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AUTHOR(S):
M. C. Krupka
J. E. Moore
W. E. Keller
G. A. Baca
R. I. Brasier
W. S. Bennett

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ENERGY STORAGE TECHNOLOGY-ENVIRONMENTAL IMPLICATIONS OF LARGE SCALE UTILIZATION

M. C. KRUPKA, J. E. MOORE, and W. E. KELLER
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545, U.S.A.

G. A. BACA, R. I. BRASIER, and W. S. BENNETT
Los Alamos Technical Associates, Inc.
Los Alamos, New Mexico 87544, U.S.A.

ABSTRACT

The Department of Energy has emphasized, in recent years, the development of several advanced energy storage technologies. It is expected that these technologies will have certain environmental impacts. Such impacts must be assessed so that appropriate environmental control technology, where deemed necessary, can be developed on a schedule compatible with the development of the specific energy storage technology. A number of environmental assessment programs have been conducted at the national laboratories including the Los Alamos Scientific Laboratory (LASL) over the past several years. Environmental impacts for several energy storage technologies have been identified. State-of-the-art control technology options were similarly identified. Recommendations for research and development on new control technology were made where present controls were either deemed inadequate or non-existent. Specifically, the energy storage technologies under study included: advanced lead-acid battery, compressed air, underground pumped hydroelectric, flywheel, superconducting magnet and various thermal systems (sensible, latent heat and reversible chemical reaction). In addition, a preliminary study was conducted on fuel cell technology. Although not strictly classified as an energy storage system, fuel cells in conjunction with product recycling units can serve an energy storage function. A very large number of potential environmental impacts can be identified for all of these technologies. However, not all are of primary importance.

Detailed discussions of a number of environmental impacts from the latest LASL study as they relate to primarily operational situations are emphasized. In addition, a brief discussion on new applications for energy storage technologies and the additional costs of controls to be used for mitigation of specific impacts are also presented.

1. INTRODUCTION

In one approach to promote resource conservation, minimize foreign resource dependency, increase operational efficiency and reduce costs, consideration has been given by the Department of Energy (DOE) to the development of several advanced energy storage technologies. These have major applications in the areas of transportation, building, heating and cooling, industrial processes and electric power generation. They will permit efficient and continuous usage of otherwise intermittent renewable energy sources such as solar and wind. The general relationship of energy storage technologies to the source, distribution and end use networks is shown in Fig. 1.

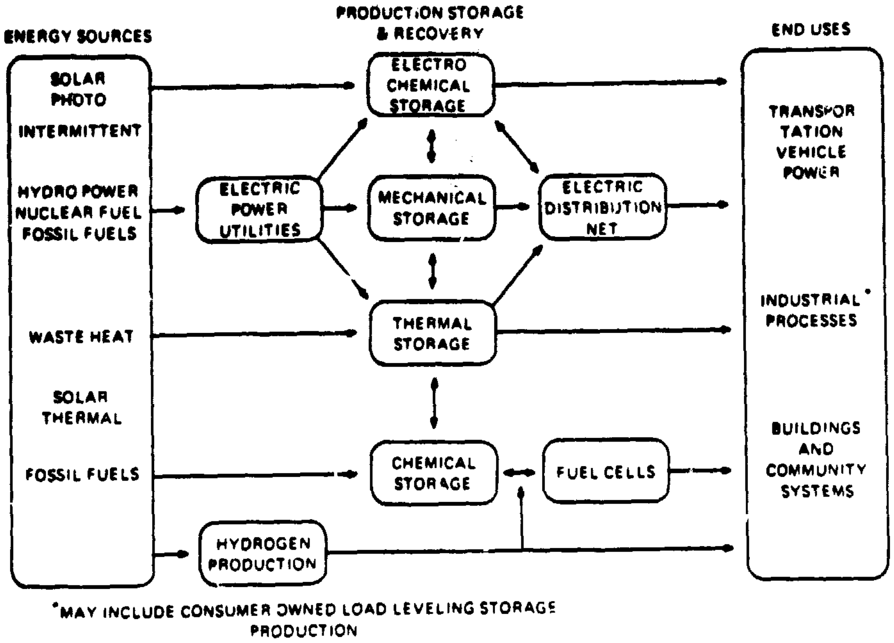

Fig. 1. Energy storage technology, source, distribution and end use networks.

As is the case with the prime energy technologies, storage technologies are projected to have a number of environmental impacts, especially if they are to be utilized on a large scale. These impacts must be identified and assessed so that appropriate environmental control technology, where deemed necessary, can be developed on a schedule compatible with the development of the specific energy storage technology.

To assist the Office of Environment of DOE in the timely development of such control technology, a number of assessment programs have been conducted at the various national laboratories over the past several years. At the Los Alamos Scientific Laboratory (LASL), two previous programs have been conducted. In March 1975, an Electrical Power Transmission and Energy Storage Systems Working Group was assembled, as part of a larger task-force, to assist in formulating that part of the DOE (then ERDA) program relating to environmental control technology.[1] In 1976, an assessment study in further detail was made expanding upon the efforts of the Working Group.[2]

This paper presents some results of an additional assessment designed to update information contained in LA-6979-MS, "Environmental Control Technology R & D Requirements for Energy Storage Systems."[2] The specific energy storage technologies under consideration include: advanced lead-acid battery, underground pumped hydroelectric, superconducting magnet, compressed air, flywheel and thermal. In addition, a preliminary environmental assessment was made concerning fuel cell technology. Strictly speaking, fuel cells per se are not energy storage devices. Many of their benefits, however, are similar to those of energy storage devices. Further, when coupled to certain recycling units, the total system operates in an energy storage capacity. A brief study was also included relating to industrial implementation of energy storage technologies for purposes other than that of centralized electric power generation by the utility industry. This survey was made in the hope that new and significant impacts specifically related to a new application would thus be identified. Finally, wherever possible, an estimate of the additional cost to the energy storage system or to its product, e.g., electricity-kWhr, due to the implementation of some form of control technology, was made.

