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An Energy Analysis of the Basic Materials Utilized in Electric Power Transmission Systems

April 30, 1979

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U.S. Department of Energy
Assistant Secretary for
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Division of Electric Energy Systems

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April 30, 1979

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ABSTRACT

The energy content per mile of installed underground and overhead power transmission systems has been calculated for the following types of systems: self-contained oil-filled cables: HPOF pipe-type cables; extruded dielectric cables; compressed-gas-insulated systems; overhead lines (ac and dc) and two proposed superconducting systems (ac and dc). The system operating voltages analyzed included 138, 230, 345, 500, 765 and 1,200 kV for ac systems, but all systems were not analyzed at the higher voltages. The dc overhead lines operated at ± 200, ± 400, ± 600 and ± 800 kV. Total installed energy content for these systems ranged from 4×10^9 to 1.2×10^{11} Btu per mile. Installation energy requirements were generally 10% or less of the inherent system energy content based on the materials used in each system. Most of the energy content in each system can be attributed to the metallic components; plastic and insulating oil also contribute significantly. The energy content of 36 materials and basic products, in terms of Btu per ton, was calculated as part of this study. Substitution of conductor materials (e.g., aluminum for copper) in cable systems resulted in changes in the total system energy content on the order of 15%.

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Program Director

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I. INTRODUCTION

The need to conserve national energy resources has emphasized the importance of reducing the energy consumed in constructing and operating the nation's electric power systems. It is therefore of great importance to the developers of new systems and to the planners of new installations that they be informed of the total energy "costs" of new systems, to ensure that the energy system of greatest overall efficiency is developed. This report is concerned with the total energy content, i.e. the energy investment, required to manufacture and install complete transmission systems. The energy content of a transmission system includes the energy used to manufacture all system components from basic materials, the total energy (in all forms) used to create these basic materials from raw materials, and the energy required to assemble and install the complete system.

Traditionally, cost and power transmission capacity have been the dominant factors affecting the choice of a transmission system to meet a particular power transmission requirement. These two factors will undoubtedly continue to be of major importance. However, as the cost of energy increases the energy content of transmission systems may become a significant factor because of its economic impact. The same driving force, higher energy cost, will also increase the importance of considering the energy losses associated with operating each type of transmission system. Analysis of such losses was outside the scope of this study, but the subject is being addressed in another study currently sponsored by the Department of Energy.* The results of this ongoing study, combined with the contents of this report, should permit a complete life-cycle energy analysis of electric power transmission systems.

The results of all transmission system energy content analyses performed during the course of this study are summarized in Chapter II. The following paragraphs describe the types of systems analyzed, the analytic procedures employed, and the organization of this report.

All of the conventional underground and overhead transmission systems in widespread use at present were analyzed, as well as several advanced systems which are not currently in use. Conventional underground systems include self-contained oil-filled (SCOF) cables, high-pressure oil-filled (HPOF) pipe-type cables, extruded dielectric (ED) cables, and compressed-

*The Electric Utility T&D Systems Study, DOE Contract No. ET-78-C-01-3146, is an examination of methods for determining losses in utility power systems. The final report should be available in the latter part of 1979.

gas-insulated (CGI) systems. Advanced underground systems consist of conventional cable types operating at voltages beyond present practice, cables with synthetic paper insulation, and superconducting cables (nominally zero conductor resistance).

Overhead ac transmission lines in the U.S. operate at standard voltages,* ranging from 138 to 765 kV; dc lines in this country operate at a maximum of ± 400 kV. This report includes ac overhead lines at the present standard voltages as well as 1,200 kV, and dc lines rated at ± 200, ± 400, ± 600 and ± 800 kV. Table I.1 lists all of the systems examined in this study, as well as the nominal operating voltages for each type of system.

The starting point for energy content analysis of all ac systems was established as the output terminals of a step-up transformer supplying the nominal transmission system voltage. For the dc systems, it was the output terminals of a transformer whose rectified output provided the desired dc voltage level; thus rectification and inversion terminals were considered as part of all dc systems.

Given these types of transmission systems, the first task was to determine the components and materials which make up each system. Tables I.2 through I.8 indicate the major components comprising each system of interest. All of the systems and components will be described in greater detail in Chapter VI.

Energy content analysis requires a set of assumptions regarding the procedures to be followed for each kind of product or material, and assumptions for the inherent energy content of basic inputs such as natural gas, fuel oil, and electrical energy. Chapter III discusses the assumptions and procedures used in this study to determine the energy content of basic materials and products. Chapter IV contains the actual derivation of energy content, starting from raw materials, of all the basic materials and products used in making transmission system components. Energy content for most materials is expressed in Btu per ton (2,000 lbs.) and joules per kilogram (J/kg).

Two examples may serve to illustrate the nature of Chapter IV. One basic product is kraft paper, usually supplied in 900-lb. rolls to a cable manufacturing plant. Energy content analysis of this product began with harvesting trees, and proceeded through pulping, papermaking and finishing operations. Another basic product is a coil of continuously-cast aluminum rod, typically weighing 6,000 lbs. as delivered to a cable manufacturing plant. Analysis of this product began with the mining of bauxite, and included ore processing, transport, reduction and casting. Figure I.1 illustrates the materials analyzed in depth and their relationship to each transmission system.

---

*Current operating levels are nominal 138, 230, 345, 500 and 765 kV.

TABLE I.1

TRANSMISSION SYSTEMS ANALYZED

System Type	Nominal Voltages
Self-contained, oil-filled (SCOF) paper-insulated* cables	138, 230, 345, 500, 765 kV
Pipe-type, high-pressure, oil-filled (HPOF) paper-insulated* cables	138, 230, 345, 500, 765 kV
Isolated-phase compressed-gas-insulated (CGI) systems	138, 230, 345, 500, 765, 1,200 kV
Extruded dielectric (ED) cables with copper and aluminum conductors	138, 230, 345 kV
Superconducting cables, ac	138, 345 kV
Superconducting cables, dc	± 100, ± 300 kV
Overhead lines, ac	138, 230, 345, 500, 765, 1,200 kV
Overhead lines, dc	± 200, ± 400, ± 600, ± 800 kV

*Laminates of paper and plastic are used at 765 kV.

TABLE I.2

Self-contained, Oil-filled (SCOF) Paper* Insulated Cable Systems
138, 230, 345, 500 and 765 kV

Components	Materials	Remarks
Cable conductor	Hollow core formed by copper or aluminum segments.	Standard area in this study: 2,000 kcmils
Conductor shield	Conducting (e.g. carbon-impregnated) paper tapes.	Total shield thickness about 20 mils.
Cable insulation	Tapes made of kraft paper, or paper/plastic laminates.	Average tape thickness is about 5 mils.
Insulation shield	Conducting paper tapes	Total shield thickness about 20 mils.
Outer shield	Copper tapes	Perforated
Cable sheath	Aluminum; lead, reinforced with bronze tapes, may also be used.	Extruded (aluminum or lead)
Cable outer jacket	Polyvinyl chloride (PVC) or polyethylene (PE)	Extruded
Insulating oil	Polybutene (a synthetic oil) or mineral oils	
Splices (joints)	Metallic shell of steel or aluminum and paper.	The metallic shell over the splice dominates all other materials used in a joint.
Potheads (terminations)	Primarily ceramics and steel	
Oil pressurizing system	Steel, concrete, copper	Pump, valves, controls, oil storage tank.

* The insulation is 100% kraft paper from 138 to 500 kV inclusive; at 765 kV a "synthetic" paper which is a laminate of plastic and kraft paper is employed.

TABLE I.3

High-pressure, Pipe-type, Oil-filled Paper* Insulated Cable Systems; 138, 230, 345, 500 and 765 kV

Components	Materials	Remarks
Cable conductor	Copper or aluminum	Stranded, segmented, compact conductor; 2000 kcmil standard area.
Binder	Metallic tape	Keeps the conductor segments in proper alignment.
Conductor shield	Conducting (e.g. carbon-impregnated) paper tapes.	Total shield thickness about 10 mils.
Cable insulation	Tapes made of kraft paper, or paper/ plastic laminates.	Average tape thickness is about 5 mils.
Insulation shield	Conducting paper tapes	Total shield thickness about 10 mils.
Outer shield	Copper tapes	Perforated.
Oil barrier	Aluminized mylar tapes	Typically 5 mils thick.
Skid wires	Stainless steel, bronze or zinc	D-shaped, typically 0.2" wide and 0.1" high.
Splices	Steel and paper, primarily	Typically 8' in length
Manholes	Concrete, steel	Typical weight: 32 tons
Pipes	Carbon steel	0.25" wall, 8.0" to 12.5" O.D.
Pipe coating	Bitumastic material	Typical coating: 0.5" thick
Trifurcator and riser pipes	Stainless steel	Each riser pipe sized to carry one cable.
Potheads	Primarily ceramics and steel.	Six used per system
Insulating oil	Polybutene (a synethic oil) or mineral oils.	Nominal pressure 200 psig
Oil pressurizing system	Steel, concrete, copper	Pump, valves, controls, oil storage tank

* The insulation is 100% kraft paper from 138 to 500 kV inclusive; at 765 kV a "synthetic" paper which is a laminate of plastic and kraft paper is employed.

TABLE I.4

Extruded Dielectric Cable (EDC) Systems; 138, 230 and 345 kV

Component	Material	Remarks
Conductor	Aluminum or copper	Stranded, segmented, compact conductor; standard area is 2,000 kcmils.
Conductor shield (also known as strand shield)	Semiconducting cross-linked polyethylene (XLPE)	Polyethylene with carbon black added; extruded over conductor; 25 mils thick.
Emission shield	Semiconducting XLPE	Extruded, 10 mils thick
Cable insulation	XLPE	Extruded, 500-1,000 mils thick
Insulation shield	Semiconducting XLPE	Extruded, 25 mils thick
Cable shield	Copper tapes	Wrapped
Cable jackets	Polyvinylchloride (PVC) or polyethylene	Extruded, 250 mils thick
Splices	PE or ethylene-propylene rubber (EPR) tapes	
Potheads	Ceramics, steel	

TABLE I.5

Compressed gas-insulated (CGI) Transmission Lines; 138, 230, 345, 500, 765 and 1,200 kV

Component	Material	Remarks
Conductor	Aluminum	Pipe, with O.D. from 4.5 inches to 11 inches depending on voltage.
Insulators	Alumina-filled epoxy resins	These support the conductor at the center of the enclosing conduit.
Enclosure (sheath)	Aluminum	Large-diameter conduit, 10 inches to 30 inches in diameter depending on voltage.
Sheath coatings	Bitumastic	Other coatings can also be used, e.g., fiberglass tape/resin combinations.
Potheads	Ceramics, steel	
Insulating gas	SF_6	Design pressure $\sim$ 45 psig

TABLE I.6

DC Superconducting Cable Systems: 100 and 300 kV

Major Components	Materials	Remarks
Helical core	Bronze	Core I.D. = 1.14 inches
Inner superconductor	Niobium-tin	Thin strands
Insulation	Synthetic paper tapes	Average tape thickness is about 5 mils
Outer superconductor	Niobium-tin	Thin strands
Cable armor	Bronze	I.D. = 4.7 inches
Inner casing	Stainless steel	Pipe, I.D. = 7.0 inches
Coolant	Liquid helium	In the cable core and inside the inner casing
Superinsulation	Aluminized mylar	Multi-layered; used between inner and outer casing.
Pipe supports	Epoxy resin or similar material	Spaced approximately 20 feet apart.
Outer casing	Carbon steel pipe	I.D. = 11.0 inches
Pipe coating	Bitumastic	0.5 inches thick
Manholes	Concrete, steel	Typical weight = 32 tons
Splice shells	Stainless and carbon steel	Surrogate form for the cable junction boxes
Potheads	Primarily ceramics and steel	Two used per system
Refrigeration system	Primarily steel, copper and aluminum	Spaced every 6.21 miles
Expanders	Primarily steel, copper and aluminum	Spaced every 6.21 miles
DC terminals	Many materials; see text	Located at each end of the line.

TABLE I.7

AC Superconducting Cable Systems: 138 and 345 kV

Major Components	Materials	Remarks
Helical core	Bronze	Core I.D. = 1.0 inches
Conductor backing	Aluminum	Thin strips
Inner superconductor	Niobium-tin	Thin strips
Insulation	Polyethylene tapes	Average tape thickness is about 5 mils
Outer superconductor	Niobium-tin	Thin strips
Conductor backing	Aluminum	Thin strips
Sheath/gas barrier	Lead	Thickness = 80 mils
Sheath reinforcement	Bronze	Tapes
Skid wires	Stainless steel	D-shaped, typically 0.2 inches wide and 0.1 inches high
Inner casing	Stainless steel	Pipe, I.D. = 12.0 inches
Coolant	Liquid helium	In core of each cable and inside the inner casing
Superinsulation	Aluminized mylar	Multi-layered; fills space between inner and outer casing
Pipe supports	Stainless steel	Positions inner casing
Outer casing	Carbon steel	Pipe, I.D. = 19.5 inches
Pipe coating	Bitumastic	0.5 inches thick
Manholes	Concrete, steel	Typical weight = 32 tons
Splice shells	Stainless and carbon steel	Surrogate form for the cable junction boxes
Potheads	Primarily ceramics and steel	Six used per system
Refrigeration system	Primarily steel, copper and aluminum	Spaced every 7.08 miles

TABLE I.8

Overhead Lines: 138, 230, 345, 500, 765 and 1,200 kV AC; ± 200, ± 400, ± 600, ± 800 kV DC

Component	Materials	Remarks
Conductor core	High-strength steel wire	Core diameters are in the range of .35 to .50 inches
Conductor*	Aluminum wire	3 to 4 layers of strands; conductor O.D.s range from 1.1 to 1.8 inches
Spacers**	Aluminum or steel	Used approximately every 300 feet for bundled conductors
Shield wires	High-strength steel wire	O.D. typically less than 0.5 inches
Line mounting hardware	Steel	Various clamps, brackets, bolts, nuts, etc.
Suspension insulators	Ceramics, steel	
Towers or poles	Steel or aluminum	
Tower/pole footings	Steel and/or concrete	

*Two conductors per phase are commonly used at 345 kV and 500 kV; four per phase is common at 765 kV, and 8-10 may be used at 1,200 kV.

**Spacers keep the bundled conductors in proper orientation.

	SCOF Cables	HPOF Pipe-Type Cables	CGI Systems	Extruded Dielectric Cables	Superconducting Systems	Overhead Lines
Steel (various types and forms)		•			•	•
Copper	•	•		•		
Aluminum (various types and forms)	•	•	•	•	•	•
Lead	1			1	1	
Bronze					•	
Superconductors					•	
Paper	•	•			•	
Polyethylene	2			•	•	
Plastics (assorted)	•	3	2	2	3	
Epoxy Resin			•		•	
Ceramics[4]	•	•	•	•	•	•
Insulating Oil	•	•				
Bitumastic coatings		•	•		•	
Cement		•				•
Liquefied Helium					•	
Sulfur Hexafluoride			•			
Support Systems						
Oil Pressurizers	•	•				
Refrigeration Systems					•	
Terminals for dc systems					•	•

Notes:
1. May be used as sheath material.
2. May be used as an exterior jacket.
3. May be used in paper/plastic laminated tapes.
4. Ceramic materials are used in the insulating terminals (potheads) of cable systems, and as suspension insulators for overhead lines.

FIGURE I.1

MATRIX OF TRANSMISSION SYSTEMS ANALYZED AND THE DOMINANT MATERIALS, PRODUCTS AND SUPPORT SYSTEMS

The energy requirements of manufacturing processes employed in converting basic products into finished transmission system components are described in Chapter V. HPOF pipe-type cable manufacturing is typical of the type of processes covered. Continuing with the previous examples, coils of aluminum rod are drawn into strands, cabled and formed into finished conductor segments. Rolls of paper are dried, slit into tapes, wrapped around the conductor and impregnated with insulating oil. A completed HPOF cable is only part of an HPOF transmission system, of course; manufacture of the other components (e.g. steel pipe and potheads) is also analyzed in this chapter.

Chapter VI combines the results of preceding chapters, resulting in energy content estimates on a per-mile basis for all the transmission systems of interest (uninstalled). Prior to the energy content analysis of each system, tables indicate the types of components in use at each voltage, their physical characteristics (e.g. weight per unit, dimensions, etc.) and other pertinent information such as the spacing of overhead line towers and underground cable manholes. Support systems such as oil pressurizing plants and refrigeration units are included in the discussion of each system as appropriate. The energy content per mile as a function of voltage is displayed graphically for each system.

Installation of transmission systems is the focus of Chapter VII. The general assumptions employed in estimating the energy content of construction activities are presented first, followed by tables of installation energy requirements for the various transmission systems studied. These energy requirements were calculated for urban, suburban, and rural terrain.*

Chapter VIII is relatively brief, consisting of the combined results from Chapters VI (system energy content) and VII (installation energy requirements), but it contains the major findings of this study. Graphs illustrate the total installed energy content of all transmission systems studied as a function of voltage and terrain. This chapter also contains tables which indicate the system energy content per mile normalized to system power handling capacity, i.e. energy content per mile per MVA of capacity.

The issue of variation in energy content as a function of conductor size and material for a given system is addressed in Chapter IX. Tables indicate the effects of substituting aluminum for copper in SCOF, HPOF and extruded dielectric cables while holding conductor area constant at 2,000 kcmils, and the effects of substituting 3,200 kcmil aluminum for 2,000 kcmil copper conductors. The latter substitutions represent equivalent conductor resistance.

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*Certain combinations were excluded as inappropriate, e.g. 1,200 kV overhead lines in urban areas.

Chapter X presents the conclusions of this study, and discusses other factors which bear upon the energy content analysis of transmission systems.

The Appendices contain computer printouts of selected transmission system energy content analyses, a detailed analysis of dc terminals in terms of energy content, and supporting data for the assumptions used in determining the energy content of installation activities, mylar and epoxy resin.

II. SUMMARY

The total energy content of most conventional power transmission systems operating at voltages from 138 to 765 kV lies in the range of 4 to 90 billion Btu per mile. Figure II.1 contains the energy content values obtained for these conventional systems and all others analyzed in this report. The system abbreviations shown in the figure are identical to those defined previously in Chapter I.

Several conclusions can be drawn from Figure II.1. One observation is that there is relatively little difference between conventional cable systems at the lower transmission voltages, 138 to 345 kV. This is particularly true for SCOF and HPOF pipe-type cables. Extruded dielectric cables contain approximately 60% of the energy associated with oil-filled cables.

Compressed-gas-insulated systems are the highest in energy content per mile of all conventional* systems. This occurs primarily because aluminum, the most energy-intensive common metal on a Btu per pound basis, is used extensively to provide both high electrical conductivity and minimum weight. The large dimensions of each CGI phase conductor require correspondingly large quantities of aluminum.

One major finding of this study is that metals are the dominant contributor to total energy content for all systems. The fraction associated with metals is always 50%, or greater. Oil, plastics and paper are the other materials with a significant fraction of total energy content for most systems. Table II.1 lists the energy content of all materials and products analyzed during the course of this study.

The manufacturing process whereby basic materials are converted into complete cables is not particularly energy-intensive compared to the energy content inherent in the materials. For example, the drawing, annealing, stranding and compacting of copper conductors only adds about 1% to the energy in the copper itself. Manufacturing of complete cables adds between 4% and 10% to the inherent energy content of the materials used.

Installation of transmission systems has been analyzed for all of the systems indicated in Figure II.1. In general, the energy required to install a system is a small fraction of the inherent system energy content. Two examples may illustrate this: a 345 kV HPOF pipe-type cable system in an urban environment, and a 500 kV overhead line in a rural environment. The urban installation requires 3% of the inherent system energy content; the rural installation requires 9%.

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* Only superconducting systems are regarded as non-conventional.

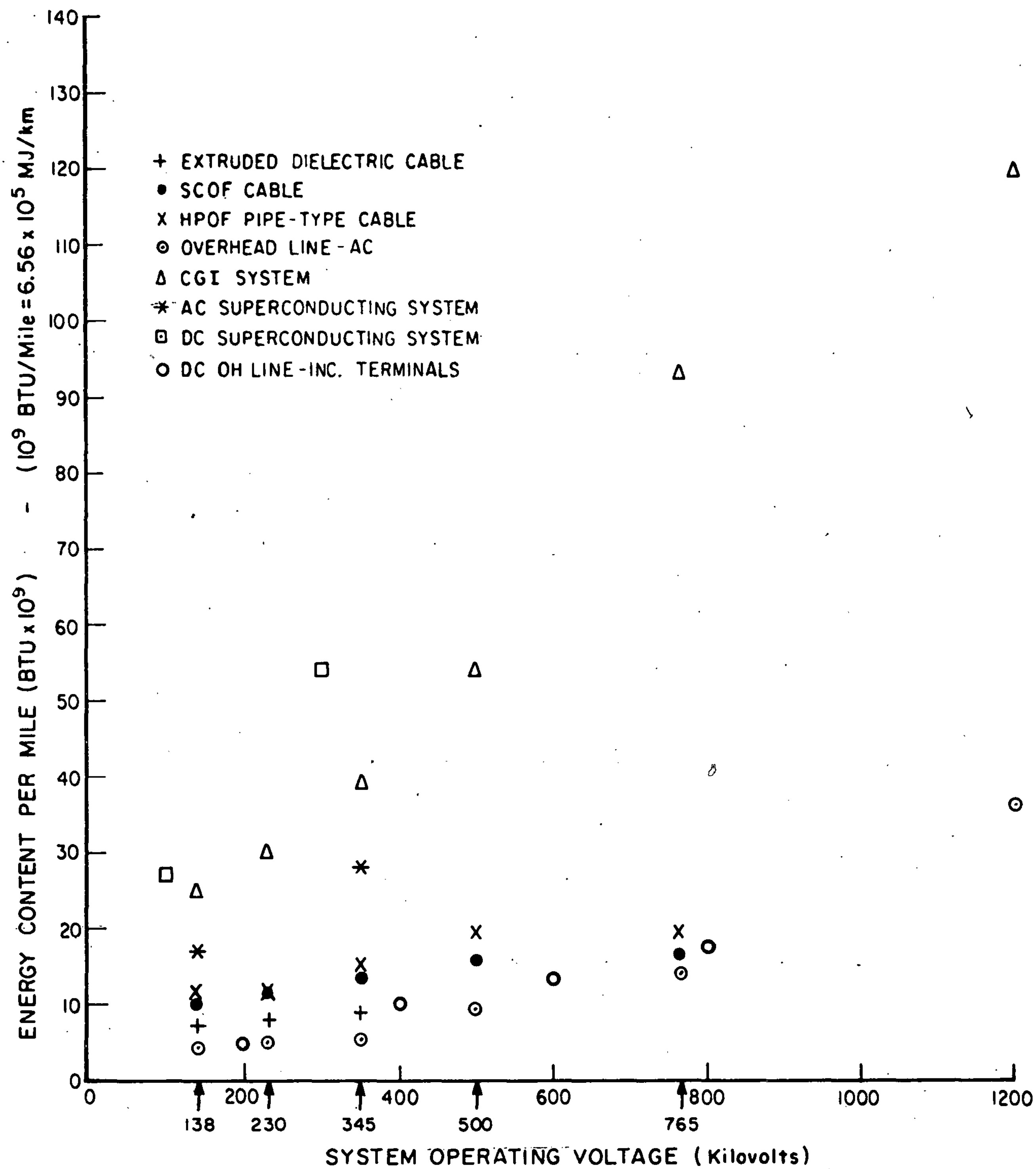

FIGURE II.1

ENERGY CONTENT OF ELECTRIC POWER

TRANSMISSION SYSTEMS VERSUS OPERATING VOLTAGE

TABLE II.1

ENERGY CONTENT OF MAJOR MATERIALS AND PRODUCTS USED IN TRANSMISSION SYSTEMS

Material	Density		Energy Content	
	(lbs/ft^3)	(kg/l)	($Btux10^6$/ton)	(MJ/kg)
1. Aluminum ingot/CCWR*	168.75	2.70	224.0	259.8
2. Aluminum wire	168.75	2.70	228.0	264.5
3. Aluminum pipe	168.56	2.70	232.0	269.1
4. Aluminum, structural	174.00	2.79	226.0	262.2
5. Copper ingot/CCWR	555.00	8.89	93.2	108.1
6. Copper wire/tape	555.00	8.89	94.5	109.6
7. Steel ingot	490.07	7.85	19.4	22.5
8. Steel rod	490.07	7.85	31.2	36.2
9. Steel wire	490.07	7.85	34.1	39.6
10. Steel pipe	490.07	7.85	39.8	46.2
11. Steel plate	490.07	7.85	35.4	41.1
12. Steel, structural	490.07	7.85	29.2	33.9
13. Stainless steel ingot	500.69	8.02	36.7	42.6
14. Stainless steel plate	500.69	8.02	87.0	100.9
15. Stainless steel wire	500.69	8.02	59.0	68.4
16. Stainless steel pipe	500.69	8.02	75.3	87.3

*Continuously-cast wire rod.

TABLE II.1

ENERGY CONTENT OF MAJOR MATERIALS

AND PRODUCTS USED IN TRANSMISSION SYSTEMS

Material	Density (lbs/ft^3)	Density (kg/l)	Energy Content (Btux10^6/ton)	Energy Content (MJ/kg)
17. Lead ingot	708.60	11.4	17.0	19.7
18. Niobium	535.00	8.57	510.0	591.6
19. Bronze	540.00	8.65	115.9	134.4
20. BNL superconducting alloy	252.00	4.04	215.0	294.4
21. LASL superconducting alloy	551.98	8.84	116.0	134.6
22. Kraft paper	46.82	0.75	52.6	61.0
23. Synthetic paper	49.91	0.80	57.2	66.4
24. Conducting paper	54.62	0.87	54.2	62.9
25. Portland cement	196.00	3.14	7.61	8.8
26. Concrete	146.00	2.34	1.49	1.7
27. Polyethylene (LDPE)	57.44	0.92	70.2	81.4
28. Polyvinyl chloride (PVC)	84.28	1.35	61.4	71.2
29. Polypropylene (PP)	56.19	0.90	66.5	77.1

TABLE II.1

ENERGY CONTENT OF MAJOR MATERIALS

AND PRODUCTS USED IN TRANSMISSION SYSTEMS

Material	Density		Energy Content	
	(lbs/ft^3)	(kg/l)	($Btu x 10^6/ton$)	(MJ/kg)
30. Mineral oil	55.54	0.89	67.9	78.8
31. Polybutene oil	51.17	0.82	70.2	81.4
32. Liquid helium	7.62	0.12	581.0	674.0
33. Sulfur hexafluoride (SF_6)	N.A.	N.A.	112.0	129.9
34. Aluminized mylar	87.40	1.40	158.0	183.3
35. Epoxy resin	124.86	2.00	55.0	63.8
36. Bitumastic	89.0	1.43	5.7	6.6

The rectifying and inverting terminals required for a dc transmission system are highly energy intensive. Hundreds of tons of steel and insulating oil are required, in addition to considerable amounts of copper, aluminum, paper, porcelain (ceramics) and concrete. As a result of this high energy content, dc terminals overwhelm the material energy content of dc lines on a per-mile basis unless one assumes a substantial distance. A 200-mile distance has been selected as a minimum length for dc systems in this study. Using this assumption, dc terminals contribute between 50 and 60% of the per-mile energy content of complete dc systems.

The effects of substituting aluminum, in various sizes, for copper conductors were predictable and small compared to total system energy content. Taking an SCOF cable as an example, replacing copper with aluminum while keeping conductor area constant decreased system energy content about 11%. Substituting more aluminum, so that equivalent conductor resistance was maintained, increased the system energy content by 13% above the standard copper value.

III. GENERAL ASSUMPTIONS REGARDING ENERGY CONTENT ANALYSIS

A. INTRODUCTION

Energy content analysis can be carried out at four levels of complexity. The simplest procedure, Level 1, requires nothing more than measurement of the direct energy input required to transform raw materials into a given product. Energy input can be measured in kWh, Btu, gallons of oil or whatever form is convenient. However, the final energy content is usually expressed in Btu per pound of product, or joules per kilogram. A Level 2 analysis includes determination of the energy needed to extract, process and transport raw materials, in addition to the direct energy input required to transform the raw materials into a given product. All of the materials and products used to manufacture transmission system components were analyzed on a Level 2 basis in this study. Level 3 requires a determination of the energy needed to manufacture production equipment (e.g. a wire drawing machine) in addition to the Level 2 analysis, and Level 4 requires a determination of the energy needed to manufacture machine tools which make production equipment in addition to a Level 3 analysis.

The following paragraphs describe the assumptions that have been made regarding the energy content of liquid petroleum fuels, natural gas, electricity, transportation of materials and recycling.

B. PETROLEUM FUELS

The energy content per unit of volume or weight of petroleum fuels, and fuels in general, can vary considerably depending on the nature of the source. Taking crude oil as an example, its specific gravity at the wellhead may vary from 1.0 (a thick, almost asphaltic consistency corresponding to 10° API gravity) to .8 (50° API gravity), which is a fairly light crude oil.* The corresponding range of energy content is 21% based on 6.3×10^6 Btu per barrel for 10° crude and 5.0×10^6 Btu per barrel for the light crude[1].

Previous studies pertaining to energy consumption have selected the higher value, rather than an average or medium figure. In particular, the 1972 Census of Manufacturers[2] performed by the U.S. Department of Commerce, and a study by Battelle[3] on energy use patterns in selected industries for the U.S. Bureau of Mines both used 6.3×10^6 Btu per 42-gallon barrel of "fuel" oil.**

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*The range shown here encompasses most of the oil found worldwide; both heavier and lighter crudes exist. The API index runs from 0° (ρ = 1.08) to 100° (ρ = .61).

**It is implicit from this number that the oil is "residual" fuel oil, which is decidedly different from household fuel oils. Residual fuel oils consist of the heavy, viscous material found at the lower levels of a distillation tower (residuum), mixed with lighter density distilled fuels (distillate fuels). For example, residuum blended with 5 to 20% distillate is No. 6 fuel oil (once known as Bunker C oil); its gravity is about 13° API.

In the past, ADL has usually assumed an energy content of 5.5×10^6 Btu per barrel of crude oil. Such a choice has the advantage of reflecting a typical or average energy content. However, for the two purposes of maintaining comparability with previous studies and adopting a conservative approach to determining the energy content of materials, a value of 6.3×10^6 Btu per barrel has been selected for this study.

The other petroleum fuels of primary interest are diesel fuel and gasoline. Diesel fuels vary seasonally in terms of energy content per gallon, due to blending with kerosine which is done to maintain an acceptable viscosity. A value of 5.8×10^6 Btu per barrel of diesel fuel has been selected based on discussions with suppliers. The energy content of gasoline was assumed to be 5.3×10^6 Btu per barrel.

C. NATURAL GAS

Pipeline natural gas, as supplied by the utilities, is a mixture consisting of 80 to 95% methane, with various amounts of ethane, propane, butane, other hydrocarbons and noncombustible gases added. The heating value of "natural gas" as defined above may vary from 900 to 1,200 Btu/ft^3 at S.T.P.* as a result of this variable composition. In practice, however, the range was considerably more narrow in a survey of 14 cities in the U.S. performed by the American Gas Association[4]. The lowest heating value was 945 Btu/ft^3, and the highest was 1,093.

A figure of 1,000 Btu/ft^3 is commonly used as a measure of the energy content of natural gas; the Bureau of Mines study cited previously[3] employed this value. However, the Census of Manufacturers used 1,033 in their study, and a simple (non-weighted by production) average of the AGA survey data yields a figure of 1,050 Btu/ft^3.

Given this range, one could argue for any particular value. The figure of 1,000 Btu/ft^3 has been selected because the Bureau of Mines study is the most detailed analysis of industries. The Census of Manufacturers is, by contrast, a very broad survey of industries.

D. OTHER FUELS

The following values of energy content have been selected.

Coke (metallurgical grade)	-	3.15×10^7 Btu per ton
Petroleum coke	-	3×10^7 Btu per ton
Anthracite coal	-	2.54×10^7 Btu per ton
Propane (LPG)	-	4.3×10^7 Btu per ton
Wood bark and scraps	-	4.2×10^6 Btu per ton

*Standard temperature and pressure; 32°F, 14.7 psi.

E. ELECTRICITY

The amount of energy required to produce 1 kWh of electricity (3,410 Btu) varies from about 4,000 Btu equivalent (hydro facilities) to 13,600 (gas turbines in the 2-3 MW range). Nuclear plants are approximately 34% efficient, which corresponds to 10,000 Btu per kWh. Most of the electric energy produced in the U.S. comes from fossil-fired generating plants in sizes ranging from 50 to 1,100 MW; depending on age and size, the heat rate may vary from 11,400 to 8,600 Btu per kWh.

The Census of Manufacturers used 10,500 Btu per kWh, as did the Bureau of Mines study. This translates to an efficiency of 33%. The national average for fossil-fired units has been 33% for the years 1974 through 1976, according to the Edison Electrical Institute Statistical Year Book[5]. It seems appropriate, therefore, to use 10,500 Btu per kWh as the conversion ratio of thermal energy to electrical energy.

F. TRANSPORTATION

The following values were used for the energy required to transport materials using various modes of transportation. These figures correspond to those used in the Bureau of Mines study.

Trucks	-	2,400 Btu per ton-mile
Railroads	-	670 Btu per ton-mile
Ships	-	250 Btu per ton-mile

G. MISCELLANEOUS ITEMS

There are a number of items which are minor constituents in selected materials. These items have been identified and the assumed energy content per unit weight or volume has been stated in each product or material analysis as appropriate.

H. RECYCLING

The most critical issue in the energy content analysis of common metals is recycling, because metal reclaimed from scrap is commonly assigned a zero or near-zero (depending on the amount of processing required) energy content. Thus metal produced primarily from scrap can have an energy content significantly less than metal produced from ore. The difference can be as high as 94%, in the case of aluminum.

Following common practice in energy content analysis, all of the analyses performed in this study assume a zero energy content for scrap material. The final energy content calculated for each metal is a weighted average based on the amount produced from ore and that produced from scrap.

References for Chapter III

1. See Figure 9-3, page 9-10, Chemical Engineering Handbook, Fifth Edition, 1973.

2. "Fuels and Electrical Energy Consumed", Special Report MC72 (SR)-6, 1972 Census of Manufacturers, U.S. Dept. of Commerce.

3. "Energy Use Patterns in Metallurgical and Non-metallic Mineral Processing; Opportunities to Improve Energy Efficiency", prepared for the Bureau of Mines by Battelle Columbus Laboratories, Ohio, September, 1975.

4. Chemical Engineering Handbook, Table 9-15.

5. "Statistical Year Book of the Electric Utility Industry", Edison Electric Institute, New York, 1977.

IV. ENERGY CONTENT OF BASIC MATERIALS

A. INTRODUCTION

The basic materials of interest in this chapter are those used in the manufacture of transmission system components. The energy content of each material has been determined in terms of energy per ton or per unit volume, as appropriate relative to the form of output. In most cases, the output form is suitable for shipment directly to a cable manufacturing plant. In other cases, the material form is appropriate for component manufacturing or installation of transmission systems. Chapter V describes the manufacture of transmission system components, using the basic materials analyzed in this chapter as inputs.

B. COPPER

Copper production in the U.S. is based upon primary copper (from ore) and secondary copper (from a variety of scrap types). The steps involved in producing cast copper wire rod from ore are shown in simplified schematic form in Figure IV.B.1, and in detail in Table IV.B.1. The result is 1.08×10^8 Btu per ton of electrical grade refined copper.

Most of the copper used for electrical purposes in the U.S. comes from ore, but about 20% is produced from scrap. The secondary copper industry consumes various types of scrap which include No. 1, No. 2, light copper scrap, copper bearing scrap and others. Furthermore, each scrap type was consumed in various proportions not only by secondary producers but also by primary producers and brass mills. The following analysis is based upon ADL estimates of how the various grades of scrap are distributed.

No. 1 copper scrap is primarily recycled into brass mills, so that No. 2 scrap is the most important type for analysis. Table IV.B.2 delineates the steps involved in producing copper from this source, which results in a total energy content of 1.73×10^7 Btu per ton. Some electrical copper is also derived from low-grade scrap, which has an energy content of 4.24×10^7 Btu per ton.

Using an average figure of 3×10^7 Btu per ton of copper from secondary sources, it is possible to develop a weighted average energy content of copper wirebar. The weights in this case are the tonnage of each type produced in 1976 (latest available data), as shown on the following page of text.

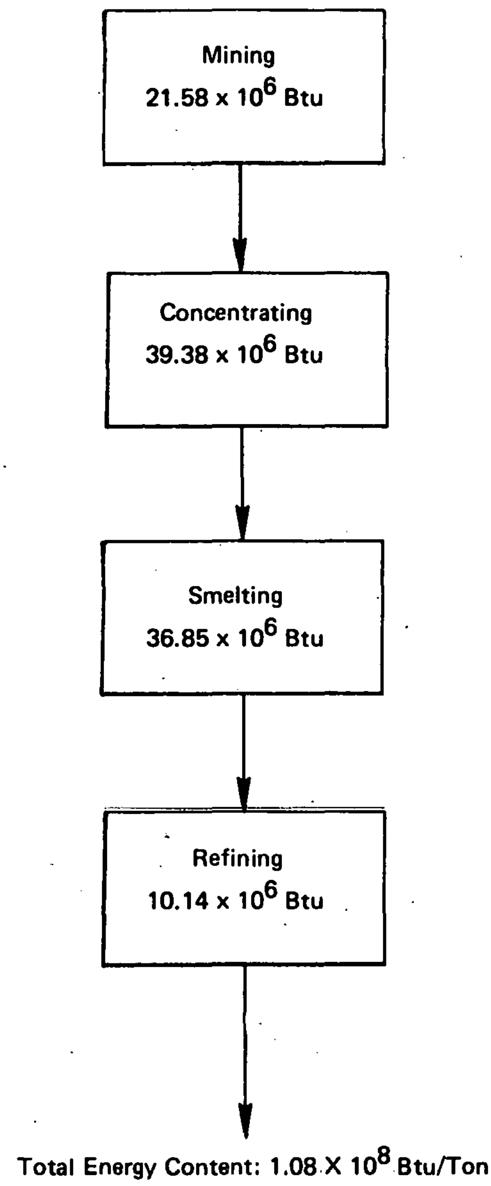


FIGURE IV.B.1

PRODUCTION OF ONE TON OF ELECTRICAL

GRADE REFINED COPPER BY CONVENTIONAL MINING AND SMELTING PROCESSES

TABLE IV.B.1. PRODUCTION OF REFINED COPPER FROM ORE

(Step Number) Process	Unit	Units Per Net Ton of Copper	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Copper
Excavation				
Electrical Energy	kWh	786.0000	0.010500	8.28
Natural Gas	Cu.Ft.	220.5000	0.001000	0.22
Distillate Fuels	Gal	38.6200	0.139000	5.37
Explosives	Lb	155.0000	0.030000	4.65
			Sub-Total	18.52
Transportation				
Truck (Waste Rock to Dumps)	Ton/Mi	921.4000	0.002400	2.21
Rail (Ore to Mill)	Ton/Mi	1261.3000	0.000670	0.85
			Sub-Total	3.06
* Total Energy for Mining				21.58
Crushing				
Electrical Energy	kWh	350.0000	0.010500	3.68
			Sub-Total	3.68
Grinding				
Electrical Energy	kWh	2013.9000	0.010500	21.15
Steel Balls & Rods	Lb	273.0000	0.017500	4.78
			Sub-Total	25.93
Flotation				
Electrical Energy	kWh	547.0000	0.010500	5.74
Residual Fuels	Gal	1.6200	0.150000	0.24
Steam	Lb	366.6000	0.001400	0.51
Inorganic Reagents	Lb	541.0000	0.005000	2.71
Organic Reagents	Lb	28.5000	0.020000	0.57
			Sub-Total	9.77
* Total Energy for Concentrating				39.38
Smelter				
Cement Copper	Net Iron	0.1000	87.000000	8.70
			Sub-Total	8.70

TABLE IV.B.1 (CONTINUED)

(Step Number) Process	Unit	Units Per Net Ton of Copper	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Copper
Charge Preparation & Drying				
Electrical Energy	kWh	53.1500	0.010500	0.56
Natural Gas	Cu.Ft.	1395.0000	0.001000	1.40
			Sub-Total	1.96
Reverberatory Furnace				
Electrical Energy	kWh	59.6500	0.010500	0.63
Natural Gas	Cu.Ft.	12799.0000	0.001000	12.80
Residual Fuels	Gas	74.8000	0.150000	11.22
Steam (Credit)	Lb	-6675.0000	0.001400	-9.33
			Sub-Total	15.32
Converter				
Electrical Energy	kWh	38.5800	0.010500	0.41
Natural Gas	Cu.Ft.	890.0000	0.001000	0.89
Steam (Process)	Lb	3265.0000	0.001400	4.57
			Sub-Total	5.87
Anode Refining Furnace				
Electrical Energy	kWh	6.4400	0.010500	0.07
Natural Gas	Cu.Ft.	1900.0000	0.001000	1.90
Steam (Process)	Lb	169.2200	0.001400	0.24
Metallurgical Coke	Net Ton	6.0050	31.500000	0.16
			Sub-Total	2.37
Gas Cleaning				
Electrical Energy	kWh	30.7600	0.010500	0.32
			Sub-Total	0.32
Acid Plant				
Electrical Energy	kWh	257.1400	0.010500	2.70
Natural Gas	Cu.Ft.	1510.0000	0.001000	1.51
Sulfuric Acid (Produced)	Net Ton	-2.3000	0.830000	-1.90
			Sub-Total	2.31
* Total Energy for Smelting				36.85

TABLE IV.B.1 (CONTINUED)

(Step Number) Process	Unit	Units Per Net Ton of Copper	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Copper
Electrolytic Refining				
Electrical Energy	kWh	307.4900	0.010500	3.23
Natural Gas	Cu.Ft.	1350.0000	0.001000	1.35
Residual Fuels	Gal	19.9200	0.150000	2.99
Sulfuric Acid	Net Ton	0.0165	0.830000	0.01
			Sub-Total	7.58
Cathode Melting				
Electrical Energy	kWh	7.3700	0.010500	0.08
Natural Gas	Cu.Ft.	1869.7000	0.001000	1.87
			Sub-Total	1.95
Transportation				
Railroads (Anodes Transport)	Ton/Mi	910.0000	0.000670	0.61
			Sub-Total	0.61
* Total Energy for Refining				10.14
* TOTAL ENERGY PER NET TON OF COPPER				107.95 (125.22 MJ/kg)

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.B.2. RECYCLING OF NO. 2 COPPER SCRAP

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Product
(1) Scrap Transportation				
Truck	Ton/Mi	400.0000	0.002400	0.96
			Sub-Total	0.96
(2) Scrap Preparation				
Electrical Energy	kWh	0.5000	0.010500	0.01
Distillate Fuel Oil	Gal	0.3600	0.139000	0.05
			Sub-Total	0.06
(3) Anode Refining & Casting				
Distillate Fuel Oil	Gal	41.0000	0.139000	5.70
Natural Gas, Poling	Cu.Ft.	660.0000	0.001000	0.66
Metallurgical Core	Net Ton	0.0090	31.500000	0.28
Electrical Energy	kWh	24.8000	0.010500	0.26
Steam (Waste Heat Credit)	Lb	-1250.0000	0.001400	-1.74
			Sub-Total	5.16
(4) Electrolytic Refining (Battelle)	MM/Btu	7.5750	1.000000	7.58
			Sub-Total	7.58
(5) Cathode Melting (Battelle)	MM/Btu	1.9470	1.000000	1.95
			Sub-Total	1.95
* Total Process Energy				15.71
Air Pollution Control				
Electrical Energy	kWh	19.6000	0.010500	0.21
			Sub-Total	0.21
* Total Pollution Control Energy				0.21
Space Heating				
Distillate Fuel Oil	Gal	9.7000	0.139000	1.35
			Sub-Total	1.35
* Total Space Heating Energy				1.35
* TOTAL ENERGY PER NET TON OF PRODUCT				17.27 (20.03 MJ/kg)

Source: Reference 2.

Type	Tons Produced	Energy Content Per Ton	Weighting Factor	Energy Content
Primary Copper	1.54×10^6	1.08×10^8	.81	8.75×10^7
Secondary Copper	3.6×10^5	3.0×10^7	.19	5.7×10^6

Weighted Average Energy Content for Copper Wire Rod: 9.32×10^7 Btu/ton (108.11 MJ/kg)

C. ALUMINUM

Approximately 90% of the aluminum produced today is derived from ore; the remainder is based upon recycled scrap metal. Table IV.C.1 lists the steps required to produce one ton of aluminum in ingot form from ore. The total energy content is 3.44×10^8 Btu per ton. Table IV.C.2 describes the inputs of energy and materials needed to make a ton of aluminum from various kinds of scrap. Clearly, the energy content of 2.42×10^7 Btu per ton is substantially below that of aluminum derived from ore.

As with copper products, a weighted average figure of energy content for aluminum ingots is the most appropriate single value to use in subsequent calculations. The derivation of this weighted average value is shown below, where the production data is again based on 1976 figures.

Type	Tons Produced	Energy Content Per Ton	Weighting Factor	Energy Content
Primary Aluminum	4.25×10^6	2.44×10^8	.91	2.22×10^8
Secondary Aluminum	4.09×10^5	2.42×10^7	.09	2.18×10^6

Weighted Average Energy Content per Aluminum Ingot: 2.24×10^8 Btu/ton (259.84 MJ/kg)

Most of the aluminum wire used in ACSR transmission line conductors is made using coils of continuously-cast aluminum rod as input. It is assumed that the difference in energy content between cast rod and cast ingots is negligible, so that the energy content of continuously-cast wire rod is taken to be 2.24×10^8 Btu per ton also. Production of large-diameter aluminum pipe for compressed-gas-insulated (CGI) systems will be discussed in Chapter V, starting with cast ingots.

TABLE IV.C.1. PRODUCTION OF ALUMINUM FROM ORE

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF ALUMINUM	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF ALUMINUM
MINING				
DRILLING	KWH	1.0000	0.010500	0.01
DRILL BITS, MACHINES	LB	0.0000	1.000000	0.00
EXPLOSIVES	LB	0.8000	0.030000	0.02
			SUBTOTAL	0.03
SHOVEL LOADING				
ELECTRICAL ENERGY	KWH	10.2500	0.010500	0.11
MATERIALS AND MAINTENANCE	MM BTU	0.0300	1.000000	0.03
			SUBTOTAL	0.14
TRUCK TRANSPORTATION				
DISTILLATE FUEL OIL	GAL	0.7000	0.139000	0.10
TRUCK MATERIALS & MAIN.	MM BTU	0.0200	1.000000	0.02
			SUBTOTAL	0.12
CRUSHING, WASHING, AND SCREENING				
CRUSHING AND SCREENING	KWH	12.5000	0.010500	0.13
ELECTR. ENERGY(PUMPING)	KWH	6.4000	0.010500	0.07
MACHINERY MAINTENANCE	MM BTU	0.0200	1.000000	0.02
			SUBTOTAL	0.22
DRYING				
	MM BTU	1.9000	1.000000	1.90
			SUBTOTAL	1.90
TRANSPORTATION				
WATER TRANSPORTATION	TON MI	9500.0000	0.000250	2.38
			SUBTOTAL	2.38
BAYER PROCESSING				4.79
CRUSHING AND GRINDING				
ELECTRICAL ENERGY	KWH	31.4300	0.010500	0.33
LIME	NET TON	0.1000	8.500000	0.85
			SUBTOTAL	1.18
DIGESTION				
STEAM	LB	12143.0000	0.001400	17.00
CAUSTIC SODA	NET TON	0.1500	29.900000	4.49
			SUBTOTAL	21.49
CLARIFICATION				
ELECTRICAL ENERGY	KWH	30.4800	0.010500	0.32
STARCH	---	0.0000	0.000000	0.00
			SUBTOTAL	0.32
COOLING				
ELECTRICAL ENERGY	KWH	5.7100	0.010500	0.06
			SUBTOTAL	0.06
PRECIPITATION-FILTRATION				
ELECTRICAL ENERGY	KWH	66.6700	0.010500	0.70
			SUBTOTAL	0.70

TABLE IV.C.1. PRODUCTION OF ALUMINUM FROM ORE (Cont'd.)

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF ALUMINUM	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF ALUMINUM
EVAPORATION				
STEAM	LB	6829.0000	0.001400	9.56
			SUBTOTAL	9.56
SPENT LIQUOR RECOVERY				
ELECTRICAL ENERGY	KWH	69.5200	0.010500	0.73
STEAM (NET USAGE)	LB	593.0000	0.001400	0.83
			SUBTOTAL	1.56
CALCINATION				
NATURAL GAS	CU. FT.	7720.0000	0.001000	7.72
			SUBTOTAL	7.72
* TOTAL ENERGY FOR BAYER PROCESSING				42.59
CARBON ANODE MANUFACTURE				
PETROLEUM COKE (RAW)	NET TON	0.4250	30.000000	12.75
RAIL (COKE TRANSPORT)	TON MI	212.5000	0.000670	0.14
HYDROCARBONS (CALCINING)	MM BTU	1.0000	1.000000	1.00
ELECTR. ENERGY(CALCINING)	KWH	20.0000	0.010500	0.21
CRUSHING AND GRINDING	KWH	5.0000	0.010500	0.05
PITCH BINDER	GAL	28.4400	0.160000	4.55
RAIL (PITCH TRANSPORT)	TON MI	52.4000	0.000670	0.04
NATURAL GAS FOR BAKING	CU. FT.	2094.0000	0.001000	2.09
			SUBTOTAL	20.83
CARBON CATHODE MANUFACTURE				
ANTHRACITE COAL	NET TON	0.0200	25.400000	0.51
RAIL (COAL TRANSPORT)	TON MI	10.0000	0.000670	0.01
ELECTR. ENERGY(CALCINING)	KWH	40.0000	0.010500	0.42
CRUSHING AND GRINDING	KWH	0.2000	0.010500	0.00
PITCHBINDER	GAL	0.7400	0.160000	0.12
RAIL (PITCH TRANSPORT)	TON MI	0.1700	0.000670	0.00
ELECTR. ENERGY FOR BAKING	KWH	8.0000	0.010500	0.08
			SUBTOTAL	1.14
REDUCTION				
CRYOLITE(MAKEUP NA3ALF6)	NET TON	0.0350	155.000000	5.43
RAIL(CRYOLITE TRANSPORT)	TON MI	10.5000	0.000670	0.01
ALUMINUM FLUORIDE(MAKEUP)	NET TON	0.0200	51.400002	1.03
RAIL(ALF3 TRANSPORT)	TON MI	6.0000	0.000670	0.00
FLUORSPAR (CAF2)	NET TON	0.0030	1.590000	0.00
ELECTRICAL ENERGY	KWH	16000.0000	0.010500	168.00
			SUBTOTAL	174.47
* TOTAL ENERGY PER NET TON OF ALUMINUM				243.82

(282.83 MJ/kg)

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.C.2. REVERB FURNACE MELTING OF ALUMINUM SCRAP TO INGOTS

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF PRODUCT	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF PRODUCT
(1) REVERB MELTING				
NATURAL GAS	CU. FT.	10000.0000	0.001000	10.00
ELECTRICAL ENERGY	KW HR	14.8000	0.010500	0.16
SODIUM CHLORIDE	NET TON	0.0420	0.490000	0.02
KCL BY FLOTATION	NET TON	0.0420	2.590000	0.11
CRYOLITE	NET TON	0.0040	155.000000	0.62
ALUMINUM FLOURIDE	NET TON	0.0200	51.400002	1.03
GASEOUS NITROGEN	NET TON	0.0053	2.900000	0.02
GASEOUS CHLORINE	NET TON	0.0013	18.000000	0.02
REFRACTORY	NET TON	0.0018	26.600000	0.05
SILICON	NET TON	0.0500	182.000000	9.10
SCRAP-CLIPPINGS	NET TON	0.1110	0.910000	0.10
SCRAP-BORINGS & TURNINGS	NET TON	0.3330	3.050000	1.02
SCRAP-CONCENTRATES	NET TON	0.3330	1.060000	0.35
SCRAP-SWEATED SOWS	NET TON	0.1110	9.280000	1.03
SCRAP-SHEET AND CAST	NET TON	0.1670	1.180000	0.20
			SUBTOTAL	23.83
(2) INGOT CASTING				
ELECTRICAL ENERGY	KW HR	2.8500	0.010500	0.03
			SUBTOTAL	0.03
• TOTAL PROCESS ENERGY				14.76
AIR POLLUTION CONTROL				
ELECTRICAL ENERGY	KW HR	23.4000	0.010500	0.25
			SUBTOTAL	0.25
• TOTAL POLLUTION CONTROL ENERGY				
SPACE HEATING				
NATURAL GAS	CU. FT.	50.0000	0.001000	0.05
			SUBTOTAL	
• TOTAL SPACE HEATING ENERGY				0.05
• TOTAL ENERGY PER NET TON OF PRODUCT				24.16
				(28.03 MJ/kg)

Note: This table is based upon information given in Reference 2, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

D. STEEL

1. Carbon Steel

Most of the steel produced in this country is carbon steel, as opposed to stainless steel. In this discussion, "steel" refers to carbon steel.

Several types of iron-bearing materials can be used as input for steelmaking, e.g. iron ore, pellets, sinter, mill scale and small amounts of scrap. The starting point for analysis will be a mixture of all these, with each component weighted in proportion to its extent of usage in recent years. This assumption was made in the Bureau of Mines study, from which the initial data have been taken.

Figure IV.D.1 shows the approach that has been adopted to determine a representative value of the energy content per ingot of carbon steel. The left-hand side of Figure IV.D.1 represents primary steel production, i.e. steel produced mainly from iron-bearing raw materials. Tables IV.D.1 through IV.D.3 list the steps required to process each raw material, namely iron ore, pellets and sinter, and the energy content per ton of each material.

Reduction of iron-bearing raw materials is performed almost exclusively using blast furnaces in the U.S. Table IV.D.4 describes the process inputs and total energy required per ton of "hot metal", which is the primary output of a blast furnace.

Steelmaking in the U.S. is carried out using basic oxygen furnaces (BOF), electric furnaces or the open hearth process. We have focused on BOF and electric furnace steelmaking, since the open hearth process is regarded as obsolescent. Table IV.D.5 shows the materials and energy inputs required to make one ton of molten steel.

Secondary steel production is based on the use of scrap ferrous materials, and electric furnace steelmaking is the most common process. The process steps and energy inputs required to produce one ton of molten steel are shown in Table IV.D.6. As noted previously, scrap materials are traditionally assigned a zero intrinsic energy content. The energy shown in Table IV.D.6 for each kind of scrap material is the energy required to process that particular scrap type into a form suitable for charging an electric arc furnace.

Casting of molten steel into ingots is a relatively simple and low-cost operation in terms of energy content, as shown in Table IV.D.7. Analysis was focused on ingot casting, versus continuous casting of billets, because 85 to 90% of industry production uses the former process.

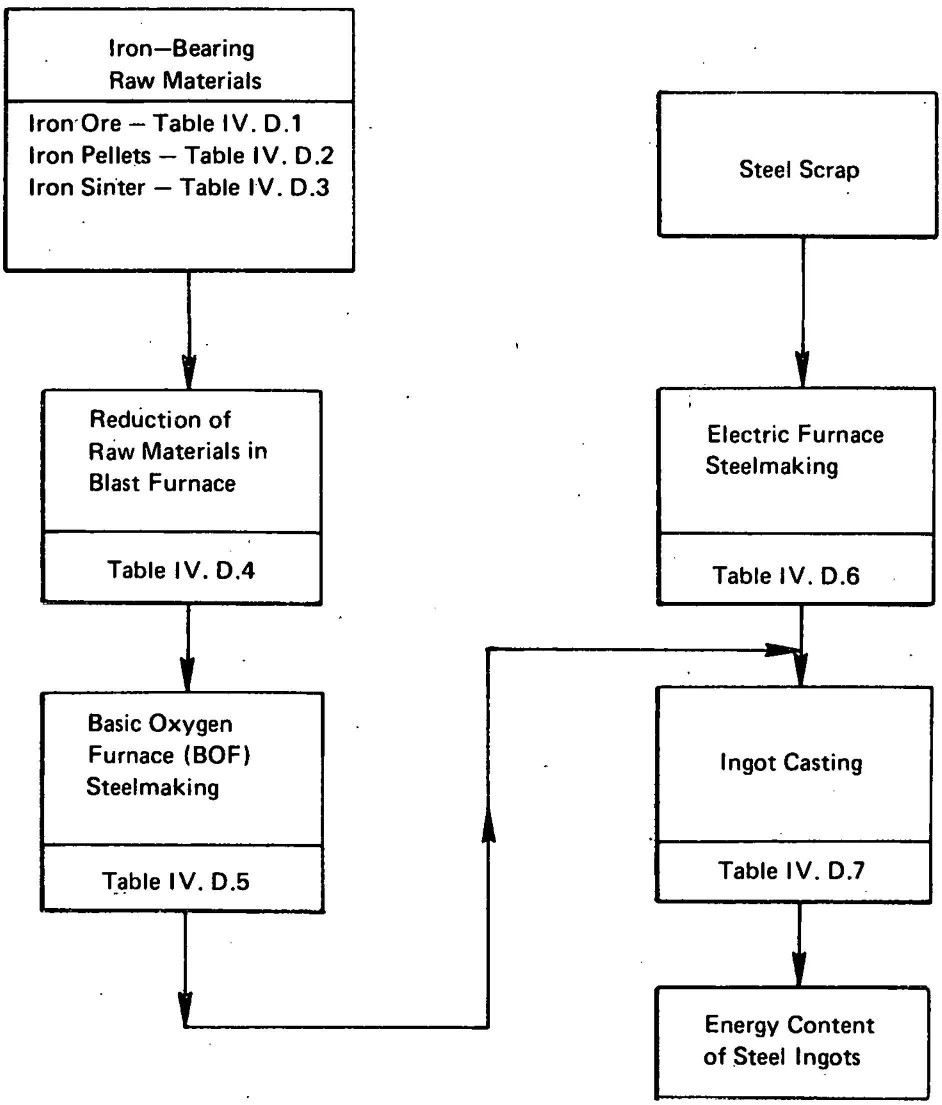


FIGURE IV.D.1

PROCEDURE USED TO DETERMINE THE ENERGY CONTENT OF CARBON STEEL INGOTS

TABLE IV.D.1. ENERGY REQUIREMENTS FOR IRON ORE PRODUCTION

	Unit	Units Per Net Ton of Iron Ore	Million Btu Per Unit	Million Btu Per Net Ton Iron Ore
Mining				
Explosives	lb	0.7	0.030	0.021
Electrical energy	kWh	25.0	0.0105	0.263
Diesel oil	gal.	0.16	0.139	0.023
Gasoline	gal.	0.010	0.125	0.001
Natural gas	ft^3	0.143	0.001	0.000
			Subtotal	0.31
Transportation				
Rail	net ton-mile	175	0.00067	0.117
Water	net ton-mile	1,150	0.00025	0.288
			Subtotal	0.405
			TOTAL	0.715
				(0.83 MJ/kg)

Source: Reference 1.

TABLE IV.D.2. ENERGY REQUIREMENTS FOR PRODUCTION OF IRON ORE PELLETS

	Unit	Units Per Net Ton of Pellets	Million Btu Per Unit	Million Btu Per Net Ton of Pellets
Mining				
Diesel oil	gal.	0.631	0.139	0.088
Gasoline	gal.	0.039	0.125	0.005
Electrical energy	kWh	38.9	0.0105	0.408
Explosives	lb.	3.5	0.030	0.105
			Subtotal	0.606
Concentration				
Crushing	kWh	12.8	0.0105	0.134
Grinding	kWh	49.6	0.0105	0.521
Concentrating	kWh	4.8	0.0105	0.050
Water handling	kWh	4.8	0.0105	0.050
Tailings disposal	kWh	3.8	0.0105	0.040
Balls, rods and liners	lb.	20.0	0.0175	0.350
			Subtotal	1.145
Pelletizing				
Natural gas	ft^3	275.0	0.001	0.375
Fuel oil	gal.	1.5	0.150	0.125
Electrical energy	kWh	4.86	0.0105	0.051
Bentonite	lb.	16	0.0006	0.010
			Subtotal	0.561
Transportation				
Rail	net-ton mile	125	0.00067	0.084
Water	net-ton mile	900	0.00025	0.225
			Subtotal	0.309
			TOTAL	2.621 (3.04 MJ/kg)

Source: Reference 1.

TABLE IV.D.3. ENERGY REQUIREMENTS FOR THE PRODUCTION OF IRON SINTER

	Unit	Units Per Net Ton of Sinter	Million Btu Per Unit	Million Btu Per Net Ton of Sinter
Ore fines	net ton	0.610	0.715	0.44
Returns	net ton	0.267	0.00	0.00
Flue dust and fines	net ton	0.143	0.00	0.00
Mill scale	net ton	0.122	0.00	0.00
Limestone	net ton	0.049	0.24	0.01
Coke breeze	net ton	0.074	21.00	1.55
Natural gas	ft^3	150.0	0.001	0.15
Electrical energy	kWh	30.0	0.0105	0.32
			TOTAL	2.47
				(2.87 MJ/kg)

Source: Reference 1.

TABLE IV.D.4. BLAST FURNACE ENERGY REQUIREMENTS

	Unit	Units Per Net Ton of Hot Metal	Million Btu Per Unit	Million Btu Per Net Ton of Hot Metal
Consumption				
Iron containing Materials*	net ton	1.7	2.01	3.41
Coke	net ton	0.597	31.50	18.81
Limestone	net ton	0.232	0.24	0.06
Refractories	lb	5.0	0.0125	0.06
Liquid and gaseous fuels	million Btu	1.13	1.0	1.13
Oxygen	ft^3	207.0	0.000183	0.04
Electrical energy	kWh	25.0	0.0105	0.26
Steam	lb	1,200.0	0.001	1.20
			Subtotal	24.97
Net blast furnace gas exported	MCF	19.5	0.000095	- 1.85
Net energy consumption				23.12
				(26.82 MJ/kg)

*Represents average mix of

0.408 net tons iron ore @ 0.715 million Btu per ton
0.759 net tons pellets @ 2.62 million Btu per ton
0.459 net tons sinter @ 2.47 million Btu per ton
0.05 net ton mill scale @ zero million Btu per ton, and
0.027 net ton scrap @ zero million Btu per ton

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.D.5. BASIC OXYGEN FURNACE STEELMAKING

Unit	Units Per Net Ton Of Product	Million Btu Per Unit	Million Btu Per Net Ton Of Product
Hot Metal - net ton	0.778	23.12000	17.99
Scrap - net ton	0.314	0.0	0.0
Scrap Transporation - net ton-mile	40.000	0.00067	0.03
Ferromanganese - net ton	0.011	50.00000	0.55
Ferrosilicon - net ton	0.001	123.00000	0.12
Aluminum - net ton	$5x10^{-4}$	224.00000	0.11
Lime - net ton	0.075	5.45000	0.41
Limestone - net ton	0.005	0.24000	0.00
Fluorspar - net ton	0.008	1.59000	0.01
Pellets - net ton	0.003	2.62000	0.01
Scale - net ton	0.008	0.0	0.0
Refractories - lb	13.000	0.01250	0.15
Oxygen - 1,000 ft^3	1.920	0.18300	0.35
Natural Gas - 1,000 ft^3	0.200	1.00000	0.20
Electricity (kWh)	30.000	0.01050	0.32
		TOTAL	20.25
			(23.49 MJ/kg)

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.D.6. ELECTRIC ARC FURNACE STEELMAKING WITH 100% SCRAP

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Product
(1) Electric Arc Furnace				
Scrap - Auto Guil	Net Ton	0.0103	0.650000	0.01
Scrap - Auto Shed	Net Ton	0.0764	1.280000	0.10
Scrap - Allig	Net Ton	0.0914	0.470000	0.04
Scrap - B & T	Net Ton	0.1261	0.460000	0.06
Scrap - Baling	Net Ton	0.2534	0.720000	0.18
Scrap - Guil	Net Ton	0.1956	0.510000	0.10
Scrap - Purch, Torch	Net Ton	0.1191	0.340000	0.04
Scrap - Home Torch	Net Ton	0.0510	0.020000	0.00
Scrap - Loose & Misc.	Net Ton	0.2337	0.460000	0.11
Lime	Net Ton	0.0300	5.400000	0.16
Limestone	Net Ton	0.0100	0.104000	0.00
Carbon Electrode	Net Ton	0.0060	82.000000	0.49
Refractories	Net Ton	0.0130	26.500000	0.35
Ferromanganese	Net Ton	0.0110	50.000000	0.50
Oxygen	Cu.Ft.	250.0000	0.000150	0.04
Fluorspar	Net Ton	0.0050	1.590000	0.01
Natural Gas	Cu.Ft.	100.0000	0.001000	0.10
Electrical Energy	kWh	500.0000	0.010500	5.25
			Subtotal	7.54
(2) Continuous Casting				
Electrical Energy	kWh	25.0000	0.010500	0.26
Natural Gas	Cu.Ft.	605.0000	0.001000	0.61
Refractories	Net Ton	0.0025	26.000000	0.07
Oxygen	Cu.Ft.	750.0000	0.000150	0.11
			Subtotal	1.05
				8.59
Total Process Energy				
Air Pollution Control Electrical Energy	kWh	22.9000	0.010500	0.24
			Subtotal	0.24
Waste Disposal Truck	Ton Mi	0.4500	0.002400	0.00
Total Pollution Control Energy				
Space Heating Natural Gas	Cu.Ft.	0.0000	0.001000	0.00
Total Space Heating Energy				0.00
Total Energy Per Net Ton of Product				8.83 (10.24 MJ/kg)

Note: This table is based upon information given in Reference 2, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.D.7. CASTING STEEL INGOTS

Material or Energy Form	Units	Energy/ Unit (Btu)	Units/ Ton of Product	Total Energy (Btu)
Coke Oven Gas	MCF	5.3×10^5	0.24	1.27×10^5
Electricity	kWh	1,500	2.0	2.10×10^4
Ingot Molds and Stools*	Net Ton	24,500	0.03	7.35×10^5
Casting Energy Required per Ton				8.83×10^5

Because of spillage and other factors, in actuality 1.031 tons of molten steel are required per ton of ingots. The results below incorporate this adjustment.

