Progress Report
to
Division of Thermal and Mechanical Energy Storage
U.S. Department of Energy
on the project
"Synthesis of Research and Development
in Mechanical Energy Storage Technologies"

MASTER

Project No. DE-AC02-79ET26106

Date: May 31, 1980

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This progress report is prepared and submitted in compliance with contractual requirements set forth by the U.S. Department of Energy. The report summarizes activities on the project during the nine month period from September 1, 1979 to May 31, 1980.

Some results of the investigation have already been furnished to the staff of the Department of Energy, Division of Thermal and Mechanical Energy Storage to provide timely input for

- (a) long term program planning;
- (b) decisions on program modifications;
- (c) finalization of annual operating plans by Pacific Northwest Laboratory on compressed air energy storage, underground pumped hydroelectric and seasonal thermal energy storage.

The investigation has been performed in accordance with the scope of work specified in the contract. In Task 1 an extensive survey of literature and reports has been carried out, which will be presented as appendices in the final report. In Task 2 and Task 3 the following subjects have been considered:

(1) Underground Pumped Hydro (UPH)

Hydroelectric pumped storage systems today are important components of many electric power generation utilities in the U.S., Europe and Japan. The concept of pumped storage involves the use of relatively inexpensive off-peak energy to pump water from a lower to an upper reservoir for later release through turbines to generate peak power. Such storage components improve system economy of utilities having coal or nuclear fired power plants in their system. Furthermore, it provides emergency reserve and is conducive to system regulation. Underground pumped hydro differs from conventional pumped hydro in that the lower reservoir is located underground thus reducing site dependence

of the plant. Furthermore, most components of the UPH are underground, hence their environmental impact is less than that of conventional hydroelectric pumped storage.

Review and analysis of previous and ongoing studies led to the following conclusions:

(a) 2000 - 3000 MW capacity with storage for 10 hours generation appears to be economical;

(b) Although a head of 700 m may put UPH in an economically competitive category, recent in-depth studies indicate that a total head of between 1,500 m and 2,000 m would be optimal. Present day technology of pump/turbines does not allow the increase of head beyond 2 x 750 m, i.e., the lower economic limit can be reached by a 2 drop arrangement. Further pump/turbine R&D is needed to increase head up to 1000 m with one head. Development of a two stage regulated pump/turbine with 2000 m head would considerably improve system economy.

(c) Capital investment costs range from \$400 to \$500 (1980 price levels) per kW. Costs include engineering, overhead and contingencies. AFDC and escalation are not included.

(d) Contingency allowance for underground and above ground civil works are the same.

(e) The size of the individual units should be between 250 and 350 MW.

(f) Three individual schemes have been proposed:

(1) multi-stage reversible pump/turbine units with a single underground reservoir

(2) a two drop scheme using single stage reversible units with an intermediate power house:

(3) a one drop scheme with tandem units of separate impulse turbine and pump.

The economic feasibility of (3) is questionable. Efforts

should be concentrated on schemes (1) and (2).

- (g) The construction period for a capacity of 2,000 MW, 10 hours storage and 1,500 m head from construction contract award to operation is about 9 years.
- (h) Using present day technology UPH is technically feasible and economically viable if compared with conventional pumped hydroelectric storage and other energy storage technologies.

(2) Compressed Air Energy Storage (CAES)

The basic concept of CEAS is very similar to that of UPH. The inexpensive baseload energy from coal or nuclear fired plants during off peak periods is used to run a motor-generator (in compression mode.) to produce compressed air which is cooled and then pumped into an underground storage reservoir. The reservoir has to be located thousands of feet below the surface to contain the air under a pressure varying between 50 to 80 atmospheres. When peak power is required the air is released into a combustor heated and expanded through a series of turbines. The turbines run the motor-generator (in generation mode) and supply peak power to the grid. This system can save up to two-thirds of oil or gas that a conventional gas turbine system would require. Salt cavities, hard rock caverns and aquifers are three types of underground storage media currently being considered for storing compressed air. Conditions to be considered in the selection of sites are: (1) physical characteristics of formation, which include depth, thickness, area extent, uniformity, tightness and quality, (2) geological characteristics including minability and stability, local and regional rock conditions, faulting, jointing, folding, schistosity and anisotropy; (3) hydrologic characteristics such as porosity and permeability; (4) engineering properties which include compressive strength, tensile strength, shear strength, in-site stresses, and cohesion; (5) other characteristics like seismicity, radio-activity.

For salt cavities and hard rock caverns there is flexibility in design depending on their different characteristics. For design of aquifer storage the task becomes more involved. This is due to the dynamic behavior of air in the porous media. In the case of aquifer storage the permeability should be high and the geological structure suitable to inhibit vertical and lateral losses of air from the storage space. Massive salt domes are economically attractive because relatively inexpensive solution mining techniques can be used. Presently available information on the behavior of hard rocks is sufficient to build a cavern in such a formation with acceptable degree of confidence. However, further studies on salt and porous rock behavior are needed to develop stability criteria and design guidelines.

