A Comparative Assessment Of Flow Battery Technologies

Chris Lotspeich[1]

Flow battery (FB) technologies empower large-scale energy storage (ES) systems that have the potential to transform electrical generation, transmission and distribution network operations and planning, as well as distributed power generation and facility load management. This paper compares and contrasts these technologies and their developers, and assesses their commercialization potential and pathways.

Drawing on both battery and fuel cell design elements, FBs are based on reversible chemical reactions. To discharge (DCH), two electrolyte solutions are pumped from separate tanks into half-cells and interact across an ion-exchange membrane, generating current. To store electricity, current is put back into the system to return the electrolytes to their original chemical states, charging (CH) the battery. Power and energy ratings are independent, and are a function of cell area (power), electrolyte storage (energy), and electrolyte flow rate (both power and energy). Cycling rate is a function of electrolyte flow and volume, as well as control system capabilities. Demonstrated systems allow subsecond transitions from CH to DCH. FBs can DCH rapidly and deeply, at high or low power output, and recharge at varying voltages and rates. CH and DCH do not significantly degrade either the cells or the electrolytes (which are not consumed during cycling).

FBs are the only type of batteries that can effectively CH almost instantaneously, by pumping charged electrolytes into the cells. This mechanical CH avoids the damage risk that conventional batteries face from electrical overcharging. The electrolyte solutions are stable, long-lived, and pose relatively low risks (the storage and operational hazards are comparable to lead-acid batteries). Electrolyte storage in separate tanks minimizes self-DCH and cell degradation, and reduces the risk of unintended mixing and rapid energy release.

FBs are relatively simple, durable, efficient, scalable (affording economies of scale in both modular manufacturing and ES capacity), and offer flexible output modes that optimize either power or energy as desired. An individual FB installation with proven power conditioning systems (PCS) and controls can perform a flexible set of services, ranging from high-power applications (*e.g.*, black-start provision, power quality support) to high-energy applications (*e.g.*, extended outage ride-through, load management, time-shifting electrical generation for economic arbitrage). This allows FBs to compete in a range of applications and market niches against many different, more specialized ES technologies—and in cases, against generating capacity.

Three primary FB designs are being developed, distinguished primarily by their differing electrolyte solutions. The Regenesys® system uses sodium bromide and sodium polysulfide. Another type uses two vanadium solutions at different valence states. Zinc-bromide (Zn-Br) FBs have been manufactured by at least two firms.

Regenesys®: This FB was developed during the 1980s–90s by the British firm Regenesys Technologies Ltd (www.Regenesys.com), owned by Innogy (www.innogy.com), which was bought by the German utility RWE.

TECHNICAL CHARACTERISTICS: Regenesys® uses sodium bromide and sodium polysulfide elelctrolytes (in their uncharged state). During discharge, each electrolyte flows through a half-cell on either side of a cation-selective DuPont polymer membrane (sodium bromide on the positive side and sodium polysulfide on the negative), producing about 1.5 V across the membrane in each cell. Higher voltage output is created by linking cells electrically in series in bipolar modules, with the cathode of one cell becoming the anode of the next cell. The cells are connected hydraulically in parallel by a network of distribution manifolds on a pumping loop running to the electrolyte storage tanks. A 100 kW module comprises a stack of 200 cells [3–7].

Sixteen m^3 (21 yd^3) of each electrolyte is needed for each MWh of storage [7]. In a 12 MW, 120 MWh installation, electrolytes are pumped through the cell stacks at approximately 5,000 gpm from a 475,000 gal sodium bromide tank and a 570,000 gal sodium polysulfide tank [5]. The net efficiency ("kWh in to kWh out") ranges from 55–60% to about 75% depending on its operational mode, including power conversion and energy

[1] Second Hill Group, Denver, CO. E-mail: chrislot@earthlink.net
This research was funded by E SOURCE/Platts (www.esource.com), and is the topic of a forthcoming technical brief of E Source's Distributed Energy Series.

losses due to auxiliary equipment such as pumps [1,3,4,8]. Heat generated during operation is removed by a plate cooler in the polysulfide circulation network. The electrolytes present minimal hazards in handling and storage. It emits little gaseous, liquid, or solid waste, producing modest amounts of sodium sulfate crystals and trace quantities of bromine and hydrogen gases that are managed to minimize risks [5].

