Frank Alix

Taking Out the CO_2

Powerspan Helps Utilities Capture Carbon at the Source

Innovations Case Narrative:
Powerspan Corp.

As indications of global climate change and its inherent risks have become more apparent, the urgency to limit emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) has grown. At the same time, rising worldwide demand for energy, driven by growing populations and improving living standards in the developing world, and by our increasingly electrified homes and businesses in the industrial world, has led to a steady growth in the use of fossil fuels. Today, fossil fuels account for 81% of the world's energy supply,[1] resulting in the release of 28 billion metric tons of CO_2.[2]

One of the largest sources of CO_2 emissions is coal-fueled electricity generating plants. Coal is the source of 49% of the electricity generated in the U.S.[3] and approximately 40% worldwide.[4] Economic, geographic, and political forces favor increasing use of coal as the most abundant fossil fuel, particularly in the US, China, and India; it also has the lowest cost, typically less than half of the cost of oil and natural gas per unit of energy.[5]

Experts agree that the only way to reconcile our increasing use of coal with needed CO_2 emission reductions is to deploy CO_2 capture and storage (or sequestration) systems (CCS) on coal-fueled electricity plants. The May 2007 MIT study, "The Future of Coal," concludes that CCS "is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs."[6] The Intergovernmental Panel on Climate Change (IPCC) estimates that CCS will be needed to create at least 15%, and perhaps as much as 55%, of the GHG emission reductions needed to stabilize the climate over the next century.[7]

Despite the recognized need for CCS, there are only a few commercial-scale CCS installations in the world today, and none are operating on a conventional

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coal-fueled electricity plant. The few existing CCS projects capture and store between 500,000 and three million tons of CO_2 per year.[8] This stands in stark contrast to the scale of CCS deployment needed to address climate change: the IPCC estimates that between 220 billion tons and 2,200 billion tons will need to be sequestered in the 21st century.[9] This scale is challenging for all three major aspects of a CCS system: CO_2 capture, pipeline transport, and geological storage.

The Powerspan story involves the most difficult and expensive aspect of CCS: CO_2 capture. The commercial CO_2 capture technologies that exist today are not well suited to conventional pulverized coal-fueled (PC) electric generating plants for several reasons: they are challenged by impurities normally present in the flue gas of the plant, they require up to 30% of the total plant output energy to capture and compress CO_2 for storage, and they add up to 80% additional cost to an already substantial capital investment. CCS costs are estimated to increase the cost of electricity from coal-fueled generating plants by 50% to 80%.[10] Therefore, the challenge is not only to commercially demonstrate CCS on the scale required, but also to develop a more economical approach to CO_2 capture for conventional coal-fueled electric generating plants. This objective is the focus of Powerspan today, but the road to this destination was anything but direct.

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WHAT MAKES CO_2 CAPTURE SO DIFFICULT?

It's hard to get your mind around the enormity of the task of CO_2 capture without some idea of the scale of a pulverized coal-fired electricity plant. A typical existing PC plant produces 600 megawatts (MW) of electricity at 35% thermal efficiency, while a new, state-of-the-art, supercritical PC plant (SCPC) would operate at near 40% efficiency. A supercritical plant would normally use between 200 and 300 tons of coal per hour, with flue gas flow resulting from coal combustion between 2,500 to 3,000 tons per hour, or 1.5 to 1.8 million cubic feet per minute. To give some perspective, the cross section of the ductwork carrying flue gas is nominally 15 x 30 feet and carries flue gas flowing at approximately 45 miles per hour. Another indication of scale is that the flue gas flow of a PC plant is roughly 20,000 times greater than the exhaust from a typical automobile.

The flue gas from a PC plant contains from 12% to 15% CO_2, with the balance mostly nitrogen, water, oxygen, and small concentrations of pollutants such as

Approaches for Capturing CO_2

The favored approach for capturing CO_2 from PC plants is thermal swing absorption, in which the flue gas makes contact with a solution that has an affinity for CO_2 and therefore absorbs the CO_2. Then that CO_2-rich liquid solution is taken away from the flue gas and heated, driving out the CO_2. Next, the heated solution is cooled back to flue gas temperature and returned so it can absorb additional CO_2. Finally, the CO_2 gas released from the heated solution is purified and compressed for transport and sequestration.

The cost of thermal swing absorption depends on several factors; the three most important are the speed with which the CO_2 is absorbed into solution, the amount of CO_2 absorbed into the solution (i.e., the capacity), and the amount of energy required to drive the CO_2 out of solution. The speed of absorption is important to minimize the size of the tower used to contact the solution with flue gas (approximately 70 feet in diameter and 150 feet tall for a 600 MW plant). It is vital to increase the amount of CO_2 absorbed into the solution and minimize the energy needed to release CO_2 from the solution, as that energy would otherwise go toward producing electricity.

Powerspan's process utilizes ammonia in the CO_2 absorbing solution. Ammonia provides several benefits, including a high rate of CO_2 absorption, a high capacity for absorbing CO_2 into the solution, and a low energy requirement for releasing CO_2 from the solution. These benefits provide cost advantages. First, a high absorption rate minimizes the size of the equipment needed for CO_2 capture and the energy costs associated with moving large amounts of flue gas and liquid through that equipment. Second, because it can absorb more CO_2 and needs less energy to release CO_2 from the solution, ammonia reduces the heat requirements to approximately of half what is needed in conventional amine-based capture solutions.

nitrogen oxides and sulfur oxides. The challenge of CO_2 capture is to economically remove and recover a large percentage (i.e., 90%) of the CO_2. That is, we need to reduce the CO_2 concentration to around 1% in a large gas stream moving at a substantial rate, then recover the removed CO_2 for sequestration. And since CO_2 is not a very reactive or soluble molecule, its capture becomes even more challenging.

Today, most efforts to develop CO_2 capture are focused on thermal swing absorption, which has been used in the oil and gas industry to reduce CO_2 concentrations in natural gas streams. The most popular solvents have been amine based; they offer rapid absorption of CO_2, but require great amounts of energy and the solvents degrade in the flue gas. Powerspan has focused on developing new solvents that retain the rate and capacity advantages of amines, but reduce the energy costs and solvent losses.

