CRYO-DELIVERY SYSTEMS FOR THE CO-TRANSMISSION OF CHEMICAL AND ELECTRICAL POWER

Paul M. Grant

W2AGZ Technologies
San Jose, CA 95120, USA

ABSTRACT

We present a novel concept for the simultaneous transport of chemical power in the form of natural gas or hydrogen in a cryogenic state along with the simultaneous transmission of electrical power over via superconductivity. This concept could impact future efforts to tap and deliver methane from distant geographic resources over conventional pipelines with part of the chemical potential energy converted directly to electricity at the wellhead and the remaining gas cooled cryogenically to increase volumetric density and provide the necessary support of a superconducting cable housed within the same packaging. As the fossil reserve becomes depleted, nuclear power plants would be constructed at the former remote wellhead sites to co-generate electricity and cryocooled hydrogen, the latter replacing natural gas and also serving to operate the already installed superconducting electrical service line.

KEYWORDS: Superconductivity; Hydrogen; Methane; Electricity.
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INTRODUCTION

In 2004, the United States Department of Energy report on the International Energy Outlook predicted the per capita worldwide energy consumption would increase from 400 exajoules today to well over 600 by 2025 [1]. In addition, there are many predictions that world population levels may exceed 10 billion by mid-century. Even should this estimate be exaggerated, those present on the planet will undoubtedly aspire to today's American standard of living. The challenge to develop energy supply, generation and delivery infrastructure to satisfy this desire is truly staggering.

A major element of this challenge will be to attain this goal in an enviro-eco-friendly manner, especially given the growing concerns over CO_2 forcing of global climate change. In a recent series of papers [2 – 5], the author and Chauncey Starr have proposed a future energy society be entirely based on a symbiosis of nuclear, hydrogen and superconducting technologies, a concept we have called “SuperGrids” and “SuperCities.” In this scenario, renewables play only a supporting role because of the need of wind, solar and biomass to engage large areas of land. The electricity and hydrogen centrally generated at a nuclear plant would be distributed over a network of liquid hydrogen superconducting pipelines as envisioned in Figure 1.

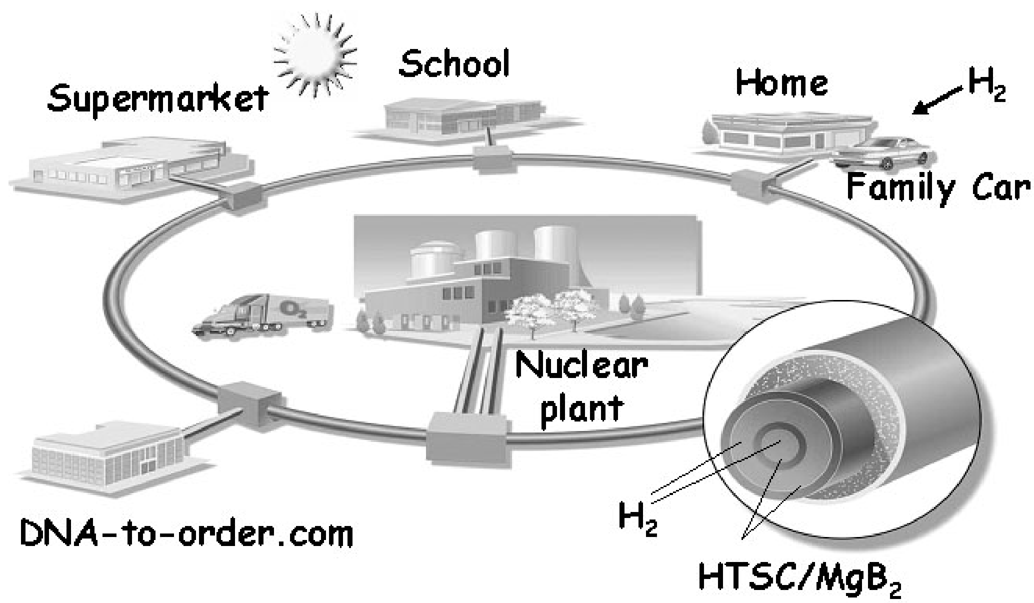

FIGURE 1. Vision concept of an urban community whose complete energy infrastructure comprises electricity and hydrogen generated by nuclear fission and solar roof power dirstributed through a liquid hydrogen/superconducting pipeline.