The power conditioning system (PCS) and controls linking Regenesys® to the grid allow "cold" start up in less than 10 mins; if held in standby mode with charged electrolyte in the stacks, the system can respond in fraction of a second (reportedly within 20 milliseconds) to supply more than 10 MW [8]. It operates ideally between 20–40°C, but tolerates a wider temperature range. It is designed to be automated and run remotely, with little or no staffing apart from quarterly maintenance and biweekly removal of sodium sulfate crystal byproducts [1,5].

APPLICATIONS: Following testing at Innogy's Aberthaw power station in Wales from 1996–2000, two Regenesys® systems are to become operational in 2002. A 15 MW, 120 MWh installation is to provide a British CCGT power station with black start, load-leveling, and other ancillary services. A 12 MW, 120 MWh facility in Mississippi is to provide distribution grid support and peak power supply for the Tennessee Valley Authority (TVA). Innogy plans MW-scale FB support for wind farms in Denmark and elsewhere, and reports customer interest in installations ranging from 12–100 MW. Systems of up to 500 MW capacity are feasible in its current configuration. At smaller scales, Regenesys® has been researched for naval shipboard applications.

Vanadium-Vanadium Flow Batteries: NASA iron-chromium (Fe-Cr) FB research inspired Australian R&D into vanadium electrolyte FBs. In the 1980s–early 1990s the University of New South Wales in Australia developed vanadium electrolytes and related processes and technologies, and sold this intellectual property (IP) to Pinnacle (www.pinnaclevrb.com.au). Sumitomo Electric Industries (SEI, www.sei.com) shifted its FB R&D to VRBs in 1991 as a licensee. A complex IP struggle ensued, and the Canadian firm Vanteck Technology Corp. (www.vrbpower.com) now controls the rights to the core patents and licenses. SEI is the sole licensee cell stack manufacturer, has the most field experience with several installations in Japan, and can make and sell VRBs worldwide. In 2000 Vanteck formed alliances in South Africa with Eskom (the world's 5th largest electric utility company) and Highveld Steel and Vanadium Company (the world's largest producer of vanadium).

TECHNICAL CHARACTERISTICS: Vanadium redox battery (VRB) electrolyte solutions contain different ionic species of vanadium solutions in sulphuric acid, at a similar pH as that found in a lead-acid battery. Ions are transferred between these species across a proton-exchange membrane (PEM) [9]. The concentration of each ionic form of the vanadium electrolyte changes during CH and DCH [10]. VRB cells produce from 1.2–1.6 V across the membrane, depending upon the electrolyte solution, temperature, and state of charge [9,10]. Cells are connected electrically in series and hydraulically in parallel. A typical stack comprises 100 cells [11].

Electrolytes are typically used at 1.6–1.8M (molarity, or moles/liter), reportedly a stable concentration that is well-suited to automated, low-maintenance VRB systems. Higher concentrations are possible and could reduce electrolyte storage requirements and increase energy density, but are not yet economic or stable [1]. Cross contamination of VRB electrolytes is not a significant problem, since both solutions consist of the same element; the desired balance can be restored by mixing. As the solutions are pumped through cell stack, the solutions act as coolants allowing for better heat exchange and reducing thermal management problems.

Cells last at least 10,000 cycles, and in the lab 25 kW modules have exceeded 16,000 cycles [9]. Stack service life is determined primarily by membrane longevity, and the life of pumps and other auxiliary components. SEI recommends that the stack be replaced be replaced every 10 ys, reflecting an expected membrane life of 8–10 ys. VRBs are designed for easy replacement, recycling or reuse of components. The electrolytes have an indefinite life, and can be reused in new FBs. VRBs can respond and switch from CH to DCH within 1/1000 second, and sustain high-power output (more than twice standard output) for up to several minutes [11].

APPLICATIONS: VRBs are scalable from Watts to MW; studies indicate that systems up to 100 MW are feasible. Cell stacks, electrolyte tanks, PCS and controls are integrated in a vanadium energy storage system (VESS). A Japanese liquid crystal factory's 1.5 MW, 1.5 MWh VRB can deliver a maximum power overload DCH (3 MW per 1.5 secs) to prevent production line stops due to momentary voltage drop, as well as curb peak load. In Japan, VRBs are used for load leveling at a substation (450 kW, 900 kWh), a university (500 kW, 5 MWh), and an office building (100 kW, 800 kWh), and stabilize the output of both wind (170 kW, 1.2 MWh)

and photovoltaic (30 kW, 240 kWh) generators. A 250 kW, 520 kWh VRB-VESS was tested at a university near Cape Town, South Africa during 2001, and is to be used by another client for load leveling. PacifiCorp is building a relocatable 250 kW, 2,000 kWh (8 h) VESS in a remote area in Utah, the first in North America. To be completed by July 2002, the unit will provide peak power and end-of-line voltage support, deferring the need for a new substation [10]. VRBs have been studied for shipboard applications and tested in electric vehicles.