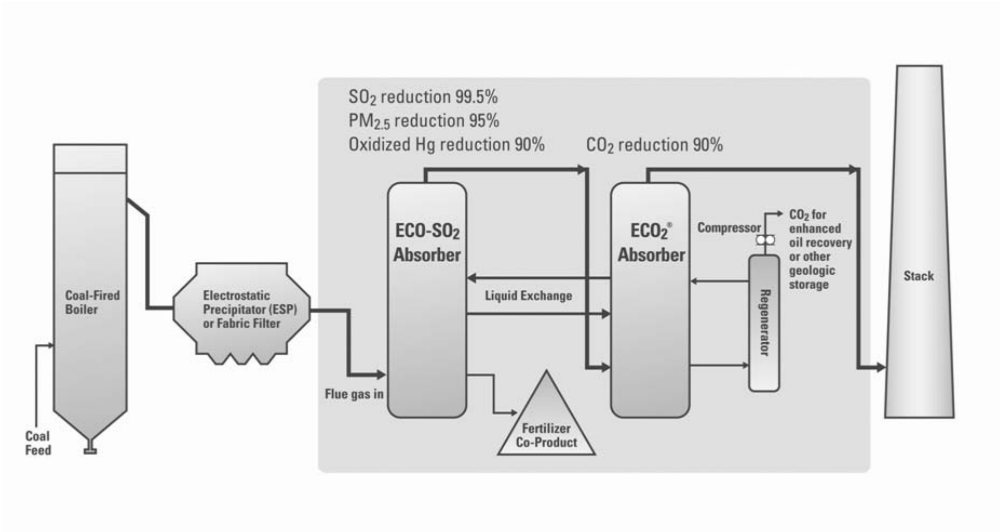

Figure 1. Power Plant with Integrated ECO-SO_2 and ECO_2 System Installed.

OVERCOMING TECHNICAL CHALLENGES

At this point, our ECO_2 process is pretty well defined, but we faced several obstacles along the way. Our major technical challenge was to identify a CO_2 scrubbing solution and process conditions that maintained the benefits of ammonia in solution, did not overwhelm our ability to control the release of ammonia vapor to the flue gas, and did not produce a corrosive scrubbing solution as a result of the high concentrations of ammonia and CO_2. A secondary challenge was to develop a scheme for releasing the captured CO_2 from the solution while minimizing the heat input and the amount of gas processing needed to recover ammonia and water from the CO_2 gas stream.

Our 10 years of experience using ammonia for sulfur dioxide (SO_2) capture in our ECO process enabled us to identify the process conditions where we could control the ammonia vapor release from CO_2 capture by integrating the process with the sulfur dioxide removal process. Early patents for SO_2 removal using ammonia required that the pH be controlled low enough to minimize the formation of ammonia vapor, which could limit the efficiency of the SO_2 capture. Powerspan's innovation was to increase the pH to maximize the SO_2 capture efficiency, and then devise a means for controlling ammonia vapor, which earlier patents had considered too difficult or expensive. Our resulting expertise in controlling ammonia vapor would become an important part of our CO_2 capture process. Ammonia is a volatile compound and its vapor is released when the CO_2-absorbing solution is brought into contact with flue gas. We choose process conditions that will minimize the ammonia release, but some release is unavoidable and we need a way to capture the ammonia to keep it from escaping into the environment. Our process integrates CO_2 capture with the removal of sulfur dioxide, which is also present in coal-combustion flue gas and must be removed before we capture CO_2.

In our ECO process, sulfur dioxide is removed through absorption into an ammonia-water-sulfate solution, forming ammonium sulfate. When SO_2 is absorbed, the pH of the solution drops and more ammonia is needed to sustain the process. Rather than directly adding ammonia into the solution to raise the pH for additional SO_2 removal, in this process the low-pH solution makes contact with the flue gas exiting the CO_2 capture process that contains ammonia vapor (see Figure 1). The low-pH solution captures the ammonia vapor, removing it from the flue gas while increasing the pH of the solution so it can remove more sulfur dioxide. This integration between the processes that capture SO_2 and CO_2 allows us to control ammonia vapor cost effectively and avoids the production of waste streams that require further processing.

Once we had established the basic process approach, we conducted extensive laboratory testing to identify and optimize the composition of the solution, and the conditions for capturing CO_2 and releasing it from the solution. As part of the testing, we developed data on physical properties, including information on the vapor-liquid equilibrium and the reaction rate data we needed to establish the requirements for contacting flue gas with the scrubbing solution. We built, and rebuilt, several test beds as we proceeded with the laboratory testing and gathered process information.

An equally important effort in the experimental work was developing sampling procedures and analytical techniques for accurately measuring the compositions of the scrubbing solutions, the treated flue gas, and the CO_2 product gas. We found that the available measurement equipment and techniques were inaccurate and inadequate, so we developed our own procedures and techniques to measure the compounds responsible for CO_2 capture, ammonium carbonate and bicarbonate, as well as undesirable compounds such as ammonium carbamate, and impurities that exist in and are picked up by the scrubbing solution when it makes contact with flue gas. This development work required several man-years of effort and included the testing and rejection of multiple measurement techniques, or, in other words, a lot of failure.

Throughout the research and development work, we kept our focus on producing a process that could be deployed in commercial power plants using available commercial equipment and construction techniques, and that could be controlled using measurement equipment that can survive in the power plant environment. Our initial pilot test results indicate that we are very close to achieving these objectives.

Overcoming the various technical barriers to CO_2 capture at conventional PC plants required the collaborative efforts of a strong, experienced, and cohesive team. The factors that went into building our company and the team behind it are as important as the evolution of the technology itself, and a story worth telling.

HUMBLE BEGINNINGS

After obtaining a degree in nuclear engineering from the University of Massachusetts at Lowell in 1979, I began my career building and testing nuclear submarines at Electric Boat in Groton, Connecticut, then moved to work on the maintenance and refueling of nuclear submarines at the Portsmouth Naval Shipyard in Kittery, Maine. In the early 1990s, after the end of the Cold War, the U.S. Navy began to downsize the nuclear fleet, and what started as an exciting career path at the forefront of technology innovation moved into a slow decline. In 1991, hoping to find an alternative career path, I entered the executive MBA program at the University of New Hampshire (UNH).

