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ENERGY STORAGE

INDUCTOR-CONVERTER SUPERCONDUCTIVE MAGNETIC ENERGY STORAGE FOR ELECTRIC UTILITY USAGE

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Superconductive magnetic energy storage is emerging from a decade of research as a real competitor to other storage systems for meeting the problems of fluctuating energy demand

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This is the last in our series of articles on energy storage techniques. The previous articles in the series were 'Physical principles of advanced battery design' by A Hooper and P McGeehin (*Phys. Technol.* 1981 **12** 45–53, 59), 'Compressed air storage' by I Glendenning (103–10), 'Thermal energy storage' by W E J Neal (213–20, 226) and 'Rechargeable metallic hydrides for hydrogen storage' by H C Angus (245–50, 257).

A superconductive magnetic energy storage system is one of the new systems proposed for the storage of energy by electric utility systems. We have called such storage units IC units in reference to the *inductor* or superconductive coil which stores energy electromagnetically and the *converter* which is an AC–DC thyristor bridge to connect the DC storage coil to a three-phase AC electric grid network (Boom and Peterson 1972). Typically, an IC unit would store inexpensive excess energy during nights and weekends for daytime delivery during peak demand periods.

This is a report of work done at the University of Wisconsin-Madison, USA during the last decade which has been supported by the Wisconsin Electric Utility Research Foundation, the National Science Foundation and the Department of Energy. Worldwide, little other work has been done on IC units for utility storage until the last three years, which have seen two magnetic storage symposia in Japan where technical activities have begun to grow (Mashuda and Shintomi 1978, Nishimura 1979). In the USA the development of IC storage has been a low priority project, pursued almost exclusively at Wisconsin. The Electric Power Research Institute (USA) has recently initiated an 18 month industrial assessment study of superconductive magnetic storage by the Bechtel Corp. and General Atomic Co.

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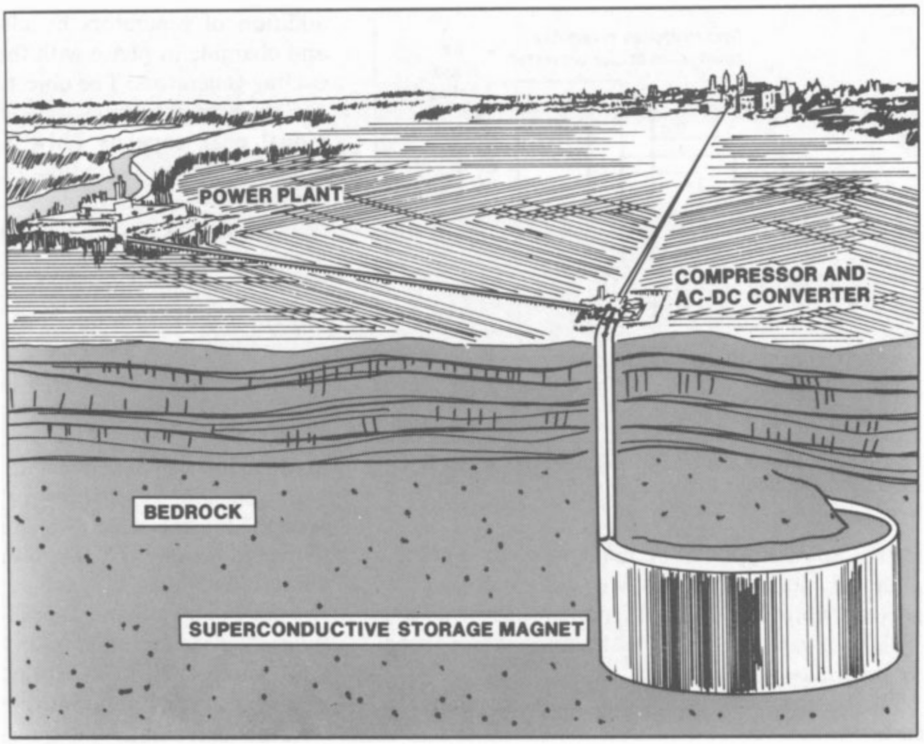


There have been several AC superconductive storage projects, including pulsed coils for fusion reactors, for high energy physics accelerators and for electrical systems stabilisers (Murakami *et al* 1981, Janocko *et al* 1979, Eyssa *et al* 1980, Shintomi *et al* 1979 and Kim *et al* 1979). In the latter case the Los Alamos National Laboratory (LANL) has built a 30 MJ energy storage system for 0.3 Hz stabilisation usage on the Northwest–Southwest transmission system (Schermer *et al* 1981 and Hoffman *et al* 1981). In addition LANL has undertaken one diurnal storage point design prior to opting for the stabilisation storage project (Rogers *et al* 1979).

This article covers the first years of the development of IC systems and reports on analytical system design, experimental component development and electric utility usage. As an example of utility usage we hypothesise storage superimposed on actual load curves of the Wisconsin Electric Power Company, Milwaukee, WI (WEPCO).

