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Assessment of Sodium Conductor Distribution Cable

June 1979

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Prepared for:

U.S. Department of Energy

Assistant Secretary for Energy Technology

Electrical Energy Systems

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Prepared by:
Westinghouse Research
and Development Center
Pittsburg, PA 15275

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U.S. Department of Energy
Assistant Secretary for
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Electrical Energy Systems
Washington, D.C. 20585

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1. SUMMARY

Due to the recent energy consciousness of the nation and the need to conserve energy, a review of the barriers and incentives for using sodium conductor distribution cable was performed. With escalating energy costs, fuel costs, material costs, etc., it was felt that more economic distribution cable conductor metals (sodium over aluminum) and distribution cable with lower losses might provide sufficient incentive for the utility and commercial markets to switch to cable constructed with other materials. The Nacon Corporation, a sodium conductor distribution cable company which operated in the sixties, its customers, and their experiences formed the primary data base for this study. A detailed computer index and library literature search was performed. Interviews with Nacon Corporation technical people, utility engineers and tradesmen, and cable manufacturers were also conducted. The design of sodium conductor cable, terminations, installation, safety, handling, dig-ins, faults, performance, etc., were analyzed in comparison with aluminum conductor cable. Economic analyses were also performed for typical distribution installations and first cost, discounted cost of losses, future cost of capital, etc. were considered in the comparison. As a result of considering these environmental, safety, energy conservation, electrical performance, and economic factors, barriers and incentives for using sodium conductor distribution cable were derived.

2. CONCLUSIONS

After extensive analysis, interviews, and discussions with interdisciplinary study team members, the following conclusions were formed for the barriers and incentives for using sodium conductor distribution cable:

Historical, Safety, Environmental

- A considerable amount of sodium cable experience (hundreds of mile-years) has been amassed over the past 13 years, and this experience is well documented in the literature.
- There is no doubt about the technical merit and performance of sodium cable as an electrical conductor, particularly for direct buried underground application.
- Terminals for sodium cable have been the cause of more than 98% of the sodium cable failures. Further connector development is required.
- Safety hazards relating to the sodium-water reaction are the greatest concern of utility personnel in relation to sodium cable use. However, the safety record relating to the manufacture, transportation, installation and operation of sodium cable over the past 13 years has been excellent.
- Most utilities report that sodium cable would have to show a clear-cut, substantial, total installed cost advantage before it would be seriously considered for widespread use.

- In addition, sodium cable terminals and other hardware would have to be reliable, with availability assured, before sodium cable would be acceptable to most utilities.
- Sodium cable should only be employed in direct buried or duct installations.

Electrical Performance

- On the basis of equivalent overload ampacity, the electrical performance of sodium conductor cable is equal to or better than that of aluminum or copper cable.
- Polyethylene insulation thicknesses specified by IPCEA, NEMA, and AEIC for conventional cable will provide sufficient mechanical pull strength for sodium cable installation in ducts. Cross-linked polyethylene will not be required.
- A vapor barrier jacket appears necessary for the long life performance of sodium conductor cable if it is operated at rated ampacity and high moisture conditions.
- The corona onset voltage behavior of sodium cable is better than that of the equivalent aluminum or copper cable.

Economic Considerations

- The present worth costs of owning and operating sodium distribution cable on a typical underground primary distribution system yields a savings of approximately 10% when compared to aluminum.

- Generally, there are no savings on a secondary distribution system with existing connector designs because of the increased cost and larger number of connectors required.
- With an optimistic market penetration, energy savings could approach 2 billion kWh annually by the year 2000. (One nuclear power plant produces 7 billion kWh annually base load).

Energy and Materials

- The difference in energy expended to obtain sodium electrical cable materials over aluminum cable materials is less than 1% of the difference in energy losses between these two equivalent cables over a 25 year life.
- Although the energy required to refine aluminum is expected to drop due to a new process, and that of copper should increase due to lower concentration ores, and sodium refining energies should remain unchanged, these considerations should present no serious impact on the relative energies or costs of sodium or aluminum cable.
- World and United States supplies of copper, aluminum, and sodium are projected to be adequate to permit manufacture of cable from any of these conductor materials.

The following tables present the barriers (Table 2-1) and incentives (Table 2-2) for using sodium conductor distribution cable. Although both tables could be of considerable length, only items considered to be of major pertinence have been presented.

TABLE 2-1

Barriers Against Using Sodium Conductor Distribution Cable

- Concern about safety because of the highly reactive nature of sodium with water.
- The reliability, expense and availability of sodium cable connectors and other hardware.
- Reluctance to change.
- Concern about special training of personnel for handling sodium cable.
- Concern about liability of abandoned sodium cable or the expense of removal and disposal of discontinued circuits.
- Possibility of sodium cable failure due to a long term slight overload causing the sodium to liquify.
- Possible requirement for a vapor barrier jacket.
- Connector costs at present are significantly higher (1.1 to 2 times) for sodium than aluminum. Even with improved designs there are reasons to believe sodium connector costs will remain above aluminum.

TABLE 2-2

Incentives for Using Sodium Conductor Distribution Cable

- Owning and operating costs 10% less than aluminum cable for a typical distribution system. This could be 30% for express type feeder.
- Lightweight and flexible nature of sodium cable makes handling easier.
- Greater resistance to installation damages.
- Ability of sodium cable to withstand high short circuit, short duration currents without insulation failure.
- High corona inception voltage of sodium cable.
- The close thermal expansion match of sodium and polyethylene.

3. INTRODUCTION

In 1965 the Union Carbide Corporation announced the development of a new underground cable using sodium as a conductor. For five years the Nacon Corporation promoted sodium conductors and over 1/2-million conductor feet of sodium conductor solid dielectric distribution cable was installed and energized at many utilities. The espoused economic advantages did not materialize - utility demand for the cable was insufficient to support the capital investment in plant and facilities. In mid-1970 Nacon announced that it was withdrawing from the sodium conductor market. The sodium cable failed commercially because the cost savings on a complete installation basis did not yet yield the advantages that the base metal cost analysis indicated and the utilities expressed serious concerns over safety and disposal (these specific problems were not at that time addressed in sufficient detail to provide informed answers).

Recently, the economic situation has changed significantly as the cost of energy has increased. From an energy conservation standpoint and an economic viewpoint, sodium distribution cables may be economically justifiable, but the utility safety concerns over the use of sodium conductor cables have never been fully quantified.

The objective of this study has been to assess the barriers and incentives for using sodium conductor distribution cable. The assessment has considered environmental, safety, energy conservation, electrical performance and economic factors. Along with all of these factors considered in the assessment, the sodium distribution cable system was also compared to the present day alternative - an aluminum conductor system.

A literature search and utility survey were conducted to determine the current use and problems associated with sodium distribution cables in service or those removed after trial evaluations. The following information was obtained: (1) Cable specifications; (2) Load history, operating experience and operating expenses; (3) Installed cable cost and difficulties encountered during installation; (4) Maintenance cost and special procedures followed; and (5) Safety problems if any.

The amount of feedstock materials required to fabricate sodium vs. aluminum vs. copper cable was found, and the energy expended to obtain those feedstocks from raw materials was noted. Continued materials availability and long-term market projections for base materials were made.

Environmental and safety considerations were developed for sodium conductor cable and included: (1) Cable handling by the manufacturer, shipper, and utility contractor; (2) Field installation; (3) Dig-in consequences; (4) Fault consequences, either system fault or cable breakdown; (5) Scrap handling; and (6) Discontinued circuit removal or abandonment.

An economic assessment was also completed. It included considerations of: (1) Cable costs; (2) Installation - both direct buried and in ducts; (3) Operating and maintenance costs over a 25 year life; (4) Cost of losses capitalized to 1977, using referenced cost and annual carrying charges; and (5) Ultimate disposal costs.

An analytic computer program was written for the economic analysis and was operated with input data for sodium and for aluminum conductor distribution cable. The program was general so that future use would be possible with appropriate data in that use period. Also, provision was made for the future inclusion of copper conductor data by others. Economics and energy use factors were considered in three time frames - present, 10 years in future, and 25 years in the future. All future extrapolation of expected costs, material availability, energy costs, etc. were based (and documented) on extrapolations by accepted industry sources. The economic analysis considered the 600V, 15 kV, 25 kV and 35 kV voltage classes with equivalent aluminum conductor sizes of 250-kcmil, 350-kcmil, 750-kcmil, and 1000-kcmil as a minimum consideration.

Considerable explanation must be presented at this point to clarify the selection for basis upon which to perform the comparative Na:Al conductor analysis. Consider Figure 3-1a. Each of the commercially rated aluminum conductor distribution cables of Table 3-1 (i.e., ampacities A_{ij}) were evaluated for rated performance at a steady state conductor temperature of 90°C at a ground temperature of 20°C and a ground thermal resistivity (rho) of 90 (°C cm/watt). The overload rating (i.e., steady state A'_{ij}) of the same aluminum conductor cable at a conductor temperature of 130°C was also identified, i.e., Figure 3-1b.

The steady state overload ampacity rating of the aluminum conductor cable for the 130°C conductor temperature was also selected as the overload ampacity of the sodium cable. However, the steady state overload temperature of the sodium conductor was selected as 95°C. Thus the sodium, for normal overload and fault conditions, was not permitted to liquify. This conservative approach was expected to be more palatable to potential utility customers, and would reserve the heat of fusion of the liquid sodium as an overload short circuit delay to permit breakers and other equipment to operate.

The A'_{ij} overload ampacity at a 95°C conductor temperature allowed the diameter of the sodium cable to be determined (Figure 3-1c). Since the electrical insulation will act as a thermal barrier, several iterations of the diameter calculation were made with varying insulation thicknesses to observe the impact of such insulation thickness variations on the overload diameter. The sodium cable insulation thickness was not influenced by other parameters such as required tensile strength for duct installation (i.e., pull strength), water vapor intrusion protection, as well as existing insulation thickness standards for voltage ratings and conductor sizes.

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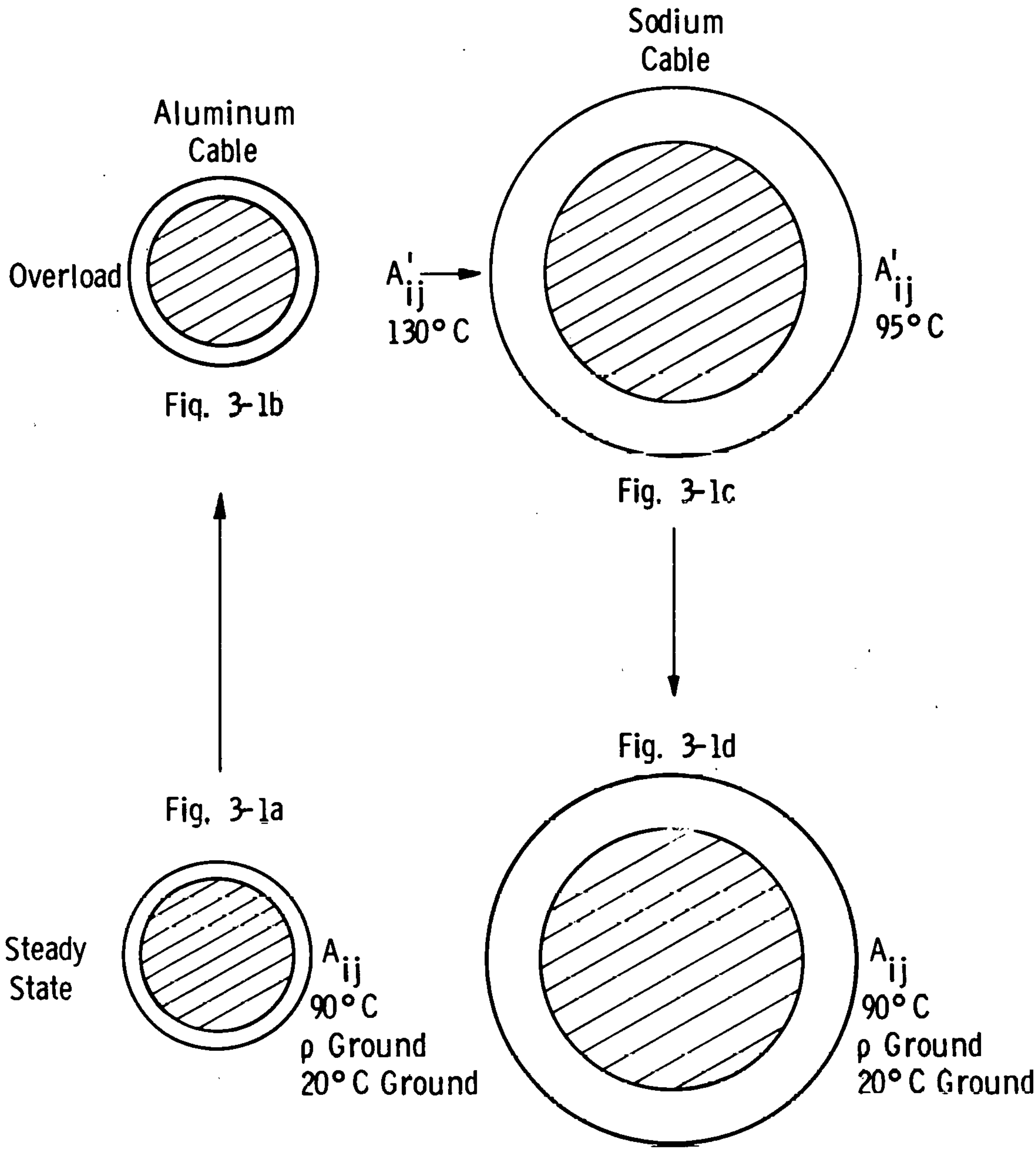

Fig. 3-1 — Deriving the equivalent diameter and steady state temperature of sodium conductor cable with respect to aluminum conductor cable

TABLE 3-1

Ampacity Ratings A_{ij} for Conductor Cables (Aluminum Cable)

Conductor Area	600V	15 kV	25 kV	35 kV
250-kcmil	A_{11}	A_{12}	A_{13}	A_{14}
350-kcmil	A_{21}	A_{22}	A_{23}	A_{24}
750-kcmil	A_{31}	A_{32}	A_{33}	A_{34}
1000-kcmil	A_{41}	A_{42}	A_{43}	A_{44}

Once the overload diameter for a 95°C conductor temperature for the sodium conductor cable was established, the steady state operating condition at normal ampacity ratings (i.e., A_{ij}) was determined. The same ground thermal resistivity and earth temperature (20°C) as those of Figure 3-1a prevailed. Thus, Table 3-2, the ampacity: diameter ratings for sodium conductor distribution cable, was formed. These diameters were the smallest diameters that one would use in fabricating a sodium conductor distribution cable of ampacity rating A_{ij}.

The ampacity ratings A_{ij} of Tables 3-1 and 3-2 were employed to generate Figures such as that shown in Figure 3-2. The y-axis is present worth in $/ft (installed) and the x-axis is conductor diameter. Plots of Figure 3-2 were made for each of the three time periods (present, 10 years, 25 years future). The materials cost increases with increasing diameter for each, whereas the cost of losses decreases with increasing diameter of each. The optimum minimum present worth occurs at a different diameter and temperature for each, but not necessarily at the same present worth. The graphics were calculated as follows:

The present worth of the cost of installed cable PW_{cc} is $/ft and/or $/mi. + installed connector + energy losses + capacity costs + operation and maintenance and salvage, and can be written as:

$$PW_{cc} = \sum_{i=1}^{N} \frac{(CAB_o + CON_o)}{(1+d)^i} ACC +$$

$$\sum_{i=1}^{N} \frac{(1+g)^{2i}}{(1+d)^i} I_o^2 r \left[(1+e_c)^i P_{c_o} + P_{\phi_o} (1+e_o)^i (L_s F)\right]$$

$$+ OAM + SAL$$

Curve 712628-A

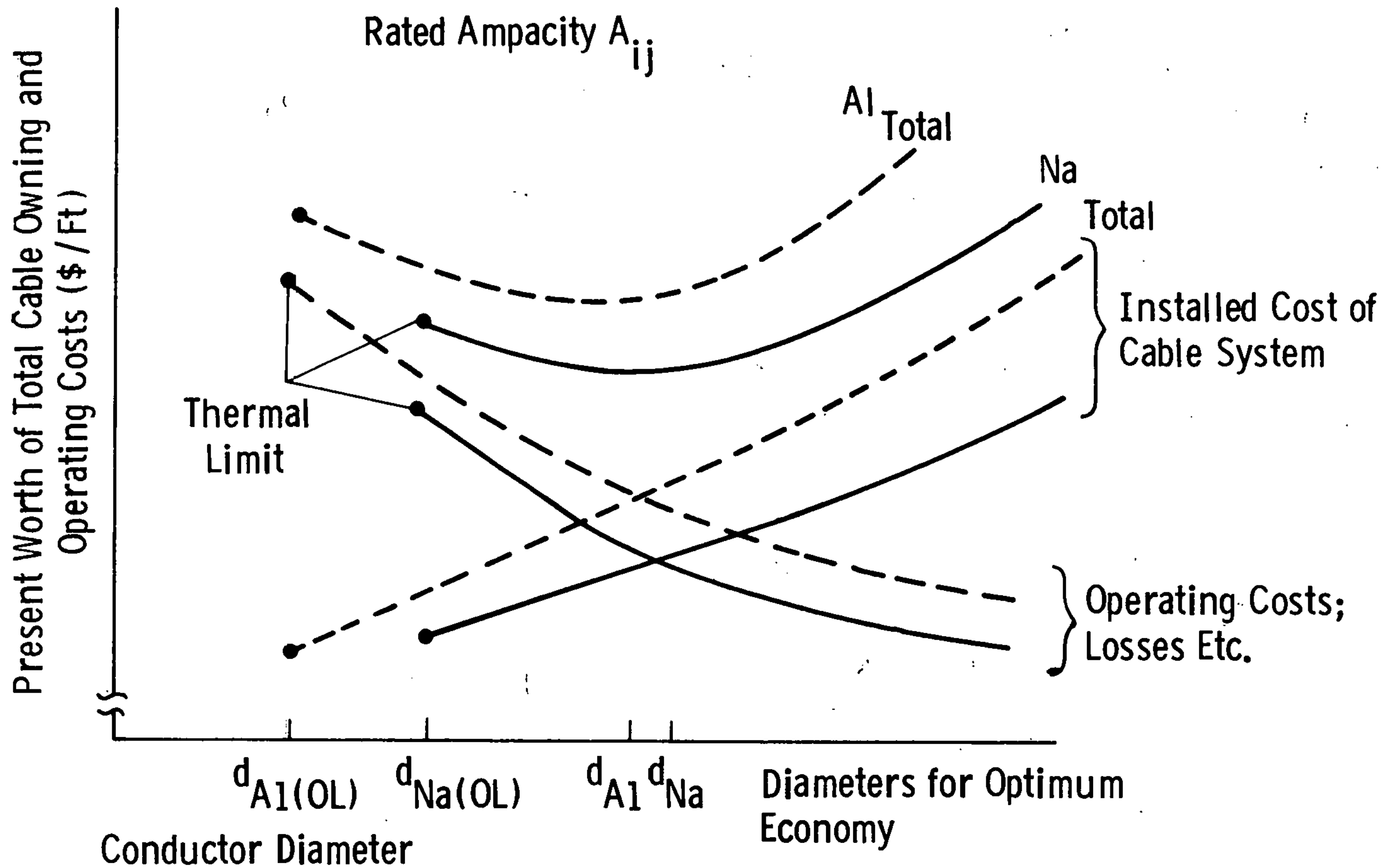

Fig. 3-2— Calculation of present worth of sodium and aluminum conductor distribution cable total cost as function of cable diameter for one rated ampacity A_{ij}. (Direct burial)

<u>TABLE 3-2</u>

Ampacity (Conductor Diameter) Ratings for
Program Conductor Cables (Sodium Cable)

A_{11} (D_{11})*	A_{12} (D_{12})	A_{13} (D_{13})	A_{14} (D_{14})
A_{21} (D_{21})	A_{22} (D_{22})	A_{23} (D_{23})	A_{24} (D_{24})
A_{31} (D_{31})	A_{32} (D_{32})	A_{33} (D_{33})	A_{34} (D_{34})
A_{41} (D_{41})	A_{42} (D_{42})	A_{43} (D_{43})	A_{44} (D_{44})

*where A_{ij} is the same as the ampacity for aluminum conductor cable shown in Table 3-1, but D_{ij} identifies a sodium conductor diameter (area).

where CAB_o = installed cable costs in base year per unit length

CON_o = installed connector costs in base year per unit length

g = growth rate of cable load over cable lifetime

e_c = growth rate of capacity power costs over time

e_o = growth rate of operating power costs over time

ACC = annual carrying charge

d = discount rate

P_{c_o} = average cost of power supply capacity in the base year ($ per kWyr)

P_{ϕ_o} = average cost of operating power in the base year ($ per kWyr)

I_o = initial cable load current in the base year

r = conductor resistance Ω/m

L_sF = loss factor of the cable (assumed 30-33%)

OAM = present worth of maintenance costs

SAL = present worth of salvage

We note that CAB_o, CON_o, r, OAM, SAL will vary for Al or Na conductor cable. Also note that CAB_o, CON_o, OAM, SAL will also be different for the three starting points; present, 10 yrs. in future, 25 yrs. in future.

Additional considerations to the above economic analysis were also made. A typical installation length and network was defined for aluminum and for sodium conductor distribution cables. Also, only new duct installations were considered for sodium conductor cable when buried in duct analysis was performed. Appropriate codes for duct void volume were followed. Cost of terminations and connectors was included (retained) in the analysis and was found to have an important bearing on the outcome of the study.

A splice to a riser was used for the sodium conductor cable analysis since most centers presently use a heavier riser to the distribution center. Different thicknesses of insulation were considered for direct burial versus duct installation of sodium conductor cable. The selection of insulation material polyethylene (PE) vs. cross-linked polyethylene (XLPE), was based upon thermal, mechanical, and electrical stress considerations. The cost of insulation was also considered as a function of time. The growth rate of load current (g) over the cable lifetime was used to show sensitivity for one voltage class for each case. The growth rates of power cost (e_c & e_o) over time can vary by factors of 6 or 7 depending upon area of country and utility selected. Appropriate rationale for the selected values of "e_c & e_o" was presented in the analysis. To cost the sodium conductor distribution cable installation, a typical network system was assumed to join an existing, operating facility, thus permitting easy expansion.

An assessment of the electrical capability of the sodium vs. aluminum conductor cables was performed and included consideration of: (1) Normal vs. emergency ampacity; (2) Fault consequences; (3) Temperature limitations and consequences of a thermal runaway situation; (4) Dig-in consequences; (5) Splice and termination limitations; and (6) Jacket limitations. A part of the electrical performance capability assessment included consideration of insulation thickness requirements for electrical, installation, and thermal performance of the sodium conductor distribution cable. Equal pulling lengths of aluminum and sodium conductor cable were used to set the cross-sectional area of polyethylene (PE) or cross-linked polyethylene (XLPE). Sidewall pressures were included in consideration in determining pull strength, i.e., bearing on insulation thickness. It was assumed that a concentric neutral (or ground wire) provides no strength. All strength was assumed to derive from the insulation and conductor. The pull strength required was calculated using the highest temperature normally found during installations ($\sim$ 100-120°F in summer); for a duct installation, the active cable was assumed to be at the lower duct temperature. A rationale for when to use or not use XLPE was developed based not only on pull strength, but temperatures, electrical stress, etc.

All of these considerations, environmental, safety, economic, energy conservation, etc., were included in the assessment of the barriers and incentives for using sodium conductor distribution cable, and are described in detail in their respective sections of this report.

4. GOALS OF THE STUDY

The goals of the study, after a thorough assessment of safety, economic, environmental, and electrical performance characteristics of both sodium and aluminum conductor distribution cable, are to project whether sufficient incentive/barriers exist for a clear decision to be made for or against the employment of sodium conductor distribution cable. The selection of the basis for comparison between these two cables was thought to be critical to this assessment in the economic and electrical performance analysis, but not to the more subjective safety, environmental, etc. analysis. The criterion of equivalent ampacity at overload conditions, with sodium cable at 95°C maximum (i.e., - solid), was conservatively chosen as being most acceptable to potential utility and commercial customers. Fortunately, the economic analysis showed larger diameter conductors for both cables to be lower in overall cost (i.e., including losses discounted to the present) and thus supported the basis for comparison as a lowest diameter allowable. Figure 4-1 reiterates earlier figures (i.e., Figure 3-1) in showing that comparing Na:Al at equal overload ampacities (maximum steady state temperatures 130°C Al:95°C Na) results in a larger sodium conductor diameter, and a lower operating temperature at rated ampacity.

The methodology of performing the study is shown in Figure 4-2, which shows the natural progression of analysis from Information Source, to Performance Analysis, to Economic Comparison, to Conclusions. Each area of analysis or consideration was performed by a specialist in that area, and crosslinking of analytical considerations was achieved in project team meetings.

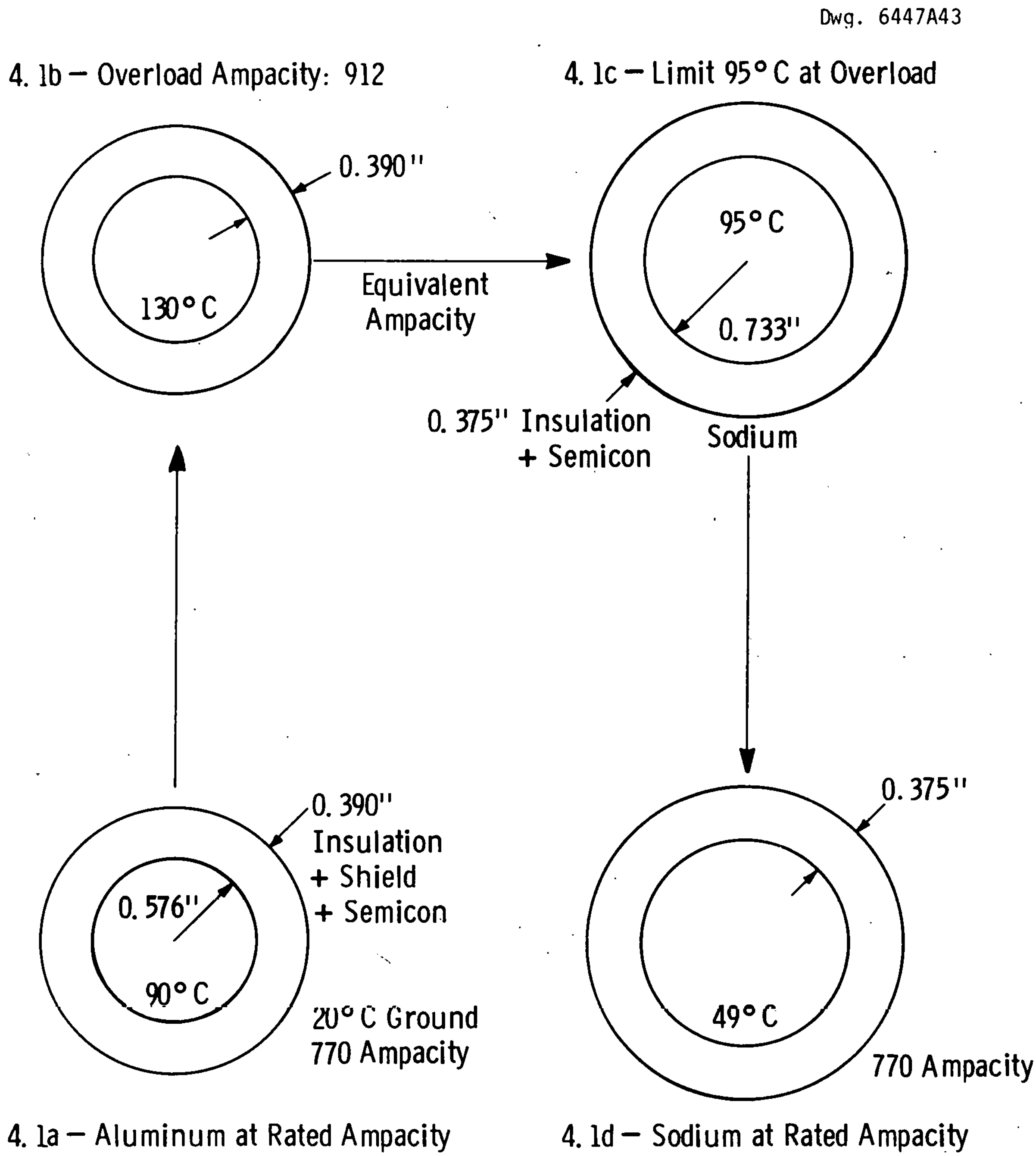

Fig. 4-1 — Example of equivalent cable dimensions (Al : Na) for 35 kV, 1000 kc mil rating (Al)

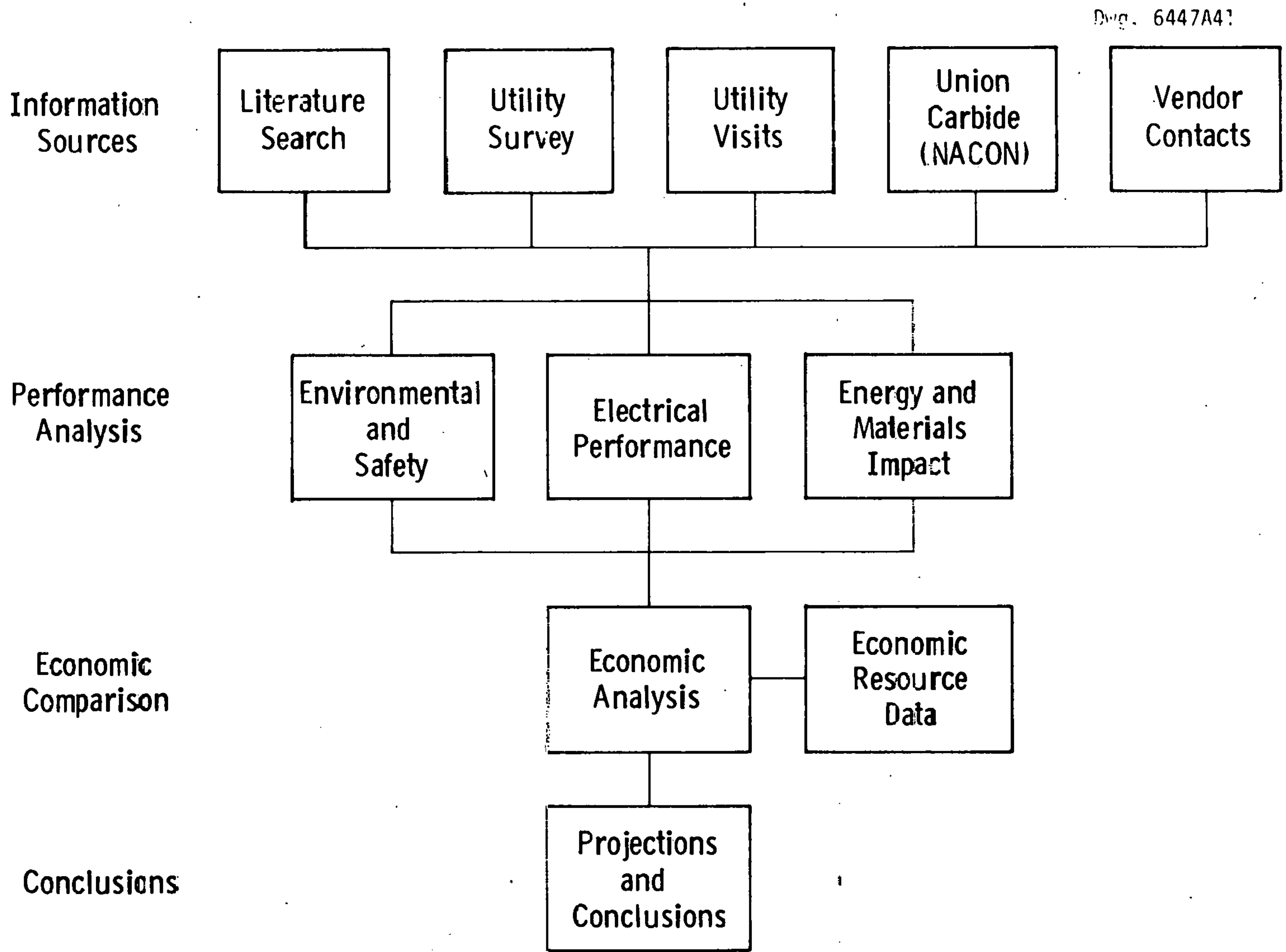

Fig. 4-2 — Methodology sequence for sodium cable assessment study

5. INFORMATION SOURCES

5.1 Literature Search

5.1.1 Methodology

A literature search was conducted for information relating to sodium conductor cable experience. The major thrust of the search centered on the computer search of relevant data bases. These include NTIS (National Technical Information Service) 1964-1977, INSPEC (Electrical and Electronics Abstracts) 1969-1977, COMPENDEX (Engineering Index) 1970-1977, and EDB (U.S. Department of Energy Data Base) 1976-1977.

Various strategies were employed in the search. The most successful coupled the keyword "sodium" with various other keywords such as "cable," "conductor" or "underground transmission." The most productive data base was COMPENDEX which produced 9 references directly applicable.

A manual search was also conducted of "Electrical Engineering Abstracts" from 1955-1975. This search was not very productive, turning up only 5 references, 4 of which had already been listed in the computer search. A search was made of the references listed in each applicable sodium cable paper received and several additional relevant publications were found.

5.1.2 Bibliography of Publications

A total of 40 publications concerned with sodium conductor cables was collected from the literature search. These are listed in Appendix A1 along with an abstract or summary of each publication if available.

5.1.3 Pertinent References

All of the 40 publications listed in Appendix A1 have some relevance for those interested in sodium cable. The 12 publications listed below, however, cover the important aspects of sodium cable experience up to the early 1970's.

1. "Evaluation of Sodium Conductor Power Cable," A. E. Ruprecht and P. H. Ware, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-86, No. 4, April 1967.

The suitability of the newly developed polyethylene insulated sodium conductor for use in electrical power cables was evaluated electrically and mechanically. Polyethylene-insulated sodium conductors are shown to lend themselves to a wide range of constructions manufactured on standard cable-fabricating equipment. Because of the plastic nature of metallic sodium, neither conductor stranding, nor helical assembly in the case of multiconductor cables, is required for flexibility.

2. "Insulated Sodium Conductors," L. E. Humphrey, R. C. Hess, and G. I. Addis, IEEE Transactions on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The development and characterization of a new polyethylene insulated sodium conductor are described. The resistivity, specific gravity, and cost of sodium are compared to corresponding properties of copper and aluminum. While the alkali and alkaline earth metals have relatively good electrical conductivity, sodium was chosen because of its light weight, low cost, and availability. Physical properties of the polyethylene insulated sodium conductor were determined. Potential areas of question, such as service life, reaction of water with damaged cables, and combustion characteristics are covered in detail.

3. "The Development of Connectors for Insulated Sodium Conductor," I. F. Matthysse and E. M. Scoran, IEEE Transactions on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The characteristics of insulated sodium conductor required the development of a new type of connector and a new installation technique. The problems involved making stable electrical contact to the sodium, sealing against chemical attack, installation with a minimum exposure of sodium, securely gripping the insulation, effects of the melting point of sodium, and temperature limitations of the insulation.

4. "Field Trials on 15-kV and 600 Volt Sodium Cable," Edward J. Steeve and James A. Schneider, IEEE Transaction on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The use of sodium conductor cable presents an opportunity for reduction in cost of cable for underground residential distribution systems. In order to evaluate its usage a direct buried test installation was made involving both 15 kV and 600 volt sodium cable. Testing the 15 kV cables consisted in load cycling, short-circuit faulting, and fault location tests. After the completion of tests on the 15 kV sodium cable, a service installation was made in a rural area west of Chicago. Load cycle tests were also made on the 600 volt sodium cable. This included an overload which resulted in the failure of the cable at the terminal. Insulation damage tests were made to determine the corrosive properties of the conductor. Fault locating tests made on the 600 volt cable, as on the 15 kV cable, showed that presently available equipment should be adequate.

5. "Improved Connectors for Insulated Sodium Conductors," S. Gerhard, Paper 45, PRN, IEEE Winter Power Conference, January 1968.

Progress toward the development of a new connector for insulated sodium power conductor is reported. Performance and design criteria are outlined and the development program to achieve the criteria is discussed. The connector construction and installation techniques are described and preliminary performance test data presented.

6. "Dig-in Tests on Sodium Cables," E. J. Steeve, IEEE Winter Power Meeting, New York, New York, January 28 - February 2, 1968.

Two sets of dig-in tests on sodium conductor, polyethylene insulated cables were made by the Commonwealth Edison Company. The first series of tests were made on de-energized 15 kV and 600 volt cables using both power machinery and hand tools. About one year later, a second series of dig-in tests was made on 600 volt cables energized at 120/240 alternating volts, using three types of power machinery. In most cases, the degree of reaction was less than expected despite extremely wet soil conditions from heavy rainfalls previous to the tests. It appears that the probability of causing human injury due to the cutting of an energized sodium conductor cable is no greater than that for either a copper or an aluminum conductor cable. However, during various digging operations, there is always a chance that small raw sodium chips can be brought to the surface of the ground; this presents a possible safety hazard if they are not removed.

7. "A Progress Report on Sodium Conductor Power Cable," T. H. Kelly and C. G. Gnerre, IEEE Paper No. 68, CP 62-PWR (1968).

Experimental sodium conductor cables, insulated with polyethylene were manufactured without strand shielding and tested to determine the suitability of this construction for service under high humidity conditions and for voltages above 15 kV. Samples were tested after five months immersion in 75°C water with no significant decrease in corona level. Cable samples rated at 34.5 kV and 69 kV and without strand shielding have been evaluated by dielectric strength and load cycle tests with satisfactory results.

8. "Irradiated Polyethylene Insulation for Sodium Conductor Cable," R. M. Eichhorn and G. I. Addis, IEEE Winter Power Meeting, New York (January 1968).

Laboratory studies of severely overloaded sodium conductor cables, insulated with both normal and irradiated polyethylene, have been made. Excessive overloads cause melting of the sodium and subsequent open circuiting of the conductor. In an overloaded vertical riser, pressure develops from the formation of a hydrostatic head. Irradiated polyethylene provides two advantages over regular polyethylene in this situation. First it withstands the hydrostatic pressure and prevents the release of molten sodium and second it provides moderately longer life under the given overload.

9. "Bistable Operating Temperatures and Current Rating of Sodium Conductors," J. Hus, IEEE, Feb. 1968, PAS-87, pp. 367-371.

Unlike conventional cables, the operating temperature of sodium cable lies close to its melting point. Although this does not affect the current rating at normal ambients, one cannot reap the full current rating benefits which normally accrue from a lowered ambient temperature. This paper describes how the ambient temperature affects the maximum operating temperature of sodium cable.

10. "Field Service Experience with Sodium Conductor Cable," R. L. Garrison, IEEE Conf. Rec. Special Tech. Conf. on Underground Distribution, Anaheim, California, pp. 386-95, May 12-15, 1969.

This paper discusses the experience with sodium conductor cables in field service installations. It includes:

1. Summary of the sizes and voltage classes of sodium cable installed by the utilities.
2. Description of typical installations of various voltage classes.
3. Accessory hardware problems encountered.
4. Observations from the field on work practices and results recorded to date.
5. Product modifications designed to assist Operating Departments in the handling of the sodium conductor cable.
6. Conclusions.

11. "Measurement of Water Vapor Transmission Through Polyethylene Electrical Insulation," R. M. Eichhorn, Polym. Eng. Sci., Vol. 10, No. 1, pp. 32-7, January 1970.

A method is described for measuring the rate of water vapor transmission through thick sections of polyethylene used as insulation on electrical conductors of pure sodium metal. The technique could be generally useful for materials which do not react with sodium, and for cylindrical samples which can be filled with molten sodium in a dry box. For samples with uniform dimensions the results are extremely precise because sensitive electrical measurements are used. Specimens of products in final form can be employed to determine the effects of variations in processing.

12. "PP&L Co. Experience with 15 kV Sodium Conductor Cables," Frank R. Nickel, Pennsylvania Power & Light Co., Allentown, Pennsylvania, Doble Client Conference, Boston, Massachusetts, April 13, 1970.

This paper describes the experience of the Pennsylvania Power and Light Company with a 15 kV sodium cable installation including preliminary background tests and acceptance testing the cable.

5.2 Utility Survey

5.2.1 Methodology

A survey was conducted to obtain sodium conductor cable experience information from utilities that have installed the cable for test or service. Forty-nine utilities with sodium cable experience were identified from records supplied by the Union Carbide Corporation. A questionnaire was mailed to forty-three of these utilities, three utilities were surveyed by telephone, and three by personal visits. These utilities were distributed geographically across the United States and were both large and small, rural and urban. The three utilities visited were "Whitley County REMC," Columbia City, Indiana, "Commonwealth Edison Company," Chicago, Illinois and "Portland General Electric," Portland, Oregon. These were selected because of their considerable experience with sodium cable and because they represent a cross section of urban and rural locations. In depth interviews were conducted at each location with discussions held not only with management and engineering personnel but also with workmen that had installed and repaired sodium cable. Information gained in these discussions is included in the survey results in Section 5.2.3.

5.2.2 Questionnaire

A questionnaire was devised (see Appendix A2) to gather the following information about sodium cable experience:

- quantity installed
- cable specifications
- installation description
- load history
- operating experience
- operating expenses
- installed cable cost
- installation experience
- maintenance
- safety provisions
- opinions, observations and recommendations
- cost of conventional distribution cable installations

5.2.3 Results of the Survey

Thirty-seven of the forty-nine utilities surveyed (75.5%) responded with at least partially completed questionnaires. (See the % of response to each question on questionnaire in Appendix A2). The respondees reported a total of 142,529 ft. (43,443 m) of sodium cable installed; 64% or 91,044 ft. (27,750 m) was rated at 600 volts while 36% or 51,485 ft. (15,693 m) was rated at 15 kV. Some of the cable was in operation for only short term tests (a few hours) while other cable has been in normal service for about 13 years. The total sodium cable experience reported was 249 mile-years (401 kilometer-years) of operation.

5.2.3.1 Cable Specifications

All of the sodium cable reported in the survey was supplied by Nacon Corporation, Boston, Massachusetts, and was rated for either 600 volts or 15 kV. Table 5-1 gives the number of circuit feet of each copper equivalent (CuE) size for each voltage class reported. A comparison of diameter, weight and d-c resistance for copper and sodium conductors

TABLE 5-1

Utility Survey: Installed Sodium Cable Specifications

Circuit ft.	Voltage Class	Size CuE	Cross Linked Polyethylene	Outer Semicon Layer	Conc. Neutral
2,838	600 V	2/0	yes	no	no
45,470	600 V	2/0	no	no	no
1,000	600 V	4/0	yes	no	no
37,786	600 V	4/0	no	no	no
350	600 V	350 kcm	yes	no	no
3,600	600 V	500 kcm	no	no	no
665	15 kV	# 4	no	yes	yes
6,025	15 kV	# 2	yes	yes	yes
640	15 kV	# 2	no	yes	yes
500	15 kV	1/0	no	yes	yes
5,300	15 kV	2/0	no	yes	yes
18,720	15 kV	4/0	no	yes	yes
19,375	15 kV	500 kcm	no	yes	yes
260	15 kV	750 kcm	no	yes	yes

reported by the Nacon Corporation is given in Table 5-2. A comparison of the ampacities of some sizes of polyethylene insulated copper and sodium conductors also reported by the Nacon Corporation is shown in Table 5-3.

Most of the sodium cable was manufactured with high molecular weight polyethylene (HMWPE) insulation (approximately 10,000 ft. of the 142,529 ft. reported was crosslinked, see Table 5-1). The 600 V secondary cable consisted of a solid core of pure sodium with 0.100 inches to 0.150 inches of HMWPE insulation. The 15 kV cable was insulated with 0.175 inches to 0.220 inches of HMWPE and typically contained a semi-conducting polyethylene outer shield 0.030 inches thick and a one third concentric neutral of tinned copper wire. These cables were reported to meet the requirements of IPCEA S-61-402.

5.2.3.2 Installation Description

Approximately 93% (132,694 ft) of all the sodium cable installations reported in the survey were direct buried. About half of these installations terminated the sodium cable below ground while the other half reported bringing the sodium cable above ground to make the termination. Approximately 7% (9,585 ft) of the sodium cable was installed in ducts and only 250 ft. ($\sim$2%) was installed as aerial cable.

5.2.3.3 Load History

Exact records of the load history of individual cables are not routinely available from the industry. However, nineteen of the thirty-seven questionnaire responses did provide some information about the load history of their sodium cables. This information is compiled in Table 5-4 and indicates a range of cable loading from very light to heavy. One cable was reported to have been operated at 138% of its rated current for 2 1/2 hours, which caused it to fail.

TABLE 5-2

Comparison of Diameter, Weight and d-c Resistance (@ 25°C and 75°C) for Copper and Sodium Conductors*

Copper Conductors N. T.						Sodium Solid Conductors				
Cond. Size AWG or MCM	Sclid or Strd.	Nom. Diam. Inch	Nom. Wt. #/M ft.	d-c Resistance ohms/M ft. @25°C	d-c Resistance ohms/M ft. @75°C	Cond. Size SE	Nom. Diam. Inch	Nom. Wt. #/M ft.	d-c Resistance ohms/M ft. @25°C	d-c Resistance ohms/M ft. @75°C
10	7 Strd.	.103	32.1	1.04	1.24	10	.168	9.3	1.062	1.311
9	"	.133	41.8	.824	.983	9	.188	11.7	.848	.047
8	"	.147	51.2	.654	.780	8	.211	14.7	.673	.831
7	"	.165	64.5	.519	.619	7	.238	18.7	.529	.653
6	"	.188	83.3	.410	.489	6	.267	23.5	.420	.519
5	"	.212	107.0	.326	.389	5	.300	29.7	.333	.411
4	"	.234	130.0	.259	.309	4	.336	37.2	.266	.328
3	"	.263	163.0	.205	.245	3	.378	47.2	.210	.259
2	"	.295	206.0	.162	.193	2	.426	59.8	.165	.204
1	19 Strd.	.338	265.6	.129	.154	1	.477	75.1	.132	.163
1/0	"	.376	330.0	.102	.122	1/0	.536	94.8	.104	.128
2/0	"	.423	416.0	.0811	.0968	2/0	.603	120.0	.0824	.102
3/0	"	.475	526.0	.0642	.0766	3/0	.676	150.8	.0656	.0810
4/0	"	.532	659.0	.0509	.0607	4/0	.760	190.6	.0519	.0641
250	37 Strd.	.580	782.0	.0431	.0514	250	.825	224.6	.0440	.0543
300	"	.637	944.0	.0360	.0429	300	.900	267.3	.0370	.0457
350	"	.687	1099.0	.0308	.0367	350	.975	313.7	.0315	.0389
400	"	.733	1249.0	.0270	.0322	400	1.040	356.9	.0277	.0342
450	"	.779	1412.0	.0240	.0286	450	1.105	402.9	.0245	.0302
500	"	.819	1561.0	.0216	.0258	500	1.165	447.9	.0221	.0273
600	61 Strd.	.900	1882.0	.0180	.0215	600	1.276	537.3	.0184	.0227
700	"	.982	2190.0	.0154	.0184	700	1.378	626.6	.0158	.0195
750	"	1.002	2333.0	.0144	.0172	750	1.427	672.0	.0147	.0181
800	"	1.035	2491.0	.0135	.0161	800	1.473	716.0	.0138	.0170
900	"	1.098	2801.0	.0120	.0143	900	1.563	806.2	.0123	.0152
1000	"	1.158	3118.0	.0108	.0129	1000	1.650	898.4	.0110	.0136
1250	91 Strd.	1.312	3894.0	.00863	.0103	1250	1.845	1123.3	.00881	.0109
1500	"	1.416	4656.0	.00719	.00858	1500	2.021	1347.9	.00733	.00905
1750	127 Strd.	1.546	5442.0	.00616	.00735	1750	2.183	1572.6	.00629	.00777
2000	"	1.634	6202.0	.00539	.00643	2000	2.333	1796.2	.00551	.00680

*From the Nacon Reference Manual, Courtesy of R. M. Eichhorn of the Union Carbide Corporation.

TABLE 5-3

Ampacities of Polyethylene Insulated Copper and Sodium Conductors in Air and Earth[†]

I. Stranded Copper Conductor

Cond. Size	Diameter	Cable Volts KV	Ohms/M ft. Rdc 25°C	Rac 75°C	In Air* R'ca	Amps	Direct Buried* R'ca	Amps
2	.295"	5	.162	.193	7.34	157	5.73	226
4/0	.532"	5	.0509	.0609	5.82	316	5.55	405
750	1.002"	5	.0144	.0178	4.10	695	5.14	775
2	.295"	15	.162	.193	6.49	168	6.09	217
4/0	.532"	15	.0509	.0609	5.14	335	5.60	402
750	1.002"	15	.0144	.0178	3.93	708	5.36	760

II. Solid Sodium Conductor

2-SE	.426"	5	.165	.204	6.42	163	5.33	225
4/0-SE	.760"	5	.0519	.0642	4.65	343	4.93	417
750-SE	1.426"	5	.0147	.0187	3.26	760	4.83	783
2-SE	.426"	15	.165	.204	5.75	173	5.65	218
4/0-SE	.760"	15	.0519	.0642	4.38	354	5.16	408
750-SE	1.426"	15	.0147	.0187	3.21	765	5.02	767

*R'ca = Total thermal resistance of the circuit.

