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

Garwin-Matisoo Revisited 40 Years Later!

Paul M. Grant
Visiting Scholar in Applied Physics, Stanford University
EPRI Science Fellow (*retired*)
IBM Research Staff Member Emeritus
Principal, W2AGZ Technologies
w2agz@pacbell.net
www.w2agz.com

Oral Session: Power Cable – 1
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www.w2agz.com/asc06.htm

Generational Axioms of History

- There is nothing new under the sun

  Ecclesiastes 1:9-14
- What's past is prologue

  The Tempest, by Bill S.
- Those who cannot remember the past are bound to repeat it

  George Santayana
- History is more or less bunk

  Henry Ford
- I can't think about tomorrow...I'm as lost as yesterday

  Tomorrow, by Bob Seger

PROCEEDINGS

THE INSTITUTION OF ELECTRICAL ENGINEERS

Volume 113 Power

Prospect of employing conductors at low temperature in power cables and in power transformers

K. J. R. Wilkinson, D.Sc., C.Eng., M.I.E.E.

Submitted 28 February 1966

PROC. IEE, Vol. 113, No. 9, SEPTEMBER 1966

- ac Cables: 760 MVA (3ϕ), 275 kV, 1600 A
  - Be 77 K
  - Al 20 K
  - Nb 4 K (a "soft" superconductor!)
- *Objective: Efficiency, not increased capacity!*

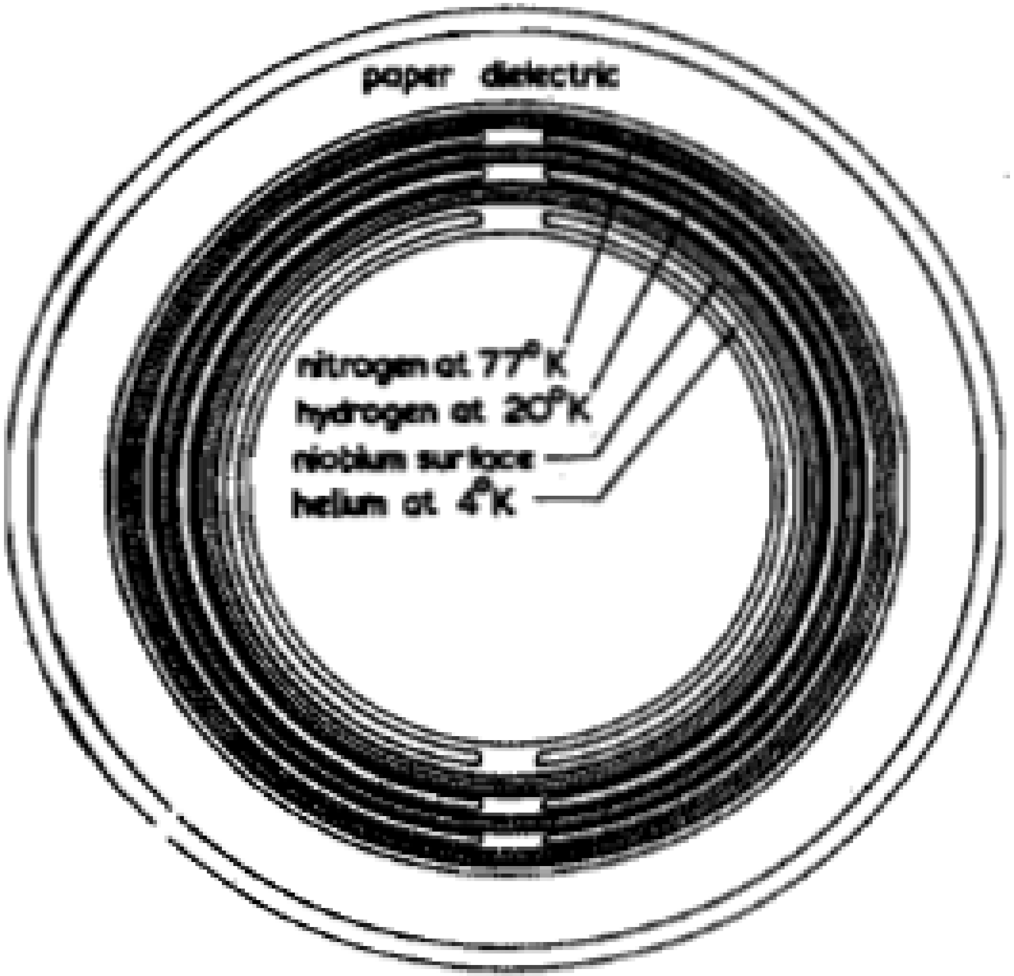


Fig. 2

Superconducting thin-walled niobium core cooled internally by liquid He and protected externally by liquid H_2 and liquid N_2

