SUPER MAGNET ENERGY STORAGE. "THE STATE OF THE ART"

Hisham Hamdi Abdelmohsen

Structural Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria 21544 - Egypt

ABSTRACT

This is an attempt to keep the Egyptian civil engineers abreast with the latest, and new technology envisaged in Super Magnet Energy Storage System SMES. The system has gone, by now, through the second phase "Engineering Testing Model ETM". By the beginning of the new century, a commercial unit shall be ready for full usage. The article presents a comprehensive review coverage for various energy systems competitors to SMES. Details of SMES's components are summarized, to reflect the engineering merits of the system. A long list of References is provided to illustrate the historical path of SMES, from being a research subject, to becoming an engineering testing unit.

Keywords : Storage Systems, Magnets, Super Magnets, Design

INTRODUCTION

Why do we attempt to store energy in an electric power system? Since selling electric energy is a business, the obvious answer is to reduce the cost of generating and delivering electric energy to the customer, thereby maximizing the return of the capital investment.

The load on an electric - power system and of the individual customers varies over a daily cycle, a weekly cycle, and an annual cycle. The daily system peak usually occurs in the morning or afternoon. the annual system peak occurs either in the mid winter or mid summer, depending on the location of the system. Typical daily system profiles are shown in Figure 1. The typical ratio of daily peak - to - valley load is 2 - to - 1. The annual ratio of average-to-peak load is termed the load factor; the typical value is 60%. The margin between the annual system peak load and the installed generating capacity is termed the reserve; the typical value is 20%. At every instant, the system operators must match the instantaneous demand of customers with power from generators and from neighboring systems on the interconnections.

Looking at the histogram of Figure 1, we see that the answer to many fuel, environmental, and energy cost problems is apparently staring us in the face. That is, build centrally located, non-polluting, non-critical-fuel (nuclear) plants. Operate them continuously at the average system load level, store the off-peak energy in dispersed sites around the system and release it to the customers on-peak, during the period when the system load exceeds the average value. The capital equipment would be used to its utmost. Is this concept technically and economically realistic?

The basic problem of this proposal is that electric energy deliverable by alternating current can not be stored. It must be converted to other forms for storage: potential, kinetic, chemical, thermal, and converted back to electrical form when needed. Each storage method has a capital cost, energy cost, efficiency, state of technical development and environmental impact. Certainly, energy storage systems that could be located at dispersed substations, store energy for 8 - to - 12 hours of operation, have a high cycle efficiency and low capital cost, would reduce the delivered energy costs of the electrical -power industry. Reliability would improve, environmental problems would decrease, and many of the complexities of operation would disappear. However, the overall costs of the storage system must be less than the costs of the conventional approach for them to be considered realistically.

ELECTRICAL POWER SYSTEMS

Pumped - Hydro Storage

Storing energy in water is the oldest method for the electric-power industry.

Hydroelectric plants generated a considerable proportion of the industries energy requirements. These plants operated either "run -of-the river" or from water pounded or stored in dams on a daily or seasonal basis. The operation of hydro-electric and steam plants required advanced analytical work in the field of economic dispatch. Even if the site can be found today, it will be difficult to justify the cost of hydro-electric plants unless part of the cost be written off to flood control, recreation, or area renewal. The pumped-hydro storage plant, such as is shown in Figure 2 is a modern concept in power system design.

