Academic-Industry Partnership Between University of Houston (UH) and Oil India Ltd. (OIL) Has Immensely Benefitted Both Sides – Phase 3 Completion

An innovative partnership between the University of Houston and Oil India Ltd. (OIL) has offered benefits for both partners, improving Oil India fields and boosting production there while providing UH researchers and graduate students with research opportunities and practical experience.

- Two UH students completed internships at OIL. Eight graduate students have completed their research work using the OIL field data. Five postdocs and several professors have performed extensive industrial research on this project.
- The $4.80 million partnership, launched in late 2016, has completed its third phase in May 2021, a project to enhance oil recovery in oilfields in the Indian state of Assam, using carbon dioxide captured from nearby petrochemical plants. That project, slated to continue through 2022-23 (implementation time) , is designed to both increase the country's ability to fulfill its energy needs and to reduce its carbon footprint.
- India currently imports more than 80% of the fossil fuel it uses, making it critical to increase domestic production without worsening air quality.

The collaboration has included training opportunities for Oil India executives and employees, both in Houston and in India.

The project is led by Ganesh Thakur, director of Energy Industrial Partnerships for UH Energy and Distinguished Professor of Petroleum Engineering; it is an outgrowth of a trade mission to India led by Texas Gov. Greg Abbott in early 2016.

Thakur, a member of the National Academy of Engineering, was recruited to UH in 2016 with a $3.0 million grant from the Governor's University Research Initiative (GURI). This was matched dollar for dollar by UH, making a total research budget of $6.0 million from 2016 to 2021.

Thakur, an expert and a world recognized leader in reservoir management and Enhanced Oil Recovery, he is a former industry executive and spent years working with carbon capture and sequestration techniques for conventional wells in the Permian Basin for Chevron Corp.

- In addition to Thakur, the UH team is composed of more than a dozen scientists and engineers, including faculty members, post-doctoral researchers and graduate students, in disciplines including petroleum and chemical engineering and the geosciences.
- Based upon the first MOU signed between OIL (represented by Mr. Utpal Bora, CMD) and UH (represented by Dr. Ramanan Krishnamoorti, Interim VP-Research and Chief Energy Officer) on October 5th, 2016, UH and OIL agreed to collaborate starting November 2016, in an effort to assess the field performance of Makum-North Hapjan and provide recommendations towards quick win in production. In addition, UH agreed to collaborate with the OIL CoEES to develop enhanced oil recovery (EOR) capabilities and to upgrade the in-house laboratory facilities.

Phase 1

The project began in December 2016 with a $500,000 Reservoir Screening Study and focused on analyzing wells in the Makum-North Hapjan field, located in the northeastern corner of India, in order to provide recommendations that could quickly boost oil production.

It was successful – UH researchers calculated that oil reserves controlled by Oil India, the national oil company of India, are substantially higher than previously thought. Another recommendation – which discouraged drilling in one area under consideration – resulted in a potential savings of $4 million.

Among other accomplishments during Phase 1, which concluded in May 2017:

- All pertinent field data was reviewed in order to complete a broad characterization of the MKM-NHJN field
- A classical reservoir engineering study indicated that effective integrated reservoir management is critical to maintain the field production rate and achieve a recovery rate of 43%
- Detailed integrated well reviews were performed on 58 wells, resulting in immediate production gains, including an increase of 35 kiloliters per day, or 220 barrels per day in one well, Makum-53.
- The UH team also reviewed surface facilities and recommended implementing effective surface facilities management and lowering surface separator pressure from 21 kilograms per square centimeter (ksc) to 18 ksc
- Other recommendations dealt with well cementing, sand control and bringing surveillance and monitoring practices up to industry standards.

In addition, UH researchers screened 50 OIL reservoirs and ranked their potential for enhanced oil recovery/improved oil recovery. Seven reservoirs, including the top five ranked reservoirs, were selected for more detailed studies using a patented UH technique. The more detailed study found that with effective reservoir management, four out of the top five reservoirs offer the potential for adding at least 17 million barrels of oil to the country's reserves, with a 33% probability of success.