Zinc-Bromide (Zn-Br) Flow Batteries: Zn-Br FBs were developed by Exxon in the early 1970's, which sold the IP to companies in the U.S., Austria, Japan, and Australia. Numerous multi-kWh (*e.g.*, 1 MW, 4 MWh FB) Zn-Br FBs have been tested [4]. The primary developer is the U.S./Australian firm ZBB Energy (www.zbbenergy.com). ZBB combines 25 kW, 50 kWh standard modules with PCS and controls into containerized 250 kW, 500 kWh turn-key units; power output can be doubled with appropriate PCS [12,13]. U.S./Austrian developer Powercell sold 100 kW, 100 kWh modules, but shut down in April 2002.

TECHNICAL CHARACTERISTICS: Zn-Br batteries are FBs, but their design and electrochemistry differ from Regenesys® and VRBs. A Zn-Br electrolyte flows through two half-cells divided by a microporous polyolefin membrane, with a Zn negative electrode and a Br positive electrode. Unlike other FBs and a bit like conventional batteries, the electrodes serve as substrates for the reactions and their performance capacity can be degraded if the battery is not completely and regularly discharged.

During DCH, zinc and bromine combine into zinc bromide, generating 1.8 V across each cell. This increases the Zn^{2+} and Br^{-} ion density in both electrolyte tanks. During CH, bromine evolves as a dilute solution in the positive half-cell, settling as a thick oil in a separate part of the electrolytic tank, and remixing with the electrolyte during DCH. Also during CH, metallic zinc is deposited (plated) as a thin film on the negative carbon-plastic composite electrode. The metal zinc is once again dissolved into the electrolyte during DCH, so it is important to fully DCH the battery regularly to maintain performance. The battery can be left in its fully discharged state indefinitely. Its operational temperature range is 0–120°F. Heat generated during operation is typically removed with a small chiller. The system's net efficiency is about 75% [4,12,13].

Modules can be linked electrically but not hydraulically. Hermetic electrolyte tanks isolated within each module limit energy storage economies of scale in larger installations of aggregated modules. ZBB sizes PCS and control systems to serve the number of modules in each application. ZBB reports that it has developed injection-molded HDPE stack components to reduce parts count and improve manufacturability [13].

APPLICATIONS: Zn-Br FB modules provide facility-scale UPS and load management; supply ES in remote Malaysian villages; support microturbines and solar generators as well as substations and T&D grids; and have been demonstrated on trailer-mounted mobile systems at both 1.8 MW, 1.8 MWh and 200 kW, 400 kWh scales.

Comparative costs: FB technologies are evolving as they enter the marketplace. Orders are few, current capital costs are high, and comparisons between firms and technologies are neither simple nor direct. Technical characteristics are roughly equivalent, with no system offering clearly superior performance. Power and energy capacity costs are useful but vary considerably between different applications and systems. Life-cycle cost of ownership is arguably the most useful metric. Cost data varies and is hard to get from competing developers, but some information is available. A proprietary 2000 EPRI study evaluated total costs of ownership for VRBs, Zn-Br FBs, and Regenesys® for a large system (10+ MW, 100+ MWh). TVA used the study to select its Mississippi FB system, and summarized the results [5]. In 2001 Sandia National Laboratories (SNL) and Black & Veatch (B&V) surveyed Vanteck, SEI, ZBB, and Powercell to evaluate technical and cost factors for a 2.5 MW, 10 MWh battery demonstration project in Nevada [14]. (Regenesys® did not participate, reportedly due to the small system size.) These studies and interviews with analysts and developers informed this analysis.

POWER CAPACITY COSTS: FB $/kW varies by application and DCH rate, complicating direct comparisons [9,13]. The three FBs are in a roughly equivalent range of a few to several thousand dollars per kW for initial systems, decreasing towards $1,500–2,000/kW (ZBB reports that ~$800/kW and lower is achievable). EPRI concluded that Regenesys® had the lowest capital costs of the three main designs. VRBs and Zn-Br FBs developers focus on smaller, modular systems, which might reduce capacity costs faster as production volumes build over the mid- to long-term. SNL/B&V indicated that Zn-Br systems offer lower capacity costs than VRBs.