Ampacity calculations based on:

(a) In air; T_C = 75°C, T_A = 40°C, 3-1/C triplexed in air, 30-100% LF.

(b) D.B.; T_C = 75°C, T_A = 20°C, 3-1/C spaced 7.5" in trench, 3-ft. deep,

Thermal resistivity of polyethylene = 360°C cm/watt.

[†] From the Nacon Reference Manual, Courtesy of R. M. Eichhorn of the Union Carbide Corporation.

TABLE 5-4

Utility Survey: Sodium Cable Load History

Circuit Ft.	Rated Voltage	Energized Voltage	Size CuE	Rated Current	Average Current	Max Current	Time at Max Current	Time in Service
9,000	15 kV	12.47 kV	500kcm	649***	240 A	300 A	4 hrs.	9 yr.
500	15 kV	7.62 kV	#2	210***	2 A	--	--	5 yr.
800	15 kV	7.20 kV	#2	210***	20 A	--	--	6 yr.
10,000	15 kV	13.00 kV	500kcm	649***	377 A	550 A	2 hrs.	9 yr.
500	15 kV	13.80 kV	1/0	210**	160 A	290 A	2 1/2 hrs.	9 mo.
1,200	15 kV	7.20 kV	#2	210***	10 A	42 A	few hrs.	11 yr.
500	15 kV	18.00 kV	#2	210***	--	--	--	10 yr.
800	15 kV	12.47 kV	#2	210***	14 A	20 A	9 hrs.	10 yr.
150	15 kV	2.40 kV	#2	210***	15 A	30 A	--	9 yr.
75	15 kV	7.20 kV	#2	210***	10 A	15 A	--	10 yr.
17,400	15 kV	12.47 kV	4/0	403***		(Heavily Loaded)		10 yr.
5,000	600 V	120/240 V	4/0	394*	70 A	200 A	--	7 yr.
375	600 V	480/277 V	500kcm	625*	--	214 A	--	9 yr.
1,410	600 V	120/240 V	2/0	306*	60 A	140 A	--	9 yr.
100	600 V	120/240 V	2/0	306*	70 A	--	--	9 yr.
300	600 V	600 V	350kcm	516*	325 A	630 A	--	8 mo.
200	600 V	120/240 V	2/0	306*	75 A	200 A	few hrs.	11 yr.
200	600 V	120/240 V	4/0	394*	75 A	200 A	few hrs.	11 yr.
3,600	600 V	240 V	500kcm	625*	216 A	360 A	4 hrs.	9 yr.

*Ampacity of direct buried, single conductor, polyethylene insulated, sodium cable.

**Industry rating of similar copper conductor cable located in a "U" guard with the conductor temperature at 75°C and air ambient at 20°C.

***Industry rating of single conductor, direct buried, shielded copper, 1/C groups buried 36" deep, 7 1/2" center, conductor temperature 90°C, earth ambient 20°C, earth RHO 90.

5.2.3.4 Operating Experience

The operating experience reported for sodium cable does not differ greatly in most cases from that for aluminum or copper. In a few instances a very high failure rate for sodium cable compared to other types of cable was reported. See section 5.2.3.5 for a discussion of sodium cable failures. At one utility, customer complaints about lights dimming, TV picture roll, and other problems associated with low or fluctuating voltage have been fewer for homes serviced with sodium cable than for those serviced by aluminum cable.

5.2.3.5 Sodium Cable Failures

Twenty-seven of the 37 reporting utilities, representing 432,591 ft-years (∿82 mile-years) of sodium cable operation, reported zero sodium cable failures. The remaining ten utilities reported a total of 237 failures, indicating an overall failure rate of about one failure per mile-year of operation. Table 5-5 lists the sodium cable failure history for all 37 respondees.

The sodium cable failure rate was much higher for 600 volt secondary cables than for 15 kV primary cables. Two hundred thirty-two failures were reported for the 600 volt cables, indicating a failure rate of 1.59 failures per mile-year, while there were only 5 failures reported for the 15 kV cable indicating a failure rate of .0556 failures per mile-year. The main reason for this difference in failure rate can probably be related to the mode of failure.

Two hundred thirty-four of the 237 reported failures (98.7%) occurred at the sodium cable terminals. Most of the terminal failures were related to the penetration of moisture to the sodium. The moisture reacted with the sodium gradually, causing the conducting area to diminish. At some point the increased resistance caused overheating at the terminal causing the polyethylene insulation to fail. The 15 kV terminals appear to be more effective in preventing moisture ingress into the cable than the 600 volt terminals, thus the lower failure rate. Of course, there are normally fewer terminals per mile of 15 kV cable than for 600 volt

TABLE 5-5

Utility Survey: Sodium Cable Failure History

Utility No.	Circuit Ft.	Voltage Class	Operation Ft-Yrs	Failures Reported	Failure Mode	Failures per Ft-Yr
1	17,400	15 kV	1[illegible],200	0	-	-
	4,500	600 V	43,875	1	don't know	2.28×10^{-5}
2	665	15 kV	8,645	0	-	-
	2,100	600 V	18,900	0	-	-
3	33,000	600 V	313,000	~108	all at connectors	3.45×10^{-4}
4	9,400	15 kV	102,600	0	-	-
5	500	15 kV	2,500	0	-	-
6	800	15 kV	5,200	2	potheads	3.85×10^{-4}
7	10,000	15 kV	90,000	0	-	-
8	5,000	600 V	35,300	90	at connector	2.55×10^{-3}
9	1,200	600 V	12,000	0	-	-
10	90	600 V	135	1*	(prefaulted)	-
11	90	600 V	27	1*	(prefaulted)	-
12	500	15 kV	375	1	overcurrent insulation melted	2.67×10^{-3}
13	340	15 kV	4,080	0	-	-
	770	600 V	6,930	0	-	-
14	200	600 V	400	0	-	-
15	1,838	600 V	20,218	0	-	-
16	1,410	600 V	6,345	20	at connector	3.15×10^{-3}
17	100	600 V	900	0	-	-
18	300	600 V	225	-	-	-
19	1,200	15 kV	13,200	0	-	-
	400	600 V	4,400	0	-	-
20	1,000	15 kV	10,500	0	-	-
	320	600 V	3,520	0	-	-
21	800	15 kV	8,000	0	-	-
22	1,600	600 V	12,800	0	-	-
23	5,000	15 kV	45,000	1	mech. stress	2.22×10^{-5}
	2,000	600 V	18,000	0	-	-
24	10,500	600 V	94,500	-	-	-
25	3,600	600 V	32,400	0	-	-
26	3,500	600 V	21,000	0	-	-
27	400	15 kV	2,300	1	connector	4.35×10^{-4}
	26	600 V	234	0	-	-
28	1,320	15 kV	15,840	0	-	-
	15,840	600 V	190,080	12	at connector	6.31×10^{-5}
29	1,000	15 kV	8,000	0	-	-
	600	600 V	4,800	0	-	-
30	160	15 kV	16	0	-	-
	300	600 V	30	1	overcurrent insulation melted	3.33×10^{-3}

TABLE 5-5 (Cont'd)

Utility Survey: Sodium Cable Failure History

Utility No.	Circuit Ft.	Voltage Class	Operation Ft-Yrs	Failures Reported	Failure Mode	Failures per Ft-Yr
31	150	15 kV	1,350	0	-	-
32	90	600 V	45	0	-	-
33	300	600 V	410	1*	(prefaulted)	-
34	150	600 V	75	1*	(prefaulted)	-
35	75	15 kV	750	0	-	-
36	300	15 kV	2,700	0	-	-
	1,300	600 V	11,700	0	-	-
37	0	0	0	-	-	-

*A failure occurred but was not counted because the cable had been prefaulted as part of a test.

cable, therefore the number of failures is higher for 600 V circuits. One utility reported that a plastic sleeve designed to protect the terminal of 600 volt sodium cables had resulted in a near 100% failure rate when utilized. Experience showed that taping the terminal with rubber tape covered with plastic tape was effective in preventing terminal failure. This utility reported that there have been no terminal failures when this taping method was employed. Two of the 237 reported failures were caused by sustained overcurrents. If the sodium cable is operated above its rated ampacity for an extended period of time, the resulting heat buildup can cause the sodium to liquify and/or the polyethylene insulation to fail. The failure is most likely to occur in an area of poor cooling such as a riser in a "U" guard. The final failure of the 237 was attributed to mechanical stress on the cable, which was an aerial installation.

5.2.3.6 Operating Expense

None of the 37 survey respondees professed any knowledge of the power loss or other operating expenses associated with their installed sodium cable. Two did venture that the losses appeared to be less than with similar aluminum cable.

5.2.3.7 Installed Cable Cost

Information about installed sodium cable cost was not well reported in the survey. Information that was reported is compiled in Table 5-6. Some of this information is qualitative with statements that the sodium cable installation cost was more, less or the same as that for aluminum cable. The two cases that give fairly complete information indicate that the installed cost for secondary sodium cable is higher than that for primary sodium cable. This is probably because of the high cost of terminals, and because the number of terminals per unit length is greater for secondary cable than primary.

A section of the survey questionnaire was devoted to the average installed cost for aluminum and copper cables. Table 5-7 is a compilation of these reported costs and Table 5-8 gives a breakdown on the distribution of these costs. There is considerable variation in

TABLE 5-6

Utility Survey: Sodium Cable Installed Cost

Circuit Ft.	Voltage Class	Size CuE	Total Installed Cost Sodium	Aluminum	Cable Cost	Preparing Ditch or Duct	Installing Cable	Making Terminations	Terminal Cost
800	15 kV	#2	$1.01/ft	-	19%	31%	5%	15%	30%
1,838	600 V	2/0	$1.82/ft		44.3%	16.9%		14.4%	24.4%
9,000	15 kV	500kcm	Na 10-15¢/ft	less than $1.00/ft.		same	same	Higher for Na	Higher for Na
500	15 kV	#2	Sodium more expensive than Aluminum					-	-
3,600	600 V	500kcm	Na same as Al		$ .861/ft	-	-	-	-
150	15 kV	#2	Na less than Al		$ .45/ft	-	-	-	-

TABLE 5-7

Utility Survey: Compilation of Reported Installed Cost for Direct Buried Al and Cu Cable

Voltage Class	Size	Conductor Material	Installed Cost* Per Conductor Ft.
600 V	2/0	Al	$1.15
600 V	3/0	Al	1.97
600 V	4/0	Al	1.02
600 V	4/0	Cu	1.55
600 V	250kcm	Al	2.59
600 V	250kcm	Cu	2.31
600 V	350kcm	Al	1.46
15 kV	#2	Al	2.31
15 kV	#2	Cu	2.65
15 kV	1/0	Cu	2.41
15 kV	3/0	Al	1.94
15 kV	4/0	Al	1.75
15 kV	750kcm	Al	2.85
15 kV	750kcm	Cu	6.85
25 kV	250kcm	Al	9.26
35 kV	250kcm	Al	4.43
35 kV	750kcm	Cu	6.85

*Utility survey conducted in 1978, however, no common base for dollars was established.

TABLE 5-8

Utility Survey: Compilation of Reported Cost Breakdown for Installing Direct Buried Al and Cu Cable

	Cable Cost	Preparing Ditch	Installing Cable	Making Terminations	Terminal Cost	Total Installed Cost
Secondary 600 V	33.5%	51.5%	7.5%	4.5%	3%	100%
Primary 15 kV	35%	16%	11%	21%	17%	100%
TOTAL All Classes	45%	29%	10%	8%	8%	100%

these reported costs, but as expected, in most cases the copper cable is more costly than aluminum cable. Also, the higher the voltage and size, the more costly the cable. A comparison of the breakdown of costs for sodium, aluminum, and copper cables show that terminal cost for sodium cable is higher, but the cable cost is less. These costs are analyzed in more detail in Section 9.

5.2.3.8 Installation Experience

Generally, there were no major difficulties reported in installing sodium conductor cable. The more frequent remarks were that more care had to be exercised with sodium cable than with aluminum. More problems with connectors and more personnel training were also mentioned. Table 5-9 lists the installation experience summary of the 37 responding utilities. Thirteen indicated that sodium cable was more difficult to install, 3 said it was easier, and 17 stated it was about the same as aluminum for installation effort.

5.2.3.9 Maintenance

There was no routine maintenance performed and no maintenance problem reported by any of the respondees except for the failures discussed in section 5.2.3.5 and a few accidental dig-ins.

5.2.3.10 Safety Provisions

Most of the survey respondees reported that the workmen installing sodium cable wore eye protection and gloves. One utility stated that their workmen wore face shields because eye protection alone was not considered sufficient. Special precautions were also taken in the sodium cable storage area. The cable ends were taped to exclude moisture and the cable was stored out of the weather. Signs identifying the sodium were posted and special fire extinguishers were located nearby.

In most cases the cut-off ends of the sodium cable were reported to be sealed in a bag or can and sent back to the manufacturer for disposal. A few of the utilities reported axially slitting the

TABLE 5-9

Utility Survey: Summary of Installation Experience for Sodium Conductor Cable

Utility No.	Circuit Ft.	600 V	15 kV	No. of Terminals	Installation Difficulties	Na compared to Al harder	easier	same
1	17,400		✓	*	Availability	✓		
	4,500	✓		*	of terminals	✓		
2	665		✓	*	None			✓
	2,100	✓		*	None			✓
3	33,000	✓		Hundreds	None			✓
4	9,400		✓	26	None			✓
5	500		✓	2	None	✓		
6	800		✓	10	None			✓
7	10,000		✓	12	More training	✓		
8	5,000	✓		100	Connectors	✓		
9	1,200	✓		*	None	✓		
10	90	✓		1	*			
11	90	✓		*	*			
12	500		✓	0	None			
13	340		✓	3	None	✓		
	770	✓		15	None	✓		
14	200	✓		*	*			
15	1,838	✓		70	None			✓
16	1,410	✓		60	Connectors	✓		
17	100	✓		6	*			
18	300	✓		12	None			✓
19	1,200		✓	10	Installing			✓
	400	✓		128	Connectors			✓
20	1,000		✓	24	Safety concern			✓
	600	✓		*				
21	800		✓	12	None	✓		
22	1,600	✓		*	*			
23	5,000		✓	10	Disposal			✓
	2,000	✓		50	of scrap			✓
24	10,500	✓		115	None		✓	
25	3,600	✓		16	Special handling			✓
26	3,500	✓		*	None	✓		
27	400		✓	*	*			
	26	✓		*	*			
28	1,320		✓	*	*			
	15,840	✓		*	*			
29	1,000		✓	*	None		✓	
	600	✓		*	None		✓	
30	160		✓	6	None			✓
	300	✓		8	None			✓
31	150		✓	2	Getting Connectors			✓
32	90	✓		7	None	✓		
33	300	✓		*	*			
34	150	✓		6	Terminals	✓		
35	75		✓	*	*			
36	300		✓	3	New splicing			✓
	1,300	✓		3	method			
37	0			*	*			
		TOTAL		717 + hundreds		13	3	17

*Not reported

insulation on short cable sections and burying them. A few also reported disposing of the sodium cable ends directly in water or by burning.

In answer to the question, "What was done or what do you plan to do with the sodium cable when removed from service," 43% said they would remove the cable, 24% said they would abandon the cable in place, and 5% didn't know what they would do. Forty-six percent considered an abandoned cable a hazard while 22% said it was not.

5.2.3.11 Opinions, Observations and Recommendations

In answer to the question, "What are your observations and feelings about the sodium cable used by your organization?": Fifty-one percent indicated that the sodium cable experience has been satisfactory, 22% indicated that it was unsatisfactory, 19% had no comment, and 8% thought the advantages and disadvantages cancelled.

The question, "Would you recommend that your organization use sodium cable if it were readily available and if there was a cost advantage?" was answered as follows: Twenty-four percent indicated yes, 19% indicated no, 43% indicated possibly (with some qualifications stated), and 14% didn't know or did not respond. The major advantages and disadvantages reported by the respondees are listed in Table 5-10. The percentage figures at the left in the table show the percent of the respondees that indicated each of these advantages and disadvantages.

5.3 Conclusions

- Sodium cable experience has been well reported in the literature with more than forty publications;
- Response to the utility survey was very high (>75%) indicating a willingness on the part of the utilities to share their sodium cable experience and let their views be known;

TABLE 5-10

Major Advantages and Disadvantages of Sodium Cable as Reported in the Utility Survey

ADVANTAGES:	
(51%)*	Possible Lower Cost
(32%)	Easier Handling, Lighter Weight, More Flexible
(11%)	Future Availability of Sodium Assured
(5%)	None
(3%)	Less Susceptible to Installation Damage
DISADVANTAGE:	
(51%)	Safety Hazard of Sodium
(49%)	Terminal Installation, Cost and Reliability
(27%)	Disposal of Scrap Sodium
(27%)	Need for Special Training and Installation Techniques
(8%)	Liability Problem with Abandonment and Storage
(8%)	Low Emergency Ampacity
(5%)	No Economic Advantage
(5%)	Need to Stock Special Cable Accessories

*Percent of survey respondees citing this factor

- Generally, the utilities with the greatest sodium cable experience were the most positive about sodium cable, while utilities with very limited sodium cable experience were the most negative about it;
- Most of the survey respondees mentioned a problem with sodium cable connectors or an opinion that more connector development is required;
- Information about sodium cable operating and installation costs is not readily available or kept by the utilities.

6. ENVIRONMENTAL AND SAFETY CONSIDERATIONS

6.1 Sodium Description and Properties

Sodium is the sixth most abundant metal on earth and the most abundant of the alkali metals. It is a silvery metal, soft and ductile and has a density slightly less than that of water. (Density of sodium @ 20°C = 0.968 g/cm^3). Sodium melts at about 98°C (208°F) to form a silvery liquid having about 0.7 the viscosity of water at 20°C. Its volume change on melting is +2.7% at one atmosphere[(1)].

Sodium metal is manufactured commercially by the electrolysis of a eutectic mixture of NaCl-$CaCl_2$. It is used principally in chemical manufacturing[(2)] and as a heat transfer medium. Approximately 300 million pounds of sodium are consumed annually in the U.S.A.

Sodium reacts violently with water to form sodium hydroxide and hydrogen. The reaction is exothermic and may ignite the hydrogen gas liberated. Sodium forms an explosive mixture with halogenated hydrocarbons, carbon tetrachloride, and with carbon dioxide in any form. Refer to the National Fire Protection Association[(3)], "Manual of Hazardous Chemical Reactions," for a compilation of such reactions of sodium.

The sodium/water reaction rate depends on a number of factors (i.e., temperature, contact area, pressure, ratio of sodium-water, and mixing rate). If the sodium is in the solid state and the water is in the liquid state and complete reaction is assumed, the final condition of a sodium/water reaction can be expressed by the following equation[(1)]:

$$Na + H_2O \rightarrow NaOH + 1/2\ H_2 + 33.92\ \text{Kcal (per mole) at } 25°C \qquad (6\text{-}1)$$

Calculations of the free energies show that the reaction of sodium and water below the melting point of sodium hydroxide ($\sim$ 315°C) will proceed to sodium hydroxide and hydrogen even in excess sodium. If the temperature is allowed to exceed the melting point of sodium hydroxide, then sodium hydroxide will react with additional sodium to produce sodium oxide and hydrogen.

The physical properties and characteristics of sodium are given in Table 6-1. This information is from The Manufacturing Chemists Association[4] Chemical Safety Data Sheet SD-47 on the properties and essential information for safe handling and use of sodium. It is recommended that anyone involved with sodium handling become familiar with Chemical Safety Data Sheet SD-47.

6.2 Cable Handling by Manufacturer, Shipper and Utility Contractor

Sodium electrical cable manufactured by coextruding sodium and polyethylene[5] is inherently safer than bulk sodium because the polyethylene insulation functions as an effective barrier to air and water. The major danger occurs at the ends of the cable or if the polyethylene insulation is breached. The danger is in the form of fire, explosion and/or corrosivity.

The ignition temperature of sodium in air is above 115°C (239°F), but the high thermal conductivity of sodium makes maintenance of combustion in electrical cables difficult. L. E. Humphrey et al[5] reported on experiments to study the effects of igniting insulated sodium conductors with a torch. A 0.5 inch (1.27 cm) diameter sodium cable was held in a horizontal position and the open end ignited with a gas torch. The insulation took fire and burned until the torch was removed and then extinguished itself. The sodium did not take fire but reacted rapidly, forming a hard tenacious crust of oxide or carbonate which protected it from further reaction.

Another sample of the same insulated conductor, held in a vertical position, was similarly ignited at the lower end. Again the polyethylene insulation took fire as expected, but upon removal of the torch it soon extinguished itself. The sodium was expected to melt and flow from the insulation, but again the oxide or carbonate

TABLE 6-1

Physical Properties and Characteristics of Sodium*

Physical state and Density	Solid at 0°C 0.9725 Solid at 20°C 0.9684 Liquid at M.P. 0.9516 Liquid at 882.9°C 0.7414
Boiling Point (760 mm)	882.9°C (1621°F)
Color	Silvery white changing to gray on exposure to air
Corrosivity	In presence of moisture, it will be caustic
Critical Pressure	343 atm
Critical Temperature	2000°C (3632°F)
Deliquescence	With moisture from the air, it forms caustic which is deliquescent
Heat of Fusion	27.05 cal/gm
Heat of Vaporization	1138.9 cal/gm at 882.9°C (1637°F)
Hygroscopicity	Hygroscopic
Ignition Temperature	In excess of 115°C (239°F)
Ignition Temperature; Autogenous	In dry air, near its boiling temperature
Melting Point	97.83°C (208°F)
Odor	Odorless
Resistivity	4.879 microhm-cm at 20°C (68°F)
Reactivity	Very active; violently reactive with water, halogen hydrocarbons and solid CO_2
Specific Heat	Solid at 0°C 0.2930 cal/gm Solid at 97.6°C 0.3266 cal/gm Liquid at 97.7°C 0.334 cal/gm Liquid at 150°C 0.337 cal/gm
Thermal Conductivity	At 0°C 0.335 cal/cm deg. sec. At 75°C 0.270 cal/cm deg. sec.
Water Solubility	Reacts, to form NaOH and Hydrogen
Threshold Limit Value (OSHA)	2 mg/cu.m. in moist air, as NaOH

*Chemical Safety Data Sheet SD-47, Manufacturing Chemists Association, Washington, D.C. 20009 crust which formed at the surface prevented dripping of the sodium even though the lower portion of the sodium in the conductor was molten. Thus, in either case, ignition proceeds in much the same manner as with a conventional conductor with the sodium contributing little, if any, toward combustion.

The major difference, then, between sodium cable and conventional cable as far as fire is concerned is the possibility of starting a fire with water. L. E. Humphrey et al[5] also reported on experiments to study the effects of water on insulated sodium conductors subjected to varying degrees of insulation damage. A series of holes ranging in size from 1/32 inch (.794 mm) to 1/4 inch (6.35 mm) were drilled through the insulation to the sodium. The prefaulted cable was then immersed in water and the reaction studied. Even with the 1/4 inch (6.35 mm) hole size the reaction subsided within a few minutes due to formation of a salt layer and a gas cushion in the drilled hole. The 1/4 inch (6.35 mm) hole represents approximately the largest size hole which will automatically seal itself against reaction with free water.

The open end of a 0.5 inch (1.27 cm) sodium conductor was partially immersed in free water with the result that evolved hydrogen gas caught fire. The flame was readily extinguished by covering the exposed end with loose sand, soil or even mud. In another case the open end of a 0.5 inch (1.27 cm) sodium conductor was plunged into a puddle of mud. There was essentially no reaction except for a few gas bubbles percolating to the surface of the mud.

Frank R. Nickel of Pennsylvania Power and Light Company (PP&L) reported[8] results of tests on 15 kV, #2 CuF sodium cable:

1. "A short length of cable was cut and a blowtorch played over the exposed cable end. The polyethylene insulation burned just as it does with copper or aluminum cable. The sodium conductor burned back into the polyethylene insulation approximately one-half inch and stopped burning. The polyethylene insulation stopped burning approximately 10 seconds after the flame was removed.

2. A heavy, sharp-edged piece of steel arranged like a guillotine was dropped on a section of sodium cable energized at 7200 volts to ground and buried under approximately five inches of wet earth. When the guillotine was dropped on the energized cable, the protective fuse link operated immediately and there was very little visible reaction of the exposed sodium conductor with the wet earth. Water was poured onto the cable which had been cut approximately three-quarters of the way through. The sodium reacted with the water as it was poured, but the reaction was not at all explosive.

3. Short pieces of cable were cut and completely submerged in a pail of water in order to demonstrate the violent reaction of sodium metal with water. Our tests confirmed that the degree of violence resulting from the reaction with water depends upon the amount of surface exposed.

These tests convinced PP&L Co. that their personnel could safely handle and install sodium conductor cable if they utilized safe work practices."

Corrosivity connected with sodium conductors is a result of moisture reacting with sodium to form sodium hydroxide. Sodium hydroxide is hygroscopic and will form an aqueous solution which is highly caustic and can cause chemical burns upon contact with the skin. It is also highly corrosive to most common metals and could thus result in damage to equipment stored, transported or installed with the sodium conductor.

Possible hazards that could be encountered in the handling of sodium are listed in Table 6-2. Although these hazards are real, some simple precautions reduce the potential hazard to a very low probability. These are listed in Table 6-3.

TABLE 6-2

Possible Personnel Hazards from Handling Sodium

a. Fire and explosion from hydrogen evolved if the sodium comes in contact with water.

b. Sodium hydroxide burns from the residue of a sodium water reaction.

c. Eye injuries from small pieces of sodium or caustic soda.

d. Burns from clothing ignited by clinging particles of burning sodium.

e. Irritation of the eyes and mucous membranes of the nose and throat due to breathing fumes from burning sodium.

f. Flesh burns from contact with sodium.

TABLE 6-3

Safety Precautions for Handling Sodium Conductors

a. Education and training of all personnel involved with handling sodium is essential.

b. Precautionary labeling must be used to identify the sodium, the possible danger, and to specify methods of fire fighting and first aid.

c. Store and transport sodium conductors so that contact with water is avoided.

d. Do not store sodium conductors in an area without adequate ventilation (to prevent the buildup of hydrogen).

e. Wear eye protection and dry gloves when handling sodium.

f. Avoid contact of sodium with any part of the body.

6.3 Field Installations

More than 1/4 million conductor feet of sodium cable reportedly have been installed and energized at more than 50 utilities around the country. These installations range from small 30 foot long test installations to thousands of conductor feet in normal electrical service. No serious sodium related accident has been reported with workmen installing sodium cable in the field.

The major environmental and safety concern with sodium conductors being installed in the field involves the cable terminations. Terminating sodium conductors[(6)] requires cutting the cable to the desired length thus exposing the sodium core. The exposed sodium must not be allowed to come into contact with water or any part of the person. Also tools or equipment that contact the sodium must be wiped clean of any residue. When the cable is terminated, there are usually scrap end sections which must be disposed. See Section 6.6 for a discussion of scrap handling.

The most serious accident that is likely to occur when terminating a sodium conductor is eye damage due to particles of sodium or sodium hydroxide entering the eye. This can be prevented by the workmen wearing safety goggles. Thermal and chemical burns can occur if the sodium comes into contact with wet or damp skin. Protective clothing such as dry leather gloves and heavy work clothes should prevent this kind of a burn. In the event that sodium gets smeared on the clothing, sodium hydroxide will form and probably cause chemical burns if the clothing is not removed soon after. Serious personnel injury can be avoided by immediate removal of the contaminated clothing and flushing the affected area with copious quantities of water. The clothing should be washed before being worn again.

Most sodium conductor field installation safety hazards involve water. If there is standing water around the handling area and the exposed end of a sodium conductor is accidently dropped in, then sparking, small explosions, smoke, fire, and flames could result.

In most cases the fire would extinguish itself in a short time, but secondary fires could result if flammable materials were nearby. Also, some of the burning sodium could be sprayed on personnel. This could be prevented by not allowing sodium conductor work to proceed when there is standing water in the vicinity.

Another possible danger involves the accumulation of hydrogen in areas that are not properly ventilated. If sodium is exposed to moisture, hydrogen will be generated at a rate determined by the mixing rate of the moisture and the sodium. If the hydrogen were allowed to accumulate, an explosive mixture could result. Although this is not likely to happen in open trench installations, occurrence in ducts, transformer vaults and other enclosures is a possibility.

Field installations, where sodium conductors are used above ground, present a possible hazard to the general public. A sodium conductor in a trial installation(7) failed due to a sustained overload with the result that sodium escaped the polyethylene insulation and caught fire. No one was injured in this accident and the fire caused no extensive damage, but the potential for injury and property damage is obvious. It would appear from an environmental and safety viewpoint that sodium conductors can best be utilized underground.

6.4 Dig-in Consequences

The consequences of an accidental dig-in to sodium conductor cable has concerned potential cable customers since the cable was first introduced. In 1968, E. J. Steeve reported(9) the results of sodium conductor cable dig-in tests by Commonwealth Edison Company. The following are conclusions based on these tests:

1. "The hazard of injury to personnel during the damaging of live secondary, sodium conductor cables is no greater than with conventional copper or aluminum cables. Because of the stretch and snap-breaking action of the sodium cable, the danger to electrical shock is probably less than it is for other type cables.

2. It is difficult to cut sodium conductor cable with hand digging tools. If a workman does manage to cut a cable there is probably no serious hazard presented to him unless free standing water is in contact with the raw sodium.

3. The reaction of the exposed sodium conductor to wet soil during or after dig-ins does not appear to be a serious safety hazard. Apparently free water must be present before serious flare ups or explosions can take place. The auger, because of its grinding action, exposes a relatively large amount of raw sodium to the loosened soil and some of the sodium may be brought to the surface as the tool is raised. However, the limited supply of oxygen in the auger hole minimizes the reaction.

4. There does not appear to be any great problem in handling the damaged cable in wet soil so that repairs can be made to restore service. However, gloves and goggles should always be worn as a minimum safety precaution."

An accidental dig-in was reported by E. P. Verheiden[(10)] of Portland General Electric as follows:

"A water district crew in PGE's service territory cut an energized sodium secondary to an incomplete house, and several weeks passed before PGE crews knew it. After roughly locating the break by inspecting the terrain, PGE's crew had to pump water from the hole before they could get down and locate and repair the cable. The break, once located, was easily repaired by cutting off several inches of cable on each side of the open spot and installing two sodium cable terminators. The terminators were connected with a compression sleeve, taped and buried again.

The damaged PE jacket around the sodium allowed it to react to water, and the reaction quickly subsided sealing itself off with a caustic layer."

Other accidental dig-ins were reported by R. L. Garrison[11] of Nacon Corporation as follows:

"Three actual dig-ins have been reported in service installations by two utilities through October, 1968. All three were secondary cables, and were repaired by splicing in short lengths of equivalent copper cable and returned to service with no difficulty."

During the utility survey (see Section 5.2) several dig-in incidents were mentioned. None of these resulted in injury, however, there were reports of unaware equipment operators being frightened when a sodium conductor was dug into in the presence of water.

Two main conclusions can be drawn from these reported dig-ins:

1. The consequence of a dig-in to a powered sodium conductor is no greater than a similar occurrence with a conventional cable.

2. A dig-in to an unpowered sodium conductor could be a greater safety hazard. In the presence of water, small explosions and burning of sodium could results. In dry conditions, the sodium particles could be handled by unaware persons and cause skin burns or eye injury.

6.5 Fault Consequences

The consequences of an electrical fault in respect to sodium conductor cables can be considered from two aspects:

1. A fault in the sodium conductor cable such as a dig-in or insulation breakdown.

2. A fault at some other location in the circuit other than the sodium conductor that subjects the cable to high currents.

The most likely type of fault in the first case is the result of a dig-in. Results of dig-in tests by Commonwealth Edison Company were reported by Edward J. Steeve(9) and by Steeve and Schneider(12). Dig-in tests were conducted on 600 volt 2/0 CUE sodium cable energized at 120/240 volts from a 37 1/2 kVA transformer. The primary of the transformer was protected by a 15-A type-K fuse and oil circuit breaker, but there was no circuit protection on the secondary side. The circuit was loaded to about 60 amperes and an oscillograph was installed to record values of fault current.

Three separate dig-in tests were made, one each using an eight inch chain type trencher, a 21-inch power auger, and an 18-inch back hoe. There was no visual or audible evidence of a cable failure when it was dug through by the trencher. There were no flare-ups or other indications of serious reaction. No fault current was recorded and the load current was broken cleanly.

The dig-in with the auger produced some minor muffled explosions from beneath the loosened dirt. Fault currents recorded by the oscillograph showed evidence of the grinding action of the auger with a peak value of 145 amperes for four cycles, followed by about 36 cycles and the connected load of 68 amperes before a clean break to zero current. During the next six seconds about ten small disturbances were recorded, ranging from four amperes up to 85 amperes and lasting from one to six cycles each.

The records of the back hoe dig-ins showed a clean break of load to zero current with no evidence of fault current. The sodium conductor necked down to about 50% of the original cross section before it broke. There were no flare-ups or other indications of serious reactions by the exposed sodium conductors.

Simulated dig-in tests were conducted on 15 kV sodium cable by inflicting deliberate damage on 20-foot lengths of energized sodium conductor cable on top of the ground. Faulting was accomplished by driving a needle through the insulation by means of a 0.22 caliber blank fired by a device positioned vertically over the cable.

Repeated strikes of fault current were obtained by the use of an oil circuit recloser and fuse connected in series with the 7200 volt source and test cable. Variations in current magnitude and duration were obtained by using different size fuses and by inserting or bypassing a line reactor at the generating station 12 kV bus.

Six fault tests were made with fault currents from 2300 amperes to 6000 amperes for durations from 1 1/2 to 8 1/4 cycles and recloser spacings from 2 to 3 1/2 seconds. Observations indicated that the sodium cable behaves much like a standard aluminum conductor cable. Heat generated by the arc from the fault melted the polyethylene around the fault. Some conductor material was melted out or eroded away by the arc. There was no subsequent reaction of the sodium after the circuit breaker recloser locked out except when the test was conducted under water. When the cable was faulted under water, the reaction continued for approximately six minutes after the recloser locked out. See Section 6.4 for dig-in test conclusions.

Other likely types of damage to sodium conductor cables besides dig-ins are:

1. Damaged insulation caused by handling and installation.

2. Failure at the terminations and connectors.

3. Insulation breakdown due to a high voltage spike such as from lightning.

4. Failure of the insulation due to excessive overcurrent.

Experience has indicated that sodium conductor cables are more resistant to handling and installation damage than conventional cables. This is because the soft sodium core yields under pressure, preventing damage to the polyethylene, while aluminum and copper are quite hard by comparison. Steeve reported[9] that "a long-handled, pointed garden shovel was used to dig a hole directly over some 600 volt sodium cables. Despite numerous attempts by two persons, none of the 600 volt cables could be severed by the shovel. Had the cables been against a solid surface such as a rock then it probably would have been possible to sever them."

This resistance to damage was noted in field tests reported in Residential Underground Distribution Research Program No. 51[13] which states:

"The appearance of the cable samples after being installed, energized for 18 months in the earth, and removed was of interest. There was a noticeable absence of tool marks which are usually present on cables with copper or aluminum conductors that have been removed from the earth. A possible explanation is that the sodium conductor offers almost no resistance to external pressure. The polyethylene insulation tends to distort rather than be cut when struck by a digging tool such as the edge of a shovel."

If the polyethylene insulation is breached, chances are quite high that the cable will fail. Results of field tests[13,14,15] indicated a 75% failure rate of buried sodium cable after 6 months where the polyethylene insulation had been deliberately punctured. These results contradict the predicted reaction of the sodium self sealing a small hole in the insulation that was demonstrated in the laboratory tests[5]. The differences between the laboratory tests and the field tests were that the field tests were conducted over a longer period of time and the sodium core was energized at 120V to 480V. The energized core possibly caused an electrochemical reaction which prevented the puncture from plugging and accelerated the sodium-moisture reaction.

Sodium cable experience has indicated that this mode of failure is very rare where the cable is used in normal service. There have been no reported failures of a sodium cable at an insulation breach except at connectors, and with the exception of an extended overcurrent[7] where the insulation was melted or where the cable was under mechanical stress.

Failure at the termination or connector is the most frequent mode of sodium cable failure. The utility survey (see Section 5.2) revealed that the connector and terminator failure rate with sodium cable is much higher than that with aluminum or copper. The probable mechanism for failure in most cases is the ingress of moisture causing the sodium cross section to decrease thereby increasing electrical resistance. This causes the temperature of the cable-connector interface to increase until the insulation melts, causing the cable circuit to open. The failure rate of 600 volt secondary cable connectors is higher than 15 kV primary connections. The probable reason for this is that the 15 kV connectors are better protected from moisture ingress.

Sodium cable performance during a fault at some other part of the circuit has been investigated. Fault conditions were simulated in tests reported by Steeve and Schneider[12] by short circuiting one end of a sodium cable to ground, then subjecting the other end to 7.2 kV. An oil circuit recloser was used in series with fuses of various sizes to provide a group of fault loadings. A recorder was placed in the circuit to monitor the magnitude and duration of the fault currents. Temperature was monitored by means of a thermocouple taped to the surface of the cable. Short circuit currents were: 2400 amperes for 2 cycles, 3200 amperes for 3 cycles and 2700 amperes for 4 cycles. Eight to fifteen minutes elapsed between each current level. No temperature change could be detected at the surface of the jacket of the sodium cable. Resistance measurements showed that continuity of the conductor was maintained after each high momentary overload.

Several utilities in the survey (Section 5.2) indicated that their sodium cable had been subjected to through fault currents. L. B. Burleson of P.U.D. No. 1 of Snohomish County (WA) stated that, "each 3ϕ circuit has had approximately 25 through faults. The magnitude of these faults ranged up to 8700 amps at 13 kV. These cables withstood these through faults without any problem." There has been no sodium cable failure reported as a result of a through fault.

6.6 Scrap Handling

One problem that is unique to sodium cable installations is the disposal of scrap containing sodium. Cut off ends and unused sodium cable cannot be left scattered around a job site. These could become a hazard if picked up by the public or if somehow placed in a standard rubbish container. The result could be a burn, or eye injury, or the starting of a fire.

R. L. Garrison[11] reported the following on scrap handling:

"Scrap Disposal. Original recommendations of the manufacturer were to tape all loose ends in the field, collect them in a container, and return them to the manufacturer's plant for disposal. Containers were made available for this purpose. Also, a triangular metal container has been developed that fastens between the radial spokes of the returnable shipping reel. Scrap can be put into this container and returned to the manufacturer with the reel. Longer sections of cable have been returned on the metal reel after re-applying the thin sheet metal liner and wood lagging to the reel.

Some utility operating departments have expressed concern for the extra time and labor required to handle scrap in this manner, and suggested burying small scrap pieces directly in the trench. Initial results of sodium cable scrap buried directly in the ground indicate that burial of short lengths of scrap having exposed ends would be an effective method of disposal in areas of moderate rainfall (Table 6-4).

Sodium cable scraps three inches or less in length with ends exposed will completely decompose within seven months. If the cable scraps are slit longitudinally before burial complete decomposition will occur in less than two months. It is seldom necessary to cut more than two inches off the end of the cable to prepare it for the connector."

An incident was related in the utility survey (see Section 5.2) that emphasized the importance of sodium cable scrap control:

TABLE 6-4

Sodium Scrap Disposal Test[11]

Cable Set #1

Conductor Size (CuE)[a]	Buried[b]	Examined	Rainfall	Sodium Reacted
2/0 - ends exposed[c]	4/6/68	6/3/68	11.14 in.	.75 in.
4/0 - ends exposed	"	"	"	.88 in.
500MCM - ends exposed	"	"	"	.75 in.
2/0 - slit[d]	"	"	"	Complete
4/0 - slit	"	"	"	"
500MCM - slit	"	"	"	"

Cable Set #2

Conductor Size (CuE)	Buried	Examined	Rainfall	Sodium[f] Reacted
2/0 - ends exposed	4/6/68	11/3/68	25.53 in.	1.63 in.
4/0 - ends exposed	"	"	"	1.5 in.
500MCM - ends exposed	"	"	"	1.56 in
2/0 - slit	"	"	"	Complete
4/0 - slit	"	"	"	"
500MCM - slit	"	"	"	"

a - All samples 6 inches long

b - All samples buried in 14 inches of loam

c - Both ends of sample exposed

d - Samples slit into half cylinders

e - Third set still under test

f - Several ends were partially plugged with a crust sodium hydroxide but this did not appear to inhibit decomposition.

A lineman making a repair on a sodium cable accidently disposed of several small pieces of cable in a standard trash can. When the can was emptied into a garbage truck, a fire started. The truck operator poured water on the fire which caused several small explosions as the sodium reacted. No serious damage was done but the potential for property damage and injury is obvious.

6.7 Discontinued Circuit Removal and Abandonment

What should be done with a buried sodium cable once it is removed from service? Every user of sodium cable will have to resolve that question sooner or later. The choices are:

1. Abandon the cable.

2. Dig-up, remove and dispose of the cable.

3. Develop a technique for removing the sodium without digging up the cable.

The consequence of abandoning the cable is the possibility of injury or property damage at some later date due to a dig-in and handling of sodium cable pieces by inexperienced people. The location of the buried cable could have an effect on the decision. If the cable were located on utility property, dig-ins could be controlled by proper record keeping. If located elsewhere, however, record keeping would not prevent dig-ins.

The utility could seek insurance for this type of hazard. The underwriter would need to assess the probability of the occurrence of an injury or property damage. The major factors affecting this probability are the amount of cable abandoned, the location of this cable and the length of time until the sodium would no longer be reactive.

Another important consideration for the underwriters would be the probable severity of an accident. The probability of the abandoned sodium cable causing death is very, very small. Also very small is the probability of several people being injured. The most severe injury that would be postulated is an eye injury or skin burns caused by handling pieces of sodium cable exposed by a dig-in. Property damage caused by a fire started by dug-up sodium cable is another possibility.

The surest method for disposing of the abandoned cable is to dig it up and dispose of it by burning[4] or controlled burial. This would be the most expensive technique but would prevent possible future liability problems.

An interesting compromise between the above two methods of removing sodium cable from service is to remove the sodium without removing the cable. The technology exists for controlled reaction of the sodium by inserting a flexible tube into one end of the cable and injecting a reactant. The tube would be pushed through the polyethylene shell as the sodium was reacted away. This technique would require development.

6.8 Conclusions

- The use of sodium conductor cable involves hazards not present with aluminum or copper cables.
- These hazards result from the highly reactive nature of sodium with water.
- Experience has shown that properly trained personnel can safely handle sodium conductor cable.
- After thirteen years of sodium cable production, installation and maintenance by more than 50 different crews, there has been no reported incident of serious injury or property damage.
- The use of sodium conductor cable above ground presents a continuous potential hazard because of the possibility of sodium escaping the polyethylene insulation.
- The potential for serious injury to personnel installing and maintaining sodium conductor cable is much less than the hazard presented by electrically active cable.

7. ELECTRICAL PERFORMANCE OF SODIUM CABLE

7.1 Electrical Basis for Comparison of Cables

In order to compare sodium cable to aluminum cable, it is of course first necesssary to decide what sodium and what aluminum cables shall be compared. In this study, aluminum cables of four voltage classes and four conductor sizes, specified in Paragraph 7.4.3, were compared with sodium cables of the same voltage class and same overload ampacity. The definition of this equivalence is given in Section 3 and in Paragraph 7.1.1, and the required calculations are described in Section 7.4.

7.1.1 Definition of Equivalent Sodium Cable

In comparing sodium cable to aluminum cable, it is first necessary to define the parameters for the particular sodium cable which is considered equivalent to a given aluminum cable. In this study, equivalence implies equal overload ampacities for both cables. The definition is made by a four-step process:

1. The ampacity I_1 of the aluminum cable at normal conditions (conductor at 90°C) is determined.
2. The overload ampacity I_2 of this same aluminum cable (conductor at 130°C) is also determined.
3. The conductor diameter for a sodium cable which, for the same overload current I_2, will operate at a conductor temperature of 95°C, is determined.
4. The conductor temperature at which this sodium cable will operate with the normal current I_1 is determined.

The sodium cable with conductor diameter determined as in Step 3 above is defined as the equivalent of the aluminum cable of Steps 1 and 2. The methods of calculation used in these steps are described in section 7.4.

7.2 Choice of Type of Cable for Comparison

In this section we discuss the general type of construction of the cables to be compared, and the chosen types of installation and the installation parameters. The chosen structure is the only one in which both sodium and aluminum cable have been made; the installation is typical of a majority of URD cable, and the installation parameters are in accord with IPCEA[16,18,19] NEMA[16,18,19] and AIEC[17] specifications.

7.2.1 Type of Construction

The construction of the cables considered in this study is shown in Figure 7-1. For 600 volt operation, each cable is simply a heavy insulated wire, comprising only a central conductor (stranded for the aluminum, solid for the sodium) and a surrounding insulation; no semiconducting shields or outer jackets are employed. For the 15, 25, and 35 kV cables, concentric neutral wires and a semiconducting outer shield are employed, and a semiconducting conductor shield around the stranded aluminum conductor (but none around the solid sodium) is also included. This type of construction was chosen as a basis for comparison because aluminum cable of this type is approved by IPCEA [16,18,19] (Insulated Power Cable Engineers Association) and AEIC[17] (Association of Edison Illuminating Companies) and is widely used, and because the only sodium cable ever made, that produced by the NACON Corporation, is of this design.[20]

7.2.2 Types of Installation

For illustration, two types of installation have been considered - installation in ducts and direct burial in earth. In each case a single balanced three-phase circuit of three equally-spaced cables buried at a common depth is assumed; all calculations will refer

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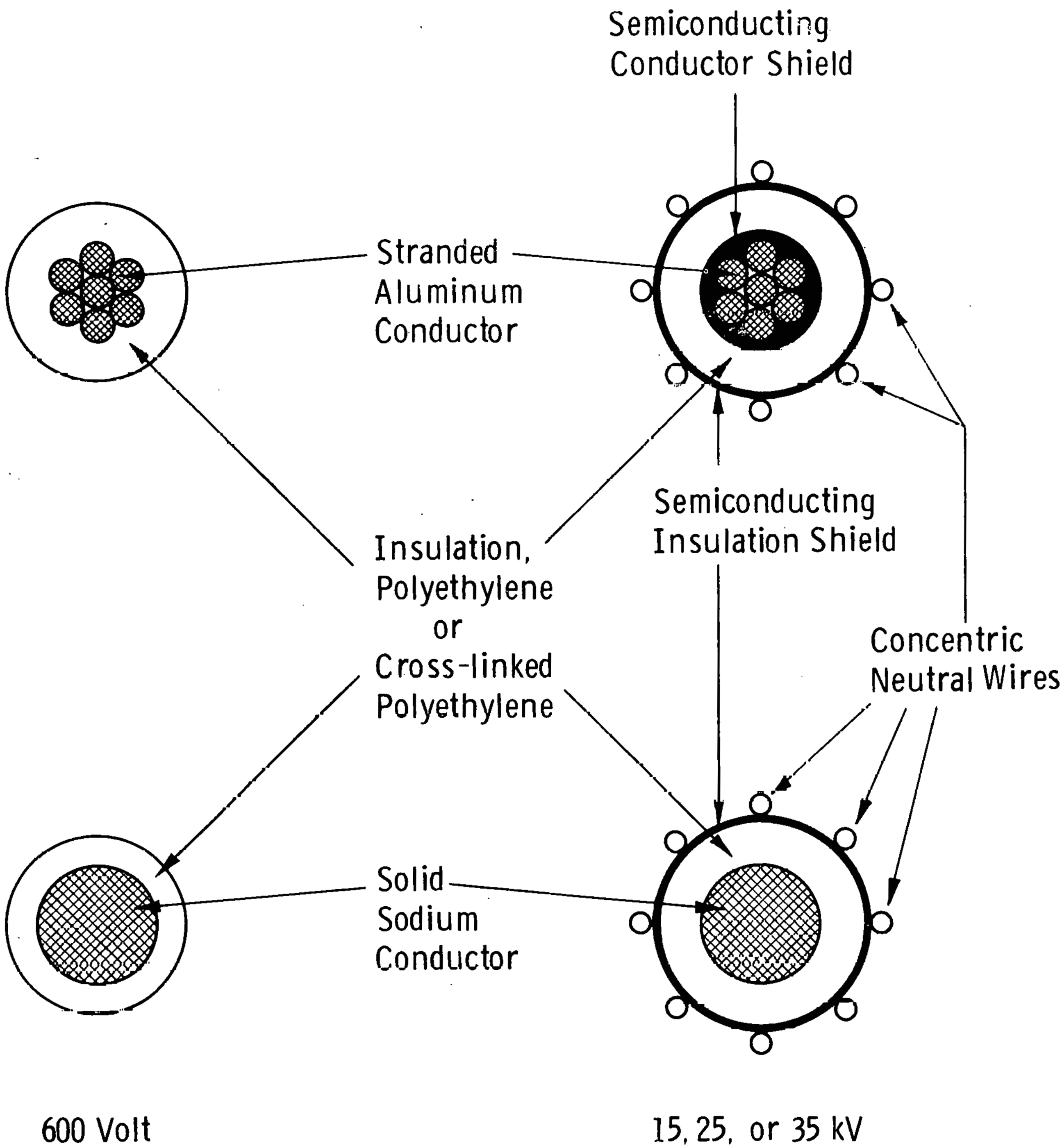

Fig. 7.1—Construction of cables of this report

to the central cable, the hottest of the three by virtue of being heated by both outer cables as well as by its own losses. No special backfill material has been assumed. In the duct case, fiber ducts embedded in concrete or placed directly buried in earth (these two cases are considered equivalent by IPCEA[16]) were assumed. It was further assumed that each installation of cable requires a new installation of duct as well, so that each cable is installed in an otherwise vacant duct.