Early in my MBA studies, I had the good fortune to meet Bill Wetzel, who was my financial accounting professor. Bill had founded the Center for Venture Research at UNH, where he pioneered research into the role of "angels," or self-made, high-net-worth individuals who provide seed capital and street smarts to the early-stage ventures that drive innovation and economic growth. Bill's passion for early-stage venture formation ignited a fire in me.

I decided to get directly involved in facilitating angel investments in new ventures. After a year of working diligently at this task as a "second job," I found that angel investors and entrepreneurs are generally not looking for a middleman to facilitate the venture process, particularly one with no experience. Despite my lack of success at this venture and the admonition of several advisors to "not give up my day job," I decided the next best thing to facilitating venture formation would be to start my own venture. So, with $10,000 of personal funds and a great deal of optimism, I founded Zero Emissions Technology in 1994 along with Ed Neister, a physicist, and Nat Johnson, an electrical engineer. This company would eventually become Powerspan.

I had met Ed through a friend of Bill Wetzel and he was looking for an angel investor. He and Nat had come up with an innovative electrical filter for the power supplies of electrostatic precipitators (ESPs), which they called an "Arc Snubber." ESPs were being used by over 90% of PC plants to remove smoke particles from the flue gas. An ESP operates by slowing down the flow of flue gas and passing it between large grounded plates with high-voltage electrodes suspended in the center. The high-voltage electrodes charge the smoke particles and set up an electric field to attract them to the plates, which remove them from the gas stream. Our innovation was to filter the high-voltage power supply to remove high-frequency noise and reduce sparking; because this improved the characteristics of the electric field, it made the ESP collection more efficient.

Ed had convinced Public Service of New Hampshire to give the Arc Snubber filter a try on its local PC plant, and on the strength of this $50,000 order, I decided to jump on board, but kept my day job for the time being. The initial Arc Snubber modification was successful, which led to a second job, and finally to our first outside investment by a real angel investor, Mort Goulder. Mort had founded a local angel investing group called the Breakfast Club, named after the breakfast meetings his group held at the Nashua Country Club to grill entrepreneurs and make its investment decisions. Mort was a 1942 MIT graduate with a degree in Applied Physics. He was one of the engineering managers who left Raytheon in 1951 to form Sanders Associates, where he was Director and Vice President for 22 years, growing the business to over $1 billion in annual sales.

After our first meeting, Mort decided to invest $50,000 and joined our board of directors. He didn't perform any due diligence, other than asking questions to see if we knew what we were talking about. He trusted us. The deal was documented on a single page, part typewritten, part in his handwriting. Mort had made a lot of money as an entrepreneur and then spent the last 30 years of his life helping "give others a shot," as he would say. He definitely saw angel investing as part investment, part philanthropy; lucky for us, because what we were doing probably would not have held up under the intense scrutiny of a disciplined investment evaluation.

Mort's investment led to more angel investment and helped us grow the business to $2 to $3 million in annual sales and achieve profitability. However, after a few years, we recognized that the Arc Snubber business was limited, and we would have to expand our product line if we wanted to build a meaningful company. We were faced with the reality that we needed to "go big or go home."

BIGGER IDEAS REQUIRE VENTURE CAPITAL: WHAT DOESN'T KILL YOU MAKES YOU STRONGER

We thus began a series of development initiatives with the goal of expanding our proprietary product line in the air pollution control business using different gas-processing techniques. We initially looked to expand further into ESP performance enhancement by developing a flue gas conditioning system based on sulfur trioxide (SO_3) injection. SO_3 injection had been shown to improve ESP performance in plants burning low-sulfur coal, and the two companies that were selling commercial SO_3 injection systems had done quite well in the market. Our particular innovation was to create SO_3 in situ from SO_2 in the flue gas stream, using a non-thermal plasma oxidation device. We called this product the "SO_x Converter."

In order to fund our new R&D initiative, it was clear we would need venture capital because our existing products were not sufficiently profitable. We turned to Zero Stage Capital of Cambridge, Massachusetts, where I had had the good fortune to work part time over the two previous years while I had also been part-time CEO of Zero Emissions Technology. Based on our initial success with the Arc Snubber, and a personal relationship that I had developed with Gordon Baty, a Zero Stage founder, we were able to raise our first million dollars of venture capital.

However, we were never successful in persuading any potential customers to buy our SO_x Converter, because they considered our approach too risky—a refrain we would hear again and again from prospective utility customers. But that didn't stop us. Instead, we saw the potential for our non-thermal plasma oxidation device to oxidize nitrogen oxides (NO_x) as well as SO_2, which would facilitate their downstream capture in an ESP or scrubber. This provided the opportunity to treat flue gas to remove multiple pollutants in a completely unique and innovative way: when nitrogen and sulfur compounds in flue gas are converted to higher oxides, they form aerosols that can be captured in particulate collection equipment. Our approach was to remove several gaseous pollutants in the same control device by first converting them to aerosols. Thus was born our multi-pollutant control technology, Electro-Catalytic Oxidation, or ECO.

The ECO story would have been just another great idea with no commercial future if not for the interest of Ohio Edison in Akron, Ohio (later named FirstEnergy). Ohio Edison had a reputation for technology leadership as one of the first U.S. utilities to deploy SO_2 scrubbers on its Bruce Mansfield Plant in Pennsylvania. People there had also pilot-tested a number of unique air pollution control technologies and were intrigued by the potential of ECO. Two of their principal pollution control engineers, Dale Kanary and Morgan Jones, visited our lab test facility and became believers. Their CEO at the time, Pete Burg, met with us and was persuaded to invest, committing $5 million to fund ECO pilot testing at their R.E. Burger Plant near Shadyside, Ohio.

The ECO pilot test program did not go well initially, as most of the equipment we designed for this application was not sufficiently robust. That's a polite way of saying our plasma power supplies blew up and our plasma reactor bodies melted, but fortunately no one was hurt. However, we were able to "make a lot of mistakes fast," which became something of a mantra for us, and we eventually modified the pilot system to meet our performance objectives at just about the time we ran out of money. This resulted in the company's first layoff and what we now refer to as a "near death experience," which is common among venture-backed companies.

Inventors and company founders are by necessity quite optimistic and in some cases even naïve. We certainly were both at the start. But R&D is difficult to schedule and venture investors have limited patience. And therein lies the structural conflict that weeds out the weak and makes the survivors stronger. If we had known how hard this would be at the beginning, it's unlikely any one of us would have undertaken the journey. But once you start down the path, you end up doing everything possible not to fail.

