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COST AND SIZE ESTIMATES FOR AN ELECTROCHEMICAL
BULK ENERGY STORAGE CONCEPT

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ABSTRACT

Preliminary capital cost and size estimates were made for an electrochemical bulk energy storage concept. The electrochemical system considered was an electrically rechargeable flow cell with a titanium trichloride|titanium tetrachloride*|| ferric chloride|ferrous chloride ($TiCl_3|TiCl_4 || FeCl_3|FeCl_2$) redox couple. The preliminary calculations were made to help determine whether the redox-flow-cell system has an attractive potential as a bulk energy storage system for power load leveling.

With the rise in demand for electric power, the problem facing the electric utility industry of meeting peak power demands has been growing more acute. Because present methods of meeting peak power demands are not entirely adequate, the electric utility industry has been interested in new methods for meeting peak power demands.

On the basis of preliminary capital cost estimates, size estimates, and several other important considerations, the redox-flow-cell system emerges as having great promise as a bulk energy storage system for power load leveling. The size of this system would be less than 2 percent of that of a comparable pumped hydroelectric plant. The capital cost of a 10-megawatt, 60- and 85-megawatt-hour redox system is estimated to be $190 to $330 per kilowatt. This cost compares well with that of competing systems, especially when one considers that for many sites a saving in transmission costs (up to $200 per kW) could be realized with the redox system. This saving could be achieved because the redox systems could be built in various sizes and located near the load centers. The other important features of the redox system contributing to its load leveling application are its low adverse environmental impact, its high efficiency, its apparent absence of electrochemically-related cycle life limitations, and its fast response.

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*Current electrochemical evidence suggests that for titanium in acid solution in its +4 valence state, the titanyl ion, TiO^{+2}, rather than $TiCl_4$ or Ti^{+4}, is the predominent participant. However, for the purposes of this paper the reactions will continue to be written and discussed in the simpler form indicating $TiCl_4 \rightarrow TiCl_3$ ($Ti^{+4} \rightarrow Ti^{+3}$)

INTRODUCTION

The problem of meeting peak power demands is a very important concern of the electric utility industry. The problem is growing more acute as the pressure of rapidly rising demand is being felt.

For future power needs, it would be uneconomical to simply "overdesign" new base-load plants to meet peak power needs. The capital costs of base-load plants are higher than those of most power peaking equipment in use today (ref. 1). But the methods of power generating for peak periods used today are not entirely adequate. Most modern peaking is done with internal combustion equipment, gas turbines and diesel engines, which run on natural gas or petroleum derived fuel. Not only is the efficiency of this equipment lower than that of base-load plants, but also, and more importantly, the fuel cost can be expected to increase greatly and the fuel availability can be expected to continue to decline. Finally, this type of equipment presents potential air pollution problems.

Another method of power peaking which has been attracting increased interest is the pumped hydroelectric system (ref. 1). Aside from relatively low cost, it is appealing because of its bulk energy storage capacity. There is an increasing desire t.... ... base-load plants operating at capacity, even during off-peak hours, ... to store the energy for periods of peak demand. In some cases it is because the base-load plants use cheaper fuel (e.g., coal) than the power peaking plants (oil or gas). For a nuclear powerplant, maximum economy requires running at full load. Thus, pumped storage offers a means of accomplishing this objective.

However, even the very efficient (on the order of 66 percent) pumped hydroelectric plants have their disadvantages. Siting and environmental limitations restrict this type of energy storage system. Thus, the growing demands will require development of new energy storage systems to meet the particular requirements of a powerplant in the region it serves.

The present report looks into the use of an electrochemical system for bulk energy storage to meet peak power demands. In many ways, electrochemical systems make ideal energy storage and peaking systems. They could be free of siting and environmental problems, provide instant startup in emergencies, operate at high efficiency, permit minimum distance peak load transmission, and require short construction lead times.

