Technical Paper
BR-1854

B&W PGG's Demonstration-Ready RSAT™ Technology for Post-Combustion Carbon Capture

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Presented to:
10th Annual Conference on Carbon Capture and Sequestration

Date:
May 2-5, 2011

Location:
Pittsburgh, Pennsylvania, U.S.A.

AND

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Introduction

For more than 140 years, The Babcock & Wilcox Company (B&W) has been a leading provider of fossil-fired steam generating equipment for utility and industrial applications. Responding to coal-fired power plant air emissions regulations in the early 1970s, B&W began designing and supplying air quality control systems (AQCS) for sulfur dioxide (SO_2) and particulate control.

As clean air laws were amended to regulate additional pollutants, B&W expanded its capabilities to include emissions control systems for nitrogen oxides (NO_x), mercury and other hazardous air pollutants. Recognizing the growing emphasis on reducing carbon dioxide (CO_2) emissions from coal-fired boilers, B&W began development of its oxy-combustion carbon capture technology in 2000.

Following successful pilot testing of oxy-combustion technology, Babcock & Wilcox Power Generation Group, Inc. (B&W PGG) was selected by the United States (U.S.) Department of Energy (DOE) in 2010 as the technology supplier for the FutureGen 2.0 large-scale test of the oxy-combustion CO_2 capture process at Ameren Energy Resources' Meredosia Plant in central Illinois.

In response to the requirements of existing utility power plants for partial CO_2 capture capability, B&W began development in 2005 of a post-combustion CO_2 capture process. Since that time, B&W PGG's research and development (R&D) efforts in post-combustion capture (PCC) have led to the construction of a 7.5 metric ton per day PCC pilot plant (Figure 1).

Post-combustion capture using solvent absorption

B&W PGG's RSAT™ system is a post-combustion carbon capture technology, which works by absorbing CO_2 directly from flue gas in an absorber using a regenerable solvent. The CO_2-laden solvent is sent to a solvent regenerator where it is heated and the CO_2 is released as a concentrated stream for compression and transport to a CO_2 storage facility. The solvent is then recycled to the absorber for additional CO_2 capture (Figure 2).

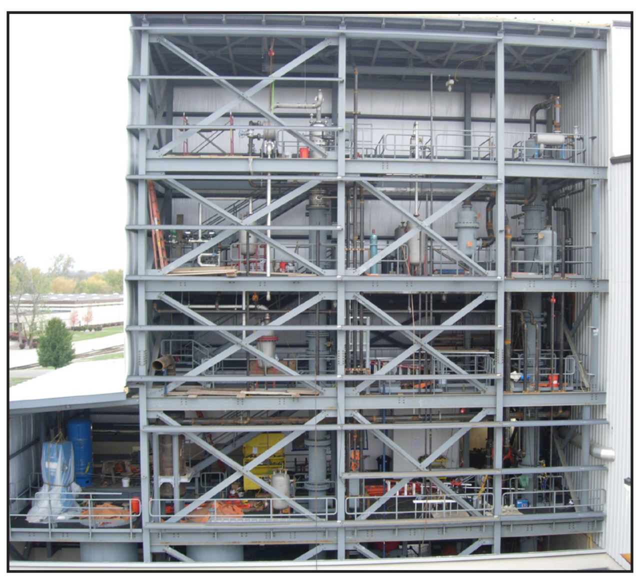

Fig. 1 B&W PGG's post-combustion pilot test facility.

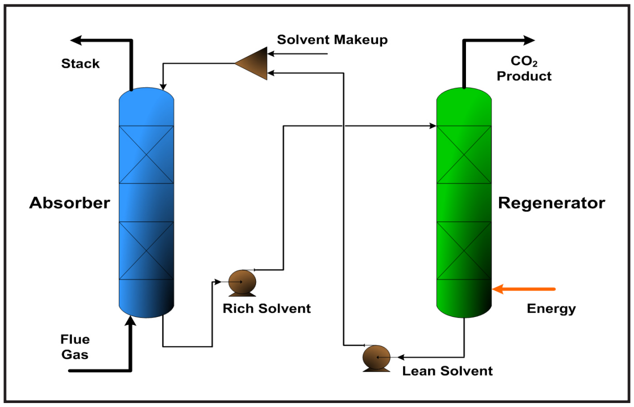

Fig. 2 Overview of the regenerable solvent absorption process.