Certain guidelines and assumptions were used in the course of the latest investigation as follows:

a. Emphasis has been placed primarily upon operational impacts. Previous studies have shown that both preoperational (mostly construction) and decommissioning environmental impacts for most storage technologies have a reasonable degree of commonality (with the possible exception of specific decontamination procedures).[2] Control technologies for these categories of impacts are well known and little or no new control technology is generally required.

b. The general time frame for the investigation covers the period 1985-1990. In view of the many uncertainties involved with funding of research and development programs, this time range for near term energy storage implementation may conceivably be extended. It is also clear that for a number of potential applications, large scale utilization will almost certainly be later than the dates specified above.

c. The environment under consideration is the area located beyond the site boundary and in general would not include activities within the storage technology complex. Thus, those activities regulated by the USEPA and the OSHA were <u>not</u> considered here. However, there does appear to be certain "grey areas" where such activities cause or influence impacts extending beyond the complex perimeter. To this extent, some data has been presented with regard to excursion (accident) situations and certain other operational impacts.

d. Systems concerned with the generation, distribution and storage of hydrogen were <u>not</u> included in this investigation.

e. The methodology used included a computerized reference literature survey, review of present storage programs under development including state-of-the-art control technology, personal contacts with private and governmental organizations and attendance at specific storage technology seminars.

The primary environmental impacts and suggested control technologies associated with the specific energy storage technology will now be discussed. In view of the many technical details and designs associated with these technologies, it is suggested that appropriate engineering references be consulted.

2. TECHNOLOGIES

Those environmental impacts deemed to be of primary concern as determined in this study and associated with the normal operational phase are summarized in Table 1.[3] Included are suggested mitigation control technologies as well as cost estimates for such control technology. It should be noted, however that an in-depth economic study was not made, hence significant deviation from the values quoted is possible.

2.1. Advanced Lead-Acid Battery

The responsibility for the Department of Energy's battery research, development, and demonstration program lies within its Division of Energy

Storage Systems (STOR). STOR is divided into several activities with battery development programs under the guidance of the Electrochemical Systems Activity. The goals of this branch include the development of batteries for utility and vehicle applications, industrial processes, and solar/wind energy utilization. To meet these goals, part of the program is concentrating on upgrading the performance characteristics (energy density, power density, and cycle life) of the state-of-the-art lead-acid battery. A lead-acid battery that meets the upgrading performance characteristics is referred to as an "Advanced Lead-Acid Battery" Detailed specifications for such a battery include:[4]

A. The battery* shall be capable of operating for its rated life under indoor ambient temperatures ranging from 0° to 40°C with a maximum relative humidity of 99%. The battery shall be capable of delivering full output at an ambient temperature of 25°C.

B. The battery shall be capable of withstanding without damage exposure to accidental acid spills and a water fog operation of 0.25 gal/min./ft^2.

C. The capability of the battery measured at the direct current (dc) bus shall be as follows:

- Discharge - The battery shall be capable of being discharged routinely between its 1 and 10 hr rates with infrequent discharges at a 15-min rate.

Condition	Time hr	Power kW	Current A
Constant Current	1/4	--	10,000
Constant Power	10	180	--

- Charge - The battery shall be capable of being charged to 70% of its 10 hr rated capacity in ampere-hours within 2 hr followed by not more than 5 hr of additional charging to achieve 100% ampere-hour capacity.

- The end of charge voltage and/or equalization voltage for all four strings in series shall be 1,000 (+0, -2) volts, and the maximum end of charge voltage for all strings in parallel shall be 250 (+0, -2) volts.

- The allowable voltage and current ranges shall be

dc Current Range for any Voltage Within the Voltage Range	dc Voltage Range for any Current Within the Current Range
Amperes	Volts
60 to 2,500	500 to 1,000
60 to 10,000	125 to 250

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*The battery may be composed of any number of cells.

