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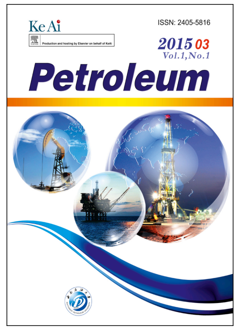


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**(Special short communication on Carbon Capture, Utilization and Storage)**

# The history and development of the IEA GHG Weyburn-Midale $CO_2$ Monitoring and Storage Project in Saskatchewan, Canada (the world largest $CO_2$ for EOR and CCS program)

By:

Ken Brown, Steve Whittaker, Malcolm Wilson*,

Wayuta Srisang, Heidi Smithson and Paitoon Tontiwachwuthikul*

* Corresponding author

**Authors' Note:**

This paper is written as a retrospective on the development of the major research project evaluating carbon dioxide storage at Weyburn Field, Saskatchewan, Canada and not as a scientific paper. As such, any inconsistencies and errors are entirely the result of the authors' memories. It is hoped that this retrospective will provide the reader with a sense of the history of this field and the reasons for its importance in assessing the safe storage of $CO_2$ in an EOR field. *(For more information, please contact Dr. Malcolm Wilson at Malcolm.alan.wilson@gmail.com or Dr. Paitoon Tontiwachwuthikul at paitoon@uregina.ca )*

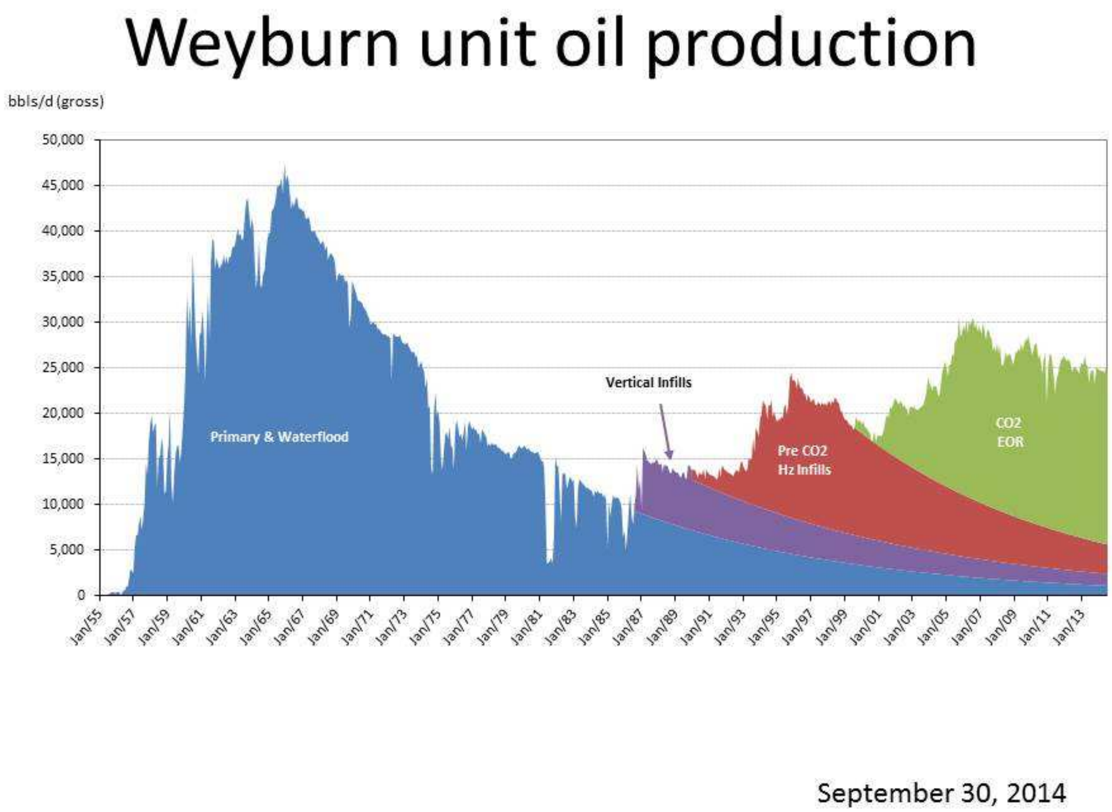
**Introduction:**

The Weyburn oil field occurs within a larger trend of similar oil accumulations in Mississippian-aged carbonates. The history of discovery of these oil accumulations resulted in the fields being given several different names. The Weyburn field and the immediately-adjacent Midale field are effectively part of a larger oil pool with OOIP (original oil in place) reserves of over 2 billion barrels. This is certainly a large conventional oil pool for Canada even if not large by world standards. These pools are found in truncated stratigraphic traps and occur at about 1450 to 1550 metres depth making them ideal for $CO_2$ storage [1].

