Title

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Publication Date

1979-09-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Presented at the NATO Conference Series VI, Aussois, France, September 9-14, 1979, and published in "Materials for Advanced Batteries, Vol.2, D.W. Murphy, J. Broadhead, B.C.H. Steele, eds., Plenum Pub. Corp., New York, NY

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September 1979

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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in

MATERIALS FOR ADVANCED BATTERIES, VOLUME 2
NATO Conference Series VI
Aussois, France
D.W. Murphy, J. Broadhead, B.C.H. Steele, eds.
Plenum Publishing Corporation
New York, NY

This work was supported by the U.S. Department of Energy
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I. Introduction

Since 1973, the energy economy of the U.S. has been changing very rapidly. Our perceptions of the value of energy, and the price of petroleum are very different from what they were just a few short years ago. It is interesting to examine the total energy economy of the U.S., and to consider in which directions the shifts of supply and demand will go. As members of the scientific and electrochemical communities, we ask ourselves where our field can contribute to achieving a more nearly optimal distribution of energy supplies and energy demands, and how can electrochemical energy storage help them mesh in an effective, economically sound manner.

A diagram of the energy economy of the United States is shown in Figure 1, based upon projections made a few years ago. On the left hand side of the diagram are shown the primary energy sources, and the numbers indicate the size of the energy supply in units of millions of barrels per day in oil equivalent. The widths of the various bands on the diagram are drawn proportional to the size of the energy supply. Overall, the projections made in Figure 1 are rather accurate with a few minor exceptions, such as the fact that the U.S. is already importing more oil than it is producing, and the transportation sector is using slightly less energy than the projected 12.0 million barrels per day oil equivalent. The general features of the diagram are clear: About 45% of all of the energy consumed in the U.S. is in the form of oil. About half of this oil is used in the transportation sector. About 27% of all of the energy is consumed for the purpose of generating electrical energy. This sector of the energy economy has been growing faster than any other, historically at the rate of 7% per year except during the last few years. The combination of rapid growth in the electrical generating industry and its lesser dependence upon oil make this an attractive opportunity for more effective utilization of non-petroleum energy resources.

The varying load placed upon a typical electric utility is shown as a function of the time of day in Figure 2. The four curves show the load for days selected from each of the four seasons of the year for a midwestern utility. In each curve there is a much larger demand during the daytime and evening hours than there is during the middle of the night. This large variation in load results in a large excess of electrical generating capability during the nighttime hours because the size of the equipment must exceed the peak demand by some safety margin. If it were possible to operate electrical generating equipment at the same power level for nearly all of the time, then less generating equipment would be required. In principle, the storage of energy in batteries could make an important contribution in this direction. Large blocks of batteries located at the substation level could accept energy during the nighttime hours, and could deliver that energy during the heavy load periods in the daytime and early evening. This would level the load on the central power plants and on the distribution network down to the substation level. Additional advantages to this approach are the building-block nature of batteries, allowing them to be used only in the precise numbers necessary to meet the local demand at the substation. As demands change with time, additional battery modules could be installed or removed as necessary. Other unique opportunities exist for energy storage in batteries in the centers of large metropolitan areas where addition of more electrical capacity is extremely expensive because of the expense of installing additional underground distribution lines and equipment. Battery modules could be installed, for example, in the basements of large buildings, leveling the load for that building and effectively increasing the peak capability of the distribution network. For these special situations rather high cost could be justified.

Referring again to the energy diagram of Figure 1, it is clear that there are strong advantages to be realized by shifting at least a part of the transportation energy demand to electricity instead of oil. This can of course be accomplished by the use of battery-powered electric vehicles. The batteries could be recharged during the low demand period at night, making use of excess generating capacity. The relatively high efficiency of the electric vehicles compensates for the efficiency losses in the generation of the electricity, the result being merely a shift in energy demand away from petroleum toward coal and nuclear primary energy sources. The main problem with this idea is the fact that batteries of sufficiently high energy storage capabilities to provide an attractive vehicle range, for example 100 kilometers or more, have not been available.

One additional growing area of opportunity for batteries to contribute to easing the energy problem is in the area of storage of the energy generated by solar-powered and wind-powered electrical energy generators. The attractiveness of these methods of energy generation includes the fact that they don't use conventional fuels, and the primary energy source is available even in remote locations. Storage of energy from solar- and wind-powered devices is an attractive opportunity for batteries. Whenever the energy demand is less than the energy being supplied, the excess energy being generated can be stored in the battery for later use. Depending upon the design of the system the battery could supply energy for extended dark or cloudy or windless periods.

The above three major energy storage opportunities which could make significant contributions to the U.S. energy independence will be discussed in terms of specific needs and specific battery requirements in the sections below.

II. Energy Storage for Electric Utilities

The electric utility load curves shown in Figure 2 offer the opportunities discussed above for energy storage during the low demand period and energy delivery during the peak demand period. Examination of the curves of Figure 2 indicates that a period of 5 to 7 hours is available during the late night hours for battery recharge. This means that the battery must be capable of accepting a full charge of energy during those hours. The daytime and evening peak demand period varies in duration from season to season. It may be as short as 3 hours in the afternoon in the summertime or as long as 8 or 10 hours during spring or fall. In addition to having the charge acceptance and charge delivery capabilities just discussed, the battery must operate very efficiently in order to avoid loss of the energy which is stored. The efficiency of pumped hydroelectric storage is between 65 and 70%, so batteries should do at least this well in order to be fully competitive in the storage of large blocks of energy. For storage of energy at the substation level it may be possible to tolerate somewhat lower efficiencies depending upon the features of the local utility network.

In principle, utilities have the choice of either storing energy or generating energy as needed. The main source of electrical energy during the peak demand periods is gas turbines, which are rapidly started and very responsive to changes in load. These units are relatively inexpensive and can provide energy at a cost which is somewhat higher than that generated by the large plants. Unfortunately, gas turbines rely upon oil as the fuel making this less attractive than it was a few years ago. The combination of the disadvantage of using oil for gas turbines and the relative lack of availability of appropriate sites for pumped hydroelectric storage make the battery choice an attractive one providing that the performance, durability, and cost requirements can be met.

The economics of providing land and buildings for battery stations indicate that it is necessary for the battery to be compact enough that floor space of only one square meter for every 80 kilowatt hours of energy storage capability be allowed. This corresponds to something above 30 Wh/l, depending upon the details of the system design. The durability and cost requirements for the battery are set in such a manner that the battery is competitive with alternative means of providing power during peak demand periods, and the lifetime is compatible with reasonable projections of present technology. The longer the battery life, the higher is the tolerable initial cost. For a cycle life of 2000, an initial cost of \$30/kWh is acceptable, corresponding to a storage cost of 1.5¢/kWh for the battery alone.* If the battery is cycled 200 times per year, then it should last 10 years. Longer lives, of course, would result in lower storage costs, or might allow a higher initial cost.

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*The cost of peaking energy from a gas turbine using \$3.50/10^{6}BTU fuel is about 6¢/kWh. [1]

If batteries were to be used for dispersed energy storage in locations having very high costs for installation of additional distribution hardware, such as in the center of a large city, where these costs may be over \$200/kW, then higher battery costs are allowable--perhaps \$100/kWh or more, depending upon the situation and the load curve.

At the small substation level, the battery may be required to provide 20-50 MW for a few hours, requiring an availability of 100-200 MWh on a daily basis. Smaller installations may be used in large office buildings, apartment complexes, and shopping centers.

A summary of the requirements for off-peak energy storage batteries is presented in Table 1, reflecting the characteristics discussed above. At present, no batteries meet all of the requirements. Many batteries can meet the charge and discharge times and the efficiency (e.g., Pb/PbO_2), and a few can meet the cycle life and lifetime values (Pb/PbO_2, Fe/NiOOH), but none can meet all of these, plus the cost goal. As costs of a given battery type are reduced, the cycle life and performance also tend to be reduced, making the simultaneous achievement of performance, durability, and cost goals a difficult task, requiring complex compromises.