TABLE 1. SUMMARY OF PRIMARY ENVIRONMENTAL IMPACTS, CONTROL TECHNOLOGY AND COST ESTIMATES

Storage Technology	Operation	Affected Environment	Impact	Mitigation Control Technology	Mitigation Technology Cost Estimate*
Advanced Lead-Acid Battery	**Normal**	Air, Land	Hydrogen, Arsine, Stibine	Catalytic recombination, special scrubbing system including instrumentation	**18% plus land fill costs- $7-9/ton waste ($1979)**
	Excursion (fire, acid spill)	Air, Land, Water	Noxious gases, particulates, acid water	Venting, scrubbing (CaO), dilution	
Underground Pumped Hydro-Electric	**Normal**	Land, Water, Biosystems	Chemical and biological contamination, cyclic stress, entrainment	Design and site selection criteria, fracture detection instrumentation	**Not available**
	Excursion (structural failure)	Land, Water	Leakage, flooding, collapse	Stabilization, diversion, design and site selection criteria	
Superconducting Magnet	**Normal**	Land, Biosystems	Magnetic field, cyclic stress	Structure reinforcement, distance, shield coil	**4.3% of main coil or land < $10,000/acre for 10 G spec. - $2,000/acre for 0.3 G spec.**
	Excursion (structural failure, explosion)	Land	Fracture - Wall collapse, emergency shutdown	Stabilization	
Compressed Air	**Normal**	Air, Land, Water, Biosystems	Chemical - Biological contamination, wall degradation, subsidence	Cavern design and site selection criteria development, cyclic stress studies, detection instrumentation	**Aquifer - not available Water injection equip.-$5-50/kW, Wells and instrumentation - 5%**
	Excursion (structural failure)	Air, Land, Water	Blowout, cave-in, subsidence, seismicity	Stabilization, sealants, design and site selection criteria	
Flywheel	**Normal**	Land	Safety	Design of flywheel and containment system, Sensors	**5% of installed system-utility and residential Moving base-5-10%**

TABLE 1. SUMMARY OF PRIMARY ENVIRONMENTAL IMPACTS, CONTROL TECHNOLOGY AND COST ESTIMATES (cont)

Storage Technology	Operation	Affected Environment	Impact	Mitigation Control Technology	Mitigation Technology Cost Estimate*
	Excursion (structural failure)	Land	Rotor burst, vacuum bearing failure, secondary-particulates	Design	
Thermal	Normal				
a. Sensible		Air, Land, Biosystems, Water	Leakage	Leakage design, dilution, biodegradation	3%
b. Sensible-Aquifer		Land, Biosystems, Water	Contamination, Chemical, Biological, Subsidence (See list of potential impacts in text)	Site selection, geohydrological studies	Not Available
c. Latent Heat		Air, Land, Biosystems, Water	Leakage	Leakage design, detection instrumentation	8% plus land fill costs - $7-9/ton waste ($1979)
d. Reversible Chemical Reaction		Air, Land, Biosystems, Water	Chemical and solution leakage	Leakage design, detection instrumentation	8% plus land fill costs - $7-9/ton waste ($1979)
	Excursion (major leakage, fire, explosion)	Air, Land, Water	Chemical and solution leakage	Scrubbing, land fill disposal	
Fuel Cell	Normal	Air, Land	Electrolyte disposal, thermal (2nd gen.)	Neutralization, land fill disposal	10% plus land fill costs - $7-9/ton waste ($1979)
	Excursion, (fire, leakage)	Air, Land	High temperature chemical release	Neutralization, land fill disposal, safety shield (2nd gen.)	

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*Percentage costs are related to total capital cost of the energy storage system.

D. The battery shall be capable of 1,750 cycles over a minimum of 10 yr.

E. The electrolyte shall be within 1.205 to 1.215 specific gravity at 25°C and filled to the high-level mark.

F. The battery shall not evolve more than 140 mg/min of stibine and 10 mg/min of arsine during any charge or discharge regime.

G. The amount of hydrogen gas emitted by the battery on charge or equalization charge shall be less than 600 ft^3 during any half-hour period at an ambient temperature of 35°C.

H. The amount of acid emitted by the battery at any time shall be less than 280 mg/min and/or 50 g in any 8-hr period.

I. All materials should be noncombustible or fire-retardant. If combustible, provision for placing 1 in. of noncombustible material between modules shall be provided.

J. The cells shall be capable of withstanding, without rupture of the fluid-containing cell cases, an explosion of the hydrogen mixture within the cell. The explosion shall not cause the failure or rupture of adjacent cells or modules.

K. The maximum ripple current that may be applied to the battery is:

Condition	Ripple Current as Percent of dc Current Peak-to-Peak
Charge or Discharge	20%
Equalization Charge	100%

Lead-acid batteries will be installed at the National Battery Energy Storage test (BEST) facility initially for shakedown purposes. This facility is funded jointly by the DOE, the Electric Power Research Institute (EPRI), and Public Service Electric and Gas Company of New Jersey (PSE&G). The objectives of the BEST facility are 1) to serve as a testing site for evaluating and assessing the performance of advanced battery systems for load-leveling and peak-shaving applications by electric utilities and 2) to evaluate new power conversion equipment associated with new batteries. The BEST facility will be completed in 1981 with the test program beginning in FY'82.

The DOE also plans a Storage Battery Electric Energy Demonstration (SBEED).[5] The objective of SBEED is to demonstrate the technical and operational characteristics of dispersed lead-acid battery energy storage on a commercial scale. The contractor consortium for SBEED is being selected at the time of this writing. Construction of the SBEED plant is to begin in late FY'81 and plant operation is scheduled to begin in mid FY'84.

As noted in Table 1, the primary impacts from large scale battery usage involves the production of hydrogen, stibine and arsine gases. The hydrogen evolved can have serious safety impacts if its concentration in air is not kept below its explosive limit of 4%.

The arsine and stibine evolved can also have potential adverse occupational and environmental impacts. These two compounds are extremely toxic, as exemplified by their low threshold limit values (TLV) of 0.2 mg/m^3 (arsine) and 0.5 mg/m^3 (stibine). The advanced lead-acid battery specifications limit production to 10 mg/min of arsine and 140 mg/min of stibine. This generation rate occurs for a short period during the recharging of the battery. These compounds would normally be released to the facility environment and should react readily with the oxygen in the environment to produce antimony oxide and arsenic oxide--both solids at the facility operating conditions. The TLV for arsenic oxide (0.5 mg/m^3) is higher than that of arsine. The oxidation of arsine and stibine can be accomplished with various oxidants, e.g., air, manganese dioxide.