IC systems

Energy storage with superconductive magnets became a viable possibility in 1970 when H A Peterson suggested that a three-phase Graetz bridge would be an ideal interface between a DC magnet and an AC three-phase transmission system (Boom and Peterson 1972). Prior to that suggestion several magnetic storage studies in France, England and the USA in the 1960s had looked at various storage magnet designs, none of which had acceptable energy transfer systems (Carruthers 1962, Stekly 1963, Sole 1967, Ferrier 1969 and Brechna *et al* 1972). A particularly valuable property of the thyristor bridge circuitry is that the roundtrip energy efficiency for charge–discharge can easily be better than 95%.

The circuit is shown in figure 1. The converter impresses $\pm E$ on the inductor to (+) charge or (−) discharge. If E is zero then there is no energy transfer and the DC current in the magnet remains constant. On the AC side of the converter the phase angle between voltage and current is 90° when no energy is transferred, about 20° for maximum charge and about 155° for maximum discharge. Charge and discharge are easily controlled and quickly changed within a few cycles by simply changing the delay angle α of the signal which controls the sequential firing of the thyristors. The real power P is given by

$$P = IV \cos \alpha \qquad (1)$$

The reactive load Q is a variable inductive load imposed on the utility grid by the IC unit and generally must be compensated for externally (capacitively). Q can be minimised or kept more constant by switching in and out capacitor modules

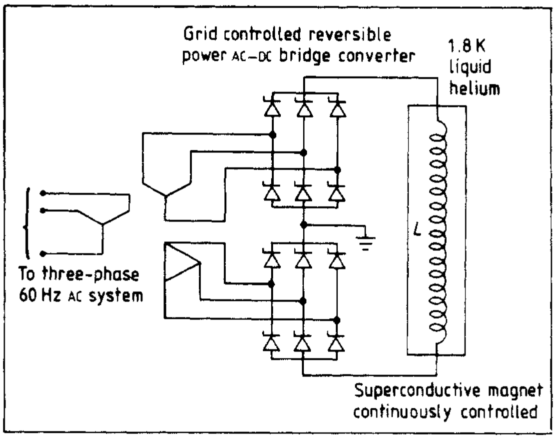


Figure 1 Circuit diagram of AC–DC power converter and inductor (*after Boom, Peterson et al 1974*)

so that an attempt can be made to control system voltage by adding modules with less variation of α. This possibility and other circuit refinements are straightforward available techniques which need not be discussed here.

Three important properties of converter units are the following.

- The storage efficiency is greater than or equal to 95%. This includes all losses from thyristors, leads, snubber circuits and transformers between the superconducting magnet and a 345 kV (or other) AC transmission line.
- Full power reversal time is less than 50 ms without switching.
- The converter technology is fully developed and available due to its current use on DC transmission lines.

Electric utility usage

The three main objectives of energy storage are (i) to reduce the overall cost of delivered energy, (ii) to reduce the overall fuel input and (iii) to improve the operation of a utility. The cost of energy is reduced by charging from less expensive base load generators at night and during weekends and discharging such inexpensive energy daily instead of using more expensive oil, gas or coal cycling generators. The absolute amount of fuel might be reduced because base load generation varies between 33 and 38% thermal efficiency for nuclear and coal while competing daytime peaking units might be combustion turbines at 25–28% thermal efficiency; thus storing 35% heat rate energy at night with acceptable storage losses may be more efficient than instantaneous generation at a 25% heat rate regardless of fuel used. System operation can be improved by rapid load following with storage units. For example, the more efficient storage units can follow the load plus the scheduled addition of generators by alternately discharging and charging in phase with the switching on of the cycling generators. The object here is to operate all cycling generators most efficiently near their individual peak capacity only. Spinning reserve and pollution control credits are other operational values in addition to the load following capability.

The example utility load curve in figure 2 is a load curve for January 1995 produced by the WEPCO planning department as the basis for new generation plans (Boom *et al* 1981). The duration of the peak load, the shape of the load curve and absolute difference between peak and minimum load as shown are predicted to be about the same in 1995 as in 1981. The annual growth rate is predicted to be 3%, almost all of which appears as base load increase. Seasonal differences would account for about 25% differences in total energy delivered per day. The planning process produces a similar load curve for each day of the year. On the right ordinate of figure 2 is plotted the non-uniform differential or incremental production cost for the 1981 mix of WEPCO equipment and fuel. Note that very little oil or gas turbine energy is used and that the incremental costs vary from \$12/MW h to \$24/MW h for coal in the intermediate load region. Base load in 1981 is about 50% nuclear, with the remainder coal.

