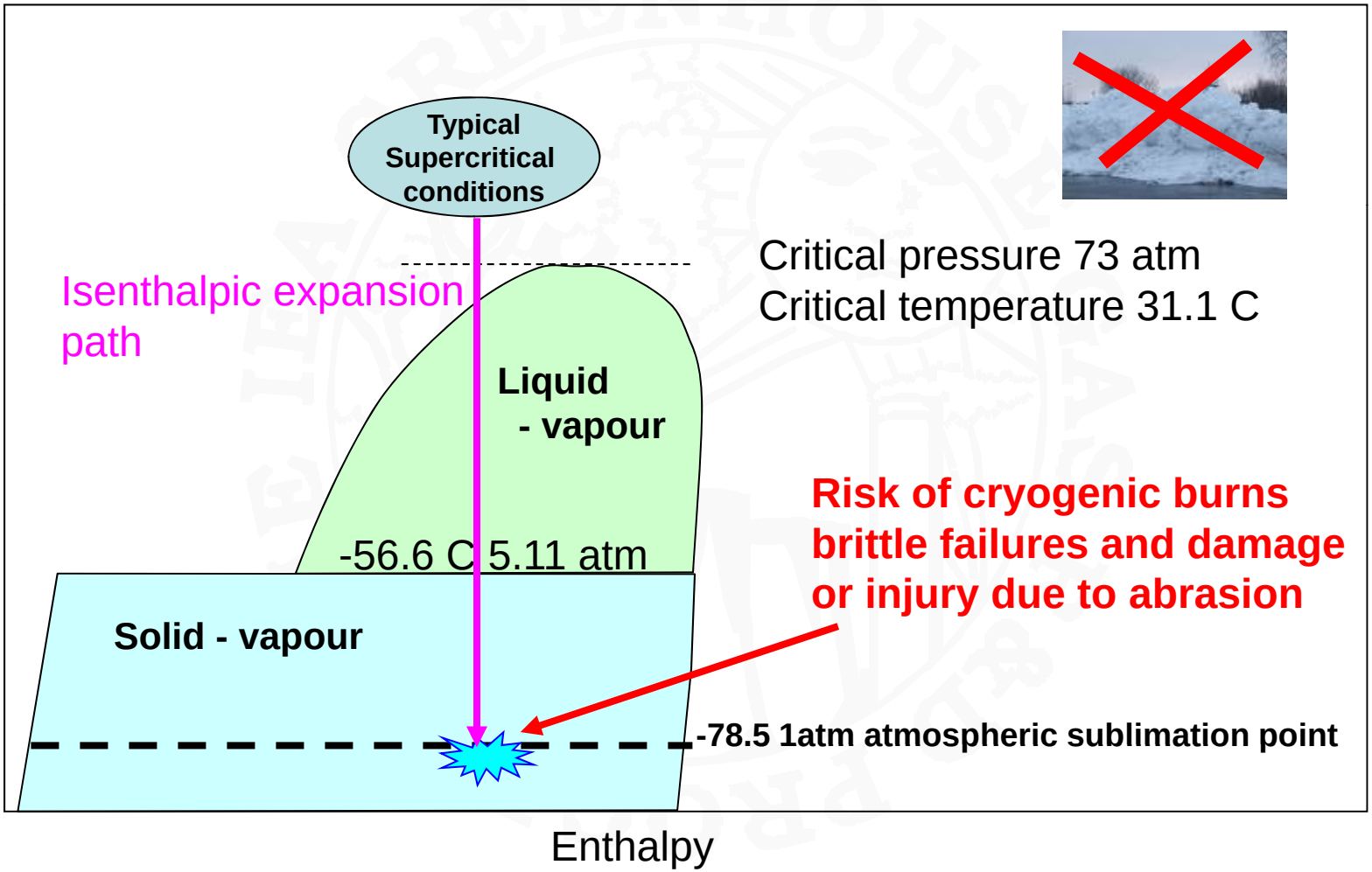
Impairment

- CO_2 can be tolerated in quite high concentrations without permanent risk to health
- BUT if those exposed have key tasks to execute their response may be impaired
- THUS need to consider effects during emergency situations

Atmosphere in submarines is typically 4000ppm CO2!!
Just below the TLV. Crews should not be impaired.
However levels up to 10,000ppm are reported



Low temperature hazard

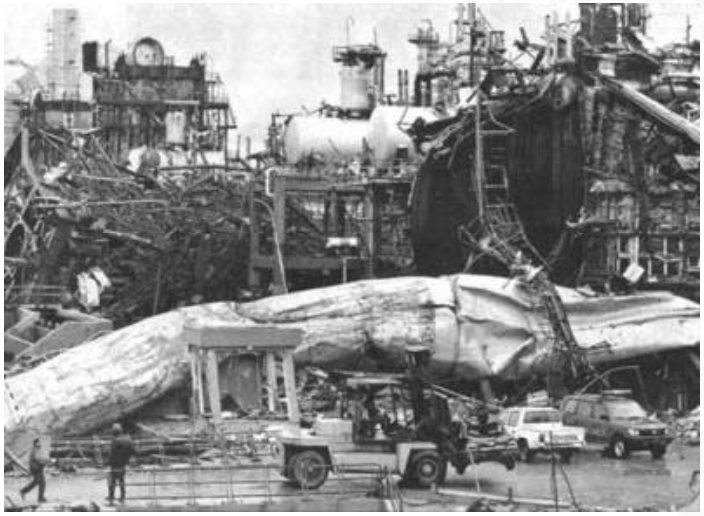


High pressure and corrosion

- Usual risks of vessel or pipe rupture
  - Low temperature embrittlement is a risk factor
- Consequences
  - Flying objects
  - Injuries if hit by jet
- Have to keep CO_2 dry to avoid corrosion
  - Effects of other acid gases – H_2S, SO_2?
- Effects of trace amounts of oxygen
  - Further research needed on O_2 induced corrosion

A running fracture – result of a test

Fractured gasoline line– undetected damage



Results of metal embrittlement

15th January 2009 Vancouver- line rupture

High vapour density

- Vapour accumulates in low points
  - Need to review layouts to identify areas at risk
  - Cold vapour has even higher density and will seek out low areas
  - Need to consider pipeline routes
- Location of safe haven
  - Dilemma offshore – high or low on platform?
- Spill collection
  - Solid floors prevent CO_2 dispersion

Detection issues

- Location of detectors different for heavy gases
- Flammable gas detectors do not detect CO2
  - May not work in CO2 atmosphere
  - Low temperatures can deactivate detectors

Other substances

- Absorption chemicals
  - Amines, can be mildly toxic and mists might be flammable
- Oxygen
  - Cleanliness, concentration limits - oxygen burning of deposits or steel
  - Increased flammability of combustible substances
- Hydrogen
  - Wider explosion limits but faster dispersion

Other substances – cont.

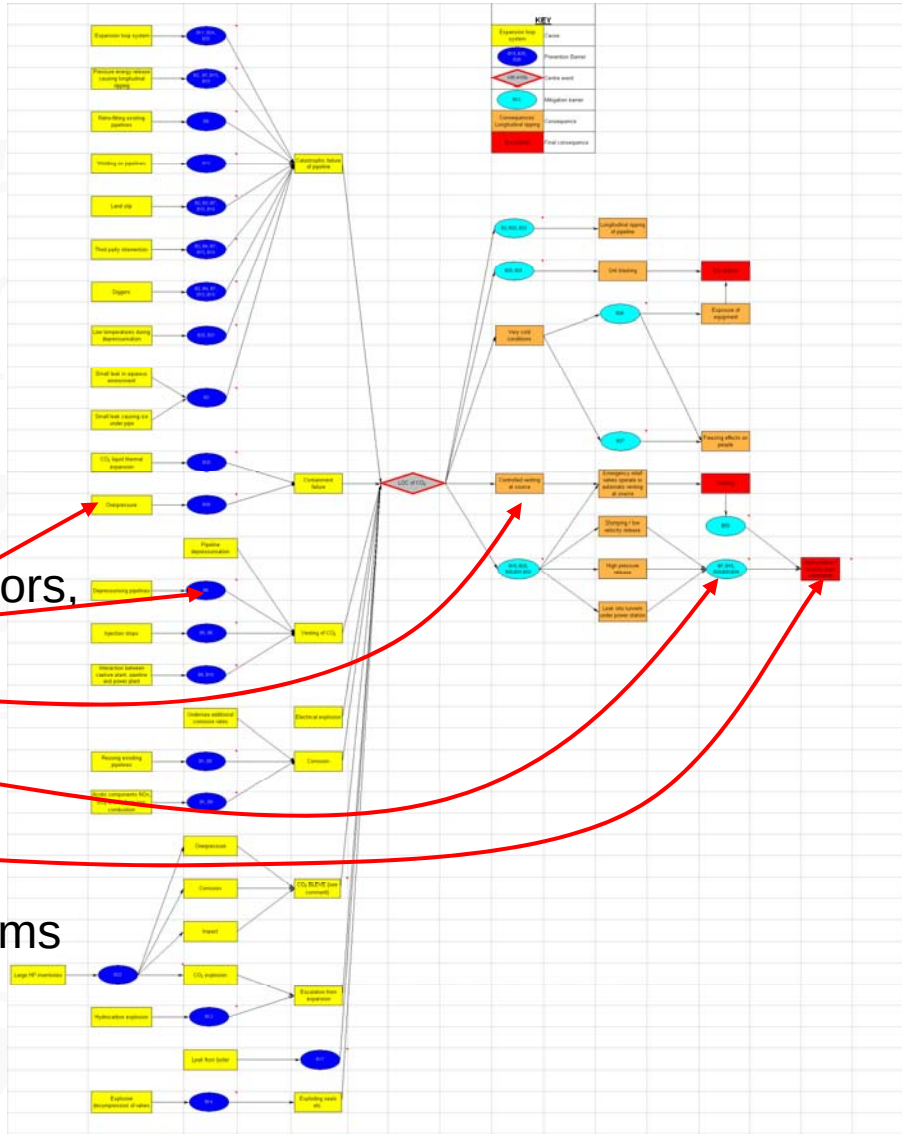
- Ammonia (if chilled ammonia process used)
  - Moderately toxic (TLV25ppm STEL 35ppm)
- Nitrogen – used to dilute hydrogen
  - Increase asphyxiation risk e.g in turbine hood

Putting it all together

IEAGHG conducted a study of safety in CCS
Resulted in identification of potential hazards.

Results are summarized in “Bow Tie” diagrams. These show “top event” initiators, barriers to their development as well as the further consequences, barriers and recovery measures and further escalations.

Computerised interactive generic diagrams have been published with the report.



The biggest risk

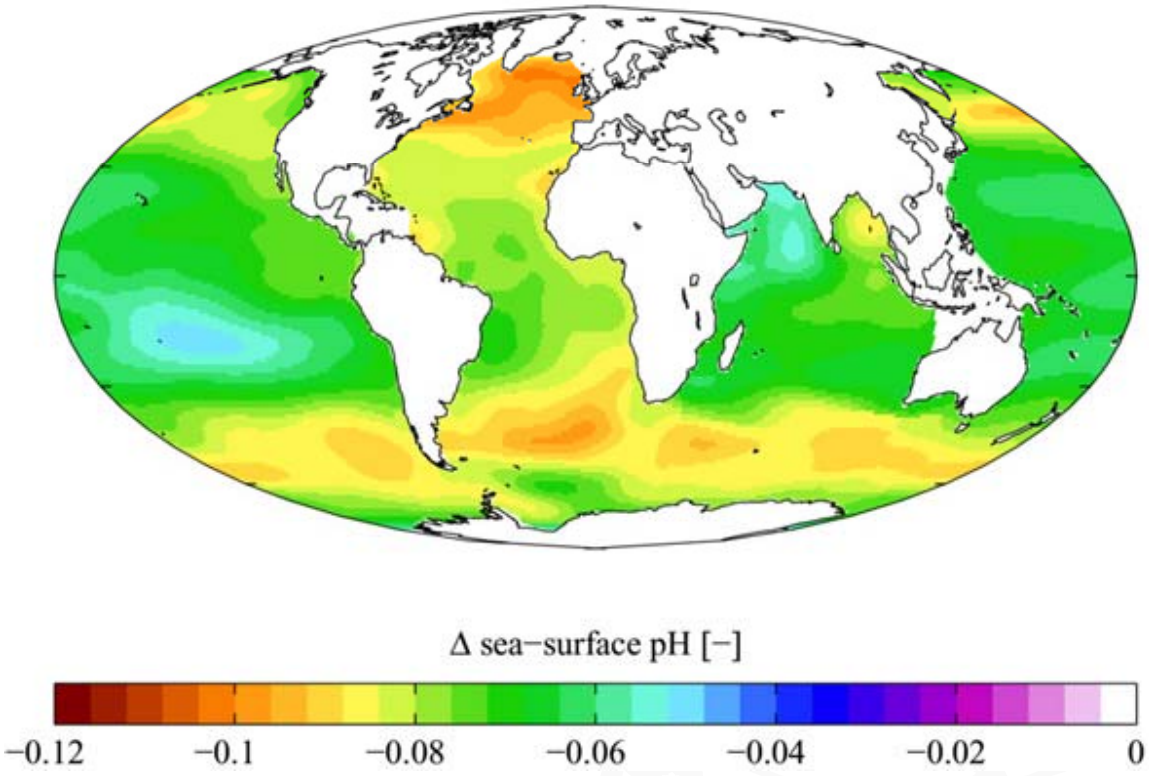
CHANGE

Altering and adapting established designs and practices could be a significant contributor to accidents in the emerging CCS industry