H_{C1} = 0.16 T
Fault I = 40 kA

Cable Properties

Operating I = 1.6 kA
Surface H = 7 mT

Metal	T (K)	ρ ($\Omega\times$cm)	Outer Diameter (cm)	Loss (W/km)
Cu	340	2×10^{-6}	6[illegible]	46,500
Be	77	2×10^{-8}	[illegible].0	460
Al	20	3×10^{-9}	6.0	470
Nb	4	0	10.4	0

Table 7

A COMPARISON OF COSTS, EXCLUDING CONSTRUCTION AND LAYING, BUT INCLUDING THOSE OF LOSSES, REFRIGERATION PLANT, AND CONDUCTOR MATERIAL

Core	Refrigerant	Capitalised costs of cable			
		I^2R loss	Plant and drive power	Conductor material	Approximate total
		£/km	£/km	£/km	£/km
Cu	—	3200	—	10000	13000
Al	H_2, N_2	17	21 260	3000	24000
Be	N_2	62	5170	800000	800000
Nb	He, N_2	—	9203	3000	12000

Cost of "Extra" Generation to Offset I^2R Losses (CEGB, 1965): 220 £/kw

Wilkinson’s Conclusion (1966)

- “...only niobium has any hope of defraying its refrigeration costs by savings in conductor material”
- “But its impracticably large core diameter” (10.4 cm rules out Type I superconductors)
- A Type II superconductor with $J_C = 10^6$ A/cm^2 at a diameter of 6 cm would quench under a fault current of 40 kA
- “Such a hazard is clearly unacceptable.”