Ingots from BOF Steel: $(2.03 \times 10^7 \times 1.031) + 8.83 \times 10^5 = 2.18 \times 10^7$ Btu/ton

Ingots from EAF Steel**: $(7.78 \times 10^6 \times 1.031) + 8.83 \times 10^5 = 8.90 \times 10^6$ Btu/ton

*Energy values for ingot molds and stools are Arthur D. Little, Inc. estimates based on related work.

**The value of 7.78×10^6 is derived from Table IV.D.6 by subtracting 1.05×10^6 (the energy associated with continuous casting) from 8.83×10^6, the total value.

Note: This table is based upon information given in Reference 3, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

The final value for the representative energy content of carbon steel is developed by weighting the figures of BOF and electric furnace steel according to the tonnage produced in this country. The results are shown below, using 1976 production data.

Type	Tons Produced	Energy Content Per Ton	Weighting Factor	Energy Content
Primary Steel (BOF)	7.35×10^7	2.18×10^7	.81	1.77×10^7
Secondary Steel (Electric Furnace)	1.70×10^7	8.90×10^6	.19	1.69×10^6

Weighted Average Energy Content per Steel Ingot: 1.94×10^7 Btu/ton (22.50 MJ/kg)

2. Stainless Steel

Stainless steels are produced using electric arc furnaces with scrap steel (both carbon and stainless) input. As a result, the representative energy content of stainless steels is comparable to that of carbon steels. The process inputs required to make stainless steel billets are listed and evaluated in Table IV.D.8.

The representative energy content of a stainless steel ingot can be found by subtracting the energy associated with continuous casting of billets (1.05×10^6 Btu per ton) from the total shown in Table IV.D.8 (36.82×10^6 Btu per ton), and adding the energy cost of ingot casting (8.83×10^5 Btu per ton). The final value is shown below.

Average Energy Content per Stainless Steel Billet: 3.67×10^7 Btu/ton (42.57 MJ/kg)

E. LEAD

The lead industry has both primary and secondary forms of production, like the metals discussed previously. Primary lead production starts with the excavation of ore, and is described in Table IV.E.1. Secondary lead production begins with recycled scrap lead in several forms. The complete process is shown in Table IV.E.2.

As before, a weighted average value of energy content based on annual tonnage produced in 1976 in each category has been computed. The results are as follows:

TABLE IV.D.8

PRODUCTION OF STAINLESS STEEL BILLETS

(Step Number) Process	Unit	Units per Net Ton of Product	Energy Req. per Unit (Btu x 10^6)	Btu x 10^6 per Net Ton of Product
(1) ELECTRIC MELTING FURNACE				
Scrap - home	Net ton	0.321	0.025	0.01
Scrap - SS turnings	Net ton	0.103	1.930	0.20
Scrap - SS light	Net ton	0.257	1.130	0.28
Scrap - SS solids	Net ton	0.026	0.980	0.03
Scrap - # 1 bundles	Net ton	0.129	0.720	0.09
Scrap - steel auto-shred	Net ton	0.036	1.280	0.05
Scrap - steel guill.	Net ton	0.015	0.510	0.01
Scrap - steel misc.	Net ton	0.013	0.462	0.01
Grinding swarf	Net ton	0.026	0.000	0.00
Scale	Net ton	0.026	0.000	0.00
Scrap - superalloys	Net ton	0.051	1.000	0.05
Ferroalloys*	Net ton	0.283	82.000	23.18
Electrical energy	MWH	0.500	10.500	5.25
Refractory	Net ton	0.007	76.600	0.19
Graphite electrodes	Net ton	0.004	160.000	0.64
			Subtotal	30.00
(2) AOD REFINING				
Lime	Net ton	0.059	5.450	0.32
Refractory	Net ton	0.022	26.600	0.53
Ferrosilicon	Net ton	0.028	123.000	3.44
Silicomanganese**	Net ton	0.007	73.000	0.51
Fluorspar	Net ton	0.005	1.590	0.01
Argon	Cu. ft.	690.000	0.000	0.14
Oxygen	Cu. ft.	910.000	0.000	0.14
			Subtotal	5.08

*The ferroalloys are assumed to consist of 50% nickel and 50% steel.

**Silicomanganese is assumed to consist of 17% silicon and 83% ferromanganese.

TABLE IV.D.8

PRODUCTION OF STAINLESS STEEL BILLETS (Cont'd.)

(Step Number) Process	Unit	Units per Net Ton of Product	Energy Req. per Unit (Btu x 10^6)	Btu x 10^6 per Net Ton of Product
(3) CONTINUOUS CASTING				
Electrical energy	kWh	25.000	0.010	0.26
Natural gas	Cu. ft.	605.000	0.001	0.61
Refractory	Net ton	0.003	26.600	0.07
Oxygen	Cu. ft.	750.000	0.000	0.11

			Subtotal	1.05
*TOTAL PROCESS ENERGY		Total of Above		36.14
Air pollution control	kWh	65.000	0.011	0.68
Waste disposal-truck	ton-mi.	0.450	0.002	0.00

TOTAL ENERGY CONTENT PER NET TON OF STAINLESS STEEL:				36.82
				(42.71 MJ/kg)

Note: This table is based upon information given in Reference 2, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.E.1. PRODUCTION OF PRIMARY LEAD

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF LEAD	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF LEAD
MINING				
ELECTRICAL ENERGY	KWH	274.7000	0.010500	2.88
EXPLOSIVES	LB	12.5500	0.030000	0.38
DISTILLATE FUEL OIL	GAL	5.5100	0.139000	0.77
GASOLINE	GAL	0.4400	0.125000	0.06
STEEL	LB	1.4000	0.017500	0.02
			SUBTOTAL	4.11
CRUSHING				
ELECTRICAL ENERGY	KWH	28.6000	0.010500	0.30
			SUBTOTAL	0.30
GRINDING AND CLASSIFICATION				
ELECTRICAL ENERGY	KWH	244.5000	0.010500	2.57
STEEL	LB	23.4400	0.017500	0.41
			SUBTOTAL	2.98
BENEFICIATION				
ELECTR.(CON.,FLOT.,PUMP.)	KWH	89.3000	0.010500	0.94
ELECTR.(THICK. & FILTER.)	KWH	11.7000	0.010500	0.12
ORGANIC REAGENTS	LB	1.4600	0.020000	0.03
INORGANIC REAGENTS	LB	9.2900	0.005000	0.05
OTHER ELECTRICAL ENERGY	KWH	4.0000	0.010500	0.04
			SUBTOTAL	1.18
TRANSPORTATION OF CONCENTRATES				
RAIL TRANSPORT	TON MI	507.0000	0.000670	0.34
			SUBTOTAL	0.34
CHARGE PREPARATION				
ELECTRICAL ENERGY	KWH	5.0000	0.010500	0.05
NATURAL GAS	CU. FT.	160.0000	0.001000	0.16
LIMESTONE	NET TON	0.1200	0.240000	0.03
IRON ORE	NET TON	0.0700	0.710000	0.05
SAND (SILICA)	NET TON	0.0900	0.042000	0.00
RAIL (SAND TRANSPORT)	TON MI	9.0000	0.000670	0.01
			SUBTOTAL	0.30
SINTERING				
ELECTRICAL ENERGY	KWH	44.0000	0.010500	0.47
NATURAL GAS	CU. FT.	454.2500	0.001000	0.45
COKE BREEZE	NET TON	0.0190	21.000000	0.40
RAIL(BREEZE TRANSPORT)	TON MI	9.5000	0.000670	0.01
			SUBTOTAL	1.33
BLAST FURNACE				
ELECTRICAL ENERGY	KWH	42.5000	0.010500	0.45
NATURAL GAS	CU. FT.	220.0000	0.001000	0.22
METALLURGICAL COKE	NET TON	0.2300	31.500000	7.25
RAIL (COKE TRANSPORT)	TON MI	115.0000	0.000670	0.08
			SUBTOTAL	8.00
DROSSING				
ELECTRICAL ENERGY	KWH	2.3000	0.010500	0.02
NATURAL GAS	CU. FT.	520.0000	0.001000	0.52
SULFUR	NET TON	[illegible]	[illegible]	0.01
RAIL (SULFUR TRANSPORT)	TON MI	[illegible]	0.000670	0.00
			SUBTOTAL	0.55

TABLE IV.E.1. PRODUCTION OF PRIMARY LEAD (Cont'd.)

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF LEAD	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF LEAD
DROSS REVERBERATORY FURNACE				
ELECTRICAL ENERGY	KWH	2.0000	0.010500	0.02
NATURAL GAS	CU. FT.	782.5000	0.001000	0.78
COKE BREEZE	NET TON	0.0060	21.000000	0.13
RAIL (BREEZE TRANSPORT)	TON MI	3.0000	0.000670	0.00
SODA ASH	NET TON	0.0100	18.299999	0.18
RAIL (SODA ASH TRANSPORT)	TON MI	3.0000	0.000670	0.00
			SUBTOTAL	1.11
MOBILE EQUIPMENT FUEL				
DISTILLATE FUEL	GAL	0.4000	0.139000	0.06
			SUBTOTAL	0.06
SULFURIC ACID PLANT				
ELECTRICAL ENERGY	KWH	40.5000	0.010500	0.43
NATURAL GAS	CU. FT.	600.0000	0.001000	0.60
SULFURIC ACID PRODUCT	NET TON	-0.7300	0.830000	-0.60
			SUBTOTAL	0.43
DUST COLLECTION SYSTEM				
ELECTRICAL ENERGY	KWH	63.6900	0.010500	0.67
			SUBTOTAL	0.67
SAMPLING				
ELECTRICAL ENERGY	KWH	1.4400	0.010500	0.02
NATURAL GAS	CU. FT.	86.6100	0.001000	0.09
			SUBTOTAL	0.11
REFINING AND SOFTENING				
ELECTRICAL ENERGY	KWH	2.6000	0.010500	0.03
NATURAL GAS	CU. FT.	754.0000	0.001000	0.75
			SUBTOTAL	0.78
DESILVERIZING KETTLES				
ELECTRICAL ENERGY	KWH	14.0000	0.010500	0.15
NATURAL GAS	CU. FT.	610.0000	0.001000	0.61
ZINC SPELTER	NET TON	0.0056	65.000000	0.36
RAIL (ZINC TRANSPORT)	TON MI	1.6800	0.000670	0.00
			SUBTOTAL	1.12
HOWARD PRESSES				
ELECTRICAL ENERGY	KWH	1.0000	0.010500	0.01
			SUBTOTAL	0.01
RETORTING				
NATURAL GAS	CU. FT.	20.0000	0.001000	0.02
			SUBTOTAL	0.02
VACUUM DEZINCING				
ELECTRICAL ENERGY	KWH	6.0000	0.010500	0.06
NATURAL GAS	CU. FT.	270.0000	0.001000	0.27
			SUBTOTAL	0.33

TABLE IV.E.1. PRODUCTION OF PRIMARY LEAD (Cont'd.)

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF LEAD	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF LEAD
DEBISMUTHIZING				
ELECTRICAL ENERGY	KWH	14.0000	0.010500	0.15
NATURAL GAS	CU. FT.	1300.0000	0.001000	1.30
CALCIUM	NET TON	0.0007	238.600000	0.16
TRUCK (CALCIUM TRANSPORT)	TON MI	0.6600	0.002400	0.00
MAGNESIUM	NET TON	0.0017	358.000000	0.62
RAIL(MAGNESIUM TRANSPORT)	TON MI	0.8700	0.000670	0.00
			SUBTOTAL	2.23
REFINING AND CASTING				
ELECTRICAL ENERGY	KWH	3.0000	0.010500	0.03
NATURAL GAS	CU. FT.	220.0000	0.001000	0.22
CAUSTIC SODA	NET TON	0.0010	29.900000	0.03
RAIL (SODA TRANSPORT)	TON MI	0.3000	0.000670	0.00
NITER (NANO3)	NET TON	0.0003	42.250000	0.01
RAIL (TRANSPORT)	TON MI	0.0800	0.000670	0.00
			SUBTOTAL	0.29
GENERAL PLANT(HEAT, LIGHTS, ETC.)				
ELECTRICAL ENERGY	KWH	14.0500	0.010500	0.15
NATURAL GAS	CU. FT.	150.0000	0.001000	0.15
			SUBTOTAL	0.30
TOTAL ENERGY PER NET TON OF LEAD				26.55
				(30.80 MJ/kg)

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

TABLE IV.E.2. PRODUCTION OF SECONDARY LEAD BY REVERB/BLAST FURNACE PROCESS

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Req. Per Unit (Million Btu)	Million Btu/ Net Ton of Product
(1) Reverberatory Furnace				
Broken Battery Scrap	Net Ton	1.6000	0.620000	0.99
Prompt Industrial Scrap	Net Ton	0.2000	0.240000	0.05
General Lead Scrap	Net Ton	0.1000	0.240000	0.02
Blast Furnace Dust	Net Ton	0.1000	0.000000	0.00
Natural Gas	Cu.Ft.	4000.0000	0.001000	4.00
Electrical Energy	kWh	25.0000	0.010500	0.26
Propane	Lb	6.3000	0.021500	0.01
Gasoline	Gal	0.5000	0.125000	0.06
Distillate Fuel Oil	Gal	0.5000	0.139000	0.07
			Sub-Total	5.46
(2) Kettles				
Natural Gas	Cu.Ft.	1300.0000	0.001000	1.30
Electrical Energy	kWh	5.0000	0.010500	0.05
Caustic Soda	Net Ton	0.0020	29.900000	0.06
Niter (Nanus)	Net Ton	0.0030	42.250000	0.13
Aluminum	Net Ton	0.0006	224.000000	0.13
Zinc	Net Ton	0.0014	56.000000	0.08
Foundry Coke	Net Ton	0.0005	33.000000	0.02
			Sub-Total	1.77
(3) Casting				
Electrical Energy	kWh	7.0000	0.010500	0.07
			Sub-Total	0.07
* Total Process Energy				7.30
Air Pollution Control				
Electrical Energy	kWh	85.0000	0.010500	0.89
			Sub-Total	0.89
* Total Pollution Control Energy				0.89
Space Heating				
Natural Gas	Cu.Ft.	70.0000	0.001000	0.07
			Sub-Total	0.07
* Total Space Heating Energy				0.07
* TOTAL ENERGY PER NET TON OF PRODUCT				8.26 (9.58 MJ/kg)

Note: This table is based upon information given in Reference 2, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

Type	Tons Produced	Energy Content Per Ton	Weighting Factor	Energy Content
Primary Lead	6.59×10^5	2.66×10^7	.48	1.28×10^7
Secondary Lead	7.27×10^5	8.26×10^6	.52	4.30×10^6

Weighted Average Energy Content per Lead Ingot: 1.71×10^7 Btu/ton (19.84 MJ/kg)

F. NIOBIUM

Niobium is a key component of many superconducting alloys. Analysis begins with open-pit mining of columbite* ore in Brazil, and concludes with a determination of the energy content per ton of a pure niobium ingot. Figure IV.F.1 shows the processing in schematic form; Table IV.F.1 lists the supporting data behind each process step.

Niobium is highly energy-intensive, at 5.10×10^8 Btu per ton (591.60 MJ per kg). However, relatively little niobium is needed in the thin strip or fine wire alloys used as superconductors.

G. PORTLAND CEMENT

Table IV.G.1 lists the process steps and energy inputs required to make portland cement. The representative energy content is 7.61×10^6 Btu per ton (8.83 MJ per kg) of cement produced.

Cement is only part of a concrete mixture, which also contains water, sand and aggregate. A common mixture is one part of cement (volume) to two parts sand to four parts stone. Water is typically added at the ratio of seven gallons per 94 pound sack of cement. This mixture has a density of 146 pounds/ft^3, and an energy content of 1.1×10^5 Btu/ft^3. On a weight basis, concrete has an energy content of 1.49×10^6 Btu per ton (1.73 MJ per kg).

H. BRONZE

Bronze is an alloy composed mainly of copper and tin. The copper fraction can vary from 70% to 90%, but 75% is a common value. An estimated energy content value for bronze has been developed using the simple procedure shown on the following page.

(Copper energy content = 93.2×10^6 Btu/ton) x .75 tons = 69.90×10^6 Btu

(Tin energy content = 180×10^6 Btu/ton) x .25 tons = 45.00×10^6 Btu

Energy Content of 75/25 bronze: 114.90×10^6 Btu/ton (133.28 MJ/kg)

*Niobium is also known as columbium.

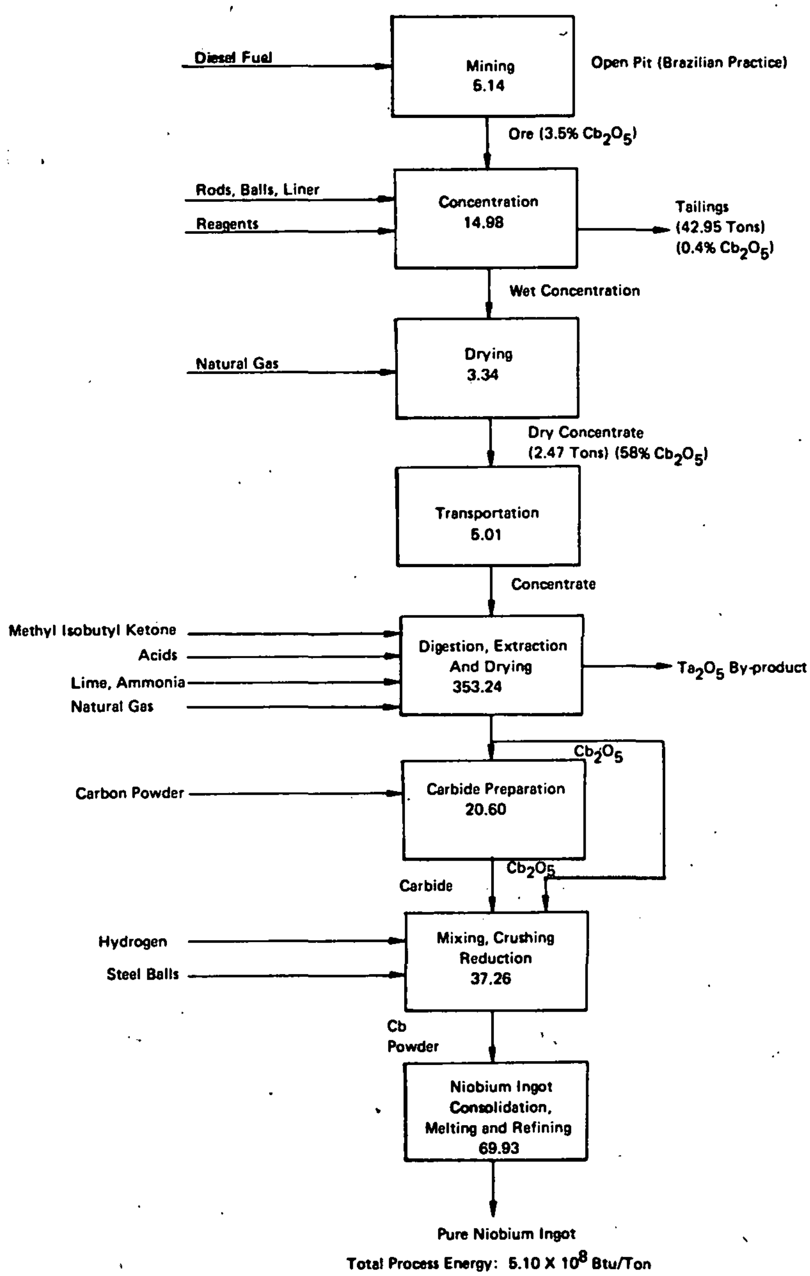


FIGURE IV.F.1

PRODUCTION OF NIOBIUM FROM ORE

TABLE IV.F.1

PRODUCTION OF NIOBIUM FROM ORE

Step Number	Process	Unit	Units/net ton of Product	Energy Required per Unit (MBtu)	Million Btu per net ton of Product
1	MINING (diesel fuel)	gallon	36.98	0.139	5.14
				Subtotal	5.14
2	CONCENTRATION				
	Crushing, electricity	kWh	90.8	0.0105	1.07
	Grinding, electricity	kWh	681.0	0.0105	8.08
	Rods, balls, liners	lb	68.1	0.0175	1.34
	Flotation, electricity	kWh	227.0	0.0105	2.69
	Organic reagents	lb	45.4	0.020	1.03
	Inorganic reagents	lb	136.2	0.005	0.77
				Subtotal	14.98
3	DRYING				
	Natural gas	ft^3	3343	0.001	3.34
				Subtotal	3.34
4	TRANSPORTATION OF CONCENTRATE				
	Water transportation (4500 miles)	net ton/mi	12555	0.00025	3.14
	Rail transportation (1000 miles)	net ton/mi	2790	0.00067	1.87
				Subtotal	5.01
5	Cb_2O_5 DIGESTION, EXTRACTION AND DRYING				
	Hydrofluoric Acid	net ton	4.0	14.35	57.4
	Sulfuric Acid	net ton	0.5	0.04	0.02
	Lime	net ton	0.25	8.5	2.12
	Anhydrous Ammonia	net ton	3.0	39.0	117.00
	Natural Gas	ft^3	3000	0.001	3.00
	Electricity	kWh	162	0.0105	1.70
	MIBK	net ton	4.0	43.0	172.00
				Subtotal	353.24

TABLE IV.F.1

PRODUCTION OF NIOBIUM FROM ORE (Cont'd.)

Step Number	Process	Unit	Units/net ton of Product	Energy Required per Unit (MBtu)		Million Btu per net ton of Product
6	CARBIDE PREPARATION					
	Carbon powder	net ton	0.11	25		2.75
	Electricity	kWh	1700	0.0105		17.85
					Subtotal	20.60
7	MIXING, CRUSHING, AND REDUCTION					
	Steel Balls(Ball mill)	net ton	0.025	35.0		0.87
	Hydrogen	net ton	NEGL.	106.9		0.00
	Electricity	kWh	3466	0.0105		36.39
					Subtotal	37.26
8	NIOBIUM INGOT CONSOLIDATION, MELTING AND REFINING					
	Electricity (Consolidation)	kWh	660	0.0105		6.93
	Electricity (1st EB melting)	kWh	4000	0.0105		42.00
	Electricity (2nd EB melting)	kWh	2000	0.0105		21.00
					Subtotal	69.93

ENERGY CONTENT PER TON OF NIOBIUM INGOT: 5.10×10^8 Btu/ton

(592 MJ/kg)

TABLE IV.G.1. PRODUCTION OF PORTLAND CEMENT

(STEP NUMBER) PROCESS	UNIT	UNITS PER NET TON OF CEMENT	ENERGY REQUIRED PER UNIT (MILLION BTU)	MILLION BTU PER NET TON OF CEMENT
LIMESTONE				
MINING	NET TON	1.3700	0.046000	0.06
TRUCK TRANSPORTATION	TON MI	4.1000	0.002400	0.01
NATURAL GAS (DRYING)	CU. FT.	320.0000	0.001000	0.32
			SUBTOTAL	0.39
CLAY AND SHALE				
MINING	NET TON	0.1440	0.070000	0.01
TRUCK TRANSPORTATION	TON MI	0.4320	0.002400	0.00
			SUBTOTAL	0.01
SAND AND MISCELLANEOUS				
MINING	NET TON	0.0060	0.005000	0.00
RAIL TRANSPORTATION	TON MI	5.7000	0.000670	0.00
			SUBTOTAL	0.00
CRUSHING AND MILLING				
CRUSHING	KWH	7.0000	0.010500	0.07
MILLING	KWH	23.0000	0.010500	0.24
OTHER	KWH	2.2000	0.010500	0.02
			SUBTOTAL	0.33
CLINKER BURNING				
ANTHRACITE COAL	NET TON	0.0908	25.400000	2.31
RAIL(COAL TRANSPORTATION)	TON MI	36.3000	0.000670	0.02
RESIDUAL FUEL OIL	GAL	6.8334	0.150000	1.03
NATURAL GAS	CU. FT.	2636.0000	0.001000	2.64
REFRACTORIES	NET TON	0.0010	26.600000	0.03
ELECTRICAL ENERGY	KWH	19.0000	0.010500	0.20
			SUBTOTAL	6.23
AIR POLLUTION CONTROL				
ELECTRICAL ENERGY	KWH	5.0000	0.010500	0.05
			SUBTOTAL	0.05
CLINKER MILLING				
ELECTRICAL ENERGY	KWH	50.0000	0.010500	0.52
OTHER	KWH	4.0000	0.010500	0.04
GYPSUM	NET TON	0.0480	0.070000	0.00
RAIL (GYPSUM TRANSPORT)	TON MI	4.8000	0.000670	0.00
GRINDING BALLS	LB	2.0000	0.017500	0.04
			SUBTOTAL	0.60
TOTAL ENERGY PER NET TON OF CEMENT				7.61
				(8.83 MJ/kg)

Note: This table is based upon information given in Reference 1, with the energy content of certain processes and materials revised by Arthur D. Little, Inc.

I. PAPER

More than 95% of the paper used in paper-tape cables is used as insulation, in contrast to conducting paper which is used as a shield. Accordingly, insulating kraft paper is the primary topic of this section. Conducting paper is discussed as a special case of insulating paper.

The two principal steps in the manufacture of insulating paper are pulp production (including wood procurement) and papermaking. This type of paper is produced by approximately 20 manufacturers in the U.S. A pulp-making and a paper-making installation have been selected which represent typical production facilities. The analysis was performed by establishing a set of assumptions regarding material characteristics and typical manufacturing practices.

1. Pulp Production

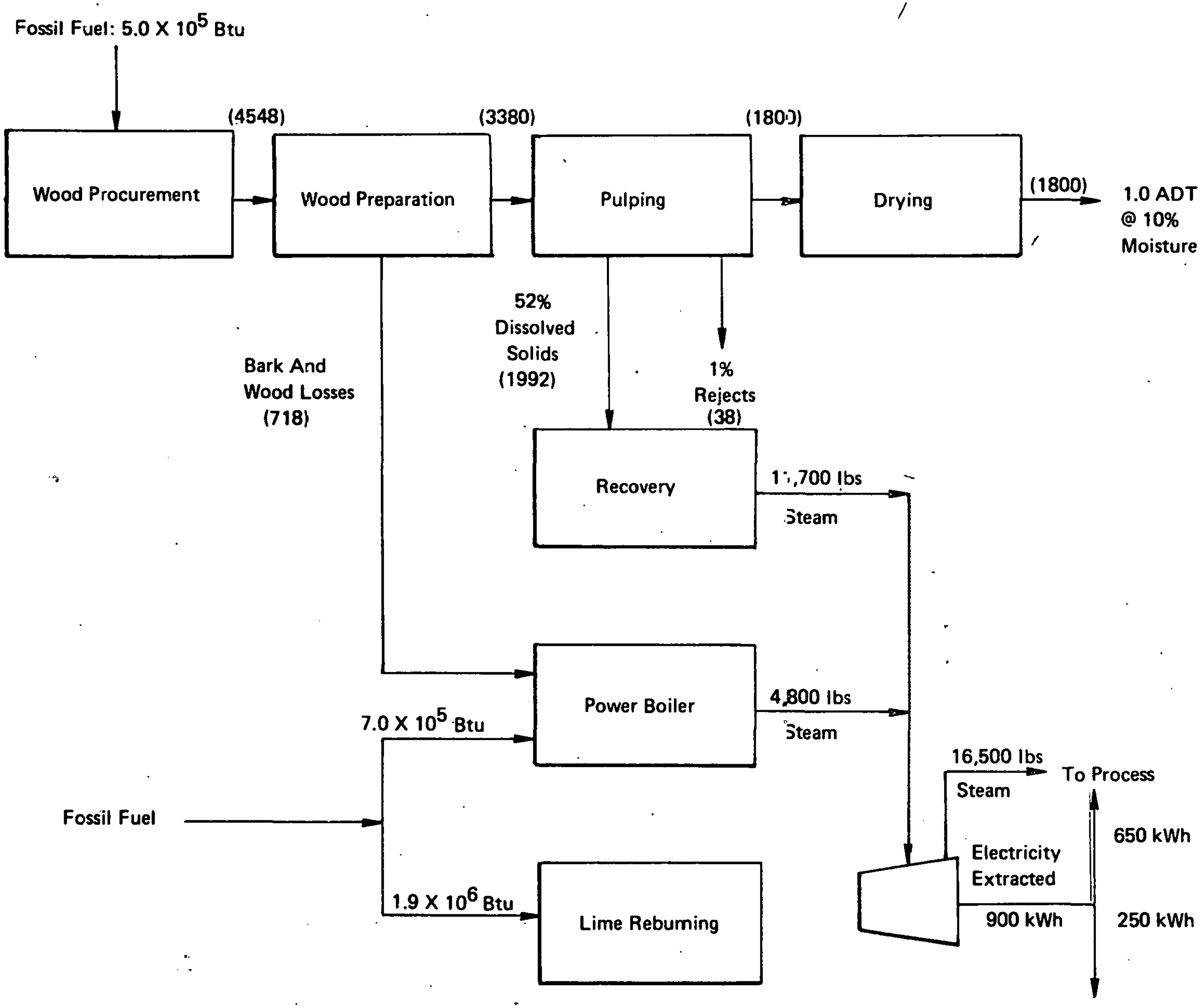
The pulp production model shown in Figure IV.I.1 produces electrical grade market pulp (i.e. unbleached kraft). Electrical grade market pulp is produced from 100% virgin softwood fiber furnish and differs from conventional unbleached kraft market pulp only in that it goes through special washing steps. The mill is assumed to be located in the northeastern U.S., although considerable electrical grade pulp is also imported from Canada and, to a lesser extent, Scandinavia.

Table IV.I.1 lists the processes and energy requirements of pulpmaking. This model assumes the extensive use of wood preparation and pulping residual materials for in-plant production of steam and electric power. The total energy supplied amounts to 32.9 x 10^6 Btu per airdryed ton (ADT). Most of this energy (90%) is supplied from the combustion of waste and residual fuels; the remainder comes from fossil fuels. In mills lacking the facilities for waste heat utilization a much larger proportion of the total heat requirement would have to come from fossil fuels.

2. Papermaking

The papermaking model shown in Figure IV.I.2 produces electrical insulating paper from specially washed 100% virgin northern softwood pulp. The mill is assumed to be a non-integrated (paper production only) mill located in the northeastern U.S. Table IV.I.2 shows process details. The total energy supplied amounts to 19.7 x 10^6 Btu per machine-dried ton (MDT) of paper produced.

A non-integrated paper producing facility has the disadvantage of not being able to utilize the steam and power which are generated as a byproduct of a modern pulping operation. Wherever such steam and power are available, a considerable reduction in fossil fuel and electric power usage would be possible.



Note: Values in ( ) indicate bone dry pounds.

FIGURE IV.I.1. PULP PRODUCTION

TABLE IV.I.1. PULP PRODUCTION

ASSUMPTIONS

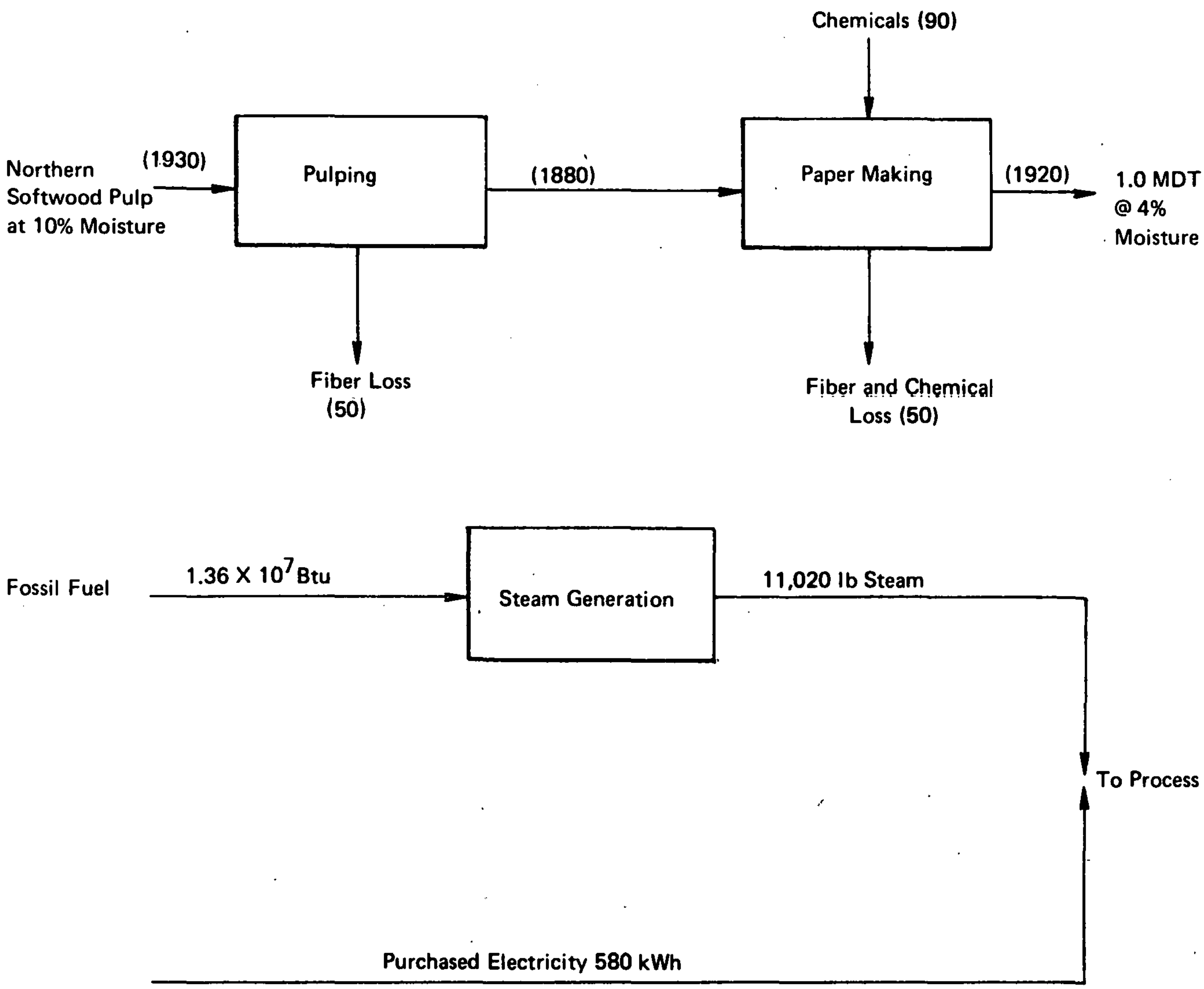
Process:	Continuous sulfate kraft pulping
Mill Location:	Northeast USA
Fiber Furnish:	100% soft roundwood
Product:	Electrical grade pulp (special washing) 10% Moisture
Pulp Yield:	47%
Output:	730 ADT/day 252,000 ADT/year 345 net operating days
Boundary Limits:	From wood procurement through production of dried market pulp.
Calculations:	Heat and energy balances based on the production of one (1) ADT of pulp.

ENERGY REQUIREMENTS	Fossil Fuel (10^6 Btu/ADT)	Steam (lb/ADT)	Power (kWh/ADT)	
Wood Procurement	0.5	-	-	
Wood Preparation	-	-	110	
Pulping	-	3,900	120	
Drying	-	6,000	120	
Power & Steam Generation (Including Recovery & Liquor Preparation)	-	3,600	200	
Effluent Treatment	-	-	40	
Lime Reburning	1.9	-	-	
Misc & Aux.	-	3,000	60	
Power Credit	-	-	(250)	
Subtotals	2.4	16,500	400	
Energy Required in 10^6 Btu/ADT	2.4	17.3(1)	1.8(2)	Total: 21.5

ENERGY SOURCES	Heat Value (10^6 Btu/ADT)	Conversion Efficiency	Total (10^6 Btu/ADT)
Spent Liquor	25.6	.63	16.1
Bark & Hogged Fuel	4.2	.57	2.4
Fossil Fuel - Wood Procurement	0.5	1.00	0.5
- Steam & Power	0.7	.85	0.6
- Lime Reburning	1.9	1.00	1.9
	32.9		21.5

TOTAL ENERGY REQUIREMENTS: 32.9×10^6 Btu/ADT (38.16 MJ/kg)

(1) Steam - 1,050 Btu/lb
(2) On-Site Generated Power - 4,400 Btu/kWh



Note: Values in ( ) indicate bone dry pounds.

FIGURE IV.I.2

MATERIALS AND ENERGY BALANCE IN PAPER MAKING

TABLE IV.I.2

ENERGY REQUIREMENTS FOR PAPERMAKING

BASIS	Process:	Fourdrinier Machines
	Mill Location:	Northeast USA
	Fiber Furnish:	100% virgin northern softwood pulp
	Product:	Electric Cable Paper 59# BW (Basis Weight) 0.005 Thickness, 0.75 g/cc density, 4% moisture
	Pulp Yield:	95%
	Output:	120 MDT 39,600 MDT/year 330 net operating days
	Boundary Limits:	Repulping of dried pulp through production of cable paper in roll form
	Calculations:	Heat and energy balances based on the production of one (1) MD ton of cable paper.

ENERGY REQUIREMENTS	Steam (lb/MDT)	Power (kWh/MDT)	
Pulping & Stock Preparation	--	240	
Paper making	9,700	110	
Water & Effluent Treatment	--	60	
Misc. & Auxilliaries	1,320	160	
Total Energy Requirement	11,020	570	
Heat Equivalent (10^6 Btu)	11.57[(1)]	5.99[(2)]	Total: 1.76×10^7 Btu

ENERGY SOURCES	Heat Value (10^6 Btu/MDT)	Conversion Efficiency (%)	Total (10^6 Btu/MDT)
Fossil Fuel	13.6	.85	11.56
Purchased Power	6.14	.98	6.02
	19.7		17.58

TOTAL ENERGY REQUIREMENTS: 19.7×10^6 Btu/ton (22.85 MJ/kg)

(1) Steam – 1,050 Btu/lb.

(2) Purchased electricity - 10,500 Btu/kWh.

Combining the energy used to make pulp and electrical grade kraft paper, the energy content is 5.26×10^7 Btu per ton. The physical form of paper as it leaves the mill for a cable plant is a roll weighing 900 pounds (nominally), about 2 1/2 feet wide. Subsequent drying, slitting and wrapping operations performed in the cable plant will be described in Chapter V.

<u>Energy Content of Insulating Paper</u>: 5.26×10^7 Btu/ton (61.02 MJ/kg)

3. <u>Conducting Paper</u>

Conducting papers are made in a manner similar to that discussed above, and then impregnated with a conducting material. Carbon is the most common impregnant. An estimated energy content value for conducting paper has been developed using the simple procedure shown below.

(Paper energy content = 5.26×10^7 Btu/ton) x .90 tons = 4.73×10^7 Btu

(Carbon energy content = 6.86×10^7 Btu/ton) x .10 tons = 6.86×10^6 Btu

<u>Energy Content of Conducting Paper</u>: 5.42×10^7 Btu/ton (62.87 MJ/kg)

J. <u>INSULATING OILS</u>

The oils used in HPOF systems may be either natural (often called "mineral" oil) or man-made (synthetic) oils such as polybutenes. Both types have been analyzed. Figure IV.J.1 illustrates the process steps used in producing mineral oil, and Table IV.J.1 shows the derivation of energy inputs. The representative value for the energy content of mineral oil is 1.06×10^7 Btu per barrel (42 gal.) of oil. Approximately 85% of this value is due to the energy inherent in the feedstock, which is crude oil. The representative density of mineral oil was taken to be 55.54 lbs/ft^3.

<u>Energy Content of Mineral Insulating Oil</u>: 6.79×10^7 Btu/ton (78.79 MJ/kg)

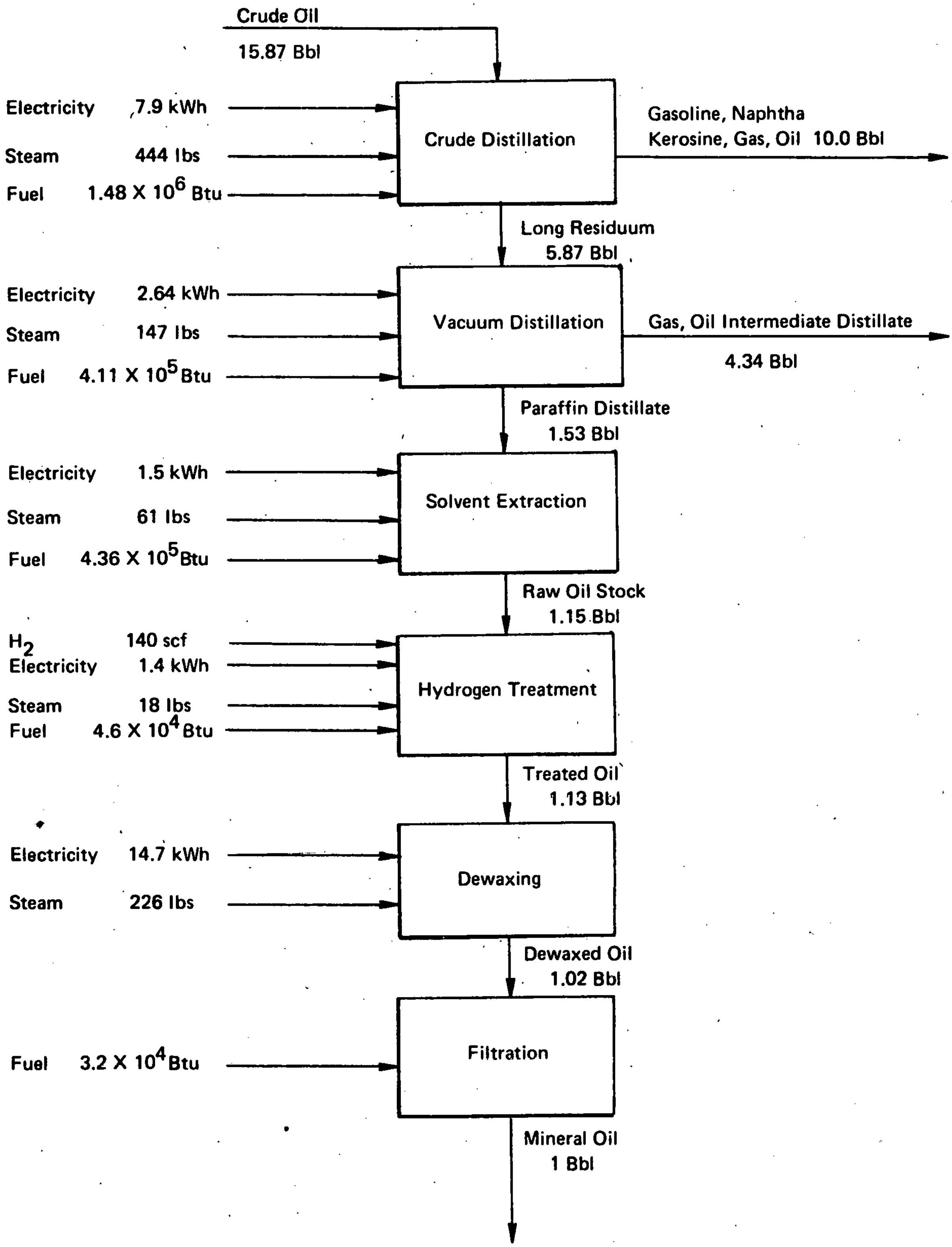


FIGURE IV.J.1

PRODUCTION OF NATURAL (MINERAL) INSULATING OIL

TABLE IV.J.1. ENERGY CONSUMPTION IN THE PRODUCTION OF MINERAL OIL

Process	Electricity*	Steam**	Fuel	Other	10^3 Btu/bbl Mineral Oil
Atm Distillation	$\frac{1.53}{15.87}$ x 7.9 kWh	$\frac{1.53}{15.87}$ x 444 lbs.	$\frac{1.53}{15.87}$ x 1.48×10^6 Btu		201
Prorated feedstock				1.53(bbl)x6(10^3Btu/bbl)	9,180
Vacuum Distillation	$\frac{1.53}{5.87}$ x 2.64 kWh	$\frac{1.53}{5.87}$ x 147 lbs.	$\frac{1.53}{5.87}$ x 4.11×10^5 Btu		160
Solvent Extraction	1.5 kWh	61 lbs.	4.36×10^5 Btu		524
H_2 Treatment	1.4 kWh	18 lbs.	4.60×10^4 Btu		82
H_2 Consumption				140^{scf} x 325 $(\frac{Btu}{scf})$	46
Dewaxing	14.7 kWh	226 lbs.			423
Filtration			3.20×10^4 Btu		32
					10,648

Energy Content of Mineral Insulating Oil: 1.06×10^7 Btu/bbl

(78.88 MJ/kg)

*1 kWh = 10,500 Btu

**1 lb. of steam = 1,188 Btu

Production of synthetic oil starts with mixed butenes, commonly derived from crude oil. The process is shown in Figure IV.J.2, and described in Table IV.J.2. At 1.01 x 10^7 Btu per barrel, the energy content of this oil is obviously not far from mineral oil. The major difference is that energy inherent in the feedstock represents 65% of the total. Synthetic oil is lower in density than mineral oil; the representative density was taken to be 51.17 lbs/ft^3.

<u>Energy Content of Synthetic Insulating Oil</u>: 7.02 x 10^7 Btu/ton (81.43 MJ/kg)

K. PLASTICS

The plastics used most extensively in transmission systems are polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP) and poly (ethylene terephthalate), which is commonly referred to as Mylar.* PE and PP are used primarily for electrical insulation. PVC is high in abrasion resistance, and is often employed as an exterior jacketing material. Mylar, in the form of metallized thin films, is used both for HPOF pipe-type cables and superconducting cable systems.

1. Polyethylene

The simplicity of the polyethylene production process is evident from Figure IV.K.1. Starting with crude oil, only distillation, cracking and polymerization are required. The calculated value for the energy content of low-density polyethylene (LDPE) is 7.02 x 10^7 Btu per ton (81.43 MJ per kg), of which 65% is the inherent chemical energy content. The representative density of LDPE was taken to be 57.44 lbs/ft^3. The following assumptions were made:

A. The chemical energy associated with the carbon and hydrogen in the LDPE (22,680 Btu/lb) is essentially the same as for the equivalent mass in the crude oil. This figure is based on the high heating value (HHV) of ethylene (21,600 Btu/lb).

B. The energy consumed in crude distillation was prorated based on the volumetric yield of naptha which was assumed at 25%.

*Mylar is the registered trade name for resin produced by E.I. Dupont de Nemours.

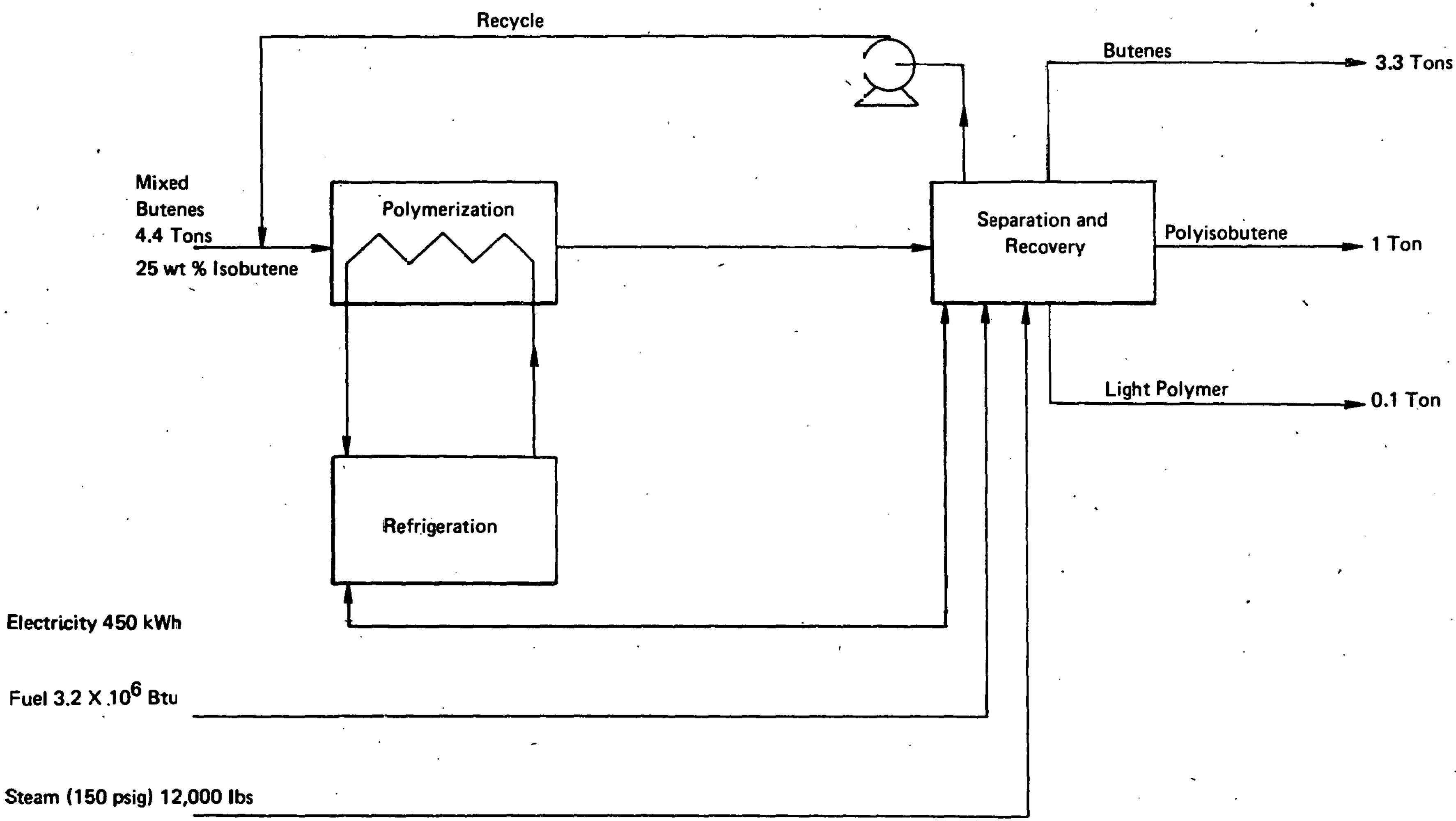


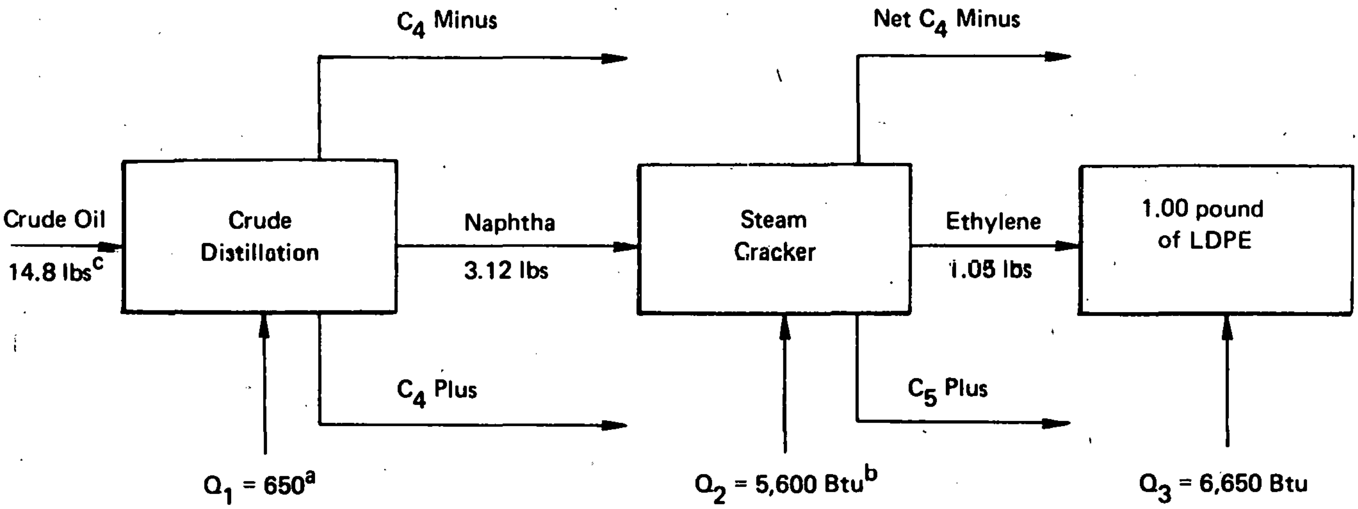
FIGURE IV.J.2. PRODUCTION OF POLYISOBUTENE OIL

TABLE IV.J.2

PRODUCTION OF POLYISOBUTENE OIL

		Btu/lb of Oil
Production of Mixed Butenes		
Pro Rata Share of FCU Utilities		460
Polymerization/Separation of Polyisobutene		
Feedstock Energy	(1.1 lb/lb product) 20,700 Btu/lb	22,770
Electricity	(0.30 kWh/lb) 10,500 Btu/kWh	3,150
Steam	(6 lbs/lb) 1,188 Btu/lb	7,130
Fuel		1,600
		35,110

Energy Content of Polyisobutene Oil: 70.2×10^6 Btu/ton (81.43 MJ/kg)



a. Prorated share of distillation utilities to naphtha, Btu/lb LDPE.

b. Prorated share of utilities for ethylene, Btu/lb LDPE.

c. Crude gravity 300 lb/bbl; naphtha gravity 250 lb/bbl.

FIGURE IV.K.1

PRODUCTION OF POLYETHYLENE (LDPE)

C. The steam cracker utilities were prorated by the ratio of ethylene product over total products, less tailgas and pyrolysis fuel oil which are consumed internally as fuel. The numerical value of this ratio is 0.424.

2. Polyvinyl Chloride (PVC)

The production process selected for PVC is based on ethylene and brine, and is shown in Figure IV.K.2. This analysis is based on a diaphragm cell caustic-chlorine plant using brine produced from on-site brine wells which is common practice in the U.S. Gulf Coast area. The vinyl chloride monomer is produced using oxychlorination technology. PVC is produced from the suspension process, producing general purpose resin.

In the caustic-chlorine plant the energy allocation between chlorine and the 50% caustic solution produced has been based upon a weight allocation on a 100% basis. That is to say, the chlorine is assigned 48.7% of the energy requirements and the caustic stream the balance.

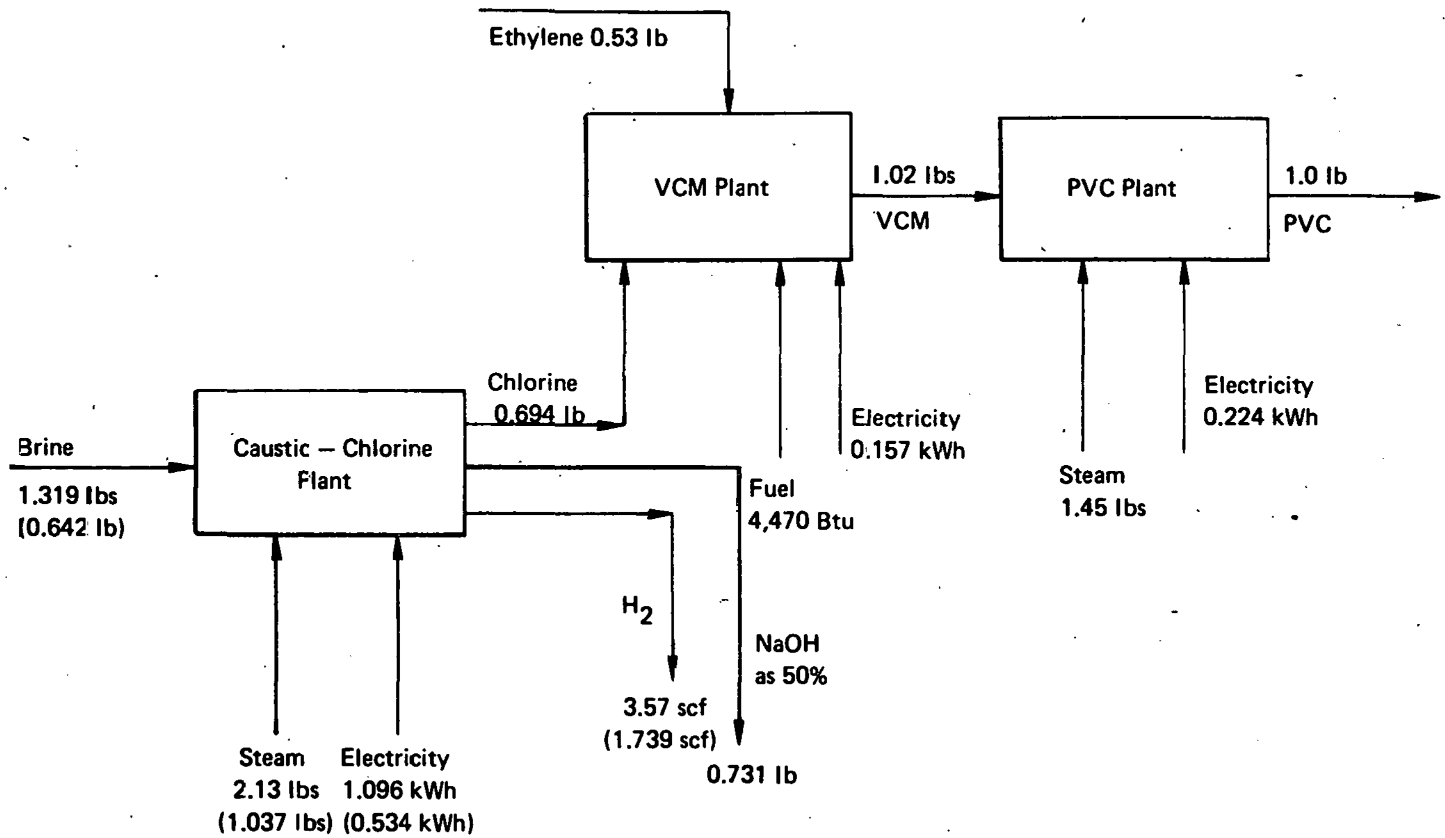
Table IV.K.1 discusses the energy inputs for each process step in detail. The energy content of PVC is 6.14×10^7 Btu per ton (71.22 MJ per kg); the representative density was taken to be 84.28 lbs/ft^3.

3. Polypropylene (PP)

Polypropylene film appears to be the most successful material to laminate with paper to produce so-called "synthetic" paper tapes for pipe-type cables. The analysis begins with naptha as input to an olefin plant, as shown in Figure IV.K.3. The total energy content for polypropylene is 6.65×10^7 Btu per ton (77.14 MH per kg), which is derived in Table IV.K.2. The representative density of PP was taken to be 56.19 lbs/ft^3.

4. Mylar

Production of mylar is extremely complex, compared to the preceding resins. Table IV.K.3 indicates the final results of an energy content analysis. Appendix A.2 describes the production process in detail. The estimated energy content of mylar film is 1.58×10^8 Btu per ton (183.24 MJ per kg); its density is 87.40 lbs/ft^3.



Note: Values in ( ) are the quantities allocated to production of chlorine.

FIGURE IV.K.2. PRODUCTION OF POLYVINYL CHLORIDE

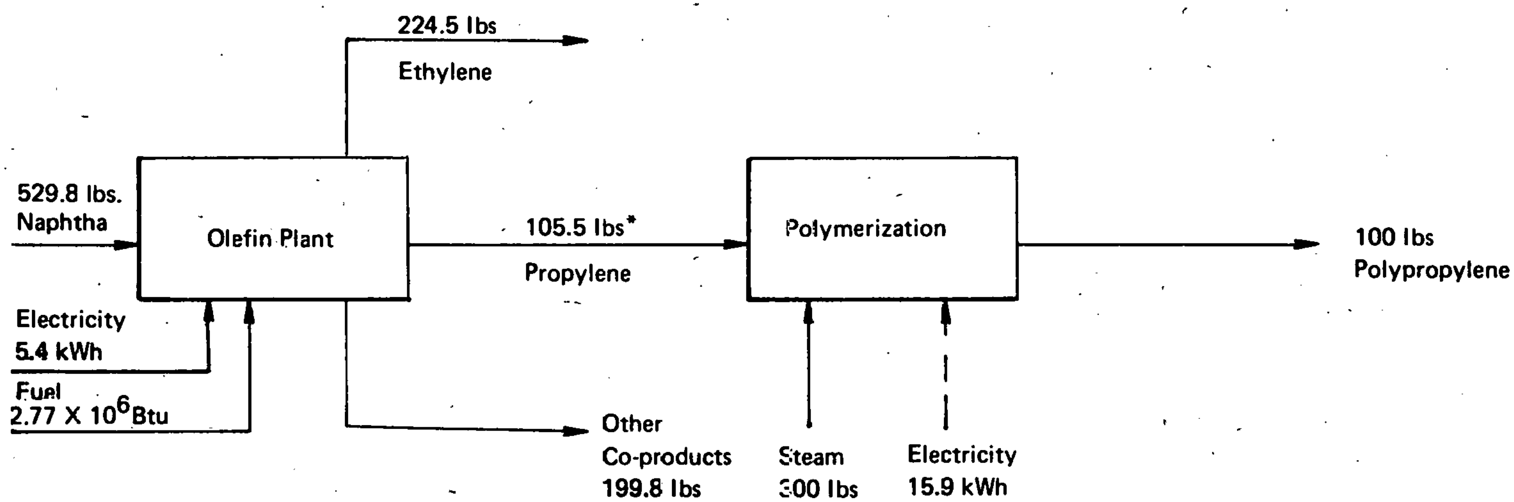
TABLE IV.K.1

ENERGY REQUIREMENTS FOR THE PRODUCTION OF POLYVINYL CHLORIDE

	Quantity	Energy
Caustic-Chlorine Plant		
Brine	0.642 lbs	0
Electric Power*	0.534 kWh	5,607 Btu
Steam**	1.037 lbs	1,303 Btu
Byproduct H_2	(1.739 SCF)	(563) Btu
Net Energy		6,347 Btu/0.694 lbs Cl_2
VCM Plant		
Chlorine	0.694 lbs	6,347 Btu
Ethylene	0.52 lbs	14,087 Btu
Electric Power	0.157 kWh	1,648 Btu
Fuel	4,470 Btu	4,470 Btu
Net Energy		26,552 Btu/1.02 lbs VCM
PVC Plant		
VCM	1.02 lbs	26,552 Btu
Steam	1.45 lbs	1,822 Btu
Electric Power	0.224 kWh	2,352 Btu
Net Energy		30,726 Btu/lb PVC
	Energy Content of Polyvinyl Chloride:	61.4×10^6 Btu/ton
		(71.22 MJ/kg)

*Electricity rated at 10,500 Btu per kWh.