From its discovery well in 1954, to the inception of waterflooding in the mid-60s, through the development of horizontal wells for waterflood optimization, and finally to the use of $CO_2$ starting in 2000, the Weyburn field has been a technology leader in Canada and a field with much to offer to the study of $CO_2$ storage. Indeed, Weyburn is arguably the most intensively studied oil field in the world. Part of this success can be attributed to forward thinking individuals in Saskatchewan in the 1940s and 1950s, combined with a government willing to make regulatory innovations that resulted in the centralized collection of core, logs, and production and injection reports from all oil and gas development in the province. The initial suggestion for the storage of core was made in the 1940s along with the wartime drilling for oil in the province [1, 3]. This extensive public database has been of significant importance to the ability of scientists to understand the geology of Weyburn (and associated fields) for improving oil production and also for the purpose of geological storage of $CO_2$. In effect, virtually all core ever taken in Weyburn, and over 800 individual wells have been cored at Weyburn (in the earlier days of the field, core was given a higher priority due to the poorer quality of geophysical logging techniques), is still available for examination along with all geophysical logs, well reports, workover and cementing records, and production information.

In 1953, a significant oil-strike in Saskatchewan was made at Shell's Midale No. A-18, revealing a reservoir in dolomitic limestone sealed between two anhydrite beds (AAPG Explorer Historical Highlights). Active field development soon began, as well as a step out well leading to the discovery of the Weyburn field [1, 2].

Aside from the important step of collecting core and other well information in a public database, the Province of Saskatchewan also created a supportive environment for waterflooding and EOR activities by ensuring that unitization would occur, either voluntarily or by mandate from the government regulator. Unitization creates a situation where previously competing industry producers now own a 'fair share' of the whole pool. This allows recovery decisions to be made on the best technology for the pool rather than for an individual producer's interest. Units were created in the Weyburn field and Midale field that permitted the use of waterflooding in the early to mid-1960s. In the case of Weyburn, this pushed production up to a peak of close to 50,000 bbls. per day, with a slow decline occurring from there. The following figure, provided courtesy of Cenovus and seen in many public presentations, shows production up to 2014 [3].




**Production History of Weyburn and Midale:**

The Weyburn field was discovered in 1954, and in the few years following discovery, rapid field development occurred. Between 1954 and 1964, primary production increased to a peak of over 45,000 bbls. per day. At this point, waterflooding was introduced to the Weyburn Unit (not all wells in the Weyburn field are included within the Unit, but it does contain most productive portions of the field) pushing production briefly over the 45,000 bbls. per day mark. After this, the field's production declined through the 1970s and '80s to around 10,000 bbls/d at which an attempt was made during the late 1980s to reverse the production decline by means of vertical infill drilling. This drilling effort briefly pushed production back up over 15,000 bbls/d [1].

During the late 1980s and early 1990s horizontal wells were first being utilized to increase production, and Weyburn became a pioneer field and a significant beneficiary of the technology. While the first horizontal wells in Saskatchewan were drilled in 1987 in the heavy oil area along the western margin of the province (Tangleflags North and Winter Fields), the technology was most rapidly adopted and effectively applied to the light and medium oil fields of the southeast (Mississippian oil) [1, 3]. Horizontal wells drilled in the 1990 to 1994 period served to stabilize Weyburn production and then increase production in the post-1994 period to almost 25,000 bbls as shown by the portion of the production graph labelled Pre-$CO_2$ Hz. Infill drilling also included a period of waterflood optimization with horizontal wells used to maximize waterflood production. The horizontal program was also used in the development of the $CO_2$ EOR program to come later in the life of the horizontal program. Most of these horizontal wells were successful enough to more than cover their own costs of drilling and operation with incremental oil production.

With the horizontal program as the base, the field went into $CO_2$ flood in 2000 with $CO_2$ purchased from Dakota Gasification Company (a subsidiary of Basin Electric in North Dakota). The pipeline, built from Beulah ND to the Weyburn field with a terminus at Goodwater, Saskatchewan, originally carried 5,000 tonnes per day of $CO_2$. It later increased to over 7500 tonnes with 6500 tonnes going to Weyburn and the incremental $CO_2$ going to the Midale field). The $CO_2$ flood has now pushed production up to around 25,000 bbls per day in Weyburn and has held this level due to expansion of the flood as recycled $CO_2$ became available.