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

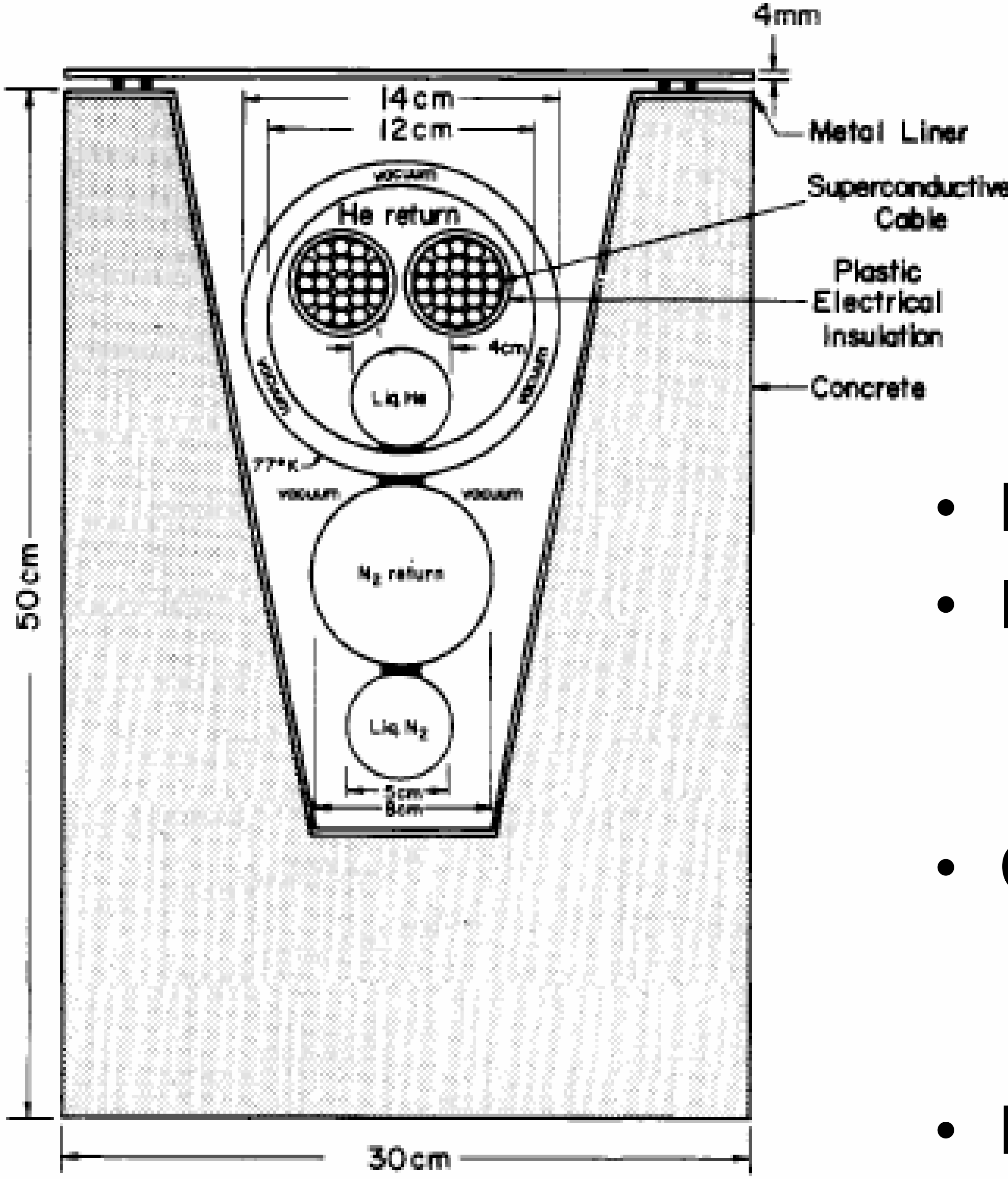
R. L. GARWIN AND J. MATISOO

Submitted 24 June 1966

PROCEEDINGS OF THE IEEE, VOL. 55, NO. 4, APRIL 1967

Rationale: Huge growth in generation and consumption in the 1950s; cost of transportation of coal; necessity to locate coal and nuke plants far from load centers.

Furthermore, the utilities have recently become aware of the advantages of power pooling. By tying together formerly independent power systems they can save in reserve capacity (particularly if the systems are in different regions of the country), because peak loads, for example, occur at different times of day, or in different seasons. To take advantage of these possible economies, facilities must exist for the transmission of very large blocks of electrical energy over long distances at reasonable cost.



Specs

- LHe cooled
- Nb_3Sn (T_C = 18 K)
  - J_C = 200 kA/cm^2
  - H* = 10 T
- Capacity = 100 GW
  - +/- 100 kV dc
  - 500 kA
- Length = 1000 km