**This steam requires 980 Btu per pound; a production (thermal) efficiency of 78% has been assumed for this plant.



*High heating value for propylene is 21,032 Btu/lb.

FIGURE IV.K.3. PRODUCTION OF POLYPROPYLENE

TABLE IV.K.2

ENERGY REQUIREMENTS FOR THE PRODUCTION OF POLYPROPYLENE

Category	Amount, Btu/lb$(-C_3H_6-)_x$		%
Feed Stock	1.055(21,032)	22,189	(67)
Polymerization			
Electricity	.159 x 10,500	1,670	(16)
Steam	.3 x 1,250	3,750	
Pro Rata Olefin Plant			
Electricity	(.199).054 x 10,500	113	(17)
Fuel	(.199)2.769 ÷ 100	5,510	
		33,232	(100)

Energy Content of Polypropylene: 66.46×10^6 Btu/ton (77.10 MJ/kg)

TABLE IV.K.3

ENERGY CONTENT ANALYSIS OF MYLAR

Raw Materials	Amount (lbs)	Energy Content (Btu/lb)	Energy Content of Resin (Btu/lb)
Dimethyl terephthalate	1.12	46,720	52,330
Ethylene glycol	0.40	29,970	11,990
		Subtotal	64,320
Utilities			
Heat			650
Electricity 0.2 kWh @ 10,500 Btu/kWh			2,100
		Total	67,070
Conversion to Film			6,562
Aluminizing			2,000

Assuming a 5% loss in conversion and aluminizing, the total energy content of aluminized mylar film is calculated as shown below.

1.05 x 67,070 Btu/lb of resin =	70,420 Btu/lb of film
Conversion to film	6,562
Aluminizing	2,000
Energy Content of Mylar:	78,982 Btu/lb of film (1.58×10^8 Btu/ton) (183.24 MJ/kg)

L. EPOXY RESINS

Epoxy resins, with fillers added, are used to cast insulators for compressed-gas-insulated systems and pipe supports for dc superconducting systems. The production of cycloaliphatic epoxy resin (CER) and the hardener, hexahydrophthalic anhydride (HHPA), is similar in complexity to mylar production. Thus the table below only indicates the final results of energy content analysis; production process details can be found in Appendix A.3.

Raw Materials	Energy Content of Insulators (Btu/lb)
Aluminum trihydrate: 0.7 lb x 7615 Btu/lb	5,330
HHA: 0.1 lb x 44,200 Btu/lb	4,420
CER: 0.2 lb x 74,900 Btu/lb	14,980
Subtotal:	24,730
Mixing: 0.1 kWh x 10,500 Btu/kWh	1,050
Curing: 0.2 kWh x 10,500 Btu/kWh	2,100
Subtotal:	3,150
Energy Content of Cast Epoxy Insulators:	27,880 Btu/lb. (64.68 MJ/kg)

M. PIPE COATING

Most of the pipes used in HPOF pipe-type cable systems are protected from corrosion by bitumastic (asphaltic) coatings from 1/2 inch to 3/4 inches thick. This type of coating has been selected for use on all buried pipes and CGI enclosures, to maintain comparability among transmission systems. Figure IV.M.1 illustrates the process of producing these coatings starting with crude oil input. The actual energy calculations are shown in Table IV.M.1. The coatings are not particularly energy intensive, at 5.68 x 10^6 Btu per ton (6.59 MJ per kg), due to the large proportion of sand and lime dust used.

N. SULFUR HEXAFLUORIDE (SF_6)

The production of SF_6 is relatively straightforward. It is made in commercial quantities by burning lump sulfur in the presence of fluorine gas, and then removing impurities such as SF_4, S_2F_{10} and water in a series of dewatering, scrubbing, purification and drying steps. The gas is then compressed and stored prior to filling tanks for shipment and sale.

As outlined in Table IV.N.1, the raw material inputs are sulfur, fluorine, potassium hydroxide, soda-lime and charcoal. Process energy inputs are steam to melt the sulfur, fuel to heat the drier purge gas, and electricity to compress the purified gas. The representative figure for the energy content of SF_6 is 1.12 x 10^8 Btu per ton (129.92 MJ per kg)

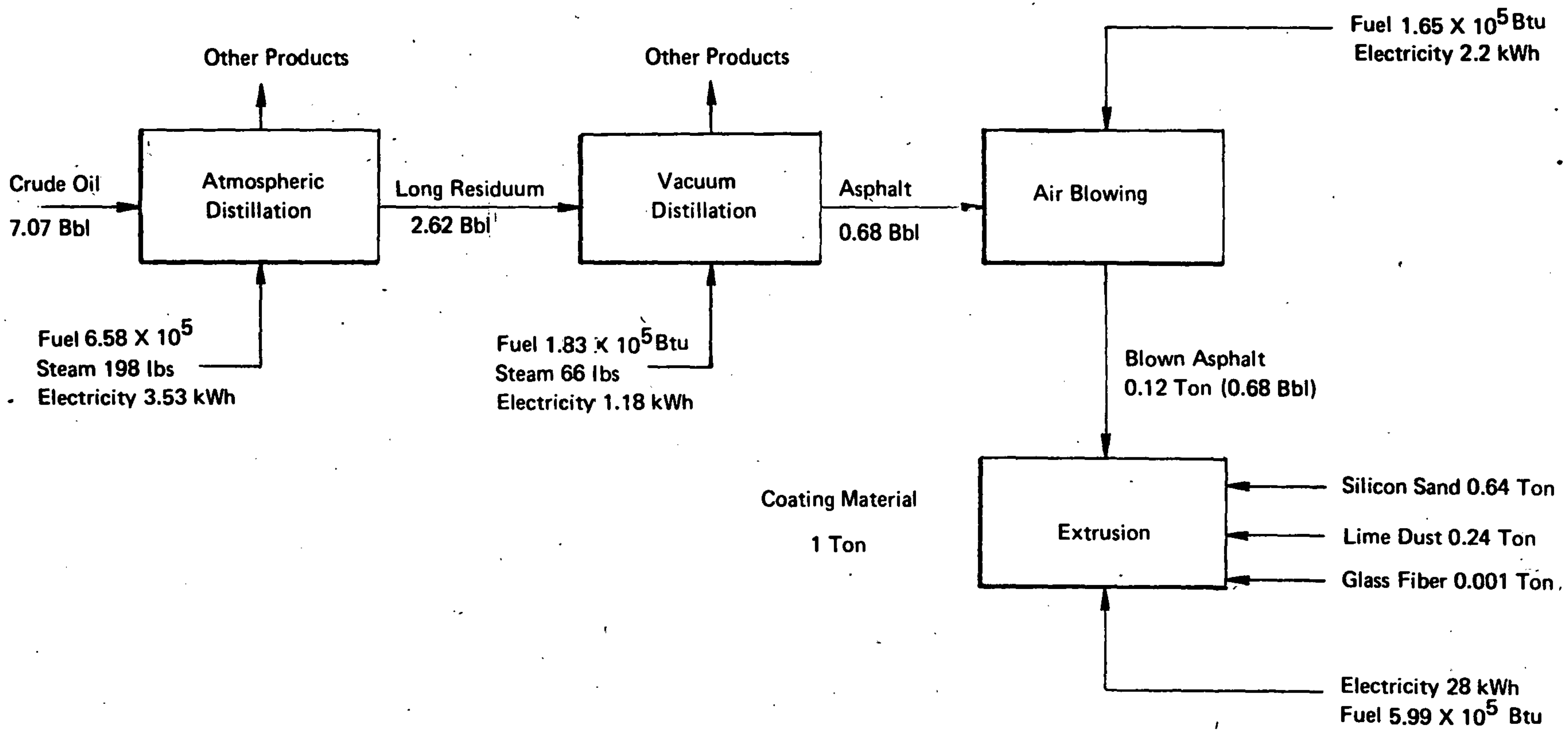
In view of the fact that fluorine represents 95% of this total energy content, another table has been prepared describing the energy analysis of fluorine. Table IV.N.2 contains the data and assumptions.

O. LIQUID HELIUM

Helium occurs naturally in its gaseous elemental form in the atmosphere and in natural gas. Since the concentration of helium in air is very low (about 5 ppm* by volume), natural gas is the principal commercial source of helium in the U.S. Typically, helium is being recovered today from natural gas streams containing no less than about 0.3% helium.

Figure IV.O.1 shows a typical flowsheet for helium recovery and purification. After removal of water vapor, carbon dioxide, and hydrogen sulfide, which would otherwise freeze and plug the downstream cryogenic equipment, the natural gas is chilled by reheating the condensed gas, which is returned to the pipeline from the separation unit. The chilled natural gas is then substantially condensed by indirect contact with gaseous nitrogen refrigerant, leaving only nitrogen,

*Parts per million is often abbreviated as ppm.



Source: H.C. Price, Inc., Gulf States Asphalt, and Arthur D. Little, Inc.

FIGURE IV.M.1. PRODUCTION OF BITUMASTIC PIPE COATINGS

TABLE IV.M.1. ENERGY CONSUMPTION IN THE MANUFACTURE OF PIPE COATINGS

Process	Electricity*	Steam**	Fuel	Other	10^3 Btu/ton Coating
Atm Distillation	$\frac{0.68}{7.07}$ x 3.53 kWh	$\frac{0.68}{7.07}$ x 198 lbs.	$\frac{0.68}{7.07}$ x 6.58×10^5 Btu		89.5
Vacuum Distillation	$\frac{0.68}{2.62}$ x 1.18 kWh	$\frac{0.68}{2.62}$ x 66 lbs.	$\frac{0.68}{2.62}$ x 1.83×10^5 Btu		67.8
Air Blowing	2.2 kWh		1.65×10^5 Btu		188
Extrusion	28 kWh		5.99×10^5 Btu		893
Asphalt feedstock				0.12 ton x 3.7×10^4 Btu	4,440
					5,678

Energy Content of Bitumastic Coatings: 5.68×10^6 Btu/ton

(6.59 MJ/kg)

*1 kWh = 10,500 Btu

**1 lb. of steam = 1,188 Btu

TABLE IV.N.1

MATERIAL AND ENERGY REQUIREMENTS FOR THE PRODUCTION OF SULFUR HEXAFLUORIDE

Material Inputs	Material Tons /ton SF_6	Energy, Btu x 10^6 /Ton Material	Energy, Btu x 10^6 /Ton of SF_6
Sulfur	0.231	5.8	1.34
Fluorine	0.808	131.5	106.25
Potassium Hydroxide	0.161	23.3	3.75
Soda-Lime	negl.	--	--
Charcoal	negl.	--	--
Total Material Energy Inputs			111.34
Energy Inputs			
Steam (lbs)			0.05
Fuel (kWh)			0.01
Power			0.26
Total Energy Inputs			0.32
Energy Content of Sulfur Hexafluoride:			112.66 x 10^6 Btu/ton (129.92 MJ/kg)

TABLE IV.N.2

PRODUCTION OF FLUORINE

Basis

The energy content of fluorine (F_2) was estimated by calculating the electrolyte energy requirement for converting hydrogen fluoride (HF) to (F_2) and adding the result to the published energy value[4] of the required quantity of HF. Assuming the product purity is 96%, the reaction is as follows:

$$100\ HF + \text{Electrical Energy} \rightarrow 4HF + 48H_2 + 48F_2$$

Process inputs are as shown below.

Inputs

HF - 1.1 ton/ton F_2 x 14.35 MMBtu/ton	15.79×10^6 Btu/ton F_2
Electrical energy - 6.07 kWh/lb F_2 x 2,000 lb/ton x 10,500 Btu/kWh	127.47*
Gross Input	143.26
Less: byproduct energy credit** - H_2 - 0.11 ton/ton F_2 x 106.9 MMBtu/ton	11.76
Net Energy Content	131.50×10^6 Btu/ton F_2 (152.54 MJ/kg)

* Electrical energy input: Arthur D. Little, Inc. estimate.

** H_2 energy content is based on its lower heating value (heat of combustion) of 53,450 Btu/lb.

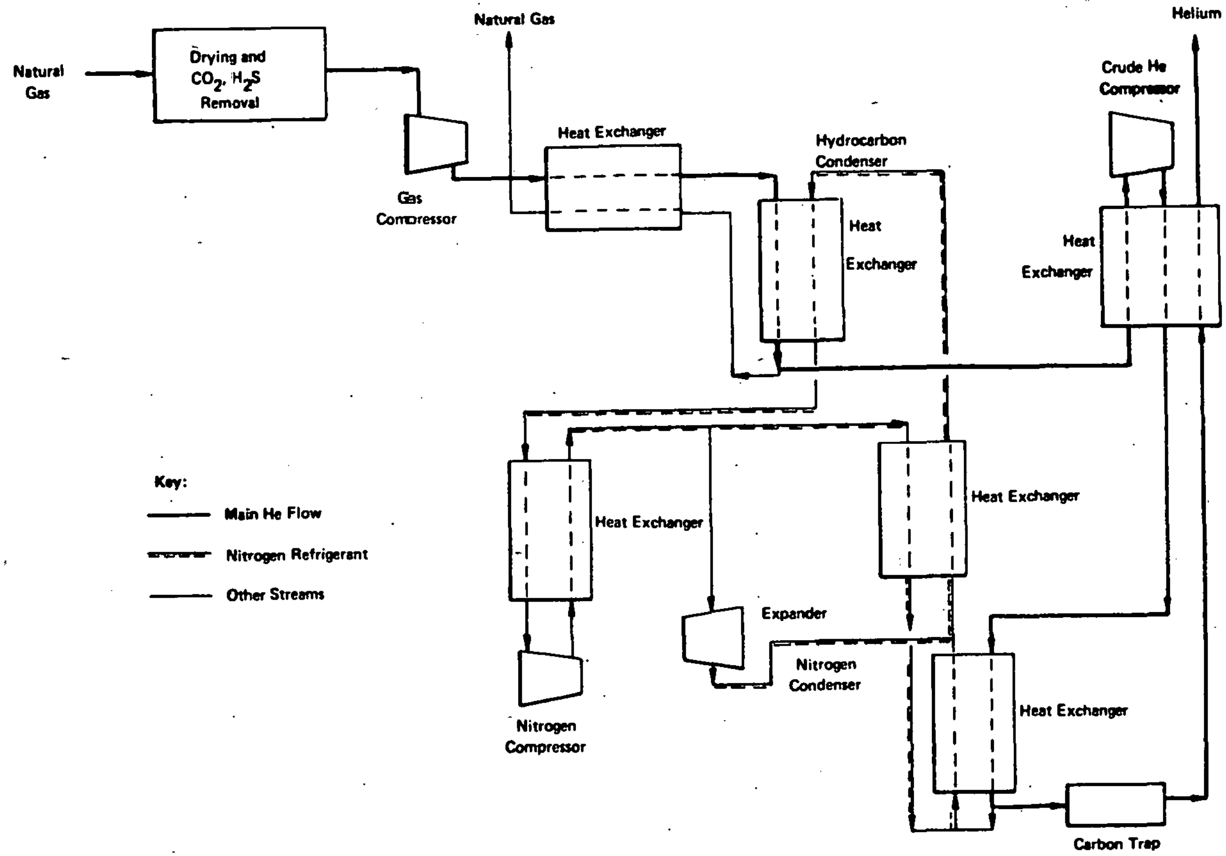


FIGURE IV.O.1. PRODUCTION OF HELIUM FROM NATURAL GAS helium, and traces of hydrocarbons in the gaseous state. The crude helium stream is then compressed to permit the condensation of the bulk of the nitrogen against a colder, vaporizing nitrogen refrigerant stream. Final traces of nitrogen are then removed from the helium product in a charcoal purifier.

There are several factors which complicate the determination of the energy content of helium. Seemingly, the calculation would be relatively straightforward using a thermodynamic analysis of Figure IV.0.1. However, problems arise from the following:

1. The helium concentration in natural gas varies from field to field, and the energy requirement for helium recovery is a significant function of its initial concentration.

2. The production of various natural gas wells is a matter of economics. Unfortunately, from a helium production viewpoint, natural gas wells containing attractive helium concentrations usually also contain very high nitrogen concentrations -- high enough to prohibit practical utilization and sale of the natural gas because of its relatively low heating value.

3. In many instances, helium recovery from natural gas is carried out in conjunction with other by-product recovery such as propane or butene. There is then the question of how to allocate the total energy cost among the products.

The U.S. Department of Energy has proposed a simplified model[5] which relates the energy requirement for a dedicated helium recovery plant to the initial helium concentration. This model is

$$E = 150/P$$

where E is the total electric energy consumption in kWh/Mscf* and P is the helium concentration in volume percent. The model is based on various plant operating data, calculated extrapolations to other conditions, and other estimates. The product is crude helium containing about 60 to 80% He, which is typical of governemnt plants intended solely for the conservation of helium. To produce pure liquid helium for use in superconducting power transmission lines would require additional purification and liquefaction. We estimate that this incremental energy is about 50 kWh/Mscf equivalent of helium produced.

*Mscf represents thousand standard cubic feet.

Table IV.O.1 contains sample calculations using the DOE model. Using this model with an appropriate increment for purification and liquefaction, the energy content of helium is estimated to be 6.96 x 10^8 Btu per ton when it is produced from natural gas containing 0.5% helium. This is typical of plants which are now operating and are likely to be operating for the next several years.

Table IV.O.2 is based on specific data for the National Helium Corporation plant, which utilizes a feed composition of 0.4% He. Helium energy content from this plant is estimated to be 5.81 x 10^8 Btu per ton. Since this is based on an actual plant operation, it has been selected as the representative value for the energy content of liquid helium.

<u>Energy Content of Liquid Helium</u>: 5.81 x 10^8 Btu/ton
(673.96 MJ/kg)

TABLE IV.O.1

ENERGY CONTENT OF LIQUID HELIUM USING SIMPLIFIED DOE MODEL

Basis: Helium concentration in natural gas = 0.5%

DOE model: E = 150/P - 150/0.5 = 300 kWh/Mscf

Add energy for purification and liquefaction 50 kWh/Mscf

Total: 350 kWh/Mscf

Btu equivalent:

$$350 \frac{\text{kWh}}{\text{Mscf}} \times 10{,}500 \frac{\text{Btu}}{\text{kWh}} \times \frac{1}{1000} \times \frac{\text{Mscf}}{\text{scf}} \times \frac{379 \text{ scf}}{416} \times \frac{2000 \text{ lbs}}{\text{ton}} =$$

696×10^6 Btu/ton (807.36 MJ/kg)

TABLE IV.O.2

ENERGY CONTENT OF LIQUID HELIUM USING NATIONAL HELIUM CORPORATION DATA

Basis: Helium concentration in natural gas = 0.4%

Energy consumption: 242 kWh/Mscf

Add energy for purification and liquefaction 50 kWh/Mscf

292 kWh/Mscf

Btu equivalent:

$$292 \frac{\text{kWh}}{\text{Mscf}} \times 10{,}500 \frac{\text{Btu}}{\text{kWh}} \times \frac{1}{1000} \times \frac{\text{Mscf}}{\text{scf}} \times \frac{379}{4} \times \frac{\text{scf}}{\text{lb}} \times \frac{2000 \text{ lbs}}{\text{ton}} =$$

581×10^6 Btu/ton (673.96 MJ/kg)

References for Chapter IV

1. "Energy Use Patterns in Metallurgical and Non-metallic Mineral Processing, Phase 4": prepared for the Bureau of Mines, U.S. Department of the Interior, by Battelle Columbus Laboratories, 1975; NTIS PB-245 759.

2. "Energy Use Patterns for Metal Recycling": prepared for the Bureau of Mines by Arthur D. Little, Inc., 1978; Bureau of Mines document number IC-8781.

3. "Potential for Energy Conservation in the Iron and Steel Industry", prepared for the Federal Energy Administration (now part of the Department of Energy) by Gordian Associates, New York, New York.

4. "Energy Use Patterns in Metallurgical and Non-Metallic Mineral Processing", Phase 5 (Energy Data and Flowsheets), Intermediate-priority Commodities, Battelle Columbus Laboratories, Ohio, September, 1975.

5. "The Energy-Related Applications of Helium", ERDA-13, U.S. Energy Research and Development Administration (now part of the Department of Energy), 1975.

V. ENERGY CONTENT OF MAJOR SYSTEM COMPONENTS

A. INTRODUCTION

This chapter describes the manufacturing of transmission system components, starting from the basic materials analyzed in Chapter IV, and the energy analysis of support systems. The three support systems are oil pressurizing plants, terminals for dc systems and refrigeration systems for superconducting transmission lines.

B. STEEL PRODUCTS

Three predominant types of steel products are used in electric power transmission systems. These include structural steel forms (used in lattice-type towers), steel pipe (used in HPOF pipe-type and superconducting systems) and steel cable, drawn from wire rod. Figures V.B.1 through V.B.3 illustrate the manufacturing operations required to transform steel ingots into structural forms, pipe and wire rod, respectively. Tables V.B.1 through V.B.3 summarize the energy accounting for each step.

Wire rod must be drawn and stranded to produce cable. Based on our field trips to cable manufacturing plants and traditional industry practice, it is estimated that 2.90×10^6 Btu per ton is a good representative value for the energy content of wire drawing for strand sizes less than 0.150 inches in diameter. Stranding requires little additional energy, approximately 1.0×10^6 Btu per ton. Combining these values with the energy content of wire rod, the estimated energy content of steel cable is 34.1×10^6 Btu per ton. The steel energy content of ACSR overhead conductors is calculated using this value. All of the steel product energy content figures are summarized below.

Structural steel:	2.92×10^7 Btu/ton (33.87 MJ/kg)
Steel pipe:	3.98×10^7 Btu/ton (46.17 MJ/kg)
Steel cable:	3.41×10^7 Btu/ton (39.56 MJ/kg)

C. ALUMINUM PRODUCTS

The major aluminum products of interest are stranded aluminum wire for overhead lines and aluminum pipe for CGI systems. Cables are produced from coils of cast wire rod. Pipes can be made from cast slabs or ingots.

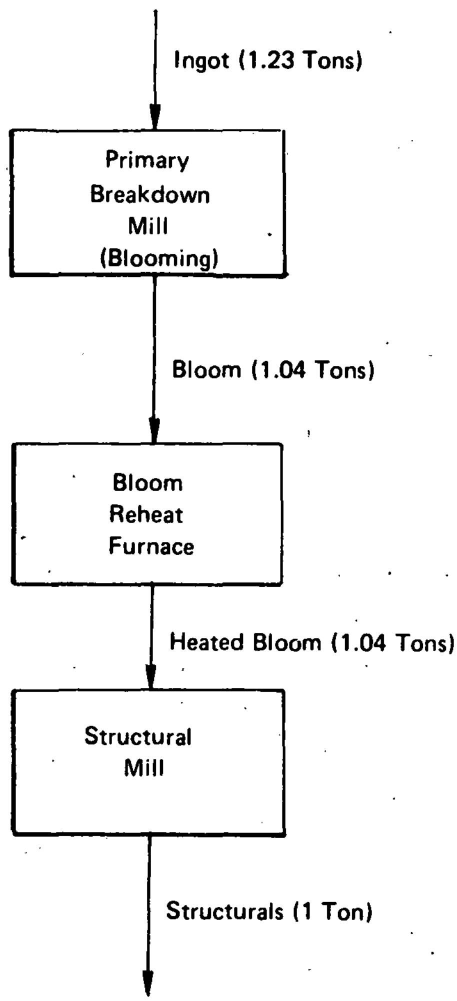


FIGURE V.B.1

PRODUCTION OF STRUCTURAL STEEL ITEMS

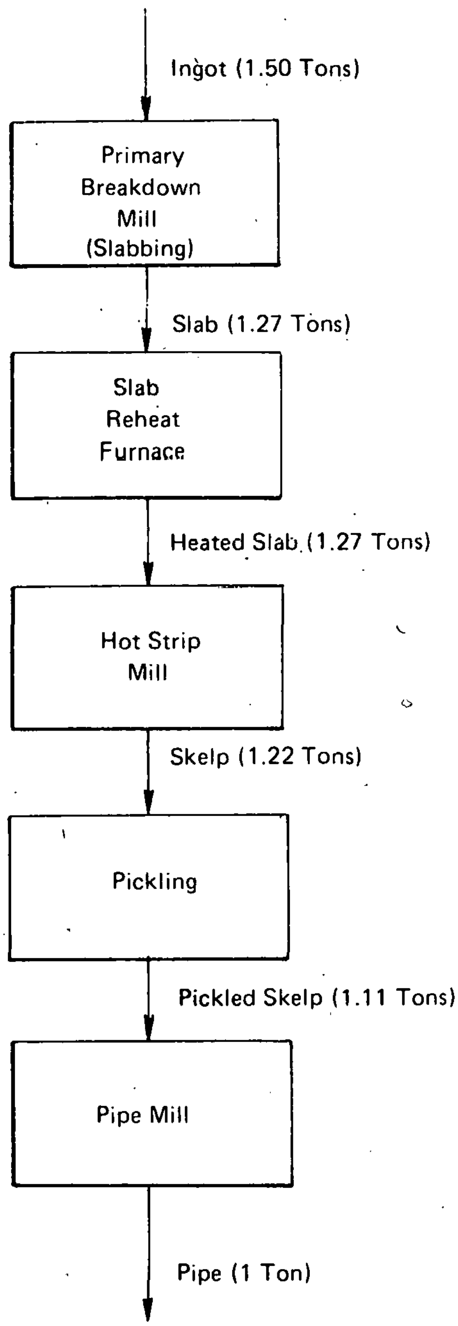


FIGURE V.B.2

PRODUCTION OF STEEL PIPE

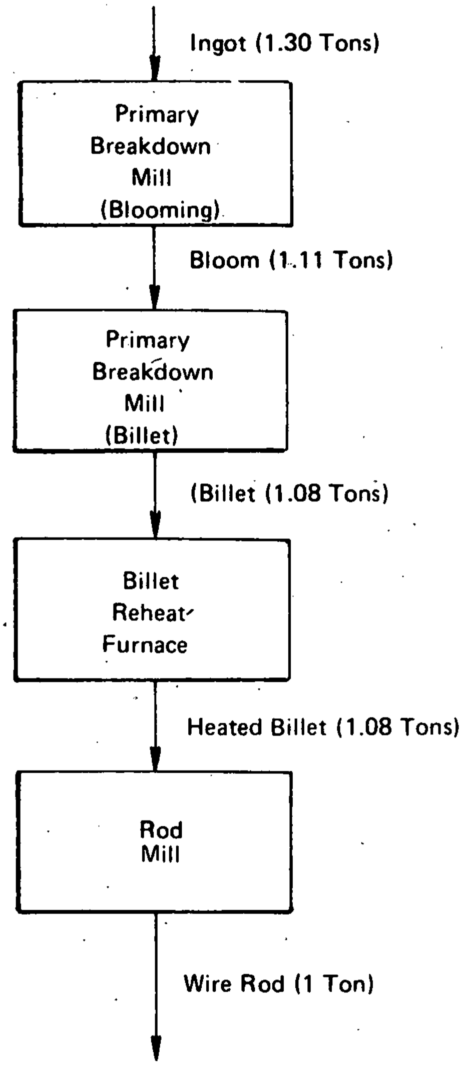


FIGURE V.B.3

PRODUCTION OF WIRE ROD

TABLE V.B.1. ENERGY REQUIREMENTS FOR CONVERSION OF INGOTS TO STRUCTURALS

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Required Per Unit (Million Btu)	Million Btu Per Net Ton of Product
(1) PRIMARY BREAKDOWN MILL TO BLOOMS (Yield = 85%)				
Coke Oven Gas	10^3 ft^3	3.15	0.5	1.58
Natural Gas	10^3 ft^3	0.06	1.0	0.06
Electricity	kWh	31.25	0.0105	0.33
Oxygen	10^3 ft^3	0.12	0.183	0.02
Rolls and Bearings	lb	0.16	0.015	0.002
Subtotal				1.992
(2) BLOOM REHEAT FURNACE (Yield = 100%)				
Natural Gas	10^3 ft^3	2.15	1.0	2.15
Coke Oven Gas	10^3 ft^3	1.35	0.5	0.68
Fuel Oil	gal	0.49	0.15	0.07
Electricity	kWh	3.13	0.0105	0.03
Refractories	lb	1.04	0.0125	0.01
Subtotal				2.94
(3) STRUCTURAL MILL (Yield = 96%)				
Electricity	kWh	42	0.0105	0.44
Subtotal				0.44
TOTAL				5.372
				(6.23 MJ/kg)

<u>Note:</u> This table is based upon ADL data and Reference 1.

TABLE V.B.2. ENERGY REQUIREMENTS FOR CONVERSION OF INGOTS TO WELDED PIPE

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Required Per Unit (Million Btu)	Million Btu Per Net Ton of Product
(1) PRIMARY BREAKDOWN MILL TO SLABS (Yield = 85%)				
Coke Oven Gas	10^3 ft^3	3.84	0.5	1.92
Natural Gas	10^3 ft^3	0.08	1.0	0.08
Electricity	kWh	38.2	0.0105	0.40
Oxygen	10^3 ft^3	0.15	0.183	0.03
Rolls and Bearings	lb	0.19	0.015	0.003
Subtotal				2.433
(2) SLAB REHEAT FURNACE (Yield = 100%)				
Natural Gas	10^3 ft^3	2.62	1.0	2.62
Coke Oven Gas	10^3 ft^3	1.65	0.5	0.83
Fuel Oil	gal	0.60	0.15	0.09
Electricity	kWh	3.82	0.0105	0.04
Refractories	lb	1.27	0.0125	0.02
Subtotal				3.60
(3) HOT STRIP MILL (Yield = 96%)				
Electricity	kWh	122.1	0.0105	1.28
Rolls and Bearings	lb	3.3	0.0125	0.04
Subtotal				1.32
(4) PICKLE LINE (Yield = 91%)				
Steam	10^3 lb	0.14	1.0	0.14
Electricity	kWh	13.3	0.0105	0.14
Hydrochloric Acid	net ton	0.019	9.25	0.17
Subtotal				0.45
(5) PIPE MILL (Yield = 90%)				
Coke Oven Gas	10^3 ft^3	3.92	0.5	1.96
Electricity	kWh	85	0.0105	0.89
Subtotal				2.85
				10.653
				(12.36 MJ/kg)

Note: This table is based upon ADL data and Reference 1.

TABLE V.B.3. ENERGY REQUIREMENTS FOR CONVERSION OF INGOTS TO WIRE ROD

(Step Number) Process	Unit	Units Per Net Ton of Product	Energy Required Per Unit (Million Btu)	Million Btu Per Net Ton of Product
(1) PRIMARY BREAKDOWN TO BLOOMS (Yield = 85%)				
Coke Oven Gas	10^3 ft^3	3.36	0.5	1.68
Natural Gas	10^3 ft^3	0.07	1.0	0.07
Electricity	kWh	33.4	0.0105	0.35
Oxygen	10^3 ft^3	0.13	0.183	0.02
Rolls and Bearings	lb	0.17	0.015	0.003
Subtotal				2.123
(2) PRIMARY BREAKDOWN TO BILLETS (Yield = 97%)				
Electricity	kWh	48.6	0.0105	0.51
Subtotal				0.51
(3) BILLET REHEAT FURNACE (Yield = 100%)				
Natural Gas	10^3 ft^3	1.33	1.0	1.33
Coke Oven Gas	10^3 ft^3	1.33	0.5	0.67
Fuel Oil	gal	3.15	0.15	0.47
Steam	lb	3.98	0.0027	0.01
Electricity	kWh	3.23	0.0105	0.03
Refractories	lb	1.08	0.0125	0.01
Subtotal				2.52
(4) ROD MILL (Yield = 93%)				
Electricity		78	0.0105	0.82
Subtotal				0.82
				5.973
				(6.93 MJ/kg)

Note: This table is based upon ADL data and Reference 1.

Drawing and stranding of aluminum into cables is estimated to require 4.0 x 10^6 Btu per ton, based on observations of equipment made during inspections of cable manufacturing plants. This is about 2% of the inherent energy content of aluminum wire rod. The estimated aluminum energy content of ACSR cables is 2.28 x 10^8 Btu per ton (264 MJ per kg).

Aluminum pipe is produced by rolling slabs or ingots to the desired thickness, forming the plate into a circular shape and welding the seam. It is estimated that these operations require 8.0 x 10^6 Btu per ton of pipe. Thus the total energy content of aluminum pipe is taken to be 2.32 x 10^8 Btu per ton (269 MJ per kg).

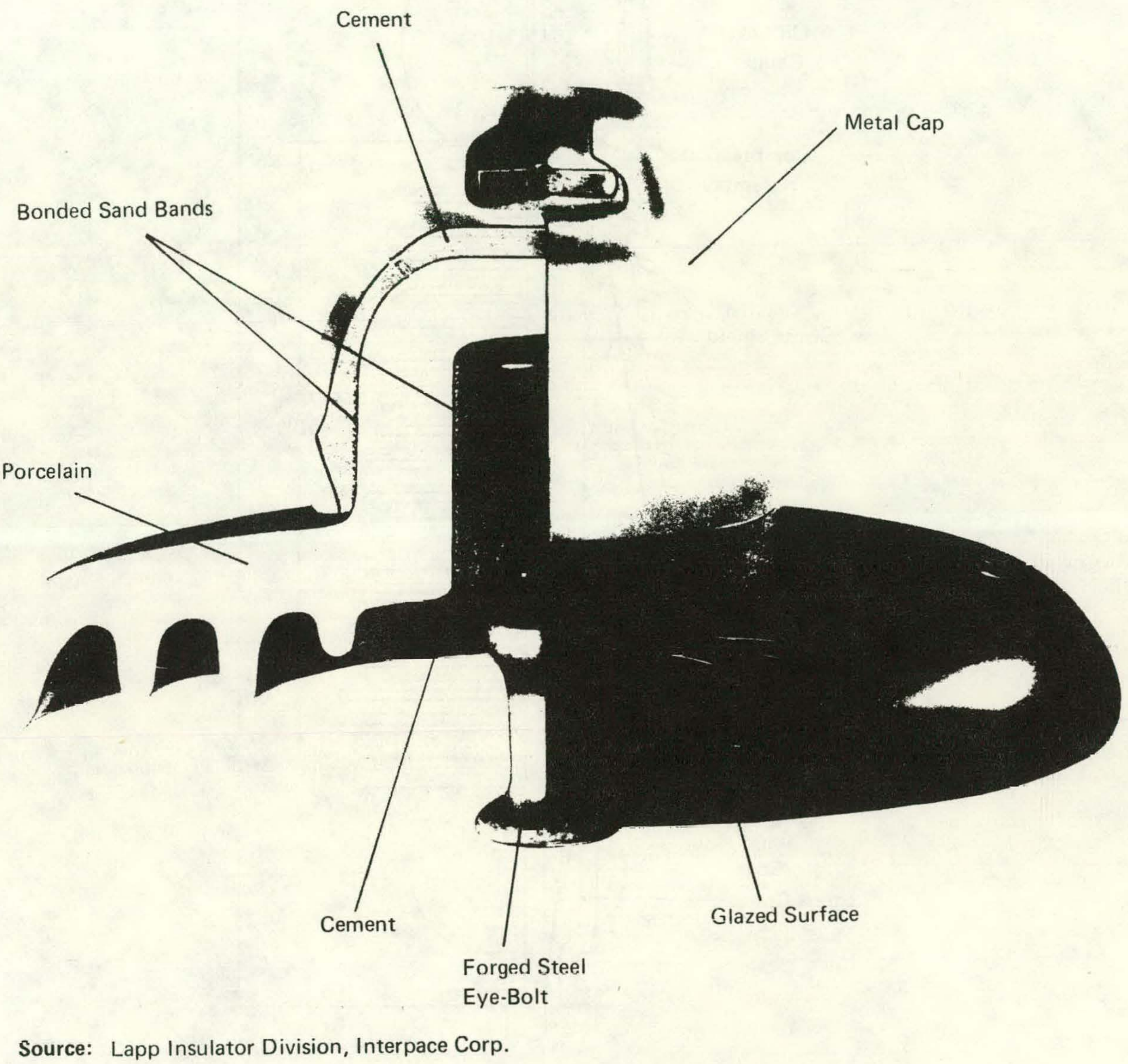
D. CERAMIC PRODUCTS

The major ceramic products used in transmission systems are suspension insulators, potheads (cable terminations) and station posts. Figures V.D.1 through V.D.3 show the construction of suspension insulators, potheads and station posts, respectively. The material processing and manufacturing operations required to produce these products are indicated in Figure V.D.4.

The primary raw materials which go into the making of ceramic insulating products are kaolin, ball clay, feldspar and quartz. Each of these materials is mined in the U.S. and depending upon location of the insulator manufacturing facility is either transported by rail in covered hopper cars or by truck. In addition to these raw materials, alumina is sometimes used as a replacement for the quartz in order to make high-strength bodies. Since bauxite is essentially no longer mined in the U.S., but rather mined in South America or Jamaica, a 2,000 mile ocean shipping energy charge was added.

Given these various assumptions it was calculated that mining of the raw materials consumes approximately 260 Btu per pound, while transportation of these raw materials consumes 245 Btu per pound. As will be evident later, these energy charges are inconsequential when compared to the total energy requirements for manufacturing insulators.

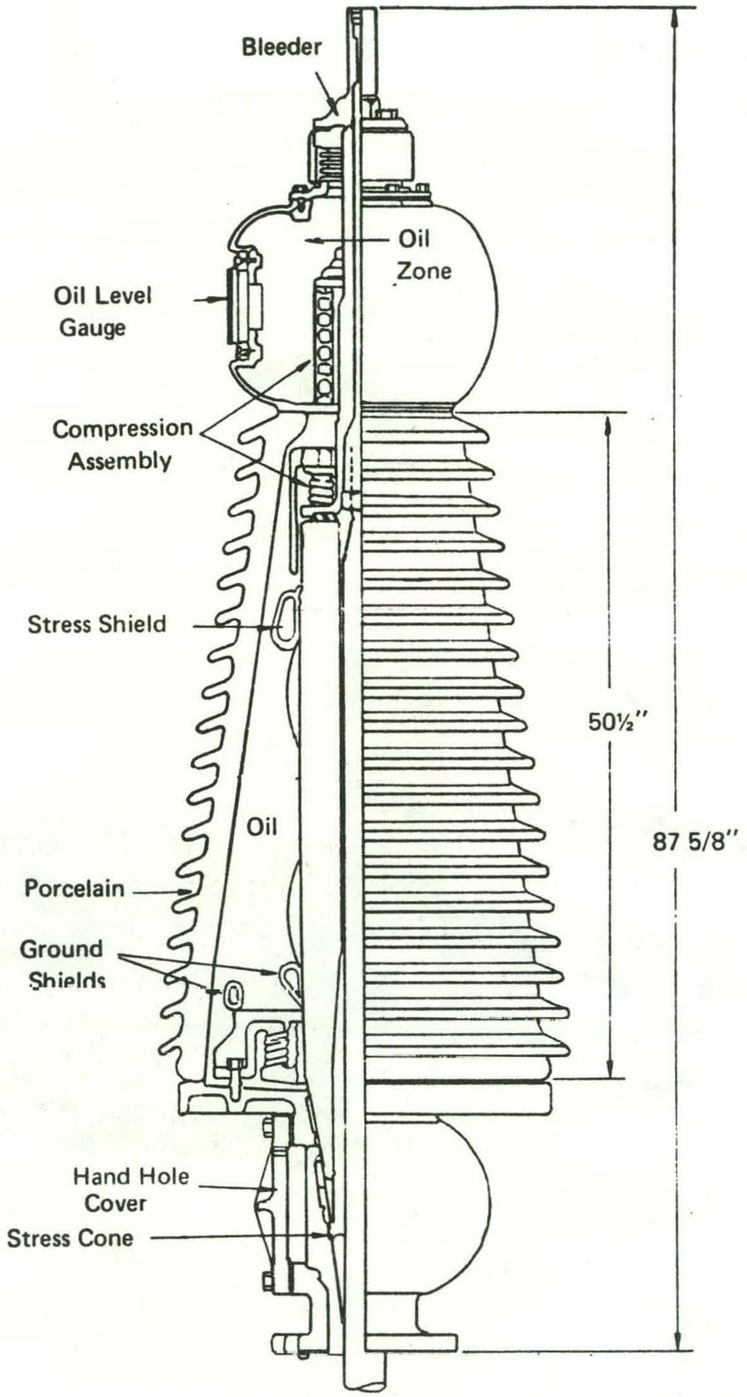
Prior to forming the insulators into a desired shape, the raw materials must be weighed and mixed with water appropriately. These steps consist of weighing in the proper amounts of the various raw materials, then conveying them to a blunger which is merely a large tank with a revolving gate. Water is added such that a fluid mix is attained. This suspension or slip is next screened and passed through magnetic separators to remove any tramp iron and then filter pressed to remove a large portion of the water. The material is then in a form which is "plastic" or moldable. It is next pugged which is like a kneading operation and this is done under vacuum to remove trapped air. Following these operations the pugged material is extruded into



Source: Lapp Insulator Division, Interpace Corp.

FIGURE V.D.1

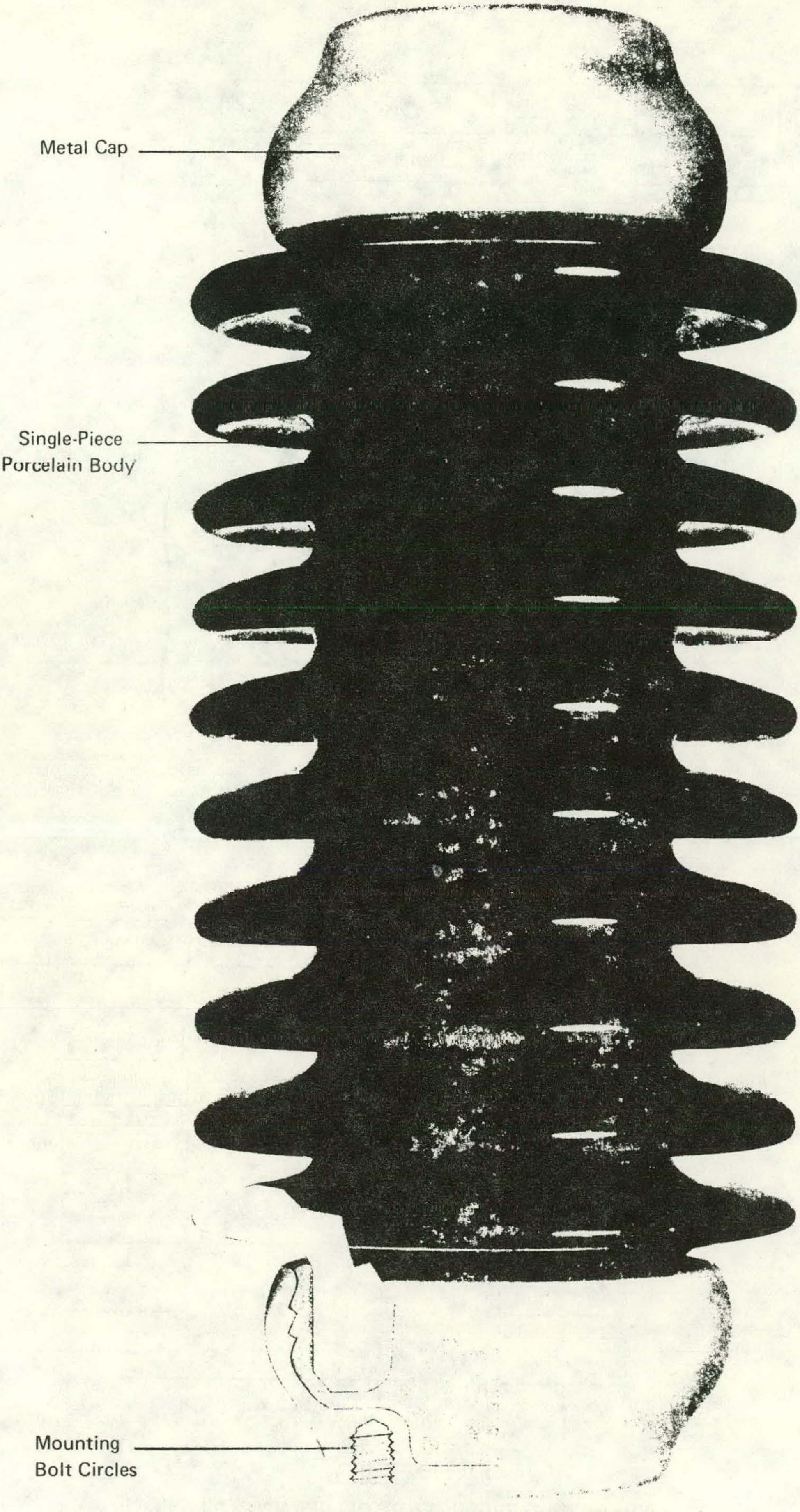
TYPICAL SUSPENSION INSULATOR



Source: *Underground Systems Reference Book,* Edison Electric Institute, 1957

FIGURE V.D.2

TYPICAL POTHEAD FOR HPOF SYSTEMS



Source: Lapp Insulator Division, Interpace Corporation

FIGURE V.D.3. STATION POST INSULATOR

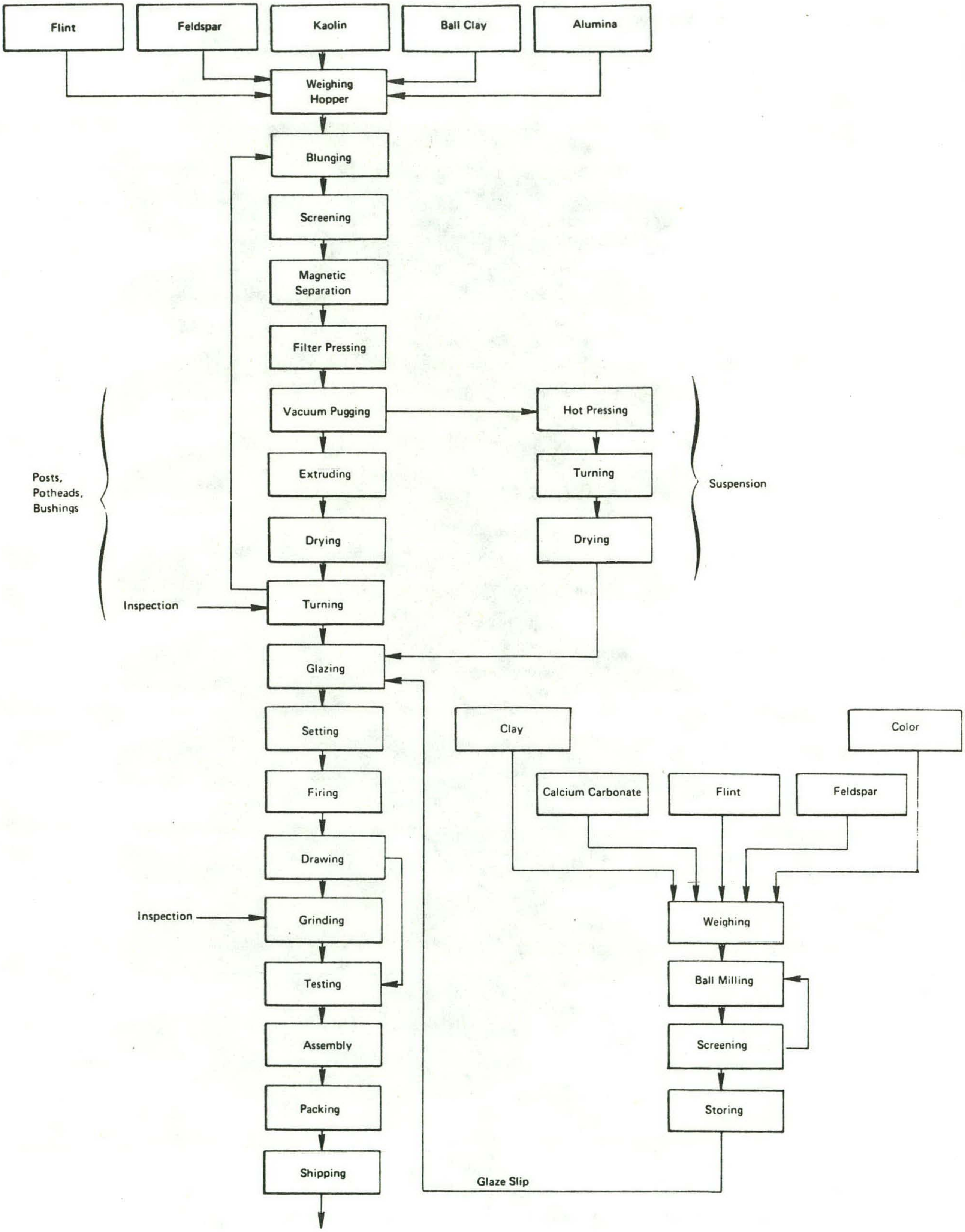


FIGURE V.D.4

FLOWSHEET FOR PRODUCTION OF CERAMIC PRODUCTS either solid or hollow cylinders upwards of about 3 feet in diameter, before being formed into shape. All of these various material preparation steps consume about 1,100 Btu per pound of finished product. The energy consumed is in the form of electricity.

The products are dried to a moisture content of 1 to 3% prior to turning, or about the same after hot pressing. Drying consumes typically 14% of total plant electricity usage and 30% of the plant natural gas requirements.

Ceramic insulators are formed by either turning or hot pressing. The post and pothead types are formed by turning, which consists of turning the appropriate size cylinder on a lathe. Suspension insulators are hot pressed in plaster molds. Both of these forming operations consume about the same amount of energy. The energy used is primarily electricity, and represents roughly 6% of total plant energy requirements.

The raw materials which go into glazes are similar to those in the body, which have been included in the mining and transportation of the raw materials. Application of the glaze does require an additional energy input, which is electrical, corresponding to 4% of the total energy requirements.

As one might expect, firing is the processing step which consumes the greatest amount of energy. It represents somewhat more than half of the total energy requirement to manufacture an insulator, or about two-thirds of the natural gas consumption. Firing is done in tunnel kilns or periodic kilns, which are continuous and batch operations, respectively. Size, complexity, and production volume requirements determine which type of kiln would be used. Suspension insulators and the smaller post and bushing types are fired in tunnel kilns, whereas the larger posts, bushings and potheads are fired in periodic kilns. At a zero refire* rate the periodic kiln uses about 20% more fuel per unit weight of insulator to fire than a tunnel kiln, 10,500 Btu per pound versus 8,500 per pound. However, refire rates in a tunnel kiln are about 6 to 8%, whereas in the periodic they could be nearer to 50%. More realistic values might be 9,300 Btu per pound in a tunnel kiln versus 2,100 Btu per pound in a periodic kiln.

Grinding and cutting of the fired ceramic is necessary in order to finish off the ends of both post and pothead insulators. This operation consumes less than 1% of the total in-plant energy requirement, all of which is electrical. Inspection and testing consume even less energy.

---

*Items are put through the kiln again (re-fired) if defects in the glaze are observed.

Although most of the metal hardware is purchased and used directly in manufacturing insulators, some machining is required for certain metal parts. The energy consumed is electrical, and represents about 4% of the total plant energy requirements.

Assembling the insulators requires a variety of tasks, which are different for the various types of insulators. In each a portland cement mix is used to cement on the metal hardware. Oil, paper and resin may also be required. The in-plant energy requirement for this operation is about 3% of the total plant energy requirements.

The energy required for space heating depends primarily on a plant's geographic location, of course. However, even for plants in northern locations the energy used for space heating is a small percentage of total plant energy requirements. For the plant we analyzed, which is located in central New York state, space heating consumed about 2% of the total plant energy requirements.

Table V.D.1 summarizes the energy content by component of suspension insulators, station posts and bushings. Bushings, which are essentially identical to potheads with respect to ceramic content and size, were analyzed due to a lack of data on pothead manufacturing during the plant visit. The data contained in the table have been used to estimate the energy content of potheads that are not commercially available items, such as those suitable for service at 765 and 1,200 kV.

E. HPOF PIPE-TYPE CABLE MANUFACTURING

Figure V.E.1 illustrates the procedures used to manufacture paper-tape cables used in HPOF systems. Conductors are formed by successive steps of drawing, annealing, stranding and compacting. Rolls of kraft paper are slit into tapes, dried and wrapped around the conductor. Oil is applied following vacuum drying, and the impregnated cable is wrapped with an oil barrier and skid wires.

Table V.E.1 indicates the energy content associated with each processing step. The heating and lighting (H&L) estimates are based upon plants located in the northeast part of the country, and will be lower for southern plants. In any event, the H&L fraction of the total is small.

Based on the data contained in Table V.E.1, the generalized relationships shown below have been developed to estimate the total energy content of paper-tape cables.

TABLE V.D.1

TOTAL ENERGY CONTENT OF SPECIFIC INSULATOR TYPES

	Approximate Weights of Components					Ceramic Energy Content				Total Energy Content					
	Ceramic lbs	Metal lbs	Oil gal.	Paper lbs	Cement lbs	Mining Btu/lb	Transp. Btu/lb	In-plant lb/Btu	Total Btu/lb	Ceramic Btu/pc	Metal Btu/pc	Oil Btu/pc	Paper Btu/pc	Cement Btu/pc	TOTAL ENERGY Btu/pc
Suspension															
20,000 lb	8.2	3.8	—	—	.5	29*	215	18,730+	18,970	155,600	38,000	-0-	-0-	1,900	195,500
30,000 lb	9.2	5.3	—	—	.5	260**	245	18,730	19,240	177,000	53,000	-0-	-0-	1,900	231,900
40,000 lb	9.2	7.1	—	—	.5	260	245	18,730	19,240	177,000	71,000	-0-	-0-	1,900	249,900
50,000 lb	12.0	7.6	—	—	.5	1,685***	433	18,730	20,850	250,200	76,000	-0-	-0-	1,900	328,100
Station Post															
650 kV	275	87	—	—	.75	260	245	18,730	19,240	5,289,600	870,000	-0-	-0-	2,850	6,162,450
1,050 kV	464	137	—	—	1.0	260	245	30,900++	31,410	14,570,000	1,370,000	-0-	-0-	3,800	15,943,800
1,550 kV	543	158	—	—	1.5	260	245	30,900	31,410	17,050,000	1,580,000	-0-	-0-	5,700	18,635,700
2,050 kV	912	334	—	—	2.0	260	245	30,900	31,410	28,640,000	3,340,000	-0-	-0-	7,600	31,987,600
2,425 kV	1,098	414	—	—	3.0	260	245	30,900	31,410	34,480,000	4,140,000	-0-	-0-	11,400	38,631,400
Bushings															
138 kV	360	65	5	32	2.0	260	245	30,900	31,410	11,305,800	650,000	690,000	928,000	7,600	13,581,000
230 kV	925	135	36	230	3.0	260	245	30,900	31,410	29,049,300	1,350,000	4,963,000	6,670,000	11,400	42,048,700
345 kV	1,210	135	36	230	3.0	260	245	30,900	31,410	38,000,100	1,350,000	4,968,000	6,670,000	11,400	50,999,500
500 kV	2,100	210	67	440	3.0	260	245	30,900	31,410	65,950,500	2,100,000	9,246,000	12,760,000	11,400	90,067,900
765 kV	2,650	190	120	750	3.0	260	245	30,900	31,410	83,223,250	1,900,000	16,560,000	21,750,000	11,400	123,444,650

*Assumes no alumina body

**Assumes average mix - 10% alumina production

***Assumes only high alumina body

+Assumes firing in tunnel kiln

++Assumes firing in periodic kiln

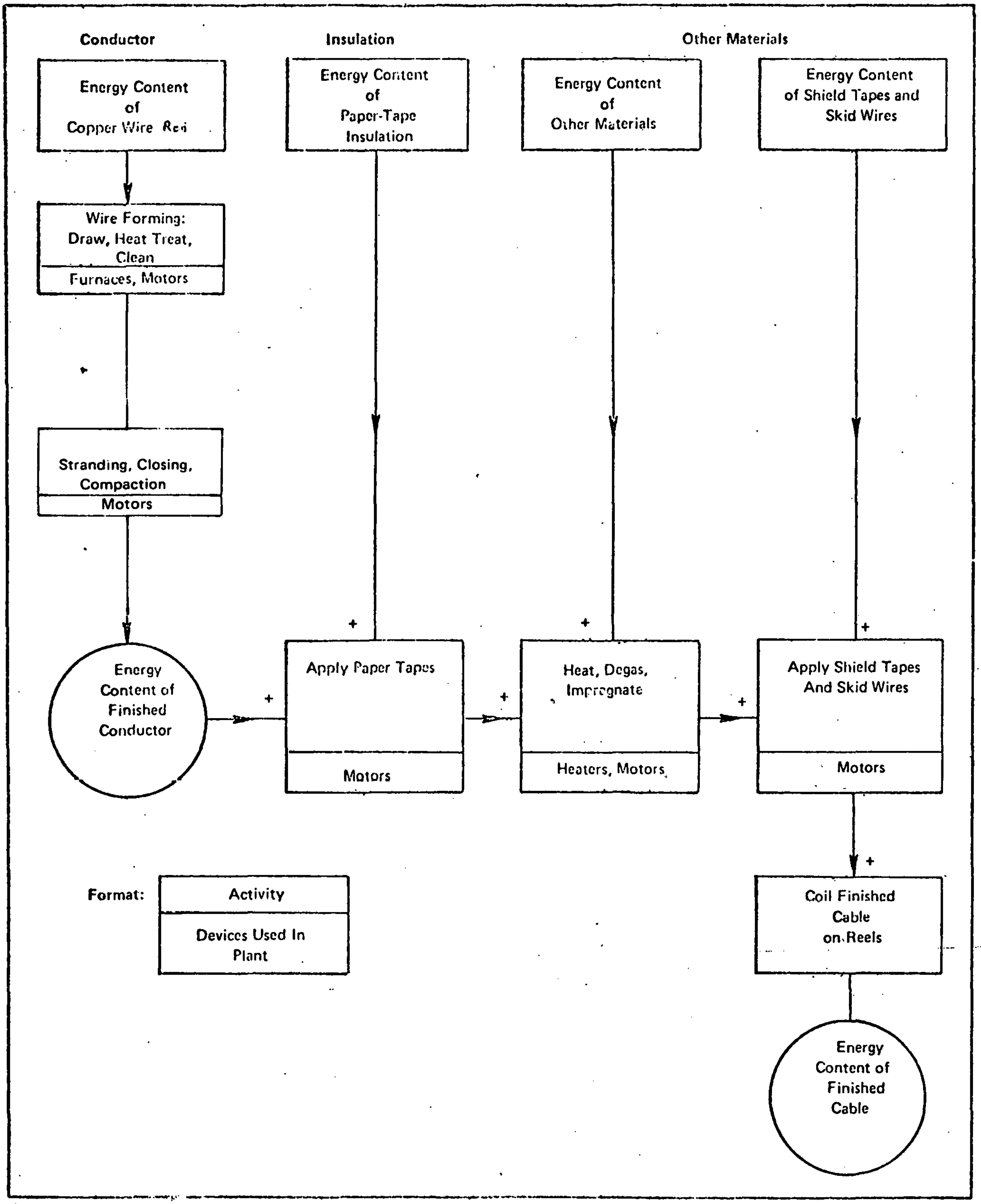


FIGURE V.E.1

MANUFACTURING OF HPOF PIPE-TYPE CABLES

TABLE V.E.1

MANUFACTURING OF HPOF PIPE-TYPE CABLES

	Copper	Aluminum
1. Conductor Processing		
Drawing strands from wire rod	278 Btu/lb	308 Btu/lb
Annealing: copper (elec); aluminum (gas)	209	1092
Stranding and compacting into sectors	59	299
Heating and Lighting (H&L)	78	78
	624 Btu/lb	1777 Btu/lb
Cabling machine (wraps 4 sectors)	18 Btu/lb	18
H&L	6	6
	24 Btu/lb	24
Complete conductor total:	648 Btu/lb	1801 Btu/lb
	(1.50 MJ/kg)	(4.18 MJ/kg)
2. Insulation Preparation and Application		
Drying	180 Btu/lb	
Slitting	132 "	
H&L	28 "	
	340 Btu/lb	
Wrapping (in dehumidified room)	1.13×10^4 Btu/lb	
Total: wrapped (dry) cable	1.16×10^4 Btu/lb of paper	
	(26.94 MJ/kg)	
3. Impregnation of Insulation		
Conductor heating	359 Btu/lb of copper 821 Btu/lb of aluminum	
Insulation heating	507 Btu/lb of paper	
Oil Processing, vacuum pumping, and tank cooling	2.75×10^3 Btu/lb of paper	
H&L	978 Btu/lb of paper	
Totals:	359 Btu/lb (0.83 MJ/kg) of copper 821 Btu/lb (1.91 MJ/kg) of aluminum 3.257×10^3 Btu/lb (7.56 MJ/kg) of paper	
4. Finishing Operations		
Apply mylar tapes, copper tapes and skid wires	170 Btu/lb (0.39 MJ/kg) of paper	

Completed Conductor:	9.45×10^7 Btu/ton (110 MJ/kg) of copper
	2.28×10^8 Btu/ton (264 MJ/kg) of aluminum
Insulation Preparation:	1.16×10^4 Btu/lb (26.9 MJ/kg) of dry paper
Impregnation:	3.26×10^3 Btu/lb (7.56 MJ/kg) of dry paper
	359 Btu/lb (0.83 MJ/kg) of copper
	821 Btu/lb (1.91 MJ/kg) of aluminum
Finishing:	170 Btu/lb (0.39 MJ/kg) of dry paper

F. SCOF CABLE MANUFACTURING

Although the hollow conductor of SCOF cables is different in form from the compact round conductor of pipe-type cables, the energy required to make SCOF conductors is approximately equivalent to that of pipe-type cables: both are on the order of 1% of the inherent energy content. Insulation impregnation energy requirements are also similar, so that values for both finished conductors and impregnation of SCOF cables are assumed equal to pipe-type cable values.

One feature of SCOF cables not found on pipe-type cables is the thick metallic sheath which permits pressurization of the insulating oil. Aluminum has been selected as the sheath material, for reasons discussed in Chapter VI. The aluminum sheath is cold-extruded around the wrapped cable. This extrusion process is estimated to require 426 Btu per pound of aluminum. The table below summarizes manufacturing energy requirements for SCOF cables.

