System Study of Long Distance Low Voltage Transmission Using High Temperature Superconducting Cable

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ABSTRACT

High temperature superconductors (HTS) offer a potential opportunity for long distance transmission of electricity at relatively low voltage. An HTS transmission line could be less expensive than high voltage dc transmission (HVDC) because of reduced convertor costs and lower line losses.

The objectives of this system study were three-fold:

1) To investigate possible configurations for a 1000 mile, 5000 MW HTS dc transmission line, including cooling system options
2) To estimate capital and operating costs of an HTS dc transmission line, and
3) To compare capital and life cycle costs of electricity for a long distance HTS low voltage dc (LVDC) system with an HVDC system and a gas pipeline with the same power capacity.

This preliminary analysis of an HTS low voltage dc transmission system suggests that such a system could be economically competitive with both HVDC and gas pipeline transport of bulk energy over long distances. The largest single cost item is the superconducting layer. If this can be provided at a cost around $5/kA-m at the selected operating temperature, then the system is an attractive option. The cost of delivered electricity (¢/kWh) is strongly dependent on the cost of fuel at the source. The trade-off between systems is impacted most by capital costs and parasitic requirements.

The development of long distance HTS transmission would provide a large commercial market not only for HTS material, but also for liquid nitrogen refrigerators in the size range of several hundred kW_t.

CONTENTS

1

INTRODUCTION AND BACKGROUND

High temperature superconductors (HTS) offer a potential opportunity for long distance transmission of electricity at relatively low voltage. An HTS transmission line could be less expensive than high voltage dc transmission (HVDC) because of reduced convertor costs and lower line losses.

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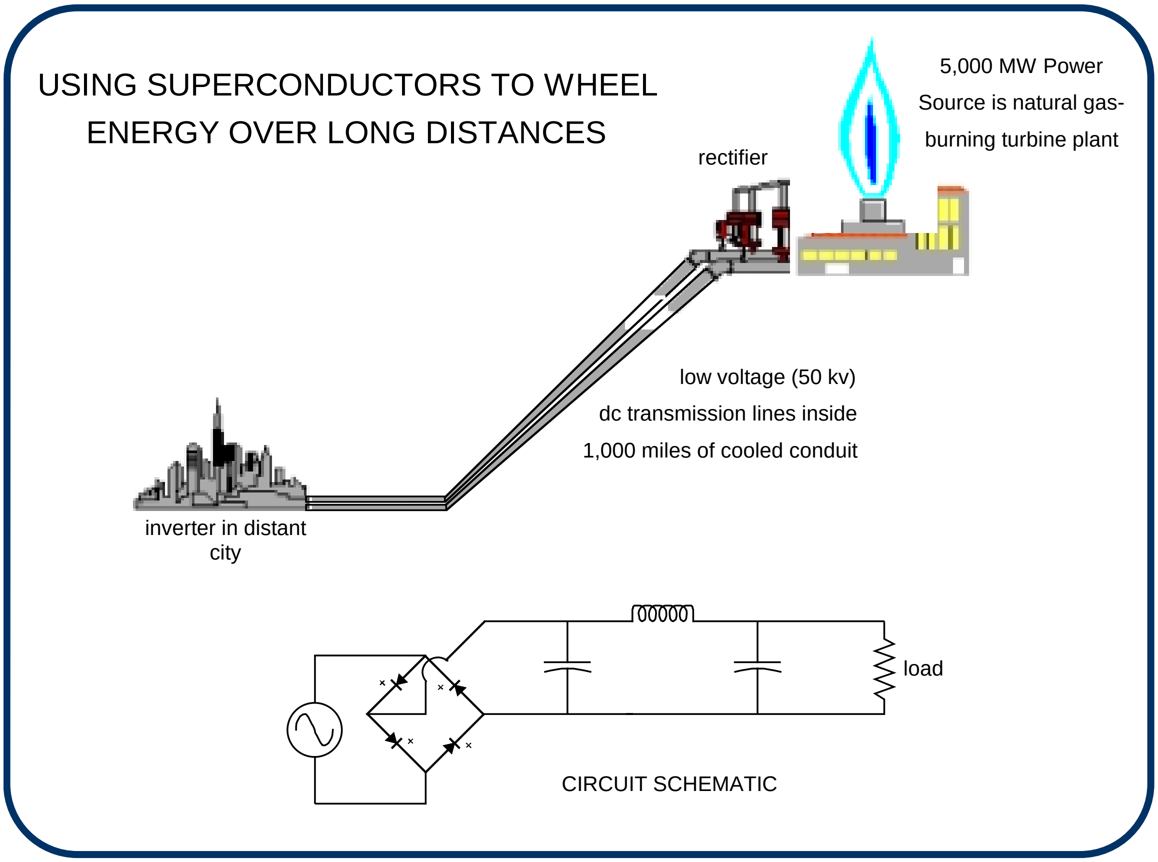


Figure 1-1 Power Plant and Transmission Line

This study was motivated, in part, by an earlier study by ABB [1], in which HVDC was compared with gas pipelines for long distance, high power transmission of bulk energy from large natural gas fields to distant urban electric loads. In that study, several routes (in Africa and South America) were examined. Another possibility is in the Middle East, from the gas fields of Qatar to the load centers in Saudi Arabia.

The general configuration of the system is indicated in Figure 1-1. The baseline distance was taken as 1000 miles (1610 km). A 5000 MW advanced gas turbine power plant was assumed to produce power at either the source end (for dc lines), or the load end (for gas lines). Systems analysis, including evolution of cost and cooling requirements, was carried out for the base case and then parametrized to investigate sensitivity to line length and other factors, including fuel cost and HTS operating temperature.

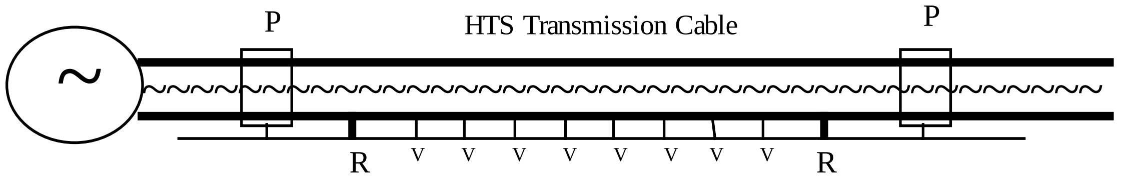
2

SYSTEM DESCRIPTION

2.1 Superconducting Transmission Line

The superconducting transmission system is shown schematically in Figure 2-1. The baseline system is selected to be 1000 miles (1610 km) long. A 50,000 Amp conductor carrying 5000 MW will see 100 kV across the conductors or ±50 kV to ground. This requires a power conditioning system (PCS) with 50 kV, 5000 MW converters at each end of the line. Refrigerator stations are located each 10 km, and vacuum stations each 1 km, as described in section 2.1.2 below.

An auxiliary low-current power line at about 1.5 MW must also be provided to power the refrigerators and vacuum pumps. This line could be fed from taps on the dc line. Design of the converters for auxilliary power and for the main PCS and for the line was beyond the scope of this study.



R = Refrigerator station (100 kW$_e$, every 10 km)

V = Vacuum pumping station (20 kW$_e$, every 1 km)

P = Converter station (3 MW$_e$, every 100 km)

Figure 2-1 LVDC Transmission System Schematic

2.1.1 HTS Material Assumptions

Since their discovery in 1986, HTS materials have been developed from a laboratory curiosity to engineering materials serving commercial markets [2]. AC transmission cable is currently being produced by Pirelli [3], and several studies of dc distribution cables have been completed [4,5].

The key features of HTS cable are high current density (compared to metallic conductors) and low losses (due to the superconductive nature). The high current density results in a compact conductor and allows operation at a lower voltage and higher current at a conventional line. Low losses are possible with adequate cooling to maintain superconducting conditions. DC cables have inherently low loss because there is no time-varying magnetic field, only ripple. Careful cable design (including twisting) is required to minimize ac losses in ac cables.

For this study, the properties of the bismuth compound 2223 were used [6]. These include critical current density, J_c, at 77 K and zero magnetic field equal to 55 kA/cm^2. The relative values for decreasing temperature are shown in Figure 2-2. These are present day performance values. Improvements in the future will only help the performance of HTS products. An operating margin of $J_{op}= 0.8\ J_c$ was used in this study. In addition, a 10% penalty due to restive loss was assumed at 77K due to convention of starting J_c at measurement conditions of 1μ^v/cm. At 65 K, resistive loss is assumed to be zero.

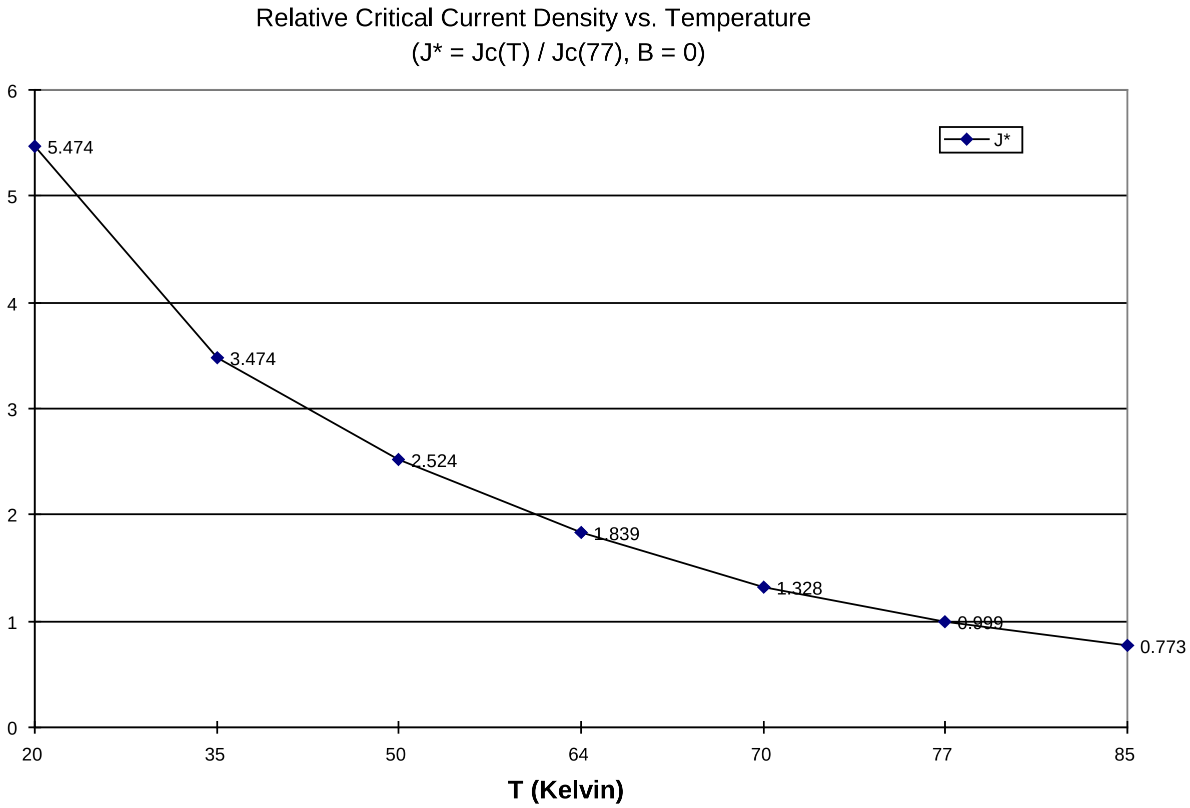


Figure 2-2 J_C for Bi-2223 [6]

2.1.2 Configuration

The study configuration for a 50 kA HTS transmission line is shown in Figure 2-3. The conductor has a parallel return path with a center ground. Electrical insulation separates the conductor paths from the support tubes and ground plane. The conductor is cooled by a flow of liquid nitrogen in the central tube. The entire conductor is supported in an evacuated conduit to reduce convection and conduction heating. Multilayer thermal insulation reduces radiation heating.