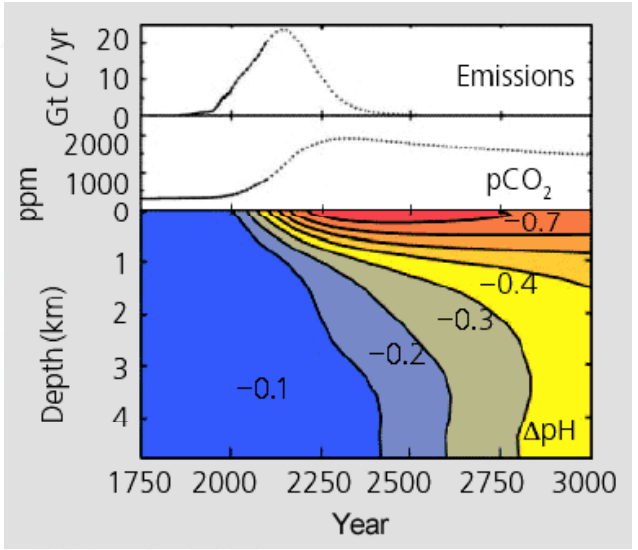
The environment

- IEAGHG study on applicability of EIA
  - Likely to be required for major CCS projects
  - Some effects of CO_2 on flora and fauna not fully researched or documented
- Observations on natural systems show quite high tolerances
  - Most plants OK up to 15-20%, Grasses to much higher.
  - Sea bed effects little understood
  - Reduced ocean acidification due to capturing CO_2 may be the biggest effect (and it is positive).

Typical prediction of future ocean acidification



Change in sea surface pH caused by anthropogenic CO2 between the 1700s and the 1990s



Future predictions of global ocean pH change

Closing remarks

- CCS can be very safe providing:-
  - Safety is given adequate attention from an early stage
  - Good safety management practices are adopted throughout CCS project lifecycles

SAFETY IS ALWAYS GOOD BUSINESS

ECN

Energy research Centre of the Netherlands

Overcoming barriers to CCS

Heleen de Coninck

CCS workshop, November 18th, 2009, Algeria

www.ecn.nl

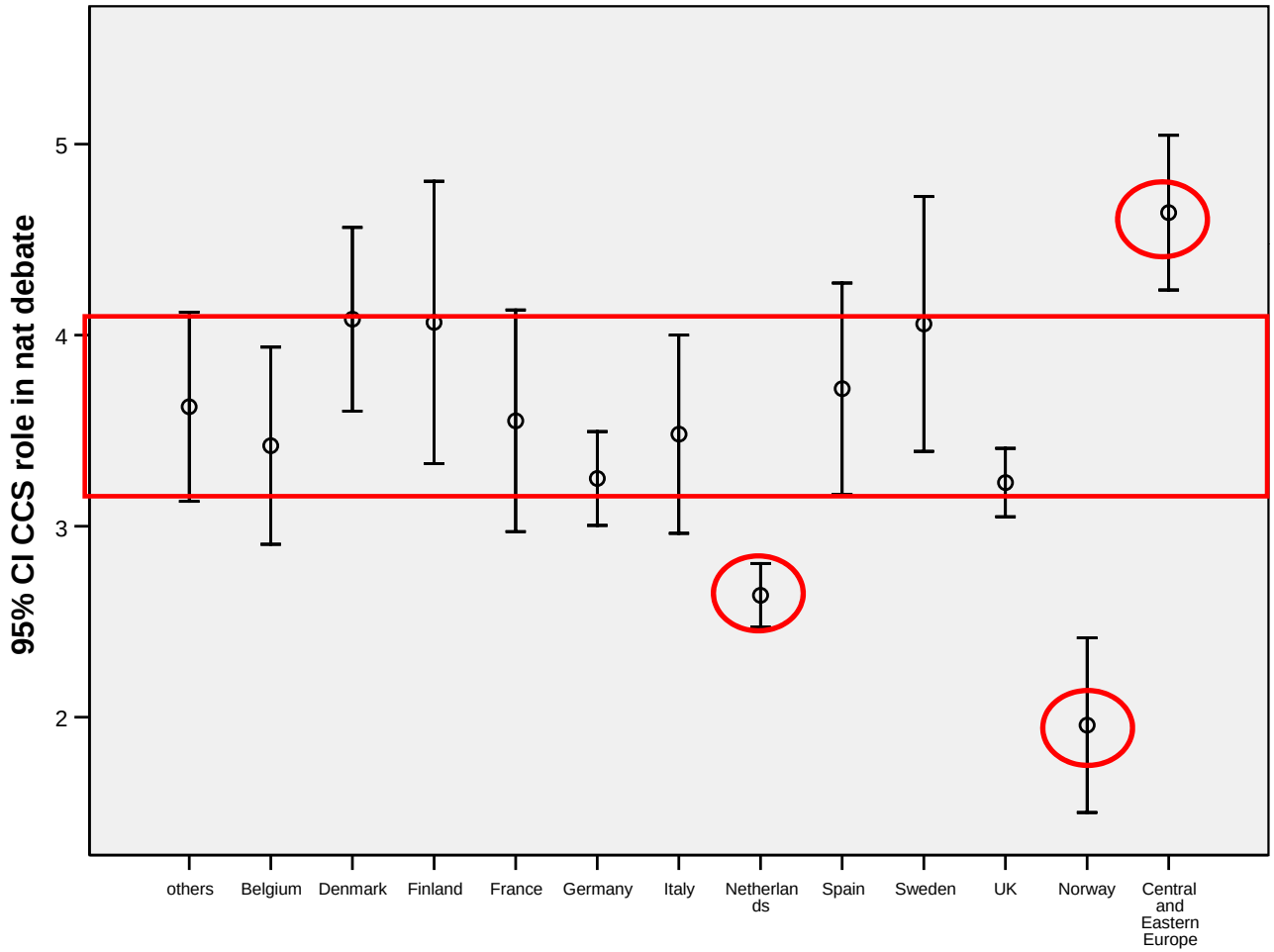
How to identify barriers?

- Surveys
- Policy research
- Observations and reconstructions existing projects
- Brainstorm

Understand the problem to arrive at a solution

ACCSEPT project: survey results (2007)

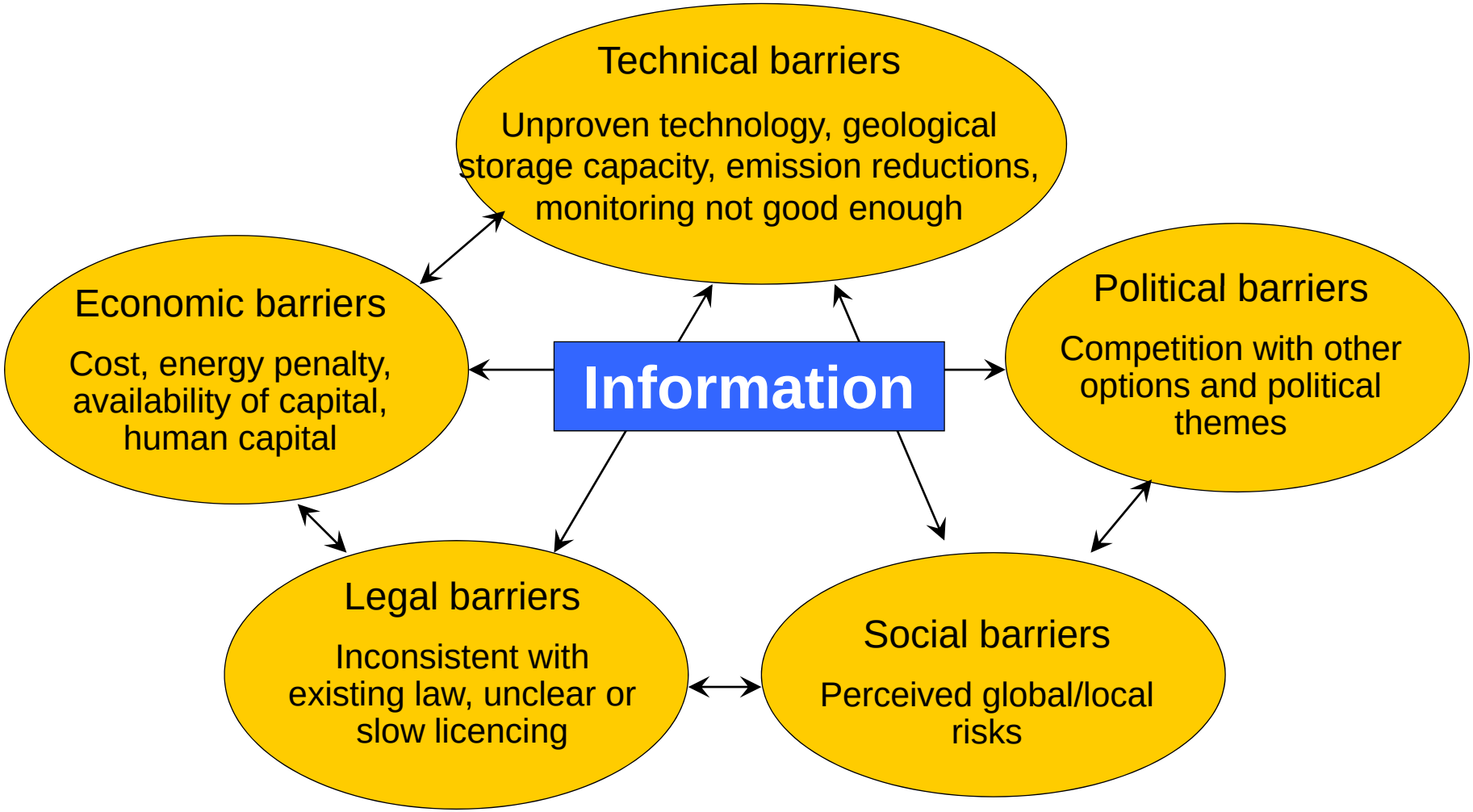
- Stak
- Gove
- Neec
- Sign
  acro



Barriers most often mentioned

- availability of suitable geological storage sites
- price of carbon under EU ETS
- reduction in costs of CO_2 capture
- development of R&D base
- a post-Kyoto phase with tighter national emission reduction requirements
- development of legal & regulatory basis
- public perceptions

Overview of barriers



Role of information

- Public, political and stakeholder awareness
- Information on costs with policymakers and operators
  - Information basis seems large but in reality is quite small and rarely based on real data
  - Variation: Fuel and material costs
  - Confidentiality of information
  - Optimism in cost assessments
  - Incorporating technological and policy risks in decisions, depending on external developments

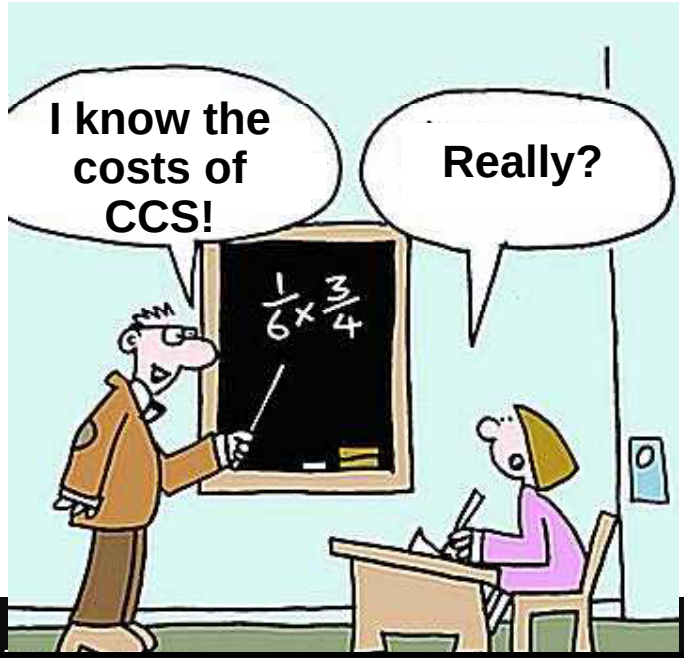
- We don't know what we don't know
  - ➢Unlikely or hidden barriers are hard to address

Do we know what CCS costs?