7.2.3 Installation Parameters

Directly buried cables are assumed buried 91.4 cm (36 in.) deep and 19 cm (7.5 in.) apart (dimensions to cable centers). Ducts, when used, are assumed buried 91.4 cm (36 in.) deep to duct center and spaced 19 cm (7.5 in.) between centers. Fiber ducts of 12.7 cm (5 in.) I.D. and .64 cm (1/4 in.) wall are used, the material having a thermal resistivity of 480°C cm/watt. Earth thermal resistivity is taken as 90°C cm/watt, and the earth ambient temperature as 20°C.

7.3 Basis for Choice of Type and Thickness of Insulation

The comparisons made in this report will for the most part be based upon polyethylene or cross-linked polyethylene insulation, using the same values for thickness for sodium cable as are presently specified and used for aluminum and copper cable. IPCEA specifies the insulation thickness for 15 kV, 1000 KCM (KCM denotes thousands of circular mils; 1000 KCM = 0.78654 in^2 = 5.067 cm^2) and smaller as 0.445 cm (0.175 in.)[16]; for 15 kV, over 1000 KCM, 0.483 cm (0.190 in.); for 35 kV, 1000 KCM or less, 0.876 cm (0.345 in.); and for 35 kV, over 1000 KCM, 0.914 cm (0.360 in.). AEIC[17] agrees, adding a specification of 0.660 cm (0.260 in.) for 25 kV, 1000 KCM or less. For 600 volt cable, NEMA and IPCEA both specify polyethylene thicknesses as 0.241 cm (0.095 in.) for a 225 to 500 KCM[18] (0.239 cm (0.094 in.) for cross-linked polyethylene)[19]; 0.279 cm (0.110 in.) for 501 to 1000 KCM (0.277 cm (0.109 in.) for cross-linked)[19]; and 0.318 cm (0.125 in.) for over 1000 KCM. The semiconducting insulator shield thickness was assumed as 0.076 cm (0.030 in.) for all cables but the 600 volt, for which it was omitted. The bases for these choices will be discussed in the following sections.

7.3.1 Polyethylene vs. Cross-Linked Polyethylene vs. Ethylene-Propylene Rubber

Ethylene-propylene rubber (EPR) was initially considered as a candidate insulation material because it is extensively used by Okonite Company[21] in its cables. However, no aluminum cable of the construction described in 7.2.1,and no sodium cable, is available with EPR insulation. EPR was therefore not considered further in this study. Instead, polyethylene and cross-linked polyethylene were considered. The difference between these two materials will appear primarily in the thermal and mechanical properties of the materials.

7.3.2 Electrical Strength

The electrical strengths of polyethylene (PE) and of cross-linked polyethylene (XLPE) are not significantly different, and their electrical loss tangents are also similar;[22] further, the insulation dielectric losses are negligibly small compared to conductor ohmic losses in the cases studied here. Electrically, therefore, these two may be considered equivalent. There is some divergence of opinion on the relative susceptibility of the two to treeing (the formation, by repeated electrical discharge, of elongated treelike void channels in the material, eventually resulting in electrical failure). Okonite, for instance, does not use XLPE in their higher-voltage cables because of concern for its susceptibility to treeing.[21] Recent comparative studies indicate that XLPE is more resistant to treeing than PE.[23,24] For purposes of this study, the electrical differences are insignificant.

7.3.3 Thermal and Mechanical Properties: Cable Installation

The thermal and mechanical properties of the insulation are significant in relation to the installation of the cable, and to its overload and short-circuit operation. Regarding installation, since the sodium has negligible tensile strength, the insulation must furnish the entire tensile strength needed to pull the cable into the duct or to deploy it from a reel and protect the conductor during burial or plowing-in. The required pulling strength for duct installation depends on the length of the cable run, the coefficient of friction of the cable aginst the duct inner surface, the weight of the cable, the number and severity of the bends in the duct, and the stiffness of the cable (horizontal runs are assumed). The insulation tensile strength depends on the temperature of the cable when installed; utilities generally specify this as up to 35°C (95°F), but 49°C (120°F) was used in this study as a possible upper limit. The question is whether the insulation thicknesses normally specified for PE-insulated aluminum cable will provide sufficient pulling strength in sodium cable, or whether thicker insulation, or XLPE, will be required.

Before looking at this question, some specific examples of actual tensile measurements and pull tests can be cited. Ruprecht and Ware[25] report that a set of three PE-insulated sodium conductors, of 1.27 cm (0.500 in.) conductor diameter and with 0.127 cm (0.050 in.) thick insulation, were pulled into a 6.35 cm (2-1/2 in.) diameter steel duct 30.5 m (100 ft.) long, with four standard 90° bends, with a total pulling force of 289 newtons (65 pounds), or 96.4 newtons (21.7 pounds) per cable (temperature not reported). Each conductor weighed 0.174 kg/m (0.117 lbs/ft.). Since the PE cross-section per cable was 0.557 cm^2 (0.0864 in^2), these results give a stress of 173 N/cm^2 (251 psi) on the PE. No difficulty was experienced in this pull, and on the basis of this stress none would be expected, as the next example will show. Humphrey, Hess and Addis[26] report tensile tests on 15 kV sodium cable, which they rated equivalent to #4 copper. These cables had sodium conductors of 1.27 cm (0.500 in.) diameter, and were insulated with 0.559 cm (0.220 in.) of PE covered with a 0.076 cm (0.030 in.) semi-conducting PE shield, giving a total PE cross-section of 3.85 cm^2 (0.589 in^2); cables of both high molecular weight PE of specific gravity about 0.92 and XLPE insulation were tested for tensile strength vs. temperature. Their results for yield strength, to which we have added yield stress calculated by dividing the yield strength by the above insulation cross-section, are given in Table 7-1.

TABLE 7-1

PE and XLPE Cable Yield Strength vs. Temperature
(After Humphrey, Hess and Addis[26])

Temp.		PE				XLPE			
		Yield Strength		Stress		Yield Strength		Stress	
°C	°F	lbs	N	psi	N/cm^2	lbs	N	psi	N/cm^2
25	77	690	3070	1170	807	746	3318	1266	873
75	167	230	1023	390	269	275	1223	466	321
90	194	145	645	246	170	181	805	307	212
125	257	0	0	0	0	60	267	102	70

From these stress values it appears that the 173 N/cm^2 (251 psi) stress in the installation reported by Ruprecht and Ware[25] was less than 22% of the PE yield stress at 25°C, and about one-third of the expected yield stress at 120°F or 49°C. These figures indicate that, for this installation, even this rather thin PE insulation wall would have possessed adequate strength at 49°C (120°F). Similar tensile strengths have been reported by Matthysse and Scoran.[28]

Consider now the more general case of pulling a cable into a duct, which we assume unoccupied by any other cables. We denote the total cable cross-sectional area in square inches as B, and the fraction of this which is insulation as λ, so that the insulation cross section is λB. Since the specific gravity of sodium is 0.97 while that of the PE normally used for cable insulation is about 0.92, the average density of the cable is very nearly 0.94 gms/cc no matter what λ is, and the cable weight in lbs/ft is then 0.41 B. If the cable length is F feet, its weight is then 0.41 BF; and if the coefficient of friction between cable and duct surface is η, the frictional pulling force is 0.41 $BF\eta$. The tensile stress S on the insulation is then, in pounds per square inch,

$$S = \frac{0.41\ BF\eta}{\lambda B} = \frac{0.41\ F\eta}{\lambda} \qquad (7\text{-}1)$$

From this relation we can estimate the required insulation fraction λ from values of S, F, and η. Typical utility pull distances are about 180 meters (600 feet), and a reasonable maximum appears to be about 240 meters (800 feet). The coefficient of friction for polyethylene-insulated conductors, with or without concentric neutral wires,has been measured against fiber surfaces at 25°C, as about 0.3 to 0.4. The data from the tensile tests of Humphrey et al[26], interpolated, suggest a PE yield stress at 49°C (129°F) of about 503 N/cm^2 (730 psi) which is about 63% of that at 25°C (77°F). Tensile strength data reported by commercial suppliers for polyethylene of this density is somewhat higher than these values; one report[27] gives 1310 N/cm^2 (1900 psi) at 25°C (77°F), with about 65% of this value ratained at 49°C (120°F). This latter value is for an elongation rate, as specified by ASTM D638,of 0.085 cm/sec (2 in/min). The elongation rate for the cable tests of Humphrey et al is not specified, but was probably considerably less than 2 in/min and would thus be expected to show a lower yield stress. One can therefore assume S = 730 psi at 120°F, which with $\eta = 0.4$ and F = 800 ft gives

$$\lambda = \frac{0.41\ F\eta}{S} = .18 \qquad (7\text{-}2)$$

i.e., the polyethylene must occupy 18% of the cable cross-section, or its thickness must be at least 10.5% of the conductor radius in order for conventional polyethylene insulation to afford sufficient strengths for a 240 m (800 foot) duct pull-in at 49°C (120°F). The insulation thicknesses assumed in the sodium cables to be described are all well in excess of this value; the smallest λ for any case is that for a 600-volt sodium cable of conductor radius 1.89 cm (0.745 in.) and insulation thickness 0.318 cm (0.125 in.), giving $\lambda = 0.27$, a safety factor of 1.5 even under these extreme conditions. It is possible that at such high installation temperatures the coefficient of friction η will exceed 0.4; this might affect the preceding conclusion for the largest cables of the 600 volt class. For the smaller cables, and for all of the higher-voltage cables, λ is considerably larger; further, all of the higher-voltage cables are wrapped with concentric neutral wires whose coefficient of friction with the duct will not vary appreciably with installation temperature. The insulation tensile strength is thus still more adequate for these cases.

Some idea of the relative effects of bends in the ducts may be gained from consideration of the installation reported by Ruprecht and Ware[25]. The weight of their conductors, quoted by them and verified by calculation,was 0.174 kg/m (11.7 lbs/100 feet). With a coefficient of friction of $\eta = 0.4$, the pulling force due to friction alone for a straight duct would have been 21 N (4.7 lbs) per conductor. Since the total was 96.5 N (21.7 lbs) per conductor, the remaining

75.5 N (17 lbs) can be ascribed to the four 90° bends. If evenly distributed, this would mean about 19 N (4.3 lbs) per bend, making a 90° bend equal to about 27 m (90 feet) of straight duct as regards pulling force. If instead n = 0.3 is assumed, this figure becomes 40 m (130 ft). It is not expected that the effects of these bends would add linearly; the tension, and therefore the friction, at the bend closest to the pulled end of the cable must be more than at the next bend, and so on. However, as a rough guide, these figures suggest that a 90° standard bend is about the equivalent of 30 m (100 feet) of duct in pulling force.

Many thousands of feet of sodium cable with conventional PE insulation have been installed in ducts and directly buried. No difficulties have ever been reported in installing any of these cables. On the basis of this field experience and the foregoing analysis, it appears that sodium cables insulated with conventional polyethylene in accordance with IPCEA, NEMA, and AEIC recommendations as described at the beginning of Section 7.3 will have adequate strength for direct burial or new duct installation under all anticipated circumstances, including lengths up to 240 m (800 feet) at cable temperatures up to 49°C (120°F), and that the extra strength afforded by XLPE or by thicker insulation is not required on the basis of tensile strength for installation.

7.3.4 Thermal and Mechanical Properties: Overload Performance

The second area in which the thermal and mechanical properties of the insulation are important is the cable overload performance. For buried or duct installations, the mechanical strength of conventional polyethylene is quite adequate in all cases where the sodium conductor remains solid. This study has recommended that the sodium stay solid even under overload conditions. However, since short circuits or inadvertent excessive overloads might result in core melting, this circumstance must be considered.

The fact that the heat of fusion of the sodium is advantageous in limiting the cable temperature rise in short circuits of a few cycles to a few seconds duration is well recognized.[25,29,30] Ruprecht and Ware[25] have analyzed such fault behavior in detail, and find that the short circuit ampacity of sodium cable is roughly 1.5 times that of copper or aluminum for short-circuit durations of a few seconds or less, assuming that in each case the initial temperature is 75°C, the conductor temperature rise is 150°C, and the duration is short enough that the heat transferred to the insulation is negligible.

For longer-duration faults, this advantage is reversed, because the resistivity of sodium increases by about 42% upon melting resulting in more rapid heating thereafter. Hus[29] has discussed this case in detail, noting that after melting, a new, higher steady-state temperature will be attained. See also Paragraph 7.5.4 of this report.

The course of events after melting is initiated will vary with the cable insulation and installation. If the insulation is PE, sustained operation with a molten conductor will very likely cause considerable softening of the PE. If the cable is buried, the surrounding earth will probably maintain the insulation nearly in its original shape if the overload is not too severe; if the insulation eventually ruptures, a small amount of sodium will escape and possibly interrupt the current. It is unlikely that any damage will result other than the need to repair the cable at the rupture. In a duct installation of PE cable, this same process might occur more readily because of the lack of earth restraint around the cable; alternatively, sufficient local softening and swelling might develop a gap in the conductor which would terminate the current without insulation rupture. This self-fusing action of sodium cable has been noted by several investigators, some of whom consider it an advantage.[31,32,36]

Another mode of failure on sustained overload has also been observed in PE cables[31] in which, after softening, the insulation slowly contracts on the liquid sodium, constricting the conductor and eventually completely pinching it off and interrupting the current. This is another example of a self-fusing mechanism. This type of failure does not occur with XLPE, nor with thick PE; only fairly thin PE fails in this manner.

In aerial installations, such as overhead cables or vertical pole risers, the possibility of molten sodium being forcibly expelled represents a significant hazard. One such failure of an overhead cable actually occurred on September 23, 1966, after 2-1/4 hours at a 40% overload.[33,34] Laboratory tests of risers under overload have shown[31] that PE-insulated cables may fuse (i.e., interrupt the current) with or without rupture of the insulation and expulsion of sodium; XLPE-insulated cables, on the other hand, likewise fused under overload but never ruptured or expelled sodium, and in fact distorted only very slightly. More work in this area is required to establish safe practice. On the basis of available data, it is recommended that for aerial installations, either overhead or riser, that XLPE insulation be used because there seems to be no way of insuring that occasional long-term overloads may not occur, which could result in discharge of molten sodium. For direct-buried or ducted cable, the likelihood of sodium escape and the hazard if it does are both much reduced, and PE appears satisfactory for these applications.

7.3.5 Moisture Diffusion

The diffusion of moisture into the insulation of sodium cable is potentially a more significant problem than for copper or aluminum cable. The indiffusing water will react with the surface of the sodium conductor to form nonconducting sodium hydroxide, thereby progressively reducing the conductor cross-section. This well-recognized process[26,28,33] has indeed been used by Eichhorn[35] as the basis for a rather complete and accurate determination of the rate of moisture diffusion in the particular polyethylene (high molecular weight, melt index 0.2; low density, about 0.92 gms/cc) used for cable insulation. He measured the change in resistance with time for cables (sodium conductor diameter 0.508 cm (0.200 in.), insulation thickness 0.102 cm (0.040 in.)) immersed in water at controlled temperatures between 40 and 80°C, or in air at controlled relative humidity and temperature. The results were consistently described by the relation

$$t = \frac{.00085\ d^2 \times f}{P\ (d+x)\ H} \qquad (7\text{-}3)$$

where d = conductor diameter, mils

x = insulation thickness, mils

f = fraction of Na converted to NaOH ($0 \leq f \leq 1.0$)

P = permeability of insulation to water, $\frac{\text{gram mils}}{100\ \text{in}^2\ \text{day}}$

H = relative humidity fraction ($0 \leq H \leq 1.0$)

t = time in years to convert a fraction f of the Na cross-reaction to NaOH

The permeability calculated from these data was found to vary with temperature according to the relation

$$P = 9.63 \times 10^{11} \exp(-8580/T) \qquad (7\text{-}4)$$

where P is in the preceding units, chosen by Eichhorn for practical reasons, and T is average insulation temperature in °Kelvin. (Some of the units of the above equations differ from those used by Eichhorn).

Values of P calculated from Equation 7-4 are presented in Table 7-2 for a range of tempratures from 0 to 95°C. With these values and Equation 7-3 it is possible to calculate, for various cable geometries, the service lifetime for a sodium cable conductor to be reduced 10% in area. On the basis of such calculations, Humphrey et al (26) have said, "A useful service life of 40 years under normal ambient conditions is predicted for direct-buried [polyethylene insulated sodium] cable." For unjacketed cable of the construction of Figure 7-1, as made by Nacon, these predictions appear to be far too optimistic if the cable is assumed to operate at full rated load and high humidity from the date of installation. The relevant calculations by Humphreys were not published, but appear to have been based on an average insulation temperature in the neighborhood of 25°C, indicating a very lightly loaded

TABLE 7-2

Permeability of Cable Polyethylene to Moisture (After Eichhorn)[35]

T°C	$\frac{\text{gm mils}}{100\ \text{in}^2\ \text{day}}$	$\frac{\text{gm}}{\text{cm sec}}$
0	.0216	9.84×10^{-13}
5	.0380	1.73×10^{-12}
10	.0656	2.99×10^{-12}
15	.111	5.06×10^{-12}
20	.185	8.43×10^{-12}
25	.302	1.38×10^{-11}
30	.485	2.21×10^{-11}
35	.768	3.50×10^{-11}
40	1.20	5.47×10^{-11}
45	1.84	8.38×10^{-11}
50	2.80	1.28×10^{-10}
55	4.20	1.91×10^{-10}
60	6.22	2.83×10^{-10}
65	9.10	4.15×10^{-10}
70	13.2	6.01×10^{-10}
75	18.9	8.61×10^{-10}
80	26.8	1.22×10^{-9}
85	37.6	1.71×10^{-9}
90	52.3	2.38×10^{-9}
95	72.1	3.29×10^{-9}

cable. It will be shown in Section 7.5 that the full-load conductor operating temperature for sodium cable, as defined in Section 7.1, is about 69°C (ambient 20°C, rise 49°C) for most circumstances, and that the thermal drop across the insulation is no more than 10°C in nearly all cases. The average insulation temperature is then about 65°C, and the appropriate value of P is, from the table, 9.1 gm·mils/100 in^2 day. Assuming the pessimistic combination of constant full load and 100% relative humidity, we may then calculate a minimum life for sodium cable from Equation 7-3 by setting f = 0.1, P = 9.1, and H = 1. Choosing, for example, a 15 kV sodium cable equivalent to 1000 KCM of aluminum (which from Table A3-6 has d = 3.73 cm (1468 mils). x = 0.521 cm (205 mils)) one finds that t = 2.46 years. Choosing as another example a 600 volt cable equivalent to 750 KCM of aluminum (which from Table A3-8 has d = 3.246 cm (1278 mils) and x = 0.406 cm (125 mils), the same insulation thickness actually used by Nacon for cable of this voltage class but with d = 1165 mils) one finds that t = 1.36 years.

These disturbingly low predicted lives raise the questions, "What about the service record of cables already installed?" and "What other data are available to check these predictions?" Regarding the second question, Kelly and Gnerre[37] report on measurements on three cables which were immersed in water at 75°C for five months; conductor resistance measurements were made monthly at 25°C. Table 7-3 shows their cable dimensions and the resistance change over five months; added in the last two columns are the times which are predicted by Equation 7-3 to reach those resistance changes, using H = 1.0 and P = 18.9 gm mils/100 in^2 day. It can be seen that these are from 1 to 3 months, in fair agreement with observed values. It is curious that Kelly and Gnerre were not alarmed by this rapid degradation; apparently they too felt that service temperatures would be far below 75°. It should be added here that they found no decrease of corona onset voltage with time; apparently the sodium hydroxide forms as a dense and void-free insulator.

TABLE 7-3

Resistance Increases of Five-Month Water-Immersed Sodium Cables (After Kelly and Gnerre [37]) and Calculated Times* for This Increase to Occur (Equation 7-3)

Cable	d,mils	x,mils	Resistance Initial	Resistance Final	f	t_{yrs}*	t_{mos}*
#4 CuE	335	175	.281	.266	.0564	.097	1.2
#2/0 CuE	603	100	.0871	.0810	.0753	.174	2.1
#1/0 CuE	534	50	.143	.117	.222	.243	2.9

Concerning the service record of installed sodium cable, it is probable that their observed longevity is due to the fact that high temperature and high humidity have not occurred simultaneously. (In this connection see Table 5-4, which shows very light load service for almost all sodium cables). It is in fact to be expected that if the cable is hot, water will migrate away from it;[16,38,39] this, and the consequent increase in local soil thermal resistivity, is the basis on which IPCEA specifies[16] a maximum earth interface temperature. Conversely, if soil is wet, the temperature of the cable may be below tabulated values, reducing the permeability P. Further, in a practical case, it is to be expected that newly installed cable will initially be lightly loaded, and will not approach rated load and temperature for some years. In such a situation the assumptions of maximum temperature and humidity are probably too stringent; an operating temperature of, for example, 45°C rather than 65°C, and humidity of H = 0.5 rather than unity, would result in ten times the life calculated for T = 65°C and H = 1.0. For any assumed curve of load vs. time (and corresponding humidity) Equation 7-3 can be used to determine the fraction of reacted sodium for each time segment and thus the expected life. In the extreme cases where one must assume constant full load and wet conditions (T = 65°C, H = 1.0, P = 9.1 gm mils/100 in^2 day), it is clear from Equation 7-3 that no reasonable insulation thickness will provide enough moisture resistance to assure a 40 year life. To pick an extreme case, if one considers a sodium conductor diameter of 3.73 cm (1468 mils) as in the first case, and an insulation thickness of 1.27 cm (500 mils), then t = 5.1 years for 10% sodium reaction. It appears, therefore, that for operation at rated ampacity and wet conditions polyethylene-insulated sodium cable should have a vapor-barrier jacket, although in many practical installations load and humidity may be low enough that a jacket can be omitted.

This jacket, when required, must furnish an adequate vapor barrier at a cable surface temperature of about 65°C. This might be provided by, for example, either a very thin metallic sheath, or a PVC jacket. PVC is stated[(40)] to have a permeability to water vapor of less than 2% of that of cable polyethylene. However, this value depends very strongly on crystallinity and presence of fillers; the foregoing ratio is stated to be for crystalline PVC and "somewhat crystalline" PE. Even in conventional (aluminum or copper) cables it is sometimes argued that a waterproof sheath is necessary to prevent cable failure by water treeing caused by indiffusing moisture. Opinion of both utilities and cable manufacturers is divided on this point; some manufacturers will only furnish, and some utilities only install, lead-sheathed cable, while others find unsheathed cable satisfactory. Even a thin layer of helically half-lapped aluminum adhesive tape (probably protected from abrasion by a plastic outer jacket) would probably be adequate, even though small amounts of moisture might diffuse through along the adhesive layer. Since it is not at this time clear what the jacket will be, the jacket has been ignored in the ampacity calculations of this study. In Paragraphs 7.3.6 and 7.7.4, which describe the sensitivity of ampacity to insulation thickness, it is shown that the effect of the jacket on ampacity will be very small.

The effect of crosslinking on the moisture permeability of polyethylene is generally negligible; crosslinking links chains together locally but does not greatly affect the overall molecular structure. On the basis of moisture transmission, therefore, PE and XLPE are essentially equivalent. In the following presentations, it will be assumed that moisture protection, if deemed necessary, will be provided by a jacket, and will therefore not be a determining factor in the choice of insulation material or thickness.

7.3.6 Sensitivity of Ampacity to Insulation Thickness

IPCEA[16,18,19] and AEIC[17] have specified insulation thicknesses for polyethylene-insulated cables with aluminum or copper conductors. Since, however, in sodium cable the mechanical tensile strength is derived almost entirely from the insulation, it is a priori possible that thicker insulation might be required than for aluminum or copper. It is therefore of interest to know how such thicker insulation will affect the ampacity of sodium cable, and this was accordingly calculated by methods which are described in Section 7.4. Results are shown in Figure 7-2 for several conductor sizes, both for duct installation and for direct burial. The conductor temperature assumed for this calculation is 69°C, because this is the operating temperature obtained in Step 4 of the comparison equivalency procedure of Section 7.1.1 for a wide range of cable sizes. It can be seen that for the direct burial case, increasing the insulation thickness reduces the ampacity as is to be expected on the basis that thickening the insulation merely replaces some of the earth, having a thermal resistivity of 90°C cm/watt, with insulation of a higher thermal resistivity). For the duct case, the dependence is much less and may be in either direction. The 2196 KCM cable shows a slight but continuous decrease in ampacity as insulation thickness increases over the range of 0.318 to 1.067 cm (0.125 to 0.420 in.). The 530 KCM shows a slight continuous increase, and the 1000 and 1690 KCM sizes show broad maxima of ampacity at about 0.838 and 0.457 cm (0.330 and 0.180 in.) thicknesses respectively. For practical purposes, in these duct cases, the ampacity is independent of insulation thickness. The figure also demonstrates the variation of ampacity with conductor cross-section.

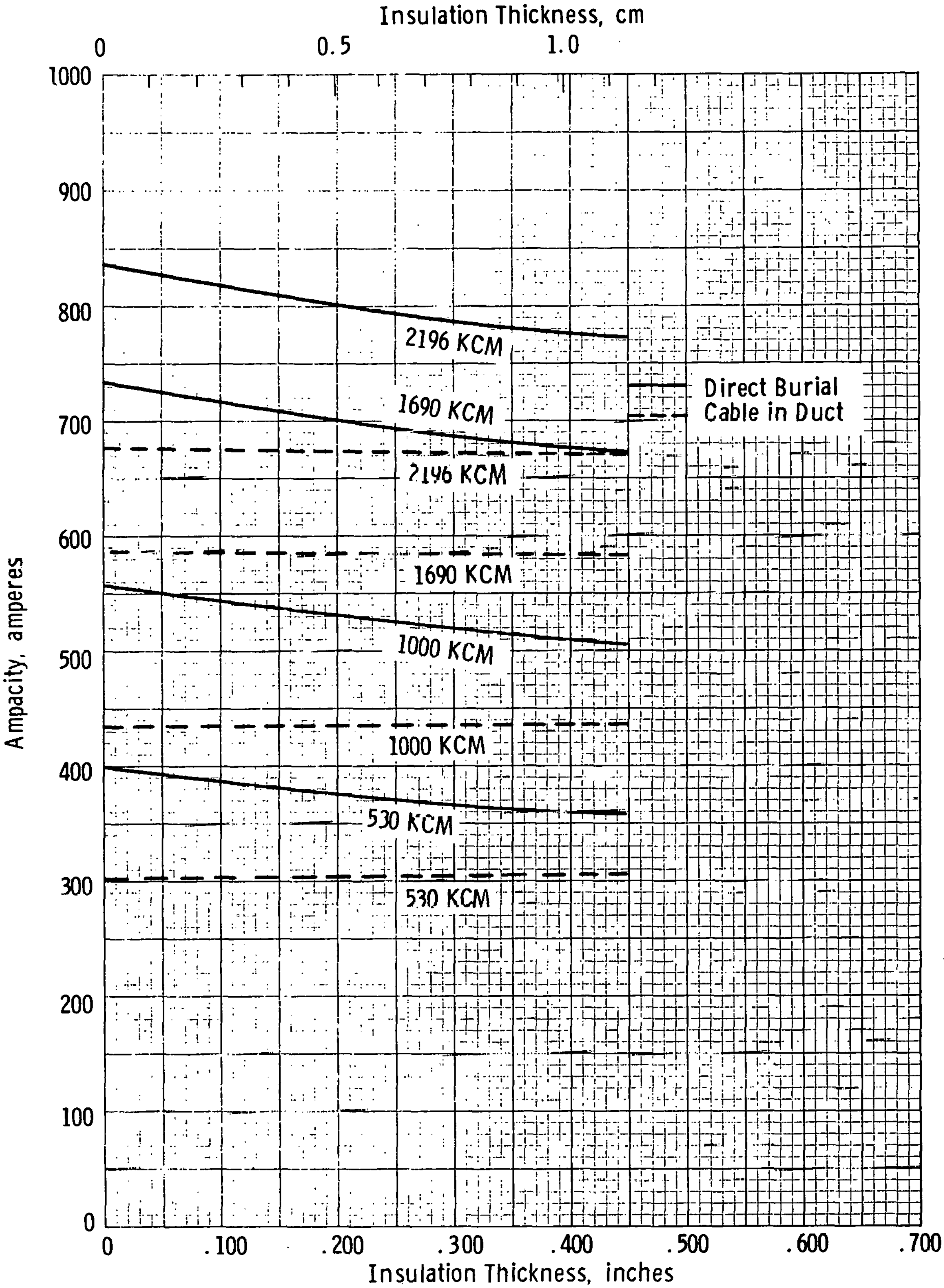

Fig. 7-2—Ampacity of sodium cable as a function of insulation thickness and conductor size

7.4 Description of Ampacity Calculation

The calculation of cable ampacity is rather complicated and depends on many variables. The procedure which is used here is based on the work of Neher and McGrath,[41] which has, since its publication in 1957, become the accepted standard of the cable industry. Because of its sound mathematical basis and wide industrial acceptance, this work has been adhered to as closely as possible in developing a set of equations for ampacity calculation. These equations were then tested by comparing their predictions for conventional aluminum and copper cable to the standard IPCEA ampacity tables,[16] with which they agreed excellently. Following this verification, the equations were used to determine sodium and aluminum equivalent cables. The following sections describe the calculations in detail.

7.4.1 Derivation of Basic Equations

The following procedure, like that of Neher and McGrath,[41] is based upon treating the cable system as a set of line heat sources, and calculating the cable current required to cause a specified temperature rise at the conductor as a result of the flow of the generated heat from the conductors, through the cable insulation, into the surroundings. It is conventionally assumed[39,41] that the earth surface is an isotherm at the ambient temperature, here taken as 20°C. Considering first the case of directly buried cable, it was assumed that within the cable all heat is generated in the conductor and flows radially and uniformly outward. Outside the cable, heat flow is as though from parallel line sources of strength Q and -Q watts/cm, located a distance h below and above a horizontal midplane respectively, in an infinite and thermally uniform medium. Then the midplane temperature T_o will be uniform and will be that of the medium far away. The midplane then represents the surface of the earth, and the heat flow below the midplane models the actual heat flow in the earth.

Referring to Figure 7-3, one defines:

Q = cable conductor dissipation, watts/cm

ρ_e = earth thermal resistivity, °C cm/watt

L = burial distance, earth surface to center of cable, inches

h = depth (inches) below earth surface of fictitious line heat source of strength Q which, with its image, generates circular isotherms coinciding with earth surface and cable surface

R = outer radius of cable, inches

The temperature rise δT above ambient at any point x,y distant d_1 from the lower heat source and d_2 from the upper (image) heat source is then given by

$$\delta T = \frac{Q\rho_e}{2\pi} \ln \frac{d_2}{d_1} \tag{7-5}$$

where

$$d_1 = \sqrt{x^2 + (y-h)^2} \text{ and } d_2 = \sqrt{x^2 + (y+h)^2} \tag{7-6}$$

Note that h is <u>not</u> the location of the cable center; the circular isotherm generated by this heat source and its image, and which represents the outside of the cable, is centered at a depth L slightly greater than h. It can be shown[39] that $h = \sqrt{L^2-R^2}$. Then for the particular case where y = L

$$\delta T = \frac{Q\rho_e}{2\pi} \ln \frac{[x^2 + (L + \sqrt{L^2-R^2})^2]^{1/2}}{[x^2 + (L - \sqrt{L^2-R^2})^2]^{1/2}} = \frac{Q\rho_e}{4} \ln \frac{x^2 + (L + \sqrt{L^2-R^2})^2}{x^2 + (L - \sqrt{L^2-R^2})^2}$$

Dwg. 6450A23

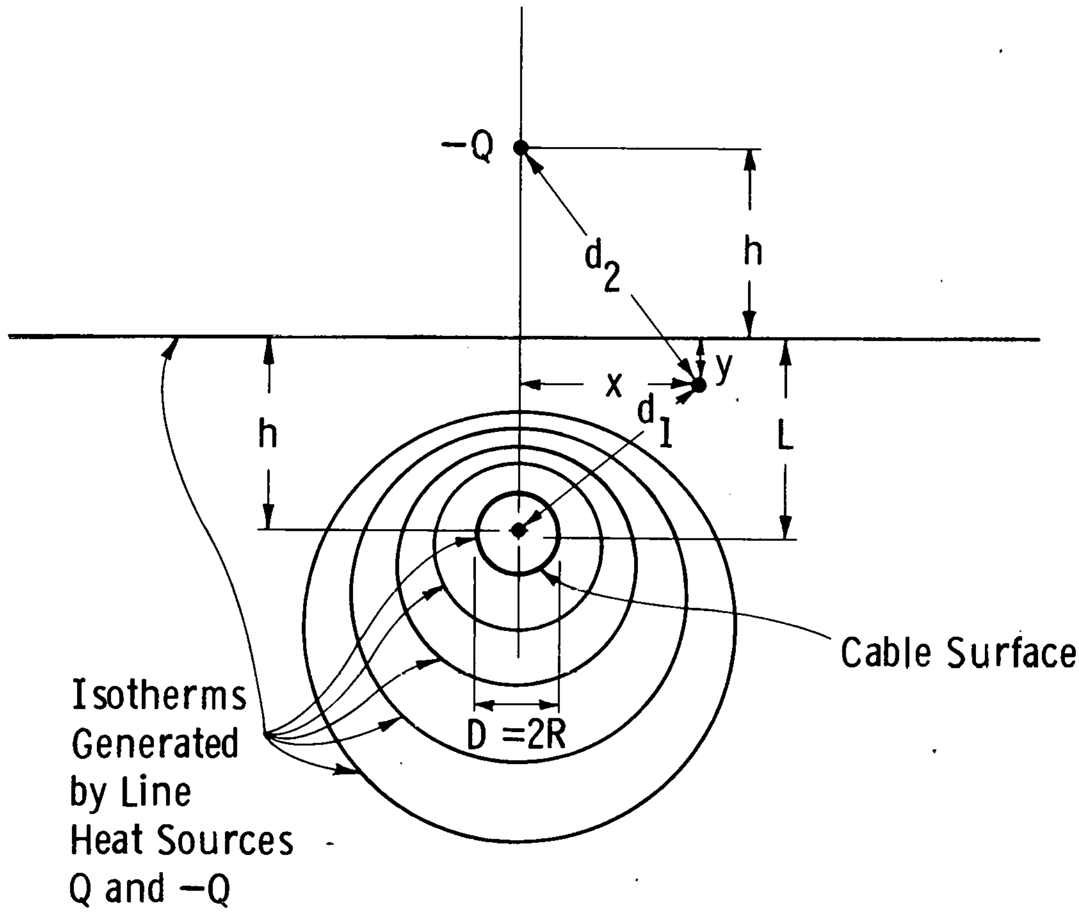

Fig. 7-3—Thermal geometry of a buried cable

For a three-phase group of three cables buried at equal depths L and separated by x, the rise δT_m (mutual heating) at the central cable caused by the heat from both outer cables will be twice this figure. To this must be added the rise δT_s (self-heating) caused by the heat from the central cable itself, which is

$$\delta T_s = \frac{Q\rho_e}{2\pi} \ln \frac{L + \sqrt{L^2 - R^2}}{R} \qquad (7\text{-}8)$$

Thus the total rise δT_{cs} at the surface of the central cable is given by

$$\delta T_{cs} = \delta T_m + \delta T_s \qquad (7\text{-}9)$$

This assumes that all three cables are identical heat sources of Q watts/cm. If losses in conducting shields are significant, this Q should be replaced by $(1+\alpha)Q$ where α is the ratio of shield losses to conductor losses.

Within the cable all heat is assumed to be generated at the conductor and to flow radially outward. (Because of the very low losses in polyethylene, dielectric heating can be neglected as in the IPCEA tables). The temperature rise δT_I (internal heating) from the cable outer surface to the conductor surface caused by this heat flow is given by

$$\delta T_I = \frac{Q\rho_i}{2\pi} \ln \frac{R}{r_1} \qquad (7\text{-}10)$$

where ρ_i is the thermal resistivity of the insulation in °C cm/watt, r_1 is the conductor radius in inches and R and Q are as defined earlier. The insulation thickness t_i is then given by $R-r_1$. In calculating δT_I, the insulation thermal resistance must include not only that of the electrical insulation but also that of the semiconducting shields at the conductor and at the cable outer surface, if these are present.

Since these are composed of a carbon-loaded polyethylene and have thermal characteristics essentially identical to those of the unfilled polyethylene, they are properly accounted for by taking the insulation thickness to include all three.

The total temperature rise δT of the conductor above the ambient (earth surface) temperature is then given by

$$\delta T = \delta T_m + \delta T_s + \delta T_I \quad \text{or} \tag{7-11}$$

$$\delta T = \frac{Q}{2\pi}\left[\rho_e\left\{\ln\frac{x^2 + (L + \sqrt{L^2-R^2})^2}{x^2 + (L - \sqrt{L^2-R^2})^2} + \ln\frac{L + \sqrt{L^2-R^2}}{R}\right\}(1+\alpha) + \rho_i \ln\frac{R}{r_1}\right] \tag{7-12}$$

The loss Q in watts/cm is in turn euqal to $10^6 I^2 R_{ac}$ where I is the current in amperes and R_{ac} is the conductor alternating-current resistance in microhms/cm. Then $I = \sqrt{Q/10^6\, R_{ac}}$, or

$$I = \frac{2\pi\delta T}{10^6\, R_{ac}}\left[\rho_e\left\{\ln\frac{x^2 + (L + \sqrt{L^2-R^2})^2}{x^2 + (L - \sqrt{L^2-R^2})^2} + \ln\frac{L + \sqrt{L^2-R^2}}{R}\right\} +\alpha) + \rho_i \ln\frac{R}{r_1}\right] \tag{7-13}$$

This is the relation used to calculate the ampacity for directly buried cable. Although the units of x, L, R, and r_1 were all specified as inches, they can equally well all be specified as cm in Equation 7-13.

The conductor resistance R_{ac} which is required for this calculation is greater than the direct-current resistance R_{dc} because of the phenomenon called skin effect, in which alternating currents in a conductor are crowded toward the outer surface of the conductor by the magnetic fields produced by the current. Because the effect depends on the rate of change of the magnetic field, it is a function of frequency. A rigorous mathematical treatment of this effect can be given for a solid round conductor [43], for this case, numerical results are given by Dwight in the Radio Engineers Handbook.[42] Values for conventional stranded conductors are given in the Standard Handbook for Electrical Engineers.[44] If the skin-effect ratio $\beta = R_{ac}/R_{dc}$ is plotted against the ratio of conductor cross-sectional area A to the dc resistivity ρ_{dc}, it is found that the curves for solid and stranded conductors are identical to within the tabulated accuracy, so that a single relation suffices for both. A plot of A/ρ_{dc} vs. $R_{ac}/R_{dc} - 1$, i.e., β-1, is given in Figure 7-4. Here A is in thousands of circular mils and ρ_{dc} in microhm cm. This curve applies, within its range, to both solid and stranded conductors of any material.

It is also necessary to know the relation between conductor radius and cross-sectional area. For solid conductors, this is just $A = 4000\ r^2$, where again A is in thousands of circular mils and r is in inches. For stranded conductors, the data given in the Standard Handbook for Electrical Engineers[44] are described very closely by the relation $A = 3016\ r^2$.

With these relations it is possible to write a simple calculator program for calculating ampacity. For this purpose it is convenient to have an analytical relation for the dependence of β on A/ρ_{dc} from Figure 7-4. This curve is very closely fit by the relation

$$\beta - 1 = 2.388 \times 10^{-7}\ x^2 \left[1 + \frac{0.6605}{\frac{x}{172} + \frac{172}{x}}\right] \qquad (7\text{-}14)$$

which was employed in our program.

It is also necessary to know the conductor dc resistivity as a function of temperature. For aluminum, the resistivity is taken as[45]

$$\rho_{Al} = 2.8624 + 0.0115\ (T-20) \qquad (7\text{-}15)$$

Curve 713171-B

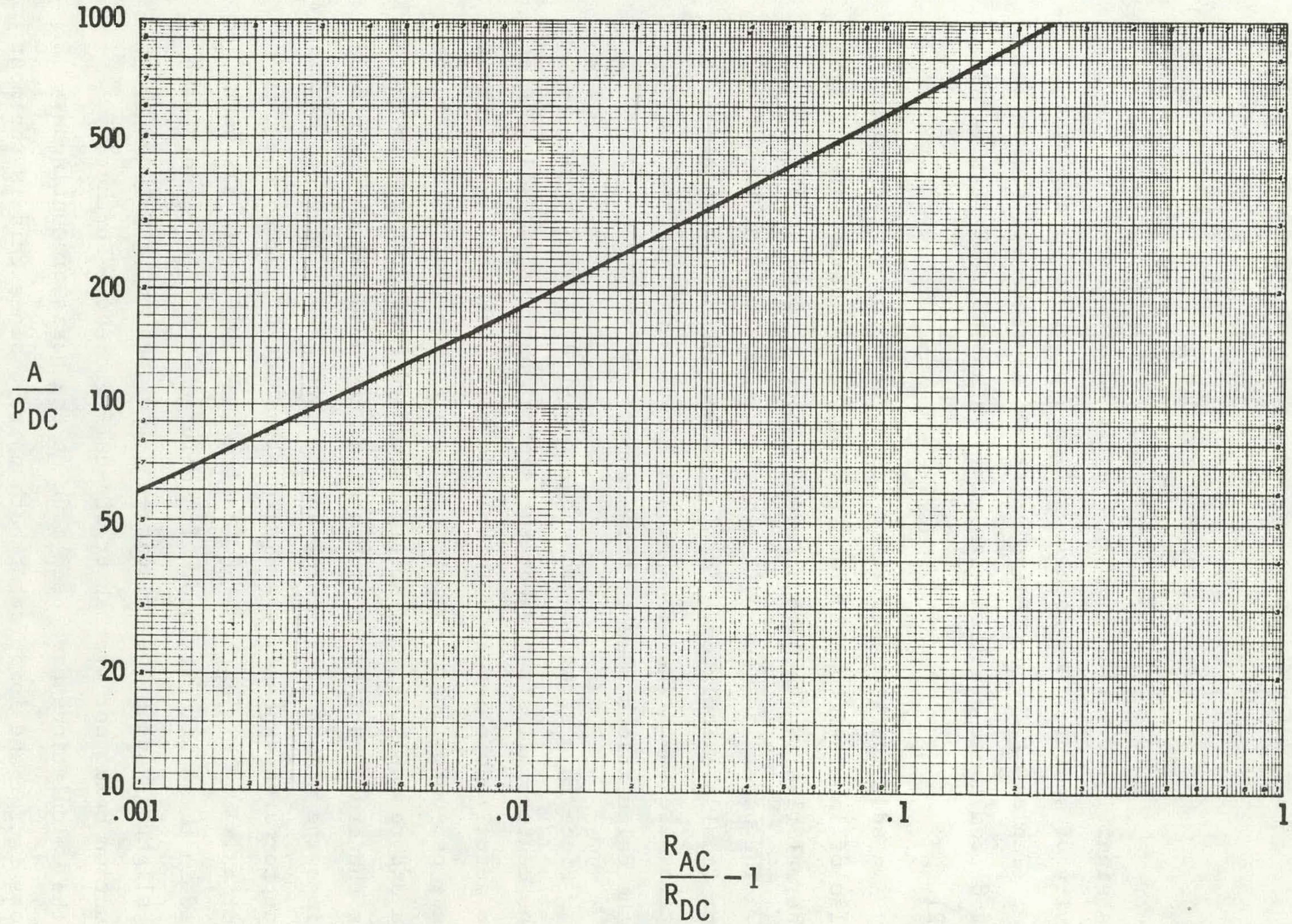

Fig. 7-4—Skin-effect @ 60 Hz for round wire or stranded cable vs. ratio of cross-sectional area A to resistivity ρ_{DC}

A in thousands of circular mils (KCM), ρ_{DC} in microhm cm where ρ is in microhm cm and T in °C. For sodium the resistivity is[46]

$$\rho_{Na} = 4.290 + 0.01993T + 9.848 \times 10^{-6} T^2 \qquad (7\text{-}16)$$

There is significant variability in the literature concerning the resistivity of sodium. The relation given appears to be the most reliable. Tables of the dc resistivities of aluminum and sodium as calculated from these equations are given in Appendix A3 (Tables A3-1 and A3-2).

In addition to calculating the ampacity of a given cable, it is also of interest to calculate the individual components of the total thermal rise, which have already been designated as δT_m, δT_s, and δT_I. The power loss per unit length, Q, in watts/cm, in the conductor is also calculated. The inputs and outputs for these calculations are summarized in Appendix A3 which contains tables of all of the calculations used in this report.

Since in a stranded conductor the strands wind helically about the center, all strands but the central one are somewhat longer than the actual cable length. This leads to a slightly higher actual resistance per unit length for stranded cable than that calculated on the area and resistivity (the area of stranded conductor is conventionally taken as the cross-section of each strand, taken normal to the strand axis, times the number of strands, and is thus less than would be the conductor area exposed by a single plane cut normal to the conductor axis). This correction, called the lay factor, has been neglected in these calculations. If included, its effect would have been to slightly reduce the ampacities calculated for stranded cable, the reduction being not over about one-half precent. Further, all of the calculations have been made on the basis of continuous load (loss factor and load factor both unity), since this is the most severe circumstance.

For cable installed in buried ducts, the calculation must be modified to include the thermal resistance of the duct walls and of the cable-to-duct air gap. Referring again to the direct-burial ampacity equation, it is evident that this can be considered as of the form

$$\delta T = Q \sum_k R_k \tag{7-17}$$

or

$$I = \sqrt{\frac{\delta T}{10^6 \; R_{ac}} \left[\sum_k R_k \right]^{-1}} \tag{7-18}$$

where the coefficients R_k are effective thermal resistances, relating the heat flow Q to the various thermal drops. In the cable-in-duct case, one now has for R_m (the thermal resistance relating Q to the thermal rise of the outside wall of the center duct due to the heat from the outer two cables) the relation

$$R_m = \frac{\rho_e}{2\pi} \ln \frac{x^2 + (L + \sqrt{L^2 - R_D^2})^2}{x^2 + (L + \sqrt{L^2 - R_D^2})^2} \tag{7-19}$$

where R_D is the outside radius of the duct. The thermal resistance R_s relative to the corresponding thermal rise due to the central cable is given by the relation

$$R_s = \frac{\rho_e}{2\pi} \ln + \frac{L + \sqrt{L^2 - R_D^2}}{R_D} \tag{7-20}$$

IPCEA (16) defines a standard duct as being 5, 6, or 8 inches inside diameter. The standard wall thickness for fiber duct is 1/4 inch. Minimum diametral clearance between cable O.D. and duct I.D. is specified as 3/4 inch, so that a 5-inch I.D. duct could accommodate a 4-1/4 inch O.D. cable. Since none of the cables considered in this report is that large, and since every new cable-in-duct installation is assumed to involve new duct as well, a 5-inch I.D. fiber duct of 1/4-inch wall has been assumed throughout, with a thermal resistivity of ρ_D of 480°C cm/watt. Again a burial depth of L = 36 inches and spacing of x = 7.5 inches has been assumed. With R_D = 2.75 inches, these values yield

$$R_s = 0.5194\ \rho_e \tag{7-21}$$

$$R_m = 0.7212\ \rho_e \tag{7-22}$$

where R_s, R_m, and ρ_e are all in °C cm/watt. The duct wall thermal resistance R_{dw} is a constant throughout the calculations since the duct is fixed; from Neher-McGrath[41]

$$R_{dw} = 0.0104\ \rho_D \frac{t}{D-t} \tag{7-23}$$

where ρ_D is the thermal resistivity of the duct material and D and t are the outside diameter and wall thickness. The foregoing values then yield

$$R_{dw} = 7.246 \tag{7-24}$$

For the cable-to-duct air-gap thermal resistance R_{ag}, Neher and McGrath[41] specify a semi-empirical expression which, for this duct, reduces to

$$R_{ag} = 30.48\ \left[\frac{17}{1 + R\ (4.84 + 0.0488T)}\right] \tag{7-25}$$

where R is, as before, the cable outer radius. The internal thermal resistance of the cable is the same as for direct burial. The ampacity equation for cable in duct then becomes

$$I = \sqrt{\frac{\delta T}{10^6 R_{ac}}} \left[(1+\alpha) \quad 1.2406 \rho_e + 7.246 + \frac{518.2}{1 + R (4.84 + 0.048 \delta T} + \frac{\rho_I}{2\pi} \ln \frac{R}{r_1} \right] \tag{7-26}$$

for the foregoing assumed conditions. In this equation R and r_1 must be in inches, because the numerical constants are not dimensionless.

For the cable-in-duct case, the program was written to calculate the same components of the thermal rise as were done for direct burial, and in addition the differences δT_{dw} across the duct wall and δT_{ag} across the cable-to-duct air gap. These results are included in the ampacity tables in Appendix A3.

7.4.2 Verification of Ampacity Equations by IPCEA Tables

Before applying these equations to sodium cable, it was felt desirable to compare their predictions for conventional aluminum and copper cables to the standard IPCEA ampacity values; this was done for 15 and 35 kV cable, of 1000, 750, 500, 350 and 212 KCM size, for assumed ρ_e values of 90 and 120°C cm/watt, for both direct and duct burial. A 100% load factor and no shield losses ($\alpha = 0$) were assumed. Results generally agreed with IPCEA values to within a percent or less; a table of the comparisons is given in Appendix A3. This close agreement indicates that ampacities calculated by the foregoing formulae are consistent with industry standards, and that they are reliable for the cases of this report.

