Superconductive Energy Storage

PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON SUPERCONDUCTIVE ENERGY STORAGE

OSAKA 8–10 OCTOBER 1979

Editor: M. Nishimura

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Opening Speech

I would like to thank you for attending this symposium on superconductive energy storage and would like to express our heartiest welcome to this meeting. We would be happy if all the participants could enthusiastically discuss the problems of superconductive energy storage and also could enjoy the meeting.

This is the place situated far from the urban noise, and the place suitable for discussing and meditating on energy problems. So to speak, this is the place of our Camp David. And we would like to thank professors emeritus and former presidents of Osaka University, Dr. Shiro Akabori and Dr. Minoru Okada, who have prepared this place for us, their juniors, and they named this place, Inter University Seminar House of Kansai.

Almost two years have passed since the second internal meeting on superconductive energy storage was held at Tsukuba Academic Town under the auspice of Professor M. Masuda of the National Laboratory for High Energy Physics. Professor Boom was invited to this meeting. At this meeting, these professors and the professors of Osaka University talked with about planning the international symposium on superconductive energy storage.

From that time on endeavors to hold this symposium have continued. In spite of many difficulties encountered, we can now hold this symposium. We owe it to the members of international commitee and executive commitee. First of all, we owe to Professor Boom international arrangement. This symposium although small scale is worth calling international and we owe it perfectly to Professor Boom. Also we would like to remember and thank for the supports given by Yamada Science Foundation, Japan Exposition Commemorated Fund, and we would like to appreciate contributions given by many private companies.

In the first half of 1950's, the basics of superconductivity matured. And to our surprise, just that time the superconductive energy storage was proposed. From that time on, the research on feasibility of superconductive energy storage have been continued in U. S. A. and Europe. In Japan, we must say, the research efforts have just started and we must accelerate. Because this problem is indispensable to the energy developement and the energy saving.

On the energy problems, they are not only most severe to Japan but also we must share the responsibility equally with U. S. A. and Europe, that is, equal partnerships. From this point of view, it is meaningful that this symposium is held first in Japan and that we can invite the brilliant researchers in this field from abroad. We hope again all the participants could enjoy this meeting. Thank you.

M. Nishimura
Chairman
International Symposium
on
Superconductive Energy Storage

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on
Superconductive Energy Storage

Oct. 8, 1979

Opening Talk by M. Nishimura

SESSION I Generals of Superconductive Energy Storage
(Chairman: W. V. Hassenzahl, Y. Aiyama)

SESSION II Projects of Superconductive Energy Storage
(Chairman: R. W. Boom, F. Irie)

Oct. 9, 1979
SESSION III Power Supplies and Protection
(Chairman: H. A. Peterson, T. Anayama)

SESSION IV Cryognics
(Chairman: P. Komarek, M. Kobayashi)

SESSION V Structures
(Chaiman: J. Purcell, T. Okada)

Oct. 10, 1979

SESSION VI Superconductors and Coils
(Chairman: K. Yasukochi, H. Desportes)

(Chairman: D. N. Cornish, Y. Murakami)

SESSION VII Systems and Future Problems
(Chairman: W. C. Young, T. Ohtsuka)

Review of Diurnal Superconductive Energy Storage at the University of Wisconsin

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University of Wisconsin
Madison, Wisconsin

INTRODUCTION

Superconductive energy storage for diurnal use as developed at the University of Wisconsin is reviewed in this paper. A summary of an A. D. Little assessment of the Wisconsin and Los Alamos designs is included.

The diurnal use envisioned is for the storage of large blocks of energy during off-peak hours at night or during the weekend for delivery back to the electric power system during peak use daytime periods. Diurnal storage magnets would be large, conservative, fully stable, dc type superconductive magnets designed with primary emphasis on cost, efficiency and reliability. Three-phase Graetz bridges would be used to interface a dc storage magnet to a three-phase ac power system.

Feasibility studies, design studies and component development studies have been under way in the U.S.A. and to a lesser extent in Japan, France and Germany. No substantial models have been funded although proponents recommend construction within the next few years of a model in the size range of 10 to 100 MWh.