The electrochemical system proposed for consideration is an electrically rechargeable flow cell, which is a new concept for bulk energy storage. The heart of the flow cell are two redox couples (a pair of oxidation-reduction reactions in which the ions of the pair remain soluble in their electrolytes in either their oxidized or reduced states). The two redox couples considered were titanium trichloride|titanium tetrachloride||ferric chloride|ferrous chloride ($TiCl_3|TiCl_4||FeCl_3|FeCl_2$, or $Ti^{+3}|Ti^{+4}||Fe^{+3}|Fe^{+2}$). Preliminary measurements were made with laboratory cells at the NASA Lewis Research Center (ref. 2). In the present report, size and cost calculations are presented for this redox-flow-cell system. The size calculations include electrochemical characteristics and physical size of the power unit and characteristics of the principal auxiliaries. In the cost calculations an estimate is made of the possible cost of a 10-megawatt, 85-megawatt-hour plant for load leveling.

The cost estimates for the redox-flow-cell system are quite preliminary. They were made to help determine whether this system has an attractive potential for bulk energy storage in load leveling applications.

DESCRIPTION OF REDOX-FLOW CELL

The redox-flow cell consists of two compartments containing separate electrolytes and inert carbon electrodes separated by an anion permeable selective ion exchange membrane. On one side an aqueous electrolyte containing a $TiCl_3$-$TiCl_4$ solution (the anolyte) is circulated from its storage tank into the cell and then back to its tank. On the other side an aqueous electrolyte containing an $FeCl_3$-$FeCl_2$ solution (the catholyte) is similarly circulated into the cell and back to its tank (fig. 1). On discharge, $FeCl_3$ is reduced to $FeCl_2$, while $TiCl_3$ is oxidized to $TiCl_4$. The ion exchange membrane allows the passage of chlorine ions (Cl^-) from one compartment to the other to preserve electroneutrality. Alternatively, a hydrogen ion (H^+) membrane may also be used. (See fig. 2 for details of electrochemical reactions with either membrane.) The redox-flow cell is electrically rechargeable by simply reversing the direction of flow of current. The redox-flow cell operates at relatively low temperatures, from room temperature to perhaps 80° C.

SIZE OF REDOX-FLOW-CELL POWERPLANT

The basis of the size calculation was a 10-megawatt peak-power-load-leveling plant operating a maximum of 8.5 hours, with an overall efficiency of 70 percent and with both electrolytes at 4-molal concentration. The results of this analysis are shown in table I. The table gives electrochemical characteristics and physical size of the power unit and the characteristics of the principal auxiliaries. Table II contains selected data from a new pumped hydroelectric facility (Northfield, Mass., ref. 3) which are useful for purposes of comparison. Also see figure 3 for a pictorial representation of the 10-MW, 85-MWh redox system.

COST ESTIMATES FOR REDOX-FLOW-CELL POWERPLANT

A cost estimate was made for a 10-megawatt, 85-megawatt-hour powerplant. A current density of 108.0 milliamperes per square centimeter (100 A/ft^2), 70-percent overall efficiency, (Wh(ac)out/Wh(dc)in), and 4-molal concentrations of electrolytes were assumed.

Pricing

The capital cost estimates were made during the summer of 1973. The costs of electrochemical materials were obtained from suppliers or from

trade publications. The unit costs used in the calculations are shown in table III. The cost estimates for process equipment were made chiefly with the assistance of process equipment manufacturers.

A good deal of judgment was involved in making these cost estimates. For example, judgment had to be used in selecting the grade of chemical required and also in securing the estimate of electrochemical materials costs. It was obvious that the estimated costs of the electrochemical materials were not necessarily the lowest. The membrane manufacturers, for instance, predicted that future development and increased production savings could have the present cost of the membrane. Furthermore, one research worker in membrane technology predicted that the membrane cost might even be reduced to less than one-tenth of its present cost. For reasons such as these two types of electrochemical materials costs were calculated. One was higher or conservative, the other lower or optimistic.