Calculations conducted in this study based upon battery specifications and assuming a constant stibine and arsine generation rate (worst case)[3], suggest that the TLV's will be exceeded and therefore these gases or oxidation products should not be permitted to escape into the facility environment. Work done at ANL suggests a lower generation rate for stibine and arsine.[6]

The evolution of hydrogen during the charge mode of a lead-acid battery can have a potentially serious impact on safety. The concentration of hydrogen in the battery facility can be kept below the explosive limit by diluting the cell vent gas and installing a catalytic recombiner.

The processing of the cell offgas to recombine the hydrogen and oxygen to form water offers the opportunity for further processing to control the emissions of compounds of arsenic and antimony and sulfuric acid mist. Figure 2 is a diagram of a conceptual process for this purpose. The vent gas stream is diluted with oxidizer (air), before it enters any manifolding, to assure that the concentration of hydrogen does not exceed its explosive limit of 4% and to promote the oxidation of arsine and stibine to their particulate oxides. The gas is then scrubbed to remove these particulates. The scrubber is equipped with a deentrainment pad to separate the entrained water/sulfuric acid mist from the gaseous stream. After passing through the scrubber, the gases enter a hydrogen-oxygen recombiner. This device catalytically produces water from the hydrogen and oxygen in the gas stream. These recombiners are currently and extensively used in the nuclear reactor industry.

This process illustrates that control technology is currently available to control the possible environmental impacts associated with the normal operation of an advanced lead-acid battery storage system.

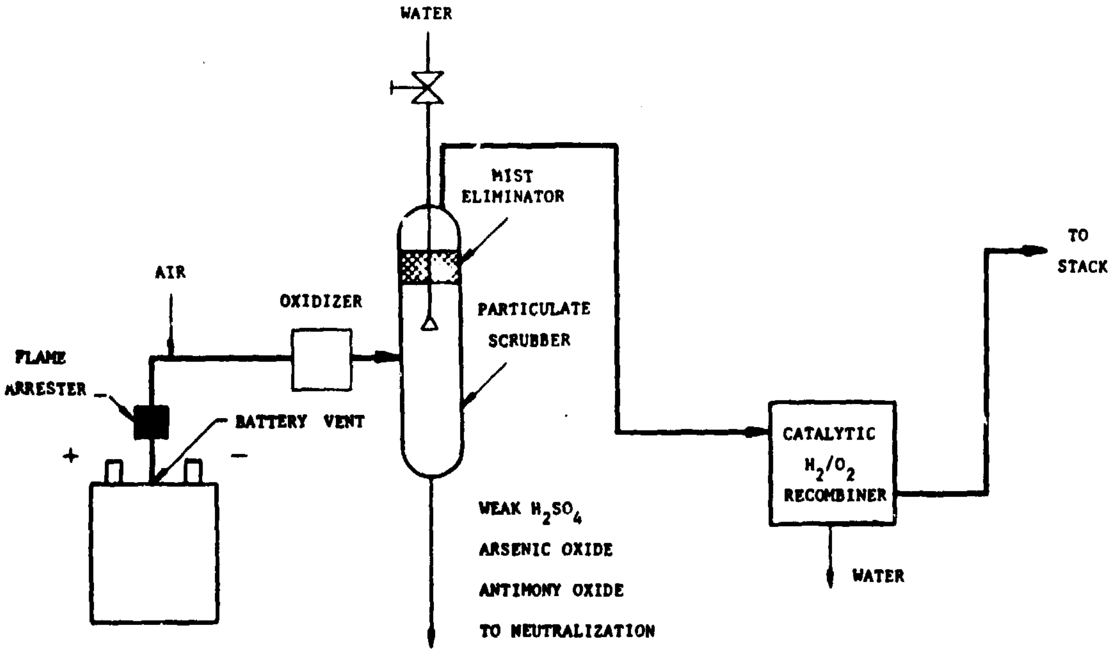

Fig. 2. Conceptual control process for advanced lead-acid battery facilities.

The mitigating control technology is comparable to pollution control technology and processes used in the chemical process industry. The cost of such pollution control processes is not expected to exceed 10% of the capital costs of the facility.

The cost of electrolyte neutralization and subsequent disposal of the neutralization products, for the case of potential impacts from spillage, leakage, or disposal upon decommissioning, are estimated to be 8% of the capital cost of the facility. The major cost is attributed to the neutralization process as land-fill costs for the disposal of the neutralization products. This cost escalated to July 1979 is from $7 to $9 per ton.[7]

2.2 Underground Pumped Hydroelectric

Although pumped hydroelectric storage, using above-ground reservoirs, has been used by utilities for almost 50 years, underground pumped hydroelectric storage (UPHS) has been considered only recently. UPHS plants have not yet been constructed, but at least two electric utilities, Commonwealth Edison Co. in Chicago and Potomac Electric Power Co. (PEPCO) in Washington, DC are conducting feasibility studies. The U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) are also involved in the PEPCO study.

The DOE goals include development of the necessary technology for the completion of a demonstration plant in the late 1980's.[8] Argonne National Laboratory (ANL), the lead laboratory, is currently assessing markets and potential for UPHS commercialization and sponsoring development of reversible pump-turbines that can operate at very high heads.

