The SuperCable: Dual Delivery of Hydrogen and Electric Power

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***Abstract*--The prospect of transporting of large amounts of electric power over long distance superconducting dc cables was first considered in the 1960s by Garwin and Matisoo [1]. They envisioned the construction of a 100 GW, 1000 km, dc superconducting transmission line based on the then newly discovered type II compound, Nb_3Sn, refrigerated throughout its entire length by liquid helium at 4.2 K. With the advent of practical and commercially available long length high temperature superconductor tapes in recent years, and the desire to move the US to a hydrogen-based transportation economy, their original concept takes on an additional dimension – the use of hydrogen as a cryogen to both enable superconductivity and as an energy delivery agent in and of itself. The author has addressed previously the significant societal benefits to be derived from the dual delivery of hydrogen and electricity over such a "SuperCable [2, 3]". In the present paper, we present an engineering scoping design for a bipolar cable system to carry 1000 MW dc bipolar via superconducting wires and 500 MW hydrogen thermal equivalent through each pole separately in liquid state, over 100 km scale distances. Finally, we point out the capability of a long distance SuperCable, not only to deliver hydrogen, but to store it for subsequent conversion to electricity in amounts on the energy scale of large pumped hydro facilities. Realization of such an energy storage capacity would truly revolutionize the marketing of electricity.**

***Index Terms*-- DC power transmission, High-temperature superconductors, Hydrogen, Superconducting cables**

I. Nomenclature

One quad equals one quadrillion (10^{15}) Btu (British thermal unit), or 3×10^{11} kilowatt-hours. On average, one quad per year is enough to power about three New York Cities. MMTCE denotes million metric tonne carbon equivalent, and HTSC denotes "high temperature superconductors," defined as those metals with a transition temperature above 30 K. The use of the terms "hard" or "type II" are equivalent descriptions of practical superconductors.

II. Introduction

According to the DOE International Energy Outlook 2004, world energy consumption is expected to grow from its present level around 400 quads per annum to well over 600 by 2025, a more than 50% increase [4]. Moreover, many predict human population levels to approach 10 billion by mid-century with global industrialization rates far outpacing those of the United States. As the world aspires to reach an American standard of living, IEO 2004 predicts the present energy consumption rate, 215 quads per year in the industrialized nations and 185 in emerging countries, to evolve toward 270 to 330, respectively. How to supply and configure the energy economy and infrastructure for such a world is perhaps the principal long-range challenge facing human civilization at the dawn of this new century. A major component of the challenge will be to attain this goal in the most environmentally benign and least eco-invasive manner possible.

A principal uncertainty in this social equation is the extent to which the earth's remaining fossil fuel reserves can be exploited. Even though the possible link between observed increasing global temperature and concommitant increasing carbon dioxide emmissions (currently at 6,000 MMTCE/year and expected to reach 10,000 by 2025) remains open, all agree that such a link is at least physically plausible, and the coming decades are likely to see an internationally agreed upon "no regrets" policy adopted severely restricting or eliminating the use of fossil fuels for both transportation and the production of thermal and electrical energy. One major harbinger of this trend is the concentrated effort globally to develop technology to displace hydrocarbons with hydrogen to fuel surface transportation. We have argued that the production of sufficient hydrogen to displace present consumption of petroleum in automobile and truck vehicles in the United States alone, either by electrolysis or thermal splitting of water or methane would require additional power production equivalent to doubling the nation's current electricity generation capacity [5]. Given the massive amounts of CO_2 to be sequestered should hydrogen be generated either directly or indirectly from fossil fuels, and the enormous land areas needed for biomass, wind or solar required in its place, it was concluded that only nuclear power could feasibly enable a complete hydrogen economy.

In a certain sense, hydrogen and electricity can be considered "mutually fungible." In a number of instances, each can replace or be transformed into the other – hydrogen as potential energy and electricity kinetic. However, it will be most realistic to provide both and let the end user decide the choice to employ. Figure 1 depicts just such a scenario on an urban scale, where both hydrogen and electricity are produced centrally in a nuclear power plant, supplemented by roof-top solar photovoltaics and perhaps the combustion of waste

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biomass, and distributed throughout the community via a SuperCable conveying cryogenic hydrogen and electricity using superconducting wires refrigerated by the former.

