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Report

Prepared for
Alberta Research Council Inc.

Independent Technical Evaluation of a Research Program for Use of Hollow Fibre Membranes for Separation of CO_2 from Gas Streams

Project 017221 **April, 2006**

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1.0 INTRODUCTION AND SCOPE OF SERVICES

Use of membranes for separation of specific gases from gas mixtures is well known and understood. Yet, such technology is in limited commercial use today owing to its high capital and operating costs.

Alberta Research Council Inc. (ARC) is engaged in a research program focused on bringing hollow fibre membrane (HFM) gas separation and absorption technology to a stage where it can be successfully employed on a commercially attractive basis, specifically in applications where the desire is to separate CO_2 from gas mixtures. According to ARC, a potential funder of this research requires ARC to carry out an independent engineering review of the present state of the research and its likelihood of advancing the science to technical and economic viability.

In completing this review SNC-Lavalin Inc. (SLI) was asked to evaluate both the proposed research program and the proposed technology in order to provide an opinion on:

- Technical viability;
- Scale-up feasibility;
- Economic viability;
- Market and/or process niche(s);
- Size of the prize (e.g. tonnes of CO_2 separated/captured);
- Rough economics for commercial scale operation (+/- 50%).

Two recent studies carried out by SNC-Lavalin have had requirements to research the state of development of membrane technology in applications involving CO_2 removal. In the course of these studies SNC-Lavalin has acquired non-proprietary knowledge of such devices. It is on the basis of that information that we evaluated the ARC program.

In SLI's opinion successful developmental research is carried out by organizations and individuals who are able to combine their passion for innovation with a sense of pragmatism and clear vision of the path to commerciality. When SLI evaluates the research work of third parties for internal purposes we look for the following key success factors. We are using them as the basis for this evaluation.

- Clear understanding and knowledge of the present state of development of the process or apparatus as being investigated elsewhere, and realistic analysis of why efforts by ARC and others to date have not resulted in widespread commercial applications;
- Clear understanding by the researchers and their organization of the objectives that must be met for the process or product to achieve commercial status in the applications proposed;
- Evidence of a budget/schedule/work plan, both for previous and future work, that shows discipline in the research process and the steps required to achieve commerciality;

- ❑ Records of past work that indicate progress toward the objectives;
- ❑ Dispassionate evaluation and analysis of work to date;
- ❑ Demonstrated capability of the researchers to innovate and to work around roadblocks in the research program as they are identified.

In carrying out these services, SLI:

- ❑ Reviewed existing public and SLI technical information in our possession;
- ❑ Reviewed previous work by ARC:
  - Literature searches and related reports;
  - Program objectives;
  - Progress reports;
  - Internal program evaluation / assessment documents;
  - Experimental results and associated reports;
  - Technical publications;
  - Patents, granted or pending;
- ❑ Examined experimental apparatus. We were not able to observe an experiment in progress, nor were we able to review equipment drawings. The opinion expressed here is based on our observation of the construction of the relevant equipment;
- ❑ Interviewed the key researchers and their ARC supervisors;
- ❑ Completed the technical evaluation and developed our opinions, assisted by an internal checklist we use to evaluate new technologies;
- ❑ Assessed potential economics.

We received excellent co-operation and support from ARC throughout our evaluation.

This is an evaluation of the probability of commercial success at a very early stage of research and development. The level of scrutiny is superficial; imposed by both schedule and budget. These factors significantly limit the accuracy of our predictions.

SLI did not assess and no opinion is expressed herein as to whether the activities and outcomes proposed by the program represent delivery of reasonable value for funds expended by the program.

As we are not involved with or directly aware of other research programs in related fields being carried out elsewhere, SLI did not assess and no opinion is expressed herein regarding the likelihood of ARC's work being more or less successful on a shorter or longer schedule than other similar activities.

We have relied on in-house information and expertise for our economic evaluations. They should be considered as directional rather than definitive.

2.0 ASSESSMENT SUMMARY

The proposed research program involves a collaborative effort between ARC, who construct the equipment and do the actual research work, and University of Waterloo, who possess the machine for manufacturing the hollow fibres and who carry out fundamental hollow fibre research to develop suitable membrane materials.