When someone tells you he knows the costs of CCS:

1) Be sceptical
2) Ask questions on the project specifics
3) Ask questions on the underlying assumptions
4) Apply rule #1

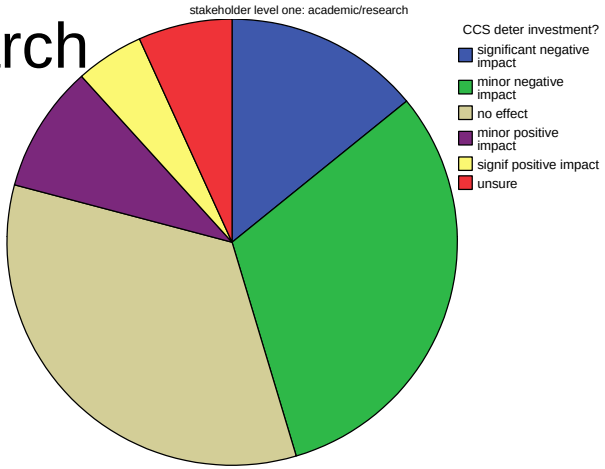
Rehearse this!

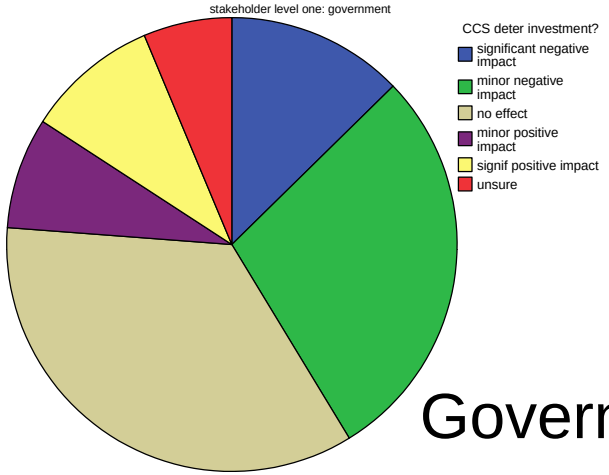


Not hard science…

Impacts of CCS investment upon investment in other LZCTs?

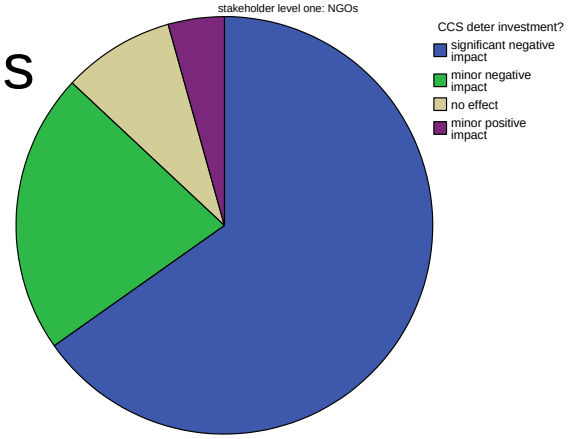
Research

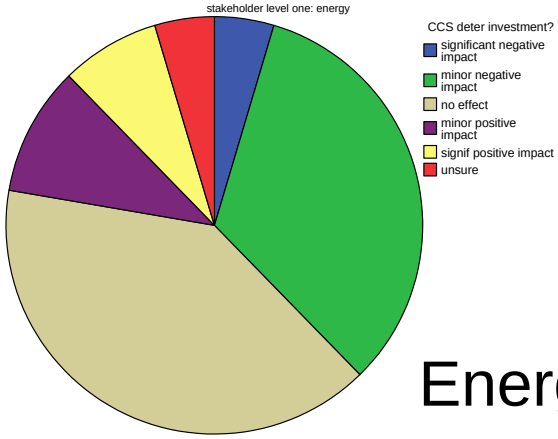




Government

NGOs





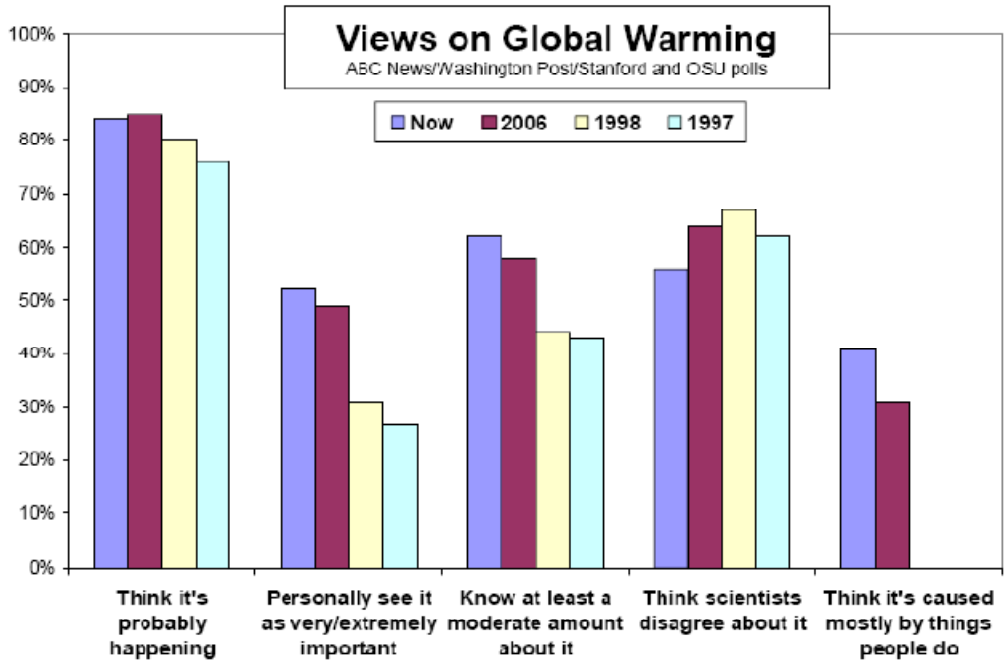
Energy

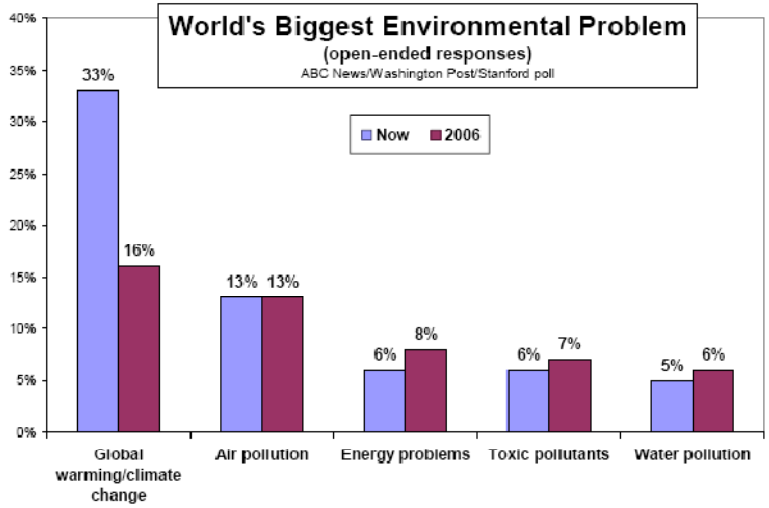
Perception of CCS is important

Perception of CCS is important

Public awareness of climate change

- Curry et al (2007): environment 11th highest ranked priority for Americans
- Palmgren et al (2004): “Reducing climate change” lowest social priority of the 15 choices provided





Public awareness of CCS

- Low awareness in Australia, USA, Japan, Canada, UK, Sweden, France, Germany, the Netherlands:

  Between 4% and 29.9% can give some kind of answer as to what CCS is.

  (*Ashworth et al, 2006, 2009; de Best-Waldhober et al, 2006, 2008; Ha Duong et al, 2009; Itaoka et al, 2008; Reiner et al, 2006; Sharp et al, 2006)*

- Dutch representative samples in 2004, 2005, 2007, 2008: No increase in awareness over time

Measuring public opinion of unknown technology

Many researchers inform their respondents

- In focusgroups with experts explaining
- In surveys with information to read or to evaluate

Both difficult and time consuming, risk of bias

➢Issue: lay ideas that experts would have never guessed

Instinctive responses

"Carbon dioxide could change the DNA of organisms, and this will cause a vicious circle" (by a chemist!)

"Leakage could lead to bad air, health problems for people living nearby, for example lung cancer"

(Wallquist et al, 2009)

"This is among the DUMBEST ideas that I've ever seen. There is no way anyone with a brain would ever get near a suffocation pocket like that."

"… when I was a kid in school I seem to recall being taught plants eat CO2 and crap out oxygen...maybe we need to plant more plants to eat all the CO2? probably too simple an idea, Shell can't make a profit on it!"

(Houston Chronicle website, day before yesterday)

Public perception may not be what you think

- Take the perspective of a lay person living near a potential storage site
  - What is this technology? Sounds scary.
  - I wonder: why me?
  - Worried about safety, the value of my property
  - The experts do not make the impression that they understand my concerns
  - Nobody is listening
- Stop convincing, start involving

Barendrecht, the Netherlands

Actors:

- Shell and NAM
- Dutch government
- Barendrecht city council
- Greenpeace and Green party
- EIA commission

CO_2 from refinery, storage in depleted gas fields

EIA conducted and approved

Information meeting

Fully legal: what went wrong?

What went wrong? (tentative…)

Government and Shell in a hurry, seemed the ideal project

Environmental Impact Assessment

- Information or consultation?
- Who pays for the EIA?
- Who provides information?
- What kind of information?

Public relies on trusted sources

Barendrecht already under pressure

Industry, government afraid of public

The role of CCS experts

- CCS community: a multidisciplinary mix of academic researchers, policymakers, service companies, power sector, manufacturers, etc.
- “Group think” can be observed:
  - Leading to strong, coherent message to policymakers
  - As a community: possibly blind to drawbacks, selective listening and dismissing certain categories of criticism
- Public trust needs an independent expert community that improves, not promotes the technology
- **Including YOU!**

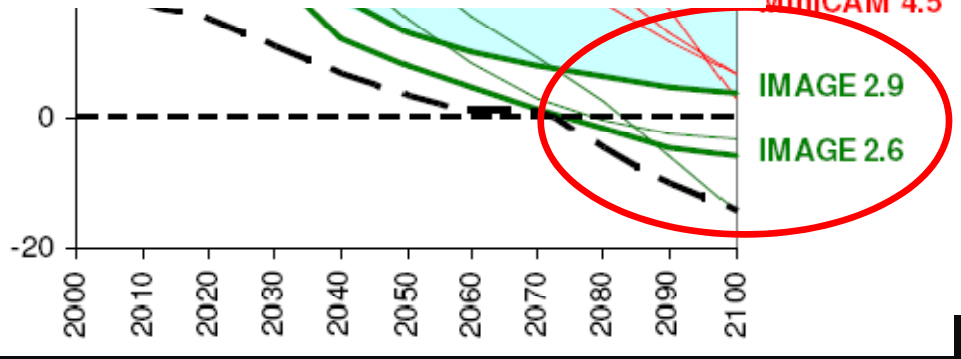
CCS: are emission reductions sufficient?