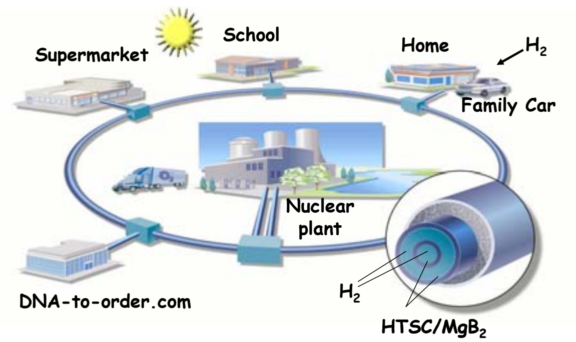

Fig. 1. Vision concept of an urban community whose complete energy infrastructure comprises electricity and hydrogen generated by nuclear fission and solar roof power distributed through a SuperCable ring bus [2].

In a paper delivered to the American Nuclear Society, Chauncey Starr expanded this concept to engender a vision of a "Continental Energy SuperGrid," a nationwide network of nuclear power plants linked by SuperCables [6]. The publication of his paper was followed by a subsequent workshop organized by the University of Illinois, Urbana-Champaign to explore the engineering feasibility of various aspects of the SuperGrid, including the topics of system stability, reliability and physical security, which concluded such a project, despite its immense scale and cost, could in principle be carried out using present or soon to be available technology [7]. .

III. SuperCable Design Concepts

We now examine in more detail several of the engineering and design issues embedded in the SuperCable.

A. Background

Almost immediately after its discovery in 1911, superconductivity and superconducting wires, with their ability to carry direct current without loss, were proposed for electricity transmission and distribution cable application. However, the early superconductors were primarily elemental metals whose superconducting properties disappeared for even moderate currents and magnetic fields. Furthermore, the necessity to supply large amounts of liquid helium for their operation was a major, if not overwhelming, barrier. Not until the discovery of "hard" superconducting alloys such as NiTi and Nb_3Sn capable of sustaining practical levels of current in the years following World War II, the ability to manufacture long wire lengths of these materials, and the increasing availability of efficient helium liquefaction equipment, could transmission of electricity via superconductivity be seriously considered.

In 1967, Richard Garwin and Juri Matisoo at IBM published a paper proposing the construction of a 100 GW, 1000 km, dc superconducting transmission line based on the then newly discovered type II compound, Nb_3Sn, refrigerated throughout its entire length by liquid helium at 4.2 K [1]. At the time it was thought remote nuclear power plant farms or hydroelectric facilities would provide a major portion of the then burgeoning national demand for electricity, and that the "high power bandwidth" transmission at near zero loss available from deployment of superconducting cables would become economical. In principle, their idea presaged many aspects of the SuperGrid concept. In the 1970s and early 1980s, more studies on the feasibility of both ac and dc superconducting cables appeared, and two watershed ac superconducting cables were built and successfully tested at Brookhaven, NY, and Graz, Austria, the latter actually undergoing live grid service for several years [8]. At least two reports published during this period explored the joint use of hydrogen with superconducting wires for electricity transmission. Bartlit, Edeskuty and Hammel considered an energy transmission line employing low temperature superconductors cooling by liquid helium with liquid hydrogen serving as a heat shield, the hydrogen to be delivered eventually as rocket fuel for NASA [9]. In 1975, a report assembled by Stanford University and NIST examined the use of "slush hydrogen" at 14 K as cryogen for a cable using Nb_3Ge with a transition temperature near 20 K as the superconductor [10]; however, no attention was given the use of hydrogen as an energy agent itself.