Renewable, but intermittent, energy resources such as solar or wind require efficient energy storage systems to make them viable. Small scale low-head UPHS, as well as flywheels and compressed air, are under consideration as options. Sandia Laboratory (Albuquerque, NM) is currently the lead laboratory in this development program.[9]

Basic elements of a UPHS system have been described previously.[2] These elements are generally similar to those in above-ground plants with the main difference being in the powerhouse and lower reservoir which are located below ground (2000-5000 ft.). The greater the distance between the upper and lower reservoirs (head), the less water that will be required to be pumped for a given energy output. This distance is limited by present reversible turbine design (maximum of about 2000 ft of head), necessitating the use of an intermediate reservoir and powerhouse for greater depths. New research is directed towards reversible turbines that can operate at heads considerably in excess of 2000 feet.

Many potential impacts can be identified for UPHS systems but the primary ones relate to chemical and biological water contamination and cyclic stressing of the walls of the underground reservoir.[3] Reduction in water quality could result from mineralization, entrainment of fish and other biota and turbidity. Local aquifers could be contaminated during construction. A permanent pathway for contamination could result. Cyclic stressing of reservoir walls due to daily water level fluctuations could result in significant erosion and fracturing leading to ultimate wall collapse.

Siting and design considerations are perhaps the most important tools available for mitigating environmental impacts. In addition, the development of fracture detection instrumentation would be helpful.

Because the environmental impacts for UPHS are so closely linked with siting and design considerations, it is difficult, if not impossible, to assign costs to their controls at this time. The costs for environmental controls <u>can</u> be determined for a project once a specific site and equipment design is chosen, but cost estimates for an "average" UPHS plant are not likely to be meaningful.

2.3 Superconducting Magnet

Details of superconducting magnetic energy storage (SMES) devices have been given previously.[2] At the present time, devices have been planned or constructed for diurnal energy storage (large amounts of energy), system stabilization and reactive power control (VAR).[3]

Of the various proposed designs and applications of SMES, only the large units to be used for diurnal storage (1000-10,000 MWh) in electric utility grids pose significant problems for the environment. Smaller magnets might, in some instances, involve shielding of personnel against the effects of magnetic fields; but this concern should be easily manageable by conventional methods.

The primary environmental impacts associated with large SMES systems involve the effects of high magnetic fields upon animals and man, cyclic stressing of rock walls induced by high magnetic forces and potential problems arising from emergency shutdown of the SMES system.[3] As yet no standards have been decided upon for exposure tolerances of animals and man to magnetic fields. Hassenzahl et al have considered this problem and selected three field levels (200 G, 20 G and 0.3 G) for consideration.[10] In general, tradeoffs exist between additional land area (the field falls off roughly as $1/r^{-3}$ where r is the distance from the solenoid axis) and the introduction of superconducting shield coils. Iron shielding is very expensive in all cases. Proper site selection, design criteria, and further attention to microfracture and fatigue strengths of rock should assist in mitigating cyclic stress problems. Magnet quenching (irreversible transition from the superconducting to the normal state) is the most probable cause for an emergency shutdown. The following items could lead to such a shutdown:

- Loss of Dewar vacuum;
- Loss of refrigeration
- Major rock fracture;
- Earthquake or other natural disaster;
- External power system failure.

Technological controls now available, as well as improvements that will be developed can be effective in protecting a SMES system against those events which could lead to a quench. The general philosophy guiding the shutdown planning to date has been: first, to limit the extent of the quench; second, to retard the growth of the quench; and third, to transfer from the cryogenic environment the energy development in a quench. More specifically, the schemes involve: the control of the normal zone propagation velocity by means of heat sinks; electrical and thermal isolation; and the transfer of excess energy from the cryogenic environment. Cost estimates relating to the magnetic field control technology are shown in Table 1. Costs are not available concerning mitigation of cyclic stress and emergency shutdown effects.

2.4 Compressed Air

Compressed Air Energy Storage (CAES) is perhaps the nearest to commercialization of the new energy storage schemes under consideration for use by utilities for meeting peaking power needs. One CAES plant has been built in West Germany, and at least three other plants are in the planning stage in the United States. The DOE in conjunction with the Electric Power Research

Institute (EPRI) is actively pursuing commercialization of the CAES technology for utilities through the preliminary system design and site selection of three CAES plants, one in each of the technically feasible geologic storage media--hard rock, salt, and aquifer. Battelle Pacific Northwest Laboratory (PNL) has been designated by DOE as the lead laboratory for CAES research and development. Near term goals are for the commercialization of isothermal CAES plants which require some petroleum-based fuels for operation. Long-term goals for 1990 and beyond are for the development and commercialization of CAES cycles which do not use petroleum-based fuels (no-oil). Consideration has also been given to the small scale use of compressed air for energy storage (<100 kWh) for renewable, but intermittent energy sources such as solar and wind. Near term goals for this program are the completion of feasibility studies in FY'79, and the technical development of the concept by FY'82.