2.1 Research Program

In SLI's opinion:

- Progress to date indicates that ARC is in the process of establishing "proof of concept" for the proposed scheme. The applied research and test runs necessary to develop demonstration plant design parameters would be subsequent to what is proposed here and no opinion is expressed herein on such subsequent research or tests.
- ARC's staff appear to be well aware of the hurdles to be overcome in order to reach commercialization of the technology. Their program proposes to address some of those.
- ARC's proposed program for the next two years appears to be focused on the use of hollow fibre membranes ("HFMs") as sparging devices to increase the gas surface area available to the absorbent and thereby increase the efficiency of CO_2 capture. This could allow replacement of conventional amine solutions by other chemicals such as K_2CO_3 that would not be detrimental to the fabric of the membrane and are not subject to degradation issues associated with amines in flue gas service. ARC plans to test the apparatus on two actual flue gas streams. Their program is appropriate, to the extent it is presently defined.
- This is one of several opportunities offered by HFMs. Others might involve further development of HFMs as chemical absorption interfaces, gas separation interfaces and promoters of the chemical solution regeneration process.
- There is a need for the ARC staff involved to define the longer term research and development programs necessary to bring the technology to the market. This would provide a better focus for the research in the short term.
- Continued collaboration with and access to the time and efforts of Dr. Feng at the University of Waterloo are essential to the success of the program. We were told that suitable arrangements are in place for at least the two-year duration of the proposed program but we did not review relevant agreements.

2.2 Technology

In SLI's opinion:

- Membranes used as promoters of gas/liquid contact in CO_2 capture applications represent the most promising route to achieving reductions of 20-30% in the unit cost of CO_2 capture in the next 5-10 years. They could do this through a combination of increasing both the capture and regeneration efficiency of chemical absorption systems, and by simplifying and reducing the size of the necessary equipment.

- Based on conventional amine absorption systems, our calculations indicate that present projected flue gas CO_2 capture costs are in the neighbourhood of USD 30 - 80 per net tonne of CO_2 captured, depending on the application.
- Coal fired CO_2 sources are among the most attractive prospects because of their relatively high CO_2 concentration (~16% dry basis), but their costs are in the top half of this range, as removal of NO_x and SO_2 is required to lower levels than mandated by present environmental regulation in order to protect the amine solutions from costly degradation. Potassium carbonate based recovery systems overcome some of the contaminant issues but as they exist today they are not efficient enough at low flue gas pressures to be used commercially.
- Amine technology on its own is likely capable of reductions of 15-20% in these costs, through a combination of close heat integration with new power plants, increases in new power plant efficiency, and continuing innovation and incremental improvements in the capture process itself.
- A delivered cost of about USD 15-25 / tonne CO_2 at a potential EOR site in north central Alberta could result in spontaneous project development. Bearing in mind the present high oil price, a key issue becomes whether capital-constrained oil companies can see better (i.e. lower operating cost; lower technical risk) opportunities elsewhere.
- A combination of membrane technology, incremental improvements in the base capture processes and carbon credits could reduce the delivered cost of CO_2 to USD 25 /tonne or less. At a constant carbon credit value of $15 per tonne, without the membrane component, incremental improvements in existing amine systems are likely to be able to yield delivered CO_2 values in the neighbourhood of USD 30 per tonne.
- Realistically, in the next 10-15 years Canada can expect to see construction of one, perhaps two, new large coal fired power plants that are fitted with CO_2 capture equipment for a large portion of their capacity. CO_2 produced from one plant would be sufficient to support one large scale EOR project. Membrane technology that enhances the performance of existing capture processes and can be declared commercially ready in 5-6 years faces some chance of being employed in the second, if not the first, of those plants.