Applying regenerable solvent technology to coal firing

Capturing CO_2 from gas streams by solvent absorption has been in use in the oil and gas and chemical processing industries for approximately 75 years. The technology is well proven. The basic equipment for CO_2 capture from coal-fired applications will be similar to that used in refinery applications, and will not require major changes in the technology to meet the required criteria. In addition, many of the operating characteristics will be similar and the issues surrounding safe operation of a regenerable solvent absorption facility are understood by the chemical process industry and should easily transfer to utility applications. However, adapting this technology for use in coal-fired utility power plants will still present challenges, including accommodating differences in process chemistry, temperature and operating pressure. One important difference between a typical utility and a typical industrial application is the scale of equipment required due to the low flue gas pressure and large volume of flue gas which must be treated from a utility coal plant.

With a long history of deployment of conventional AQCS for sulfur oxides (SO_x) and NO_x, the industry recognizes the challenges which will be faced in deploying PCC systems. Commercialization of large-scale flue gas desulfurization (FGD) systems began in the 1970s. Throughout the next 40 years, the industry developed and implemented many design improvements to FGD systems which have resulted in significant increases in removal efficiencies while reducing auxiliary power requirements. The FGD system deployment faced many challenges, and similar challenges will also face the initial PCC system deployment. System configuration changes and process improvements to PCC systems will be developed and implemented over time, which will result in efficiency improvements and operating cost reductions. The successful development and deployment of large FGD systems over the past 40 years is a strong foundation to build upon for commercialization of PCC systems.

Technology development roadmap

Using a consistent and logical technology development roadmap will aid in accelerating the commercial deployment of post-combustion capture processes such as the RSAT system. B&W PGG's RSAT development process is shown in Figure 3. The program has been conducted using a stage-gate approach. Solvent and process developments have been carried out in a deliberate step-by-step program to progress from discovery to commercial demonstration in the shortest reasonable time.

In 2005, B&W began efforts to develop the RSAT process, and a team was assembled at B&W's Research Center (BWRC) in Barberton, Ohio. The team initiated an in-depth technology review which included existing and developing solvent-based, post-combustion capture technologies, design methods, solvents, academic research and other sources to establish a basis for development of the B&W PGG RSAT product. A dedicated CO_2 control laboratory was built and outfitted with the latest equipment to screen candidate solvents and obtain physical and chemical data for the design of the RSAT system.

CO_2 control laboratory The CO_2 control laboratory is used to quickly assess potential solvents, which are evaluated with regard to their rate of absorption, capacity to hold CO_2, and the energy required to regenerate the solvent. The lab contains two primary test facilities: a wetted-wall column for precise measurements of fundamental mass transfer and chemical kinetics data (Figure 4), and a fully integrated bench-scale RSAT simulator used to evaluate solvent and process design concepts (Figure 5). These laboratory-scale tools facilitate the characterization and selection of solvents and help to quickly and effectively evaluate process changes.

Wetted-wall column The wetted-wall column (Figure 4) is a gas-liquid contactor in which CO_2 absorption or desorption can be studied under precisely controlled conditions. Due to its simple geometry, the area of contact between the gas and liquid solvent is accurately known. The solvent flows upward through the tube in the center of the column, exits at the top and flows over the outside surface of the tube in a thin film. The solvent is contacted with a gas mixture containing CO_2 which flows upward in the annular space around the tube.

Careful control of temperature, pressure, and gas and solvent concentrations produces high quality fundamental data on mass transfer, chemical reaction kinetics and thermodynamic properties of the solvent. This information is then used in computer simulation models to predict process performance in both the bench- and pilot-scale systems. These computer modeling tools have been utilized to size

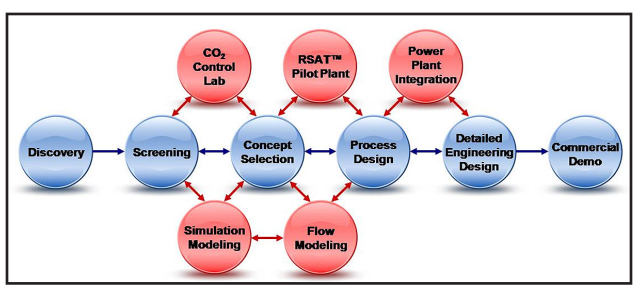

Fig. 3 B&W PGG's RSAT process development program.

