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System, Construction and Integration Issues for Long Distance, High Capacity, Ceramic HTSC dc Cables

Garwin-Matisoo Revisited!

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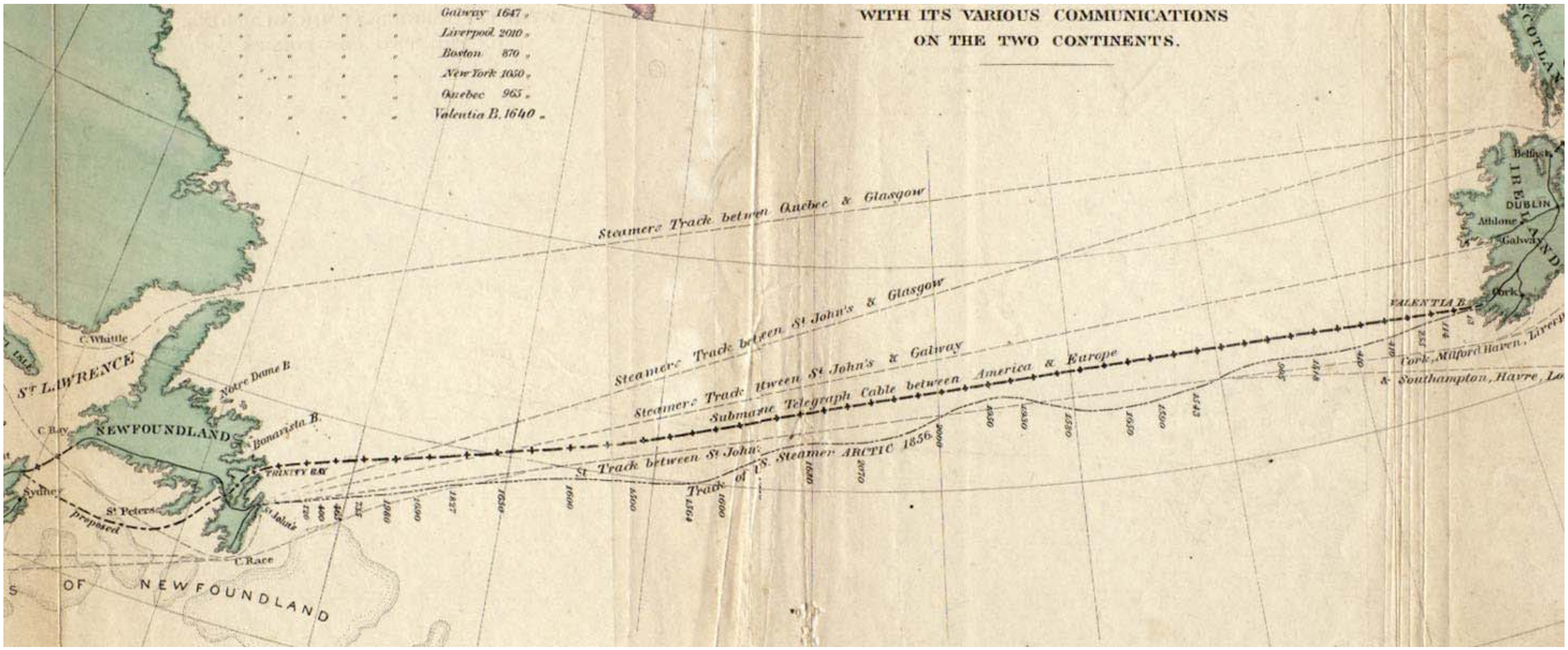
www.w2agz.com/pacrim6.htm

"A Thread Across the Ocean"

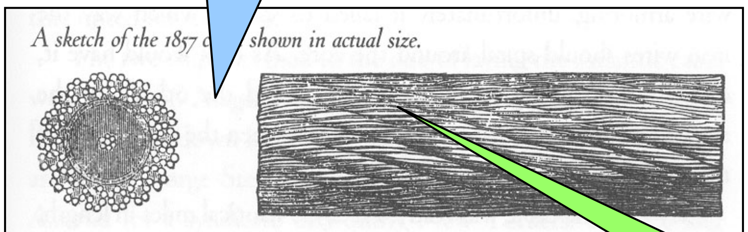


"The Story of the Trans-Atlantic Cable (1854 – 1866)"

John Steele Gordon

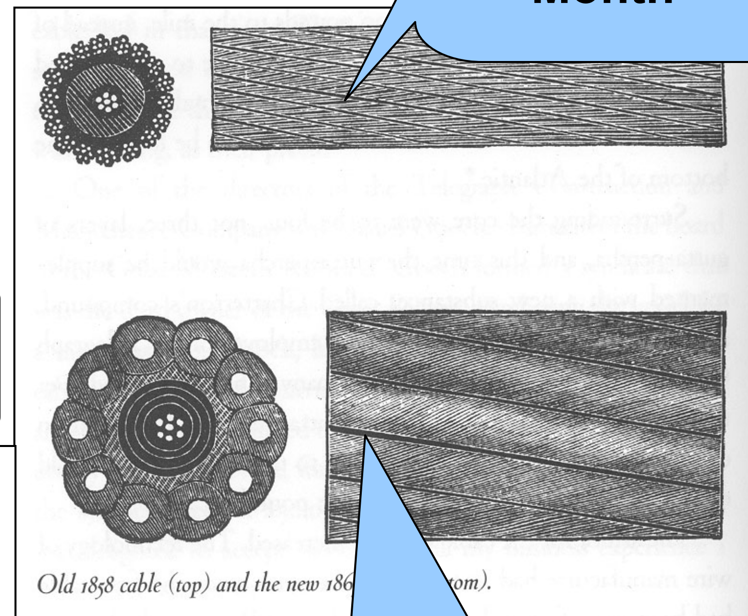
Atlantic Cable Timeline & Designs

1857
"Broke"



A sketch of the 1857 c... shown in actual size.

1858
"Worked for a Month"

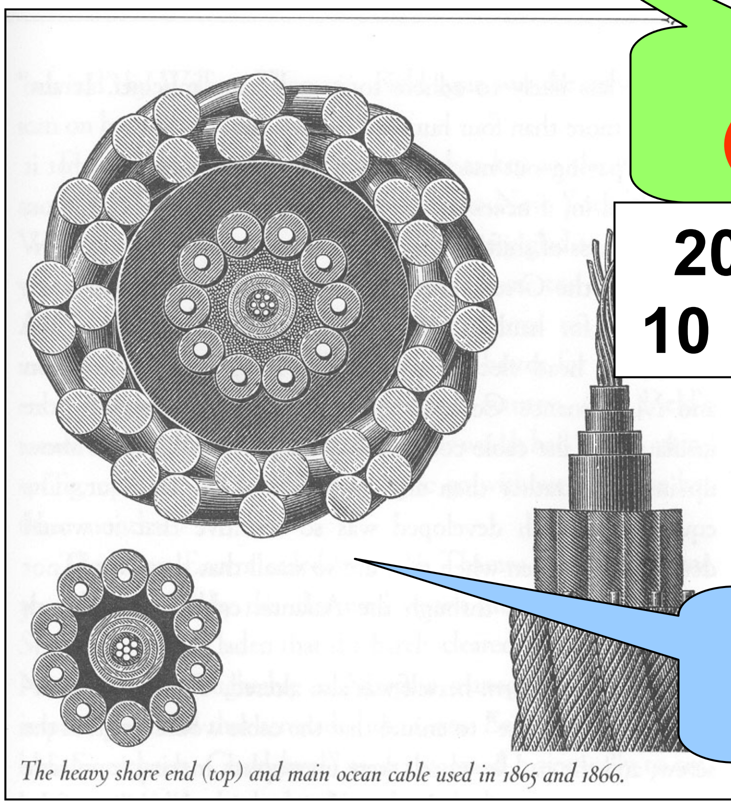


Old 1858 cable (top) and the new 186... om).