Scenario category	Region	2020	2050
A-**450** ppm CO_2 –eq[b]	Annex I	**–25% to –40%**	**–80% to –95%**
	Non-Annex I	Substantial deviation from baseline in Latin America, Middle East, East Asia and Centrally-Planned Asia	Substantial deviation from baseline in all regions
B-**550** ppm CO_2 - eq	Annex I	**–10% to –30%**	**–40% to –90%**
	Non-Annex I	Deviation from baseline in Latin America and Middle East, East Asia	Deviation from baseline in most regions, especially in Latin America and Middle East
C-**650** ppm CO_2 - eq	Annex I	**0% to –25%**	**–30% to –80%**
	Non-Annex I	Baseline	Deviation from baseline in Latin America and Middle East, East Asia

MES-A2R 8.5

AIM 6.0

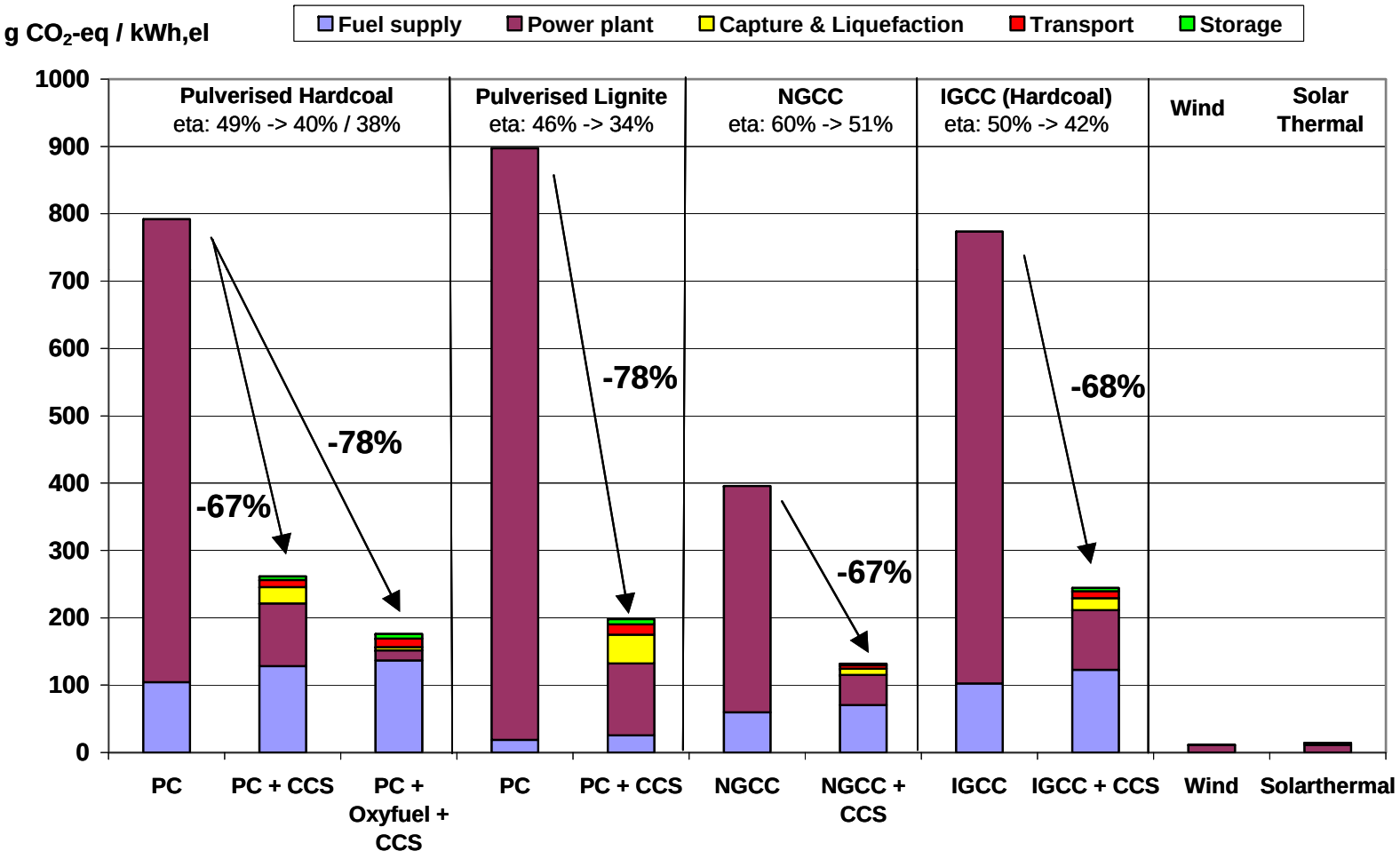
MiniCAM 4.5



Negative emissions required

Den Elzen and Hoehne (2008); van Vuuren (2009)

CCS: are emission reductions sufficient?

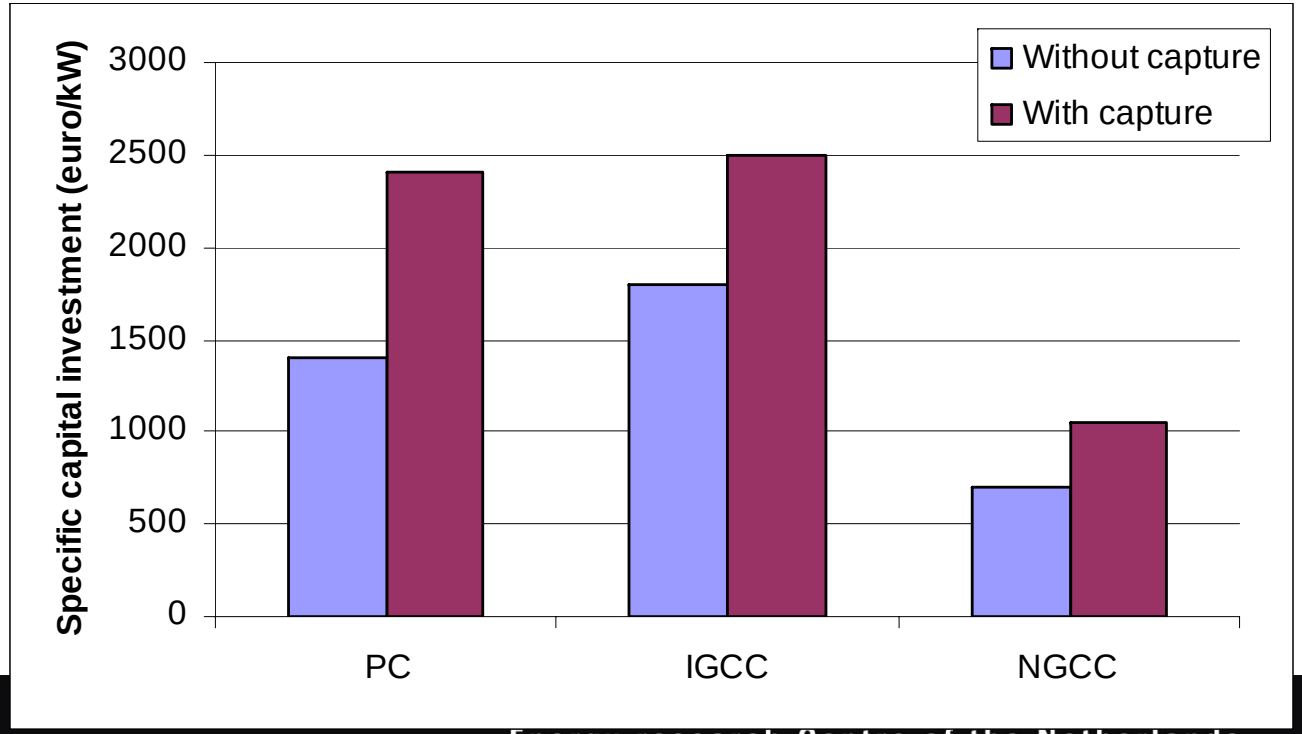


Finance does not equal costs

Numbers expressed in US$/kWh or US$/tCO_2 hide the distribution between capital and O&M costs

Competition for capital based on return on investment

Capital-intensive options require different incentives



Source: Seebregts and Groenenberg, 2008

Take-home messages

Delving into barriers is useful

- Explains why things are not happening
- Provides basis for a solution
- Identify areas of further research
- Basis for policy, legislation and practices in industry
- Moving field: new barriers emerge and go away

Independent experts have a responsibility to be critical of CCS, to see, highlight and repair the disadvantages

What is the most unlikely CCS barrier you can think of?

Thank you!

Heleen de Coninck: deconinck@ecn.nl

IEA Greenhouse Gas R&D Programme

What have we learnt from large-scale CCS demonstration projects?

Neil Wildgust, Tim Dixon

OPEC-IEA GHG CCS workshop for scientists and professionals in OPEC Member Countries

Hassi Messaoud, Algeria

16th – 19th November, 2009

What have we learnt to date - projects?

- Review current operational large-scale CCS projects
  - Assess learning from projects
  - Identify gaps in the global CCS project portfolio
- Focus on projects relevant to full-commercial scale operation
  - Includes:
    - Large-scale pilot
    - Demonstration
    - Commercial
  - Excludes
    - Small and medium pilot
    - Lab scale
  - Define criteria – Identify projects – Collect information - Analyse

Criteria for large-scale operational projects

- Indicative criteria defined for ‘large-scale operational projects’
- Was, or had been, operational by the end of 2008, and either:-
  - Captured over 10,000 tCO_2 per year from a flue gas
  - Injected over 10,000 tCO_2 per year with the purpose of geological storage with monitoring
  - Captured over 100,000 tCO_2 per year from any source
  - Coal-bed storage of over 10,000 tCO_2 per year
- *Commercial CO2-EOR was excluded unless there was a monitoring programme to provide learning*
- *Did not need to be fully integrated*
- Added term ‘*large-scale operational*’ to IEA GHG Projects Database

Projects identified

Bellingham Cogeneration Facility	IFFCO CO2 Recovery Plant – Aonla
CASTOR Project	Prosint Methanol Plant
Great Plains Synfuel Plant	Rangely CO2 Project
IMC Global Soda Plant	Schwarze Pumpe
In Salah	SECARB - Cranfield II
K12-B	Shady Point Power Plant
Ketzin Project	Sleipner
MRCSP - Michigan Basin	Snohvit LNG Project
Nagaoka	SRCSP - Aneth EOR-Paradox Basin
Otway Basin Project	SRCSP - San Juan Basin
Pembina Cardium Project	Sumitomo Chemicals Plant
Petronas Fertilizer Plant	Warrior Run Power Plant
IFFCO CO2 Recovery Plant - Phulpur	Weyburn
Chemical Co. “A” CO2 Recovery Plant	Zama EOR Project

Projects identified

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- Capture over 100ktCO_2
- Injection over 10ktCO_2 for storage
- Monitored EOR over 10ktCO_2
- Capture over 10ktCO_2 from flue gas
- Coal bed storage over 10ktCO_2

Project Locations

- Capture over 100ktCO_2
- Injection over 10ktCO_2 for storage
- Monitored EOR over 10ktCO_2
- Capture over 10ktCO_2 from flue gas
- Coal bed storage over 10ktCO_2

Extent of coverage vs ZEP project matrix

Archetype 1	• Lignite/co-firing with Biomass	• Pre-combustion, variant A	• Cross-border pipeline	• Offshore depleted oil & gas field
Archetype 2	• Gas	• Post-combustion, variant A	• Pipeline	• Onshore structural deep saline aquifer
Archetype 3	• Hard Coal	• Oxy-fuel, variant A	• Ship	• Offshore open deep saline aquifer
Archetype 4	• Hard Coal	• Post-combustion, variant A	• Pipeline	• Onshore depleted oil & gas field
Archetype 5	• Lignite	• Oxy-fuel, variant B	• Pipeline	• Onshore structural deep saline aquifer
Archetype 6	• Hard Coal	• Pre-combustion, variant B	• Pipeline	• Offshore depleted oil & gas field
Archetype 7	• Hard Coal	• Post-combustion, variant B	• Pipeline	• Onshore open deep saline aquifer

Demonstrated in operational large projects

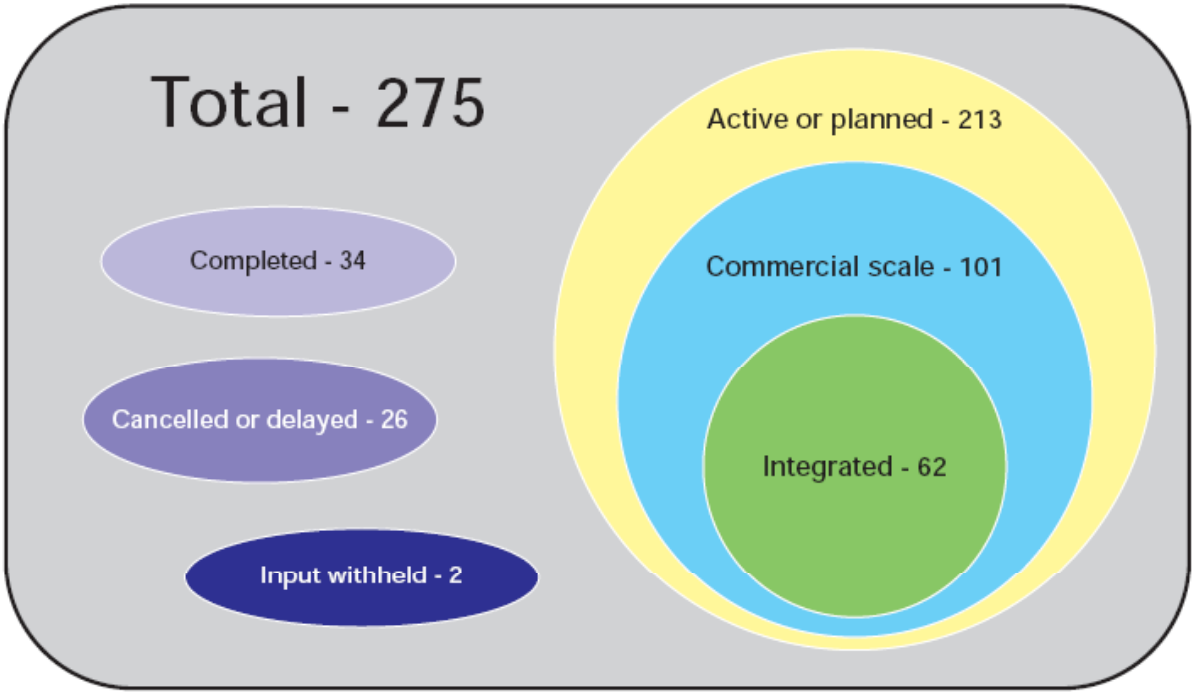
Not demonstrated in operational large projects