If successful model experience is obtained and if superconductive storage proves to be the best form of storage for power systems then there is apparent justification to cycle 5% to 20% of the world's electrical energy through superconductive storage. The potential worldwide market is enormous, amounting to tens of billions of dollars immediately. This use for superconductors would dwarf all other planned uses for superconductors and be the basis for a huge new industry.

Pulsed superconductive energy storage magnets might be used to power fusion reactor subcomponents and would be especially appropriate for pulsing periods of a few seconds or longer. The pulsed storage magnets would be very small compared to diurnal magnets and might be designed and constructed according to "ac" magnet principles rather than the "dc" magnet principles for diurnal storage. Professor Masuda in his introduction to last year's Energy Storage Conference at KEK mentioned additional pulsed uses such as for particle accelerators, steel mills and to stabilize long ac transmission lines [1]. These and other pulsed uses are all covered at this conference. Of all the uses above for pulsed storage none approach the magnitude of use possible for diurnal storage.

The features common to both diurnal and pulsed storage are:

- superconductivity
- helium based cryogenic systems
- three phase Graetz bridges

The main differences between diurnal and pulsed storage are:

- large dc coils for diurnal storage
- smaller ac coils for pulsed storage

The major studies of diurnal superconductive energy storage systems have been undertaken at the University of Wisconsin and at the Los Alamos Scientific Laboratory. This paper will generalize on those two studies but will not attempt to detail present activities at those or other laboratories since many of those activities are described in other papers at this conference. It is the object of this paper to discuss general principles of diurnal storage and to report on a recent independent assessment by the A.D. Little Company for the U.S. Department of Energy.

REVIEW

Inductive storage concepts have developed over the past twenty years. Walker and Early [2] and Carruthers [3] considered inductors as sources of pulsed energy. Stekly [4] suggested superconducting inductors for energy storage, discussed toroidal configurations, and emphasized structural problems. Sole [5] reported on various magnet configurations for pulsed use. Ferrier [6] estimated the optimum shape of magnets and calculated operating losses for large superconducting inductors useful in a power system. Irie and Yamafuji [7] computed hysteresis losses for layer wound magnets carried through charge-discharge cycles. Brechna, Arendt and Heinz [8] considered different magnet structures and concluded that superconducting magnets are best used for millisec to second discharge times. Powell and Bezler [9] suggest that the superconducting magnet structural costs may be reduced by using warm reinforcement structure and suggest the use of in situ bedrock as inexpensive structure, following an earlier suggestion by Thomas [10] to use bedrock support for a proposed underground bubble chamber magnet.

The 1970-1979 era was launched by the originating idea of H. A. Peterson in 1970. He suggested that a three-phase Graetz bridge could be used to convert dc current in a superconducting storage magnet into ac current in a three-phase power system. The first Wisconsin publication was in April 1972 at the INTERMAG conference in Kyoto by Boom and Peterson [11].

They showed that large storage magnets are more efficient than small magnets, that high pinning strength $\alpha = Hj$ is the important superconductor parameter, and that low-field units are as satisfactory as high-field units if cryogenic losses do not become excessive. The basic six-pulse Graetz bridge was introduced with a discussion of how controlled power reversibility is achieved by varying the delay angle of firing thyristors in the bridge. Operating losses from the converter bridge and the refrigeration required to balance electrical, magnetic, mechanical, and thermal losses into the cryogenic enclosure were estimated to be as low as 10% total for a 10,000-MWhr system. A preliminary cost graph indicated possible satisfactory economies for large units. It was shown that system electromechanical oscillations can be damped effectively within one or two cycles which is typically about 0.1 sec.

Los Alamos published their first results in an IEEE Exposition in New York in March 1973 in a paper by Hassenzahl, Rogers and McDonald [12]. They included the possibility for bedrock support from discussions with Powell. Hassenzahl also discussed the Graetz bridge method for controlled power reversibility and presented a good case for the utility of small, medium, and large units. Subsequent LASL early cost studies [13] showed the expected benefit of warm (bedrock) support structure.