An example of a system which may meet the goals of Table 1 in the future is the high-temperature battery $Li_4Si/LiCl\text{-}KCl/FeS_2$, which operates at 450°C. The active materials are sufficiently inexpensive that the \$30/kWh cost goal may be met if the materials of construction problems can be solved (see below).

A schematic cross section of a typical Li_4Si/FeS_2 cell is shown in Figure 3. [2] The positive electrode (center) is comprised of powdered FeS_2 mixed with graphite powder (as a current collector), in contact with a molybdenum mesh current collector. A zirconia cloth serves as a particle retainer around the positive electrode. Between the electrodes is a boron nitride fibrous mat separator, which contains the molten LiCl-KCl electrolyte. The negative electrodes are comprised of Li_4Si powder and a fibrous mickel current collector, attached to the stainless steel cell case. The cell is hermetically sealed.

Typical discharge curves for a Li_4Si/FeS_2 cell are shown in Figure 4. [2] The plateaus correspond to various steps in the overall discharge reaction:

$$Li_4Si + FeS_2 \rightarrow 2Li_2S + Fe + Si \qquad (1)$$

The theoretical specific energy for this reaction is 944 Wh/kg; cells such as that of Figure 3 have achieved 180 Wh/kg, [2] or 19% of theoretical. It should be feasible to obtain up to 25% of the theoretical value, or 230-240 Wh/kg.

Cycle lives in excess of 700 cycles have been demonstrated for high specific energy Li_4Si/FeS_2 cells, corresponding to a lifetime of almost two years. Energy efficiencies of 80-90% have been achieved, exclusive of thermal losses. [2] The current status of the Li_4Si/FeS_2 cell is summarized in Table 2. A gradual increase of internal resistance results in a decline of cell performance, especially at high specific power. The present cost of these cells is very high because no mass production facilities exist. The active materials costs, however, are compatible with the goal of $30/kWh.

The use of molybdenum and stainless steel in significant amounts is not consistent with the cost goal; substitutes must be found. The presently-used boron nitride separator is far too expensive. Lower cost forms of boron nitride separator, or substitute materials are necessary. Recent cost projections for BN felt are encouraging, [3] indicating a cost below $\$10/m^2$ in large volume. Materials problems in general hold the key to economic viability of this system. Both corrosion-resistant electronic conductors and electronic insulators are needed. Probably the current collector and feedthrough problem for the positive electrode will prove to be the most difficult.

If the problems above can be solved, then energy storage systems such as the one in Figure 5 may be feasible.

III. Batteries for Electric Automobiles

In the introduction to this paper, it was indicated that the use of electric vehicles could help to shift the energy demand away from petroleum, and toward such primary energy sources as coal and nuclear fuels. This is a very attractive concept, especially if the overall effectiveness of energy utilization is not reduced. This means that the amount of primary energy to accomplish a given vehicle mission should not be increased by the shift to electric vehicles. Two major components comprise the overall consideration: the efficiency of energy conversion for the overall process (energy resource in the earth to energy at the wheels of the vehicle), and the energy required by the vehicle (at the wheels) in executing its mission.

With regard to the energy efficiency issue, Figure 6 summarizes the efficiencies for each step in the process for conversion of petroleum to energy at the wheels of a vehicle, comparing the standard spark-ignition (SI) vehicle as it is now used to the electric vehicle. Note that the overall efficiencies are similar--about 13%. Of course, the objective is not to use petroleum, but to shift to other sources. Figure 7 shows the overall efficiency for the use of coal in vehicles. The overall efficiency of the SI engine vehicle suffers because of the efficiency loss in converting coal into a liquid fuel for a vehicle, yielding the efficiency advantage to the electric vehicle (EV). In Figure 8, the efficiency values for the nuclear fuel situation are shown. Again, the advantage goes to the EV, by a significant margin: 4% vs. 14%. In Figures 7 and 8, relatively high efficiencies were estimated for the preparation of liquid fuels, so the actual efficiency advantage of EV's is likely to be somewhat greater than shown.

With regard to the issue of energy consumption by the vehicle, it is possible to calculate with good accuracy the amount of energy required, knowing a few characteristics of the vehicle, and the velocity vs. time profile (driving profile). Since electric vehicles are limited to modest range and performance by the batteries, it is reasonable to perform calculations for urban and suburban driving profiles only. The applicable equations are:

$$P_b = \frac{P_r}{E_m \cdot E_e} + \frac{P_a}{E_a} \tag{2}$$

$$P_r = 9.8\ V\ (R_r + R_w + R_g + 1.1\ R_a) \tag{3}$$

$$R_r = \frac{W}{65}\ (1 + 4.68 \times 10^{-3} V + 1.3 \times 10^{-4} V^2) \tag{4}$$

$$R_w = \frac{\rho_a}{g}\ C_d\ A_f\ \frac{V^2}{2} \tag{5}$$

$$R_g = W\ \sin\Theta \tag{6}$$

$$R_a = \frac{W}{g}\ \frac{dV}{dt} \tag{7}$$

where P_b = power from the battery, W

P_r = power required at the wheels, W

E_m = mechanical efficiency of the transmission and differential

E_e = electrical efficiency of the drive train

P_a = power required by the accessories

E_a = electrical efficiency of the accessories, W

V = velocity, m/s

R_r = rolling resistance of the tires, kg_f

R_w = wind resistance, kg_f

R_g = gravitational resistance, kg_f

R_a = acceleration resistance, kg_f

W = vehicle test weight, kg

ρ_a = density of the air, kg/m^3

C_d = air drag coefficient, demensionless

A_f = frontal area of the vehicle, m^2

Θ = angle of inclination

g = gravitational acceleration, 9.8 m/s^2

When the above equations are applied point-by-point (by computer) to driving profiles such as those of Figure 9, it is found that the energy and power required by the vehicle are essentially proportional to the vehicle mass, so that the requirements may be expressed simply in terms of kWh/T-km and kW/T, summarized as shown in Table 3. [4] Note from the table that the battery must provide about 0.15 kWh/T-km for urban driving, that the peak power needed is up to 35 kW/T, and the average power is 4-5 kW/T.

From the standpoint of good vehicle design practice, it is desirable not to exceed 0.25-0.30 of the vehicle mass as the fraction assignable to the battery. The urban range of an electric vehicle may be calculated from the expression:

$$R = \frac{S_pE}{0.150} \frac{M_b}{M_v} \tag{8}$$

where R = vehicle range, km

S_pE = specific energy of battery, Wh/kg

M_b = battery mass, kg

M_v = vehicle test mass, kg

Equation 8 is plotted in Figure 10. Note that a range of 100 km requires a battery having a specific energy of 60 Wh/kg if the battery fraction is 0.25, and a 150 km range requires a specific energy of 75 Wh/kg at a battery fraction of 0.3. These considerations provide the battery performance requirements shown in Table 4: a specific energy of at least 70 Wh/kg, for an urban range of 140 km at a battery fraction of 0.3. In order to provide the battery with an acceptably small volume (from a vehicle design point of view) the energy density should be at least 140 Wh/l. The specific power for safe acceleration (0 to 50 km/h, ∿9 sec.) should be about 130 W/kg.

Aside from vehicle and battery performance, the efficiency, durability, and cost are all important to the acceptability of a battery for use in an electric vehicle. The efficiency should be at least 70%, keeping the heat rejection rate to an acceptable value. As before, the cycle life and cost are compromises, based on what might be achieved. A minimum life of 300 deep cycles, and a cost of \$70/kWh correspond to an amortized battery cost of 3.5¢/km. This is about the maximum tolerable cost, unless new factors come into consideration.

