The SuperCable: Dual Delivery of Chemical and Electric Power

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***Abstract*—We consider the general design of an "Energy SuperCable" capable of efficient simultaneous transmission of chemical and electric power over long distances. The electrical component consists of wires or tapes of high temperature ceramic superconductors or MgB_2, while the chemical element comprises liquid or cold gaseous hydrogen or liquid methane. In principle, hydrogen or methane can also serve as cryogens, although for the latter, practical superconducting wire does not yet exist that is able to operate at the required temperature. On the other hand, liquid hydrogen would suffice for present HTSC wire, but one could also consider a "hybrid" design whereby liquid nitrogen is the primary refrigerant and the chemical agent is liquid methane or cold hydrogen gas under pressure. We point out that hydrogen in the SuperCable can perform the dual function of energy delivery and electricity storage on the scale of a pumped hydro facility, the realization of which would revolutionize the marketing of electric power.**

***Index Terms*—DC power transmission, high-temperature superconductors, hydrogen, superconducting cables.**

I. INTRODUCTION

ACCORDING to the US Department of Energy (DOE) International Energy Outlook (IEO) for the year 2004, world energy consumption is expected to grow from its present level around 400 exajoules (EJ) per annum to well over 600 by 2025, a more than 50% increase [1]. 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 EJ 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. It has been suggested supplanting a dependence on fossil fuel for transportation, especially in the face of growing concerns about CO_2 forcing of global climate change, with a "hydrogen economy," would ameliorate some of these issues. To produce enough hydrogen to displace even current petroleum consumption in the US, however, would require doubling the nation's current electricity generation capacity [2].

Therefore, as we move toward this goal, it is likely that for the next decade or so, both electricity and hydrogen will be generated using natural gas, later via coal gasification, and eventually by water electrolysis employing nuclear power.

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—irrespective of which source the hydrogen was originally derived. Thus we are motivated to consider the transport of both from generation to end use over a single pipeline structure, perhaps using liquid hydrogen as the refrigerant for an enclosed superconducting cable, or a "SuperCable" [3]–[6].

II. SUPERCABLE DESIGN ELEMENTS

A. Superconducting Power Cable Background

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 [7]. In principle, their idea presaged many aspects of the SuperCable 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 proposed an energy transmission line employing low temperature superconductors cooled 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 (HTSC) 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 cable demonstrations are planned or actually

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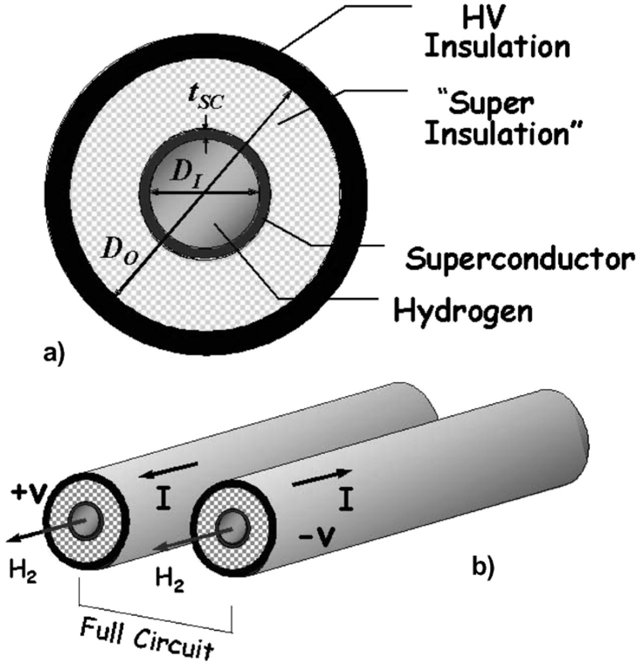

Fig. 1. SuperCable cross-section schematic (roughly to scale) for (a) one pole of (b) a bipolar circuit.

undergoing test worldwide [12], all target ac applications at transmission and distribution voltage levels below 135 kV, 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 sometimes 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. These, and other thermal load issues, will be deferred for future consideration being currently outside the scope of the present paper.

B. Balance Between Chemical and Electric Power Delivery

Perhaps the most important design issue for the "Hydricity SuperCable," defined in Fig. 1, surrounds both the absolute and relative amounts of chemical and electric power to be delivered within a given scenario. As an example, we will now configure a SuperCable to deliver 1000 $\mathrm{MW_e}$ via superconductors and 1000 $\mathrm{MW_t}$ via flowing hydrogen to service a community of 200 000 households, a typical load scenario in the United States for both natural gas and electricity.

