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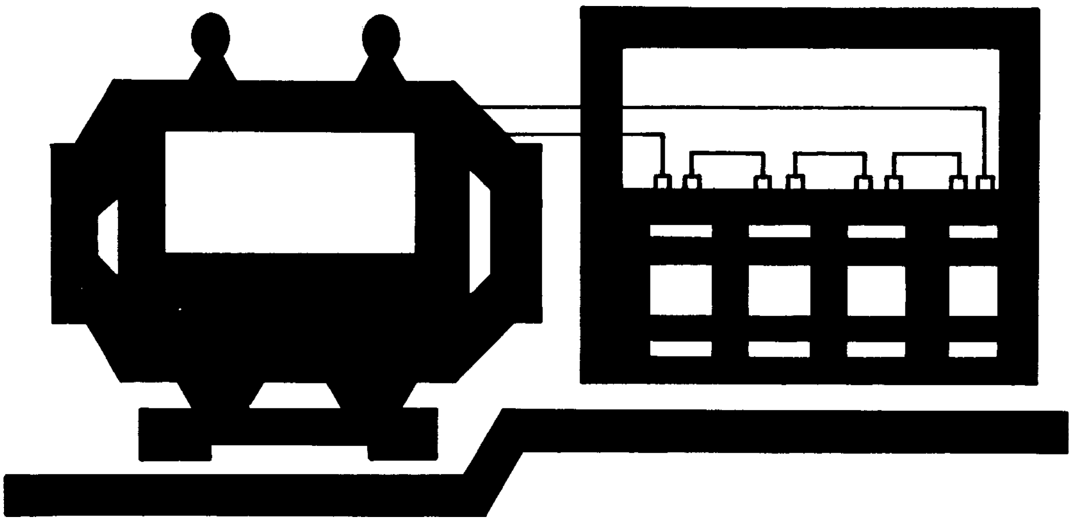
Energy Efficiency and Electric Motors



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ENERGY EFFICIENCY AND ELECTRIC MOTORS

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We appreciate your interest in the recently reprinted "Energy Efficiency and Electric Motors" publication.

The electric motors which power our household, commercial and industrial machinery, have undergone a marked decline in efficiency over the last 30 years. Modern motors waste more energy than their ancestors because they have been built at minimum cost--motor design reflects a cut back on the quality and quantity of materials essential to efficiency. While today's motors may be cheaper initially, the extra power they convert to waste heat rather than to useful work makes them more costly to run. Modern designs often waste both money and energy.

The days of cheap electricity are gone forever, with electric power costs projected to increase at an annual rate of 7 percent over the next 15 years. Rising costs, other market pulls, and the President's stronger conservation ethic have contributed to motor end-user demand for a more accurate portrayal of motor efficiencies and power factors. Some motor manufacturers have responded by putting these percentages on the motor nameplates and accompanying literature. Several innovative manufacturers, realizing the predominant basis of motor choice by the commercial and industrial end-user is not always lowest first cost for the highest quality, offer a line of high efficiency motors.

The report you hold in your hand estimates the potential for increased motor efficiency, coupled with possible replacement rates of lower to higher efficiency motors, as savings by 1990 of almost 5 percent of total U.S. electric power consumption in that year. This would amount to 35 billion kW-hr/year, 60 million barrels of oil, or annual savings of about $1.5 billion in 1975 dollars.

We hope this report is informative and of value to you and others in your organization who are interested in energy management.

G. S. Chaconas

George S. Chaconas
Energy Conservation Specialist
Consumer Products and Technology Branch

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EXECUTIVE SUMMARY

A. BACKGROUND

For some years motor drives in industry and commerce have been known to consume the greatest single coherent segment of electric power generated in this country. However, motor efficiency generally is not even considered by these users in their normal selection process. Even energy management programs brought on by the energy crunch have largely ignored the lonely motor.

All of this is somewhat puzzling, because even a cursory review of catalog data reveals that competitive, comparable motors (especially in the smaller sizes) vary significantly in their published efficiencies. The associated economies of using the more efficient models when usage is heavy are obviously not insignificant. Why then is electric motor efficiency so invisible an issue with commercial and industrial end-users? To answer these questions the Federal Energy Administration (FEA) on 1 July 1975 awarded Arthur D. Little, Inc. (ADL) an eight-month contract for the purpose of:

- identifying areas of greatest conservation potential in the use of electrical motors operated in the industrial and commercial sectors of our economy;
- assessing and projecting the technological potential and economic trends that might influence the usage of more efficient electric motors; and
- generating and obtaining reactions of industry leaders to possible governmental strategies to encourage such usage.

To summarize, we found that the 1- to 125-HP polyphase motors were the predominant energy consumers. They are principally used to drive pumps, compressors, and blowers in the process industries such as chemicals, primary metals, paper, and the like. In fact, we found that these motors consumed about 26% of the total electric power generated in this country. Estimates of their potential for increased efficiency, coupled with possible replacement rates of lower to higher efficiency motors, indicated potential savings by 1990 of almost 5% of total U.S. electric power consumption in that year. This would amount to 35 billion kW-hr/year, 60 million barrels of oil, or annual savings of about $1.5 billion (1975).