7.4.3 Description of Procedure for Calculation of Equivalent Sodium Cable

With the previously developed ampacity relations, the process outlined in Section 7.1.1 can now be implemented. This was done for a matrix of sixteen cases each for direct burial and for duct; 600 volt, 15 kV, 25 kV, and 35 kV in sizes of aluminum conductor of 1000, 750, 350, and 250 KCM. For each case, the aluminum cable ampacity at normal load (conductor at 90°C, ambient 20°C, therefore $\delta T = 70$°C) and at overload (conductor at 130°C, δT = 110°C) was determined. The sodium conductor size required to give a conductor temperature of 95°C for the aluminum overload current was then found, and finally the conductor operating temperature was calculated for this sodium conductor at the normal-load aluminum current.

7.4.4 Choice of Shield Loss Factor, and Other Parameters

It was desirable to choose fixed values of some of the parameters, such as α and ρ_e, for the equivalence calculations. This then required that the sensitivity of the results to these choices be estimated. For α, it seemed reasonable and convenient to choose $\alpha = 0$ (open or ungrounded shields, no shield losses); for ρ_e, the generally-accepted value of 90°C cm/watt was chosen.[38,41] The effect of other choices for these parameters is discussed in Section 7.6. Ambient temperature was taken as 20°C, excepting for the calculations to verify the procedure against IPCEA tables where it was taken as 25°C as in the IPCEA tables. Burial depth and spacing were everywhere taken as 91.5 cm (36 in.) and 19.1 cm (7.5 in.), as specified by IPCEA.[16]

The insulation thicknesses for the sodium cable were chosen to be equal to those for the corresponding aluminum cable. This was done because, as stated earlier, these thicknesses appear to be mechanically sufficient, and because they satisfy IPCEA and AEIC electrical requirements. The IPCEA-AEIC thickness specification for outer semiconducting shield thickness was also followed for sodium, but no semiconducting conductor shield was assumed. This is because, as might be expected and as has been experimentally found, the sodium conductor surface is very smooth and tightly bonded to the polyethylene.[25] The conductor shield, whose purpose is to present to the inner surface of the insulation an electrically smooth and void-free conducting surface without stress-concentrating asperities, is thus unnecessary with sodium (see also Paragrph 7.7.1).

7.5 Results of Equivalence Calculations

This section discusses the results of the equivalence calculations, whose basis has already been described. Complete results of all calculated cases are tabulated in Appendix A3. Table 7-4 summarizes the results of these calculations. Several interesting conclusions which appear to be valid for all voltage and ampacity ratings are presented. In connection with the discussion of temperature distribution and power losses, it was also appropriate to consider molten sodium conductor operation, which has some properties quite different from those found with aluminum or copper conductors.

7.5.1 Tables of Equivalence Results

The results of the calculations described above show that the diameter of the sodium conductor corresponding to a given aluminum conductor is quite insensitive to the voltage classification or type of installation of the cable. Table 7-4 shows a summary of the cross-sections for sodium equivalent to 1000, 750, 350, and 250 KCM of aliminum, in 600V, 15 kV, 25 kV, and 35 kV ratings, buried directly or in duct, and also shows the ratio of the sodium cross-section to that of the aluminum. For the cases considered, this ratio ranges from 2.108 to 2.220. Thus follows the general conclusion that, with a 2-1/2 percent accuracy, the sodium cross-section equivalent to a given aluminum cross-section is 2.16 times that of the aluminum, independent of cable rating or installation.

7.5.2 Operating Temperatures at Thermal Full Load

The temperature at which the conductors of these equivalent sodium cables will operate at the normal full load current of the equivalent aluminum cable (conductor at 90°C) is also included in the table. Again it is observed that this number, 69°C, or 65°C for 600 volt cables, is practically independent of rating or installation, except that it is lower for 600V cables than for the others. One can conclude that, to within one-half degree accuracy, the conductor

TABLE 7-4

Summary of the Properties of Sodium Cable Compared to the Equivalent Aluminum Cable

Aluminum Area, KCM	Sodium	Direct Burial 600 V	Direct Burial 15 kV	Direct Burial 25 kV	Direct Burial 35 kV	Cable in Duct 600 V	Cable in Duct 15 kV	Cable in Duct 25 kV	Cable in Duct 35 kV
1000	Area, KCM	2196	2155	2149	2149	2220	2214	2214	2208
	Ratio to Al Area	2.196	2.155	2.149	2.149	2.220	2.214	2.214	2.208
	Normal Temp. Rise	45	49	49	49	44.5	48.5	48.5	48.5
	Power Loss Ratio to Al	.647	.736	.738	.738	.655	.720	.719	.721
	δ^2 Te	22.9	16.8	15.9	15.1	12.9	10.5	10.6	10.5
750	Area, KCM	1633	1608	1603	1598	1654	1649	1649	1649
	Ratio to Al Area	2.177	2.144	2.137	2.131	2.205	2.199	2.199	2.199
	Normal Temp. Rise	45	49	49	49	44.5	48.5	48.5	48.5
	Power Loss Ratio to Al	.643	.736	.740	.741	.654	.717	.717	.717
	δ^2 Te	22.5	16.4	15.5	14.8	12.4	10.2	10.1	10.1
350	Area, KCM	760	740	740	740	764	767	764	764
	Ratio to Al Area	2.171	2.114	2.114	2.114	2.183	2.191	2.183	2.183
	Normal Temp. Rise	44.5	49	49	49	44.5	48.5	48.5	48.5
	Power Loss Ratio to Al	.624	.739	.740	.744	.656	.715	.716	.714
	δ^2 Te	22.6	15.3	14.3	13.6	10.9	9.1	9.2	9.2
250	Area, KCM	542	530	527	527	545	548	548	545
	Ratio to Al Area	2.168	2.120	2.108	2.108	2.180	2.192	2.192	2.180
	Normal Temp. Rise	44.5	49	49	49	44.5	48.5	48.5	48.5
	Power Loss Ratio to Al	.623	.740	.741	.742	.655	.712	.714	.715
	δ^2 Te	22.4	14.9	13.9	13.1	10.3	8.8	8.8	9.0

operating temperature at rated current for the equivalent sodium cable (selected by our overload criterion) will be 65°C for 600V cable and 69°C for 15, 25, or 35 kV cable, regardless of rating or installation.

7.5.3 Temperature Distributions and Power Losses

It is also of interest to compare the power dissipated by the equivalent sodium cable at normal current (or at any other current) to that for the aluminum cable at the same current. This ratio is also given in the table; for the 600 volt cable it is between 0.623 and 0.656; for the higher-voltage classes it is between 0.736 and 0.744 for direct burial and between 0.712 and 0.721 for duct installations. Therefore, within about 2-1/2 percent error, one can conclude that, over the entire range studied, power dissipation losses in 600 volt sodium cable will be 64% of that in the equivalent aluminum cable, and for the higher voltages will be 73% of that in equivalent aluminum cable.

All of these conclusions are based on the assumption that the insulation thicknesses presently specified for aluminum cable will be mechanically strong enough for sodium. In view of the earlier calculations of Section 7.3.3, and of operating experience, this assumption appears reasonable. If thicker insulations are deemed necessary, the ratio of the equivalent sodium cross-section to the aluminum will increase. The amount of that increase can be readily determined from Figure 7-2, which shows the variation of ampacity with insulation thickness and conductor area. The first of these three conclusions will thus be modified. The other two, however, are essentially independent of insulation thickness, assuming of course that for each choice of thickness the sodium cross-section is chosen according to Section 7.1.1. Detailed calculations from which these conclusions are drawn are included in Appendix A3.

The distribution of the total temperature rise among the various cable components has already been discussed in Section 7.4.1. These temperature increments are, as noted, individually tabulated in Appendix A3. In this connection it may be noted that the "earth interface temperature" T_e, i.e., the temperature at the cable outer surface for direct burial or of the duct outer surface for cable in direct-buried ducts, is often of some concern. If too high, it results in a drying of the soil[16,38,39] and a resulting increase in the soil thermal resistivity ρ_e, thus causing further rise of temperature and possibly even thermal runaway. Because of the lower heat loss in the equivalent sodium installations selected, T_e is less and the problem of thermal runaway is therefore less severe. For either directly buried cable, or duct installation, one finds $\delta T_e = \delta T_m + \delta T_s$, where $\delta T_e = T_e - T_{ambient}$; the different $\delta^2 T_e = \delta T_{e\ Al} - \delta T_{e\ Na}$ is a measure of how much lower the earth interface temperature will be for sodium cable than for aluminum. This difference is also tabulated in Table 7-4. It will be seen that T_e is from 9 to 23°C lower for sodium than for aluminum, thus reducing the likelihood of thermal runaway.

7.5.4 Molten Conductor Operation

It has been recommended throughout this report that both normal and overload operation of sodium cable should occur with a solid conductor. All cable ratings have been calculated on that basis, reserving the heat of fusion of the conductor for the absorption of short circuit current or similar thermal transients. Occasionally, utility operation of cables at sustained overloads beyond the overload rating of the cable will occur[33,34]. The behavior of a sodium cable in this situation is quite different from that of an aluminum or copper cable. If the sodium cable is operating near but below its conductor melting point (e.g., at the overload ampacity as we have defined it), and if a moderate increase of current temporarily occurs, sufficient to melt the conductor but not to trip associated protective devices, the conductor will not resolidify when the current is reduced to its previous overload value. The sodium conductor will remain molten, and its temperature will rise to a new equilibrium value near 140°C. In order to resolidify the core, the current will have to be reduced below a steady-state value no more than 85 percent of the original overload rating. The aluminum or copper, on the other hand, will return to its overload temperature when the current returns to its overload value. This situation has been treated in detail by Hus.[29] One can easily establish the aforementioned temperature figures as follows. At normal overload ampacity, the sodium temperature is 95°C, just below the 97.8°C melting point. The heat flow from the I^2R losses to the surroundings generates a rise of 75°C above the 20°C ambient. Assuming that the same current is maintained after core melting by a temporary current increase, and that the thermal resistances of the surroundings do not change, one finds the higher resistivity of the liquid just above the melting point (9.6 Ω cm) to be 1.4 times that of the solid just below melting. Thus, the heat evolution, and temperature rise above ambient, will be 1.4 times as great, or 105°C, leading to a temperature of 125°C. The further rise in resistivity at this temperature, in turn, causes a still higher rise in temperature, and an eventual equilibrium temperature is reached at which the resistivity is in the same ratio to that of the solid just below melting as the ratio of the temperature rise is to 75°C. Values of the liquid-sodium resistivity from Sittig[47] are given in Table 7-5; from these this equilibrium temperature is simply found as about 141°C. In order to resolidify the sodium, the heat dissipation must be reduced to its previous overload value, but since the liquid sodium at the melting point will have a resistivity 1.4 times that of the original solid, the current will have to be reduced below the original overload current divided by the square root of 1.4, or about 85 percent of the original overload rating. This analysis makes the pessimistic assumption (in the case of three direct-buried cables in three-phase) that all three conductors melt, whereas in fact only the central one will melt, at least at first. However, the extra heat from the central cable will probably then melt the outer two as well. Temperatures of this order would almost surely result in failure of PE insulation with release of a quantity of sodium, although XLPE could probably survive such temperatures for a considerable time without rupture. Even though such a usage is well beyond the cable rating, its

TABLE 7-5

Resistivity of Molten Sodium at Various Temperatures

T °C	Liquid Sodium Resistivity, Ω cm
97.8	9.6
100	9.68
110	10.02
120	10.37
130	10.71
140	11.06

possible occurrence must be considered because of the different behavior of sodium cable. It should also be noted that while in the molten state, the sodium cable does not have the advantage of its heat of fusion for absorption of transients, and is in fact at a considerable disadvantage because of its higher resistivity when molten.

7.6 Sensitivity of Results to Changes in Assumed Parameters

Some examples were calculated to show the effect of variations in the selection of the cable or earth parameters, particularly α and ρ_e. For example, for 25 kV 1000 KCM direct buried aluminum cable, the radius of the equivalent sodium conductor is 1.862 cm (0.733 in.) for $\alpha = 0$, and 1.877 cm (0.739 in.) for $\alpha = 1$ (equal conductor and shield losses). From this consideration, it appears that the results will be essentially independent of the choice of α. These results are for ρ_e = 90°C cm/watt. For $\alpha = 0$ but ρ_e = 130°C cm/watt, the radius of the sodium is 1.869 cm (0.736 in.) rather than 1.862 cm (0.733 in.). These results suggest that the selected values of α and ρ_e are reasonable and that the equivalence results are not significantly sensitive to these choices. Sensitivity of ampacity to insulation thickness has already been discussed in Paragraph 7.3.6 and Figure 7-2. All of the remaining parameters are well specified, and sensitivity to variations in them is not relevant.

7.7 Possibilities for, and Consequences of, Thinner Insulation

This section explores the possibility of reducing the insulation thickness for sodium cable below the values specified by industry for aluminum cable, and considers the effects on electrical stress, thermal distribution, mechanical strength, ampacity, and moisture penetration, and the cost savings which might result. The general conclusion of these considerations is that appreciable reductions in thickness of insulation are probably permissible; it is not yet clear if the savings in cable cost, installation, and operation will be significant.

7.7.1 Electrical Stresses

The possibility of using thinner insulation on sodium cable is suggested by the observed fact that the surface of the sodium conductor in coextruded cable as manufactured by Nacon appears very smooth and tightly bonded to the polyethylene. There is therefore considerably reduced likelihood of voids between conductor and insulation or of electrical stress concentrations at the conductor surface such as are sometimes caused by mechanical damage to aluminum or copper conductors before their insulation is applied. Such voids are absent in sodium because the conductor is liquid at the time of cable manufacture, and because the sodium is soft and flexible to mechanical impact. For these reasons, as well as because of the stranded nature of aluminum and copper conductors, a semiconducting conductor shield of carbon-filled polyethylene is applied directly over the conductors of conventional cable. However, in addition to this extra cost and complication, this shield also causes its own electrical problems in the form of conducting protrusions into the surrounding insulation, caused primarily by die bleed at the face of the conductor shield die.[48] This process can also inject conducting clumps into the high-field regions of the insulation. This would not occur with sodium cable, which has no conductor shield. A recent study [48] on extruded-dielectric transmission cables listed the three most important factors in dielectric strength, in order of importance, as electrical smoothness of the conductor shield, conductive contaminants within the insulation, and voids within the insulation and at the insulation-conductor shield interface. Sodium cable has evident advantages on all three counts. It should further be noted that because sodium conductors are larger than their equivalents in copper or aluminum, the electric field at the sodium conductor will be somewhat less, typically 3 to 4 percent less.

A significant indicator of the electrical quality of the insulation in a cable is the corona onset voltage, the voltage at which internal partial discharges begin. The few data reported for sodium cable in the literature[25,39] give values typically 1.5 to 2 times the minimum specified by IPCEA. On the above basis, it is reasonable to expect that, insofar as electric strength is concerned, significant reductions in insulation thickness are permissible for sodium cable, perhaps to 65 percent of presently accepted values for aluminum and copper cables. Further measurements would be necessary to confirm this.

7.7.2 Thermal Distribution and Ampacity

The effect of a reduced insulation thickness on the thermal distribution would be to reduce the insulation thermal drop which has been denoted as δT_I. This assumes that the conductor cross-section and current were held the same. This would also result in a lower conductor temperature and resistance, and hence a small increase in ampacity for the same loss. Also, a larger increase in ampacity would result for the same (original) conductor temperature, or a smaller power loss for the original current. Thus, the conductor diameter might be decreased for the original current and temperature, or still other tradeoffs can be made. These effects will probably not be very large, however If the same conductor temperature is maintained, the effect of a reduced insulation thickness would also be to raise the earth interface temperature T_e slightly, although not to the values presently found in the equivalent aluminum cable. However, this rise would not be significant. As can be seen from the tables of Appendix A3, the insulation thermal drop δT_I is generally only a rather small part of the total thermal rise δT. Thus, moderate insulation thickness reductions will not alter the thermal distribution significantly nor will they significantly raise ampacities. For low voltage cables, especially the 600 volt class, δT_I is so small that even if it were eliminated entirely the increase in ampacity would only be of the order of 3%. For the higher voltage cables, the possible increases are not much greater, as is evident from Figure 7-2. It can be concluded that moderate insulation thickness reductions are permitted by thermal considerations and would yield small increases in ampacity.

7.7.3 Mechanical Strength

It has already been shown in Section 7.3 that if the ratio λ of insulation cross-section to total cable cross-section were at least 18 percent (insulation thickness at least 10.5 percent of the conductor radius), then PE insulation would provide sufficient tensile strength for duct installation in 240 m (800 foot) straight runs at a cable temperature of 49°C (120°F). In all of the cables tabulated in this report, λ is considerably above 18 percent, the closest case being the largest 600 volt cable (conductor radius 1.892 cm (.745 in.), insulation thickness 0.318 cm (0.125 in.), λ = 27 percent). A possible exception to this 18 percent figure was noted for large 600 volt cable at high installation temperatures, if the coefficient of friction of PE on the duct surface were to rise above 0.4. For the higher-voltage cables, the presence of concentric neutral wires will prevent insulation-to-duct contact so that the friction is not dependent on installation temperature. It appears that so far as tensile strength for installation is concerned, the insulation thicknesses for all of the high-voltage PE-insulated cables (15 kV or more) could be reduced considerably. For the tabulated thicknesses, the range of λ for those cables is from 38 percent to 76 percent, while, for the 600-volt class, λ ranges from 27 percent to 41 percent. Reduction of these to 30 percent would still leave a comfortable safety factor over the 18 percent necessary for installation strength.

7.7.4 Cost Savings

To the extent that the material cost of the insulation is a significant part of the total cost of the cable, it may be possible in the higher-voltage classes to make an appreciable saving by reducing insulation thickness. For the high-voltage cables, the insulation thickness specified by IPCEA(16) appears to be more than adequate for mechanical strength (since it has been concluded that for the same conductors, the much lower insulation thickness of the 600-volt class is mechanically adequate). If the projections of Paragraph 7.7.1 are realized, perhaps one-third of the insulation could be eliminated. This would also result in a somewhat lighter, smaller, and more flexible cable, which might reduce installation costs. However, until firm data on electrical and mechanical performance and installation become available, the matter remains speculative.

7.7.5 Moisture Penetration: Jacket Requirements

The subject of moisture diffusion through the PE or XLPE insulation was discussed in detail in Paragraph 7.3.5. It was concluded that earlier predictions by others[26] of 40-year life times for unjacketed cables were probably in error by virtue of their choice of an unrealistically low cable operating temperature (25°C). Typical expected lifetimes at a reasonable operating temperature of 65°C are 1 to 5 years. It was therefore recommended that all PE or XLPE-insulated sodium cable have a vapor-barrier jacket. With this provision, moisture resistance is no longer a determining factor in insulation thickness. Thus, if thickness reductions are permitted by other considerations, they may be carried out.

The proposed jacket will be entirely responsible for moisture protection of the cable. Such protection is certainly attainable by a metallic foil covering which is so thin that it is completely insignificant in the thermal analysis. Such a foil barrier would require a mechanically protective covering, for example of PE or PVC, but this can also be negligibly thin as shown by the thermal analysis in Figure 7-2. Even if the barrier is to be furnished entirely by a plastic jacket, it is probable that this will have only a small effect on cable ampacity.

7.7.6 Other Materials

Insulations other than PE or XLPE have not been discussed in this report because these are the only ones with which sodium cable has yet been manufactured. Other possibilities which might be considered are butyl rubber, and ethylene-propylene rubber (EPR) or terpolymer.

These have been widely used as cable insulation, and are reported[18,19] to have less permeability to water vapor than PE (quoted relative values, in gm mils/100 in^2 day at 25°C, are butyl rubber at 0.04 and EPR at 0.18 compared to PE at 0.30). It is possible that butyl rubber might be sufficiently impermeable to permit its use in an unjacketed cable which would still have an acceptable service life (compare Paragraph 7.3.5). This cannot be decided without data on moisture permeability at higher temperatures. It would also be necessary to determine whether adverse chemical reactions might occur with the sodium, especially if molten, or with sodium hydroxide formed at the sodium surface by whatever moisture diffusion occurred. There is also evidence[50] that water vapor transmission through some polymers is greatly enhanced by electric fields of the magnitudes found in cables, although this did not appear to occur for polyethylene. Other information and further reference on water vapor permeability of polymers are given in References 36 and 37.

7.8 Connectors

The most critical technical needs for the implementation of sodium cable appear to be in the development of connectors. Two general types of connectors have been made; one[28] had an auger-shaped bit which was screwed into the sodium, while the other[53] employed a cylindrical element with a conical point which was pushed into the sodium without rotation. Opinions of the utilities[54-58] who tried these were quite varied. Some reported that the connectors were quite satisfactory while others felt that major developments were still needed. Primary concern in the present report is the cable itself, and the design of connectors was not addressed. However, the nature of sodium cable generates connector requirements which are not shared by conventional cable, and it appears appropriate to denote those requirements here.

7.8.1 Availability

The Burndy Corporation, Norwalk, Connecticut, in cooperation with the Union Carbide Corporation, developed connectors[16,17] for the sodium cable produced by the Nacon Corporation. These connectors were manufactured by Burndy in the late 1960's and distributed through the normal Burndy representatives. The manufacture of sodium cable connectors was discontinued by the mid 1970's and these connectors are no longer available commercially. Several utilities with large quantities of installed sodium cable still have a small inventory of connectors for their own use. The Utility Survey (Section 5.2) indicated, however, that most utilities have very few, if any, sodium connectors in stock. The lack of availability of these connectors is a major concern to many of the utilities with sodium cable in service.

7.8.2 Cost

This section summarizes a detailed cable connector cost analysis which appears in Section 9.3.5.

The expense of connectors associated with the sodium cable installation in the 1966-1969 period were a frequently cited source of concern in the Task 1 Survey. It is also recognized that these first sodium connectors (see Figure A5-3) were hastily designed and were not cost-improved in any measure. In our comparison of connectors, some might argue that optimized and cost improved aluminum designs are being compared to prototype sodium designs. While this is true, the connector data and costs available at present preclude any other analysis. The connector systems used in this cost comparison could be available now with very minor design modifications.

There are two basic facts which imply that sodium cable connectors might be more expensive than those for aluminum cable even with an improved design. The first involves the low tensile strength of the sodium metal. Relatively complicated designs (Figure A5-7) are needed to take advantage of the strength of the insulation in making connections. This is especially a concern in 600V secondary and service applications where "standard aluminum practice" involves tightening an Allen type set screw directly against a stranded aluminum conductor (Figure A5-4). The second fact is that since sodium and aluminum react, copper is most probably required in even the improved designs. Just on a materials cost basis, this results in a 25% cost penalty over aluminum.

For an aluminum cable system, deadbreak type elbow connectors similar to those shown in Figures A5-1 and A5-2 might be used. In calculating these costs, list prices were used for the various size connectors as given below:

Voltage	Size	Deadbreak Elbow Connector Cost
15 kV & 25 kV	250-400 MCM	$ 42.50 each
	500-1000 MCM	$ 94.00
	1000-1500 MCM	$141.00
35 kV	250-400 MCM	$ 85.50
	500-1000 MCM	$169.40
	1000-1500 MCM	$254.10

These costs were allocated over a total of 2 miles (10,560 ft) of three phase primary feeder circuit to obtain per foot costs for aluminum cable. For the sodium cable system "copper pin type" connectors similar to those shown in Figure A5-3 and A5-7 were assumed to be used. The copper rod or pin extension of the sodium conductor was then used with a standard loadbreak elbow connector as in the aluminum cable connections. These "copper pin type" connectors were priced by comparing their size, weight and conductor termination with a price list for similar copper connectors shown in Figure A5-6. Thus the sodium per foot connection costs were increased over the aluminum by the cost of a "copper pin type" connector. Sodium cable connectors were found to be approximately 0.5-3.0 cents per 3ϕ foot more expensive than aluminum cable connectors for 3ϕ primary feeder.

While it is recognized that splice costs would also be higher for sodium than aluminum, these costs have been neglected. The number of splices would be considerably less than the number of connections and would not alter the comparative economics significantly.

For single phase laterals, a connector cost analysis for 12 customers per pad-mounted transformer and 37.5 KVA per transformer resulting in 14 transformers per lateral and a total lateral length of 5400 ft was performed.

Two "loop through" type primary connections were used at each transformer with two connections at the switch tie point to the primary feeder. This resulted in 26 connections per lateral. Deadbreak elbow connectors were used for the aluminum and "copper pin type" connectors with elbow connectors for the sodium. The resulting per unit length costs showed sodium cable connectors to be 0.7 to 5.0 cents per foot more expensive than aluminum cable connectors for single phase laterals.

Costs for both aluminum and sodium connectors were estimated based on list prices from Reference 80 as shown below:

600V Secondary-Service

Size	Aluminum Connector Costs ($ ea.)	Sodium Connector Costs ($ ea.)
250 MCM	$ 2.15	$ 3.70
350	$ 2.48	$ 4.35
750	$ 6.24	$11.45
1000 MCM	$12.50	$23.28

The costs on a per unit length basis showed sodium connectors to cost roughly double that of aluminum connectors. Many more connections are made in the secondary-service system than in the primary system on a per unit length basis. This results in a cost penalty for sodium connectors that negates the savings made in the cable itself for the secondary service system (see Section 9.3.5).

7.8.3 Ease of Installation

Installation of connectors on sodium cable requires cutting off the end of the cable to expose new unoxidized sodium. First generation Burndy connectors utilized a copper cork screw that threaded into the soft sodium core. The joint was sealed by compressing the outer sleeve of the cork screw assembly with a standard compression tool. Although this type of connector was adequate electrically, the cost was relatively high; therefore a second generation connector was developed.

The second generation connector was constructed of a pointed copper rod with a lug attached to the end. The penetrator rod was installed by first threading a thermoplastic fitting into the ID of the sodium cable insulation, then driving the penetrator into the sodium by threading a thermoplastic nut onto the fitting. The cost of this connector was lower because less copper was used and installation was claimed to require only a pair of pliers and a wrench.

The extra safety precautions required (i.e., safety glasses and leather gloves) and disposal of the scrap sodium ends was claimed by some to be a nuisance. Other installation groups claimed that the ease with which the cable could be cut, its lightweight, and its flexibility made terminating sodium cable easier then aluminum cable. See Section 5.2 for results of the Utility Survey.

7.8.4 Reliability Requirements

A satisfactory connector for sodium cable must be reliable in several respects, particularly regarding mechanical strength, watertight integrity, electrical continuity and thermal stability. These will be discussed in turn, although all are closely interrelated.

a. Mechanical strength. It is not likely that cable connectors will intentionally be subjected to large long-term mechanical forces, but it must be anticipated that situations may occur where a connector is inadvertently put into long-term tension or bending. Because of the softness and chemical reactivity of sodium, it is important, much more than in the case of copper or aluminum, that the connector not transmit stress to the conductor nor expose it to atmosphere. It must therefore maintain a firm mechanical contact with the insulation.

b. Watertight integrity. Ingress of water into the connector may lead to failure either by high-voltage breakdown across wet insulator surfaces, or by chemical reaction with the sodium conductor at the termination. It is therefore essential that the connector remain watertight, or more specifically, that it not permit water to reach either the sodium conductor or the electrically-stressed surface of the insulation at the end of the cable between conductor and outer insulation shield.

c. Electrical continuity. Because of the softness and low mechanical strength of sodium, it is necessary that the connector make reliable electrical contact to the sodium without subjecting the sodium itself to tension, or indeed to any forces excepting compression. Corkscrew connectors of the type originally made by Burndy Corporation[28] would appear to be a good design concept from the point of view, since the insertion of the corkscrew not only provides a large surface area of contact to the sodium but also puts the local sodium into compression, any tensile forces being almost all carried by the insulation. In their paper on these connectors, Matthysse and Scoran[28] note the necessity for suitable surface treatment of the screw to maintain a low electrical contact resistance; the nature of this treatment is described elsewhere as the application of a mercury coating. In selection of the screw material, consideration should be given to the possibility that some metals may, promptly or slowly, form alloys with the sodium at the contact surface. Such alloying occurs, for example, with the mercury coated surface described above. It is not clear whether such alloying will always be desirable, but its effects on conductor performance may be significant. Copper, however, has shown excellent long-term compatibility with sodium at ambient temperatures.

d. Thermal stability. It is clear that all of the foregoing requirements must be maintained over the limits of the operating temperature range, including the effects of thermal cycling. Matthysse and Scoran[28] have described a series of thermal tests made on two versions of screw-type connectors, and have noted the need for a NEMA standard to apply to this case. Their results suggest that adequate performance can be obtained with such connectors, although further development and testing are needed.

7.8.5 Corona Performance

For cables of sufficiently high voltage, above about 5 kV, care must be taken to insure that the cables and connectors are free of corona (partical discharges). These discharges appear when gas-filled spaces, such as voids in the cable insulation or exposed insulation surfaces at the termination, are highly electrically stressed. Such discharges are undesirable because they locally erode the insulation and may ultimately cause failure, and because they locally erode the insulation and may ultimately cause failure, and because they cause radio interference. There is little discussion of, or data on, discharges in sodium cable connectors. This aspect must be considered in the design of connectors for high-voltage cable, although this problem is not likely to occur in 600 volt cable. It is probable that a connector of the type described by Matthysse and Scoran[28] can be made corona-free (the voltage rating of the one they describe is not specified, but was later identified as 600 volt). The termination which they show makes electrical contact to the sodium while isolating it from the atmosphere, and the problem of preventing corona over the insulation surface from the termination to the end of the stripped-back semiconducting shield is not significantly different than for aluminum cable connectors (for which the corona problem has been solved). It is thus expected that corona-free connectors can be readily designed for sodium conductor cable but it will be necessary to verify the corona performance by test.

7.9 Conclusions for Electrical Performance

This section summarizes the significant comparisons between the electrical performance of sodium cable and conventional cable, and the technical developments yet needed for the practical implementation of sodium cable.

7.9.1 Overall Electrical Comparison: Sodium vs. Aluminum

On the basis of the electrical performance of an aluminum cable compared to its sodium cable equivalent, as defined in Paragraph 7.1.1, the sodium cable appears to be equal to or superior to the aluminum cable. The ampacities at normal load and at overload are, be definition, equal. The normal-load resistance of the sodium cable is lower than that of the aluminum; for all of the cables studied in this report, the ratio R_{Na}/R_{Al} is 0.65 to 0.66 for 600 volt cable and 0.71 to 0.74 for all others. This results in less voltage drop at houses serviced by these cables, and (in the same ratio) less resistive power loss in the cables. The corona performance and voltage endurance of these cables would be expected to be excellent because of the very smooth surface of the sodium and its intimate bond to the polyethylene. This expectation is supported by observed corona data,[25,37] although the necessary definitive voltage endurance tests have not yet been reported.

A situation in which sodium cable behaves differently from aluminum or copper is that of sustained heavy overload, leading to conductor melting.[25,29,31,33,34] Paragraph 7.5.4 described the bistable nature of this case, and probable consequences of such operation. This circumstance is far in excess of the cable rating, and failures in such a situation should probably not be blamed on the cable; nonetheless such overloads do sometimes occur in the course of utility operation, and sodium cable behavior in such a case should be considered.

7.9.2 Remaining Electrical Requirements for Sodium Implementation

The major remaining requirement for implementing the use of sodium cable is, by far, an assurance of the availability of satisfactory connectors. The connector status has been described in Section 7.8. Opinion of utilities on the merits of the two connector designs which have been manufactured has been divided. Agreement has been universal that sodium cable will not see significant use until suitable connectors are not only designed and manufactured at an acceptable cost, but are assured available in the future. This assurance of availability is at least as important as the connector performance.

The other area in which development is still required is that of a vapor-barrier jacket for sodium cable. Such a jacket has not been present on the sodium cable so far manufactured. As detailed in Paragraph 7.3.5, a 40-year service life may be unlikely without it. It is still to be shown that a suitable jacket can be provided at a competitive cost. The presence of such a jacket will of course have some bearing on connector design as well.

8. ENERGY AND MATERIALS IMPACT

A comparison of the energy expended to obtain cable materials was performed. The energy expended to mine, refine, and create cable feed stocks was evaluated. Although these energies were found to be fractions of the total energy lost during cable operation (i.e., I^2R losses) for the projected cable lifetimes (25 years), a review of their comparative values is presented. Also, long term projections of base material availability and costs were made.

8.1 Energy Requirements of Cable Material

Several sources were searched for recent information concerning energy expended to obtain refined feedstock material for cable manufacture. Computer library searches of NTIS and EI sources using keywords such as sodium, copper, aluminum, plastics, polyethylene and intersecting them with energy consumption, energy demand, energy accounting, production, manufacturing, industry, etc. failed to yield major references with the information sought. Telephone discussions with various industry associations:

Society of the Plastics Industry
Society of Plastics Engineers
Copper Development Association
Aluminum Association, etc.

were surprising in that none could supply the information sought. Several organizations had on-going active search projects in this area, but had not completed their compilations. Telephone calls to several manufacturers found them to be cooperative and interested, except that energy expended to obtain various cable materials or expended in various fabrication processes were deemed proprietary, and were thus unavailable.

Library and journal searches were used to assemble the data presented in Table 8-1. As can be seen, the data in Table 8-1 was compiled from many sources. Energy expended to obtain raw feedstock was presented in Btu/lb, Btu/ton, kW(t)hr/ton , kWh(e)/ton, etc. An effort was made to reduce all of the data to a comparative baseline, or reference energy units. Good agreement was found for aluminum between data from the U.S. Bureau of Mines,[59] Banbury Conference,[60] Underground Cable Corp.,[61] Battelle Memorial Institute,[62] and Copper Development Association.[63] Similarly, good cross comparisons were found for copper (refined) from the same sources. Values for sodium metal, as produced by Downs cells, as found in references 64 and 65 were in good agreement with the U.S. Bureau of Mines data[59] and with industry sources.[66]

Extreme problems were encountered in determining the energy expended to manufacture polyethylene into a form amenable to cable fabrication. Several references[61,62,63] chose to include the energy content (i.e., combustion energy) with the energy expended for manufacture. This was argued against by Roberts[60] on the premise that the energy content was still recoverable through combustion. Most sources followed this tenet.

Variations in the data in Table 8-1 were found to be large in several cases and can be attributed to several factors: (1) Some data includes recycle of materials. There is an internal process plant scrap recycle, as well as an external recycle. (2) The efficiency of plant in each data base may vary depending on the process used, type of fuel consumed, plant operating practice. (3) As ore grades vary (deplete), the amount of energy expended to refine the mineral becomes greater (i.e., - more energy intensive and thus costly). (4) Some data bases will include energy costs for mining, drilling, and transporation, as well as for processing and manufacture.

Table 8-2 summarizes the findings of Table 8-1, and presents the information necessary to calculate the energy expended to obtain feedstock materials for each unit length of cable manufactured.

TABLE 8-1

Energy Expended to Obtain Materials

	U.S. Bureau Mines [59]	Banbury Conference [60]	Underground Cable Corp. [61]	Battelle to U.S. Bur. Mines and to Copper Dev. Assoc. [62] [63]	Other
Aluminum (Al-ingot)	244×10^6 Btu/ton				
(50% bauxite ore Bayer Process)	(71.5×10^5 W(t)hr/ton)	80×10^6 W(t)hr/ton	(64×10^6 W(t)hr/ton)	(68.4×10^6 W(t)hr/ton)	
			16×10^6 W(e)hr/ton	17×10^6 W(e)hr/ton	16.4×10^6 W(e)hr/ton [67]
Copper (Cu-refined)	112×10^6 Btu/ton			(95.6×10^6 Btu/ton)	80×10^6 Btu/ton [66]
(1-1/2% ores)	(32.8×10^6 W(t)hr/ton)	16.5×10^6 W(t)hr/ton		28×10^6 W(t)hr/ton	
Sodium (Na-metal)	92×10^6 Btu/ton				
(Downs Cells)	(26.9×10^6 W(t)hr/ton)		(32×10^6 W(t)hr/ton)		40×10^6 W(t)hr/ton [66]
	(~ 7×10^6 W(e)hr/ton)		8×10^6 W(e)hr/ton		16.5×10^6 W(e)hr/ton [64]
					9.6×10^6 W(e)hr/ton [65]
Polyethylene (PE)		12×10^6 W(t)hr/ton		44.6×10^6 W(t)hr/ton (PUC)	7×10^6 W(t)hr/ton [68]
			12×10^6 W(e)hr/ton		

NOTE: Btu/ton x $2.93 \times 10^{-4} \frac{kW(t)hr}{Btu}$ = kW(t)hr/ton

kW(t)hr ÷ 4 = kW(e)hr

Metric Ton x 2204.6 = lbs (avoir)

TABLE 8-2

Data to Calculate Energy Expended to Obtain Feedstock Materials for Cable

Material	Energy Expended to Obtain (kW(e)hr/ton)	Density (lb/in^3)
Aluminum	16,500	0.102
Copper	7,500	0.323
Sodium	8,250	0.034
Polyethylene	3,000	0.034

8.2 Energy Expended per Length of Cable

The information presented in Table 8-2 was used to calculate the energy expended to obtain feedstock materials for each foot of cable. Table 8-3 presents the dimensions for the equivalent sodium and aluminum distribution cables that were compared. The energy expended for materials per unit length of cable was then found by calculating the volume of each material per foot of length, and then multiplying by the density and energy expended per unit weight in order to obtain energy values for each feedstock material. These calculations are summarized in Table 8-4 and illustrated in Figures 8-1 (a and b).

8.3 Energy Requirements and Savings

As can be seen in Table 8-4, for all cases, the energy expended to obtain feedstock materials for sodium cable is roughly one-third of that needed for aluminum cable. Although the sodium conductor is larger for equivalent cable, it requires less energy for its refining and it does not use insulation for shield or conductor; thus the savings. The savings in energy expended for equivalent sodium conductor cable over aluminum conductor cable is never greater than 8 kWhr(e)/ft.

Section 9 of this report describes the economics of sodium vs. aluminum conductor cable and shows that for 35 kV cable, the difference in losses between the two equivalent conductors is approximately 790 kWhr(e)/ft for 20 years service at rated loads. Thus, over the cable rated lifetime, 1% of the savings in losses would equal the savings in energy expended to obtain feedstock if one used sodium conductor cable over aluminum. The energy expended to obtain sodium cable materials over aluminum cable materials is far less than the energy of losses saved by selecting equivalent sodium conductor cable over aluminum conductor.

The energy expended for materials is also a minor consideration when you increase the conductor diameter from 250 kc mils to 1000 kc mils in all three kV ranges. The resulting increment in energy expended is 10 kWhr(e)/ft for aluminum, or 3 kWhr(e)/ft for sodium. Yet the savings in reduction in losses is considerably greater. This is described in greater detail in Section 9.

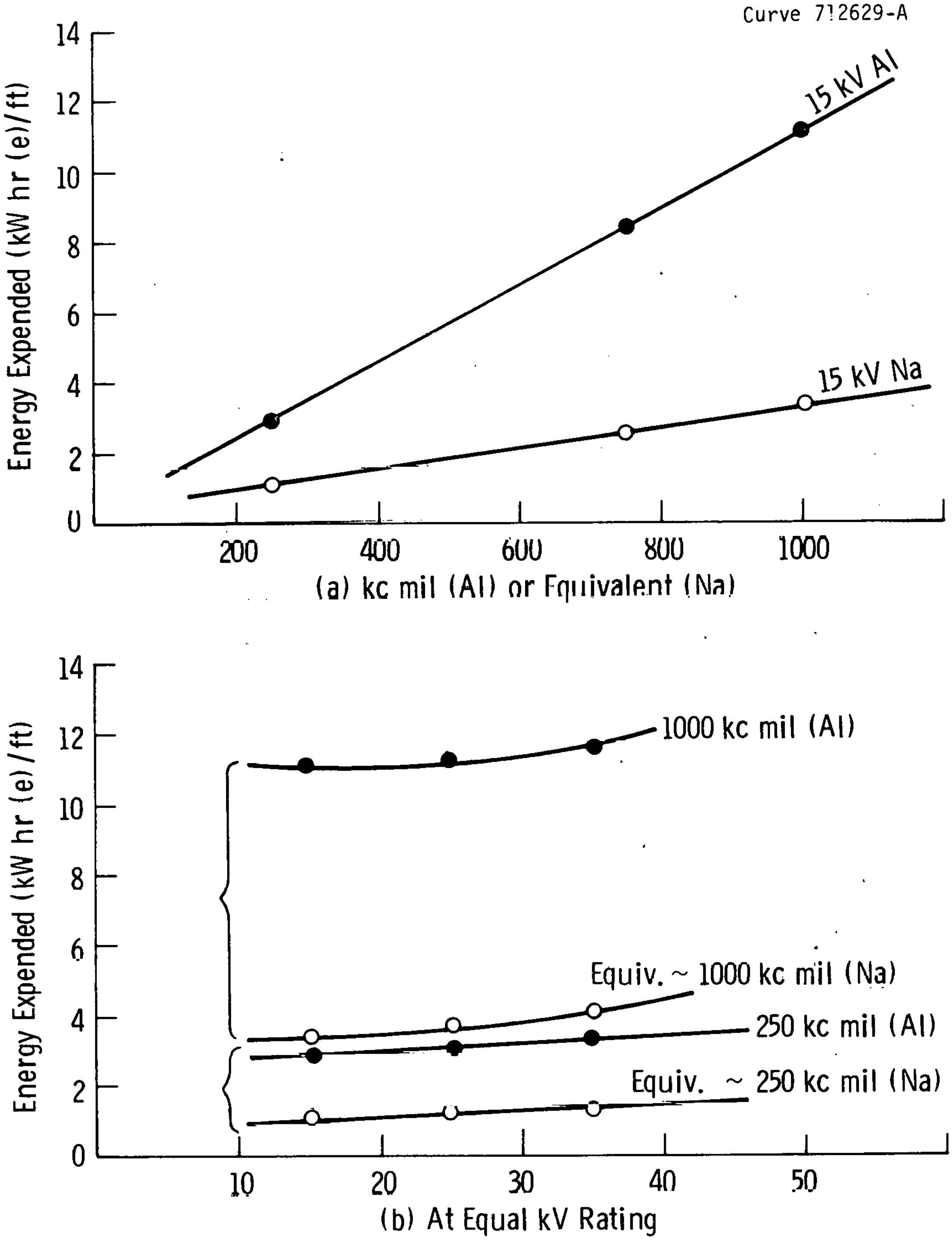

Fig. 8-1 — Relationship of energy expended to obtain materials for sodium vs. aluminum conductor cables

TABLE 8-3

Comparison of Equivalently Rated Aluminum and Sodium Cable to Obtain Energy Expended for Materials

Cable Conductor	Al			Na		
Rating (kV)	15	25	35	15	25	35
Conductor Shield (in)	.015	.015	.015		None	
Insulation Shield (in)	.030	.030	.030		None	
Insulation Thickness (in)	.175	.260	.345	.175	.260	.345
Conductor Radius (in)						
250 kc mil		.288			.365	
350		.340			.430	
750		.498			.634	
1000		.576			.734	

TABLE 8-4

Comparison of Energy Expended for Base Materials for Aluminum and Equivalent Sodium Cable

Energy Expended in kWhr(e)/ft

Cable Equivalence (kc mil)	Cable Material	Cable Rating 15 kV	25 kV	35 kV
250	Al	2.97	3.15	3.35
	Na	1.00	1.18	1.40
750	Al	8.38	8.63	8.91
	Na	2.61	2.88	3.19
1000	Al	11.10	11.37	11.68
	Na	3.39	3.70	4.04

A comparison of the energy expended to manufacture the two cables from their feedstock materials has been done indirectly in Section 9. These values are reflected in the direct cost and cost of losses curves, since these first costs (direct) include energy costs (i.e., are largely energy costs).

8.4 Materials Availability and Long Term Market Projections

There appears to be little immediate concern over the availability of copper, aluminum, or sodium for the balance of this century.[59, 60,69] Aluminum makes up about 8 percent of the earth's crust. However, the bauxite ore from which the metal is processed is found in only a limited number of places. World reserves of bauxite have increased considerably over the last two decades. Present Australian reserves alone are equal to the known total of the earth in 1950.[69] A recently announced new Alcoa smelting process indicates reduction in energy requirements to refine aluminum of up to 30 percent.[70] Within the next few decades aluminum is expected to be smelted in a wider variety of plants than at present. The newer processes (Toth[60] and Alcoa[60,70]) may be operating on a large scale, providing a considerable savings in electrical energy compared with the Hall-Heroult process. Predictions are that as good quality bauxite ores become scarce and are exhausted (Figure 8-2) use of the more plentiful resources of anorthosite and clay type minerals will occur. No increase in energy consumption per unit output is projected.[60] Alcoa has recently purchased 8000 acres of land in Wyoming with a deposit of anorthosite that is larger than all of the world's bauxite reserves combined.[69]

Copper constitutes only one part in 20,000 of the earth's crust, yet ranks third in industrial importance.[69] Up to now, discoveries of new copper deposits have kept pace with demand. Although uncertainty clouds the future reliability of high grade copper ores in Chile, Zambia, and Zaire, much low grade ore is being developed in British Columbia, Panama, Bougainville, etc. The United States,

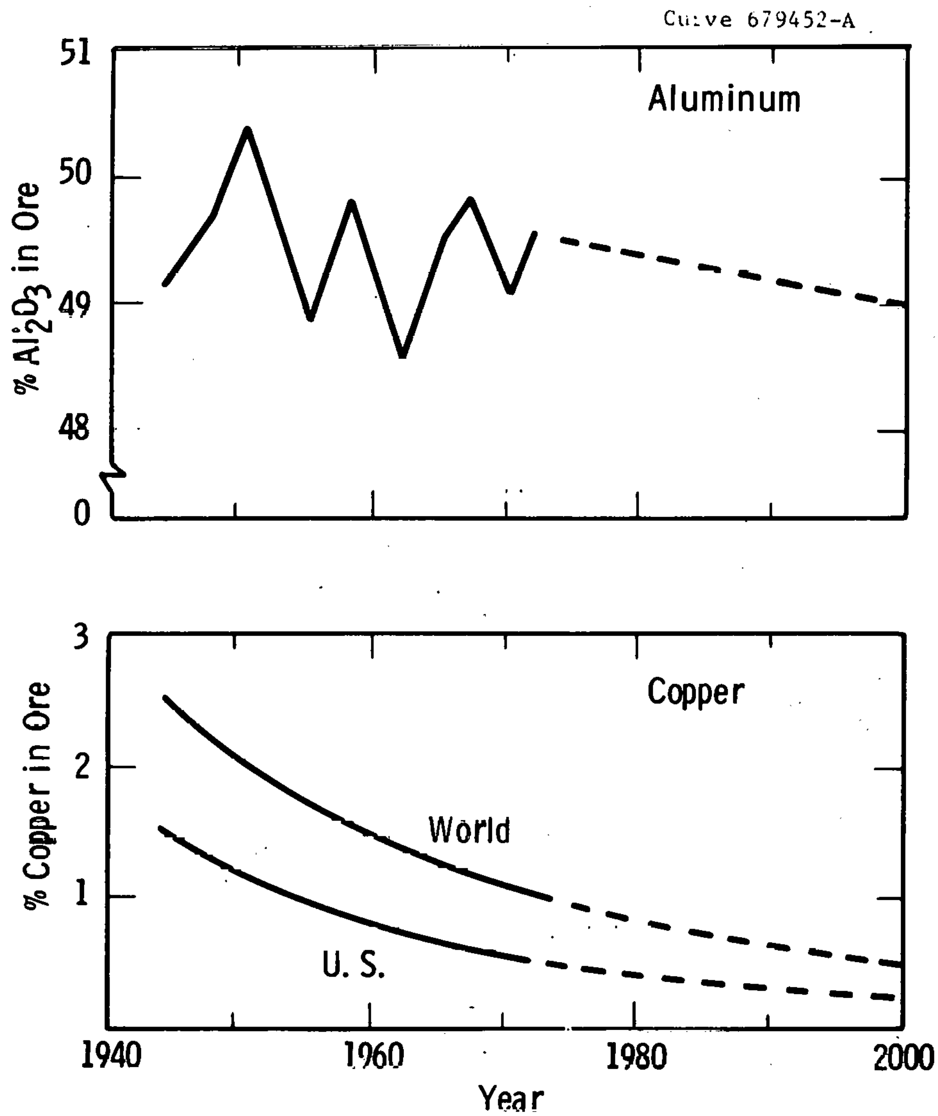

Fig. 8-2—Ore grade variation, World Al and Cu

which relies almost entirely on low grade ores (Figure 8-2), has nearly one-fourth of the world's reserves.[69] The average grade of the U.S. ore is declining as shown in Figure 8-2, and ores containing as little as 0.4 percent are now being mined in the Southwest. If the world average copper ore being worked were to go to 0.6 percent from the 1.5 percent being worked today, then the energy to refine copper would double, approaching that of aluminum (Figure 8-3). It is unlikely that the world will run out of copper, but it will be used more selectively.

Sodium is one of the most abundant elements found in the earth's crust and is commonly formed by electrolysis processes from common salt (NaCl) mixed with halogen fluxing agents. There is no apparent concern over sodium's long range availability, nor are any technical breakthroughs anticipated to reduce its energy requirements for manufacture.

When one considers the area of the three cable conductor materials, Al, Cu, Na, only copper appears to be in danger of escalating refining costs due to depleted ores. The long term availability of both sodium and aluminum can be assumed.

8.6 Conclusions

Both sodium and aluminum ores are very plentiful, with the energy required to manufacture sodium being about one-half that required for aluminum. The energy required to manufacture aluminum is expected to decrease about 30 percent with the introduction of the new Alcoa smelting process, but increased energy costs could offset the gain. Sodium, also produced electrolytically, projects no changes in technology or energy for its manufacture.