Weyburn has had a favourable response to $CO_2$ but did not quite reach the production peaks predicted before implementation. This is typical of most of the larger miscible floods in Canada where production generally has not reached the predicted peaks but continued at an elevated level for much longer than the original predictions.

**A personal retrospective on Weyburn:**

The development of $CO_2$ as a flood mechanism for Weyburn has a long history and goes back to an innovative approach from Shell Canada which was operator of the Midale field and eventually a significant partner in the Weyburn field. Initial work by Shell in the early 1980s used Shell's supercomputer in Europe to run simulations to investigate $CO_2$ flooding options at Midale that went against the then current wisdom that fractured reservoirs were not suitable for $CO_2$ flooding. The simulations suggested that a $CO_2$ flood could work in these types of reservoirs, and this resulted in a small-scale $CO_2$ injection pilot at Midale in the late 1980s and a subsequent larger-scale pilot that extended into the early 1990s [1, 2]. The small pilot was 4.4 acres (roughly 2 hectares) and ran from 1984 to 1989 with the results consistent with the Shell simulator's predictions for field-scale production of an incremental 20% recovery.

This work by Shell was truly innovative and proved that it was feasible to use $CO_2$ successfully as a miscible solvent in a fractured reservoir. Part of the reason for success was the geometry of the reservoir having a less permeable Marly (dolostone) zone overlying a Vuggy (limestone) zone. The more permeable Vuggy contributed the dominant portion of oil recovery in both primary and waterflood leaving a substantial portion of residual oil in the overlying Marly. This reservoir configuration allowed for effective use of the gravity over-ride of $CO_2$. In addition, the oil was quite amenable to $CO_2$ flooding with a good swelability index.

It was during the late 1980s that Shell started to look for sources of $CO_2$ should the flood go beyond pilot or demonstration scale [1]. In 1987, Shell, Dome Petroleum, and SaskOil, with funding from the federal and provincial governments, installed a capture pilot to test the removal of $CO_2$ from the flue gases of a coal-fired electrical generating station. This pilot was an advance over previous tests using amines (MEA basically) to remove the $CO_2$ from the flue gases by adding a sulphur capture unit ahead of the amine $CO_2$ capture unit. Previous tests had just used the amine to remove the sulphur, but found the cost of amine replacement to be too high. This unit used an Anderson 2000 unit (NaOH) to remove the SOx from the flue gas. There was also an assumption that the spray wash of the NaOH solution over the flue gas stream would be adequate to remove any residual fly ash from the gas stream. This turned out to create problems with the spray nozzles as the fly ash recycled in the fluid stream, plugging jets, eroding the nozzles and generally resulting in a less than adequate coverage. The resolution was the installation of a water wash ahead of the Anderson unit to remove the particulates [5-7]. The pilot ran in 1988, testing the Dow and Union Carbide amine systems. It was interesting that 1988 was a particularly hot and dry year, but the pilot operated well, with the chemicals demonstrating the capacity to effectively remove the $CO_2$ and producing a pure stream of the gas that could be used for EOR.

As a side note, the pilot plant was then moth-balled and was not re-opened for testing until around 2000 when it became part of the University of Regina's program for $CO_2$ capture testing operated in conjunction with

SaskPower's Boundary Dam Power Station. It was finally demolished in 2012-13 when SaskPower started building the world's first commercial unit for $CO_2$ capture from a coal-fired electrical generating station at the site. The $CO_2$ from this new commercial facility now goes by pipeline to Weyburn for EOR (and some is shunted for dedicated storage in Cambrian sandstones).

The larger Shell field pilot was originally designed as a four pattern unit, each with a central injector, with a total injection of 200 tonnes per day of $CO_2$. The $CO_2$ was liquefied cryogenically and brought by tanker truck from either Brandon, Manitoba, or Medicine Hat, Alberta (both sources were used at times). At Midale, the $CO_2$ was warmed and pressured up for injection into the reservoir. The pilot was started in 1992 (February) representing about 10% of the Midale unit (from Belliveau, Payne, and Mundry, 1993). The cost of this commercial pilot was estimated to be about $40 million CDN (1993 $).

The cost of the $CO_2$ was significant due to both the purchase price and the transportation and handling at the Midale site. In addition, the province continued to charge tax (then termed as E&H tax, Education and Health, now PST or Provincial Sales Tax) on the $CO_2$ used in spite of Shell's requests to have the tax removed. The end result of the high cost was to have Shell reduce the size of the project to 2 patterns and 100 tonnes per day.