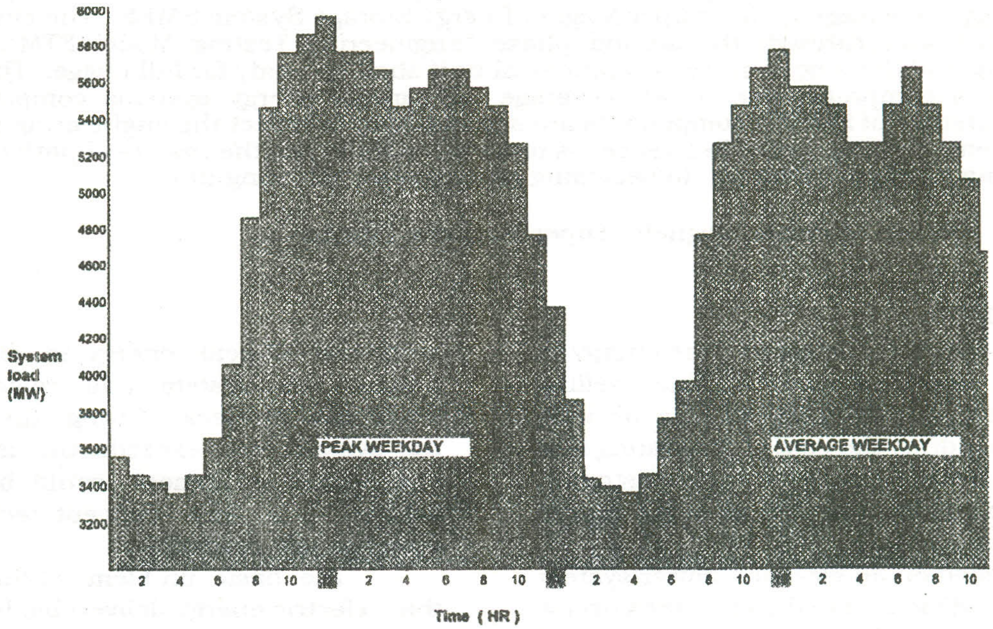

Figure 1 Typical hourly load for week-days [1]

The problems of hydro-storage are geography and cost. Because the hydro-storage plant is a large central facility, it usually requires the construction of transmission line delivering pumping power from the source and the generation power to the load. In addition to the costs, there are many other factors to be considered for pumped-hydro storage plants, such as system reliability, land use, pollution and fuel use.

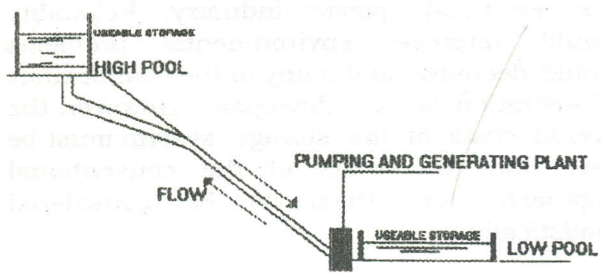

Figure 2 Diagram of two-reservoir-pumped storage [2]

Pumped - Air Storage

A conventional gas turbine consists of a compressor and expansion turbine on the same shaft. In normal operation, about 2/3 of the turbine output is mechanically fed to the compressor and the remaining 1/3 is available for useful work. The pumped-air storage system has four components of unit cost: the energy for compression; the fuel cost for expansion and generation; the fixed charges on the above ground equipment; and the fixed charges on the cavern. As with pumped-hydro storage, the system is economical when the energy for compression is supplied by nuclear plants at reasonable rate.

Combining the element of the energy storage and on-site fuel, the air-storage system provides flexibility for cycling operation, stand-by service, emergency long term generation and synchronous condenser operation.

The system is promising for areas which do not have geological conditions for pumped-hydro storage, yet have rapid nuclear-power development.

Flywheel Energy Storage

Flywheels are being seriously considered for energy storage in vehicles, subways and electric power system. Flywheels using fibers such as steel win, fiberglass, and tungsten carbide can store for 30 and up to 180 Wh/Ib. Flywheels have been proposed for dispersed electric -power system peaking units, which will change during off-peak periods and discharge in-peak. The problem with flywheel storage, aside from the safety and structural aspect, is that energy is "pumped in" by increasing the velocity and "pumped out" by decreasing the velocity of the flywheel. To exchange energy with an electric power system, some form of transmission or clutch is required between the motor-alternator and the flywheel to accommodate the speed change.