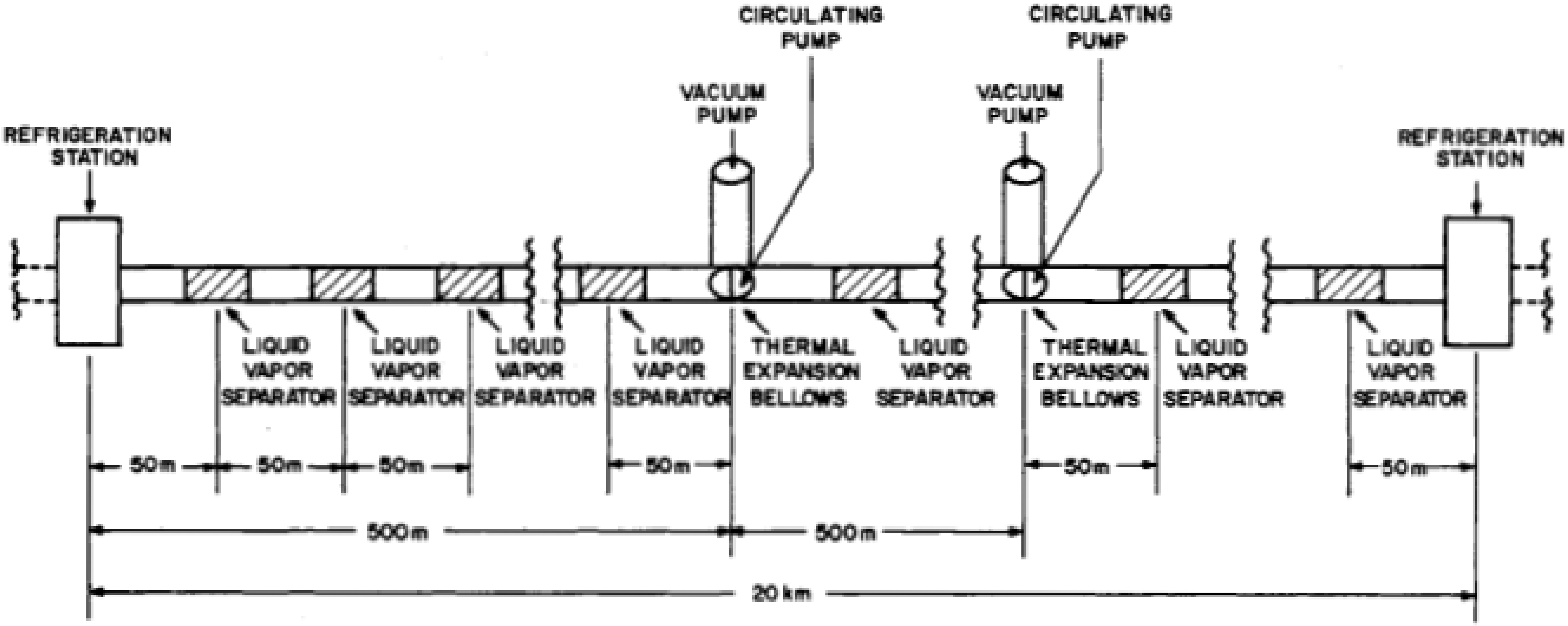


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

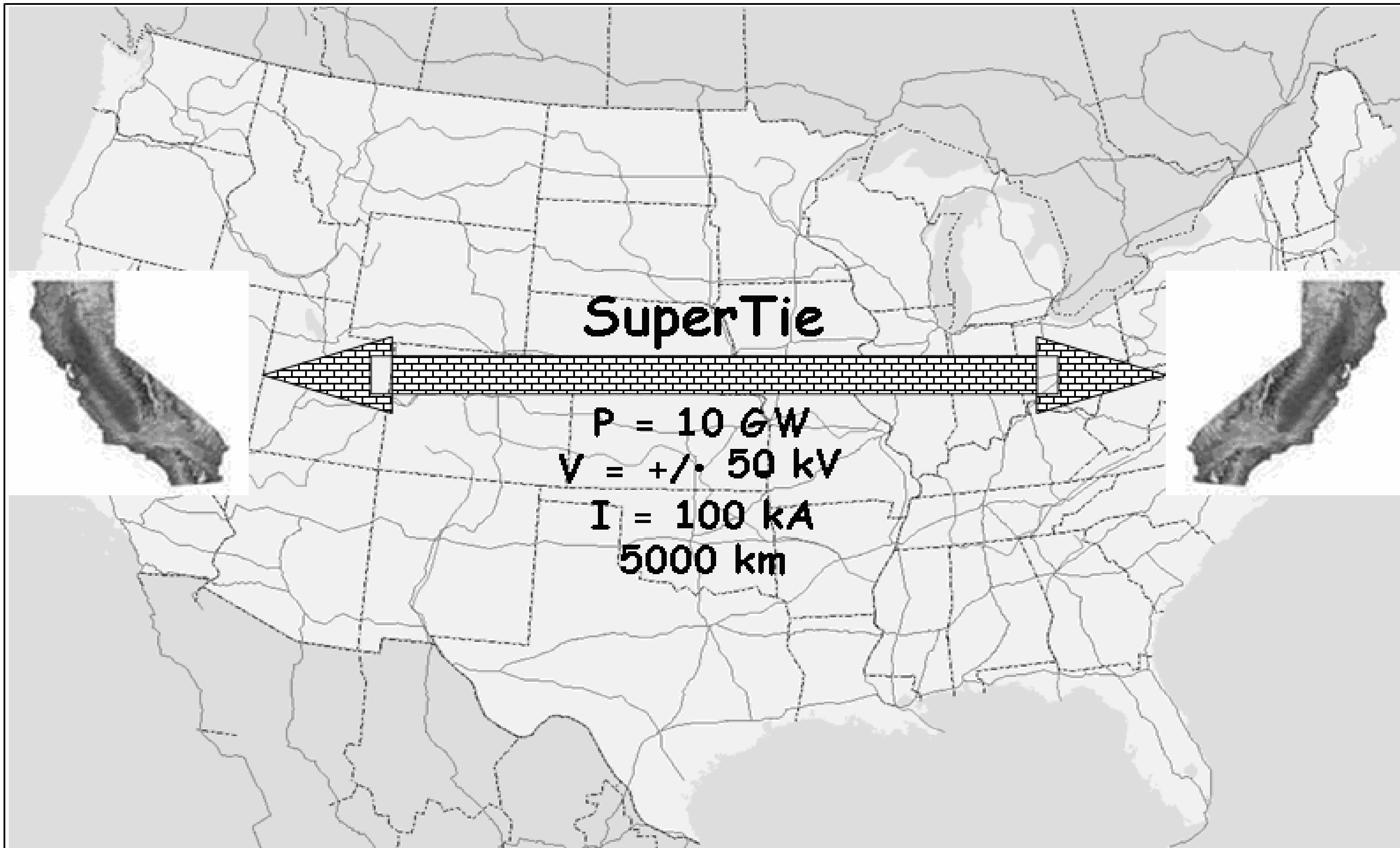
- Refrigeration Spacing 20 km
- G-L Separator Distance 50 m
- Booster Pump Intervals 500 m
- Vacuum Pump Spacing 500 m