The extensive bibliography of reports, design studies and publications from each institution is covered in the companion papers from Wisconsin and from Los Alamos.

In the years after 1975 a growing interest and activity in Japan is evidenced by the Superconductive Energy Storage conferences at KEK, Tsukuba edited by Masuda and Shintomi which preceded this conference [1,14]. In those two conferences Graetz bridge circuitry, load leveling considerations, dynamic properties in utility systems, coil design, stabilization of ac and dc coils, cooling and properties of materials were all covered.

Diurnal Storage

The concept is that large but simple superconducting solenoids store energy $1/2\ LI^2$ in the form of dc currents in an inductance where L is the inductance and I the dc current. The solenoid turns are superconducting to eliminate I^2R losses, where R is zero resistance for superconductors. The use of superconductors necessitates the use of cryogenic systems and a liquid helium coolant. The solenoid would be mounted in bedrock which is the least expensive mechanical support structure available. A system sketch is shown in Fig. 1.

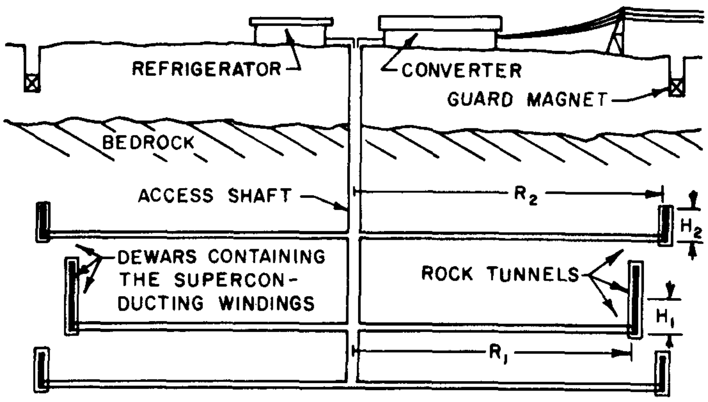

FIG. 1 SEGMENTED SOLENOID. ONE LAYER COIL IN EACH DEWAR. GUARD COIL PARTIALLY CANCELS EXTERNAL DIPOLE MOMENT; GUARD COIL RADIUS SHOULD BE ~ 5 x OUTER COIL RADIUS, R_2.

According to the virial theorem, $M \geq \rho/\sigma\ E$, the structural mass M per kWh of stored energy E must be greater than 80 kg/kWh for stainless steel with $\sigma = 3.45 \times 10^8$ N/m^2. The weight per kWh can be reduced only by using lighter material at higher stress levels. The practical result is that such structural requirements absolutely forbid any purchased structure, only inexpensive bedrock is available.

The three-phase ac/dc Graetz bridge and the dc energy storage magnet coil form an inductor-converter (I-C) unit. Typical uses for large I-C units are 2-12 hour discharges at rates of 100 to 2000 MW for nighttime charging and daytime discharging.

Large central storage I-C units are unique in that 90-95% efficiency is possible. Another unique property is the speed of response; within 50 milliseconds an I-C unit can change its power level from full charge to full discharge. There are no other storage systems with these two advantages.

Requirements

The desirable amount of power from storage in electric utility systems is generally estimated to be between 5% and 10% of the peak available power from generators. The duration of the power delivered from storage would vary from 2 to 10 hours in different utilities with a trend towards needing 12 hours from storage. The peak power period starts in the morning after 8 a.m. and persists through the late afternoon on weekdays. Occasionally peak needs for storage even arise during a weekend. The peak power in Wisconsin two years ago was on a Sunday that was exceptionally hot and humid.

As an example let us take the state of Wisconsin whose power requirements are about average for the 50 states. The peak power is about 8000 MW which implies that 800 MW would be desirable from storage for about 10 hours, as has been determined by our utility collaborating engineers. Thus 8,000 MWh might be needed for the average state. We predict economic competitiveness for I-C units larger than 1000 MWh and therefore might recommend for Wisconsin, as an example, two I-C units of 4000 MWh each. Larger units are less expensive per unit of storage but lack the system reliability of redundant smaller units. Thus compromise between size, cost and redundancy would be made after operating experience is obtained.