The optimized conduit diameter is approximately 0.7 m, a suitable dimension for installing in a surface trench.

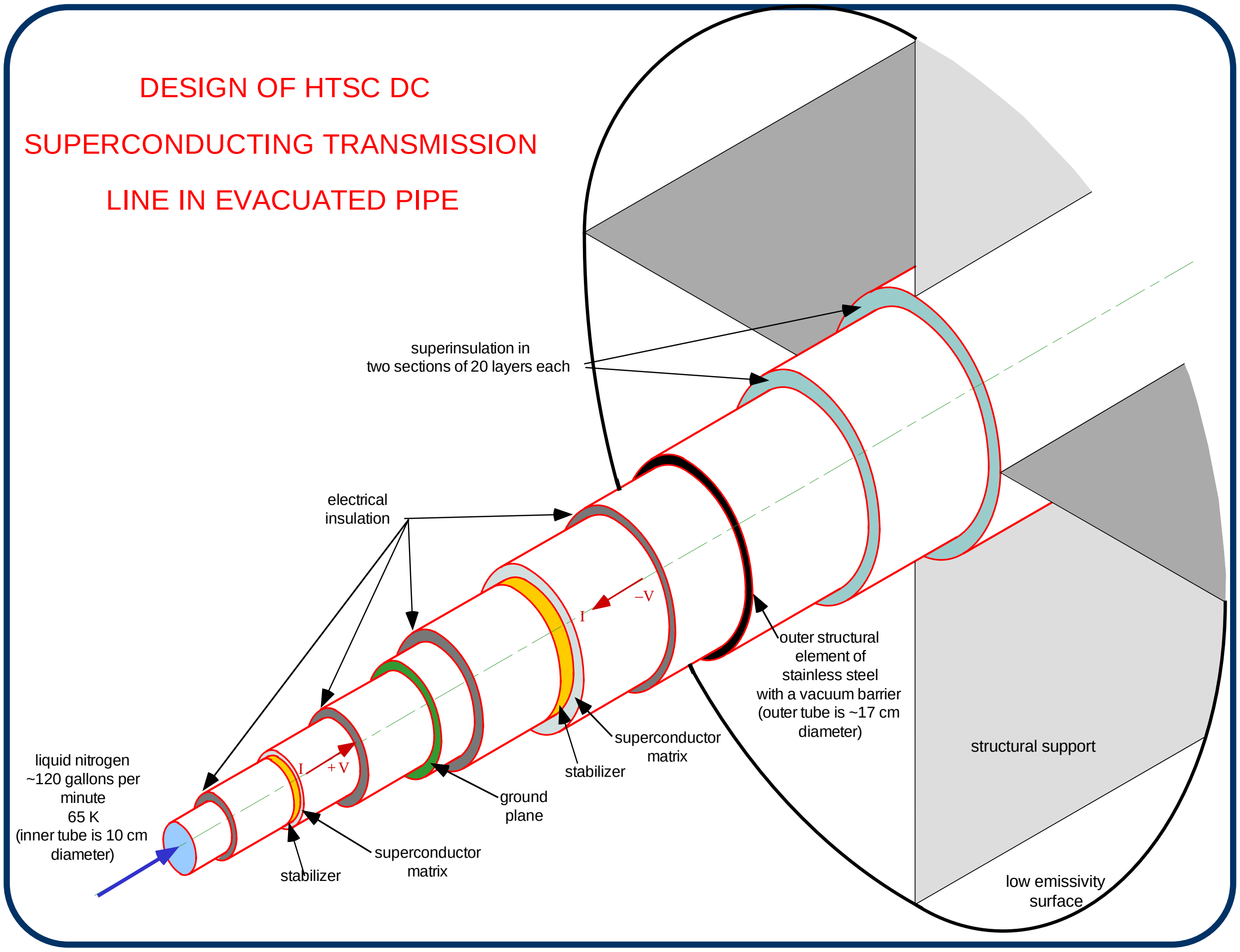


Figure 2-3 Isometric of HTS LVDC Conductor Layers

2.2 Cooling System and Trade-Offs

The baseline cooling approach for the HTS LVDC cable is liquid nitrogen at 65 K flowing in a central tube. The conductor is supported in an evacuated conduit. This approach keeps the heat flow to the conductor acceptably low, while also minimizing system cost and maintenance requirements. A heating rate of 1 Watt/m was selected as a target for design of the cooling system.

Other approaches were considered including filling the conduit with polystyrene (rather than evacuating it), cooling with gaseous helium, and cooling with the liquid nitrogen at 77 K. As described in the Appendix, these other approaches were found to be more expensive or more complicated either because of greater heat load (and hence, refrigeration requirements), more expensive cooling system components, or decreased superconductor performance. In particular, the choice of 65 K rather than 77 K as an operating temperature results in almost a factor of 2 improvement in conductor current density, as shown previously in Figure 2-2, thus reducing the cost of superconductor. The refrigerator and conductor cost trade-offs for liquid nitrogen vs. gaseous helium cooling, including the cost of the coolant is shown in Figure 2-4.

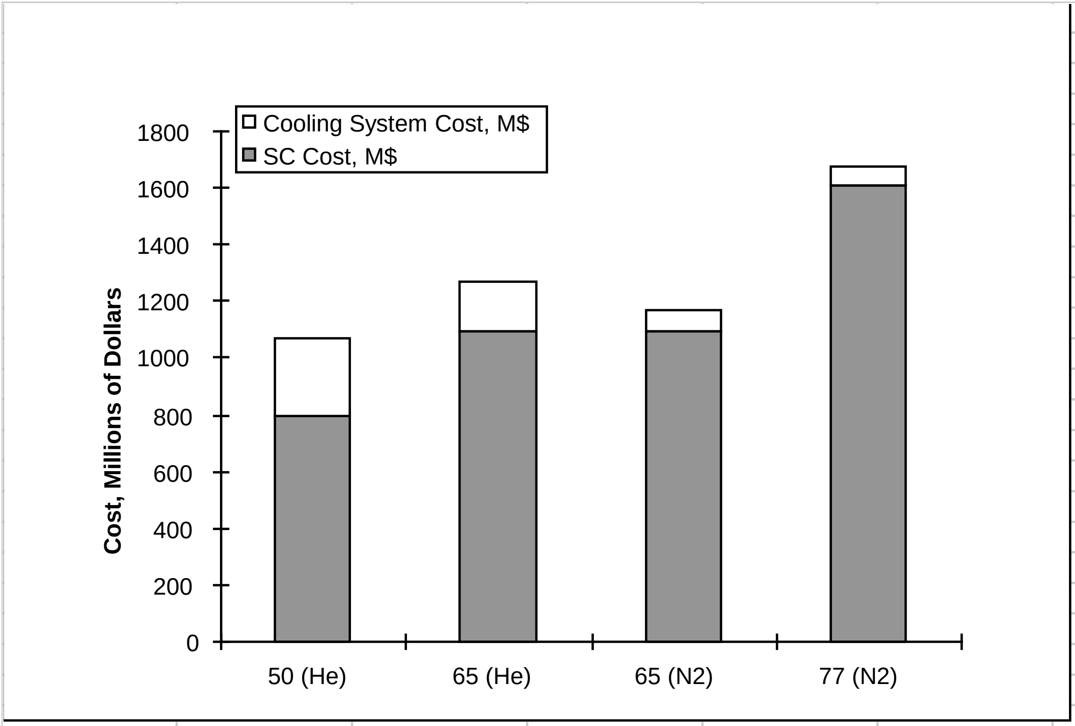


Figure 2-4 Coolant Selection Trade-Offs

The baseline system requires a total of 20 Megawatt-electric (MW_e) of refrigerator power, including a 4 MW_e nitrogen liquifier. The flow of liquid nitrogen is about 120 gallons per minute. Refrigerators with a thermal rating of 10 kilowatts-thermal (kW_t)are located at 10 km intervals along the line. The temperature rise between stations is at most 1 K, ensuring stable operation of the superconductor. Vacuum stations at each 1 km maintain a vacuum of 10^{-5} to 10^{-4} Torr in the conduit. The heat load components, in thermal Watts per meter of length (W_t/m) are listed in Table 2-1, which is also found in the Appendix.

Table 2-1
Heat Load Components

Table 2-1
Heat Load Components

Heat Source	Heat Input (W_t/m)
Radiation and Gaseous Convection	0.50
Support Conduction	0.05
Viscous heating (pumping loss)	0.20
Miscellaneous, including leads	0.20
ac losses	0.05
Total	**1.00**

3

ECONOMIC ANALYSIS

This section describes the economic analysis performed in this study, including capital cost estimates for the LVDC line, HVDC line and gas pipeline, as well as life-cycle costing analysis to generate electricity costs for all three systems. A flowchart of the analysis approach is shown in Figure 3-1.

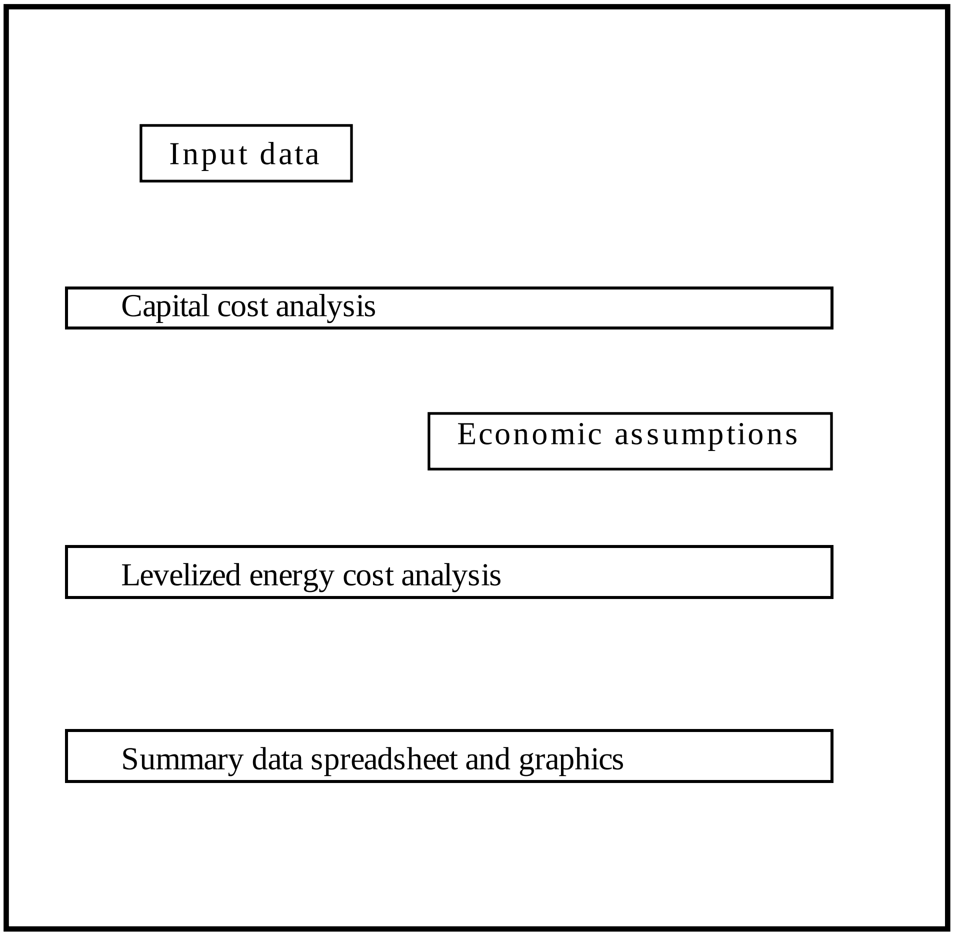


Figure 3-1 Economic Analysis Flowchart

3.1 Capital Costs

3.1.1 HTS Transmission Line

The major cost component of the HTS transmission line is the superconductor itself. The cost basis for the superconductor capital cost is \$10/kA-m for Bi-2223 operating at 77 K (i.e., J_c=55 kA/cm^2) [7]. Based on the temperature curve shown previously in Figure 2-2, this translates to \$550/m for each of the two 50 kA superconductor layers operating at 65 K. No change in the material is assumed.