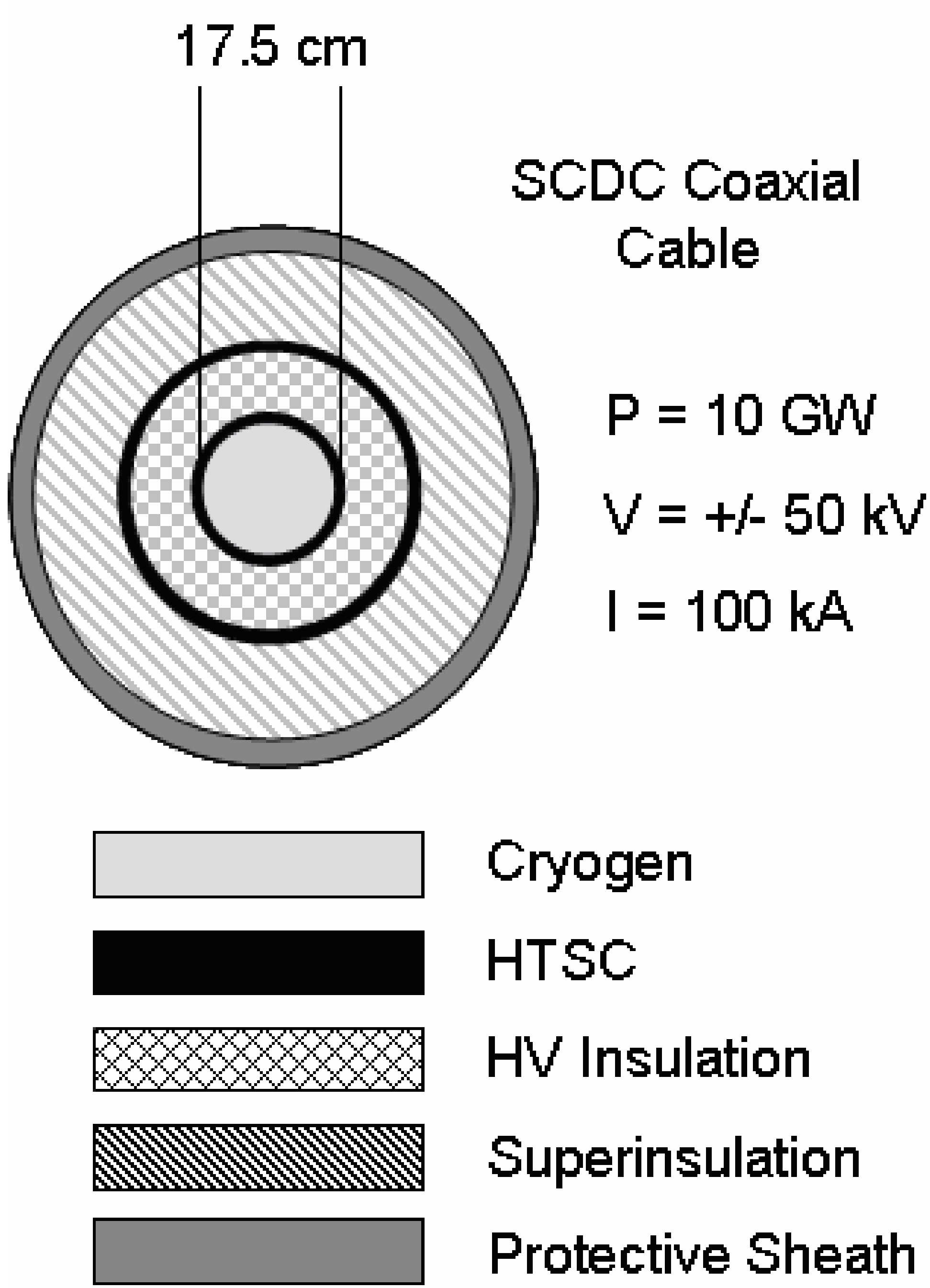
G-M Engineering Economy - Yesterday & Today -

VARIOUS COMPONENT COSTS OF A 1000 KM, NB-SN CABLE IN 1966 AND NOW

Item	Description/Quantity	1966 Cost (M$)	2006 Cost (M$)*
Superconductor	10^4 Tons Nb_3Sn	550	3405
Line Refrigeration	0.5 M$ for 1 kW LHe station every 20 km	25	155
End-Station Refrigeration	10 kW each	5	31
Vacuum Pumps	$500 per station (2000)	1	6
Fabricated Metal	$1/lb, linear line weight = 100 gm/cm	20	124
Concrete	$10/yd^3 for a total volume of 0.5 yd^2 times 1000 km	5	31
ac/dc Converters	Thyristors at $1/kW	200	1238
Total:		806	4990

“Two Californias”




17.5 cm
SCDC Coaxial Cable
P = 10 GW
V = +/- 50 kV
I = 100 kA
Cryogen
HTSC
HV Insulation
Superinsulation
Protective Sheath

SCDC SUPERTIE CABLE DESIGN AND PERFORMANCE PARAMETERS

Item	Value/Quantity	Units
HTSC Tape Parameters (77 K, 0.3 T)		
- Critical Current Density, J_C	15,000	A/cm^2
- Tape Critical Current, I_C	150	A/tape
- Cost/Performance	50	$/(kA×m)
- Width	0.4	cm
- Thickness	0.025	cm
- Single Tape Length	800	m
- Integration "wasteage"	5	%
- Joint Resistance	0.92	mW
- I^2R Dissipation per Joint	0.8	mW/m
SuperTie SCDC Cable Parameters and Performance		
- Overall Length	5000	km
- Number of Conductors*	2	1 per pole
- Conductor Annular Radius	8.75	cm
- Maximum Power	10	GW
- dc Voltage	50	kV per pole
- dc Amperage	100	kA
- Field at Conductor Surface	0.23	T
- Conductor X-Section Area	6.62	cm^2
- # HTSC Tapes/X-Section	667	
- Total Tape Length/Pole	3,475,600	km per Conductor-Pole
- Total # Joints per Pole	4,345,000	
- Power Lost in Joints/Pole	4.0	kW
- HTSC Tape Cost per Pole	26.3	B$