Fig. 1(a) outlines the essential dimensional characteristics of a basic SuperCable circuit using liquid hydrogen as both cryogen and chemical energy delivery agent. Note that each "monopole" will deliver half the total hydrogen power.

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 at 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.

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

Hydrogen Power ($\mathrm{MW_t}$)	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 ($\mathrm{MW_e}$)	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

The respective electric and hydrogen power flow equations, given the geometry of Fig. 1(a) are,

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

for $t_{SC} \ll D_I$, 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 same, J is the practical critical current density of the given superconductor, and D_I, t_{SC}, were defined previously in Fig. 1(a), and for hydrogen;

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

where P_H is the hydrogen $(\mathrm{H_2})$ chemical power flow in watts-thermal, Q =Gibbs oxidation potential of $\mathrm{H_2}$ (2.46 eV/mol, or 1.18×10^5 kJ/kg), ρ the mass density of liquid hydrogen (70.8 $\mathrm{kg/m^3}$), 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 in Tables I and II.

In view of issues surrounding the relative power delivery capabilities of hydrogen and electricity, it is interesting to compare the relative "current densities" of the two material mediums using the voltage level of the latter, ±5,000 V, and the velocity flow of the former, 3.39 m/s, as calibration. The value obtained for "hydrogen critical current," 283 $\mathrm{A/cm^2}$, is given in the right hand column of Table I. Clearly, superconductivity dominates the relative delivery of charge, given the Fig. 1(a) design parameters.

Moreover, (1) and (2) suggest that a SuperCable dimensionless and geometry-independent scaling factor, $R_{\mathrm{e/h}}$ to determine the relative transport of electrical and hydrogen power can be defined as follows,

$$R_{\frac{e}{h}} \equiv \left(\frac{J}{Q\rho}\right)\left(\frac{|V|}{\nu}\right), \tag{3}$$

where the individual symbols are as previously indicated. The first term in parentheses represents "charge" as determined by the intrinsic material parameters of a given superconductor and hydrogen, and the second contains the extrinsic SuperCable "pressures," voltage and hydrogen fluid flow.

Finally, we should point out that the hydrogen in the SuperCable can serve not only as a cryogen and an energy delivery agent, but as a possible medium for storage of electricity as well. For example, suppose in the circuit in Fig. 1(b), the liquid hydrogen circulated through both "poles," rather than flowing unidirectionally in each, with only small amounts tapped off for delivery, the rest remaining for future conversion back to electricity. A 500 km SuperCable circuit would store the equivalent of TVA's Raccoon Mountain reservoir, 32 GWh, the largest pumped hydro unit in the US with a considerable smaller footprint, subject to the caveat that the "round trip efficiency" of reversible fuel cells is yet to be optimized. 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.

C. Hybrid SuperCable Configurations Employing Gaseous Hydrogen or Liquid Methane

1) Cold Gaseous Hydrogen: Although liquid hydrogen would prove a viable cryogen for present commercially available perovskite superconductors, we should consider in addition the use of liquid nitrogen for such purposes and then examine the transport of hydrogen in a low temperature, high pressure gaseous state, as depicted in Fig. 2.

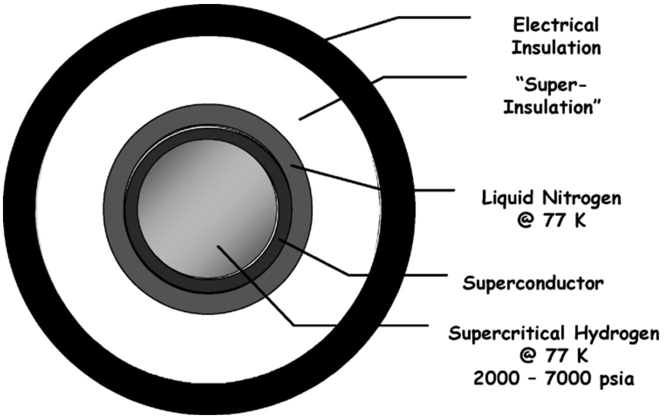

Fig. 2. Hybrid SuperCable with liquid nitrogen as the primary cryogen and high pressure, low temperature hydrogen as the chemical energy transfer fluid. The scale is roughly that of Fig. 1.