1865
"Parted"
(Recovered in 1866)

2 $/m
(2005)

200 A @
10 $/kA×m

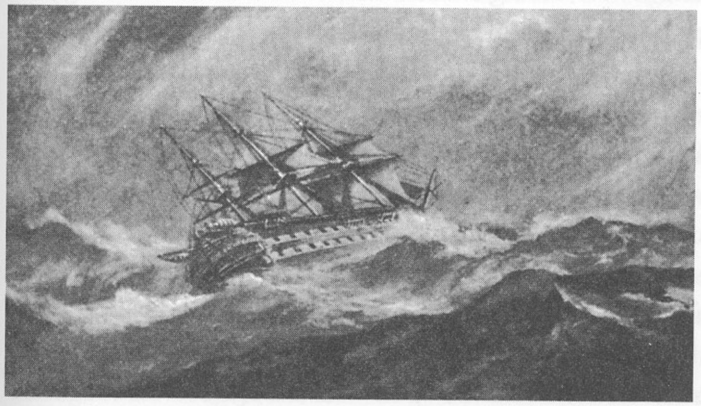


The heavy shore end (top) and main ocean cable used in 1865 and 1866.

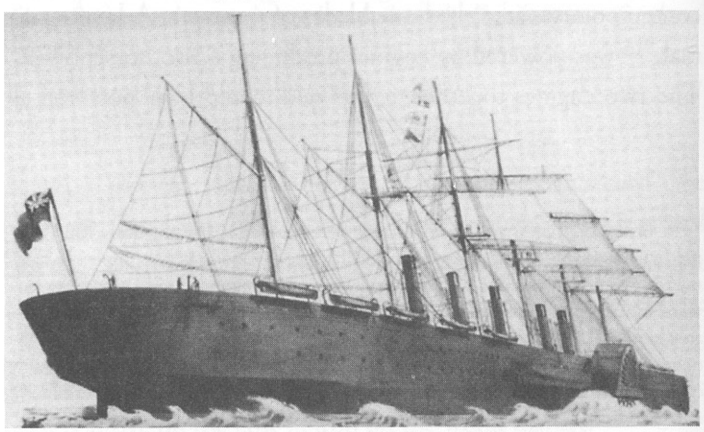
1866
Success!

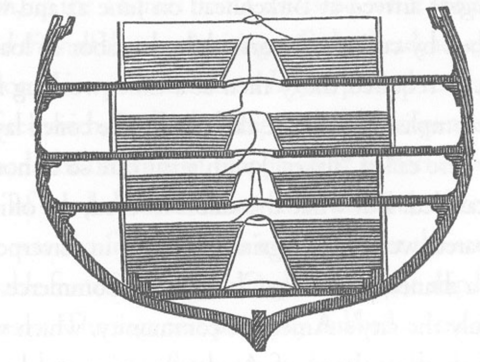
Cable Laying by Ship

The Agamemnon *in the storm.*

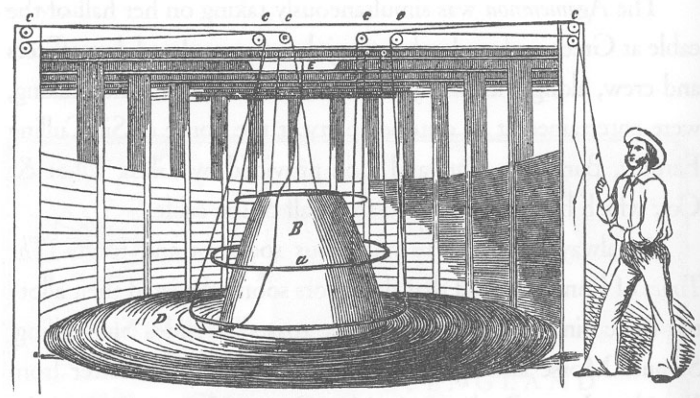


A Currier and Ives lithograph of the Great Eastern.





Storage of coils of cable on the Niagara.