While Shell was the operator of the Midale unit, PanCanadian also held a very small working interest. As a result of what PanCanadian informally referred to as its "library card," it received all the information from the operation of the pilots in the Midale field. This situation allowed PanCanadian to review the production history, undertake its own simulations of field performance, and, most importantly, forego the necessity for undertaking an expensive pilot test in Weyburn. This, along with the rapid expansion in the use of multi-leg horizontal wells in the '90s, gave PanCanadian all the technical data necessary and a working field to test the technical and economic models used to design the commercial $CO_2$ flood implemented in 2000.

In order to proceed with the $CO_2$ flood, the operator, PanCanadian, had to follow the Unitization Agreement developed to protect smaller working interest owners in the unit. Under this agreement, PanCanadian had to obtain the permission of a significant majority of both working interest owners and of a majority of the ownership of the oil in the field. This was not a rapid process and took several years to accomplish. Indeed, PanCanadian was faced with the interesting situation of Shell, the proponent of the field pilot in Midale and a major percentage owner of Weyburn resources, potentially voting against moving ahead with $CO_2$ flooding due to the high capital costs and Shell Canada's other strategic priorities at the time. This resulted in a land swap between Shell and PanCanadian for a sour gas field in the Foothills of Alberta giving PanCanadian a significant majority ownership of the Weyburn field.

The move to $CO_2$ flooding introduced two of the authors, Brown and Wilson, and created a lifelong friendship. At the time, Brown worked for PanCanadian and Wilson worked for the province (Energy and Mines). In the mid 1990s when the oil price was low and capital was scarce, it took a great deal of trust between the government (usually expecting industry to present only facts favourable to industry) and industry (usually presenting facts to negotiate the absolute minimum government 'take' possible) to create an environment where both sides could have honest open discussions of what was needed to make this mega project happen. The trust required to move to $CO_2$ EOR began with Brown and Wilson and then progressed through both organizations.

**$CO_2$ Supply for the Weyburn Field**

In the mid 1990s, PanCanadian sent out a request for proposals and chose Dakota Gasification Company, a subsidiary of Basin Electric, as the tentative supplier of $CO_2$. Dakota Gasification's primary asset is a coal gasification plant in North Dakota. After the oil price shocks of the early '70s, several gas (methane) pipelining companies and the US government combined to build the gasification facility for purposes of both diversification and security of supply. The plant was opened in the early '80s, producing a synthesized stream of methane for distribution in the US pipeline system. It was unfortunate that oil and gas prices dropped about this time. The result of this decline was the abandonment of plant ownership by the pipeline companies and the ownership reverting to the US government, which held the loan guarantees. After running the plant for a number of years, the US government sold it to Basin Electric in 1988. Since the gasification plant sits beside Basin Electric's Antelope Valley generating station, there were some synergies in terms of the shared cost of coal mining and the use of electricity by the plant itself. Over the years of ownership by Basin Electric, the Dakota Gasification Company had developed a number of by-product streams to enhance its economics. The ability to add $CO_2$ sales to its stream of products was finally put in place in 2000.

Saskatchewan Energy and Mines was very supportive of PanCanadian moving ahead with the $CO_2$ flood. It did, however, request that PanCanadian undertake a thorough review of other options for $CO_2$ supply, including the use of one of SaskPower's coal-fired plants in the Estevan area, given the technical success of the pilot plant for capture operated by Shell and others in the late 1980s. The company duly undertook the study, investigating the Shute Creek facility (Exxon) in SW Wyoming, the potential for a supply from the oil sands at Fort McMurray in Alberta, natural sources in SW Saskatchewan and the SaskPower coal-fired generating plants in Saskatchewan.

The Shute Creek (Rock Springs, Wyoming) facility was too far away without an intermediate offtaker in Wyoming or Montana (for example the Cedar Creek Anticline) to share the cost of an extensive pipeline. At the time, with low oil prices and a lack of confidence in $CO_2$ flooding everywhere except the Permian Basin of Texas, which used mostly natural sources of $CO_2$, this did not appear to be a feasible alternative. There were also some commercial issues over a separate company owning the source and another owning the transmission line. PanCanadian needed a single company to supply and deliver to ensure the source had a strong stake in reliable long-term delivery. The success of the Weyburn flood has provided the necessary impetus for the increased use of the Shute Creek supply.

The oil sands (Suncor and Syncrude) both had an exhaust stream from reformers that had high purity $CO_2$. The total volume of $CO_2$ was about 5,000 tonnes per day. To increase the volumes, the pipeline could be run past the Bi-Provincial Upgrader in Lloydminster, Saskatchewan, and the Co-op Upgrader in Regina, Saskatchewan, to add in $CO_2$ from their reformers. It should be noted that when these studies were underway, the expected $CO_2$ requirement was estimated to be about 7,000 tonnes per day. The pipeline cost was high but not insurmountable. The high cost of electricity to compress and pump the $CO_2$ was the biggest factor in rejecting this option. It was also felt that the volume of $CO_2$ might be too low for the flood project.