The only pieces of process equipment for which conservative and optimistic costs were calculated were the reactant tanks. If lined carbon-steel tanks would be suitable for this process, they would be approximately half as costly as stainless-steel tanks.

As can be seen in table III, the differences between the conservative and optimistic capital cost totals are considerable. For the base case powerplant (operation at 10 MW for 8.5 hr with 70-percent efficiency) the difference was over a million dollars; the conservative total cost was $2 867 000, while the optimistic total cost was $1 846 000.

In addition to this basic cost estimate, conservative and optimistic costs were projected for three other cases. One reflected an assumption of a higher efficiency system, 85 percent instead of the 70 percent for the base case. The other two cost projections were for a shorter period of power-load-leveling operation, 6 hours instead of the 8.5 hours for the base case. One of these cost projections was made for 70-percent efficiency, the other for 85-percent efficiency.

Design Basis

Some pieces of process equipment, such as pumps, heat exchanger, and filters, were more or less within the standard series of types available. Other pieces of process equipment would have to be custom-fabricated, which could make their cost estimates more uncertain. However, storage tanks are normally custom-fabricated. In the opinion of a leading tank manufacturer, the requirements of the redox-flow-cell system would present no special difficulties.

Estimating the cost of the redox-cell frames did present a unique problem, since redox-cell frames had never been built. However, the redox battery of cells containing graphite sheet electrodes, a diaphragm, and flowing liquids resembles the filter press to a reasonable extent. Consequently, cost estimates were obtained in cooperation with filter press manufacturers.

DISCUSSION

The redox-flow-cell system has several attractive features. Electrochemically the system is a simple one. Unlike batteries, there are no apparent cycle life limitations due to morphology changes in the active materials of the electrodes. Furthermore, repeated deep discharges should be possible without reducing cycle life. The cell should operate at very high overall efficiency. Finally, high efficiency does not require high cell temperatures.

The preliminary cost estimates made in this report show that the redox-flow-cell system is also attractive from a cost standpoint for use in bulk energy storage for power peaking. The estimate for the 10-megawatt plant ranged from $150 to $290 per kilowatt, depending upon whether the plant is designed for 6- or 8.5-hour use and whether optimistic or conservative costs are used. In keeping with the paper by Heredy and Parkins (ref. 4), a $40-per-kilowatt cost was added for ac-dc converters, transformers, and switchgear, so that the cost range was brought up to $190 to $330 per kilowatt. In the same paper the capital cost of a pumped hydroelectric system in the 10-megawatt range (2.4- to 10-hr daily operation) is estimated to range from $85 to $200 per kilowatt, while a gas turbine system was estimated to cost $100 to $200 per kilowatt.

On the basis of these cost estimates plus others reflecting cost of operation, the pumped hydroelectric storage system is potentially the cheapest. (In ref. 4 the delivered energy cost estimate for the pumped hydroelectric system is the lowest.) However, as mentioned in the INTRODUCTION, geographic or environmental considerations or both may preclude its use. No doubt the high end of the capital cost estimate represents the case where geographic conditions are considerably less than optimum. Also, because of environmental considerations, it may not be possible to create a lake holding 17.1 meters (56 ft) of water and covering 1.31×10^6 square meters (323 acres) or to have a site which could provide a 252-meter (825-ft) head, as was done, for example, for the Northfield hydroelectric project (table II). On the other hand, a redox bulk energy storage plant of the same output as the Northfield plant would occupy less than one-fiftieth of the volume (tables I and II). Furthermore, the fact that the redox-flow-cell system can be built in different sizes can be put to good advantage. For example, significant savings in transmission costs can be achieved by dispersing suitably sized redox energy storage devices throughout the system near the load centers rather than using a very large pumped hydroelectric facility at a single site. One report estimates that this transmission cost saving would range between $60 and $200 per kilowatt (ref. 5). This estimate would hold for a typical utility system where the average transmission length would be about 100 miles and the dispersed energy storage facilities would be sited within urban areas.