By inspection one can see that a line drawn across figure 2 at about 4000 MW would give an opportunity to charge and discharge 5500 MW h daily in the intermediate load region. Charging time is 9 h with a peak power of 930 MW. The discharge for a 95% efficient IC unit would be 349 MW for 15 h. This result of IC storage is shown in the hatched areas in figure 2. The unit which would be displaced is a 349 MW cycling coal unit, costing \$1000/kW at 1981 prices, which can be converted to a capacity credit for IC storage. Production cost credits can be determined from figure 2 where \$6/MW h is the average incremental cost difference between \$15/MW h for charging and \$21/MW h for discharging. The parameters for IC storage are listed in table 1.

The capacity credit is $\$1000 \times 349 \div 5235 =$ \$67/kW h. The production cost credit is \$6/kW h extrapolated to an average value of \$17/kW h for 30 years usage which accounts for the (noninflated) more expensive fuel which will not be purchased during the 30 year period. The allowance of \$84/kW h for an IC unit is an attractively large value and appears to be within expectations for the cost of 5500 MW h IC storage units. It should be noted that the replacement of cycling coal generators is the *least favourable* opportunity for IC superconductive storage. J Nicol and R Chapman have undertaken a more complex study of 365 days

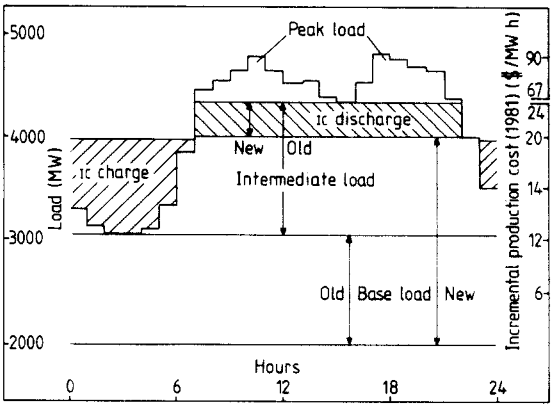


Figure 2 Load curve for January 1995 produced by WEPCO planning department; hatched areas show possibilities of IC charging and discharging

for a typical utility which uses oil for intermediate and peaking generation (table 2). Benefits for IC usage are substantial for either coal or oil utility generation systems, with capital savings greater for coal systems and fuel savings greater for oil systems.

Other storage options

It is appropriate to ask if other storage systems, either available pumped hydrostorage or developmental compressed air storage or developmental batteries, could compete to supply intermediate load. The answer is that other systems have difficulty in the intermediate region because the efficiencies are all low, typically 70% or less (Nicol and Winer 1979). At 70% efficiency the production cost credit of \$17/kW h in table 1 disappears since the 30% storage loss is about equal to the production cost improvement for storage. More importantly, about 30% of the energy is lost so that in our example only 3857 MW h is delivered daily. The extra 1378 MW h per day would need to be supplied during the weekend which implies that the storage unit size would need to be 15 353 MW h. This converts to a capital cost (size) advantage for an IC unit of about *3* compared to any other storage. If IC credits are \$100/kW h for IC unit construction then credits of only \$33/kW h would apply to batteries, pumped hydrostorage and compressed air storage for the above example.

Other more specific problems exist for each system. Compressed air storage burning oil or gas is one of the least efficient energy converters, requiring about 12 900 Btu (~ 13.6 MJ) per kW h of output. This value comes from the Huntdorf, Germany experience which is: 1 kW h output for 0.8 kW h storage input (to compress air) and an additional 5300 Btu (~ 5.6 MJ) of gas to burn the compressed air (Kalhammer 1979). In comparison, using the same charging base load heat rate of 9500 Btu/kW h (~ 10.0 MJ/kW h) an IC unit (counting all losses) at 93% efficiency requires 10 200 Btu (~ 10.8 MJ) input per kW h output. Adiabatic compressed air storage without oil or gas at 70% efficiency would need 13 600 Btu (~14.3 MJ) of fuel. Batteries have deep discharge problems, require reversing switches and are about 70% efficient. Pumped hydrostorage is usually 66% efficient and would need generator pump and pipe combinations larger by a factor of 2.7 in order to charge at 930 MW while discharging at 349 MW. The summary conclusion is that only IC units look attractive for intermediate use. The other storage systems may be most useful for small peaking use where efficiency is less important. The major uncertainty for the use of IC units for intermediate storage is not the competing storage technologies, which are too inefficient, but the final cost of IC units in comparison to intermediate generation. Only after R and D is completed and IC model usage is accomplished will IC costs be available for comparisons.