Several small $CO_2$ fields that exist in the southwest corner of Saskatchewan were also investigated as potential sources of $CO_2$ following the example of the Permian Basin of Texas drawing its supply from natural sources such as McElmo Dome. The deliverability of these fields would, however, have been inadequate to supply the required $CO_2$.

The final part of the study looked at the supply coming from the Shand generating station near Estevan, the newest of SaskPower's fleet of coal-fired generating capacity. Shand is a 300 MW (approximately) generation unit, with an output of around 6,000 tonnes per day of $CO_2$. Saskatchewan Energy and Mines and the University of Regina were actively involved in the discussion of the Saskatchewan supply, looking at such factors as increased employment to estimate the value of such a development. Unfortunately, even taking into account the extra value of taxes and royalties from the coal used, this was still not an economic solution for the Weyburn $CO_2$ supply. It was to be nearly 20 years before SaskPower would open its current capture facility at the Boundary Dam generating station using technology similar to that investigated for Shand.

The end result of this extensive investigation was the confirmation that Dakota Gasification was the preferred source for the $CO_2$. By 2000, the gasification facility would be almost 20 years old. Given that $CO_2$ would be required for Weyburn for at least another 15 years, the investigation included a review of one of the Sasol plants in South Africa to determine its longevity (particularly of the Lurgi gasifiers). There were no concerns with the longevity of the coal gasifiers employed at Dakota Gasification based on practical experience, which has certainly proved to be true for the Dakota Gasification facility.

In September, 2000, the $CO_2$ began to flow from Beulah North Dakota to Weyburn Saskatchewan. The pipeline to Goodwater, Saskatchewan, is owned by Dakota Gasification. From there, custody was transferred to PanCanadian (the operating oil company at the time) and is distributed to the oil field. The early contract called for 5,000 tonnes per day (a lower volume than originally contemplated) with a take-or-pay contract for 15 years, and with a reduction in overall delivery in the last few years of the contract.

There was no environmental review of the pipeline to Weyburn field at the federal level due to the short length of the pipeline connecting from the border to the transfer point at Goodwater. The project was given approval under provincial regulations however. There was some minor pressure to link the enhanced oil recovery project and the pipeline and initiate a more formal federal review. It was felt, however, that the field was already developed and that further review beyond those conducted by the province under its acts and regulations was unnecessary. The initial injection was into the phase 1A area of the field, some 19 injectors and the surrounding production wells. As the volume of recycled $CO_2$ increased with time, so the expansion of the flood could continue. There was a limit on how much recycling could be done as the $CO_2$ gets contaminated (from an EOR point of view) by methane from the reservoir, and no methane separation facilities were contemplated.

At that time, oil prices were in the range of $20.00 US per barrel, and $CO_2$ was being purchased for around $18.00 per tonne (the exact value of the $CO_2$ was held within commercial contracts). Both oil and $CO_2$ were projected to increase in value by about 2% per year. With an estimated incremental recovery of 3 barrels per injected tonne of $CO_2$, the payout for this project would be around 7 years. The long payout period would have dissuaded most oil companies from taking on the economic and technical risk of such a project.

PanCanadian deserves great credit for its willingness to take on this risky venture. During this time period, PanCanadian was growing quickly from a $150 million capital budget to close to $1 billion per year. This growth made the high initial investment in the large Weyburn project a much smaller percentage of the overall corporate budget.

In November, 1998, while decisions were being made and expenditures underway, oil dropped as low as $18.53. By October of 2000, shortly after start-up, prices were up to $44.96, dropping again to $25.88 in December, 2001. From here the trend was generally up, reaching $86.46 in July 2006 and a peak of $143.45 in July 2008 [3]. The success of the flood and the increasing price of oil allowed for a more rapid payout of the project than had been predicted in 1998.

The negotiations with Saskatchewan Energy and Mines and other provincial agencies also went well for the company. Unlike Shell's requests, the government agreed to waive the 5% sales tax on the purchased $CO_2$. In addition, the project was eligible for reduced royalties for EOR projects until payout – approximately 1%. Furthermore, to help offset the risk of the expenditures required by PanCanadian to prepare the field for $CO_2$ flooding, the EOR royalties were extended backwards for 18 months prior to the start of first injection. This allowed PanCanadian to use saved royalty money for the capital and other costs leading up to the receipt of $CO_2$. Naturally, the benefits of this to the government were that the project would go ahead - extending the life of the field for some 25 to 30 years - and that payout would come sooner allowing for royalties to increase again.