Project matrix courtesy of EU Technology Platform for Zero Emission Fossil Fuel Power Plants - ZEP (2008)

Extent of Coverage

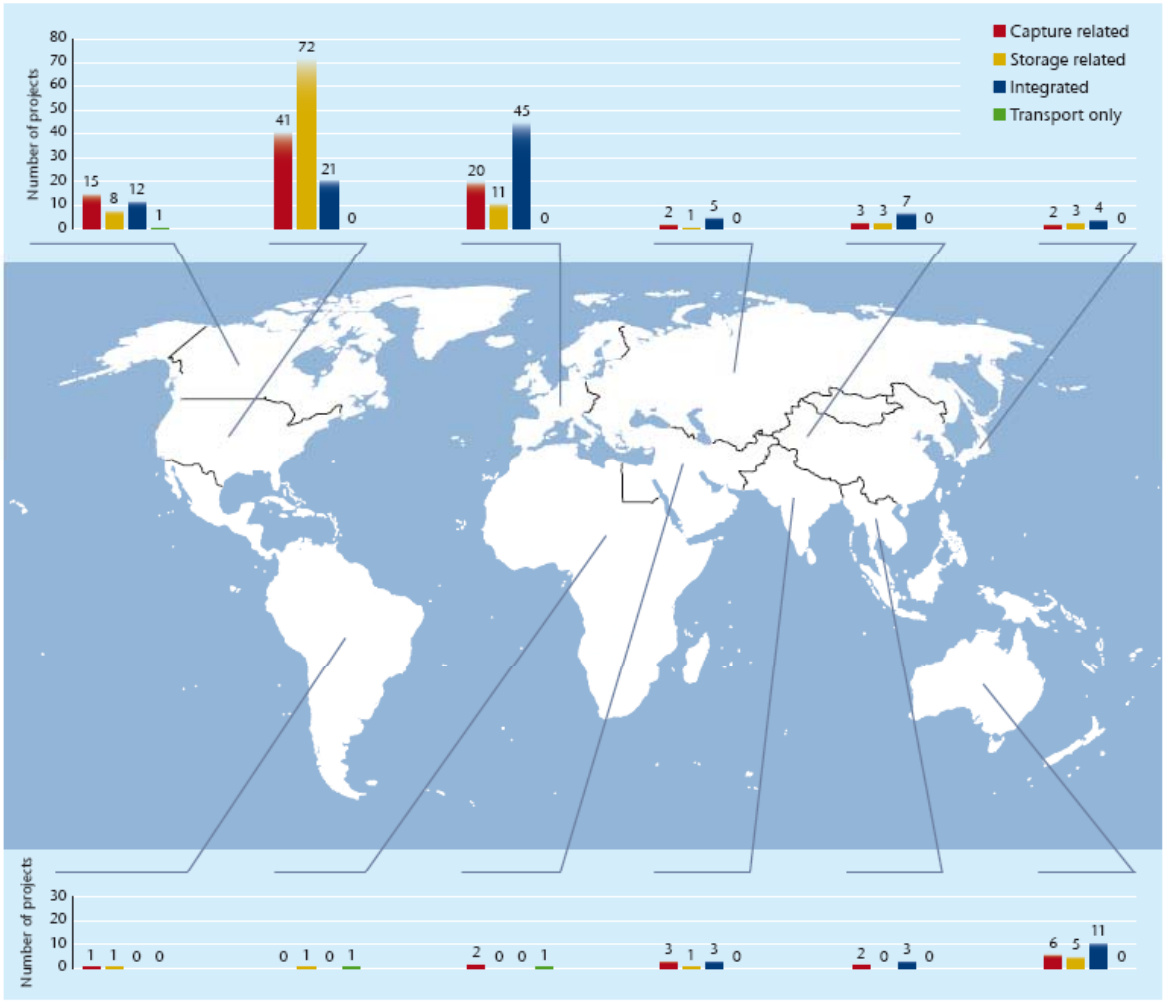
- If integrated CCS from electricity production is a 4 link chain:
  - Electricity production
  - Capture
  - Transport
  - Storage
- 2 and 3 link chains have been demonstrated over 1Mt CO_2 per year

Current Status of CCS Projects



Source: Strategic Analysis of the Global Status of CCS. Report 5. GCCSI report. May 2009

Planned and operational large-scale CCS projects



62 planned and 7 operational large-scale integrated CCS projects

Source: Strategic Analysis of the Global Status of CCS. Report 5. GCCSI report. May 2009

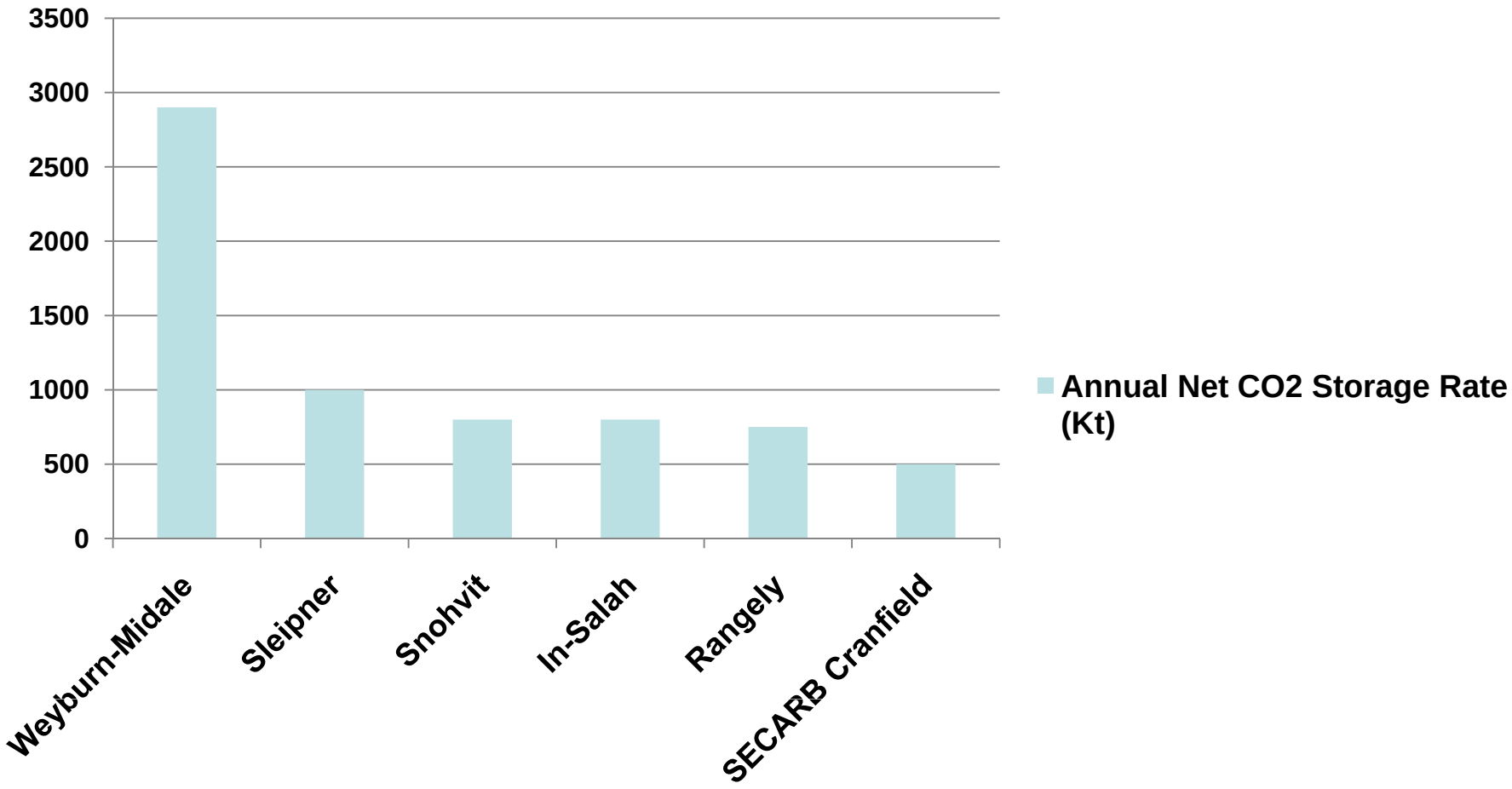
Operational large-scale CCS projects

Project	Country	Capture	Transport	Storage	CO2 storage rate
Rangely	USA	NG processing	285 km pipeline	EOR	1.0 Mtpa
Sleipner	Norway	NG processing	Pipeline	Geological	1.0 Mtpa
Valverde	USA	NG processing	132 km pipeline	EOR	1.0 Mtpa
Weyburn	Canada	Precombustion	330 km pipeline	EOR	2.4 Mtpa
In Salah	Algeria	14	285 km pipeline	Geological	1.2 Mtpa
Salt Creek	USA	NG processing	201 km pipeline	EOR	2.4 Mtpa
Snohvit	Norway	NG processing	160 km pipeline	Geological	0.7 Mtpa

Extent of coverage - Transport

- Pipeline
  - Single sink source pipelines
  - Multiple source-multiple sink pipeline networks
- Truck
- Cross-border transport
- Transport over 860km

Net CO_2 Storage per Year



Extent of coverage – Monitoring

- 2D seismic
- 3D seismic
- 4D seismic
- Vertical seismic profiling
- Cross-well seismic
- Electrical conductivity
- Microseismic
- Passive seismic
- Soil gas sampling
- Detector arrays
- Eddy covariance
- Observation wells
- Time lapse microgravity
- Well temperature and pressure
- Well logs
- Tracers
- Ground water geochemistry
- Interferometry
- Satellite imaging
- Tilt meters

Common Monitoring Techniques

Technique	No of Sites	Positive comments	Negative comments
DH temp/pressure	11		
Surface seismic	10	2	3
Soil gas	9		
Geochemical	8	1	
VSP	8		1
Microseismic	7		1
Gravity	4		1
Crosswell seismic	3	1	1
Electrical Conductivity	3	1	
Satellite	3	1	

Questionnaire Comments on Surface Seismic (*Site-Specific!*)

- "Seismic is unlikely to be cost-effective in the long run"
- "Glacial till cover made seismic difficult to use"
- "A recent attempt at 3D seismic did not reveal useful information – so we do not consider effective for monitoring CO_2 floods"
- "The seismic survey clearly demonstrated an ability to detect anomalies in the reservoir caused by CO_2 invasion"
- "Detecting pressure propagation using seismic signals is sometimes easier than detecting the CO_2 itself"
- "Pre-injection surface seismic MIGHT have made subsequent seismic more useful"

Emerging Themes

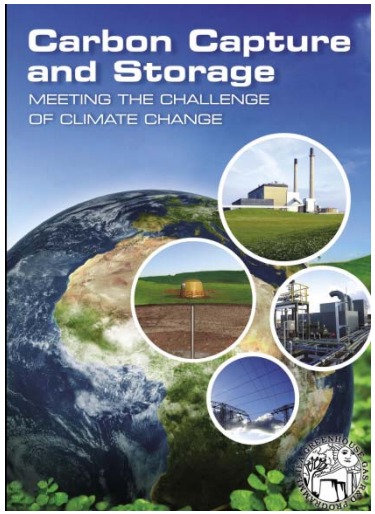
- **Injectivity** – importance, problems, solutions
- **Material corrosion** – less than anticipated
- **Seismic**
  - Effective for monitoring the CO_2 plume - where it can be used
  - Not quantitative beyond a certain resolution
  - Expensive
- **Other monitoring** – e.g. electrical conductivity viewed as promising; desire for better direct sampling at reservoir conditions; can we move from R&D to commercial suite of tools?