The two major components of a CAES system include: a) the above-ground turbomachinery and energy conversion equipment, and b) the underground geologic storage media. An extensive discussion of both the above-ground turbomachinery and the three generic underground geologic storage formations has been given previously.[2]

As was the case with UPHS, many potential and similar impacts can be identified for CAES systems. In addition, storage emphasis in aquifers and in salt generate additional potential environmental impacts. The primary impacts nevertheless are similar to those of UPHS and include chemical and biological aquifer (water) contamination, cyclic stressing of cavern walls, perturbations of ground-water flow and possible subsidence. NO_X emissions from CAES turbines may not be a serious problem. Initial design studies and operation of the Huntorf plant (West Germany) indicate that NO_X emissions can be significantly lower than those from a standard gas turbine peaking plant burning the same amount of fuel depending upon the equipment configuration. The high pressure cavern air (200 - 1000 psi) used with different fuel ratios and reheat between the high and low pressure power turbines allows lower flame temperatures to be used (1000° - 1200°F) and therefore less NO_X is formed. Low NO_X emissions from a CAES plant would eliminate the need for water or steam injection systems used for NO_X control.

The Huntorf West Germany CAES plant built by Brown Boveri Corporation for NWK (a German utility) has been in operation since 1978 and should provide an excellent resource base for determining environmental impacts associated with salt cavern operation as well as certain types of turbomachinery. Operating experience of the plant to date has shown the following:[12]

- There has been no significant leakage of air from the cavern. The leakage rate was estimated at 1/1000 (0.001) to 1/10,000 (0.0001) of a percent per day.

- There has been no significant carryover of salt with the compressed air.

- The only significant environmental control that was necessary for the plant was that concerned with the rate at which solution-mining brine could be disposed of in the ocean.

Siting and design criteria are important considerations in mitigating many of the environmental impacts. Accurate geohydrologic knowledge is required. Fracture detection instrumentation should be developed and a well monitoring system similar to that used in the natural gas industry will also be required.

Many of the potential environmental impacts associated with CAES plants are either very site-specific or are so poorly defined at this time that cost estimates on their controls are very difficult, if not impossible to determine with any sort of confidence. Since many of the environmental impacts can be mitigated by proper site selection and/or equipment and cavern design there will be no costs directly attributable to these control techniques. Environmental controls such as grouting to control air leakage from a cavern could potentially be so expensive as to make a CAES plant uneconomical at that site. Water injection equipment for NO_x control (if it is needed) can add anywhere from $5 to $50/kW to the construction costs depending upon the availability of water and the water treatment needed ($10/kW might be considered an average value). Assuming that three observation wells (including instrumentation) are needed to determine the integrity of the operation of a hard rock or aquifer storage cavern, this equipment would likely add less than 5 percent to the cost of developing the cavern.

2.5 Flywheel

Energy storage through the kinetic energy stored in rotating masses (flywheels) is a technology that has been used by man for hundreds of years. Flywheel energy storage systems (FESS) can thus make a contribution to our future needs for energy storage in both large and small scale applications.

Near term objectives of DOE for flywheel energy storage research are the development of regenerative braking systems for vehicles (both electric and heat engine) and energy storage for solar-photovoltaic and wind energy systems.[11]

Most of the flywheel energy storage devices of importance will have the following components:

- Flywheel Rotors - using different materials and geometries.
- Bearings - that use roller, fluid film or advanced magnetic designs.
- Vacuum Systems - using a vacuum pump or a sealed and periodically maintained container.
- Seals - magnetic couplings or integration of the electric motor inside the vacuum contained so power can be transmitted outside the container without the loss of vacuum.

Of these components, the flywheel rotor has the greatest potential to produce environmental effects. Current flywheel research and development is directed towards rotor materials that have high strength to weight ratios and geometries that make the best use of these materials. Metal flywheels have been used extensively, have well-known design strengths and manufacturing techniques, but unfortunately, have poor energy densities, have catastrophic failure modes into chunks of shrapnel which requires a heavy containment ring, and are costly. Composite materials such as E-glass, kevlar, or graphite in an epoxy matrix have much higher energy densities and have potential for lower costs. They also have the potential for a much more benign failure mode in which the outer layers of material delaminate and slow the wheel down without catastrophic failure. Cellulose, in the form of plywoods, fiberboards or paper rolls, is also being seriously considered as a flywheel material because of its low cost, good strength to weight ratio and the possibility of a benign failure mode like the composites.

During normal operation of a flywheel energy storage system, either in a fixed or moving base application, there are no known significant environmental impacts. For a large utility type FESS peaking plant, some concern has been voiced about noise problems from the motor/generators and related machinery, but these are problems associated with any large scale power generating operation and should be considered site-and design-specific and relatively minor. Aesthetic and land use considerations are site-specific potential problems, but the land requirements for a FESS are relatively small and can be placed on existing utility-owned sites. Residential and industrial FESS land requirements are similarly small and can be easily built underground.

The only major environmental impacts from flywheel energy storage systems appear to be health and/or safety problems related to flywheel rotor failures and accidents, which are excursions from normal operation. The primary method of controlling these impacts will be to ensure that excursions are extremely uncommon occurrences. Thus, research into material properties and stress failure modes are required. Proper design of containment systems is necessary. Possibly sensor development indicating a forthcoming rotor failure is also required.

Mitigation technology costs related to containment and sensor systems for utility and industrial applications are estimated to be on the order of 5% of the installed system costs. Slightly higher costs (5%-10%) are estimated for vehicular applications.

2.6 Thermal

The DOE has recognized the importance of the development of thermal energy storage (TES) by establishing several programs under its Division of Energy Storage Systems (STOR).[13] Table 2 shows the division of responsibilities at the national laboratories and NASA.

Discussion of these systems is best considered by type, i.e., sensible heat, latent heat and reversible chemical reaction. For purposes of this paper, sensible heat systems are further subdivided into standard liquid or solid materials and aquifers.