PanCanadian initiated the project, but in 2002 there was a merger with the Alberta Energy Company to create EnCana. The project was operated under Encana until, in late 2009, the company was split into EnCana and Cenovus with Cenovus taking control of the Weyburn field.

In 2000, the volume of $CO_2$ contracted with Dakota Gasification was 5,000 tonnes per day. At this time, the injection pressure to the pipeline system was about 2600 to 2700 psi with no booster stations along the way. In 2005, the volume of $CO_2$ shipped by Dakota Gasification increased to a little over 7500 tonnes per day, with the addition of new pumping facilities at Beulah and a booster station along the line. At this stage, EnCana increased its take of $CO_2$ to about 6500 tonnes per day with the remainder (about 1200 tonnes per day) going to Apache which had assumed operatorship of the Midale portion of the field from Shell. Cenovus was injecting 6500 tonnes of newly purchased $CO_2$ and recycling a similar amount for a total injection in the order of 13,000 tonnes per day.

In 2014, SaskPower commissioned a $CO_2$ capture facility at its Boundary Dam coal-fired electrical generating station. This $CO_2$ production, about 3,000 tonnes per day, is contracted to Cenovus and is delivered via a separate pipeline to Weyburn. While SaskPower suffered some start-up problems with its "first of kind" project, the unit is now fully functional and delivering the $CO_2$ to Weyburn. At the time of writing, there are still articles being released by the media asserting less than full name-plate performance. Commercial contracts prevent these articles from being confirmed as to accuracy.

**Climate Change Challenge and Weyburn IEAGHG Program:**

The above discussion gives a brief history of the commercial project for the recovery of incremental oil from Weyburn oil field. There is a secondary benefit to this use of $CO_2$, and that is its storage in the subsurface. While the $CO_2$ produces more oil, which will deliver more $CO_2$ to the atmosphere, there is a significant benefit to using the $CO_2$ from a low grade energy source (lignite) and converting it into a more efficient source (crude oil). While not a perfect solution, it certainly reduces the $CO_2$ entering the atmosphere for a given energy consumption.

What about the value of the project at Weyburn in addition to the obvious benefits of increased employment, more oil, etc? Once the project had been discussed with Energy and Mines, it became public that it was proceeding. Indeed, PanCanadian also undertook townhall meetings in Weyburn (the town for which the field was named and housing many of the field work staff) to talk about the issues and benefits of the project. This led to a discussion between one of the authors (Wilson) and an employee of Natural Resources Canada (Bruce Stewart, now retired) about other aspects of the project, in particular the ability to use the incredible public database to understand the geological context and to look at the safety of storage of $CO_2$ in the subsurface.

It was agreed that it would be worth trying to pull together some of the best scientists globally to work through the Petroleum Technology Research Centre and with PanCanadian to undertake a research project to examine the safety of geological storage of $CO_2$ in a mature oil field. The only project underway looking at storage was the Sleipner project initiated in 1996 and run by Statoil and European scientists on a saline aquifer storage project beneath the North Sea. While there were a large number of $CO_2$ EOR projects in the US, particularly Texas, none of these had the amount of information available as Weyburn Field, and none had undertaken a baseline survey of field characteristics ahead of $CO_2$ injection – an element that the Sleipner study had demonstrated was important.

To this end, a workshop was held in Regina in mid-1999 to look at the concept of a research project and to determine who should be engaged in the project. The workshop was a great success with representation from Canada, US, and Europe. The result was a significant enthusiasm for the project and the start of a research plan. The important part of the plan was the need for a baseline study of the field prior to the injection of any $CO_2$, requiring about $1 million (CDN) to be in place before the middle of 2000.

There was an interesting sideline to the discussion on the research program. While the technical team at PanCanadian, including the co-author (Brown), felt that the high calibre of researchers looking at the project would be both interesting and helpful, management within the company were more concerned with safety and researchers getting in the way of the work being done in the field. A compromise was reached allowing for the safe collection of samples and other activities in the field and PTRC (then under the direction of Roland Moberg) was instructed to have commitments for $10 million in place (50% of the estimated budget of the project) before the end of 2000 to allow the project to proceed. It was also agreed that researchers would not wander the field but would have experienced field personnel with them – this field produces sour oil and gas so $H_2S$ is a significant safety issue.