An example of an ambient-temperature battery that might be acceptable for urban electric automobiles is the zinc/nickel oxide battery, which has a potassium hydroxide electrolyte, and operates according to the overall reaction:

$$Zn + 2NiOOH = H_2O \rightarrow ZnO + 2Ni(OH)_2 \qquad (9)$$

and has a theoretical specific energy of 373 Wh/kg. At the present stage of development, these cells display 55-75 Wh/kg (15-20% of theoretical), making them capable of giving a range in excess of 100 km in an electric vehicle. Specific power values in the range of 150 W/kg have been achieved by Zn/NiOOH cells of light-weight construction.

The cycle life of the zinc electrode has been shorter than needed: 100-200 deep cycles. Failure is traceable to combinations of the following problems: [5] a) dendrite formation, b) zinc redistribution (shape change), c) densification, and d) passivation. Dendrite formation can be minimized or eliminated by proper choice of separators with extremely small pore diameters. Zinc redistribution is the gradual movement of zinc away from the edges of the electrode toward the center as cycling proceeds. It is related to the formation of soluble zinc species on discharge, and their redeposition during recharge on sites closer to the center of the electrode. No existing theory is capable of a quantitative explanation of this complex process. Its rate is significantly reduced by making the current density uniform, and by the use of K_2TiO_3 fibrous mats against the zinc electrode. Densification occurs with repeated cycling of the zinc electrode, and is the loss of porosity and surface area in the zinc deposit, finally resulting in passivation of the zinc because the current density exceeds the critical value ($\sim$20 mA/cm^2) for the formation of a passive oxide film, preventing further electrochemical reaction. These problems continue to receive attention, and gradually the cycle life of the zinc electrode is being improved. For a more detailed discussion, see reference 6.

The current cost of Zn/NiOOH cells is significantly above \$100/kWh, but projected values are near \$70/kWh, for cells with polymer-bonded electrodes. Achievement of the performance and durability goals requires better separators and zinc electrodes. These are the areas of current emphasis. The current status of the Zn/NiOOH cell is summarized in Table 5. Batteries of more than 10 kWh have been tested in electric automobiles, and have yielded the expected range and performance: more than twice the range available from the Pb/PbO$_2$ cell, and better acceleration. [7]

IV. Energy Storage for Solar and Wind Powered Systems

In contrast to the two areas for the application of batteries discussed above, the storage of energy generated by solar- and wind-powered systems is not an established technology with clearly-defined requirements. At this point, it is not clear what the sizes, load profiles, and other characteristics of the systems will be because very few solar- and wind-powered installations exist. Therefore, it is extremely difficult to list the performance, durability, and cost requirements for the energy storage batteries that might be used.

In spite of the above difficulties, some general indications of desirable battery features can be given. There are a number of options available:

1) Short-term (minutes to hours) storage to level the supply as well as the demand, to provide better matching between the generator and load.

2) Intermediate term (several hours) storage to provide energy for a period such as the whole evening or night, when solar (or wind) input is unavailable.

3) Longer-term storage to provide energy for days, when solar or wind energy may be insufficient to meet the demand.

In the case of short-term storage, the battery would probably be designed in such a manner that is is usually on "float charge," only providing a small fraction of its capacity before being recharged. This sort of service is similar to automotive starting-lighting-ignition service, and could probably be handled well by a Pb/PbO_2 battery.

Intermediate-term storage, to a first approximation, is similar to the off-peak energy storage for electric utilities, and probably would be satisfied by a battery having the characteristics given in Table 1. A higher cost and/or a shorter lifetime than those shown in the table might be acceptable, especially for remote installations with no reasonable alternative for energy storage.

Longer-term storage of energy in relatively large amounts has usually been outside of the proposed area of applicability of conventional batteries, partly because of the relatively high cost implied. There are some battery systems that could prove attractive in this application, however. These are flow systems, in which the reactants and products are stored in tanks. The tanks are sized for the desired capacity, without affecting the electrochemical cells, which are sized for the desired power. This feature tends to reduce the total system cost for large capacities below what it would be for a system in which the size of the electrochemical converter is proportional to capacity. Examples of such systems are redox systems, and to some degree zinc/halogen systems (in which the halogen only is stored externally).

As more experience is gained in the use and the identification of specific applications for solar- and wind-powered systems, a clearer definition of battery requirements can be provided. In the meantime, analytical studies and experimental programs can be carried out to gain more information regarding the power vs. time profiles of both the generators and the loads.

V. Conclusions

Based on the above discussion, the following points can be made in the way of summary and conclusions.

- The general requirements for rechargeable batteries in electric utility networks, electric vehicles, and solar/wind-electric systems have been presented and discussed.
- No presently-available batteries meet all of the performance, durability, and cost requirements for use in off-peak energy storage, electric vehicles, or solar/wind energy storage systems.
- Materials problems are among the most important in achieving the goals for widespread use of batteries in major energy storage applications. The rate of progress in this area may determine the rate at which the goals can be met.
- Overall, batteries have a number of important opportunities to contribute to energy independence by shifting part of the energy demand away from petroleum, both in the transportation and in the electrical energy generation sectors.

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This work was supported by the U.S. Department of Energy
under Contract W-7405-ENG-48.

TABLE 1

REQUIREMENTS FOR OFF-PEAK ENERGY STORAGE BATTERIES

Discharge time	3-8 hours
Charge time	5-7 hours
Overall efficiency	>70%
Energy/floor area (6.1 m max. height)	80 kWh/m^2
Typical size	100-200 MWh
Cycle life	2000
Lifetime	10 years
Cost	$30/kWh

TABLE 2

$Li_4Si/LiCl-KCl/FeS_2$

$Li_4Si + FeS_2 \rightarrow 2Li_2S + Fe + Si$

$E = 1.8, 1.3$ V; 944 Wh/kg Theoretical

<u>Status</u>	
Specific Energy	120 Wh/kg @ 30 W/kg 180 Wh/kg @ 7.5 W/kg
Specific Power	100 W/kg peak
Cycle Life	700 @ 100% DOD
Lifetime	∿15,000 h
Cost	>100/kWh

<u>Recent Work</u>

Bipolar cells

Li-Si electrodes

BN felt separators

70 Ah cells

<u>Problems</u>

Materials for FeS_2 current collector

Leak-free feedthroughs

High internal resistance

Low-cost separators needed

Thermal control

TABLE 3

ENERGY AND POWER REQUIREMENTS FOR URBAN ELECTRIC VEHICLE

ENERGY CONSUMPTION*

At Axle	0.10 - 0.12 kW•h/T•km
From Battery	0.14 - 0.17 kW•h/T•km
From Plug	0.18 - 0.23 kW•h/T•km

PEAK POWER REQUIRED (0 to 50 km/h, ≤ 10 s)

At Axle	25 kW/T (Test Wt.)
From Battery	35 kW/T (Test Wt.)

AVERAGE POWER REQUIRED

	At Axle	From Battery
Urban Driving (Avg. 32 km/h)	3-3.5 kW/T	4-5 kW/T
50 km/h Cruise	3-3.5 kW/T	4-5 kW/T

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*These energy consumption figures correspond to urban driving profiles such as the Federal Register driving profile, and represent an average speed of about 32 km/h.

TABLE 4

REQUIREMENTS FOR URBAN ELECTRIC AUTOMOBILE BATTERIES

Specific energy	⩾70 Wh/kg*
Energy density	⩾140 Wh/l
Specific power, 15 sec. peak	130 W/kg
Energy efficiency	⩾70%
Cycle life, 80% DOD	⩾300
Lifetime	3 years
Cost	⩽$70/kWh
Typical size	20-40 kWh

*Corresponds to 140 km range for a battery mass of 30% of the vehicle test mass.