THE HYDRICITY SUPERCABLE

Liquid Hydrogen as Cryogen and Energy Delivery Agent

In 1974, Bartlit, et al. [6], proposed a dual energy pipeline system whereby natural gas, hydrogen and superconductivity could be transported together using 4 K liquid helium and with a liquid nitrogen heat shield as the cryosystem for a NbTi superconductor. However, it was not until the discovery of the high temperature superconductors that the opportunity arose to employ the cryogen itself (liquid hydrogen or perhaps even methane) as an energy delivery agent as well. Figure 2 depicts a conceptual embodiment of a bipolar Hydricity SuperCable circuit. We have already addressed the question of electrical capacity and thermal insulation issues surrounding the design of a SuperCable elsewhere [7, 8], and in this paper we will focus on issues of hydrogen, and also methane, transport. However, it will be useful to restate the power flow equations from Ref. [7] for background.

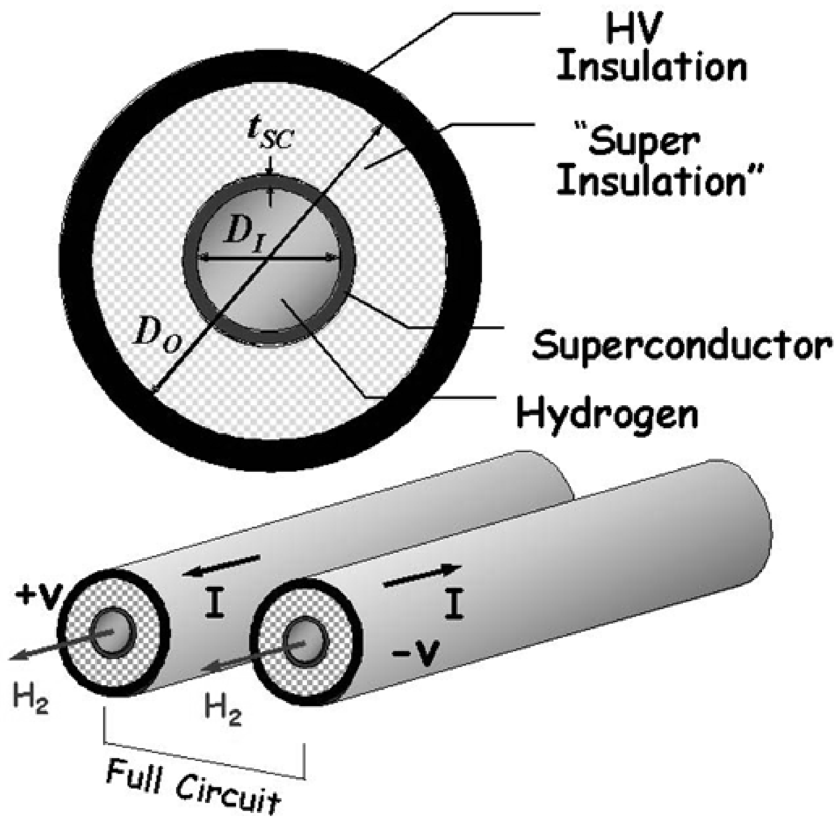

FIGURE 2. Schematic of a possible Hydricity SuperCable configuration consisting of a bipolar superconducting dc electrical circuit cooled by liquid hydrogen. The upper diagram depicts the cross-section of one monopole. The superconducting component, shown as an annulus in the diagram, can in fact be of rather arbitrary diameter as long as it remains immersed in the hydrogen cryofluid.

The electric power carried by the superconductivity component of the SuperCable is given by the following general expression,

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

where P_{SC} is the electric power conveyed the superconducting assembly, V to pole-to-ground potential of the dc circuit, J the practical superconducting current density, under the conditions where t_{SC}, the thickness of the superconducting layer shown in Fig. 2, will usually be much less in magnitude than the diameter of the inner cryogen tube, D_I. The chemical power transported, in the present case by hydrogen, can be written as,

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

where P_H is the electrical power equivalent of as would consumed by an ideal electrolysis cell subsequent generated by an ideal fuel cell. Q is the Gibbs oxidation potential (the lower heat value) of the H_2 molecule (2.46 eV/mol, or 1.18×10^5 kJ/kg), ρ its mass density (70.8 kg/m^3 in the liquid state), and v the linear flow velocity through the cross-sectional area defined by D_I.