Completed Conductor:	9.45×10^7 Btu/ton (110 MJ/kg) of copper
	2.28×10^8 Btu/ton (264 MJ/kg) of aluminum
Impregnation:	3.26×10^3 Btu/ton (7.57 MJ/kg) of dry paper
	359 Btu/lb (0.83 MJ/kg) of copper
	821 Btu/lb (1.91 MJ/kg) of aluminum
Sheath Extrusion:	426 Btu/lb (0.99 MJ/kg) of aluminum

G. EXTRUDED DIELECTRIC CABLES

The cable design* developed for extruded dielectric (ED) cables by the General Cable Company Research Laboratory requires five extrusions. Figure V.G.1 shows the proposed production line for manufacturing ED cables rated at 138, 230 or 345 kV. Figure V.G.2 illustrates the polyethylene purification system, which is an important aspect of the General Cable manufacturing process. Reference 2 describes the process in detail.

Based on a visit to this laboratory and another ED cable manufacturing plant, estimates of energy content for production of cross-linked polyethylene (XLPE) cable have been calculated. Table V.G.1 contains the results.

Generalizing from this table, a value of 1.36 x 10^4 Btu per pound has been selected as the estimate of energy content for extruding and curing polyethylene. Extrusion of a PVC jacket over the four layers of polyethylene is the final manufacturing step. This process is estimated to require 5.53 x 10^3 Btu per pound of polyvinyl chloride. All of these manufacturing processes are summarized below.

Completed Conductor:	9.45 x 10^7 Btu/ton (110 MJ/kg) of copper
	2.28 x 10^8 Btu/ton (264 MJ/kg) of aluminum
Insulation Processing:	1.36 x 10^4 Btu/lb (31.6 MJ/kg) of PE
Jacket Extrusion:	5.53 x 10^3 Btu/lb (12.8 MJ/kg) of PVC

H. COMPRESSED-GAS-INSULATED (CGI) SYSTEMS

The two U.S. manufacturers of CGI systems purchase the aluminum conductor and enclosure (both in the form of pipe) directly from aluminum producers. Insulators of alumina-filled epoxy resin are cast in-house. The remaining components are SF_6, connectors and a protective coating, of which all but the connectors have been analyzed in terms of energy content. Connectors have been analyzed in surrogate form in Chapter VI.

Given the insulators, conductor, enclosure and connectors, manufacturing of CGI systems consists principally of cleaning and assembly operations. It is estimated that assembly operations, which are labor intensive, represent considerably less than 1% of the material energy content. In view of this estimate, and the accuracy of other component

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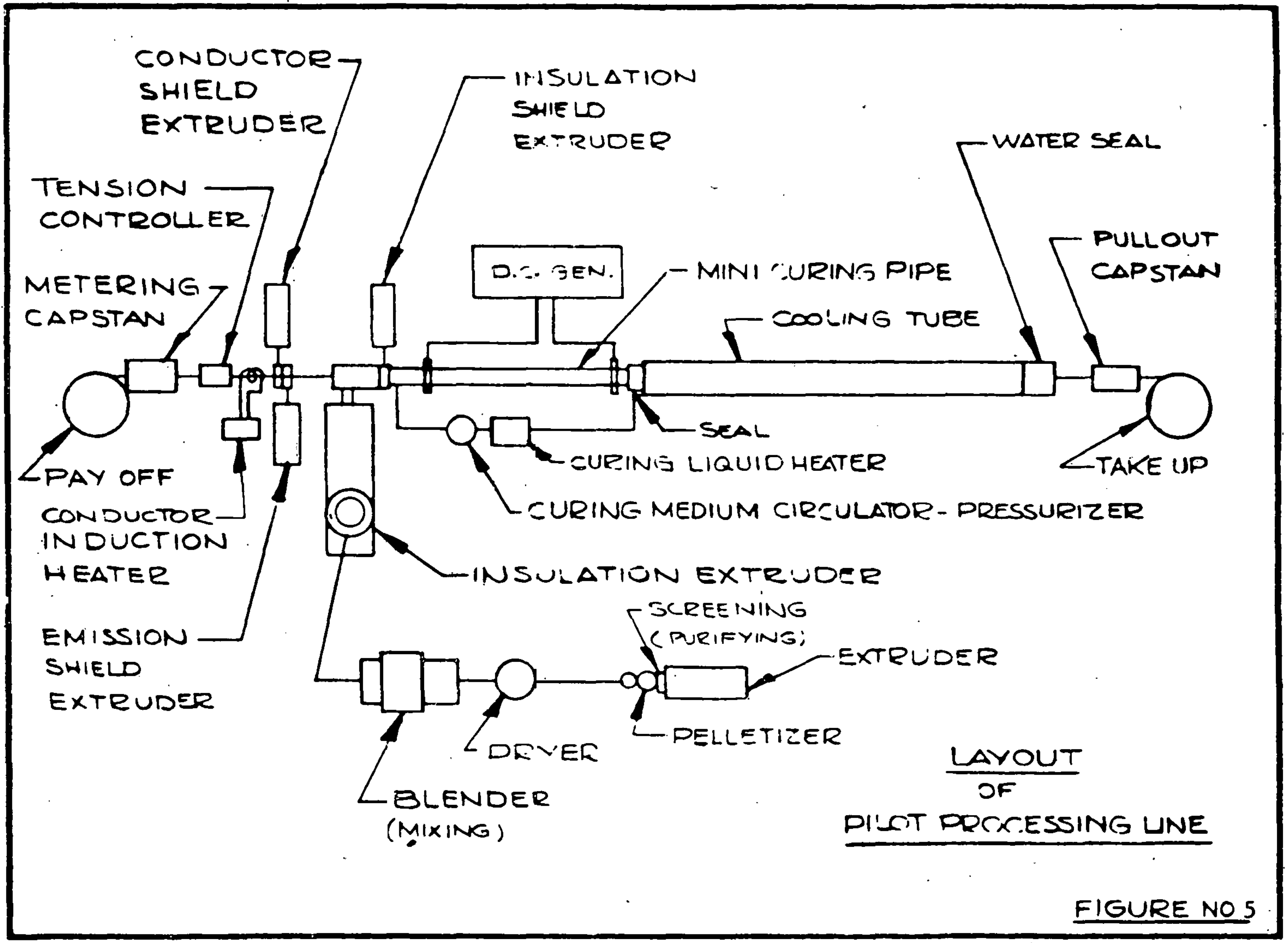
*A drawing of this type of cable is shown in Chapter VI, Figure IV.D.1; specifications for all cable designs are given in Table VI.D.1.



LAYOUT OF PILOT PROCESSING LINE

FIGURE NO 5

FIGURE V.G.1

PROPOSED EXTRUDED DIELECTRIC CABLE PRODUCTION LINE

(from Reference 2)

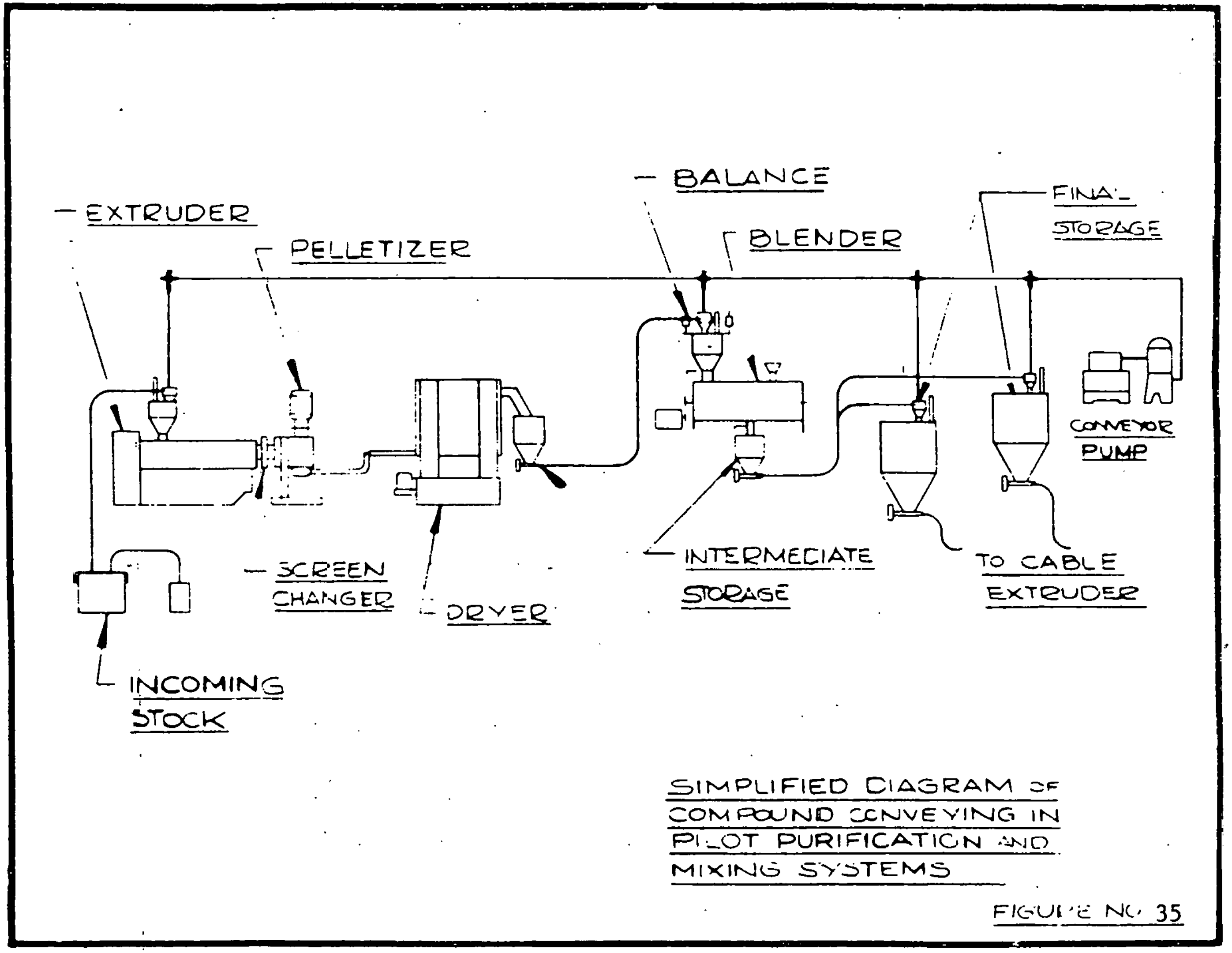


FIGURE V.G.2

POLYETHYLENE PURIFICATION SYSTEM

(from Reference 2)

TABLE V.G.1

PRODUCTION OF EXTRUDED DIELECTRIC CABLE*

Design Voltage (kV):	138	230	345
Production Speed (ft/min):	1.30	0.80	0.50
Pounds of PE per Foot of Cable:	1.07	1.87	2.76
Compounding Energy Use (Btu/ft):	6,825	11,970	17,640
Curing Energy Use (Btu/ft):	7,455	12,075	21,630
Total Energy Consumption (Btu/ft):	14,280	24,045	39,270
Total Energy Consumption (Btu/lb of PE):	13,345	12,858	14,228
Total Energy Consumption (MJ/kg of PE):	31.0	29.9	33.0

*This particular table is only accurate for a conductor size of 1,000 kcmils, and insulation specifications as given in Table VI.D.1.

energy content estimates, a detailed calculation of the manufacturing energy required to construct CGI systems has not been performed.

I. SUPERCONDUCTING SYSTEMS

Considering the fact that even the designs of superconducting systems are not known with certainty at this time, no attempt has been made to calculate the energy required to manufacture such systems. Since all superconducting systems use laminated dielectrics, like standard paper-tape cables, a very rough estimate of the manufacturing energy required for superconducting systems lies in the range of 5 to 15%.

J. OIL PRESSURIZING SYSTEMS

An oil pressurizing plant for HPOF systems typically services several circuits. Most pressurizing plants are self-contained units that can be trucked to the site and set upon a concrete base. The major components are an oil storage tank, a supporting frame, two pressurizing pumps, two motors, piping, control equipment and a protective enclosure. Table V.J.1 provides a breakdown by materials and energy content.

K. DC TERMINALS

Each dc system requires two terminals, one to rectify (ac to dc) and one to invert (dc to ac). The analysis performed in this study is based upon the Square Butte HVDC 500 MW transmission system, which uses solid-state devices (thyristors) for rectification and inversion. Component data for this terminal have been supplied by the General Electric Company.

The major components of a dc terminal are power transformers, high-voltage switches, thyristor valve assemblies, smoothing reactors, harmonic filters, lightning arresters, bushings, a protective housing and switchyard equipment. Appendix A.4 describes these components in detail. The results of this terminal energy content analysis are summarized in Table V.K.1, which lists the type, quantity and energy content of materials comprising the terminal. It will be apparent in Chapter VI that the terminal energy content is extremely high compared to the per-mile energy content of any dc line.

L. REFRIGERATION SYSTEMS

The energy content of large cryogenic refrigeration systems suitable for the proposed superconducting transmission lines has not been calculated to the same degree of accuracy as other system components for several reasons. The first is that there are no firm designs for such systems, which must provide on the order of 5 kW of cooling capacity

TABLE V.J.1

ANALYSIS OF OIL PRESSURIZING PLANT

	Component		Weight	Energy Content
1.	Base:	concrete slab, 1.5'x12'x43'	56.5 tons	8.4×10^7 Btu
2.	Steel:	tank, frame, piping, enclosure and misc.	25 tons	7.3×10^8 Btu
3.	Copper:	wiring, motors	400 lbs (est.)	1.89×10^7 Btu
4.	Oil in Tank:	20,000 gallon capacity; assume it is half full		2.4×10^9 Btu
		TOTAL ENERGY CONTENT OF OIL PRESSURIZING PLANT:		3.23×10^9 Btu (3.4×10^{12} J)

TABLE V.K.1

ENERGY CONTENT OF A 500 MW DC TERMINAL

Material	Weight (tons)	Material Energy Content (Btux10^6/ton)	Energy Content (Btux10^9)
Aluminum	61.6	224.0	13.8
Carbon steel and iron	745.0	29.2	21.8
Silicon steel	313.0	36.7	11.5
Stainless steel	1.5	36.7	.1
Copper	92.0	94.5	8.7
Transformer insulation*	114.2	52.6	6.0
Insulating oil	496.5	70.2	34.9
Porcelain	57.3	62.8	3.6
Mylar	77.5	180.0	14.0
Epoxy resin	31.5	55.8	1.8
Silicon	.57	182.0	.1
Concrete	1675.	1.5	2.5
			118.8
			(1.25 x 10^{14} J)

*Paper has been assumed.

at 12°K. Second, a cryogenic refrigeration system is far more complex than any other support system, so that an estimate of high accuracy would take considerable effort. Third, and perhaps the most compelling reason, is that a rough estimate of the total energy content of a cryogenic refrigeration unit based simply on gross weight indicates that it will not contribute more than 6% to the per-mile energy costs of the least energy-intensive superconducting line (the ± 100 kV system).

The rough estimate cited above is based upon a survey of cryogenic refrigerators performed by Strobridge,[3] from which the data shown in Figure V.L.1 have been taken. These graphs relate refrigeration requirements at a given temperature to the weight of the refrigeration units. Using 5 kW at 12°K, the weight found from the middle graph is 2×10^4 kg (22 tons). If one assumes that the refrigerator is composed entirely of stainless steel plate (50%) and pipe (50%), with an average energy content of 7.12×10^6 Btu per ton, the unit energy content is 4.7×10^9 Btu. This may be a high estimate, because a substantial part of the unit should be carbon steel pipe or plate (approximately 3.8×10^7 Btu per ton). Using three refrigeration units per station, and a spacing of 6.21 miles between stations*, the energy content per mile is 7.6×10^8 Btu per mile (5.0×10^{11} J/km). It will be shown in Chapter VI that this corresponds to about 6% of the energy contained in the cryogenic cable system on a per mile basis.

The refrigeration system energy content of all superconducting transmission systems has been estimated using Figure V.L.1 and the assumptions stated above.

*The refrigeration requirements and spacing have been specified by the Los Alamos Scientific Laboratory (LASL) for the ± 100 kV dc system; please refer to Section VI.F.

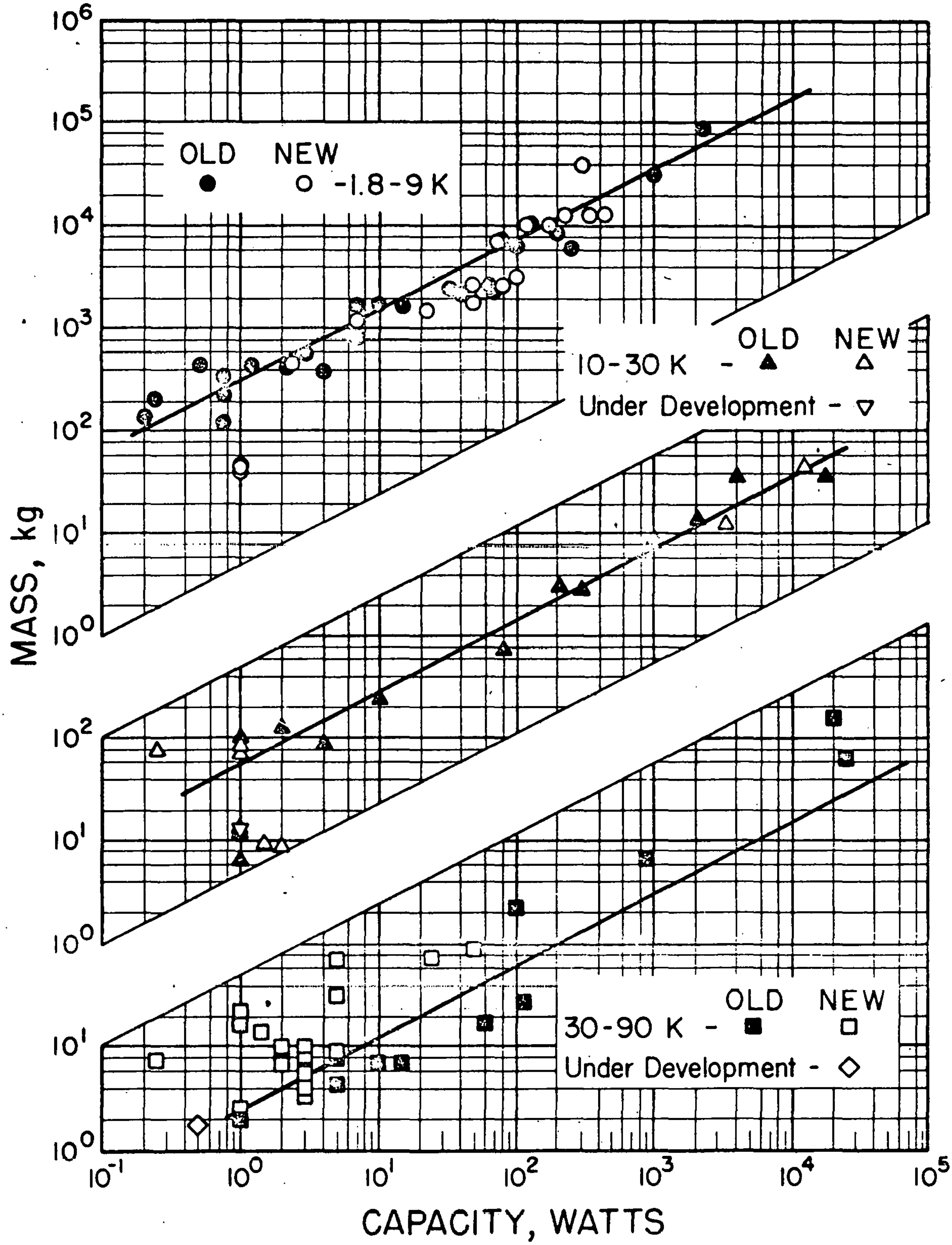


FIGURE V.L.1

MASS OF LOW TEMPERATURE REFRIGERATORS AND LIQUEFIERS AS A FUNCTION OF REFRIGERATION CAPACITY

(from Reference 3)

<u>References for Chapter V</u>

1. "Potential for Energy Conservation in the Steel Industry": prepared for the Federal Energy Administration by Battelle Columbus Laboratories, 1975: NTIS PB-244-097.

2. "Development of Extruded Dielectric Underground Transmission Cables Rated at 138 kV, 230 kV and 345 kV", Electric Power Research Institute, Report EL-428, 1977. Prepared by the General Cable Corporation, Union, New Jersey.

3. "Cryogenic Refrigerators - An Updated Survey", Dr. Richard Strobridge, National Bureau of Standards Technical Note 655, June, 1974.

VI. ENERGY CONTENT OF COMPLETE TRANSMISSION SYSTEMS (UNINSTALLED)

A. INTRODUCTION

This chapter provides the following information for each type of transmission system studied: a verbal description of the system; illustrations of cables or major components; detailed specifications of system components; a sample of the computer analysis performed on that particular type of system, and a graph of system energy content at all voltages of interest.

Although many transmission system components are standardized, the majority are not. One utility's 345 kV HPOF pipe-type cable system may differ from another utility's system in terms of conductor size (and material), pipe size, choice of insulating oil, pipe coating and so on. Consequently, it was necessary to select a single representative value for most component parameters in order to permit reasonable comparisons of transmission systems. The values selected for all components of a given system are identified in a table at the beginning of each section.

Conductor size (area) for all conventional cable systems has been standardized at 2,000 kcmils (1.5708 in^2). Insulation thickness for paper-tape cables follows AEIC specifications for 138, 230 and 345 kV. The insulation thickness values chosen for 500 and 765 kV are based upon cables developed by British Insulated Callender's Cables (BICC) Limited (References 1 and 2), and the Phelps-Dodge Wire and Cable Company, respectively (References 3 and 4).

All extruded dielectric cable specifications were taken from prototype cables developed by the General Cable Corporation. Compressed gas-insulated system information was supplied by the I-T-E Division of Gould, Inc. and the Westinghouse Electric Corporation.

The Brookhaven National Laboratory (BNL) has developed prototypical designs[5] for ac superconducting cable systems operating at 138 and 345 kV. The systems analyzed in this study are based upon the BNL designs. Los Alamos Scientific Laboratory (LASL) is performing research on superconducting cable systems also, but their work is focused on dc systems operating at 100 and 300 kV. The dc systems analyzed in this study are based upon the LASL system design[6,7,8].

The choices of conductor size and tower design for overhead lines operating at a given voltage are considerable. Conductors are normally sized to carry a particular current and meet particular strength requirements based upon span between towers. Other factors, such as minimizing corona loss and audible noise can also affect the choice of conductor specifications. The conductors selected for this study represent sizes currently in use at each operating voltage, and may be considered as average or nominal sizes for each voltage.

Overhead line support structures are also designed to meet specific requirements. The operating voltage, terrain and line route can result in differing tower or pole designs based upon span variations, clearance to ground or obstacles, function (e.g., dead-end towers versus tangent structures) and right-of-way limitations. Nevertheless, the support structures selected for use in this study have been chosen to represent typical or average structures employed at each operating voltage. Specifications for all of the ac structures analyzed were taken from poles or towers currently in use. Structures for dc lines are based upon the ± 250 kV Square Butte line and the ± 375 kV Pacific Intertie.

Table VI.A.1 lists a number of conversion factors which may be useful if metric (SI) units are of interest.

B. SELF-CONTAINED OIL-FILLED (SCOF) SYSTEMS

This type of transmission system uses a cable with an annular conductor , as shown in Figure VI.B.1. Insulating oil fills the central core and impregnates the paper insulation. The oil is kept under pressure to prevent the formation of voids in the insulation. Three types of SCOF cables are used in transmission systems. These include low-pressure oil-filled cables (commonly known as LPOF cables) which operate at 2-15 psig, medium-pressure (MPOF) cables operating at 30 to 100 psig, and HPOF cables which operate at a nominal pressure of 200 psig. SCOF cables are widely used in Europe for underground power transmission systems, but are used minimally in the U.S. where HPOF pipe-type cable systems dominate.

LPOF cables use a single or double sheath of lead; MPOF cables employ lead sheaths reinforced by bronze tapes, double lead sheaths or aluminum. HPOF cables can be manufactured using either highly-reinforced lead or extruded aluminum sheathing. All of the SCOF cables analyzed in this report employ extruded aluminum sheaths. This type has been selected because initial analyses indicated it would be the most energy-intensive SCOF cable.

Oil pressure in the cables can be maintained either through so-called "pressure tanks", which use compressed gas acting upon an oil reservoir, or a pressurizing station utilizing motor-driven pumps. LPOF and MPOF systems use pressure tanks predominately. The pressurizing station has been selected for analysis, since it can be used for both self-contained and pipe-type cables. The components of an oil pressurizing station were described in Section V.J. One third of the total station energy content has been allocated to each SCOF system, because such stations normally serve several systems.

TABLE VI.A.1

METRIC CONVERSION FACTORS

Length	Area
1 inch = 2.54 cm	1 $inch^2$ = 6.4516 cm^2 = 645.16 mm^2
1 mil = 0.001 inches = 0.0254 mm	2,000 kcmils = 1.5708 in^2
1 foot = 30.48 cm = .3048 m	2,000 kcmils = 1013.42 mm^2
1 mile = 1.61 km	1 $foot^2$ = 0.0929 m^2 = 929 cm^2

Miscellaneous

10^6 Btu = 1,055 MJ = 1,055 x 10^6 Joules

1 Btu/lb = 2,322 J/kg

10^3 Btu/ft^3 = 3.73 x 10^4 J/l

10^6 Btu/bbl = 6.64 MJ/l

10^6 Btu/ton = 1.16 MJ/kg

10^6 Btu/mile = 656 MJ/km

1 lb/ft^3 = 16.02 kg/m^3

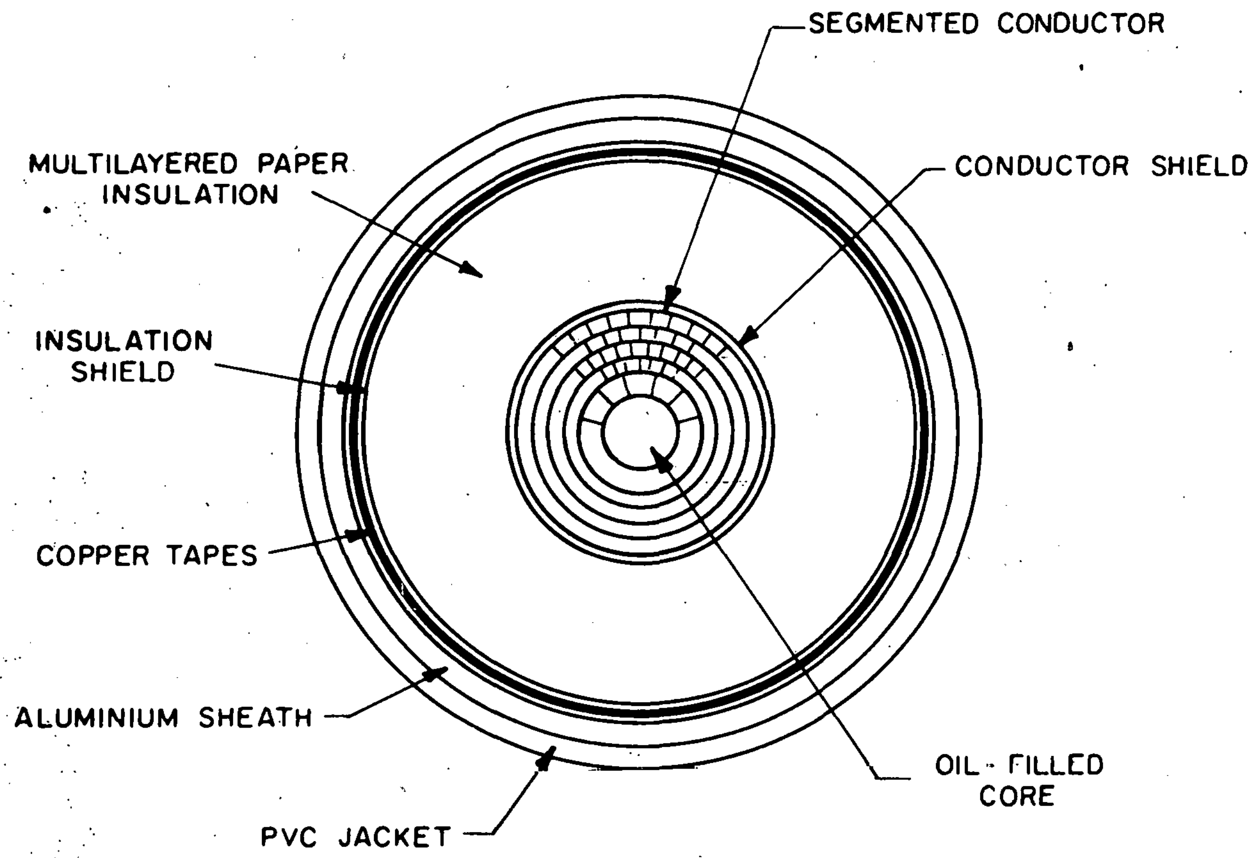


FIGURE VI.B.1

COMPONENTS OF A SELF-CONTAINED OIL-FILLED CABLE

To facilitate comparison with other types of cable systems, it has been assumed that cable joints (splices) will be made every half mile*. The only exceptions to this assumption occur for certain large-diameter cables used at 345, 500 and 765 kV, where limitations on the maximum size of a shipping reel and minimum permissible cable bending radii limit cable lengths to values less than one-half mile.

Table VI.B.1 describes the SCOF systems analyzed in this study. The type of computerized analysis performed on each system is shown in Table VI.B.2, which provides the energy content breakdown of a 138 kV SCOF system in terms of system components. Figure VI.B.2 illustrates the variation in system energy content as a function of operating voltage for all SCOF systems analyzed. Computer printouts of the analyses performed at 230, 345, 500 and 765 kV appear in Appendix A.1, in a format similar to Table VI.B.2.

C. HIGH-PRESSURE OIL-FILLED (HPOF) PIPE-TYPE CABLE SYSTEMS

HPOF pipe-type cable systems are the most common type of underground power transmission system used in the United States. Figure VI.C.1 depicts a typical 345 kV HPOF pipe-type cable. The nominal oil pressure used in systems of this type is 200 psi.

Table VI.C.1 lists and describes the components of all HPOF pipe-type systems analyzed in this study. The standard manhole spacing is 0.5 miles, except for large-diameter cables which cannot be shipped in half-mile lengths. These exceptions are noted in the table.

The energy content analysis of a typical HPOF pipe-type transmission system is shown in Table VI.C.2; this particular analysis applies to a 138 kV system. Figure VI.C.2 indicates system energy content variation at each voltage of interest. The energy content of a 765 kV cable system is lower than a 500 kV system because the thicker insulation (paper) at 765 kV "displaces" more oil from within the casing. Computer printouts of the analyses performed at 230, 345, 500 and 765 kV appear in Appendix A.1, in a format similar to Table VI.C.2.

D. EXTRUDED DIELECTRIC CABLE SYSTEMS

Extruded dielectric (ED) cables are currently in use at the 115-138 kV voltage level in the U.S. Cables for 230 and 345 kV service are under development. Figure VI.D.1 represents a design proposed by the

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*In some U.S. cities, limitations are placed upon the maximum length of open trench that is allowed. If this length is on the order of 600-800 feet, practical considerations would require 7 to 9 splices per mile.

TABLE VI.B.1

SCOF CABLE SYSTEM SPECIFICATIONS

1. Operating Voltages: 138, 230, 345, 500 and 765 kV

2. Conductor: self-supporting segmented core, overlaid with layers of flat strips; refer to Figure VI.B.1

   Material: copper or aluminum

   Conductor area: 2,000 kcmils (1.5708 in.^{2})

   Dimensions: Inner diameter = 0.6165 inches
   Outer diameter = 1.5748 inches

3. Conductor Shield:* conducting (carbon impregnated) paper tapes; total thickness = 0.010 inches.

4. Insulation: kraft paper tapes, average thickness 0.005 inches, for voltages of 138 to 500 kV inclusive; laminated paper tapes of paper/polypropylene/paper (PPP), average thickness 0.005 inches, 33.3% polypropylene, used for 765 kV cables.

Voltage (kV)	Insulation -	Radial Thickness of Insulation (inches)
138	100% paper	0.5050
230	100% paper	0.7600
345	100% paper	1.0350
500	100% paper	1.3300
765	PPP	1.4350

5. Insulating Oil: polybutene, a synthetic insulating oil with a density of 51.17 lbs/ft^3, has been selected as the standard oil for SCOF systems; it is used in the hollow core, and impregnates the paper tapes.

6. Insulation Shield:* conducting (carbon impregnated) paper tapes; total thickness = 0.010 inches.

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.B.1

SCOF CABLE SYSTEM SPECIFICATIONS (Cont'd.)

7. Outer Shield:* copper tapes, perforated; total thickness = 0.0160 inches.

8. Sheath: aluminum, extruded over the cable; sheath thickness is 0.1811 inches.

9. Jacket: polyvinyl chloride (PVC), extruded over the aluminum sheath; jacket thickness is 0.1220 inches.

10. Completed Cable: the table below lists cable outer diameter (O.D.) and weight per foot for each voltage.

Voltage (kV)	O.D. (inches)	Weight per Foot (lbs/ft)
138	3.2400	11.04
230	3.7550	12.81
345	4.3050	14.97
500	4.8950	17.56
765	5.1050	18.79

11. Joints:* the dominant material in a cable joint (splice) is the metallic shell enclosing the splice. Steel has been selected as the standard shell material, but aluminum could be used. Standard shell length is 8.0 feet; outer diameters range from 6.5 inches to 10.5 inches, and wall thickness is 0.25 inches.

12. Potheads:* the table below indicates pothead weight and energy content for each voltage.

Voltage (kV)	Weight (lbs)	Energy Content (Btu x 10^6)
138	494	13.58
230	1545	42.05
345	1830	51.00
500	3220	90.07
765	4430	123.40

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.B.2

138 kV SCOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.59
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	45.40
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.01
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		447.35	4.48
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17009.65		
OIL IN KRAFT PAPER		382.04	3.83
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10884.43		
INSULATION SCREEN		11.39	0.11
CONDUCTING PAPER			
INNER RADIUS(IN)	1.29		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	420.16		

TABLE VI.B.2

138 kV SCOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		380.28	3.81
COPPER TAPE			
INNER RADIUS(IN)	1.30		
OUTER RADIUS(IN)	1.32		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	8048.21		
CABLE SHEATH		3335.40	33.42
ALUMINUM			
INNER RADIUS(IN)	1.32		
OUTER RADIUS(IN)	1.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	29780.37		
CABLE JACKET		340.67	3.41
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.50		
OUTER RADIUS(IN)	1.62		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11096.67		
CABLE MANUFACTURING ENERGY CONTENT		290.62	2.91
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	1.05
SPLICE SHELLS		15.98	0.16
STEEL PIPE			
INNER RADIUS(IN)	3.00		
OUTER RADIUS(IN)	3.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	6.00		
TOTAL WEIGHT(LBS/MILE)	802.90		
POTHEADS		81.48	0.82
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 9980.92 MILLION BTU/MILE

(6.55×10^6 MJ/km)

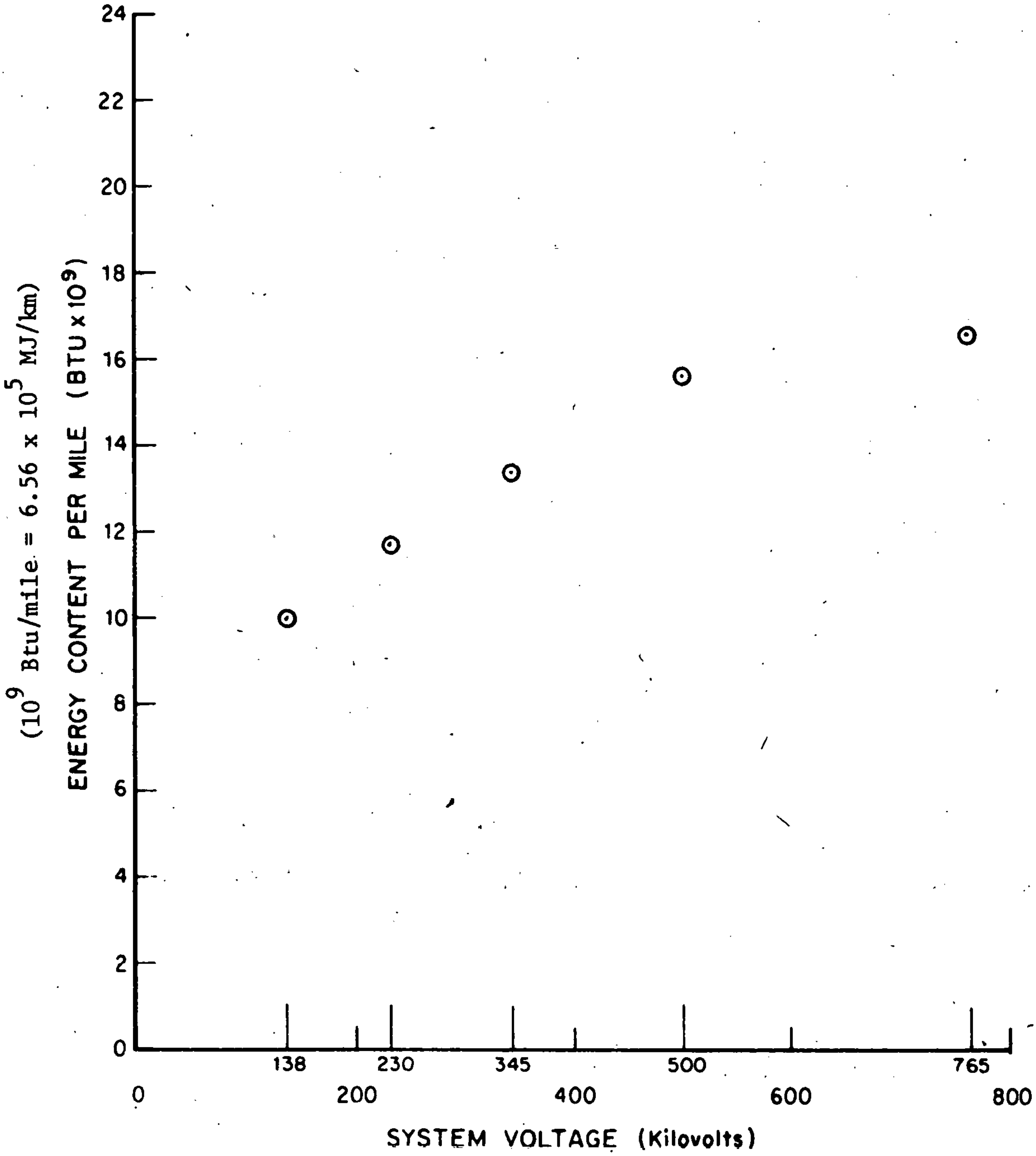

FIGURE VI.B.2

ENERGY CONTENT OF SCOF SYSTEMS

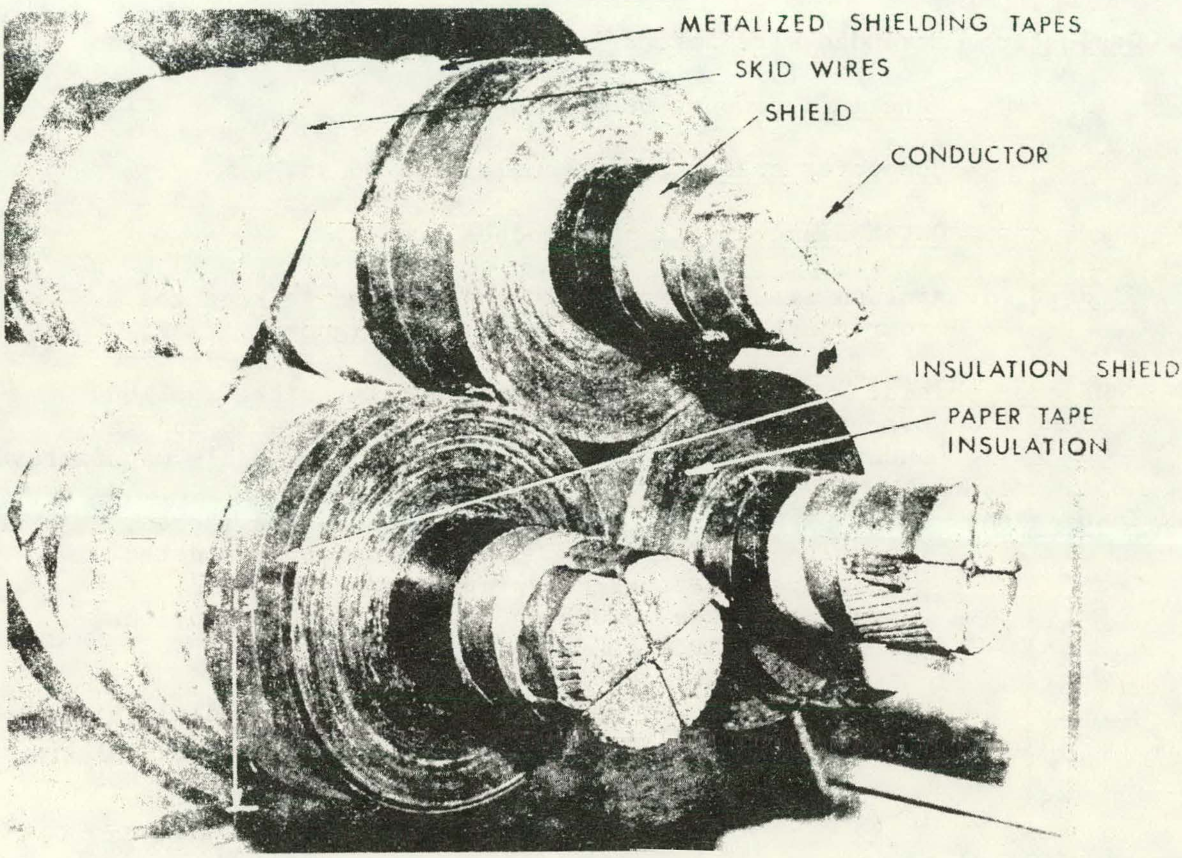

FIGURE VI.C.1

PHOTOGRAPH OF TYPICAL HIGH PRESSURE OIL-FILLED PIPE-TYPE CABLE

(Courtesy of Northeast Utilities Service Co.)

TABLE VI.C.1

HPOF PIPE-TYPE CABLE SYSTEM SPECIFICATIONS

1. Operating Voltages: 138, 230, 345, 500 and 765 kV

2. Conductor: stranded wire formed into four segments and compacted

   Material: copper or aluminum

   Conductor area: 2,000 kcmils (1.5708 in.^{2})

   Outer diameter: 1.5500 inches

3. Binder:* stainless steel tape, 5 mils thick, used to keep the four conductor sectors in proper alignment.

4. Conductor shield:* conducting paper tape, 5 mils thick; applied over the binder (note: a 5 mil tape is also applied under the binder, simultaneously, during cable manufacture).

5. Insulation: kraft paper tapes, average thickness 0.005 inches, for voltages of 138 to 500 kV inclusive; laminated paper tapes of paper/polypropylene/paper (PPP), average thickness 0.005 inches, 33.3% polypropylene, used for 765 kV cables.

Voltage (kV)	Insulation -	Radial Thickness of Insulation* inches
138	100% paper	0.5050
230	100% paper	0.7600
345	100% paper	1.0350
500	100% paper	1.3300
765	PPP	1.4350

6. Insulating oil: polybutene, a synthetic insulating oil with a density of 51.17 lbs/ft^3, has been selected as the standard oil for HPOF pipe-type systems; it impregnates the paper tapes and fills the pipe which encloses the three cables.

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*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.C.1

HPOF PIPE-TYPE CABLE SYSTEM SPECIFICATIONS (Cont'd.)

7. Insulation shield:* conducting paper tapes; total thickness = 10 mils

8. Outer shield:* perforated copper tape; thickness = 5 mils.

9. Oil barrier:* aluminized mylar tape; thickness = 5 mils.

10. Skid wires:* stainless steel, D-shaped; width = 0.2 inches, height = 0.1 inches.

11. Completed cables: the table below lists cable outer diameter (O.D.) and weight per foot for each voltage.

Voltage (kV)	O.D. (inches)	Weight per Foot (lbs/ft)
138	2.62	8.31
230	3.14	9.60
345	3.70	11.23
500	4.28	13.27
765	4.48	13.42

12. Joints:* the dominant material in a cable joint (splice) is the steel shell enclosing the joint. Shell lengths range from 8 to 10 feet; wall thickness is 0.25 inches; outer diameters range from 12.5 inches to 19.5 inches.

13. Pipe: carbon steel pipes with a 0.25 inch wall are commonly used. Pipe size as a function of system voltage is shown below.

Voltage (kV)	I.D. (inches)
138	7.500
230	8.125
345	10.125
500	12.125
765	12.125

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.C.1

HPOF PIPE-TYPE CABLE SYSTEM SPECIFICATIONS (Cont'd.)

14. Pipe coating:* bitumastic material, 0.5 inches thick.

15. Manholes:* the table below indicates manhole material content and spacing (distance between manholes) as a function of system voltage.

Voltage (kV)	Steel (tons)	Concrete (tons)	Spacing (miles)
138	2.76	27.94	0.50
230	2.76	27.94	0.50
345	3.24	32.76	0.50
500	3.33	33.65	0.38
765	3.33	33.65	0.27

16. Trifurcators:* stainless steel; the table below indicates total weight versus system voltage.

Voltage (kV)	Weight (lbs)
138	83
230	92
345	127
500	171
765	171

17 Riser pipes:* stainless steel, 30 feet in length, 6 per systems; the table below indicates size and total weight vs. system voltage.

Voltage (kV)	I.D. (inches)	Weight (lbs)
138	3.50	854
230	3.76	915
345	4.70	1412
500	5.00	1833
765	5.64	2060

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.C.1

HPOF PIPE-TYPE CABLE SYSTEM SPECIFICATIONS (Cont'd.)

18. Potheads:* the table below indicates pothead weight and energy content for each voltage.

Voltage (kV)	Weight (lbs)	Energy Content (Btu x 10^6)
138	494	13.58
230	1545	42.05
345	1830	51.00
500	3220	90.07
765	4430	123.40

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.C.2

138 kV HPOF PIPE-TYPE CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	42.82
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.38
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		448.04	4.23
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17035.80		
OIL IN KRAFT PAPER		382.63	3.62
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10901.17		

TABLE VI.C.2

138 kV HPOF PIPE-TYPE CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		11.40	0.11
CONDUCTING PAPER			
INNER RADIUS(IN)	1.30		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	420.67		
COPPER TAPE		118.49	1.12
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2507.82		
MYLAR TAPE		35.67	0.34
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	396.34		
SKID WIRES		86.15	0.81
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	1.31		
TOTAL WEIGHT(LBS/MILE)	2920.19		
CABLE MANUFACTURING ENERGY CONTENT		290.47	2.74
CASING PIPE		2179.33	20.59
STEEL PIPE			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	4.00		
TOTAL WEIGHT(LBS/MILE)	109514.25		
PIPE COATING		123.74	1.17
BITUMASTIC COATING			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.50		
TOTAL WEIGHT(LBS/MILE)	43570.43		

TABLE VI.C.2

138 kV HPOF PIPE-TYPE CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		1836.10	17.35
POLYBUTENE OIL			
RADIUS(IN)	3.75		
CABLE RADIUS(IN)	1.31		
TOTAL WEIGHT(LBS/MILE)	52310.44		
MANHOLES--CONCRETE		83.25	0.79
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.63
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		20.45	0.19
STEEL PIPE			
INNER RADIUS(IN)	5.75		
OUTER RADIUS(IN)	6.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1027.72		
TRIFURCATOR-STUBS		2.35	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	1.63		
OUTER RADIUS(IN)	1.75		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	79.75		
TRIFURCATOR-CASING		2.50	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	4.00		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	84.66		

TABLE VI.C.2

138 kV HPOF PIPE-TYPE CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		25.20	0.24
STAINLESS STEEL			
INNER RADIUS(IN)	1.75		
OUTER RADIUS(IN)	1.87		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	854.12		
POTHEADS		81.48	0.77
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.99

TOTAL ENERGY CONTENT = 10582.48 MILLION BTU/MILE

(6.94×10^6 MJ/km)

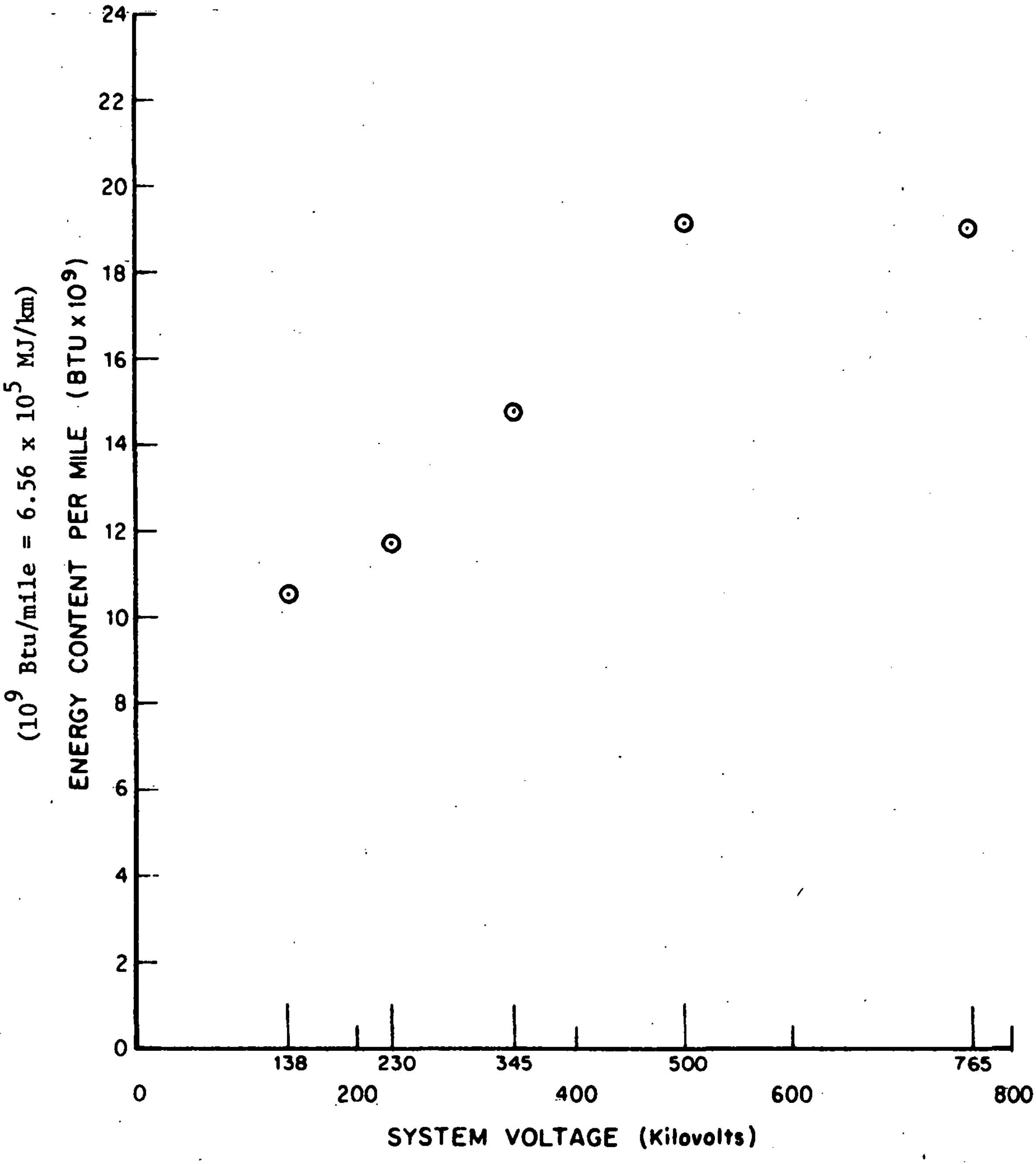
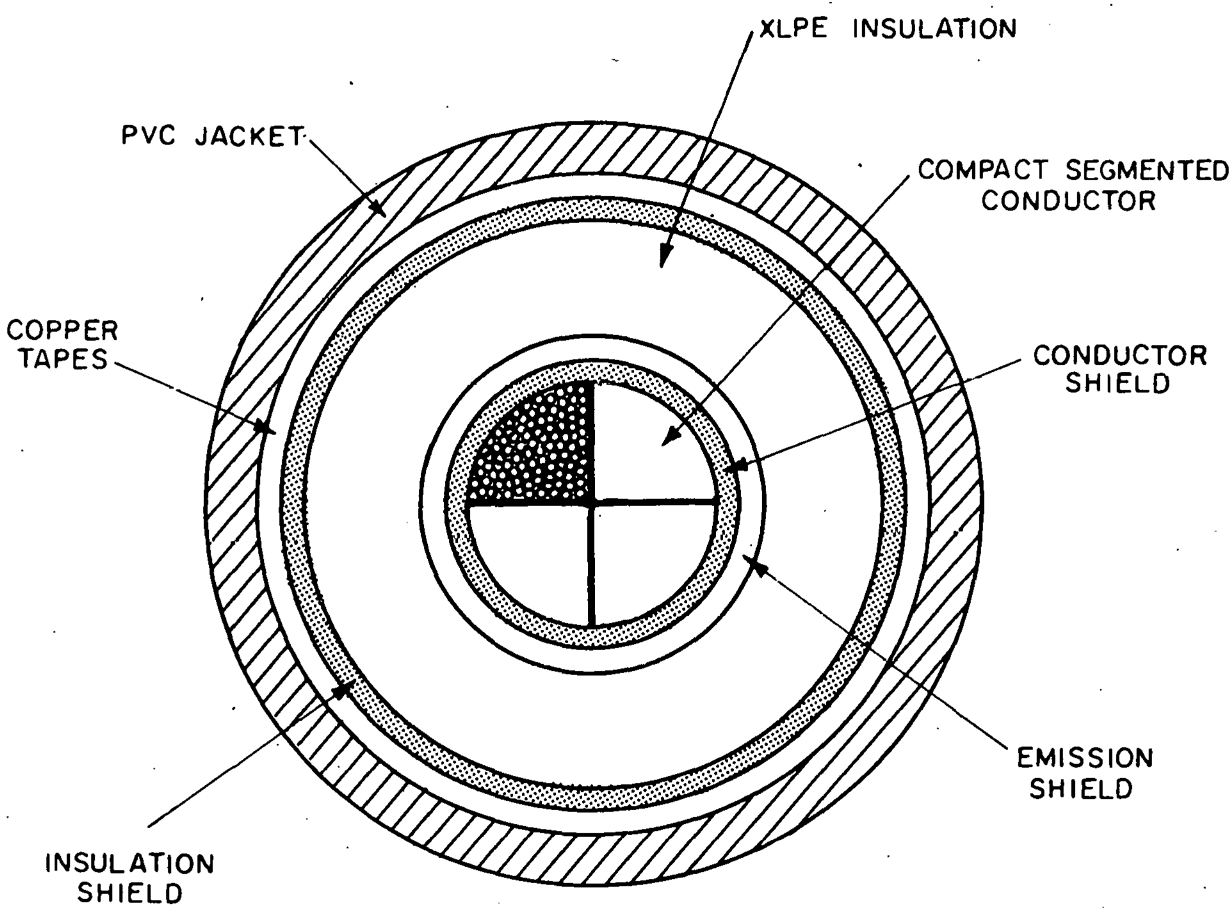


FIGURE VI.C.2

ENERGY CONTENT OF HPOF SYSTEMS



Note: The thickness of each shield has been exaggerated for clarity.

FIGURE VI.D.1

COMPONENTS OF AN EXTRUDED DIELECTRIC CABLE

General Cable Corporation* for ED transmission cables rated at 138, 230 and 345 kV. Cables currently operating at 138 kV and below do not have the emission shield shown in Figure VI.D.1, and have thicker XLPE insulation than the proposed General Cable designs. Table VI.D.1 provides additional information on the proposed design.

The energy content analysis of a 138 kV extruded dielectric cable system appears in Table VI.D.2; similar analyses have been performed for 230 and 345 kV. Figure VI.D.2 indicates the variation in total energy content of extruded dielectric cable systems at these three voltages. Appendix A.1 contains computer printouts of all ED cable system analyses.

E. COMPRESSED-GAS-INSULATED SYSTEMS

The compressed-gas-insulated transmission system investigated in this study is an isolated phase system. Thus a complete three-phase system requires three coaxial conductors of the type shown in Figure VI.E.1. The major components of a CGI system are described in Table VI.E.1.

Unlike other pressurized systems, the CGI system does not employ a pressurizing plant. The complete system is filled with sulfur hexaflouride (SF_6) to the desired pressure and effectively sealed. For example, a filling of 45 psi at 68°F will permit operation in the temperature range of -40°F to 190°F. Gas pressure is monitored during operation. Alarms are sounded at decreases of 10% and 20° below normal density.

Manufacturers presently offer systems at the standard voltages from 138 to 765 kV; 1200 kV systems are under development.

CGI phase conductors are manufactured in 60 foot lengths, which are connected in the field and welded together. The joints are essentially extensions of the conductor and enclosure, so that the energy content of a joint is comparable to an equivalent length of phase conductor.

Table VI.E.2 indicates the results of an energy content analysis performed on a 138 kV CGI system. Similar analyses were performed for the other voltages of interest; these results are shown in Figure VI.E.2. Please note that the energy content units on the vertical axis are ten times that used on previous graphs. Computer printouts of all CGI analyses can be found in Appendix A.1.

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*See Reference 2, Chapter V.

TABLE VI.D.1

EXTRUDED DIELECTRIC CABLE SYSTEM SPECIFICATIONS

1. Operating Voltages: 138, 230, 345 kV

2. Conductor: stranded wire formed into four segments and compacted

   Material: copper or aluminum

   Conductor area: 2,000 kcmils (1.5708 in.^{2})

   Outer diameter: 1.5500 inches

3. Strand Shield:* semiconducting cross-linked polyethylene (XLPE), extruded over the conductor with a thickness of 25 mils.

4. Emission Shield:* semiconducting XLPE, extruded over the strand shield with a thickness of 10 mils.

5. Insulation: XLPE, extruded over the emission shield. The table below indicates insulation thickness as a function of design voltage.

Voltage (kV)	Radial Thickness of Insulation (inches)
138	0.500
230	0.760
345	1.000

6. Insulation Shield:* semiconducting XLPE, extruded over the insulation with a thickness of 25 mils.

7. Cable Shield: copper tapes, wrapped over the insulation shield; total thickness = 10 mils.

8. Cable Jacket: Polyvinylchloride (PVC), extruded over the copper tapes with a thickness of 250 mils.

---

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.D.1

EXTRUDED DIELECTRIC CABLE SYSTEM SPECIFICATIONS (Cont'd.)

9. Completed Cables: the table below lists cable outer diameter (O.D.) and weight per foot for each voltage.

Voltage (kV)	O.D. (inches)	Weight per Foot (lbs/ft)
138	3.20	9.21
230	3.70	10.47
345	4.20	11.78

10. Joints:* ED cable splices are made using tapes of polyethylene or ethylene-propylene rubber (EPR). There is no metallic splice shell comparable to SCOF or pipe-type cable joints. Consequently, the energy content of a joint is comparable to an equivalent length of cable.