TABLE 5

Zn/KOH/NiOOH

$$Zn + 2NiOOH + H_2O \rightarrow ZnO + 2Ni(OH)_2$$

E = 1.74 V; 373 W•h/kg Theoretical

Status

Specific Energy	55-75 W•h/kg @ 30 W/kg
Specific Power	80-150 W/kg @ 35 W•h/kg
Cycle Life	100-200 @ 25-50 W/kg 80% DOD
Cost	>$100/kW•h

Recent Work

Inorganic separators (e.g., K_2TiO_3, ZrO_2, others)

Sealed cells

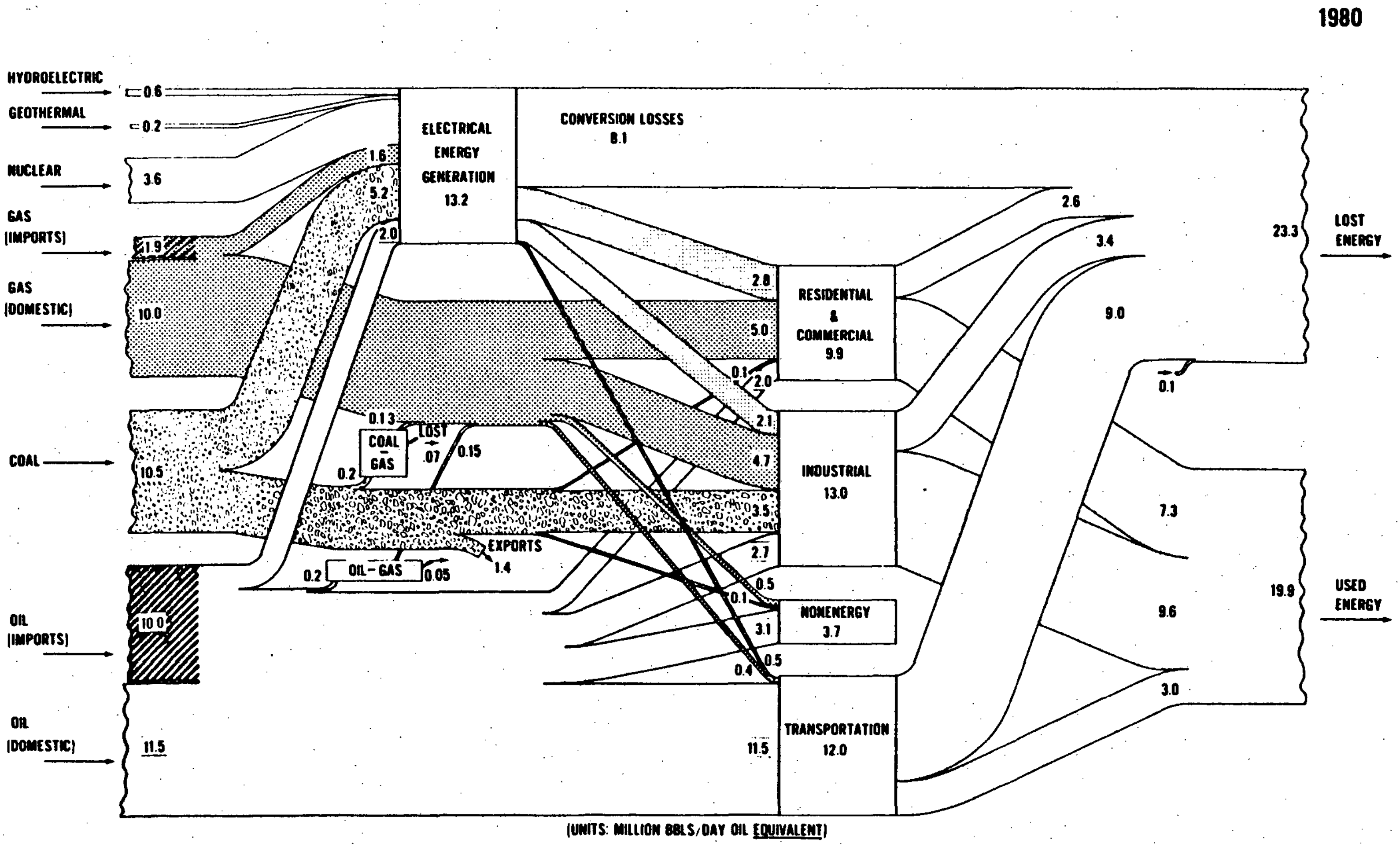
Nonsintered electrodes

Problems

Sealing of cells - O_2 evolution and recombination

Shape change and densification of zinc electrode

Separators



XBL 817-10590

Figure 1. Diagram of the energy economy of the U.S., projected to 1980, in units of millions of barrels of oil equivalent per day, after A.L. Austin, B. Rubin, and G.C. Werth, "Energy: Uses, Sources, Issues" in Lawrence Livermore Laboratory Report, UCRL-51221, May 30, 1972.