Naturally, to advance the redox-flow-cell system toward commercialization will require a great deal of effort. In the research and development area there are numerous performance questions and problem areas which will have to be resolved. Some of these are discussed in this

report. In the performance category are the as-yet-unattained 648-watt-per-square-meter (60-W/ft^2) power density and the assumed electrochemical performance at the 4-molal concentrations. In this connection, calculations were made to determine the sensitivity of the capital cost to reduced electrochemical performance, a power density of 324 watt/m^2 instead of 648 watt/m^2. These are shown in table IV. In this case the battery stack costs were affected. Also shown in table IV are the results of calculations made to determine the sensitivity of the capital cost to operation at much lower reactant concentrations, 1 molal instead of 4. In this case the process equipment costs are affected. Comparing these capital costs with the original costs in table III, it is obvious that the capital costs are quite sensitive to both electrochemical performance (power density) and reactant concentration. The assumed decrease in power density to $\frac{1}{2}$ the original adds between \$63/kw and \$110/kw; the assumed decrease in reactant concentration to $\frac{1}{4}$ the original adds between \$52/kw and \$104/kw. Apparently the capital cost is more sensitive to power density than to reactant concentration. The effects of concentration and power density upon power plant size are shown pictorially in figure 4.

Current laboratory work at NASA Lewis Research Center on redox systems is producing some encouraging results. A number of redox couples show promise. The Lewis work on the Ti/Fe system, which has been given the greatest emphasis thus far, indicates that the performance goals cited in this paper are still reasonable. Part of the Lewis redox program involves work on the membrane, a major technical consideration in this redox concept. Presently, no membrane is available with very low ionic resistance coupled with very good selectivity. In addition, a suitable membrane must be compatible with the reactants, dimensionally stable for long periods, and inexpensive to produce in large sheets. A conclusion of the laboratory work is that membrane life does not appear to be a major problem thus far. While the membranes tested permitted some ion-crossover, they exhibited no signs of degradation after several thousand hours of operation. This was evident from the fact that with replacement of the reactant solutions with fresh reactant solutions, the inital performance of the cells was restored.

Another phase of the NASA Lewis Research Center redox work involved the important question of circulating electrical currents between the cells and of the distribution of the reactant flow within the cells. The conclusion of this analytic treatment was that proper design of the cell flow passages is required in order to minimize ionic shunt currents without creating excessive parasitic pumping requirements.

CONCLUDING REMARKS

On the basis of capital cost estimates, size estimates, and several other very important considerations the redox-flow-cell system emerges as having great promise as a bulk energy storage system for power load leveling. The size of this system was estimated to be less than 2 percent of the size of a comparable pumped hydroelectric storage plant.

The capital cost of a 10-megawatt, 60- and 85-megawatt-hour redox-flow system was estimated to range from $190 to $330 per kilowatt.

This capital cost range compares well with that for other peaking systems ($85 to $200 per kW), especially when one considers that no transmission credit ($60 to $200 per kW) was included in the redox-system capital cost estimates. The transmission savings could be achieved because of the possibility of building redox systems of various sizes and dispersing them throughout the electrical network near the load centers. Coupling these attractive estimates of capital costs and size of the redox-flow system with its low environmental impact, its high efficiency at low temperatures, its apparent absence of electrochemically-related cycle life limitations, and its fast response produces a power-load-leveling system of strong potential.

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TABLE I. - ELECTROCHEMICAL AND SIZE CHARACTERISTICS OF

REDOX-FLOW-CELL POWERPLANT

[10-MW, 85-MWh system; redox flow cell, $TiCl_3 | TiCl_4 \| FeCl_3 | FeCl_2$; operating temperature, 80° C;[a] efficiency, 70 percent.]