11. Potheads:* the table below indicates pothead weight and energy content for each voltage.

Voltage (kV)	Weight (lbs)	Energy Content (Btu x 10^6)
138	494	13.58
230	1545	42.05
345	1830	51.00
500	3220	90.07
765	4430	123.40

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.D.2

138 kV EXTRUDED DIELECTRIC CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		4531.05	66.58
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
STRAND SHIELD		27.43	0.40
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.80		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	781.57		
EMISSION SHIELD		11.22	0.16
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.80		
OUTER RADIUS(IN)	0.81		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	319.58		
INSULATION		738.52	10.85
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.81		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	21040.43		
INSULATION SHIELD		46.07	0.68
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.34		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1312.52		
COPPER TAPE		242.87	3.57
TWO LAYERS,0.005			
INNER RADIUS(IN)	1.34		
OUTER RADIUS(IN)	1.35		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	5140.01		

TABLE VI.D.2

138 kV EXTRUDED DIELECTRIC CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE JACKET		657.18	9.66
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.35		
OUTER RADIUS(IN)	1.60		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	21406.54		
CABLE MANUFACTURING ENERGY CONTENT		469.17	6.89
POTHEAD		81.48	1.20
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 6804.96 MILLION BTU/MILE

(4.46×10^6 MJ/km)

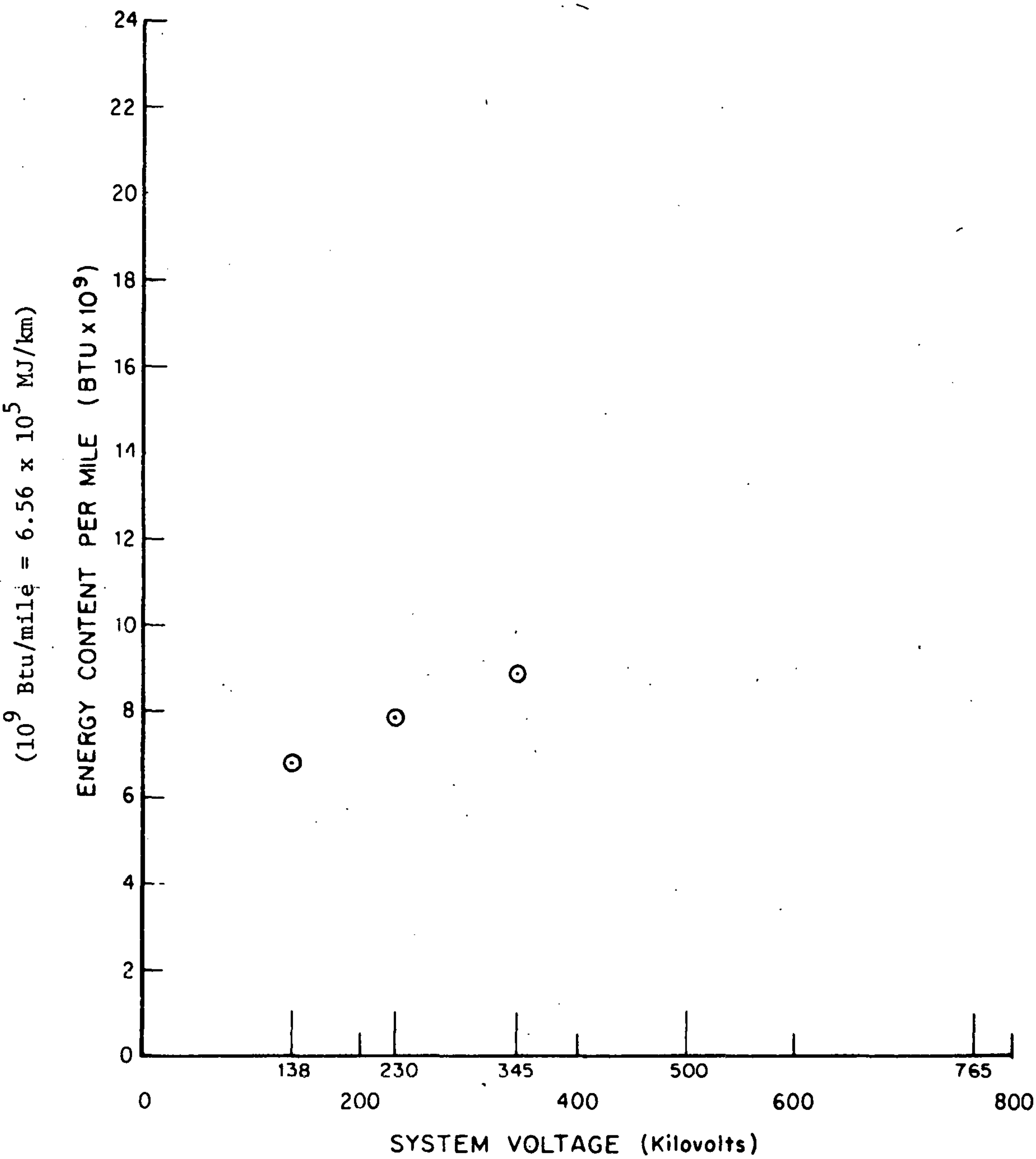

FIGURE VI.D.2

ENERGY CONTENT OF ED CABLE SYSTEMS

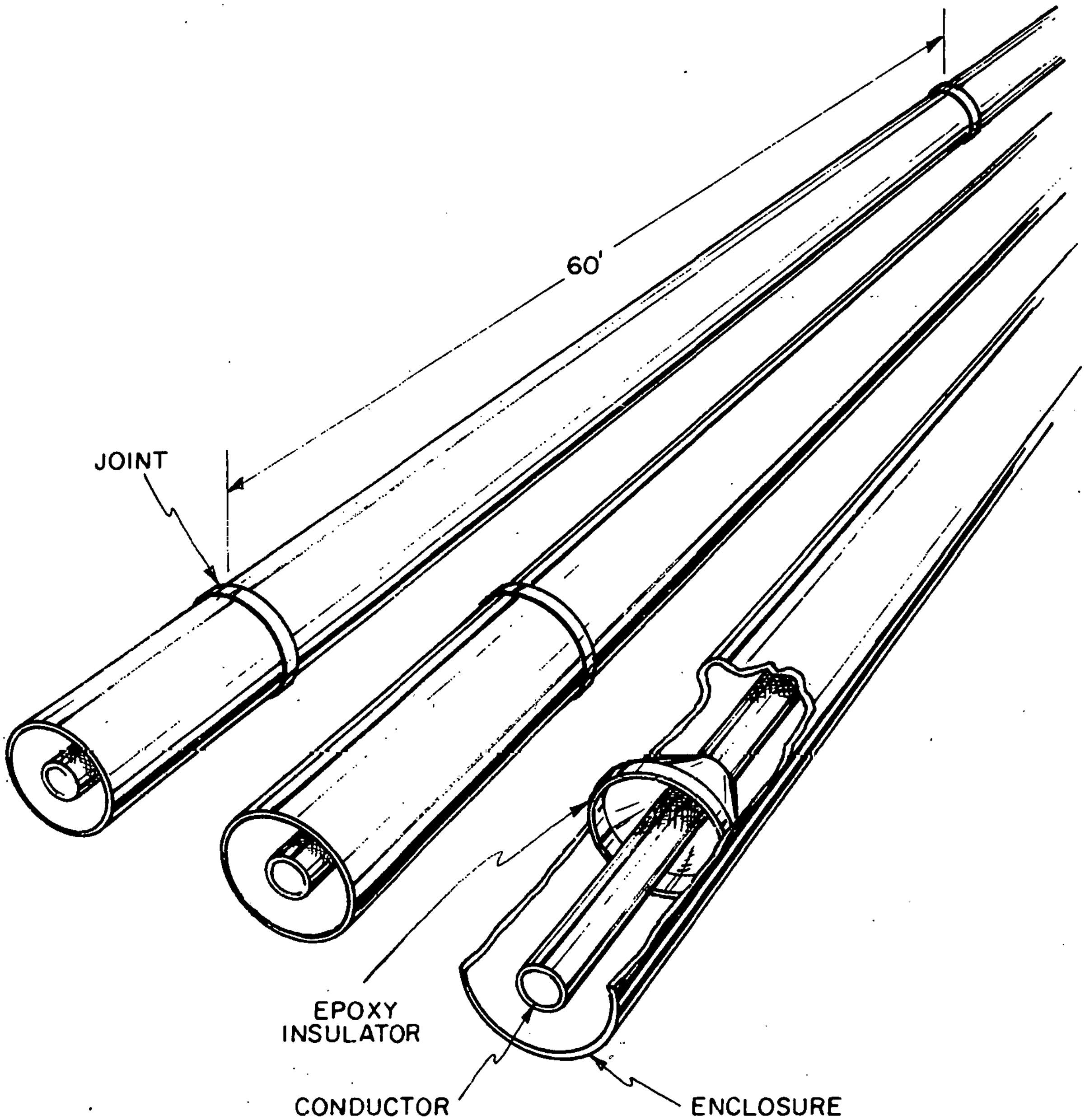

FIGURE VI.E.1

ILLUSTRATION OF CGI SYSTEM

TABLE VI.E.1

COMPRESSED GAS INSULATED SYSTEM SPECIFICATIONS

1. Operating Voltages: 138, 230, 345, 500, 765 and 1,200 kV.

2. Conductor: aluminum pipe, with O.D. from 4.5 inches to 11.0 inches depending on voltage; see table below.

Voltage (kV)	O.D. (inches)	Wall Thickness (inches)	Area ($in.^2$)
138	4.5	0.25	3.34
230	5.5	0.25	4.12
345	6.0	0.25	4.52
500	7.0	0.38	7.80
765	8.0	0.50	11.78
1200	11.0	0.50	16.49

3. Insulators:* cast cyloaliphatic alumina-filled epoxy resin, spaced every 20 feet along the conductor. Weight per insulator as a function of voltage is shown in the table of enclosure parameters found below.

4. Enclosure: aluminum pipe, with O.D. from 10.0 inches to 30.0 inches depending on voltage; see table below for details.

Voltage (kV)	O.D. (inches)	Wall Thickness (inches)	Area ($in.^2$)	Insulator Weight (lbs)
138	10.0	0.25	7.66	3.0
230	12.0	0.25	9.23	6.0
345	16.0	0.25	12.37	13.0
500	20.0	0.25	15.51	25.0
765	25.0	0.38	29.01	40.0
1200	30.0	0.38	34.90	110.0

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.E.1

COMPRESSED GAS INSULATED SYSTEM SPECIFICATIONS (Cont'd.)

5. Enclosure Coating:* bitumastic material has been selected to maintain comparability with other transmission systems; the coating is 0.5 inches thick.

6. Completed Phase Conductors: the table below lists the weight of completed single-phase conductors as a function of voltage.

Voltage (kV)	Weight of Standard 60' Length (lbs)	Weight per Foot (lbs/ft)
138	1387	23.11
230	1672	27.86
345	2160	36.00
500	2857	47.61
765	4390	73.17
1200	5496	91.60

7. Potheads:* the same type of pothead used for SCOF, pipe-type and ED cables has been selected for CGI systems to maintain comparability among systems. The table below indicates pothead weight and energy content for each voltage rating. Both weight and energy content for the 1200 kV pothead are ADL estimates.

Voltage (kV)	Weight (lbs)	Energy Content (Btu x 10^6)
138	494	13.58
230	1545	42.05
345	1830	51.00
500	3220	90.07
765	4430	123.40
1200	6800 (est.)	189 (est.)

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.E.2

138 kV COMPRESSED GAS INSULATED SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		7179.19	29.01
ALUMINUM PIPE			
INNER RADIUS(IN)	2.00		
OUTER RADIUS(IN)	2.25		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	61889.58		
INSULATORS		22.10	0.09
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	792.00		
ENCLOSURE(SHEATH)		16469.90	66.54
ALUMINUM PIPE			
INNER RADIUS(IN)	4.75		
OUTER RADIUS(IN)	5.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	141982.00		
INSULATING GAS		539.60	2.18
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	2.25		
OUTER RADIUS(IN)	4.75		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	9635.67		
PIPE COATING		458.57	1.85
BITUMASTIC COATING			
INNER RADIUS(IN)	5.00		
OUTER RADIUS(IN)	5.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	161466.87		
POTHEADS		81.48	0.33
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 24750.82 MILLION BTU/MILE

(1.62×10^7 MJ/km)

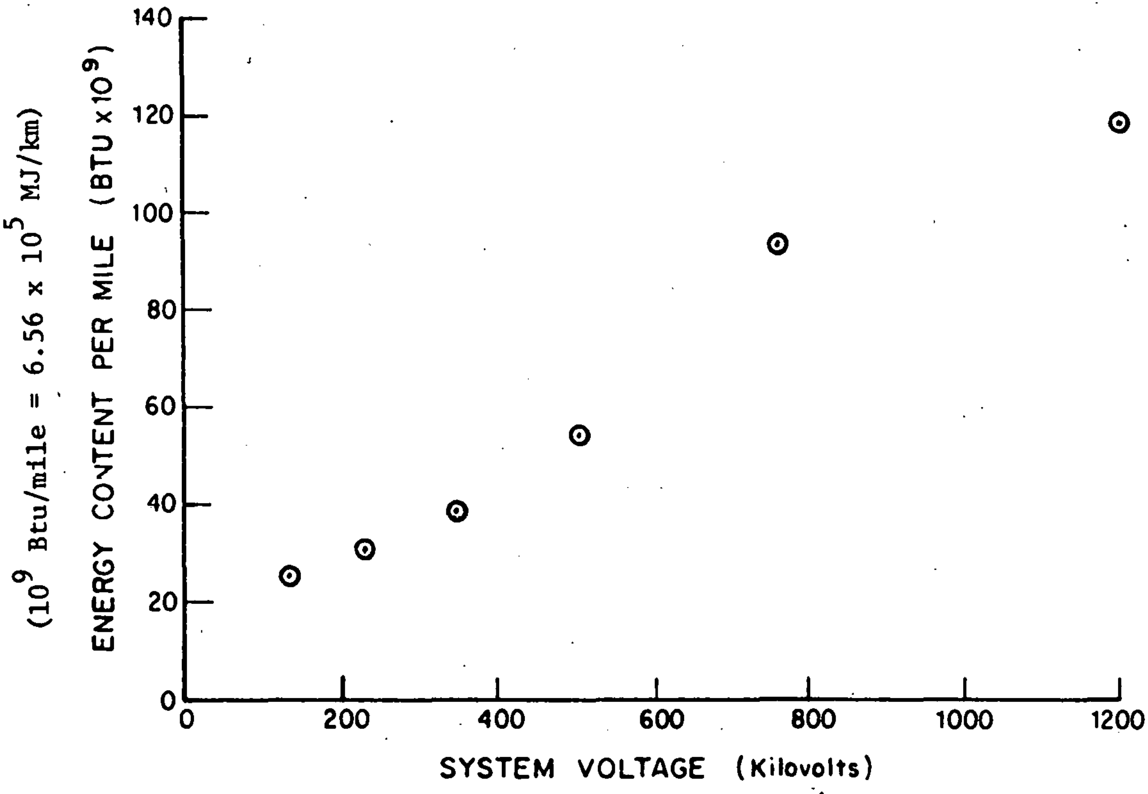

FIGURE VI.E.2

ENERGY CONTENT OF CGI SYSTEMS

F. SUPERCONDUCTING CABLE SYSTEMS

1. AC Systems

The superconducting ac system analyzed in this report is based upon a system design proposed by the Brookhaven National Laboratory (BNL); it is not identical to the BNL design. In several respects, it is similar to an HPOF pipe-type cable system; the cables are insulated with tapes of polyethylene applied in a manner similar to paper-tape cables; three cables are employed inside a casing of pipe, and the cables are pulled into the casing after it has been installed. Figure VI.F.1 illustrates the ac superconducting cable system. The cable components are described in Table VI.F.1.

Due to the hypothetical nature of these ac superconducting systems, it has been necessary to employ rough estimates of material quantity for some components and to employ surrogate components for other particular system components. These exceptions to the higher-quality information provided for most cable system components are identified in Table VI.F.1. Fortunately, in all cases these particular components contribute minimally to total system energy content.

Table VI.F.2 is an energy content analysis of a complete 345 kV ac superconducting system, which includes both the cables and refrigeration stations. Figure VI.F.2 indicates the energy content of 138 and 345 kV systems.

2. DC Systems

The dc superconducting system analyzed in this study is based upon the system design being developed by Los Alamos Scientific Laboratory (LASL). The system analyzed in not identical to the LASL system; rather, it is a simplified version. Figure VI.F.3 illustrates the nature of a single monopolar conductor. Two conductors are used per system, each corresponding to one polarity (+ or −) of a direct current system. The ± 100 kV system is rated at 5,000 MW; the ± 300 kV system is rated at 15,000 MW.

As with the ac system, the hypothetical nature of the dc systems has resulted in a number of rough estimates regarding certain components. For the purposes of this study, it is favorable that all such components contributed minimally to total energy content. All system components are described in Table VI.F.3.

The dc system employs expanders, located between refrigeration stations, to provide additional cooling capability. Figure VI.F.4 shows the proposed system configuration.

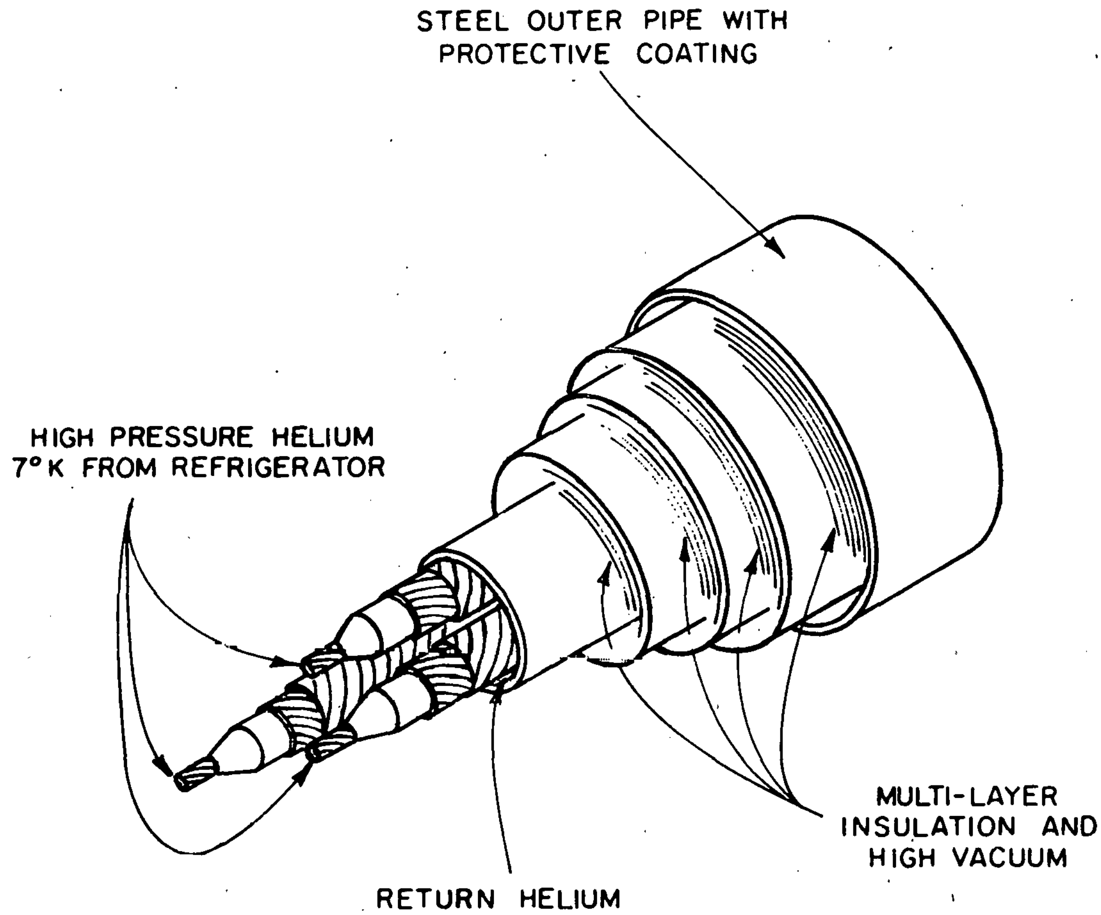

FIGURE VI.F.1

THEORETICAL DESIGN FOR AN AC SUPERCONDUCTING CABLE

(after Reference 5)

TABLE VI.F.1

AC SUPERCONDUCTING SYSTEM SPECIFICATIONS

1. Operating Voltages: 138 and 345 kV

2. Cable Components:

   a. Helical core of bronze; I.D. = 2.16 inches, thickness = 0.079 inches.

   b. Superconductor backing; aluminum strips, two layers, total thickness = 0.008 inches.

   c. Inner superconductor; laminate of aluminum (40 microns), niobium-tin (Nb_3Sn, 25 microns), and aluminum (40 microns); two layers, total thickness = 0.010 inches.

   d. Insulation; polyethylene tapes, total thickness = 0.360 inches at 138 kV and 1.110 inches at 345 kV.

   e. Outer superconductor; two layers as described above, total thickness = 0.010 inches.

   f. Superconductor backing; aluminum strips, two layers, total thickness = 0.008 inches.

   g. Polyethylene tape; thickness = 0.010 inches.

   h. Pressure barrier; lead, thickness = 0.079 inches.

   i. Polyethylene tape; thickness = 0.005 inches.

   j. Lead reinforcement; bronze tapes, total thickness = 0.020 inches.

   k. Polyethylene tape; thickness = 0.005 inches.

   l. Skid wires; stainless steel, D-shaped; width = 0.2 inches, height = 0.1 inches.

TABLE VI.F.1

AC SUPERCONDUCTING SYSTEM SPECIFICATIONS (Cont'd.)

3. Complete Cable: the table below indicates cable outer diameter (O.D.) and weight per foot for each voltage.

Voltage (kV)	O.D. (inches)	Weight per Foot (lbs/ft)
138	3.19	6.36
345	4.88	14.89

4. Inner Casing: stainless steel pipe, 0.125 inch wall thickness; 7.5 inch O.D. at 138 kV, 12.0 inch O.D. at 345 kV.

5. Coolant: liquid helium, which flows in the core of each cable at 7°K and inside the casing at 9°K.

6. Superinsulation: aluminized mylar, 0.002 inches thick, which is wrapped around the inner casing in layers; spacing between layers is 0.025 inches (40 layers per inch in the radial direction). Superinsulation fills the annular space between the inner casing and the outer casing.

7. Pipe Supports:* stainless steel wire[9]; the supports position the inner casing at the center of the outer casing; support weight is 4 lbs (estimated); spacing between supports is 12 feet.

8. Outer Casing: carbon steel pipe, 0.25 inch wall thickness; O.D. is 16.0 inches at 138 kV and 20.0 inches at 345 kV.

9. Protective Coating:* a 0.5 inch bitumastic coating has been selected to maintain comparability with other systems.

10. Manholes:* manholes designed for 345 kV HPOF pipe-type systems have been selected for both 138 and 345 kV superconducting systems, in the absence of detailed information from BNL.

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.F.1

AC SUPERCONDUCTING SYSTEM SPECIFICATIONS (Cont'd.)

11. Joints:* large-diameter stainless and carbon steel splice shells have been selected as surrogate components for superconducting cable splices, in the absence of detailed information from BNL.

12. Potheads:* standard 345 kV HPOF pipe-type cable potheads have been selected as surrogate components for superconducting cable potheads, due to the lack of any prototype design.

13. Refrigeration Stations:* the refrigeration units must meet the following cooling requirements: 2.60 kW in the 6-9°K range; 8.84 kW at 85°K. Total station weight is 18.2 tons; energy content is 1.30 x 10^9 Btu per station. Spacing between stations is 7.08 miles.

*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.F.2

345 kV AC SUPERCONDUCTING SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		893.56	3.32
LIQUID HELIUM			
RADIUS(IN)	1.08		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	3075.95		
HELICAL CORE		1906.29	7.09
BRONZE			
INNER RADIUS(IN)	1.08		
OUTER RADIUS(IN)	1.16		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	32901.13		
SUPERCOND. BACKING		243.68	0.91
ALUMINUM STRIP			
INNER RADIUS(IN)	1.16		
OUTER RADIUS(IN)	1.18		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2137.55		
SUPERCONDUCTOR		216.53	0.81
BNL SUPER. ALLOY			
INNER RADIUS(IN)	1.18		
OUTER RADIUS(IN)	1.19		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2014.19		
INSULATION		2692.23	10.02
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.19		
OUTER RADIUS(IN)	2.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	76701.75		
SUPERCONDUCTOR		422.10	1.57
BNL SUPER. ALLOY			
INNER RADIUS(IN)	2.30		
OUTER RADIUS(IN)	2.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	3926.48		

TABLE VI.F.2

345 kV AC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SUPERCOND. BACKING		482.79	1.80
ALUMINUM STRIP			
INNER RADIUS(IN)	2.31		
OUTER RADIUS(IN)	2.32		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	4235.00		
PLASTIC TAPE		32.41	0.12
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.32		
OUTER RADIUS(IN)	2.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	923.34		
CABLE SHEATH		776.49	2.89
LEAD			
INNER RADIUS(IN)	2.33		
OUTER RADIUS(IN)	2.41		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	91351.62		
PLASTIC TAPE		16.80	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.41		
OUTER RADIUS(IN)	2.41		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	478.78		
REINFORCEMENT		1048.52	3.90
BRONZE TAPE			
INNER RADIUS(IN)	2.41		
OUTER RADIUS(IN)	2.43		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	18096.63		
PLASTIC TAPE		16.98	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.43		
OUTER RADIUS(IN)	2.44		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	483.75		

TABLE VI.F.2

345 kV AC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SKID WIRES		76.53	0.28
STAINLESS STEEL			
NO. PER PHASE	1.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	2.44		
TOTAL WEIGHT(LBS/MILE)	2594.34		
INNER CASING		3158.12	11.75
STNLS. STEEL PIPE			
INNER RADIUS(IN)	6.00		
OUTER RADIUS(IN)	6.12		
TOTAL WEIGHT(LBS/MILE)	83880.87		
HELIUM COOLANT		4645.72	17.29
LIQUID HELIUM			
RADIUS(IN)	6.00		
CABLE RADIUS(IN)	2.43		
TOTAL WEIGHT(LBS/MILE)	15992.16		
SUPER INSULATION		3653.68	13.59
ALUMINIZED MYLAR			
INNER RADIUS(IN)	6.12		
OUTER RADIUS(IN)	9.75		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	46249.08		
PIPE SUPPORTS		51.92	0.19
STAINLESS STEEL			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	440.00		
TOTAL WEIGHT(LBS/MILE)	1760.00		
OUTER CASING		5553.79	20.66
STEEL PIPE			
INNER RADIUS(IN)	9.75		
OUTER RADIUS(IN)	10.00		
TOTAL WEIGHT(LBS/MILE)	279084.75		

TABLE VI.F.2

345 kV AC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
PIPE COATING		298.43	1.11
BITUMASTIC COATING			
INNER RADIUS(IN)	10.00		
OUTER RADIUS(IN)	10.50		
TOTAL WEIGHT(LBS/MILE)	105081.62		
MANHOLES--CONCRETE		97.62	0.36
CONCRETE			
WEIGHT/UNIT (TON)	32.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	131039.94		
MANHOLES--STEEL		202.18	0.75
STEEL ROD			
WEIGHT/UNIT (TON)	3.24		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	12960.00		
SPLICE SHELLS		45.75	0.17
STNLS. STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1215.22		
SPLICE SHELLS		38.67	0.14
STEEL PIPE			
INNER RADIUS(IN)	15.00		
OUTER RADIUS(IN)	15.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1943.05		
POTHEADS		306.00	1.14
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		
REFRIGERATION STATION ENERGY CONTENT		183.	.67

TOTAL ENERGY CONTENT = 27060. MILLION BTU/MILE

(1.78×10^7 MJ/km)

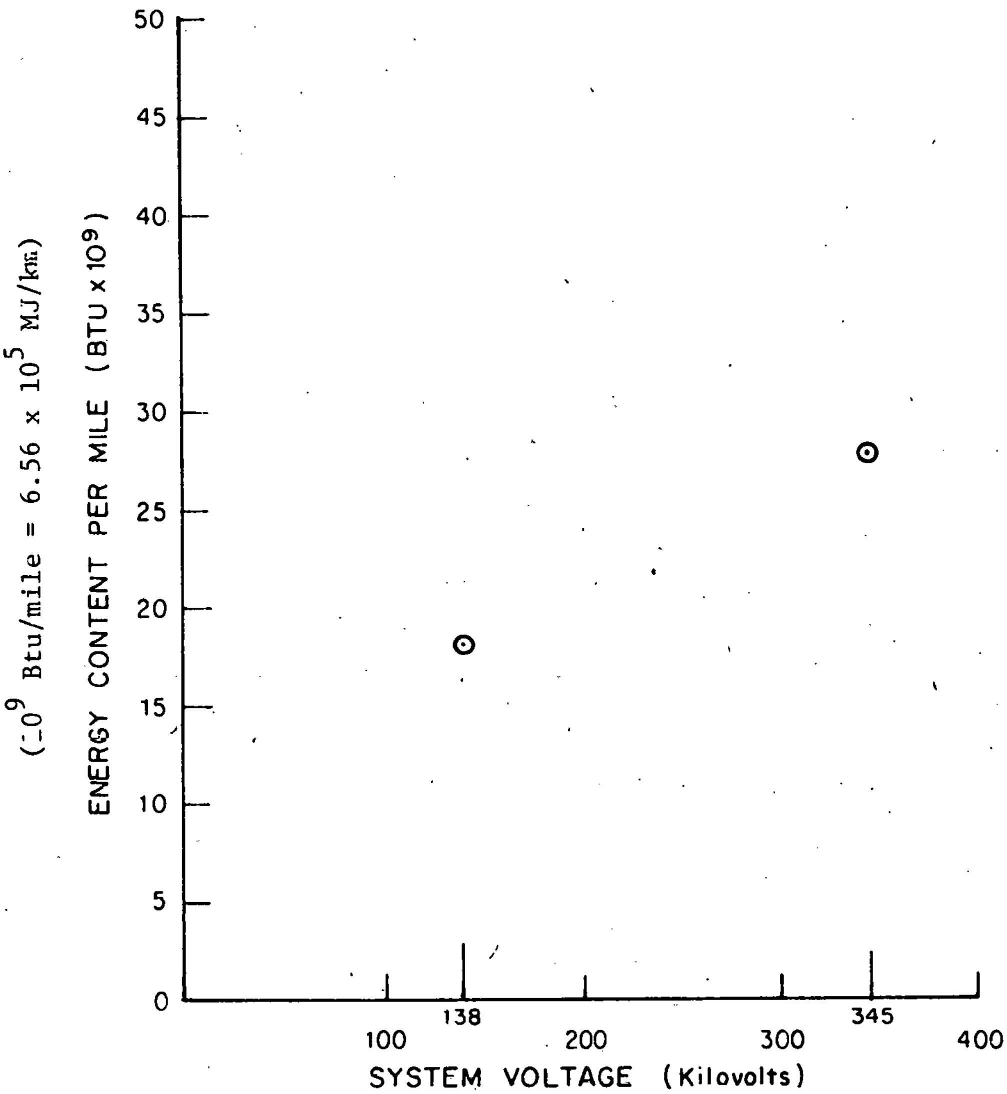

FIGURE VI.F.2

ENERGY CONTENT OF AC SUPERCONDUCTING SYSTEMS

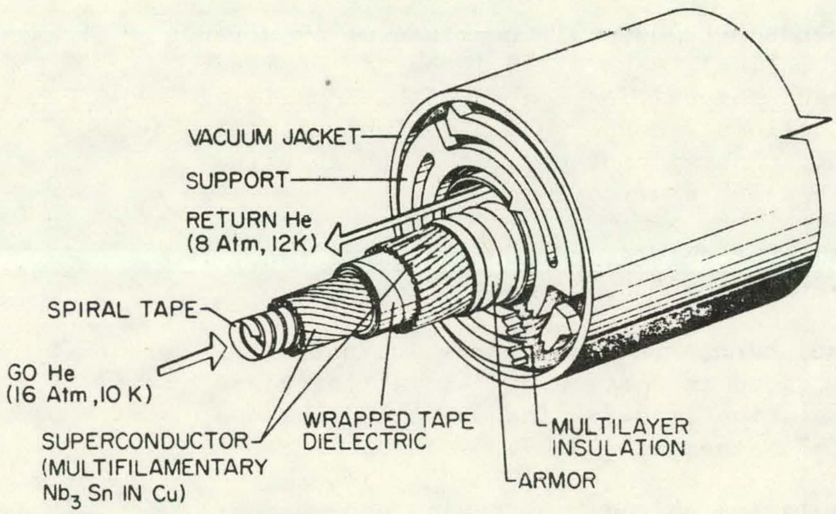

FIGURE VI.F.3

DC SUPERCONDUCTING CABLE DESIGN PROPOSED BY LASL

(from Reference 8)

TABLE VI.F.3

DC SUPERCONDUCTING SYSTEM SPECIFICATIONS

1. Operating Voltages: 100 and 300 kV

2. Cable Components:

   a. Helical core of bronze; I.D. = 2.283 inches, thickness = 0.039 inches.

   b. Inner superconductor; consists of 49 strands (subcables), each 0.150 inches in diameter. Strand composition, on a weight-% basis, is as follows: copper, 93.5%; niobium, 4.8%; tin, 1.7%. Energy content of the subcable is 1.16×10^8 Btu/ton.

   c. Conductor shield; conducting paper tape; two layers, each 0.005 inches thick.

   d. Insulation; synthetic paper laminate (PPP) as described in Section B. Radial thickness of insulation is 0.544 inches at 100 kV, and 0.753 inches at 300 kV.

   e. Insulation shield; conducting paper tape; two layers, each 0.005 inches thick.

   f. Outer superconductor; consists of 141 subcables, each 0.087 inches in diameter.

   g. Bronze "armor"; wall thickness = 0.039 inches.

3. Complete Cable: the tables below indicate cable outer diameter (O.D.) and weight per foot for each voltage.

Voltage (kV)	O.D. (inches)	Weight per Foot (lbs/ft)
100	4.20	11.21
300	4.80	13.90

TABLE VI.F.3

DC SUPERCONDUCTING SYSTEM SPECIFICATIONS (Cont'd.)

4. Inner Casing: stainless steel pipe, 0.250 inch wall thickness; I.D. = 7.00 inches at 100 kV and 8.50 inches at 300 kV.

5. Coolant: liquid helium, which flows in the hollow core at 10°K and between the bronze armor and the inner casing at 12°K.

6. Superinsulation: aluminized mylar, 0.002 inches thick, which is wrapped around the inner casing in layers; spacing between layers is 0.025 inches (40 layers per inch in the radial direction). Superinsulation fills the annular space between the inner casing and the outer casing.

7. Pipe Supports:* epoxy resin; these maintain the inner casing at the center of the outer casing; support weight is 2.0 lbs (estimated); spacing between supports is 7.0 feet.

8. Outer Casing: carbon steel pipe, 0.25 inch wall thickness; O.D. is 11.50 inches at 100 kV and 14.5 inches at 300 kV.

9. Protective Coating:* a 0.5 inch bitumastic pipe coating has been selected to maintain comparability with other systems.

10. Manholes:* manholes designed for 138 and 345 kV HPOF systems have been selected as surrogates for the junction boxes proposed by LASL.

11. Joints:* annular splice shells of stainless and carbon steel have been selected as surrogates for the joint coverings proposed by LASL.

12. Potheads:* standard 138 and 345 kV HPOF-type cable potheads have been selected as surrogate components for superconducting cable potheads to maintain comparability with the ac system.

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*Components marked by an asterisk contribute minimally to total energy content, i.e. they represent 3% or less of the total.

TABLE VI.F.3

DC SUPERCONDUCTING SYSTEM SPECIFICATIONS (Cont'd.)

13. Refrigeration Stations: the refrigeration units must be able to provide 5 kW of cooling capacity at 12°K. Three units are used per station, each weighing 22 tons. Total energy content is 4.7×10^9 Btu per station. Spacing between stations is 6.21 miles.

14. Expanders: the estimated weight of three expanders located at each expansion site is 6 tons; the estimated energy content is 6.8×10^8 Btu per site.

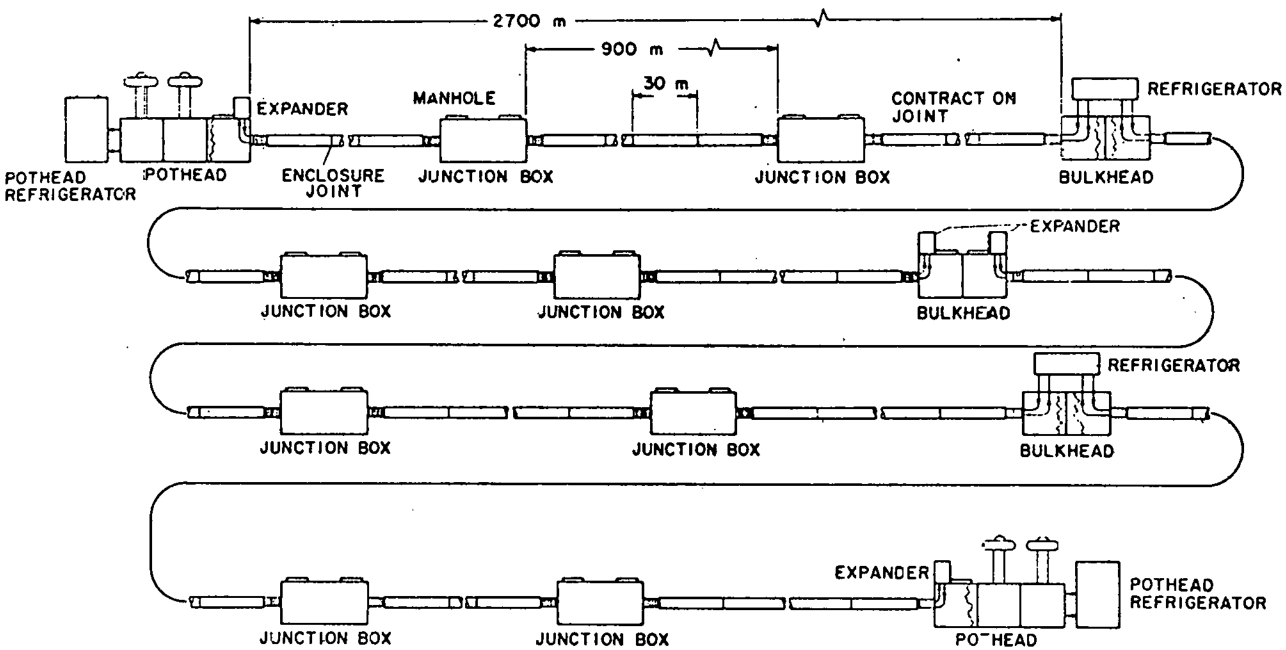


FIGURE VI.F.4

DC SUPERCONDUCTING CABLE SYSTEM PROPOSED BY LASL

(after Reference 8)

The type of superconductor used in the dc system differs considerably from that used in the ac system. Figure VI.F.5 illustrates one of the filamentary dc conductors, which is produced from bronze-filled niobium tubes embedded in a copper matrix. LASL refers to these filamentary conductors as "subcables".

Table VI.F.4 contains the results of an energy content analysis performed on the ± 100 kV dc superconducting system. Upon examination of this table, it will be evident that treatment of the dc terminals (one rectifying, one inverting) is the most important factor in determining system energy content on a per-mile basis. A typical line length of 200 miles has been selected since that value is commonly used as a rough estimate of the minimum economic length for dc overhead lines. If a much shorter length is considered, say 20 miles, the system energy content would increase from 28.03×10^9 to 142.33×10^9 Btu per mile.

Figure VI.F.6 indicates the energy content per mile for dc superconducting systems rated at 100 and 300 kV. The computer analysis of the 300 kV system appears in Appendix A.1.

G. OVERHEAD LINES

This section includes both ac and dc overhead transmission systems. Conductors for all systems are aluminum conductor, steel reinforced (ACSR). Energy content analyses of overhead (OH) systems determined that conductors represented 38 to 65% of the total energy content, and were the dominant system component for voltages of 345 kV and above. As a result of this finding, the specifications of overhead conductors selected for this study are given in considerable detail in Table VI.G.1.

Standard suspension insulators of porcelain and steel were selected for all of the overhead systems analyzed. Table VI.G.2 lists the size used at each voltage, the configurations employed, number and total weight of insulators per tower. In the absence of data on ± 800 kV insulation practice, estimates were supplied by ADL.

It is standard practice in the utility industry to use mulitple conductors per phase (bundled conductors) for overhead lines operating at 345 kV or higher. Bundled conductors are kept in the desired alignment by spacers, which may be constructed of steel or aluminum. Aluminum has been selected as the standard material for all OH lines analyzed in this study. Table VI.G.3 provides information on spacer weight and usage per mile for each operating voltage.

Various types of yokes, clamps, shackles and other miscellaneous items are required at each tower to make proper connections between the conductors, insulator strings and towers. These connecting items are usually made of galvanized steel. All such items are referred to collectively as line mounting hardware in this study. Table VI.G.3 also indicates the total weight of line mounting hardware per tower at each voltage.

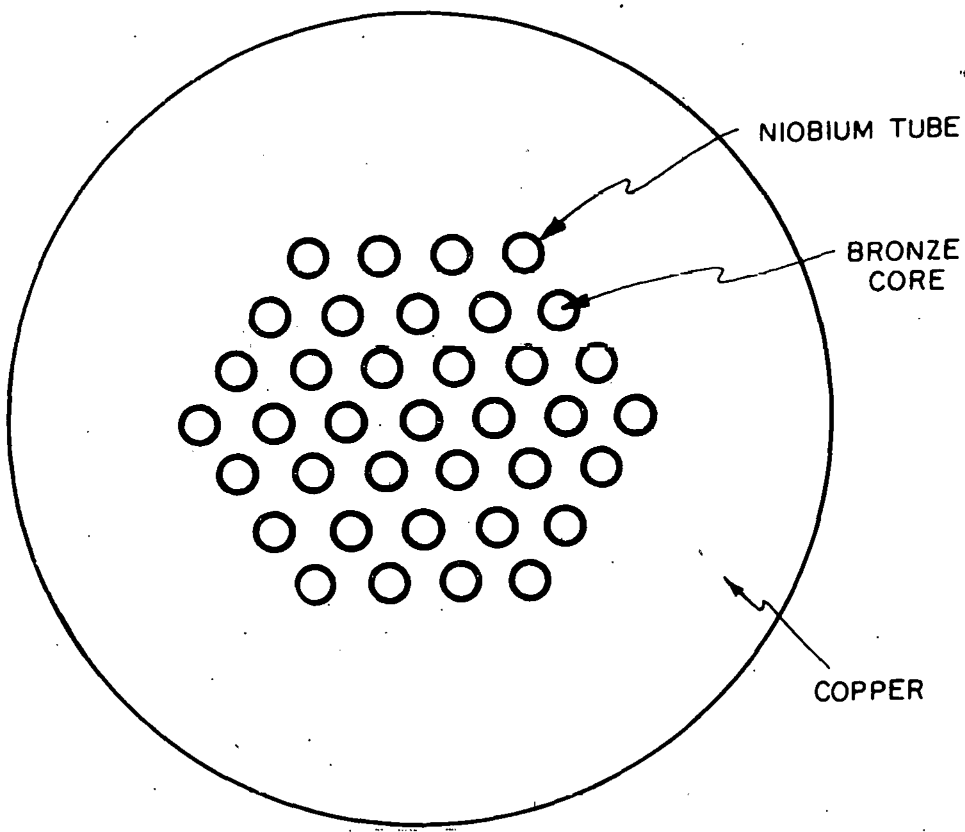


FIGURE VI.F.5

DRAWING OF SUPERCONDUCTING SUBCABLE: LASL DESIGN

TABLE VI.F.4

100 kV DC SUPERCONDUCTING SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		332.37	2.34
LIQUID HELIUM			
RADIUS(IN)	1.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1144.12		
HELICAL CORE		329.83	2.32
BRONZE			
INNER RADIUS(IN)	1.14		
OUTER RADIUS(IN)	1.18		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	5692.66		
INNER SUPERCONDUCTOR		1011.61	7.12
LASL SUPER. ALLOY			
INNER RADIUS(IN)	1.18		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17438.48		
COND PAPER TAPE		3.86	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	1.32		
OUTER RADIUS(IN)	1.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	142.58		
INSULATION		283.56	2.00
SYNTHETIC PAPER			
INNER RADIUS(IN)	1.33		
OUTER RADIUS(IN)	1.87		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	9914.59		
COND PAPER TAPE		5.47	0.04
CONDUCTING PAPER			
INNER RADIUS(IN)	1.87		
OUTER RADIUS(IN)	1.88		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	201.88		

TABLE VI.F.4

100 kV DC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SUPERCONDUCTOR		881.14	6.20
LASL SUPER. ALLOY			
INNER RADIUS(IN)	1.88		
OUTER RADIUS(IN)	1.94		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	15189.45		
CABLE ARMOR		615.02	4.33
BRONZE			
INNER RADIUS(IN)	2.15		
OUTER RADIUS(IN)	2.19		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10614.79		
INNER CASING		3935.73	27.71
STNLS. STEEL PIPE			
INNER RADIUS(IN)	3.50		
OUTER RADIUS(IN)	3.75		
TOTAL WEIGHT(LBS/MILE)	104534.56		
HELIUM RETURN		1905.87	13.42
LIQUID HELIUM			
INNER RADIUS(IN)	2.19		
OUTER RADIUS(IN)	3.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	6560.66		
SUPER INSULATION		1027.35	7.23
ALUMINIZED MYLAR			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	5.50		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	13004.38		
INSULATORS		42.07	0.30
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	754.00		
TOTAL WEIGHT(LBS/MILE)	1508.00		

TABLE VI.F.4

100 kV DC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER CASING		3163.55	22.27
STEEL PIPE			
INNER RADIUS(IN)	5.50		
OUTER RADIUS(IN)	5.75		
TOTAL WEIGHT(LBS/MILE)	158972.25		
PIPE COATING		174.69	1.23
BITUMASTIC COATING			
INNER RADIUS(IN)	5.75		
OUTER RADIUS(IN)	6.25		
TOTAL WEIGHT(LBS/MILE)	61511.19		
MANHOLES--CONCRETE		83.25	0.59
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.21
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		33.42	0.24
STNLS. STEEL PIPE			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	887.52		
SPLICE SHELLS		28.44	0.20
STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1429.17		

TABLE VI.F.4

100 kV DC SUPERCONDUCTING SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
TERMINATION		27.16	0.19
100KV RATING			
UNITS PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	988.00		

TOTAL ENERGY CONTENT = 14204.10 MILLION BTU/MILE

B. Refrigeration Stations

Spacing: every 6.21 miles (10 kilometers)

Number: three (3) at each site

Capacity: 5 kW of cooling capacity (each) at 12°K

Input: 1,000 kW per unit

Total weight: 66 tons (three units)

Dominant material: stainless steel; plate and pipe (50% each)

Total energy content: 4.7 x 10^9 Btu/station

REFRIGERATION ENERGY CONTENT = 760 x 10^6 Btu/mile

TABLE VI.F.4

100 kV DC SUPERCONDUCTING SYSTEM (Cont'd.)

C. Expanders

Spacing: every 6.21 miles (10 kilometers)

Number: three (3) at each site

Materials: stainless steel (76%), aluminum 24%)

Est. total weight: 6 tons (three units)

Est. total energy content: 6.75×10^{8} Btu/station

EXPANDER ENERGY CONTENT = 109×10^{6} Btu/mile

D. DC Terminals

Energy content = 2.38×10^{8} Btu/MW of capacity

5,000 MW terminal = 1.19×10^{12} Btu; two (2) required

Total terminal energy content = 2.38×10^{12} Btu

Assume 200-mile length (comparable to dc overhead lines)

DC TERMINAL ENERGY CONTENT = 11.9×10^{9} Btu/mile

E. Totals

The cable and support systems for the 100 kV, 5,000 MW superconducting transmission line are listed and summed below.

A.	Cable and enclosure	14.204×10^{9} Btu/mile
B.	Refrigeration systems	$.704 \times 10^{9}$ Btu/mile
D.	Expanders	$.109 \times 10^{9}$ Btu/mile
E.	DC terminals	11.880×10^{9} Btu/mile

COMPLETE SYSTEM TOTAL = 26.953×10^{9} Btu/mile

(1.77×10^{7} MJ/km)

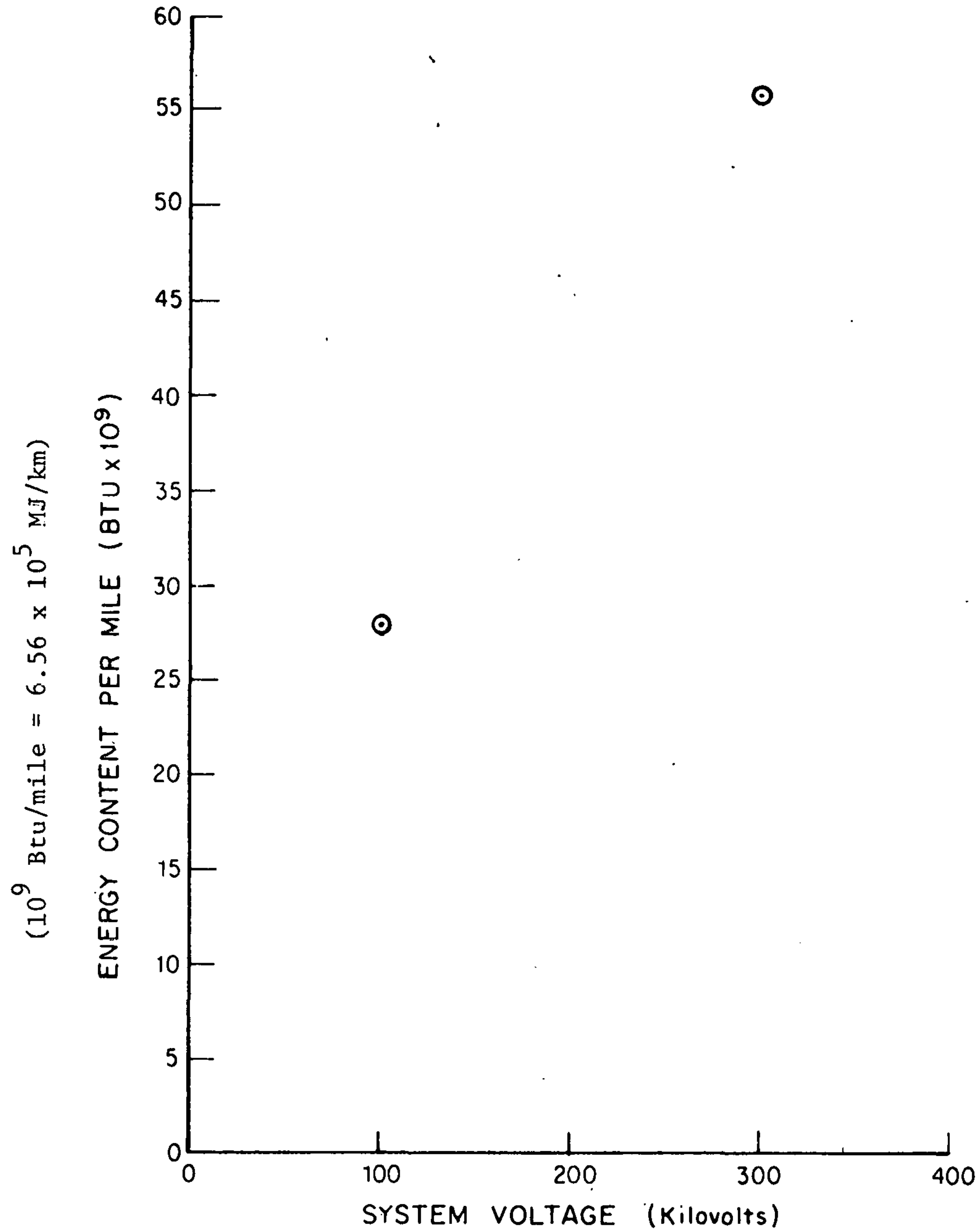


FIGURE VI.F.6

ENERGY CONTENT OF DC SUPERCONDUCTING SYSTEMS

TABLE VI.G.1

OVERHEAD CONDUCTOR SPECIFICATIONS

Voltage (kV)	Number of Conductors per Phase or per Pole -	Conductor Size (Area) (kcmils)	Code Name -	Conductor O.D. (inches)	Conductor Weight (#/mile)	Number of Aluminum Strands -	Aluminum Strand Diameter (in.)	No. of Steel Strands -	Steel Strand Diamete[r] -
138	1	954	Cardinal	1.196	6,479	54	.1329	7	.1329
230	1	1,114	Finch	1.293	7,544	54	.1436	19	.0862
345	2	954	Cardinal	1.196	6,479	54	.1329	7	.1329
500	3	1,193	Grackle	1.338	8,082	54	.1486	19	.0892
765	4	1,352	Martin	1.424	9,160	54	.1582	19	.0949
1,200	8	1,781	Chukar	1.602	10,951	84	.1456	19	.0874
± 200	1	2,167	Kiwi	1.735	12,160	72	.1735	7	.1157
± 400	2	2,312	Thrasher	1.802	13,337	76	.1744	19	.0814
± 600	4	954	Cardinal	1.196	6,479	54	.1329	7	.1329
± 800	4	1,352	Martin	1.424	9,160	54	.1582	19	.0949

Notes: 1,200 kV based on BPA data; ± 200 kV based on Square Butte (± 250 kV) line; ± 400 kV based on Pacific Intertie (± 375 kV); ± 600 kV based on Project UHV-DC test line; ± 800 kV based on ADL estimates. All other voltages reflect nominal values of conductor sizes in use.

TABLE VI.G.2

SUSPENSION INSULATOR DATA

Voltage (kV)	Insulator String Config.*	Type of Insulator Used (Rating) and Weight (lbsx10^3; lbs)	Number of Strings per Phase or per pole	Number of Insulators per String	Number of Insulators per Tower	Total Weight of Insulators per Tower
138	SS	20; 12.5	1	8	24	300
230	SS	20; 12.5	1	14	42	525
345	SS, CVS	30; 15.0	1,2,1	19, 20	78	1,170
500	SS, CVS	40; 16.8	1,2,1	24	96	1,613
765	2V	40; 16.8	4	35	420	7,056
1,200	V	120; 45.0	2	29	174	7,830
± 200	SS	30; 15.0	1	17	34	510
± 400	SS	40; 16.8	1	24	48	806
± 600	V	40; 16.8	2	26	104	1,747
± 800**	2V	40; 16.8	4	39	312	4,930

*SS = single string per phase or pole.
CVS = center V - suspension.
2V = double V (four strings).

**Note: ± 800 kV data based on ADL estimates.

TABLE VI.G.3

CONDUCTOR SPACERS AND LINE MOUNTING HARDWARE DATA

Voltage (kV)	Number of Conductors per Phase or per Pole -	Number of Spacers per Mile -	Spacer Weight (lbs)	Total Spacer Weight in System per Mile (lbs)	Total Weight of Hardware per Tower (lbs)
138	1	0	0	0	38
230	1	0	0	0	38
345	2	18	15.61	843	71
500	3	19	17.30	986	75
765	4	21	22.34	1,407	393
1,200	8	70	45.00	9,450	3,150
± 200	1	0	0	0	25
± 400	2	18	15.61	562	48
± 600*	4	21	22.34	938	100
± 800*	4	21	22.34	938	263

*ADL estimates.

Overhead line supporting structures, i.e., towers and poles, are designed to meet particular geographic requirements in terms of span length, vertical clearance requirements and function, as discussed perviously in Section A. Table VI.G.4 lists the specifications of line support structures that are representative of typical structures used at each operating voltage. Lattice towers of steel have been selected for most of the systems, to maximize comparability. Figure VI.G.1 illustrates several of these towers. The primary exception to this practice occurs for the ± 200 kV dc line, where aluminum lattice towers were used. These towers were selected because the sole ± 250 kV line operating in the U.S. employs this particular design.

Overhead ground conductors, also known as shield wires, are designed to carry lightning stroke currents and are essentially independent of line voltage. A nominal 7/16 inch O.D. Class A galvanized EHS steel wire with a 6/1 strand configuration has been selected as the shield wire to be used for all systems. Individual strands are 0.145 inches in diameter, the O.D. of the complete wire is 0.455 inches, and it weighs 2,107 pounds per mile. All dc lines and the two lowest voltage ac lines (which are pole-mounted) use one shield wire per circuit. All other ac lines use two shield wires per circuit.

Table VI.G.5 and VI.G.6 are energy content analyses of 138 kV and 345 kV systems respectively. The latter is presented here since it is the lowest voltage to require bundled conductors. The ± 400 kV dc system is analyzed in Table VI.G.7. Figure VI.G.2 shows the energy content of all overhead lines analyzed, as a function of line voltage. Computer printouts of all the analyses represented in Figure VI.G.2 appear in Appendix A.1.

Inspection of Figure VI.G.2 reveals again that the energy content of rectifying and inverting terminals adds considerably to the total energy content of direct current systems. The energy cost of going from a 765 kV system (with four conductors per phase) to a 1,200 kV system (with eight conductors per phase) is also significantly higher, on a percentage basis, than the increase between any other consecutive line voltages.

TABLE VI.G.4

OVERHEAD LINE SUPPORT STRUCTURE DATA

Voltage (kV)	Type of Structure	Weight[1] (lbsx10^3)	Spacing Between Structures (feet)	Height Above Ground (feet)	Dimensions of Base (ftxft)	Foundation Details		
						Type	Steel (lbsx10^3)	Concrete (yds^3)
	-					-		
138	Pole	12.0	640	63	N.A.[2]	PC[3]	-	6.35
220	Pole	16.0	640	75	N.A.[2]	PC	-	9.31
345	Lattice Tower	14.3	800	96	25x25	G[4]	3.6	-
500	Lattice Tower	30.0	1,000	105	29x29	G	6.4	-
765	Lattice Tower	54.0	1,320	139	40x40	G	11.2	-
1,200	Lattice Tower	148.0	1,320	226	50x50	G	26.1	-
± 200	Lattice Tower	2.0	800	75	N.A.	PF[5]	1.3	2.92
± 400	Lattice Tower	10.0	1,000	116	22x22	G	3.0	-
± 600	Lattice Tower	25.0	1,320	125	25x25	G	5.0	-
± 800	Lattice Tower[6]	54.0	1,320	139	40x40	G	11.2	-

Notes:
1. All towers and poles are assumed to consist of structural steel, except the ± 200 kV tower (see 5 below).
2. Not applicable is abbreviated as N.A.
3. Poured-in-place concrete foundation.
4. Grillage foundation of steel.
5. The ± 200 kV towers are aluminum, and use precast foundations of concrete with steel reinforcement.
6. The ± 800 kV towers were assumed to be identical to 765 kV towers, since no ± 800 kV towers have been built.

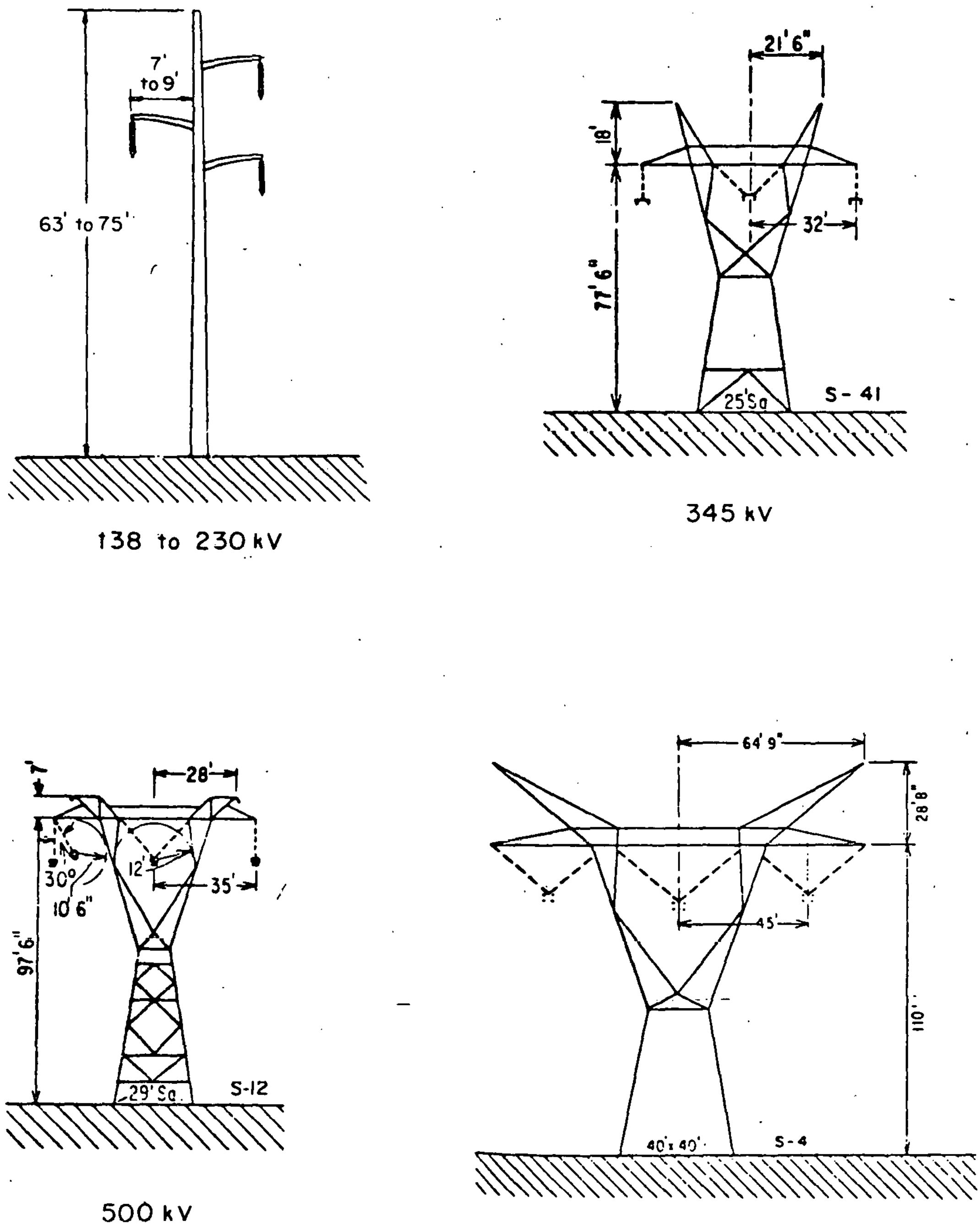


FIGURE VI.G.1

OVERHEAD TRANSMISSION TOWER DESIGNS

(after Reference 10)

TABLE VI.G.5

138 kV AC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		95.79	2.46
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	5618.33		
CONDUCTOR		1585.13	40.79
ALUMINUM WIRE			
NO. PER PHASE	1.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	954.00		
TOTAL WEIGHT(LBS/MILE)	13904.69		
CONDUCTOR SPACERS		0.0	0.0
ALUMINUM			
WEIGHT/UNIT (TON)	0.0		
NO. UNIT PER MILE	0.0		
TOTAL WEIGHT(LBS/MILE)	0.0		
LINE HARDWARE		4.89	0.13
STEEL			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	313.50		
SUSPENSION INSULATOR		38.61	0.99
20K RATING			
UNITS PER MILE	198.00		
TOTAL WEIGHT(LBS/MILE)	2475.00		
TOWERS		1970.10	50.69
STEEL PIPE			
WEIGHT/UNIT (TON)	6.00		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	99000.00		

TABLE VI.G.5

138 kV AC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--CONCRETE		153.66	3.95
CONCRETE			
WEIGHT/UNIT (TON)	12.50		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	206250.00		
SHIELD WIRES		38.01	0.98
EHS STEEL CABLE			
NO. PER PHASE	0.33		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	2229.30		

TOTAL ENERGY CONTENT = 3886.19 MILLION BTU/MILE

(2.55×10^6 MJ/km)

TABLE VI.G.6

345 kV AC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		191.59	3.56
EHS STEEL CABLE			
NO. PER PHASE	2.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	11236.66		
CONDUCTOR		3170.27	58.89
ALUMINUM WIRE			
NO. PER PHASE	2.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	954.00		
TOTAL WEIGHT(LBS/MILE)	27809.39		
CONDUCTOR SPACERS		94.41	1.75
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	54.00		
TOTAL WEIGHT(LBS/MILE)	842.94		
LINE HARDWARE		7.31	0.14
STEEL			
WEIGHT/UNIT (TON)	0.04		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	468.60		
SUSPENSION INSULATOR		119.38	2.22
30K RATING			
UNITS PER MILE	514.80		
TOTAL WEIGHT(LBS/MILE)	7722.00		
TOWERS		1377.95	25.59
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	7.15		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	94379.94		

TABLE VI.G.6

345 kV AC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		346.90	6.44
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	1.80		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	23759.99		
SHIELD WIRES		76.01	1.41
EHS STEEL CABLE			
NO. PER PHASE	0.67		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.19		

TOTAL ENERGY CONTENT = 5383.81 MILLION BTU/MILE

(3.53×10^6 MJ/km)

TABLE VI.G.7

± 400 kV DC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		130.05	2.01
EHS STEEL CABLE			
NO. PER PHASE	2.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.04		
TOTAL WEIGHT(LBS/MILE)	7627.83		
CONDUCTOR		5122.33	79.29
ALUMINUM WIRE			
NO. PER PHASE	2.00		
NO. STRANDS	76.00		
STRAND RADIUS(IN)	0.09		
CROSS SECTION(KCMIL	2312.00		
TOTAL WEIGHT(LBS/MILE)	44932.73		
CONDUCTOR SPACERS		62.94	0.97
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	36.00		
TOTAL WEIGHT(LBS/MILE)	561.96		
LINE HARDWARE		3.95	0.06
STEEL			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	253.44		
SUSPENSION INSULATOR		63.10	0.98
40K RATING			
UNITS PER MILE	253.40		
TOTAL WEIGHT(LBS/MILE)	4257.12		
TOWERS		770.88	11.93
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	5.00		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	52799.98		

TABLE VI.G.7

$\pm$ 400 kV DC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		231.26	3.58
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	1.50		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	15840.00		
SHIELD WIRES		76.02	1.18
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.64		

TOTAL ENERGY CONTENT = 6460.52 MILLION BTU/MILE

(4.24×10^6 MJ/km)

Note: The energy cost of two $\pm$ 400 kV dc terminals (one rectifying, one inverting) is 6.85×10^{11} Btu. If we assume that a minimum length for dc lines is 200 miles, the apportioned energy cost of terminals is 3.43×10^9 Btu/mile. This is about 53% of the total above.