In late 1999, when the emerging energy technology market was experiencing great investor interest (some call it a "bubble"), we were fortunate to catch the attention of Jeff Miller, one of the managing partners of the Beacon Group. He was one of the few in the energy investing space who still believed in the future of coal, and he made a bet on Powerspan as an emerging leader in the pollution control technology market for coal-fired plants. It helped that FirstEnergy and American Electric Power, two large potential customers, joined in the $26 million investment round. The purpose of the investment was to build a commercial demonstration facility for our ECO technology at FirstEnergy's Eastlake Plant. But once again, this didn't work out as we had planned.

Date	Amount Raised	Major Investors	Purpose of Funding
1997	$1.4 million	Zero Stage Capital, Calvert Group	Develop SO_x Converter for conditioning electrostatic precipitators.
1998	$5 million	FirstEnergy	Pilot-test ECO multi-pollutant technology at FirstEnergy's R.E. Burger Plant.
2000	$26 million	FirstEnergy, Beacon Group, American Electric Power	Install a 50-MW ECO system at FirstEnergy's Eastlake Plant, as commercial demonstration of ECO technology. Due to the anticipated sale of the Eastlake Plant, the project was moved to FirstEnergy's Burger Plant and started in 2004.
2003 - 2006	$35 million	NGEN Partners, RockPort Capital, Fluor, Angeleno Group, FirstEnergy, Beacon Group	Complete 50-MW ECO unit and associated performance testing in 2005. This marked the major transition point from ECO development to commercialization. In 2004, announced the CRADA with DOE for CO_2 capture technology development ("ECO_2").
2008	$50 million	George Soros, Tenaska Energy, AllianceBernstein, NGEN Partners	ECO_2 pilot test and commercial deployment. Fund early ECO projects (provide adequate liquidity to secure ECO commercial orders).

Table 1. Venture Capital Funding Timeline

After we had spent a good deal of money on design work for the ECO commercial demonstration unit (CDU), we realized that our pilot design was not readily adaptable to commercial-scale equipment. At about the same time, FirstEnergy reached an agreement to sell the Eastlake Plant, so we had to move the project. Once again, we had to move fast to come up with a new design that we could show was commercially viable, along with a new location to build the CDU. Fortunately, we were able to accomplish both at just about the time we ran out of money again, which led to layoffs and near death experience number two.

The next funding round was a "down round," which means the price per share was lower than the price in the previous round. These are very unpleasant things. Completing this round would not have been possible but for the continued commitment of FirstEnergy, along with NGEN Partners, a new investor led by Steve Parry. This money was sufficient to build the ECO commercial demonstration unit and largely achieve the performance results we had promised. However, this did not immediately lead to commercial success.

Our next challenge was to overcome the risk aversion of this market. There are good reasons why power plant owners are so cautious. The power industry is the most capital-intensive business in the world, as measured by the ratio of invested capital to sales. Power companies only make money when their costly plants are running and meeting all requirements for air emissions. So in order to sell a new air pollution control technology, you not only have to be much better and cheaper than the competitors; the buyers also need a good reason to take on the technology risk. Providing that reason was much harder than we anticipated. That brings us to CO_2 capture.

GOOD FORTUNE PLAYS A ROLE

One myth I have come to reject is that of the great company founder or CEO who must have had a brilliant plan to create an amazing company, and then brought it forth with tremendous vision, courage, leadership, tenacity, etc. That's not how it really happens. Individual leadership is important, but the make-up and contributions of the whole team are far more critical to success. Having a plan is important, but the objectivity and flexibility to adjust the plan quickly matters more. Finally, circumstances that are completely out of your control play such a critical role in success. When you look at it all objectively, the reality is quite humbling, compared to the conventional view of CEO as hero in the case of success, or loser in the case of failure.

So where have we experienced good fortune? In early 2004, the U.S. Department of Energy (DOE) National Energy Technology Laboratory contacted us to discuss research they were doing on CO_2 capture using ammonia. We were the only company in the U.S. developing wet scrubbing technology using ammonia as a reagent. They were wondering how we controlled the ammonia vapor and asked to visit our demonstration plant. We agreed to share our knowledge as long as they shared theirs. This meeting led to a cooperative research and development agreement (CRADA) with the DOE to develop and commercialize their ammonia-based CO_2 capture technology; later, Powerspan acquired a license for the DOE patent once it was issued. We named this new process ECO_2.

With that, we embarked on a multi-year R&D effort to develop the ECO_2 process in our labs. It would be four years before we were ready to build the ECO_2 pilot test unit in Ohio. Although we believed that at some point limits on GHG emissions would be imposed that would jumpstart the supplier market, it would be three years before we saw any meaningful movement on this front, despite periodic attempts by key members of Congress to garner majority support for federal climate legislation.

On April 2, 2007, the U.S. Supreme Court made a landmark decision. It ruled that, under the Clean Air Act, the EPA has the authority to regulate GHG emissions from automobiles, and that the agency could not abdicate its authority to regulate these emissions unless it could provide a scientific basis for refusing to do so. Although the court did not require the agency to regulate GHG emissions, the agency would face legal action if it did not. At the time, observers generally agreed that this decision marked the beginning of GHG regulation in the U.S.; apparently if Congress did not act, the EPA surely would.

So, it would be difficult to observe the confluence of events that led Powerspan to this moment and not feel fortunate. We thought we were way ahead of our time when we entered into the CRADA with DOE to develop CO_2 capture technology. Little did we know back then that we would be in exactly the right place at the right time, which is where we find ourselves today in the emerging market for commercial CCS systems.

As the interest in CO_2 capture technology grows, we find ourselves well positioned for a few important reasons. First, this is one air pollution control technology that no one has installed on a PC plant, so there are no entrenched competitors or established technologies to overcome, which as we learned with ECO is no small thing. Next, the skill set needed to bring a technology from the lab to commercial scale is one we have developed and mastered over the last 15 years. To our knowledge, none of our competitors has this skill set. Lastly, the ECO system we developed as an integrated, multi-pollutant control system ended up as the perfect complement to an ammonia-based CO_2 capture system, though we had no idea it would become that when we started.

WHY POWERSPAN?