Note that equations (1) and (2) can be combined to yield a general Hydricity SuperCable dimensionless and geometry-independent scaling factor,

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

where the parameters are as defined previously. The first term in parentheses on the right hand side of equation (3) represents "electrical and chemical charge," and the second the "pressure" forcing the flow of each. Equation (3) provides a useful expression to scale the relative delivery proportions of chemical and electrical power to deliver for any particular market or societal scenario.

One of the unique features of the Hydricity SuperCable concept is that not only can it deliver hydrogen power, but also to store electricity in the form of hydrogen due to the "electron – proton fungible" nature of electrolyzers and fuel cells. Table 1 compares the hydrogen storage capacity of a 250 mile bipolar SuperCable with two very large pumped hydro and compressed air facilities found in the United States.

TABLE 1. Comparison of the potential for electricity storage as hydrogen in the Hydricity SuperCable with respect to conventional technologies.

Facility	Energy Storage Capacity (GWh)
TVA Raccoon Mountain (pumped hydro)	32
Alabama CAES.(compressed air)	20
400 km SuperCable Circuit (15 cm pipe)	33

Table 1 gives the potential energy in equivalent electrical units of the total hydrogen tn the SuperCable independent of flow velocity. Of course, how much is actually "stored," depends on the relative demands for electricity and hydrogen. It is worth pointing out that a virtue of a direct current superconducting cable, as opposed to alternating current, is that the former, in principle, is free of the hysteretic losses that plague the latter and are the source of major calorimetric losses which require the continual flow of the cryogen fluid (in a very real sense, the liquid nitrogen in a superconducting ac cable not only serves as a cryogen, but as a heat removal agent similar to oil in conventional underground transmission cables. In a dc superconducting cable, the main source of heat is thermal radiation in-leak, which Ref. [7] estimated to result in a temperature rise of merely 0.2 K over 10 km for a liquid hydrogen flow rate of 4 m/s. On the other hand (see below), the cryogen fluid frictional flow .can result in thermal losses at least as high as radiative inleak. The balance and role of hydrogen in the Hydricity SuperCable as power delivery or energy storage is complex. In a bipolar SuperCable, the hydrogen can be continually re-circulated and remain as storage, but when drawn off for power, timely replacement will be required. This unique opportunity offered by the SuperCable to store excess electric power production as hydrogen may prove to finally create the long-sought "commoditization" of electricity markets.

Supercritical Hydrogen at 77 K as Energy Delivery Agent

Concerns over the issues of safely handling hydrogen, especially in its liquid "rocket fuel" state, both perceived and real, are inevitably raised when discussing the arrival of the "hydrogen economy." Granted, liquid hydrogen is a high energy density fluid requiring special management and cryogenic support. However, it is instructive to examine cold, pressurized H_2 gas as an alternative to the liquid, particularly as a "plug-in" replacement for the present and ubiquitous methane distribution system.

Very early in the exploration of the thermophysical properties the hydrogen molecule in the 19^{th} century, it was recognized that the gas did not follow the "perfect gas law," a fact that was not understood until the arrival of quantum mechanics and the appreciation of van der Waals forces. The critical temperature of H_2 is very low, around 30 K. Nonetheless, the energy density of cold hydrogen gas can be quite significant, as shown by Figure 3.