Obtaining such a massive research project was a major coup for PTRC as a fledgling organization. Roland Moberg launched himself into the funding process fully. With his persistence, the project was able to obtain commitments to $9 million by the deadline and PanCanadian agreed to let the research proceed. In the end, the project obtained in excess of $20 million in cash contributions from governments and industry, as well as about $20 million in in-kind (non-cash) commitments from PanCanadian and others.

The Weyburn $CO_2$ EOR project was broken into a number of phases, starting with 19 injection patterns in what was called Phase 1A. Phase 1A included some of the best reservoir quality in the field, and from a development perspective, this allowed optimum use of the $CO_2$ purchased from Dakota Gasification. Once recycle volumes built up, the flood area could be extended into successive phases, and as greater volumes of $CO_2$ became available, the rate of expansion could be increased. The research project on long-term storage aspects associated with the flood started with Phase 1A, and the baseline study was initially implemented on this 19 pattern area of the Weyburn field. Included in this baseline study was the 3D seismic survey shot by PanCanadian as part of field operations and contributed to the research program by the company. Baseline surveys also included geochemical surveys of the reservoir fluids, surface soil geochemistry, a tomographic survey between two horizontal wells, and vertical seismic profiling. PanCanadian was, at the time, a member of the Reservoir Characterization Project (RCP) at the Colorado School of Mines and brought this program into the project as well, with the RCP trying some innovative new seismic techniques such as 9 component surveys and shear wave investigations in a portion of Phase 1A. The resources for the baseline survey were contributed by the Canadian federal government and the Province of Saskatchewan [1, 2].

The size and scope of the research program catapulted the project into the world of Carbon Capture and Storage on a par with Sleipner. There were the inevitable criticisms about Weyburn being a unique field and so questioning the relevance of the field. It goes without saying that all fields are “unique” and so the criticism bore little weight. In addition, the volume of available information on the field made it an excellent candidate for this kind of work. As discussed in the introductory section, the provincial government had created a large public database of oil and gas core and other information from before the drilling of the discovery wells in Midale and Weyburn providing a unique historical dataset from which to build historical geological models of the field to create a truly comprehensive baseline.

It is not the intent of this paper to go into depth on the work that was undertaken in the research program, but rather to provide some insight into the overall goals. Detailed information on the work undertaken can be found in the literature, with the first report released in 2004 available from the PTRC website (www.ptrc.ca). The fundamental thinking behind the project was to understand storage of $CO_2$ in the subsurface, not the process of EOR. Within this basic framework, numerous tools were used, particularly geophysics, geochemistry (surface and reservoir) and a broad geological interpretation. This was all integrated into an understanding of the risks associated with storage in a reservoir with numerous wellbores, recognizing that human intrusions into the reservoir would be the weak points, particularly with wells dating back 50 years (at the time).

The geochemistry sought to understand the changes occurring in the reservoir with the addition of an acid given that the reservoir was carbonate. The isotopic signature of the carbon in the $CO_2$ entering reservoir could also be used as a tracer to determine the arrival of the $CO_2$ at the production wells. The geophysical work really answered the question of viewing the movement of $CO_2$ in the subsurface. It became clear that changes to the response seen in the reservoir from successive 3D surveys allowed the operator to “see” the $CO_2$ movement in the subsurface.

The geological work developed a detailed understanding of the geological framework for an area of about 100 $km^2$ centred on Phase 1A. Beyond this an area, a 200 km by 200 km zone was studied in less detail, providing an understanding of where migration pathways might exist. This work looked at the entire geological column. The geological study at this scale provided information that was beneficial far beyond use to only the project.

Based on the work undertaken, the risks of underground storage in a mature oil reservoir were predicted as being extremely low. While this was expected in a well-managed reservoir, it was gratifying to see.

The final report from the project (first Phase) was completed in 2004 in time for the IEA Greenhouse Gas R&D Programme biannual conference, which was held in Vancouver. The report served a dual function, being the summary of the work over four years as well as being an input to the generation of the IPCC Special Report on Carbon Dioxide Capture and Storage. This latter report, still quoted extensively, was released in late 2005 and coincided with the Conference of the Parties meeting in Montreal, Canada. The Vancouver conference dedicated considerable time to the findings of the project as well.

The first phase of research included researchers from Canada, the US and four European countries, together with some research engagement from Japan, bringing together some of the most experienced researchers on the topic of geological storage from around the globe.

There was a hiatus in the research (although samples continued to be collected) for a couple of years before the second (the Final Phase) was initiated. This project was led by the other author (Whittaker) and continued the excellent work of the researchers from Phase 1 and used many of the same researchers, providing continuity for this important project. The number of European researchers decreased due to a lack of funding from the European Commission. The approximately $20 million raised by the Final Phase was enough, however, to assist a number of European researchers to continue with the work. This Final Phase technically included Midale as part of the storage study with this field (now operated by Apache Canada) receiving $CO_2$. In fact, however, little work was undertaken in Midale Field.