Following on the discovery of high temperature superconductors in 1986 and the appearance of practical tape and wire in the early 1990s, Schoenung, Hassenzahl and Grant revisited the work of Garwin and Matisoo in light of these new events, and concluded that an HTSC dc "electricity pipeline" cooled by liquid nitrogen could compete economically with conventional high voltage dc transmission lines or gas pipelines for distances greater than 200 km [11]. Although today several prototype HTSC superconducting cable demonstrations are planned or actually undergoing test worldwide [12], all target ac applications at transmission and distribution voltage levels at 66 kV and greater, we must emphasize that the major advantage of superconductivity is the ability to transport very large dc currents at relatively low voltage. Only under constant current conditions are superconductors perfect conductors, otherwise heat-producing hysteretic losses occur requiring additional cryogenic capacity above and beyond that to remove ambient thermal in-leak to the cable. Moreover, the use of lower voltages will reduce dielectric stress and improve cable reliability and extend lifetime.

B. Balance Between Hydrogen and Electric Power Delivery Capacity

Perhaps the most important design issue for the SuperCable surrounds both the absolute and relative amounts of hydrogen and electric power to be delivered. In a total "hydricity economy," such questions remain to be socially and economically settled, and much of the answer will depend on other means to transport hydrogen and the end use it will receive. Will the latter be as thermal energy, transportation fuel or energy storage, or, as is likely, a combination of all three and in what proportion? For purposes of our preliminary design discussion, we will employ the principle of "greatest social transparency," or "least interference" with current individual energy consumption customs. That is, we will simply assume hydrogen as a domestic energy agent will completely supplant current consumption of hydrocarbons (natural gas, LPG or heating oil) and household electricity demand will remain more or less the same. Hydrogen for transportation will assumed to be distributed independently. The typical California residential household (such as the author's) consumes roughly equal amounts of electricity and thermal energy in the form of natural gas annually. We will assume the peak demand at any given time to be 5 kW equivalent for each, we will configure a SuperCable to deliver 1000 MW_e via superconductors and 1000 MW_t via flowing hydrogen to service a community of 200,000 households (even though utilities design for much larger local capacity, e.g., wire size a split phase 200 ampere service for ~ 50 kW, transmission and generation capacity are probabilistically determined on the assumption only a small number of consumers will actually need this amount of power at any given time!).

Figure 2 outlines the essential physical characteristics and cross-section of a basic SuperCable circuit. Note that each "cable" delivers half the total hydrogen power.

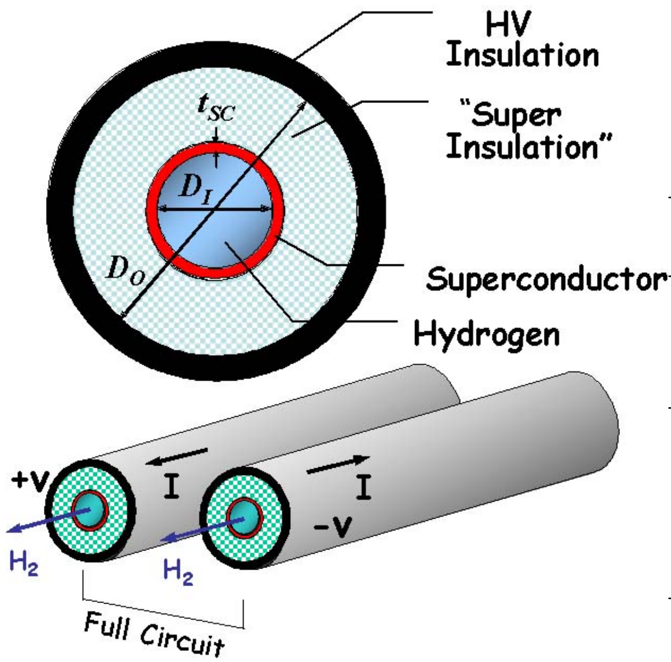

Fig. 2. SuperCable cross-section schematic (roughly to scale) for one pole of a bipolar circuit.