(a) First Generation Compressed Air Energy Storage. In first generation CAES technology the compressed air is cooled during and after compression. This avoids compressor damage and minimizes compression work and air storage reservoir volume. The heat of compression is rejected into the atmosphere. This stored air must later be heated in a combustor before being expanded in a turbine. The heating requires up to 40% of the energy consumption of a conventional gas turbine (60 - 65% of the fuel is used for compression in a conventional gas turbine). The first large scale CAES system became operational in 1978 in Huntorf near Hamburg, West Germany. Investigation started in 1969 and construction began in 1974. The first-of-a-kind plant has a rated capacity of 290 MW. The main features of the plant may be summarized as follows:

- a single shaft arrangement of the turbomachinery with self shifting clutches between the motor/generator and the turbine and the compressor respectively.
- operating mode per storage cycle, 2 hours full load generation and 8 hours pumping.
- underground storage consists of two caverns of $150,000 \text{ m}^3$ volume each.

These caverns are suited for operation at pressures varying between 70 and 50 atm at a rate of up to 10 atm/hr.

- (b) Second Generation Compressed Air Energy Storage. Second generation CAES concepts have been advanced to eliminate dependence on petroleum fuels by:
- (1) use of alternate fuels such as coal
 - (2) reducing and/or eliminating the need for fuel by storing the heat of compression in thermal energy storage beds (TES).
- Second generation systems include: (a) hybrid CAES/TES, in which only part of the heat of compression is stored and some fuel is used to supplement the required energy (b) adiabatic CAES/TES, in which all of the energy of compression is stored and recovered (c) coal gasification (CG) system by converting coal to clean, ash and sulfur free, fuel. (The economy of CG is questionable). (d) Fluidized bed combustion (FBC) offers the promise of using coal as fuel economically. The advantages and disadvantages of the various second generation technologies will be discussed in detail in the final report. In this project the advantages and disadvantages of various CAES systems are evaluated and recommendations will be made on further development.
- (3) Seasonal Aquifer Thermal Energy Storage (SATES). The concept of aquifer thermal energy storage involves the conservation of heat and chill in aquifers. In 1978 a workshop sponsored by Lawrence Berkeley Laboratory was held in Berkeley, California, where the various problems associated with aquifer thermal energy storage were discussed. The system was proposed for (a) interseasonal storage of solar heat, (b) recovery of unused industrial thermal effluent mostly from power plants, (c) storage of energy from thermal nuclear reactors during summer, (d) thermal recharge of a depleted geothermal field. The stored energy could be used for heating during winter. Using aquifer for space cooling in summer has the same significance as heating for winter. Preliminary field studies conducted by Auburn University and Texas A&M University have indicated technical and economic feasibility of the concept. Further studies are needed to develop system components, analyze environmental impact and institutional

constraints. Developmental strategy includes experiments at Leading Edge Test Facilities (LETF) and field studies at three demonstration sites. The shortcoming of the program is manifested by the relatively small number of demonstration projects in that they would not cover a wide geographic area and various geologic conditions. Without additional funds to support more demonstration projects, development of SATES systems would be unnecessarily delayed.

(4) Economic Analysis and Comparison of Energy Storage Systems for Utility Applications.

The purpose of this component of the project is to present a critical review of various methodologies which have been used for the economic analysis of various storage systems for utility applications. Based on the results modifications of economic analysis will be recommended. Four systems are included in the analysis:

- (a) Underground Pumped Hydro;
- (b) First Generation Compressed Air Energy Storage
- (c) Second Generation Compressed Air Energy Storage
- (d) Superconducting Magnetic Energy Storage

Activities in this project have produced sufficient information for critical review of methods which have been in use for economic analysis of utility storage systems. Work on modification will be completed in June and the comparative economic analysis will be performed in July.

It should be noted that review of technological feasibility of superconducting magnetic energy storage (SMES) is outside the scope of this project, but comparison of SMES economy with UPH and CAES is included in the project, since it may become a competitive technology for utility applications beyond the year 2000.

In assessing the economic advantages of UPH the so-called secondary benefits are also considered. These benefits are related to generating capacity, rate of

load change, response to changing system load demand, and emergency reserve in the system. - In this respect the following modes of operation are of import:

- (a) Stationary standby with scroll case/draft tube watered and inlet valve closed.
- (b) Spinning reserve with scroll case/draft tube unwatered with unit running at synchronous speed.
- (c) Speed no load with scroll case/draft tube watered with unit running at synchronous speed.
- (d) Hot spinning or immediate reserve with scroll case watered, guide vanes and inlet valve closed, draft tube unwatered with unit running at synchronous speed.

Assigning values for secondary benefits or secondary modes of operation is difficult. These values depend on particular system characteristics. Specific values will vary from system to system and depend on standards set for system reliability. An economic assessment of the Dinorwic plant in England by Central Electricity Generating Board in United Kingdom attributed 60% of the net operating savings to the secondary mode of operation. The items of (a) and (d) mentioned above as immediate reserve constituted 47% of the total savings. Reliability of the system is also a significant component of the economic value of a storage system, consequently it is included in the analysis.