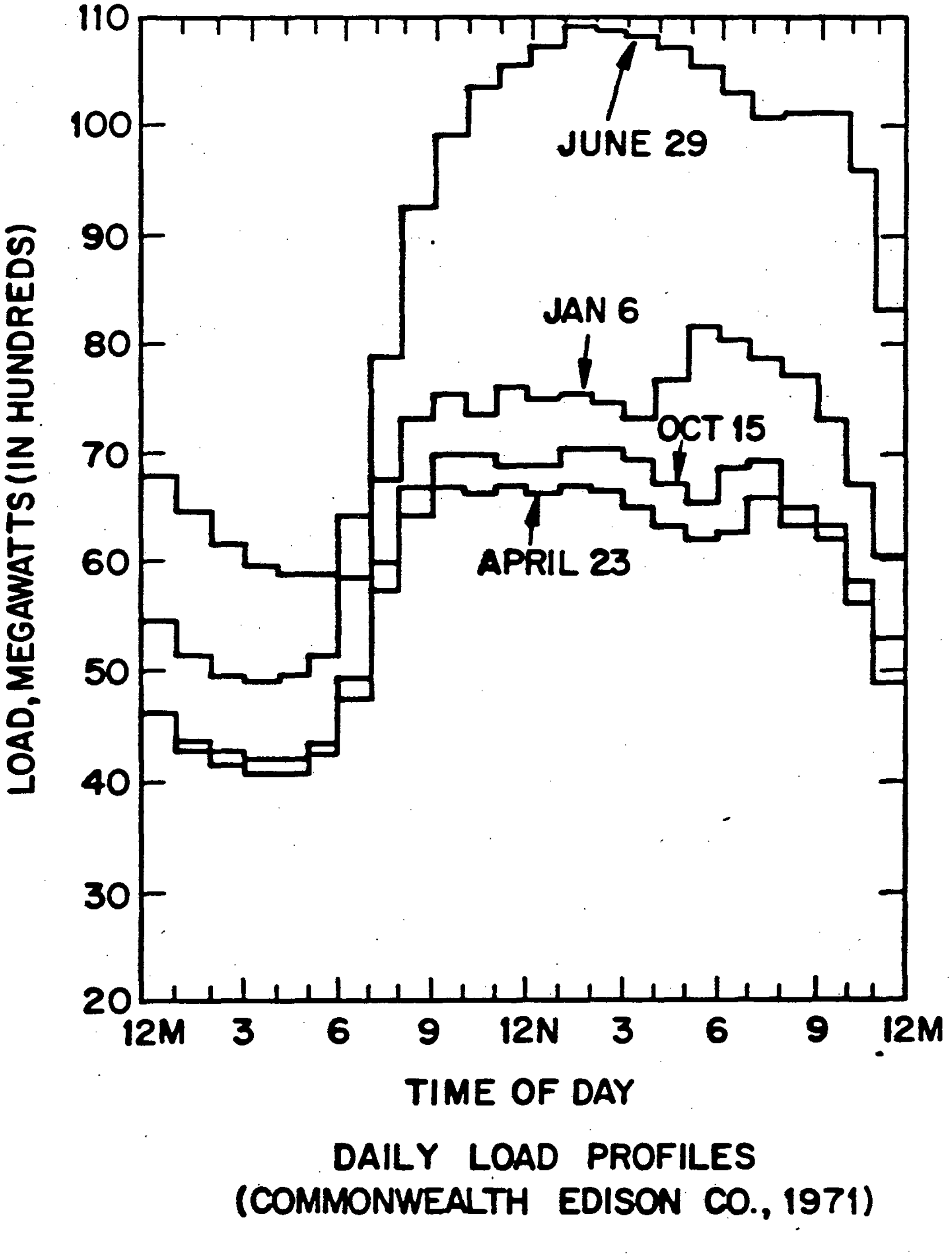
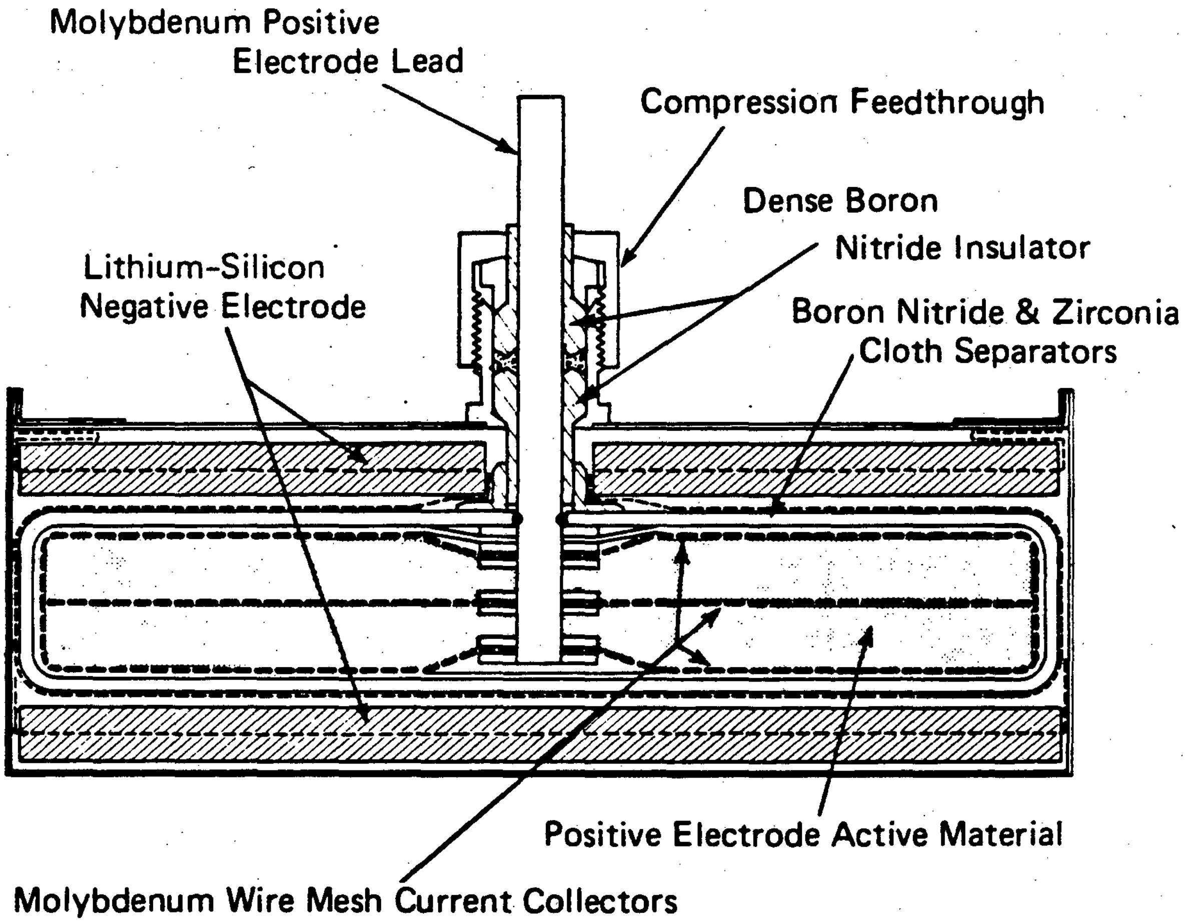
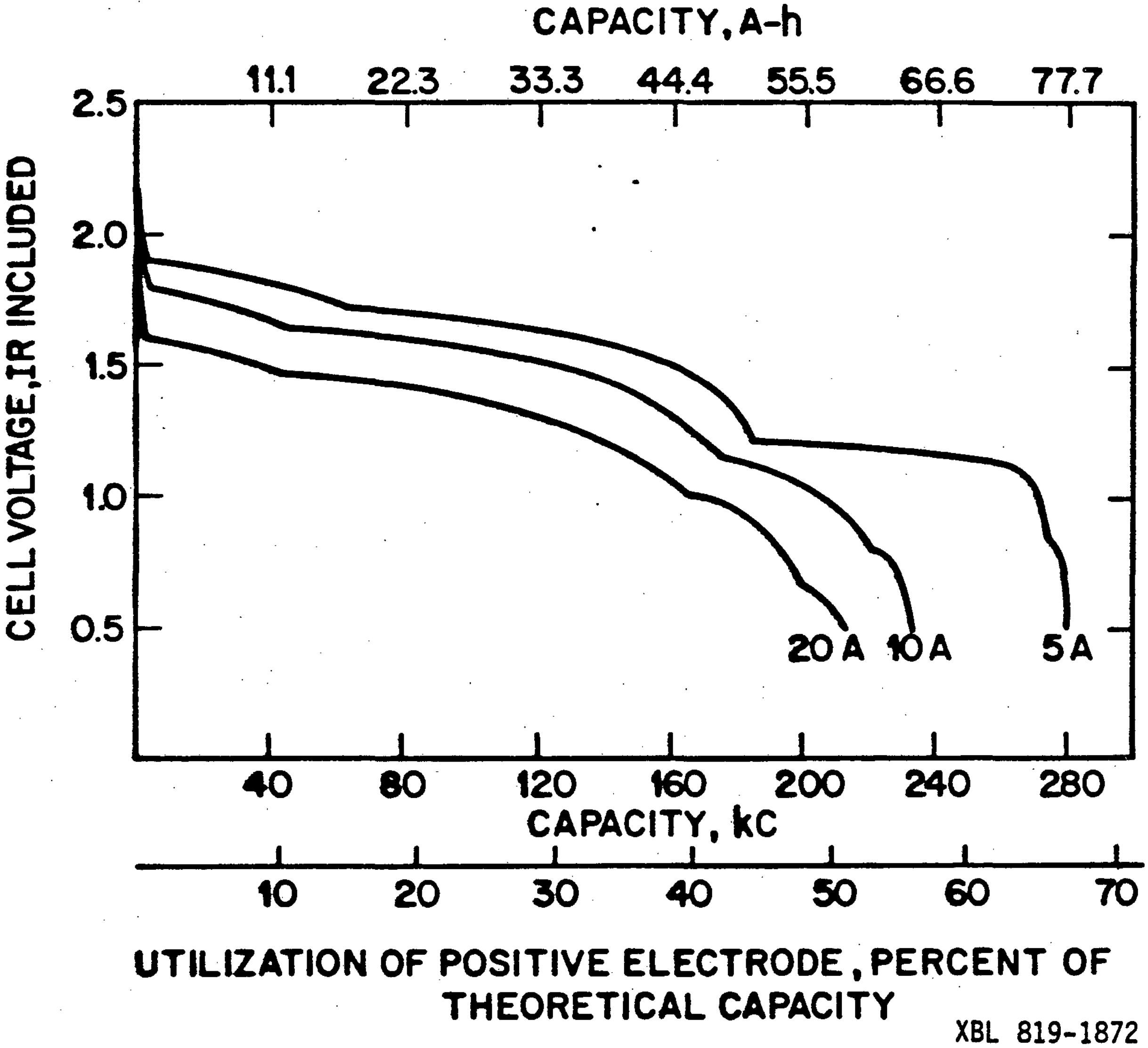


Figure 2. Daily load profiles of the Commonwealth Edison Company for sample days in each of the four seasons of 1971, from M.L. Kyle, E.J. Cairns, and D.S. Webster, Argonne National Lab Reports, ANL-7958, March, 1973.