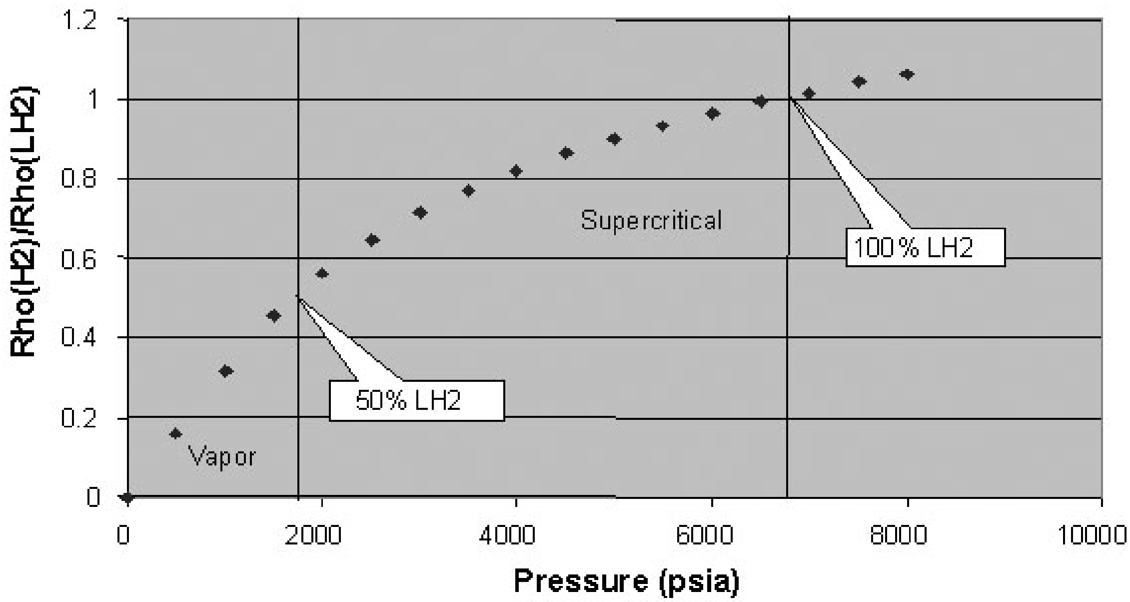

FIGURE 3. Mass density of gaseous hydrogen relative to the liquid state as a function of pressure. Those pressures at which the mass density is equivalent to 50% (1850 psia) and 100% (6800 psia) of liquid hydrogen are flagged.

Note H_2 at a pressure of 1850 psia and 77 K has half the mass density of liquid hydrogen. This pressure range is well within that used for methane transmission pipelines, and the cryogen, liquid nitrogen (LN_2), is "safe" and "easy to handle." Thus, we can envision a "supercritical" Hydricity SuperCable as suggested in Figure 4. Pressure also provides a very convenient parameter for adjusting the amount of hydrogen mass available for storage of electricity.

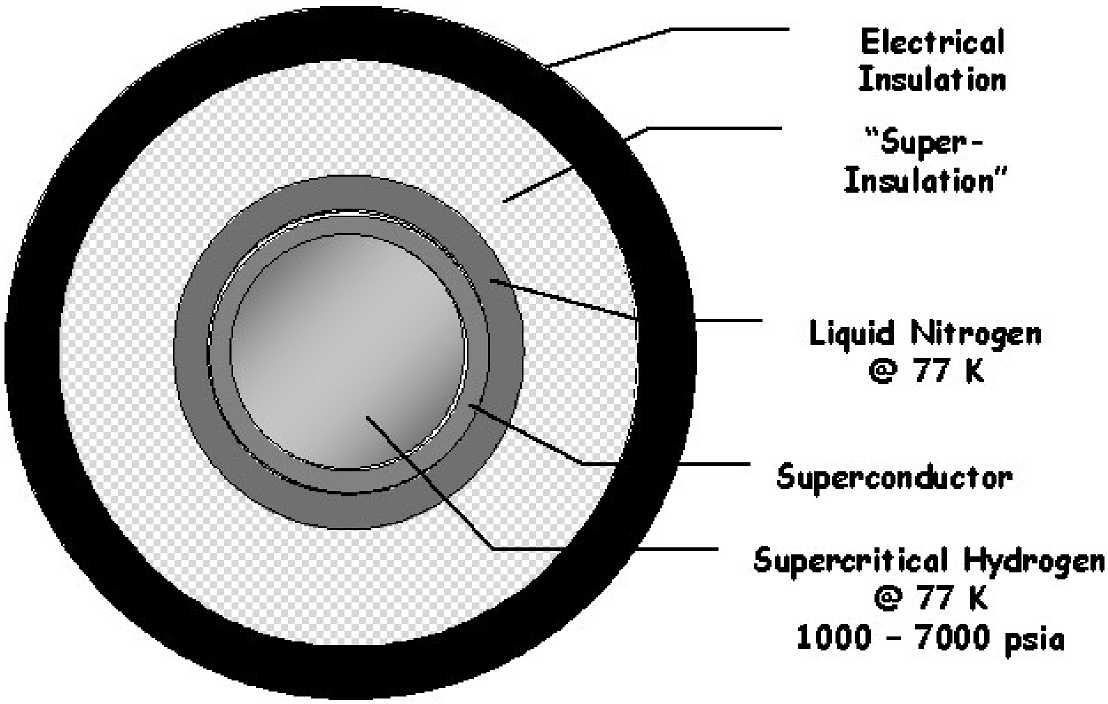

FIGURE 4. Hydricity SuperCable configuration employing gaseous hydrogen in the supercritical state at 77 K and high pressure. Here the pressurized hydrogen gas is surrounded by a shell of liquid nitrogen which is the principal cryogen.