3.0 DETAILED DISCUSSION

In reviewing ARC's proposed program, SLI began with the list of deliverables found in ARC's application for funding to AERI. It is reproduced below. Our discussions with ARC indicate that the last two years should be one year later than indicated, based on delays in commencing the funding.

b) Deliverables: *(point form, concise; please indicate what the project output would be):*

The expected results are increased understanding and knowledge regarding:

- *The environmental and economic performance of micro-porous hollow fibre membrane technology as a gas-liquid contactor to achieve efficient low cost CO_2 capture from flue gas.*
- *The application of this technology for natural gas sweetening; and;*
- *The potential of incorporating this technology with liquid absorption processes in next the 5-6 years.*

Deliverables attained during FY 04-05:

- *A set of data under the simulated conditions for flue gas application;*
- *A set of data under the simulated conditions for natural gas cleaning application;*
- *A set of data under higher CO_2 concentrations;*
- *Cost reduction analysis based on the acquired data;*
- *Design and specification of liquid regeneration unit;*
- *Year-end report.*

Deliverables proposed during FY 05-06:

- *Absorbing liquid regeneration unit;*
- *The design and specifications of the interface between the liquid absorption system and the industrial flue gas stream;*
- *Installation of the unit on-site;*
- *On-site operation data;*
- *Year-end report.*

Deliverables proposed during FY 06-07:

- *On-site operation data from natural gas stream;*
- *The business plan for technology commercialization including identified markets and identified partners;*
- *Preliminary engineering design of an industrial scaled pilot plant;*
- *Project final report".*

3.1 Staff and Equipment Evaluation

Two members of SLI's staff, Sorin Andrei and Doug Macdonald, visited ARC's Mill Woods facility on March 20 and 21, 2006 in order to carry out the interviews with

ARC and University of Waterloo personnel and to observe the experimental equipment in use.

We interviewed:

Dr. Hongqi Yuan (ARC), the person responsible for the research;

Dr. Xianshe Feng (University of Waterloo), the person responsible for delivering appropriate hollow fiber membrane material to ARC;

Dr. Sam Wong (ARC), nominally the technical manager of the research;

Dr. Bill Gunter (ARC), the senior person from ARC responsible for carbon management research;

Brent Lakeman (ARC), business manager for the research;

Bernice Kadatz (ARC), the person who has built and is operating the research apparatus.

Our objective was to evaluate:

- ❑ Dedication and enthusiasm toward the project;
- ❑ Ability to be innovative;
- ❑ How well the staff understand the commercial drivers of the work.

The staff appeared to be both dedicated and very enthusiastic. The key researchers (Yuan and Feng) have been continuously involved in this research for several years. A review of previous progress reports indicates an ability to work around problems, identify new approaches and abandon dead ends as necessary.

One area for improvement would be for the research team to develop their vision of success through to commercialization, and envision the subsequent research steps beyond the present ones that would be required to achieve success. In our opinion that would add significantly to the focus and direction of the research. For example, the team needs better to understand how their equipment as it is presently constructed avoids facing some of the realities of commercial applications.

We observed the experimental apparatus to be used for the research. The equipment was not in use at the time, so we were unable to observe an experiment in progress. Equipment drawings were not available but in our opinion the construction of the apparatus permitted relatively easy observation and understanding. In the respects we were able to evaluate, in our opinion ARC's experimental protocols and measurement equipment met reasonable standards.

3.2 Technical Evaluation

Using the information gathered from the documents and interviews and our own in-house expertise and experience, SLI developed its opinions of:

- Technical viability;
- Scale-up feasibility;
- Economic viability;
- Market and/or process niche(s);
- Size of the prize (e.g. tonnes of CO_2 separated/captured).

We used an internal checklist we developed for evaluating emerging technologies to assess their state of development and their potential technical and commercial feasibility.

The issue of commercial economics is more difficult to assess. It is a certainty that were we to carry out an assessment of the economics based on the state of development today, the result would be unfavourable. Otherwise, ARC would be constructing a demonstration plant, not carrying out laboratory and applied research.

SLI approached the issue of economics from the standpoint of conceptualizing the process conditions and costs that would be required to create spontaneous commercial use of the process and equipment.

3.2.1 Technology Assessment: Membranes in CO_2 Capture Applications

Gas Separation: The conventional use of membranes utilizes their ability to pass some molecules but not others. Such applications in CO_2 separation use generally depend on high pressure differentials across the membrane to drive the separation process. This technology is presently in use in the SW USA, particularly in conjunction with separation of CO_2 from produced gas in CO_2 - EOR applications. It competes with amine, carbonate and cryogenic approaches, depending on the unique circumstances of the produced fluids. It is not considered applicable to flue gas applications, owing to the need to compress large amounts of flue gas to separate relatively small amounts of CO_2. The ARC researchers mentioned some efforts in this area associated with using HFMs for separation of CO_2 from produced natural gas (Gas sweetening).