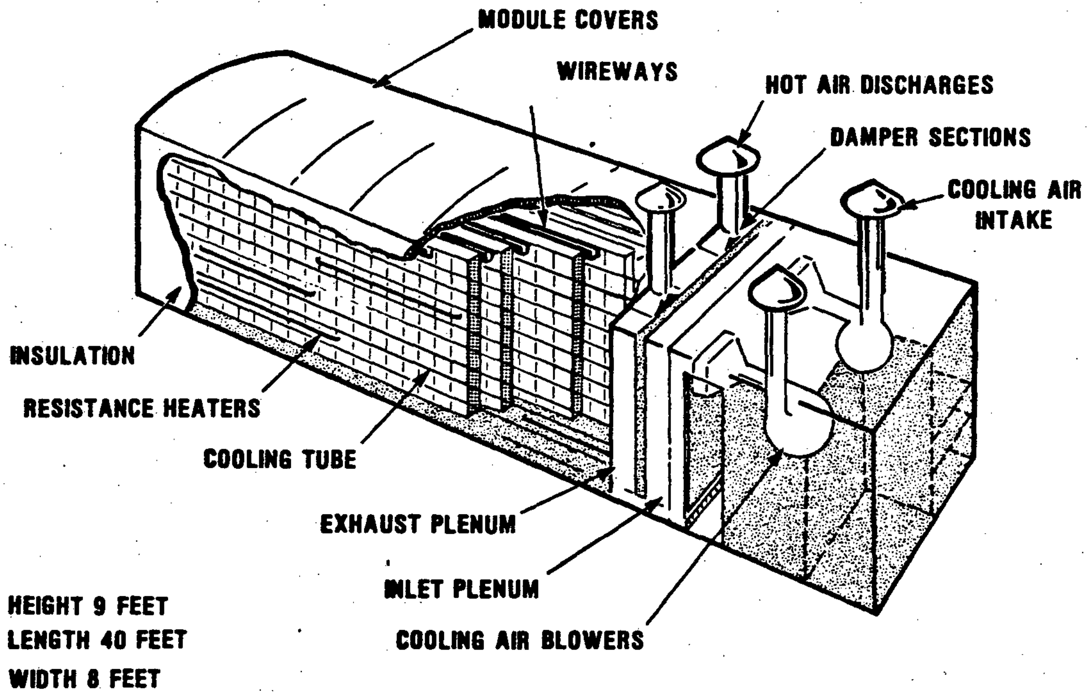
XBL 802-8075

Figure 3. Schematic cross section of a typical $Li_4/Si/LiCl\text{-}KCl/FeS_2$ cell, from E.J. Zeitner and J.S. Dunning, "High Performance Lithium/Iron Disulfide Cells," in Proceedings of 13th IECEC, SAE, Warrendale, PA, 1978, p. 697.



XBL 819-1872

Figure 4. Typical voltage vs. capacity curves for constant current discharges of a $Li_4Si/LiCl-KCl/FeS_2$ cell like that of Figure 3. See reference in caption of Figure 3.



XBL 818-10951

Figure 5. Artist's concept of a truckable lithium/iron sulfide battery module for off-peak energy storage in the electric utility network. See S.M. Zivi, in Annual DOE Review of the Lithium/Metal Sulfide Battery Program, June 20, 21, 1979.

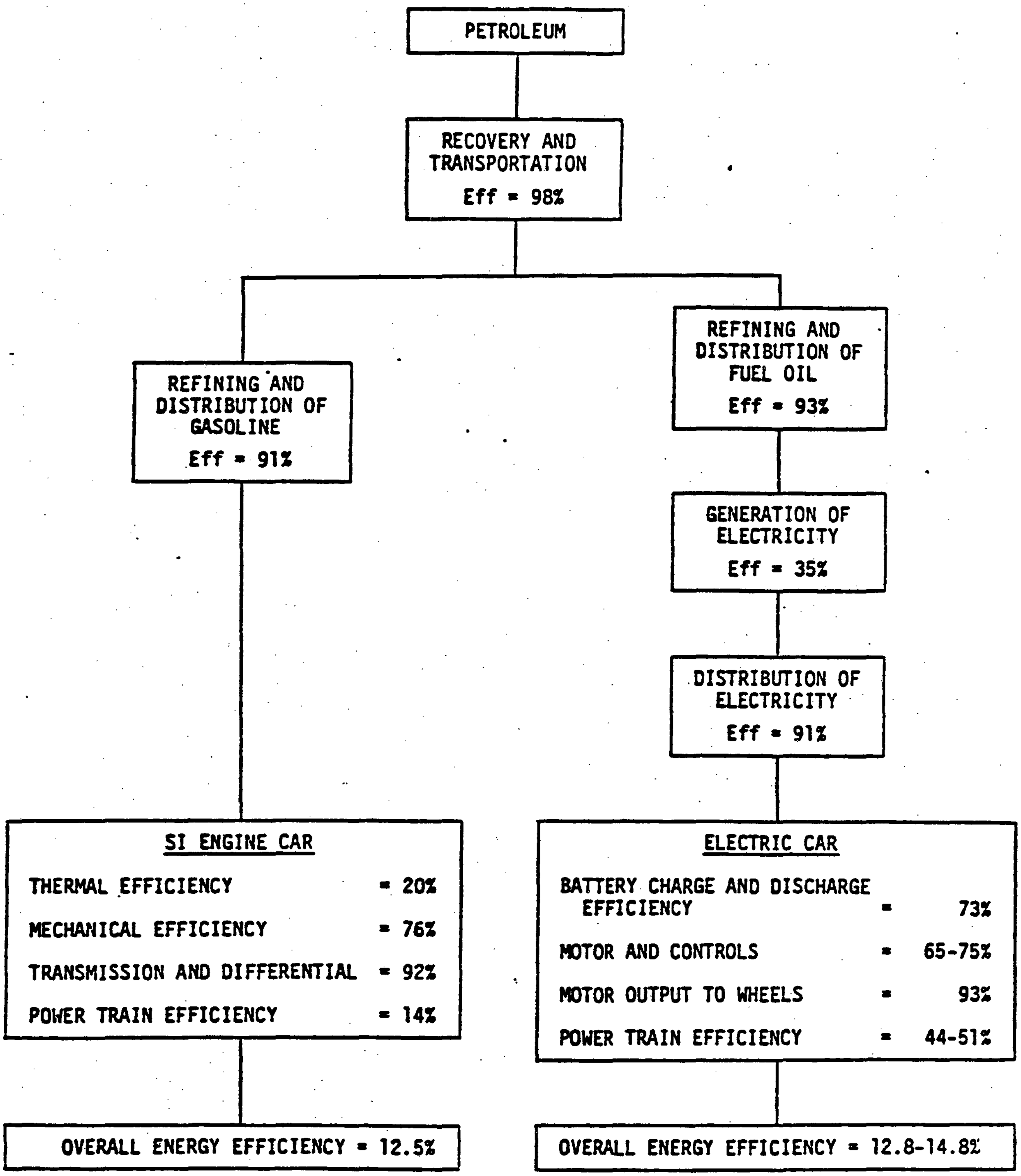


Figure 6. Overall energy efficiency comparison for the use of petroleum to power spark-ignition engine cars and electric cars. Based on M.C. Yew and D.E. McCulloch, in Proceedings of 11th IECEC, AIChE, NY, 1976, p. 363; and E.J. Cairns and E.H. Hietbrink, in Volume VII of Comprehensive Treatise of Electrochemistry, Bockris, Conway, and Yeager, eds., Wiley & Sons, 1980.