Above, we alluded to the possibility that frictional flow losses of the cryofluid can approach those of ambient temperature inleak. Table 2 details the relevant physical properties pertaining to both liquid hydrogen and to 1850 psia supercritical H_2 at 77 K.

TABLE 2. Fluid properties comparison of liquid to supercritical hydrogen capable of transporting 500 MW (LHV) through an effective D = 10 cm diameter tube. The Reynolds Number, $\mathrm{Re} = \rho v D / \mu$, when large expresses the ratio of inertial to viscous forces exerted on fluid flow.

T (K)	P (psia)	ρ (kg/m^3)	μ (μPa×s)	μ^2/ ρ (ndyne)	v (m/s)	Re (10^6)
22.	14.7	70.8	13.6	261	4	2.08
77	1850	35.4	5.6	87	8	5.06

An interesting observation to draw from Table 2 is the expectedly very high value of the Reynolds number, Re, for both the liquid and supercritical state of molecular hydrogen. At such large magnitudes, Re expresses the ratio the inertial forces necessary to overcome the native viscous properties of the fluid. In the case of either fluid, the inertial force is of the order 0.5 dynes and is thus trivial, as we shall see, to the frictional force. These forces are encompassed in equations (4 – 6),

$$W_{loss} = MP_{loss} / \rho \,, \tag{4}$$

where W_{loss} is the total power dissipated per unit length of the pipe, M the total mass under transport, ρ the fluid mass density, and P_{loss} the pressure drop per unit length as follows,

$$P_{loss} = \lambda\left(l / d_h\right)\left(\rho v^2 / 2\right). \tag{5}$$

Here l is the total length of the duct or pipe (we choose 1 m for normalization), v the linear fluid velocity, and λ is a dimensionless empirical constant defined by the following iterative equation,

$$1/\lambda^{1/2} = -2\log_{10}\left[\left(2.51/\left(\mathrm{Re}\,\lambda^{1/2}\right)\right)+\left(\varepsilon / d_h\right)/3.72\right]. \tag{6}$$

Re is the relevant fluid Reynolds Number, d_h the "hydraulic pipe diameter" (approximately the pipe diameter adjusted for "roughness" and "corrugations), and ε the roughness factor for a given material surface and preparation.

TABLE 3. Losses due to frictional flow forces for supercritical and liquid hydrogen from parameters given in Table 2 using equations (4 - 6), taking the roughness factor ε = 0.015 for smooth stainless steel surfaces.

Temperature (K)	W_{loss} (W/m)
22.	0.72
77	1.30

Table 3 displays the linear flow losses for the two given hydrogen fluid states based on the parameters and assumptions of Table 2. We see the per length power dissipation is of the order found in Ref. [7] for radiative heat inleak. These are well within tolerable range accommodated by cryogen removal throughput and thermal insulation surrounding a Hydricity SuperCable.

Using gaseous hydrogen introduces an additional possible challenge not present in the liquid state. The two protons which constitute the hydrogen molecule nuclei can take on two possible topological arrangements, one where the proton spins align anti-parallel to each other (para-hydrogen), and one where they are parallel (ortho-hydrogen). Para-hydrogen is the more stable form, and liquid hydrogen is almost entirely p-H_2. However, at higher temperature, the ortho phase can form and as much as 50% of hydrogen gas is o-H_2. The reconversion to para is exothermic, resulting in the release of an amount of heat in excess of the heat of evaporation of liquid hydrogen, either a source of annoyance for its storage, or an advantage if one wants rapid evaporation to boost pressure as a rocket propellant. It is known that the field from permanent magnets in the presence of a paramagnetic catalyst can induce a para-ortho transition. The magnetic field at the surface of a superconducting conductor transporting 100 kA of current can be as high as 1 T, depending on the overall diameter of the conductor. If this field results in significant amounts of otherwise para-hydrogen relative to ortho, this additional o-H_2 could release substantial amounts of energy by transforming back to para should the cable become suddenly de-energized.