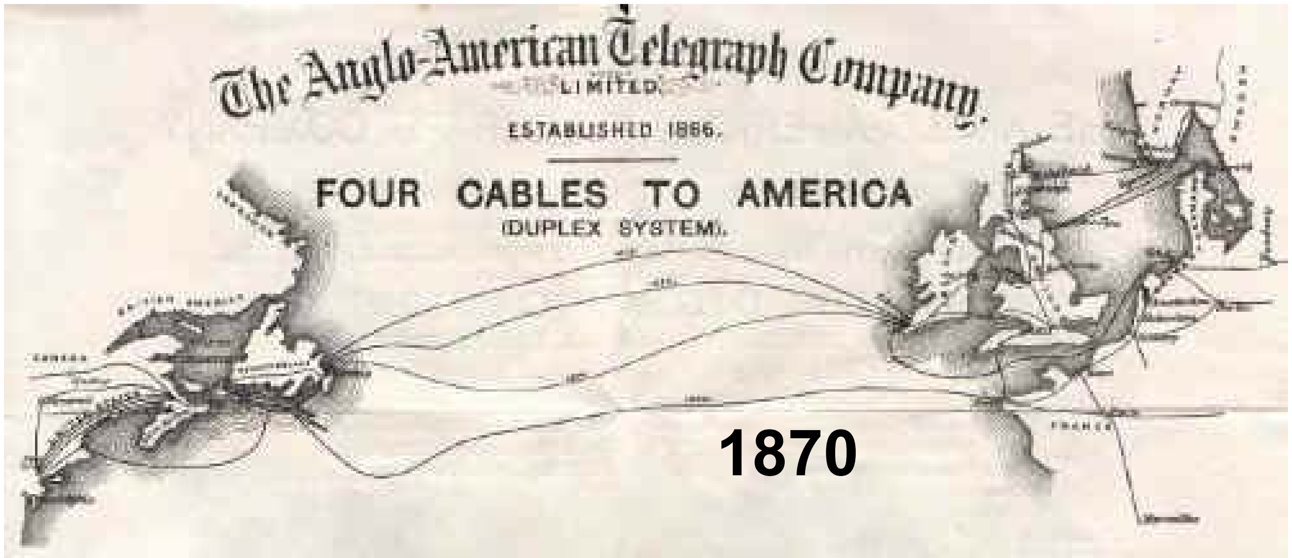


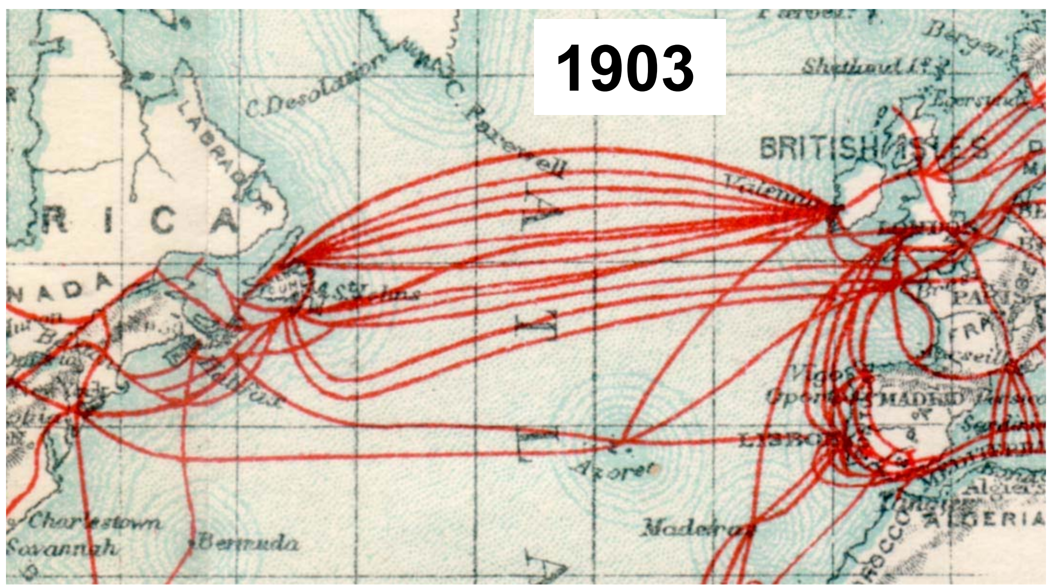
Large iron rings (A) prevent the cable from kinking as it is drawn up over the cone (B) by pulleys (C) and through the hatchway (E) until the remaining coil of cable (D) had been payed out.

What Kept Them Going?

- The investors knew, that if communications with Europe could be cut from 2 weeks to 2 minutes, they'd all get…
- FILTHY RICH!
  - Estimates are that the total cost of the project in 2005 dollars was $100 M
  - 1867 revenue in 2005 dollars was $10 M
  - Go figure…