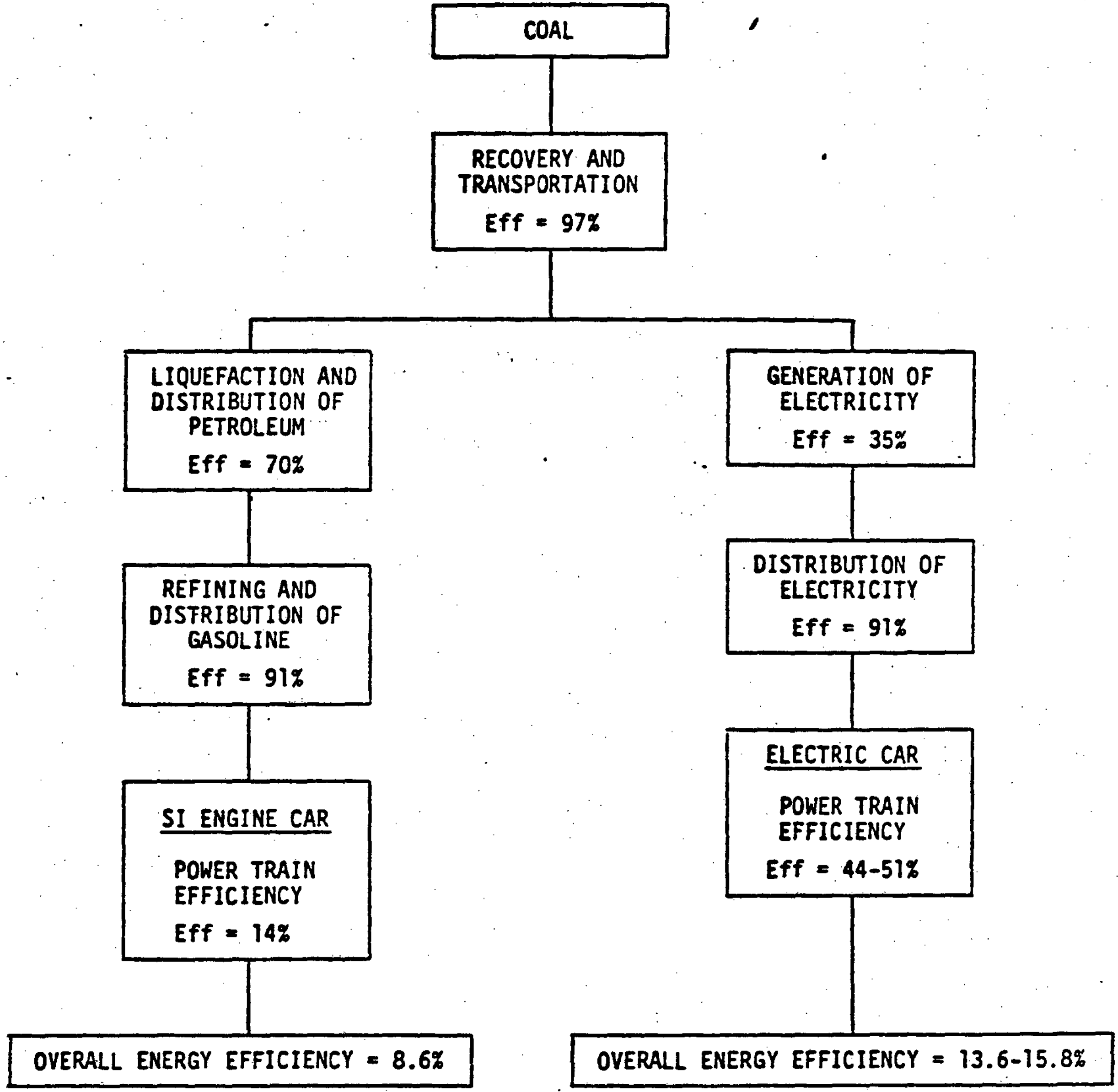


Figure 7. Overall energy efficiency comparison for the use of coal to power spark-ignition engine cars and electric cars. See references in caption of Figure 6.

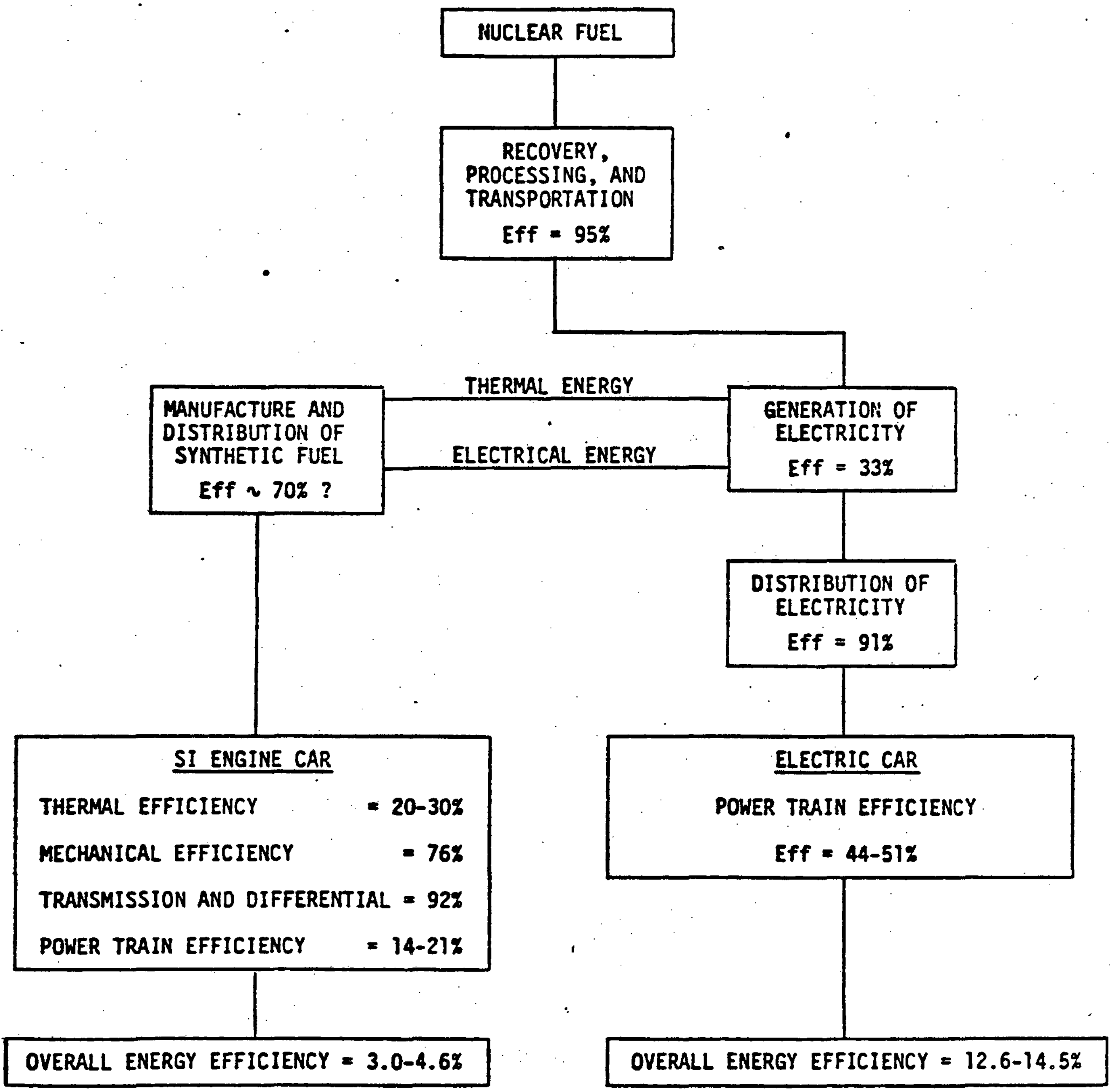


Figure 8. Overall energy efficiency comparison for the use of nuclear fuel to power spark-ignition engine cars and electric cars. See references in caption of Figure 6.