The rush to develop a cost-effective CO_2 capture technology for coal-fired electric plants has been compared to our nation's effort to put a man on the moon in the 1960s. On the campaign trail, President Obama compared development of clean coal technology to that famous effort: "This is America. We figured out how to get a man on the moon in 10 years. You can't tell me we can't figure out how to burn coal that we mine right here in the United States of America and make it work."

Several large companies are involved in this effort, including G.E., Siemens, and Alstom. The resources available to these companies for R&D total in the billions of dollars annually, with G.E. alone committing $1.5 billion annually to clean energy research. By comparison, Powerspan's average annual engineering and R&D expense over the last five years was $6.5 million, orders of magnitude less than our competitors. So a reasonable question would be, with the tremendous importance of CCS as a climate mitigation tool, and with the anticipated worldwide CCS market of $1.3 to $1.5 trillion from 2010 to 2050, how could a company like Powerspan develop a leading technology position for post-combustion CO_2 capture? There are some important reasons why, some perhaps more obvious than others.

The first reason is that large companies generally make decisions based on conventional wisdom, which is often wrong. The innovations they bring to market are usually incremental improvements to existing product lines. Breakthrough innovations require one to think outside of convention and take risks, acting in ways that could threaten a profitable business line. As Clayton Christensen points out in *The Innovator's Dilemma*, the actions required to create disruptive technologies are nearly impossible for the well-established company to undertake.

A good example of conventional wisdom gone awry was the early rush to Integrated Gasification Combined Cycle (IGCC) power plants as the future of coal-based electricity production in a climate-constrained world. IGCC plants

The Makings of a Team

In venture capital, there is a saying that you "bet the jockey, not the horse." That means that the assumptions one makes about how a specific technology or market (i.e. horse) may evolve are invariably wrong. As the Nobel Prize winning physicist Niels Bohr stated, "Prediction is very difficult, especially of the future." However, the right team (i.e., jockey) will adapt to unexpected challenges and find a way to succeed.

How did we build the right team? It started with connections we made through the U.S. Naval Nuclear Propulsion Program (NNPP) and the University of New Hampshire (UNH). Powerspan's top technical leaders (Phil Boyle, Chris McLarnon, Dave Bernier, and myself) all started our professional careers in the NNPP, working together at Portsmouth Naval Shipyard through the 1980s and 1990s. The legendary Admiral Hyman Rickover, who founded the NNPP and served in its leadership role for over 30 years, established a well-deserved reputation for technical discipline. The program's tough standards are ingrained in participants at all levels, and the resulting culture of constant and sometimes pointedly direct questioning, challenging, and checking becomes second nature. Having this common background and approach to technical work and problem-solving has been a key to our technical success. It has also helped us stand up well under the constant scrutiny of prospective customers and investors.

The UNH connection also facilitated building up the team. Our first directors of sales and manufacturing were MBA classmates of mine. Our Vice President of Communications and Government Affairs, Stephanie Procopis, was an MBA student referred by Bill Wetzel, who started with Zero Emissions Technology as our Director of Marketing. Our CFO, Lynn Friedel, was a graduate of Plymouth State College in New Hampshire and came to us from the Breakfast Club (Mort Goulder). So the principal connections that brought the team together were from the Naval Nuclear Program and the local business school/angel investing network. What keeps the team together is harder to understand.

produce electricity by first gasifying the coal and then running the synthesis gas (syngas) through a combustion turbine.

Although coal gasification by itself is a well-established technology, there are only three commercial-scale IGCC plants in the world, each with about 250 MW capacity, and the consensus is that these plants are more costly, less flexible, and less reliable than conventional pulverized coal (PC) plants. However, despite these drawbacks, conventional wisdom held that IGCC plants would be able to capture CO_2 more easily than PC plants, and therefore they would be the low-cost option for coal-based electricity production when the cost of CO_2 capture was included.

All the members of the management team had been very successful in their prior careers and had good employment opportunities outside the company. We recently sat down as a team to answer the question of what has held us together for so long. We recounted the occasions in our past when we had nearly run out of money. Twice we had to withhold a portion of employees' salaries while we awaited new financing. It so happens that in both cases, we obtained financing just before the end of the year and paid employees their back salary around Christmas. So we nicknamed this event the Powerspan "Christmas Club" (survival requires humor!). We also went through two substantial layoffs, a significant down round in venture financing that nearly killed us, and even a somewhat hostile takeover attempt by a large energy company, during which the board and management team split on the best path forward.

So what holds a team together through such turmoil when much safer and more rational employment alternatives exist? For one, our common backgrounds in the Naval Nuclear Program and UNH created a bond that went beyond common employment. Next, as we had weathered the storms, we had lost our false confidence based on ignorance or naiveté, and had gained real confidence based on surviving another battle and learning from it.

Most of us had come from modest, blue-collar backgrounds and worked our way through college, so the work ethic and commitment was deeply ingrained in us all. I was the middle child of 13 (not a typo) and my father had a garage where he repaired cars. I started working for him at age 12 and continued until I went to college. I was never paid for it and was not encouraged to go to college. I just wanted something different for myself. Most of the Powerspan management team had similarly modest backgrounds, which led to a common drive to create something better, and a work ethic that never allows you to quit. This motivation is apparent not only in our leadership, but throughout the organization, and has enabled Powerspan to compete with, and in some cases surpass, the work of industry giants.

Because of this assumption, much of the early CCS research focus and funding was directed toward IGCC.

However, more recent studies have called this conclusion into doubt, as the full cost of CO_2 capture in IGCC plants becomes better known and companies like Powerspan drive down the anticipated cost of CO_2 capture from PC plants. Another more obvious consideration is that over 99% of existing coal-based electricity production comes from conventional PC plants. These plants represent trillions of dollars in asset value and could not be readily replaced. Therefore, from the perspective of climate change mitigation, the primary need is for cost-effective CO_2 capture from PC plants, but it took conventional wisdom a few years to come back around to this obvious point.

Another reason for Powerspan's leading position in this market is that for decades, the suppliers of air pollution control equipment have not been in the technology development business. The basic technologies used to capture SO_2 and NO_x from commercial PC plants—calcium-based scrubbing for SO_2 and ammonia-based selective catalytic reduction for NO_x—were first developed and commercialized in Europe and Japan over 30 years ago. The process engineering know-how and R&D skills needed to develop such technologies have largely disappeared from contemporary equipment suppliers. Today, the market for air pollution control equipment is a commodity market dominated by large companies with very little product differentiation.