Electrochemical Energy Storage

A high energy storage density of about 18 kWh/Ib can be obtained with liquid hydrogen, which can be manufactured by electrolysis from electric energy. Hydrogen is a standard industrial product, which although potentially explosive, is manufactured, transported, and used in liquid and gaseous form for processes from heat treating metals to space travel. The technology is well established. The vast availability of water as a source of hydrogen, the ease of transportation, the zero air-pollution effects, has prompted the concept of a " hydrogen economy". Figure 3 shows a system which calls for manufacture of hydrogen at a power plant site, distribution of the hydrogen by pipeline to dispersed electric generating units and other loads, and storage of hydrogen in supplementary tanks to level the load on the central plant. Many variation of this concept are proposed. All schemes incorporate the energy storage to obtain maximum usage of the capital equipment. The overall efficiency of the hydrogen system from power plant fuel to delivered electric energy is only about 11%, compared to 33 % for a conventional nuclear plant and electric system.

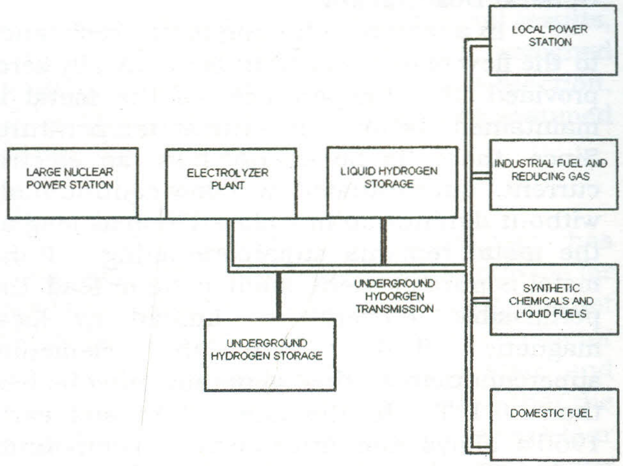

Figure 3 Proposed system for a hydrogen economy, [3]

Thermal Storage

Energy storage systems can be used not only to transfer energy from off-peak to on-peak periods, but to store solar-derived energy and to store energy between winter and summer seasons. Storing energy thermally in water is usually uneconomical because of the large volume (tank) required and other factors. Meyer [4] proposes a heat - storage well, into which water at 340°F is pumped at a rate of one million gal/day. As the hot water is pumped into the well, it moves outward in the acquifer maintaining a conical interface with the cold ground water.

Studies showed that 86 % of the heat can be recovered after 90 days. Cooling water from conventional fossil and nuclear steam - electric plants is at too low temperature (~100°F) to be used. The stored water after recovery can be used seasonally for space heating, process heat and water heating. The heat storage well provides both electric and heat-load leveling. Lavi and Zener [5] propose using the surface of the ocean to collect solar energy and store it by temperature rise of the surface water. A power plant could utilize in its cycle the temperature difference between the surface temperature of 25° C and deep temperature of 5°C.

SUPERCONDUCTING MAGNET ENERGY STORAGE SYSTEMS [6-15]

General Description

In a superconducting metal, resistance to the flow of direct current is identically zero, provided the temperature of the metal is maintained below its critical temperature. Since there is no energy loss, an electric current, once initiated, will flow continuously without diminution in a closed loop as long as the metal remains superconducting. If the metal is pure element, such as tin or lead, the permissible current is limited by local magnetic field. In the elemental superconductors, this generally must be less than 0.1 T. In the late 1950's and early 1960's alloys and inter-metallic compounds were discovered which were capable of carrying substantial current in magnetic fields that in some cases could exceed 10 T. Since the energy in a magnetic field of 10 T is approximately 40 MJ/m^3 (11 KWh/m^3), it was realized that substantial amounts of energy could be stored in a superconducting magnet. During the 1960's various superconducting coil configuration, simple solenoids, and toroids were evaluated in a preliminary manner for use in a storage system. The simple solenoid appears to be the most effective solution since it was the simplest to construct and required the smallest amount of superconductor per unit of energy stored. It became apparent that a major technical problem to be resolved was the provision of adequate structural strength to withstand the substantial pressures exerted by the magnetic field upon the current carrying conductors and their supports. It was proposed that the superconductig solenoid be contained within a cavern excavated within solid bedrock.