High-Amplitude Transient (ac) Losses According to Bean

$$W_H(n) = 2\times10^{-9} I_n^2 f$$

Where:

I_n = current amplitude for harmonic n, and
f = frequency for harmonic n (<u>here 60 Hz</u>)

I_n (kA)	W_H (W/m)
500 (G-M)	6,000,000
100 (SuperTie)	240,000

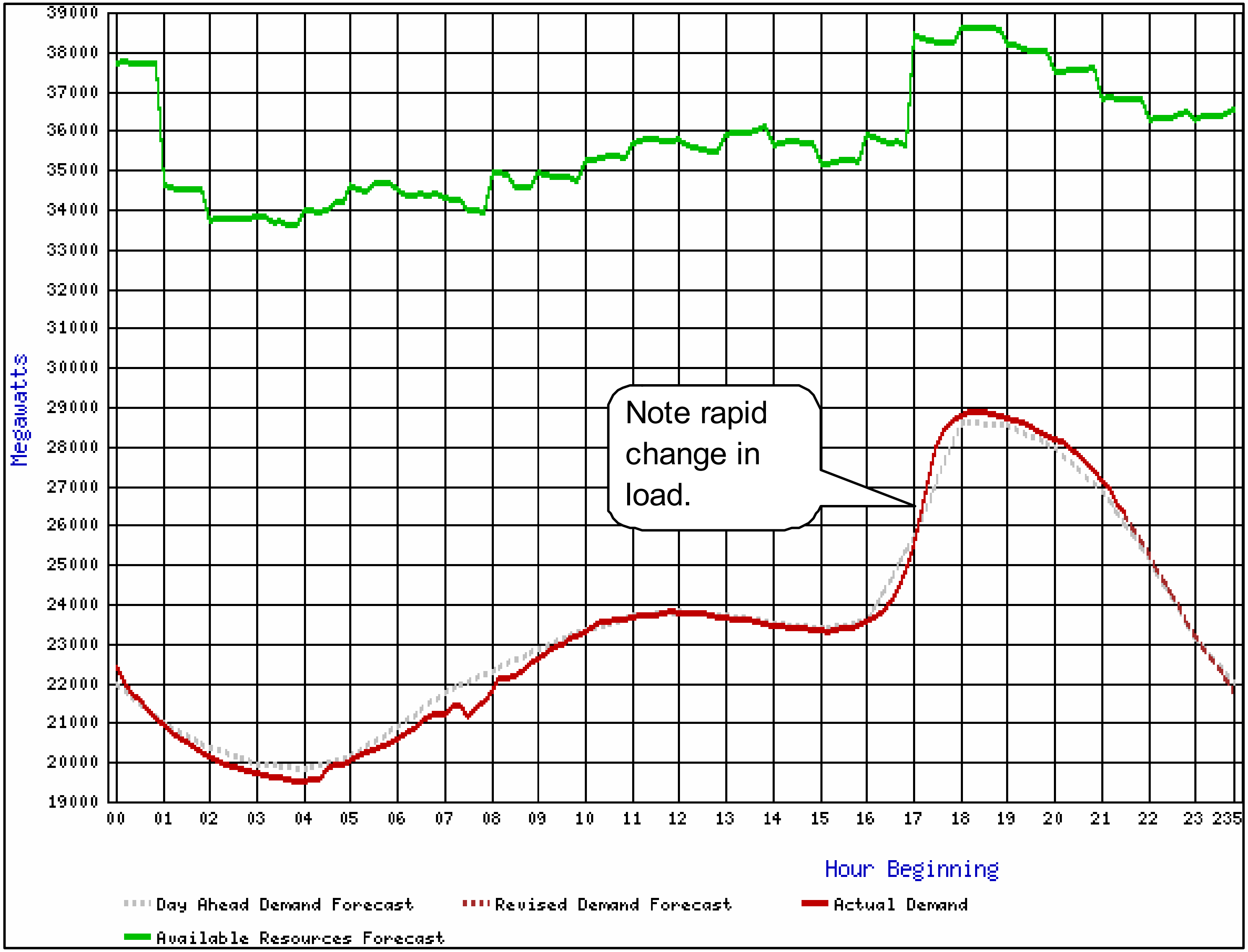
Low-Amplitude Transient (ac) Losses According to Bean