The After-Story

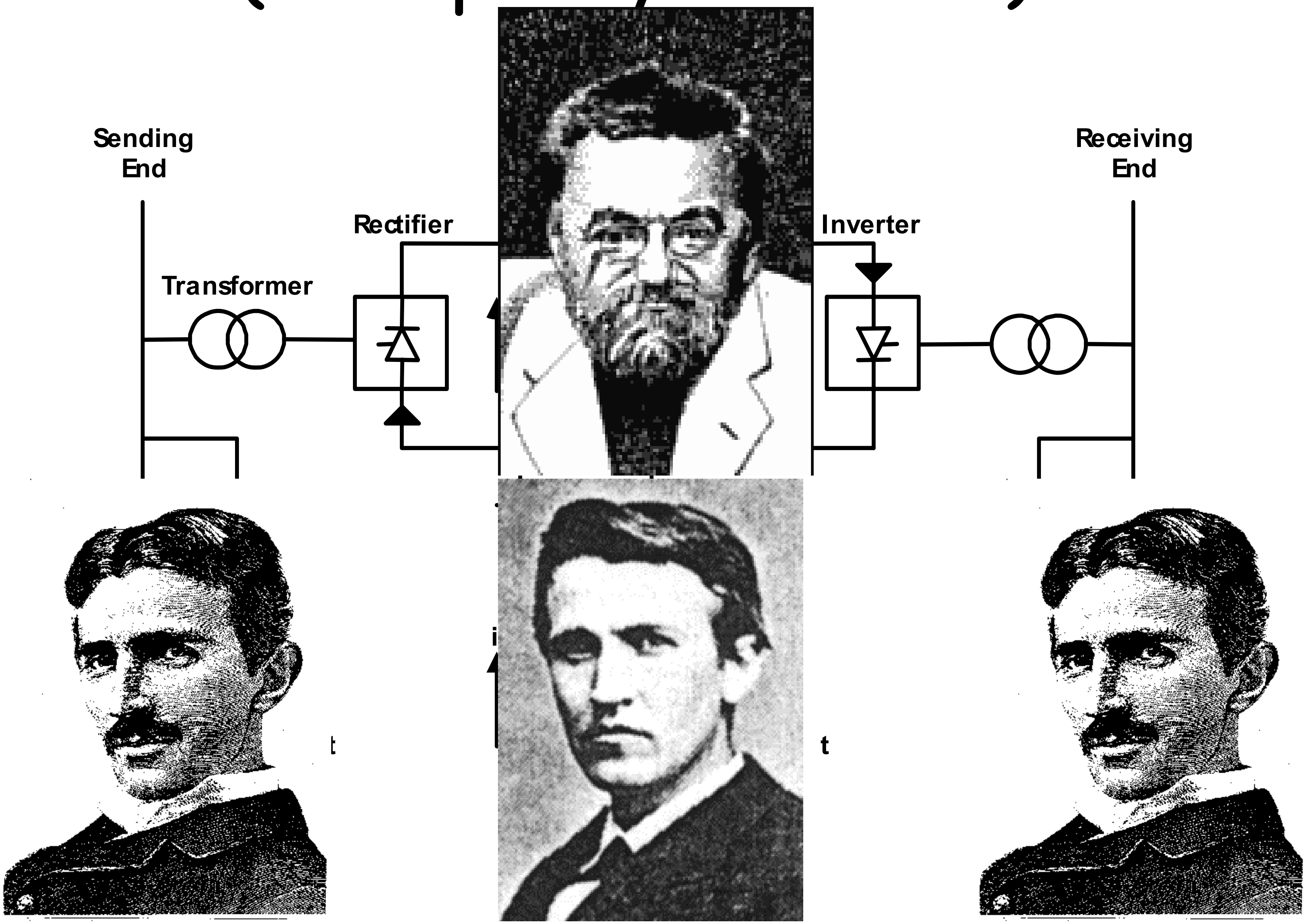




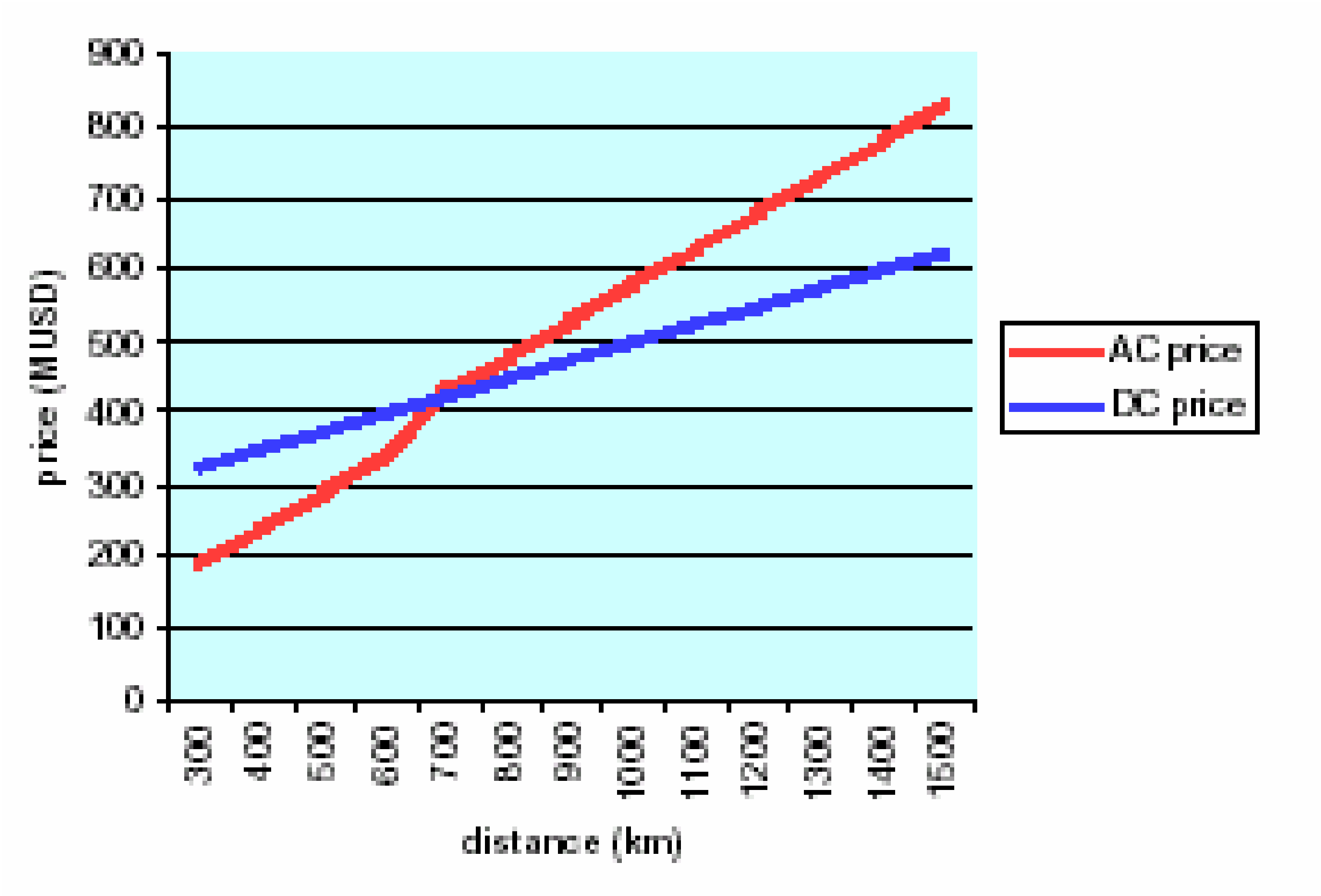
Could dc Cables be the HTSC "Thread?"

- Advantages of dc
  - Only dc can go long distances
  - Allows asynchronous connection of ac grids
  - Power flow can be controlled quickly (HTSC?)
- Advantages of HTSC dc
  - Can wheel enormous amounts of power over very long distances with minimal loss

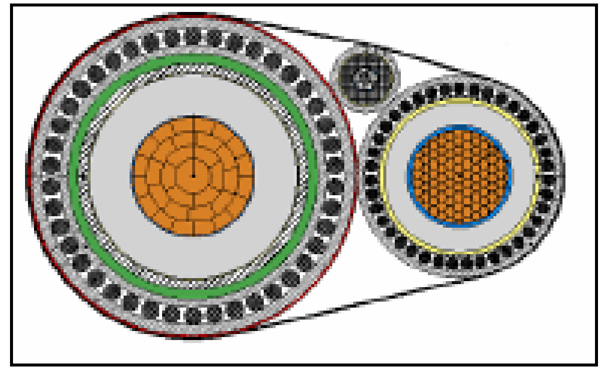
dc Transmission Lines 101
(for "policy makers")



dc vs. ac: ABB Itaipu Study



NEPTUNE
Regional Transmission System™



HVDC Cable Cross-Section

Pirelli (GS) Energy Cables

$190 M

Sayerville, NJ → Levittown LI, NY

- 600 MW (+/- 250 kV, 1200 A)
- 65 miles (105 km)
- $400 M
- 2007

Financials

40 yrs @ 4%:	$ 20M
LOM:	1 M
NOI (100%):	5 M

T 77 K	C/P $/kA×m	Cost ($M)
Cu	7	1.8
HTSC	100	25.1

EMPIRE CONNECTION

HTSC Cost = $87 M

Specifications

2-1000 MW HVDC Bipolar Circuits

- Circuit 1: 130 miles, Greene County → Bronx County
- Circuit 2: 140 miles, Albany County → New York County
- Each Circuit: +/- 500 kV, 1000 A Bipolar (2 cables ea.)

Financials

$750 M ($400 M "VC", $350 M "Futures")

Loan Payment (4%, 40 yrs, 750 M$) =	35 M$/yr
Labor, Overhead, Maintenance =	5 M$/yr
Tariff =	0.5 ¢/kWh
Profit (NOI) @ 50% Capacity =	4 M$/yr
Profit (NOI) @ Full Capacity =	48 M$/yr

Why didn't it go forward?

Two IBM Physicists (1967)

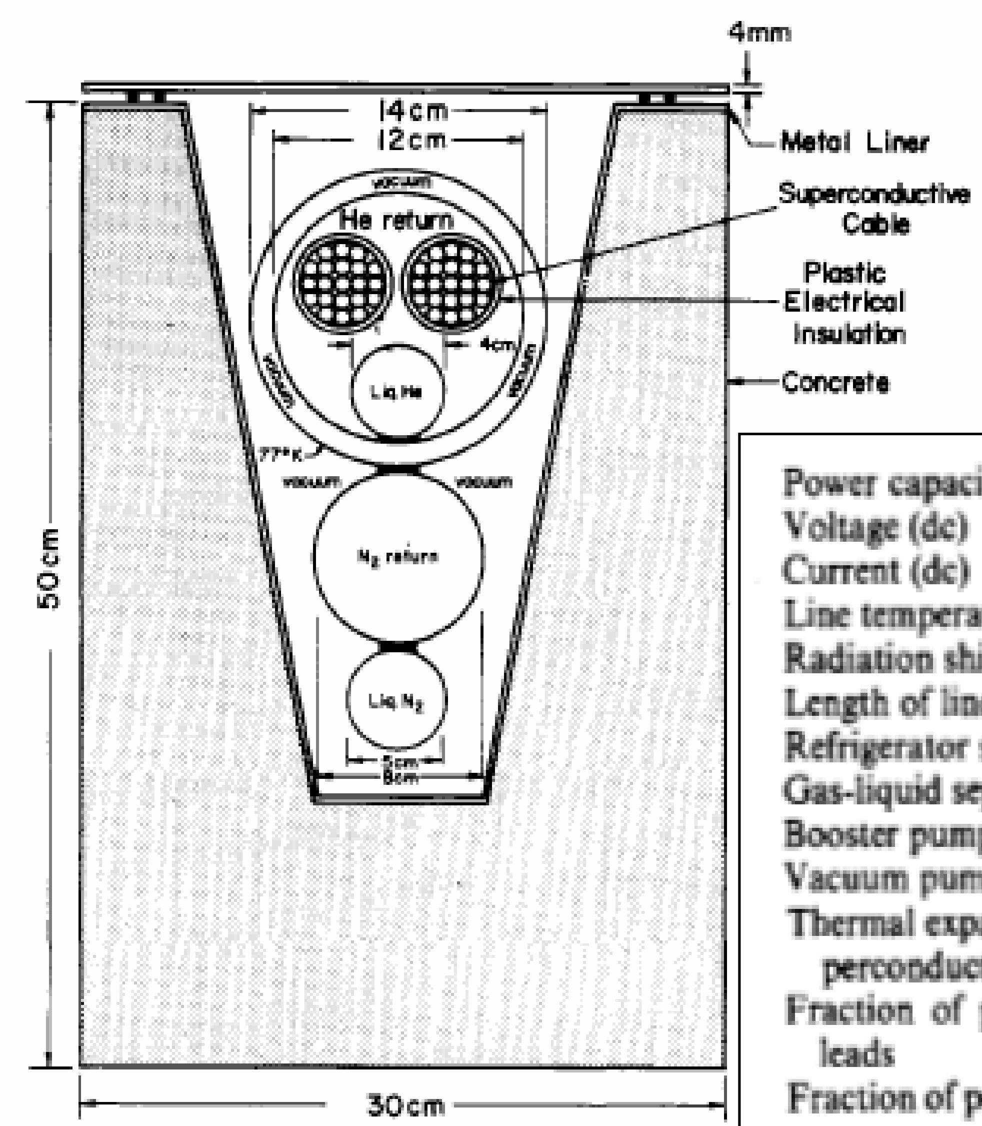
Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOO

- Nb_3Sn (T_C = 18 K) @ 4.2 K
- 100 GW (+/- 100 kV, 500 kA)
- 1000 km
- Cost: $800 M ($8/kW) (1967)

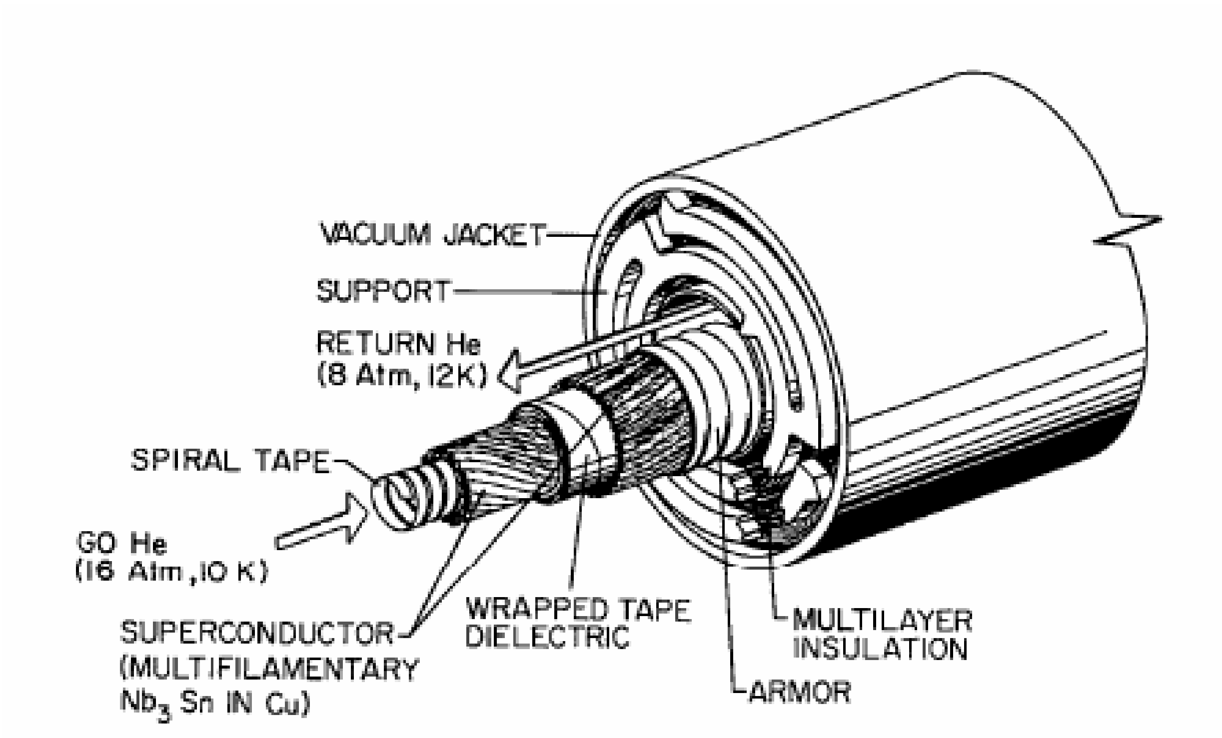
$4.7 B Today!

G-M Specs



Power capacity	100 GW (10^{11} W)
Voltage (dc)	200 kV (2×10^5 V)
Current (dc)	0.5×10^6 A
Line temperature	4.2°K (liquid helium)
Radiation shield	77°K (liquid nitrogen)
Length of line	1000 km
Refrigerator spacing	20 km
Gas-liquid separator spacing	50 m
Booster pump spacing	500 m
Vacuum pump spacing	500 m
Thermal expansion bellows 1.5 m long (superconductors wound helically) spacing	500 m
Fraction of power dissipated in line and leads	$<10^{-7}$
Fraction of power used for refrigeration	$<10^{-3}$

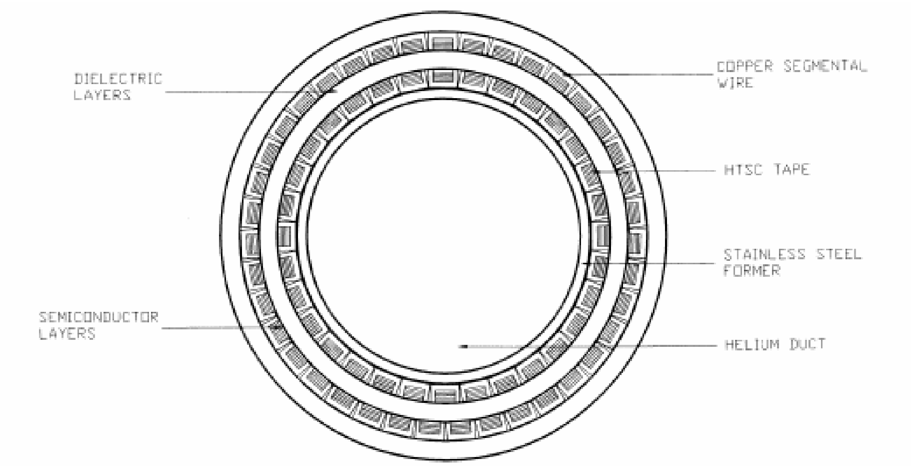
LASL SPTL (1972-79)



Specifications

- 5 GW
  (+/- 50 kV, 50 kA)
- PECO Study
  (100 km, 10 GW)

BICC HTSC dc Cable (1995)