By the early 1970's enough attention had been given to the problems of system size, conductor performance and availability, magnet construction and design, and power interface between a DC superconducting storage magnet and the 60-Hz electric utility network. The variation of the size of a SMES system with storage capacity and magnetic field is illustrated in Figure 4 The optimal ratio of solenoid radius to solenoid length is approximately three for this application.

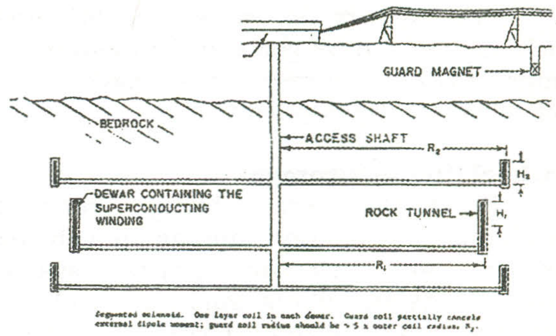

Figure 4 Schematic of SMES system installed in bedrock, [6]

A SMES system is complex and consists of several major subsystems. In addition to the conductor, and the magnet, there are refrigeration and vacuum systems and the power interfaces.

Subsystems

Rock and Tunnel Excavation

The SMES design calls for installing the magnet in hard rock several hundred meter below the surface of the earth. Previous above-ground designs required huge structures to contain the forces on the magnet, and the estimated cost of these structures was prohibitive.

There is, unfortunately, very little information available on the ability of rock to withstand the type of stresses proposed to be imposed on the walls of the cavern, i.e. , large stresses, with both shear and normal components, which vary from a maximum to a minimum and back again each day.
For SMES, bedrock offers the only practical and relatively inexpensive magnet containment structure. As an example, 770,000 tons of steel is required to hold together a magnet containing 10,000 MWh of energy. Yet, bedrock is cheap, and available almost anywhere in Egypt in various properties and composition. There exists the experience of using it for many diverse underground power houses and tunnels.

There are three major aspects by which SMES caverns differ from other underground structures. These are related to tunnel geometry, types of rock loading, and the constraints on magnet deformability. The typical shape of SMES is a thin walled cylinder. The corresponding rock chamber capable of housing a superconductor solenoid magnets is an annular shaped tunnel.

For improved rock quality and reduced magnetic field at the surface,, the mean depth of excavation is typically 100 - 400 meters. Near-surface low aspect ratio caverns have also been considered. Due to the long tunnel course, regions of potential instability might exist. Care should be taken to identify those regions, and investigate the means for stabilizing them.

The most unusual aspect of SMES tunnels is the type of loading to which they are subjected. External loads due to gravitational forces and anisotropic tectonic stress are complicated, and their effect could not be modeled but as three dimensional case. A major problem arises from the internal loads due to magnetic forces developed by the charged magnet. These loads are transferred to the rock via specially designed struts and base plates, which induce loads on the rock rather than the distributed ones. Moreover, magnetic forces are acting in both axial and radial directions. An additional complication related to the loading of the tunnel walls is its cyclic aspect. The magnet will be charged and discharged every 24 hr. so that, the internal loads will cyclically alternate from zero to their top value at a daily frequency.

Cavern design

Only numerical models, such as Finite Element Method (FEM) and Boundary Element Method (BEM), can approach the complexity demanded for magnetic energy storage cavern design. The three dimensional nature of the crystal stress field, the mechanical anisotropy of the rock mass, and the circular geometry of the annular tunnels require a three- dimensional modeling approach. A plane strain formulation is probably inaccurate for all but very few large diameter cavern designs (radius > 500 m), in which the rock formations are transversely isotropic. Axisymmetric FEM formulation was found to provide a realistic simulation to axisymmetric tunnel and strut loading, yet it is far less expensive and troublesome compared to a three- dimensional analysis. A probabilistic assignment of mechanical properties, be they isotropic, orthotropic, or fully anisotropic, using Monte Carlo method is assessed to simulate rock mass uncertainty and variability. In cases where the distribution function of a particular property can be calculated from experimental results, each finite element can be assigned properties in accordance with this function. Otherwise, rock properties may be assumed to be perfectly random.