The magnitude of U.S. storage needs is taken as 50 states x 4000 MWh = 200,000 MWh, which assumes that the average state wants storage at half the Wisconsin rate. Wisconsin is fortunate in having 30% of its power capacity from inexpensive new base load nuclear generators which are available 90% of the time, a notably reliable performance. As expected, storage couples well with efficient generation. In addition, storage couples well with intermittent generation, as would be available from future photovoltaic cells, for example.

Dispersed Storage

The magnitude of the utility storage needs seems to preclude widely distributed small storage units. Most utility advisors would not want 80 I-C units of 100 MWh each and would prefer only two or three units of equivalent total energy. Small units are generally inefficient and costly to build per unit power. I-C units costs scale as $E^{2/3}$, where E is the total stored energy. In Table 1 these cost trends are illustrated. We can predict 200,000 MWh of storage countrywide in 50 large units would cost 27% of the cost for 2500 smaller units. In addition, maintenance, siting and environmental controls scale even less favorably for many small units.

Table 1

Relative Capital Costs of I-C Storage Units
Compared to 1000 MWh Reference

Size	Capital Cost/MWh
10,000 MWh	0.46
8,000 MWh	0.50
5,000 MWh	0.58
2,000 MWh	0.79
1,000 MWh	1.00
500 MWh	1.26
100 MWh	2.14

Pollution and Siting

One of the very few pollution problems associated with I-C storage is the electromagnetic interference arising from the three-phase Graetz bridges. This problem is common to most forms of electrical storage, especially storage batteries, which rely on ac/dc conversion. The bridges must be shielded to prevent interference on telephone systems. It is much easier to shield 50 interference sources than 2500 sources, which again mitigates against widely dispersed storage.

The allowable human exposure to magnetic fields is not known. Panel recommendations to the Division of Operational and Environmental Safety under the Assistant Secretary for Environment (DOE) by Dr. Edward L. Alpen, Chairman, were made July 23, 1979. The recommendations are: whole body or head exposure < 0.01 tesla for an 8 hour day and up to 0.5 tesla for 10 minutes and exposure of extremities < 0.1 tesla for 8 hours and up to 2 tesla for 10 minutes or less. There is no proof that more or less exposure is tolerable. These guidelines are for occupational exposure only. Population exposure will be considered later.

Superconductive storage magnets need exclusion perimeters set at the legal magnetic field levels, whatever those limits become. External opposing guard ring coils at a cost of 10 to 20% additional can cancel the dipole fields of the smaller radius storage coils. However, it is preferred that sites be remote enough so that guard ring magnets are unnecessary. It should be expected that magnetic field tolerances will become better understood.

There is no need to locate storage units near generators, it is only required that adequate transmission lines exist between the storage unit and the power system.

Alternatives

The two main competitors for load leveling today are pumped hydro storage and load management through time of day metering. Pumped hydro storage is economic and would be attractive wherever the terrain allows for upper/lower bodies of water and environmental standards can be met. There are very few sites available in the central U.S. and environmental disadvantages are extensive.

Time of day metering is a costly metering and billing process which adds nothing productive to a system. Wisconsin Power and Light, the 60th largest utility in the U.S.A., is a leader in time of day metering. It will require $100 M to completely install meters in the WPL system. We estimate that $100 M might buy a 1000 MWh I-C unit. Such storage is 7% of WPL peak power for 10 hours and would probably eliminate the need for time of day metering with its implied disruption in life style.

Additional Credits

Supplementary uses for I-C units in power systems, such as AGC (automatic generation control), transient stability regarding major disturbances and voltage regulation have been discussed in the U.W. reports. The major use, of course, is the diurnal storage and release of energy. What makes I-C storage high quality is its speed of response. No other storage system can reverse power direction within 50 milliseconds. Such speed might prevent system blackouts following losses of load or generators. Load following second by second can be provided by an I-C unit simultaneously with its major charge-discharge function. Such load following is otherwise unavailable and should greatly reduce the wear and tear on "old" generators which normally provide load following functions.