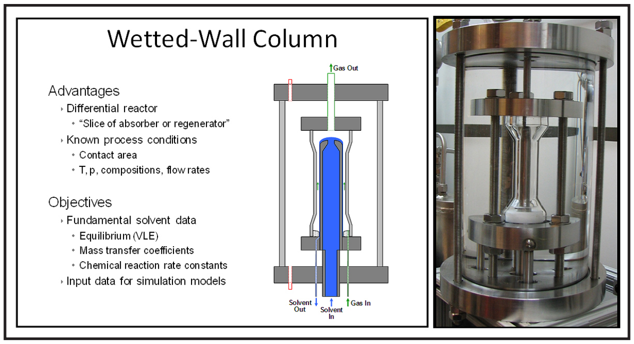

Fig. 4 Wetted-wall column.

equipment and predict system performance, and are continuously validated against actual data from lab-, bench- and pilot-scale equipment.

Bench-scale RSAT unit The bench-scale RSAT simulator (Figure 5) is a fully functional process test facility. The unit contains most of the equipment which would be included in a large-scale facility, including the absorber column on the left, the regenerator column at right, and the electrically heated reboiler in the lower right of the photograph. The bench-scale unit is designed to capture approximately one kilogram of CO_2 per hour. The columns are of modular design, and the process can be operated in a variety of modes which provide excellent flexibility for process analysis and development work. The unit provides an initial indication of the performance of a new solvent in an integrated system. This fully integrated bench-scale process also facilitates parametric studies of independent process variables and provides data for validating computer simulation models.

RSAT pilot plant Following laboratory and bench-scale evaluations, the most promising solvents are tested at large scale in B&W PGG's RSAT pilot plant (Figures 1 and 6). Relative to the data provided by the CO_2 control lab, the RSAT pilot plant provides high quality, quantitative data which is representative of full-scale systems. Different process flow schemes which can affect CO_2 absorption rates and regeneration energy for a given solvent are tested and evaluated in the pilot unit, with a focus on minimizing the overall energy consumption of the CO_2 capture process.

Fig. 5 Bench-scale RSAT simulator.

Fig. 6 B&W PGG's RSAT pilot plant.

The RSAT pilot plant is installed in a building adjacent to B&W PGG's small boiler simulator (SBS). The SBS facility replicates a coal-fired power plant from fuel handling to the stack. The RSAT pilot plant can process approximately 3,100 lb of flue gas per hour and capture approximately 7 tons/day of CO_2 (approximately 50% of the flue gas produced by the SBS). The pilot plant can also be operated in recirculation mode, wherein the captured CO_2 is mixed with nitrogen and other gases to simulate actual flue gas from a coal-fired power plant before being recycled to the inlet of the absorber.

Construction of the RSAT pilot plant began in June 2008. The plant installation was completed and commissioning of the facility began in January 2009. First operation on an amine solvent was achieved in June 2009. Baseline tests to characterize pilot plant performance were first run on a 30 wt% monoethanolamine (MEA) solvent. Results of these tests serve as a basis for comparison to other solvents and were used to validate computer-based process simulation models. The most promising solvents identified in the laboratory by bench-scale testing and computer simulation modeling were then run through a series of test campaigns in the RSAT pilot plant.

Results from B&W PGG laboratory and pilot testing

The work performed by the research team at the BWRC, coupled with B&W PGG's commercial experience, are being combined to develop solvents, process designs and test methods which offer a high probability of success for the RSAT system. As a result of its extensive pilot test program, the research team selected the most promising solvent candidate for more in-depth development and testing. B&W PGG's OptiCap™ solvent has been tested extensively at lab and pilot scale.

To date, pilot testing of the OptiCap solvent has shown favorable performance characteristics. Under similar test conditions, a lower reboiler heat duty was attained for the OptiCap solvent, as compared to 30 wt% MEA solvent. The minimum reboiler heat duty attained was comparable to the heat duties claimed by other solvent and process providers of 122 to 130 kJ/mol. Additional properties of the OptiCap solvent which are expected to provide additional savings in capital and operating costs (e.g., resistance to degradation, high mass transfer rate, high CO_2 carrying capacity), have been verified in these campaigns, and will be further quantified in future test campaigns.

The results described above are considered to be only an early indication of the potential of the OptiCap solvent. B&W PGG has simulated several process design cases which could further reduce the energy penalty of solvents by using heat integration with the power plant. Some of these design cases are specifically related to the unique properties of the OptiCap solvent—for example, the ability to regenerate at higher temperatures and pressures. Computer models indicate that these process improvements are feasible, and projected energy requirements of approximately 1,100 Btu/lb CO_2 are possible for the OptiCap solvent. These specific design cases have not yet been proven in the field, but further pilot testing will provide the information and operating experience required to validate these predictions.