Magnet Design

The University of Wisconsin has considered the problem of how to provide for magnet protection and continued magnet operation should a portion of the conductor return to the normal conducting state and remain there. They have proposed that the magnet be separated into twenty-four independent sections (with separate dewar and leads) with multiple shorting switches which would allow each section to be discharged independently. The proposed placement of the SMES system underground was the result of analyses which indicated that the cost of providing structural containment above ground would be prohibitive.

New design proposals were also considered by The University of Wisconsin. These proposals carry ideas for creating rippling in the magnet initial configuration, to reduce stresses due to the process of charge and discharge of the magnet. Despite that,saving in the structure supporting material is anticipated, the mechanism of manufacturing is expected to bear some complexity and costs.

The Superconducting Conductor

Historically, superconducting materials such as NbTi and Nb_3Sn have been stabilized by encasement in copper to prevent thermal runaway should the superconductor convert to normal phase. This provides an alternative path to the superconducting current in which the heat generated is small enough to be carried away by the refrigeration helium. In principle, aluminum is an attractive alternative to copper because it is much less expensive although the volume will be greater.

Two types of conductor designs have been considered for use in the SMES system magnet: modular cable with copper-stabilized conductor, and aluminum stabilized conductor in which the superconductor braid is disposed around a cruciform core of high strength Al alloy containing high purity Al segments the whole being enclosed within an Al containment skin. The modular design is attractive because the basic components could be manufactured off-site then shipped to the site in relatively long lengths and assembled into the finished cable. The use of the Al-stabilized conductor would require either on-site manufacture from basic components or manufacture in a very short lengths and assembly on-site with a large number of conductor joints. Both of these alternatives appear to be more risky than a modular design.

Dewar and Solenoid Support

The sketch presented in Figure 5 shows the dewar and solenoid system. The principal components are a vertical solenoid which is contained within a liquid helium dewar that bathes the magnet conductors in superfluid helium 1.8 K; struts that penetrate the outer wall of the liquid helium dewar and transfer the load of the magnet forces upon the conductor to bedrock; refrigerated stations (cooling tubes) on the struts at approximately 11K and 70 K to reduce the heat leak through them; and other walls to provide vacuum protection of the helium dewar, the outer of which is close to the rock that provides support for the radial forces on the magnet. The conductor , the walls of the liquid helium dewar, and the vacuum walls are rippled to reduce movement of the conductors under cool down and magnetic pressure variation as the magnet system is charged and discharged. Thermal super insulation between the outer vacuum walls and the liquid helium dewar reduces the heat leakage radiation into the 1.8 K bath.

Refrigeration and Vacuum Systems

The refrigeration and vacuum systems being considered for SMES systems differ from current commercial and industrial practice only in scale and performance. The refrigeration system is the source of the major energy loss in the system and must therefore be designed for optimum efficiency.

The vacuum technology required is compatible with existing practices. It

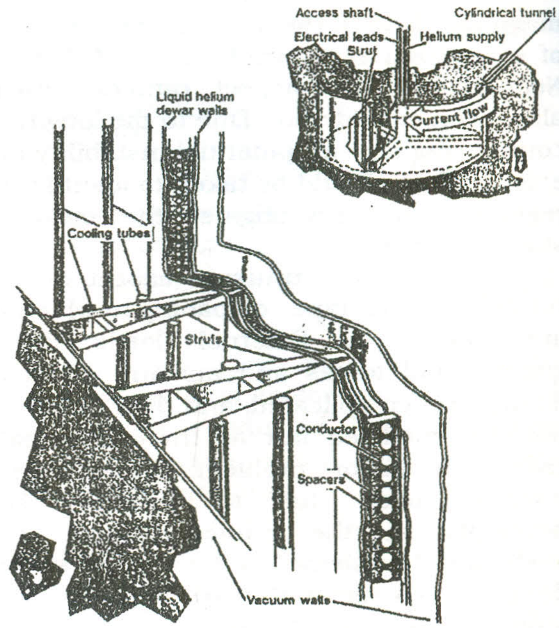

Figure 5 Artist,s rendering of Dewar and magnet system, system,[6].

demands only that careful attention be paid to the detailed design and redundancy of the vacuum system to ensure reliable operation. In the event of failure, the subsystems must be reliable without having to withdraw the SMES system from service to warm it to ambient temperature.