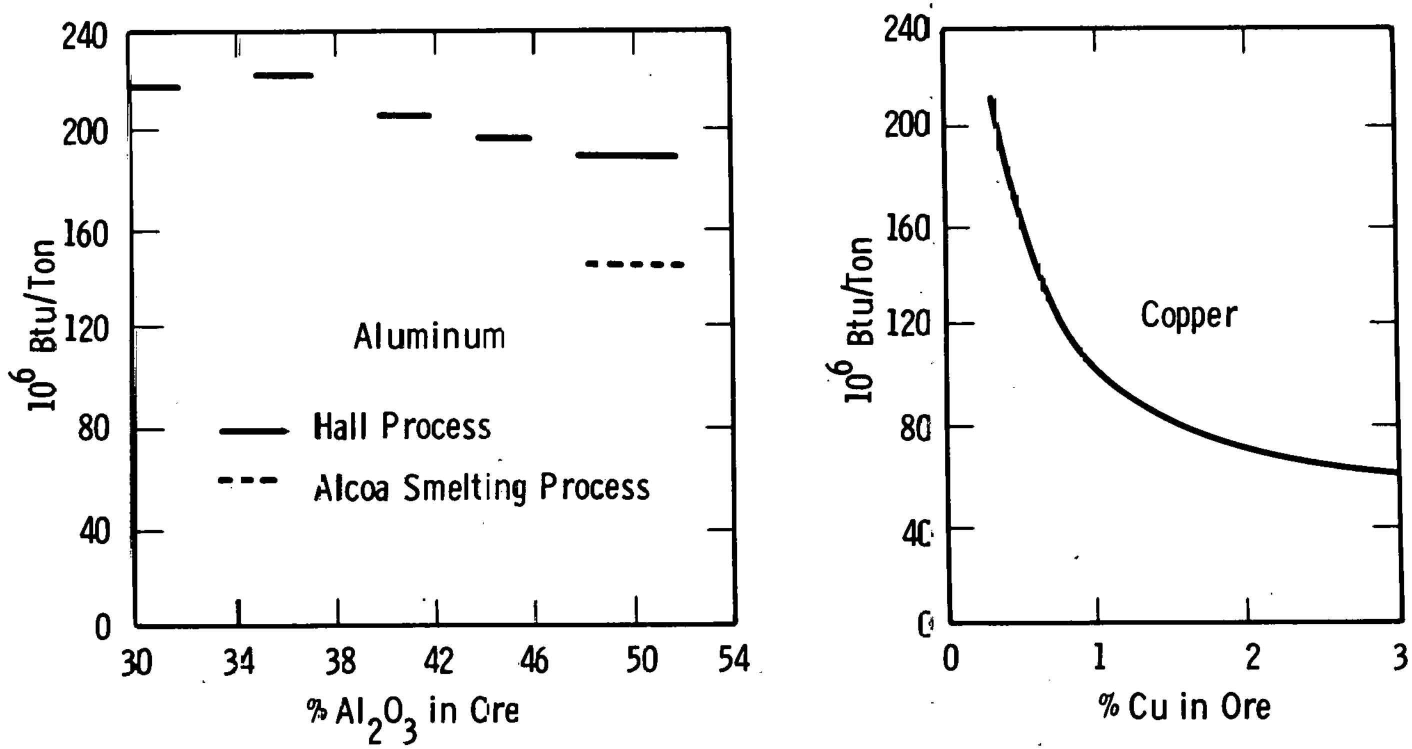

Fig. 8-3—Effect of ore grade on energy required per ton of product shipped

9. ECONOMIC ANALYSIS

The purpose of the Economic Analysis Task is to provide an objective comparison between the costs of owning and operating aluminum and sodium underground distribution cable. A comparison of cable costs and the present worth of operating losses for cables operating at unity load factor and at their thermal limit is first performed. Then the comparisons are evaluated for more practical application; primary feeders, laterals, and secondary service. Subsequently, the effect of connector costs, installation in ducts, salvage, and disposal are introduced into the analysis. The comparison is performed based on present costs, and costs estimated for 10 and 25 years in the future. For the applications defined, energy savings based on assumed market penetration are calculated.

9.1 Methodology Used

The total owning and operating costs of cables over an assumed lifetime was selected as the parameter to be compared between aluminum and sodium cables. As discussed in Section 7, the basis of comparison is the requirement that both the sodium and aluminum cables have equal overload and normal load ampacities. This is required because of the impracticality of an electric utility treating sodium and aluminum cable differently for an emergency overload condition.

The total costs for comparing cables is calculated from

$$PW_t = CI + CON + CAB + PW_L \qquad (9\text{-}1)$$

where PW_t = present worth of total costs (\$/ft) (\$/m)

CI = installation costs of cable and connectors (\$/ft) (\$/m)

CAB = cable costs (\$/ft) (\$/m)

CON = connector costs

(NOTE: Actual costs are used rather than annual carrying charges. Since sodium and aluminum costs are relatively close, the present worth difference between the two methods would be negligible).

PW_L = present worth of cable operating losses over the life of the cable (\$/ft) (\$/m)

The present worth of losses, PW_L, is evaluated using

$$PW_L = [(LSF \times POENG) + (PKRESB \times POCAP)] \times PWR_L \times PWF \qquad (9\text{-}2)$$

where PWR_L = peak power dissipation in the cable at the time of cable peak load current (kW)

PWF = present worth factor over cable lifetime

LSF = average loss factor of the cable defined as the ratio of cable average loss to peak loss [71,72]

PKRESB = peak responsibility factor defined as the ratio of cable peak load that is present at the time of total electric utility system peak load [71]

POENG = average annual cost of energy supplied to the distribution system (\$/kW-yr)

POCAP = average annual cost of supplying capacity to meet the electric utility system peak load (\$/kW-yr)

The present worth factor summarizes the effects of cable load growth, electric power and energy cost increases, and discounting effect of costs in the future over the assumed cable lifetime.

The present worth factor is calculated using

$$PWF = \sum_{i=1}^{N} \frac{(1+g)^i \ (1+e)^i}{(1+d)^i} \qquad (9\text{-}3)$$

where N = number of years of assum[illegible]able lifetime (25 years)

e = annual rate of increase of electric power and energy costs

g = annual growth rate of cable load

d = annual discount rate for future operating costs

To evaluate the present worth of losses PW_L (Equation 9-2) one must first evaluate the peak power loss PWR_L. This power loss is calculated(73) by

$$PWR_L = K_p \ (I_1{}^2 + I_1 I_2 + I_2{}^2) \ R \qquad (9\text{-}4)$$

where I_1 = peak input or feed phase current to the uniformly loaded cable being analyzed (amperes)

I_2 = peak output current from the cable section (amperes)

R = a-c phase conductor (conductor + concentric neutral for single phase lateral) resistance (ohms) at operating temperature determined by I_1 and I_2

K_p = constant depending on the application
e.g., uniformly loaded feeder
3ϕ balanced main feeder, $K_p = 1$
1ϕ lateral feeder, $K_p = .6667$
secondary and service, $K_p = 1$

Equations 9-1 through 9-4 are used to evaluate the total present worth for comparing all cable sizes, voltages and applications appearing in the following sections of this analysis.

9.2 Construction of Cable Costs

The essential basis for any economic analysis is an accurate description of costs and prices. Ideally, one would like a detailed representation of all cost components as shown in Figure 9-1. For an established cable product with a known volume, a given manufacturer might be able to quantify these costs. However, for a cable no longer in production such as sodium, this type of detailed cost data is unavailable.

First, an examination of what data is available guides one in the approach to be used. Prices of materials that are used in constructing both the aluminum and sodium cables are available. The purchased prices of aluminum cable in the sizes used by the electric utilities are available and were obtained in the Task 1 Survey. Selling prices for sodium cable (NACON Corp. to electric utilities) in the 1966-1968 period are available. Because of the proprietary nature manufacturers generally will not release information on scrap rates for product lines, specific fabrication costs and indirect product costs.

The U.S. Census of Manufacturers publishes data on cost of materials, value added by manufacture, and value of shipments for particular product groups within the total wire and cable industry. Included in the cost of materials is the cost of scrap so that the actual cost of material used in manufacturing the volume of cable shipped is not known. However, the numbers do provide a general guide for estimating how much value is added for the input cost of materials. The ratio of the cost of materials to the value of shipments varies from approximately 95% for aluminum wire involving only a drawing operation to 67% for more complex products in the insulated wire and cable product group.

The approach finally selected for estimating the cable costs to electric utilities began with calculating the volume of material of each type used per unit length for each voltage class and size. Then using the specific gravities (Table 9-1) the weight of each material component per unit length was calculated. Using the material prices (Table 9-2), the cost of each component (e.g., conductor, conductor screen etc.) was evaluated and summed to get total material costs as given in the following.

CABLE COST COMPONENTS

- direct product costs
  - materials
    - conductor
    - conductor screen
    - insulation
    - insulation screen
    - concentric neutral
    - scrap
  - fabrication
    - stranding (pumping)
    - extrusion
    - vulcanization
    - handling
    - testing
  - inventory
  - packing
  - transportation
- indirect product costs
  - sales expenses
  - general & administrative
  - taxes
  - depreciation
  - research & development
  - profits

Figure 9-1

TABLE 9-1

Material Specific Gravities and Insulation Thickness Used In Constructing Cable Material Costs

	Specific Gravity
Aluminum	2.70
Copper	8.89
Sodium	.97
Polyethylene (thermoplastic)	.92
Polyethylene (thermosetting)	1.18
Semi-Conductive Polyethylene	1.25

	Insulation Thickness (mils)
600V	.095" & .110"
15 kV	.175"
25 kV	.260"
35 kV	.345"

TABLE 9-2

Material Prices Used in Estimating the Cable Costs

Aluminum	54¢/lb.
Copper	67¢/lb.
Sodium	37¢/lb.
Semiconducting Thermosetting Screen	76¢/lb.
Polyethylene (thermoplastic)	40¢/lb.
Polyethylene (thermosetting)	51¢/lb.

*Aluminum conductor and copper concentric neutral is stranded and spiraled (assumed 3% increase in weight per foot for spiraling)

The cross-sectional area, A, in circular mils of any uniform covering on a cylindrical core is D^2-d^2 where D and d are the outside and inside diameters, respectively, of the covering in mils. Knowing this area A, the volume for a unit length is also known and the weight per unit length is calculated from

$$W = \frac{SG \times A}{2.94 \times 10^6} \qquad (9-5)$$

where W = weight per unit length of a particular component of the cable (lb.)

SG = specific gravity of material (Table 9-1)

A = cross-sectional area of the material being considered, in circular mils

Cable material cost forecasts for 10 years and 25 years in the future are given in Table 9-3. These cost forecasts were taken directly from the Data Resources Inc. Cost Forecasting Service.[74] These costs will be used in Section 9.3.6.5 to estimate how the cost difference between aluminum and sodium cable might change in the future.

From a telephone survey of cable manufacturers and the Task I survey the selling prices of some aluminum distribution cables to electric utilities were obtained. These prices are shown in Table 9-4. The total material costs of these aluminum cables were calculated. The difference between the selling price and the materials cost was used as an aggregate for the "other direct and indirect product costs."

In developing the prices for sodium cable the "other direct and indirect product costs" for an equivalent ampacity aluminum cable were used. The reasoning for this was that a competing sodium cable would have scrap rates, sales volume, and indirect costs comparable to the aluminum in a mature market. The fabrication processes for both sodium and aluminum cable are similar enough that costs should be comparable.

TABLE 9-3

Cable Material Cost Forecasts ($/lb)

	1978	1988*	2003**
Copper (WPI 10220106)	0.67	2.126	4.1
Aluminum (WPI 10220101)	0.54	2.291	6.8
Sodium (Electricity Price Index)	0.37	1.842	4.6
Semiconductive PE (Thermosetting) (WPI 061)	0.76	1.870	4.07
Semiconductive PE (Thermoplastic) (WPI 061)	0.56	1.870	4.07
XLPE (WPI 061)	0.52	1.870	4.07
Thermoplastic PE (WP 061)	0.40	1.870	4.07
CPI (consumer price index)	1.0	1.634	3.07
WPI (wholesale price index)	1.0	1.738	3.36

*Relative to 1978 (includes inflation) from Data Resources Inc. Cost Forecasting Service, First Quarter, 1978.

**Extrapolated from DRI Cost Forecasting Service using average of 1988, 1989, 1990 increases in cost index.

TABLE 9-4

ESTIMATED COST OF CABLE TO ELECTRIC UTILITIES (¢/ft)

(Aluminum)[1]

Conductor Area	600 V	15 KV[2]	25 KV[2]	35 KV[2]
250 MCM	41.12[3][7]	78.35[5]	85.53[5]	97.60[5]
300	48.72	87.21	96.74	108.82
350	57.50[3][7]	93.32[4]	106.14[4]	116.64[6]
400	63.81	104.13	115.16	129.95
500	78.81	120.03	132.40	149.82
600	93.75	135.19	148.94	168.75
750	110.00[3]	157.02[5][7]	172.62[5]	195.89[5]
1000	154.21[3]	181.38[5]	209.25[5]	238.80[5][7]
1250	189.96	224.72	245.74	279.62
1500 MCM	226.73	256.92	280.30	318.95

Sodium[8]

Conductor Area	600 V	15 KV	25 KV	35 KV
250 MCM	18.13	52.04	56.11	63.67
300	21.22	57.16	62.73	70.07
350	24.89	60.18	68.08	74.27
400	27.34	66.76	73.14	81.96
500	33.38	75.59	82.70	92.98
600	39.36[9]	83.85[9]	91.75	103.34
750	50.00	90.30	104.50	118.03
1000	63.50	113.67	123.71	140.91
1250	77.57	130.66	142.77	162.34
1500 MCM	92.07	146.96	160.45	182.76

(1) Aluminum conductor, 600 volt with 100 mils XLPE
15 KV, 25 KV, 35 KV with 175, 260, 345 mils of XLPE, 15 mil conductor and 30 mil semiconductive insulation screen.

(2) 1/3 reduced Cu concentric neutral.

(3) List prices Kaiser Aluminum, May 11, 1978.

(4) From P. L. Fontaine, "Underground Distribution To Large Shopping Centers and Industrial Parks," IEEE Conference Record, 1976, Underground Transmission and Distribution Conference.

(5) Ratios developed from April 1978 Phelps Dodge and Okonite list prices. These ratios used to extrapolate values in (4).

(6) Proportioned from 25 KV based on materials cost ratios.

(7) These prices agree with task 1 survey data within 25%.
Survey data not available for other sizes or voltages.

(8) Sodium conductor, no conductor screen, copper concentric neutral.

(9) Checked against NACON price lists as follows:

$$\frac{\text{WPI 1026 (1978)}}{\text{WPI 1026 (1968)}} \times \text{NACON price} < \text{Na cable prices.}$$

Whereas sodium requires a pumping plant, aluminum requires a wire drawing and stranding operation. A similar extruding process is used for both. The major advantage of this approach is that differences between sodium and aluminum cable costs are traceable to differences in quantity and cost of materials used rather than some fluctuating and difficult to define "markup." Consultation with cable manufacturers has assured the author that this is a more reliable approach to use. The sodium price is then estimated by adding its materials cost to the "other direct and indirect costs" as shown in Table 9-5.

Comparing sodium and aluminum cable costs in Table 9-4 shows a significant advantage for sodium for the same size and voltage class. However, one must remember that the same size sodium and aluminum cable are not equivalent electrically as explicitly shown in Section 7.

A more valid comparison between equivalent cables (see Section 7) is given in Table 9-5 for the 15 kV voltage class. The cables both have a concentric copper neutral with conductivity 1/3 of that of the main conductor. As shown in Section 7, to have equal ampacity in the overload condition a 15 kV, 250 MCM Al cable must be replaced with a 15 kV, 530 MCM sodium cable.

Comparison of the conductor costs in Table 9-5 shows a metal savings of approximately 50% relative to aluminum. The required metal volume for sodium is approximately twice that for aluminum but the relative weight is 1/3 and relative cost only 2/3. No conductor screen is required with sodium (Section 7) yielding a slight savings. Since the sodium diameter is larger, both insulation and insulation screen costs are increased relative to the aluminum. The requirement that the copper concentric neutral must have "1/3 of the conductor resistance per foot" at overload condition results in a cost disadvantage to sodium for the concentric neutral. Examination of the electrical design tables in Section 7 shows a resistance per unit length for sodium that is 73% of that for aluminum at normal full load and operating temperatures. Requiring this lower resistance in the neutral requires about 35% more copper than in the aluminum case. This "extra conductivity" would most

TABLE 9-5

COMPARISON: SODIUM AND ALUMINUM CABLE COSTS (¢/ft)

15 KV

m a t e r i a l	Al 250 MCM	NA 530 MCM
conductor	12.79	6.67
conductor screen (Al=15, NA=0)	1.02	0.0
insulation (175 mils)	10.02	11.61
insulation screen (30 mils)	3.41	3.84
concentric neutral (1/3)	10.59	13.55
material subtotal	37.85	35.66
other direct and indirect product costs	40.5	40.5
electric utility price	78.3	76.16

	Al 1000 MCM	NA 2155 MCM
conductor	51.17	27.10
conductor screen (Al=15, NA=0)	2.02	0.0
insulation (175 mils)	17.41	21.11
insulation screen (30 mils)	5.41	6.40
concentric neutral (1/3)	42.37	55.09
material subtotal	118.38	109.71
other direct and indirect product costs	63.00	63.00
electric utility price	181.38	172.71

(Note: If a vapor barrier is required, then the Cu drain wires would be removed and a lead sheath concentric (80 mils) might be used as both vapor barrier and concentric neutral. This would add approximately 50¢/ft to the cable prices shown. If the barrier is required on both Al and Na cable, the cost comparison is essentially unchanged. Please see Section 7 (7.3.5, 7.7.5) for a technical discussion of this issue. If the barrier is required only for Na, then for typical case (15 kV, 250 kcmil), the Na cable would cost approximately 40% more than the Al and total present worth cost of Na would be 6% higher than Al.

If an LC ("copper foil") construction with PE were used as the jacket (hermetically sealed) then jacket costs would be approximately equal to the lead sheath. Section 7.3.5 indicates that a helically wound aluminum adhesive tape may serve as an adequate moisture barrier; a lower cost than sheath barriers.

probably be needed in the case of a fault while in the overload condition. As explained previously, the other direct and indirect costs are assumed equal for sodium and aluminum. This cost number was calculated by subtracting the total aluminum cable materials cost (37.85¢) from the electric utility purchase price (78.3¢).

Comparison of costs for this case (Table 9-5) shows only about a 2¢ per foot cost advantage for sodium for this particular cable. However, one must remember that the full load losses for this sodium cable are only 74% of those for the aluminum cable. A decision on savings based only on cable cost would be incorrect. A value for reduced losses is included in the comparison made in Section 9.3.

Component cost breakdowns for sodium and aluminum cable 600V, 15 kV, 25 kV, 35 kV, 250 MCM, 350 MCM, 750 MCM and 1000 MCM are given in Appendix A4 Tables A4-1 through A4-4.

9.2.1 Substitution of High Molecular Weight Polyethylene (HMWPE) for XLPE

It is interesting to evaluate the influence on cost of substituting high molecular weight polyethylene (HMWPE) for cross linkable type polyethylene (XLPE). Essentially we are substituting a thermoplastic type insulator (41¢ per lb.) for the thermosetting type insulation (51¢ per lb.). A thermoplastic screen material (56¢/lb.) is also substituted for the thermosetting screen (76¢/lb.). These substitutions reduce the 15 kV 530 MCM sodium cable cost (Table 9-5) to 72.88¢/ft. and double savings relative to aluminum to 5.42¢/ft. This substitution will be evaluated more fully in Section 9.3.

9.3 Comparision of Aluminum and Sodium Cable Costs

The total present worth of aluminum and sodium cable costs as defined by Equation 9-1 are evaluated within various applications.

9.3.1 Comparison at Unity Load Factor and Rated Thermal Ampacity

A comparison of sodium and aluminum cable total present worth costs at unity load factor and full load rated ampacity is presented in Table 9-6. The simplifying assumption of unity load factor and rated

TABLE 9-6

Aluminum and Sodium Cable Owning and Operating Costs;
Thermal Ampacity Limit (Section 7) Loss Factor = 1.0
Peak Responsibility Factor = 1.0

Voltage, Al Size-Na Size	Aluminum Cable Costs ($/ft.)	Aluminum Cost of Losses ($/ft.)	Sodium Cable Costs ($/ft.)	Sodium Cost of Losses ($/ft.)	Total PW Difference Al-Na ($/ft.)
600 V, 250 MCM - 542 MCM*	.41	56.03	.36	40.35	15.73
600 V, 350 MCM - 760 MCM*	.57	57.20	.50	41.37	15.90
600 V, 750 MCM - 1633 MCM*	1.16	60.37	1.003	42.28	18.25
600 V, 1000 MCM - 2196 MCM*	1.54	59.97	1.320	42.54	17.65
15 kV, 250 MCM - 530 MCM**	2.35	76.46	2.302	55.14	21.37
15 kV, 350 MCM - 740 MCM**	2.88	77.97	2.796	56.75	21.30
15 kV, 750 MCM - 1608 MCM**	4.53	84.33	4.332	59.36	25.17
15 kV, 1000 MCM - 2155 MCM**	5.44	85.19	5.179	60.42	25.03
25 kV, 250 MCM - 530 MCM**	2.57	73.38	2.530	52.83	20.59
25 kV, 350 MCM - 740 MCM**	3.19	75.56	3.129	54.62	21.01
25 kV, 750 MCM - 1608 MCM**	5.17	82.38	5.016	57.60	24.93
25 kV, 1000 MCM - 2155 MCM**	6.28	82.55	6.073	58.44	24.32
35 kV, 250 MCM - 530 MCM**	2.93	70.41	2.910	50.70	19.73
35 kV, 350 MCM - 740 MCM**	3.64	73.10	3.60	52.82	20.32
35 kV, 750 MCM - 1608 MCM**	5.90	79.82	5.79	55.80	24.73
35 kV, 1000 MCM - 2155 MCM**	7.16	80.13	7.008	56.72	23.56

*single phase cable, conductor and insulation only
**3 phase cable, 1/3 Cu concentric neutral

ampacity makes the cable cost comparison independent of the cable application. Both sodium and aluminum cables compared in Table 9-6 are operating at the same full load currents with operating temperatures specified as in Section 7.

For the 600 V comparisons, full load single phase current (1 conductor) is assumed and for all higher voltages a balanced three phase system (3 conductors) is considered. Cable costs for the 3 phase system are 3 times those shown in Table 9-4 for single cables.

Examination of cable costs and cost of losses in Table 9-6 shows costs of losses an order of magnitude or more higher than cable costs. This greatly increases sodium cable savings over aluminum. The savings are composed almost wholly of a savings in losses (30% of aluminum, PW cost). This unity load factor and full load current evaluation leads to an overemphasis of the savings in losses. From References 71 and 72 and other general information it is believed that most distribution system cables are "lightly loaded" and thus the high savings in losses would not be realized. In Sections 9.3.3 and 9.3.6 the cost of losses are evaluated under what is believed to be more realistic assumptions for load and loss factors.

Comparison of the cases in Table 9-6 shows that maximum savings is achieved for the lowest voltage, largest size conductor (600 V, 1000 MCM Al, 2196 MCM Na). The cable cost savings is largest because of the relatively higher percentage of metal in the total cables. The loss saving is higher because of the higher ampacity rating of the 600 V cable as compared to the higher voltage.

To provide clarification on how the numbers in Table 9-6 were calculated, the 15 kV, 250 MCM entries are calculated below using Equation 9.2 through 9.4 in reverse order.

$$PWR_L = K_p \, (I_1{}^2 + I_1 I_2 + I_2{}^2) \, R \qquad (9\text{-}6)$$

$$= 1 \, (375^2 + (375)(375) + 375^2) \; 2.898\text{x}10^{-6} \, \frac{\Omega}{cm} \, 30.5 \, \frac{cm}{ft} = 37.66 \, \frac{watts}{ft} \text{ (for Al)}$$

$$= 1 \, (375^2 + (375)(375) + 375^2) \; 2.133\text{x}10^{-6} \, \frac{\Omega}{cm} \, 30.5 \, \frac{cm}{ft} = 27.445 \, \frac{watts}{ft} \text{ (for Na)}$$

$$PWR = \sum_{i=1}^{N} \frac{(1+g)^i \; (1+e)^i}{(1+d)^i} = \sum_{i=1}^{25} \frac{(1.)^i \; (1.05)^i}{(1.12)^i} = 12.012 \qquad (9\text{-}7)$$

$$PW_L = [(LSF \text{ x } POENG) + (PKRESB \text{ x } POCAP)] \text{ x } PWRL \text{ x } PWF \qquad (9\text{-}8)^*$$

$$PW_L = [(1 \text{ x } .094 + (1 \text{ x } .075)] \text{ x } 37.66 \text{ x } 12.012 = \$76.46/ft \text{ (for Al)}$$

$$PW_L = [(1 \text{ x } .094) + (1 \text{ x } .075)] \text{ x } 27.445 \text{ x } 12.012 = \$55.14/ft \text{ (for Na)}$$

Unity Load factor implies unity loss factor which implies a unity peak responsibility factor.

The operating costs and capacity costs of the electric utility are taken from Referencco 75 and are converted to the proper units for Equation 9.2 by

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*POENG and POCAP taken from the 20th Steam Station Cost Survey, Electric World, Nov. 16, 1977.

"e"-bus bar energy cost escalation approximately from 15th, 16th, 17th Electrical World Steam Station Survey. Thinking at the time of these calculations (mid 1978) was that long term electric cost escalation would approximate long term inflation (5.5%). Recent forecasts (March 14, 1979) indicate that this number might be increased to about 8%. Using 8% for e in Eq. (9-7) would increase the PWF by 35%. For the typical 15 kV case, this would increase Na savings to 11.6% from 10% of Al costs.

The 25 year life used is a planning life of the distribution cable system and is used throughout the economic analysis. The 40 year life represents the physical life (degradation, effective cross-section reduction etc.) of the cable. Because of the high discount factor, 12% of the PWF factor increases only 15% if planning life is increased to 40 years. For the nominal 15 kV case, this would increase sodium savings by 0.8% (e.g., 10.8% of Al costs as contracted with 10%).

$$POENG = \left(\frac{\$.01077}{kwhr}\right)\left(\frac{1\ kw}{1000w}\right)\left(\frac{8760\ hr}{yr}\right) \quad (9\text{-}9)$$

$$= \frac{\$.094}{w\text{-}yr}$$

POCAP = Average Capacity Cost at Peak x Annual Carrying Charge

$$= \frac{\$415}{kw}\ (.18) = \frac{\$75}{kw\text{-}yr} = \frac{\$.075}{w\text{-}yr} \quad (9\text{-}10)$$

As an added indication of the impracticality of unit load factor full load current for evaluating losses, one can examine the voltage drop system regulation problem.

The necessary sending end voltage to obtain 7200 volts phase to ground (15 kV class line to line) at the distribution transformer would be[76]

$$V_s = \sqrt{(V_R \cos\theta + RI)^2 + (V_R \sin\theta + XI)^2} \quad (9\text{-}11)$$

where V_R = voltage at receiving end of line

$\cos\theta$ = power factor

R = phase conductor resistance

X = phase inductive reactance

I = phase current

If we assume a 10,000 foot feeder then

$$V_s = \sqrt{(7200\ (.85) + .88\Omega\ 375\ amps)^2 + (7200\ (.526) + .44\ 375a)^2}$$

= 7564 volts

$$\%\ regulation = \frac{|V_s| - |V_R|}{|V_R|} \times 100 = 5.05\%$$

This voltage drop is well above the usual upper limit for good regulation of 3%.

9.3.2 Comparison of Cable Costs Neglecting Losses

The results of comparing sodium and aluminum cable when losses are neglected are presented in Table 9-7. Cost savings for sodium over aluminum cable are dramatically lower than the previous comparison in Table 9-6. The maximum savings are in the lowest voltage, largest size case (600 V, 1000 MCM Al - 2196 MCM Na). The cable cost savings increase with size of conductor because of the larger percentage of metal content for a given volume per unit length. The cost savings decrease with increasing voltage because of the increased insulation costs required by the largerdiameter sodium cable. If HMWPE is substituted for XLPE,then savings for 600 V 1000 MCM - 2196 MCM case increase from \$.22 to \$.25 or about 15%. Savings increase much more significantly for higher voltage cases. For example for 15 kV 1000 MCM - 2155 MCM savings increase to \$.44 or 168% of the former. For the 35 kV case savings are increased to \$.40, 263% of the former.

9.3.3 Sensitivity of Costs To Application Parameters

The data presented in Table 9-8 examine the effect on the present worth of losses of changing loss factor and peak responsibility factor. Case 1 represents the unity load factor, unity peak responsibility factor case. Case 2 reduces the loss factor and peak responsibility factors to values more typical of secondary applications.[71] However, the load is still at the ampacity rating which would most likely result in too large a voltage drop. Case 4 reduces load current to a tolerable voltage drop level as well as lowering loss factor and peak responsibility factor, probably a more practical comparison. Case 5 neglects losses thus underestimating savings.

9.3.4 Definition of the Application for Distribution System Comparison

In the previous sections aluminum and sodium cable have been compared in what might be called a "theoretical sense." To achieve added insight these cables are now evaluated for two particular applications which are schematically shown in Figures 9-2 and 9-3. A goal of the study

TABLE 9-7

Aluminum and Sodium Cable Costs Neglecting Losses

Voltage, Al Size - Na Size	Aluminum Cable Costs ($/ft)	Sodium Cable Costs ($/ft)	PW Difference Al-Na ($/ft)
600 V, 250 MCM - 542 MCM*	.41	.36	.05
600 V, 350 MCM - 760 MCM*	.57	.50	.07
600 V, 750 MCM - 1633 MCM*	1.16	1.003	.157
600 V, 1000 MCM - 2196 MCM*	1.54	1.32	.22
15 kV, 250 MCM - 530 MCM**	2.35	2.302	.048
15 kV, 350 MCM - 740 MCM**	2.88	2.796	.084
15 kV, 750 MCM - 1608 MCM**	4.53	4.332	.198
15 kV, 1000 MCM - 2155 MCM**	5.44	5.179	.261
25 kV, 250 MCM - 527 MCM**	2.57	2.53	.0429
25 kV, 350 MCM - 740 MCM**	3.19	3.12	.07
25 kV, 750 MCM - 1603 MCM**	5.17	5.016	.154
25 kV, 1000 MCM - 2149 MCM**	6.28	6.073	.207
35 kV, 250 MCM - 530 MCM**	2.93	2.91	.02
35 kV, 350 MCM - 740 MCM**	3.64	3.60	.043
35 kV, 750 MCM - 1608 MCM**	5.90	5.79	.111
35 kV, 1000 MCM - 2155 MCM**	7.15	7.008	.152

*single phase cable, conductor and insulation only
**3 phase cable, 1/3 Cu concentric neutral

TABLE 9-8

Sensitivity of Aluminum and Sodium Cable Owning and Operating Costs to Changes in Application Parameters (See Notes)

Voltage, Al Size - Na Size	Aluminum: Cable Costs ($/ft.)	Aluminum: Cost of Losses ($/ft.)	Sodium: Cable Costs ($/ft.)	Sodium: Cost of Losses ($/ft.)	Total PW Difference Al-Na ($/ft.)
(1) 600 V, 1000 MCM - 2196 MCM*	1.54	59.97	1.32	42.54	17.65
(2) 600 V, 1000 MCM - 2196 MCM*	1.54	13.99	1.32	9.92	4.29
(3) 600 V, 1000 MCM - 2196 MCM*	1.54	9.08	1.32	6.44	2.86
(4) 600 V, 1000 MCM - 2196 MCM*	1.54	0.80	1.32	.60	.42
(5) 600 V, 1000 MCM - 2196 MCM*	1.54	0.00	1.32	0.00	.22

(1) Thermal ampacity limit (814 amps)
Loss factor = 1.0, Peak responsibility factor = 1.0

(2) Thermal ampacity limit (814 amps)
Loss factor = .18, Peak responsibility factor = .3

(3) Thermal ampacity limit (814 amps)
Loss factor = .06, Peak responsibility factor = .266

(4) Reduced load (271 amps)
Loss factor = .06, Peak responsibility factor = .266

*Maximum savings case from Table 9-7.

DISTRIBUTION FEEDER APPLICATION

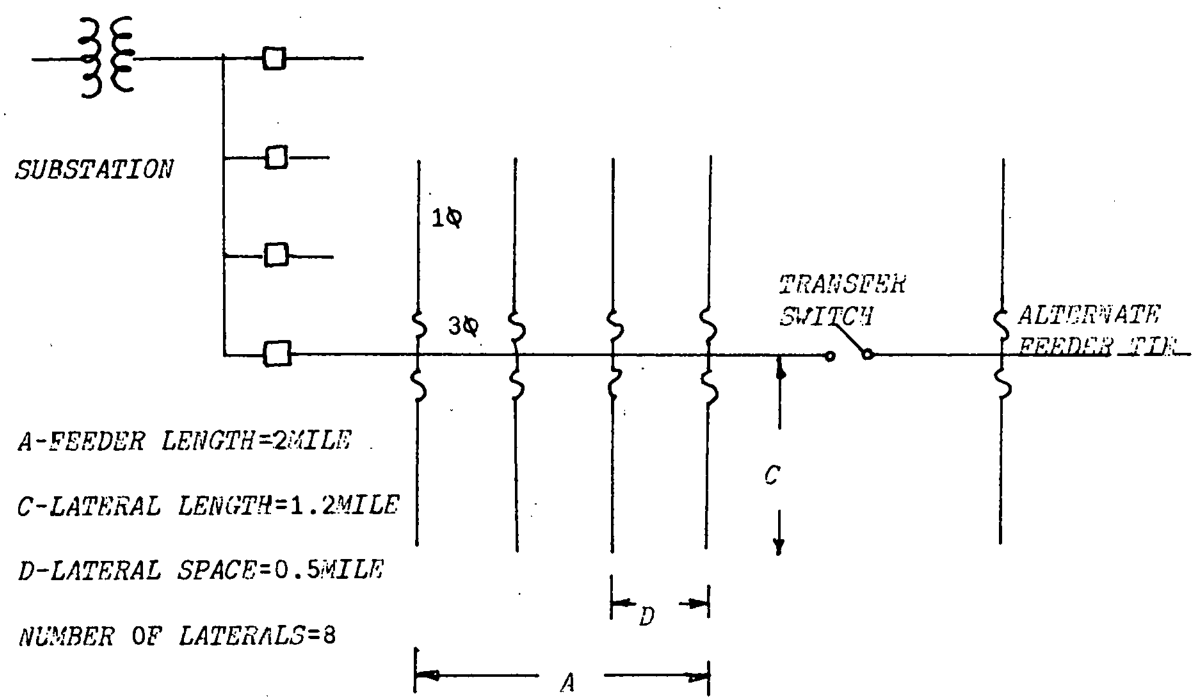
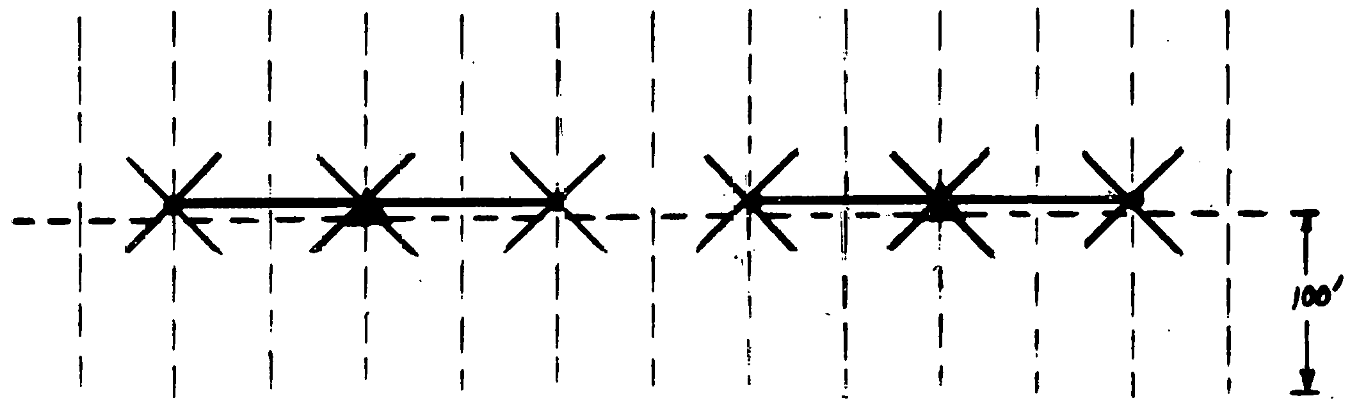


Figure 9-2

TRANSFORMER-SECONDARY-SERVICE APPLICATION



▲ Transformer

– – – Primary

——— Secondary

✕ Services (4)

12 CUSTOMERS/TRANSFORMER

75' LOT WIDTH

100' LOT DEPTH

PRIMARY LENGTH:

$$\frac{75 \text{ Feet} \times 6 \text{ Lots}}{12 \text{ Customers}} = 37.5'/\text{CUST.}$$

SECONDARY LENGTH:

$$\frac{75 \text{ Feet} \times 4 \text{ Lots}}{12 \text{ Customers}} = 25'/\text{CUST.}$$

SERVICE LENGTH

$$1/2 \times \sqrt{(75)^2 + (100)^2} = 62.5'/\text{CUST.}$$

*(FROM 'TRANSMISSION AND DISTRIBUTION SYSTEM LOSS STUDY' FINAL DOE REPORT REPORT NO. 77-112, SEPTEMBER 1977, REFERENCE 1)

Figure 9-3

required evaluating the relative cost of connectors for the two cable systems. The connector number, size, voltage rating and current rating depend on the particular application. Defining an application also helps one select more practical values for load factors, loss factors, peak load currents, and cable structure (e.g., neutral or none).

In Figure 9-2 a feeder design schematic is shown. This feeder arrangement with three phase primary and a single phase lateral is used to compare 15 kV, 25 kV, and 35 kV aluminum with sodium cable. A single tie point is used thus allowing the laterals to be fed from either of two substations[77] in an emergency condition. This contingency for emergencies requires a 40% reserve capacity in the 3 phase main feeder. Under emergency conditions the 3 phase main must feed its own laterals plus those of the adjoining feeder through the tie point. The normal peak load current must then be equal to or less than one-half of the overload rating. In the cable comparison the peak load current was set at one-half the overload rating as specified in Section 7. The load factors and loss factors for a practical feeder of this type were chosen from Reference 71.

In Figure 9-3, a schematic diagram of the secondary service application which was used to compare sodium and aluminum cables is shown. From References 78 and 71 this is selected as a practical and probably typical underground distribution application.

9.3.5 Estimating Connector Costs

The connector costs developed in the following are based on the 3 phase main feeder design shown in Figure 9-2.

The expense of connectors associated with the sodium cable installàtion in the 1966-1969 period were a frequently cited source of concern in the Task 1 Survey. It is also recognized that these first sodium connectors (see Figure A5-3) were hastily designed and were not cost-improved in any measure. In our comparison of connectors some might argue that optimized and cost improved aluminum designs are being compared to prototype sodium designs. While this is true, the connector data and costs available at present preclude any other analysis. The connector systems used in this cost comparison could be available now with very minor design modifications.

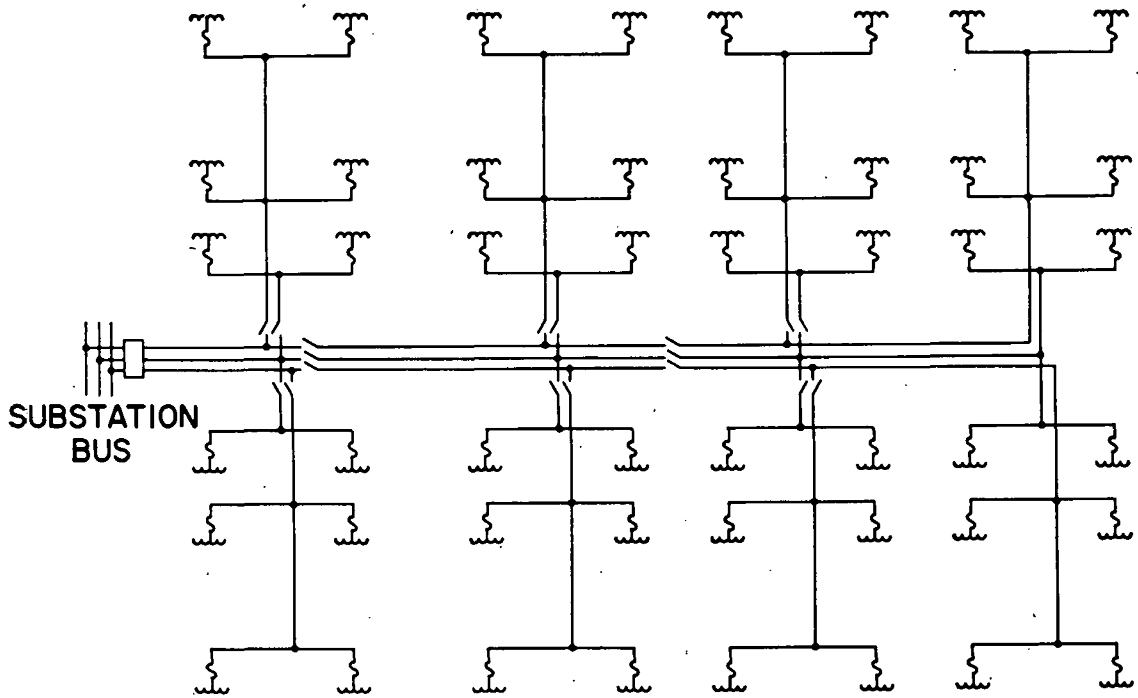
There are two basic facts which imply that sodium cable connectors might be more expense than those for aluminum cable even with an improved design. The first involves the low tensile strength of the sodium metal. Relatively complicated designs (Figure A5-7) are needed to take advantage of the strength of the insulation in making connections. This is especially a concern in 600V secondary and service applications where "standard aluminum practice" involves tightening an Allen type set screw directly against a stranded aluminum conductor (Figure A5-4). The second fact is that since sodium and aluminum react, copper is most probably required in even the improved designs. Just on materials cost basis this results in a 25% cost penalty over aluminum.

9.3.5.1 Three-Phase Main Feeder Connector Costs

Figure 9-4 provides circuit detail for the three phase main feeder and single phase laterals shown schematically in Figure 9-3. Examining Figure 9-4 shows that there are 32 connections needed in the 3 phase primary feeder. It is assumed that each tap point and disconnect switch point is brought up to a junction box. Each of these tap and switch points require two connections to the cable.

For the aluminum cable system deadbreak type elbow connectors similar to those shown in Figures A5-1 and A5-2 might be used. In calculating these costs list prices were used for the various size connectors as given below:

Voltage	Size	Deadbreak Elbow Connector Cost
15 kV & 25 kV	250-400 MCM	\$ 42.50 each
	500-1000 MCM	\$ 94.00
	1000-1500 MCM	\$141.00
35 kV	250-400 MCM	\$ 85.50
	500-1000 MCM	\$169.40
	1000-1500 MCM	\$254.10



An extensive primary feeder circuit showing extended use of three-phase mains and single-phase laterals—suburban-urban area distribution.

★(*FROM WESTINGHOUSE ELECTRIC UTILITY ENGINEERING REFERENCE BOOK;DISTRIBUTION SYSTEMS,VOL.*3 *E. PGH.* 1959)

Figure 9-4

These costs were allocated over the total 2 miles (10,560 ft.) of three phase circuit to obtain the costs shown for aluminum in Table 9-9(a).

For the sodium cable system "copper pin type" connectors similar to those shown in Figure A5-3 and A5-7 are assumed to be used. The copper rod or pin extension of the sodium conductor is then used with a standard loadbreak elbow connector as in the aluminum cable connections. These "copper pin type" connectors are priced by comparing their size, weight and conductor termination with a price list for similar copper connectors shown in Figure A5-6. Thus the sodium per foot connection costs are increased over the aluminum by the cost of a "copper pin type" connector for each of the 32 connections (Table 9-9(a)).

While it is recognized that splice costs would also be higher for sodium than aluminum, these costs have been neglected. The number of splices would be considerably less than the number of connections and would not alter the comparative economics significantly.

9.3.5.2 Single-Phase Lateral Connector Costs

For the single phase laterals shown in Figure 9-2, it has been assumed that there will be 12 customers per pad-mounted transformer and 37.5 KVA per transformer resulting in 14 transformers per lateral and a total lateral length of 5400 ft.

Two "loop through" type primary connections will be used at each transformer with two connections at the switch tie point to the primary feeder. This results in 26 connections per lateral. Deadbreak elbow connectors are again used for the aluminum and "copper pin type" connectors with elbow connectors for the sodium. The resulting per unit length costs are shown in Table 9-9(b).

9.3.5.3 Secondary-Service Connector Costs

Connector costs for the secondary-service system are based on the typical system shown in Figure 9-3. This system has secondary extending over 4 lots (4 lots x 75 ft. = 300') and service connection to 12 customers with an average length of 63' (12 x 63 ft. = 756').

TABLE 9-9

Connector Cost Per Foot of Cable; Based on Application Shown in Figures 9-2 and 9-3

(a) Three Phase Primary Feeder (see Figure 9-2)

	Aluminum (¢ per 3ϕ ft.)		
	15 kV	25 kV	35 kV
250 MCM	12.9	12.9	25.9
350	12.9	12.9	25.9
750	28.5	28.5	51.3
1000 MCM	28.5	28.5	51.3
	Sodium (¢ per 3ϕ ft.)		
	15 kV	25 kV	35 kV
250 MCM	13.4	13.4	26.4
350	13.5	13.5	26.5
750	30.1	30.1	52.9
1000 MCM	31.8	31.8	54.6

TABLE 9-9

Connector Cost Per Foot of Cable; Based on Application Shown in Figures 9-2 and 9-3

(b) Single Phase Lateral (see Figure 9-2)

	Aluminum (¢ per ft.)		
	15 kV	25 kV	35 kV
250 MCM	20.5	20.5	41.2
350	20.5	20.5	41.2
750	45.3	45.3	81.6
1000 MCM	45.3	45.3	81.6
	Sodium (¢ per ft.)		
	15 kV	25 kV	35 kV
250 MCM	21.2	21.2	41.9
350	21.4	21.4	42.1
750	47.8	47.8	84.1
1000 MCM	50.4	50.4	86.8

The total 1,056 ft. of secondary and service requires 3 wire service (3 wired cables) x 1056 ft. = 3168 ft. of insulated 600V conductor cable). There are 14 segments in the secondary-service system requiring a total of 84 connections (14 segments x 3 cables x 2 connectors).

For the aluminum system an aluminum bus bar (Figure 12.5-4) is threaded onto the secondary stud of the pad-mounted transformer. The stranded aluminum conductors are inserted directly into the bus bar and secured by tightening the set screws. The entire assembly is covered with a device as shown in Figure A5-5.

For the sodium cable an identical aluminum bus system is assumed to be used. Again "copper pin type" connectors are first inserted into the sodium cables which are secured to the bus.

Costs for both aluminum and sodium connectors are estimated based on list prices from Reference 80 as shown below:

600V Secondary-Service

Size	Aluminum Connector Costs ($ ea.)	Sodium Connector Costs ($ ea.)
250 MCM	$ 2.15	$ 3.70
350	$ 2.48	$ 4.35
750	$ 6.24	$11.45
1000 MCM	$12.50	$23.28

The costs on a per unit length basis are as shown in Table 9-9(c). Examination of Table 9-9(c) data shows a considerable increase in sodium connection costs over aluminum. Many more connections are made in the secondary-service system than in the primary system on a per unit length basis. This results in cost penalty for sodium that negates the savings made in the cable itself.

TABLE 9-9

Connector Cost Per Foot of Cable; Based on Application Shown in Figures 9-2 and 9-3

(c) 600V Secondary and Service Cable (¢ per ft.)

	Aluminum	Sodium
250 MCM	5.7	9.8
350	6.6	11.6
750	16.6	30.42
1000 MCM	33.2	61.84

9.3.6 Comparison of Cable Costs for the Applications

A pictorial representation of the total present worth savings of sodium over aluminum cable systems is given in Figure 9-5. The diagram represents relative costs for the scope of this study in terms of voltage class and cable size.

The message of Figure 9-5 is three-fold in terms of (1) cable costs, (2) connector costs and (3) present worth of losses.

The cable cost savings of sodium over aluminum increase with conductor size and decrease with increased voltage. On a cable cost basis alone the largest savings occurs at 600V, 1000 MCM because of the relatively large metal content of the cable.

Sodium connectors are more expensive than aluminum and this penalty increases with size. More connectors are needed for the 600V secondary-service system so connector costs on a per unit length basis decrease from 600V to 15 kV then rise again as voltage increases to 35 kV.

Ampacity rating decreases with increasing voltage level. This is required because the thicker insulation for higher voltages results in an increased thermal drop from conductor to ground source. Thus to maintain the same operating temperature of the conductor the load current and subsequently the cable losses must be reduced. Since losses decrease for both sodium and aluminum, the present worth savings in losses also decreases with increasing voltage in proportion to the drop in losses. As size increases, the difference in resistance per unit length between sodium and aluminum decreases more slowly than the rate of the current squared. This results in slightly higher present worth loss savings at larger sizes.