B&W PGG testing at the National Carbon Capture Center

In 2010, the OptiCap solvent was selected by DOE for further testing and verification in the pilot solvent test unit (PSTU) located at the National Carbon Capture Center (NCCC) at Southern Company's Plant Gaston in Wilsonville, Alabama.

Lab and pilot testing at the BWRC have been invaluable in providing a firm basis for the process design and selection of the OptiCap solvent. However, additional data and operating experience is required to fully commercialize the RSAT system. Pilot-scale field testing is a beneficial means of determining the operating performance of both the process and the solvent. Testing at the PSTU will provide essential information and insight into the commercial design requirements for regenerable solvent systems.

Many of the solvents considered for use in regenerable processes such as the RSAT system are susceptible to degradation in the presence of oxygen, acid gases and high temperatures. Also, many candidate solvents can be highly corrosive when used under the operating conditions present in coal-fired power plants. Depending on the solvent, a wide range of gaseous, liquid and solid wastes can be generated in the capture process. The design of equipment such as solvent reclamation and waste water treatment systems, instrumentation, and materials of construction for process vessels all rely on accurate characterization of critical solvent design parameters. These factors must be well understood to design a robust and reliable CO_2 capture process.

To obtain the necessary knowledge and operating experience to successfully design future commercial plants, test campaigns at the PSTU are currently being developed to closely represent the operating conditions found in commercial-scale coal-fired power plants. Information and data from these tests will be invaluable in designing commercial systems. Long-term testing under actual coal flue gas conditions in a facility such as the PSTU at NCCC is a critical step in the development and commercialization of post-combustion CO_2 capture processes.

The work at NCCC will add to the existing body of knowledge by providing long-term operating experience on coal flue gas. Some of the OptiCap solvent characteristics that will be confirmed and further quantified during testing at NCCC include:

- ***Resistance to oxidative degradation*** Certain solvents degrade in the presence of high concentrations of oxygen which can occur in coal combustion flue gas. Preliminary testing of the OptiCap solvent indicates a relatively high level of resistance to this phenomenon, which offers the potential for lower solvent make-up rates and lower solid waste generation rates.
- ***Resistance to thermal degradation*** Testing thus far has shown the OptiCap solvent to be stable at operating temperatures up to 150C. This attribute offers the potential for regeneration at higher operating temperatures and pressures, which could lead to significant energy savings in terms of CO_2 compression.
- ***Ease of reclaiming*** Results thus far indicate that thermal reclaiming is likely the primary technology for removing degradation species formed using the OptiCap solvent. Thermal reclaiming is a well-known technology which has been used successfully for decades for solvent regeneration. Other potential technologies for solvent regeneration include systems such as carbon beds and ion exchange systems.
- ***Lower volatility*** Compared to 30 wt% MEA, the OptiCap solvent shows decreased volatility. Lower volatility reduces solvent losses to the exhaust stack, and decreases energy requirements for heat exchanger cooling in the solvent wash section of the absorber.
- ***Increased mass transfer rate*** The rate of absorption of CO_2 for the OptiCap solvent is approximately twice that of 30 wt% MEA. This kinetic advantage allows the absorber towers to be designed with less packing than towers designed for 30 wt% MEA. This

characteristic offers capital cost savings with reduced absorber tower height, quantity of packing, structural steel, foundations and installation cost. Also, reduced tower height results in auxiliary power consumption savings, due to decreased pressure drop through the absorber and decreased pump power required for solvent recirculation due to decreased head pressure. Approximately 75% of the electrical power required to operate the RSAT system is consumed by the fan or blower to move the flue gas through the flue gas cooler and absorber, so cost savings generated by decreased pressure drop through the absorber towers can be substantial.

- ***Increased CO_2 carrying capacity*** Because the OptiCap solvent can be loaded with approximately twice the amount of CO_2 per unit of solvent, the solvent recirculation rate is decreased, saving not only the energy required to pump the solvent within the system, but also the energy required to heat and cool the solvent in the various process stages.

Testing under actual power plant flue gas conditions at NCCC will confirm the research performed to date in both the lab and pilot plant regarding the characteristics of the OptiCap solvent. In addition, phenomena such as solvent degradation, system corrosion and waste stream formation must be studied across time periods which exceed the duration of most lab- or bench-scale test campaigns. Therefore, long-term testing is critical to gaining a complete understanding of both the technical and financial risks associated with any PCC capture technology.