SUPERCONDUCTIVE ENERGY STORAGE SYSTEM DESIGN STUDIES

Early Results

The early work between 1970 and 1976 was primarily a feasibility study which indicates that superconductive storage is technically and economically feasible. The major results of the early studies are:

1. Bedrock structure is needed.
2. Cryogenic stability for the conductor is required.
3. Pool cooling with superfluid helium is preferred.
4. An aluminum stabilized NbTi composite conductor is planned.
5. The conductor, dewar, and associated structure are to be rippled at approximately 1 meter radius of curvature.
6. A one layer, thin wall, high current solenoid is probably best.
7. A multi-tunnel, sectored solenoid results in less cold structure and greater safety.

The Los Alamos reference design [15] shows some variance with the above list, notably in the use of one tunnel only, and several layers of turns. The major aspects of rippled units in bedrock and superfluid helium are accepted by both groups.

COST ESTIMATES

Over the years cost estimates and cost reduction engineering research has been emphasized. In 1976 a particularly careful cost optimization and design was undertaken. The following tables outline engineering progress and development over the years. The cost basis in all cases is the 1976 dollar and changes in costs result only from engineering improvements. The cost in mills/kWh (10^{-3} $/kWh) delivered is based on delivering 90% of the stored energy in a 10 hour day. The yearly cost of the unit is taken as 16% of the original capital cost for interest, taxes, dividends, maintenance, etc. and 20% for interest during construction. These were typical rates for 1975-76.

In Table 2 the 1970 initial cost estimate for storage is 101 mills/kWh delivered. The copper in the composite conductor and the stainless steel structure are too expensive. The storage cost in mills/kWh delivered is a better measure than $/kW because different discharge times drastically affect the kilowatt rate for a given storage magnet. The reader is referred to Vol. II for a complete set of cost presentations [16].

In Table 2 the design status in 1974 shows substantial improvement resulting from replacing copper with less weight aluminum and replacing steel structure with bedrock structure. The storage cost estimate of 27.1 mills/kWh is tolerable when one notes that in 1976 a cost of 60 mills/kWh was attached to gas turbine peaking power.

Table 2 - Design cost estimates* in 1976 dollars in mills/kWh (10^{-3} $/kWh)

		1970		1974	1976		1978
Conductor	Niobium Titanium	3.9		3.3	3.9		2.7
Conductor	Copper	25.0	Aluminum	6.4	4.0		4.2
Structure	Cold Stainless Steel	66.0	Rock	4.0	0.7		1.4
Power Equipment	Converter Bridges	3.3		2.2	3.3		3.3
Cryogenic Container	Stainless Steel	2.2	Al Alloy	5.8	2.3		4.4
Refrigerator	Liquid Helium	0.6	Superfluid	0.7	2.0		1.5
Liquid Helium		0.5		0.4	0.5		1.0
Struts		X	Epoxy Fiberglass	4.3	2.0	Polyester Fiberglass	0.7
Total	mills/kWh	101		27.1	18.7		19.2

*10,000 MWh units - 10 hours/day and 365 days/year
(1,000 MWh units at 2.16 times higher cost)

Conclusions: 1970 - copper and structure too expensive
1974 - aluminum and rock cavern make good prospects
1976 - conductor unacceptable
1978 - round conductor acceptable, component design under way

In 1976 the benefits of engineering optimized component design is evident. Costs are now reduced to 18.7 mills/kWh due to the proper selection of magnetic field, strut length and conductor.

In 1978 the revised design costs slightly more at 19.2 mills/kWh. The main advance is that a new round conductor is now deemed to be manufacturable. Heat transfer data is measured to be better than previously predicted and epoxy struts are replaced by better and less expensive reinforced polyester struts.

A. D. LITTLE, INC. ASSESSMENT

On April 2, 1979 a preliminary report of the A. D. Little, Inc. (ADL) Assessment on Superconductive Energy Storage was presented by J. Nicol and B. Winer [17]. The conclusions were that SMES is a very attractive possibility if cost goals can be met.

The first ADL conclusion in Table 3 means that SMES competes with all forms of storage and with peaking generators. The third conclusion is that SMES may be the only storage system which is useful. The fourth conclusion emphasizes the unique high efficiency and fast response of SMES.