Storage magnet design

Superconductive magnets, all of which store energy, have become routinely available during the past 20 years. The present challenges of superconductive magnet design usually fall into the category of extending the limits of easy operation towards higher magnetic fields, higher current densities, pulsed operation, new cooling schemes, improved electrical insulation and better structure. The challenge for superconductive storage is to design

Table 1 *WEPCO credits for* IC *storage (predominant coal use)*

349 MW	Capacity
5510 MW h	Needed daily
5235 MW h	Delivered daily
9 h	Charge time
15 h	Discharge time
930 MW	Bridge capacity
\$67/kW h	Capacity credit
\$17/kW h	Production cost credit
\$84/kW h	IC credits

Table 2 *Credits for* IC *storage using scenario D of the EPRI SEUS (predominant oil use) (R Chapman, private communication)*

\$31/kW h	Capacity credit
\$72/kW h	Production cost credit
\$103/kW h	IC credits

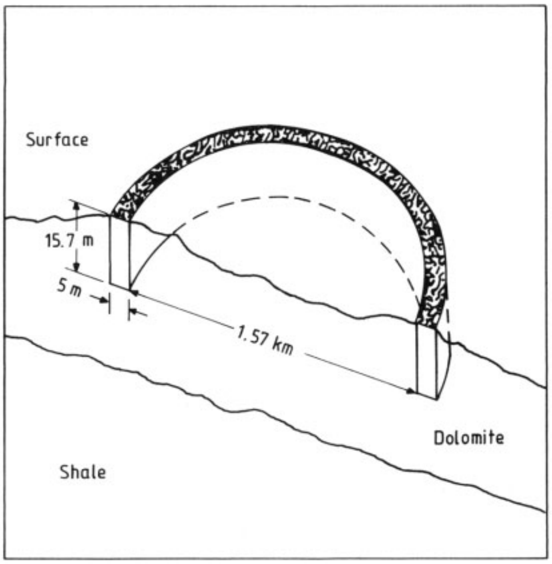


Figure 3 Three dimensional view of low aspect ratio 5500 MW h solenoid in a surface trench in bedrock

the most reliable magnet possible within the imposed economic constraints. Fortunately, we find that storage magnets require low, easily achieved magnetic fields, currently in the 2–5 T region (Boom 1981). Since diurnal storage magnets are DC magnets they avoid the major superconductive problems which are associated with the AC, pulsed, higher current density, lossy, unstable, poorly cooled, overstrained magnets which often require many training steps. The all too frequent, well publicised magnet project difficulties (pulsed high energy physics accelerators magnets, for example – see Broad 1980, 1981) are well described by the list of pulsed magnet problems given above.

We attempt to use for storage the reliability achieved for DC stable bubble chamber magnets. The oldest such large magnets, the ANL 12 ft (3.7 m) and Fermi 15 ft (4.6 m) bubble chamber solenoids, have operated over 15 years together with only one unusual nonscheduled outage (ANL, private communication). This resulted from incorrect operation without full liquid helium coverage and incorrect operator actions. The ultimate cause of the superconducting to normal transition was the operator decision to discharge the coil into the dump resistor. Prior to that decision helium vapour cooling of the top uncovered turns was adequate for DC operation. The fully stable magnet safely underwent a predictable L/R decay with energy deposited both internally and externally.

Table 3 *Major design choices*

Bedrock support
Three-phase Graetz bridge
Single layer solenoid
Fibreglass epoxy struts
Rippled conductor and dewar
Aluminium plus NbTi conductor
1.8 K superfluid helium cooling

The main design problem is structural. The virial theorem of Clausius (1870) as extended to electromagnetics by Longmire (1963) and Levy (1962) states that a minimum structure is required to contain magnetic field energy. In the simplest case for unidirectional stresses the structure mass is

$$M_t - M_c \geqslant \rho W/\sigma \qquad (2)$$

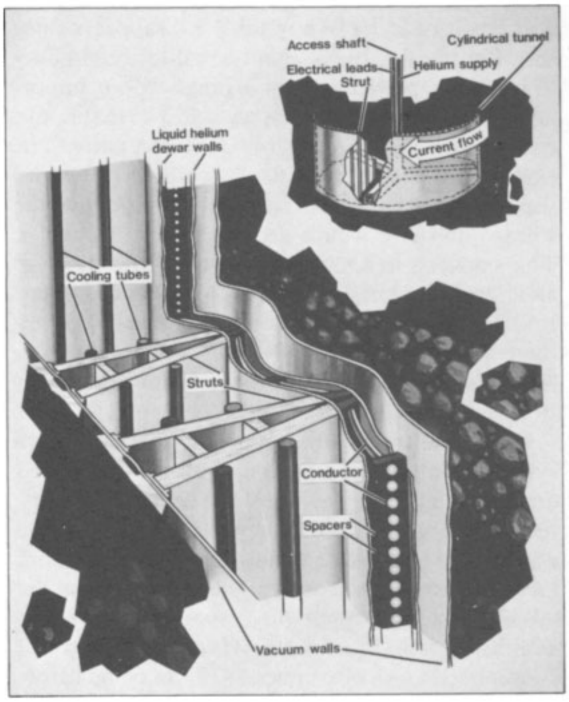
where M_t is the mass in tension, M_c the mass in compression, ρ the structure density, σ the average stress and W the stored energy $(=\int B^2/(2\mu_0)\,\mathrm{d}V)$.