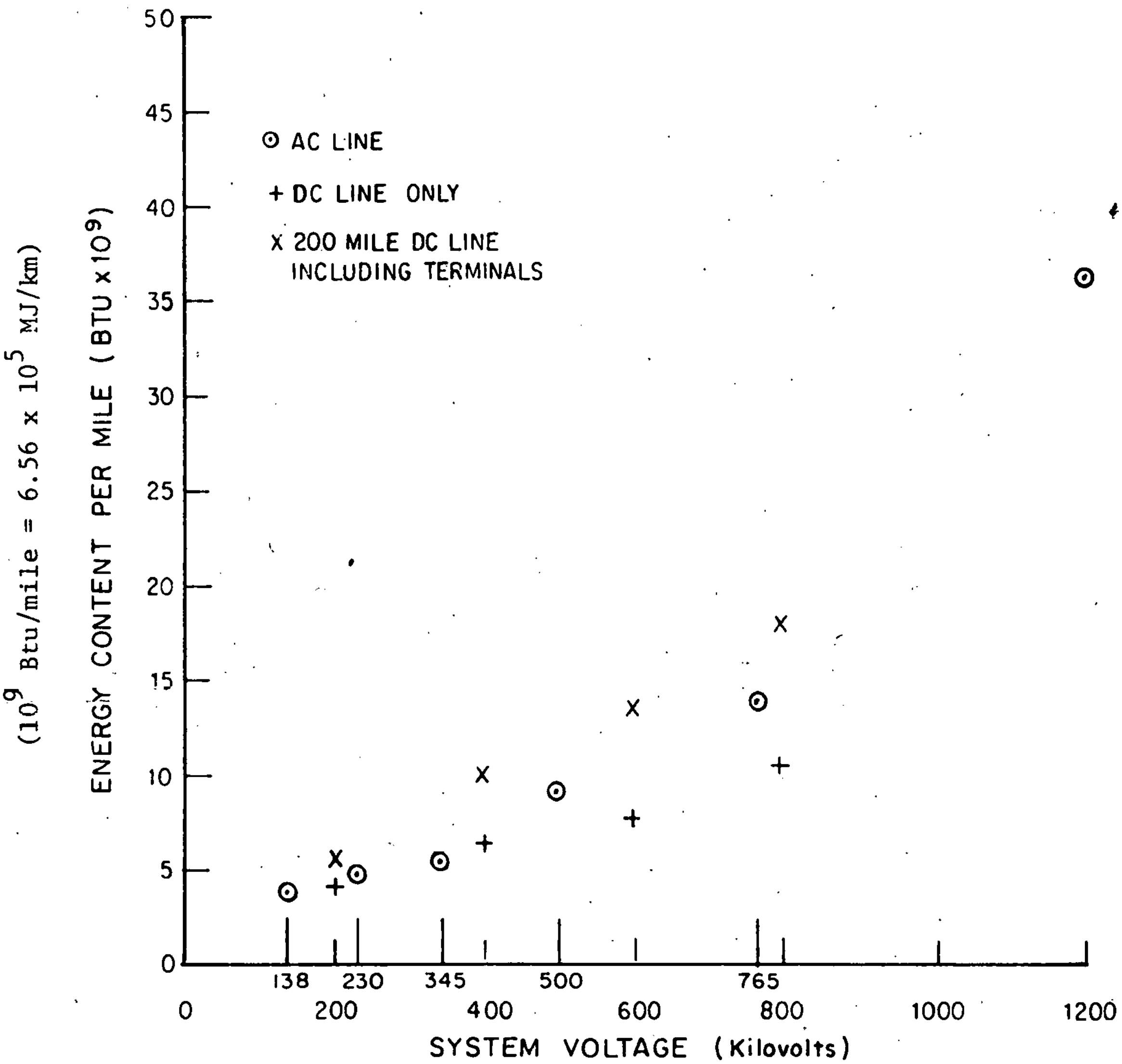


FIGURE VI.G.2

ENERGY CONTENT OF OVERHEAD LINES

<u>References for Chapter VI</u>

1. "Oil-filled Cable Systems", British Insulated Callender's Cables (BICC) Limited, 1970; U.S. address: P.O. Box 223, Media, Pennsylvania 19063.

2. "525 kV Self-contained Oil-filled Cable Systems for Grand Coulee Third Powerplant Design and Development", Arkell, et al., IEEE Transmission Paper T 73 492-6, 1973.

3. "Low-loss 765 kV Pipe-type Power Cable", Allam, et al., IEEE F 78 175-2, 1978.

4. "Low-loss 765 kV Pipe-type Power Cable - Part II", Allam, et al., IEEE F 79 278-3, 1979.

5. "The Theoretical and Economic Feasibility of Superconducting Power Transmission: A Case Study", Beck, et al., IEEE T 74 462-8, 1974.

6. "Some Electrical Characteristics of a DC Superconducting Cable", Chowdhuri, et al., IEEE Transactions on Power Apparatus and Systems; Vol. PAS-97, No. 2, March/April, 1978.

7. "Development and Prospects for Application of Superconducting DC Cables", W.E. Keller, Los Alamos Scientific Laboratory (LASL) Report LA-UR-77-712, 1977.

8. "DC Superconducting Power Transmission Line Project at LASL", Progress Report No. 19, LA-7116-PR, Bartlett, et al., September, 1977.

9. "Engineering Cost Analysis for Cryogenic Cable Enclosures", H.M. Lutgen, Minnesota Valley Engineering, New Prague, Minnesota; prepared for BNL Purchase Order No. 414286-S.

10. <u>Transmission Line Reference Book, 345 kV and Above</u>, published by the Electric Power Research Institute, Palo Alto, California 94304.

VII. INSTALLATION OF TRANSMISSION SYSTEMS

A. INTRODUCTION

The energy requirements associated with installation of a given transmission system depend strongly upon the types of environment encountered. For the purposes of this study, three standard environments have been selected. These correspond to rural, suburban and urban installations of each system, as appropriate.* Suburban areas have been treated as a mixture of urban and rural requirements in terms of energy content. For example, clearing rights-of-way (ROWs) in suburban areas is estimated to require only 25% of the energy needed to clear rural areas.

The types of construction activities associated with installation of transmission systems are listed below.

Underground Cables	Overhead Lines
Transport of materials	Clearing rights-of-way
Breakup and disposal of pavement	Transport of materials
Excavation	Excavation
Trench shoring	Erection of towers or poles
Emplacement of pipe	Attachment of insulator strings
Pipe welding	Stringing of conductors and shield wires
Emplacement of thermal sand	Grading
Backfilling	
Pouring of concrete	
Handling of precast concrete items	
Repaving	

*Certain combinations are regarded as unlikely, e.g. 1,200 kV overhead lines in an urban environment.

Due to the literally hundreds of assumptions required to define and estimate the energy content of these activities, all of the details regarding the procedures and equipment used appear in Appendix A.5. This chapter simply states the general assumptions made, defines the installation parameters for each system and indicates the results.

B. GENERAL ASSUMPTIONS

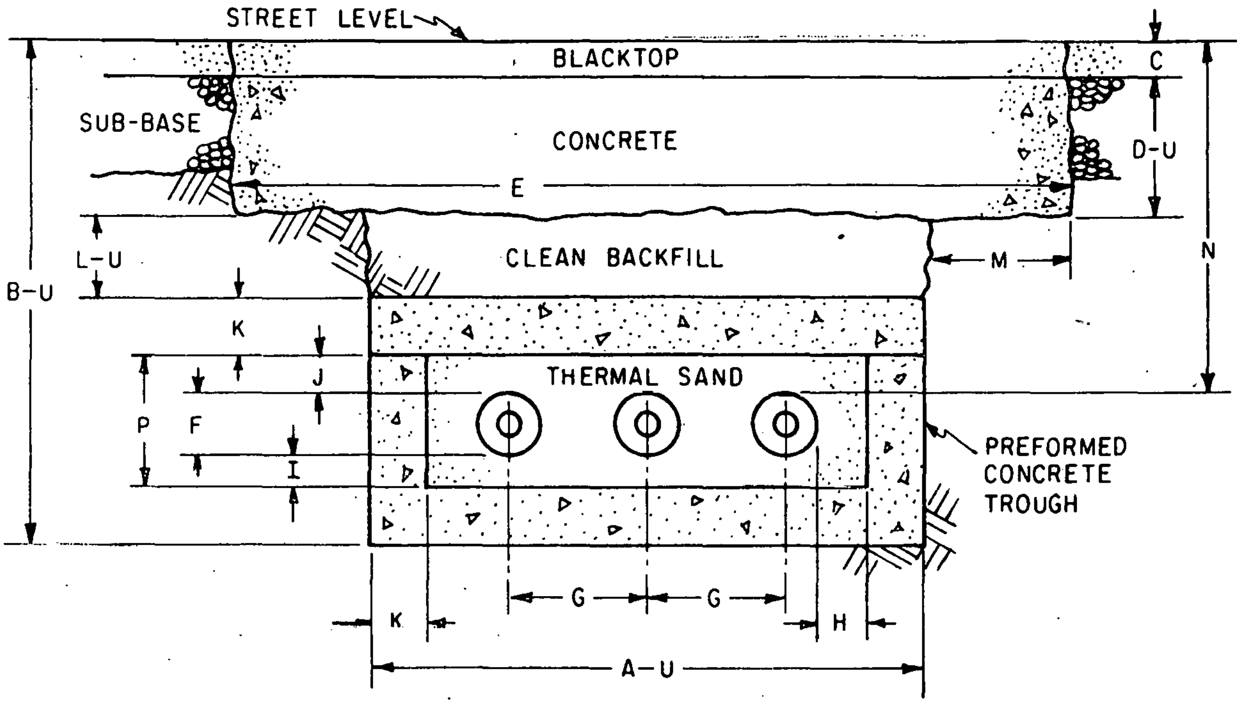
It has been assumed that all materials and transmission system components require a 20-mile truck haul, being either brought to or removed from the site. Many components may be transported via some other mode from their source but will require this type of haulage from terminal to installation site. The only exceptions to this practice are mobilization of equipment and transport of high-quality treated thermal sand, where a figure of 50 miles has been selected as more appropriate.

Most of the energy used in construction activities is consumed by diesel-powered equipment, e.g. backhoes, trucks, bulldozers and truck-mounted hydraulic cranes. An average efficiency of 27.5% has been assumed for diesel engines in the range of 75 to 400 horsepower, based on examination of material provided by the producers of construction equipment. Since the energy content of diesel fuel has been established as 5.8×10^6 Btu per bbl, or 1.38×10^5 Btu per gallon, diesel-powered equipment has an average fuel consumption requirement of 0.0671 gallons per hour per horsepower; this is equivalent to 9260 Btu per HP-hour.

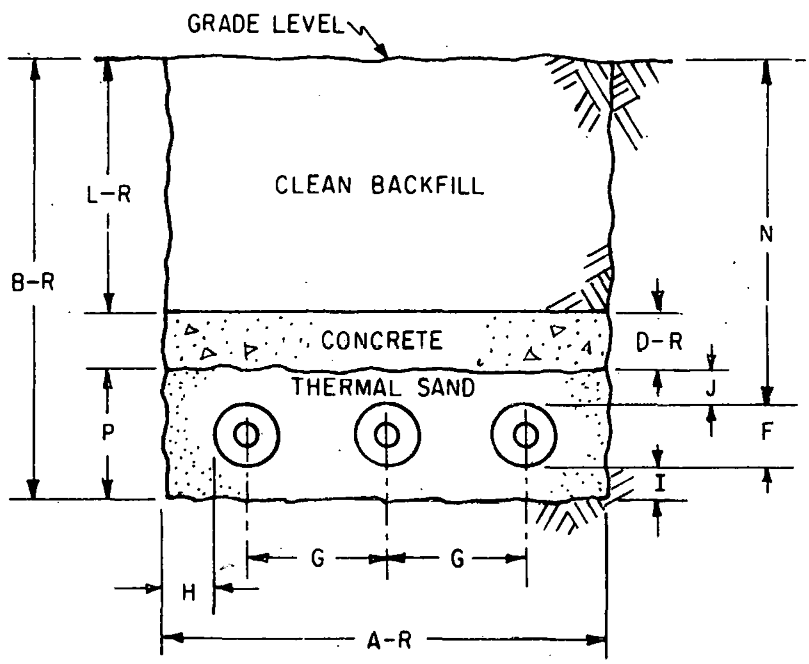
A working man expends energy at a rate of approximately one-tenth to one-eighth horsepower. Most of the construction equipment used during installation of transmission systems develops more than 100 horsepower, typically. Consequently, manpower has not been considered in the energy content analyses performed in this report because the additional contribution is quite small and considerably below the bounds of accuracy associated with most activities.

C. INSTALLATION PARAMETERS

Figures VII.1 through VII.4 indicate the types of installations assumed for underground transmission systems in urban and rural areas. Tables VII.1 through VII.4 contain dimensions for each type of system as a function of voltage. The parameters given in these tables have been established based upon discussions with many utilities, and are believed to reflect typical utility practice regarding conventional systems. Installation parameters for the advanced systems have been estimated using present practice as much as possible. In most cases, trench dimensions are similar to those assumed in the recent study of transmission systems performed by the Philadelphia Electric Company (Reference 1). Their practice of using a protective concrete slab over transmission systems in urban areas has been adopted for this report, as well as that of using a concrete enclosure for SCOF and ED cable systems in urban areas.



URBAN INSTALLATIONS

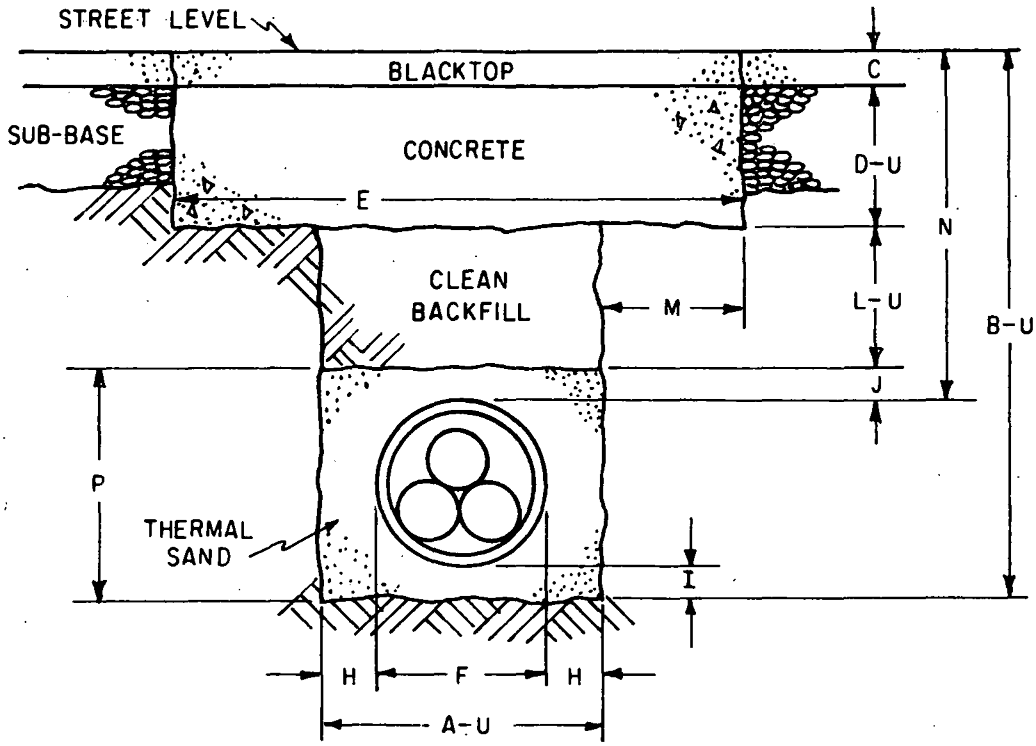


RURAL INSTALLATIONS

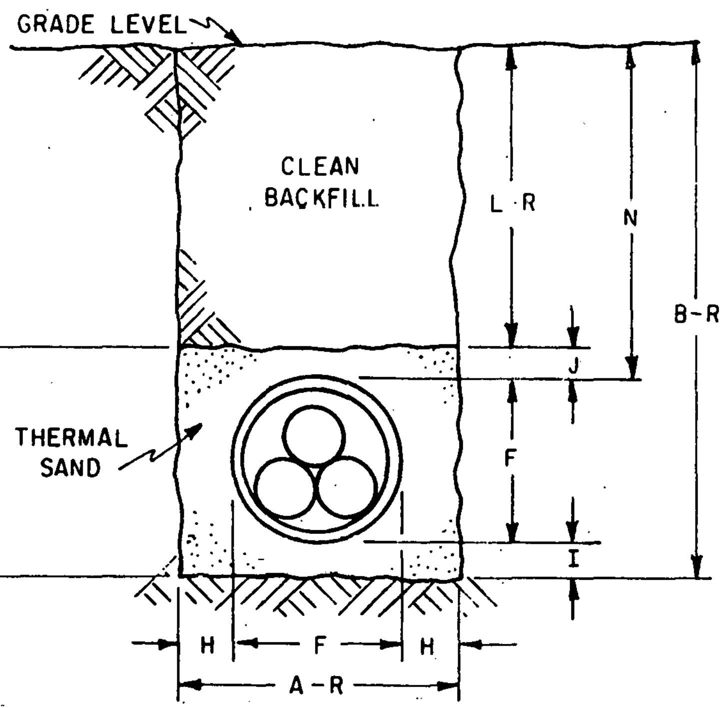
FIGURE VII.1

TYPICAL TRENCH CROSS-SECTIONAL VIEW

FOR SCOF AND EXTRUDED DIELECTRIC CABLE SYSTEMS



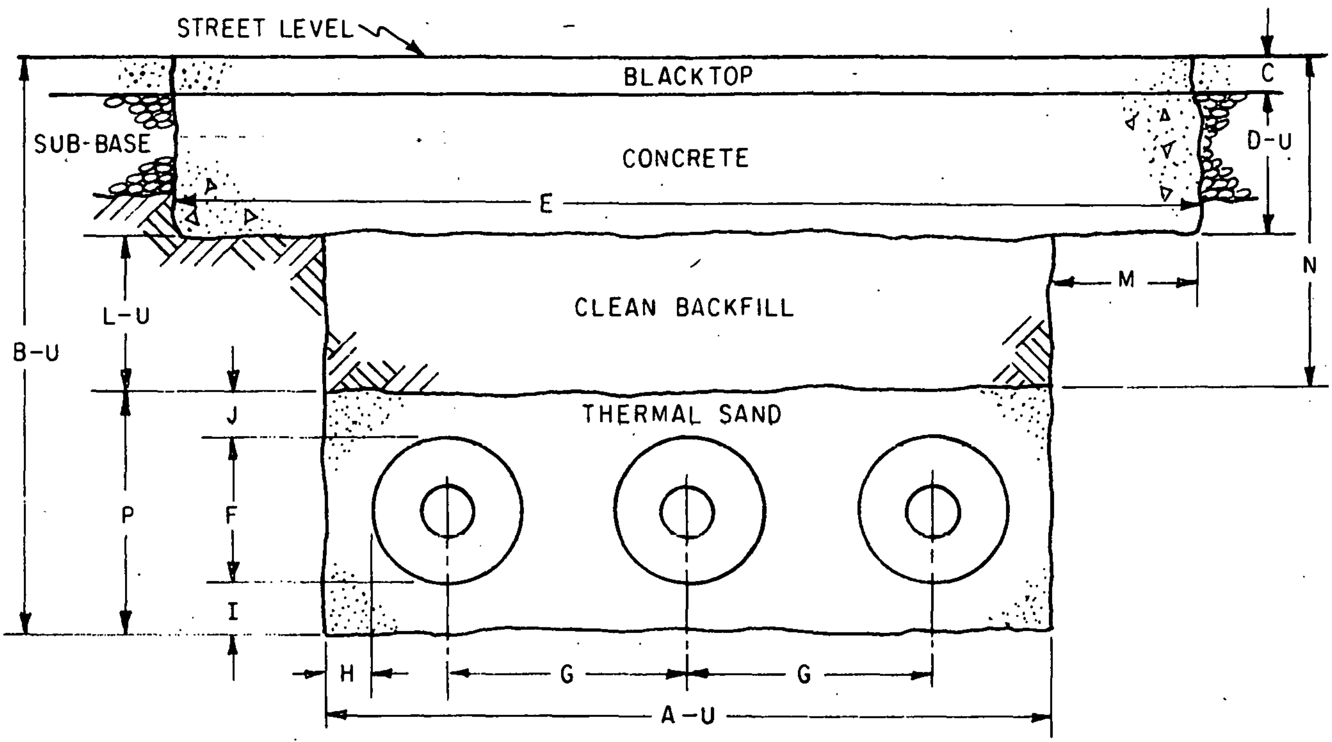
URBAN INSTALLATIONS



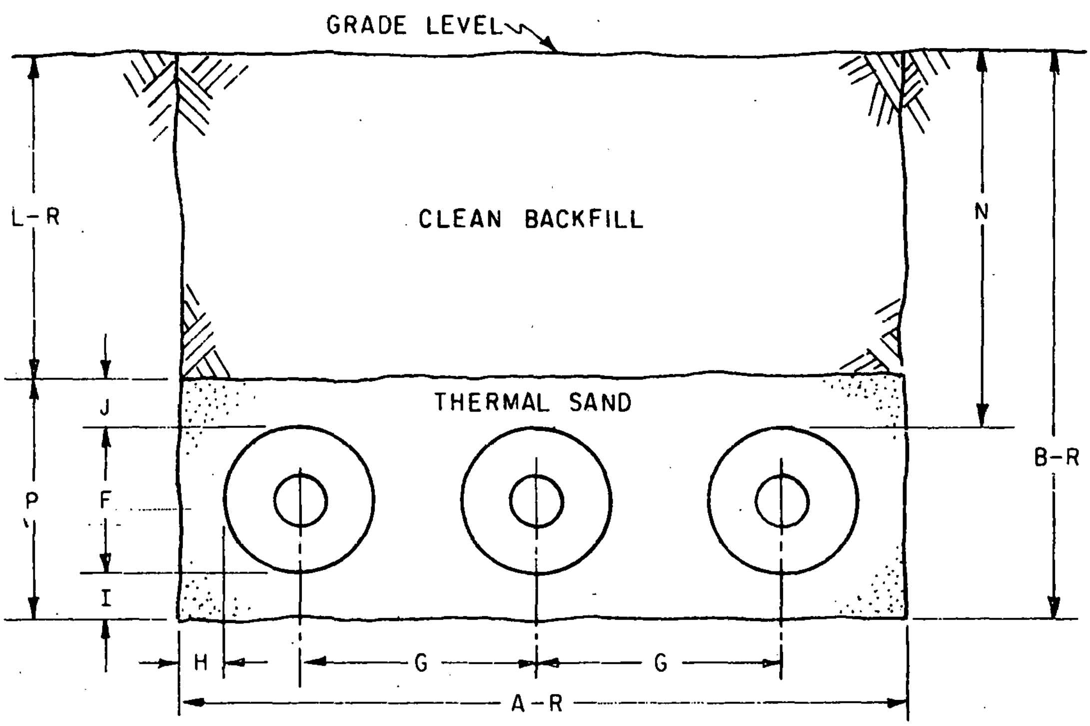
RURAL INSTALLATIONS

FIGURE VII.2

TYPICAL TRENCH CROSS-SECTIONAL VIEW FOR HPOF PIPE-TYPE CABLE



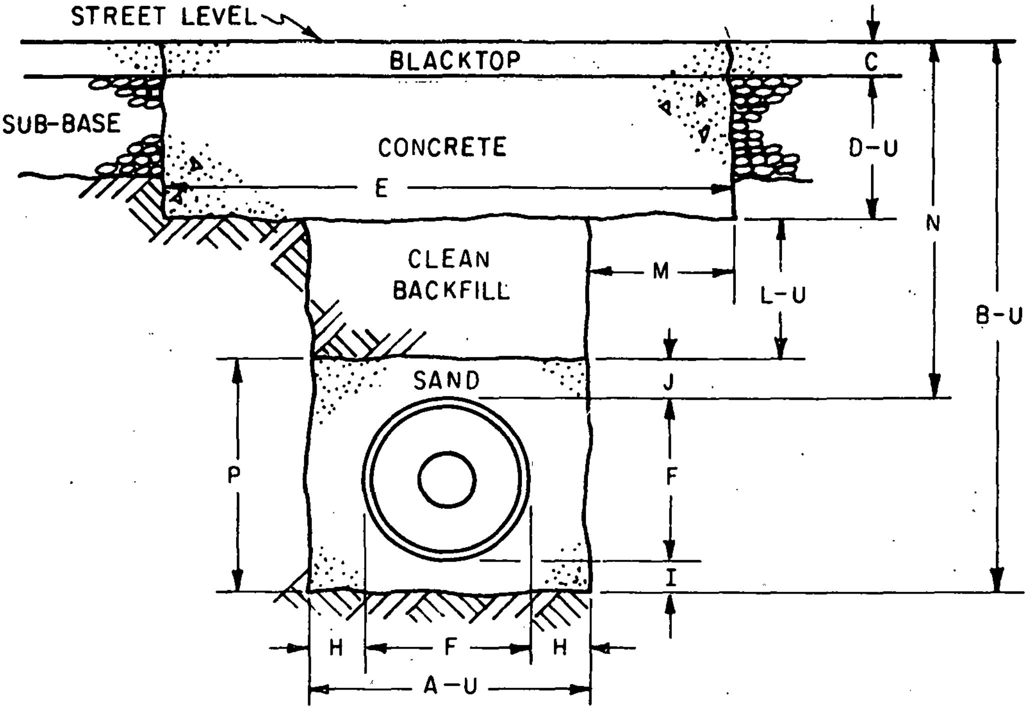
URBAN INSTALLATIONS



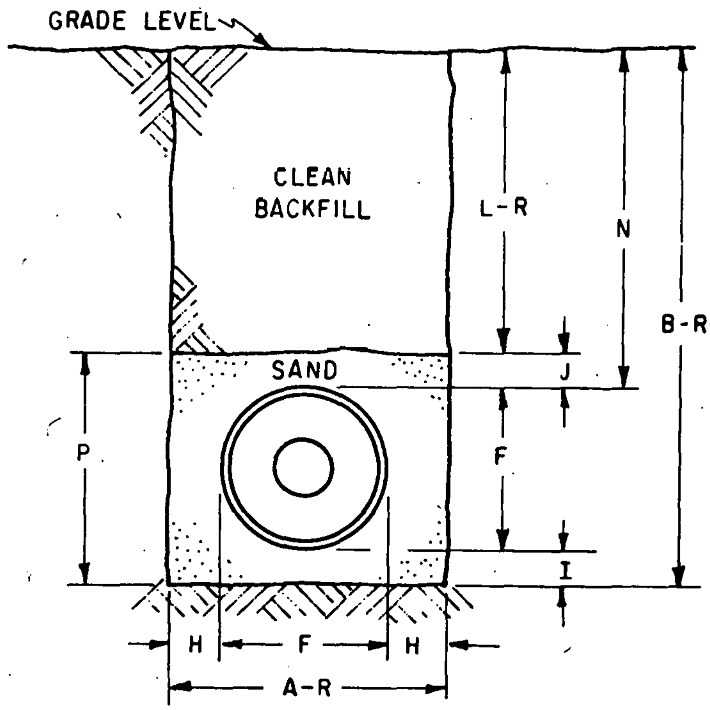
RURAL INSTALLATIONS

FIGURE VII.3

TYPICAL TRENCH CROSS-SECTIONAL VIEW FOR COMPRESSED-GAS-INSULATED SYSTEMS



URBAN INSTALLATIONS



RURAL INSTALLATIONS

FIGURE VII.4

TYPICAL TRENCH CROSS-SECTIONAL VIEW FOR SUPERCONDUCTING CABLE SYSTEMS

TABLE VII.1

SPECIFICATIONS FOR SCOF AND ED CABLE INSTALLATIONS

Dimension	Description	138	230	345	500	765
		System Voltage (kV) (all dimensions in inches*)				
A-U	Trench width, urban	50	50	50	52	52
A-R	Trench width, rural	40	40	40	42	42
B-U	Trench depth, urban	48	48	48	50	50
B-R	Trench depth, rural	42	42	42	44	44
E	Concrete slab width, urban	74	74	74	76	76
F	Cable outer diameter	3.24	3.76	4.31	4.90	5.11

Dimension	Description	Value for All Voltages (inches)
C	Blacktop thickness	3
D-U	Concrete slab thickness, urban	12
D-R	Concrete slab thickness, rural	5
G	Cable separation, center-to-center	13
H,I,J	Clearance, cable edge to boundaries	5
K	Concrete envelope thickness	5
L-U	Clean backfill thickness, urban	7
L-R	Clean backfill thickness, rural	22
M	Urban trench width extension	12
N	Grade level to top of cables	36
P	Thermal sand layer thickness	13 to 15

*1 inch = 2.54 cm.

TABLE VII.2

SPECIFICATIONS FOR HPOF PIPE-TYPE CABLE INSTALLATIONS

		System Voltage (kV)				
		138	230	345	500	765
Dimension	Description	(all dimensions in inches*)				
A-U, A-R	Trench width	18	20	24	26	26
B-U, B-R	Trench depth	50	50	52	54	54
E	Concrete slab width, urban	42	44	48	50	50
F	Pipe outer diameter	7.50	8.13	10.13	12.13	12.13

Dimension	Description	Value for All Voltages (inches)
C	Blacktop thickness	3
D-U	Concrete slab thickness, urban	12
B,I,J	Clearance, pipe edge to boundaries	3 to 5
L-U	Clean backfill thickness, urban	12
L-R	Clean backfill thickness, rural	27
M	Urban trench width extension	12
N	Grade level to top of pipe	30
P	Thermal sand layer thickness	14 to 22

*1 inch = 2.54 cm.

TABLE VII.3

SPECIFICATIONS FOR CGI SYSTEM INSTALLATIONS

Dimension	Description	System Voltage (kV) 138	230	345	500	765	1,200
		(all dimensions in inches*)					
A-U, A-R	Trench width, urban	66	72	84	96	111	128
B-U, B-R	Trench depth, urban	52	54	58	62	67	72
E	Concrete slab width, urban	90	96	108	120	135	152
F	Pipe outer diameter	10	12	16	20	25	30
G	Spacing between centers	22	24	28	32	37	43

Dimension	Description	Value for All Voltages (inches)
C	Blacktop thickness	3
D-U	Concrete slab thickness, urban	12
H,I,J	Clearance, pipe edge to boundaries	5 to 6
L-U	Clean backfill thickness, urban	12
L-R	Clean backfill thickness, rural	27
M	Urban trench width extension	12
N	Grade level to top of pipes	30
P	Thermal sand layer thickness	25 to 45

*1 inch = 2.54 cm.

TABLE VII.4

SPECIFICATIONS FOR SUPERCONDUCTING CABLE INSTALLATIONS

Dimension	Description	System Voltage (kV) 138	345	±100	±300
		(all dimensions in inches*)			
A-U, A-R	Trench width, urban	26	30	22	25
B-U, B-R	Trench depth, urban	51	55	47	50
E	Concrete slab width, urban	50	54	46	49
F	Pipe outer diameter	16	20	11.5	14.5

Dimension	Description	Value for All Voltages (inches)
C	Blacktop thickness	3
D-U	Concrete slab thickness, urban	12
H,I,J	Clearance, pipe edge to boundaries	5
L-U	Clean backfill thickness, urban	10
L-R	Clean backfill thickness, rural	22 to 25
M	Urban trench width extension	12
N	Grade level to top of pipe	30
P	Thermal sand layer thickness	22 to 30

*1 inch = 2.54 cm.

D. RESULTS

The installation energy content of underground and overhead transmission systems is shown in Tables VII.5 and VII.6 respectively. Energy content has been estimated for each system, at all operating voltages of interest, in urban, suburban and rural terrain (as appropriate).

Referring back to Chapter VI, it becomes apparent that the energy required to install a given underground system is a relatively small fraction of the system's inherent energy content. For example, the ratio of installation energy to inherent energy content is about 6% for a 345 kV SCOF system. The ratio is roughly 4% for a 345 kV HPOF pipe-type system, and 3% for a 345 kV CGI system. The trend in energy content is downward, for each system, as one moves from urban to suburban to rural environments. This trend reflects the smaller excavation requirements of rural installations, and the lack of a protective concrete slab there.

The energy required to install overhead lines is also a small fraction of the system's inherent energy content, but the ratio is not quite as small as for underground systems. In general, the installation energy content of overhead lines is 10% or less of the inherent system energy content. The trend in installation energy content increases from urban to rural areas because rights-of-way must be cleared in suburban and rural areas.

TABLE VII.5

INSTALLATION ENERGY CONTENT OF UNDERGROUND TRANSMISSION SYSTEMS

(all results expressed in terms of Btu x 10^6 per mile*)

System Type	Terrain**	Operating Voltage, kV 138	230	345	500	765	1,200
SCOF	U	1,100	1,110	1,140	1,160	1,230	-
Cables	S	770	790	810	840	890	-
	R	480	500	520	550	590	-
HPOF	U	570	700	740	820	810	-
Pipe-type	S	450	470	520	570	560	-
Cables	R	420	440	490	520	520	-
Extruded	U	1,100	1,100	1,130	-	-	-
Dielectric	S	770	780	800	-	-	-
Cables	R	480	490	510	-	-	-
CGI	U	1,260	1,370	1,600	1,860	2,200	2,600
Systems	S	880	970	1,170	1,380	1,670	2,010
	R	770	850	1,020	1,210	1,470	1,780

System Type	Terrain	Operating Voltage, kV 138	345	+100	+300
Superconducting, ac	U	800	890		
	S	560	640	-	-
	R	520	590	-	-
Superconducting, dc	U			710	770
	S	-	-	500	550
	R	-	-	460	510

4

*10^6 Btu per mile = 656 MJ per km.

**U = urban, S = suburban, R = rural terrain.

TABLE VII.6

INSTALLATION ENERGY CONTENT OF OVERHEAD TRANSMISSION SYSTEMS

(all results expressed in terms of Btu x 10^6 per mile*)

Terrain	AC Operating Voltage, kV					
	138	230	345	500	765	1,200
Urban	360	420	-	-	-	-
Suburban	450	510	580	650	750	-
Rural	570	670	770	880	1,070	1,830

Terrain	DC Operating Voltage, kV			
	±200	±400	±600	±300
Urban	340	-	-	-
Suburban	430	520	650	740
Rural	620	740	940	1,090

*10^6 Btu per mile = 656 MJ per km.

References for Chapter VII

1. "Evaluation of the Economical and Technological Viability of Various Underground Transmission Systems for Long Feeds to Urban Load Areas", Department of Energy Report HCP/T-2055/1, prepared by the Philadelphia Electric Company, 1977.

VIII. ENERGY CONTENT OF COMPLETE, INSTALLED TRANSMISSION SYSTEMS

A. UNDERGROUND SYSTEMS

The installed energy content of an SCOF transmission system as a function of operating voltage is shown in Figure VIII.A.1. The upper value at each voltage applies for an urban installation; the lower value represents a rural installation. Suburban installations lie between these two values. Figures VII.A.2 and VII.A.3 present the same kind of data for HPOF pipe-type and ED cables, respectively. All three figures indicate that installation energy requirements are a minor part of the total, installed system energy content.

CGI systems have a very high energy content at each voltage, as noted previously. The differences between rural and urban installations are so small that a graph could not effectively show them. Consequently, Table VIII.A.1 contains the data for installed CGI systems in urban, suburban and rural areas.

Installation energy requirements for superconducting systems are also quite low compared to system energy content. The results for installed superconducting systems are shown in Table VIII.A.2.

B. OVERHEAD LINES

Although installation energy requirements do add about 10% to the inherent (uninstalled) energy content of an overhead line, the difference between rural and suburban locations* is only about 2%. Considering the range of inherent energy content in overhead lines, 4.0 to 36.5 x 10^9 Btu per mile, it would not be feasible to show a 2% difference on a graph covering the whole range of operating voltages. Table VIII.B.1 provides more precise estimates of the installed energy content of all overhead lines.

C. NORMALIZATION

All of the transmission system energy content graphs and tables discussed previously provide information on a "per system" basis. No attempt has been made to consider the variation in power transmission capacity among systems, because the capacity of conventional uncompensated overhead and underground systems is a function of line or cable

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*It is more appropriate to examine suburban versus rural differences because EHV and UHV overhead lines are not normally constructed in urban environments.

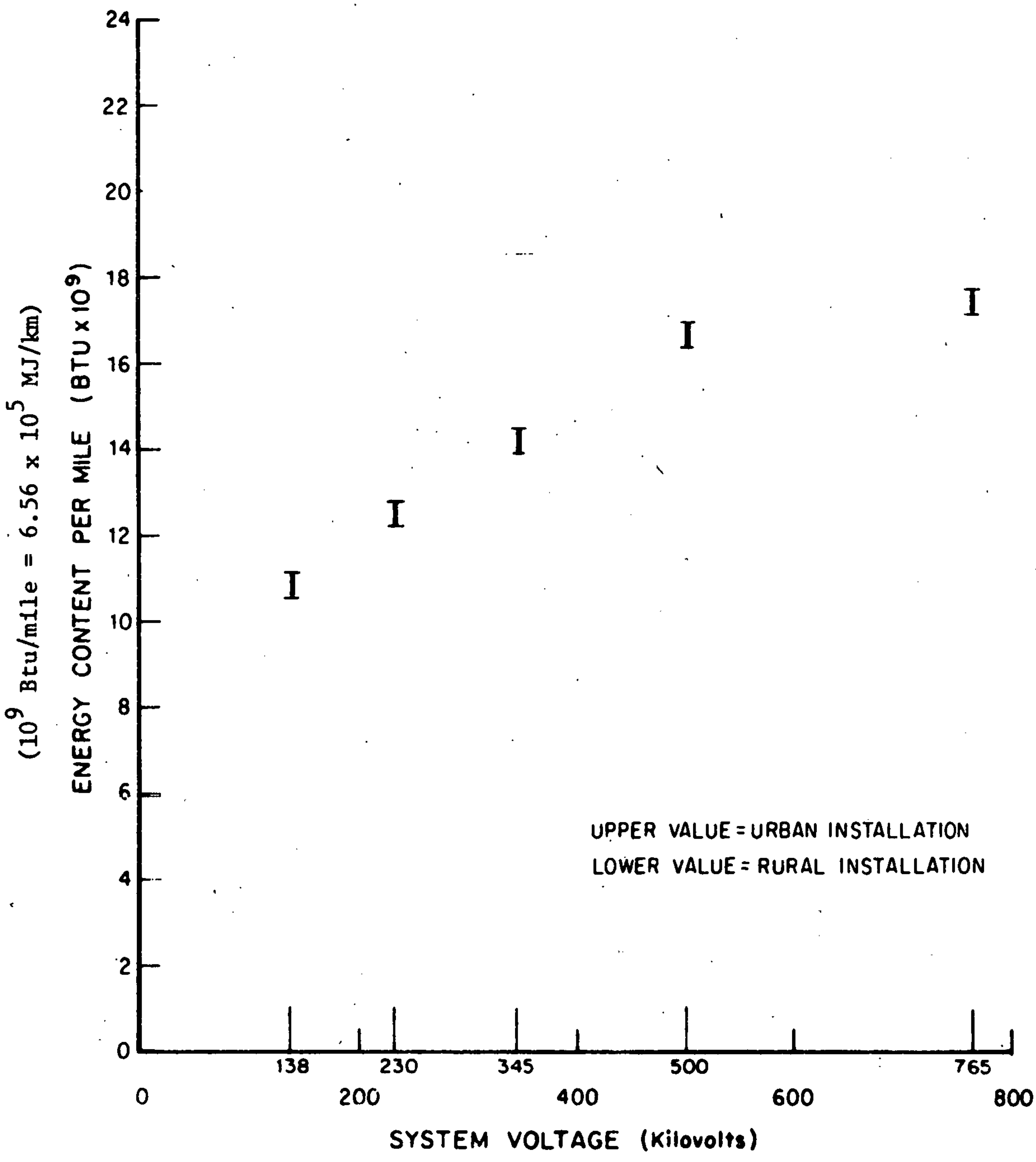

FIGURE VIII.A.1

INSTALLED ENERGY CONTENT OF SCOF SYSTEMS

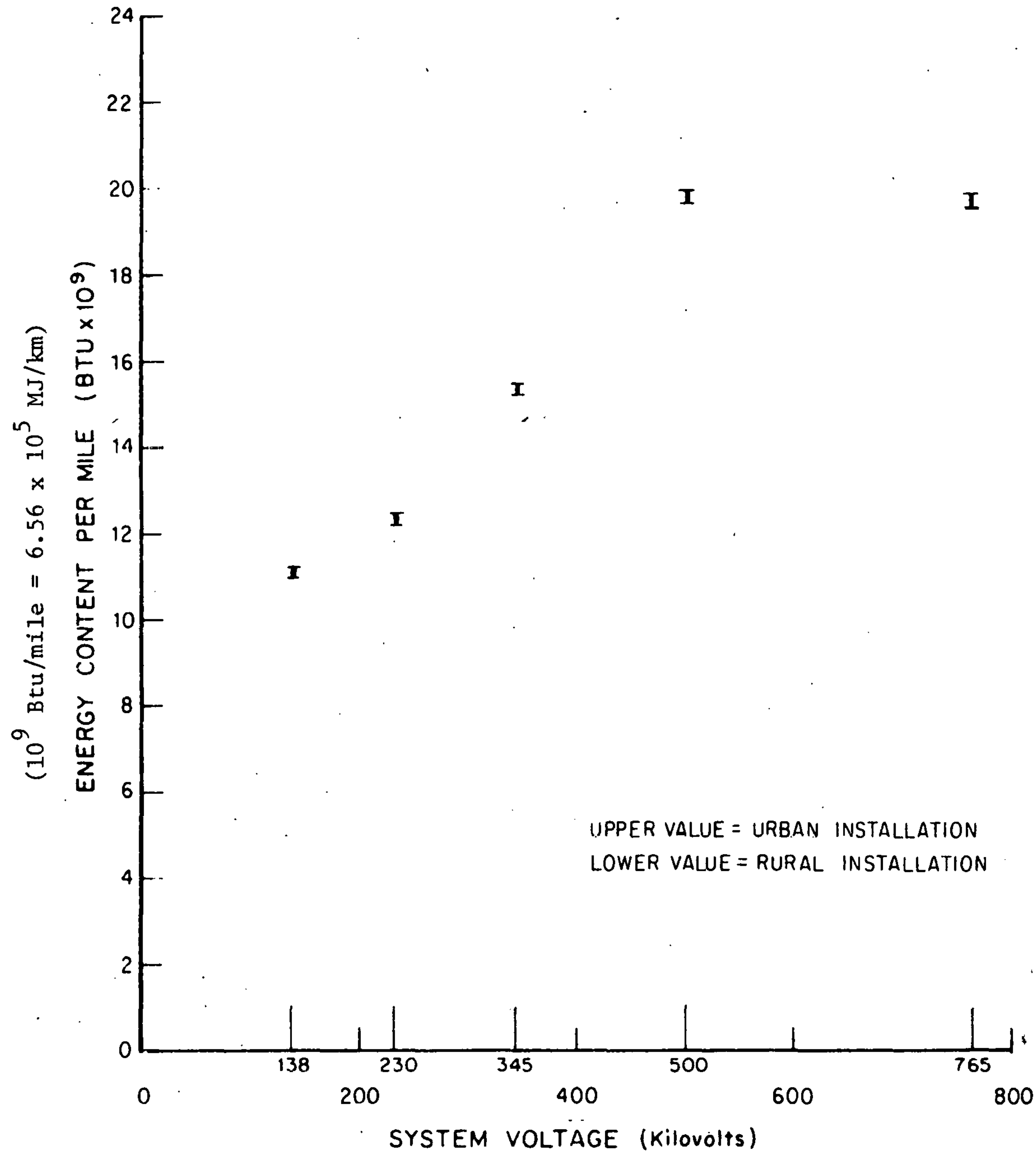

FIGURE VIII.A.2

INSTALLED ENERGY CONTENT OF HPOF PIPE-TYPE SYSTEMS

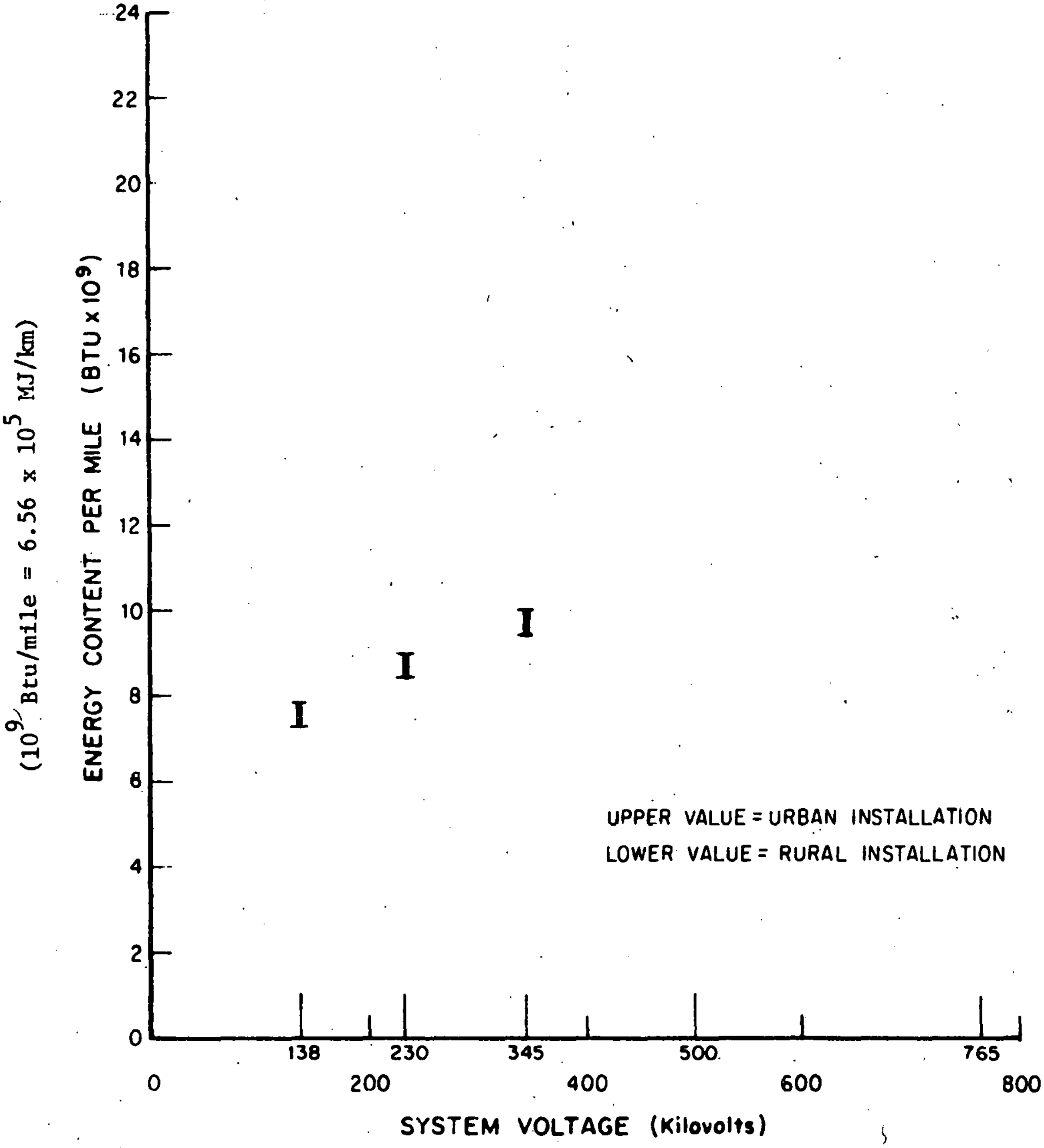

FIGURE VIII.A.3

INSTALLED ENERGY CONTENT OF ED SYSTEMS

TABLE VIII.A.1

ENERGY CONTENT OF INSTALLED CGI SYSTEMS

(Btu x 10^9 per mile*)

		Environment	
Voltage	Urban	Suburban	Rural
138	26.1	25.7	25.6
230	31.7	31.3	31.2
345	40.6	40.2	40.0
500	56.1	55.6	55.4
765	96.0	95.5	95.3
1,200	121.6	121.0	120.8

* 10^9 Btu/mile = 6.56×10^5 MJ/km

TABLE VIII.A.2

ENERGY CONTENT OF INSTALLED SUPERCONDUCTING TRANSMISSION SYSTEMS

($Btu \times 10^9$ per mile*)

Voltage	Urban Environment	Suburban Environment	Rural Environment
138 kV, ac	18.1	17.86	17.82
345 kV, ac	27.95	27.70	27.65
100 kV, dc	27.66	27.45	27.41
300 kV, dc	55.34	55.12	55.08

* 10^9 Btu/mile = 6.56×10^5 MJ/km

TABLE VIII.B.1

ENERGY CONTENT OF INSTALLED OVERHEAD LINES

($Btu \times 10^9$ per mile*)

Terrain	AC Operating Voltage, kV 138	230	345	500	765	1,200
Urban	4.25	5.34	-	-	-	-
Suburban	4.34	5.43	5.96	10.07	14.75	-
Rural	4.46	5.59	6.15	10.30	15.07	38.36

Terrain	DC Operating Voltage, kV ±200	±400	±600	±800
Urban	5.46	-	-	-
Suburban	5.55	10.41	13.72	18.25
Rural	5.74	10.63	14.01	18.60

* 10^9 Btu/mile = 6.56×10^5 MJ/km

length. For example, a 300-mile 345 kV overhead line may have a surge impedance loading* of 950 MVA; a 100-mile line of identical construction may be rated at 1,900 MVA, and a 400-mile line may carry only 760 MVA. A typical 345 kV HPOF pipe-type cable, uncompensated, may be rated at 450 MVA if the circuit length is a few miles; the same cable 20 miles long may have approximately one-half of that capacity.

Nevertheless, the question of how system energy content per MVA of capacity varies between transmission systems is of interest. In order to resolve this question a single representative power rating was determined for each type of transmission system at each operating voltage. This rating corresponds to cable lengths of a few miles for underground systems, and to the SIL of overhead lines. The normalization factor (N-factor) is defined as the system energy content per mile divided by the system capacity in MVA. Table VIII.C.1 lists the total installed energy content, the representative power rating, and the N-factor of each ac system. Table VIII.C.2 contains similar information for dc systems. These data are presented in tabular form because the N-factors vary so much from system to system and from one voltage to another that the trends are difficult to discern from a graphic display.

Perhaps the most important conclusion to be drawn from these tables is that overhead lines (ac and dc) above 600 kV and the dc superconducting systems are roughly comparable in terms of energy content per MVA of capacity.

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*The surge impedance loading (SIL) of a line corresponds to the amount of power it can deliver to a purely resistive load, when the load resistance is equal to the line impedance. More precisely, SIL = Z_o where $Z_o = (L/C)^{1/2}$, L is the series inductance of the line per unit length and C is the shunt capacitance of the line per unit length.

TABLE VIII.C.1

ENERGY CONTENT, POWER RATINGS AND N-FACTORS

FOR AC TRANSMISSION SYSTEMS

Type	Item	138 kV	230 kV	345 kV	500 kV	765 kV	1,200 kV
SCOF	E.C.[1]	10.75	12.44	14.25	16.59	17.45	
	Rating[2]	290	480	670	770	890	*
	N-factor[3]	37.07	25.92	21.27	21.55	19.61	
HPOF	E.C.	11.03	12.25	15.33	19.82	19.63	
	Rating	224	344	453	571	900	*
	N-factor	49.24	35.61	33.84	34.71	21.81	
ED	E.C.	7.57	8.68	8.70			
	Rating	300	470	700	*	*	*
	N-factor	25.23	18.47	12.43			
CGI	E.C.	25.63	31.33	40.19	55.70	95.59	121.11
	Rating	410	800	1,310	2,170	4,640	8,300
	N-factor	62.51	39.16	30.68	25.67	20.60	14.59
S.S.	E.C.	17.86		27.70			
	Rating	1,300	*	2,400	*	*	*
	N-factor	13.74		11.54			
OH	E.C.	4.34	5.43	5.96	10.07	14.75	38.36
	Rating	80	130	400	950	2,200	9,000
	N-factor	54.25	41.77	14.90	10.60	6.70	4.26

1. Energy content, suburban installation; Btu x 10^9 per mile.
2. Representative power rating (capacity) in MVA.
3. Normalization factor; Btu x 10^6 per MVA-mile.

TABLE VIII.C.2
ENERGY CONTENT, POWER RATINGS AND N-FACTORS FOR DC TRANSMISSION SYSTEMS

Type	Item	± 100 kV	± 200 kV	± 300 kV	± 400 kV	± 600 kV	± 800 kV
OH	E.C.[1]		5.55		10.41	13.72	18.25
	Rating[2]	*	400	*	1,440	2,160	2,880
	N-factor[3]		13.88		7.44	6.35	6.34
SS	E.C.	27.45		55.12			
	Rating	5,000	*	15,000			
	N-factor	5.49		3.67			

1. Energy content, suburban installation; Btu x 10^9 per mile.
2. Representative power rating (capacity) in MVA.
3. Normalization factor; Btu x 10^6 per MVA-mile.

IX. SENSITIVITY ANALYSES

A. INTRODUCTION

Standardization has been of primary concern in specifying all of the transmission systems analyzed, to permit maximum comparability. For example, all conventional cable systems employed a 2,000 kcmil copper conductor. Given a particular system operating at a particular voltage, the question of how energy content varies with conductor size and choice of conductor material was of interest to the Department of Energy. A number of analyses were performed on conventional systems in response to this question.

B. UNDERGROUND SYSTEMS

Figure IX.1 indicates the results of substituting aluminum for copper while maintaining an area of 2,000 kcmils for SCOF cable systems operating at 138 through 500 kV. Energy content per system declines, because aluminum is less energy-intensive than copper on a volume basis. However, if the aluminum conductor area is increased to 3,200 kcmils, such that the conductor resistance is equivalent to a 2,000 kcmil copper conductor, the previous result is reversed. Figure IX.1 also indicates the results of this substitution at 345 and 500 kV. Now the electrically-equivalent aluminum SCOF system has a higher energy content than the standard 2,000 kcmil copper system.

Tables IX.1 and IX.2 are energy content analyses of 345 kV SCOF systems employing 2,000 kcmil copper and 3,200 kcmil aluminum conductors, respectively. The aluminum conductor system is 13% higher in energy content. Examination of the tables reveals that the conductor substitution only added 6%, and that energy content increased due to greater insulating paper volume, oil requirements and the larger cable sheath.

Figures IX.2 and IX.3 indicate the variation in energy content resulting from substitutions of the types described above, for HPOF pipe-type cables and extruded dielectric cables. The trends are similar for all three types of cable: equal-area substitution of aluminum for copper lowers energy content, while equal conductor resistance substitutions increase energy content above the standard 2,000 kcmil copper conductor system.

C. OVERHEAD LINES

Sensitivity analyses were performed at 345 and 500 kV on overhead lines to determine the effect of changing conductor size. The standard conductor for 345 kV systems analyzed in this report is 954 kcmils.

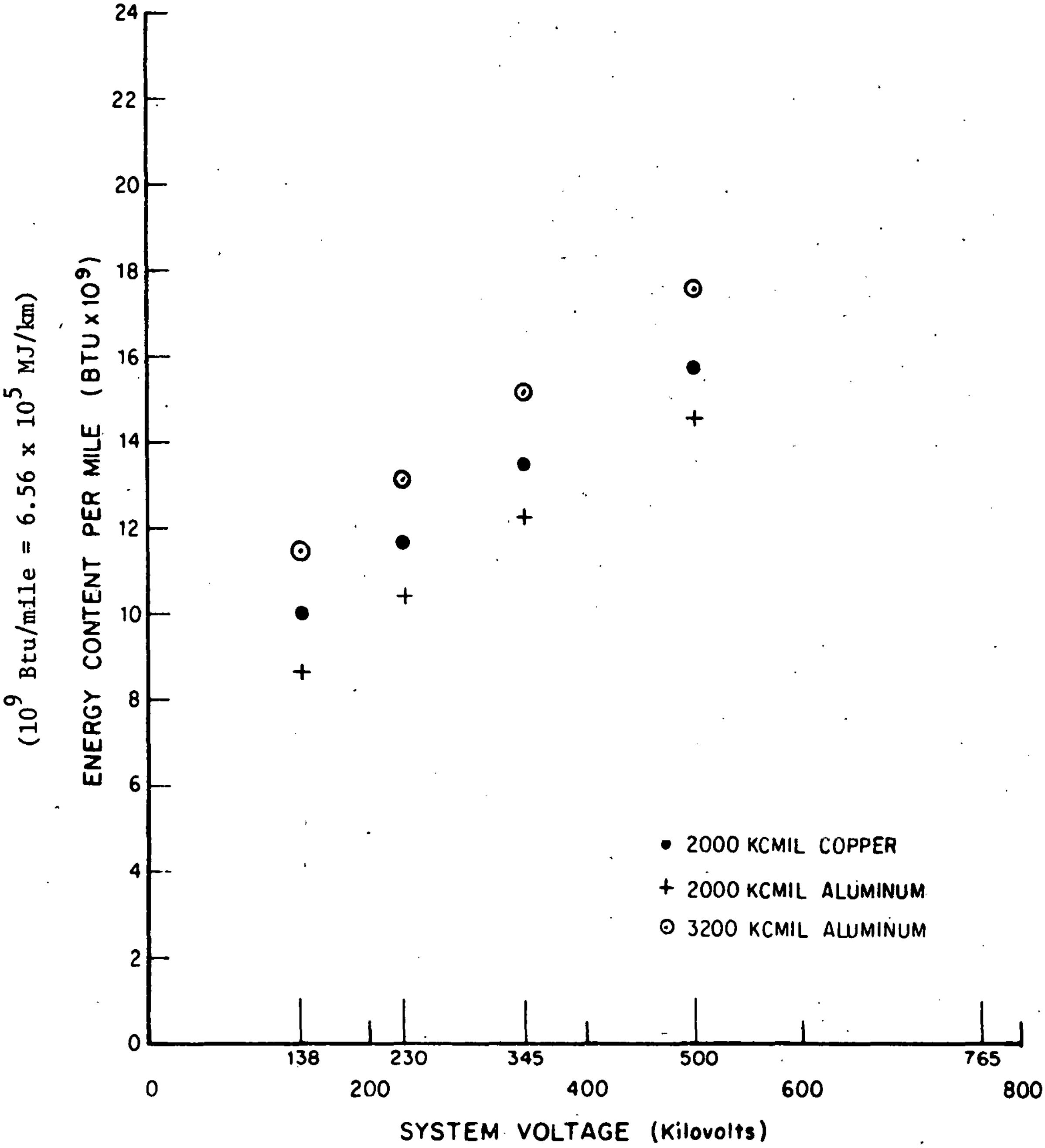

FIGURE IX.1

ENERGY CONTENT OF SCOF SYSTEMS WITH VARIOUS CONDUCTOR SIZES AND MATERIALS

TABLE IX.1

345 kV SCOF CABLE SYSTEM: 2,000 KCMIL COPPER CONDUCTOR

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL (CORE)		58.99	0.44
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	33.70
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.01
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		1150.27	8.56
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	43736.63		
OIL IN KRAFT PAPER		982.34	7.31
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	27986.96		
INSULATION SCREEN		16.03	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	1.82		
OUTER RADIUS(IN)	1.83		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	591.66		

TABLE IX.1

345 kV SCOF CABLE SYSTEM: 2,000 KCMIL COPPER CONDUCTOR (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		533.98	3.97
COPPER TAPE			
INNER RADIUS(IN)	1.83		
OUTER RADIUS(IN)	1.85		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11301.19		
CABLE SHEATH		4589.20	34.13
ALUMINUM			
INNER RADIUS(IN)	1.85		
OUTER RADIUS(IN)	2.03		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	40974.98		
CABLE JACKET		456.29	3.39
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	2.03		
OUTER RADIUS(IN)	2.15		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	14862.95		
CABLE MANUFACTURING ENERGY CONTENT		689.17	5.13
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.78
SPLICE SHELLS		25.63	0.19
STEEL PIPE			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	7.29		
TOTAL WEIGHT(LBS/MILE)	1287.70		
POTHEADS		306.00	2.28
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 13444.62 MILLION BTU/MILE

TABLE IX.2

345 kV SCOF CABLE SYSTEM: 3,200 KCMIL ALUMINUM CONDUCTOR

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.39
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		5318.30	35.16
ALUMINUM WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	3200.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	46651.75		
CONDUCTOR SHIELD		0.84	0.01
CONDUCTING PAPER			
INNER RADIUS(IN)	0.96		
OUTER RADIUS(IN)	0.96		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	31.15		
CABLE INSULATION		1304.13	8.62
KRAFT PAPER			
INNER RADIUS(IN)	0.96		
OUTER RADIUS(IN)	2.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	49586.81		
OIL IN KRAFT PAPER		1113.74	7.36
POLYBUTENE			
INNER RADIUS(IN)	0.96		
OUTER RADIUS(IN)	2.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	31730.48		
INSULATION SCREEN		17.57	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	2.00		
OUTER RADIUS(IN)	2.01		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	648.20		

TABLE IX.2

345 kV SCOF CABLE SYSTEM: 3,200 KCMIL ALUMINUM CONDUCTOR (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		584.62	3.87
COPPER TAPE			
INNER RADIUS(IN)	2.01		
OUTER RADIUS(IN)	2.02		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	12373.02		
CABLE SHEATH		5002.42	33.07
ALUMINUM			
INNER RADIUS(IN)	2.02		
OUTER RADIUS(IN)	2.21		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	44664.45		
CABLE JACKET		494.40	3.27
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	2.21		
OUTER RADIUS(IN)	2.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	16104.25		
CABLE MANUFACTURING ENERGY CONTENT		780.43	5.16
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.69
SPLICE SHELLS		39.62	0.26
STEEL PIPE			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	11.27		
TOTAL WEIGHT(LBS/MILE)	1990.72		
POTHEADS		306.00	2.02
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 15126.05 MILLION BTU/MILE

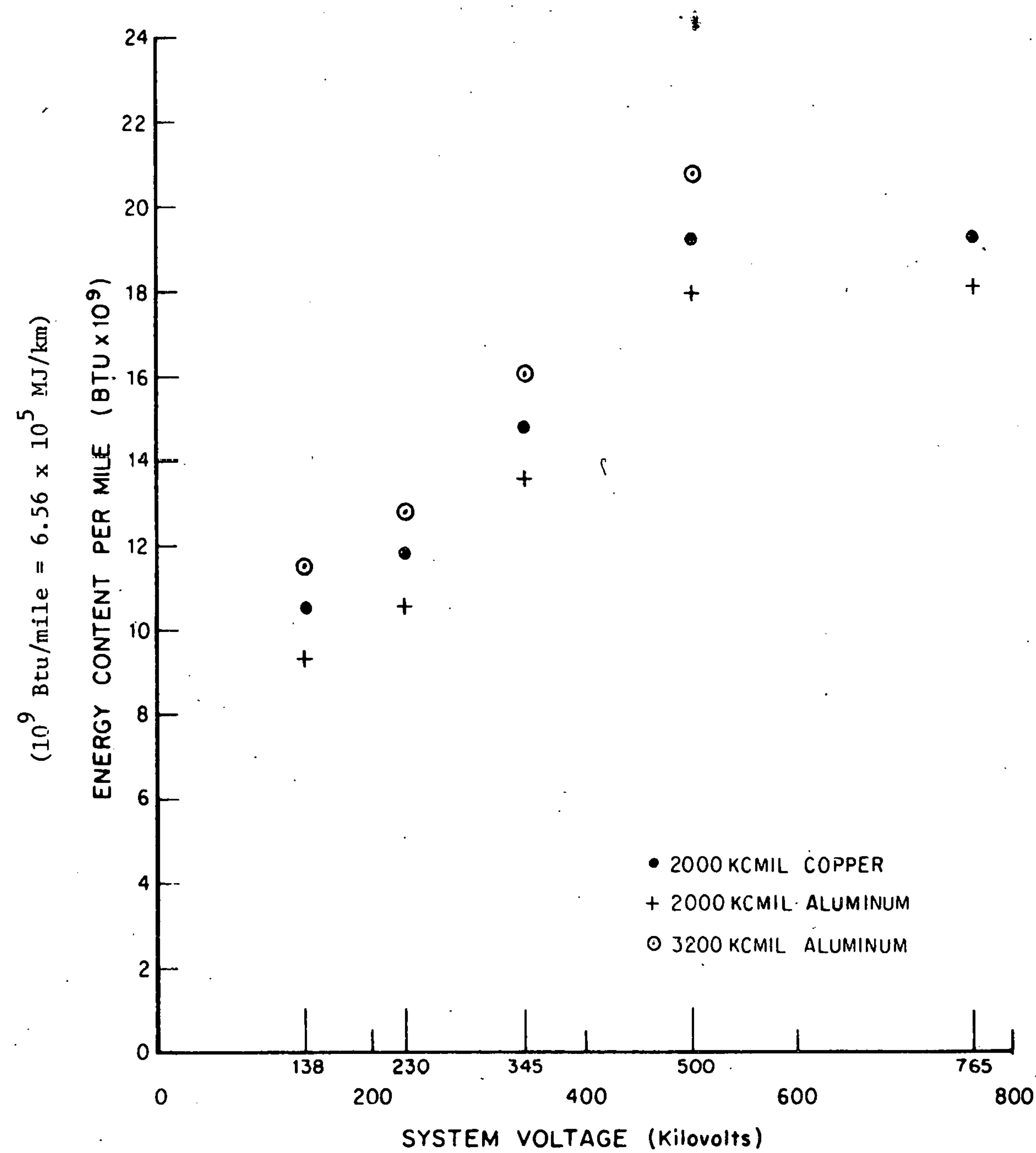

FIGURE IX.2

ENERGY CONTENT OF HPOF SYSTEMS WITH VARIOUS CONDUCTOR SIZES AND MATERIALS

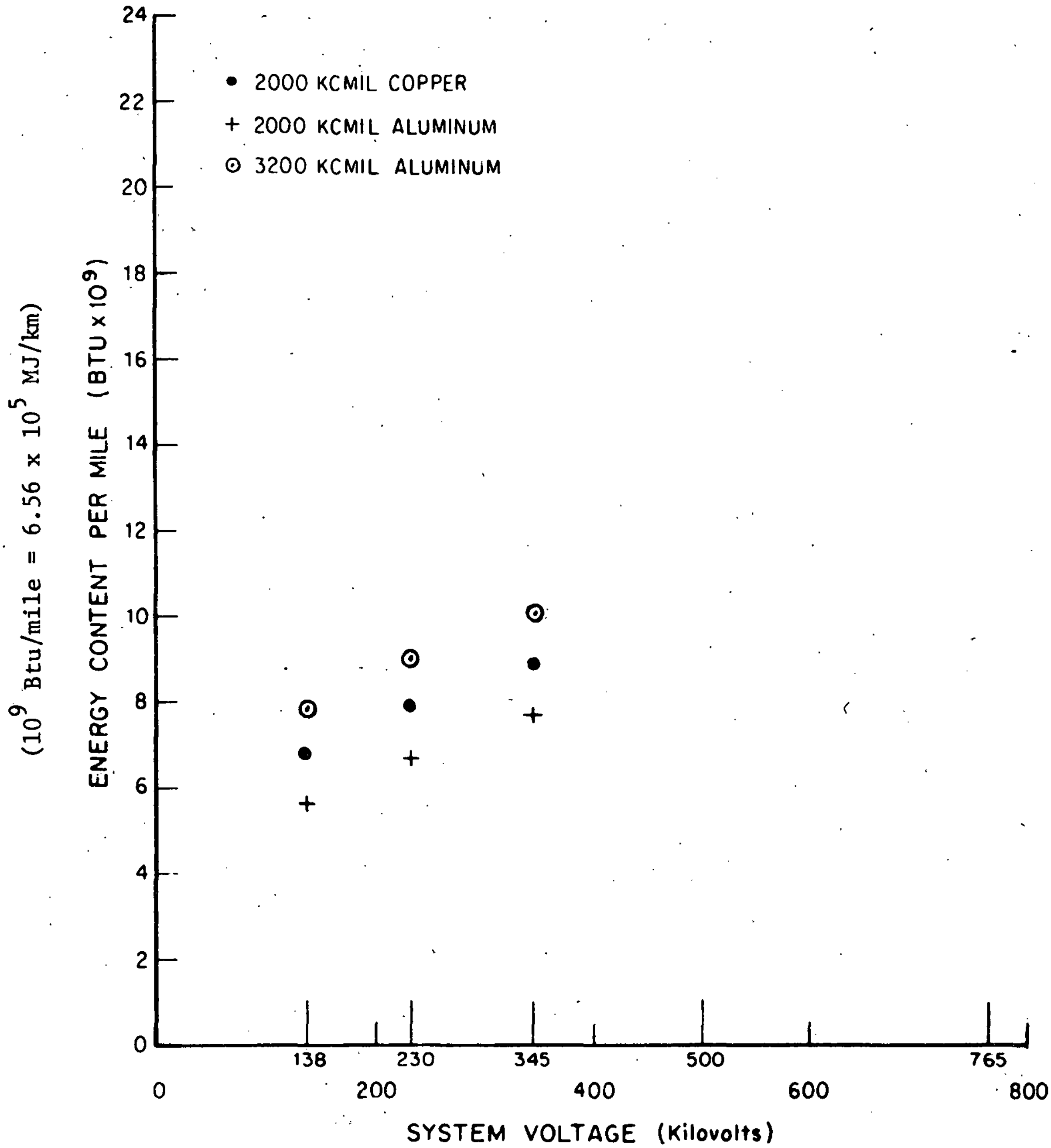

FIGURE IX.3

ENERGY CONTENT OF ED SYSTEMS WITH

VARIOUS CONDUCTOR SIZES AND MATERIALS

Conductors of approximately equal weight were selected that increased area* by 17% (1,113 kcmil "Bluejay") and decreased area by 17% (795 kcmil "Skimmer"). Figure IX.4 indicates the results of these substitutions. The larger conductor increased system energy content by 9%, and the smaller conductor decreased it by 8%.