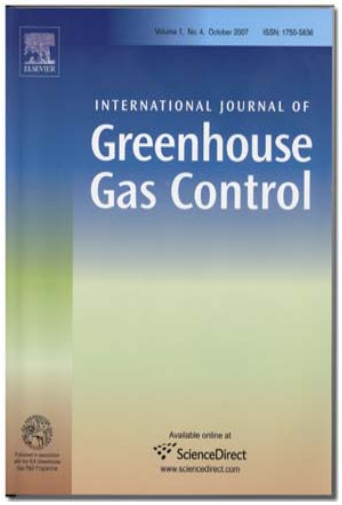
Conclusions

- Elements of CCS are operating at large scale
- Integrated CCS is operating at large scale, just not from power plant
- **There is a lot that has been learnt from existing projects, but more can be done to share the learning**
- CCS industry can build on existing projects' experience
- Increased IPR issues may limit knowledge sharing

IEA Greenhouse Gas R&D Programme

- General - www.ieagreen.org.uk
- CCS - www.co2captureandstorage.info
- GHGT – www.ghgt.info





OPEC-IEA Workshop

Hassi Messaoud, 16-20 Nov. 2009

Can CCS be PART of an integrated, sustainable, secured energy system?

Group 1

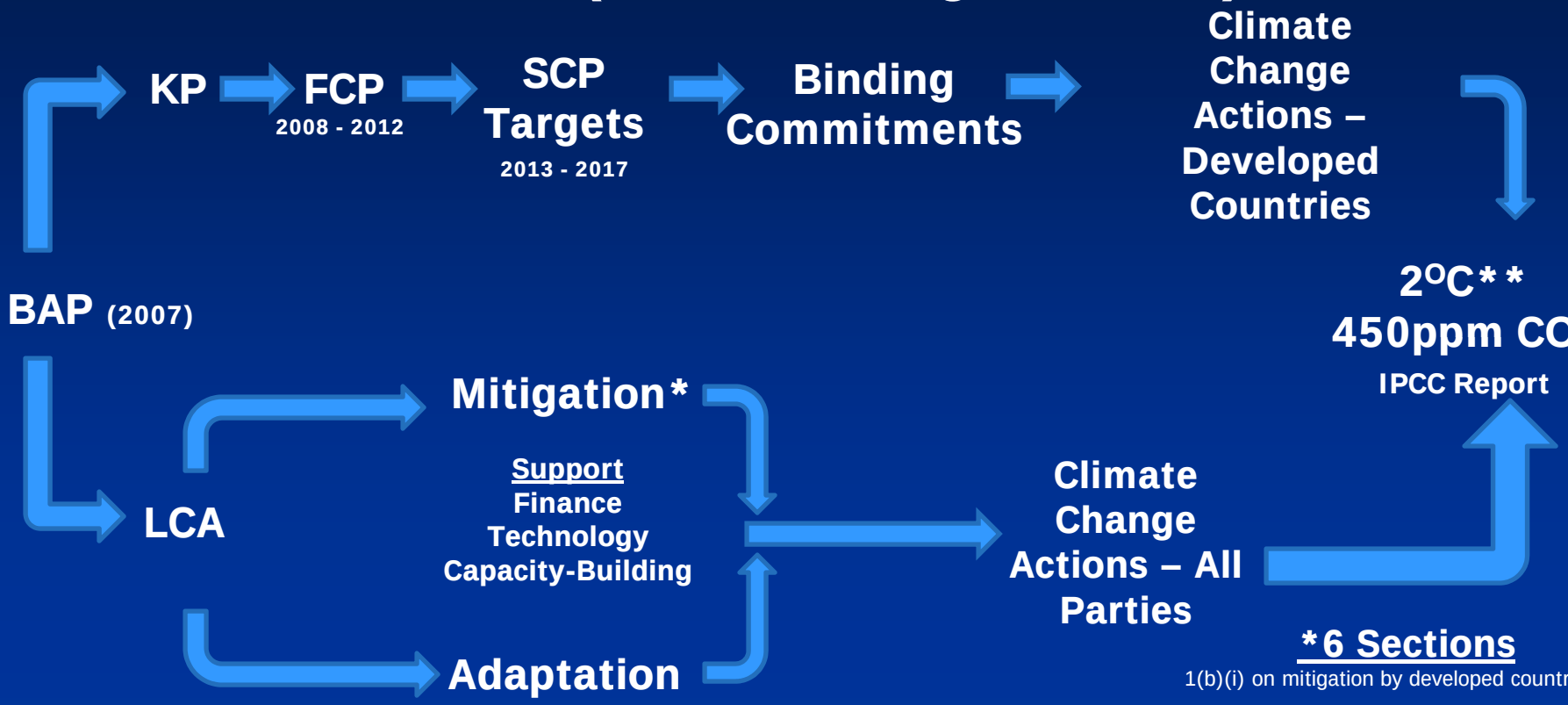
Outline

- UNFCCC negotiations
- Commitment
- Integration
- SD
- Energy security
- Challenges
- Players
- Conclusions

Definitely YES!

But...

Climate Change Overview of the Process(UNFCCC negotiations)



***6 Sections**

1(b)(i) on mitigation by developed countries;

1(b)(ii) on mitigation by developing countries;

1(b)(iii) on reducing deforestation and forest degradation in developing countries, plus conservation (REDD-plus);

1(b)(iv) on sectoral approaches;

1(b)(v) on various approaches to enhance the cost-effectiveness of mitigation action, including markets; and

1(b)(vi) on consequences of response measures

** Many scenarios- 350/400ppm CO_2 - Deep cuts

Why CCS?

- Global warming happening & agreed on by most countries
- Stabilization levels – 450 ppm & 2^{o} C CO_2 by 2030
- As of now, UNFCCC - Climate Change authority & IPCC is the scientific advisory body to UNFCCC
- IPCC- 40% emission reduction from 1990 level by 2030.(4^{th} assessment report)
- CCS could be 70ppm technology(by end of this century)- & each year delay- add 1ppm of CO_2
- IEA report – CCS would account 20% (?) of GHG emission reduction by 2050.

CO_2 Abatement- (450 ppm scenario at 2030)

	Abatement (Mt CO_2)		Investment ($ 2008 billion)	
	2020	**2030**	**2010-2020**	**2021-2030**
Energy efficiency	**2517(65%)**	**7880 (57%)**	**1999(73%)**	**5586 (60%)**
End use	2284	7145	1933	5551
Power plants	223	735	66	35
Renewables	680	2741	527	2260
Biofuels	57	429	27	378
Nuclear	493	1380	125	491
CCS	**102 (3%)**	**1410 (10%)**	**56(2%)**	**646(7%)**

Annex I countries -Information on QELRO of select countries under Kyoto Protocol- (Based on FCCC/KP/AWG/2009/10/Add.4/Rev.2) dt. 19th Oct.2009

Country	Present commitment	Other conditions /Remarks
New Zealand	10-20% below 1990 values by 2020	Officially announced.
Australia	5- 15 % or 25% below 2000 values by 2020	5- 15 % based on previous policy commitment 25% - May 4th announcement by PM. Officially announced.
Canada	20% below 2006 levels by 2020 60-70% of 2006 level by 2050	Officially announced
EU-27	20% below 1990 values by 2020 30% below 1990 values	20%- LULUCF Not included 30%- LULUCF Included and **if other developed and advanced developing countries reduce. Adopted legislation**
Japan	25% below 1990 levels by 2020	Officially announced
Norway	40% below 1990 levels by 2020	Officially announced.

Integration

For	Against
Co- exist with all other mitigation technologies	Only few countries could implement (Coal, oil & gas)
Power companies can merge with Oil companies	Beneficial to only large Corporates.
Carbon markets -Sectoral crediting /trading	Carbon markets will fall due to high supply- not supportive - many developing countries
Achieving the commitment will be easier for the developed countries	No commitment as of now for developing countries- common but differentiated responsibility – **No driving force**

Sustainability
(Social, Economic & environment)

For	Against
Society- helps in creating more jobs	Little direct impact on local people and in general for the most developing countries
Economic- Internationally may competitive in the longer run and new market development CDM and other incentives	Economic implications – Energy price will increase, trade barriers due to conditions
Environment- clean energy. Reduce global warming Studies done prove the integrity of the solution (QRA, EIA)	Effects due to potential leakage and Liability. Regulatory system not yet developed

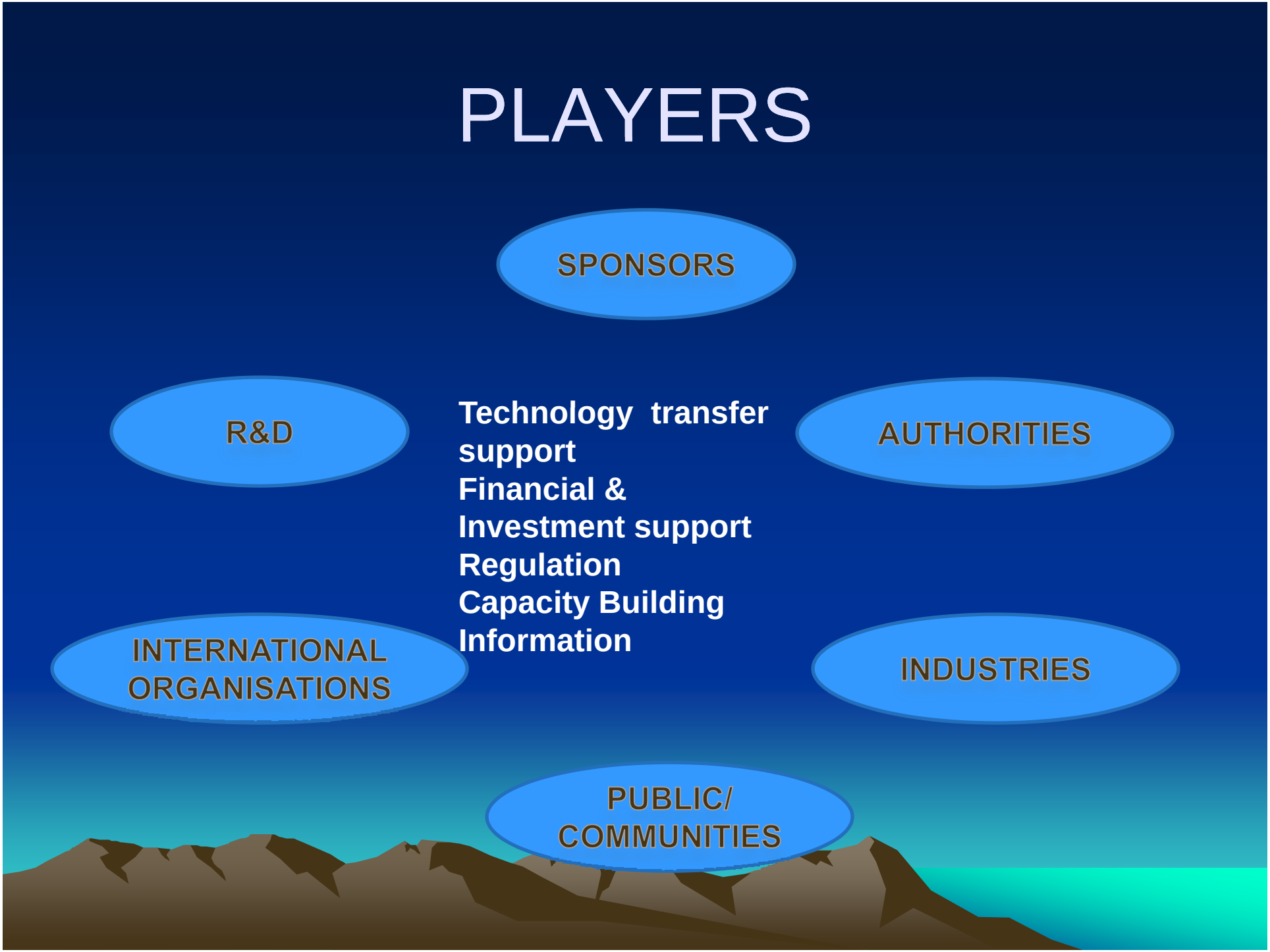
Energy security

For	Against
Alternative sources insufficient to meet energy demand	Increase fossil fuel consumption and faster depletion of sources.
Cost of energy will go up for end users. Cost could come down as the whole chain of technology matures	Reduce R&D in renewables

Challenges

- Regulatory, Financial, Public support & Technical
- Regulatory- long term (National/Regional/International)
- Financial- funding, cost of power/ CO_2, Incentives/ CDM or other new mechanism
- Public support- awareness
- Technical- Uncertainty around scale up
- CCS combined with EOR / EGR / ECBM makes the agreement of participants but appears as limited and not applicable everywhere.