It is interesting to extend the reasoning in Figure 9-5 somewhat. The results shown are for the specific sizes of aluminum and sodium cable given the approximate full load ampacity equivalent. If sodium cable sizes are reduced relative to aluminum sizes then cable

HISTOGRAM REPRESENTATION OF THE PRESENT WORTH SAVINGS FOR CASE STUDIES

ALUMINUM SIZE	SODIUM SIZE	600 VOLT	15KV	25KV	35KV
250MCM	530MCM	LL ΓΓ LL CC ΓΓ LL CC ΓΓ LL			LL ΓΓ LL CC ΓΓ LL
350MCM	740MCM				
750MCM	1603MCM				
1000MCM	2155MCM	CC ΓΓ CC ΓΓ LL CC ΓΓ LL CC ΓΓ LL CC ΓΓ LL CC ΓΓ LL			LL CC ΓΓ LL CC ΓΓ LL CC ΓΓ LL

C-CABLE COST SAVINGS SODIUM RELATIVE TO ALUMINUM
L-RELATIVE SODIUM OPERATING LOSS SAVINGS
Γ-RELATIVE SODIUM CONNECTOR COST PENALTY

Figure 9-5

savings increase, connector penalties are reduced, but loss savings reduce and at some point become loss penalties. Likewise if sodium cable sizes are increased relative to aluminum then just the opposite effect occurs.

9.3.6.1 Selecting the Optimal Size Sodium and Aluminum Cable

When selecting either a sodium or an aluminum cable for a particular application one would like the optimal or best selection in either case. The optimal selection here is defined as the one which minimizes the total present worth costs of the cable (Equation 9-1) including installation, cable costs, connector costs and cost of losses. When one selects the optimal cables for a given application, one usually does not arrive at the exact thermal ampacity equivalents shown in Table 9-6. For example, if the cables are "heavily loaded", then larger sizes are dictated to bring cost of losses in line with cable costs. For "lightly loaded" cables, first cost of cable becomes the primary criterion and cable sizes may be reduced as far as voltage regulation limits will allow.

Table 9-10 displays the total present worth savings of sodium over aluminum cable for the different voltage classes and sizes as evaluated for the applications defined by Figures 9-2, 9-3 and 9-4. In each of the 16 cases shown the phase current is 60% (1/2 of overload current) of the full load ampacity rating of the designated aluminum cable. More detail on the components of the total present worth savings is shown in Table 9-11.

Examination of Tables 9-10 and 9-11 shows that maximum savings for sodium cable occurs at the largest sizes analyzed. Aluminum is less expensive for the 600V secondary applications only because of the cost of connectors. If cost of connectors are disregarded, then the 600V, 1000 MCM case results in the maximum savings for sodium over aluminum.

The savings for the large sizes (1000 MCM case) stays relatively constant with increasing voltage. Examination of Table 9-11 shows that

TABLE 9-10

Total Present Worth Savings ($/ft.) Including Savings for Cable, Connectors, and Present Worth of Losses

Based on 50% of Overload Current of Al Cable	600 V*	15 kV**	25 kV**	35 kV**
250 MCM	(.0881)	.55	.56	.55
350 MCM	(.12)	.682	.67	.68
750 MCM	(.28)	1.04	.981	1.20
1000 MCM	(.363)	1.11	1.18	1.15

*Single Phase Secondary System
**3 Phase Primary Feeder (Balanced)

(Note: Both the Al and Na cable used in calculating the savings were optimally sized. The peak normal load current used was 60% of ampacity rating (50% of overload rating) allowing margin for emergency overload conditions).

TABLE 9-11

Details of Present Worth Savings ($/ft.)

600V, 250 MCM Al Overload Current Capability (see Figure 9-6 for added details)

	Cable Cost	Connector Cost	Losses	Total
Al 530 MCM	.8418	.1481	1.0499	2.0399
Na 900 MCM	.5773	.5384	1.0123	2.1280
Savings	.2645	(.3903)	.0376	(.0991)

600V, 1000 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 1200 MCM	1.835	.4185	2.0427	4.296
Na 1700 MCM	1.026	1.2545	2.3787	4.659
Savings	.809	(.836)	(.336)	(.363)

15 kV, 250 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 500 MCM	3.576	.204	2.310	6.09
Na 950 MCM	3.231	.322	1.985	5.538
Savings	.345	.(118)	.325	.552

15 kV, 1000 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 1300 MCM	6.375	.388	4.031	10.794
Na 2500 MCM	5.643	.624	3.416	9.683
Savings	.732	(.236)	.615	1.111

35 kV, 750 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 850 MCM	6.450	.4734	4.2912	11.215
Na 1700 MCM	6.030	.6990	3.2860	10.015
Savings	.420	(.2256)	1.0052	1.20

while savings due to lower sodium cable costs drop with increasing voltage, the loss savings increases. This increase in loss savings is a result of changes in cable size dictated by the optimal selection.

The total present worth savings for sodium over aluminum are about 10% of the present worth costs.

If the use of HMWPE is substituted for XLPE then an added $.40 savings is possible for the 35 kV case, thus increasing total savings to $1.60 or 14.2% of aluminum present worth costs.

The following sections present more detail on some of the cases summarized in Tables 9-10 and 9-11.

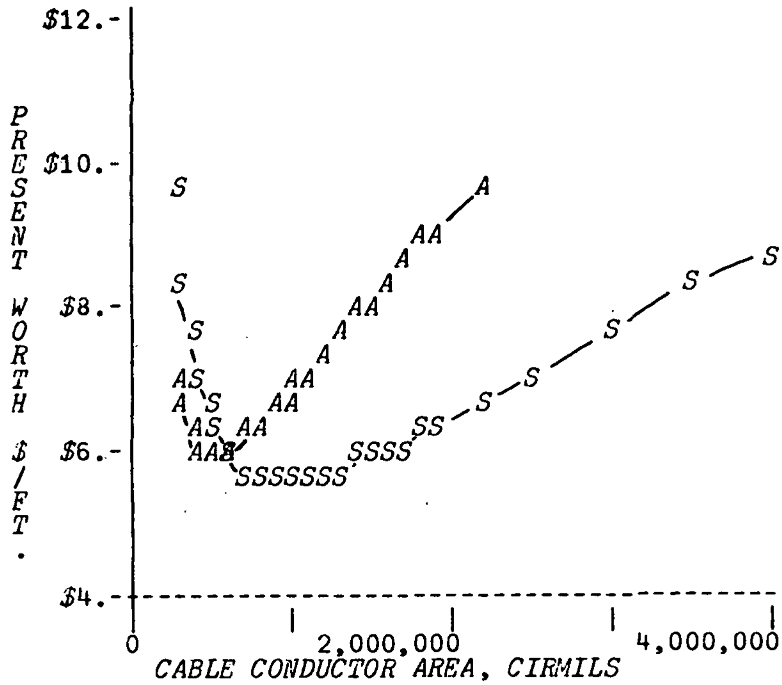
9.3.6.2 Analysis of 15 kV Direct Buried Cable

The information in Figure 9-6 and 9-7 provides added detail on the 15 kV case. As shown in Figure 9-6, total present worth costs for sodium are minimum at 950 MCM and for aluminum at 500 MCM. The full load current, loss factors and peak responsibility factors are as shown in Figure 9-6. Figure 9-7 shows the present worth cost breakdown for losses, cable, and connectors for both sodium and aluminum. Because of the minimal number of three phase connectors considered in the application, the connector costs for this case are a relatively small addition to total present worth costs.

9.3.6.3 Analysis of 15 kV Cable in Ducts

Section 7 presents the cable engineering details for the sodium and aluminum cable in ducts. Only the costs associated with the 15 kV case are explicitly presented here. The costs for other voltages and sizes are related in the same manner as the 15 kV case. Therefore, no new information could be presented through an exhaustive treatment of these other cases.

Figures 9-8 and 9-9 present the detailed data on the 15 kV cable in ducts. A three phase feeder is considered with one phase cable in each non-metallic duct (see Section 7). For the sizes of interest in the study (250 MCM to 1000 MCM) no change in duct size is necessary. Therefore duct costs are the same for both sodium and aluminum.



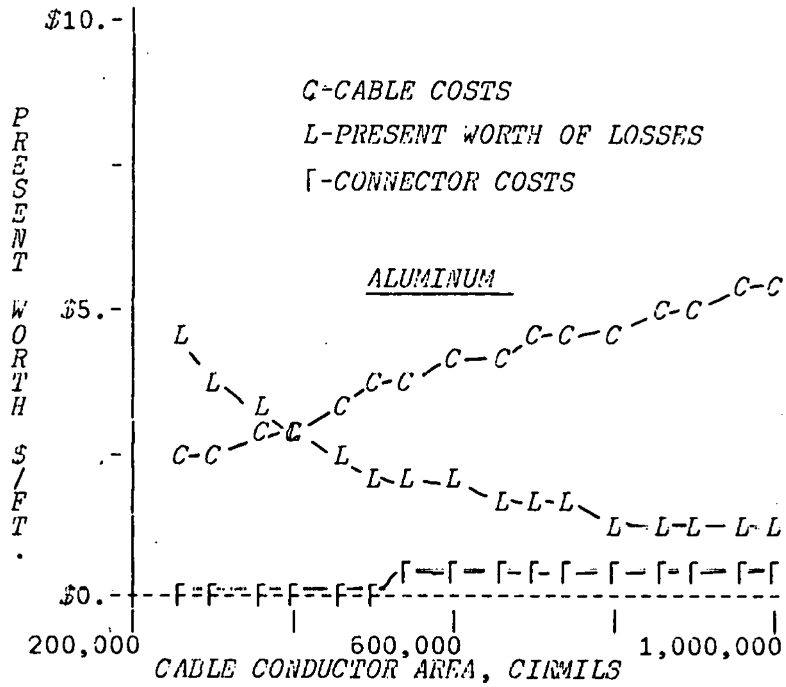
SODIUM AND ALUMINUM CABLE PRESENT WORTH
COSTS VS. CONDUCTOR SIZE-15KV DIRECT BURIED

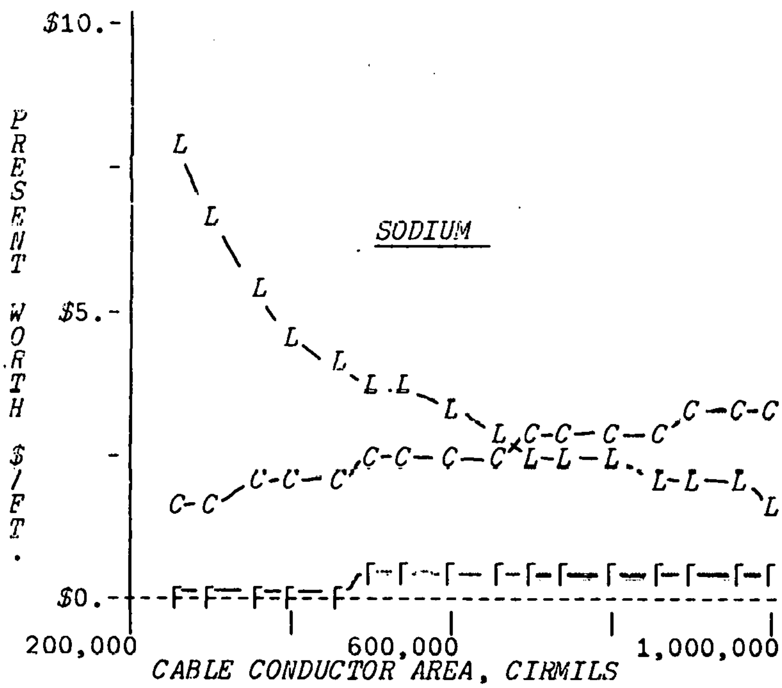
ALUMINUM OPTIMUM: 500MCM $6.09 PER FT.
SODIUM OPTIMUM: 950MCM $5.54 PER FT.

CABLE PARAMETERS:
- UNIFORMLY LOADED 3 PHASE MAIN FEEDER
- 175MILS XLPE INSULATION
- 15 MILS CONDUCTOR SHIELD FOR AL,0 FOR NA
- 30 MILS INSULATION SHIELD FOR NA AND AL

OPERATING PARAMETERS:
- LOSS FACTOR=.18 PEAK RESPOSIBILITY FACTOR=.82
- FEEDER INPUT CURRENT 222 AMPS
- FEEDER OUTPUT CURRENT 70 AMPS
- PRESENT WORTH FACTOR=12
- AVERAGE AC RESISTANCE
  - AL 1.15 MICROOHMS PER CM
  - NA .99 MICROOHMS PER CM

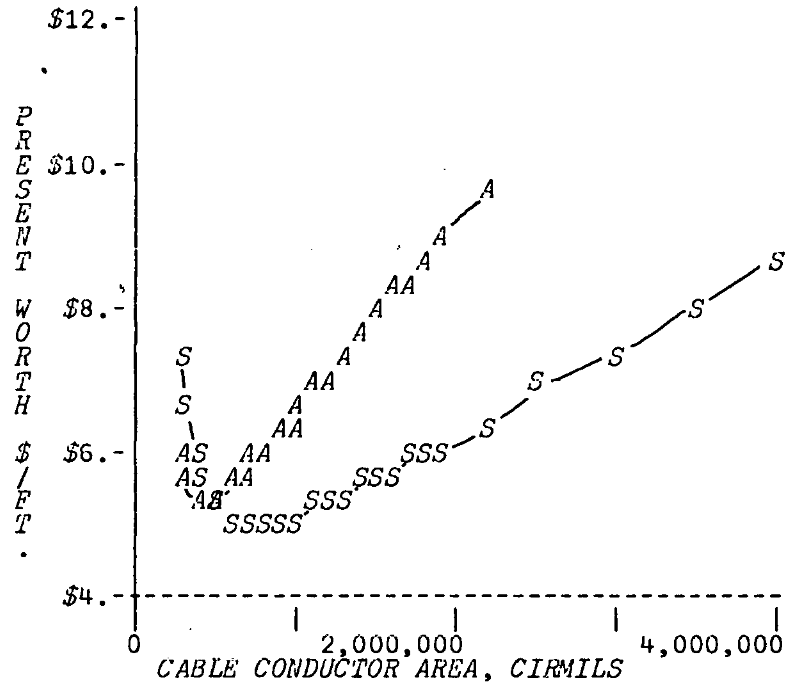
Figure 9-6





PRESENT WORTH OF CABLE COSTS AND OPERATING LOSSES VS. SIZE-15KV DIRECT BURIED.

Figure 9-7



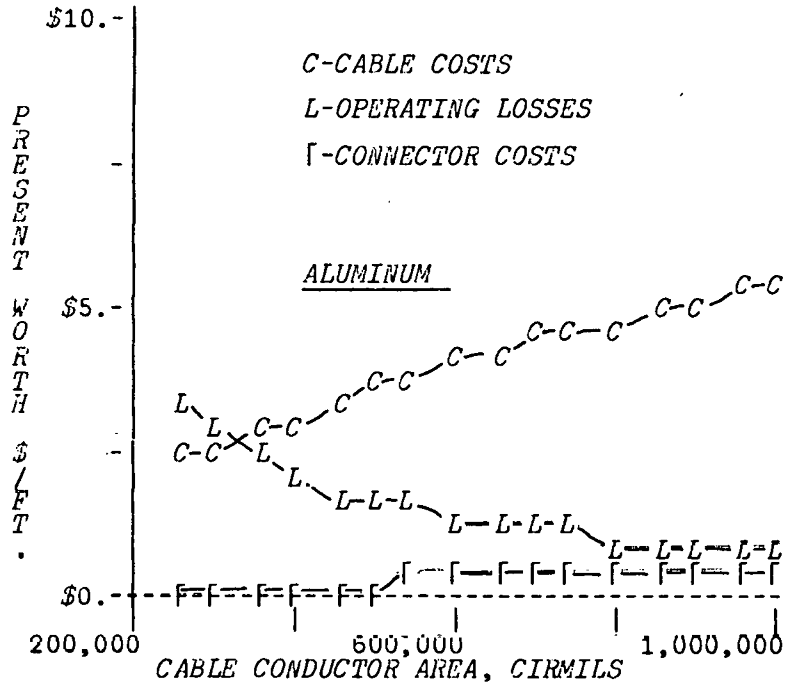
SODIUM AND ALUMINUM CABLE TOTAL PRESENT WORTH COSTS VS. CONDUCTOR SIZE-15KV IN DUCTS.

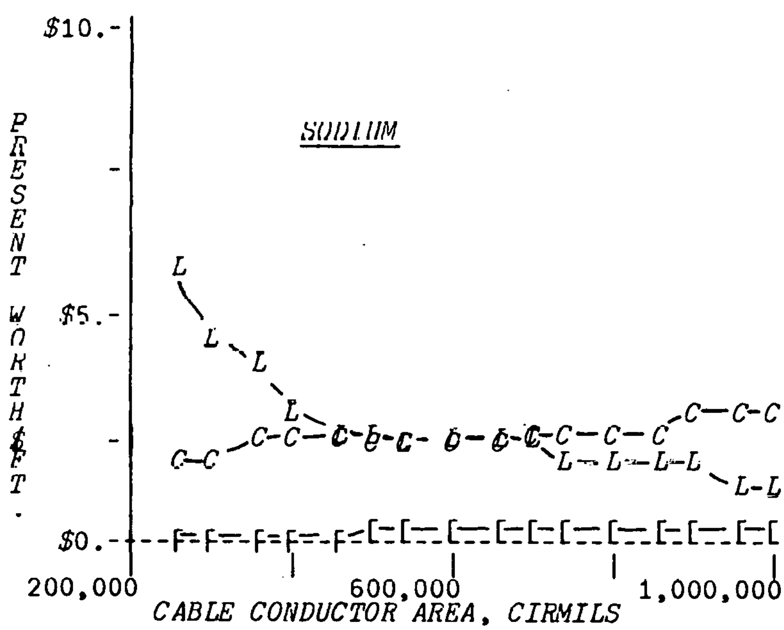
ALUMINUM OPTIMUM: 400*MCM* $5.38 *PER FT*.
SODIUM OPTIMUM : 740*MCM* $4.99 *PER FT*.

CABLE PAPAMETERS:
3 *PHASE UNIFORMLY LOADED FEEDER*
5 *INCH FIBER DUCT*
175 *MILS XLPE INSULATION*
15 *MILS CONDUCTOR SHIELD FOR AL*,0 *FOR NA*
30 *MILS INSULATION SHIELD FOR AL AND NA*

OPERATING PARAMETERS:
LOSS FACTOR=.18 *PEAK RESPOSIBILTY FACTOR*=.82
FEEDER INPUT CURRENT 188 *AMPS*
FEEDER OUTPUT CURRENT 59 *AMPS*
PRESENT WORTH FACTOR=12
AVERAGE AC RESISTANCE;*MICROOHMS PER CM*
AL 1.45
NA 1.28

Figure 9-8





PRESENT WORTH OF CABLE COSTS AND OPERATING LOSSES VS. SIZE-15KV IN DUCTS.

Figure 9-9

As discussed in Section 7, the thermal resistance is increased because of the added duct air space, therefore ampacity levels are reduced relative to the direct buried case. This results in lower losses (Figure 9-9) for both the sodium and aluminum cables. The reduction in losses results in the optimum sodium and aluminum cable being smaller in size thus reducing the net savings of sodium over aluminum. The optimum aluminum size for the duct case is 400 MCM and for sodium is 740 MCM. The total present worth savings for the 15 kV 250 MCM case is $0.39 or about 70% of that achieved in the direct buried case. The peak load current used in the evaluation is 188 amps or about 85% of the current in the 15 kV, 250 MCM direct buried case.

The 30% reduction in present worth savings may be extrapolated to other sizes and voltage ratings.

9.3.6.4 Analysis of the 600 Volt Secondary Application

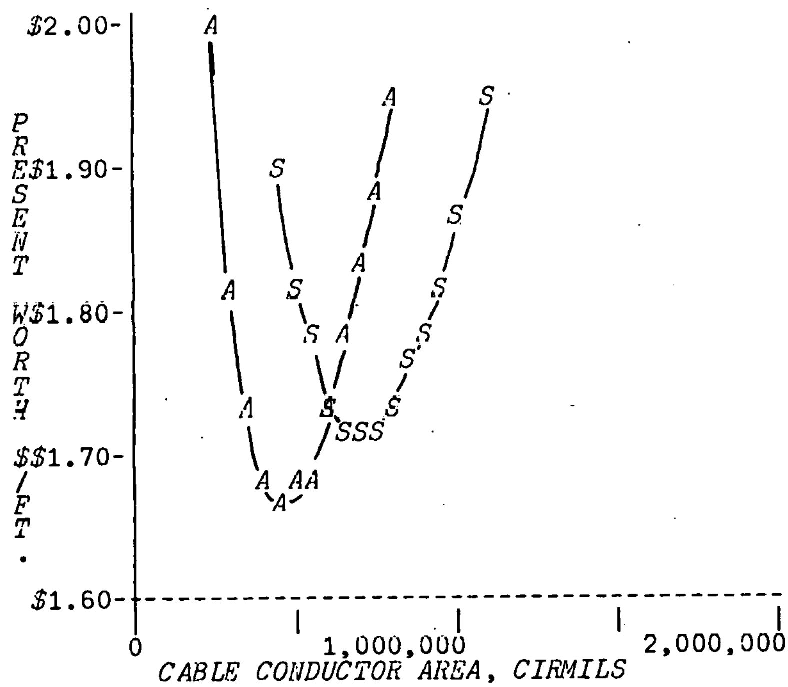
Detailed information on the 600 volt secondary application is shown in Figures 9-10 through 9-13. Figures 9-10 and 9-11 present the case with connector costs included while Figures 9-12 and 9-13 neglect connector costs.

9.3.6.5 Total Present Worth Savings 10 Years and 25 Years in the Future

Present worth savings in future years is presented in Tables 9-12 and 9-13. Cable and connector costs in the future are projected by using the indices in Table 9-3 to estimate component material cost. The indirect costs are escalated at an annual rate of 6%. Power costs are escalated at 5% annual to estimate losses in future years.

Since the indices in Table 9-3 project sodium and polyethylene costs to grow more slowly than aluminum costs, cable cost savings increase significantly in the future. Since power costs also are assumed to escalate, the savings in losses increases proportionally.

Savings for the 35 kV case (Table 9-13) increase by 2 in 1988 and by 5.73 by 2003. For the 15 kV case (Table 9-12), savings increase by 2.4 by 1988 and 6.6 by 2003.



SODIUM AND ALUMINUM CABLE TOTAL PRESENT WORTH COSTS VS. CONDUCTOR SIZE -600 VOLT SECONDARY APPLICATION

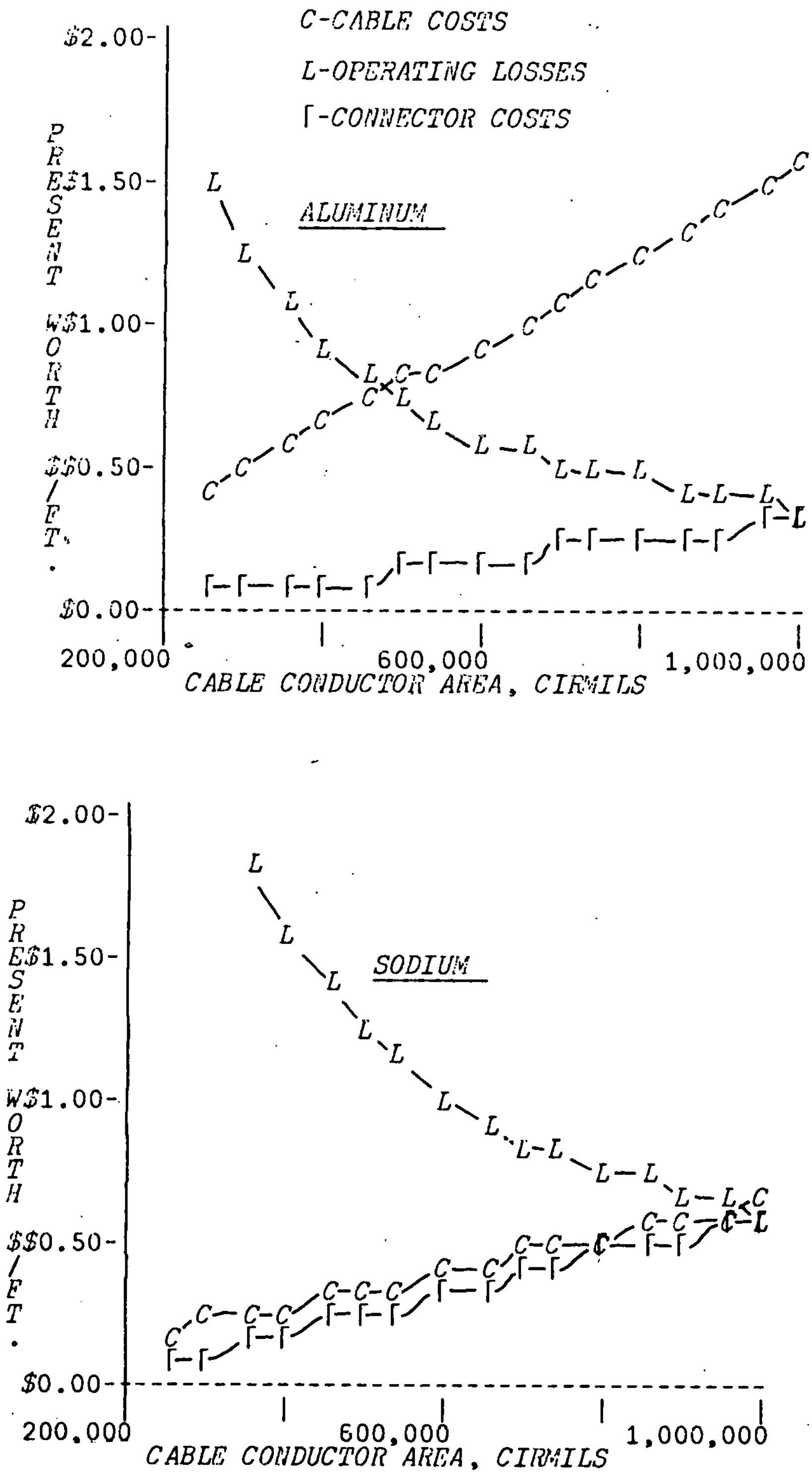
ALUMINUM OPTIMUM:	530MCM	$2.04 PER FT.
SODIUM OPTIMUM :	900MCM	$2.13 PER FT.

CABLE PARAMETERS:
600 VOLT DIRECT BURIED SINGLE PHASE SECONDARY
125 MILS XLPE INSULATION

OPERATING PARAMETERS:

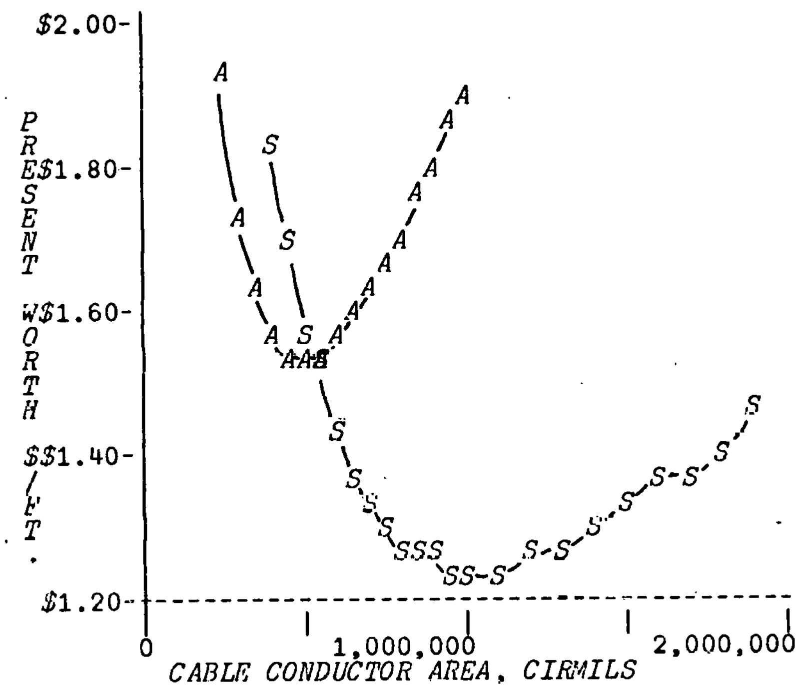
LOSS FACTOR=.074 PEAK RESPOSIBILITY FACTOR=.3
SECONDARY CURRENT 171 AMPS
PRESENT WORTH FACTOR=12

Figure 9-10



PRESENT WORTH OF CABLE AND OPERATING COSTS VS. SIZE - 600 VOLT SECONDARY

Figure 9-11

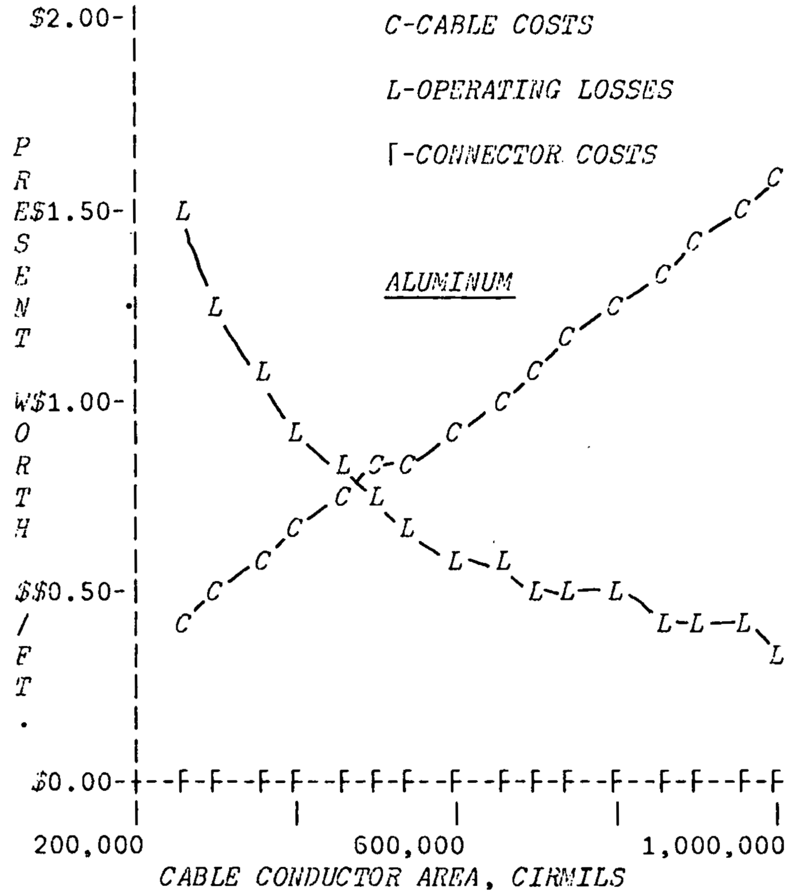


SODIUM AND ALUMINUM CABLE TOTAL PRESENT WORTH COSTS VS. CONDUCTOR SIZE-600 VOLT SECONDARY ,NEGLECTING CONNECTOR COSTS.

ALUMINUM	OPTIMUM:	500MCM	$1.54 PER FT.
SODIUM	OPTIMUM:	1000MCM	$1.24 PER FT.

(SEE FIG. 9.10 FOR OPERATING DETAILS)

Figure 9-12



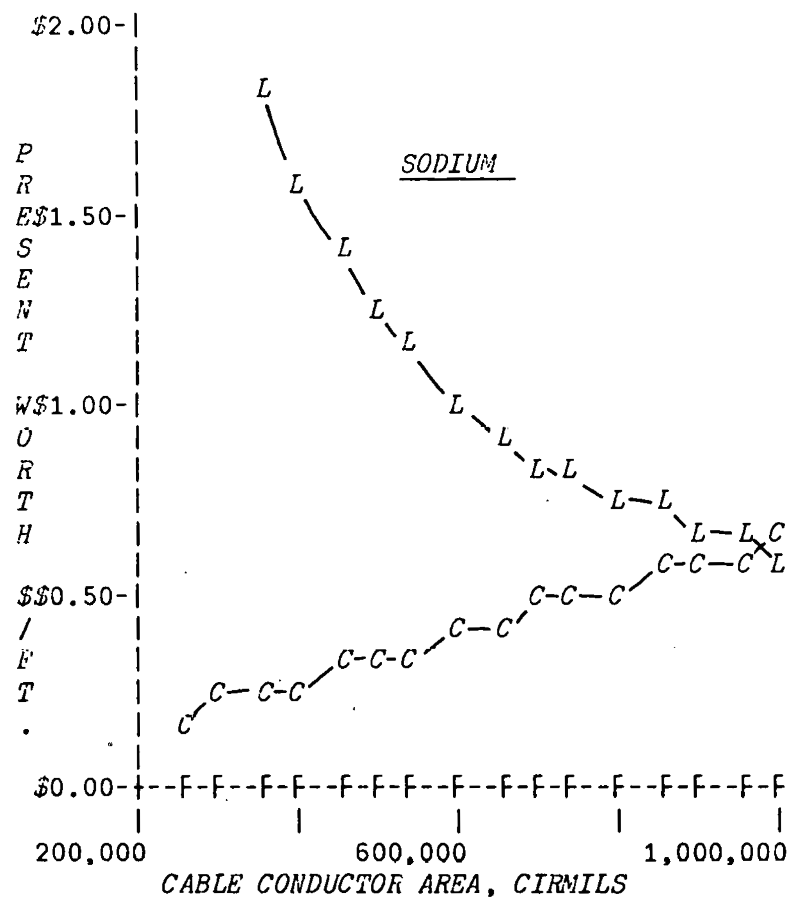


FIGURE 13. PRESENT WORTH OF CABLE COSTS AND OPERATING LOSSES VS. CONDUCTOR SIZE-600V SECONDARY.NO CONNECTORS.

Figure 9-13

TABLE 9-12

Present Worth Savings; Present, 10 Years, and 25 Years In the Future for 15 kV Cable

Present (from Table 9-11)

15 kV, 250 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 500 MCM	$3.576	$.204	$2.310	$6.09
Na 950 MCM	$3.231	$.322	$1.985	$5.538
	$ .345	$(.118)	$ .325	$ .552

10 Years In Future

	Cable Cost	Connector Cost	Losses	Total
Al 500 MCM	$7.120	$.424	$3.762	$11.306
Na 950 MCM	$6.093	$.665	$3.233	$ 9.991
	$1.027	$(.241)	$ .529	$ 1.315

25 Years In Future

	Cable Cost	Connector Cost	Losses	Total
Al 500 MCM	$16.82	$1.11	$7.82	$25.75
Na 950 MCM	$13.71	$1.66	$6.72	$22.09
	$ 3.11	$(.55)	$1.10	$3.66

TABLE 9-13

Present Worth Savings; Present, 10 Years, and 25 Years In the Future for 35 kV Cable

Present (from Table 9-11)

35 kV, 750 MCM Al Overload Current Capability

	Cable Cost	Connector Cost	Losses	Total
Al 850 MCM	$6.450	.4734	4.2912	11.215
Na 1700 MCM	6.030	.6990	3.2860	10.015
	.420	(.2256)	1.0052	1.20

10 Years in Future

	Cable Cost	Connector Cost	Losses	Total
Al 850 MCM	12.636	.984	6.99	20.61
Na 1700 MCM	11.397	1.444	5.35	18.10
	1.239	(.46)	1.64	2.42

25 Years in Future

	Cable Cost	Connector Cost	Losses	Total
Al 850 MCM	30.315	2.576	14.53	47.42
Na 1700 MCM	25.869	3.603	11.07	40.542
	4.446	(1.027)	3.46	6.88

Savings increase from approximately 10% of total present worth costs in 1978 to 15% by 2003.

9.3.6.6 Comparison of Installed Costs

The installed costs for the 15 kV and 600V cable systems are shown in Table 9-14. The cable and connector costs are those previously developed based on Figures 9-2, 9-3 and 9-4. Installation costs are taken from the Task I survey of electric utilities.

From the survey of utilities using sodium cable, it was determined that installation costs were approximately the same for either the sodium or aluminum system. Although connectors were mentioned to be much more expensive for sodium, they were not claimed to be any more time consuming or expensive to install.

Examination of Tables 9-11 and 9-14 shows total present worth savings for the 15 kV system to be approximately 10% of the sum of total present worth costs and total installed connector and cable costs.

9.4 Salvage and Disposal Costs

Once a particular sodium distribution cable has reached the end of its useful life, two logical procedures may be followed. Either the cable is de-energized and abandoned or it is dug up and reprocessed.

Because of the hypothesized hazards of sodium, some have conjectured that the sodium cable must be recovered and recycled. The estimated costs for this recovery and recycle are shown in Table 9-15.

Recovering and recycling results in added cost for the smaller sizes that offsets almost 50% of the initial savings. Recovery for the larger sizes results in an added scrap value due mainly to the copper recovery.

Consideration of salvage and disposal costs with preceding cost analysis in Tables 9-10 and 9-11 once again emphasizes the increased savings for sodium in larger sizes.

TABLE 9-14

Estimated Installed Costs Per Foot For
Sodium and Aluminum Cable

15 kV 3ϕ Primary

	Al (500 MCM)	Na (950 MCM)
Prepare Ditch	$ .45	$ .45
Cable Cost	$3.576	$3.231
Installing Cable	$ .31	$ .31
Connector Cost	$ .204	$ .322
Installing Connectors	$ .60	$ .60
Total Installed Connector and Cable Cost	$5.14	$4.91

600V Secondary

	Al (530 MCM)	Na (900 MCM)
Prepare Ditch	$ .45	$ .45
Cable Cost	$ .84	$ .58
Installing Cable	$ .16	$ .16
Connector Cost	$ .15	$ .54
Installing Connectors	$ .09	$ .09
Total Installed Connector and Cable Cost	$1.69	$1.82

TABLE 9-15

Cable Salvage and Disposal Costs Per Foot

15 kV 3ϕ Primary

Operation	Na (950 MCM)	Na (2155 MCM)
Redigging and Refilling Trench	$(.45)	$(.45)
Land Reclamation	$(.20)	$(.20)
Pulling Cable	$(.31)	$(.31)
Cable Reprocessing	$(.04)	$(.08)
Sodium Salvage Value	.25	.57
Copper Salvage Value	.53	1.03
Net Recovery Value	$(.22)	$ .56

9.5 Future Market Survey for Energy Savings

In Table 9-16 the annual energy savings of sodium over aluminum cable for a specified market penetration is estimated. It is assumed that sodium cable would achieve a 10% market share by 1980, 50% by 1985 and 100% by 2000. This optimistic scenario is used only to get a maximum credible savings for sodium. With this scenario and the assumptions footnoted in Table 9-16, almost 2 billion kWh could be saved annually by year 2000 or equivalently 3.4 million barrels of oil.

9.6 Conclusions from the Economic Analysis

A summary of the analyses performed in this section may be expressed in terms of the economic incentives and barriers for using sodium distribution cable.

- The present worth costs of owning and operating sodium cable on a typical underground primary distribution feeder yields a savings of approximately 10% when compared to aluminum.
- For an "express type feeder" operating at unity load factors a present worth savings of 30% for sodium relative to aluminum is possible.
- A comparison of equivalent ampacity sodium and aluminum cable costs only, yields a range of savings from 1% to 15% depending on size and voltage and choice of insulation. The maximum savings in the scope of this study is the lowest voltage, largest size (Al 600V, 1000 MCM - Na 600V, 2196 MCM).
- With an optimistic market penetration, energy savings could approach 2 billion kWh annually by the year 2000. (One nuclear power plant produces 7 billion kWh annually base load).

TABLE 9-16

Annual Energy Savings of Sodium Over Aluminum Cable for Specified Market Penetration

	1980	1985	2000
Na Loss Savings Relative to Al			
peak loss (kW/mi)	6.336*	6.336*	6.336*
avg. loss (kW/mi)	1.140	1.140	1.140
Total UG Distribution Cable Installation each year (mi)**	9730	11,280	17,575
Sodium UG Distribution Cable Installed Cumulative (mi)	973	14,973	196,973
Annual Energy Savings Due to Cumulative Na Cable Installation	9717	159,512	1,967,041
Electric Generation Fuel*** Annual Savings			
million Btu's	$.097 \times 10^6$	1.595×10^6	1.967×10^7
equiv. 10^6 bbls of oil	.017	.28	3.4

*Calculation of peak and average loss assume uniformly loaded 3ϕ feeder 250 kcmil cable size used for this estimate since it is closest to typical utility size.

Average ampacities for 15 kV, 25 kV, and 35 kV taken from Tables A3-3 and A3-6:

		feeder in; I_1	feeder out; I_2
amapcity	367	367	367
full load current (amps	367	217	70
R_{ac} μΩ/cm Al	2.9	2.73	2.24
R_{ac} μΩ/cm Na	2.14	2.03	1.75
Conductor Temp Al	90°C	∿70°C	∿20°C
Conductor Temp Na	69°C	∿50°C	∿20°C

$$PWL_{peak} \; (I_1^2 + I_1 I_2 + I_2^2) \; R_{ac(avg.)} \times 30.5 \frac{cm}{ft} \times 5.28 \frac{ft\text{-}kW}{w\text{-}mi}$$

$$PWL_{peak} \; (Al) = (217^2 + 217 \times 70 \times 70^2) \; 2.49 \times 30.5 \times 5.28 = 26.9 \frac{kW}{mi}$$

$$PWL_{peak} \; (Na) = (217^2 + 217 \times 70 \times 70^2) \; 1.89 \times 30.5 \times 5.28 = 20.5 \frac{kW}{mi}$$

$$PWL_{peak} = 6.336 \text{ kW/mi}; \quad PWL_{avg} = PWL_{peak} \times LSF; \quad PWL_{avg} = (6.336)\,(.18) = 1.14 \frac{kW}{mi}$$

**13th Electrical World T&D Survey, August 15, 1978, Reference 81
Single Phase Converted to Equivalent 3 Phase miles

***Assumed 10,000 Btu/kWh Heat Rate

- Connector costs at present are significantly higher (1.1 to 2 times) for sodium than aluminum. Even with improved designs there are reasons to believe sodium connector costs will remain significantly above the aluminum.
- A salvage and disposal cost penalty for sodium cable for sizes below 1000 MCM is possible.

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APPENDIX A1

Annotated Bibliography of Publications Related to Sodium Conductor Cable

BIBLIOGRAPHY OF PUBLICATIONS RELATED TO SODIUM CONDUCTOR CABLE

1. "A 4000-Ampere Sodium Conductor", R. H. Boundy, Trans. Electrochem. Soc., 62, (1932).

   The installation of a 4000 amp. conductor, 850 feet (259 m) long consisting of iron piping filled with sodium metal is described in detail. The weight per unit conductivity is decidedly less than for copper, and the cost per running foot of conductor is approximately the same. The installation has been in successful use for several years.

2. "Surface and Volume Phenomena in Dielectric Breakdown of Polyethylene", E. J. McMahon, J. R. Perkins, AIEE Transactions, Vol. PAS-82, pp. 1128-35 (December 1963).

   This is a progress report on the authors' studies of the mechanism of long-term dielectric breakdown in polyethylene; the report was first given in 1948. Testing has been accelerated by using higher than power frequencies. Earlier testing concerned the effects of surface ionization on life; current studies include solid breakdown. To date the authors have been unable to produce solid breakdown in polyethylene which was not preceded and caused by surface ionization.

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6. "Evaluation of Sodium Conductor Power Cable", A. E. Ruprecht and P. H. Ware, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-86, No. 4, April 1967.

The suitability of the newly developed polyethylene insulated sodium conductor for use in electrical power cables was evaluated electrically and mechanically. Polyethylene-insulated sodium conductors are shown to lend themselves to a wide range of constructions manufactured on standard cable-fabricating equipment. Because of the plastic nature of metallic sodium, neither conductor stranding, nor helical assembly in the case of multiconductor cables, is required for flexibility.

Within the limitations of polyethylene insulation, sodium conductors withstand greater short circuit currents for any given duration than do copper or aluminum conductors. Corona levels and over-voltage test results are satisfactory. Conductor shielding appears to be unnecessary up to 15 kV. Higher ac step-rise dielectric strengths are obtained than those normally found in conventional cables using the same insulation. Impulse and load cycle tests show normal results.

Polyethylene-insulated sodium conductors may be pulled into conduits much more easily than insulated copper conductors. Experience with field handling of aerial and of direct-buried sodium-conductor cables has been excellent. The cables withstand moderately severe physical abuse without damage. They have the unique ability to be stretched 25 percent and then to recover substantially their original length and electrical resistance.

7. "Sodium as a Conductor of the Future", L. E. Whitmore, New Scientist, May 11, 1967, pp. 347-348. No Abstract.

8. "Drawing of Insulated Sodium Conductor", L. E. Humphrey, G. I. Addis, and Raymond C. Hess, IEEE Transactions on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The preparation of high strength, small diameter sodium wire is discussed. A new production method consisting of spontaneous extrusion of conductor and insulation followed by high speed drawing and annealing of the composite is described. The influence of polyethylene properties and process conditions on the characteristics of the wire is shown. Resistance to damage through crushing is of particular note because the soft conductor does not act as an anvil to cut the insulation. The wire has high tensile strength, especially in the smaller sizes. Permeability to water vapor is a problem but practical means of combating it already are in use in other services. Development of reliable long life connectors is required for future applications.

9. "Insulated Sodium Conductors", L. E. Humphrey, R. C. Hess, and G. I. Addis, IEEE Transactions on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The development and characterization of a new polyethylene insulated sodium conductor are described. The resistivity, specific gravity, and cost of sodium are compared to corresponding properties of copper and aluminum. While the alkali and alkaline earth metals have relatively good electrical conductivity, sodium was chosen because of its light weight, low cost, and availability. Physical properties of the polyethylene insulated sodium conductor were determined. Potential areas of question, such as service life, reaction of water with damaged cables, and combustion characteristics are covered in detail.

10. "The Development of Connectors for Insulated Sodium Conductor", I. F. Matthysse and E. M. Scoran, IEEE Transactions on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The characteristics of insulated sodium conductor required the development of a new type of connector and a new installation technique. The problems involved making stable electrical contact to the sodium, sealing against chemical attack, installation with a minimum exposure of sodium, securely gripping the insulation, effects of the melting point of sodium, and temperature limitations of the insulation.

11. "Field Trials on 15-kV and 600 Volt Sodium Cable", Edward J. Steeve, and James A. Schneider, IEEE Transaction on Power Apparatus and Systems, Vol. 86, No. 7, July 1967.

The use of sodium conductor cable presents an opportunity for reduction in cost of cable for underground residential distribution systems. In order to evaluate its usage a direct buried test installation was made involving both 15 kV and 600 volt sodium cable. Testing the 15 kV cables consisted in load cycling, short-circuit faulting, and fault location tests. After the completion of tests on the 15 kV sodium cable, a service installation was made in a rural area west of Chicago. Load cycle tests were also made on the 600 volt sodium cable. This included an overload which resulted in the failure of the cable at the terminal. Insulation damage tests were made to determine the corrosive properties of the conductor. Fault locating tests made on the 600 volt cable, as on the 15 kV cable, showed that presently available equipment should be adequate.

12. "Comparative Costs of European Distribution Cables in Economics of Reliability of Supply", N. B. Hennett, IEEE cont. Publ. 34, 1967, pp. 277-287. No Abstract.

13. "The Economics of Sodium Cable Changes the Design of Underground Systems", by E. P. Verheiden, Portland General Electric (T&D). No Abstract.

14. "Improved Connectors for Insulated Sodium Conductors", S. Gerhard, Paper 45, PRN, IEEE Winter Power Conference, January 1968.

Progress toward the development of a new connector for insulated sodium power conductor is reported. Performance and design criteria are outlined and the development program to achieve the criteria is discussed. The connector construction and installation techniques are described and preliminary performance test data presented.

15. "Dig-in Tests on Sodium Conductor Cables," E. J. Steeve, IEEE Winter Power Meeting, New York, New York, January 28 - February 2, 1968.

Two sets of dig-in tests on sodium conductor, polyethylene insulated cables were made by the Commonwealth Edison Company. The first series of tests were made on de-energized 15 kV and 600 volt cables using both power machinery and hand tools. About one year later, a second series of dig-in tests was made on 600-volt cables energized at 120/240 alternating volts, using three types of power machinery.

In most cases, the degree of reaction was less than expected despite extremely wet soil conditions from heavy rainfalls previous to the tests. It appears that the probability of causing human injury due to the cutting of an energized sodium conductor cable is no greater than that for either a copper or an aluminum conductor cable. However, during various digging operations, there is always a chance that small raw sodium chips can be brought to the surface of the ground; this presents a possible safety hazard if they are not removed.

16. "A Progress Report on Sodium Conductor Power Cable", T. H. Kelly, IEEE Paper No. 68, CP 62-PWR (1968).

Experimental sodium conductor cables, insulated with polyethylene were manufactured without strand shielding and tested to determine the suitability of this construction for service under high humidity conditions and for voltages above 15 kV. Samples were tested after five months immersion in 75°C water with no significant decrease in corona level. Cable samples rated at 34.5 kV and 69 kV and without strand shielding have been evaluated by dielectric strength and load cycle tests with satisfactory results.

17. "Irradiated Polyethylene Insulation for Sodium Conductor Cable," R. M. Eichhorn and G. I. Addis, IEEE Winter Power Meeting, New York, Paper No. 68 CP 61-PWR (1968).

Laboratory studies of severely overloaded sodium conductor cables, insulated with both normal and irradiated polyethylene, have been made. Excessive overloads cause melting of the sodium and subsequent open circuiting of the conductor. In an overloaded vertical riser, pressure develops from the formation of a hydrostatic head. Irradiated polyethylene provides two advantages over regular polyethylene in this situation. First it withstands the hydrostatic pressure and prevents the release of molten sodium and second it provides moderately longer life under the given overload.

18. "Bistable Operating Temperatures and Current Rating of Sodium Conductors", J. Hus, IEEE, 1968, PAS-87, pp. 367-371.