The remainder of the conductor/conduit package shown previously in Figure 2-3. For costing purposes, dimensions were chosen and material properties and unit costs estimated. These are given in Table 3-1. Unit cost assumptions are listed in Table 3-2, which have been adapted from References [8] and [9].

Table 3-1
Conductor Layer Dimensions and Costs

Layer	Thickness, mm	Cost, $/m
Inner tube	2	21.8
Electrical Insulator	4	12.9
Stabilizer	2	30.1
HTS	0.5	550
Electrical Insulator	4	14.6
Ground	0.5	1.6
Electrical Insulator	4	15.7
Stabilizer	2	36.0
HTS	0.5	550
Electrical Insulator	4	17.3
Outer Tube	4	64.2
MLI 1	20 layers	8.3
MLI 2	20 layers	8.6
Conduit	4	131.0

Table 3-2
Material Cost Assumptions

Layer	Representative Material	$/kg
Tubing	Stainless Steel	4.4
Conduit	Steel	2.0

Table 3-1
Conductor Layer Dimensions and Costs

Electrical Insulator	G - 10	6.6
Stabilizer	Copper	4.8
MLI	MLI	17 ($/m^2)

Combining the superconductor and conductor package costs results in a total cost of $1450/m for the LVDC line if operated at 65 K, or $2350/m if operated at 77 K. The relative size of the component costs are indicated in Figure 3-2 for the 65 K case.

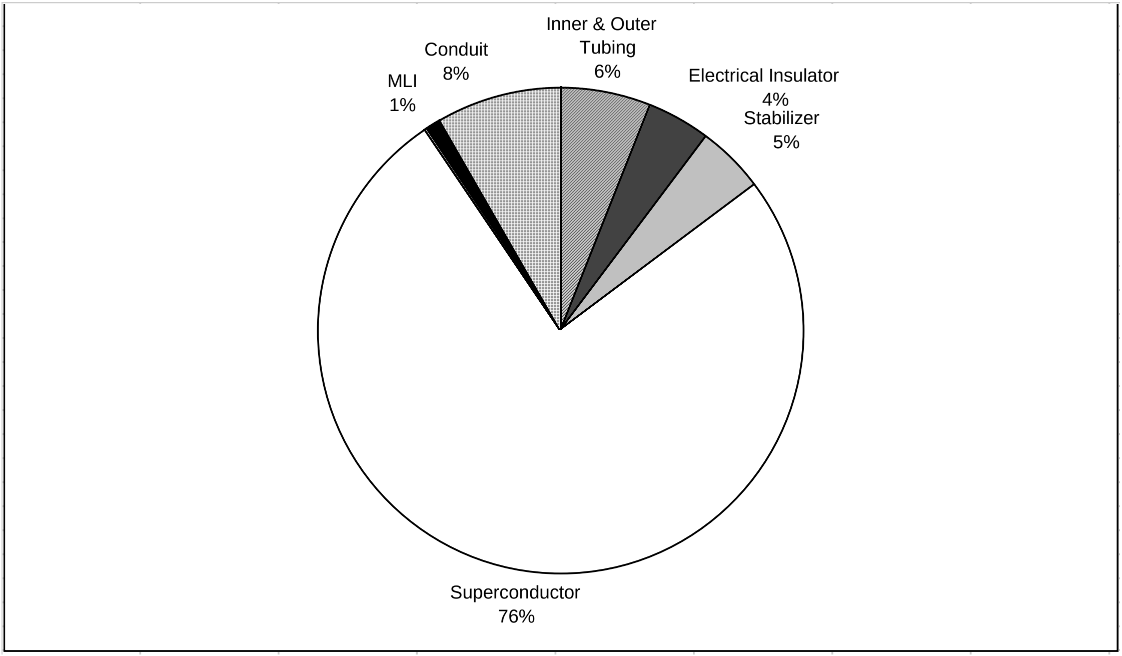


Figure 3-2 Cost Components of HTS LVDC Conductor at 65 K

The total system cost also includes converters (estimated at $36/kW) [10] and the cooling system, which includes liquid nitrogen, nitrogen refrigerators and a nitrogen liquifier and vacuum pumping stations. This system cost is $77 million for the 1000 mile line, as detailed in the Appendix. Capital and operating costs for the LVDC systems are summarized in Table 3-3.

Table 3-3
Costs and Operating Parameters for the 1000 miles LVDC system.

Component	**Unit Cost**	**Source**
Superconductor matrix (including silver)	\$10 / kA-m (J_C=55 kA / cm2 @ 77K, 0T)	7
Conductor components	\$350 / m (see Section 2.1)	8, 9
Refrigeration and vacuum system (LN2 @ 65 K)	\$45 / m + \$5 M liquifier	Appendix
Convertors	\$36 /kW	10
Steady state parasitic power	32 kW/km = 4 MW (liquifier)	Appendix
Fixed O&M (for 1000 mi. line)	2% of installed cost / year	
Variable O&M	0.30 ¢/kWh	8, 11

3.1.2 High Voltage Line and Gas Pipeline Costs

For comparison, capital cost estimates were obtained for long distance, high power HVDC lines and for large capacity gas pipelines. For HVDC, the primary sources were the ABB report mentioned previously [1] and product guide [10] and an Oak Ridge National Laboratory report [12]. For the gas pipelines, sources were published literature [13], an EPRI report [14], and ABB estimates [1].

For the HVDC system, the line and converter costs were calculated, along with the value of line losses. For the gas pipeline system (requiring 2 parallel lines, each carrying 500 million SCF/day), line costs and compressor station costs were estimated, along with the compressor power requirements. These assumptions are listed in Table 3-4. Capital cost components for all 1000 mile systems are compared in Figure 3-3.

Table 3-4
Cost Assumptions for HVDC Transmission Line and High Capacity Gas Pipelines

Component	**Unit Cost**	**Source**
HVDC Line	$1M / mile	1, 10
HV convertors	$100 / kW	1, 10
Steady state losses	8%	1
HVDC Fixed O&M	2% of installed cost/yr	
HVDC Variable O&M	0.15 ¢/kWh	1, 12
Gas Pipeline	$1.2 M / mile each x 2 lines	1, 13
Compressor power required	5000 HP / 100 mile per line	14
Compressor	$131 / HP	14
Gas Pipeline Fixed O&M	2% of installed cost/yr	
Gas Pipeline Variable O&M	0.15 ¢/kWh	14

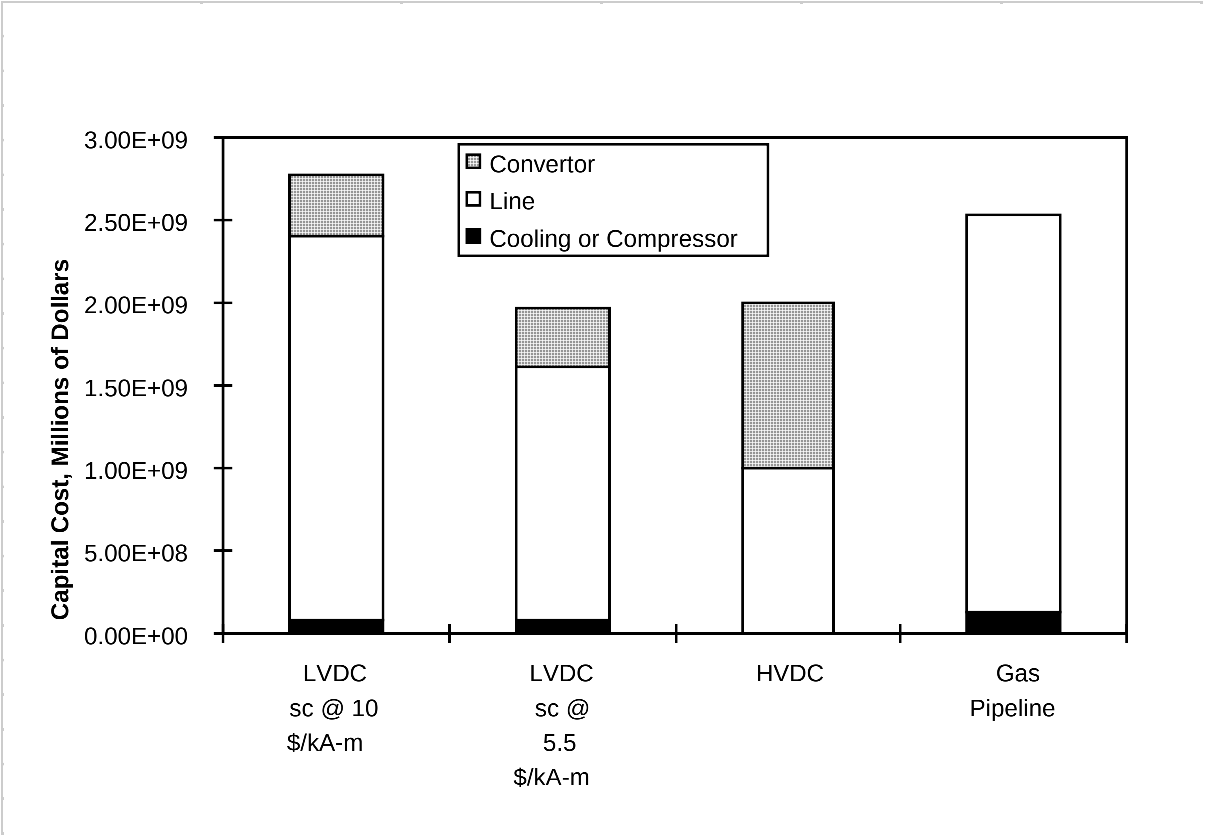


Figure 3-3 Capital Costs of 1,000 Mile Systems

3.2 Levelized Cost Analysis

Beyond capital cost comparisons, it is desirable to compare delivered electricity costs at the load for all three systems. Although the major component of the levelized or life cycle cost will be the capitalized expense, other factors also contribute, including cost of fuel and O&M costs. The fuel usage and fuel cost component varies because parasitic power requirements differ. For the LVDC system, refrigeration and vacuum system power must be accounted for, and it will scale with line length; for the conventional HVDC system, the transmission loss is typically a fraction of the power carried; for the gas pipeline, compressor power must be provided, and this also scales with line length.

The levelized cost or revenue requirement (RR) in ¢/kWh is given by Equation 1: [15]

$$RR(\$/kW/yr) = FCR * TCC + Omf * Lom + [Omv * Lom + Ucg * HR * 10^{-6} * Lg + Uce * .01Le * (1/\eta)] * D * Ho + Uce * .01Le * R * HY/P \qquad \text{(eq. 1)}$$

where:

FCR = Fixed Charge Rate or Charge Rate (1/yr)

TCC = Total Capital Cost ($/kW)

Omf = Fixed O&M Costs ($/kW/yr)

Omv = Variable O&M Costs (¢/kWh)

Lom = Levelization Factor for O&M Costs

Ucg = Unit Cost of Natural Gas ($/MBTU)

HR = Heat Rate (Btu/kWh)

Lg = Levelization Factor for Gas

Uce = Unit Cost of Input Electricity (¢/kWh)

η = Storage Efficiency (kWh_{out}/kWh_{in})

Le = Levelization Factor for Electricity

R = Steady State Parasitic Power, kW

P = Output Power, kW

Ho = Operating Time per day (hr/d)

D = Operating Days per Year (d/yr)

HY = Hours per Year = 8760

In performing the electricity cost analysis, economic assumptions and operating assumptions are made. These are listed in Table 3-5.