Table 3* Conclusions

- SMES can compete economically with the alternatives for all scenarios considered
- The key issue is the proper sizing of the storage systems to meet the needs of the utility
- SMES can be used by utilities which cannot economically use any other type of storage system
- Its high cycle efficiency and fast response time also allows SMES to be used to improve system efficiency during periods when the load is changing

*ADL Assessment, April 2, 1979

The specifications in Table 4 and the sketch in Fig. 1 describe the 3 tunnel system studied by ADL. The unit is the University of Wisconsin design estimated in Vol. II [16].

Table 4* Description of SMES

Vertical superconducting solenoids	
Three tunnels embedded in bedrock	
Magnetic fields up to 5 T (50,000 G)	
Storage capacity:	1000 to 10,000 MWh
Power (typ.):	100 to 1,000 MW
Superconductors:	NbTi in Cu or Al
Cooling:	superfluid liquid He at 1.8°K

*ADL Assessment, April 2, 1979

The costs shown in Table 5 are for comparison with other forms of storage and with conventional generation alternatives. ADL has assigned the +62% - 8% variation to U.W. cost estimates in Vol. II, Energy Storage Report, page II-26 [16].

Table 5* Summary of Cost Analysis

Base:	10,000 MWh delivered per cycle		
	1,000 MW ave.		
	Field 2.5 T		
	Temp. 1.8°K		
Capital Costs:	System:	$437M	+62% - 8%
	Unit costs:	$ 43.7	per kWh
		437	per kW (ave.)
		291	per kW (peak)
Cost of Storage and Delivery:	24.8 mills/kWh	Note 1	
Note 1:	If system is cycled 260 days/yr vs. 365 days/yr this cost increases by 40%		

*ADL Assessment, April 2, 1979

The ADL studies were made for an "average" utility whose power demand as a function of time is shown in Fig. 2. The average utility could use any of the storage units listed in Table 6 or competing conventional generators. CAES also requires 3980 Btu's of fuel/kWh.

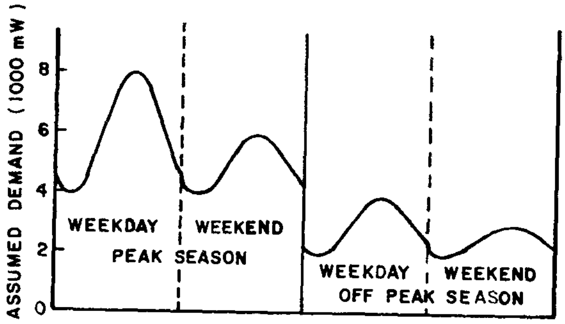

FIG. 2 POWER DEMAND AS A FUNCTION OF TIME.

Table 6* Storage Systems Considered*

	efficiency
. Underground pumped hydrostorage (UPH)	.67-.72
. Compressed air energy storage (CAES)	.7
. Lead acid batteries (Pb/H+ BaH)	.75-.80
. Advanced batteries (Adv. Batt.)	.75-.80
. Superconducting magnetic energy storage (SMES)	.93-.97

* ADL Assessment, April 2, 1979

The basic storage cycle is a weekly cycle, as sketched in Fig. 3. Since partial recharging takes place each night a highly efficient unit is useful throughout a week while a less efficient unit might become totally discharged before Saturday, unless it is larger size. This difference in storage unit size (capital cost) is largely the reason to select high efficient storage units.

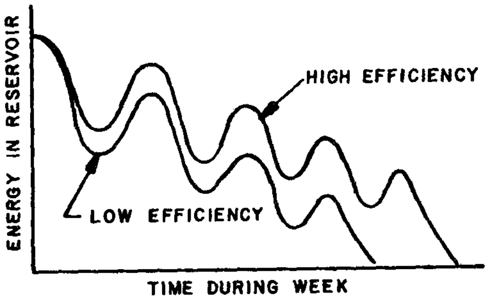

FIG. 3. ENERGY IN RESERVOIR AS A FUNCTION OF TIME - WEEKLY CYCLE.