Although this activity is mentioned in the funding application, it does not appear to be a part of the proposed program as described to us by ARC. In SLI's opinion it does represent a potentially attractive line of investigation.

Gas Absorption: In this application the porous nature of the membrane provides a greatly enhanced surface area on which an absorbent liquid such as amine or K_2CO_3 can contact a CO_2-laden gas. At the same time the nature of the membrane must maintain the overall separation between absorbent liquid and the gas. This technology is presently in use in specialized applications such as Statoil's Sleipner platform for removal of CO_2 from produced gas. In an offshore application its ability to greatly reduce the size of the separation equipment is a large part of its attractiveness and makes it useful despite high equipment costs.

Previous ARC research determined that the materials from which hollow fibres can be readily made are attacked by amines, which quickly render the membranes inoperative. This occasioned a change to the use of K_2CO_3 solution as an absorption medium, because it does not attack the membranes. Initial work gave positive indications that this combination could work.

In SLI's opinion, although this is not part of the proposed program it continues to represent a potentially attractive line of investigation.

Sparging: A slight increase in the pressure of the gas inside the hollow fibres results in the gas passing through the membrane pores and dispersing into the absorbing liquid in extremely fine bubbles. ARC has determined that this substantially improves the contact surface between the gas and the liquid, resulting in more efficient absorption of the CO_2 by the liquid. The proposed work focuses on this phenomenon and on trying it with real flue gas streams.

Seeing the possible advantages of this approach, ARC has commenced some work using sintered metal tubes to see if the phenomenon with the HFMs can be duplicated using materials less susceptible to chemical attack by amines.

In SLI's opinion this is a potentially attractive application and the proposed program appears appropriate to exploring it. Developing a better understanding of the scale-up requirements to large volume applications could help to focus both this and future research paths.

Absorbent Regeneration: ARC has an idea that membranes could prove useful in increasing the efficiency of solution regeneration; traditionally the heat-intensive part of chemical absorption processes. If it could reduce required heat input this would further increase thermal efficiencies, the main place where chemical absorption processes must be improved before widespread use is seen. This is not part of the proposed program.

In SLI's opinion this is less likely to prove a fruitful line of research, although simple experiments using the existing equipment could confirm or deny this.

3.2.2 Scale Up Feasibility and Requirements for Commercialization

HFM technology appears to have aspects that will in some ways make scale up relatively easy and in others more difficult. Some of the issues requiring resolution if HFM technology is to become commercial in CO_2 capture applications are:

- ❑ Demonstration in "real" flue gas situations;
- ❑ Confirmation of operating parameters that show possible economic advantages;
- ❑ Conceptual design of a larger scale unit, taking into account limitations of about 1-2 m fibre length;
- ❑ Consistent test runs of several weeks;
- ❑ Understanding of how heat and mass transfer take place in a vessel more tightly filled with fibres;
- ❑ Inexpensive mass manufacture of fibre bundles;

- Even distribution of gas to large arrays of fibre bundles;
- Replacement of failed fibres or bundles in operating units;
- Confirmation of fibre longevity in real situations;
- Transient performance and control such as startups and upsets.

Our discussions with ARC team members indicated that they understand the need for enlarging the group to include persons with engineering design backgrounds, in order to move the concept toward commercialization. This is reflected in the AERI funding application description of activities for FY 2006/07 (actually FY 2007/08). In our opinion the early application of this kind of engineering support to the existing program would be advisable sooner rather than later, as it would also help to focus ongoing research.

3.2.3 Economic Viability

Carrying out commercially based economic comparisons at this point is not possible. The only operating commercial applications involving any kind of recovery of CO_2 from flue gas exist in niches where the value of the CO_2 is much higher and the production is much smaller than it would be in the circumstance where the CO_2 volume is coal fired power plant size (millions of tonnes per year).

Present applications include:

- Production of food-grade CO_2 (Bellingham, MA, USA);
- Production of carbonates (Trona, CA, USA);
- CO_2 for Urea production (Malaysia).

