PROCEEDINGS OF THE

Fourth International Cryogenic Engineering Conference

EINDHOVEN 24/26 MAY 1972

ICEC 4

Sponsored by the International Cryogenic Engineering Committee, Commission A2 of the International Institute of Refrigeration, and the Eindhoven University of Technology

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Published by IPC Science and Technology Press Ltd

Multiple use of cryogenic fluid transmission lines*

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A multi-use energy transmission line is envisaged which derives environmental and economic advantages by concurrently transporting liquefied natural gas, liquid hydrogen, and electricity conducted along either cryogenic (20 K) or superconducting (4 K) cables. Operating parameters are given for a potential application of a 600-mile pipeline carrying gas and electricity flowing from New Mexico to Los Angeles, California, and liquid hydrogen flowing from Los Angeles to New Mexico for use in the space shuttle program. Estimated flow-rates, pipe sizes, pressure and voltage losses, heat leaks, and refrigeration requirements are given and compared with losses incurred in conventional transmission.

INTRODUCTION

Economic advantages accruing from transporting two energy sources concurrently through a single pipeline have been recently discussed.[1] Proposed was the concurrent transport of electricity at liquid-hydrogen (LH_2) temperatures (20 K), utilizing the greatly reduced resistivity of copper, and liquefied natural gas (LNG) at 110 K, utilizing decreased pumping costs, thermal shielding and energy for driving the hydrogen refrigerator offered by LNG. This idea is carried a step further here by exploring environmental as well as economic advantages which may be realized by distributing three energy sources concurrently: LNG, LH_2 and electricity.

A pattern of energy utilization developing in the south-west of the United States can serve as an example of advantages possible from transmitting more than two energy forms concurrently.

Consideration has been given to building a space shuttle port at White Sands, New Mexico. During the testing period and on an operational basis thereafter, 220 000 kg per day of LH_2 would be required as propellant and 1 280 000 kg per day of liquid oxygen as oxidizer. Large producers of LH_2 exist in Southern California. To supply the space shuttle by road transport would take 65 tank trucks per day each unloading 50 000 litres of liquid at White Sands and starting back toward Los Angeles, 1200 km away. The pollution caused by these trucks, the hazards and the cost are far from negligible.

In addition, due both to the critical air pollution control measures necessary in Los Angeles and to an abundance of cheap coal in Northwest New Mexico and the Lake Powell region, 2000 MW of electric power is presently generated near Farmington, New Mexico, for consumption in Phoenix and Los Angeles. An expansion in capacity by 7000 MW is planned for Lake Powell, 300 km west of Farmington. The scenic destruction caused by the above-ground transmission lines already has caused controversy and days of public hearings in two states.

Of greater environmental impact is the potential air pollution from the proposed supersized coal-fired power plants. With controls presently proposed, over 110 000 kg of particulates and 1 110 000 kg of SO_2 will be emitted daily. US Senate hearings have examined these problems. Better and more costly pollution control equipment could be used. However an alternate approach is to gasify the coal at the mine site. Already in the planning state are gasification plants to produce daily 50 million cubic metres of gas from the Farmington area coal, assuming strip-mining and sulphur-removal problems can be resolved. The resulting gas, predominantly methane, can be used for production of power on site and the remainder for transmission to population centres.

Large amounts of natural gas are now piped to Southern California from the second and third largest gas fields in North America[2] located in the Four Corners region (conjunction of New Mexico, Colorado, Utah and Arizona) and south-eastern New Mexico, respectively. Demands for cleaner energy in cities can be expected to increase these amounts substantially. For example, if Los Angeles converted its 3000 government-owned vehicles to LNG, about 8.5 million cubic metres of additional natural gas would be required yearly.[3] Popularization of home fuel cells, either natural gas-air cells or hydrogen-oxygen cells holds potential for increasing future demands for both LNG and hydrogen. Jones[4] has concluded that LH_2 is the

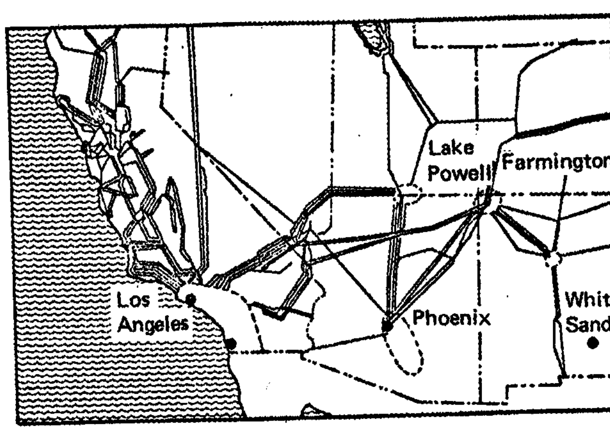

Fig.1 230 kV transmission lines (1990)

* Work performed under the auspices of the United States Atomic Energy Commission.