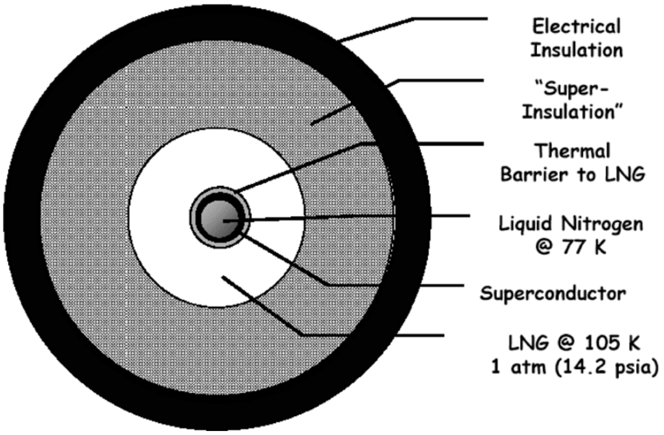

Fig. 3. Hybrid SuperCable with liquid nitrogen as the primary cryogen and liquid methane as the chemical energy transfer fluid (not to scale).

Gaseous hydrogen at 77 K under 12.8 MPa (1850 psia) pressure (on the scale used in natural gas transmission pipelines) has half the energy density of the liquid at 20 K. If it were to flow at twice the velocity given in Table I over the same cross-sectional area as that of the inner tube shown in Fig. 1(a) (177 cm^2), the same chemical power could be delivered. The velocity-viscosity product, and Reynolds number, of each fluid under the stated temperature-pressure conditions are about equal, thus roughly equivalent friction losses would be expected over the same pipeline length.

Deferred for further study is whether the energy required for pressurization is offset by that saved by refrigerating to 77 K instead of 20 K.

2) Liquid Methane: It is quite likely that natural gas resources, especially in North America, will be intensively exploited in the next two decades, followed by coal gasification into CH_4, or CO and H_2, and perhaps eventually the cracking of tar sands into lighter hydrocarbons for both electricity production and transportation. Only if CO_2 forcing of global climate change becomes scientifically and publicly accepted would this scenario be aborted. Several large North American pipeline projects on the 1000 km scale are in the planning stage to deliver Canadian and Alaskan North Slope natural gas to the lower 48 US states. One example is the Mackenzie Valley Gas Pipeline Project running 1300 km from the Mackenzie River delta on the Arctic Ocean to Northern Alberta [13]. If completed at maximum capacity design, this pipeline would deliver 18 GW-thermal power in the form of natural gas in a 30-in (0.76 m) diameter pipe.

Generation of electricity by natural gas in North America is approaching 25% of total. Using the Mackenzie Project as a paradigm for future gas pipeline efforts, let us consider the case where 25% of its energy capacity is converted into electricity by 50% efficient combined cycle gas turbine generators at the wellheads in the Northwest Territories and transmitted to its terminus via superconductivity, the remaining gas liquefied and carried in a hybrid SuperCable sketched in Fig. 3.

Thus, the total power delivered would consist of around 2 GW-electric by superconductivity and 14 GW-thermal as liquid methane.

There are a number of economies of scale evident in this concept. The same compressor infrastructure could be used to liquefy both the nitrogen cryogen and the methane. Most major remaining natural gas reserves are remotely located from consumption and population centers, and as these reserves become depleted or uneconomical to operate over the next several decades, such sites would become ideally suited for the construction of nuclear hydrogen/electric power plants, inasmuch as the long-distance transmission infrastructure would already be place. Additionally, if we assume "port generation" of electricity at LNG reception points, it is probable that the energy released by vaporization can be recuperated to aid the liquefaction of nitrogen for use in the SuperCable whether or not the methane chemical energy is delivered in a gaseous or liquid state.

III. CONCLUSION

The SuperCable is, of course, a highly speculative concept. Nonetheless, past studies such as [9] and [11], indicate it as both practical and economical under certain circumstances and worthy of much more detailed consideration than that given in this paper. In late October, 2004, a workshop was held on the University of Illinois campus which focused on engineering issues such as [14]:

1. How does one structurally accommodate the substantial forces between two monopole cables created from the magnetic fields surrounding the flow of 100 kA currents...would a coaxial design serve better despite a more complex design?
2. What sort of power converter design is necessary to maintain the lowest possible ripple factor and manage load/supply variation at constant current?
3. What are the tradeoffs between fluid friction losses among various design concepts? Again is a coaxial configuration better? Will these losses exceed those from other sources, for example, convective and radiative heat inleak?
4. What is the enthalpic synergism between the cryogen requirements of the SuperCable which might synergize with other aspects of the support infrastructure—high pressure hydrolysis, cryo-electronics, natural gas liquefaction, pressurization and evaporation?
5. Safety issues—bolted (short circuit) fault events on a high current superconducting cable and the interplay with large amounts of highly combustible fluids.

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