Prototype Specs

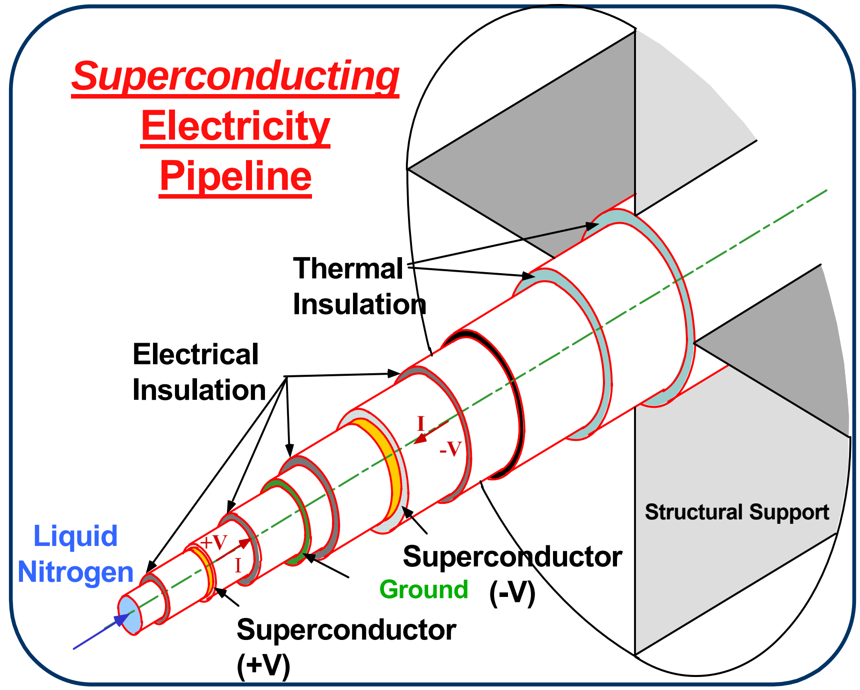
- 400 MW
  - +/- 20 kV, 10 kA
- Length: 1.4 m
- Diameter: 4 cm
- He (4.2 – 40 K)

Design Target

- 400 MW, 100 km
- Flowing He, 0.2 kg/s, 2 MPa, 15 – 65 K
- Cooling Losses: 150 kW

e-Pipe

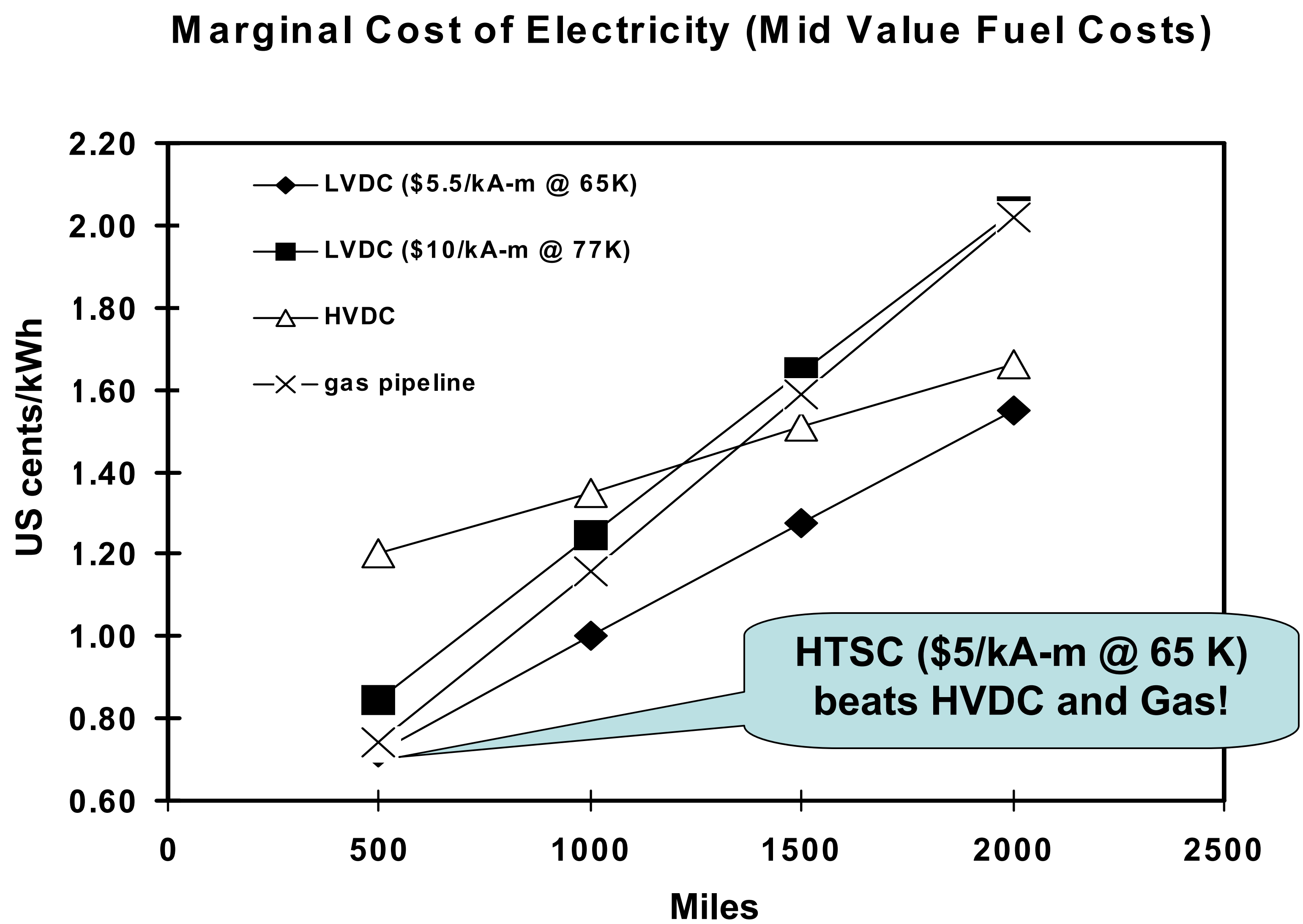

CYPRUS
Nicosia
Mediterranean Sea
LEBANON
Beirut
SYRIA
Latakia
Hims
Damascus
Golan Heights
ISRAEL
Haifa
Jerusalem
Gaza Strip
Amman
JORDAN
Al Aqabah
IRAQ
Mosul
Karkūk
Baghdad
Al Hillah
Al Kūt
An Nāsiriyah
Al Basrah
KUWAIT
Kuwait
Tehrān
Qom
Bākhtarān
Arak
Dezful
Ahvāz
Ābādān
Bandar-e Būshehr
Persian Gulf
EGYPT
Alexandria
Cairo
Luxor
Aswān
Tropic of Cancer
Administrative Boundary
Tabūk
Ha'il
Hafar al Bātin
Dhahran
Manama
Riyadh
Medina
Yanbu al Bahr
Hala'ib
SAUDI
ARABIA


Superconducting Electricity Pipeline
Thermal Insulation
Electrical Insulation
Liquid Nitrogen
Superconductor (+V)
Superconductor (-V)
Ground
Structural Support
+V
-V
I