Electrochemical characteristics	
Current density, mA/cm^2 (A/ft^2)	10.8 to 108.0 (10 to 100)
Voltage per cell, V/cell	0.6
Energy density, Wh/kg reactants + water (Wh/lb reactants + water) . . .	13.25 (6.0)
Power unit size	
Total electrode area, m^2 (ft^2)	
10.8 mA/cm^2 (10 A/ft^2)	1.55×10^5 (1.67×10^6)
108.0 mA/cm^2 (100 A/ft^2)	1.55×10^4 (1.67×10^5)
Total cell volume, m^3 (ft^3)	
10.8 mA/cm^2 (10 A/ft^2)	[b]1.98×10^3 (7×10^4)
108.0 mA/cm^2 (100 A/ft^2)	[b]1.98×10^2 (7×10^3)
Total power unit volume, m^3 (ft^3)	
10.8 mA/cm^2 (10 A/ft^2)	6.43×10^3 (2.27×10^5)
108.0 mA/cm^2 (100 A/ft^2)	4.63×10^3 (1.64×10^5)
Characteristics of principal auxiliaries	
Weight of reactants including water, kg (tons)	6.42×10^6 (7.09×10^3)
Shape of reactant tanks	cylindrical with height equal to diameter
Reactant tank volume, m^3 (ft^3)	
Catholyte tank	[c]2.225×10^3 (7.86×10^4)
Anolyte tank	[d]2.225×10^3 (7.86×10^4)

[a]$TiCl_4$ decomposes in hot water to insoluble titanium dioxide (TiO_2) and hydrochloric acid (HCl). Operation in HCl solution would aid solubility and stability. Solubility and stability data lacking to fix operating temperature accurately.

[b]Assumed 1.27-cm (1/2-in.) spacing between cells.

[c]Based on 14.2-m (46.4-ft) height and diameter, 4-molal $FeCl_3$ concentration, and 90-percent discharge.

[d]Assumed value (solubility data lacking).

TABLE II. - SELECTED DATA FROM NORTHFIELD

HYDROELECTRIC PUMPED STORAGE FACILITY

[1000-MW, 8500-MWh (max) system; emergency reserve, 2500 MWh.]

Upper (man-made) reservoir	
Volume of water, m^3 (ft^3)	
Total	2.22×10^7 (7.9×10^8)
Usable portion	1.59×10^7 (5.6×10^8)
Surface area, m^2 (acres)	1.31×10^6 (323)
Maximum water depth, m (ft)	17.1 (56)
Operating head, m (ft)	
Maximum	252 (825)
Minimum	220 (720)
Powerhouse	
Equipment	
Turbine generators (250-MW)	4
Pumps and motors	4
Cavern	
Dimensions, m (ft) . . .	$100 \times 21.3 \times 36.6$ ($328 \times 70 \times 120$)
Volume, m^3 (ft^3)	7.81×10^4 (2.76×10^6)
Rock excavated, kg (tons) . . .	$2.\ldots7 \times 10^8$ (2.5×10^5)

TABLE III. - COST ESTIMATE FOR REDOX-FLOW-CELL

BULK ENERGY STORAGE SYSTEM

[10-MW, 85-MWh system; redox flow cell, $TiCl_3 | TiCl_4 ‖ FeCl_3 | FeCl_2$; Cl^- membrane; efficiency, 70 percent; 108.0 mA/cm^2 (100 A/ft^2); 4-molal electrolyte concentration.]