Power Conditioning

The two types of power conditioning systems (ac/dc converters) that can be used in a SMES installation are characterized by: either constant voltage across the magnet—implying that the unit power delivery or charging rate capability will depend on the SMES unit state of charge, or, constant input/output power capability—independent of the SMES unit state of charge but implying higher cost.

ENVIRONMENTAL AND SAFETY RELATED PROBLEMS

These problems stem from the presence of the stray magnetic field of the solenoid. At ground level, the magnetic field ranges from a value approximately twice that of the earth's field at a distance of 2,800 meters from the center of the solenoid to a maximum value of approximately 800 Gauss (1600 times of earth's field). Figure 6 shows the field strength as a function of radial distance from the magnet for various heights above the magnet. Figure 7 shows the location of various field strength surfaces. In each case, the calculations were for a magnet 300 meters in diameter with an axial field of 2.5 T.

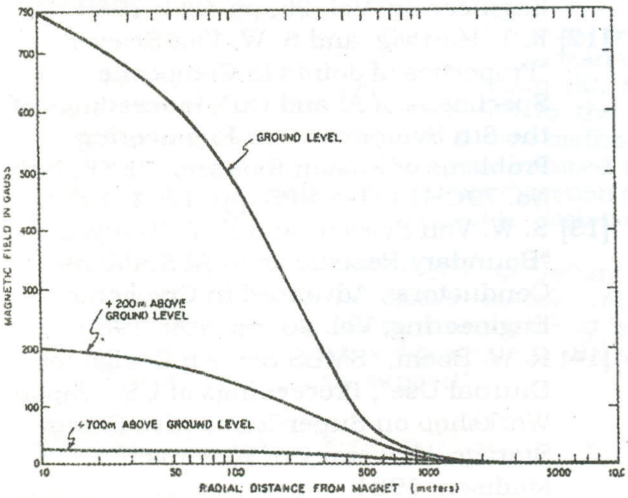

Figure 6 2.5 tesla SMES - Magnetic field as a function of distance [14], {Magnet diameter = 200 m, depth of mid-coil plane = 300 m}

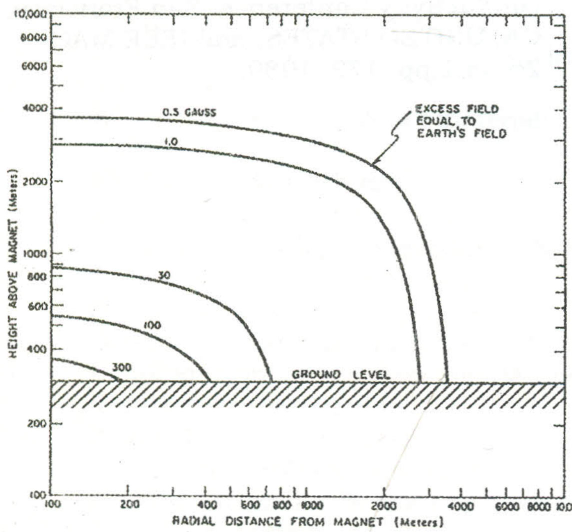

Figure 7 2.5 Tesla SMES—Location of constant field surfaces, (14). (Magnet diameter=300m, depth of mid-coil plane=300 m)

The field of the coil will remain at 1 Gauss level or higher within a volume that extends to a height of approximately 2,600 meters over the coil's center. This field introduces problems in three areas : the effects upon life, in particular upon animals; the effects upon mankind and devices, and the effects on instrumentation such as magnetic compasses used by aircraft. Consequently, it is clear, it might be desirable to ensure a region of approximately 1,200 meters in radius that should be closed to access by man and perhaps animals at ground level. The effect upon aircraft magnetic compasses is limited to a region of approximately 3,000 meters in diameter above SMES unit. Such region could presumably be closed to aviation by appropriate regulation.