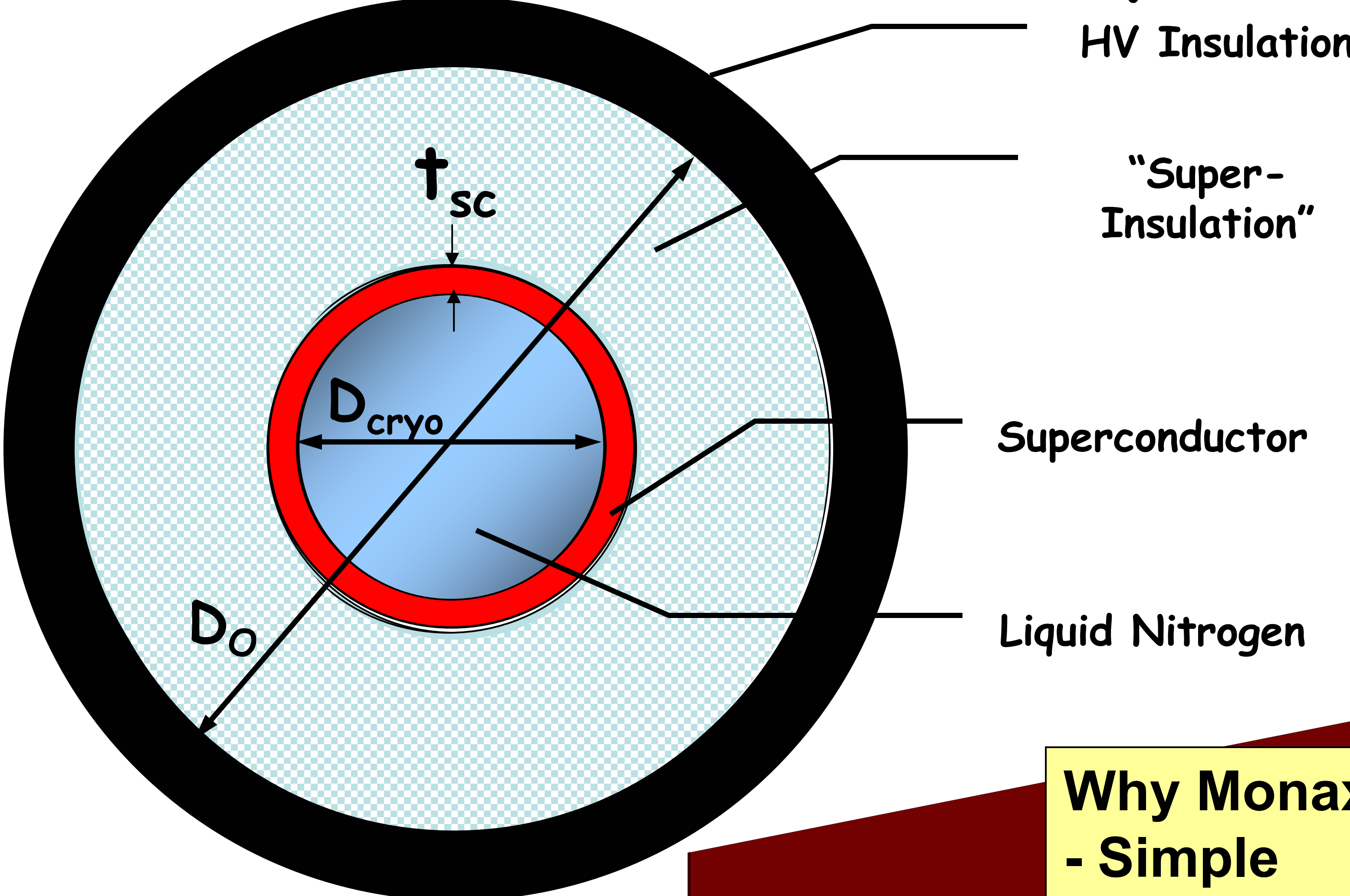
e-Pipe Specs (EPRI, 1997)

Capacity	5 GW (+/- 50 kV,50 kA)
Length	1610 km
Temperature Specs: - 1 K/10 km @ 65 K - 1 W/m heat input	- 21.6 kliters LN_2/hr - 100 kW coolers - 120 gal/min
Vacuum: - 10^{-5} – 10^{-4} torr	- 10 stations - 10 km spaced - 200 kW each

e-Pipe/Gas/HVDC Cost Comparison

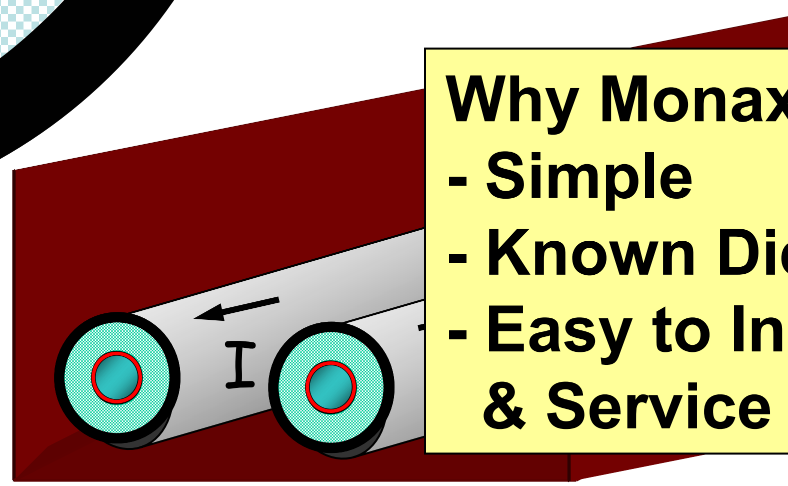


HTSC SuperCable



Garwin – Matisoo

Revisited !