Interaction wasn't limited to the oil field, however. Three workshops for Oil India executives were conducted, two at UH and one in India, followed by a series of recommendations to build and maintain executive team competencies. That was in addition to training by UH experts in enhanced oil recovery techniques.

Phase 2

Phase 1 of the project served as an introduction to the potential benefits it could provide Oil India. In Phase 2, conducted between September 2017 and December 2018, the collaboration deepened as University researchers identified specific reservoir management opportunities in the Makum-North Hapjan Field, as well as in the Greater Jorajan Field and Dikom Field, and began working to prepare the fields for eventual carbon capture and utilization projects.

Phase 2 came with funding of $1.4 million, with an additional $325,000 for lab-based research, for a total of $1.725 million.

Among a number of significant accomplishments and recommendations, the UH team developed a new petrophysical model for Oil India for the Makum-North Hapjan Field. Together with new core data and reservoir simulation work, this modeling revealed a significantly higher original oil in place, or OOIP, suggesting Oil India's reserves are higher than originally estimated.

Additional screenings and simulation studies of the field led to recommendations of where to drill and techniques best suited to improve production, including the use of water injection for pressure maintenance in selected areas, rather than conducting waterflooding everywhere in the reservoir.

Two additional oilfields – the Greater Jorajan Field and Dikom Field – were reviewed, yielding specific recommendations on where to drill, along with identifying concerns about oil migrating into the gas cap at some wells. Oil India was provided with recommendations to avoid or minimize the concern.

Other results from Phase 2 included:

- A proposal to use horizontal wells with hydraulic fracturing to revive the tight Lower Tipam reservoir to improve oil recovery in the Jorajan
- A provisional patent filed involving researchers from both UH and Oil India dealing with carbon dioxide miscibility.
- Identified opportunities to recover more than 16 million barrels of previously unrecognized incremental oil

OIL employees were given four weeks of training on enhanced oil recovery, while a UH expert on well completions, Dr. George Wong, visited field operations in India to review operations and recommended potential changes to improve oil recovery.

The learning opportunities went both ways. Two UH graduate petroleum engineering students completed internships at the Oil India field headquarters (FHQ) and at Center of Excellence for Energy Studies (CoESS).

Phase 2 ended with the recommendation that OIL leverage its association with UH to launch a complete internal executive training program using UH experts – who together have decades of industry and academic experience in delivering practical training – to identify necessary resources and create a comprehensive program.

Phase 3

- Phase 3 of the Oil India-UH collaboration that started in October 2019 has just been completed (a three-volume 660-page report), and management presentations to Oil India Ltd. are planned to be conducted in June, 2021. The $2.6 million project and lab-research work was focused on enhancing oil production by using carbon dioxide captured from nearby petrochemical plants to boost oil recovery in several fields in Assam and builds upon the field improvements undertaken in Phase 2.
- This carbon capture, utilization and storage project will help to reduce the country's carbon footprint, a critical step for India to participate in the future energy economy.
- Dr. Thakur (the Principal Investigator) and his team members were able to visit FHQ in Duliajan and CoEES in Guwahati in the state of Assam to collect key data for conducting the collaborative research in Phase 3 right before the pandemic during November 2019 and February 2020. Since then, they conducted 28 bi-weekly videoconferencing with the FHQ and CoEES executives utilizing the state of the art technologies to advance the research project in an effective manner. All these VCs were conducted in the nighttime from Houston so that the customers could have their meetings in the morning times in India.
- UH, FHQ and CoEES coordinated an excellent training program for Oil India Limited executives, focused on EOR (enhanced oil recovery), seismic technology, petrophysical analysis, reservoir simulation, and lab capability development. In the five training courses, advanced theoretical concepts and practical approaches were delivered by various UH experts. The instructors for these training programs included subject matter expert world-renowned professors, such as, Dr. Ganesh Thakur (NAE and Former SPE President), Dr. Farouq Ali (NAE), Dr. Rob Stewart (Former SEG

President), and Dr. Mike Myers. Supporting researchers, post-docs and PhD students included: Dr. Sushanta Bose, Dr. Peila Chen, Dr. Zeinab Zargar, Mr. Anand Selveindran, and Mr. Veer Denduluri. The five executive training courses were attended by over 150 participants from Oil India and have drawn accolades from both FHQ and CoEES.