D_O is the cable diameter exclusive of the high voltage insulating sheath, in most cases for low voltages on the order 5 kV considered here, will also approximate the overall diameter (we assume the thermal superinsulation has some level of electrical conductivity such that at D_O the potential is the same as the superconductor). D_I is the diameter of the inner cryostat tube carrying flowing liquid hydrogen, and t_{SC} is the thickness of the annular ring of superconductor wire or tape surrounding it.

The respective electric and hydrogen power flow equations, given the geometry of Fig. 2 are,

$$P_{SC} = |V| J \pi D_I t_{SC}, \tag{1}$$

for $t_{SC} << D_I$, where P_{SC} is the power delivered in watts-electric through the superconducting sheath surrounding D_O, V is the pole-to-ground potential of the sheath, J is the practical critical current density of the given superconductor, and D_I, $t_{SC,}$ were defined previously in Fig. 2., and for hydrogen;

$$P_H = Q \rho v \pi D_I^2 / 2, \tag{2}$$

where P_H is the hydrogen chemical power flow in watts-thermal, Q = Gibbs oxidation potential of H_2 (2.46 eV/mol), ρ the mass density of liquid hydrogen (70.8 kg/m^3), and v its flow velocity through the cryostat of diameter D_I .

Equations (1) and (2) subsequently permit estimating the physical dimensions and superconductor material performance parameters necessary to achieve the target 1000 MW power capacities chosen for both hydrogen and electricity. The results are summarized below in Tables I and II.

TABLE I
NOMINAL SUPERCABLE PARAMENTERS ENABLING 1000 MW-THERMAL HYDROGEN DELIVERY CAPACITY

Hydrogen Power (MW_t)	Cryostat Tube Diameter D_I (cm)	H_2 Flow Rate v (m/s)	"Equivalent" Electrical Current Density J (A/cm^2)
1,000	15	3.39	283

TABLE II
SUPERCONDUCTOR CURRENT DENSITY AND ANNULAR WALL THICKNESS ENABLING 1000 MW-ELECTRIC GIVEN PARAMETERS FROM TABLE I

Electric Power (MW_e)	Voltage (V)	Current (A)	HTSC Current Density J (A/cm^2)	Annular Wall Thickness t_{SC} (cm)
1,000	± 5,000	100,000	25,000	0.085

Some comments and observations on the above assumptions and results are in order:

1. The cryostat diameter and fluid flow rate are the principle factors determining hydrogen power delivery aside from the physical constants of liquid hydrogen itself. The choice of an inner diameter of 15 cm we believe to be quite reasonable and on the scale of LH_2 fuel transfer lines used in the US and European space programs.
2. A flow rate of 3-4 m/s is approximately that used both for liquid hydrogen fuel delivery and for cryogenic liquid nitrogen in the far more confined

diameters (2-4 cm) employed in the aforementioned ac superconducting transmission demonstrations. The question of viscosity losses remains an issue to be addressed.

3. Operational critical current densities of 25,000 A/cm^2 are readily achievable at 20 K with presently available HTSC wire technology, and are expected to be reached soon for wires made from the newly discovered 39 K MgB_2 superconductor as well.
4. We note the exceptionally thin superconductor layer –- approximately 1 mm, about the thickness of a single HTSC tape –- required surrounding the exterior of the cryostat to achieve a net current flow of 100,000 A. For our electric power delivery goal of 1000 MW, the ability to sustain this magnitude of current allows the voltage to be reduced to only 5 kV to ground greatly simplifying insulation material requirements.
5. Finally, it is interesting to compare the "equivalent electrical current density" of the volume flow of hydrogen calculated in the right hand column of Table I with that attainable with superconductors. In terms of an energy corridor or right-of-way cross-sectional area, electricity-by-superconductivity wins by a major margin. This is an example of one of those "social/economic" factors that will enter into future discussions over the relative needs and uses of each type of energy.