Similar analyses were performed on the 500 kV system, which employs a 1,193 kcmil "Grackle" conductor. Figure IX.4 also shows the effects of substituting a 1,351 kcmil "Dipper" and a 954 kcmil "Merganser" for the standard conductor. At this voltage, increasing conductor area by 13% increased system energy content by 7%; decreasing conductor area by 20% decreased energy content by 17%. These effects are straightforward, and similar effects may be anticipated for conductor substitutions at other voltages.

*"Area" as used above refers to the aluminum area, which is the conducting area.

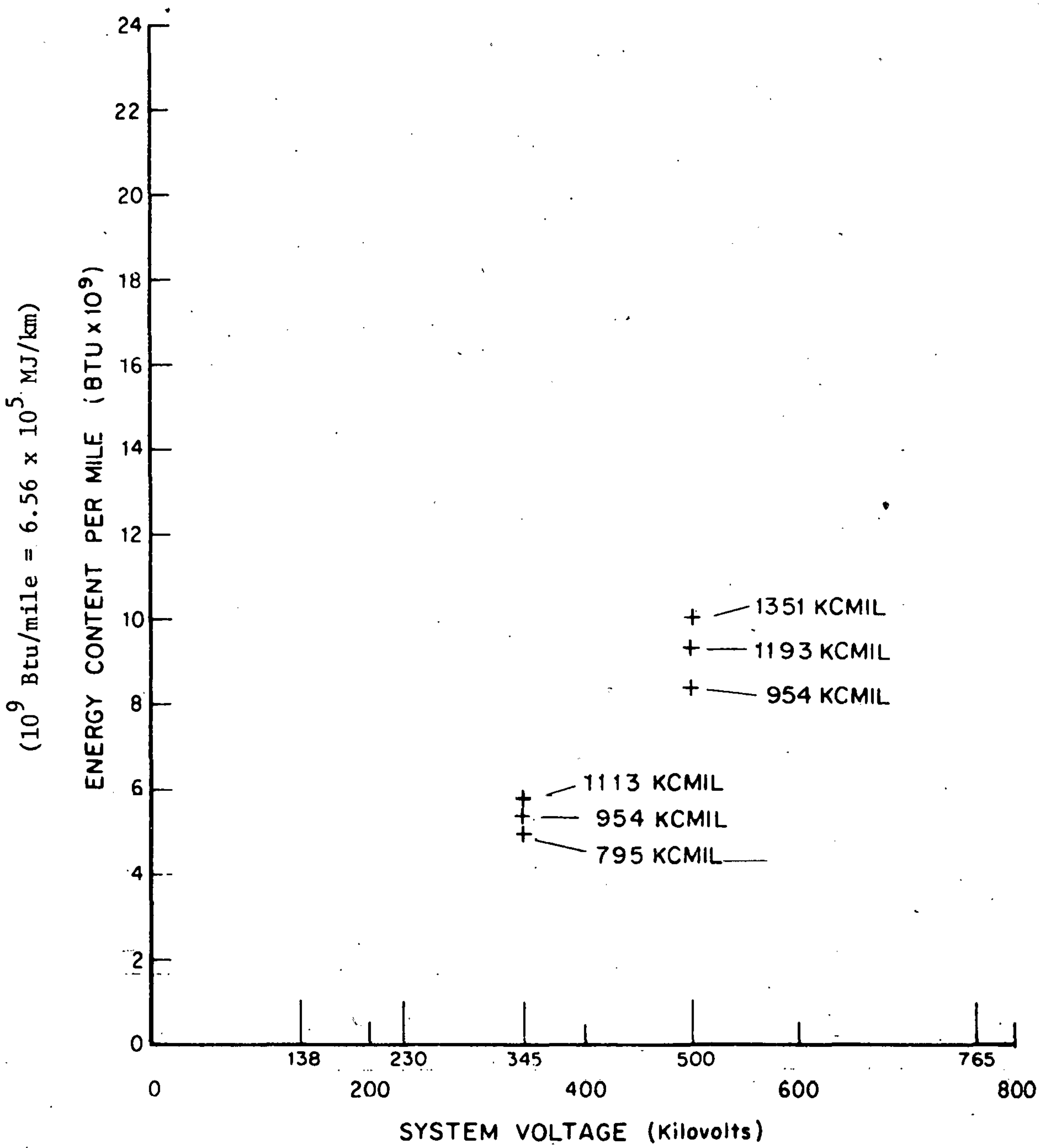

FIGURE IX.4

ENERGY CONTENT OF OVERHEAD SYSTEMS WITH VARIOUS CONDUCTOR SIZES

X. CONCLUSIONS

Perhaps the foremost conclusion of this study is that metals dominate a transmission system in terms of energy content. In particular, the combined contribution of aluminum, copper and steel in any system will typically represent from 50% to 95% of the total system energy content. Aluminum is considerably higher than copper or steel in energy content on a weight basis (Btu per ton) but the three are not as far apart on a volume basis as shown below.

Material	Energy Content	Energy Content
-	(Btu per ton)	(Btu per ft^3)
Aluminum	224.0	1.89×10^7
Copper	93.2	2.59×10^7
Steel	19.4	4.76×10^6

Another finding of interest is that the difference in energy content between conventional underground cable systems is not large. For example, considering SCOF and HPOF pipe-type cable systems in the voltage range from 138 to 500 kV, the two are always within 10% of each other. Extruded dielectric systems are lower than either on the same per-mile basis, but ED systems are never less than 60% of HPOF systems.

Compressed-gas-insulated (CGI) systems clearly are far more energy-intensive than all conventional* systems. This is due primarily to the large amount of aluminum used in each system, which accounts for 92 to 95% of the total energy content. CGI systems also require more energy to install than other systems analyzed. The larger diameter of each phase conductor assembly results in a higher excavation requirement per mile, and excavation is a major part of installation energy.

The energy content of all systems was determined on the basis of the materials employed and the installation practices used. Because each system has a different power transmission capacity, the question of how all systems compare on a per-MVA basis arose. Tables VIII.C.1 and 2 present data responsive to this question, but these results are subject to several modifying factors. The first is that short (5 to 50 miles) overhead lines are often operated at 2 to 3 times SIL; thus the N-factor of overhead lines operating at 138 to 500 kV could be several times smaller than shown. Second, there is no SIL constraint on dc lines so that capacity depends solely upon the system components selected. The third factor is that capacities of all uncompensated paper-tape and extruded dielectric cables are a strong function of distance; capacities may be half that shown in the table for circuits 15 to 20 miles long. Keeping these considerations in mind, the table does clearly indicate

*The superconducting systems are not regarded as conventional.

that overhead ac and dc lines operating at 600 kV and higher are comparable to superconducting systems in terms of energy content per MVA of capacity.

Manufacturing energy content of transmission systems was lower than generally expected. For conventional cable systems, it was always less than 10%. This result is due to a higher energy content of the materials than was expected prior to the study. For example, it was not anticipated that the oil and paper of pipe-type cables would contribute approximately 25% to the energy content of each cable.

Substitution of conductor materials in conventional cables also produced some unexpected findings. Simply replacing copper with aluminum, while maintaining the same conductor size, lowered the system energy content by roughly 10%. It also increased conductor resistance, of course. If a larger aluminum conductor was substituted, one equal in resistance, the system energy content increased about 9% compared to the standard copper system. Thus, it appears that cable systems using copper conductors are slightly superior to systems employing aluminum conductors, in terms of minimizing total system energy content.

The energy content analysis of superconducting systems provided some very interesting results. Despite the fact that they used the most energy-intensive materials (niobium and liquid helium, both around 500 x 10^6 Btu per ton) total system energy content was typically in the range of conventional CGI systems operating at similar voltages. The energy-intensive materials were simply used in lesser quantities than anticipated. The energy content of cryogenic refrigeration systems also contributed much less than expected, on a per-mile basis, for both ac and dc systems.

Finally, it has been determined that dc terminals require major energy investments. Each terminal contains far more energy content than the dc transmission lines they support. It is only when system line lengths get to a distance on the order of 200 miles that the terminal energy content falls to the region of 50 to 60% of the line energy content on a per-mile basis.

APPENDIX A.1

COMPUTER PRINTOUTS OF ENERGY ANALYSES

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FOR APPENDIX A.1

TABLE OF CONTENTS

FOR APPENDIX A.1 (Cont'd.)

TABLE A.1

138 kV SCOF SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.59
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	45.40
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.01
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		447.35	4.48
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17009.65		
OIL IN KRAFT PAPER		382.04	3.83
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10884.43		
INSULATION SCREEN		11.39	0.11
CONDUCTING PAPER			
INNER RADIUS(IN)	1.29		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	420.16		

TABLE A.1

138 kV SCOF SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		380.28	3.81
COPPER TAPE			
INNER RADIUS(IN)	1.30		
OUTER RADIUS(IN)	1.32		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	8048.21		
CABLE SHEATH		3335.40	33.42
ALUMINUM			
INNER RADIUS(IN)	1.32		
OUTER RADIUS(IN)	1.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	29780.37		
CABLE JACKET		340.67	3.41
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.50		
OUTER RADIUS(IN)	1.62		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11096.67		
CABLE MANUFACTURING ENERGY CONTENT		290.62	2.91
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	1.05
SPLICE SHELLS		15.98	0.16
STEEL PIPE			
INNER RADIUS(IN)	3.00		
OUTER RADIUS(IN)	3.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	6.00		
TOTAL WEIGHT(LBS/MILE)	802.90		
POTHEADS		81.48	0.82
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 9980.92 MILLION BTU/MILE

TABLE A.2

230 kV SCOF SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.51
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	38.88
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.01
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		755.71	6.49
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	28734.29		
OIL IN KRAFT PAPER		645.38	5.54
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	18387.00		
INSULATION SCREEN		13.62	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	1.55		
OUTER RADIUS(IN)	1.56		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	502.68		

TABLE A.2

230 kV SCOF SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		454.23	3.90
COPPER TAPE			
INNER RADIUS(IN)	1.56		
OUTER RADIUS(IN)	1.57		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	9613.34		
CABLE SHEATH		3938.63	33.80
ALUMINUM			
INNER RADIUS(IN)	1.57		
OUTER RADIUS(IN)	1.76		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	35166.34		
CABLE JACKET		396.30	3.40
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.76		
OUTER RADIUS(IN)	1.88		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	12908.70		
CABLE MANUFACTURING ENERGY CONTENT		465.51	3.99
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.90
SPLICE SHELLS		35.79	0.31
STEEL PIPE			
INNER RADIUS(IN)	3.25		
OUTER RADIUS(IN)	3.75		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	6.00		
TOTAL WEIGHT(LBS/MILE)	1798.51		
POTHEADS		252.30	2.17
230KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	9270.00		

TOTAL ENERGY CONTENT = 11653.20 MILLION BTU/MILE

TABLE A.3

345 kV SCOF SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL (CORE)		58.99	0.44
POLYBUTENE			
RADIUS (IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT (LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	33.71
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION (KCMIL)	2000.00		
INNER RADIUS (INCHES)	0.31		
TOTAL WEIGHT (LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.01
CONDUCTING PAPER			
INNER RADIUS (IN)	0.79		
OUTER RADIUS (IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT (LBS/MILE)	25.50		
CABLE INSULATION		1150.27	8.56
KRAFT PAPER			
INNER RADIUS (IN)	0.79		
OUTER RADIUS (IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT (LBS/MILE)	43736.63		
OIL IN KRAFT PAPER		982.34	7.31
POLYBUTENE			
INNER RADIUS (IN)	0.79		
OUTER RADIUS (IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT (LBS/MILE)	27986.96		
INSULATION SCREEN		16.03	0.12
CONDUCTING PAPER			
INNER RADIUS (IN)	1.82		
OUTER RADIUS (IN)	1.83		
NO. PER PHASE	1.00		
TOTAL WEIGHT (LBS/MILE)	591.66		

TABLE A.3

345 kV SCOF SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		533.98	3.97
COPPER TAPE			
INNER RADIUS(IN)	1.83		
OUTER RADIUS(IN)	1.85		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11301.19		
CABLE SHEATH		4589.20	34.15
ALUMINUM			
INNER RADIUS(IN)	1.85		
OUTER RADIUS(IN)	2.03		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	40974.98		
CABLE JACKET		456.29	3.40
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	2.03		
OUTER RADIUS(IN)	2.15		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	14862.95		
CABLE MANUFACTURING ENERGY CONTENT		689.17	5.13
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.78
SPLICE SHELLS		21.09	0.16
STEEL PIPE			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	6.00		
TOTAL WEIGHT(LBS/MILE)	1059.83		
POTHEADS		306.00	2.28
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 13440.09 MILLION BTU/MILE

TABLE A.4

500 kV SCOF SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.37
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	28.77
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.00
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		1645.08	10.44
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.12		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	62550.70		
OIL IN KRAFT PAPER		1404.91	8.92
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.12		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	40026.03		
INSULATION SCREEN		18.62	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	2.12		
OUTER RADIUS(IN)	2.13		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	687.13		

TABLE A.4

500 kV SCOF SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		619.52	3.93
COPPER TAPE			
INNER RADIUS(IN)	2.13		
OUTER RADIUS(IN)	2.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	13111.59		
CABLE SHEATH		5287.02	33.56
ALUMINUM			
INNER RADIUS(IN)	2.14		
OUTER RADIUS(IN)	2.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	47205.59		
CABLE JACKET		520.66	3.31
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	2.33		
OUTER RADIUS(IN)	2.45		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	16959.49		
CABLE MANUFACTURING ENERGY CONTENT		969.52	6.16
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.67
SPLICE SHELLS		50.18	0.32
STEEL PIPE			
INNER RADIUS(IN)	5.00		
OUTER RADIUS(IN)	5.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	11.49		
TOTAL WEIGHT(LBS/MILE)	2521.60		
POTHEADS		540.42	3.43
500KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	19320.00		

TOTAL ENERGY CONTENT = 15751.64 MILLION BTU/MILE

TABLE A.5

765 kV SCOF SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATING OIL(CORE)		58.99	0.36
POLYBUTENE			
RADIUS(IN)	0.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1680.72		
CABLE CONDUCTOR		4531.05	27.37
COPPER SEGMENTS			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.31		
TOTAL WEIGHT(LBS/MILE)	95895.31		
CONDUCTOR SHIELD		0.69	0.00
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25.50		
CABLE INSULATION		2120.94	12.81
SYNTHETIC PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.22		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	74158.69		
OIL IN KRAFT PAPER		1046.72	6.32
OIL IN S. PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.22		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	29821.00		
INSULATION SCREEN		19.50	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	2.22		
OUTER RADIUS(IN)	2.23		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	719.49		

TABLE A.5

765 kV SCOF SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SHIELD		648.52	3.92
COPPER TAPE			
INNER RADIUS(IN)	2.23		
OUTER RADIUS(IN)	2.24		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	13725.24		
CABLE SHEATH		5523.59	33.36
ALUMINUM			
INNER RADIUS(IN)	2.24		
OUTER RADIUS(IN)	2.43		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	49317.80		
CABLE JACKET		542.47	3.28
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	2.43		
OUTER RADIUS(IN)	2.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17669.98		
CABLE MANUFACTURING ENERGY CONTENT		1142.27	6.90
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.63
SPLICE SHELLS		75.20	0.45
STEEL PIPE			
INNER RADIUS(IN)	5.00		
OUTER RADIUS(IN)	5.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	17.22		
TOTAL WEIGHT(LBS/MILE)	3779.11		
POTHEADS		740.40	4.47
765KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	26580.00		

TOTAL ENERGY CONTENT = 16555.32 MILLION BTU/MILE

TABLE A.6

138 kV HPOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	42.82
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.38
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		448.04	4.23
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17035.80		
OIL IN KRAFT PAPER		382.63	3.62
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10901.17		

TABLE A.6

138 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		11.40	0.11
CONDUCTING PAPER			
INNER RADIUS(IN)	1.30		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	420.67		
COPPER TAPE		118.49	1.12
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2507.82		
MYLAR TAPE		35.67	0.34
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	396.34		
SKID WIRES		86.15	0.81
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	1.31		
TOTAL WEIGHT(LBS/MILE)	2920.19		
CABLE MANUFACTURING ENERGY CONTENT		290.47	2.74
CASING PIPE		2179.33	20.59
STEEL PIPE			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	4.00		
TOTAL WEIGHT(LBS/MILE)	109514.25		
PIPE COATING		123.74	1.17
BITUMASTIC COATING			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.50		
TOTAL WEIGHT(LBS/MILE)	43570.43		

TABLE A.6

138 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		1836.10	17.35
POLYBUTENE OIL			
RADIUS(IN)	3.75		
CABLE RADIUS(IN)	1.31		
TOTAL WEIGHT(LBS/MILE)	52310.44		
MANHOLES--CONCRETE		83.25	0.79
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.63
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		20.45	0.19
STEEL PIPE			
INNER RADIUS(IN)	5.75		
OUTER RADIUS(IN)	6.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1027.72		
TRIFURCATOR-STUBS		2.35	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	1.63		
OUTER RADIUS(IN)	1.75		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	79.75		
TRIFURCATOR-CASING		2.50	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	4.00		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	84.66		

TABLE A.6

138 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		25.20	0.24
STAINLESS STEEL			
INNER RADIUS(IN)	1.75		
OUTER RADIUS(IN)	1.87		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	854.12		
POTHEADS		81.48	0.77
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.99

TOTAL ENERGY CONTENT = 10582.48 MILLION BTU/MILE

TABLE A.7

230 kV HPOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	38.45
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.34
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		756.75	6.42
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	28773.65		
OIL IN KRAFT PAPER		646.27	5.48
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	18412.18		

TABLE A.7

230 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		13.64	0.12
CONDUCTING PAPER			
INNER RADIUS(IN)	1.55		
OUTER RADIUS(IN)	1.56		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	503.19		
COPPER TAPE		141.58	1.20
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.56		
OUTER RADIUS(IN)	1.56		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2996.36		
MYLAR TAPE		42.61	0.36
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.56		
OUTER RADIUS(IN)	1.57		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	473.41		
SKID WIRES		101.05	0.86
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	1.57		
TOTAL WEIGHT(LBS/MILE)	3425.32		
CABLE MANUFACTURING ENERGY CONTENT		466.89	3.96
CASING PIPE		2350.52	19.95
STEEL PIPE			
INNER RADIUS(IN)	4.06		
OUTER RADIUS(IN)	4.31		
TOTAL WEIGHT(LBS/MILE)	118116.62		
PIPE COATING		132.85	1.13
BITUMASTIC COATING			
INNER RADIUS(IN)	4.31		
OUTER RADIUS(IN)	4.81		
TOTAL WEIGHT(LBS/MILE)	46779.30		

TABLE A.7

230 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		1885.43	16.00
POLYBUTENE OIL			
RADIUS(IN)	4.06		
CABLE RADIUS(IN)	1.57		
TOTAL WEIGHT(LBS/MILE)	53715.88		
MANHOLES--CONCRETE		83.25	0.71
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.46
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		22.16	0.19
STEEL PIPE			
INNER RADIUS(IN)	6.25		
OUTER RADIUS(IN)	6.75		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1113.36		
TRIFURCATOR-STUBS		2.70	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	1.88		
OUTER RADIUS(IN)	2.00		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	91.55		
TRIFURCATOR-CASING		2.70	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	4.06		
OUTER RADIUS(IN)	4.31		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	91.49		

TABLE A.7

230 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		27.01	0.23
STAINLESS STEEL			
INNER RADIUS(IN)	1.88		
OUTER RADIUS(IN)	2.00		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	915.46		
POTHEADS		252.30	2.14
230KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	9270.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.89

TOTAL ENERGY CONTENT = 11782.91 MILLION BTU/MILE

TABLE A.8

345 kV HPOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	30.59
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.27
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		1151.68	7.77
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	43790.23		
OIL IN KRAFT PAPER		983.55	6.64
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	1.82		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	28021.26		

TABLE A.8

345 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		16.05	0.11
CONDUCTING PAPER			
INNER RADIUS(IN)	1.82		
OUTER RADIUS(IN)	1.84		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	592.19		
COPPER TAPE		166.52	1.12
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.84		
OUTER RADIUS(IN)	1.84		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	3524.23		
MYLAR TAPE		50.08	0.34
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	1.84		
OUTER RADIUS(IN)	1.85		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	556.48		
SKID WIRES		117.35	0.79
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	1.85		
TOTAL WEIGHT(LBS/MILE)	3978.01		
CABLE MANUFACTURING ENERGY CONTENT		692.59	4.68
CASING PIPE		2917.77	19.70
STEEL PIPE			
INNER RADIUS(IN)	5.06		
OUTER RADIUS(IN)	5.31		
TOTAL WEIGHT(LBS/MILE)	146621.50		
PIPE COATING		161.97	1.09
BITUMASTIC COATING			
INNER RADIUS(IN)	5.31		
OUTER RADIUS(IN)	5.81		
TOTAL WEIGHT(LBS/MILE)	57031.16		

TABLE A.8

345 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		3190.60	21.54
POLYBUTENE OIL			
RADIUS(IN)	5.06		
CABLE RADIUS(IN)	1.85		
TOTAL WEIGHT(LBS/MILE)	90900.37		
MANHOLES--CONCRETE		97.62	0.66
CONCRETE			
WEIGHT/UNIT (TON)	32.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	131039.94		
MANHOLES--STEEL		202.18	1.36
STEEL ROD			
WEIGHT/UNIT (TON)	3.24		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	12960.00		
SPLICE SHELLS		27.27	0.18
STEEL PIPE			
INNER RADIUS(IN)	7.75		
OUTER RADIUS(IN)	8.25		
LENGTH OF UNIT(FT)	8.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1370.29		
TRIFURCATOR-STUBS		4.17	0.03
STAINLESS STEEL			
INNER RADIUS(IN)	2.35		
OUTER RADIUS(IN)	2.50		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	141.19		
TRIFURCATOR-CASING		3.34	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	5.06		
OUTER RADIUS(IN)	5.31		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	113.34		

TABLE A.8

345 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		41.65	0.28
STAINLESS STEEL			
INNER RADIUS(IN)	2.35		
OUTER RADIUS(IN)	2.50		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	1411.92		
POTHEADS		306.00	2.07
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.71

TOTAL ENERGY CONTENT = 14813.20 MILLION BTU/MILE

TABLE A.9

500 kV HPOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	23.54
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.21
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		1646.89	8.56
KRAFT PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.12		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	62619.59		
OIL IN KRAFT PAPER		1406.46	7.31
POLYBUTENE			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.12		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	40070.12		

TABLE A.9

500 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		18.63	0.10
CONDUCTING PAPER			
INNER RADIUS(IN)	2.12		
OUTER RADIUS(IN)	2.13		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	687.64		
COPPER TAPE		193.26	1.00
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	2.13		
OUTER RADIUS(IN)	2.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	4090.13		
MYLAR TAPE		58.10	0.30
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	2.14		
OUTER RADIUS(IN)	2.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	645.60		
SKID WIRES		135.01	0.70
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	2.14		
TOTAL WEIGHT(LBS/MILE)	4576.74		
CABLE MANUFACTURING ENERGY CONTENT		975.60	5.07
CASING PIPE		3479.90	18.08
STEEL PIPE			
INNER RADIUS(IN)	6.06		
OUTER RADIUS(IN)	6.31		
TOTAL WEIGHT(LBS/MILE)	174869.44		
PIPE COATING		191.07	0.99
BITUMASTIC COATING			
INNER RADIUS(IN)	6.31		
OUTER RADIUS(IN)	6.81		
TOTAL WEIGHT(LBS/MILE)	67277.81		

TABLE A.9

500 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		5401.61	28.06
POLYBUTENE OIL			
RADIUS(IN)	6.31		
CABLE RADIUS(IN)	2.14		
TOTAL WEIGHT(LBS/MILE)	153891.94		
MANHOLES--CONCRETE		130.37	0.68
CONCRETE			
WEIGHT/UNIT (TON)	33.65		
NO. UNIT PER MILE	2.60		
TOTAL WEIGHT(LBS/MILE)	174987.75		
MANHOLES--STEEL		270.01	1.40
STEEL ROD			
WEIGHT/UNIT (TON)	3.33		
NO. UNIT PER MILE	2.60		
TOTAL WEIGHT(LBS/MILE)	17308.20		
SPLICE SHELLS		52.62	0.27
STEEL PIPE			
INNER RADIUS(IN)	9.25		
OUTER RADIUS(IN)	9.75		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.60		
TOTAL WEIGHT(LBS/MILE)	2644.23		
TRIFURCATOR-STUBS		6.08	0.03
STAINLESS STEEL			
INNER RADIUS(IN)	2.82		
OUTER RADIUS(IN)	3.00		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	205.98		
TRIFURCATOR-CASING		3.99	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	6.06		
OUTER RADIUS(IN)	6.31		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	135.18		

TABLE A.9

500 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		54.08	0.28
STAINLESS STEEL			
INNER RADIUS(IN)	2.50		
OUTER RADIUS(IN)	2.68		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	1833.29		
POTHEADS		540.42	2.81
500KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	19320.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.55

TOTAL ENERGY CONTENT = 19246.91 MILLION BTU/MILE

TABLE A.10

765 kV HPOF CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE CONDUCTOR		4531.05	23.77
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
PAPER TAPE		3.41	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.78		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	125.80		
STEEL TAPE		39.94	0.21
STAINLESS STEEL			
INNER RADIUS(IN)	0.78		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1353.92		
COND. PAPER TAPE		3.45	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	0.79		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	127.41		
CABLE INSULATION		2134.16	11.19
SYNTHETIC PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.23		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	74620.94		
OIL IN SYN PAPER		1053.24	5.52
OIL IN S. PAPER			
INNER RADIUS(IN)	0.79		
OUTER RADIUS(IN)	2.23		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	30006.89		

TABLE A.10

765 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSULATION SCREEN		19.55	0.10
CONDUCTING PAPER			
INNER RADIUS(IN)	2.23		
OUTER RADIUS(IN)	2.23		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	721.55		
COPPER TAPE		202.77	1.06
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	2.23		
OUTER RADIUS(IN)	2.24		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	4291.33		
MYLAR TAPE		60.96	0.32
ONE LAYER,0.005 IN			
INNER RADIUS(IN)	2.24		
OUTER RADIUS(IN)	2.24		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	677.31		
SKID WIRES		141.33	0.74
STAINLESS STEEL			
NO. PER PHASE	2.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	2.24		
TOTAL WEIGHT(LBS/MILE)	4790.89		
CABLE MANUFACTURING ENERGY CONTENT		1155.98	6.06
CASING PIPE		3479.90	18.25
STEEL PIPE			
INNER RADIUS(IN)	6.06		
OUTER RADIUS(IN)	6.31		
TOTAL WEIGHT(LBS/MILE)	174869.44		
PIPE COATING		191.07	1.00
BITUMASTIC COATING			
INNER RADIUS(IN)	6.31		
OUTER RADIUS(IN)	6.81		
TOTAL WEIGHT(LBS/MILE)	67277.81		

TABLE A.10

765 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
INSUL. OIL(CASING)		4475.78	23.48
POLYBUTENE OIL			
RADIUS(IN)	6.06		
CABLE RADIUS(IN)	2.24		
TOTAL WEIGHT(LBS/MILE)	127515.12		
MANHOLES--CONCRETE		189.03	0.99
CONCRETE			
WEIGHT/UNIT (TON)	33.65		
NO. UNIT PER MILE	3.77		
TOTAL WEIGHT(LBS/MILE)	253732.19		
MANHOLES--STEEL		391.51	2.05
STEEL ROD			
WEIGHT/UNIT (TON)	3.33		
NO. UNIT PER MILE	3.77		
TOTAL WEIGHT(LBS/MILE)	25096.89		
SPLICE SHELLS		76.30	0.40
STEEL PIPE			
INNER RADIUS(IN)	9.25		
OUTER RADIUS(IN)	9.75		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	3.77		
TOTAL WEIGHT(LBS/MILE)	3834.14		
TRIFURCATOR-STUBS		6.08	0.03
STAINLESS STEEL			
INNER RADIUS(IN)	2.82		
OUTER RADIUS(IN)	3.00		
LENGTH OF UNIT(FT)	3.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	205.98		
TRIFURCATOR-CASING		3.99	0.02
STAINLESS STEEL			
INNER RADIUS(IN)	6.06		
OUTER RADIUS(IN)	6.31		
LENGTH OF UNIT(FT)	2.00		
NO. PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	135.18		

TABLE A.10

765 kV HPOF CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
RISER PIPES		60.76	0.32
STAINLESS STEEL			
INNER RADIUS(IN)	2.82		
OUTER RADIUS(IN)	3.00		
LENGTH OF UNIT(FT)	30.00		
NO. PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2059.80		
POTHEADS		740.40	3.88
765KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	26580.00		
OIL PRESSURIZING PLANT(1/3 SHARE)		105.00	0.55

TOTAL ENERGY CONTENT = 19065.61 MILLION BTU/MILE

TABLE A.11

138 kV EXTRUDED DIELECTRIC CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		4531.05	66.58
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
STRAND SHIELD		27.43	0.40
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.80		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	781.57		
EMISSION SHIELD		11.22	0.16
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.80		
OUTER RADIUS(IN)	0.81		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	319.58		
INSULATION		738.52	10.85
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.81		
OUTER RADIUS(IN)	1.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	21040.43		
INSULATION SHIELD		46.07	0.68
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.31		
OUTER RADIUS(IN)	1.34		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1312.52		
COPPER TAPE		242.87	3.57
TWO LAYERS,0.005			
INNER RADIUS(IN)	1.34		
OUTER RADIUS(IN)	1.35		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	5140.01		

TABLE A.11

138 kV EXTRUDED DIELECTRIC CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE JACKET		657.18	9.66
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.35		
OUTER RADIUS(IN)	1.60		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	21406.54		
CABLE MANUFACTURING ENERGY CONTENT		469.17	6.89
POTHEAD		81.48	1.20
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 6804.96 MILLION BTU/MILE

TABLE A.12

230 kV EXTRUDED DIELECTRIC CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		4531.05	57.39
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
STRAND SHIELD		27.43	0.35
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.80		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	781.57		
EMISSION SHIELD		11.22	0.14
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.80		
OUTER RADIUS(IN)	0.81		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	319.58		
INSULATION		1260.22	15.96
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.81		
OUTER RADIUS(IN)	1.57		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	35903.64		
INSULATION SHIELD		55.13	0.70
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.57		
OUTER RADIUS(IN)	1.60		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1570.63		
COPPER TAPE		289.97	3.67
TWO LAYERS,0.005			
INNER RADIUS(IN)	1.60		
OUTER RADIUS(IN)	1.60		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	6136.85		

TABLE A.12

230 kV EXTRUDED DIELECTRIC CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE JACKET		773.41	9.80
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.60		
OUTER RADIUS(IN)	1.85		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	25192.68		
CABLE MANUFACTURING ENERGY CONTENT		695.08	8.80
POTHEAD		252.30	3.20
230KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	9270.00		

TOTAL ENERGY CONTENT = 7895.79 MILLION BTU/MILE

TABLE A.13

345 kV EXTRUDED DIELECTRIC CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		4531.05	50.83
COPPER WIRE			
NO. PER PHASE	1.00		
CROSS SECTION(KCMIL)	2000.00		
INNER RADIUS(INCHES)	0.0		
TOTAL WEIGHT(LBS/MILE)	95895.31		
STRAND SHIELD		27.43	0.31
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.77		
OUTER RADIUS(IN)	0.80		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	781.57		
EMISSION SHIELD		11.22	0.13
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.80		
OUTER RADIUS(IN)	0.81		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	319.58		
INSULATION		1825.40	20.48
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	0.81		
OUTER RADIUS(IN)	1.81		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	52005.59		
INSULATION SHIELD		63.49	0.71
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.81		
OUTER RADIUS(IN)	1.84		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1808.75		
COPPER TAPE		333.49	3.74
TWO LAYERS,0.005			
INNER RADIUS(IN)	1.84		
OUTER RADIUS(IN)	1.85		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	7057.96		

TABLE A.13

345 kV EXTRUDED DIELECTRIC CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CABLE JACKET		880.71	9.88
POLYVINYL CHLORIDE			
INNER RADIUS(IN)	1.85		
OUTER RADIUS(IN)	2.10		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	28687.67		
CABLE MANUFACTURING ENERGY CONTENT		935.95	10.50
POTHEAD		306.00	3.43
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 8914.72 MILLION BTU/MILE

TABLE A.14

138 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		7179.19	29.01
ALUMINUM PIPE			
INNER RADIUS(IN)	2.00		
OUTER RADIUS(IN)	2.25		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	61889.58		
INSULATORS		22.10	0.09
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	792.00		
ENCLOSURE(SHEATH)		16469.90	66.54
ALUMINUM PIPE			
INNER RADIUS(IN)	4.75		
OUTER RADIUS(IN)	5.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	141982.00		
INSULATING GAS		539.60	2.18
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	2.25		
OUTER RADIUS(IN)	4.75		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	9635.67		
PIPE COATING		458.57	1.85
BITUMASTIC COATING			
INNER RADIUS(IN)	5.00		
OUTER RADIUS(IN)	5.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	161466.87		
POTHEADS		81.48	0.33
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 24750.82 MILLION BTU/MILE

TABLE A.15

230 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		8868.41	29.21
ALUMINUM PIPE			
INNER RADIUS(IN)	2.50		
OUTER RADIUS(IN)	2.75		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	76451.81		
INSULATORS		44.19	0.15
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	1584.00		
ENCLOSURE(SHEATH)		19848.34	65.38
ALUMINUM PIPE			
INNER RADIUS(IN)	5.75		
OUTER RADIUS(IN)	6.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	171106.50		
INSULATING GAS		799.44	2.63
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	2.75		
OUTER RADIUS(IN)	5.75		
PRESSURE(PSIG)	46.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	14275.75		
PIPE COATING		545.91	1.80
BITUMASTIC COATING			
INNER RADIUS(IN)	6.00		
OUTER RADIUS(IN)	6.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	192222.44		
POTHEADS		252.30	0.83
230KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	9270.00		

TOTAL ENERGY CONTENT = 30358.59 MILLION BTU/MILE

TABLE A.16

345 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		9713.02	24.90
ALUMINUM PIPE			
INNER RADIUS(IN)	2.75		
OUTER RADIUS(IN)	3.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	83732.94		
INSULATORS		95.75	0.25
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	3432.00		
ENCLOSURE(SHEATH)		26605.23	68.19
ALUMINUM PIPE			
INNER RADIUS(IN)	7.75		
OUTER RADIUS(IN)	8.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	229355.50		
INSULATING GAS		1574.47	4.04
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	3.00		
OUTER RADIUS(IN)	7.75		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	28115.51		
PIPE COATING		720.60	1.85
BITUMASTIC COATING			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	253733.62		
POTHEADS		306.00	0.78
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 39015.06 MILLION BTU/MILE

TABLE A.17

500 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		16786.63	30.90
ALUMINUM PIPE			
INNER RADIUS(IN)	3.13		
OUTER RADIUS(IN)	3.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	144712.37		
INSULATORS		184.14	0.34
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	6600.00		
ENCLOSURE(SHEATH)		33362.12	61.42
ALUMINUM PIPE			
INNER RADIUS(IN)	9.75		
OUTER RADIUS(IN)	10.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	287604.62		
INSULATING GAS		2553.45	4.70
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	3.50		
OUTER RADIUS(IN)	9.75		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	45597.37		
PIPE COATING		895.30	1.65
BITUMASTIC COATING			
INNER RADIUS(IN)	10.00		
OUTER RADIUS(IN)	10.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	315244.87		
POTHEADS		540.42	0.99
500KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	19320.00		

TOTAL ENERGY CONTENT = 54322.05 MILLION BTU/MILE

TABLE A.18

765 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		25338.32	26.98
ALUMINUM PIPE			
INNER RADIUS(IN)	3.50		
OUTER RADIUS(IN)	4.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	218433.87		
INSULATORS		294.62	0.31
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	10560.00		
ENCLOSURE(SHEATH)		62395.64	66.43
ALUMINUM PIPE			
INNER RADIUS(IN)	12.13		
OUTER RADIUS(IN)	12.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	537893.50		
INSULATING GAS		4039.75	4.30
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	12.13		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	72138.44		
PIPE COATING		1113.66	1.19
BITUMASTIC COATING			
INNER RADIUS(IN)	12.50		
OUTER RADIUS(IN)	13.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	392133.62		
POTHEADS		740.40	0.79
765KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	26580.00		

TOTAL ENERGY CONTENT = 93922.31 MILLION BTU/MILE

TABLE A.19

1,200 kV CGI SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR		35473.64	29.68
ALUMINUM PIPE			
INNER RADIUS(IN)	5.00		
OUTER RADIUS(IN)	5.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	305807.37		
INSULATORS		810.22	0.68
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.05		
NO. UNIT PER MILE	264.00		
TOTAL WEIGHT(LBS/MILE)	29040.00		
ENCLOSURE(SHEATH)		75064.75	62.81
ALUMINUM PIPE			
INNER RADIUS(IN)	14.63		
OUTER RADIUS(IN)	15.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	647110.25		
POTHEADS		1161.23	0.97
1200 kV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	40,800.00		
INSULATING GAS		5662.39	4.74
SULFUR HEXAFLUORIDE			
INNER RADIUS(IN)	5.50		
OUTER RADIUS(IN)	14.63		
PRESSURE(PSIG)	45.00		
TEMPERATURE(C)	20.00		
TOTAL WEIGHT(LBS/MILE)	101114.25		
PIPE COATING		1332.02	1.12
BITUMASTIC COATING			
INNER RADIUS(IN)	15.00		
OUTER RADIUS(IN)	15.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	469022.69		

TOTAL ENERGY CONTENT = 119504.14 MILLION BTU/MILE

TABLE A.20

138 kV AC SUPERCONDUCTING CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		698.83	4.08
LIQUID HELIUM			
RADIUS(IN)	0.96		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2405.60		
HELICAL CORE		1693.56	9.90
BRONZE			
INNER RADIUS(IN)	0.96		
OUTER RADIUS(IN)	1.03		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	29229.54		
SUPERCOND. BACKING		217.59	1.27
ALUMINUM STRIP			
INNER RADIUS(IN)	1.03		
OUTER RADIUS(IN)	1.05		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1908.64		
SUPERCONDUCTOR		193.59	1.13
BNL SUPER. ALLOY			
INNER RADIUS(IN)	1.05		
OUTER RADIUS(IN)	1.06		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1800.84		
INSULATION		612.74	3.58
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.06		
OUTER RADIUS(IN)	1.42		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17457.09		
SUPERCONDUCTOR		260.58	1.52
BNL SUPER. ALLOY			
INNER RADIUS(IN)	1.42		
OUTER RADIUS(IN)	1.43		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2424.04		

TABLE A.20

138 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SUPERCOND. BACKING		299.10	1.75
ALUMINUM STRIP			
INNER RADIUS(IN)	1.43		
OUTER RADIUS(IN)	1.44		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2623.72		
PLASTIC TAPE		20.15	0.12
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.44		
OUTER RADIUS(IN)	1.45		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	573.99		
CABLE SHEATH		488.19	2.85
LEAD			
INNER RADIUS(IN)	1.45		
OUTER RADIUS(IN)	1.53		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	57434.10		
PLASTIC TAPE		10.67	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.53		
OUTER RADIUS(IN)	1.53		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	304.11		
REINFORCEMENT		667.94	3.90
BRONZE TAPE			
INNER RADIUS(IN)	1.53		
OUTER RADIUS(IN)	1.55		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11528.22		
PLASTIC TAPE		10.85	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.55		
OUTER RADIUS(IN)	1.56		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	309.07		

TABLE A.20

138 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SKID WIRES		50.21	0.29
STAINLESS STEEL			
NO. PER PHASE	1.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	1.56		
TOTAL WEIGHT(LBS/MILE)	1702.18		
INNER CASING		1923.02	11.24
STNLS. STEEL PIPE			
INNER RADIUS(IN)	3.63		
OUTER RADIUS(IN)	3.75		
TOTAL WEIGHT(LBS/MILE)	51076.31		
HELIUM COOLANT		1511.42	8.83
LIQUID HELIUM			
RADIUS(IN)	3.63		
CABLE RADIUS(IN)	1.55		
TOTAL WEIGHT(LBS/MILE)	5202.82		
SUPER INSULATION		3170.87	18.53
ALUMINIZED MYLAR			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	8.00		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	40137.61		
PIPE SUPPORTS		51.92	0.30
STAINLESS STEEL			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	440.00		
TOTAL WEIGHT(LBS/MILE)	1760.00		
OUTER CASING		4569.57	26.70
STEEL PIPE			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.25		
TOTAL WEIGHT(LBS/MILE)	229626.56		

TABLE A.20

138 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
PIPE COATING		240.20	1.40
BITUMASTIC COATING			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.50		
TOTAL WEIGHT(LBS/MILE)	84577.87		
MANHOLES--CONCRETE		83.25	0.49
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.01
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		45.75	0.27
STNLS. STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1215.22		
SPLICE SHELLS		38.67	0.23
STEEL PIPE			
INNER RADIUS(IN)	15.00		
OUTER RADIUS(IN)	15.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1943.03		
POTHEADS		81.48	0.48
138KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	2964.00		

TOTAL ENERGY CONTENT = 17112.54 MILLION BTU/MILE

<u>TABLE A.21</u>

<u>345 kV AC SUPERCONDUCTING CABLE SYSTEM</u>

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		893.56	3.32
LIQUID HELIUM			
RADIUS(IN)	1.08		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	3075.95		
HELICAL CORE		1906.29	7.09
BRONZE			
INNER RADIUS(IN)	1.08		
OUTER RADIUS(IN)	1.16		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	32901.13		
SUPERCOND. BACKING		243.68	0.91
ALUMINUM STRIP			
INNER RADIUS(IN)	1.16		
OUTER RADIUS(IN)	1.18		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2137.55		
SUPERCONDUCTOR		216.53	0.81
BNL SUPER. ALLOY			
INNER RADIUS(IN)	1.18		
OUTER RADIUS(IN)	1.19		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	2014.19		
INSULATION		2692.23	10.02
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	1.19		
OUTER RADIUS(IN)	2.30		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	76701.75		
SUPERCONDUCTOR		422.10	1.57
BNL SUPER. ALLOY			
INNER RADIUS(IN)	2.30		
OUTER RADIUS(IN)	2.31		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	3926.48		

TABLE A.21

345 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SUPERCOND. BACKING		482.79	1.80
ALUMINUM STRIP			
INNER RADIUS(IN)	2.31		
OUTER RADIUS(IN)	2.32		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	4235.00		
PLASTIC TAPE		32.41	0.12
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.32		
OUTER RADIUS(IN)	2.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	923.34		
CABLE SHEATH		776.49	2.89
LEAD			
INNER RADIUS(IN)	2.33		
OUTER RADIUS(IN)	2.41		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	91351.62		
PLASTIC TAPE		16.80	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.41		
OUTER RADIUS(IN)	2.41		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	478.78		
REINFORCEMENT		1046.52	3.90
BRONZE TAPE			
INNER RADIUS(IN)	2.41		
OUTER RADIUS(IN)	2.43		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	18096.63		
PLASTIC TAPE		16.98	0.06
POLYETHELENE(LDPE)			
INNER RADIUS(IN)	2.43		
OUTER RADIUS(IN)	2.44		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	483.75		

TABLE A.21

345 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
SKID WIRES		76.53	0.28
STAINLESS STEEL			
NO. PER PHASE	1.00		
DIAMETER(IN)	0.20		
CABLE RADIUS(IN)	2.44		
TOTAL WEIGHT(LBS/MILE)	2594.34		
INNER CASING		3158.12	11.75
STNLS. STEEL PIPE			
INNER RADIUS(IN)	6.00		
OUTER RADIUS(IN)	6.12		
TOTAL WEIGHT(LBS/MILE)	83880.87		
HELIUM COOLANT		4645.72	17.29
LIQUID HELIUM			
RADIUS(IN)	6.00		
CABLE RADIUS(IN)	2.43		
TOTAL WEIGHT(LBS/MILE)	15992.16		
SUPER INSULATION		3653.68	13.59
ALUMINIZED MYLAR			
INNER RADIUS(IN)	6.12		
OUTER RADIUS(IN)	9.75		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	46249.08		
PIPE SUPPORTS		51.92	0.19
STAINLESS STEEL			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	440.00		
TOTAL WEIGHT(LBS/MILE)	1760.00		
OUTER CASING		5553.79	20.66
STEEL PIPE			
INNER RADIUS(IN)	9.75		
OUTER RADIUS(IN)	10.00		
TOTAL WEIGHT(LBS/MILE)	279084.75		

TABLE A.21

345 kV AC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
PIPE COATING		298.43	1.11
BITUMASTIC COATING			
INNER RADIUS(IN)	10.00		
OUTER RADIUS(IN)	10.50		
TOTAL WEIGHT(LBS/MILE)	105081.62		
MANHOLES--CONCRETE		97.62	0.36
CONCRETE			
WEIGHT/UNIT (TON)	32.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	131039.94		
MANHOLES--STEEL		202.18	0.75
STEEL ROD			
WEIGHT/UNIT (TON)	3.24		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	12960.00		
SPLICE SHELLS		45.75	0.17
STNLS. STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1215.22		
SPLICE SHELLS		38.67	0.14
STEEL PIPE			
INNER RADIUS(IN)	15.00		
OUTER RADIUS(IN)	15.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1943.03		
POTHEADS		306.00	1.14
345KV RATING			
UNITS PER SYSTEM	6.00		
TOTAL WEIGHT(LBS/SYSTEM)	10980.00		

TOTAL ENERGY CONTENT = 26876.75 MILLION BTU/MILE

TABLE A.22

100 kV DC SUPERCONDUCTING CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		332.37	2.34
LIQUID HELIUM			
RADIUS(IN)	1.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1144.12		
HELICAL CORE		329.83	2.32
BRONZE			
INNER RADIUS(IN)	1.14		
OUTER RADIUS(IN)	1.18		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	5692.66		
INNER SUPERCONDUCTOR		1011.61	7.12
LASL SUPER. ALLOY			
INNER RADIUS(IN)	1.18		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17438.48		
COND PAPER TAPE		3.86	0.03
CONDUCTING PAPER			
INNER RADIUS(IN)	1.32		
OUTER RADIUS(IN)	1.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	142.58		
INSULATION		283.56	2.00
SYNTHETIC PAPER			
INNER RADIUS(IN)	1.33		
OUTER RADIUS(IN)	1.87		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	9914.59		
COND PAPER TAPE		5.47	0.04
CONDUCTING PAPER			
INNER RADIUS(IN)	1.87		
OUTER RADIUS(IN)	1.88		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	201.88		

TABLE A.22

100 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SUPERCONDUCTOR		881.14	6.20
LASL SUPER. ALLOY			
INNER RADIUS(IN)	1.88		
OUTER RADIUS(IN)	1.94		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	15189.45		
CABLE ARMOR		615.02	4.33
BRONZE			
INNER RADIUS(IN)	2.15		
OUTER RADIUS(IN)	2.19		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	10614.79		
INNER CASING		3935.73	27.71
STNLS. STEEL PIPE			
INNER RADIUS(IN)	3.50		
OUTER RADIUS(IN)	3.75		
TOTAL WEIGHT(LBS/MILE)	104534.56		
HELIUM RETURN		1905.87	13.42
LIQUID HELIUM			
INNER RADIUS(IN)	2.19		
OUTER RADIUS(IN)	3.50		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	6560.66		
SUPER INSULATION		1027.35	7.23
ALUMINIZED MYLAR			
INNER RADIUS(IN)	3.75		
OUTER RADIUS(IN)	5.50		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	13004.38		
INSULATORS		42.07	0.30
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	754.00		
TOTAL WEIGHT(LBS/MILE)	1508.00		

TABLE A.22

100 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER CASING		3163.55	22.27
STEEL PIPE			
INNER RADIUS(IN)	5.50		
OUTER RADIUS(IN)	5.75		
TOTAL WEIGHT(LBS/MILE)	158972.25		
PIPE COATING		174.69	1.23
BITUMASTIC COATING			
INNER RADIUS(IN)	5.75		
OUTER RADIUS(IN)	6.25		
TOTAL WEIGHT(LBS/MILE)	61511.19		
MANHOLES--CONCRETE		83.25	0.59
CONCRETE			
WEIGHT/UNIT (TON)	27.94		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	111747.94		
MANHOLES--STEEL		172.41	1.21
STEEL ROD			
WEIGHT/UNIT (TON)	2.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	11052.00		
SPLICE SHELLS		33.42	0.24
STNLS. STEEL PIPE			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	887.52		
SPLICE SHELLS		28.44	0.20
STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1429.17		

TABLE A.22

100 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
TERMINATION		27.16	0.19
100KV RATING			
UNITS PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	988.00		

TOTAL ENERGY CONTENT = 14204.10 MILLION BTU/MILE

TABLE A.23

300 kV DC SUPERCONDUCTING CABLE SYSTEM

COMPONENT		ENERGY (MILLION BTU)	PERCENT
COOLANT IN CORE		332.37	1.85
LIQUID HELIUM			
RADIUS(IN)	1.14		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	1144.12		
HELICAL CORE		329.83	1.83
BRONZE			
INNER RADIUS(IN)	1.14		
OUTER RADIUS(IN)	1.18		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	5692.66		
INNER SUPERCONDUCTOR		1011.61	5.62
LASL SUPER. ALLOY			
INNER RADIUS(IN)	1.18		
OUTER RADIUS(IN)	1.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	17438.48		
COND PAPER TAPE		3.86	0.02
CONDUCTING PAPER			
INNER RADIUS(IN)	1.32		
OUTER RADIUS(IN)	1.33		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	142.58		
INSULATION		564.99	3.14
SYNTHETIC PAPER			
INNER RADIUS(IN)	1.33		
OUTER RADIUS(IN)	2.28		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	19754.95		
COND PAPER TAPE		6.68	0.04
CONDUCTING PAPER			
INNER RADIUS(IN)	2.28		
OUTER RADIUS(IN)	2.29		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	246.43		

TABLE A.23

300 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER SUPERCONDUCTOR		1071.75	5.95
LASL SUPER. ALLOY			
INNER RADIUS(IN)	2.29		
OUTER RADIUS(IN)	2.35		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	18475.31		
CABLE ARMOR		673.61	3.74
BRONZE			
INNER RADIUS(IN)	2.35		
OUTER RADIUS(IN)	2.39		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	11625.98		
INNER CASING		4478.58	24.88
STNLS. STEEL PIPE			
INNER RADIUS(IN)	4.00		
OUTER RADIUS(IN)	4.25		
TOTAL WEIGHT(LBS/MILE)	118953.06		
HELIUM RETURN		2621.31	14.56
LIQUID HELIUM			
INNER RADIUS(IN)	2.39		
OUTER RADIUS(IN)	4.00		
NO. PER PHASE	1.00		
TOTAL WEIGHT(LBS/MILE)	9023.43		
SUPER INSULATION		1964.27	10.91
ALUMINIZED MYLAR			
INNER RADIUS(IN)	4.25		
OUTER RADIUS(IN)	7.00		
LAYER THICKNESS(IN)	0.00		
LAYER SPACING(IN)	0.02		
TOTAL WEIGHT(LBS/MILE)	24864.12		
INSULATORS		42.07	0.23
EPOXY RESIN			
WEIGHT/UNIT (TON)	0.00		
NO. UNIT PER MILE	754.00		
TOTAL WEIGHT(LBS/MILE)	1508.00		

TABLE A.23

300 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
OUTER CASING		4007.16	22.26
STEEL PIPE			
INNER RADIUS(IN)	7.00		
OUTER RADIUS(IN)	7.25		
TOTAL WEIGHT(LBS/MILE)	201364.87		
PIPE COATING		211.09	1.17
BITUMASTIC COATING			
INNER RADIUS(IN)	7.00		
OUTER RADIUS(IN)	7.50		
TOTAL WEIGHT(LBS/MILE)	74326.00		
MANHOLES--CONCRETE		97.62	0.54
CONCRETE			
WEIGHT/UNIT (TON)	32.76		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	131039.94		
MANHOLES--STEEL		202.18	1.12
STEEL ROD			
WEIGHT/UNIT (TON)	3.24		
NO. UNIT PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	12960.00		
SPLICE SHELLS		33.42	0.19
STNLS. STEEL PIPE			
INNER RADIUS(IN)	8.00		
OUTER RADIUS(IN)	8.25		
LENGTH OF UNIT(FT)	10.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	887.52		
SPLICE SHELLS		28.44	0.16
STEEL PIPE			
INNER RADIUS(IN)	11.00		
OUTER RADIUS(IN)	11.25		
LENGTH OF UNIT(FT)	12.00		
NO. PER MILE	2.00		
TOTAL WEIGHT(LBS/MILE)	1429.17		

TABLE A.23

300 kV DC SUPERCONDUCTING CABLE SYSTEM (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
TERMINATION		27.16	0.15
100KV RATING			
UNITS PER SYSTEM	2.00		
TOTAL WEIGHT(LBS/SYSTEM)	988.00		

TOTAL ENERGY CONTENT = 18001.52 MILLION BTU/MILE

TABLE A.24

138 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		95.79	2.46
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	5618.33		
CONDUCTOR		1585.13	40.79
ALUMINUM WIRE			
NO. PER PHASE	1.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	954.00		
TOTAL WEIGHT(LBS/MILE)	13904.69		
CONDUCTOR SPACERS		0.0	0.0
ALUMINUM			
WEIGHT/UNIT (TON)	0.0		
NO. UNIT PER MILE	0.0		
TOTAL WEIGHT(LBS/MILE)	0.0		
LINE HARDWARE		4.89	0.13
STEEL			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	313.50		
SUSPENSION INSULATOR		38.61	0.99
20K RATING			
UNITS PER MILE	198.00		
TOTAL WEIGHT(LBS/MILE)	2475.00		
TOWERS		1970.10	50.69
STEEL PIPE			
WEIGHT/UNIT (TON)	6.00		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	99000.00		

TABLE A.24

138 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--CONCRETE		153.66	3.95
CONCRETE			
WEIGHT/UNIT (TON)	12.50		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	206250.00		
SHIELD WIRES		38.01	0.98
EHS STEEL CABLE			
NO. PER PHASE	0.33		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	2229.30		

TOTAL ENERGY CONTENT = 3886.19 MILLION BTU/MILE

TABLE A.25

230 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		109.38	2.22
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.04		
TOTAL WEIGHT(LBS/MILE)	6415.46		
CONDUCTOR		1850.65	37.58
ALUMINUM WIRE			
NO. PER PHASE	1.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	1114.00		
TOTAL WEIGHT(LBS/MILE)	16233.80		
CONDUCTOR SPACERS		0.0	0.0
ALUMINUM			
WEIGHT/UNIT (TON)	0.0		
NO. UNIT PER MILE	0.0		
TOTAL WEIGHT(LBS/MILE)	0.0		
LINE HARDWARE		4.89	0.10
STEEL			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	313.50		
SUSPENSION INSULATOR		67.57	1.37
20K RATING			
UNITS PER MILE	346.50		
TOTAL WEIGHT(LBS/MILE)	4331.25		
TOWERS		2626.80	53.34
STEEL PIPE			
WEIGHT/UNIT (TON)	8.00		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	132000.00		

TABLE A.25

230 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--CONCRETE		227.41	4.62
CONCRETE			
WEIGHT/UNIT (TON)	18.50		
NO. UNIT PER MILE	8.25		
TOTAL WEIGHT(LBS/MILE)	305250.00		
SHIELD WIRES		38.01	0.77
EHS STEEL CABLE			
NO. PER PHASE	0.33		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	2229.30		

TOTAL ENERGY CONTENT = 4924.71 MILLION BTU/MILE

TABLE A.26

345 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		191.59	3.56
EHS STEEL CABLE			
NO. PER PHASE	2.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	11236.66		
CONDUCTOR		3170.27	58.89
ALUMINUM WIRE			
NO. PER PHASE	2.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	954.00		
TOTAL WEIGHT(LBS/MILE)	27809.39		
CONDUCTOR SPACERS		94.41	1.75
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	54.00		
TOTAL WEIGHT(LBS/MILE)	842.94		
LINE HARDWARE		7.31	0.14
STEEL			
WEIGHT/UNIT (TON)	0.04		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	468.60		
SUSPENSION INSULATOR		119.38	2.22
30K RATING			
UNITS PER MILE	514.80		
TOTAL WEIGHT(LBS/MILE)	7722.00		
TOWERS		1377.95	25.59
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	7.15		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	94379.94		

TABLE A.26

345 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		346.90	6.44
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	1.80		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	23759.99		
SHIELD WIRES		76.01	1.41
EHS STEEL CABLE			
NO. PER PHASE	0.67		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.19		

TOTAL ENERGY CONTENT = 5383.81 MILLION BTU/MILE

TABLE A.27

500 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		351.39	3.73
EHS STEEL CABLE			
NO. PER PHASE	3.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.04		
TOTAL WEIGHT(LBS/MILE)	20609.35		
CONDUCTOR		5945.31	63.10
ALUMINUM WIRE			
NO. PER PHASE	3.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	1193.00		
TOTAL WEIGHT(LBS/MILE)	52151.86		
CONDUCTOR SPACERS		110.44	1.17
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	57.00		
TOTAL WEIGHT(LBS/MILE)	986.10		
LINE HARDWARE		6.18	0.07
STEEL			
WEIGHT/UNIT (TON)	0.04		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	396.00		
SUSPENSION INSULATOR		126.24	1.34
40K RATING			
UNITS PER MILE	507.00		
TOTAL WEIGHT(LBS/MILE)	8517.60		
TOWERS		2312.64	24.55
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	15.00		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	158399.94		

TABLE A.27

500 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		493.36	5.24
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	3.20		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	33791.99		
SHIELD WIRES		76.01	0.81
EHS STEEL CABLE			
NO. PER PHASE	0.67		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.19		

TOTAL ENERGY CONTENT = 9421.56 MILLION BTU/MILE

TABLE A.28

765 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		530.31	3.79
EHS STEEL CABLE			
NO. PER PHASE	4.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.05		
TOTAL WEIGHT(LBS/MILE)	31103.25		
CONDUCTOR		8984.41	64.18
ALUMINUM WIRE			
NO. PER PHASE	4.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.08		
CROSS SECTION(KCMIL	1352.00		
TOTAL WEIGHT(LBS/MILE)	78810.56		
CONDUCTOR SPACERS		157.63	1.13
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	63.00		
TOTAL WEIGHT(LBS/MILE)	1407.42		
LINE HARDWARE		24.52	0.18
STEEL			
WEIGHT/UNIT (TON)	0.20		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	1572.00		
SHIELD WIRES		76.01	0.54
EHS STEEL CABLE			
NO. PER PHASE	0.67		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.19		
SUSPENSION INSULATOR		418.32	2.99
40K RATING			
UNITS PER MILE	1680.00		
TOTAL WEIGHT(LBS/MILE)	28224.00		

TABLE A.28

765 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
TOWERS		3153.60	22.53
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	27.00		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	216000.00		
FOOTINGS--STEEL		654.08	4.67
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	5.60		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	44799.98		

TOTAL ENERGY CONTENT = 13998.87 MILLION BTU/MILE

TABLE A.29

1,200 kV OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		899.60	2.46
EHS STEEL CABLE			
NO. PER PHASE	8.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.04		
TOTAL WEIGHT(LBS/MILE)	52762.60		
CONDUCTOR		23676.32	64.82
ALUMINUM WIRE			
NO. PER PHASE	8.00		
NO. STRANDS	84.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	1781.00		
TOTAL WEIGHT(LBS/MILE)	207687.12		
CONDUCTOR SPACERS		1058.40	2.90
ALUMINUM			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	210.00		
TOTAL WEIGHT(LBS/MILE)	9450.00		
LINE HARDWARE		196.56	0.54
STEEL			
WEIGHT/UNIT (TON)	1.57		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	12600.00		
SUSPENSION INSULATOR		466.32	1.28
120K INSULATOR			
UNITS PER MILE	696.00		
TOTAL WEIGHT(LBS/MILE)	31320.00		
TOWERS		8631.51	23.63
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	73.90		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	591199.69		

TABLE A.29

1,200 kV OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		1524.24	4.17
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	13.05		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	104399.94		
SHIELD WIRES		76.01	0.21
EHS STEEL CABLE			
NO. PER PHASE	0.67		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.19		

TOTAL ENERGY CONTENT = 36528.96 MILLION BTU/MILE

TABLE A.30

± 200 kV DC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		48.40	1.16
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.06		
TOTAL WEIGHT(LBS/MILE)	2838.79		
CONDUCTOR		2401.39	57.65
ALUMINUM WIRE			
NO. PER PHASE	1.00		
NO. STRANDS	72.00		
STRAND RADIUS(IN)	0.09		
CROSS SECTION(KCMIL	2167.00		
TOTAL WEIGHT(LBS/MILE)	21064.82		
CONDUCTOR SPACERS		0.0	0.0
ALUMINUM			
WEIGHT/UNIT (TON)	0.0		
NO. UNIT PER MILE	0.0		
TOTAL WEIGHT(LBS/MILE)	0.0		
LINE HARDWARE		2.57	0.06
STEEL			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	165.00		
SUSPENSION INSULATOR		51.95	1.25
30K RATING			
UNITS PER MILE	224.00		
TOTAL WEIGHT(LBS/MILE)	3360.00		
TOWERS		1461.77	35.09
3ALUM. STRUCTURAL			
WEIGHT/UNIT (TON)	0.98		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	12936.00		

TABLE A.30

± 200 kV DC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		123.34	2.96
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	0.64		
NO. UNIT PER MILE	6.60		
TOTAL WEIGHT(LBS/MILE)	8448.00		
SHIELD WIRES		76.02	1.83
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.64		

TOTAL ENERGY CONTENT = 4165.43 MILLION BTU/MILE

TABLE A.31

± 400 kV DC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		130.05	2.01
EHS STEEL CABLE			
NO. PER PHASE	2.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.04		
TOTAL WEIGHT(LBS/MILE)	7627.83		
CONDUCTOR		5122.33	79.29
ALUMINUM WIRE			
NO. PER PHASE	2.00		
NO. STRANDS	76.00		
STRAND RADIUS(IN)	0.09		
CROSS SECTION(KCMIL	2312.00		
TOTAL WEIGHT(LBS/MILE)	44932.73		
CONDUCTOR SPACERS		62.94	0.97
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	36.00		
TOTAL WEIGHT(LBS/MILE)	561.96		
LINE HARDWARE		3.95	0.06
STEEL			
WEIGHT/UNIT (TON)	0.02		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	253.44		
SUSPENSION INSULATOR		63.10	0.98
40K RATING			
UNITS PER MILE	253.40		
TOTAL WEIGHT(LBS/MILE)	4257.12		
TOWERS		770.88	11.93
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	5.00		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	52799.98		

TABLE A.31

± 400 kV DC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		231.26	3.58
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	1.50		
NO. UNIT PER MILE	5.28		
TOTAL WEIGHT(LBS/MILE)	15840.00		
SHIELD WIRES		76.02	1.18
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.64		

TOTAL ENERGY CONTENT = 6460.52 MILLION BTU/MILE

TABLE A.32

± 600 kV DC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		255.45	3.22
EHS STEEL CABLE			
NO. PER PHASE	4.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	14982.22		
CONDUCTOR		4227.02	53.32
ALUMINUM WIRE			
NO. PER PHASE	4.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.07		
CROSS SECTION(KCMIL	954.00		
TOTAL WEIGHT(LBS/MILE)	37079.18		
CONDUCTOR SPACERS		105.09	1.33
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	42.00		
TOTAL WEIGHT(LBS/MILE)	938.28		
LINE HARDWARE		6.24	0.08
STEEL			
WEIGHT/UNIT (TON)	0.05		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	400.00		
SUSPENSION INSULATOR		103.58	1.31
40K RATING			
UNITS PER MILE	416.00		
TOTAL WEIGHT(LBS/MILE)	6988.80		
TOWERS		2628.00	33.15
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	22.50		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	180000.00		

TABLE A.32

+ 600 kV DC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		525.60	6.63
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	4.50		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	36000.00		
SHIELD WIRES		76.02	0.96
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.64		

TOTAL ENERGY CONTENT = 7926.99 MILLION BTU/MILE

TABLE A.33

+ 800 kV DC OVERHEAD LINE (Cont'd.)