Sensible heat systems use the internal energy of the material for heat storage. The materials composing the system experience no phase change. The quantity of heat that can be stored is dependent upon the mass and heat capacity of the material as well as the differential temperature during the heat transfer process. Some materials that are currently in use are commercial heat transfer oils, rock, and building materials such as concrete and water. These materials are confined by containers, or by their own structural strength, insulated, and exposed to a source of thermal energy. Heat is transferred to the material by conduction, convection, radiation, or by a combination of these heat transfer modes. Some typical heat transfer fluids include: Caloria HT43, Exxon (petroleum distillate); SF-96-(50), General Electric (silicone oil); Dowtherm SR-1, Dow Chemical (glycol type); Therminol 66, Monsanto Chemical (high aromatic hydrocarbon).

Storage of a liquid in an aquifer is also a form of sensible heat storage. In this process, water is heated above ground (by solar energy, waste heat, etc.) then injected into a confined aquifer. The over- and underburden act as efficient insulation to prevent heat transfer out of the aquifer. The water is stored until it is needed for utilization aboveground. Such utilization is easily adaptable to seasonal heating and cooling requirements of large facilities such as airports, shopping centers, office buildings, etc.

Latent heat energy storage systems utilize the heat absorbed or released by a material undergoing a change in phase, i.e., liquid to solid or liquid to gas, change in composition (loss or gain of waters of hydration). The heat can be extracted from the system by effecting heat transfer from the system to a utilization medium. Some typical materials under investigation at the present time include: Glauber's salt, sodium pyrophosphate decahydrate, calcium chloride hexahydrate and copper sulfate pentahydrate.

TABLE 2. SUBPROGRAM RESPONSIBILITIES

National Laboratory	Thermal Energy Storage Subprogram
Oak Ridge National Laboratory	Low Temperature Thermal Energy Storage (LTTES) (Sensible and latent heat, < 250°C)
NASA Lewis Research Center	High-Temperature Thermal Energy Storage (HTTES) (Sensible and latent heat, > 250°C)
Sandia Laboratories, Livermore	Thermochemical Energy Storage and Transport (TEST) (Reversible chemical reaction)
Argonne National Laboratory	Thermal Energy storage for electric load-leveling behind the meter and thermal energy storage for solar applications.
Battelle Pacific Northwest Laboratories	Thermal energy storage in aquifers.

Storage utilizing the heat of reaction of reversible chemical reactions is considered as another form of TES. Chemical heat pipes or pumps are one form of this type of system. Included are such typical reaction systems as sulfuric acid-water, sulfur dioxide-oxygen, calcium oxide-carbon dioxide, ethylene-hydrogen, etc.

The environmental impacts associated with thermal energy storage systems relate primarily to the loss of the energy storage material from the system. While this is true of all the systems discussed, additional potential impacts can be associated with the aquifer storage system. Toxicity, corrosion and in many cases, fire hazard problems also exist with many of the materials in use.

Impacts associated with aquifers are similar to and typical of those previously discussed under UPHS and CAES systems. Site selection criteria and adequate geohydrologic knowledge should help mitigate many potential concerns.

In general, practical control technologies for sensible, latent heat and reactive systems would include: a) engineering design for chemical solution leakage, material biodegradation, scrubbing systems, development of leakage detection instrumentation and land fill disposal. Mitigation costs associated with these activities should not exceed 3%-8% of the system plus some additional land fill costs. Costs relating to aquifers are unknown.

?.7 Fuel Cell

A fuel cell is an electrochemical device in which the chemical energy of a fuel is converted directly into low voltage direct current (dc) electrical energy. This process theoretically occurs isothermally and is therefore not limited by the Carnot efficiency; that is, the fuel cell makes it possible to eliminate the high temperature combustion and mechanical-to electrical processes associated with conventional power producing schemes.

Although the production of electricity is isothermal, the process releases the heat of combustion (or reaction) and this heat can be removed and utilized. Since fuel cells produce dc, an inverter is an integral part of a fuel cell system. The inverter transforms the dc to alternating current (ac).

In the strict sense fuel cells are not energy storage systems but rather are highly efficient power producing devices. Although they have often been described as primary batteries with their fuel and oxidant stored externally, only one reference in the literature described the development of a fuel cell as an energy storage device. This "water battery" operates in the discharge mode as an H_2/O_2 fuel cell and in the charge mode as a water electrolyzer.[14] Another fuel cell system that approaches the concept of energy storage systems is the regenerative fuel cell system in which the products of the fuel cell process are recycled to a fuel producing process.[15]

The DOE is developing fuel cells in an effort to conserve fossil fuels. The DOE program objectives are to develop fuel cell power plants leading to commercialization for electric power generation (peaking, intermediate and base load), cogeneration (electrical power and waste heat), Onsite Integrated Energy Systems (OS/IES), and waste conversion-fueled systems.

Fuel cells utilizing phosphoric acid as an electrolyte are generally referred to as first generation fuel cell systems. The 4.8 MW Utility Demonstration Program utilizing phosphoric acid cells is intended to demonstrate the viability of fuel cells on a utility grid. The delivery of the power plant to the demonstration facility is to be complete in October 1979. To date the stack performance is meeting design goals, and testing of the facility is to begin in February 1980. The fuel cells have been designed by United Technologies Power Systems Division.[16]

The fuel cells commonly referred to as second generation are those that utilize a molten carbonate electrolyte. The DOE development objectives are to advance the state-of-the-art of molten carbonate electrolyte fuel cells, thus providing for early commercialization. The schedule for development of the molten carbonate fuel cell is to have a full scale cell/stack by 1982.