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

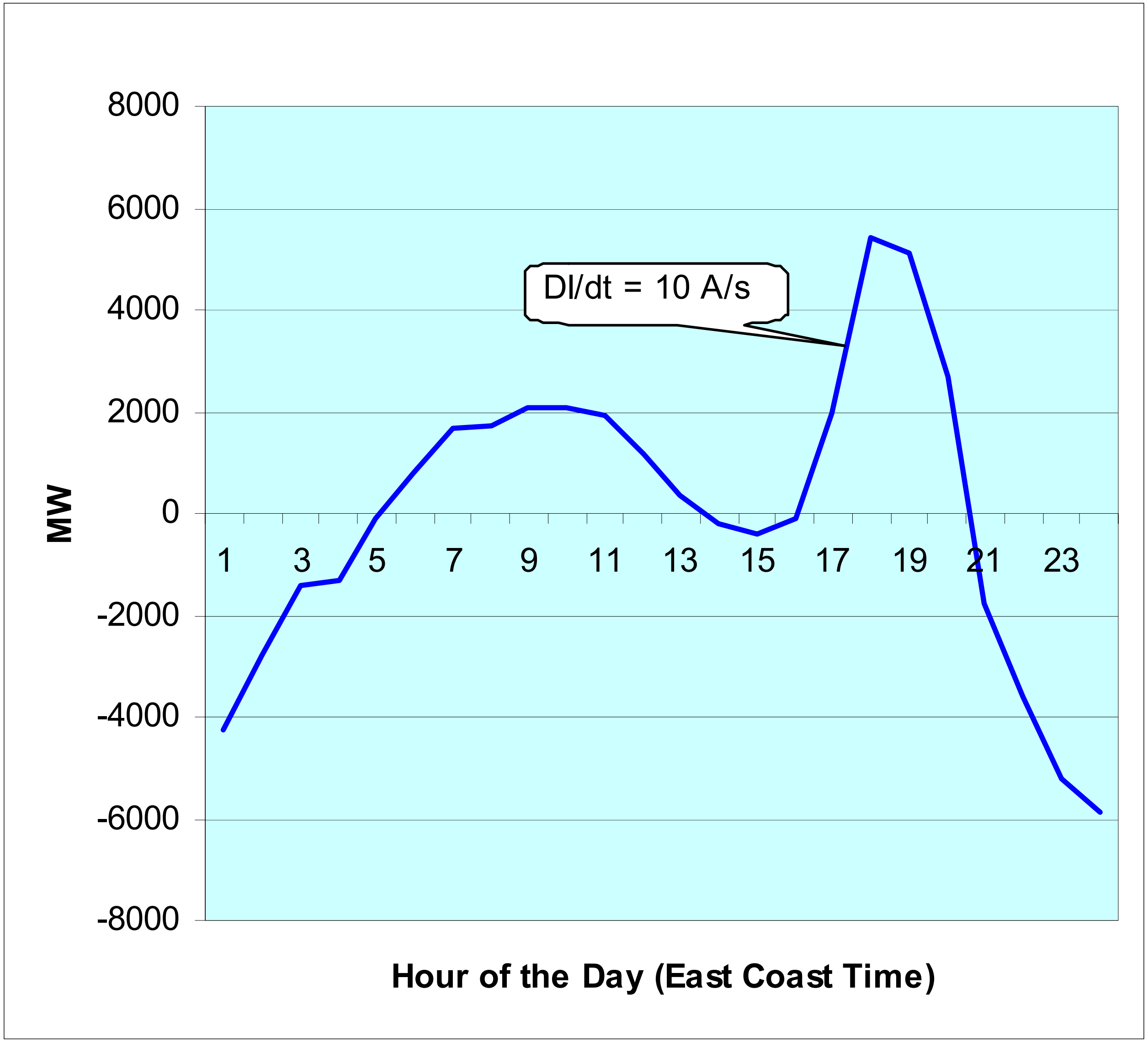
1% Ripple

J_C(kA/cm^2)	R (cm)	ΔI (A)	F (Hz)	H (W/m)
15	1	1000	360	1

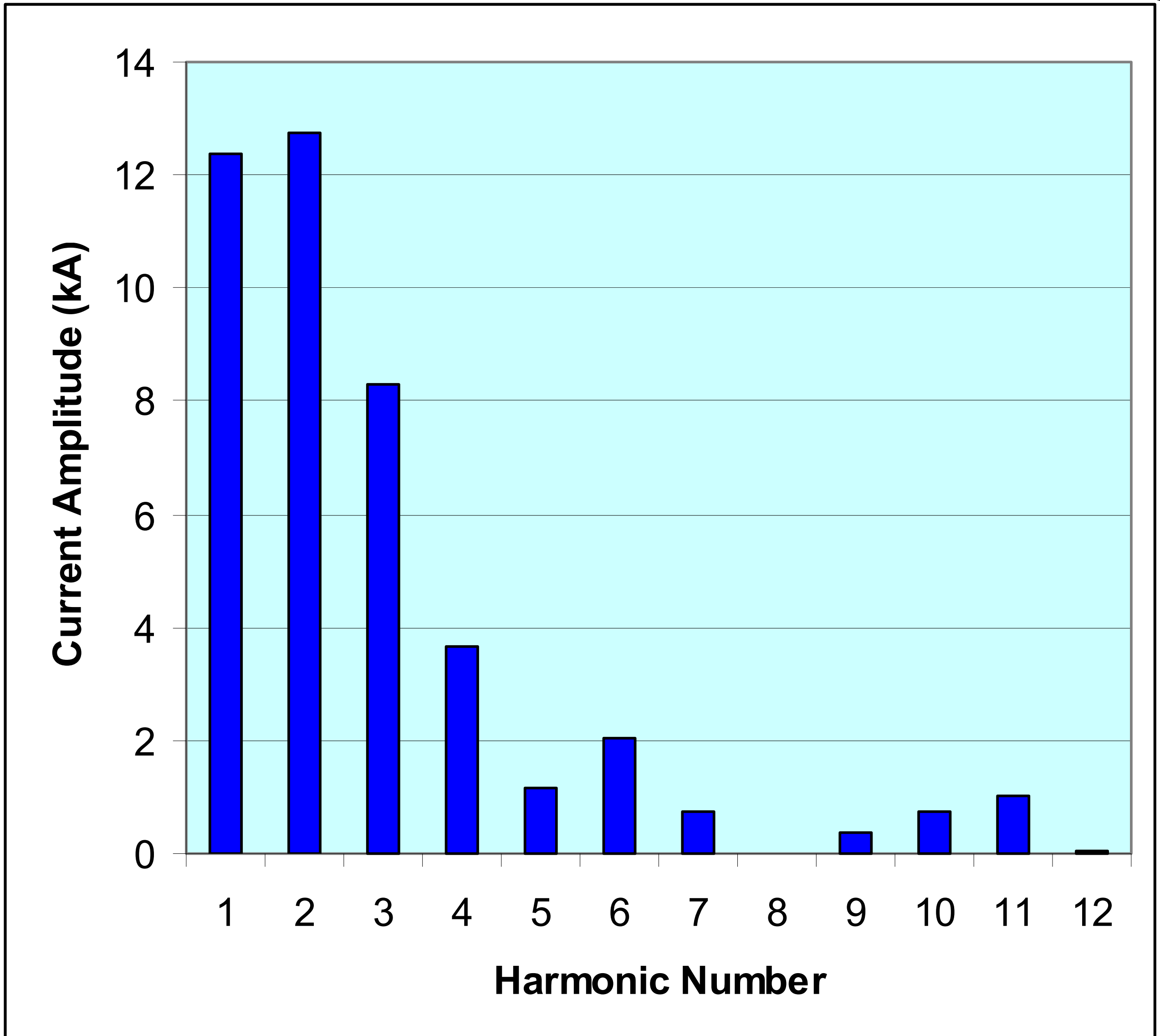
Hotel California, 8 January 2006



“Twin Californias”



Current Harmonics for "Twin Californias" Diurnal Trading



"Twin California" Trading Losses

Harmonic, n	I_n (kA)	f (μHz)	W_H (kW/5000 km)
1	12.4	11.6	1.8
2	12.8	23.2	3.8
3	8.31	34.7	2.4
4	3.67	46.3	6.2
		Total	8.7

No Problem!

“Sanity Check”

- Worst Case: Assume a “toleration loss” no larger than 1 W/m, then the entire SuperTie could be reversed in only 2 hours.
- The “fastest” change would be ~ 10 A/s between 5 and 6 PM EST. Compare with 1% ripple on 100 kA at the 6^{th} harmonic of 60 Hz which is 720,000 A/s!

5000 km SuperTie Economics

Base Assumption: C/P "Gen X" = $50/kA×m

Cost of Electricity ($/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 10 GW Transmission Line @ 50% Capacity (M$)	Additional Capital Costs for HTSC and Refrigeration (M$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	110	52,574	5.5 %	62

"Deregulated Electricity" will <u>not</u> underwrite this ROI, only a "public interest" investment analogous to the Interstate Highway system makes sense

Possible SuperTie Enablers

- Active public policy driving energy efficiency
- Carbon tax
- Tariff revenue from IPPs accruing from massive diurnal/inter-RTO power transactions

Garwin-Matisoo Bottom Line

This is not an engineering study but rather a preliminary exploration of feasibility. Provided satisfactory superconducting cable of the nature described can be developed, the use of superconducting lines for power transmission appears feasible.

Whether it is necessary or desirable is another matter entirely!