Table 3-5
Economic and Operating Assumptions for Levelized Cost Calculations

Variable	Value
Inflation rate	1%
Discount rate	6%
Levelization period	25 years
Carrying charge rate	10%
System output power	5000 MW
Days of operation per year	333
Fuel input (to gas turbine)	14520 Btu/kWh-out
Real escalation rate, fuel	1%
Real escalation rate, electricity	1%
Real escalation rate, O&M	0%

Capital cost values are those indicated previously, plus $500/kW for the gas turbine power plant [16].

Fuel costs vary tremendously around the world. The ABB study which motivated this work used extremely low fuel costs of 0.57 ¢/MBTU (2¢/m^3). Typical delivered U.S. prices are $3.00/MBTU. In this study, three values were considered as shown in Table 3-6. The cost of electricity as generated by the gas turbine power plant is also indicated.

Table 3-6
Fuel and Electricity Costs for Three Cases

	Gas Cost	Generated Electricity Cost (¢/kWh)
Low	0.57 $/MBTU	2.51
Mid	1.41 $/MBTU	4.01
High	3.00 $/MBTU	6.86

3.3 Results

Delivered electricity costs for the three systems for line lengths ranging from 500 to 2000 miles are shown for mid-value fuel costs in Figure 3-4. The figure shows that the slope of the cost vs. distance curve varies for each technology. The figure also shows the dramatic impact of superconductor performance on cost. In this case, the difference is due to the difference in operating temperature. However, similar effects would result from reductions in the HTS material costs or improvements in HTS performance.

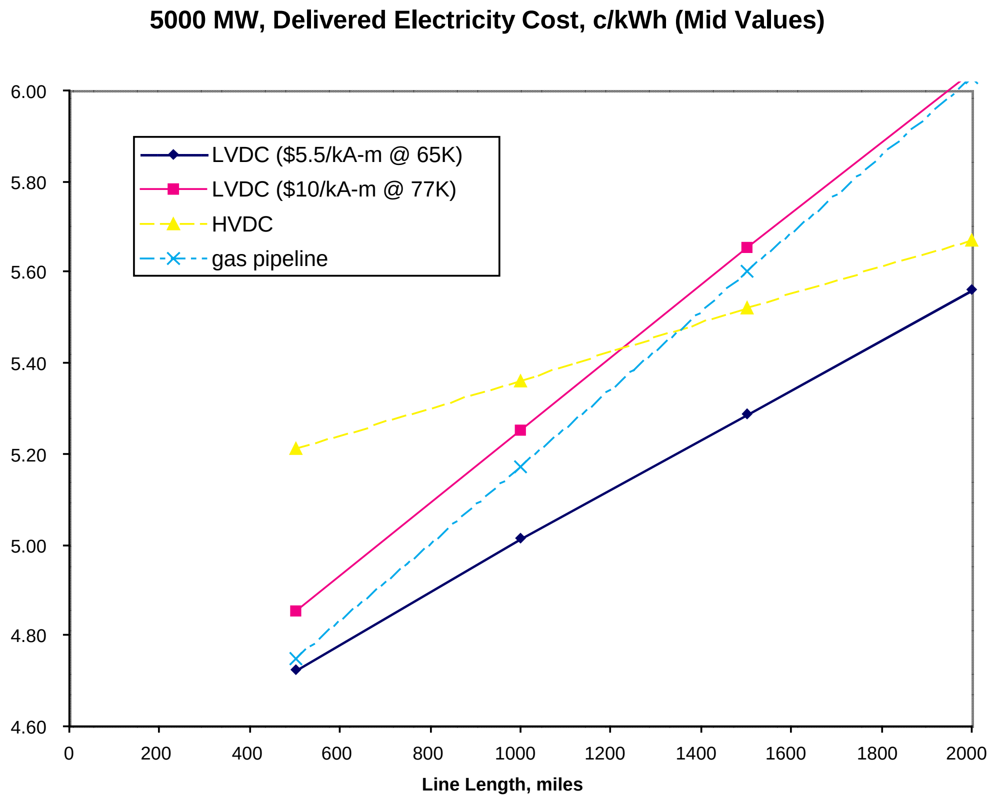


Figure 3-4 Delivered Electricity Cost for mid-value fuel

The electricity costs shown in Figure 3-4 include the levelized cost of the gas turbine generator and its fuel and O&M costs. Subtracting these out leaves the marginal or incremental cost of transporting energy by each of the three modes. These incremental costs are shown for the mid-value fuel costs in Figure 3-5. The trends are, of course, the same.

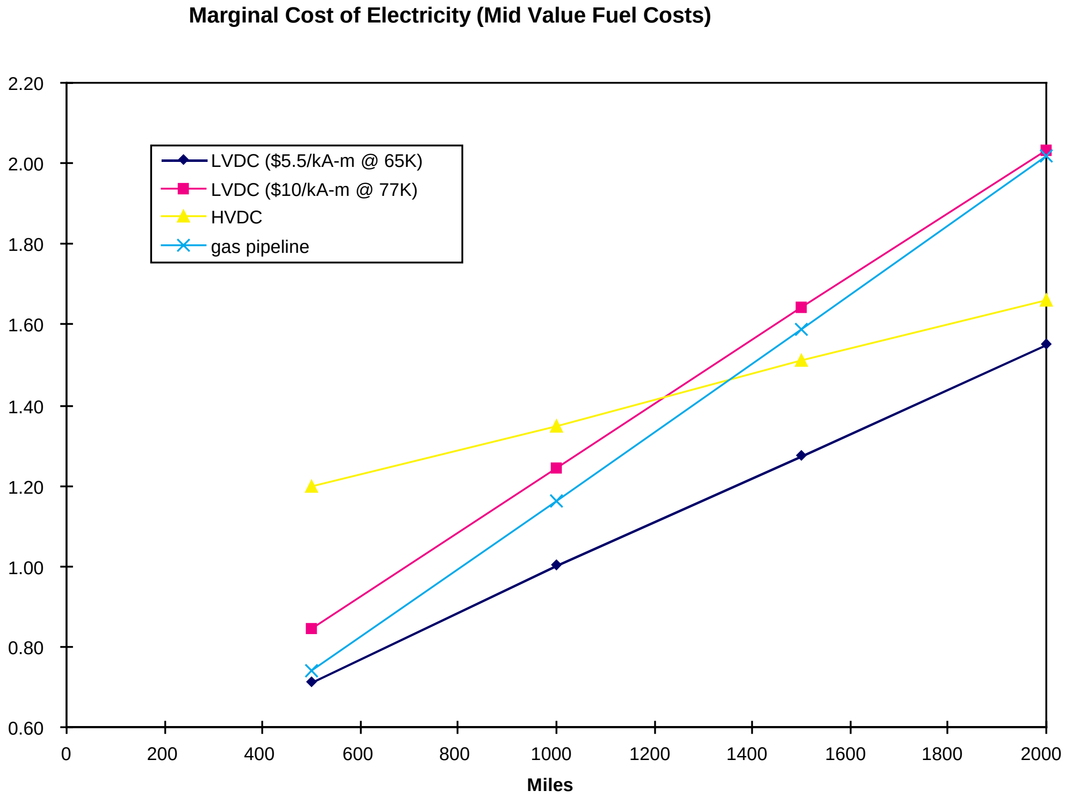
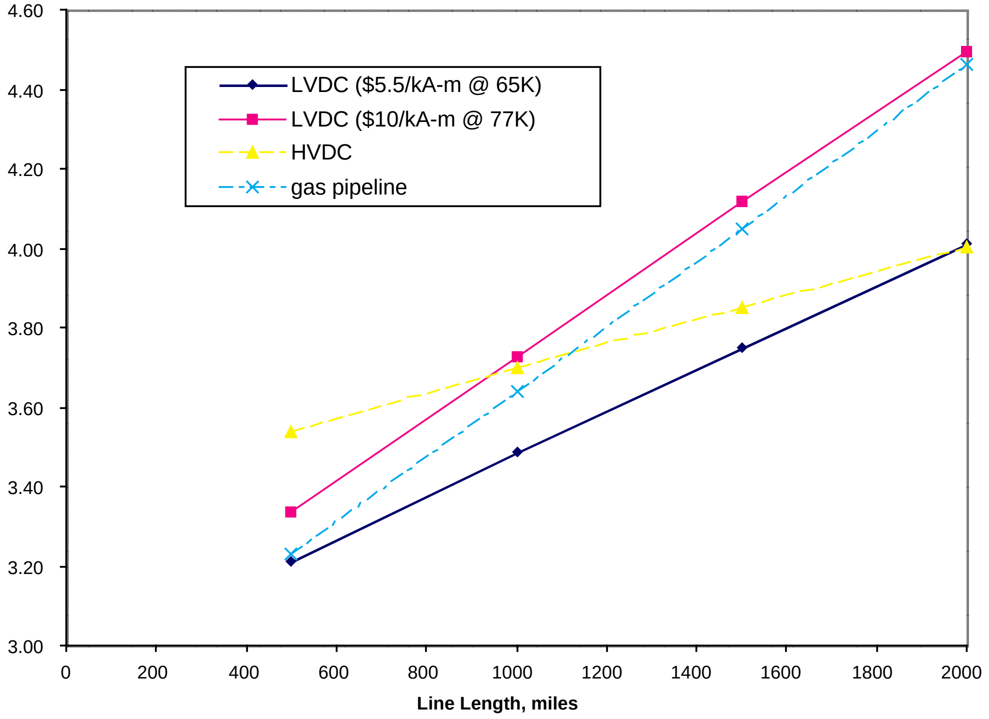
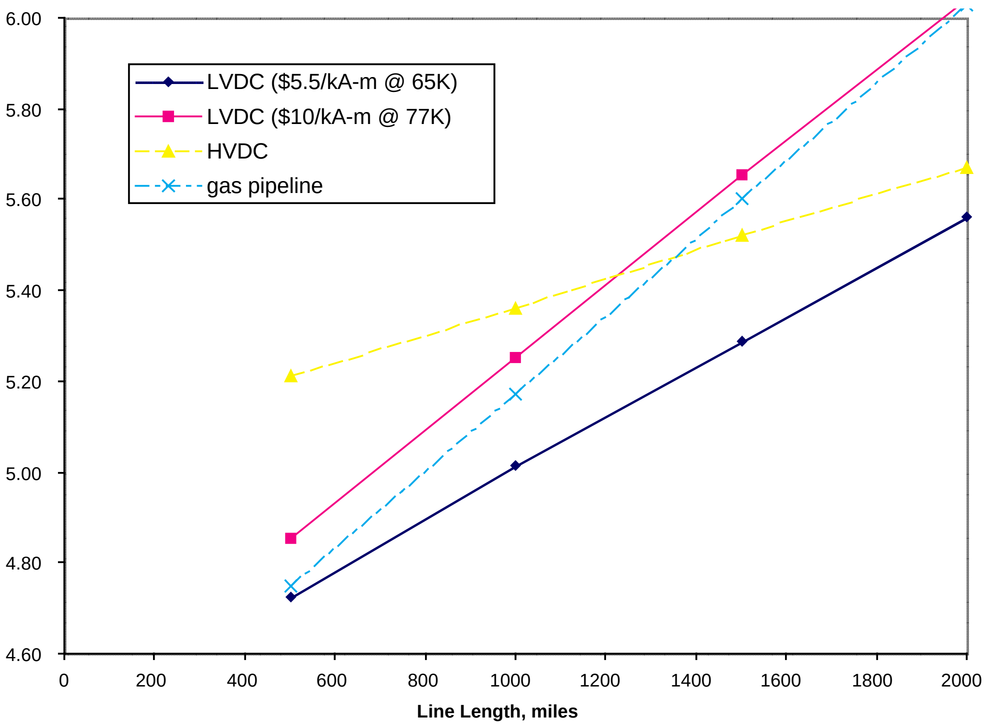


Figure 3-5 Incremental Electricity Cost for mid-Value Fuel

The extreme sensitivity of the results to the cost of fuel is shown in Figures 3-6 and 3-7, where electricity costs and incremental costs for low, medium, and high input fuel costs are shown side-by-side. The variations result from the cost of the varying parasitic power requirements for each transmission mode. A comparison of marginal electricity costs of a function of gas cost for 1000 mile lines is shown in Figure 3-8. A breakdown of the cost contributions is shown in Figure 3-9 for the mid-value incremental case at 1000 miles.