In our opinion, based on previous evaluations, the only existing commercial application for large volumes of CO_2 is Enhanced Oil Recovery (EOR). Advancements in Enhanced Coal Bed Methane recovery (ECBM) using CO_2 injection may also result in commercial applications in the next 5-10 years, but that is not yet proven.

Existing CO_2-EOR operations are based on naturally occurring CO_2 (SW USA) and on relatively high purity CO_2 streams (Weyburn, SK) where the major costs of production and delivery to site are compression and transportation.

All enhanced oil recovery schemes are inherently risky because of the uncertainty that the reservoir's response will match the predictions. Only water flooding and steam stimulation have been applied to such an extent that there is some reduction in the risk associated with greater certainty of results. CO_2, like any other miscible flooding agent, requires large capital expenditures just to get the CO_2 into the formation as well as additional costs to separate CO_2 from produced fluids for recycle. It is, however, worth noting that even in a non - carbon constrained environment such as SW USA in the1970's it was still deemed economically more attractive to recover the CO_2 from the produced fluids and recycle it than to vent it and replace it with fresh CO_2 from the pipeline.

SLI's previous work suggests that the cost of producing and delivering CO_2 from coal fired flue gas sources is in the neighbourhood of USD 50–80 per net tonne of CO_2. The same studies indicate that the purchase value of CO_2 sustainable by a commercially-attractive CO_2 EOR project in central Alberta would be USD 15-25 / tonne FOB wellhead.

In our opinion, improvements over the coming 5-10 years could result in a 15-20% reduction in the per-tonne cost of flue gas sourced CO_2, based on use of conventional amines supercritical power boiler technology, high levels of heat integration with CO_2 and incremental improvements in the amine recovery process itself. A reduction of this size may not be sufficient even if a USD 15 / tonne carbon credit is applied.

The simple economics advanced by ARC for the HFM process assume that amines could be replaced by K_2CO_3, whose undesirable characteristic of low CO_2 absorption capacity would be overcome by the much higher contact efficiency offered by the HFMs. The resulting savings would be realized by using a less expensive absorbent fluid and eliminating the operating costs for replacing that portion of the amines degraded by impurities in the flue gas.

On that basis the HFM technology offers a 20-30% savings in operating costs, and in conjunction with a USD 15/tonne carbon credit could potentially make the technology feasible for EOR sourcing. SLI acknowledges that ARC's calculations ignore potential increases in capital charges and risks associated with an emerging process, but we point out that proposed and future research is aimed at addressing those issues.

3.2.4 Market and Process Niches

ARC appears to be aiming at the large scale flue gas CO_2 capture market.

In our opinion, opportunities exist especially in the area of CO_2 capture from produced natural gas that could prove interesting. Even in a non-carbon constrained environment there is room for more economical ways to control CO_2 slip into sales-quality natural gas. We observe that ARC's staff are aware of these opportunities and they are mentioned in the funding proposal we reviewed, but they are not the focus of the proposed work.

3.2.5 Potential Market Volume

As of today there are no full scale coal fired power plant CO_2 capture projects operating or close to construction anywhere in the world.

In our opinion, in Canada the best we can expect is two new capture-ready plants in the next 10-15 years. Should ARC be able to meet their goal of proof of concept in two years and design of a demonstration – scale unit in 5-6 years, it is possible that the HFM technology could be in use on one of those plants. SLI notes that this could be a conservative assessment, in that success in Canada would likely result in international interest.

3.2.6 SWOT Analysis

Strengths:

- Membranes are in service in other parallel applications and demonstrate some of the possibilities;
- HFMs are in use in water desalination service;
- ARC / U of W joint team appear to work well together and complement each others' strengths;
- Researcher's skills appear appropriate.

Weaknesses:

- Some team changes over the past years have interrupted the long-term continuity of the program;
- Expertise is presently incumbent in a few individuals and is partly in an organization over which ARC has limited control;
- Needs a clearer path to commercialization defined;
- Small fibres are susceptible to plugging, fouling is likely to be an issue in real flue gas applications.

Opportunities:

- Results suggest possible niche applications and applications in other industries.

Threats:

- Possible parallel research activities by third parties may overtake ARC.