By comparison, during all of the 15-plus years of Powerspan's existence, we have been in the product development business. As we moved to larger visions of our product offering, particularly our ECO technology, which we designed as an integrated system to compete directly with the best available control technologies for capture of SO_2, NO_x, mercury (Hg), and particulate matter, we necessarily had to develop critical skill sets in order to succeed. It is not easy to develop or acquire these skills: (1) a disciplined approach to lab testing, measurement, and analysis; (2) sophisticated process modeling, including the development of new models based on proprietary empirical data; and (3) critical thinking skills, including the ability to find innovative solutions when the inevitable road blocks appeared. We believe this skill set is unique in our industry, and we've been at it long enough to become quite proficient, easily surpassing the well-known 10,000-hour rule for mastering a profession (see Malcolm Gladwell's *Outliers: The Story of Success*).

HOW IMPORTANT IS CCS?

The importance of CCS cannot be overemphasized with respect to climate change mitigation. The Intergovernmental Panel on Climate Change (IPCC) estimates that CCS will be needed to supply at least 15%, and perhaps as much as 55%, of the GHG emission reductions needed to stabilize the climate over the next century.[11] According to the International Energy Agency (IEA), CCS is the only technology that can control CO_2 emissions from large-scale fossil fuel usage, and it will need to provide at least 20% of the reductions in GHG emissions required to meet the IPCC goal of cutting global emissions 50% from 2005 levels by 2050.[12]

The IEA has put forth a scenario that explores the least costly solutions to achieve the IPCC goal. Under this scenario, by 2050, 30% of all power will be generated by plants equipped with CCS.[13] In order to achieve this ambitious goal, CCS installations would be required in 55 fossil-fueled power plants every year between 2010 and 2050. Further, this same IEA scenario without CCS would have the highest emissions and would also have an annual incremental cost of $1.28 trillion in 2050, a 71% increase over the base scenario with CCS.[14] This underscores the importance of CCS in climate policies from the perspectives of reducing both costs and emissions.

As an alternative, many see renewable energy as the most important climate mitigation tool. However, a recent study conducted for a large California public utility estimated the levelized cost of avoiding CO_2, using solar power, at $230 per ton, while the cost for avoiding CO_2 using CCS was estimated at $59 to $63 per ton. In addition, renewable energy sources such as solar and wind power suffer from regional resource limitations, interruptions in supply, and transmission constraints.

Although no region has developed the comprehensive legal and regulatory framework necessary to effectively guide CCS, last year the G8—an economic and political organization consisting of Canada, France, Germany, Italy, Japan, Russia, the U.S., and the U.K.—endorsed the IEA recommendation that 20 large-scale CCS demonstration projects need to be committed by 2010, with broad deployment beginning in 2020.[15] The IEA believes that up to $20 billion will be needed to fund these near-term CCS demonstrations.

Lastly, CCS is needed to help sustain our lowest-cost electricity supplies and move us toward energy independence, since approximately half of the electricity in the U.S. is generated from domestically sourced coal. According to the DOE's Energy Information Administration (EIA), 36% of our CO_2 emissions in 2006 came from coal consumption.[16] Broadly deploying CCS with 90% capture efficiency could potentially reduce those emissions to 4% or 5%. EIA predicts that CCS will have to provide at least 30% of the CO_2 emission reductions needed worldwide in order to stabilize GHG concentrations in the atmosphere. Since the transportation sector accounts for another 34% of U.S. CO_2 emissions,[17] transforming this sector with electric vehicles powered by low-carbon electricity sources could reduce U.S. CO_2 emissions by another 20% to 30%. Therefore, CCS could potentially provide over half of the emission reductions required to meet the nation's goals for climate change mitigation.

WHEN WILL CCS BECOME A COMMERCIAL REALITY?

CCS technology will be commercially available soon, based on successful completion of ongoing pilot-scale test programs. The term "commercially available" means that qualified vendors are willing to sell commercial-scale CCS equipment with industry-standard performance guarantees. However, despite broad recognition of the pressing need for CCS technology, plant owners are not motivated to get large-scale CCS demonstrations up and running because they are very costly to build and operate, and the early projects carry considerable technology risk. It's the classic chicken-and-egg scenario. Most plant owners do not want climate regulations to force CCS installation until the technology is commercially proven. But owners will not proceed with early CCS installations to prove out the technology in the absence of either regulations or financial incentives. Therefore, the timing of when commercial CCS systems will begin operating depends on when the legal requirements, regulatory drivers, and financial incentives are established to motivate plant owners to proceed with the initial CCS installations. I discuss this issue in more detail later on.

Currently, a limited number of CO_2 capture pilot tests are being conducted at power plants worldwide to demonstrate ammonia-based, amine-based, and oxygen-fired technologies on a small scale. Pilot-scale testing of our ECO_2 technology began in December 2008 at FirstEnergy's Burger Plant in southeastern Ohio. The ECO_2 pilot was designed to treat a 1-MW flue gas stream and produce 20 tons of CO_2 per day. Testing to date has demonstrated over 90% CO_2 capture efficiency, with energy use in the range of our estimates. Future testing is focused on increasing CO_2 output and finalizing design parameters for our first commercial systems.

The ECO_2 pilot plant was built using the same type of equipment that we will use in commercial systems. Therefore, successful operation of the pilot unit will confirm our design assumptions and cost estimates for large-scale CCS projects. Although commercial-scale projects still have some risk, that risk is manageable because the major equipment used in the ECO_2 process—large absorbers, pumps, heat exchangers, and compressors—has all been used in other commercial applications at the scale required for CCS. The advanced technology in ECO_2 is innovative process chemistry. Commercial application of this unique technology involves no special challenges and therefore is highly likely to succeed.

Our experience in the emerging market for commercial-scale CCS projects supports our optimism. In 2007, Basin Electric Power Cooperative conducted a competitive solicitation for a post-combustion CO_2 capture technology to retrofit its Antelope Valley Station, a coal-fired power plant located adjacent to its Great Plains Synfuels Plant in Beulah, North Dakota. The synfuels plant currently hosts the largest CCS project in the world; it annually captures three million tons of CO_2, which it sells for enhanced oil recovery (EOR) in the Weyburn fields of Saskatchewan. The Antelope Valley project will install CO_2 capture equipment on a 120-MW flue gas slipstream taken from a 450-MW unit. Basin Electric has targeted a 90% CO_2 capture efficiency rate in order to provide an additional one million tons of CO_2 annually for EOR. Six of the leading vendors of CO_2 capture technology responded to the Antelope Valley solicitation, and after a detailed evaluation, Basin Electric selected Powerspan. This commercial CCS project is scheduled to start up in 2012.