ENERGY CAPACITY COSTS: Electrolyte costs can be assessed in terms of electricity storage capacity, and in terms of cost per unit volume; cost per kWh of stored energy is a more useful indicator. Electrolytes can be considered a capital rather than an operating or variable cost, in that they are not consumed during cycling. Analysts estimate electrolyte costs in the range of $10–20/kWh for Regenesys® and Zn-Br FBs, and $30–40/kWh for VRBs. EPRI indicated that Zn-Br electrolyte costs per kW were twice that of Regenesys®. Regenesys® appears to have provide the lowest system electrical energy storage cost, reportedly in the range of $160–185/kWh per kWh in large installations. ZBB reports Zn-Br FBs storage costs approach $400/kWh with scaled-up production. Consistent $/kWh values for VRBs were not determined. Apparently Zn-Br systems currently offer lower electrolyte and total capacity costs than VRBs. However, VRB systems offer greater scalability of electrolyte storage, probably enabling storage cost reductions in larger installations that stacks of electrically-linked but not hydraulically-connected Zn-Br modules cannot attain.

PCS AND CONTROLS COSTS: PCS costs are typically $200–400/kW for smaller (~100 kW) batteries, and are roughly equivalent components for all FBs on a capacity and cost basis [1]. Controls and PCS for ES technologies are widely available, yet FB firms are developing proprietary components, software, and integrated systems to match FBs' diverse capabilities, and anticipate cost and performance improvements. One VRB developer projects eventual PCS cost reductions of 30–50%.

O&M COSTS: Long-term operating and maintenance costs are projected as FBs are new and existing installations vary in design, capacity, and operational profile. All FB systems are designed for automated operations, but initial installations are provided with more maintenance and operational support staffing. Regenesys® might require more regular maintenance (*e.g.*, for removal of process byproducts) than VRBs or Zn-Br FBs. Regenesys® installations target a 15 y service life, but the O&M cost to attain that was not determined. SNL/B&V report that VRBs average projected O&M costs are ~$50,000, lower than the ~$90,000 median of the broad range of projected Zn-Br costs for an equivalent capacity. That study also indicates that VRBs have a shorter service life (7–15 y) than Zn-Br systems (10–20 y). SEI suggests a 10 y VRB stack service life to its customers and has demonstrated cells that exceed 10,000 cycles, while Powercell offered buyers a 5 y service guarantee and estimated a 1,500 cycle life for its Zn-Br modules.

TOTAL COST OF OWNERSHIP: EPRI concluded that Regenesys® "would most likely provide the lowest cost of operation of a life-cycle-cost basis for multi-hour utility energy storage, while providing other energy storage services that have economic value to electric utilities." Zn-Br was the second choice, but the Zn-Br developer was focused only on units for "short duration, small scale discharges (25 kW for 4 hours)." EPRI also concluded that VRBs and Zn-Br FBs had lower power and energy ratings and higher capital costs than Regenesys®, and that Zn-Br "electrolytes that are twice the cost per kilowatt of those used for… Regenesys."

Commercialization characteristics: The three major FBs have relative attributes and commercialization pathways that help define particular markets where each might compete more or less effectively. Regenesys focuses on multi-MW systems roughly tenfold larger than typical VRB and Zn-Br FBs. Each Regenesys® installation is to be built as an integrated, turnkey system, with scalable electrolyte storage. This might reflect a focus on facility scale economies of power and energy capacity. Production capacity was not determined, but Regenesys is reportedly well positioned for manufacturing. VRB and Zn-Br FB developers are concentrating on modular systems, typically (but not exclusively) below 1 MW of power capacity. This might reflect a focus on production scale economies for FB and auxiliary system components. SNL/B&V indicate that Zn-Br developers have an annual production capacity of 40–70 MWh compared to VRB developers' 30 MWh, but that VRB firms had actually produced 10 MWh in the previous year compared to Zn-Br production of 4.5 MWh. These manufacturers are planning much larger installations. VRB and Zn-Br firms that are primarily targeting utilities and network operators are more likely to directly compete with Regenesys® and each other for large-application customers. Some producers of smaller FB systems see themselves as serving different, complementary ES market segments (*e.g.*, facility managers) than larger-capacity systems. Regenesys® might compete best in multi-MW applications, *e.g.*, power trading, large generation and transmission and distribution (T&D) grid support; VRB markets span from generation and T&D grid support to facility-scale applications, while Zn-Br FBs might compete best in facility-scale and distribution- or substation-level support.