The results of the ADL study are sketched in Fig. 4. Curves for constant delivered energy are plotted vs. efficiency and storage unit size. The region above the boundary line labelled Max. Useful storage capacity is uneconomic for storage in the ideal sample utility of Fig. 2. Appropriate costs for standard generation which might be displaced by storage are used. The interpretation of Fig. 4 is:

- there is a maximum useable (economical) size of storage unit at each unit efficiency
- low efficiency units can deliver only small amounts of energy
- SMES alone is available in the 90-95% efficiency region and therefore alone can deliver large energies

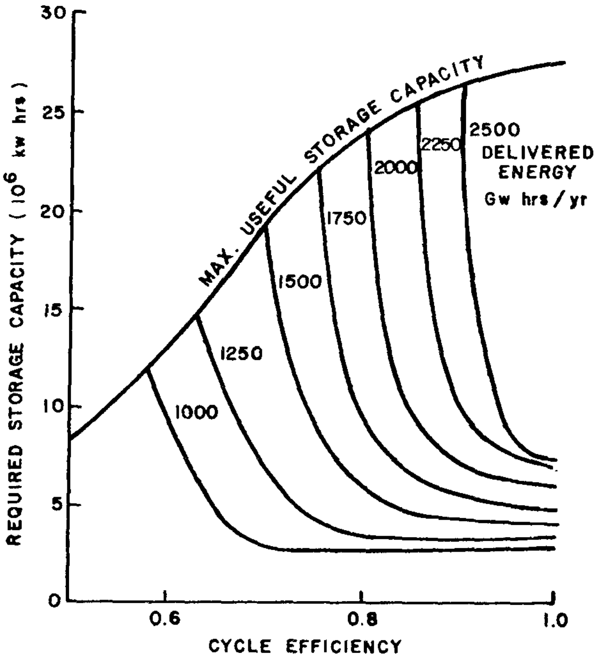

FIG. 4 REQUIRED STORAGE CAPACITY AS A FUNCTION OF CYCLE EFFICIENCY FOR ASSUMED VALUES OF DELIVERED ENERGY

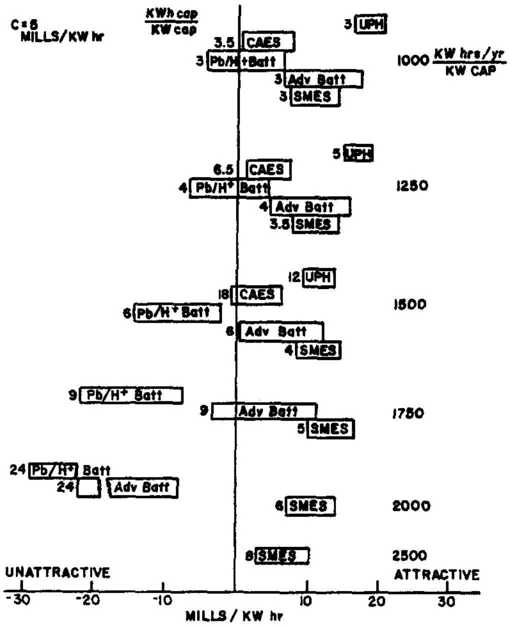

FIG. 5 LEVELIZED BUS BAR COST DIFFERENCE BETWEEN STORAGE AND COVENTIONAL GENERATION.

In Fig. 5 all storage possibilities are listed. Using current costs and cost projections and current efficiencies for the various storage possibilities note that for the standard utility system assumed (Fig. 2) SMES is equal or better than competing storage systems. In Fig. 5 conventional power generation is the vertical axis, so that SMES for any size use is attractive by 10 to 15 mills/kWh versus the standard U.S. generator which would be displaced by storage. Similar but reduced benefits are obtained for more expensive off peak power. Only SMES is attractive for very large scale usage.

CONCLUSIONS

The feasibility studies of diurnal storage are optimistic as confirmed by an independent A.D. Little assessment. The high efficiency of SMES is primarily responsible for this optimism. Component development, system tests and model studies are needed to confirm the use of SMES for diurnal storage.

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