Since Powerspan was selected for the Antelope Valley project, a feasibility study has confirmed that there are no technical limitations to deploying ECO_2 at the plant. The study estimated ECO_2 costs of less than \$40 per ton for 90% CO_2 capture and compression (in current dollars, with +/- 30% accuracy). A similar study of ECO_2 recently conducted for a new 760-MW supercritical pulverized coal plant estimates CO_2 capture costs of under \$30 per ton, including compression. A third engineering study focused on the scaling risk of ECO_2 determined that the ECO_2 pilot plant will provide enough design information so we can confidently build commercial-scale systems up to 760 MW, indicating that the ECO_2 technology scaling risk is manageable. Independent engineering firms led the feasibility, cost, and scaling studies for our prospective customers. As a sign of our confidence in the commercial deployment of ECO_2 systems, we will back our installations with industry-standard performance guarantees.

Worldwide, large-scale CCS demonstration activity is concentrated in the European Union, Australia, Canada, and the U.S. In the European Union, the European Parliament has approved a demonstration program of 10 to 12 large-scale CCS projects to be operational by 2015 in order to kick-start its urgent, wide-scale deployment.[7] Three hundred million European Union Allowances (EUAs) have been authorized to fund this initiative with an anticipated value of $6 to 10 billion.

In April 2008, the State Government of Victoria, Australia, announced a round of funding of AUD$182 million, of which AUD$110 million is available to support large-scale CCS demonstration projects. In December 2008, it issued a solicitation for proposals to be submitted by the end of August 2009. Selections are to be made in early 2010 and demonstrations are to be completed in the 2014-2015 timeframe.

In Canada, the provinces of Saskatchewan and Alberta are leading the effort to demonstrate CCS. SaskPower is currently evaluating three finalists, of which Powerspan is one, for a 140 MW CCS project (1.2 million tons of CO_2 capture annually) at its Boundary Dam Power Station in Saskatchewan. The final technology selection is scheduled for the end of 2009, with construction starting in 2011. The captured CO_2 will be used for enhanced oil recovery operations. Canada's federal government previously announced $240 million in support for this project.

In July 2008, the government of Alberta announced a $2 billion fund to accelerate the development of the province's first large-scale, commercial CCS projects, and in February 2009, legislation was passed that provides the legal authority to administer the $2 billion in provincial funding. The Carbon Capture and Storage Funding Act will enable the province to administer funding to support three to five large-scale CCS projects. The selected projects were announced in July 2009; the government expects that by 2015 the projects will be reducing CO_2 emissions by five million tons each year.

In the U.S., a limited number of large-scale CCS projects have been announced, including the Basin Electric project at Antelope Valley in North Dakota. The Troubled Assets Relief Program (TARP) bill, signed into U.S. law on October 3, 2008, contained provisions for investment tax credits and production tax credits for the capture and storage of CO_2. The American Recovery and Reinvestment Act (ARRA), signed into law on February 17, 2009, also includes unprecedented funding of $3.4 billion for CCS. While the rules for applying for U.S. government CCS funds continue to be promulgated, these steps are encouraging.

On March 30, 2009, Representative Henry Waxman, Chairman of the U.S. House of Representatives Energy and Commerce Committee introduced a comprehensive climate bill, the American Clean Energy and Security Act of 2009 (ACES, H.R. 2454). On May 21, the committee approved the bill, and on June 26, the House passed it by a vote of 219 to 212. The bill includes a greenhouse gas emissions cap-and-trade program to reduce emissions by 83% from 2005 levels by 2050. The bill also contains standards for renewable electricity and energy efficiency, along with provisions for clean transportation. At the projected allowance prices, ACES will invest over $190 billion through 2025 in clean energy and energy efficiency, $60 billion of which would be invested in carbon capture and sequestration technologies. Of that $60 billion, $10 billion would be generated through a small "wires charge" on electricity generated from fossil fuels. After 2025, 5% of allowances would be devoted to carbon capture and sequestration. The bill also creates a new carbon dioxide emissions performance standard for coal-based power plants.

WHAT IS NEEDED TO GET CCS DEPLOYED COMMERCIALLY?

CCS installations are expensive. In some regions, the use of captured CO_2 in enhanced oil-recovery operations offers opportunities to offset a portion of the costs, but a power plant owner would still face a significant shortfall in covering the cost of this investment. Without a high enough price on carbon or adequate early incentives to cover the cost of projects, power plant owners cannot assume the financial risk of large-scale CCS demonstrations. Therefore, strong government action is needed to ensure timely deployment of CCS technology to support climate change mitigation goals. Government actions should focus on three areas: (1) a strong, market-based cap on GHG emissions; (2) a CO_2 emission performance standard for new coal-based power plants; and (3) incentives for early deployment of commercial-scale CCS systems. Incentives are needed to ensure the early deployment of CCS because CO_2 capture technology is not yet commercially proven, and early CO_2 prices will not be high enough to offset CCS costs. Six aspects are most critical to the success of a CCS incentive program.

Competitive Award

CCS incentives should be awarded competitively based on a reverse auction (incentives awarded to the lowest-cost bidders per ton of CO_2 captured and sequestered) because this would preserve the primary objective of a cap-and-trade program, which is to minimize the cost of compliance, while also providing a market signal on the real costs for early CCS installations. Knowing the actual costs for CCS is extremely important to plant owners, technology developers, investors, and regulators as they evaluate future investment and regulatory decisions.

Funding the lowest-cost CCS projects will also favor those associated with enhanced oil recovery, since those projects pay for the CO_2 and avoid the added cost of geological sequestration. This will have the additional benefit of producing more domestic oil and reducing oil imports. It will also produce more jobs and the tax revenue associated with domestic oil extraction and sales.