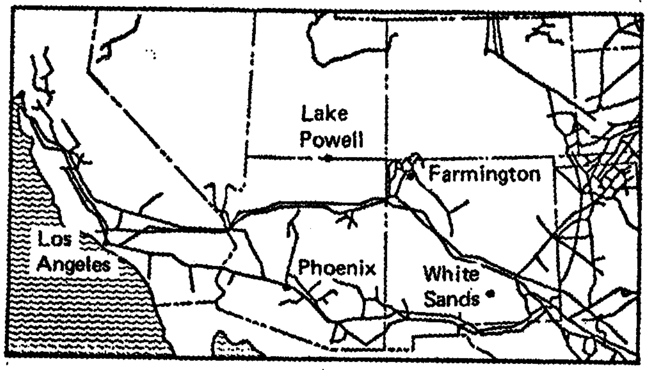

Fig.2 Existing natural gas lines

logical replacement for hydrocarbon fuels in the 21st century. Marchett[5] has even speculated that hydrogen ultimately must replace all other forms of mobile energy, including food.

Thus an energy transfer line with multiple uses appears useful. This situation is summarized in Figs 1 and 2, with increasing amounts of electric power and natural gas going from Farmington to Los Angeles and LH_2 produced near Los Angeles needed near White Sands. Figures 1 and 2 point out a similarity in the routing of existing electric and gas lines.

DISCUSSION

If LH_2 becomes marketable in large quantities, unique opportunities for economic and environmental savings are opened. It has been concluded[1] that while it is economical to refrigerate to 20 K to reduce line losses in power transmission, even greater savings are attainable by using superconductors in a d.c. mode at 4 K to eliminate resistive losses altogether. If marketable LH_2 were available in the pipeline to provide free thermal shielding at 20 K, the superconducting transmission line becomes more attractive. Or it may prove better to operate at 20 K and realize additional savings because the primary refrigerant is now marketable rather than solely an expense paid for reducing resistivity.

Rudimentary consideration of economic factors will show the feasibility of a multi-use pipeline paying its way. A 37% savings for carrying electricity at 20 K and LNG in a common installation over the costs of independently transporting 20 K electricity and LNG has been found.[1] Since no additional cost is entailed in transporting LH_2 in such an installation, the costs of shipping the same amount of LH_2 by truck represents a credit against the pipeline cost — a $25 million per year credit for the case of 65 truckloads per day from Los Angeles delivered to White Sands.

Consideration must be given to possible detrimental effects of combining energy sources in a common line. One question is that of safety. A case can be made for the multi-use line being safer than a single gas line. The inherent hazard depends on the total potential energy and not on whether that total energy is available from one or more sources. Further the extra vacuum jacket provides one additional protection against the combustibles mixing with oxygen. In the event of a massive break, the potential ignition source presented by the electricity is not necessarily more hazardous and could serve to 'flare' the gases before explosive concentrations accumulate.

The questions of system reliability and safety dictate that the total energy flowing through the line in all forms be limited to perhaps 10% of the total energy supply to a region. Obviously system reliability must be amply demonstrated on large lines before widely using new technology. This argues for beginning prototypes soon.

DESIGN PARAMETERS

To illustrate the operation of a multi-use pipeline carrying LNG, LH_2 and electricity at 20 K or 4 K and to demonstrate the operation savings over conventional energy transmission, consider a long-distance transmission line, e.g. 1000 km from Farmington to Los Angeles. For sizing this line, criteria were arbitrarily chosen as follows: to carry approximately 5% of the natural gas requirements of California, to meet LH_2 requirements of the space-shuttle program, and to transmit 1000 MW of electric power. Table 1 presents and compares calculated operating characteristics of such a line. Table 2 summarizes total energy losses incurred in transporting this energy by separate and by concurrent transmission lines.

Explanation of the terms and assumptions used will aid in understanding Table 1. Terms needing explanation include: *potential* — the maximum value of the driving force, be it pressure in atmospheres or electrical potential in volts; *flow-rate of useful energy* — the heating value times flow-rate for fuels; *pipe size* — cryoresistive and superconducting elements are part of the pipe wall; *heat leakage* — positive values designate heat in-leakage to cryogenic fluids; minus signs indicate heat out-flow (power loss) from electric lines; power loss was calculated assuming an evenly distributed 7% loss between Farmington and Los Angeles, which agrees with observation for conventional lines; power loss in lines at 20 K was estimated by using a resistance ratio (300 K to 20 K) of 1000 to 1; except in the case of the LHe line, heat leakage calculations included only the radiation component since conduction through supports was small compared to radiation figures; *power required for refrigeration* — the heat leakage figure divided by the Carnot efficiency and by the fraction of Carnot attainable in practical refrigerators of the required capacity;[6] *pumping power* — a 70% over-all efficiency was assumed.

In Table 2, the energy losses shown include only I^2R losses for electricity and refrigeration losses plus pumping losses for the fluids. The cases are the same as in Table 1 plus two additional cases which are: A_2-LNG, LH_2 and cryoresistive electricity in separate lines; A_3-LNG, LH_2 and superconducting electricity in separate lines. The reason superconducting transmission of electricity looks less favourable than cryoresistive conductors is because of the size chosen (1000 MW). Superconducting power transmission offers greater savings at greater transmitted power.