(a) Electrochemical materials

Material	Conservative estimate		Optimistic estimate	
	Unit price	Price of item, $	Unit price	Price of item, $
[a]TiCl$_4$	$0.39/kg	550 000	$0.26/kg	372 000
FeCl$_3$	$0.16/kg	194 500	$0.13/kg	160 000
Cl$^-$ membrane[b]	$43.00/m^2	812 000	$21.50/m^2	406 000
Electrodes (porous carbon)	$0.88/kg	179 500	$0.59/kg	120 000
		1 736 000		1 058 000

(b) Process equipment

Equipment	Conservative estimate, $	Optimistic estimate, $
Reactant tanks[c] (stainless-steel wall at $2.09/kg; chlorsulfonated polyethylene lining at $5%.80/m^2)	490 000	245 000
Redox-cell frames[c] (polypropylene)	150 000	150 000
Filters[c] (0.410 m^3/sec (6500 gal/min))	70 000	70 000
Heat exchangers (stainless-steel tubes at $43.00/m^2)	50 000	50 000
Pumps[c] (96.9 kW (130 brake hp); stainless steel tolerant to solids)	48 000	48 000
	808 000	563 000
Instrumentation and installation (40 percent)	323 200	225 200
	1 131 200	788 200

(c) Totals

Case	Energy, MWh	Efficiency, percent	Conservative estimate			Optimistic estimate[d]		
			Total, $	Direct current, $/kW	Alternating current, $/kW (e)	Total, $	Direct current, $/kW	Alternating current, $/kW (e)
Base	85	70	2 867 000	287	327	1 846 000	185	225
[f]Projected case 1	85	85	2 634 000	263	303	1 689 000	169	209
[f]Projected case 2	60	70	2 518 000	252	292	1 625 000	163	203
[f]Projected case 3	60	85	2 338 000	234	274	1 503 000	150	190

[a]Required TiCl$_3$ is not available in bulk quantities, while TiCl$_4$ is. Initially TiCl$_4$ must be electrochemically converted to TiCl$_3$ in redox equipment.

[b]Available membranes not developed for redox-flow cell; opinion of one membrane researcher was that a membrane developed for redox-flow might cost as little as $2.69/m^2.

[c]Estimated with assistance of manufacturer.

[d]Reactant tanks of carbon steel would cost approximately half as much as stainless-steel tanks.

[e]Includes $40/kW cost of transformers, ac-dc converters, and switchgear.

[f]Scaled down from base case with following 0.6 power rule: ratio of capacities raised to 0.6 power equals ratio of costs (ref. 6). Also see ref. 7.

TABLE IV. - SENSITIVITY OF COST ESTIMATE TO POWER DENSITY CHANGE

AND TO REACTANT CONCENTRATION CHANGE

(a) Power density changed from 648 W/m^2 to 324 W/m^2

Case	Energy, MWh	Effi- ciency, percent	Total capital costs	
			Conservative estimate	Optimistic estimate
			Alternating current, $/kW	Alternating current, $/kW
Base	85	70	437	288
[a]Projected case 1	85	85	413	272
[a]Projected case 2	60	70	402	266
[a]Projected case 3	60	85	384	253

(b) Reactant concentrations changed from 4 molal to 1 molal

Case	Energy, MWh	Effi- ciency, percent	Total capital costs[b]	
			Conservative estimate	Optimistic estimate
			Alternating current, $/kW	Alternating current, $/kW
Base	85	70	431	290
[a]Projected case 1	85	85	396	267
[a]Projected case 2	60	70	385	261
[a]Projected case 3	60	85	353	242

[a]Scaled down from base case with 0.6 power rule (ref. 6).
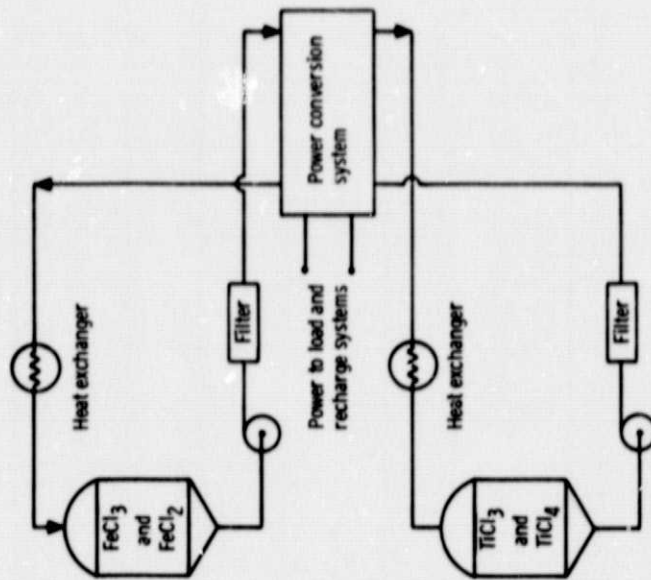[b]Used 0.6 power rule (ref. 6) and ref. 7.