In promoting early deployment of CCS through financial incentives, the U.S.

could assume a leading position in this critical technology sector and create a thriving, high-tech export business, and the quality jobs that come with it. However, to make such an outcome likely, CCS incentives will have to be awarded competitively; otherwise we could not ensure that the lowest-cost technologies would be awarded incentives, and no clear signal would be sent on technology winners or actual CCS pricing.

Competitively awarding CCS incentives is consistent with the way that renewable portfolio standards are normally administered. Market participants—power suppliers, regulated distribution companies, and state regulators—understand this process. States set a standard for the amount and type of renewable energy desired, and the potential suppliers respond to competitive solicitations to provide the renewable energy. The federal government could effectively implement the same type of approach for CCS projects and associated incentive awards.

Long-Term Price Certainty

CCS incentives must provide long-term price certainty and factor in the value of CO_2 emissions allowances, because CCS projects will likely be financed over 15 to 30 years. Current climate legislation proposals award CCS incentives over a fixed period of time (i.e., 10 years) that is too short to finance most projects.

CCS incentives would be most economical for the government if they factored in the increasing value of CO_2 emission allowances over time. As the value of these allowances rises over time, less government funding will be needed to support the CCS incentives. Current climate legislation proposals do not account for the added value of CO_2 emission allowances created by the CCS project, or for the fact that emission allowance values would be increasing over time. This approach creates a potential windfall profit opportunity for the early CCS adopters and unnecessarily increases the cost of CCS incentives to the government.

CCS Project Size

The primary objective of CCS incentives is to demonstrate CCS technology at commercial scale to accelerate market acceptance and deployment. In order to demonstrate CCS as commercially viable, minimum project size criteria should be established. Experts such as those at MIT and the DOE have established a minimum size of one million tons of CO_2 per year for CCS projects to be considered "commercial scale."[18] Once the minimum CCS project size is met, preference should be given to larger projects.

CO_2 Capture Rate

In order to meet the objective of stabilizing GHG concentrations in the atmosphere, large stationary CO_2 sources will need to capture and sequester a high percentage of their CO_2 emissions (i.e., **greater than** 90%). Therefore, CCS incentives should establish a minimum standard for CO_2 capture and should favor projects that capture higher percentages of CO_2. Available technology from leading suppliers has shown the ability to capture 90% CO_2. Therefore, establishing a minimum CO_2 capture rate as high as 80% to 90% is technically feasible and commercially acceptable.

CCS projects will normally require at least four years to implement. An incentive program that encourages CCS to be demonstrated in sequential steps (e.g., 50%, then 80%) would unnecessarily delay deployment of the high-capture-rate CCS projects needed to combat climate change; it would also increase the cost of CCS incentives to the government.

Amount of CCS Incentives

The amount of CCS incentives in tons of CO_2 should be based on the need to demonstrate CCS at commercial scale in a number of different configurations for both plant type and geological storage type. All large industrial sources of CO_2 should be considered equally. However, the government should not try to pick technology winners and losers. The primary driver in CCS incentive awards should be the lowest cost per ton, with at least three different CO_2 capture technologies selected to promote technology diversity. This would facilitate the creation of a competitive supplier market of the most cost-effective technologies.

The amount of CCS incentives should be established to avoid early market responses to a CO_2 emission cap, such as a rush to gas-fired power generation, which may not be sustainable after CCS is commercially proven and CO_2 allowance prices rise to a level where CCS would be deployed without incentives. CCS incentives should also be spread out so that multiple CCS projects are awarded each year for at least five years, given the current fast pace of technology evolution; the CCS incentive program should take advantage of and benefit from this rapid pace of improvement.

Sequestration Issues

Several sequestration issues need to be addressed, such as legal and permitting requirements for geological sequestration, including standards for site selection and requirements for measurement, monitoring, and verification. Although several states have been active in this area, a strong and consistent national approach would be beneficial. Among the issues to be addressed should be long-term liability for sequestered CO_2.

It is also important to create incentives for constructing CO_2 pipelines at optimum scale. CO_2 pipelines benefit from economies of scale up to about 24 inches in diameter. This size would provide CO_2 capacity for three to four large-scale CCS projects (nominally about 15 million tons per year; equivalent to about 2,000-MW capacity at 90% CO_2 capture). Therefore preference should be given to CCS projects that create extra capacity by constructing pipelines or other infrastructure that could be used by multiple projects.

SUMMARY

Climate change is a very real threat to our world. But carbon capture and storage (CCS), possibly the most important tool for climate change mitigation, is not in commercial operation on any coal-fired electricity plant. Subject to successful completion of ongoing pilot scale test programs, technology suppliers like Powerspan will be ready to provide needed equipment to implement CCS at commercial scale. CO_2 transport and storage needs further research, demonstration, and regulation, but over 20 years of experience in the U.S. with CO_2-based enhanced oil recovery, which currently injects over 40 million tons of CO_2 per year into depleted oil fields, has demonstrated that CO_2 transport and storage can be accomplished safely.

Independent studies show that early commercial installations of CO_2 capture technology are likely to succeed. The cost of widespread deployment of CCS technologies appears manageable, particularly when compared to the cost of other low-carbon electricity solutions. And once we gain commercial CCS experience, future costs will no doubt decrease substantially.

However, initial CCS installations will be expensive and the technology still carries substantial commercial risk. Without a price on carbon and adequate incentives to cover the cost of early CCS projects, power plant owners will be unable to assume the financial risk of building and operating large-scale CCS demonstrations. Therefore, strong government action is needed to ensure timely deployment of CCS technology to support climate change mitigation goals.

A benefit of early CCS deployment will be creation of jobs and economic growth. CCS projects require three to four years to implement and create significant economic activity over their duration. For example, a single CCS project would cost between $250 million and $750 million in capital expense and create up to 500 jobs at its peak, with the majority of materials and labor sourced domestically. But the government would not have to pay for the CCS incentive program until the project is completed and CO_2 sequestration begins. In addition, by adding incentivizes to the early deployment of CCS, the U.S. can assume a leading position in this critical sector and create a thriving, high-tech export business, and the quality jobs that come with it.

The most important reason to promote early deployment of CCS is that post-combustion CO_2 capture technologies will preserve the huge investment in existing coal-fired power plants and allow us to effectively use abundant low-cost coal reserves in the U.S. and developing nations, even in a climate-constrained world. If we do not succeed in commercializing CCS technology in the near term, it will be difficult for the world to meet its long-term goals for climate change mitigation.

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