COMPONENT		ENERGY (MILLION BTU)	PERCENT
CONDUCTOR CORE		353.54	3.32
EHS STEEL CABLE			
NO. PER PHASE	4.00		
NO. STRANDS	19.00		
STRAND RADIUS(IN)	0.05		
TOTAL WEIGHT(LBS/MILE)	20735.50		
CONDUCTOR		5989.60	56.19
ALUMINUM WIRE			
NO. PER PHASE	4.00		
NO. STRANDS	54.00		
STRAND RADIUS(IN)	0.08		
CROSS SECTION(KCMIL	1352.00		
TOTAL WEIGHT(LBS/MILE)	52540.41		
CONDUCTOR SPACERS		105.09	0.99
ALUMINUM			
WEIGHT/UNIT (TON)	0.01		
NO. UNIT PER MILE	42.00		
TOTAL WEIGHT(LBS/MILE)	938.28		
LINE HARDWARE		16.41	0.15
STEEL			
WEIGHT/UNIT (TON)	0.13		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	1052.00		
SUSPENSION INSULATOR		310.75	2.92
40K RATING			
UNITS PER MILE	1248.00		
TOTAL WEIGHT(LBS/MILE)	20966.40		
TOWERS		3153.60	29.59
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	27.00		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	216000.00		

TABLE A.33

± 800 kV DC OVERHEAD LINE

COMPONENT		ENERGY (MILLION BTU)	PERCENT
FOOTINGS--STEEL		654.08	6.14
STRUCTURAL STEEL			
WEIGHT/UNIT (TON)	5.60		
NO. UNIT PER MILE	4.00		
TOTAL WEIGHT(LBS/MILE)	44799.98		
SHIELD WIRES		76.02	0.71
EHS STEEL CABLE			
NO. PER PHASE	1.00		
NO. STRANDS	7.00		
STRAND RADIUS(IN)	0.07		
TOTAL WEIGHT(LBS/MILE)	4458.64		

TOTAL ENERGY CONTENT = 10659.08 MILLION BTU/MILE

APPENDIX A.2

ENERGY ANALYSIS OF MYLAR FILM

A. ASSUMPTIONS

This appendix describes the reactions and energy requirements for the production of the resin poly (ethylene terephthalate) which is marketed in the form of Mylar film by E.I. DuPont de Nemours. It summarizes the estimated energy content for production of this compound and its raw materials through the molten resin stage. The molten resin can be fabricated directly to products (on-site) or cast into pellets for remelting and fabrication off-site into film.

The energy content of some of the basic inputs to production of the poly (ethylene terephthalate) shown below are based upon the analyses performed in Chapter IV.

Electricity	1 kilowatt hour	=	10,500 Btu
Steam	1 lb.	=	1,190 Btu
Methanol	1 lb.	=	18,425 Btu
Ethylene	1 lb.	=	27,090 Btu
Bromine	1 lb.	=	7,400 Btu
Chlorine	1 lb.	=	9,150 Btu
Hydrogen	1 lb.	=	53,450 Btu
Silver	1 lb.	=	737,000 Btu
Cobalt	1 lb.	=	62,000 Btu
Sulfuric Acid	1 lb.	=	415 Btu

The total energy input for p-Xylene was estimated by adding the energy content (heat of combustion) of the C8 aromatic fraction to the processing energy input for crude oil to C8 aromatics and then adding the energy requirements for conversion/separation of the p-Xylene fraction from the C8 fraction. There is more than one process used in the production of p-Xylene from the C8 fraction. The two major processes used in the U.S. both involve isomerization of the C8 fraction to p-Xylene, but in one case, crystallization is used whereas the other separates them by absorption. The absorption process is gaining in popularity and should require less energy. We have used this latter process (isolene isomerization and Aromax absorption/separation) as a basis for our energy input calculations for p-Xylene.

Carbon monoxide used in the synthesis of acetic acid is often a byproduct of other processes (i.e., acetylene production). The energy input for carbon monoxide was, therefore, taken as its heat of combustion.

B. ENERGY INPUT FOR POLY (ETHYLENE TEREPHTHALATE)[1]

Poly (ethylene terephthalate), the resin used to produce Mylar film, is prepared by the reaction between methyl terephthalate and ethylene glycol as shown in the following two-step reaction:

$$C_{10}H_{10}O_4 + 2C_2H_6O_6 \xrightarrow{150-210^\circ C} C_{12}H_{14}O_6 \xrightarrow[<1mm\ Hg]{270-285^\circ C} (C_{10}H_8O_4)_n$$

dimethyl terephthalate	ethylene glycol	bis-(2 hydroxyethyl) terephthalate + CH_3OH (methanol)	poly (ethylene terephthalate) + $C_2H_6O_2$ (ethylene glycol)

The energy input for the poly (ethylene terephthalate) resin is shown in Table A.2.1.

TABLE A.2.1

PRODUCTION OF POLY (ETHYLENE TEREPHTHALATE) RESIN

Basis: 1 lb. Resin

Raw Materials		Btu/lb. Resin
Dimethyl terephthalate	1.12 lb x 46,720 Btu/lb =	52330
Ethylene glycol	0.40 lb x 29,970 Btu/lb =	11990
Utilities		
Heat (Dowtherm) Heat reactants vaporize alcohol, glycol	=	650
Electricity (Vacuum and transfer pumps) 0.2 kwh x 10,500	=	2100
Cooling	Negl.	—
		67,070 Btu/lb Resin

It is assumed that the methanol is not reused, but disposed of, while the recovered ethylene glycol is recovered and reused.

C. ENERGY INPUT FOR RAW MATERIALS

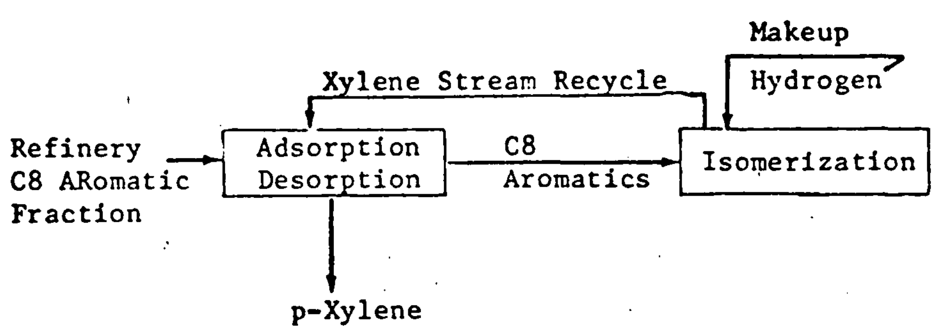
1. Dimethyl Terephthalate (DMT)[1,2,3]

C_8H_{10} (p-Xylene) —Air [0] 80%; 350°-450°F; 200-400 psi; Acetic acid CoBr Catalyst→ $C_8H_6O_4$ (Terephthalic Acid) + $2CH_3OH$ (Methanol) —95%; 400°F→ Dimethyl Terephthalate

	p-Xylene	Air	Acetic acid CoBr Catalyst	Terephthalic Acid	Methanol	Dimethyl Terephthalate
lbs	0.719	0.1	0.0001	0.9	0.347	1.0
cu/lb	53,660	17450	30,000	---	18,425	
cu/lb	38,580	1750	Negl.	---	6,390	46,720

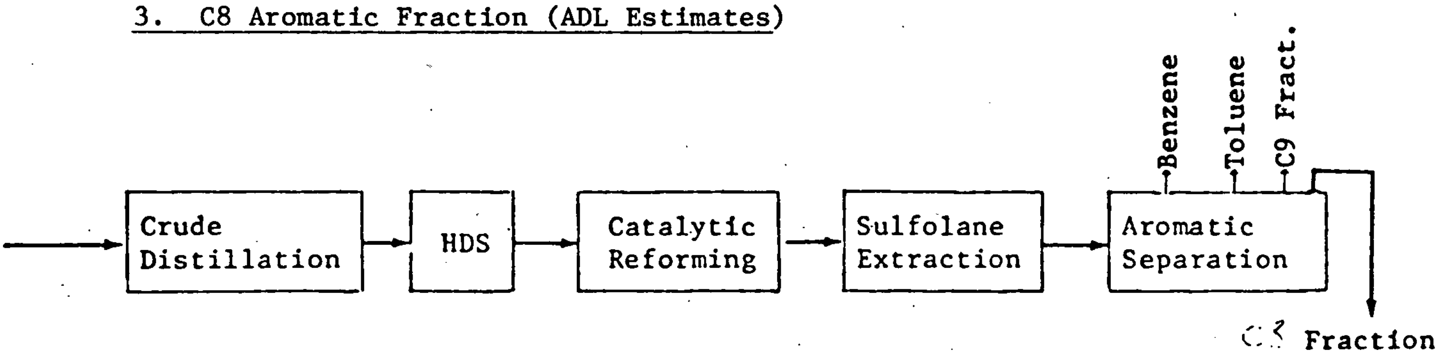
Compressed Air = 1.60 kWh/lb DMT x 10,500 Btu/kWh = 16,800 Btu/lb DMT.
(It is assumed heat generated by oxidation is used for esterification.)

2. p-Xylene[4]



Basis: 1 ton p-Xylene	1 lb. p-Xylene		Btu/lb p-Xylene
1.16 tons C8 Aromatics	1.16 lb C8 Ar. x 33,750 Btu/lb	=	39,150
2300 lbs. steam	1.15 lb. steam x 1200 Btu/lb	=	1,380
4.4×10^6 K cal =	8750 Btu heat x 1/.8	=	10,938
17.5×10^6 Btu			1,638
312 Kwh	0.156 Kwh x 10,500 Btu/Kwh	=	19
3170 gal Cooling water	1.6 gal x 12 Btu/gal	=	535
20 lbs. Hydrogen	0.01 lbs. x 53,540 Btu/lb	=	53,660

3. C8 Aromatic Fraction (ADL Estimates)



Chemical Energy C8 Fraction (Xylenes) HHV = 25,045 Btu/lb.

Process Energy

Crude Dist./Naptha HDS	2070
Cat. Reforming	4110
Sulfalone Extraction	1240
Fractionation	1285
	33,750 Btu/lb. Energy Input C8 Aromatic Franction

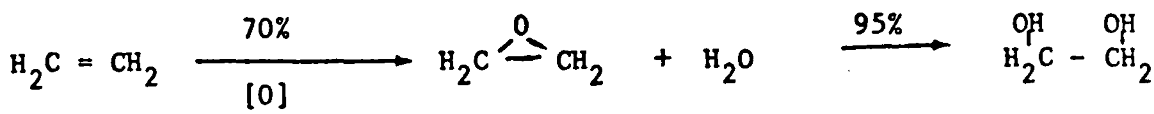
4. Acetic Acid[2]

$$CO + CH_3OH \xrightarrow[\substack{7500\ psig \\ 410°F}]{80\%} CH_3COOH$$

carbon monoxide   methanol   acetic acid (HAc)

	carbon monoxide	methanol	Compression/ Reaction/ Distillation	acetic acid (HAc)
lbs	0.582	0.666		1.0
Btu/lb	4,344	18,425		
Btu/lb HAc	2540	12,270	2,640	17,450

5. Ethylene Glycol[2,5,6]



	Ethylene	Ag Catalyst	Ethylene Oxide	Water	Sulfuric Acid	Ethylene Glycol
lbs.	0.68	.0005	0.748		.05	1

Basis:

	1 Ton Ethylene Glycol	1 lb		Btu/lb Glycol
Ethylene	1360 lb	0.68 lb x 27,090		18,420
Air	1900 lb	--		
Silver	1 lb	.0005 lb x 700,000 Btu/lb	=	350
Ethylene Dichloride	36 lb	.02 lb x 15,850 Btu/lb	=	320
Electricity	1275 Kwh	.6375 Kwy x 10,500 Btu/Kwh	=	6,690
Steam	6000 lb	3 lb x 1190 Btu/lb	=	3,570
Cooling Water	100,000 gal	50 gal x 12 Btu/gal	=	600
Sulfuric Acid		0.05 x 415 Btu/lb	=	20
				29,970

6. Ethylene Dichloride[2]

	Ethylene	+ Chlorine ⟶	Ethylene Dichloride (ED)
lbs.	0.315	0.80	1.0
Btu/lb	27,090	9150	
Btu/lb E.D.	8530	7320	15,850

References for Appendix A.2

1. K.J. Saunders, Organic Polymer Chemistry, Chapman & Hall, London 1973.
2. Faith, W.L., D.B. Keyes, and R.L. Clark, Industrial Chemicals, 2nd Ed. J. Wiley & Sons, 1957.
3. Kirk-Othmer, Encyclopedia of Chemical Technology, 2nd Ed. Vol. 15, 1968.
4. Otani, Seiya, "Adsorption Separates Xylenes." Chemical Engineering September 17, 1973, p. 106.
5. Kirk-Othmer, Encyclopedia of Chemical Technology, 2nd Ed. Vol. 8, p. 536.
6. Kirk-Othmer, Encyclopedia of Chemical Technology, 2nd Ed. Vol. 10, p. 640.

APPENDIX A.3

ENERGY ANALYSIS OF EPOXY RESIN INSULATORS

A. ASSUMPTIONS

A typical formulation for the type of epoxy used in the production of 10-20 lb electrical insulators is as follows:[1]

Cycloaliphatic Epoxy Resin (CER)	15-20%
Hexahydrophathalic Anhydride (HHPA)	10-15%
Filler Alumina Trihydrate or Silica Filler	70%

The typical processing steps are as follows:

- The ingredients are mixed in a 5-gallon vessel for 30 minutes at 100°C using a 1 AP mixer,
- The hot epoxy mixture is poured into evacuated molds at 100°C and held for 2-3 hours, and
- The 10-20 lb insulators are post cured at 150°C for ~2-3 hours.

The energy content of the finished insulators is shown in Table A.3.1.

TABLE A.3.1

TYPICAL ENERGY CONTENT OF EPOXY INSULATOR

Basis 1 lb Finished Epoxy Insulator

Raw Materials		Btu/lb Insulator
Alumina Trihydrate	0.7 lb x 7615 Btu/lb =	5,330
Hexahydrophthalic Anhydride	0.1 lb x 44,200 Btu/lb =	4,420
Cycloaliphatic Epoxy Resin	0.2 lb x 74,900 Btu/lb =	14,980
Epoxy Polymerization and Cure		
Electricity (Mechanical-Mixer & Vacuum Pump)	0.1 Kwh x 10,500 Btu/kwh =	1,050
Electricity (Heat-Polymerization & Cure)	0.2 Kwh x 10,500 Btu/kwh =	2,100
		27,880 Btu per lb of Insulation

As can be seen in Table A.3.1, the energy content of the epoxy resin and hardener are responsible for most of the energy content of the insulator. The inorganic filler which comprises 70% of the weight of the insulator contributes only 18% of the energy content. In addition, the alumina trihydrate filler is higher in energy content than would be a silica filler. Typical energy content of flint (silica) used in the production of ceramics is only about 505 Btu per pound compared with the estimated 7615 Btu per pound for alumina trihydrate.

B. ENERGY CONTENT OF RAW MATERIALS FOR EPOXY INSULATORS

1. Alumina Trihydrate

Mining	0.03	Million Btu/ton aluminum
Shovel Load	0.14	
Truck Transport	0.12	
Crushing, Washing, Screen	0.22	
Drying	1.90	
Water Transport	2.38	
Crush, Grind	1.18	Bayer Process
Digestion	21.49	Bayer Process
Clarification	0.32	Bayer Process
Cooling	0.06	Bayer Process
Precip Filtration	0.70	Bayer Process
Evaporation	9.56	Bayer Process
Spent Liquor Rec.	1.56	Bayer Process
	39.66	Million Btu per ton aluminum
	13.73	Million Btu per ton alumina trihydrate

Drying of Alumina Trihydrate @ 20% moisture & 3# steam/# water for drying

$$2000 \text{ lb Trihydrate} \times \frac{0.20}{0.80} \text{ Water} \times \frac{3\# \text{ Steam}}{\# \text{ Water}} \times 1000 \text{ Btu}/\# \text{ Steam} =$$

1.5 Million Btu/Ton Trihydrate

$$\frac{(13.73 + 1.5) \text{ Million Btu}}{2000 \text{ lb Trihydrate}} = 7615 \text{ Btu/lb Trihydrate}$$

2. Hexahydrophthalic Anhydride[2]

Maleic Anhydride	+ Butadiene	Catalyst →	Tetrahydrophthalic Anhydride	Catalyst → Hydrogen	Hexahydrophthalic Anhydride (HHPA)
0.78	0.43		1.1	0.0144	1.0
35,800	32,000			177,000	-
27,900	13,800			2,500	44,200

3. Maleic Anhydride for HHPA[3]

$$\text{Benzene} + \text{Air} \xrightarrow[\text{Catalyst}]{VO_5} \text{Maleic Anhydride}$$

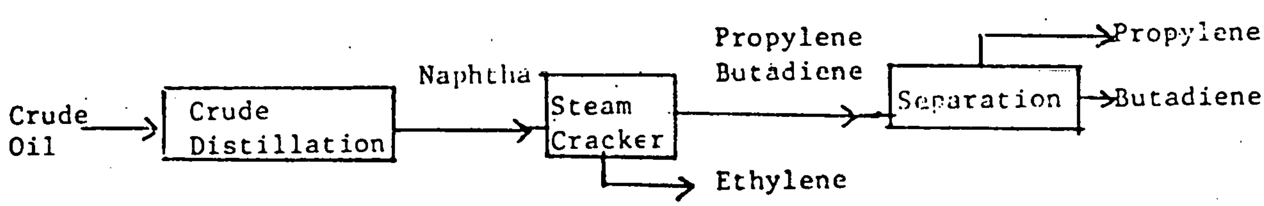
	Benzene + Air	Maleic Anhydride
Lbs	1.34	1.0
Btu/lb	26,700	-
Btu/lb Maleic Anh.		35,800

4. Benzene[3]

$$\text{Naphtha} \xrightarrow[\text{Reforming}]{\text{Catalytic}} \text{Benzene}$$

	Naphtha	Catalytic Reforming	Benzene
Btu/lb Benzene	18,000	8,700	26,700

5. Butadiene[4]



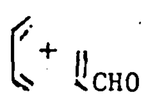
Butadiene and polypropylene are both byproducts of ethylene production. However, a more extensive post-prification of the butadiene is required. The heat value of the butadiene fraction would be about 20,100 Btu per pound. The prorated heat input for crude oil fractionation and catalytic cracking to produce the butadiene would be about 6,000 Btu per pound. For the purification steps about 5,900 Btu per pound would be required. The total energy content of butadiene would therefore be about 32,000 Btu per pound.

6. Hydrogen[3]

Basis: 1000 cu ft hydrogen (5.6 lb) from natural gas

Natural gas	250 cu ft	250,000 Btu
Fuel		350,000
Electricity	2 Kwh	21,000
Steam	360 lb	360,000
Cooling Water	1800 gal	10,500 Btu
		991,000 Btu ÷ 5.6 lb = 177,000 Btu/lb

7. Cycloaliphatic Epoxy Resin[5,6]



(1) $TiCl_4/Et_3Al$ (2) Peracetic Acid → Epoxy Resin

	Butadiene	Acrolein	(1) $TiCl_4$	(2) Peracetic Acid	Epoxy Resin
Lbs	1.071	1.111	0.1	0.6	1.0
Btu/lb	32,000	23,250	14,300	22,400	
Btu/lb Resin	34,300	25,800	1,400	13,400	74,900

8. Acrolein[3]

	$CH_2 = CHCH_3$ Propylene	+ Air	CuO Catalyst $\longrightarrow$	 Acrolein
Lbs	0.882			1.0
Btu/lb	26,362			
Btu/lb Acrolein	23,250			23,250

9. Titanium Tetrachloride, $TiCl_4$[7]

$$TiO_2 + 2Cl_2 + 2C \longrightarrow TiCl_4 + CO$$

	Rutile	Chlorine	Coke	Titanium Tetrachloride
Lbs	0.47	0.82	0.14	1.0
Btu/lb	2,000	13,600	15,750	-
Btu/lb $TiCl_4$	940	11,160	2,200	14,300

10. Chlorine[3]

$$2NaCl \longrightarrow 2NaOH + Cl_2$$

Salt caustic chlorine

Basis: One ton chlorine,	1.14 tons caustic
Steam 23,000 lb	23,000,000 Btu
Electricity 3000 kw x 10,500	31,500,000 Btu
	54,500,000 Btu total
	27,250,000 Btu per ton chlorine
	= 13,600 Btu per lb chlorine

11. Peracetic Acid[8]

	Hydrogen Peroxide +	Acetic Acid	Sulfuric Acid →	Peracetic Acid
Lbs	0.56	0.984		1.0
Btu/lb	15,400	14,050		-
Btu/lb Peracid	8,600	13,800		22,400

12. Hydrogen Peroxide

	Oxygen +	Hydrogen	catalyst →	Hydrogen Peroxide
Lbs	1.046	.0654		1.0
Btu/lb	3,760	177,000		
Btu/lb Peroxide	3,930	11,500		15,400

13. Oxygen[3]

Basis: One ton oxygen

Steam	3,325 lbs	3,325,000 Btu
Electricity	400 Kwh	4,200,000 Btu
		7,525,000 Btu per 2000 lb Oxygen
		= 3,760 Btu per lb oxygen

14. Acetic Acid[3]

	Ethlyene + Air	→ Acetic Acid
Lbs	0.518	1.0
Btu/lb	27,090	-
Btu/lb Acetic Acid	14,050	14,050

References for Appendix A.3

1. Discussion with Mr. P. Bolin, Westinghouse Corporation, Westboro, Mass.

2. U.S. Patent 2,794,811 Cis-Cyclohexane-1,2 - dicarboxylic anhydride L.O. Winstrom (Allied Chem and Dye Corp.) June 4, 1957.

3. Faith, W.L.; D.B. Keyes; R.L. Clark, Industrial Chemicals 2nd edit. J. Wiley & Sons, 1957.

4. Nelson, W.L. Petroleum Refining Engineering 4th Edit., McGraw-Hill Book Company, 1957.

5. Journal Organic Chemistry 28, 912-914, 1963.

6. Chemical Abstracts 58:5648a, 56:3639c.

7. Kirk-Othmer, Encyclopedia of Chemical Technology 2nd edit., Vol. 20.

8. Noller, Carl R., Chemistry of Organic Compounds 2nd edit., W.B. Saunders Company, 1957.

APPENDIX A.4

ENERGY ANALYSIS OF DC TERMINALS

A. HIGH VOLTAGE DC CONVERTER TERMINALS

This analysis is based upon the Square Butte solid-state HVDC system which was built by General Electric to provide a means for transmission of power from a 438 MW fossil fueled power plant located near Center, North Dakota and Arrowhead (Duluth), Minnesota. The system is designed for a normal power flow from Center to Arrowhead, but is suitable for reverse power. The Center terminal is rated at 500 MW and it is this terminal which is described in the following data. The Arrowhead terminal has a slightly lower rating of approximately 460 MW, reflecting the line losses which are not available for conversion at the receiving end. Table A.4.1 below gives a consolidation of all materials used in the Center converter station. This table is supported by detailed breakdowns of material requirements for various major components as shown in the following text.

TABLE A.4.1

SUMMARY MATERIAL LIST - ONE TERMINAL

	Weight in lbs
Aluminum	123,200
Carbon steel and cast iron	1,489,800
Core (silicon) steel	626,400
Stainless steel	3,000
Copper	184,000
Transformer insulation	228,400
Transformer oil	992,800
Porcelain	114,600
Mylar	155,000
Fiberglass reinforced epoxy	63,000
Silicon, thyristor grade	130
Lightening arrestor valve material	1,000
Concrete	850 cu. yd.

These terminals consist of the following basic components.

1. Converter Transformer (12 units per station)

Description: 52 MVA, Single-Phase, 230 kV line to 110 kV valve voltage.

	Weights in Lbs	
	Per Transformer	Per Station
Copper Windings and Leads	11,500	138,000
Core Steel	51,000	612,000
Insulation	18,000	216,000
Carbon Steel - Includes Tank, Fittings, and Core Structure	51,500	618,000
Transformer Oil	70,700	848,400
Total Weight	202,700	2,432,400

2. Switches

A total of 22 high BIL (including two vacuum bypass) and 9 low BIL switches are used per station.

	Weight per station
Carbon Steel	26,000
Porcelain	53,000
Copper	11,000
Core Steel (for operating motors)	1,000

3. Thyristor Valves

There are a total of 24 valves housed in six structures called quadravalves. There are a total of 6920 thyristor elements. The major material composition of the total valve system is as follows:

	Lbs/Terminal
Silicon, Thyristor grade	130
Aluminum	3000
Porcelain	18000
Fiberglass reinforced epoxy	63000

4. DC Smoothing Reactor (two units per station)

Description: 60 mH, 230 kV dc operating voltage.

	Weight in Lbs	
	Per Reactor	Per Station
Copper Windings and Leads	500	1,000
Core Steel	2,200	4,400
Insulation	700	1,400
Carbon Steel - includes Tank, Fittings, and Core Support	20,400	40,800
Transformer Oil	38,700	77,400
Total Weight	62,500	125,000

5. Filters: Totals of 11th & 13th Harmonic, High Pass & DC, and VAR Bank

	Lbs/Station
Copper	3,000
Core Steel	9,000
Carbon Steel	128,000

5. Filters (Continued)

Stainless Steel	3,000
Aluminum	61,800
Mylar	155,000
Transformer Insulation	4,000
Transformer Oil	64,000
Porcelain	15,600

6. Lightning Arrestors (60 units per station)

	Total Weight/Station
Porcelain	6,000 lbs
Copper	12,000 lbs
Valve Material	1,000 lbs

7. Wall Bushings

	Total Weight/Station
Porcelain	18,000 lbs
Copper	9,000 lbs
Oil	3,000 lbs

8. Neutral Conductors and Ground Electrode

This requirement is highly variable depending upon location, so a composite of several actual situations is presented here.

Yard neutral bus and connections:	19,000 lbs
Neutral-to-ground electrode - 3 miles	30,000 lbs
Total aluminum weight:	49,000 lbs
Ground mat, electrode connections, and copper clad ground rods	
Total copper weight:	16,000 lbs

9. Building and Support Equipment

Blowers & Ducting or Pumps - Variable: we have assumed 6 pumps, each with 2,000 lbs of steel.

Heat exchangers & Tubing = 5,000 lbs of copper/bronze

Building: 240'L x 92'W x 37'H

Sheathing Area: 2(240+9)x37+(240x92) = 47,000 ft^2

Assume 8 ga. steel @ 7 lb/ft^2

Weight is 7x47,000 = 33,000 lb

Assume an additional 75% for supporting structures

Total weight of steel in building = 577,000 lbs

Concrete required: 2,000 yd^3

10. Terminal Switches

Concrete	850 yd^3
Steel for bus supports	88,000 lbs
Aluminum bus & tube - 8,000 ft	10,000 lbs
Porcelain insulators, 100x40	4,000 lbs

APPENDIX A.5

INSTALLATION ACTIVITY ASSUMPTIONS

The estimates of transmission system installation energy content presented in Tables VII.5 and VII.6 are based upon a large number of assumptions for each installation activity. This appendix discusses the assumptions used for each activity.

1. Clearing Rights-of-Way

The following estimates are based on the concept that the right-of-way (ROW) must become passable for wheeled vehicles along the transmission line, that it must not present a fire hazard and indeed may serve as a fire break, and that in the case of overhead transmission lines it must be clear of all high growth.

These assumptions have been employed:

a) $7\frac{1}{2}$ hour useful working day.

b) All materials and all disposal volumes hauled 20 miles.

c) The ROW is of mixed character, 50% wooded and 50% open land. A value of 2/3 of the "wooded" energy use estimate is used as the average "per acre" value.

d) 10 tons of chips and debris (including non-organic materials) per acre must be disposed of by haulage.

The following definitions are used:

"Clearing" includes grading and leveling of a roadway, removal of rocks, pulling of stumps, and removal of slash.

"Chipping" includes moving logs to the chipper on the one hand and piling and loading digested material on the other.

"Disposal" includes the truck haul only. It is assumed that the dump trucks dispose of the material at destination without assistance of other equipment.

The following table summarizes equipment use and energy requirements for clearing rights-of-way in rural areas. The total is 2.58×10^7 Btu per acre. However, under assumption (c) only two-thirds of this value will be used on average because of the mixture of wooded and open terrain. ROW clearing in suburban terrain has been estimated to be 25% of the rural value.

Equipment	Rated HP	Average HP Used	Capacity/ Capability	Utilization
Clearing				
Cutter/tractor	250	150	8 acres/day (med. growth)	50%
Front-End Loader	200	120		Same as Cutter
Bulldozer	250	150		Same as Cutter
Chipping				
Chipping Rig	150	100	1.75 acres/day (med. growth)	
Front-End Loader	120	75		2xhrs. Chipper
Bulldozer	150	100		2xhrs. Chipper
Disposal				
10-ton Truck	200	62.7	30 mph average speed	

Equipment	Hours/ Acre	HP-Hrs.	Btu x 10^6
Clearing			
Cutter/tractor	1.88	281.25	
Front-End Loader	1.00	225.60	
Bulldozer	1.88	281.25	
		788.10	7.30
Chipping			
Chipping Rig	4.29	429.00	
Front-End Loader	8.58	643.50	
Bulldozer	8.58	858.00	
		1,930.50	17.88
Disposal			
10-ton Truck	1.33	62.7	.58

TOTAL: 25.76 x 10^6 Btu/acre

2. Slitting of Pavement

Underground transmission lines in urban and suburban areas usually are placed under public thoroughfares for reasons of authorization and access. In most cases the pavement must be removed to a minimum width of the trench to be dug. In city areas, the most common pavement consists of blacktop over a substructure, frequently concrete or crushed rock. Although general policy is to replace the same type of structure that was removed, in some instances where the original substructure is weak a new additional concrete slab is poured after the trench is backfilled. Blacktop is applied over the reinforced slab, which may be about one foot thick and which may extend one foot beyond either edge of the trench proper. This additional pavement surface, pavement volumes, and trenching volumes must be taken into account, both for new slabs and for replacement sections joining existing substructure. Any concrete to be removed must be cut by a saw and broken by a jackhammer.

In suburban areas, the blacktop most often is applied directly over compacted soil inasmuch as traffic loads are lighter and the network of vulnerable underground lines and conduits is limited. Blacktop alone, in 3- or 4-inch thickness, can be ripped up by a variety of equipment once some initial cuts have been made by saw or jackhammer. Some larger equipment is also fitted with special cutting blades, hydraulically activated, for penetrating blacktop. The following table summarizes equipment use and energy requirements for pavement slitting procedures.

Cutting or slitting pavement is independent of ROW width and is directly related to distance only. Therefore, the appropriate planning factors, generalized in regard to the type of pavement structure, must be in terms of energy units per mile of transmission line and become of the order of magnitude of 1.09×10^8 Btu per mile in urban areas and 6.06×10^7 Btu per mile in suburban areas.

3. Breakup and Piling of Pavement

Asphalt and cut concrete can be further ripped up and piled by specially fitted bulldozers. The piles of debris are consolidated by large frontend loaders and loaded into trucks for disposal. A compressor rig for jackhammers may stand by to break up unmanageable sections.

A six-foot-wide ROW equals 31,680 sq. ft. (3,520 sq. yds. or 0.727 acres) per mile. A 300-horsepower CAT Dozer-Ripper can work 3,200 sq. yds. per day on asphalt and 2,000 sq. yds. per day on concrete. On a carefully bounded strip of pavement of this type, the capability may be considerably less. It is assumed further that in urban areas the Dozer-Ripper works on concrete 50% of the time and on asphalt 50% of the time. The following table summarizes equipment use and energy requirements for breaking up and piling pavement.

PAVEMENT SLITTING

Equipment	Rated HP	Avg. HP Used	Capacity/ Capability (ft./hr.)	Utilization
Concrete Saw	75	50	120	60% of hrs./mile - urban; 0% suburban
Asphalt Saw	75	50	200	20% of hrs./mile - urban; 50% suburban
Compressor & Hammers	100	60		Urban: 2x saw hrs. Suburban: 4x saw hrs.

Equipment		Hrs./Mile	HP-hrs.	Btu x 10^6
Concrete Saw		88	4400	40.74
Asphalt Saw		52.8	2640	24.45
Compressor	(U)	152.	9720	90.01
	(S)	106.	6360	58.89
Totals				
Urban			13768	127.49
Suburban			7680	71.12
Rural			0	0

BREAKUP AND PILING OF PAVEMENT

Equipment	Rated HP	Avg. HP Used	Capacity/ Capability (sq. yd./day)	Utilization
Dozer-ripper	300	250(oper.) 65 (idle)	3200(asphalt) 2000(concrete)	2500 sq. ft./hr. - urban 3100 sq. ft./hr. - suburban
Compressor	120	75		Total D-R hrs - urban 1/2 D-R hrs - suburban
Front-end loader	200	120		Same as compressor

Equipment	Hrs/Mile	HP-hrs/m	Btu x 10^6
Urban:			
Dozer-ripper (oper.)	12.67	3168.0	29.33
Dozer-ripper (idle)	12.67	823.6	7.63
Compressor	25.33	1900.5	17.60
Front-end loader	25.33	3039.6	28.15
Totals		8931.7	82.71
Suburban:			
Dozer-ripper (oper.)	10.2	2555.2	23.66
Dozer-ripper (idle)	10.2	663.0	6.14
Compressor	10.2	765.0	7.08
Front-end loader	10.2	1224.0	11.34
Totals		5207.2	48.22

The estimating factor is desired in terms of energy per foot-width of ROW per mile. These, based on the six-foot-width calculated above, become (per foot of width per mile):

	HP-hrs.	Btu x 10^6
Urban:	1489.	13.79
Suburban:	868.	8.04
Rural:	0	0

4. Excavation for Underground Systems

The principal types of equipment used are backhoes, which do the actual digging, and front-end loaders, which rehandle the spoil and load portions of it for disposal. Backhoe size is governed by trench depth and width. It is assumed, for estimating purposes here, that the energy per cubic yard excavated remains approximately constant; i.e., the backhoe efficiency does not vary greatly with backhoe size.

Cubic yardage is the principal parameter for this operation. For trenching, it is assumed that the backhoe spends an equal amount of time engaged in actual digging as in moving and waiting. The front-end loader is assumed to work the same amount of hours as the total backhoe hours.

In suburban areas, utility connections from under-street mains (gas, water, sewer) usually lie below the frost line but within the depth range of the transmission line trench. These connections are small-diameter lines buried directly in compacted earth. The backhoes excavate to the vicinity of the lines, and then must delay until the actual line is uncovered and identified by hand labor. The backhoe may then proceed to work around the line. For this reason the low-horsepower utilization time of the backhoes is doubled in the suburban case. The following table summarizes backhoe and front-end loader use.

Equipment	HP	Avg. HP Used	Capacity/ Capability (cu. yd./hr.)	Utilization
2-cu. yd. backhoe	250	175 (oper.) 50 (idle)	240	Idle hrs. = oper. hrs.
Front-end loader	150	75		Same as total backhoe hrs.

A 4-foot by 6-foot trench equals 4693.33 cubic yards per mile. The backhoe requires 4.1667 hours of working time per 1,000 cubic yards of trench. The following table is based on a nominal 1,000-cubic-yard-per-meter trench.

Equipment	Hrs.	HP-hrs.	Btu x 10^6
Urban & Rural:			
Backhoe	4.1667	729.2	6.75
	4.1667	208.3	1.93
Front-end loader	8.333	625.0	5.79
Totals		1526.5	14.47
Suburban:			
Backhoe	4.1667	729.2	6.75
	8.333	416.6	3.86
Front-end loader	12.5000	937.5	8.68
Totals		2083.3	19.29

These toals may be used directly as estimating factors in terms of energy per 1,000 cubic yards of trench per mile, or, times 10^{-3}, for use with cubic yards.

5. Excavation for Overhead Systems

Excavation for tower foundations consists of small, separated, shaped holes of limited individual volume. In a sample calculation, each of six towers per mile is assumed to require four holes of about 3.7 cubic yards volume. It is assumed that a 1.52 cubic yard backhoe will dig such a hole, some six to eight feet deep, in 0.5 hours using 100 horsepower, or will dig one set of foundation excavations for one tower in two hours.*

It is assumed further that movement of the backhoe to the work site and between tower sites each requires 0.5 hours. Thus, excavation for three sets of foundations (3 towers) can be handled in one 8-hour day. A front-end loader follows the backhoe and is occupied an equal number of hours in moving and spreading the spoil. The following table summarizes equipment use and energy requirements for the excavation of overhead systems.

*This estimate applies to generally homogeneous soil. If boulders are encountered, and/or depths of 12 feet are required, the time required per hole could be as long as four to five hours.

Equipment	HP	Avg. HP Used	Utilization
1.5 cu. yd. backhoe	150	100	3 towers (12 holes)/day
Front-end loader	100	75	Same hours as backhoe

For one mile of transmission line, or six towers, the following table results.

Equipment	Hrs.	HP-hrs.	Btu x 10^6
Backhoe	16.0	1600.	14.82
Front-end loader	16.0	1200.	11.11
Totals:			
Per mile		2800.	25.93
Per tower		467.	4.32

It is noted that the towers considered here are relatively light lattice structures for a single-circuit, three-phase line. Considerable variations may occur due to:

(1) Tower type, size and weight

(2) Nature of the terrain and soil.

6. Trench Shoring

Shoring is not usually required for trenches less than five feet deep. When it is needed, the effort expended is highly dependent upon the site (terrain, soil, climate) and upon the job specifications (trench configuration). Shoring is used only to avoid rework or excess work, or for personnel safety.

Furthermore, many different methods and types of shoring are available and are used. The simplest temporary kinds consist of some form of restraining timbers on the sides of the trench, supported by braces across the width of the trench. These braces interfere with pipelaying and cablelaying and must be removed and replaced as work proceeds. Other forms consist of pilings driven at the sides of the trench and holding the restraining planks or timbers. In this method, no interference is presented. For permanent shoring, usually left in place after completion of the line laying process, interlocking steel sheet piling may be used. Specially designed movable caissons have also been used.

Despite the difficulties of generalization both in the need for shoring and in the method of shoring, this potential energy expenditure should be represented in these estimates. For this purpose we assume one stretch of 100 feet in each mile which requires shoring. This stretch typically may be at the crossing of a creek or ditch with soft soil, or an area of dry non-cohesive sand. We further assume that pilings will be driven along the edge of the trench every five feet to support prepared planks or forms. Braces may also be applied, but these do not require the use of machine equipment. The light piles are driven by a small crane fitted with an auxiliary piledriver attachment, and the same crane handles piles, planks, and forms from trunk to trench. The following table summarizes equipment use and energy requirements for trench shoring.

Equipment	HP	Avg. HP Used	Capacity/Capability	Utilization
Crane	100	60	.25 hrs./piling	Piledriving
		45		Misc. lifts
Truck	150	41.2	5 ton, 25 mph avg.	5-45 mph range

Equipment	Hrs.	HP-Hrs.	Btu x 10^6
Crane	10	600.0	5.56
	16	720.0	6.67
Truck	15	618.0	5.72
Total per 100 ft.		1938.0	17.95

7. Emplacement of Pipe

In systems using welded pipe, the sections are delivered to the site by tractor-trailer and distributed along the ROW. Initially, they may be stacked in small stockpiles or they may be unloaded directly to their position along the line. In either case, there may be a small travel distance involved which we assume to be less than 1/10 of a mile in all cases. A pipelayer with a hydraulic sidearm boom (or a small crane) picks up one section and travels to its exact position along the trench. It lowers the section and holds it until strongbacks are placed across the trench and chain hoists rigged to the section or until block supports are fitted. It transfers the weight of the pipe to the supports, disengages itself, and returns for the next section in line.

Pickup, travel, positioning, and lowering may each take five minutes, and holding while supports are arranged may take 10 minutes, for a total of about 30 minutes per pipe section. We consider this as an average operating time. However, the pipelayer's operations are highly dependent upon other personnel actions and upon various minor materials and equipments being on hand; therefore, we consider an equal idling time appropriate. This gives a production rate of approximately one section per hour.

Standard 10-inch diameter pipe (10.75 inch OD and 0.0279 inch thickness) weighs 31.20 pounds per foot. A 37-foot section weighs 1154 pounds and a 60-foot section would weigh 1872 pounds. A 36-inch diameter pipe of 0.50-inch thickness would weigh about 3 tons in a 37-foot length and about 5 tons in a 60-foot length. These weights are all well within the capacity of the selected typical pipelayer, and it is estimated that the time cycle of the machine would not vary greatly with pipe size. For small pipe, some speedup would be possible. The following table summarizes equipment and energy requirements for pipe emplacement per mile.

Equipment	HP	Avg. HP Used	Capacity/ Capability	Utilization
Pipelayer	105	55 (oper.) 20 (idle)	20 tons	.5 hr./sect. plus .5 hr. idle time/ sect.

Equipment	Hrs.	HP-hrs.	Btu x 10^6
37-foot sections:			
Pipelayer	71.35 (oper.)	3924.25	36.34
	71.35 (idle)	1427.0	13.21
		5351.25	49.55
60-foot sections:			
Pipelayer	44.0 (oper.)	2420.0	22.41
	44.0 (idle)	880.0	8.15
		3300.0	30.56

8. Pipe Welding

For joints in 1/4-inch thick steel pipe, fitted with an insert ring, a three-pass manual weld at 40 volts and 125 amperes at a speed of 8 inches per minute is assumed. Overall generator efficiency is taken at 0.80. In pipe up to 10 inches diameter (nominal), the pipe ends are flared by about 1/4 inch; above those diameters we neglect the flaring. Actual circumference is used in the following computations. A conversion can then be established directly from pipe size to required horsepower-hours in the form of:

0.052383 C = HP-hrs. per joint, where C is the circumference in inches.

At a common length of 37-foot per delivered nominal "40-foot" length of pipe section, there are 142.7 joints per mile. The above factor becomes:

$$7.475054 \ C \doteq \text{HP-hrs. per mile.}$$

Generator idling time is assumed to equal actual arc time, at half load, and the factor becomes:

$$11.2126 \ C = \text{HP-hrs. per mile per pipe.}$$

The following table indicates the values that result:

Nominal Pipe Dia.	Actual Circumference	Per Mile HP-hrs.	Per Mile Btu x 10^6	Max. Sect. per Day
6 in.	22.0 in.	246.67	2.28	17
8	28.3	317.32	2.94	13
10	34.6	387.96	3.59	9
14	44.0	493.35	4.57	7
18	56.5	633.51	5.87	6
20	62.8	704.15	6.52	5
24	75.4	845.43	7.82	4
30	94.2	1056.23	9.78	3
36	113.1	1268.15	11.74	2

When there are two manholes in each line per mile, two 1/2-inch thick split sleeves each about 10 pipe diameters in length add an increment of 14.73 C double thickness weld length to the previous weld length of 142.7 C. This is a 20.6% increase and raises the overall factor to 13.5274 C = HP-hrs/ per mile per pipe.

Intermediate pipe diameters may be interpolated from the above table. For heavier (thicker wall) pipe, the above energy consumptions should be increased by the ratio of the actual thickness to the 1/4-inch upon which the table is based.

The right-hand column of the table presents common values for the rate of placing sections of pipe per day, in terms of "40-foot" sections. This performance table includes the sequential times required for laying the pipe in the trench, aligning it, welding the joint, testing (X-raying) the joint, covering the joint, and proceeding to the next section. Welding of the joint is not the controlling operation in this production rate.

9. Emplacement of Thermal Sand

When this operation is carried out in two parts, the first portion is placed in the trench, tamped and leveled, and the transmission line placed thereon. The remainder is then placed in the trench and again leveled and compacted. If the thermal sand is all placed at one time, the sand is worked around the line, already in place, largely by hand. There is no major difference in machine time between the two methods. The following table summarizes the equipment use and energy requirements for the emplacement of thermal sand.

Equipment	HP	Avg. HP Used	Capacity/ Capability (cu.yd./hr)	Utilization
2 cu. yd. front-end loader	150	100 (lift) 50 (carry)	120 24	Both operations on same quantity, from stockpile to trench

Equipment	HP-hrs. per cu. yd.	HP-hrs.	Btu x 10^6	
Front-end loader	8.33	833.33	7.72	
	41.67	2083.33	19.29	[per 1000 cu. yd. of thermal sand]
Total		2916.67	27.01	
Energy use per cu. yd. of thermal sand		2.92	0.0270	

Tamping

Tamping is applicable to thermal sand emplacement as well as to backfill. Equipment with a variety of drives is available. The backhoe grades and levels. The following table summarizes tamping.

Equipment	HP	Avg. HP Used	Capacity/Capability	Utilization
Portable tamper	5	5	30 sq. yds./hr, or 20 hrs./ft. ROW width/mile	Continuous
Backhoe	150	75	170 sq. yds./hr., or 3.5 hrs./ft/ ROW width/mile	Continuous

Energy use per foot width of the ROW per mile is shown below.

Equipment	Hrs./ft./mile	HP-hrs.	Btu x 10^6
Tamper	20.0	100.0	0.93
Backhoe	3.5	262.5	2.43
Energy use per ft. per mile		362.5	3.36

10. Backfilling

Trenched spoil is stockpiled along the ROW. Part is hauled off for disposal and part is retained for backfill. A bulldozer is the principal equipment for returning the material to the trench, while a front-end loader arranges the material for the bulldozer. A tamper is used to compact the backfill. The bulldozer and the front-end loader operate on the same quantity of material; the tamper however works on the basis of trench surface area. This area is the true trench area and not the extended breadth of the trench in the way of pavement or pavement substructure. The following table summarizes the equipment use for backfilling.

Equipment	Hrs/1000 cu. yd.	HP-hrs.	Btu x 10^6
Bulldozer	16.67	1666.7	15.43
Front-end loader	8.33	625.0	5.79
Total per 1000 cu. yd.		2291.7	21.22
	Plus		
Tamper, per 1000 sq. yd.	33.33	166.7	1.55

11. Pouring and Finishing of Concrete

The hauling of concrete to the site is covered under the road haul factors. Assuming that the concrete is carried in ready-mix trucks, these can unload directly into the trench where required.

We have assumed that the concrete slabs will be lightly reinforced, in a proportion of about 2% by volume or approximately 6% by weight.*

*As an exception, it is noted that some utilities do not add any reinforcement to such a slab; it is simply poured in place. We have maintained a modest amount of steel in the interests of conservatism.

If concrete is assumed to weigh about 1.94 tons per cubic yard, then about 0.12 times the cubic yardage will give the tons of reinforcement steel.

If the steel is assumed to be carried in five-ton loads in five-ton trucks, then, 0.12 x cu. yd. x 0.2, or 0.024 x cu. yd., will equal the number of loads.

A five-ton truck at an average speed of 25 mph between 10 and 40 mph uses, as previously indicated, an average HP of 39.3 HP. This is the equivalent of:

	HP-hrs.	Btu x 10^6
Per ton-mile:	0.4716	0.0044

These factors, multipled by (cu. yd. concrete x 0.12) x (distance) x 1.5 give the energy expenditure for hauling the reinforcement steel along with the concrete mix.

It is assumed that small rotary surfacers are applied to finish and level the concrete surface. It is assumed that these surfacers use 5 HP and have a capability of finishing 44 square yards of wet surface per hour. It is noted that this surface area is the full width of the opening, at pavement level, rather than just that of the trench proper. At this rate, the surfacer would work 22.73 hours per 1000, to give:

	HP-hrs.	Btu x 10^6
Per 1000 sq. yd.	113.64	1.05

This operation therefore again is divided into two factors dependent upon different variables. It is applicable only to the urban case where such slabs are poured as pavement substructure.

Haulage of pre-cast slabs is described separately inasmuch as crane equipment also is involved. The pouring in-place of manholes also is described separately since different steel content exists and additional components must be brought to the site as well as forms.

12. Cast-in-place Manholes

The excavation for manholes is an enlarged spot in the trench line whose incremental volume per mile is negligible. We therefore neglect the excavation work involved in the assumed two manholes per mile of transmission line.

The other energy consumption is principally for hauling concrete to the site and for hauling components, plus crane work for handling the latter. A welding machine is used for connecting the reinforcement structure.

Reinforcing steel may be on the order of 3% of the volume of the structure. Taking steel at a SG of 7.85 and cement of an SG of 1.94, the tonnage of steel becomes cu. yds. x 0.1985. For a 2.5% content of steel by volume this becomes 0.1653 cy. yd., and at 3.5% it becomes 0.2315 cu. yd. For example, a 345-kV double circuit manhole requires some 14.4 cu. yd. of concrete. This is approximately three truckloads of ready-mix cement in 5 cu. yd. trucks plus three tons of reinforcing steel plus an estimated additional ton of metal fittings such as closures, sleeves, piping, etc. The total steel would make up one load for a five-ton truck.

Partially or wholly prefabricated forms would be utilized for the repetitive casting operation at roughly one-half mile intervals. The set of forms is bulky and would occupy one five-ton truck for this short trip.

A crane would be used for placing the forms and the rebar, and later for removing the forms. We have estimated two days' usage for the crane and one day for a welder on the reinforcement steel.

In relation to transmission line capacity, it is noted that individual companies have individual manhole structure designs. The quantities of concrete may vary with company, and with the characteristics of the site. For generalized purposes, we assume the following number of trips per mile.

kV	Concrete	Steel	Forms
138	4	2	2
230	4	2	2
345	6	2	2
500	8	2	2
765	10	2	2

Equipment	HP	Avg. HP Used	Capacity/ Capability	Utilization
5 cu. yd. concrete Tr.	250	68.7		25 mph, 5-45 mph
5-ton truck	150	41.2		25 mph, 5-45 mph
Crane	100	45.	Mics. lifts	2 days/manhole
Arc welder	35	15.		1 day/manhole

13. Precast Concrete Items

These items include precast slabs for pavement sub-structure, conduit troughs and lids for self-contained oil-filled cables, split pipe embedded in the thermal sand over some unprotected cables, or manholes -- either in one piece or in sections.

These various pieces cover a wide range of dimensions and unit weights. In general, the weight of individual pieces will be limited by the handling facilities on site or by the permissible truck loads on the route between manufacture and site. Therefore a number of examples are given below.

For any of these precast concrete items, the task consists of transport of the sections to the site, lifting them off the vehicle, moving them into position, lowering them into the trench or excavation, and holding them and adjusting position until they are secured in place or supported by some other means. Only two pieces of equipment are involved: the truck that carries them and the crane that lifts and places them. The following table summarizes equipment use and energy requirements for precast concrete items.

					Per ton-mile	
Truck	Load	HP	Avg. MPH	Max/Min	HP-hr	Btu x 10^6
10 T	10 T	200	25	40/10	.3144	.0029
20 T	20 T	300	25	40/10	.2948	.0027.
Heavy/oversize lift:						
50+T	40 T	500	20 (max. 50)	30/10	.2451	.0027

The latter heavy-lift tractor-trailer is noted because the weight of a complete manhole may lie in the 30 or 40 ton range. If such a manhole is completely prefabricated, and if dimensionally it is feasible to move it over the highway, then a vehicle of this type would be used.

Two crane situations are examined below.

HP	Load	Lift		Hold		Per Ton of Load	
		HP	Hrs.	HP	Hrs.	HP-hrs.	Btu x 10^6
100	5 T	75	.25	35	.5	7.25	.0572
200	40 T	150	1.00	100	3.0	11.25	.0887

The crane energy expenditures are dependent upon additional variables not indicated here, such as speed of lift and speed and distance of travel with load. Furthermore, different types of cranes with different capabilities of outreach, height or footprint pressure have different overall efficiencies. The above values indicate the general range of energy consumption values applicable to this task.

14. Transport of Materials

Transport by road is used for the majority of materials used in the construction of transmission lines, or at least the final leg of the transportation from source to site is over the highways.

Fuel consumption estimates are based upon the relationships developed in the table on the following page. These are subject to large variances dependent upon the types of equipment used and upon the roads over which the trucks move, in particular the hilliness of the terrain. The horsepower estimates developed may be on the low side, that is, they are conservative. Despite this fact, the energy consumption of the road haul components of the entire transmission line installation process forms a large part of the entire energy expenditure.

The initial system estimates use the assumption of a 20-mile haul from source for all materials. The exceptions are thermal sand and mobilization/demobilization which are increased to 50-mile distances. Return trips, empty, are taken at one-half the computed horsepower and the same speeds. Speed ranges, which affect the average horsepower used, are varied according to the type of load and the type of load and the type of area through which it is anticipated the load will move. This is a judgmental factor.

In the attached summary table, all estimates have been reduced to terms of energy units per ton-mile, or per cubic yard-mile, for ease of application to other haulage requirements.

It is noted that the thermal sand has the lowest requirements, according to these estimates. This is accounted for by the fact that it moves over longer distances (50 miles) in large loads. Conversely, smaller trucks appear as less efficient. Concrete in this case involves relatively inefficient ready-mix trucks.

Those haulage items which cannot be related to specific weight loads have been generalized (towers, mobilization). These can be portrayed only as averages for each unit over a given route distance.

ROAD HAULAGE FACTORS

Item	Truck	HP	Load	Avg. MPH	Max./Min.	Avg. HP	Units	HP-hrs.	Btu x 10^3
Concrete	5 cu. yd.	250	10 T	25	45/5	68.7	per cu. yd.-m	.8244	7.63
							per ton-m	.4122	3.82
Components	15 ton	250	10 T	25	40/10	65.5	per ton-m	.3928	3.64
Thermal Sand	20 ton	300	13.3 (cu. yd.)	25	35/15	75.8	per cu. yd.-m	.3413	3.16
							per ton-m	.2275	2.11
Pipe	Tractor	350	17.1 T	20	30/10	80.2	per ton-m	.3518	3.26
Misc.	5 ton	150	5 T	25	45/5	41.2	per ton-m	.4944	4.58
				25	40/10	39.3	per ton-m	.4716	4.37
Wood Prod.	10 ton	200	10 T	30	50/10	62.7	per ton-m	.3134	2.90
Mobilization	Tractor	300	Misc.	25	45/5	82.4	per unit per 50 miles	164.8	1526.05
Towers	Tractor	300	Misc.	15	25/5	64.3			
	5 ton	200	5 T	15	25/5	42.8			
		Weighted average, 4 trips to 1 :				60.0			
		+2.5 hrs @ 30 HP waiting time for 2.5 mile one-way trips					per unit 2.5 miles	150.0	1389.00
Spoil Disp.	25 ton	350	17 (cu. yd.)	25	45/5	96.14	per ton-m	.2307	2.14
				25	40/10	91.68	per ton-m	.2200	2.04
				25	35/15	88.33	per ton-m	.2120	1.96
Blacktop	15 ton	250	7.94 (cu. yd.)	25	40/10	65.5	per ton-m	.2619	2.43
							per cu. yd.	.4949	4.58

It is noted that large "off-road" vehciles are not specifically covered in these estimates. The scenarios used, and in particular the 20-mile haul distances, do not lend themselves to use of such vehicles for the primary functions of hauling sand and spoil. Where necessary, their energy consumption would be analogous to that of the 25-ton, 350-HP trucks, i.e., about 0.21 HP-hrs./t-m or 0.0019 x 10^6 Btu/t-m at the 25 mph average speed with a range between 35 and 15 mph.

15. Blacktop Application

This operation for replacement of pavement is a function of pavement area in the urban and suburban cases only. Road haul of the blacktop material to the site is treated separately under the transport factors. Normally, the hot blacktop is loaded at the plant into trucks which deliver it, still hot, to the spreading machine where it is kept hot. Only the spreading and rolling are considered here.

In many instances, "cold-patch" blacktop is applied immediately after closure of a trench in order to permit passage of vehicles and as a sealant against the weather. This temporary surfacing is not considered here.

It is appreciated that in some instances after a roadway has been opened for installation of a transmission line, even though the trench may be only a few feet in width, that public works authorities are reluctant to accept a patched pavement as end product.* As a result, the final course of blacktop may cover the entire width of the thoroughfare. However, only that portion of the work directly related to the installation of the transmission line, i.e., the pavement replacement area, is considered here.

The thickness of blacktop is of interest only in regard to total volume required and to the weight and volume to be transported. Pavements generally are 3 to 4 inches thick, and in this range the following surfacing estimates are valid. Spreader width is adjustable. The following table summarizes equipment use for blacktop application.

Equipment	HP	Avg. HP Used	Capacity Capability	Utilization
Roller	50	30	2mph	Multi-pass assumed at 1 hr./ft. ROW width per mile
Spreader	100	75	1/8 mph	Plus 5 gal./hr. fuel for heating

*This is usually the case only if the pavement patched is relatively new, i.e. less than five years old.

Assuming that the spreader operating width is adjustable to the required paving width and that this width does not affect its speed of operation, the estimating factor falls into two parts, one related to trench surface area and one related to distance only. The following table summarizes equipment use and energy requirements for blacktop applications.

Equipment	Hrs.	HP-hrs.	Btu x 10^6
Per ft. ROW width/mile:			
Roller	1.0	30.0	.28
Per mile:			
Spreader	8.0	600.0	5.56
			+5.52
			11.36

16. Grading

Grading involves the restoration of the disturbed areas to their original condition and outline. There is no grading involved in the urban case. In the suburban case, although the ROW proper may be only about six feet wide, the work areas adjacent to the ROW also must be cleaned up and restored. For example, areas used for stockpiles of spoil or sand must be cleared, or areas of plantings which have been disturbed must be leveled. In the rural case, for an underground line a ROW of 50-foot width has been assumed. AFter completion of the installation, dislocations caused by the temporary roadways must be eliminated and the whole ROW restored to pre-work state. In the case of overhead lines with a much wider ROW, which remains free of major vegetation or use, it nevertheless is necessary to clean up the portions of the ROW width which have been used for heavy traffic and storage and other work. We assume that the work involved in this final grading of the 50-foot ROW for underground lines and that for portions of a wider ROW for an overhead line is approximately equal. The following table summarizes equipment use and energy requirements for grading.

Equipment	HP	Avg. HP Used	Capacity/Capability	Utilization
Suburban:				
Bulldozer	150	90	250 ft./hr. of ROW	1500 sq./ft./hr. ROW plus adj. areas
Rural:				
Bulldozer	150	90	360 ft./hr.	3 passes; 50 ft. ROW
Grader	200	120	720 ft./hr.	2 passes

Equipment	Hrs./Mile	HP-hrs.	Btu x 10^6
Suburban: (per mile)			
Bulldozer	21.12	1900.8	17.60
Rural: (per mile)			
Bulldozer	44.00	3960.0	36.67
Grader	14.67	1760.4	16.30
Total		5720.4	52.97