Unlike conventional cables, the operating temperature of sodium cable lies close to its melting point. Although this does not affect the current rating at normal ambients, one cannot reap the full current rating benefits which normally accrue from a lowered ambient temperature. This paper describes how the ambient temperature affects the maximum operating temperature of sodium cable.

19. "Sodium Cable? 'Why Not, Ask PGE,' " Eric P. Verheiden, Electric Light and Power, August 1968.

Sodium cable is different, not difficult, claims PGE after installing 11,000 ft to serve 36 lots. But a complete review of URD design standards and operating practices may be needed to fully exploit this cable in the future.

20. "Sodium is New Cable Conductor," Norman Peach, Power, September, 1968.

Sodium has many advantages as a cable conductor, among them light weight, extreme flexibility, abundant supply, ease of manufacture. Its major disadvantage -- its reactivity with water and oxygen -- can be offset by reasonable precautions.

21. "Sodium Conductor for Power Cables," R. J. McAnulla, Electronics and Power, 1968, 14, pp. 434-436.

Large economies in electricity-supply costs have been achieved in the past few years owing to the changeover from copper to aluminum as a material for cable conductors; the prospect of further sizable savings has prompted the investigation and development of polythene-insulated sodium conductors. As well as giving a possible capital saving of up to 50% over aluminum cables, the use of sodium cables can also lead to great economies because of the ease of handling and jointing.

22. "Kable Mit Natriumleitern", Von Hans K. Vierfub, Köln-ETZ-B Bd. 20 (1968) H. 9. (Cables with Sodium Conductors)

In the last few years cables with sodium conductors and polyethylene insulation have been developed in the United States. In order to assess the value of this new type of cable, short lengths of sodium conductor cables have been manufactured and subjected to tests. Among the facts established is that sodium conductors withstand practically no tensile forces. After the insulation has been damaged, the conductor in a cable laid in air reacts chemically with the air moisture. The reaction with water may result in explosion. The sodium conductor in an undamaged cable is decomposed only very slowly as a result of diffusion of moisture through the polyethylene insulation. At points where there is a short-circuit it may ignite. Comparisons of costs showed that with the usual types of cable construction in Germany, and the conductor cross-sections generally used, at least when compared with cables having aluminum conductors, no price advantage is to be expected at the moment from the use of sodium cables.

23. "RF Performance Evaluation of Sodium Conductors", R. S. Hartman and R. Gardner, Tracor Inc. New York, New York Lab, Report No. Trancor-NYL-69-8, March 15, 1969.

The radio frequency performances of equivalent copper and sodium conductors in equivalent typical ground plane configurations were measured and compared. Ground plane losses derived from field measurements of both electrically short, and quarter wavelength, vertical antennas were essentially the same for radial ground planes composed of either sodium or tinned copper radials used on the surface of the ground, or buried six inches. No evidence was found of nonlinear effects in the sodium-copper metal junction used to join the sodium conductor to a copper connector in either the field measurements or in laboratory tests when a good connection and seal was in effect. Laboratory tests, conducted under severe conditions, however, showed probable failure of the connector seal with time.

24. "Sodium Conductors Selected for Both Primary and Secondaries," P. E. Watson, R. A. Siliano, Transmission and Distribution, Vol. 21, No. 5, pp. 102-4, May 1969. No Abstract.

25. "Sodium Cable Outgrows Trial Status, is Used as Feeder Main," (Author not identified), Electrical World, October 13, 1969. No Abstract.

26. "Sodium Cable Installation Yields Significant Savings in Initial Cost," (Author not identified), Transmission & Distribution, November 1969. No Abstract.

27. "Insulated Sodium Conductor -- Has it a Future in Britain?", V. S. Davey and J. Rye, Electronics & Power, pp. 395-99, November 1969. No Abstract.

28. "Sodium Conductors for Power Distribution," IB Bentzen-Biekvist, Electrical Construction and Maintenance, Vol. 68, No. 12, pp. 76-8, December 1969. No Abstract.

29. "Field Service Experience with Sodium Conductor Cable," R. L. Garrison, IEEE Conf. Rec. Special Tech. Conf. on Underground Distribution, Anaheim, California, pp. 386-95, May 12-15, 1969.

This paper discusses the experience with sodium conductor cables in field service installations. It includes:

1. Summary of the sizes and voltage classes of sodium cable installed by the utilities.

2. Description of typical installations of various voltage classes.

3. Accessory hardware problems encountered.

4. Observations from the field on work practices and results recorded to date.

5. Product modifications designed to assist Operating Departments in the handling of the sodium conductor cable.

6. Conclusions.

30. "Measurement of Water Vapor Transmission Through Polyethylene Electrical Insulation," R. M. Eichhorn, Polym. Eng. Sci., Vol. 10, No. 1, pp. 32-7, January 1970.

A method is described for measuring the rate of water vapor transmission through thick sections of polyethylene used as insulation on electrical conductors of pure sodium metal. The technique could be generally useful for materials which do not react with sodium, and for cylindrical samples which can be filled with molten sodium in a dry box. For samples with uniform dimensions the results are extremely precise because sensitive electrical measurements are used. Specimens of products in final form can be employed to determine the effects of variations in processing.

31. "PP&L Co. Experience with 15 kV Sodium Conductor Cables," Frank R. Nickel, Pennsylvania Power & Light Co., Allentown, PA, Doble Client Conference, Boston, MA, April 13, 1970. No Abstract.

32. "Sodium Secondary Cable Being Used on a Regular Basis at NW Utility," by E. P. Verheiden, Portland General Electric Co., Transmission & Distribution, August 1970. No Abstract.

33. "Battle of the Conductors," D. Edgington, Underground Eng. Vol. 1, No. 2, August-September 1970, pp. 31-3. No Abstract.

34. "Hat das Natriumkabel Aussicht in England?", ETZ-B Bd. 22 (1970), H.11. No Abstract.

35. "Kunststoffe beeinflussen Kabeltechnik," Von Ing. Joachim Hospe, Frankfurt/Main, Draft-Welt Dusseldorf 56 (1970), No. 9.

36. "Design Considerations and Applications of Permanent Power Fuse", Foshio Sto, Foshio Miyamoto, Yuichi Waao Mitsubishi Electric Corp., presentation at the IEEE Winter Meeting New York, NY Paper No. C 72 103-5, January 30 - February 4, 1972. No Abstract.

Permanent Power Fuse, which is called by the abbreviated name P.P.F., is an entirely new reusable fuse with excellent current limiting performance developed by Mitsubishi Electric Corp. of Japan. Since our first announcement on the development of the P.P.F., the low voltage series up to 800 A has been completed by establishing the refined reasonable design specifications of the P.P.F. The applications of the P.P.F. have thus been remarkably advanced. In this paper, the design considerations and the typical applications of the P.P.F.s are described.

37. "Zum Problem der Rationellen Gestaltung der Leiternennquerschnittsreike für Starkstrombabel", N. Astachov, A. A. Glasunov, V. I. Grieseav, and N. Fetzlow, Moskau, Energientechnik, 23 Jahrang, Heft 10, October 1973. No Abstract.

38. "Experience with Sodium -- A New Conductor", W. L. McVey, Electrical World, pp. 51-59, May 1, 1975. No Abstract.

39. "Experience with Sodium Conductor - Part II", Electrical World, May 15, 1975, pp. 58-59. No Abstract.

40. "Thermal Failure of High Voltage Solid Dielectric Cables", P. Graneau, IEEE Power Eng. Soc. Tempt "A" paper from the Winter Meeting, New York, New York, January 25-30, 1976.

This paper suggests that many of the failures of high voltage solid dielectric cables are the result of a mismatch in thermal expansion and deformation modulus between the metallic and dielectric components of the cable. For a number of cable designs the differential thermal expansion has been calculated. When this quantity is less than one percent the cable performance appears to be satisfactory. A qualitative analysis of the thermally induced forces and motions is presented. It reveals that a mechanically weak conductor, such as sodium, greatly reduces mechanical stresses and plastic deformation of the high voltage insulation.

APPENDIX A2

Questionnaire for Utility Survey

Utility Survey

This appendix presents the questionnaire sent to 49 utilities to obtain information about their sodium conductor cable installations. Noted on the questionnaire form are the response rates to each question. A surprising number of utilities (75%) did respond to the questionnaire, which says much about their interest in sodium cable, and their public spirit.

QUESTIONNAIRE FOR UTILITY SURVEY

Date: ______________________________

Utility Name: ______________________________

Utility Address: ______________________________

____

Telephone Number: ______________________________

Utility Site or Branch: ______________________________

1st Person Contacted: ______________________________

Title: ______________________________

2nd Person Contacted: ______________________________

Title: ______________________________

3rd Person Contacted: ______________________________

Title: ______________________________

How Contact Was Made: ______________________________

____

Remarks: ______________________________

____

____

____

____

1.0 SODIUM CABLE EXPERIENCE

	Response Rate
1.1 How much Na cable have you used or tested? ______________	100%
1.1.1 Was cable procured for normal service? _____ or special test? _____	97%
1.1.2 Was cable purchased? _____ If so what price? __________	84%
1.2 Cable Specifications	
1.2.1 Voltage class ______________	95%
*1.2.2 Size, ampacity or Cu equivalent ______________	89%
1.2.3 Was Polyethylene insulation cross linked? Yes ___ No ___	86%
1.2.4 Does cable have a semiconducting layer? Yes ___ No ___	86%
1.2.5 Is there a concentric neutral? Yes ___ No ___	86%
1.2.6 Is there a Jacket? _____ If so what type? __________	89%
1.2.7 Does cable meet any industry standards?	51%

IPCEA ________ Section ______________

AEIC ________ Section ______________

NEC ________ Section ______________

UL ________ Section ______________

Other ________

1.3 Cable Installation	89%

1.3.1 Direct Buried ______________ ft ______________

1.3.2 In Duct ______________ ft ______________

1.3.3 Aerial ______________ ft ______________

1.3.4 Other ______________

---

*Who determined the CuE Rating? Mfg. _____ Utility ________

		Response Rate
1.4	**Cable Load History**	
1.4.1	Energized Voltage ________ Time ________	89%
1.4.2	Avg. Current ________ Duty Cycle ________	65%
1.4.3	Maximum Current ________ Time ________	54%
1.5	**Operating Experience**	
1.5.1	Date cable went into service or started testing ________	86%
1.5.2	Date cable removed from service or completed test ________	86%
1.5.3	Were there any operating difficulties or failures? ________	89%
1.5.4	Was operation any different than with Cu or Al? ________	86%
1.6	**Operating Expenses**	
1.6.1	Operating cost in power loss ________	35%
1.6.2	How does this compare with equally rated Cu ________, Al ________	19%
1.6.3	Other operating costs ________	30%
1.7	**Installed Cable Cost**	
1.7.1	What was installed cable cost? ________	49%
1.7.2	How does this compare with Al ________, Cu ________	32%
1.7.3	How does cost break down?	19%
	Digging trench or installing duct ________	
	Laying or pulling cable ________	
	Cable cost ________	
	Making terminations or connections ________	
	Connector cost ________	
	Other ________	

	Response Rate
1.7.4 Depreciation Schedule ______	39%
Is it the same as for Al ______ Cu ______	
1.8 Installation Difficulties or Observations	
1.8.1 What installation difficulties were encountered ______ ______	84%
1.8.2 Compare installation experience with Al and Cu of same rating ______	62%
1.8.3 How many connections or terminations were made? ______	70%
1.8.4 Compare installation or connector with those for Al and Cu ______	59%
1.9 Maintenance	
1.9.1 What were cable maintenance costs? ______	59%
1.9.2 Were there any maintenance problems? ______	68%
1.9.3 Compare maintenance with Al ______, Cu ______	49%
1.9.4 Were there any special maintenance practices followed for Na cable? ______	62%
1.10 Safety Provisions	
1.10.1 Were there any special safety provisions followed for:	
1. Storing cable ______	70%
2. Installing cable ______	
3. Operating cable ______	
4. Disconnecting cable ______	
1.10.2 What was done with cut off sections when making connections? ______	76%
1.10.3 What was done or what do you plan to do with cable when removed from service? ______	76%
1.10.4 Do you consider an abandoned Na cable a problem? ______ If so, how? ______	73%

2.0 OPINION OF SODIUM CABLE FOR DISTRIBUTION NETWORKS

		Response Rate
2.1	What are your observations and feelings about the sodium cable used by your organization?	92%
2.2	Would you recommend that your organization use sodium cable if it were readily available and if there was a cost advantage?	89%

		Response Rate
2.3	What do you think is the biggest obstacle to the utilities accepting sodium cable for extensive use in distribution systems?	86%
2.4	What other disadvantages are there for using Na cable?	70%
2.5	What are the benefits of using Na cable?	84%
2.6	Any other comments about sodium cable?	51%
2.7	What tensile strength and what pulling temperature would you specify for sodium cable?	57%

3.0 COST OF DISTRIBUTION CABLE INSTALLATIONS

		Response Rate
3.1	What is the average installed cost (per ft. or mile) of direct buried 250 kcmil:	
3.1.1	600 V Al ______	41%
3.1.2	600 V Cu ______	24%
3.1.3	15 kV Al ______	32%
3.1.4	15 kV Cu ______	24%
3.1.5	25 kV Al ______	19%
3.1.6	25 kV Cu ______	14%
3.1.7	35 kV Al ______	22%
3.1.8	35 kV Cu ______	22%
3.2	What is average operating costs for direct buried 15 kV:	
3.2.1	250-kcmil Al ______	19%
3.2.2	250-kcmil Cu ______	19%
3.2.3	1000-kcmil Al ______	16%
3.2.4	1000-kcmil Cu ______	16%
3.3	How do these costs break down?	
3.3.1	Preparing ditch or duct ______ %	27%
3.3.2	Installing cable ______ %	27%
3.3.3	Cable cost ______ %	27%
3.3.4	Connector cost ______ %	24%
3.3.5	Installing connectors ______ %	24%
3.3.6	Operating cost ______ %	14%
3.3.7	Maintenance cost ______ %	14%
3.3.8	Other ______ %	8%

APPENDIX A3

Ampacity Tables

In order to calculate the ampacity of a sodium or aluminum cable it is necessary to know the alternating current resistivity of the conductor. This is the product of the skin-effect factor β (see Paragraph 7.4.1 and Fig. 7-4) and the direct-current resistivity. The latter is given for sodium in Table A3-1, calculated by Eq. 7-16, and for aluminum in Table A3-2, calculated by Eq. 7-15. Values are given at 1°C temperature intervals from 0°C to 98°C for sodium. (A supplementary table in the test, Table 7-5, gives some values for molten sodium).

The calculation of ampacities in the tables, when the temperature is given, proceeds straightforwardly by use of Eq. 7-13 for directly buried cable or Eq. 7-26 for cable in duct. This was conveniently done via a programmable disk calculator. When, however, the current is known and the operating temperature is desired, the calculation is not so direct since the dc resistivity (and therefore also the skin-effect factor) depends on the as-yet-unknown temperature. It was found to be very easy to run the calculation for a few temperatures and interpolate to find the temperature which yielded the known current; after a little initial experience this inverted procedure required only two or three repetitions to yield the desired temperatures. For brevity, only the final results of such calculations are tabulated. All ampacities are to the nearest ampere, and temperatures are to the closest half-degree centigrade.

Tables A3-3 through A3-6 are those for the calculation, in the direct-burial case, of the equivalent sodium cable, as outlined in Paragraph 7.1.1, for aluminum cable of conductor cross-sections of 1000, 750, 500 and 350 KCM, in voltage ratings of 15, 25, and 35 kV. Tables A3-7 and A3-8 repeat the process but for 600 volt cable, using the insulation thicknesses specified by IPCEA for that voltage. In consideration of the possibility that thicker insulation might be of interest for reasons of mechanical strength (although as concluded in Paragraph 7.3.3 the IPCEA specified thicknesses appear adequate), and in order to illustrate the variation of the equivalent sodium cross-section with choice of insulation thickness for a fixed ampacity, these equivalence calculations were repeated using (for the sodium only, not for the aluminum) greater insulation thicknesses, .160 inches in Table A3-9 and .205 inches in Table A3-10. Tables A3-11 through A3-18 repeat this same sequence of calculations for cable in duct. Tables A3-19 and A3-20, which describe the ampacity variation with insulation thickness for a fixed sodium conductor size for direct burial and for cable in duct respectively, are the basis for Fig. 7-2. Tables A3-21 and A3-22 repeat the equivalence calculation of Tables A3-3 through A3-6 for the 25 kV case but with ρ_e = 130 in Table A3-21 and with α = 1 in Table A3-22, to illustrate that the diameter of the equivalent sodium conductor is very insensitive to the choice of these parameters. Tables A3-23 and A3-24 were prepared in order to verify the calculation procedure of Paragraph 7.4.1 by comparing its predictions to the IPCEA tables. Differences from the latter, as noted in the tables, are of the order of a percent.

The definition and units for the symbols used in the tables are given in the following list.

DEFINITIONS FOR APPENDIX A3 TABLES

In these tables:

δT = temperature rise from earth ambient to cable conductor (latter assumed isothermal), °C.

α = ratio of shield (neutral, drain wires) losses to core losses.

ρ_e = earth thermal resistivity, °C cm/watt.

t_i = insulation thickness <u>including</u> conductor and insulation semiconducting shields. Values are taken as recommended by IPCEA: conductor shield .015 in., insulation shield .030 in.; insulation thickness .175 in. @ 15 kV, .345 in. @ 35 kV. AEIC agrees; specifies also .260 in. @ 25 kV.

r_1 = conductor radius, inches, <u>not</u> including conductor shield.

ρ_i = insulation thermal resistivity, °C cm/watt.

x = horizontal cable separation, inches.

L = burial depth, inches.

ρ_c = conductor dc resistivity at operating temp., μΩcm.

A = conductor cross sectional area, thousands of circular mils (KCM).

R_{DC} = conductor DC resistance at oper. temp., Ω/cm.

β = skin effect ratio, R_{AC}/R_{DC} @ 60 Hz.

R_{AC} = conductor AC resistance at oper. temp., Ω/cm.

I = calculated ampacity, amperes RMS.

δT_S = temp. rise at central cable outer surface, or duct outer surface, if present, caused by dissipation of central cable, °C.

δT_M = temp. rise at central cable outer surface, or duct outer surface, if present, caused by dissipation of both outer cables together, °C.

δT_I = temp. rise from central cable outer surface to conductor, °C.

DEFINITIONS FOR APPENDIX TABLES (Continued)

δT_{DW} = temp. rise across duct wall, °C.

δT_{AG} = temp. rise across air-gap from inside of duct to outside of cable, °C.

Q = dissipation (in conductor only) of central cable, watts/cm.

TABLES A3-1 and A3-2. DC Resistivities of Sodium and Aluminum vs. Temperature

Table A3-1 Sodium

T°C ↓ →	0	1	2	3	4	5	6	7	8	9
0	4.2900	4.3099	4.3298	4.3498	4.3698	4.3898	4.4099	4.4299	4.4500	4.4701
10	4.4902	4.5104	4.5305	4.5507	4.5911	4.5911	4.6114	4.6316	4.6519	7.6722
20	4.6925	4.7128	4.7332	4.7535	4.7739	4.7944	4.8148	4.8352	4.8557	4.8762
30	4.8967	4.9172	4.9378	4.9584	4.9790	4.9996	5.0202	5.0408	5.0615	5.0822
40	5.1029	5.1236	5.1144	5.1651	5.1859	5.2067	5.2276	5.2484	5.2693	5.2902
50	5.3111	5.3320	5.3529	5.3739	5.3949	5.4159	5.4369	5.4580	5.4790	5.5001
60	5.5212	5.5423	5.5635	5.5846	5.6058	5.6270	5.6482	5.6695	5.6907	5.7120
70	5.7333	5.7546	5.7760	5.7973	5.8187	5.8401	5.8616	5.8829	5.9044	5.9259
80	5.9474	5.9689	5.9904	6.0120	6.0336	6.0552	6.0768	6.0984	6.1201	6.1417
90	6.1634	6.1851	6.2069	6.2286	6.2504	6.2722	6.2940	6.3158	6.3377	

$$\rho_{Na} = 4.290 + .01993T + 9.848 \times 10^{-6}\ T^2$$

Table A3-2 Aluminum

T°C	0	1	2	3	4	5	6	7	8	9
0	2.6324	2.6439	2.6554	2.6669	2.6784	2.6899	2.7014	2.7129	2.7244	2.7359
10	2.7474	2.7589	2.7704	2.7819	2.7934	2.8049	2.8164	2.8279	2.8394	2.8509
20	2.8624	2.8739	2.8854	2.8969	2.9084	2.9199	2.9314	2.9429	2.9544	2.9659
30	2.9774	2.9889	3.0004	3.0119	3.0234	3.0349	3.0464	3.0579	3.0694	3.0809
40	3.0924	3.1039	3.1154	3.1269	3.1384	3.1499	3.1614	3.1729	3.1844	3.1959
50	3.2074	3.2189	3.2304	3.2419	3.2534	3.2649	3.2764	3.2879	3.2994	3.3109
60	3.3224	3.3339	3.3454	3.3569	3.3684	3.3799	3.3914	3.4029	3.4144	3.4259
70	3.4374	3.4489	3.4604	3.4719	3.4834	3.4949	3.5064	3.5179	3.5294	3.5409
80	3.5524	3.5639	3.5754	3.5869	3.5984	3.6099	3.6214	3.6329	3.6444	3.6559
90	3.6674	3.6789	3.6904	3.7019	3.7134	3.7249	3.7364	3.7479	3.7594	3.7708
100	3.7824									

$$\rho_{Al} = 2.8624 + .0115\ (T-20$$

TABLE A3-3. Aluminum Cable Ampacity at Normal Load
Direct Burial (Conductor at 90°C)

	15 kV				25 kV				35 kV			
δT	70	70	70	70	70	70	70	70	70	70	70	70
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.305	.305	.305	.305	.390	.390	.390	.390
r_1	.576	.498	.340	.288	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674
A	1000	750	350	250	1000	750	350	250	1000	750	350	250
R_{DC}	.7238	.9650	2.068	2.895	.7238	.9650	2.068	2.895	.7238	.9650	2.068	2.895
β	1.023	1.013	1.003	1.001	1.023	1.013	1.003	1.001	1.023	1.013	1.003	1.001
R_{AC}	.7404	.978	2.074	2.898	7.404	.978	2.074	2.898	.7404	.978	2.074	2.898
I	794	681	451	375	781	669	441	367	770	659	434	360
δT_S	30.1	30.0	29.3	28.9	28.5	28.2	27.3	26.8	27.1	26.8	25.7	25.1
δT_M	30.3	29.4	27.3	26.4	29.3	28.5	26.2	25.3	28.5	27.6	25.3	24.4
δT_I	9.6	10.6	13.4	14.7	12.2	13.3	16.5	17.9	14.4	15.6	19.0	20.5
Q	.466	.454	.421	.407	.451	.438	.404	.390	.439	.425	.390	.376

TABLE A3-4. Aluminum Cable Ampacity at Overload
Direct Burial (Conductor at 130°C)

	15 kV				25 kV				35 kV			
δT	110	110	110	110	110	110	110	110	110	110	110	110
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.305	.305	.305	.305	.390	.390	.390	.390
r_1	.576	.498	.340	.288	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274
A	1000	750	350	250	1000	750	350	250	1000	750	350	250
R_{DC}	.815	1.086	2.327	3.258	.815	1.086	2.327	3.258	.815	1.086	2.327	3.258
β	1.018	1.009	1.002	1.001	1.018	1.009	1.002	1.001	1.018	1.009	1.002	1.001
R_{AC}	.829	1.096	2.332	3.261	.829	1.096	2.332	3.261	.829	1.096	2.332	3.261
I	940	807	533	443	925	793	522	433	912	781	513	426
δT_S	47.3	47.1	46.0	45.4	44.7	44.3	42.9	42.1	42.6	42.0	40.3	39.5
δT_M	47.6	46.3	43.0	41.5	46.1	44.7	41.2	39.8	44.7	43.4	39.8	38.3
δT_I	15.1	16.6	21.0	23.1	19.2	21.0	25.9	28.1	22.7	24.6	29.8	32.2
Q	.733	.713	.662	.639	.709	.686	.635	.612	.689	.668	.613	.591

TABLE A3-5. Sodium Cable Ampacity at Overload
Direct Burial (Conductor at 95°C)

	15 kV				25 kV				35 kV			
δT	75	75	75	75	75	75	75	75	75	75	75	75
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.290	.290	.290	.290	.375	.375	.375	.375
r_1	.734	.634	.430	.364	.733	.633	.430	.363	.733	.632	.430	.363
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272
A	2155	1608	740	530	2149	1603	740	527	2149	1598	740	527
R_{DC}	.5743	.7697	1.673	2.335	.5759	.7721	1.673	2.349	.5759	.7745	1.673	2.349
β	1.035	1.020	1.004	1.002	1.0351	1.020	1.004	1.002	1.035	1.020	1.004	1.002
R_{AC}	.5944	.7851	1.679	2.340	.5961	.7876	1.679	2.353	.5961	.7900	1.679	2.353
I	940	807	532	444	925	793	522	433	913	781	514	426
δT_S	32.7	32.6	32.3	32.0	31.1	30.9	30.2	29.8	29.7	29.4	28.5	28.0
δT_M	34.1	33.3	30.9	29.9	33.1	32.2	29.8	28.7	32.2	31.3	28.8	27.7
δT_I	8.2	9.1	11.8	13.1	10.8	11.9	15.0	16.5	13.1	14.3	17.7	19.3
Q	.525	.512	.476	.461	.510	.496	.458	.442	.497	.482	.443	.427

TABLE A3-6. Sodium Cable Conductor Temperature at Normal Load Current
Direct Burial

	15 kV				25 kV				35 kV			
δT	49	49	49	49	49	49	49	49	49	49	49	49
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_c	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.290	.290	.290	.290	.375	.375	.375	.375
r_1	.734	.634	.430	.364	.733	.633	.430	.363	.733	.632	.430	.363
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712
A	2155	1608	740	530	2149	1603	740	527	2149	1598	740	527
R_{DC}	.5230	.7010	1.523	2.127	.5245	.7032	1.523	2.139	.5245	.7054	1.523	2.139
β	1.042	1.024	1.005	1.003	1.042	1.024	1.005	1.003	1.042	1.024	1.005	1.003
R_{AC}	.5450	.7178	1.531	2.133	.5465	.7200	1.531	2.145	.5465	.7223	1.531	2.145
I	793	682	451	376	781	670	442	367	770	660	435	361
δT_S	21.3	21.3	21.1	20.9	20.3	20.2	19.8	19.4	19.4	19.2	18.6	18.3
δT_M	22.3	21.7	20.2	19.5	21.6	21.0	19.4	18.8	21.1	20.4	18.8	18.1
δT_I	5.4	6.0	7.7	8.6	7.1	7.8	9.8	10.8	8.5	9.3	11.6	12.6
Q	.343	.334	.311	.301	.333	.324	.299	.289	.324	.315	.290	.279

TABLE A3-7. Aluminum Cable Ampacity at Normal Load (Conductor at 90°C) and at Overload (Conductor at 130°C)
Direct Burial, 600 Volt Cable

	Normal				Overload			
δT	70	70	70	70	110	110	110	110
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.110	.110	.095	.095	.110	.110	.095	.095
r_1	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36
ρ_c	3.6674	3.6674	3.6674	3.6674	4.1274	4.1274	4.1274	4.1274
A	1000	750	350	250	1000	750	350	250
R_{DC}	.7238	.9550	2.068	2.895	.8145	1.086	2.327	3.258
β	1.023	1.013	1.003	1.001	1.018	1.010	1.002	1.001
R_{AC}	.7404	.9778	2.074	2.899	.8295	1.097	2.332	3.262
I	814	700	468	391	964	828	554	462
δT_S	32.7	32.8	33.3	33.2	51.4	51.5	52.3	52.2
δT_M	31.9	31.1	29.6	28.8	50.1	48.9	46.4	45.2
δT_I	5.5	6.1	7.1	8.0	8.6	9.6	11.2	12.6
Q	.490	.479	.455	.443	.771	.753	.715	.696

Insulation thicknesses employed above are those specified by IPCEA S61 402 for normal HMWPE.

TABLE A3-8. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current Direct Burial, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	45	45	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.125	.125	.110	.110	.125	.125	.110	.110
r_1	.741	.639	.436	.368	.741	.639	.436	.368
ρ_i	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36
ρ_c	6.272	6.272	6.272	6.272	5.207	5.207	5.196	5.196
A	2196	1633	760	542	2196	1633	760	542
R_{DC}	.5637	.7580	1.629	2.284	.4679	.6293	1.349	1.892
β	1.037	1.021	1.005	1.002	1.052	1.030	1.007	1.003
R_{AC}	.5845	.7740	1.636	2.289	.4924	.6482	1.358	1.898
I	964	828	554	462	813	701	469	391
δT_S	34.4	34.5	35.2	35.1	20.6	20.7	20.9	20.8
δT_M	35.2	34.4	32.6	31.7	21.1	20.7	19.4	18.8
δT_I	5.4	6.0	7.2	8.1	3.2	3.6	4.3	4.8
Q	.543	.530	.503	.489	.326	.318	.298	.290

Insulation thicknesses employed above are those specified by IPCEA S61 402 for normal HMWPE.

TABLE A3-9. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current Direct Burial, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	45	45	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.160	.160	.160	.160	.160	.160	.160	.160
r_1	.746	.644	.441	.373	.746	.644	.441	.373
ρ_i	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	35	36	36
ρ_c	6.272	6.272	6.272	6.272	5.207	5.207	5.196	5.196
A	2226	1659	778	557	2226	1659	778	557
R_{DC}	.5561	.7461	1.591	2.222	.4616	.6194	1.318	1.841
β	1.038	1.022	1.005	1.002	1.054	1.031	1.007	1.004
R_{AC}	.5771	.7623	1.599	2.228	.4864	.6386	1.327	1.848
I	964	828	553	462	813	701	468	391
δT_S	33.6	33.7	33.6	33.4	20.1	20.2	19.9	19.8
δT_M	34.8	34.0	31.8	30.8	20.9	20.4	18.9	18.3
δT_I	6.6	7.4	9.6	10.8	4.0	4.4	5.7	6.4
Q	.536	.523	.490	.475	.321	.314	.290	.282

Insulation thicknesses above are all .160 in.

TABLE A3-10. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current Direct Burial, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	45	45	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.205	.205	.205	.205
r_1	.753	.650	.446	.378	.753	.650	.446	.378
ρ_i	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36
ρ_c	6.272	6.272	6.272	6.272	5.207	5.207	5.196	5.196
A	2268	1690	796	572	2268	1690	796	572
R_{DC}	.5458	.7324	1.555	2.164	.4531	.6080	1.288	1.793
β	1.039	1.023	1.005	1.003	1.056	1.032	1.007	1.004
R_{AC}	.5672	.7489	1.563	2.169	.4783	.6275	1.298	1.799
I	965	828	554	463	814	701	468	391
δT_S	32.6	32.6	32.3	32.0	19.6	19.6	19.2	19.0
δT_M	34.3	33.4	31.1	30.2	20.6	20.0	18.5	17.9
δT_I	8.1	9.0	11.5	12.8	4.9	5.4	6.8	7.6
Q	.528	.514	.479	.464	.317	.308	.284	.276

Insulation thicknesses above are all .205 in.

TABLE A3-11. Aluminum Cable Ampacity at Normal Load, Cable in Duct (Conductor at 90°C)

	15 kV				25 kV				35 kV			
δT	70	70	70	70	70	70	70	70	70	70	70	70
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.305	.305	.305	.305	.390	.390	.390	.390
r_1	.576	.498	.340	.288	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674
A	1000	750	350	250	1000	750	350	250	1000	750	350	250
R_{DC}	.7238	.9650	2.068	2.895	.7238	.9650	2.068	2.895	.7238	.9650	2.068	2.895
β	1.023	1.013	1.003	1.001	1.023	1.013	1.003	1.001	1.023	1.013	1.003	1.001
R_{AC}	.7404	.9778	2.074	2.899	.7404	.9778	2.074	2.899	.7404	.9778	2.074	2.899
I	674	574	372	308	673	574	373	309	671	573	374	309
δT_S	15.7	15.1	13.4	12.8	15.7	15.0	13.5	12.9	15.6	15.0	13.5	13.0
δT_M	21.8	20.9	18.7	17.8	21.8	20.9	18.8	17.9	21.1	20.8	18.8	18.0
δT_{DW}	2.4	2.3	2.1	2.0	2.4	2.3	2.1	2.0	2.4	2.3	2.1	2.0
δT_{AG}	23.1	24.2	26.7	27.5	21.1	22.0	23.8	24.4	19.4	20.1	21.5	21.9
δT_I	6.9	7.5	9.1	9.9	9.1	9.8	11.8	12.7	11.0	11.8	14.1	15.1
Q	.336	.322	.283	.274	.335	.322	.289	.276	.333	.321	.290	.277

TABLE A3-12. Aluminum Cable Ampacity at Overload, Cable in Duct (Conductor at 130°C)

	15 kV				25 kV				35 kV			
δT	110	110	110	110	110	110	110	110	110	110	110	110
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.305	.305	.305	.305	.390	.390	.390	.390
r_1	.576	.498	.340	.288	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274	4.1274
A	1000	750	350	250	1000	750	350	250	1000	750	350	250
R_{DC}	.8145	1.086	2.327	3.258	.8145	1.086	2.327	3.258	.8145	1.086	2.327	3.258
β	1.018	1.010	1.002	1.001	1.018	1.010	1.002	1.001	1.018	1.010	1.002	1.001
R_{AC}	.8295	1.097	2.332	3.262	.8295	1.097	2.332	3.262	.8295	1.097	2.332	3.262
I	821	699	454	375	818	697	454	376	814	695	453	375
δT_S	26.1	25.1	22.5	21.5	25.9	25.0	22.5	21.5	25.7	24.8	22.4	21.5
δT_M	36.3	34.9	31.3	29.8	36.0	34.7	31.3	29.9	35.7	34.4	31.1	29.8
δT_{DW}	4.1	3.9	3.5	3.3	4.0	3.7	3.5	3.3	4.0	3.8	3.5	3.3
δT_{AG}	32.0	33.7	37.4	38.8	29.0	30.3	33.1	34.1	26.5	27.5	29.6	30.3
δT_I	11.5	12.5	15.3	16.6	15.0	16.2	19.6	21.2	18.1	19.5	23.3	25.1
Q	.559	.537	.482	.459	.555	.534	.481	.460	.550	.530	.480	.460

TABLE A3-13. Sodium Cable Ampacity at Overload, Cable in Duct (Conductor at 95°C)

	15 kV				25 kV				35 kV			
δT	75	75	75	75	75	75	75	75	75	75	75	75
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.290	.290	.290	.290	.375	.375	.375	.375
r_1	.744	.642	.438	.370	.744	.642	.437	.370	.743	.642	.437	.369
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272	6.272
A	2214	1649	767	548	2214	1649	764	548	2208	1649	764	545
R_{DC}	.5591	.7506	1.614	2.259	.5591	.7506	1.620	2.259	.5606	.7506	1.620	2.271
β	1.038	1.022	1.005	1.002	1.038	1.022	1.005	1.002	1.037	1.022	1.005	1.002
R_{AC}	.5800	.7668	1.621	2.264	.5800	.7668	1.628	2.264	.5815	.7668	1.628	2.276
I	821	699	454	375	818	697	454	376	814	695	453	375
δT_S	18.3	17.5	15.7	14.9	18.2	17.4	15.7	14.9	18.0	17.3	15.6	14.9
δT_M	25.4	24.3	21.7	20.7	25.2	24.2	21.7	20.8	25.0	24.1	21.7	20.7
δT_{DW}	2.8	2.7	2.4	2.3	2.8	2.7	2.4	2.3	2.8	2.7	2.4	2.3
δT_{AG}	22.5	23.8	27.0	28.2	20.7	21.8	24.3	25.2	19.1	20.1	22.1	22.7
δT_I	6.1	6.6	8.2	8.9	8.1	8.9	10.9	11.8	10.0	10.9	13.2	14.3
Q	.391	.375	.335	.318	.338	.373	.335	.320	.385	.371	.334	.320

TABLE A3-14. Sodium Cable Conductor Temperature at Normal Load Current
Cable in Duct

	15 kV				25 kV				35 kV			
δT	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5
α	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.290	.290	.290	.290	.375	.375	3.75	.375
r_1	.744	.642	.438	.370	.744	.642	.437	.370	.743	.642	.437	.369
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014	5.7014
A	2214	1649	767	548	2214	1649	764	548	2208	1649	764	545
R_{DC}	.5082	.6823	1.467	2.053	.5082	.6823	1.473	2.053	.5096	.6823	1.473	2.065
β	1.045	1.026	1.006	1.003	1.045	1.026	1.006	1.003	1.045	1.026	1.006	1.003
R_{AC}	.5310	.6999	1.475	2.059	.5310	.6999	1.481	2.059	.5323	.6999	1.481	2.070
I	674	575	373	308	673	574	374	309	671	573	374	309
δT_S	11.3	10.8	9.6	9.1	11.3	10.8	9.7	9.2	11.2	10.8	9.7	9.2
δT_M	15.7	15.0	13.4	12.7	15.6	15.0	13.4	12.8	15.6	14.9	13.4	12.8
δT_{DW}	1.8	1.7	1.5	1.4	1.7	1.7	1.5	1.4	1.7	1.7	1.5	1.4
δT_{AG}	16.0	16.9	19.0	19.8	14.8	15.6	17.2	17.8	13.8	14.4	15.7	16.2
δT_I	3.7	4.1	5.0	5.5	5.0	5.5	6.7	7.3	6.2	6.7	8.2	8.8
Q	.242	.231	.206	.195	.241	.231	.207	.197	.240	.230	.207	.198

TABLE A3-15. Aluminum Cable Ampacity at Normal Load (Conductor at 90°C) and at Overload (Conductor at 130°C) Cable in Duct, 600 Volt Cable

	Normal Full Load				Overload			
δT	70	70	70	70	110	110	110	110
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.110	.110	.095	.095	.110	.110	.095	.095
r_1	.576	.498	.340	.288	.576	.498	.340	.288
ρ_i	400	400	400	400	400	400	400	400
ρ_c	3.6674	3.6674	3.6674	3.6674	4.1274	4.1274	4.1274	4.1274
A	1000	750	350	250	1000	750	350	250
R_{DC}	.7238	.9650	2.068	2.895	.8145	1.086	2.327	3.258
β	1.023	1.013	1.003	1.001	1.018	1.010	1.002	1.001
R_{AC}	.7404	.9778	2.074	2.899	.8295	1.097	2.332	3.262
I	674	573	369	303	824	701	452	372
δT_S	15.7	15.0	13.2	12.5	26.3	25.2	22.3	21.1
δT_M	21.8	20.8	18.3	17.3	36.6	35.0	31.0	29.4
δT_{DW}	2.4	2.3	2.0	1.9	4.1	3.9	3.5	3.3
δT_{AG}	26.3	27.8	32.0	33.4	36.8	39.1	45.8	48.0
δT_I	3.7	4.1	4.4	4.8	6.3	6.8	7.5	8.2
Q	.336	.321	.282	.267	.563	.539	.477	.452

Insulation thicknesses employed above are those specified by IPCEA S61 402 for normal HMWPE.

TABLE A3-16. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current, Cable in Duct, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	44.5	44.5	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.125	.125	.110	.110	.125	.125	.110	.110
r_1	.745	.643	.437	.369	.745	.643	.437	.369
ρ_i	400	400	400	400	400	400	400	400
ρ_c	6.272	6.272	6.272	6.272	5.1963	5.1963	5.1963	5.1963
A	2220	1654	764	545	2220	1654	764	545
R_{DC}	.5576	.7484	1.620	2.271	.4619	.6200	1.342	1.882
β	1.038	1.022	1.005	1.002	1.054	1.031	1.007	1.003
R_{AC}	.5786	.7645	1.628	2.276	.4867	.6392	1.351	1.888
I	824	701	452	372	673	573	370	304
δT_S	18.4	17.6	15.6	14.7	10.3	9.8	8.6	8.2
δT_M	25.5	24.4	21.6	20.4	14.3	13.6	12.0	11.3
δT_{DW}	2.8	2.7	2.4	2.3	1.6	1.5	1.3	1.3
δT_{AG}	24.4	26.0	30.7	32.3	16.1	17.1	19.9	20.8
δT_I	3.9	4.3	4.8	5.2	2.2	2.4	2.6	2.9
Q	.393	.376	.333	.315	.220	.210	.185	.175

Insulation thicknesses employed above are those specified by IPCEA S61402 for normal HMWPE.

TABLE A3-17. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current, Cable in Duct, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	44.5	44.5	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.160	.160	.160	.160	.160	.160	.160	.160
r_1	.746	.643	.436	.368	.746	.643	.436	.368
ρ_i	400	400	400	400	400	400	400	400
ρ_c	6.272	6.272	6.272	6.272	5.1963	5.1963	5.1963	5.1963
A	2226	1654	760	542	2226	1654	760	542
R_{DC}	.5561	.7484	1.629	2.284	.4607	.6200	1.349	1.892
β	1.038	1.022	1.005	1.002	1.054	1.031	1.007	1.003
R_{AC}	.5771	.7645	1.636	2.289	.4855	.6392	1.358	1.898
I	824	701	452	372	674	574	370	305
δT_S	18.3	17.6	15.6	14.8	10.3	9.8	8.7	8.2
δT_M	25.5	24.4	21.7	20.6	14.3	13.7	12.1	11.4
δT_{DW}	2.8	2.7	2.4	2.3	1.6	1.5	1.3	1.3
δT_{AG}	23.5	25.0	28.7	30.1	15.6	16.5	18.7	19.5
δT_I	4.9	5.3	6.6	7.3	2.7	3.0	3.7	4.0
Q	.392	.376	.333	.317	.220	.210	.186	.176

Insulation thicknesses above are all .160 in.

TABLE A3-18. Sodium Cable Ampacity at Overload (Conductor at 95°C) and Conductor Temperature at Normal Load Current, Cable in Duct, 600 Volt Cable

	Overload				Normal Load			
δT	75	75	75	75	44.5	44.5	44.5	44.5
α	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90
t_i	.205	.205	.205	.205	.205	.205	.205	.205
r_1	.747	.644	.436	.367	.747	.644	.436	.367
ρ_i	400	400	400	400	400	400	400	400
ρ_c	6.272	6.272	6.272	6.272	5.1963	5.1963	5.1963	5.1963
A	2232	1659	760	539	2232	1659	760	539
R_{DC}	.5546	.7461	1.629	2.296	.4594	.6181	1.349	1.903
β	1.038	1.022	1.005	1.002	1.054	1.031	1.007	1.003
R_{AC}	.5757	.7623	1.636	2.302	.4843	.6373	1.358	1.909
I	824	701	452	372	674	575	371	305
δT_S	18.3	17.5	15.6	14.9	10.3	9.8	8.7	8.3
δT_M	25.4	24.4	21.7	20.6	14.3	13.7	12.1	11.5
δT_{DW}	2.8	2.7	2.4	2.3	1.6	1.5	1.4	1.3
δT_{AG}	22.4	23.8	27.0	28.2	14.9	15.8	17.7	18.4
δT_I	6.0	6.6	8.2	9.0	3.4	3.7	4.6	5.0
Q	.391	.375	.334	.318	.220	.211	.187	.177

Insulation thicknesses above are all .205 in.