THE LNG HYBRID SUPERCABLE

Realistically, fossil fuels will continue to be exploited for at least three more decades. However, there is underway a major movement away from high carbon content sources as seen by the increasing movement toward natural gas (mostly methane) as witnessed by the fact that some 18% of the electricity generated in the US comes from natural gas-fired turbines, whereas it was almost zero 20 years ago, and is expected to increase dramatically as more restrictions are placed on coal generation. Natural gas production and use in the "lower 48" of the United States has begun to increase faster than new reserves are being discovered and exploited. It is anticipated that much of the future supply to the US will be by tanker transport and offload of liquefied natural gas (LNG) and additional pipelines constructed from the Artic Ocean shelf of North America.

An example of the latter is the Mackenzie Valley Project [9], a 1220 km, $18 B high capacity pipeline to be built from gas fields in the Mackenzie River delta in the Northwest Territory to existing distribution stations in Alberta, scheduled for completion by 2010 []. A map of the pipeline route and associated pressurization plants is shown in Figure 5.

FIGURE 5. Route of the projected Mackenzie Valley Pipeline running 1220 km through the Canadian Northwest Territory from the Mackenzie River Delta on the Artic Ocean to northern distribution channels in the province of Alberta [http://www.mackenziegasproject.com]. When completed, the pipeline will convey 1.6 US billion cubic feet per day, the equivalent of 18 GW thermal at the high heat value of methane, approximately that of the electric power capacity of the Three Gorges hydroelectric facility in China.

Since a significant portion of the natural gas, perhaps as much as 33%, to be eventually transported over the Mackenzie Valley pipeline will be used to generate electricity, let us then consider a possible scenario for future gas pipeline projects which would place the generation plants at the wellhead The electric power thus produced would then be subsequently transmitted, along with liquefied natural gas, in the manner of an LNG SuperCable as envisioned in Figure 6. A similar wellhead generation scenario and a cost comparison of a 5 GW dc superconducting “electricity pipe’ to an HVDC transmission line or gas pipeline was considered in 1997 by Schoenung, et al [10].