FB marketers face unique opportunities and challenges in serving—indeed, helping define and create—ES markets. No other ES technology can cycle as rapidly and deeply as FBs, nor provide both brief, power-

intensive DCH and longer-term, large-scale energy flows. But many potential FB applications and market niches are dominated by established ES systems that perform one or two of these functions effectively at lower initial costs. Early adopters have a range of new, specialized ES technologies to consider, so FBs are unlikely to capture all of those customers and opportunities. FBs' versatility offers critical advantages, and creates a marketing trade-off of sorts. They are poised to compete strongly in applications that make use of their integrated suite of services, but have to sell their multiple benefits at a disadvantage against cheaper, proven systems in each of several more narrowly focused applications. Many of these benefits and uses traditionally are neither monetized nor integrated into an ES marketplace. FBs offer life-cycle cost advantages, but that claim is based on relatively little experience, and can be a tough sell in the face of tight budgets and ES alternatives with smaller up-front price tags. Marketers would benefit from new evaluation methods and financial models that better demonstrate the total value of FBs' services and important ancillary benefits. As a new and unfamiliar technology, any FB successes that build the market's confidence will benefit all FB producers. Analysts project continued FB initial market penetration over 1–3 yrs, and growth to commercial-scale production over 3–5 yrs.

FLOW BATTERY TECHNICAL CHARACTERISITICS

ELECTROLYTES	V ACROSS MEMBRANE	EFFICIENCY (AC-AC)	SERVICE LIFE
Sodium bromide - sodium polysulfide (Regenesys®)	1.5 V	Cell: 75%+ System net: 55–75% depending on operation	Cycles: n/d Target: 15–20 y, with maintenance
Vanadium ($2^+/3^+$) – vanadium ($4^+/5^+$)	1.4–1.6 V	Cell: ~85–88% System net ~70–85% depending on operation	Cycles: ≥10,000 Target: 10 y; 7–15 with O&M
Zinc-bromide	1.8 V	Cell: n/d System net: ~75%	Cycles: ≥1,500 cycles Target: 5 y; 10–20 y with O&M

Note: n/d = not determined; y = years; ~ = approximately

ECONOMIC CHARATERISTICS

BATTERY	POWER COST	ENERGY COST	O&M COST	SYSTEM COST
Regenesys®	~$1,500/kW Projected: ~$750/kW	Electrolyte: $10–20/kWh System: n/d ($160–185/kWh)	n/d	$20–25 million for 10–15 MW, 100–150+ MWh
Vanadium	$1,500–5,500/kW Projected: $1,000/kW	Electrolyte: $30–50/kWh System: $300–1,000/kWh	~$50,000/y for 2.5 MW, 10 MWh system	~$11 million for 2.5 MW, 10 MWh system
Zinc Bromide	$1,500–2,000/kW? (ZBB: ≥$800/kW now achievable)	Electrolyte: ≥$10–20/kWh System: target ~$400/kWh	$30,000–150,000/yfor 2.5 MW, 10 MWh system	~$300,000 for 100 kW, 100 kWh module; $5.8–8 million for 2.5 MW, 10 MWh system

Note: n/d = not determined, ~ = approximately

COMMERCIALIZATION CHARACTERISTICS

BATTERY	REPRESENTATIVE SYSTEMS	PROJECTED CAPACITIES	PRIMARY DEVELOPERS
Regenesys®	12–15 MW, 120 MWh	5–50 MW, 100–250+ MWh; 500 MW feasible	Regenesys (www.regenesys.com, www.innogy.com)
Vanadium	250 kW, 520 kWh; 1.5 MW, 1.5 MWh	50 kW, 500 kWh to 5 MW, 20 MWh; 50–100 MW upper range; 500 MW feasible	Pinnacle (www.pinnaclevrb.com.au) Sumitomo Electric (www.sei.com) Vanteck (www.vrbpower.com)
Zinc Bromide	50 kW, 500 kWh module; 200 kW, 400 kWh trailer	300–600 kW, 300–1,000 kWh modular arrays; 4–5 MW, 4–10 MWh upper range ("no practical limit")	ZBB Energy (www.zbbenergy.com)

Summary: No one FB technology appears to dominate the others, the different systems' performance and costs are roughly equivalent, and typical scales and applications remain complementary among the three. Apparently Regenesys® has the lowest cost of ownership, yet is focused on applications of at least 5 MW, below which remains a sizeable capacity range and market for VRBs and Zn-Br FBs. Both VRBs and Zn-Br systems appear to offer roughly equivalent service life and overall costs of ownership, and are competitive with each other. Zn-Br FBs apparently have lower power and ES capacity capital costs than VRBs, but VRBs offer higher efficiency and more scalable ES.