This phase of the research continued the excellent work of the first phase. The summary report from this phase was completed in 2011. While the book is available, it is unfortunate that an electronic copy is not.

In both phases of the research, but particularly in the second, risk assessment and public acceptance were key issues. With a better understanding of risk procedures, risk assessment was more complete and undertaken in a more formalized way. The end results were similar, that a good risk management plan will help to keep risks of unacceptable events to a minimum. Public concerns included such things as induced seismicity, something monitored by passive seismic and demonstrated as happening as micro-earthquakes – small events in the reservoir that are too small even to be felt except by equipment designed to record tiny events. A vehicle driving by has a more significant impact on the surface.

The high level of public engagement by both the company and the research program helped considerably in 2011 when a complaint was brought to the government of Saskatchewan about $CO_2$ leakage on a piece of land within the Weyburn field area. This land and the land owners had long been in dispute with the oil company operating the Weyburn field over alleged pollution of the field. This latest concern was raised because of work undertaken in the field by a geotechnical company over the presence of $CO_2$ in the soil, although this property was not directly above a flooded portion of the field

A number of studies were undertaken to look at the issue. This included researchers engaged in the Weyburn-Midale project, notably from UK and Italy (www.ieaghg.org). Although the land owners had not allowed a baseline survey over the property before $CO_2$ injection had commenced, baseline soil gas surveys had been conducted nearby in a wide area above the field and off sites in similar agricultural settings. Indeed, this event proved the value of baseline surveys as a way of demonstrating change if such change occurs. The soil $CO_2$ contents measured at the property in question had similar ranges in concentration as the samples measured at baseline sites. The $CO_2$ was generated by bacterial action as was proven by stable isotopic analysis ($^{13}C/^{12}C$ ratios) and total gas composition (ratios of atmospheric gases $N_2$ and $O_2$ in the soil gas can indicate bacterial action that reduces the relative oxygen content). Moreover $^{14}C$ measurements firmly demonstrated that all the soil gas $CO_2$ was modern – that is, no $CO_2$ was generated from the burning of ancient coals, which is the source of the injected $CO_2$. Based on all the work undertaken, there was clear evidence that no leakage was occurring from the subsurface at this location.

In the week or so in which the media took hold of the allegations of leakage before sound science was brought to bear on the issue, the newspaper headlines were quite outrageous, at times including statements such as dead animals being spewed from wells. This was unfortunate since the allegations had no foundation in science, but a good response took time to prepare and engaged multiple scientists. It was a situation where science displays its limitations, those with the agenda of proving $CO_2$ storage wrong were not hampered by the dictates of good science; on the other hand, scientists would not speak before reviewing the evidence and providing cautions around the fact that science cannot provide absolutes, particularly in a case like this. It was an interesting lesson.

**Conclusions:**

As a result of moving ahead with $CO_2$ EOR, both Weyburn and Midale stand among the best understood oil fields in the world. The combination of forethought by Saskatchewan regulators to collect oil field information in a public database and the insight demonstrated by Shell to look at the reservoir rather than follow conventional wisdom of $CO_2$ EOR not being applicable in fractured reservoirs has led to this understanding. The work of PanCanadian to develop a plan for EOR in Weyburn, and the work of the researchers looking at safety of storage have significantly increased the understanding of Weyburn Field. The final point to make is that with the field being relatively shallow and readily accessible at surface, there are many wells drilled, further reducing the level of uncertainty about the geology of the fields.

The heavy application of multi-leg horizontal wells in the early days of drilling horizontally also made Weyburn the recipient of advanced drilling technology. Again, the credit must go to PanCanadian as a company willing to take technology risks and benefiting from the successful application of the technology.

The work undertaken by the international team of researchers has demonstrated the safety of subsurface storage of $CO_2$ in spite of the number of wells drilled in the field and the age of some of these wells. Not even allegations of leakage after a decade of injection has changed opinions of the efficacy of this process of preventing $CO_2$ from reaching the atmosphere.

This has been a very successful field and research program. An only regret would be the inability to follow Phase 1A through to the completion of $CO_2$ injection and abandonment of this portion of the field. This would have provided experience of a full cycle of $CO_2$ EOR in a commercial setting and provided additional comfort regarding subterranean storage.

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**Useful websites:**

1. www.PTRC.ca - The Petroleum Technology Research Centre (PTRC)
2. www.IEAGHG.org - IEA Greenhouse Gas R&D Programme