PLAYERS


SPONSORS
R&D
Technology transfer support
Financial & Investment support
Regulation
Capacity Building
Information
AUTHORITIES
INTERNATIONAL ORGANISATIONS
INDUSTRIES
PUBLIC/ COMMUNITIES

Conclusions

- CCS could be a PART of integrated, SD and CO_2 mitigation technology including energy system
- Country specific – driven by political commitment based on local socio-economic and environment development path of each country
- Project specific & Site specific
- Large scale deployment of CCS need international agreement in terms of support in technology transfer, financial resources and Investment and capacity building.

Is CCS viable option for Developing Countries?

Workshop Project

Working Group No. 2

- Farida Toufouti
- Karima Batouche
- Hamad Al-Marri
- Mohammad Al-Qenaei
- Saba A. Yousif
- Akila Azzirou
- Hacen Bouhadjar
- Jaffer

- Mentor: Mike and Ghaniya

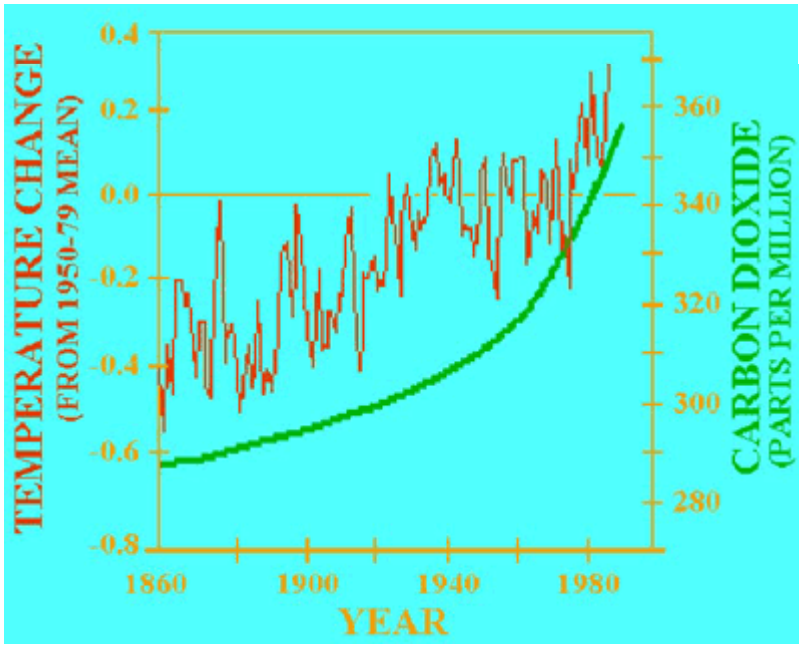
Outline

- Introduction
- Reason For CCS
- Applicabilities of CCS
  - Amount of CO2 emissions
  - Technical capabilities
  - Financial capabilities
  - Storage sites

Outline

- Advantages and Disadvantages
- Conclusions

Introduction

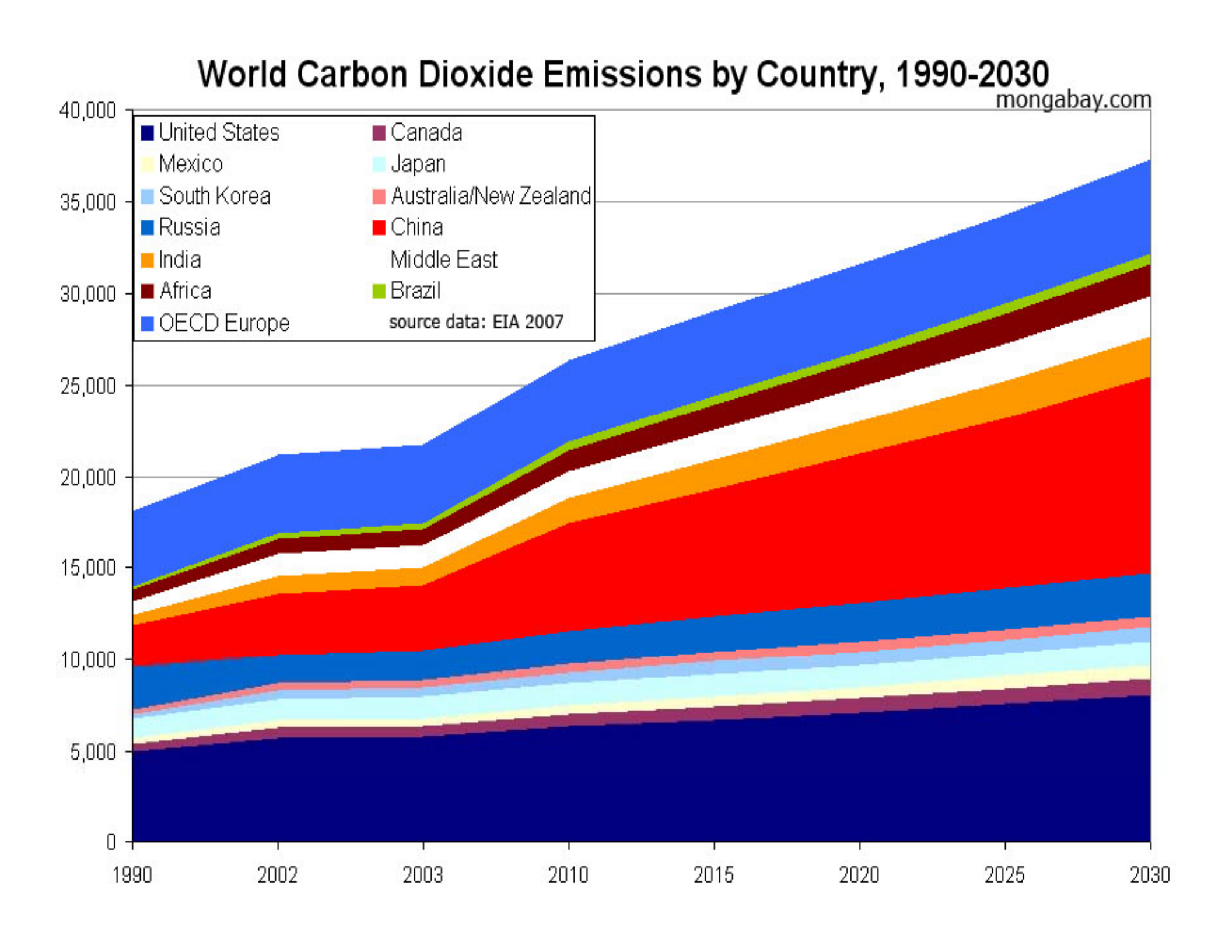


The effects of carbon dioxide in the atmosphere are controversial. However, the average temperature of the Earth is rising, especially when measured at the poles. Note that the average Earth surface temperature *correlates* well with the amount of CO_2 in the atmosphere (i.e. as the CO_2 levels in the atmosphere have increased, the surface temperature has gone up at the same time).

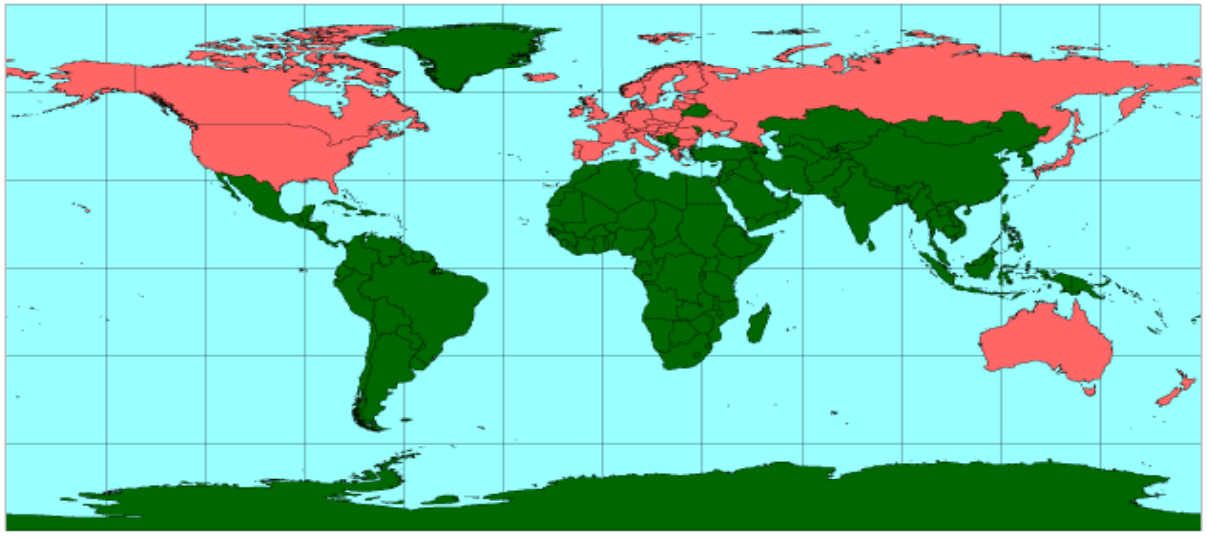
In the diagram, the average temperature is in red and the CO_2 content of the atmosphere is in green. Image source

Reason For CCS

- What is important for Developed countries today will be important for developing countries tomorrow


World Carbon Dioxide Emissions by Country, 1990-2030
mongabay.com
United States
Canada
Mexico
Japan
South Korea
Australia/New Zealand
Russia
China
India
Middle East
Africa
Brazil
OECD Europe
source data: EIA 2007
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
1990
2002
2003
2010
2015
2020
2025
2030

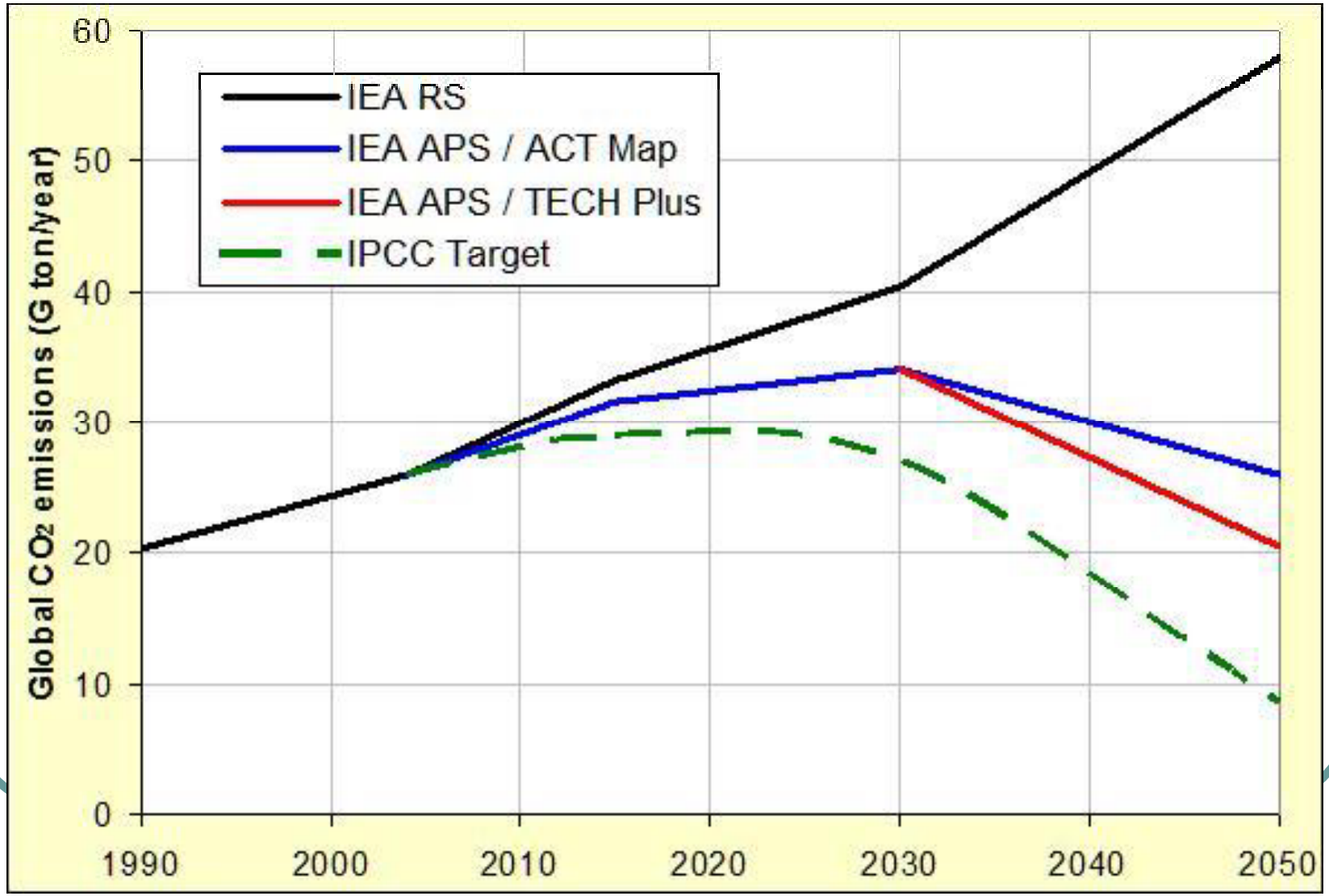
Year	Annex B Countries		Non Annex B Countries	
	Fossil-Fuel CO_2 Emissions (million metric tonnes C)	Bunkers (million metric tonnes C)	Fossil-Fuel CO_2 Emissions (million metric tonnes C)	Bunkers (million metric tonnes C)
1990	3887	90	2121	47
2006	3897	142	4077	113



Applicability of CCS

- Amount of CO2 emissions
- Technical capabilities
- Financial capabilities
- Storage sites

Amount of CO2 emissions



Technical capabilities

•Developing countries still don't have the technology

•In order to meet the future targets of CO2 emissions developing countries should build up technology capabilities today

•Fortunately the developed countries are obliged to reduce their CO2 emission today which will give the undeveloped countries the chance to learn from their experience.