For two-dimensional stresses, only $\frac{1}{2}\rho W/\sigma$ is required since the same material is used in two dimensions. The virial theorem is somewhat subtle in application: for example, any structure in compression is not only wasted but requires an additional amount of structure in tension. Therefore the mass requirement is

$$M_{total} = M_t + M_c = 2M_t - \rho W/\sigma = 2M_c + \rho W/\sigma \qquad (3)$$

as a minimum structure. The conclusion from such consideration is that any ordinary fabricated structure is too expensive. The weight of stainless steel at 3.5×10^8 Pa would be about 160 kg/kW h. If the total project cost should be less than \$100/kW h then steel structure is out of the question.

Figure 4 General sketch of IC unit construction



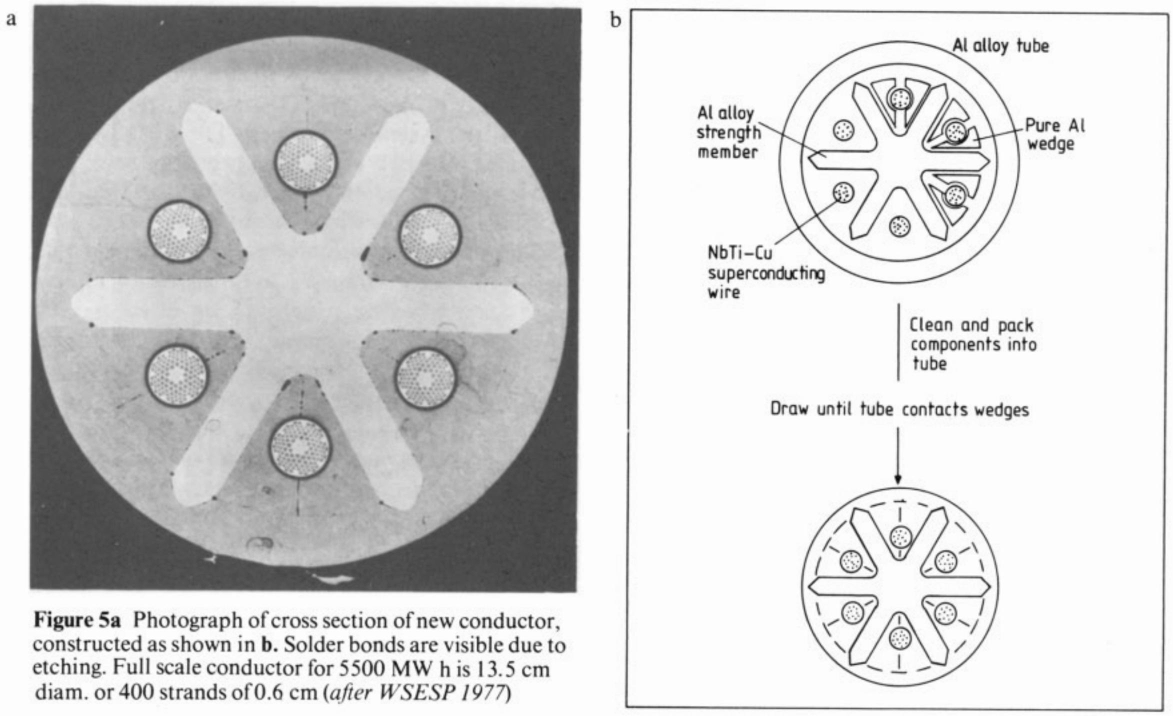


Figure 5a Photograph of cross section of new conductor, constructed as shown in **b.** Solder bonds are visible due to etching. Full scale conductor for 5500 MW h is 13.5 cm diam. or 400 strands of 0.6 cm (*after WSESP 1977*)

Such consideration led to the use of bedrock as structure. The walls of an excavated circular tunnel could bear the radial outward force from a solenoid, for example, and transmit the force to the total body of rock. Rock structure is free except for tunnelling and preparation expense. Figure 3 is the sketch of a trench for a low aspect ratio solenoid designed for the 5500 MW h use described earlier. This design embodies all of the design improvements made in the last decade (WSESP 1976, 1977 and Eyssa and Boom 1980). The major choices for all designs are listed in table 3.

The artist's sketch in figure 4 shows the general concept of the construction. A single layer solenoid is chosen to reduce the number of winding turns and to eliminate possibility for interturn friction at 1.8 K. Fibreglass epoxy struts may be plates as sketched or a similar structure composed of tubes to minimise strut cross section without buckling. The ripples in the conductor and dewar walls are needed to counteract excessive radial travel on cool down (0.4%) and to reduce magnetic tensile loads (T = conductor tension = BIR, where R is the ripple radius of curvature, which is in the region of 1–10 m, instread of 1000 m for a taut circular magnet).