The field of the coil will remain at 1 Gauss level or higher within a volume that extends to a height of approximately 2,600 meters over the coil's center. This field introduces problems in three areas : the effects upon life, in particular upon animals; the effects upon mankind and devices, and the effects on instrumentation such as magnetic compasses used by aircraft. Consequently, it is clear, it might be desirable to ensure a region of approximately 1,200 meters in radius that should be closed to access by man and perhaps animals at ground level. The effect upon aircraft magnetic compasses is limited to a region of approximately 3,000 meters in diameter above SMES unit. Such region could presumably be closed to aviation by appropriate regulation.

CONCLUSION

The article reviews the potentials of Super Magnet Energy Storage Systems SMES. We have highlighted other systems, to furnish broader grounds for system evaluation. The development of Engineering Testing Model, Phase 2, has materialized theories into a complete engineering construction unit. System reliability, integrity, and safety have been demonstrated.

REFERENCES

[1] P. J. Bernard, J.F. Dopazo and G.W. Stagg., " A Method for Economic Scheduling of a Combined Pumped Hydro and Steam Generating System", IEEE Trans., on Power Apparatus and Systems, Vol. 83, pp. 22-30, 1964.

[2] G. D. Friedlander, " Pumped Storage - An Answer to Peaking Power", IEEE Spectrum, pp. 58-75, 1964.

[3] D. P. Gregory, " The Hydrogen Economy", Scientific American, Vol. 228, No.1, pp. 13-21, 1973.

[4] C. F. Meyer, and D. K. Toddd, " Are Heat - Storage Wells the Answer?", Electrical World, pp. 42-45, Aug. 15, 1973.

[5] A. Lavi, and C. Zener, "Plumbing the Ocean Depths: A New Source of Power", IEEE Spectrum, pp. 22-27, Oct. 1973.

[6] R. W. Boom, Wisconsin Superconductive Energy Storage Project Report, Vol I , 1974, Vol II, 1976, Annual Report, 1977, University of Wisconsin, Madison, Wisconsin.

[7] A. Khalil, and K. Han, "Mechanical and Thermal Properties of Glass Fiber Reinforced Composites at Cryogenic Temperatures", Advances in Cryogenic Engineering, Vol. 28, 1981.

[8] K. Han, R. Peterson and R.E. Rowlands, "Compressive Tests of Composite Tubes at 300 and 77 K", Advances in Cryogenic Engineering, Vol. 28, 1981

[9] S. Van Sciver, "Conductor and Structural Component Studies for Diurnal Energy Storage", 1980 Annual Contractors Review of Mechanical, Magnetic and Underground Energy Storage, Washington, D. C., (1980).

[10] H. R. Segal, and T. G. Richard, " Low Temperature Resistance Studies on Cyclically Strained Al", Advances in Cryogenic Engineering, Vol 22, pp. 486, 1977.

[11] K. T. Hartwig, " Fabrication Studies of a Strengthened Aluminum- NbTi Composite Conductor", Advances in Cryogenic Engineering, Vol. 26, pp. 944, 1980

[12] K. T. Hartwig, and S. W. Van Sciever, "Properties of Joints in Composite Specimens of Al and Cu", Proceedings of the 8th Symposium on Engineering Problems of Fusion Research, IEEE, Pub. No. 79CH1441-5 NPS, pp. 1794, 1979.

[13] S. W. Van Sciever, and K. T. Hartwig, "Boundary Resistance in Al Stabilized Conductors:, Advanced in Cryogenic Engineering, Vol. 26, pp. 499, 1980.

[14] R. W. Boom, "SMES System Design for Diurnal Use", Proceedings of US - Japan Workshop on SuperConductive Energy Storage, University of Wisconsin-Madison, 1981.

[15] X-Huang, Y. Eysaa, M. Hilal, M.K. Abdelsalam and H.H. Abdelmohsen, ""Structural Optimization of Space Borne Torodial Magnets", Applied Superconductivity Conference, San Francisco, CA, UNITED STATES, and IEEE MAG-25,No.1,pp. 179, 1989.