5000 MW, Delivered Electricity Cost, c/kWh (Low End)



5000 MW, Delivered Electricity Cost, c/kWh (Mid Values)

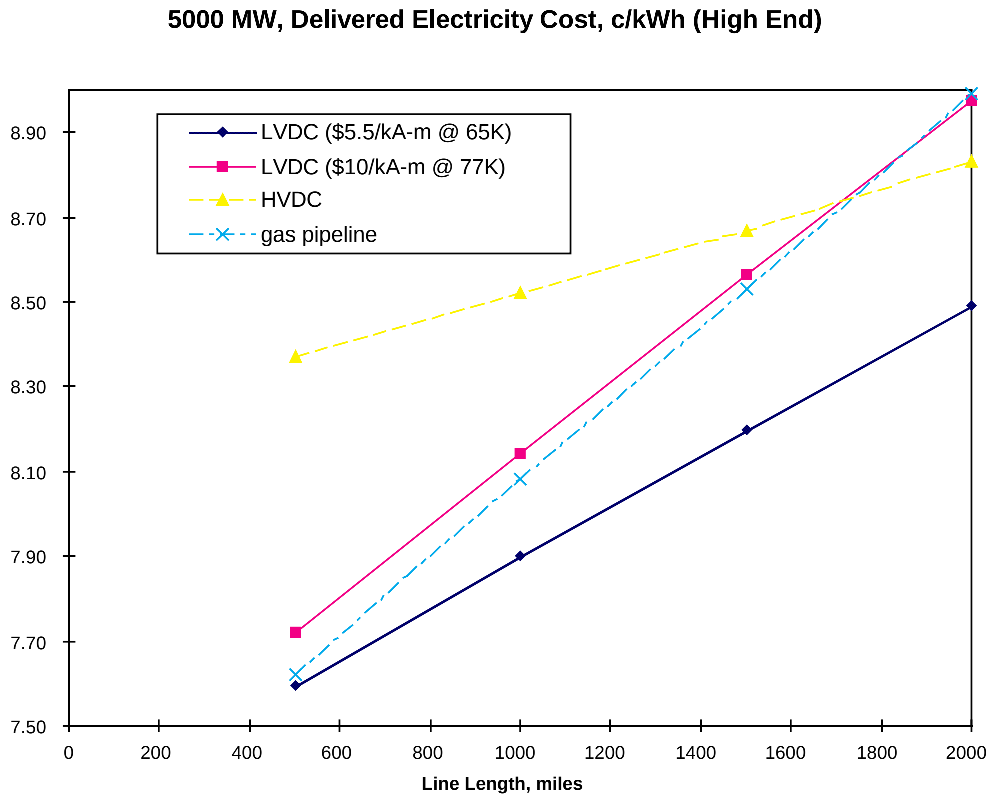


Figure 3-6 Comparative Delivered Electricity Costs

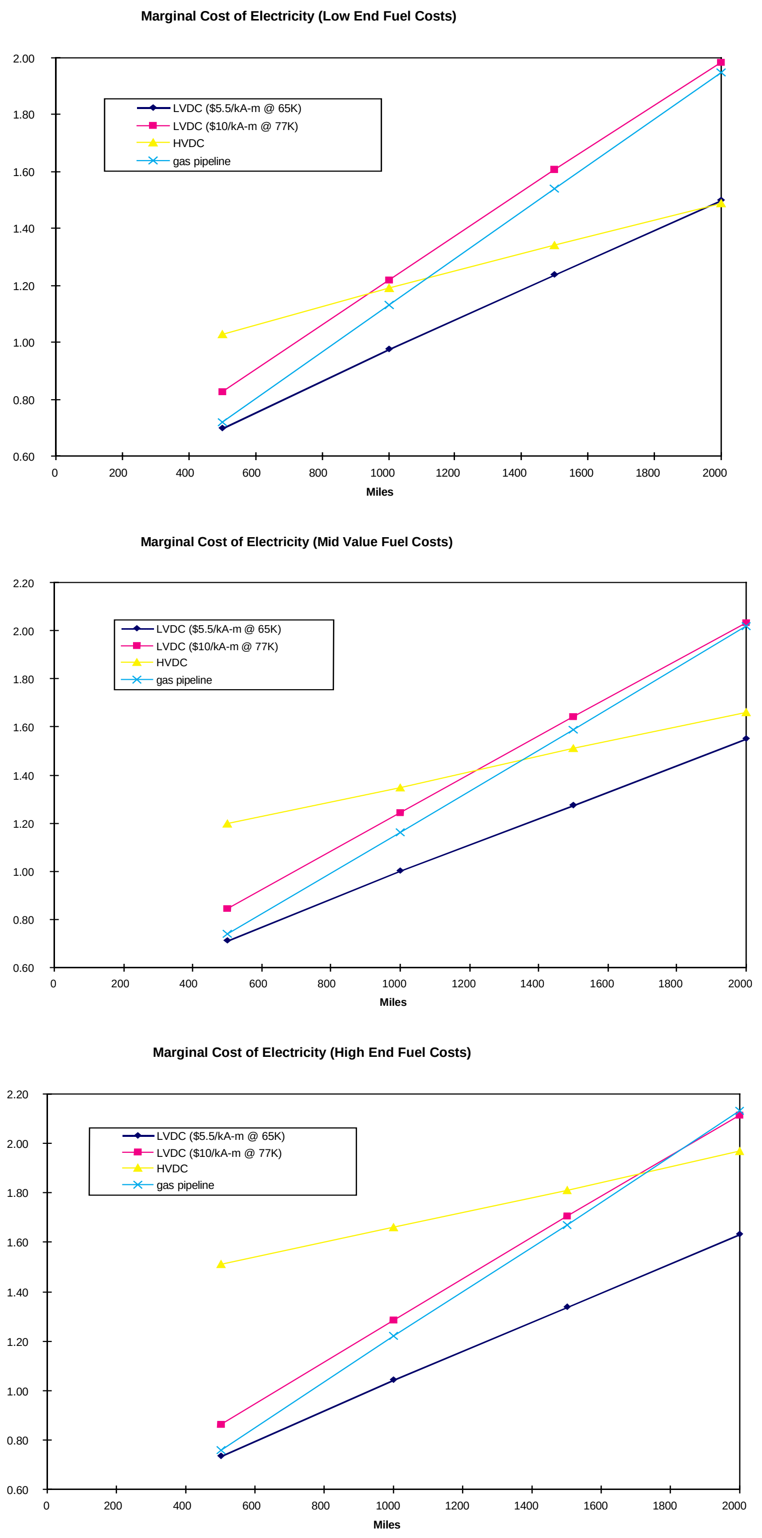


Figure 3-7 Comparative Incremental Electricity Costs

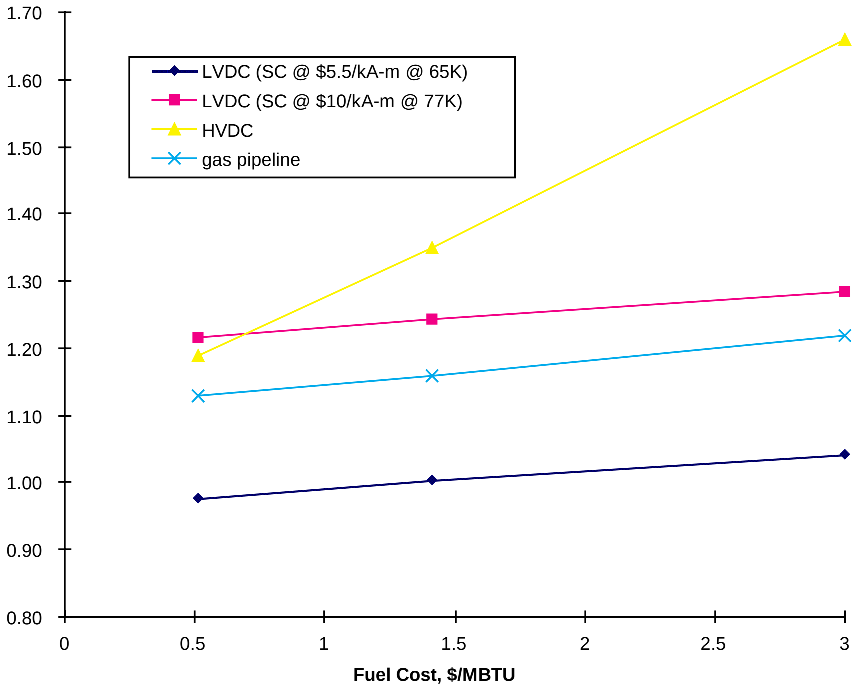


Figure 3-8 Marginal Electricity Cost as a Function of Fuel Cost for 1000 Mile System

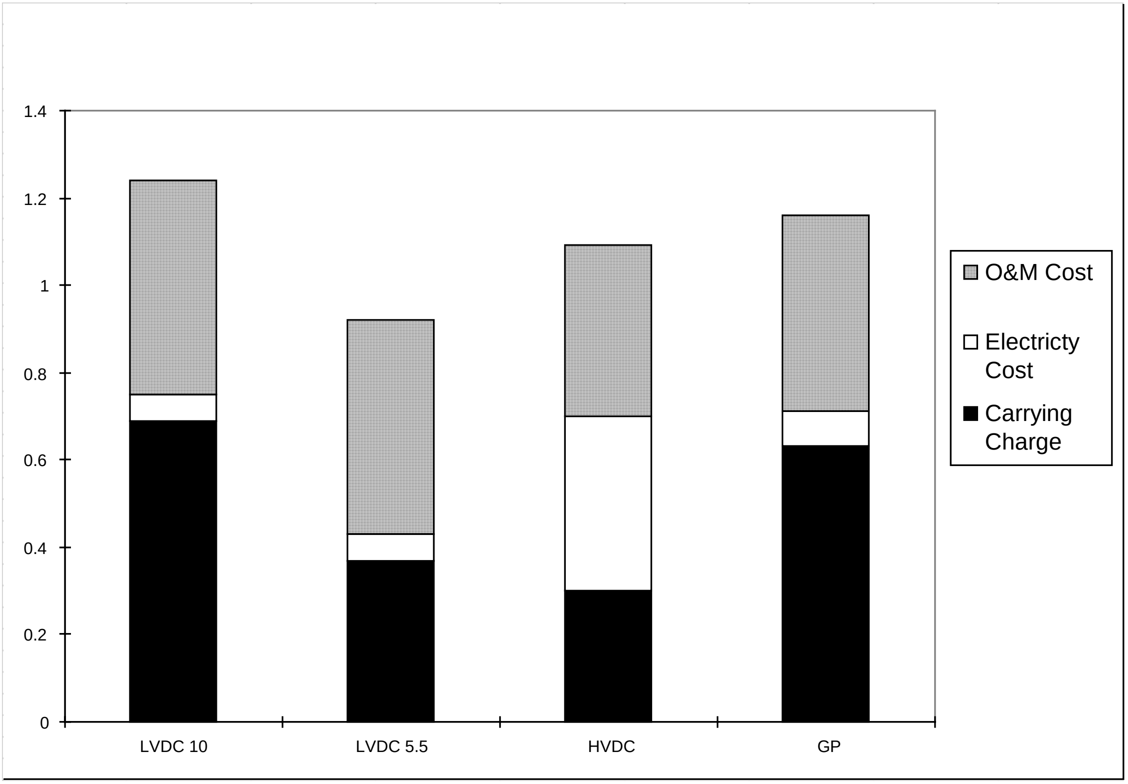


Figure 3-9 Incremental Electricity Cost Components (¢/kWh)
for 1000 mile lines

4

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

This preliminary analysis of an HTS low voltage dc transmission system suggests that such a system could be economically competitive with both HVDC and gas pipeline transport of bulk energy over long distances. The most important factor is the cost of the superconducting layer. If this can be provided at a cost around $5/kA-m at the selected operating temperature, then the system is an attractive option. The cost of delivered electricity (¢/kWh) is strongly dependent on the cost of fuel at the source, since this component contributes nearly to all the power transmission options. The trade-off between systems is impacted most by capital costs and parasitic requirements.