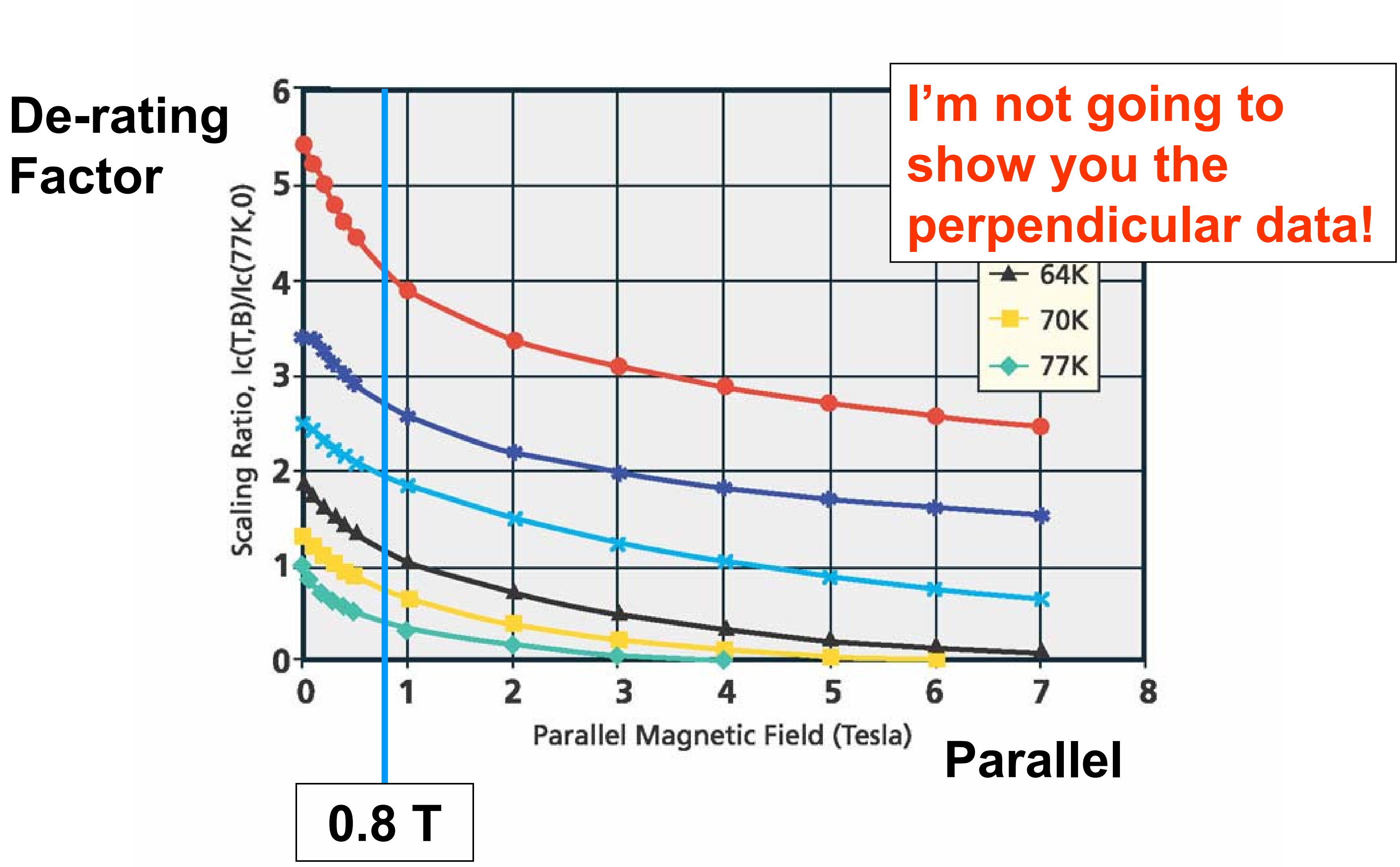


Why Monaxial?
- **Simple**
- **Known Dielectric**
- **Easy to Install & Service**

SuperCable Parameters

• Power =	5	GW
• Voltage =	25	+/- kV
• Current =	100	kA
• Jc =	25000	A/cm^2
• Dcryo =	5	cm
• A* =	3.629	cm^2
• t(sc) =	0.243	cm
• R* =	1.075	cm
• B =	0.8	T

AMSC Tape Jc(T, B)



High Amplitude Transient Current Losses (ac & energize)

"Bean Model"

$$H = 4 \times 10^{-9} I_0^2 F \quad \text{W/cm}$$

Io (A)	F (Hz)	H (W/m)
100,000	60	2.4×10^5
100,000	1/hour	0.3
100,000	1/day	0.01

Possibly could reverse line in one hour!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10} (\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

Load Fluctuation Losses over a 1 hour period

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	4×10^{-7}
10	10000	500	4×10^{-4}
20	20000	1000	3×10^{-3}
30	30000	1500	1×10^{-2}

OK, as long as changes occur slowly!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10} (\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

…and sometimes even when they're fast!

Consider 1 MW worth of customers coming in and out every millisecond, (*e.g., 10,000 teenagers simultaneously switching 100 W light bulbs on and off*) resulting in ΔI = 20 A, but a heat load of only 10 μW/m

Small Amplitude Losses (Ripple)

$$H = \frac{4 \times 10^{-10}(\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

3-Phase Converter: F = 360 Hz

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	0.50
2	2000	100	3.99
3	3000	150	13.46
4	4000	200	31.91
5	5000	250	62.32

Radiative Heat In-Leak

$W_R = 0.5\varepsilon\sigma\,(T^4{}_{amb} - T^4{}_{SC})/(n-1)$, where

- W_R = Power radiated in as watts/unit area
- $\sigma = 5.67\times10^{-12}\ W/cm^2K^4$
- T_{amb} = 300 K
- T_{SC} = 65 - 77 K
- ε = 0.05 per inner and outer tube surface
- D_{SC} = 5 cm
- n = number of layers of superinsulation (10)

Then W_R = 0.2 W/m

Fluid Dynamics of Liquid Nitrogen Flow through a 5-cm Diameter Pipe at 1 bar

T °K	ρ kg/m^3	μ μPa×s	μ^2/ρ ndyne	V m/s	Re 10^6
77	808	163	3290	4	9.91
65	860	280	9148	4	12.3

$$\mathrm{Re} = \rho VD / \mu \approx \frac{\text{Inertial Forces}}{\text{Viscous Forces}}$$

Thus, it takes about 30 - 100 dynes "push" on an object to overcome viscous forces exerted by the liquid nitrogen

Friction Losses arising from pumping LN_2 through a 5-cm pipe at a flow rate of 4 m/s

$p_{loss} = \lambda \, (l / d_h) \, (\rho \, v^2 / 2)$

where

p_{loss} = pressure loss (Pa, N/m^2)

λ = friction coefficient

l = length of duct or pipe (m)

d_h = hydraulic diameter (m)

$W_{loss} = M \, P_{loss} / \rho$,

Where ***M*** **= mass flow per unit length**
P_{loss} **= pressure loss per unit length**
ρ **= fluid density**

Colebrook- Weymouth Equation

$1 / \lambda^{1/2} = -2{,}0 \log_{10} [(2{,}51 / (Re \, \lambda^{1/2})) + (\varepsilon / d_h) / 3{,}72]$

ε = 0.015 mm (stainless steel)	
	W_{loss} (W/m)
77 K	3.81
65 K	4.05

Heat to be Removed by LN_2

$dT/dx = W_T/(\rho v C_P A)$, where

dT/dx = Temp rise along cable, K/m
W_T = Total Heat Generated per unit Length
ρ = Density
v = Flow Rate (4 m/s)
C_P = Heat Capacity
A = Tubular Area (D = 5 cm)

T °K	ρ kg/m^3	C_P J/kg × m	W_T W/m	dT/dx °K/km
77	808	2040	5	0.4
65	860	2003	5	0.4

To offset a 1 K temperature increase, refrigeration stations would be needed every 2.5 km – *way too close!*

To-Do List

- Fine-Tune All Parameters
  - Diameter, Flow Rate, Temperature, Pressure, Power
  - Site Preparation, Materials Delivery and Construction
- Magnetic Field Issues
  - Anelastic losses (conductor tapes)
  - Spacing of Monopoles (2 100,000 A cables 1 m apart experience a mutual force of 2000 N/m!)
- Engineering Economy Study
  - How important really is wire cost?
  - How big a project for a reasonable NOI (size matters!)?

Find a Commercial Opportunity!

Take-Home Reading Assignment

www.w2agz.com/pacrim6.htm

1. Garwin and Matisoo, 1967 (100 GW on Nb_3Sn)
2. Edeskuty, 1972 (LASL dc SPTL, 5 GW, PECO)
3. Lasseter, et al., 1994 (HTSC dc Networks)
4. Beale, et al., 1996 (BICC HTSC dc, 400 MW)
5. Grant, 1996 (Promises, promises…ASC 96)
6. Schoenung, Hassenzahl and Grant, 1997 (5 GW on HTSC @ LN_2, 1000 km)
7. Proceedings, SuperGrid Workshops, 2002 & 2004
8. Neptune HVDC Cable, 2005
9. Grant, "London Calling," Nature review of "Thread Across the Ocean."

…and there will be a quiz next time I see you all!