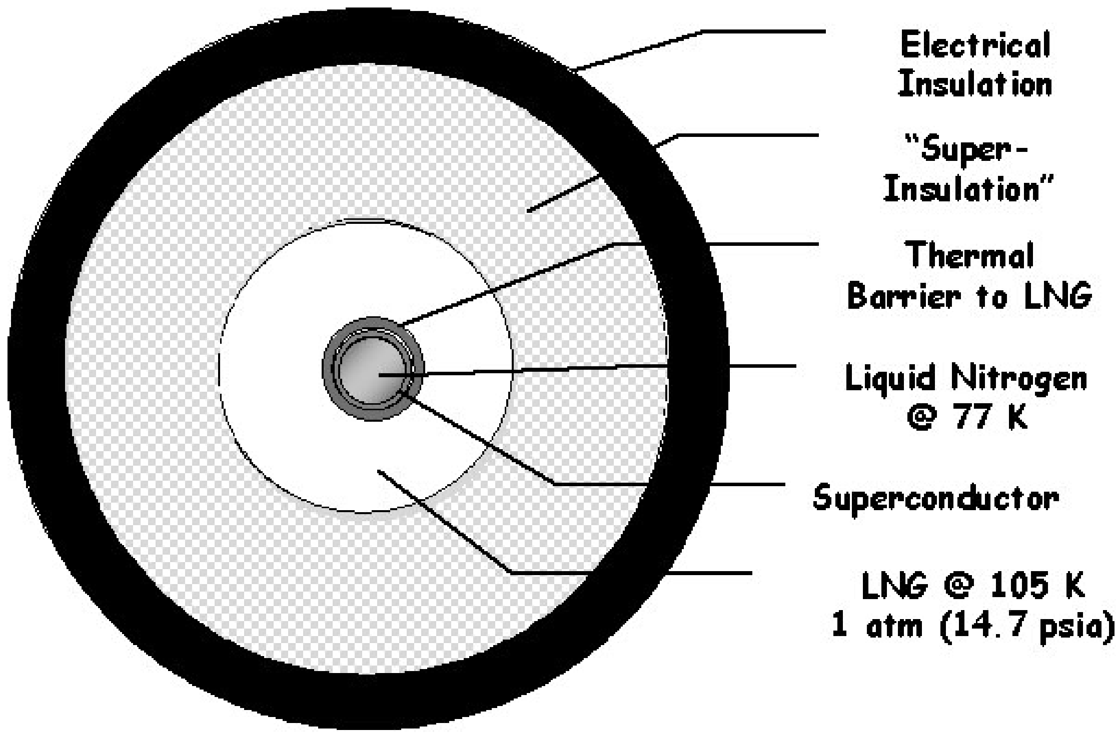

FIGURE 6. Monopole cross-section of a conceptual Liquidfied Natural Gas SuperCable. The cryogen is liquid nitrogen flowing through the center cylindrical tube. Note the presence of a heat shield between the superconductor layer and the LNG channel in order to keep its temperature above 86 K, the freezing point of methane.

Table 4 addresses a scenario using the Mackenzie Valley Project as a template. One – third of the field gas available is diverted to directly generate electricity. The remaining methane is liquefied and it and electricity are “shipped south” on an LNG Hybrid SuperCable. For a standard long distance gas pipeline, re-compression and heating (methane is cooled by expansion as it moves through the pipeline!) stations must be place periodically (100 – 250 km) along its path. For the LNG Hybrid SuperCable, these stations would be replaced by cryogen pumping and refrigeration units.

Should the LNG Hybrid SuperCable model indeed be applied to future exploitation of remote natural gas fields similar to those of the Mackenzie River Delta, when those reserves become exhausted, their very remoteness would make suitable locations for the construction of high temperature gas cooled nuclear reactors capable of both hydrogen and electricity generation with the product shipped on the former LNG SuperCable appropriately converted to carry hydricity.

TABLE 5. Wellhead electricity generation scenario via combined cycle gas turbine generators located on the gas fields of the Mackenzie River Delta delivered over an LNG SuperCable running along the route of the proposed Mackenzie Valley Pipeline.

Electricity Conversion Assumptions	
Total Wellhead Power Capacity	18 GW (HHV)
Fraction used to make electricity	33%
Gross Gas Power Consumed	6 GW (HHV)
Remainder transmitted as LNG	12 GW (HHV)
CCGT Efficiency Factor	60%
Net Electricity Wellhead Generated	3.6 GW (+/-18 kV, 100 kA)
SuperCable Parameters for 12 GW (HHV) transport as liquefied natural gas (LNG)	
Methane Mass Flow	230 kg/s @ 5.3 m/s
Density of LNG	440 kg/m^3
LNG Volume Flow	0.53 m^3/s @ 5.3 m/s
Effective Pipe Cross-Section	0.1 m^2
Effective Pipe Diameter	0.35 m (14 in)

CONCLUDING REMARKS

Although all the science and technology necessary to design and build a Hydricity SuperCable already exists and the underlying concept physically plausible, its actual design and construction would present a formidable engineering challenge. For example, it would most likely be necessary to construct or at least assemble the superconductor component in-field, a task not yet attempted for the present generation of high temperature superconducting power transmission cables, none of which yet exceed one kilometer in length.

One could foresee the outer housing, or "husk," consisting of concentric rigid steel cylinders containing the high voltage and thermal insulation blanket as shown in Figures 2, 4 and 6. This housing would be in the form of 20 meter lengths suitable for joining with methods similar to those presently employed for gas pipelines and which could be conveyed to the construction site by barge, rail, flatbed truck or helicopter. On the other hand, one would want to keep the number of joints necessary in the superconducting cable component to a minimum, perhaps no more than one per kilometer as this is the foreseeable practical manufacturing length for high temperature superconducting tape. The tape would then be strung along a flexible former of 1 km length in sufficient quantity to satisfy the required current capacity. The resulting assembly would next be threaded through 1 km of pre-joined "husks" already in place, ready to be spliced into the next SuperCable segment.

In summary, as the world moves to a carbon-free economy, the SuperCable could become an essential component in delivery of cryogenic hydrogen energy for end use as transportation fuel or the storage of electricity.

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