Commercialization of Storage Systems. The success of the energy storage projects depends on their acceptance and use by utility companies. Utilities will only use a new system if it is technically feasible and economically viable. Several factors, such as expected growth of electric power network, load management, power mix, etc. have a strong impact on future commercialization of all new storage systems. Temporary setback in nuclear power development after the Three Mile Island accident and slow downs in the economy have made some of the utility companies reconsider and delay their development Plans. Several economic

evaluations for underground pumped hydro-electric and compressed air energy storage have been prepared for utility companies. Field investigations are also underway in Illinois (Commonwealth Edison) and in Virginia (PEPCO). It is evident that utility companies will use the new concepts on energy storage if they see economic advantages. In this project a strategy is being developed which is expected to enhance commercialization of the various storage systems included in the analysis. Major technological issues hindering market penetration have also been indentified and recommendations are advanced for their resolution.

U.S. DEPARTMENT OF ENERGY
NOTICE OF ENERGY RD&D PROJECT

FORM DOE 538
(1/78)

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OMB NO. 38 R-0190

1. DESCRIPTIVE TITLE OF WORK

Synthesis of Research and Development in Mechanical Energy Storage Technology

2. PERFORMING ORGANIZATION CONTROL NUMBER

144-N739

3. CONTRACT, GRANT OR PURCHASE ORDER NUMBER

DE-AC02-79ET26106

4. CONTRACTOR'S PRINCIPAL INVESTIGATOR/PROJECT MANAGER AND ADDRESS WHERE WORK IS PERFORMED.

(414)

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5. a. NAME OF PERFORMING ORGANIZATION

College of Engineering & Applied Science Civil Engineering
University of Wisconsin Milwaukee (Department)

b. MAILING ADDRESS (If Different From 4B)

c. TYPE OF ORGANIZATION PERFORMING THE WORK (Enter applicable code from instructions).

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6. SUPPORTING ORGANIZATION

a. DOE PROGRAM DIVISION OR OFFICE (Full Name) Division of Advanced Energy
Storage Systems

b. TECHNICAL MONITOR (Last, First, MI) Strauch Saul (202) 376-4919

c. ADDRESS (If Different from DOE Hqs)

d. ADMINISTRATIVE MONITOR (Last, First, MI) Simpson Roy Chicago Operations Office

7. PROJECT SCHEDULE

(a) START DATE Sept. 1, 1979 (b) EXPECTED COMPLETION DATE Aug. 31, 1981
(Month) (Year) (Month) (Year)

8. a. FUNDING OPERATING AND CAPITAL EQUIPMENT OBLIGATION (In Thousands of Dollars)

FUNDING ORGANIZATION(S)		APPROXIMATE CUMULATIVE PRIOR FISCAL YEARS	CURRENT FY		
1. DOE		116,000	107,711		
2.					
3.					

b. DOE BUDGETING AND REPORTING CLASSIFICATION CODE

9. DIRECT SCIENTIFIC AND TECHNICAL MANPOWER

NUMBER EQUIVALENT PERSONYEARS	PROFESSIONAL	GRAD. STUDENTS	OTHER	TOTAL
	2	1		3
	1.1	0.5		1.6

DETACH HERE BEFORE SUBMITTING

10. SUMMARY OF WORK (Limit to 200 words or less – include a description, objective, approach and a final product expected.)

The proposed continuation project is restricted to underground energy storage:

- underground pumped hydro storage (UPH)
- second generation compressed air energy storage (CAES)
- seasonal aquifer thermal energy storage (SATES)

In the economic assessment component of the proposed study superconducting magnetic energy storage (SMES) will also be included for the purposes of economic comparison only.

Within the scope of the proposed effort the following specific objectives have been identified:

- (1) Continuation of extensive analysis of technical and economic information in the form of published and unpublished papers, reports and personal communication, etc.
- (2) Synthesis and critical evaluation of information retrieved under (1). (continued page)

11. PROGRESS SINCE LAST REPORT (Limit to 100 words.)

Last report was submitted on May 31, 1980. Work continues on comparative economic analysis of candidate technologies.

12. List publications in the last year that are available to the public which have resulted from the product. (Please give a complete bibliographic citation. Use additional sheets if necessary.)

None has been published.

13. GENERAL TECHNOLOGY CATEGORIES (Enter applicable code or codes from instructions.)

E 1	E 4	E 1	E 4	A 3					
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14. PHASE OF RD&U (Enter Project Percentage:
in Applicable Boxes).

a.	____	Basic Research
b.	20	Applied Research
c.	80	Technology Development
d.	____	Engineering Development
e.	____	Demonstration

15. KEYWORDS: (Minimum of 5)

Underground Pumped Storage.
Compressed Air Energy Storage.
Aquifer Thermal Energy Storage.
Cavern Stability

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4	1	4	-	9	6	3	-	5	1	6	6
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C. DATE

6/17/80

10. (3) Continuation of the comprehensive analysis of Underground Energy Storage project activities; updating results obtained in the first year of the project.
- (4) Updating and development of information to provide timely input on the progress to TMS staff for planning purposes.
- (5) Identification of major technical, economic and institutional issues having adverse effect on commercialization and advancement of strategy for resolution.
- (6) Updating of economic analyses of various storage technologies by the modified method developed during the first year.