C. Control and Removal of External Heat In-leak

Leaving aside for the moment frictional energy released by the viscous flow of liquid hydrogen, the principle heat component required to be removed by the cryogenic support for the SuperCable will be that transferred from surrounding ambient, and is primarily radiative. Ideally, for pure direct current there would be no dissipative loss in the superconductor arising from hysteretic vortex movement forced by the time-varying magnetic fields produced by ac. In superconducting ac cables, such effects are the principle source of heat, and, in some sense, the cryogen in the cable acts as a heat removal agent, much like the oil in a conventional cable, in addition to maintaining temperatures low enough for superconductivity to occur. Practically, however, the level of ripple induced in a dc line by rectification and imperfect filtering of an ac generation source could become a serious issue. For example, even if the ripple factor were only 1 %, at 100,000 A there will exist a 1000 A rms current whose heat production will have to be dealt with. Moreover, managing supply/load variations will require constant current control by changing voltage level. Energizing and de-energizing the electrical system of the SuperCable must be handled with great care, a well-known challenge with persistent current superconducting magnets. Finally, a word on heat in-leak due to thermal conduction from ambient. Normally, if the vacuum level between the inner cryostat and outer high voltage insulation sheath can be kept below 10^{-5} torr permanently, thermal conduction can be neglected, and this is the case for most commercial cryogenic fluid transfer lines. We defer discussion of other sources of thermal load to a later work in progress, and next address only radiative loss.

The Stefan-Boltzmann relation governing thermal radiation transfer for two surfaces at temperatures widely separated spatially, in our case, between D_O and D_I, can be expressed as

$$W_R = 0.5\varepsilon\sigma(T_O^4 - T_I^4), \tag{3}$$

where W_R = radiated power from ambient in watts per unit area, and we set T_O = 300 K and T_I = 20 K, with σ = 5.67×10^{-12} W/cm^2×K^4. The emissivity, ε, characterizes the "black body" nature of a given material, typically taken as 0.05 for polished metal surfaces. Taking D_I = 15 cm yields W_R = 5.4 W/m. This result can be substantially lowered by the interposition of an number of layers of "super-insulation," such as thin aluminized Mylar sheets, in the space between D_O and D_I. In practice, it is found that one can reduce the emitted radiation in inverse proportion to $n - 1$, where n is the number of superinsulation layers. Assuming n = 11, about the number of sheets used in present superconducting ac cable prototypes, the radiative heat in-leak can be reduced to nearly 0.5 watts per unit meter length of cable. The space taken up by 10-12 layers of superinsulation is about 3-4 cm, resulting in D_O in the range 21-23 cm and an overall SuperCable diameter of perhaps 25 cm.

We next estimate the temperature rise along the SuperCable cryostat length anticipated from this amount of heat input. The result will gauge the spacing and capacity of refrigeration stations necessary to remove this heat and control the temperature rise as given by

$$\frac{dT}{dx} = \frac{4W_{Tot}}{\pi\rho v C_P D_I^2}, \tag{4}$$

where W_{Tot} is the total heat in-leak power in watts per unit length and C_P = 9690 J/kg×K is the heat capacity of liquid hydrogen, the other symbols having been defined previously. If we take W_{Tot} = 1.0 W/m, that is, twice our calculated radiative loss, to approximately account for addenda thermal conduction and other miscellaneous sources, along with the values of v and D_I as given in Table I, we find dT/dx = 2.43×10^{-5} K/m or about 1/4 degree Kelvin every 10 kilometers, readily manageable with appropriately spaced "booster" cryostations.

D. Storage of Electricity as Hydrogen in the SuperCable

Finally, it is interesting to consider hydrogen in the SuperCable acting not only as a cryogen and an energy delivery agent, but as a possible medium for storage of electricity in addition. For example, suppose in the circuit in Fig. 2, the liquid hydrogen circulated through both "poles," rather than flowing unidirectionally in each, with only small amounts tapped off for delivery, and most left for future conversion back to electricity (this scenario implies LH_2 "buffering tanks" be located appropriately along the length of the circuit to assure enough would be continuously available for cryogenic purposes). Table III compares a possible SuperCable energy storage circuit configuration with two large existing pumped hydro and compressed air energy storage (CAES) facilities.