For stability the NbTi filaments must be electrically in parallel with a good cryogenic conductor such as OFHC copper, the commercially available option. Copper is not acceptable for IC units because of its high mass density and large magnetoresistance. A new conductor using a combination of high purity and high strength aluminium is shown in figure 5. We have succeeded in model construction of the conductor via ultrasonic soldering (Hartwig *et al* 1981). The bonds are adequate as to strength and exhibit acceptably small thermal and electrical resistivities. The NbTi in copper strands are Fermilab 0.686 mm diameter conductor, the major available commercial conductor, which is 1 part NbTi and 1.8 parts OFHC copper processed to 8 μm filaments of NbTi. As a measure of the extra stability and safety we note that the ratio of aluminium to NbTi is about to 100 : 1 for our storage magnet while there is no such additional metal used for Fermi pulsed accelerator magnets. Under all ordinary circumstances there can be no training for the storage magnet because of the large amount of aluminium.

To cool such large magnets we have resorted to superfluid pool cooling at 1 atm ($\sim 10^5$ Pa) and 1.8 K. While He II cooling is relatively new it is needed here as, possibly, the only satisfactory coolant for any enormous magnet. He II has a thermal conductivity three or four orders of magnitude better than copper at low temperature with surface heat transfer characteristics which may be an order of magnitude better than any type of He I. The thermal inertia of a large volume of He II is connected thermally to a potential hot spot on a conductor to limit and delay temperature rises. Van Sciver (1978) has shown that because of the thermal

Table 4 *Low aspect ratio IC unit*

Stored energy	5500.0 MW h
Aspect ratio	0.01β
Major radius	784.0 m
Solenoid height	15.7 m
Current	765 000.0 A
Turns	112
Total radial force	3.1×10^{10} N
Total axial force	3.1×10^{11} N
Average radial pressure	392.0 kPa

inertia of the total volume of helium a local conductor hot spot can exceed the DC heat transfer and transmission limits for times typically 1–10 s. In comparison hollow tube conductor cooling with supercritical helium may hold temperatures only for milliseconds. In 10 s any ordinary transition from the superconducting to normal state should recover. In effect, He II cooled magnets which are designed with sensible limits as to coolant cross section and coolant path lengths do not allow turns to become and remain normal (nonsuperconducting). The safety problem reduces to a loss of helium problem.

The coil is submerged in a narrow dewar (to minimise helium inventory) which contains confined He II at 1 atm ($\sim 10^5$ Pa). The helium is cooled by a heat exchanger with 1.8 K, 12 Torr helium which is provided by a liquefier and vacuum pumps. This is a simple system made redundant by extra liquid helium storage and extra vacuum pumps. The helium off gas is heat exchanged within an optimised single purpose refrigeration loop to achieve 900 w/w overall refrigeration efficiency at 1.8 K. One heat intercept on the strut at 77 K cooled with liquid nitrogen is adequate for the low aspect ratio coil. Extra liquid nitrogen would be stored for redundancy in addition to a separate dedicated N_2 liquefier. If two heat intercepts are needed the several designs for smaller radius typically use 11 K and 70 K intercepts (WSESP 1976).

Low aspect ratio coil

It has been implied above that the example systems were low aspect ratio coils. Such coils have large diameters, small heights (β = height/diameter) and are one-dewar coils which can be constructed in surface trenches in bedrock. Specifications for a low aspect unit suitable for the WEPCO example are listed in table 4.

The radial pressure and total radial force for $\beta = 0.01$ coils are about 10% of the values for $\beta = 0.3$ designs. Most previous Wisconsin designs were $\beta = 0.3$ solenoids of 1, 3, 5 and 15 tunnels. One reason for favouring a low aspect ratio coil is that the low radial force and low radial pressure result in a simple strut cooling scheme with one cooling station at 77 K and a low refrigeration power which requires only about 2% of the weekly stored energy to cool the system for a week. The $\beta = 0.3$ designs require about 10% of the weekly energy as well as a more complicated and expensive strut system with two cooling stations at 11 K and 77 K.

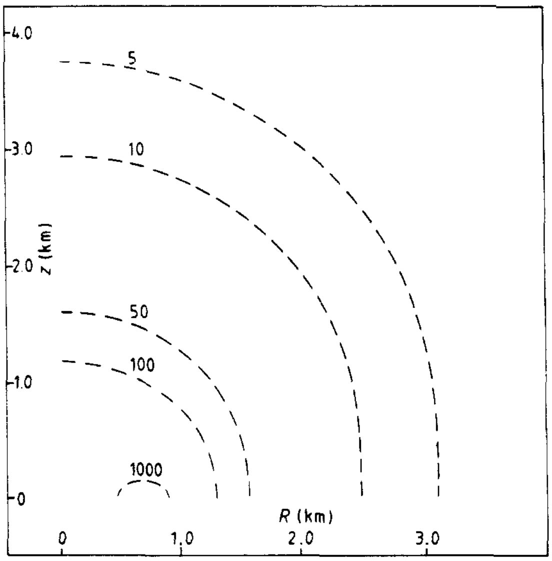
The major disadvantage for a low aspect ratio coil is that the axial load is to be carried by internal cold axial structure which can be expensive. For $\beta = 0.01$ the axial structure amounts to 18% of the virial theorem mass $\rho W/\sigma$. If high strength aluminium alloy rated at 330 MPa or higher is used then the cost of axial structure is probably acceptable, depending on an economical design which can maintain high stress levels by mechanical overlaps or tongue and groove fits, for example, instead of welding.