3.3 General Observations Regarding the Program as We Observed It

1. Currently it appears that there is a well established team working on the research. The team does recognize the need to incorporate engineering / design expertise in order to move the concept toward commercialization as rapidly as possible.
2. There are different views among team members regarding how this work should proceed. It appears that the main direction for the program is coming from the researchers themselves.
3. There needs to be a clearer long term development strategy. The team members are focused on the immediate steps, without asking "what's next?" in advance. The future development plan presented to us and to the funding organization is more like an everyday task list, than a strategy for the short and/or long term.

4. Most of the team members consider that the process has a chance to reach commercially-ready status in 5 to 6 years, but there is a work plan only for the next two. There needs to be a clearer definition of the potential roadblocks and key milestones required to be met to achieve the ultimate goal.
5. All the team members recognize that the next natural step in the technology development is to take it out of the lab controlled environment and test it in real plant conditions. The two named sites appear to have been selected based on convenience rather than with a strategic view to the most potentially successful applications.
6. The team members understand that in order to bring the technology market there is a need to raise the interest and secure the participation of potential commercial clients. There are letters of support from two potential users. There does not appear to have been discussion, either internally or with potential clients, about what the key technical and economic success factors might be that would result in more active industry participation. Such discussions could be of great assistance in focusing future research.

4.0 KEY DOCUMENTS REVIEWED

SLI was given access to a large range of related documents. We reviewed many, but not all of them, in varying degrees of detail. The following list includes those documents that we considered to be the most relevant and important to our deliberations and were considered in preparing the opinions expressed herein.

1. Micro-Porous Hollow Fibre for Greenhouse Gas Separation and Capturing; 2005-2006 Project Overview and Presentation; ARC, Oct. 2005.
2. Micro-Porous Hollow Fibre for Greenhouse Gas Separation and Capturing. Year-end Report 2004/2005 for Natural Resources Canada; ARC, March 31 2005.
3. Final Report. Micro-Porous Hollow Fiber for Greenhouse Gas Separation and Capturing, prepared for Natural Resources Canada; ARC, March 26, 2004.
4. Full Application for Industry Research Program Funding, prepared for Alberta Energy Research Institute; ARC. Nov.2004
5. Two US Patents and one Canadian Patent, as well a Canadian Patent Application directly related to assessed technology and to the main device involved.

5.0 SLI TEAM

Two persons carried out the evaluation.

Doug Macdonald, P. Eng.: *Project leader, program evaluation, report preparation*. Doug is a chemical process engineer with 40 years of experience in almost every aspect of the petroleum and petrochemical industry, from exploration to the gasoline pump. Over the past seven years he has managed and participated in several projects directly related to CO_2 capture. Of specific interest to this project are:

A. *Abu Dhabi National Oil Company, CO_2 Capture and Injection for EOR*: As part of this assignment SLI reviewed and assessed the state of development of a wide range of CO_2 separation and capture technologies, including membrane separation. Mr. Macdonald presented a paper on this project at the 11th ADIPEC Conference in Abu Dhabi, October, 2004.

B. *International Energy Agency, Co-Capture of CO_2 with Other Coal Fired Flue Gas Contaminants:* In this study SLI evaluated several CO_2 capture technologies to assess the effects of operating them with gases containing other contaminants such as SO_2, particulates, etc. Mr. Macdonald gave a paper on this project at GHGT-7 in Vancouver, September, 2004.

Doug is also SLI Chemicals and Petroleum Division's first point of contact for evaluation of emerging technologies brought to the company's attention in the course of business.

Sorin Andrei: *Program and technical evaluation, economics, report contributions.* Sorin is a chemical process engineer with 19 years experience. Through his previous employment in an eastern European petrochemical complex, he has an extensive background in research, development, design, startup and operation of petrochemical manufacturing processes. Part of his experience there included work with a membrane electrolysis process for chlorine production. His SLI experience of specific interest for this project consists of:

A. *CIDA China CUCBM Enhanced Coal Bed Methane Recovery:* [This project is being executed by SLI under a subcontract from ARC]. SLI is providing pilot and full scale conceptual designs for surface facilities for CO_2 capture, transportation and use in ECBM. As part of this Sorin has evaluated possible use of membrane technologies for separation of CO_2 from produced coal bed methane.