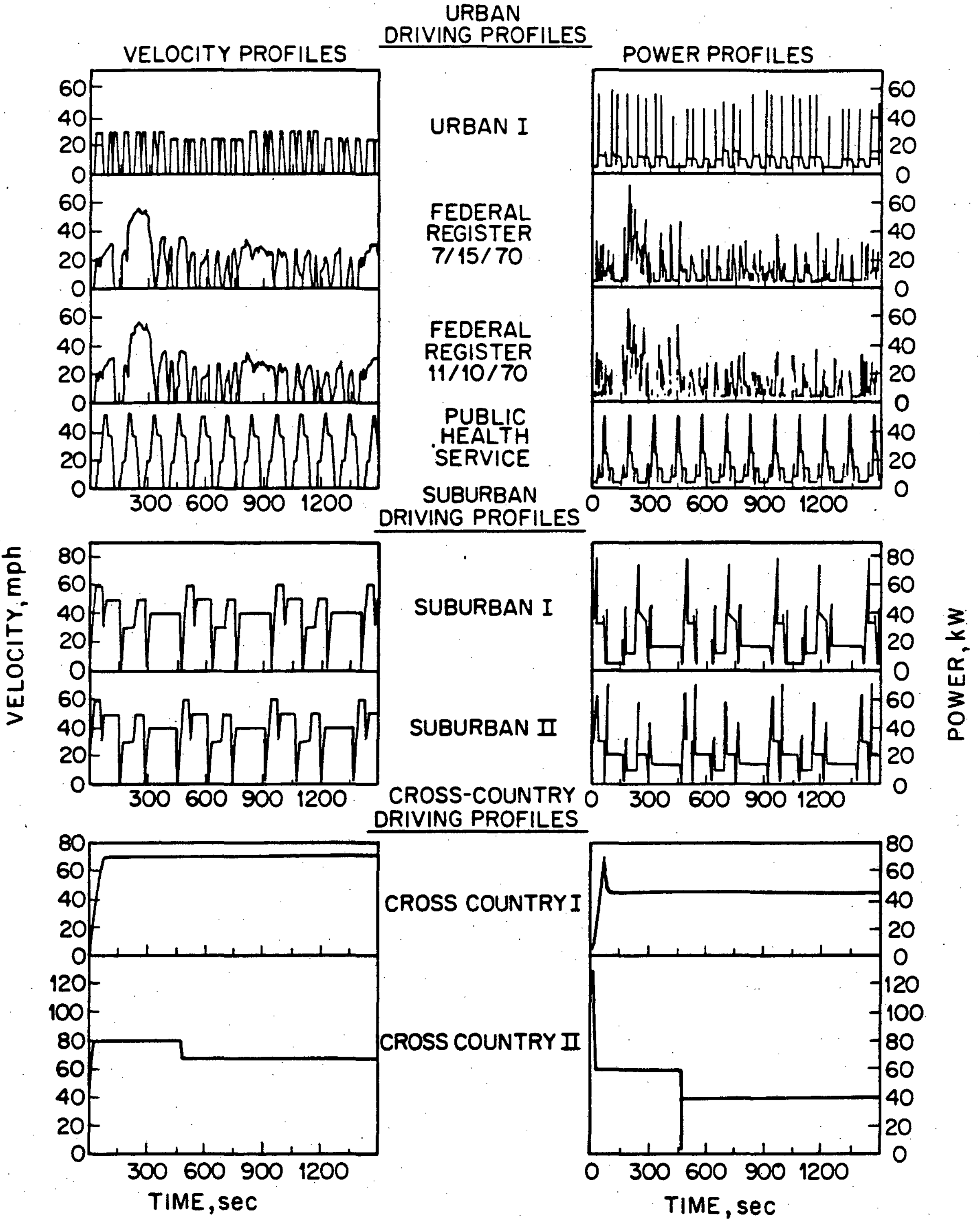


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Figure 9. Driving profiles (velocity vs. time) of several types, with corresponding power profiles for a 2000 kg automobile, as described in E.J. Cairns, et al., "Development of High-Energy Batteries for Electric Vehicles," Argonne National Laboratory Report, ANL-7888, December 1971.

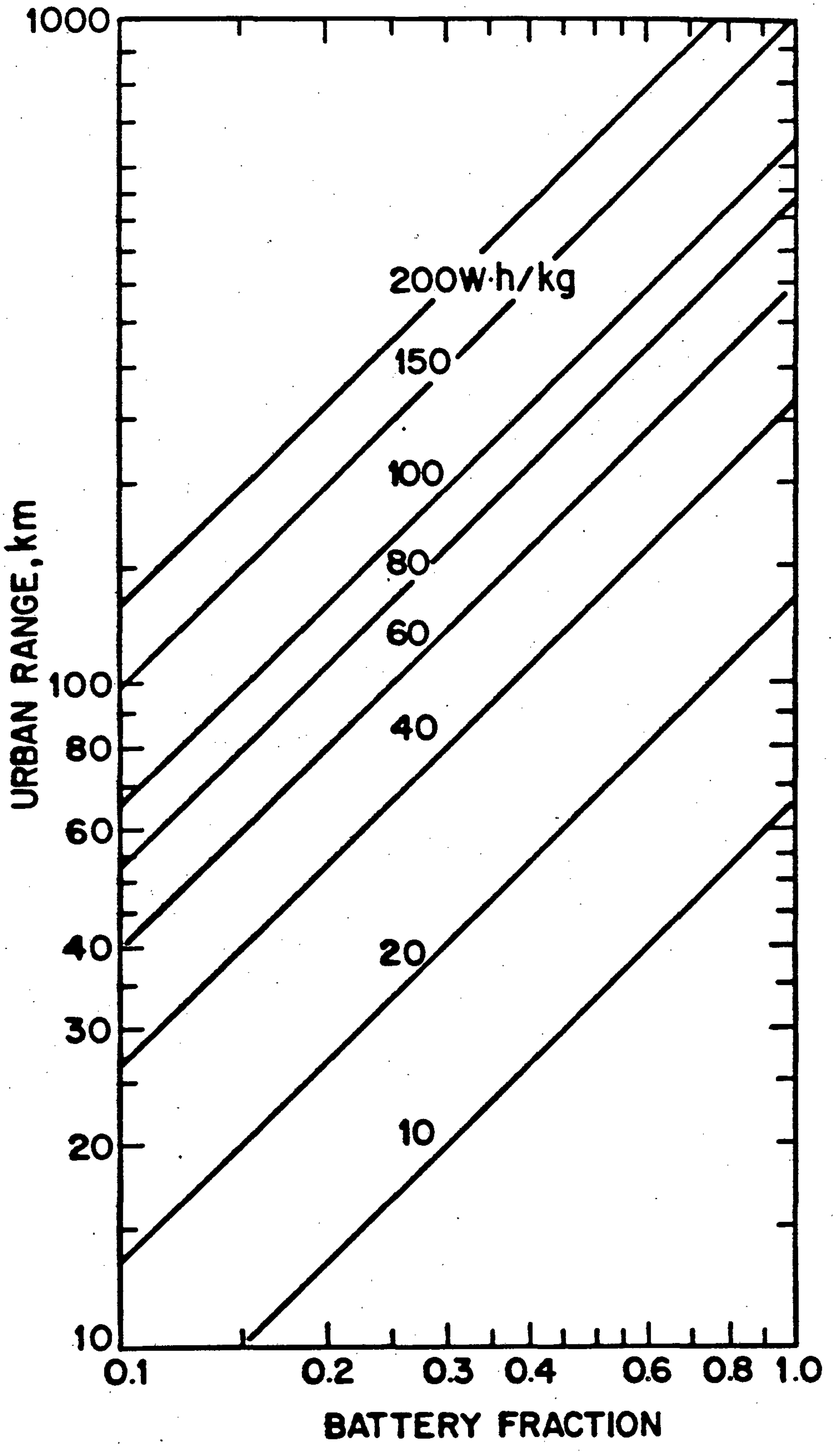

Figure 10. Urban range for electric vehicles as a function of both battery fraction and battery specific energy, using Equation 8.

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