The stray field from the IC unit listed in table 4 is shown in figure 6 (Boom *et al* 1981). Note that the fields vary as $1/r^3$ and that the 5–10 G contours extend out to 3 km. Although such small fields are not perceived to be dangerous they probably will lead to an environmental requirement such as a simple farm use for a limited surface area.

Fifteen tunnel magnet

A 15 tunnel design which reduced the need for cold axial structure was reported in 1979 (Van Sciver and Boom 1979). The 15 tunnels are arranged in a

Figure 6 Stray field from IC unit listed in table 4. External field contours are in gauss, coil centre is at origin, and windings are at 784 m. E = 5500 MW h; B = 3.5 T (*after Boom et al 1981*)



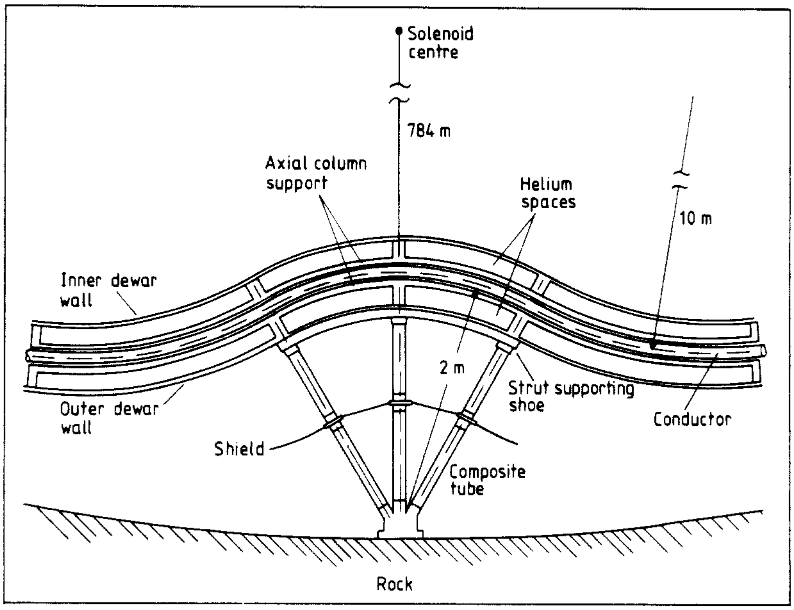


Figure 7 Details of low aspect ratio 5500 MW h solenoid with 10 m struts spacing. Not shown are inner and outer vacuum walls. Axial support is 7075–T6 aluminium

circular pattern so that forces in each tunnel are directed radially outward without shear on a rock face. Here shear is equivalent to the axial load in the low aspect ratio coil. Without shear forces the required axial structure is only 3.2% of the minimum virial theorem mass, mostly in the end two 'field adjustment' tunnels. More information is given in the paper referred to.

A main difference between the two designs is that the low radial 4 atm ($\sim 4 \times 10^5$ Pa) pressure of a low aspect ratio coil allows for surface trench construction even in weak rock. The pressure in the 15 tunnel design averages 40 atm ($\sim 40 \times 10^5$ Pa) which requires better rock in addition to a deep rock tunnel pattern.

Fabrication

The field construction of a unit can be visualised in reference to figures 7 and 4. Rock surfaces would be sealed and the walls, struts, axial structure, conductor and inner dewar walls would be welded into a ripple contour. The only non-welded components would be the axial column support members which are tempered 7075 aluminium. These parts would be keyed and pinned.

The conductor is supported by fibreglass epoxy straps, alternately over and under the conductor and fastened to the axial column so that in effect the conductor and axial support form a strong single entity rippling around 10 m and 2 m radii of curvature. The axial supports provide extra tensile load capability so that 10 m radius of curvature is possible (figure 7). Extra helium space is automatically available between the anti-buckling cross braces on the axial structure which provides additional helium enthalpy stability.

Safety

Superconductive quench and recovery considerations do not apply since the transient stability of the He II bath and the excess conductor aluminium prevent propagation of normal regions and require recovery. In case it becomes necessary to discharge quickly, due to rapid increase in helium usage, it is probably best to dump the helium and have the magnet absorb energy internally. Trap doors could be opened to drop the liquid helium out of the magnet enclosure into a cooled container to save liquid helium, a 5–10 s operation. Heaters might be switched on to drive *all* of the coil normal within 1–5 s. For a 5500 MWh unit L/R for a normal coil is about 60 s (at room temperature) with inductive and resistive voltages cancelling locally so that no high voltage results. If the energy is dumped uniformly in the conductor and in the parallel aluminium structure which becomes a switched-in shorted turn, then the maximum conductor temperature need not exceed 400 K. It appears possible to limit temperatures in this worst case by arranging for the conductor to have extra mass for enthalpy reasons or to parallel all burns in an emergency discharge scheme (Eyssa *et al* 1981). It should be recalled that large DC magnets such as the bubble chamber magnets might face a discharge emergency less than once per 10 years. It is expected that many precursors to an emergency would be evident, such as a slowly deteriorating vacuum or a steady increase in helium usage. However, systems which hold helium initially are reliable systems. Most potential leaks result from fatigue failure which is more remote for bedrock support schemes since the infinite structural mass restricts cyclic strains to small excursions.