Figure 1. - Electrically rechargeable redox-flow-cell power generation system.

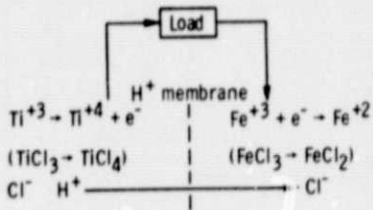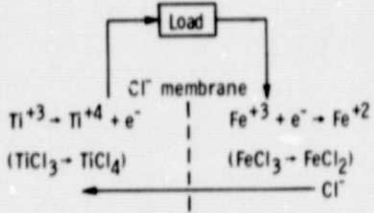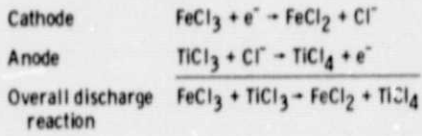| Cathode	$FeCl_3 + e^- \rightarrow FeCl_2 + Cl^-$
Anode	$TiCl_3 + Cl^- \rightarrow TiCl_4 + e^-$
Overall discharge reaction	$FeCl_3 + TiCl_3 \rightarrow FeCl_2 + TiCl_4$

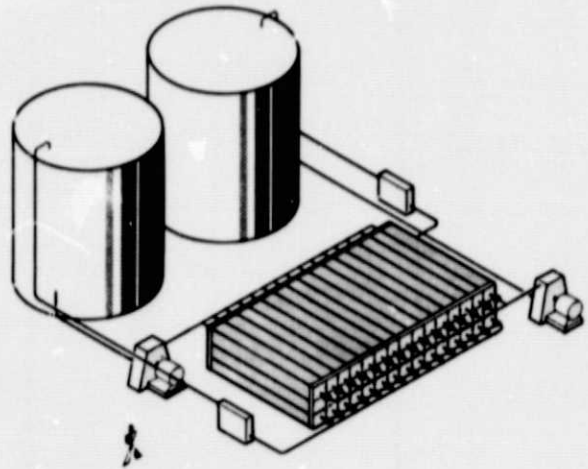Figure 2. - Electrochemical reactions for redox-flow cell.

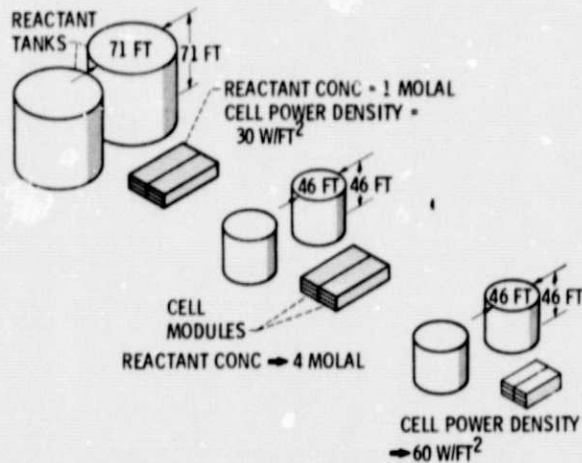Figure 3. - Pictorial representation of 10-MW, 85 MWh Redox system.

Figure 4. - Pictorial representation of effects of changes in reactant concentration and power density upon size of 10 MW, 85 MWh Redox system.