TABLE III
COMPARISON OF POTENTIAL STORAGE CAPACITY OF THE SUPERCABLE WITH CONVENTIONAL SYSTEMS

Facility	Capacity (GWh)
Raccoon Mountain (TVA)	32
Alabama CAES	20
400 km SuperCable Circuit D_I = 15 cm	33

Note a 400 km SuperCable circuit would store the equivalent of TVA's Raccoon Mountain reservoir, the largest pumped hydro unit in the US with a considerable smaller footprint, with the caveat that the "round trip efficiency" of reversible fuel cells is yet to be determined. Of course, not all this capacity would be immediately available, and a reserve supply, probably stationed at the 10 – 20 km "recooling booster" stations mentioned before, will be necessary to maintain a sufficient amount for cryogenic purposes. A nationwide development of SuperCable infrastructure could enable the long-sought "commoditization" of electricity through its storage as liquid hydrogen and thus revolutionize electricity markets.

IV. SUMMARY AND CONCLUSIONS

In this paper, we presented some rough scoping calculations for a combined hydrogen/electricity energy delivery and storage "SuperCable." The results suggest such a concept is technically feasible right now without having to anticipate future and problematic discoveries of new materials. Yet, a large number of engineering issues remain to be addressed; e.g., how to accommodate the substantial forces between between two monopole cables created from the magnetic fields surrounding the flow of 100 kA currents…would a coaxial design serve better? What sort of power electronics infrastructure is required to maintain the lowest possible ripple factor and manage load/supply variation at constant current? And then, there are a myriad of energy use variables that are really societal and economic determinants, such as the division in the deployment of electricity versus hydrogen alluded to before. To be sure, there will be no shortage of interesting and fun problems to solve while giving practical birth to the SuperCable.

V. ACKNOWLEDGEMENT

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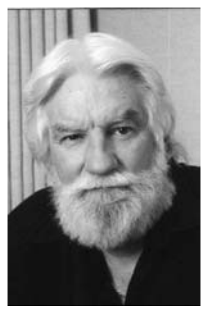

Paul M. Grant was born in Poughkeepsie, NY, on May 9, 1935. He holds a BSEE degree from Clarkson University and the AM and PhD degrees in Physics from Harvard University. His undergraduate and graduate education was underwritten by the IBM Corporation whose employ he entered in 1953 at age 17.

His early career with IBM was as a technician and system programmer on Project SAGE, the world's first supercomputer and prototype for NORAD. During college, he returned to work summers at IBM on thin magnetic film memory development, silicon epitaxial film growth and laser spectroscopy. His PhD thesis addressed the optical properties of semiconductor thin films.

Upon completing graduate school, Dr. Grant was posted to the IBM San Jose Research Laboratory where he pursued a variety of basic research studies on the physical properties of magnetic semiconductors, organic and polymer metals, and high temperature superconductors and participated in the initial development of laboratory automation software and systems. His IBM career also included management and divisional executive staff responsibilities to evaluate IBM's printer, storage and display technologies. In addition, he served a two-year sabbatical as IBM Visiting Professor of Materials Science at the National University of Mexico.

In 1993, Dr. Grant retired from IBM to accept a position as Science Fellow at EPRI where he oversaw a variety of exploratory studies on wide bandgap semiconductors and power applications of superconductivity, and served as a consultant to EPRI's executive management and utility membership on a broad range of energy science issues. He retired from EPRI in early 2004 to undertake a variety of personal and professional interests.

Dr. Grant has published over 100 papers in scientific peer-reviewed journals, as well as numerous articles on science and energy issues in the popular press and interviews on television which have earned him several awards as a science writer and commentator. He is a co-inventor on the international base patent for high temperature superconductivity and consults regularly with the US Department of Energy on power applications of superconductivity. Dr. Grant is a Fellow of the American Physical Society and sits on the Executive Committees of the Society for Industrial Physics and Education.