The ability to accurately predict cost and operating performance is essential, not only for process optimization, but also to quantify the risks and understand the remedies associated with offering performance guarantees. The ability to offer process performance guarantees will play an important role in commercial plant deployment. Field testing on coal flue gas at a facility such as the PSTU at NCCC is an important step on the path to completing the required analysis.

Final steps to commercialization

Significant B&W PGG resources and funding have been dedicated to developing the RSAT system, including creation of some important technical and financial tools. In 2008, a 75 MW RSAT reference plant design was completed. The plant was engineered for 90% CO_2 capture from a flue gas stream containing 1,500 metric tons of CO_2 per day. The size selected for the plant was based on the concept of providing a unit large enough to gain the knowledge and confidence required to make the next step to commercial size, but small enough to keep capital and operating costs manageable. The primary goal of the project was to create a scalable model which could be used as a basis for techno-economic evaluation.

The reference plant project also resulted in the creation of a standard plant design which could be scaled up or down, enabling B&W PGG to quickly respond to requests for budget-level pricing and equipment descriptions for the RSAT system. Several such requests have been addressed for projects of varying size and scope, using the reference plant design as a basis for equipment sizing and cost estimates.

The development of the RSAT reference plant design engaged all departments within B&W PGG that are typically involved in a commercial contract. Engineering, procurement, scheduling and transportation were all part of the reference plant design process. This methodology offered the benefits of early establishment of focused functional teams and helped to develop a future supply chain of vendors and fabricators of PCC process equipment. Babcock & Wilcox Construction Co., Inc. (BWCC), a subsidiary of B&W PGG, was also involved in the process, providing cost estimates for equipment installation and schedules. BWCC also offered valuable suggestions regarding modularization and plant design changes which would improve constructability and decrease the overall cost of installation.

The RSAT reference plant project resulted in a full package of engineering documentation, including piping and instrumentation drawings, a 3-D plant layout (Figure 7), equipment lists, schematics, preliminary mechanical design and fabrication drawings for major process vessels, foundation and structural steel designs, procurement packages including equipment specifications for all major equipment, construction estimates, engineering man-hour estimates, process flow diagrams, and a complete material and energy balance for the plant.

The equipment sizing and configuration for the RSAT reference plant were optimized using process simulations in AspenPlus™ and ProTreat™ (Figure 8) software. These process simulation models were created using data from industry experience as well as R&D programs conducted by many of the leading universities in the world in the area of PCC. The simulations are considered to be highly reliable for known solvents such as MEA. For solvents such

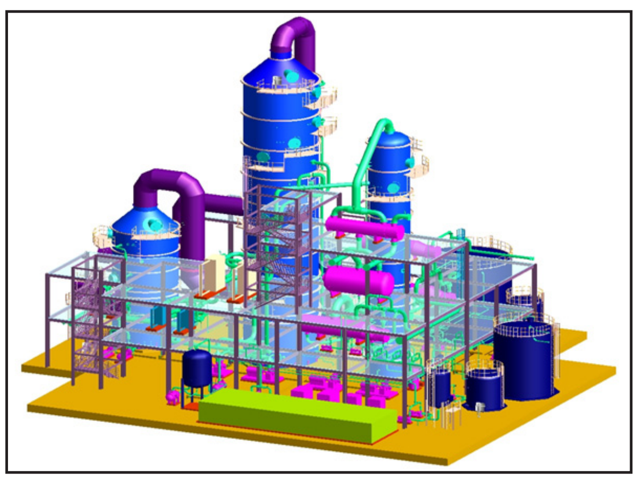

Fig. 7 B&W PGG's 1500 metric tons per day RSAT reference plant.

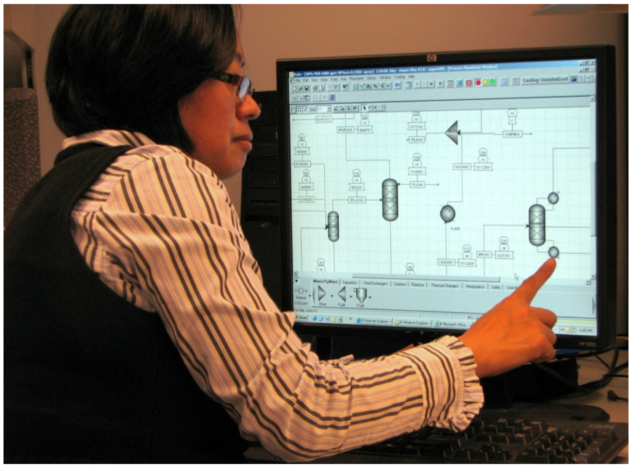

Fig. 8 Process simulation of the RSAT system.

as the OptiCap solvent, the accuracy of these models will be increased by gathering operating data from field testing such as the campaign which is currently planned for B&W PGG at NCCC.