Fuel cells in themselves (both phosphoric acid and molten carbonate) are virtually emission free.[17] Significant impacts do result however from the processing and refining of the fuel for the fuel cell systems. The latter presumably are controlled by USEPA regulations. Emissions from fuel cell operation are considerably below those for power-producing facilities. Electrolyte disposal could be another primary impact but it appears that lime (CaO) neutralization for phosphoric acid cells would be satisfactory. Molten carbonate cells could result a more serious solid waste disposal problem. The size and gravity of this problem is unknown at the present time.

Mitigation costs are not expected to be too high being related to available land fill disposal sites.

3. APPLICATIONS

Many previous studies have considered the energy storage system to be an integral portion of a utility electric power generation system. The investigation into potential applications of the various storage and fuel cell technologies had a dual objective of identifying new applications and subsequently determining any environmental impacts associated with the new application. Table 3 summarizes the applications for the various technologies. Further details may be found elsewhere.[3]

Most of the applications shown have been chosen based on a number of economic market penetration studies made by selected organizations. Not all are shown in the table. In general, most environmental impacts appear to be similar to those previously discussed although they may differ in degree. Some impacts noted previously may not even be applicable.

TABLE 3. POTENTIAL NEW APPLICATIONS FOR ENERGY STORAGE AND FUEL CELL TECHNOLOGIES*

Advanced Lead-Acid Battery	1. Electric Vehicle (includes hybrids)	18
	2. Load-leveling by user- (Power Management Battery Storage System)	19
Underground Pumped Hydroelectric	1. Small Scale Low-Head (in combination with PV or wind turbine)	20
Superconducting Magnet	1. System stabilization	3
	2. Reactive power control	21
	3. Regenerative braking	22
Compressed Air	1. Intermittent energy storage (solar and wind)	23
Flywheel	1. Vehicular-energy storage and regenerative braking	24
	2. Residential and small substation storage (also for industrial-commercial)	25
	3. Stabilization, reactive power control	26
Thermal	1. Heating and cooling (daily and seasonal)	27,28
	2. Cogeneration-district heating	29
	3. Vehicular	30
Fuel Cell	1. Water battery	31
	2. Transportation	32
	3. Cogeneration	33

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*Does not include standard load-leveling and peak-shaving applications for centralized electric power generation.

4. CONCLUSIONS

In virtually all cases it appears that some additional studies and control technology research and development are needed for most of the technologies reviewed. A brief discussion follows for each.

1. ADVANCED LEAD-ACID BATTERY: The use of the conceptual process shown in Fig. 2, if engineered properly, should prevent hydrogen, arsine and stibine from escaping from the facility and thus pose no problem beyond the site boundary. Stibine retention (or elimination) is a more serious problem since its generation is greater by at least an order of magnitude over that of arsine. Instrumentation should be available for detection and monitoring so as to assist in the overall processing of the gas mixtures. The BEST facility will be helpful in determining appropriate needs and design engineering parameters for large scale battery installations.

2. UNDERGROUND PUMPED HYDROELECTRIC: Design and site selection criteria are most important for this system (see also 4, CAES). Attention to fish and other biological contamination should be made. As with the CAES system, cyclic stress studies (in-situ) should be made and fracture detection instrumentation developed.

3. SUPERCONDUCTING MAGNET: It is readily apparent that additional research is required on the effects of various magnetic field intensities on both biosystems and electrical and electronic systems. In addition, further studies are required on rock support problems related to structural design. Research is required on the effects of microfractures and cyclic stressing of rock.

4. COMPRESSED AIR: The potential fracture development within supportive structures and subsidence induced by daily cyclic stress patterns have been determined to be an important impact. This has been identified previously.[2] In-situ stress analyses on candidate rock types should be made. Such studies should reveal the potential for mechanical failure. Development of appropriate instrumentation is implied. The use of aquifers for CAES involves a host of potential chemical and biological impacts, the degree of importance of which is difficult to assess. Many studies upon individual problems should probably be done but it may be necessary to take some risk and actually construct a practical system for total study in order to observe and measure system interactions. Finally, it is recommended that the Huntorf plant be critically observed with respect to salt cavern operation.

5. FLYWHEEL: Environmental control technology, in a strict sense, is not required for flywheel systems. Major effort, however, is required for the overall characterization of failure modes for these various flywheel configurations. Included, of course, is the characterization of a number of materials.

6. THERMAL ENERGY

   6.1 Sensible Heat: Research is required whereby biodegradable liquids are identified and modified so that their physical and chemical properties are useful for these systems.

6.2 Sensible Heat-Aquifer: Considerable geohydrologic characterization is required prior to assurance that many of these potential environmental impacts will or will not actually be a problem. Because of site specificity for this particular type of storage, this is a difficult system upon which to generalize.

6.3 Latent Heat and Reversible Chemical Reaction: Designing to minimize leakage and the development of leakage detection instrumentation are necessary for these systems. The wide range of temperatures for the materials in these systems compound these problems.

7. FUEL CELL TECHNOLOGY: No immediate development work is required for first generation cells. Most of the major materials used for second generation cells appear to be non-toxic, at least those being used at present. Considerable research and development is still in progress on the second generation cell. Thermal and safety problems may be more important especially within the facility for the second generation cells.

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