Costs and scaling optimisation

IC units are capital intensive. The cost can be divided into three general categories which relate to ampere metres of conductor, surface area and forces. For example, the conductor, helium inventory and assembly costs would be largely proportional to *IS*, the ampere metres used. Rock excavation costs, dewar walls and losses through superinsulation would be related to *A*, the inner and outer surfaces of a thin solenoid. The force bearing strut mass and refrigeration system would be proportional to the total force *F*, which is carried from the conductor to the bedrock. In terms of geometrical factors *Q* and *G* and stored energy *W* and maximum field B_M we get for thin solenoids (Boom *et al* 1974):

$$\begin{aligned} IS &= Q_{is}(\beta) W^{2/3}/B_M{}^{1/3} \\ A &= Q_a(\beta) W^{2/3}/B_M{}^{4/3} \\ F &= Q_f(\beta) W^{2/3}/B_M{}^{2/3} \\ R &= G(\beta) W^{1/3}/B_M{}^{2/3}, \end{aligned} \tag{4}$$

where W is the stored energy, B_M the maximum midplane field, $Q(\beta)$ is a function of β only, β is the solenoid length/solenoid diameter, $G(\beta)$ is a function of β only, and R is the radius.

All three of the major cost components vary as $W^{2/3}$. Thus an economy of size is available for IC units which is not available to competing storage units whose costs tend to be proportional to W. The relative costs on a per unit basis are listed in table 5.

Costs are almost totally optimised by B_M variation which recommends $B \simeq 2$–5 T for NbTi at 1.8 K. Optimisation is very broad and allows for considerable eventual compromise engineering choices. The cost trends with B are evident from equations (4).

As part of a 1975–6 optimisation (Boom *et al* 1975) we estimated that a three-tunnel 10 000 MW h IC unit would cost \$393m, an amount subsequently increased to \$456m by an independent assessment (Nicol and Winer 1979). The costs were understandably uncertain because the project is still in the initial R and D phase. Allowing for inflation at 10% per year the present cost would be \$734m or \$73/kW h which is less than the credits developed in tables 1 and 2. Thus credits might exceed cost estimates, albeit on a tentative basis. Although real costs usually exceed estimates one might expect the above predictions to be sustained since the new low aspect ratio coil is basically less expensive than the older three-tunnel coil, in part due to the simple trench instead of multiple deep tunnels.

Table 5 *Relative costs*

IC *magnet size* (MW h)	*Relative capital cost per kW h*
100	3.71
1000	1.72
5000	1.00
10 000	0.79

Projection

The most optimistic time schedule for implementation of IC storage would be to complete the component developments by 1984, to operate a 100 MW h model by 1988 and to become commercially available in the 1000 MW h range by 1990. The usual problems of scale up to larger units should be avoided since only the major radius is changed. The parameters independent of IC unit size are current, field, rock pressure, strut, ripple radii and aspect ratio all of which would be completely verified at 100 MW h.

A successful test of a 100 MW h model is excellent preparation to extend the system to commercial sizes without further research and development. The three size-dependent parameters, power, voltage and energy per gram of conductor, can predictably be accounted for by using choices in the 100 MW h model which would be satisfactory at 5500 MW h. Extrapolating to a larger AC–DC bridge is easy since bridges can be purchased at fixed price. If a 5500 MW h unit were planned at 2 kV maximum then the 100 MW h model unit should be tested to withstand 2 kV in the dewar even though operating voltages at 100 MW h are smaller. The energy per gram of conductor represents an efficiency of size, and inherently becomes more of a safety consideration at higher stored energies. However, any measured temperature rise of the 800 000 A conductor during a simulated forced outage in the 100 MW h model can easily be extrapolated to larger size units. The major lesson from the construction of a 100 MW h model is to verify construction procedures, construction costs and utility usage.

The IC storage unit described holds promise to become a significant part of the future electric utility plant in the USA.

Acknowledgments

Many engineering faculty staff and students have contributed to the storage project during the past 10 years. In view of the topics emphasised in this article, we would mention especially: H A Peterson, Professor Emeritus, who was a cofounder of the project and suggested the Graetz bridge approach; G E McIntosh, K Han and A Khalil for cryogenic and mechanical design; Y M Eyssa and R W Moses for analytical system design; B C Haimson and P LaPointe for rock mechanics; K T Hartwig for conductors research; D C Larbalestier for NbTi research; and S W Van Sciver for He II cryogenics and conductor stability.

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