Kyoto Protocol

Kyoto Protocol to the United Nations Framework Convention on Climate Change

Article 11 :
(b) Also provide such financial resources, including for the transfer of technology, needed by the developing country Parties to meet the agreed full incremental costs of advancing the implementation of existing commitments under Article 4, paragraph 1, of the Convention that are covered by Article 10 and that are agreed between a developing country Party and the international entity or entities referred to in Article 11 of the Convention, in accordance with that Article

Financial capabilities

- **There is no financial incentives for CCS for developing countries.**

- **The CCS process is not recognized by CDM**

- **Currently the CCS is highly expensive and not all developing countries can afford it.**

- **There are opportunities for the developed countries to offset some of their emission reduction obligations by investing in CDM projects with developing countries (not including CCS)**

Storage sites

- **The availability of storage sites within the developing countries is case dependent.**

- **The Oil producing countries can utilize CO2 for EOR.**

- **The availability of geological information can help in identifying storage sites**

- **There are opportunities to store CO2 in Depleted oil & Gas Reservoirs. Further investigation is required.**

Advantages and Disadvantages

- Advantages:
  - Protect the Global environment from CO2 emissions.
  - Improve the image of the developing countries (including oil producers).
  - Financial gains through utilizing CO2 for EOR
  - Possibility for financial gains if CCS considered eligible project for CDM.
  - Benefits through technology acquisition.

Advantages and Disadvantages

- Disadvantages:
  - Cost.
  - Not mature tech.
  - The unknown impact of CO2 storage.
  - Public reactions.

Conclusions

- CCS is a viable option for developing countries provided that,
  - Confirmation of success is required.
  - Cost reduction.
  - Technology improvement.
  - Financial Incentives Provided.

OPEC-IEAGHG CCS Workshop

for Scientists and Professionals in OPEC Member Countries

Group III Presentation

IS EOR A DISTRACTION TO CCS DEVELOPMENT?

HEADLINES

- Origin of CO2.
- EOR and CCS definition
- EOR advantages/disadvantages
- CCS advantages/disadvantages
- Answering Question
- Case studies:
  - In Salah
  - Weyburn
  - Sleipner
- Conclusion.

Origin of CO_2;

- ✓ **Hydrocarbon gas production with high % of CO_2.**
- ✓ **Power generation, burning fossil fuel (Coal, Oil…).**
- ✓ **Industrial Units (Chemical reactions, …).**
- ✓ **Transport**
- ✓ **Domestic uses**
- ✓ **Human breath (small amount)**

EOR definition

Enhanced Oil Recovery is widely used tech in many countries. It consists on injecting fluids in petroleum reservoir to increase oil recovery by:

1.reducing interfacial tensions
2. increasing produced fluid mobility,
3. reducing viscosity,
4.reducing capillary effects at pore size level.

EOR definition

Injected Fluids:

Water; 1. Conventional ...> 2nd Recovery

2. Treated ...> 3rd Recovery

- **Alkaline**
- **Surfactants**
- **Hydrodissolved Polymers**
- **Steam**

Gas:

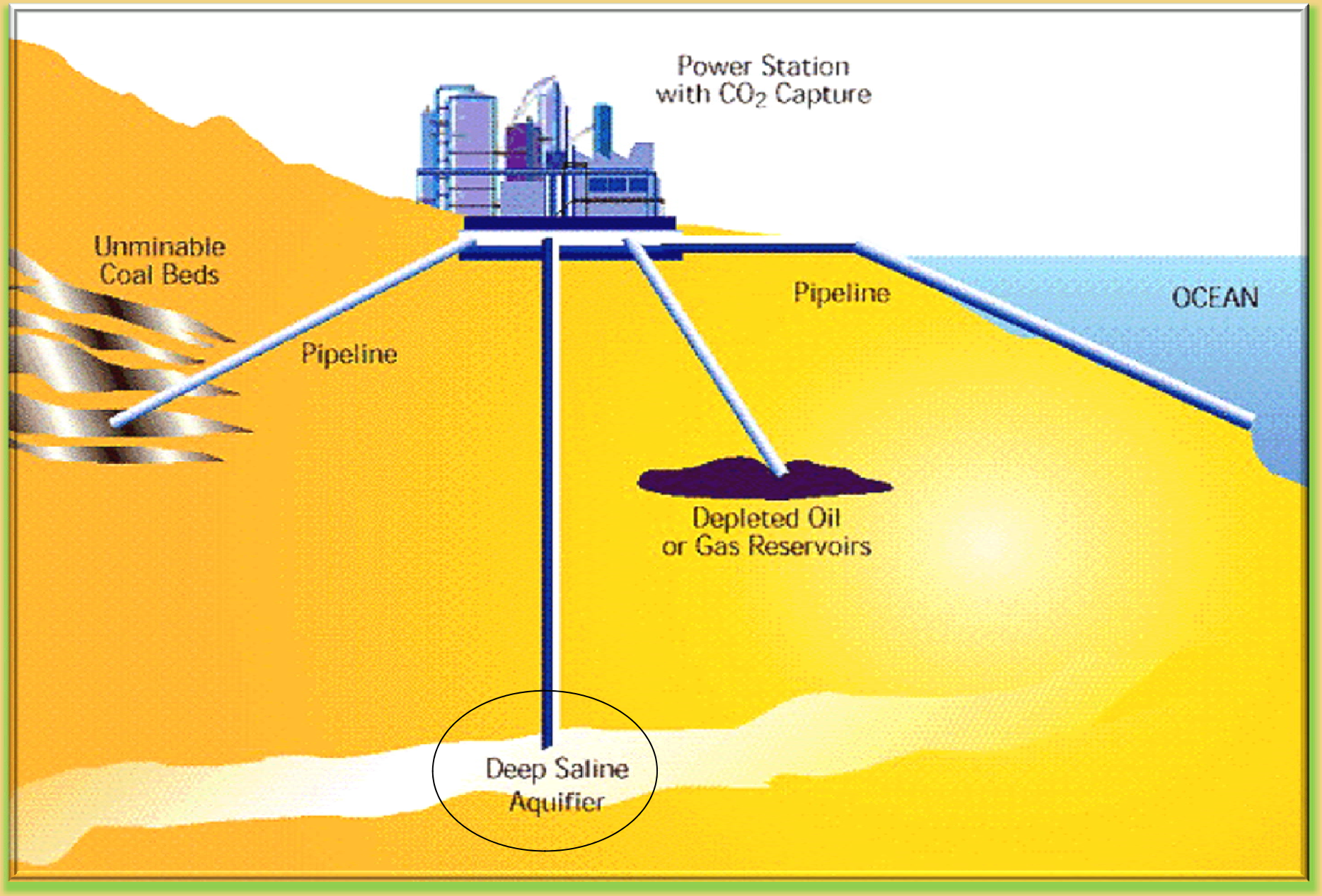
- **Dry**
- **Rich gas**
- **Lean gas**
- **CO2 at high pressure**

- **EOR definition**
- **- It delays reservoir life and reduces residual oil saturation.**
- **- Reservoir reminds at its optimal production plateau as long as possible**

CCS DEFINITION

- **Is a technology which consists on capturing and sequestrating CO2 in geological formation**

- **contributes by consequent in reducing CO2 from GHG emissions to protect environment and human health.**


Power Station
with CO_2 Capture
Unminable
Coal Beds
Pipeline
Pipeline
OCEAN
Depleted Oil
or Gas Reservoirs
Deep Saline
Aquifier

EOR Advantages /Disadvantages

Advantages

- Gain money
- To protect environment by reinjecting hydrocarbon gas that contains high percentage of CO2 for EOR inquires rather than flaring it.

Disadvantages

- Limited sources of CO2 near oil field
- Transportation high cost of CO2

CCS Advantages /Disadvantages

Advantages

- Environmental protection
- Maintain pressure equilibrium in reservoir
- Carbon market (Do not pay taxes)
- Provides clean energy.

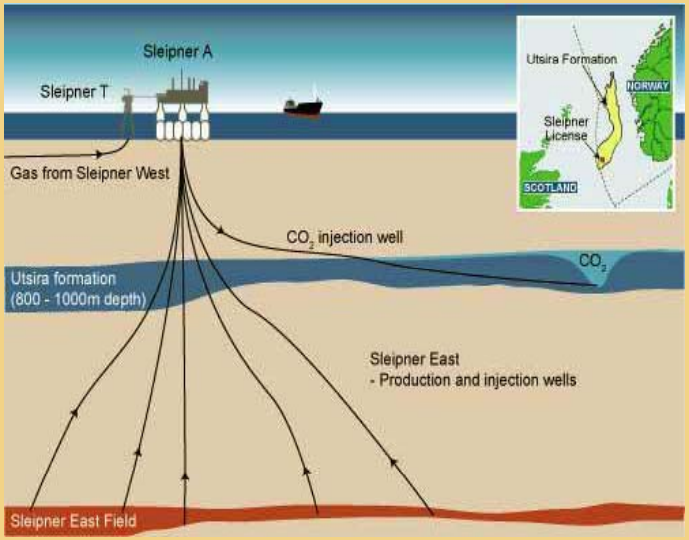
Disadvantages

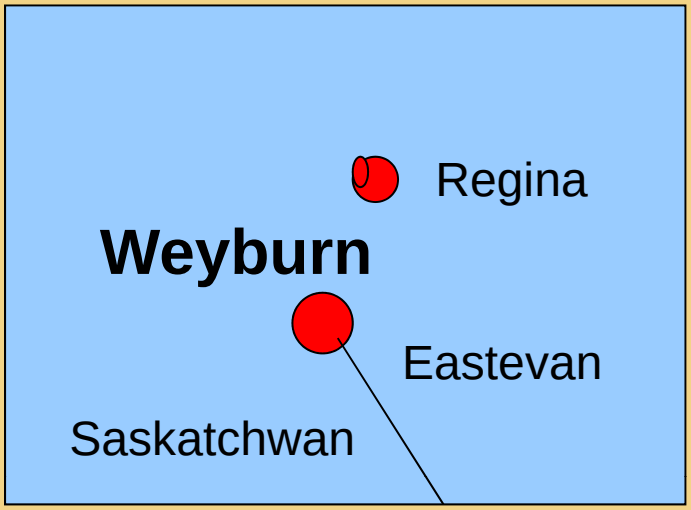
- New Tech: needs time and efforts to convince public opinion
- Intermediate to High cost due to complex infrastructures with new tech.
- Leakage, corrosion, cementation problems

Contribution

- CO2-EOR could effectively increase oil production as well powerfull recovery methods in addition to CO2 storaging technique
- CCS can store huge amount of CO2 underground and can be accepted as part of CDM project.
- EOR is not going to distract CCS development in case of any future EOR need for CO2 deployment.
- The case of In Salah:the CO2 is stored in the reservoir which can be used in any future EOR inquires (Hassi Messaoud).

1. Money Aspect





Sleipner (CCS)

1MMTPA

50 USD/T 50MM/USD/A

Weyburn (CO2-EOR)

1 T of CO2 will increase production by 7 BBL of incremental additional oil.

Ref. *July - August 2008 - carbon capture journal*

1MMTA 7MM BBL

1 BBL 70 USD 490 MMUSD/A

CCS and EOR become an investment, not just a cost.

Moral Aspect

In Salah (CCS)

1 MMTA CO_2

No Taxes

No CO_2 Emission / 10 top countries

- 6 USD 1T CO_2 -1OO MMUSD

To demonstrate that the problem is global and every country is concerned.

Thank you