As envisaged, a multiple use pipeline would incorporate the following functional parts: an external vacuum jacket, multilayer insulation surrounding the LNG pipe and its conterminous LNG-temperature thermal shield which surrounds all else. Inside this shield is an insulating vacuum containing the LH_2 pipeline with its conterminous shield at 20 K. Inside this shield is another common or separate

Table 1

Energy form and/or refrigerant	Case A_1 – separate transfer lines, conventional electricity			Case B – multi-use transfer line, cryoresistive electricity			Case C – multi-use transfer line, superconducting electricity			
	LNG	LH_2	Electricity	LNG	LH_2	Electricity	LNG	LH_2	LHe	Electricity
Temperature (K)	110	20	300	110	20	20	110	20	4	4
Potential (atm or kV)	68	20	2.3×10^5	68	20	2.3×10^5	68	20	3	2.3×10^5
Flow-rate (g/sec or A)	8.0×10^4	2500	4350	8.0×10^4	2500	4350	8.0×10^4	2500	0.056	4350
Flow-rate of useful energy (MW)	4740	350	1000	4740	350	1000	4740	350	0	1000
Pipe size (cm):										
inner diameter	41	15	–	41	15	15	41	15	0.5	0.5
wall thickness	1.2	0.2	–	1.2	0.2	0.2	1.2	0.2	0.13	0.13
Pressure drop (atm/30 km)	6.3	5.1	–	6.3	5.1	–	6.3	5.1	0.08	–
Heat leakage (kW/30 km)	82.5	31	~2200	134	5.4	~2.2	134	4.1	0.00084	~0
Power required for refrigeration (kW/30 km)	463	1710	–	752	355	–	752	283	3.4	–
Pumping power (kW/30 km)	173	26.7	–	173	26.7	–	173	26.7	4.9×10^{-6}	–

Table 2 Energy losses (kW/30 km)

	Case A_1	Case A_2	Case A_3	Case B	Case C
Conventional electricity	2200	–	–	–	–
Cryoresistive electricity	–	2.2	–	2.2	–
Superconducting electricity	–	–	0	–	0
LHe	–	–	1790	–	3.4
LNG	636	636	636	925	925
LH_2	1737	1737	1737	382	310
TOTAL =	4573	2375	4163	1309	1238

vacuum in which is supported the LHe pipeline with its adherent superconductor.

The power for refrigeration and pumping in a 1000 km multi-use superconducting transmission line (Case C) totals 40 MW compared to 70 MW loss in a conventional transmission line carrying only electricity (16½% of the total energy carried by the multi-use line). In other words, a long conventional line loses 7% of the transmitted energy, whereas the multi-use line loses 0.7% of the total transmitted energy. A 1000 km single transmission line for 11 400 litres/min of LNG would lose about 0.4% of its energy flow due to heat leak and frictional losses.

In an age of environmental concern, these reductions in losses represent decreases in power and pollution and conservation of natural resources. Present transmission losses of electric energy in the United States roughly equal the total electricity consumption of the US in 1940.

CONCLUSION

Necessary and feasible advances in technology will minimize environmental degradation resulting from industrialization. But environmentally desirable methods frequently have higher costs attached. For example, putting all transmission lines underground, although at present economically unattractive, is not only aesthetically desirable, but also of growing importance as available land grows scarcer.

A specific case has been investigated where coordinated operation of several energy transport systems in one pipeline lends economic advantages that reduce the cost of protecting the environment. In this example, advantages accrue to each of three energy forms – LNG, LH_2 and electricity – by virtue of their sharing a common line. The LNG benefits from better insulation, LH_2 receives and gives thermal shielding, and the electricity bears lower losses because of decreased or zero resistance in the conductor.

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DISCUSSION

D. W. H. CAIRNS asked if the authors had allowed for power requirements for liquefaction and refrigeration when fluid was removed from the cable at one end or was it not significant for 1000 km lengths?

J. R. BARTLIT, in reply, said that they had considered only the case where the desired form of fuel was liquid, so these costs must be paid regardless of the mode of transportation. For their length of 1000 km, the power for liquefaction of product liquid was definitely not negligible as it mounted to more than twice the total of energy losses in Case B.

D. W. H. CAIRNS asked if the authors had made any detailed study of the safety considerations of combining these three energy sources in one envelope?

J. R. BARTLIT replied that in order to realize the maximum inherent safety discussed in the paper, the detailed design of the pipeline must, of course, include appropriate safety devices such as automatic shut-off valves, vacuum monitoring and relief, vacuum bulkheads, purge and vent lines, etc. They had also considered including liquid oxygen in the same pipeline, but felt this added significantly to the hazard of transporting the fluid separately.

Z. CROITORU asked if, in addition to comparing losses of the different systems, the authors had compared the costs of the systems?

J. R. BARTLIT replied that they had not. The fabrication cost of the pipeline itself, at this point, would be highly speculative.