- Our scientists and researchers are very proud to achieve over 80% of the research work during the pandemic time-period. Thanks to the advanced technology and the hard work of our researchers in enabling this. Dr. Thakur's continuous motivational persistence played a key role in achieving this, and it was highly recognized by Mr. Saloma Yomdo of CoEES, Oil India Ltd.

Among other accomplishments during Phase 3, which concluded in May 2021:

Kathaloni (KLN001) Field:

- Our geoscientists and the reservoir engineering researchers with the help of their advanced seismic, geolological, petrophysical and reservoir engineering and simulation work identified STOOIP (stock tank original oil in place) of 33.9 MMKLS or 213 million barrels of oil and recognized new development opportunities. UH's advanced research in this area provides tremendous confidence for the resource assessment in the Kathaloni field. The OIL professionals have thoroughly reviewed this work and are adopting the results of this research work, a 25% higher oil-in-place than estimated before.
- The reservoir contains light oil with a mobility ratio of 0.40 – a very favorable condition for water injection and CO2 EOR. Water influx & injection conditions are good as confirmed by 300+ simulation runs.
- We have analyzed water influx to be strong in this reservoir, yielding good recovery factor and maintaining pressure in most areas. However, it still needs supplemental water injection and effective RM (reservoir management) area by area.
- Our recommendations will make current water influx and future waterflood more effective, CO2 EOR applicable, and increase RF from 31% to 40%, a potential to add 19 million barrels of incremental oil.
- CO2 EOR can significantly increase recovery factor, Sorm < 10% and MMP is equal to the current reservoir pressure.
- Significant potential exists to increase oil recovery and reserves by expanding waterflooding and CO2 EOR flooding in the field by pattern flooding: 7.0 million barrels of oil by waterflooding and 4.4 million additional barrels of oil by CO2 EOR method.
- Field development activities in 2-pattern area can significantly improve oil recovery with an incremental oil production of approximately 1.15 MMKLS (infill + new-perforations + CO2 injection) or 7.23 million barrels of oil.
- For the selected patterns, incremental oil from CO2 injection is 0.33 MMKLS (2.01 million barrels of oil) and estimated CO2 storage is 0.38 million metric tons (or 7.14 BCF).
- Polymer flood simulation does not show significant incremental recovery, as the mobility ratio for water injection/drive is already favorable for the Kathaloni reservoir. In addition, lab tests for low salinity waterflood (LSWF) does not yield in any incremental oil recovery, as the formation water is already relatively fresh.
- Identified new perforations, infill, WI, CO2 EOR by detailed lab analyses, petrophysics, reservoir engineering & simulation, but proper implementation is a key to success
- Project economics without cess taxes (Government of India taxes) reduction is attractive ($100-107 million NPV).
- UH utilized fresh core analysis and phase behavior studies performed by UH researchers and service companies.

- More effective well management is required to preserve wells. Right now, too many wells are being lost, and it costs about $8 million per well to drill.
- Most of the remaining oil potential exists in Zones 2, 3 and 4, so these should be the future areas for focus.
- Over 150 OIL attendees were trained by UH. However, OIL management must utilize their talents for asset management.

Langkasi (NHK384) Field:

- Identified 7.3 MMKLS or 45.9 million barrels of oil, ~15% higher OOIP than OIL's estimate (6.35 MMKLS) based upon detailed research on seismic, petrophysics, geomodeling and simulation.
- A mobility ratio of 0.56 - favorable for water influx/injection and CO2 EOR.
- Strong water influx yielding good recovery and pressure maintenance prior to 2009; water injection started in 2009 and it raised reservoir pressure and boosted oil production.
- Prediction case: 6.92 million barrels (1.1 million KLS) of incremental oil by infill, workover, peripheral WI and CO2 EOR (~50% of CO2 EOR incremental thru screening study). Recommendations are made to perform a detailed lab and simulation study in Phase 4.
- Peripheral waterflood (utilizing NHK357 and NHK420 as injectors) produces ~100,000 KLS of incremental oil without drilling any new wells.
- Simulation of infill UH-6P and UH-5P show an incremental oil of 77,000 and 65,000 KLS, respectively.
- A decline curve analysis shows that the EUR is between 2.28-2.43 MMKLS, with a high side opportunity of 0.12-0.28 MMKLS achieved by effective RM.
- Detailed studies involving seismic, petrophysics, reservoir engineering & simulation shows good potential for new perforations, infill drilling, WI, CO2 EOR, but implementation is a key to success. More effective well management is required to preserve wells.
- CO2 EOR is applicable based on the advanced UH EOR screening method. Opportunities to perform EOR/PVT laboratory studies for miscible CO2 EOR exists at the UH Lab.
- Remaining oil potential exists near well NHK422 – a future area to investigate.
- As mentioned under the Kathaloni project, over 150 OIL attendees were trained by UH. However, OIL management must utilize their talents for asset mgmt.