FBs are entering the market now, and are likely to experience sustainable growth to attain commercial-scale production in 3–5 years. Developers are positioned for mass manufacturing, are soliciting large-scale orders, and report significant interest among potential buyers. Demonstration FBs have performed well in a range of applications that showcase their technical versatility and the potential economic benefits of providing multiple services and value streams. FBs are an integrative technology, serving and tying together a range of fragmented ES market niches. FBs are also potentially a disruptive technology, furthering the true commodification of electricity. The age of liquid electricity is dawning, and the energy sector is likely to be favorably transformed.

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of many contributors and reviewers, including Garth Corey, Principal Member of Technical Staff, Energy Storage Systems Program, and Nancy Clark, Power Sources Technology Group, Sandia National Laboratories; Steve Eckroad, P.E., Manager, Substations & Energy Storage, Science & Technology Development, EPRI; Imre Gyuk, Energy Storage Research Program Manager, U.S. Department of Energy; Dr. John Hawkins, Technical Director and Don Nicholson, CEO, Vanteck; Dr. Joe Hoagland, Senior Manager, Clean and Advanced Energy, Public Power Institute/TVA; Innogy; Peter Lex, VP - Chemical Engineering and Greg Nelson, C.O.O., ZBB; Jim McDowall, SAFT America; Yasushi Santo, Green Energy.Com (Japan); Dr. Maria Skyllas-Kazacos, Director, Centre for Electrochemical and Minerals Processing, School Of Chemical Engineering and Industrial Chemistry, University Of New South Wales; John Slattery, VP - Marketing and Sales, Powercell; Sumitomo Electric Industries; Dr. Philip Symons, Co-Chair, Electricity Storage Association; and David van Holde, Director, Distributed Energy Series, E SOURCE. Any errors or omissions are the author's.

REFERENCES

[1] Analyst interviews (some conducted on background on condition of confidentiality).
[2] www.innogy.com (accessed 10 February 2002).
[3] "Electricity storage cells raise hopes for CHP and renewables," *ENDS Report*, September 2000, Issue 308, www.endsreport.com/issue/print.cfm?ArticleID=6918 (accessed 9 November 2001).
[4] www.energystorage.org (accessed 15 October 2001).
[5] "Environmental Assessment: The Regenesys™ Energy Storage System," TVA, from www.tva.gov/environment/reports/regenesys (esp. Ch. 2 and Appendixes A & B) (accessed 6 November 2001).
[6] "UK energy storage generates global interest," www.platts.com/engineering/issues/Power/0103/0103pwrmonitor.shtml (accessed 9 November 2001).
[7] Rick Bush, "How About Some Liquid Electricity?," *Transmission & Distribution World*, Sep 1, 2000 (see www.industryclick.com, accessed 2 December 2001).
[8] "Large-Scale Storage Solution? Regenesys® Regenerative Fuel Cell," by Dr. Barry Davidson, Tim Calver, Anthony Price and David Simchock, National Power, from www.gasnet.com.br/gasnet_br/cogeracao/novidades5.htm (accessed 9 November 2001).
[9] "Recent Progress With The UNSW Vanadium Battery," Dr. Maria Skyllas-Kazacos (M.Kazacos@Unsw.Edu.Au), School Of Chemical Engineering and Industrial Chemistry, University Of New South Wales, Sydney, 2052, Australia, 2000; also personal communication, 16 January and 28 April 2002.
[10] www.vrbpower.com (accessed 15 January 2002).
[11] SEI NEWS, May 2001, www.sei.co.jp/sn/0105/p1.html (accessed 30 October 2001).
[12] www.zbbenergy.com (accessed 30 October 2001).
[13] Peter Lex, VP - Chemical Engineering, p.lex@zbbenergy.com, and Greg Nelson, C.O.O., greg.nelson@zbbenergy.com, ZBB Technologies Inc., pers. comm., 15–16 April and 22 April 2002.
[14] "Boulder City Battery Energy Storage Feasibility Study", Project Number 66761.0010, Final Report (Draft 5 December 2001), by Sandia National Laboratories (SNL) and Black & Veatch (B&V).