The development of long distance HTS transmission would provide a large commercial market not only for HTS material, but also for liquid nitrogen refrigerators in the size range of several hundred kW_t. The nitrogen reaching the end of the transmission line might also have economic value, which has not been evaluated in this study.

Several issues which are recommended for further study before proceeding to system design include:

- The sensitivity analysis has been performed with line length as a variable. It would also be interesting to consider the sensitivity to power level.
- Details of the conductor packaging (e.g., specific selection of stabilizer and insulation) need additional consideration.
- Details of providing auxilliary ac power, such as low power take-offs along the line have not been established.
- Design of a subcooled refrigerator for operation at 65 K is needed.
- Vacuum requirements need more detailed evaluation, vacuum pressure needs to be optimized, and pumps including distributed pumping must be specified.
- Line cooldown must be addressed, including thermal contraction issues.

- A trade off between flow rate and refrigerator spacing is needed.

These items would provide a refinement to the system analysis and a basis for development efforts leading up to implementation of an HTS LVDC transmission system.

5

REFERENCES

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[1] A. Clerici, A. Longhi, B. Tellini, ìLong Distance Transmission: the DC Challenge,î presented at the Sixth International Conference on AC and DC Transmission IEEE Conference, London, UK. (May 1996)

[2] P. Grant, “Superconductivity and Electric Power: Promises , Promises...Past, Present, and Future,” Paper #PG-4, presented at the Applied Superconductivity Conf., Pittsburgh, Aug. 1996.

[3] D.M. Buczek, et al, “Manufacturing of HTS Composite Wire for a Superconducting Power Transmission Cable Demonstration,” Paper #MW-1, presented at the Applied Superconductivity Conf., Pittsburgh, Aug. 1996.

[4] Superconducting Low Voltage Direct Current (LVDC) Networks. Electric Power Research Institute, Palo Alto, CA: April 1994. Report TR-103636.

[5] J. Oestergaard, “Superconducting Power Cables in Denmark - a Case Study,” paper #LMB-1, presented at the Applied Superconductivity Conf., Pittsburgh, Aug. 1996.

[6] Personal communication - American Superconductor Corp., Aug. 1996.

[7] Department of Energy near term cost target

[8] Conceptual Design and Cost of a Superconducting Magnetic Energy Storage Plant. Electric Power Research Institute, Palo Alto, CA: April 1984. Report EM-3457.

[9] “Independent Cost Estimate for the SMES-ETM,” prepared by the Power Associates, Inc. and Cosine, Inc., for the Defense Nuclear Agency.

[10] L. Philipson, editor, “Introduction to Integrated Resource T&D planning,” ABB Power T&D Co., Cary, NC, 1995.

[11] S. M. Schoenung, et al, “Capital and Operating Cost Estimate for High Temperature Superconducting Magnetic Energy Storage,” Proc. 54th American Power Conference, Chicago, IL, 1992.

[12] Comparison of Costs and Benefits for DC and AC Transmission. United States Department of Energy, Oak Ridge TN: February 1987. Report ORNL-6204.

[13] Warren R. True, ìPipeline Economics,î Oil & Gas Journal, November 27, 1995, pp. 39-58.

[14] Pipelines to Power Lines: Gas Transportation for Electricity Generation. Gas Research Institute and Electric Power Research Institute Palo Alto CA: January 1995. Report TR-104787.

[15] R. B. Schainker, “A Comparison of Electric Utility Energy Storage Technologies,” presented at ASCE Energy ‘87 Conference, American Society of Civil Engineers, 1987.

[16] Technical Assessment Guide - Electricity Supply - 1989. Electric Power Research Institute, Palo Alto, CA: Sept. 1989. Report P-6587-L.

APPENDIX

REFRIGERATION, VACUUM, AND ANCILLARY POWER

Description of the System and Summary of Issues / Choices

The conductor / conduit system was shown previously in Section 2. The sketch in Figure A-1 shows the system as it was analyzed for thermal and structural parameters.

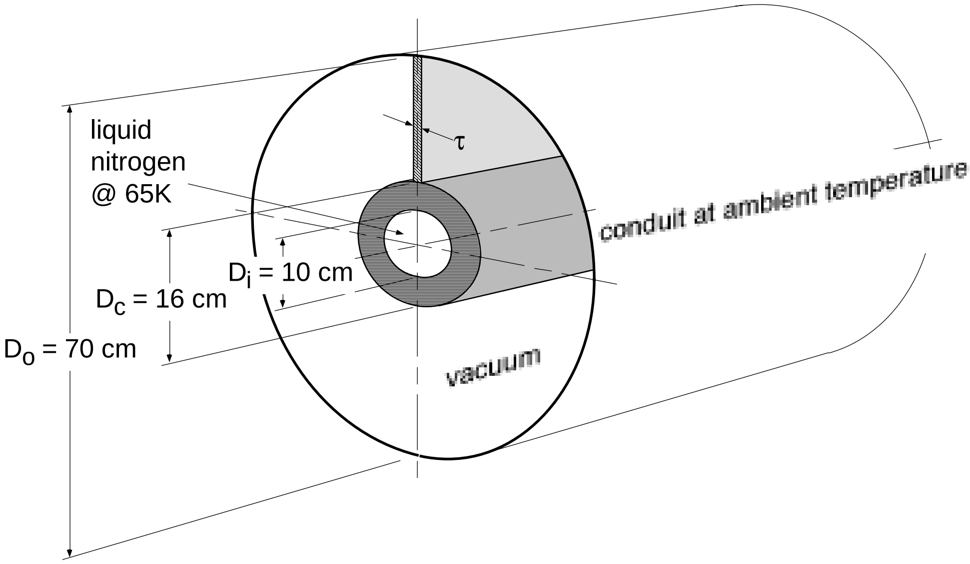

Figure A-1 Conductor/ Conduit Analysis Sketch

Several options for coolant, the refrigeration process, and vacuum level were investigated. The system selected is driven by a requirement to achieve a total heat input into the cold portion of the superconducting DC transmission line of less than about one watt per meter (1 W_t/m) of length. This total heat input is budgeted among the various heat sources, namely: radiation, gaseous convection, support conduction, miscellaneous, and pumping or friction losses. An additional heat input is the ac losses in the superconductor due to currents induced by voltage ripple.

The following temperature choices were made. First, based on the characteristics of the superconductor, the operating temperature should be below about 75 K. Second, a maximum temperature rise of 1 K between refrigeration stations was selected to achieve uniform superconductor performance. This choice also provides some operational redundancy because the superconducting dc line can perform at or near capacity with a 2 K temperature rise, which would occur if one refrigerator were out of service. Third, the use of single-phase, liquid nitrogen was selected instead of gaseous helium to reduce system complexity and friction associated with viscous flow. This choice means the operating temperature must be between the freezing point of nitrogen, about 63 K, and its boiling point, about 78 K. An operating temperature of 65 K was selected because the current carrying capacity of the superconductoróa major cost itemóis considerably improved at this lower temperature. The refrigeration costs increases by about 25 % when the temperature is decreased from 77 K to 65 K, according to system vendors. [A1]

The system requires relatively a large liquifier at the power generation end. It produces 21,600 liters of liquid nitrogen per hour at 65 K. This is a moderately large refrigeration system. Several refrigerators this size or larger are installed in industrial locations in the United States every year [A1]. This liquid nitrogen is pumped along the entire length of the line, being re-cooled by refrigerators when the temperature increase exceeds the 1 K limit. For the cooling requirement of 1 W_t/m, the separation between refrigeration stations was chosen to be 10 km.

The goal of a total heat input of 1 W_t/m is a more serious requirement on the vacuum system than on the refrigeration system. Radiation and gaseous convection are controlled by using multilayer insulation and by evacuating the space between the ambient temperature outer pipe and the core. Approximately 40 layers of superinsulation is adequate, but a vacuum of at least 10^{-4} Torr is required. This requires frequent pumping stations, approximately every kilometer, each with a combination of vacuum pumps.

The total electrical power load for each refrigerator is about 100 kW_e, including a 25 % margin. The 10 vacuum stations over the 10 km require about 200 kW_e. Power for this equipment is supplied by an ac transmission line which is powered from the dc line via taps every 100 km. If power flows in both directions from the dc tap, the maximum power in the ac line will be about 1.5 MW.

Several issues remain before proceeding to a cryogenic system design.

- Design of a subcooled refrigerator for operation at 65 K is needed.
- Vacuum requirements need more detailed evaluation, vacuum pressure needs to be optimized, and pumps including distributed pumping must be specified.
- Line cooldown must be addressed, including thermal contraction issues.
- A trade off between flow rate and refrigerator spacing is needed.

Heat Input

The total heat flow into a dc superconducting transmission line will be dominated by the average heat input per unit length. This is in contrast to the typical small and/or short cryogenic systems where heat input from power leads and supports are typically the dominant effect. It is also very different from an ac transmission line where the ac losses associated with current and field changes in the superconductor and associated stabilizer are dominant. The six major sources of heat input in a dc superconducting transmission line are:

1) thermal radiation from the ambient temperature outer vessel,

2) gaseous convection between the outer vessel and the conductor package,

3) conduction in the mechanical supports for the core conductor package,

4) miscellaneous heat flow at the location of joints, connections, power leads, etc.,

5) viscous heating associated with flowing the cryogen through the conductor, and

6) ac losses due to current ripple in the superconductor and stabilizer.

Here the different sources of heat input to the HTS dc superconducting transmission line are described and their magnitudes are estimated. These values determine the refrigerator vacuum and superinsulation requirements.

Radiation

The rate of energy emitted per unit area of a surface depends on the temperature and the emissivity of the surface. Similarly, the rate of energy absorbed by a surface depends on the effective temperature of the radiation that pervades the region near the surface and the absorptivity of the surface in the wavelength range associated with this temperature. Thus, radiation transfers energy from surfaces at one temperature to other surfaces at lower temperatures. In the case of the dc transmission line, heat flows from the ambient temperature outer shell to the 65 K conductor core. The heat that is transferred (in Joules/sec or Watts) is

$$W = \sigma\, \varepsilon\, A\, (T^4_{\text{ambient}} - T^4_{\text{cond}})$$

where ε is the emissivity of the surfaces, σ is Boltzman's constant ($= 5.67 \times 10^{-12}$ W cm^{-2} K^{-1}), and A is the area of the surfaces. This equation is only approximate because the two surfaces of the transmission line have different areas and emissivities. However, if the emissivity were about 0.3 for both surfaces, and making a small correction for the annular case, the heat input would be 75†W_t/m^2. This translates to about 45 W_t/m of length along the transmission line, which is much too high.

To reduce the heat flow to the 65 K core it is necessary to install some type of radiation absorbing material. Several approaches are available including:

- solid foam insulation in the annular space,
- particulates in gas in the annular space,
- particulates in vacuum in the annular space,
- low emissivity surfaces on the ambient and cryogenic walls, and
- superinsulation (multiple layers of aluminized mylar) in a vacuum in the annular space.