Nagajan (NHK262) Field:

- Excellent quality, relatively continuous sand (Avg. Phi ~20%, Perm ~350) with Light oil (API 25.6, viscosity 2.5 cP). Identified 87 million barrels (13.76 million KLS) of OOIP by integrated reservoir characterizations, and it was reviewed with the OIL executives.
- Strong double displacement drive - presence of large initial gas cap (m value~0.5) and strong bottom water influx. Ideal reservoir conditions exist for primary recovery, waterflood, and CO2-EOR when managed well.
- Rigorous seismic-to-simulation modeling including detailed petrophysical, geological and reservoir engineering under domain experts: Dr. Stewart, Dr. Myers, and Dr. Thakur; moreover, fresh lab research results were incorporated.
- Identified the reasons for low RF, failure of horizontal well, and unpredictable reservoir behavior (e.g., significant amount of oil migrated into the gas cap).
- Our rigorous research showed RF could have been 35% instead of 10% from an effective RM from day one.
- Potential vertical/horizontal infill wells exist with incremental oil of 0.46 MMKLS.
- Risk level is high due to the non-uniform distribution of the migrated oil; strongly recommend to run RST. If RST shows oil saturation >40%, the potential of workover/infill will be higher.

- Gas cap blow down to improve HC recovery, without any infill wells, by six (6) currently shut in wells for workovers with the four (4) current producing wells (incremental oil of 0.71 MMKLS or 4.5 million barrels of oil).
- Limited water injection opportunities exist due to high free gas and water saturations.
- EOR effectiveness is questionable due to migration of oil into the gas cap.
- As mentioned under the Kathaloni project, over 150 OIL attendees were trained by UH. However, OIL management must utilize their talents for asset mgmt.

Phase 4 Ideas:

As we are completing all the strict requirements of Phase 3 research work, we are also developing ideas for Phase 4 research that will create significant business values to Oil India Ltd. These include:

- Reservoir management (RM) of Oil India Ltd.'s key fields – developing ideas and strategies for improving their reservoir management to increase recovery efficiency and production.
- Thorough study of CO2 EOR in NHK 384 Block – lab and simulation
- Identify and study next IOR/EOR candidate – Makum-NHJN, Dikom, Moran – planning early is critical
- Identify rejuvenation candidates – Jorajan, Others as identified by OIL
- Review newly discovered / early life reservoirs to design RM approach – planning early is critical
- Continue to develop CoEES capabilities and skillset– training for entire OIL, training lab operators, build lab facilities
    - Dr. Ganesh Thakur, as VP of technology, Chevron, has led Chevron's technology teams and will be available for advising CoEES
    - Build a thorough training program for all OIL executives under CoEES with visiting domain experts
    - Lab should become operational
    - Train CoEES lab employees on new instruments under renowned experts' guidance
- Implementation of the immediate action items – UH review and support
    - Shut-in wells, manage GOR and WCUT
    - Run RSTs where recommended
    - Prepare reservoir for the EOR, i.e., water injection etc. to raise pressure
- Implement CO2-EOR - active involvement and support by UH domain experts (reservoir-production-drilling)
    - For NHK 079D
    - For KLN 001D
- Closely monitoring-reviews-decisions for effective management of ALL reservoirs
    - Analyze data regularly (suggested quarterly reviews) and update conclusions as necessary
    - Host workshops in which, data and strategy reviews will be conducted and conclusions by domain experts will be made for the critical decision points