TABLE A3-19. Sensitivity of Sodium Cable Ampacity to Insulation Thickness
Direct Burial, Sodium at 69°C

δT	49	49	49	49	49	49	49	49	49	49
α	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90
t_i	.125	.205	.290	.375	.420	.125	.205	.290	.375	.420
r_1	.500	.500	.500	.500	.500	.650	.650	.650	.650	.650
ρ_i	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36
ρ_c	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712
A	1000	1000	1000	1000	1000	1690	1690	1690	1690	1690
R_{DC}	1.127	1.127	1.127	1.127	1.127	.6670	.6670	.6670	.6670	.6670
β	1.010	1.010	1.010	1.010	1.010	1.027	1.027	1.027	1.027	1.027
R_{AC}	1.138	1.138	1.138	1.138	1.138	.6850	.6850	.6850	.6850	.6850
I	541	530	521	513	509	712	700	689	680	675
δT_S	22.6	21.2	20.0	18.9	18.4	22.5	21.3	20.2	19.3	18.8
δT_M	21.6	20.8	20.0	19.4	19.1	22.6	21.8	21.1	20.6	20.3
δT_I	4.7	7.0	9.0	10.7	11.4	3.9	5.9	7.6	9.2	9.9
Q	.333	.320	.309	.299	.295	.347	.336	.325	.316	.312

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TABLE A3-19 cont. Sensitivity of Sodium Cable Ampacity to Insulation Thickness
Direct Burial; Sodium at 69°C

δT	49	49	49	49	49	49	49	49	49	49	49	49	49	49
α	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.125	.150	.205	.250	.290	.330	.375	.420	0	.125	.205	.290	.375	.420
r_1	.741	.741	.741	.741	.741	.741	.741	.741	.741	.364	.364	.364	.364	.364
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712
A	2196	2196	2196	2196	2196	2196	2196	2196	2196	530	530	530	530	530
R_{DC}	.5133	.5133	.5133	.5133	.5133	.5133	.5133	.5133	.5133	2.1269	2.1269	2.1269	2.1269	2.1269
β	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.003	1.003	1.003	1.003	1.003
R_{AC}	.5359	.5359	.5359	.5359	.5359	.5359	.5359	.5359	.5359	2.1325	2.1325	2.1325	2.1325	2.1325
I	813	808	801	795	789	784	779	774	837	385	376	368	362	359
δT_S	22.5	21.9	21.3	20.8	20.3	19.9	19.4	19.0	24.6	22.6	20.9	19.5	18.3	17.8
δT_M	23.0	22.7	22.3	22.0	21.7	21.4	21.1	20.8	24.4	20.5	19.6	18.8	18.1	17.8
δT_I	3.5	4.4	5.3	6.3	7.0	7.7	8.5	9.2	0	5.9	8.6	10.8	12.6	13.4
Q	.355	.350	.344	.338	.334	.330	.325	.321	.375	.315	.301	.289	.279	.274

TABLE A3-20. Sensitivity of Sodium Cable Ampacity to Insulation Thickness
Cable in Duct; Sodium at 69°C

δT	49	49	49	49	49	49	49	49	49	49
α	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90
t_i	.125	.205	.290	.375	.420	.125	.205	.290	.375	.420
r_1	.500	.500	.500	.500	.500	.650	.650	.650	.650	.650
ρ_i	400	400	400	400	400	400	400	400	400	400
ρ_c	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712
A	1000	1000	1000	1000	1000	1690	1690	1690	1690	1690
R_{DC}	1.127	1.127	1.127	1.127	1.127	.6670	.6670	.6670	.6670	.6670
β	1.010	1.010	1.010	1.010	1.010	1.027	1.027	1.027	1.027	1.027
R_{AC}	1.138	1.138	1.138	1.138	1.138	.6850	.6850	.6850	.6850	.6850
I	435	436	437	437	437	585	585	585	584	583
δT_S	10.1	10.1	10.2	10.2	10.1	11.0	11.0	11.0	10.9	10.9
δT_M	14.0	14.1	14.1	14.1	14.1	15.2	15.2	15.2	15.2	15.1
δT_{DW}	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7
δT_{AG}	20.3	18.5	16.8	15.4	14.8	18.5	17.0	15.6	14.5	13.9
δT_I	3.1	4.7	6.3	7.7	8.4	2.6	4.1	5.5	6.8	7.4
Q	.215	.217	.217	.217	.217	.235	.235	.234	.234	.233

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TABLE A3-20 cont. Sensitivity of Sodium Cable Ampacity to Insulation Thickness
Cable in Duct; Sodium at 69°C

δT	49	49	49	49	49	49	49	49	49	49	49	49	49
α	0	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.125	.160	.205	.250	.290	.330	.375	.420	.125	.205	.290	.375	.420
r_1	.741	.741	.741	.741	.741	.741	.741	.741	.364	.364	.364	.364	.364
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712	5.712
A	2196	2196	2196	2196	2196	2196	2196	2196	530	530	530	530	530
R_{DC}	.5133	.5133	.5133	.5133	.5133	.5133	.5133	.5133	2.127	2.127	2.127	2.127	2.127
β	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.003	1.003	1.003	1.003	1.003
R_{AC}	.5359	.5359	.5359	.5359	.5359	.5359	.5359	.5359	2.132	2.132	2.132	2.132	2.132
I	675	675	675	674	674	673	672	671	302	304	305	306	306
δT_S	11.4	11.4	11.4	11.4	11.4	11.3	11.3	11.3	9.1	9.2	9.3	9.3	9.3
δT_M	15.9	15.9	15.8	15.8	15.8	15.8	15.7	15.7	12.6	12.8	12.9	12.9	12.9
δT_{DW}	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.4	1.4	1.4	1.4	1.4
δT_{AG}	17.5	16.9	16.2	15.5	15.0	14.5	13.9	13.4	22.3	20.0	18.0	16.3	15.6
δT_I	2.4	3.0	3.8	4.5	5.1	5.7	6.3	6.9	3.6	5.6	7.4	9.0	9.7
Q	.244	.244	.244	.244	.243	.243	.242	.241	.194	.197	.198	.199	.199

TABLE A3-21. An Example of Na-Al Equivalence at ρ_e = 130

25 kV Insulation; Al 1000 KCM
Direct Burial

	Al Normal	Al Overload	Na Overload	Na Normal
δT	70	110	75	49
α	0	0	0	0
ρ_e	130	130	130	130
t_i	.305	.305	.290	.290
r_1	.576	.576	.736	.736
ρ_i	400	400	400	400
x	7.5	7.5	7.5	7.5
L	36	36	36	36
ρ_c	3.6674	4.1274	6.272	5.712
A	1000	1000	2167	2167
R_{DC}	.7237	.8145	.5711	.5201
β	1.0230	1.018	1.035	1.042
R_{AC}	.7404	.8292	.5911	.5420
I	667.9	791	791	667.5
δT_S	30.1	47.3	32.5	21.2
δT_M	31.0	48.7	34.7	22.7
δT_I	8.9	14.0	7.8	5.1
Q	.330	.519	.370	.241

TABLE A3-22. An Example of Na-Al Equivalence at $\alpha = 1$

25 kV Insulation; Al 1000 KCM

Direct Burial

	Al Normal	Al Overload	Na Overload	Na Normal
δT	70	110	75	49
α	1	1	1	1
ρ_e	90	90	90	90
t_i	.305	.305	.290	.290
r_1	.576	.576	.739	.739
ρ_i	400	400	400	400
x	7.5	7.5	7.5	7.5
L	36	36	36	36
ρ_c	3.6674	4.1274	6.272	5.712
A	1000	1000	2184	2184
R_{DC}	.7237	.8145	.5667	.5161
β	1.023	1.018	1.036	1.043
R_{AC}	.7404	.8292	.5871	.5383
I	578	684.6	684.5	578
δT_S	31.2	49.0	33.5	21.9
δT_M	32.1	50.5	35.7	23.3
δT_I	6.7	10.5	5.8	3.8
Q	.247	.389	.275	.180

TABLE A3-23. Cable In Duct Ampacity Calculations to Verify Against IPCEA Tables

	Al 15 kV					Al 35 kV					Cu 15 kV			
δT	65	65	65	65	65	65	65	65	65	65	65	65	65	65
α	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.220	.390	.390	.390	.390	.390	.220	.220	.220	.220
r_1	.576	.498	.407	.340	.260	.576	.498	.407	.340	.260	.576	.498	.407	.340
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400	400	400
ρ_c	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	2.201	2.201	2.201	2.201
A	1000	750	500	350	212	1000	750	500	350	212	1000	750	500	350
R_{DC}	.7238	.9650	1.4475	2.068	3.414	.7238	.9650	1.4475	2.068	3.414	.4344	.5792	.8687	1.241
β	1.023	1.013	1.006	1.003	1.001	1.023	1.013	1.006	1.003	1.001	1.060	1.035	1.016	1.008
R_{AC}	.7404	.9776	1.4562	2.074	3.417	.7404	.9776	1.4562	2.074	3.417	.4604	.5994	.8826	1.251
I	646	551	438	357	268	644	550	438	359	270	820	703	562	460
δT_S	14.5	13.9	13.0	12.4	11.4	14.4	13.8	13.1	12.5	11.6	14.5	13.9	13.0	12.4
δT_M	20.1	19.2	18.1	17.2	15.9	20.0	19.2	18.2	17.3	16.2	20.1	19.2	18.1	17.2
δT_{DW}	2.2	2.1	2.0	1.9	1.8	2.2	2.1	2.0	1.9	1.8	2.2	2.1	2.0	1.9
δT_{AG}	21.9	22.9	24.1	25.1	26.3	18.3	19.0	19.7	20.3	20.9	21.9	22.9	24.1	25.1
δT_I	6.4	6.9	7.7	8.4	9.6	10.1	10.9	12.0	13.0	14.5	6.4	6.9	7.7	8.4
Q	.309	.296	.279	.265	.245	.307	.296	.280	.267	.249	.309	.296	.279	.265
IPCEA I	653	556	443	363	273	647	552	441	362	273	823	707	567	465
Difference	7	5	5	6	5	3	2	3	3	3	3	4	5	5

TABLE A3-24. Direct Burial Ampacity Calculations to Verify Against IPCEA Tables

δT	65	65	65	65	65	65	65	65	65	65	65	65	65	65
α	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ρ_e	90	90	90	90	90	90	90	90	90	90	90	90	90	90
t_i	.220	.220	.220	.220	.220	.390	.390	.390	.390	.390	.220	.220	.220	.220
r_1	.576	.498	.407	.340	.260	.576	.498	.407	.340	.260	.576	.498	.407	.340
ρ_i	400	400	400	400	400	400	400	400	400	400	400	400	400	400
x	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
L	36	36	36	36	36	36	36	36	36	36	36	36	36	36
ρ_c	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	3.6674	2.201	2.201	2.201	2.201
A	1000	750	500	350	212	1000	750	500	350	212	1000	750	500	350
R_{DC}	.7238	.9650	1.448	2.068	3.414	.7238	.9650	1.448	2.068	3.414	.4344	.5792	.8687	1.241
β	1.023	1.013	1.006	1.003	1.001	1.023	1.013	1.006	1.003	1.001	1.060	1.035	1.016	1.008
R_{AC}	.7404	.9778	1.456	2.074	3.417	.7404	.9778	1.456	2.074	3.417	.4605	.5995	.8828	1.251
I	765	656	528	434	329	742	635	509	418	316	970	838	677	559
δT_S	27.9	27.8	27.5	27.2	26.5	25.1	24.8	24.3	23.8	23.0	27.9	27.8	27.5	27.2
δT_M	28.1	27.4	26.3	25.4	24.0	26.4	25.6	24.5	23.5	22.1	28.1	27.4	26.3	25.4
δT_I	8.9	9.8	11.1	12.4	14.4	13.4	14.5	16.1	17.6	19.9	8.9	9.8	11.1	12.4
Q	.433	.421	.405	.391	.370	.407	.395	.377	.362	.341	.433	.421	.405	.391
IPCEA I	757	652	524	431	328	735	630	504	415	314	957	831	672	554
Difference	8	4	4	3	1	7	5	5	3	2	13	7	5	5

APPENDIX A4

Aluminum and Sodium Cable Cost Details

TABLE A4-1

15 kV Aluminum and Sodium Cost Details

15 kV Aluminum Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	12.79	17.91	38.38	51.17
Conductor Screen	1.02	1.21	1.75	2.02
Insulation	10.02	11.38	15.43	17.41
Insulation Screen	3.41	3.78	4.87	5.41
Concentric Neutral	10.59	14.83	31.77	42.37
Material Subtotal	37.85	49.10	92.21	118.38
Other Direct and Indirect Product Costs	40.50	44.22	42.98	63.00
Electric Utility Price	78.35	93.32	135.19	181.38

15 kV Sodium Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	3.14	4.40	9.43	12.58
Conductor Screen	0.00	0.00	0.00	0.00
Insulation	8.68	9.85	13.38	15.10
Insulation Screen	3.05	3.37	4.32	4.78
Concentric Neutral	6.39	8.95	19.17	25.56
Material Subtotal	21.26	26.57	46.30	58.02
Other Direct and Indirect Product Costs	30.78	33.81	44.00	55.65
Electric Utility Price	52.04	60.18	90.30	113.67

TABLE A4-2

25 kV Aluminum and Sodium Cable Cost Details

25 kV Aluminum Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	12.79	17.91	38.38	51.17
Conductor Screen	1.02	1.21	1.75	2.02
Insulation	16.52	18.53	24.55	27.50
Insulation Screen	4.00	4.37	5.46	6.00
Concentric Neutral	10.59	14.83	31.78	42.37
Material Subtotal	44.93	56.84	101.92	129.05
Other Direct and Indirect Product Costs	40.6	49.3	70.7	80.2
Electric Utility Price	85.53	106.14	172.62	209.25

25 kV Sodium Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	3.14	4.40	9.43	12.58
Conductor Screen	0.00	0.00	0.00	0.00
Insulation	14.51	16.26	21.50	24.06
Insulation Screen	3.64	3.96	4.91	5.37
Concentric Neutral	6.39	8.95	19.17	25.56
Material Subtotal	27.69	33.57	55.01	67.57
Other Direct and Indirect Product Costs	28.42	34.51	49.49	56.14
Electric Utility Price	56.11	68.08	104.50	123.71

TABLE A4-3

35 kV Aluminum and Sodium Cost Details

35 kV Aluminum Distribution Cable Costs (¢/ft.)

Cost Allocation	250 MCM	350 MCM	750 MCM	1000 MCM
Conductor	12.79	17.91	38.38	51.17
Conductor Screen	1.02	1.21	1.75	2.02
Insulation	24.06	26.74	34.73	38.64
Insulation Screen	4.59	4.96	6.05	6.58
Concentric Neutral	10.59	14.83	31.78	42.37
Material Subtotal	53.07	65.64	112.69	140.78
Other Direct and Indirect Product Costs	44.53	51.0	83.20	98.02
Electric Utility Price	97.60	116.64	195.89	238.80

35 kV Sodium Distribution Cable Costs (¢/ft.)

Cost Allocation	250 MCM	350 MCM	750 MCM	1000 MCM
Conductor	3.14	4.40	9.43	12.58
Conductor Screen	0.0	0.0	0.0	0.0
Insulation	21.41	23.73	30.68	34.08
Insulation Screen	4.23	4.55	5.50	5.96
Concentric Neutral	6.39	8.95	19.17	25.56
Material Subtotal	35.17	41.63	64.79	78.18
Other Direct and Indirect Product Costs	28.50	32.64	53.24	62.73
Electric Utility Price	63.67	74.27	118.03	140.91

TABLE A4-4

600V Aluminum and Sodium Cost Details

600V Aluminum Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	12.79	17.91	38.38	51.17
Conductor Screen	0.00	0.00	0.00	0.00
Insulation	4.96	5.73	8.05	9.18
Insulation Screen	0.00	0.00	0.00	0.00
Concentric Neutral	0.00	0.00	0.00	0.00
Material Subtotal	17.75	23.64	46.43	60.35
Other Direct and Indirect Product Costs	23.0	33.5	63.0	93.13
Electric Utility Price	40.75	57.14	109.43	153.48

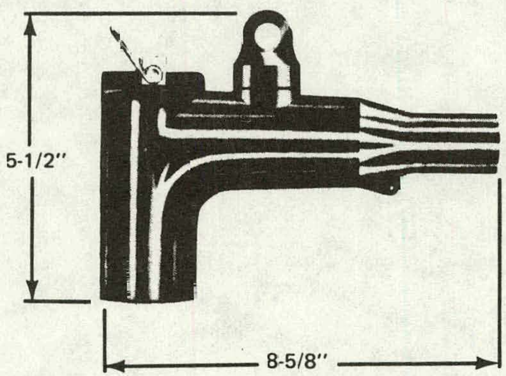
600V Sodium Distribution Cable Costs (¢/ft.)

	250 MCM	350 MCM	750 MCM	1000 MCM
Cost Allocation				
Conductor	3.14	4.40	9.43	12.57
Conductor Screen	0.00	0.00	0.00	0.00
Insulation	4.41	5.08	7.09	8.08
Insulation Screen	0.00	0.00	0.00	0.00
Concentric Neutral	0.00	0.00	0.00	0.00
Material Subtotal	7.55	9.48	16.53	20.65
Other Direct and Indirect Product Costs	10.58	15.41	33.47	42.85
Electric Utility Price	18.13	24.89	50.00	63.50

APPENDIX A5

Connector Cost Details

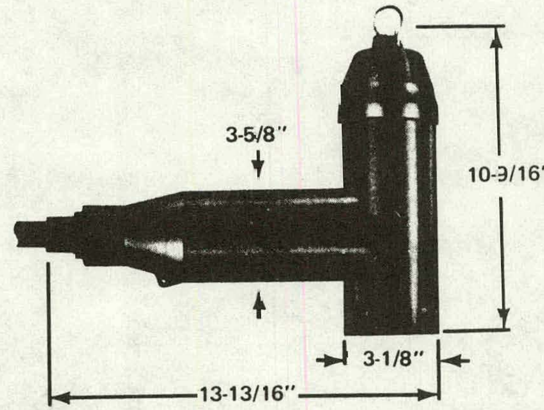
154LR
200-Amp Elbow Connector (Deadbreak)



- One-piece molded rubber; fully shieldec
- For use on dead-tront transformers, switchgear and motors.
- Hot-stick operable; plugs onto bushings installed on apparatus.
- 100% production test.

Voltage class . . . . thru 25 kv
Current rating . . . . 200 amps
Cable insulation range . . . . .495" to 1.175"
(12,6 mm to 29,9 mm)
Conductor range . . . . No. 4 Al/Cu thru 4/0 Al/Cu

650LR
600-Amp, 15-kv and 25-kv Elbow Connector (Deadbreak)

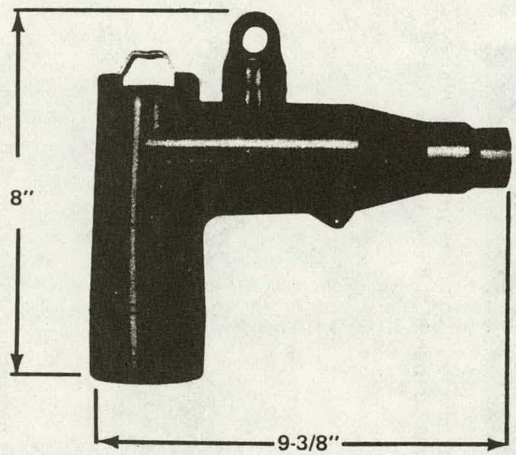


- One-piece molded rubber; fully shielded.
- For use on dead-front transformers, switchgear and motors.
- Plugs onto bushings installed on apparatus or can be used with accessories to form modular splices (see pages 23 and 49).
- 100% production test.

Voltage class . . . . thru 25 kv
Current rating . . . . 600 amps
Cable insulation range . . . . .875" to 1.785"
(22,2 mm to 45,3 mm)
Conductor range . . No. 2 Al/Cu thru 750 kcmil Al/Cu
800 kcmil Al thru 1000 kcmil Al

Figure A5-1. *TYPICAL CABLE CONNECTORS SIMILAR TO THOSE USED IN ESTIMATING COSTS FOR 15 AND 25 KV. (FROM ELASTIMOLD CATALOGUE)*

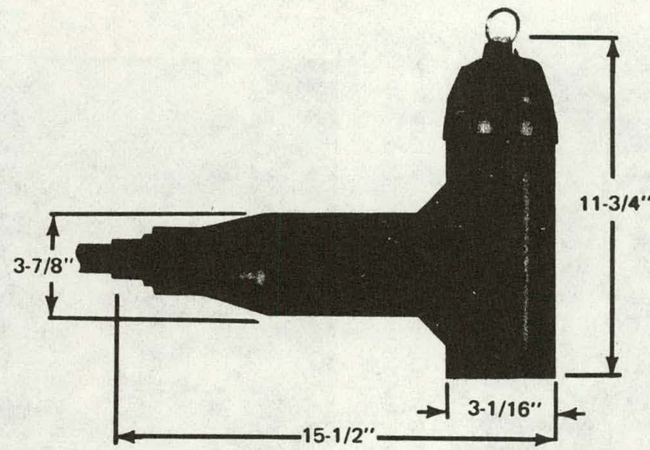
354LR
200-Amp, 35-kv Elbow Connector (Deadbreak)



- One-piece molded rubber; fully shielded.
- For use on dead-front transformers, switchgear and motors.
- Hot-stick operable; plugs onto bushings installed on apparatus.
- 100% production test.

Voltage class	35 kv
Current rating	200 amps
Cable insulation range	.825" to 1.395" (21,0 to 35,4 mm)
Conductor range	No. 1 thru 4/0 Al/Cu

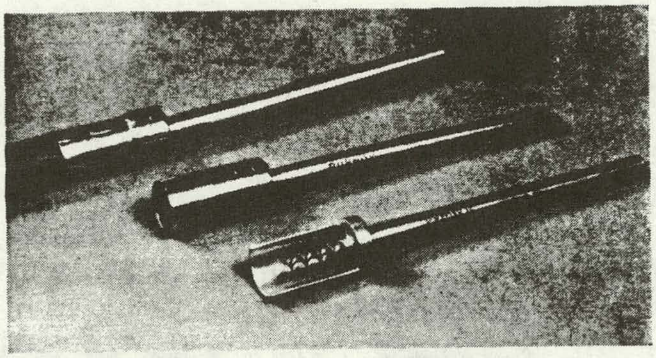
750LR
600-Amp 35-kv Elbow Connector (Deadbreak)



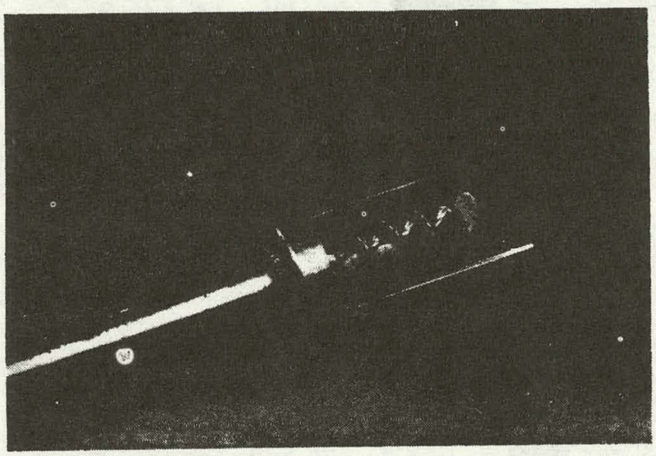
- One-piece molded rubber; fully shielded.
- For use on dead-front transformers, switchgear and motors.
- Plugs onto bushings installed on apparatus or can be used with accessories to form modular splices (see pages 26 and 51).
- 100% production test.

Voltage class	35 kv
Current rating	600 amps
Cable insulation range	.875" to 2.235" (22,2 mm to 56,8 mm)
Conductor range	1/0 Al/Cu thru 750 kcmil Al/Cu 800 kcmil Al thru 1000 kcmil Al

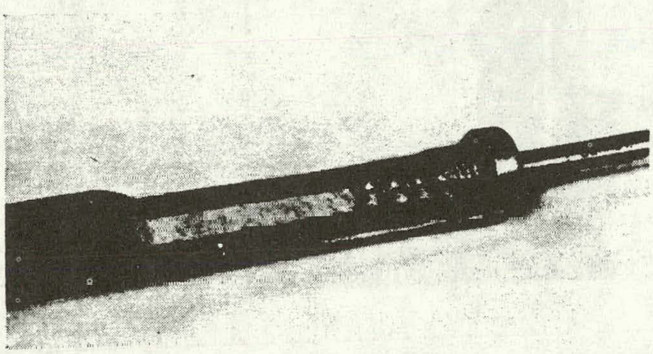
Figure A5-2. *TYPICAL CABLE CONNECTORS SIMILAR TO THOSE USED IN ESTIMATING COSTS FOR 35KV. (FROM ELASTIMOLD CATALOGUE)*



CORKSCREW CONNECTORS, shown completed, before connection and cut open, are used principally with 15-kV cable



EXPOSED END of the conductor is completely enclosed by the connector before any penetration of the sodium by the screw



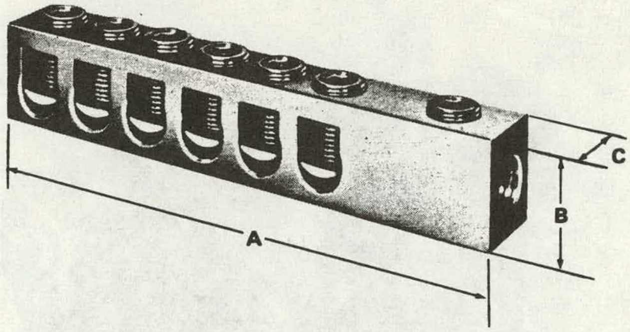
JOINT IS SEALED by compressing the sleeve with standard compression tool. Section view shows completed installation

Figure A5-3. *SODIUM CABLE CONNECTORS (FROM 'SODIUM IS NEW CABLE CONDUCTOR' POWER , SEPT.* 1968)

TYPE PTF-J

(SLIP FIT)

Figure A5-4. *TYPICAL 600 VOLT SECODARY CONNECTION SCHEME USED IN ESTIMATING COSTS.*



FOR USE ON TRANSFORMERS WITH THREADED STUD SECONDARY. DESIGNED FOR QUICK DISCONNECT WITHOUT REMOVING CONDUCTORS. INHIBITOR SUPPLIED IN STUD HOLE.

Catalog No.	Price Each		No. of Cond.	Cond. Range AWG-MCM	For Transformer Stud	Lbs. Wt. Per 100	Dimensions		
	1-99	100 and Over					A	B	C
PTF2-250-J	$ 4.95	$ 4.30	2		5/8-11	32	3-5/8	1-1/8	7/8
PTF3-250-J	6.25	5.45	3		5/8-11	36	4-3/8	1-1/8	7/8
PTF4-250-J	7.60	6.60	4	250-12	5/8-11	41	5-1/4	1-1/8	7/8
PTF5-250-J	8.85	7.70	5		5/8-11	45	6	1-1/8	7/8
PTF6-250-J	10.25	8.90	6		5/8-11	50	6-3/4	1-1/8	7/8
PTF8-250-J	12.30	10.70	8		5/8-11	58	8-3/8	1-1/8	7/8
PTF2-350-J	6.20	5.40	2		5/8-11	40	4-1/4	1-3/8	1
PTF3-350-J	7.65	6.65	3		5/8-11	46	5-1/8	1-3/8	1
PTF4-350-J	9.10	7.90	4	350-12	5/8-11	52	6	1-3/8	1
PTF5-350-J	10.60	9.20	5		5/8-11	58	6-7/8	1-3/8	1
PTF6-350-J	12.00	10.15	6		5/8-11	65	7-3/4	1-3/8	1
PTF8-350-J	14.95	13.00	8		5/8-11	77	9-5/8	1-3/8	1
PTF2-500-J	7.70	6.70	2		1-14	48	4-3/8	1-3/4	1-3/8
PTF3 500 J	9.50	8.25	3		1-14	58	5-1/2	1-3/4	1-3/8
PTF4-500-J	11.30	9.85	4		1-14	67	6 5/8	1-3/4	1-3/8
PTF5-500-J	13.15	11.45	5	500-2	1-14	77	7-3/4	1-3/4	1-3/8
PTF6-500-J	14.95	13.00	6		1-14	87	8-7/8	1-3/4	1-3/8
PTF8-500-J	18.50	16.10	8		1-14	103	11-1/8	1-3/4	1-3/8
PTF3-750-J	22.35	19.45	3		1-14	235	6	2	2-1/2
PTF4-750-J	26.45	23.00	4		1-14	282	8-5/8	2	2-1/2
PTF5-750-J	30.55	26.55	5	750-1/0	1-14	330	10-1/4	2	2-1/2
PTF6-750-J	34.65	30.15	6		1-14	390	11-7/8	2	2-1/2
PTF8-750-J	42.90	37.30	8		1-14	480	15-1/4	2	2-1/2

NOTE: Tap for street light available.

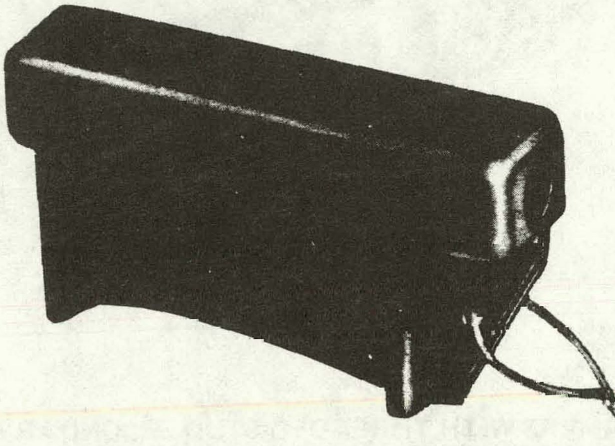
For packaging with grease inhibitor add suffix "P" and $0.20 each to price for 250/350 and $0.30 each for 500 connectors.

*For covers – Contact factory for price and delivery.

PLASTISOL COVERS FOR PTF STYLE CONNECTORS

FITS PTF AND PTF-J

Figure A5-5. *TYPICAL CONNECTOR COVER USED IN COST ESTIMATING.*



Connector Catalog Number PTF or PTF-J	Price Each		Cover Catalog Number
	1-99	100 & Up	
PTF3-250	$3.45	$3.00	R 6875
PTF4-250	3.45	3.00	R 6875
PTF5-250	3.45	3.00	R 6875
PTF6-250	4.20	3.65	R 6830
PTF8-250	4.90	4.25	R 6829
PTF3-350	3.45	3.00	R 6875
PTF4-350	3.45	3.00	R 6875
PTF5-350	4.20	3.65	R 6830
PTF6-350	4.20	3.65	R 6830
PTF8-350	4.90	4.25	R 6829
PTF3-500	5.25	4.55	R 6260
PTF4-500	5.25	4.55	R 6260
PTF5-500	5.55	4.85	R 6265
PTF6-500	5.55	4.85	R 6265
PTF8-500	5.90	5.15	R 6831
PTF-33-250	5.30	4.60	R 6880
PTF-44-250	5.30	4.60	R 6880
PTF-33-250-1	5.30	4.60	R 6880
PTF-44-250-1	5.30	4.60	R 6880
PTF-33-350	5.30	4.60	R 6880
PTF-44-350	5.30	4.60	R 6880
PTF-33-350-1	5.30	4.60	R 6880
PTF-44-350-1	5.30	4.60	R 6880
PTF-33-500	6.25	5.45	R 6881
PTF-44-500	6.25	5.45	R 6881

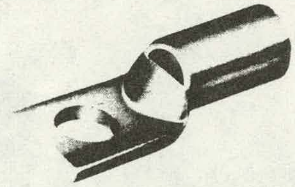
Figure A5-6. *TYPICAL COPPER TYPE SECONDARY CONNECTORS USED IN DEVELOPING THE 'PIN TYPE' CONNECTION COSTS IN THIS REPORT.*

TYPE CRA & B

LR-29801

CRIMP TYPE TERMINAL LUGS

SINGLE INDENT



Catalog No.	Price Per 100		Wire Size	Pcs. Per Carton	Shpg. Wt. Lbs/100	Bolt Size	Tang Length	Overall Length	Width
	Carton	10 or More Cartons							
CRA-8	**$ 26.30**	**$ 22.70**	8 Str.	50	1.5	3/16	1/2	1-1/8	13/32
CRA-6	**29.30**	**25.25**	6. Str.	50	1.8	3/16	1/2	1-1/2	13/32
CRB-6	**29.30**	**25.25**	6 Str.	50	1.8	1/4	1/2	1-1/2	13/32
CRA-4	**38.95**	**33.60**	4 Str.	50	2.1	3/16	1/2	1-1/2	1/2
CRB-4	**38.95**	**33.60**	4 Str.	50	2.1	1/4	1/2	1-1/2	1/2
CRA-2	**74.70**	**64.30**	2 Str.	25	3.6	1/4	3/4	1-27/32	19/32
CRB-2	**74.70**	**64.30**	2 Str.	25	3.6	5/16	3/4	1-27/32	19/32
CRA-1	**79.95**	**68.80**	1 Str.	10	3.6	5/16	3/4	1-7/8	11/16
CRA-0	**83.90**	**72.35**	1/0 Str.	10	4.3	5/16	3/4	1-7/8	3/4
CRB-0	**83.90**	**72.35**	1/0 Str.	10	4.3	3/8	3/4	1-7/8	3/4
CRA2/0	**98.75**	**85.15**	2/0 Str.	10	6.2	3/8	7/8	2-3/32	13/16
CRA3/0	**116.75**	**100.70**	3/0 Str.	10	7.6	3/8	1	2-5/16	29/32
CRB3/0	**116.75**	**100.70**	3/0 Str.	10	7.6	1/2	1	2-5/16	29/32
CRA4/0	**133.00**	**114.70**	4/0 Str.	10	7.7	3/8	1	2-11/32	1
CRB4/0	**133.00**	**114.70**	4/0 Str.	10	7.7	1/2	1	2-11/32	1
CRA-250	**154.70**	**133.45**	250 mcm	10	13	1/2	1-1/8	2-5/8	1-3/32
CRA-300	**179.55**	**154.70**	300 mcm	10	14.	1/2	1-1/8	2-5/8	1-3/16
CRA-350	**186.80**	**161.05**	350 mcm	10	19.	1/2	1-1/8	2-11/16	1-9/32
CRA-400	**220.65**	**190.25**	400 mcm	10	25.	5/8	1-1/2	3-5/16	1-3/8
CRA-500	**268.70**	**231.60**	500 mcm	10	40.	5/8	1-1/2	3-1/2	1-17/32
CRA-750	**520.55**	**448.75**	750 mcm	6	82.	5/8	1-15/16	4-11/32	1-29/32
CRA-1000	**1078.75**	**930.05**	1000 mcm	6	120	5/8	2-1/8	4-7/8	2-3/16

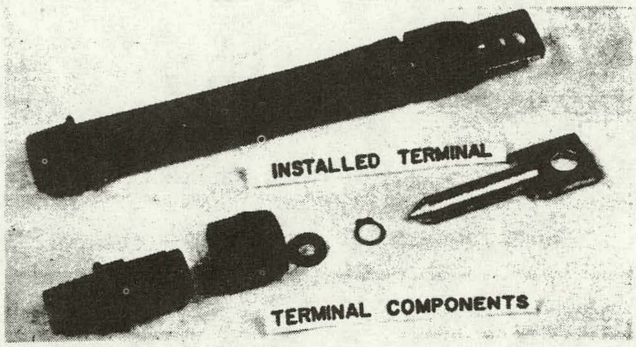
One piece construction for strength. Pure Copper for maximum conductivity. Flared cable hole for easy wire insertion. Sight hole for visual cable inspection. Dimensions in inches – approximate.

Maximum Contact surface. Uniform construction – precision made, electro-tin plated to minimize corrosion. Wire ranges clearly marked.

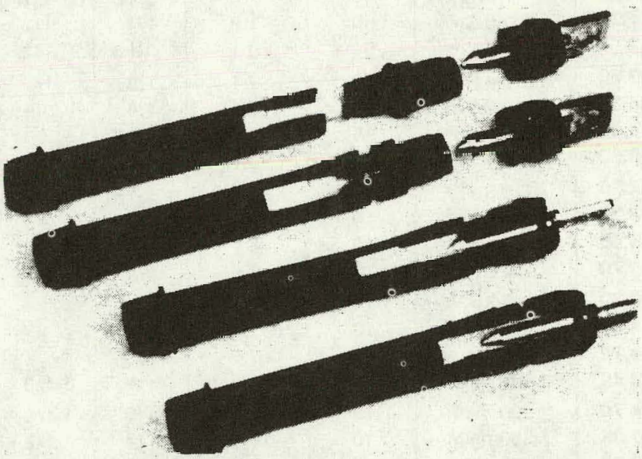
Designed to fit most compression dies.

THE UTILCO COMPANY

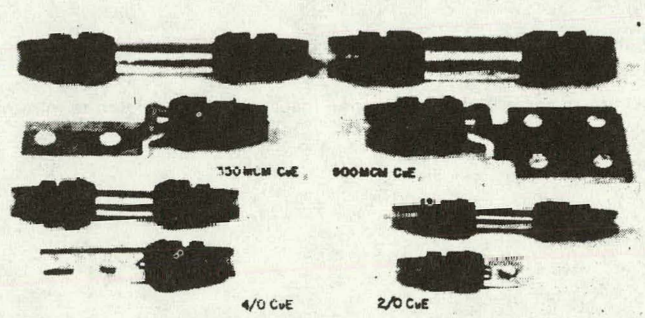
4730 MADISON ROAD, CINCINNATI, OHIO 45227 • TELEPHONE 871-4000 AREA CODE 513



PIN-AND-NUT CONNECTOR can be installed using an adjustable wrench. This latest design is specifically made for 600 V



INSTALLATION SEQUENCE, after cable preparation, is shown top to bottom. Pin is advanced into sodium by tightening nut



SPLICES are shown top and third row along with several connector variations. Ratings are in copper equivalents (CuE)

Figure A5-7. 600 *VOLT SODIUM CABLE CONNECTORS (FROM 'SODIUM IS NEW CABLE CONDUCTOR' BY N. PEACH ,*<u>*POWER*</u>, *SEPT.* 1968)

APPENDIX A6

Additional Application Cost Data

OUTPLT

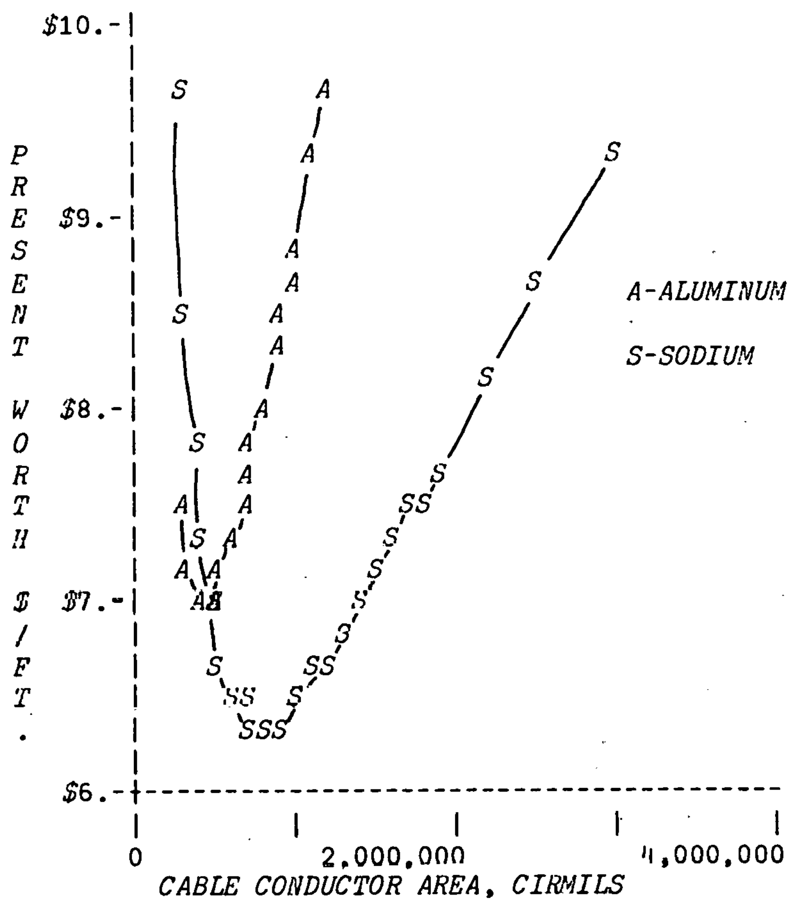


Figure A6-1. *TOTAL PRESENT WORTH COSTS VERSUS CONDUCTOR SIZE 35KV DIRECT BURIED.*

CABLE PARAMETERS:
UNIFORMLY LOADED 3 PHASE MAIN FEEDER
345 MILS XLPE INSULATION
15 MILS CONDUCTOR SCREEN FOR AL, 0 FOR NA
30 MILS INSULATION SCREEN

OPERATING PARAMETERS:
LOSS FACTOR=.18 PEAK RESPOSIBILITY FACTOR=.82
FEEDER INPUT CURRENT 213 AMPS
FEEDER OUTPUT CURRENT 67 AMPS

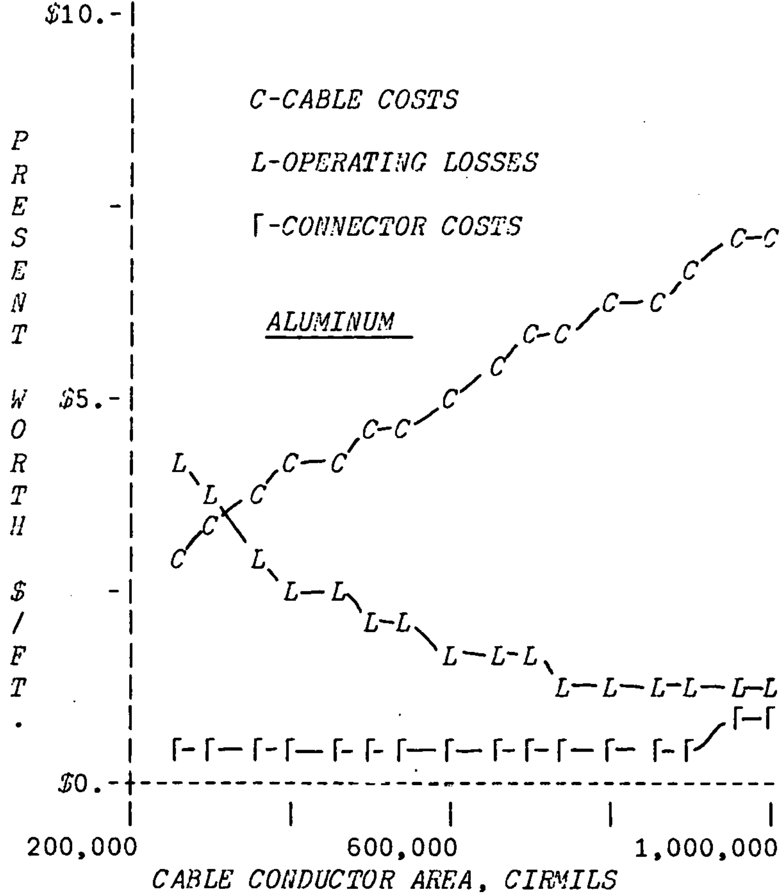


Figure A6-2. *PRESENT WORTH COSTS VS. CONDUCTOR SIZE 35KV MAIN FEEDER, 3PHASE.*

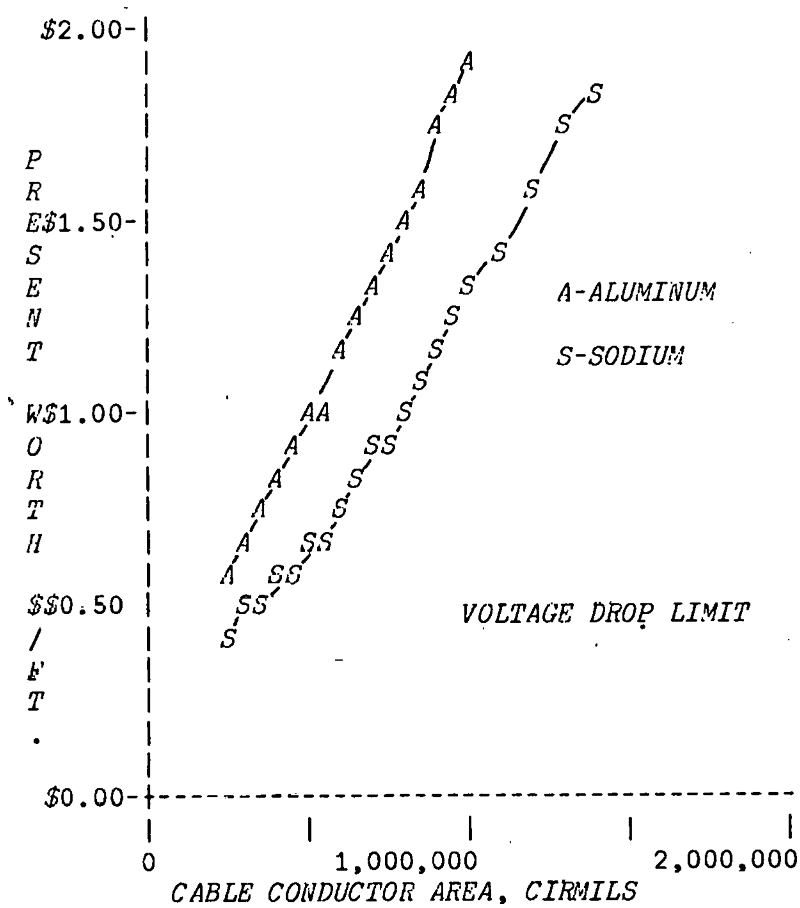


Figure A6-3. *TOTAL PRESENT WORTH COSTS VS. CONDUCTOR SIZE-600 VOLT SERVICE.*

CABLE PARAMETERS :
600V *DIRECT BURIED SINGLE PHASE SERVICE*
125 *MILS XLPE INSULATION*

OPERATING PARAMETERS:
LOSS FACTOR=.06 PEAK RESPOSIBILITY FACTOR=.3
SERVICE CURRENT FROM SECONDARY 40 AMPS

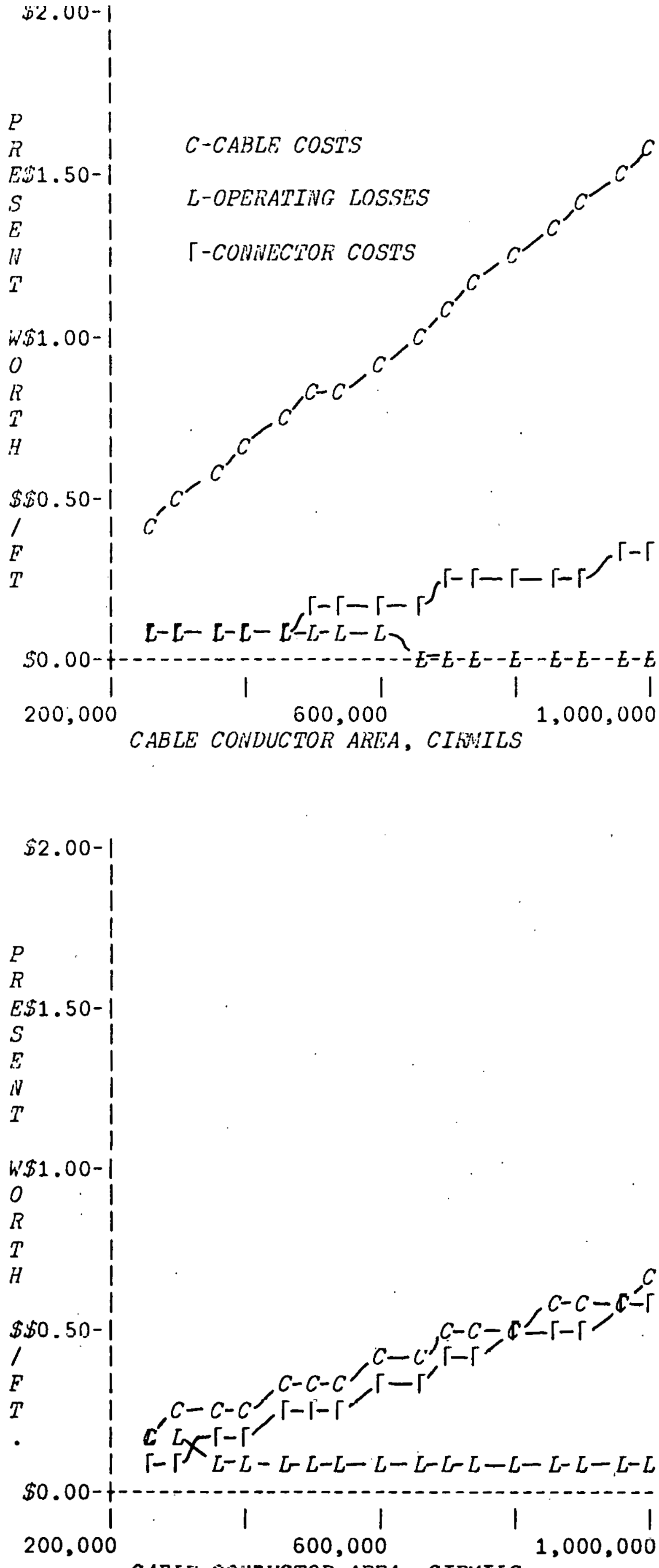


Figure A6-4. *PRESENT WORTH OF CABLE, CONNECTOR AND OPERATING LOSSES-600 VOLT SERVICE.*

APPENDIX A7

Functions Used In Computer Analysis of Present Worth Costs and Cable Material Costs

(APL Language Used on Scientific Time Sharing Corporation System)

```
     ∇CABLECST[⎕]∇
    ∇ CABLECST
[1]   TP ◇ DC←(AREAC)*0.5
[2]   DCD←DC×DCSTRD
[3]   DCS←DCD+CST
[4]   DINS←DCS+INSLT
[5]   DINSR←DINS+IST
[6]   DCN←DINSR+CNT
[7]   DJ←DCN+JT
[8]   WCOND←(DC*2)×CONDSG×1.03
[9]   CSTCOND←WCOND×PCOND
[10]  CSTCS←(((DCS*2)-(DCD*2))×SGSC)×PCS
[11]  CSTINS←(((DINS*2)-(DCS*2))×SGINS)×PINS
[12]  CSTINSR←(((DINSR*2)-(DINS*2))×SGSC)×PCS
[13]  CSTCN←(((DCNT*2)×CNC×CNSG)×PCN)×1.03
[14]  CSTJ←(((DJ*2)-(DCN*2))×4.7E¯7)×PJ
[15]  CBLCSTM←CSTCOND+CSTCS+CSTINS+CSTINSR+CSTCN+CSTJ
[16]  CBLSP←(CBLCSTM÷FABFCT)+OCST
[17]  →19×⍳(TYP=1)
[18]  CABNA←CBLSP ◇ CABNA3P←3×CABNA ◇ →35
[19]  CABAL←CBLSP
[20]  CABAL3P←3×CABAL
    ∇
     ∇TP[⎕]∇
    ∇ TP
[1]   →9×⍳(TYP=1)
[2]   DCSTRD←1
[3]   DCNT←(AREAC×0.368)*0.5
[4]   CST←0
[5]   CONDSG←3.3E¯7
[6]   PCOND←PNA
[7]   PINS←PINSNA
[8]   FABFCT←FABFCTNA ◇ →16
[9]   DCSTRD←1.15
[10]  DCNT←(AREAC×0.61)*0.5
[11]  CST←30
[12]  CONDSG←9.2E¯7
[13]  PCOND←PAL
[14]  PINS←PINSAL
[15]  FABFCT←FABFCTAL
    ∇
     ∇PWCB[⎕]∇
    ∇ PWCB
[1]   DT←((1+D)-(((1+G)*2)×(1+E)))÷(((1+G)*2)×(1+E))
[2]   PWF←(1-(1+DT)*(N))÷DT
[3]   ICON←((I1*2)+(I1×I2)+(I2*2))
[4]   PWRAL←KP×ICON×RACAL×3.05E¯5
[5]   PWRNA←KP×ICON×RACNA×3.05E¯5
[6]   LOAL←PWRAL×LSF
```

```
7]   LONA←PWRNA×LSF
8]   PWOAL←((LOAL×POENG)+(PWRAL×PKRESB×POCAP))×PWF
9]   CABALE←CABCAL×((AREAC÷250000)*ALPHAL)
10]  CNCTAL←CONCAL×((AREAC÷250000)*ALPHCAL)
11]  CABNAE←CABCNA×((AREAC÷250000)*ALPHNA)
12]  CNCTNA←CONCNA×((AREAC÷250000)*ALPHCNA)
13]  PWTAL←CABALE+PWOAL+CNCTAL
14]  PWONA←((LONA×POENG)+(PWRNA×PKRESB×POCAP))×PWF
15]  PWTNA←CABNAE+PWONA+CNCTNA
16]  CABMPLT←⍉(5 32 ⍴(AREAC,CABALE,CABNAE,PWOAL,PWONA))
17]  CABMPW←⍉(3 32 ⍴(AREAC,PWTAL,PWTNA))
18]  CABMCSTAL←⍉(4 32 ⍴(AREAC,CABALE,CNCTAL,PWOAL))
19]  CABMCSTNA←⍉(4 32 ⍴(AREAC,CABNAE,CNCTNA,PWONA))
   ∇
```

```
     ∇TEM[⎕]∇
   ∇ TEM
1]   IN←1 ◇ I←I1 ◇ ITER←0 ◇ AREA←(AREAC×1.15)
2]   R←(((AREA)*0.5)÷2)+((CST+IST+INSLT)÷2) ◇ R←R÷1000 ◇ LSQ←L*2 ◇ RSQ←R*2
3]   DELS←RHE×(⍟((L+((LSQ-RSQ)*0.5))÷R))×(1+ALP) ◇ XSQ←X*2
4]   DELM←RHE×(⍟((XSQ+(L+((LSQ-RSQ)*0.5))*2)÷(XSQ+(L-((LSQ-RSQ)*0.5))*2)))×(1+ALP)
5]   DELL←RHL×(⍟(R÷(((AREAC)*0.5)÷2000))) ◇ GTH←DELS+DELM+DELL
6]   TEMPAL←(20+((I*2)×2.8624÷(((6.28319×AREAC×5.07E¯6)÷((DELS+DELM+DELL)×1E¯6))-(0.0115×I*2))))
7]   TEMPNA←(((125.664×AREAC×5.07)÷((I*2)×(GTH)))+4.29)÷(((6.2832×AREAC×5.07)÷((I*2)×(GTH)))-0.0199
8]   TMPAL[IN;]←TEMPAL ◇ TMPNA[IN;]←TEMPNA ◇ →11×⍳(TYP=1)
9]   RHONA←4.29+0.01993×TEMPNA+9.848E¯6×(TEMPNA*2)
10]  RHO←RHONA ◇ →13
11]  RHOAL←2.8624+0.0115×(TEMPAL-20)
12]  RHO←RHOAL
13]  Z←((AREAC×5.07E¯6)÷RHO)
14]  BETA←1+0.0070664×((Z÷172)*2)×(1+(0.66046÷((Z÷172)+(172÷Z))))
15]  RAC←BETA×(RHO÷(AREAC×5.07E¯6))
16]  →19×⍳(IN=2)
17]  RAC1←RAC ◇ IN←2 ◇ I←I2
18]  →2
19]  RAC2←RAC
20]  RAC←((RAC1+RAC2)÷2)
21]  →23×⍳(TYP=1)
22]  RACNA←RAC ◇ →30
23]  RACAL←RAC
   ∇
```

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