An insulation material such as foam not only affects thermal radiation, but it also reduces components of the gaseous conduction. Experiments with foam [A2] indicate that the heat transfer is about 50†W/m^2, a reduction from the 400 W/m^2 for air at one atmosphere, but still much too high for the dc transmission line. The heat flow through particulates, even in a vacuum, are similar to that for the solid foam. Thus the only solution is to use a vacuum, to have the inner and outer surfaces coated to reduce emissivity, and to use superinsulation.

Reducing the emissivity of the inner and outer surfaces to 0.02 decreases the heat input to about 3†W/m, still higher than the acceptable level of 1†W/m for all contributions. This can be reduced further by adding layers of superinsulation or multilayer insulation (MLI).

Superinsulation is a term used for multiple very thin (≈ 0.01 mm) layers of aluminum-coated mylar. This material is in the vacuum space and has a thickness of approximately 1 cm for 40 layers. The combination of low surface emissivity in the layers limits the total radiative heat transfer.

The reduction is approximately inversely proportional to the total number of layers, n, of material [A3]. If 0.1†W/m is budgeted for radiation, then at least 31 layers is required:

$$Q = \frac{Q_{\text{initial}}}{n-1} \qquad \text{or} \quad n = 1 + \frac{Q_{\text{initial}}}{Q} = 1 + \frac{3}{0.1} \rightarrow 31 \text{ layers.}$$

Since 40 layers is often used [A4], it is selected here. This number of layers provides the maximum insulation in a single layup. More layers tend to reduce the insulating effect because their weight crushes them and causes layer to layer contact.

Gaseous Convection

Residual gas transmits heat from the ambient temperature outer shell to the 65 K core conductor. The amount of heat transmitted depends on the residual gas pressure. There are two regimes for this heat transfer. If the gas density is high, i.e., the molecules collide many times between the inner and outer surfaces, the heat transfer is nearly independent of pressure. If the density is low, i.e., the molecules are likely to travel from the outer surface directly to the inner surface without a collision, then the heat transfer is roughly proportional to the pressure. This is called the molecular flow regime. At a pressure of 10^{-5} Torr (0.01 microns, or 10^{-3} Pa), the mean free path for nitrogen gas is about 1 m. For the transmission line geometry the heat input in Watts/meter is given by [A2]:

$$W = 1.4 \times 10^{-4}\, \text{p(Torr)}$$

At 0.01 microns, gaseous conduction should contribute about 0.14 W/m.

Several measurements of the combined heat transfer from these two mechanisms radiation and convection have been made for space and high-energy-physics applications. The heat flux from ambient to 77 K decreases to about 0.5 W/m^2 (0.3 W/m for the transmission line) at 40 layers of superinsulation and a gas pressure of 10^{-5} Torr. These values are only slightly higher than the theoretical values and there is little further decrease for higher vacuums. At a vacuum of 10^{-4} Torr the heat flux increases to about 0.75 W/m^2. Achieving 10^{-4} Torr is considerably less expensive than 10^{-5} Torr, and it takes less time. Thus, a vacuum of 10^{-4} Torr is used for further estimates and a heat budget of 0.5 W/m is used for the combined heat loads from radiation and gaseous convection.

Structural Supports

The central conductor core must be supported vertically against gravity and transversely against any off-centering forces. This might be accomplished with solid disks or bobbins, however, such a structure would limit gas flow in the annulus. The result would be either a higher pressure vacuum, or an increase in the vacuum pumping requirements. Rather, the supports will be thin spider structures, with most of the forces contained by tension elements. The minimum structure occurs when the weight of the conductor bundle is supported from the top of the outer pipe by a tension member.

The support thickness and resulting conduction input were calculated as follows: The minimum thickness of support structure is that for a tension member (in this case G-10) carrying the weight of the conductor and tubing, filled with liquid nitrogen. Referring back to Figure A-1, the force per unit length is:

$$F_L = \rho V/L = \rho A = \quad (\rho_i A_i)$$

where ρ is density and A is cross sectional area of each layer, i.e. the central flow channel, the layers of tubing, and the layers of conductor.

Assuming the solid cross section has a density midway between that of steel (440 lb/ft^3) and copper (558 lb/ft^3), or $\rho_{\text{conductor}}$ = 500 lb/ft^3

then, with $\rho_{\text{liquid nitrogen}}$ = 50.4 lb/ft^3, and referring to the dimensions in Figure A-1,

$$F_L = 2.3 \text{ lb/cm}$$

The thickness required to support this weight is given by:

$$\tau = U/F_L$$

where U is the tensile strength of the support material. Assuming G-10,

U = 400 MPa. This gives the minimum τ = 2.6 microns, which is a small structural requirement!

Allowing for margins of safety and ease of fabrication, consider a practical value to be τ = 10 microns. (This is an equivalent thickness, since the actual configuration would likely be intermittent supports along the length of the conduit.)

Calculating the conduction heat input per unit length resulting from this support structure:

$$q_L = \tau \quad k(T)\, dT \,/\, l$$

where k(T) dT is the integrated thermal conductivity over the temperature range 65 to 300 K, approximately = 150 W/m for G-10,

and l is the radial distance from the cold core to the warm conduit, approximately 0.25 m. This gives q_L = 0.006 W_t/m.

There may occasionally be excessive forces (seismic, etc.) requiring some additional structure (bumpers, e.g.) for motion limitation. Thus, a budget of 0.05 W_t/m is allowed for heat flux due to the mechanical supports.

Miscellaneous Heat Load

Using an engineering rule of thumb, it is assumed that the heat load from penetrations through the superinsulation will increase the total heat flux from radiation and gaseous convection by about 20%, or 0.1 W_t/m. Extensive piping will be required at the refrigerator connection to the transmission line, and may be required for areas of stress relief that accommodate the thermal contraction of the line during cooldown. This may amount to several hundred watts for each refrigerator. Power leads contribute about 1 W_t per kA based on catalog information from America Magnetics, Inc. This contributes approximately 100 W_t at each end of the line and a few watts along the line for the smaller power leads that extract energy for refrigeration and vacuum pump power. This loss is negligible. A budget of 0.20 W_t/m is allowed for miscellaneous heat input.

Friction or pumping loss

The friction or viscous heating, loss is based on the total amount of cryogen flowing along the transmission line, $\dot{m}$, the pressure drop between refrigerators, Δp, and the density of the liquid, ρ.

$$W_t = \dot{m}\ \Delta p / \rho$$

The pressure drop in the line (for a 4" diameter pipe) is found from the following expression [A2], in English units:

$$\Delta p(\mathrm{psi/ft}) = 0.15 \times 10^{-6}\, q^2\, (\mathrm{gal/min})$$

Using 0.85 kg/liter as the density of liquid nitrogen at 65 K, the flow rate is 5.8 liter/second or about 100 gal/min. The flow velocity is 1.35 m/s. The pressure drop over 10 kilometers is 50 psi, or 0.34 MPa. Plugging this into the equation, the viscous loss or heat input is 2 kW_t or 0.2 W_t/m.

Heat Input from ac Losses in the Conductor

The power conditioning system (PCS) converts ac to dc. However, the voltage on the dc line contains some ac at frequencies associated with the characteristics of the switching method in the PCS (usually at 6 or 12 times the main frequency [A5]). These ac components produce currents in the superconductor and stabilizer. For conventional dc transmission lines the voltage distortion (ripple) is limited by ANSI/IEEE standards [A6] to a maximum of 1% for an individual frequency and 2-5% total. Losses at 1% ripple would be unacceptably large for the baseline HTS material and configuration. (A 1000A ac component would mean 0.5 W_t/m heat load for today's HTS material [A7].) The allowable current ripple in the HTS line is determined by the total refrigeration load. In order to maintain 1 W_t/m total heat input, the ac current contribution must be limited to about 0.05 W_t/m. This can be achieved by:

- Filtering the power output from the ac-to-dc convertor (a variety of methods are available [A8]).
- Selecting an HTS conductor material and configuration with inherently low ac losses.

Total Heat Input

The total heat input to the transmission line is the sum of the above individual values, as summarized in Table A-1 below. The total 1.0 W_t/m is a conservatively high value.

Table A-1 Heat sources and heat input values for dc superconducting transmission line.

Heat Source	Heat Input (W_t/m)
Radiation and Gaseous Convection	0.50
Support Conduction	0.05
Viscous heating (pumping loss)	0.20
Miscellaneous, including leads	0.20
ac losses	0.05
Total	**1.00**

Refrigeration Options

Operation over long distances at temperatures below 80 K requires the use of a cryogen that:

1) has sufficient heat capacity to remove the approximately 1 W_t/m that enters the system,

2) can be pumped without excessive heat input due to frictional losses, and

3) remains fluid at the operating temperature and pressure.

Liquid nitrogen and gaseous helium and were considered for use in the dc transmission line. A liquid nitrogen system was chosen because it has smaller capital and operating cost and a simpler transmission line cross section. The gaseous helium alternative is discussed at the end of this section.

The characteristics of liquid nitrogen of interest here are

Melting point	T_{melt}=63.14 K
Boiling point	T_{boil}=77.40 K @ 1 Atm
Specific heat	C_p=2 kJ/kg/K=13.5 Cal/mole/K.
Enthalpy Change	$H_{ambient}$ - H_{65K} = 1800 Cal/mole = 270 kJ/kg
Density	ρ = 850 kg/m^3

The melting point of 63 K establishes an operating temperature between approximately 64 K and the boiling point, 77 K. Subcooled, single-phase liquid nitrogen at 65 K was chosen as the cryogen for three reasons. First, performance of the superconductor improves as the temperature is lowered. Second, pressure drop (friction) is less for subcooled-liquid flow than for two-phase flow. Third, 65†K was chosen because the increased cost of refrigeration between 77†K and 65†K is more than offset by the reduced cost of superconductor.

The cryogenic system consists of a large liquifier at the power input end, which produces 65 K liquid nitrogen that is pumped the 1000 mile (1610 km) length of the dc transmission line. The 1.0 W_t/m heat input causes the temperature of the liquid to rise as it flows along the line. Smaller refrigerators are placed along the transmission line to ensure that under normal operation the temperature does not exceed 66†K. The 65†K liquid nitrogen leaves the refrigerators at a pressure of 10 Atm. By the time it reaches the next refrigerator along the line it has warmed up by approximately 1 K and the pressure has decreased to about 7 Atm. Each refrigerator provides cooling from 66†K to 65† K and boosts the pressure of the liquid nitrogen back up to 10 Atm.

One advantage of this system, and the margins of 25 % or so in the refrigerators, is that the line should be able to operate at the specified power level even if one refrigerator is out of service. In this case, the adjacent refrigerators can boost their cooling so that the temperature rises at most to 66.5 K and the pressure always remains greater than 3 Atm, which assures single phase flow. The 25 % margin also assists in system cooldown.

There is a trade off between liquid nitrogen flow rate and refrigerator spacing. Since the maximum temperature rise for normal operation is constrained by superconductor performance to 1 K, if the separation between refrigerators were increased, the flow rate and thus the size of each refrigerator would also increase. Total refrigeration along the line goes up slightly because frictional losses also increase. But, since the per kW cost of refrigeration decreases with unit capacity, the total cost of refrigeration along the line is not affected by increasing or decreasing refrigerator separation by a factor of two or so. Similarly, the total power required to operate the refrigerators is also relatively insensitive to separation or total flow rate. However, both the cost of the initial liquifier and the power required for its operation are roughly proportional to the total liquid nitrogen flow rate. For any given site, the refrigerator spacing and flow rate may optimized to meet the market for liquid nitrogen at the power delivery end of the transmission line.

