**Review of PhD Thesis ‘Geological Storage of CO2: Sensitivity and Risk Analysis’ by Meisam Ashraf**

**Important theoretical and/or experimental details:**

**The general impression in terms of structure and technical quality:**

* The introductory section first presents a short introduction to CCS, a brief outline of the modelling philosophy and a very brief account of the SAIGUP geological model. The latter is not really adequate because, throughout the Thesis, the reader never learns what the internal ' depositional architecture of the model is.
* A substantial section then follows on the theoretical basis for flow in porous media and on the aPC statistical analysis. The former distils fairly standard published texts and is not innovative; it is also difficult to see what it really adds to the rest of the Thesis, because the modelling actually uses the proprietary ECLIPSE flow simulator that is essentially treated as a black-box.
* Information on the implemented boundary conditions and selected input parameters is given, yet hardly an adequate description on the ECLIPSE model set up or specific options and keywords used in the simulation of CO2 storage.
* A short section on vertical averaging is interesting and quite clear, but again does not seem to be relevant because, so far as we could tell, vertical averaging was not used in the simulations.
* Papers I and II are outlines of conference presentations based on preliminary modelling and analysis. They are not well written, with exceptionally poorly labelled and captioned diagrams and very rudimentary explanations of the results.Papers III and IV comprise manuscripts submitted for publication in main-stream journals. They essentially repeat, but expand on the results in I and II and are much better written and presented.There is a high level of duplication between papers I and II, and papers III and IV.

**Scientific significance (theoretical framework, hypotheses, material, methodology, findings)**

* It is not stated which simulator version, ~ I E100 or E300, and which specific options were employed in the simulations.
* In terms of the methodology, there are issues with the resolution of the model, boundary conditions, model induced artefacts, and sensitivity to key parameters.
* The first four papers all suffer from a significant presentational defect in that the SAIGUP static model and also the flow simulations based upon it are treated as opaque ‘black-boxes’, which the reader is not able to evaluate or even able to reproduce based on the provided information .
* The SAIGUP model contains varied depositional features, delta-front lobes, beaches, prograding / aggrading sequences, faults, etc. It also has a structural dip, which is not clearly explained. Some cartoons of this are provided, but no proper cross-sections or maps to judge how the various lithofacies elements fit together. The native grid resolution of the SAIGUP model is not stated, and nor what degree of upscaling was required to produce the input for the flow modelling, if so.
* At the input interface, a number of geological parameters are varied and run as multiple flow simulations on the ‘black-box’. Output results are plotted in rather simplistic graphical form with derivative sensitivities also presented. The problem is, without seeing into the black-box - (for example to see how plume and pressure distribution with time might vary with a given parameter), it is impossible to properly understand the processes and how the fluids in the model interact with the flow property architecture. A good example of this is the result (Paper III, Figure 7), that the sensitivity of reservoir pressure to the direction of progradation actually switches polarity at the end of the injection phase. This is a rather radical result that is difficult to visualise without seeing details from the model on how the pressure field interacts with the geological architecture.
* More generally, it is difficult to assess the degree to which the results will have wider generic application or are model-specific. In particular it is difficult to assess how robust the results are and to what degree model deficiencies (size of model, boundary conditions, and internal grid resolution) are influencing the results — our intuitive feeling is that model artefacts are significant.
* It is not made clear what the grid structure of the reservoir flow model is until Paper V (Table l). The size of the model is also a cause for concern.
* Injecting 40 Mm3 of CO2 into a model of this size means that both the pressure and saturation fields interact strongly with the model ' boundaries. Thus, for example, many of the realisations suffer substantial loss of CO2 out of the model. This can lead to major artefacts, whereby for instance, some models show reduced leakage risk because most of the CO2 has left the model and has no impact on the leakage point.
* In another example of boundary-induced effects, it is suggested (Paper II, page 6) that CO2 flux out of the open boundaries near the injection point could be used as a proxy for volumetric sweep efficiency. In fact, the dominant effect is just the relative difficulty in forcing CO2 up-dip into the interior of the model compared with driving it down-dip through the nearby open boundary.
* The model outputs depend crucially on the detailed interaction between the injected CO2 and the geological complexity within the model for example whether the CO2 plume encounters low permeability rocks in the vicinity of the wellbore, or whether high permeability pathways are available to enable plume migration away from the injection well. Surprisingly, however, only one injection well location or well completion is tested, so we do not get any feel for how robust the results are with respect to well position and injection strategy. This is a key issue for CO2 storage — to know the possible effects and impacts of well placements in ' different reservoir environments.
* A similar argument can be extended to the leakage risk scenarios. Results computed are computed for a single spatial leakage probability function, but it is not clear how robust these results are. Moving the central leakage point with respect to depositional lobes or fault locations might radically change the outputs.
* We do have concerns in assessing how much of this work the Candidate carried out himself. He did run the multiple (162) flow simulations and presented the results, and on Paper IV he is sole author, but these elements of work are not particularly innovative and he does not show deep insights in the interpretation and application of his results. Paper V is more original, but it is not clear what input the candidate has made to this (see above).

**Conclusions and Recommendations:**

The Thesis has substantial shortcomings in its core part — the description and presentation of the static geological model and the dynamic flow models and in the analysis and reflection on the results.

The amount of original or creative input seems limited and the Candidate has not shown strong evidence of deep insight into the processes inherent in his modelling and in the significance and applicability of his results.

The Thesis is not recommended for public defence in its present form.

We are of the opinion that there is the potential to improve the Thesis significantly by strengthening the geological and flow modelling descriptions in the introduction section, and also by more carefully assessing the generic relevance and scientific validity of the modelling inputs and outputs.

More specifically, the static (SAIGUP) and dynamic (ECLIPSE) models should be described in detail, including internal geological (stratigraphical and structural) architecture, 3D properties and grid geometries (including any upscaling), PVT model and detailed implementation of the boundary condition. Examples should be provided of plume and pressure evolution over time for a representative suite of models. The Thesis should as such give a sufficient level of detailed description and insight into the models to allow the reader an independent evaluation of the results.

Analysis of the outputs should properly take into account deficiencies in the model and should unravel those outcomes which are model artefacts from those results which arise from realistic processes and might have generic application.

In a Discussion section, the Candidate needs to think carefully about how this type of modelling could be used in a real storage situation, needs to discuss its general applicability and could perhaps speculate on how this concept, with improvements, can be taken forward.

If the Candidate integrates and addresses these issues effectively in revising the Thesis, he will also be better equipped to defend it verbally on the day.

Papers I and II should be removed.