Using the above simulation models for the RSAT system in conjunction with models which simulate other power plant processes, such as the steam turbine and the CO_2 compression system for sequestration, B&W PGG has extended its analysis outside the boundaries of the PCC system to gain a better understanding of how the addition of PCC equipment such as the RSAT system will affect the power plant as a whole.

The primary goal of these studies is to optimize the energy balance both within as well as outside the PCC system to minimize the overall energy burden. Numerous solutions are possible for different power plant configurations, and each solution should be carefully and realistically compared to its alternatives when selecting the optimum design for a given power plant scenario.

In addition to the design of the plant equipment, robust techno-economic models were also developed for computing the levelized cost of electricity (LCOE) for PCC plant designs, including technologies in addition to the RSAT system (for example, steam integration). The financial models were based on methodologies used by DOE and include detailed inputs for a significant number of calculated and projected costs and financial assumptions. Many of the inputs for the financial models are generated by B&W PGG using the reference plant as a basis (Figure 9).

This example illustrates how the various tools created during B&W PGG's process development program (R&D and pilot test results, reference plant design, process simulation models, financial models, etc.) are used in conjunction with one another to perform the detailed analyses required to fully evaluate PCC technology options for the coal-fired power generation industry.

Technology demonstration

The final step to commercialization is a technology demonstration. Demonstration projects identify areas of technical and financial risk which can be addressed early in a technology's life cycle at smaller scale (and lower risk) in the first generation of PCC plants. If PCC technologies are to be embraced and eventually deployed on a wide scale by utility users, many key technical and financial questions must be clearly understood and answered. Full-scale chemical and physical process simulations, equipment sizing and selection, capital and operating cost evaluations, full integration of PCC systems into power plant settings, supply chain development, and intellectual property rights are some of the subjects which must be addressed if users are to gain the confidence necessary to invest in CCS technologies.

B&W PGG is prepared to engage in a technology demonstration plant for the RSAT product and is searching for a host site. The plant size is flexible; however, B&W PGG believes that the 75 MW reference plant design is an effective combination of scale and cost. The size is sufficient to gain the required experience with commercial-scale equipment, and will provide sufficient process data and operating experience to confidently design the next larger version of the RSAT system. While supplying the necessary technical design data for scale-up to larger units, the smaller size provides the required information at a reasonable cost.

Next steps for B&W PGG's development program

While the search for a demonstration host site proceeds, the research team is continuing its work to develop new and enhance existing solvent designs. The product team will continue to develop and optimize the plant design and layout in an effort to reduce both capital and operating costs. Both teams will continue to investigate ways to improve the process simulation and techno-economic models. B&W PGG is also utilizing Design for Six Sigma methodology to refine product requirements, evaluate and quantify technical and commercial risk, and verify and validate the requirements for commercialization of the RSAT product.

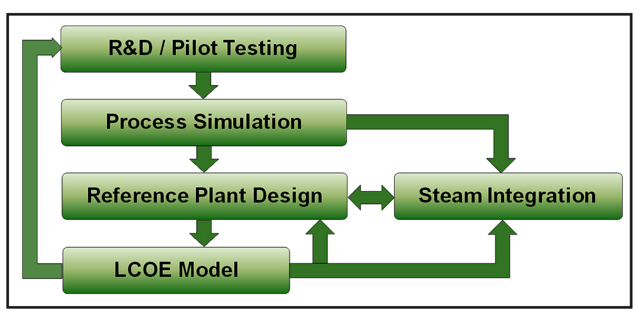

Fig. 9 Interdependence of technology development tools.

Summary

Since 2005, B&W has been fully engaged in the challenge of commercial development of CO_2 capture using post-combustion regenerable solvent-based absorption. B&W PGG's RSAT system is based on proven processes which have been applied to CO_2 capture for decades. For more than 40 years, B&W has been a major supplier of absorption-based SO_2 pollution control technologies for the electric power generation industry. Building on this experience, development and commercialization of the RSAT system at commercial scale for use in coal-fired electric power generation remains a priority. R&D efforts in developing solvent-based CO_2 capture processes, along with its proven engineering capabilities and extensive knowledge of coal-fired power plants has provided the impetus for B&W PGG to become one of the early leaders in the commercialization of CO_2 post-combustion capture technologies.