For this study of a 1000 mile long dc transmission line, a refrigerator separation of 10 km was selected. Thus, 160 identical units each delivering 10 kW_t of refrigeration at 65 K are required. Though refrigerators in this size range exist today, the market is small. Larger markets exist for both much larger, 1 MW_t equivalent, and smaller, 200 W_t, units. However, the need for 160 identical refrigerators is sufficient to warrant a special design and take advantage of large-scale production techniques, both of which will reduce cost and improve efficiency.

Since these 10 kW_t refrigerators will be designed to operate continuously in one mode (We neglect the issue of cooldown), the efficiency, at 65 K, should be better than 50 % of Carnot. This means that the electrical power per refrigerator will be about 80 kW_e. We add 25 % to cover the operation of ancillary equipment and as a safety factor to arrive at 100 kW_e per unit, or 16 MW_e for the entire transmission line.

The cost of individual refrigerators in this input power range vary from about 350 to 500k$ each. Refrigerators for lower temperatures cost somewhat more. Discussion with some manufacturers, present and past, suggests that savings of a factor of two or more will be possible for quantities of 100 or more. The cost reduction would be even greater if existing refrigerators did not use mass produced parts wherever possible, for example, the compressors. The estimated cost of the refrigerators in quantity is 200 k$ each for a total budget of 32 M$ for the entire transmission line.

The single refrigerator at the power generation end of the transmission line must have the capacity to produce 5 kg/s of liquid nitrogen from ambient air. This liquefier provides 1.35†MW of cooling at temperatures from ambient to 65 K. The total electrical power needed for this unit is about 4 MW, and it will cost about 5 M$. Refrigerator and liquifier parameters are given in Table A-2.

Table A-2 Refrigerator capacity and cost for liquid nitrogen as a function of temperature. Total cost includes liquifier.

Temperature	Liquifier	Liquifier	Refrigerator Power	Efficiency	Refrigerator Power required	System Cost
	Power	Cost			Total	Total
(K)	(MW_e)	($M)	(W_t/m)		(MW_e)	($M)
65	4	5	1	0.12	20.0	37.0
70	4	5	1	0.14	18.0	32.0
75	4	5	1	0.16	16.0	28.0
77	4	5	1	0.17	15.0	26.0

Gaseous helium

Gaseous helium was also considered for the coolant. Characteristics necessary for a comparison with a liquid nitrogen system are:

Specific heat C_p = 17 kJ/kg/K = 4 Cal/g/K = 1 Cal/mole/K

Density r = 0.80 kg/m^3 @ 1 Atm @ 65 K

Viscosity η=70 micropoise @ 80 K = 7.0x10^{-7} kg/ms

Whereas data was available for the pressure drop in flowing liquid nitrogen, it must be calculated for gaseous helium. In addition, the viscous flow losses depend on the flow regime. Thus the approach used here to obtain a comparison between a liquid nitrogen and a gaseous helium system is to assume initially that the flow characteristics are the same, and then to iterate to obtain a solution for the gaseous helium that can be compared to the liquid nitrogen system.

If the viscous heating in the flowing helium were the same as for the liquid nitrogen, about 2 kW over 10 km, then the total heat input would still be 10 kW. The helium mass flow necessary to remove 10 kW with a temperature rise of 1 K is about 0.56 kg/s, which requires a flow velocity of 4.35 m/s in the inner tube. The pressure drop in a fluid is given by

$$\Delta P = 2f\rho_{av} v^2 L / D,$$

where f is the friction factor, v is the fluid velocity, L is the length of the pipe, and D is the hydraulic diameter. The friction factor depends on the flow regime, which can be determined by calculating the Reynolds number:

$$\mathrm{Re}_D = \frac{\rho v D}{\eta} = 10.8 \times 10^6 ,$$

which implies turbulent flow. The friction factor for smooth surfaces is found from [15] to be 0.003. Thus the pressure drop is:

$$\Delta P = 2f\rho_{av} v^2 L / D = 2 \times 10^5 \, \mathrm{Pa} = 2\mathrm{Atm} .$$

The total viscous flow loss is given by the same relation used for liquid nitrogen:

$$W = \frac{\dot{m}\Delta p}{\rho} = \frac{2 \times 10^5 \times 0.56}{20 \times 0.87} = 6.44\mathrm{kW}$$

or 0.64 W/m instead of the 0.2 W/m viscous loss for liquid nitrogen. The temperature rise for this case would be 1.4 K over 10 km. Since other assumptions in the design assume the allowable temperature rise is only 1 K, some aspect of the design must be changed. The straightforward approach used here is to maintain the 10†kW for each refrigerator for line cooling. This is accomplished by reduce the spacing between refrigerators. (It also increases the total number of refrigerators.) This occurs at a refrigerator spacing of 7.0 km.

However, there are two additional heat inputs to the system. Whereas the nitrogen all flowed in one direction, the helium must be returned. There is viscous heating associated with the return helium in a separate tube, which is thermally insulated from but near the conductor tube. This is also 0.64 W/m, which requires an additional 4.5†kW for each refrigerator. The second is the additional heat input due to the increased area and cold mass that receives heat from all the same sources mentioned above. This is estimated to be an additional 3†kW. Thus the total heat load for each of the refrigerators spaced every 7 km is 17.5 kW.

The cost of the helium, based on a unit cost of \$3/liquid liter \$18/kg, is \$12 M. This amount is appropriate for a volume 20% greater than the two 10 cm diameter tubes. The cost of the additional pipe, superinsulation, and associated structure for the gaseous helium return is \$30 M.

The costs and power requirements for the gaseous helium refrigeration system are described in Table A-3.

Table A-3 Refrigerator capacity and cost for gaseous helium as a function of temperature. Total cost includes helium cost and return line.

Temperature	Helium	Line	Refrigeration Power	Efficiency	Power Required	Refrigerator System Cost
	Cost	Cost			Total	Total
(K)	(\$M)	(\$M)	(W_t/m)		(MW_e)	(\$M)
50	30	12	2.5	0.06	81.0	232.5
55	30	12	2.5	0.08	61.8	184.5
60	30	12	2.5	0.10	48.5	151.4
65	30	12	2.5	0.12	40.8	132.0
70	30	12	2.5	0.14	35.4	118.5
75	30	12	2.5	0.16	30.9	107.3
77	30	12	2.5	0.17	28.1	100.1

The costs of the liquid nitrogen and gaseous helium refrigeration systems are compared in the Figure A-2.

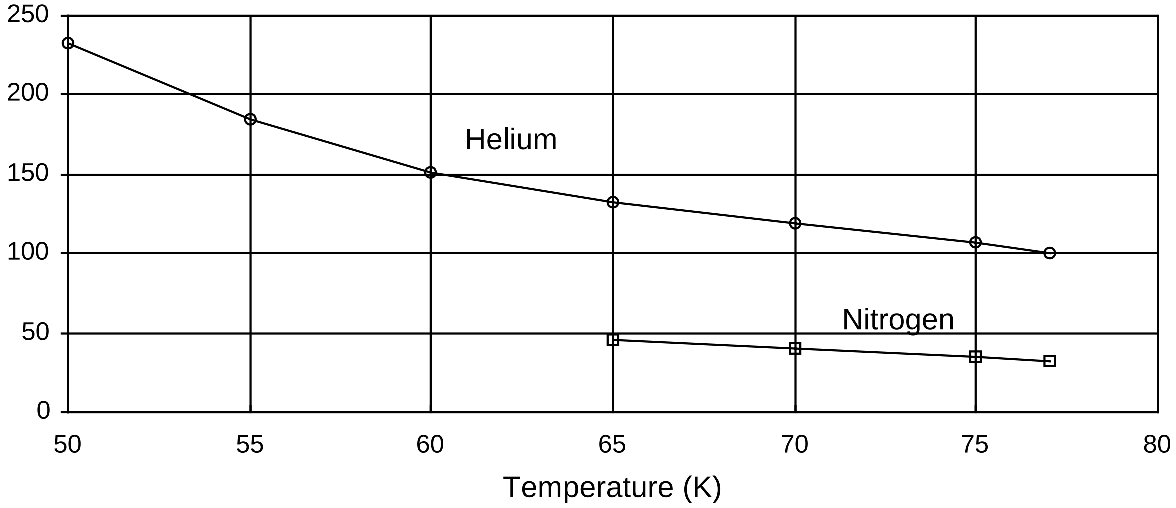

Figure A-2 Refrigerator Cost ($M) for Liquid Nitrogen and Gaseous Helium Cooling Systems

Vacuum

The goal of the vacuum system is to maintain a pressure of about 10^{-5} Torr. This implies both a high vacuum pump and a roughing pump. The capacity of these are determined by the more stringent of two conditions. The first is initial pump down time and the second is the stable vacuum that can be achieved with the outgassing load (mostly water) associated with the multilayer thermal insulation.

The roughing pump is sized for pumpdown over a length, L, of 1 km in a period, t, of about 10 hours. The capacity is given by [A9]

$$S \text{ (liters/s)} = [V/t] \ln(p_i / p_f) \cong 0.3 \text{ L (m)} = 300 \text{ liters/s},$$

where v = volume = area x length, L

Roughing pumps consisting of a mechanical booster and single stage pump of this capacity are commercially available. The cost for these pumps is about 5 k$ each and the power requirement is about 7 kW_e.

Several high vacuum pumps, e.g., turbo pumps and ion pumps, are available for the pressure range of 10^{-2} to 10^{-5} Torr. To achieve the same pumpdown time as for the backing system will require a pump with a capacity of about 100 liters/second.

Equilibrium pressure is a more difficult issue as it is difficult to estimate the outgassing rate for the superinsulation. Outgassing decreases with time, and, once it is cold, the transmission line will act as a cryopump for part of the water from the superinsulation.

The outgassing is proportional to the total area of material, i.e., to the product of the outer diameter of the conductor package times the number of layers of superinsulation. Outgassing decreases with time, so the equilibrium rate will be the value after several days. In this case , it is estimated that the total outgassing after 10 days will be about 10^{-1} Torr/s. Achieving 10^{-4} Torr will require a pump having a capacity of 1000 liters/s. This requirement is much more stringent than the pumpdown time. Pumps of this capacity cost approximately 20 k$ each in large quantities and require about 15 kW to operate. This gives a electrical power requirement of about 22 kW/km or a total of 35 MW_e for the entire line. The vacuum system is summarized in Table A-4.

Table A-4 Vacuum system components, power, and costs for HTS dc superconducting transmission line.

Component	Quantity	Unit Power	Unit Cost	Total Power	Total Cost
		(kW_e)	($k)	(MW_e)	($M)
Roughing Pump	1600	7	5	11	8
High Vacuum Pump	1600	15	20	24	32

Appendix References

[A1] Private Communication, Robert Powell, PSI, 1996

[A2] Russell B. Scott. Cryogenic Engineering. Met-Chem Research Inc., Boulder, CO 1963 Edition, reprinted 1988.

[A3] I. E. Spradley, T. C. Nast, and D. J. Frank, ìExperimental Studies of MLI Systems at Low Boundary Temperatures,î Adv. in Cryogenic Engineering. Vol. 35, p. 447 (1990).

[A4] Ted C. Nast. A Review of Multilayer Insulation, Theory, Calorimeter Measurements, and Applications. Lockheed Palo Alto Research Laboratory Report, Palo Alto, CA.

[A5] J. Arrillaga, High Voltage Direct Current Transmission. The Institution of Electrical Engineers, Power Engineering Series 6, London, 1983.

[A6] ANSI/IEEE Standard 1030-1987. IEEE Guide for Specification of High-Voltage Direct-Current Systems. Part I – Steady-State Performance. IEEE, New York, NY, 1987.

[A7] Los Alamos National Laboratory data, unpublished, 1996.

[A8] Superconducting Low Voltage Direct Current (LVDC) Networks. Electric Power Research Institute, Palo Alto, CA: April 1994. Report TR-103636.

[A9] A. Roth. Vacuum Technology. Elsvier Science Publishing, New York, NY 1990, 3rd Edition.