These potential savings are doubly important because we now realize that current fuel resources are not infinite and that – in light of population and related consumption growth – new resources, as well as far-reaching conservation measures, must be rapidly developed.

Focusing globally on the conservation of electrical energy, we perceive that economies are possible, of course, in generation, distribution, and consumption. However, when one looks more closely at the relative potential for conservation, it appears to be principally associated with consumption. Generation and, to a lesser degree, distribution are by comparison relatively coherent, well managed operationally, and highly developed technologically.

To deal with the issue of conservation in consumption, many large companies have instituted formal energy-management programs. On an informal basis, smaller companies and many homeowners are pursuing similar programs having the same goals. Many of these programs have been dramatically successful – sometimes achieving in excess of 15% savings. Moreover, these economies have been achieved rapidly; thus the accumulated conservation over a period of time will be great.

The times, however, demand more extensive programs than just those involving the energy management of existing systems. For this reason, research into solar energy, coal gasification, and fusion – to mention a few – are now of great public interest and importance. Additionally the situation is serious enough to call for re-examination of the intrinsic efficiencies of all existing power-consuming devices in light of dramatically changing economics. The electric motor is obviously an extremely important power-consuming device.

In our study to identify areas of their greatest conservation potential, we first reviewed all current literature dealing with motor-driven equipment, the motors themselves, and related electric power consumptions.

Based on our review, we were able to focus our attention on a small segment of all electric motor-driven equipment in quite specific industries. Of greatest importance was the finding that the equipment using most of the electric motor-drive power in the United States was the general-purpose type, such as pumps, and not the special industry equipment, such as rolling mills and the like.

For our detailed analysis of the energy consumption of various motors in various applications, we interviewed equipment end-users and solicited unpublished data and estimates from motor and equipment manufacturers, trade associations, consumers, and Government agencies. In addition, we reviewed the state-of-the-art of motor technology as it relates to the potential for improving motor efficiency through redesign at practical incremental costs. Our technical investigation, as well as interviews with manufacturers, revealed that motors of significantly improved efficiencies were both possible and cost-effective. This potential was found to be not materially diminished when analyzed on a net energy basis, that is, including the incremental energy to produce a more efficient motor.

However, we found that variable test methodology and a lack of specifications dictating the accuracy of published information made the currently published efficiency data unreliable. Interviewees who had tested competitive motors frequently told us that the test efficiencies they obtained often varied significantly from published catalog data.

Both here and in Europe a number of alternate efficiency test methods are specified. These alternate methods are in part necessary to accommodate the wide range of types and sizes of electric motors produced. However if one, for instance, uses a method really only suitable for a very large motor on a very small unit the result can be unnecessarily imprecise. In this instance the European, International Electrotechnique Commission (IEC) specifications are superior to the American Institute of Electrical and Electronic Engineers (IEEE) specifications. They express a preferred method for specific applications. Additionally, the IEC specifications state that actual results of motor performance testing be accurately presented in the literature, including allowable variations due to manufacturing tolerances. Europeans, in general, told us they felt they could depend on their published efficiency data.

The most precise IEEE method B (dynamometer) is thought by most American manufacturers to be superior to the comparable IEC method (segregated losses). Nevertheless the IEEE specifications in our opinion are unnecessarily vague. Little in-depth consideration appears to be given to constraining the exact mechanisms of the test method. Alternative test equipment and their allowable precisions, exact set-up and calibration procedures, and the like, are superficially covered if at all.

All of this would lead us to conclude that the professional and trade associations in this country could, perhaps with some persuasion, exceed European results.

B. PATTERNS OF ELECTRIC MOTOR DRIVE CONSUMPTION

Examining the overall pattern of electrical energy consumption in the United States, as shown pictorially in Figure ES-1 and in greater detail in Table ES-1, we see that about 64% of all the electric power generated in this country is used to power motor-driven equipment. It also shows the relative importance of HVAC and transportation equipment consumptions which were outside the scope of our study.

There were about 50 million electric motors rated over 1/6 HP sold in this country in 1972. About 40 million of them were fractional horsepower units used in home equipment, such as appliances, oil burners, shop tools, and swimming pool pumps, as well as various commercial equipment, such as business machines and the like.

Up to 200 HP there is about the same total HP (capacity) sold in each of six categories: 1/6-1/3; 1/3-1; 1-5; 5-20; 20-50; and 50-125 HP, with the exception of the 1/3-1 HP range which has about three times the capacity of all others. Over 125 HP, the aggregate capacities of motors sold drop significantly.

About 62% of electric motor drive energy (49% of the total) in the United States is consumed by the commerce and industry sectors of our economy (refer again to Table ES-1). The emphasis is in industry which consumes about 43%. This amounts to about 28% of all electrical power produced. Therefore, to achieve meaningful economies in electric motor drive consumption, one must obviously focus on the requirements of the industrial sector. Table ES-2 gives details of this industrial consumption showing the importance of pumps, blowers, and compressors.

TABLE ES-1

TOTAL U.S. ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Motor Drive (excluding HVAC)		548
Industrial, integral HP	438	
Industrial, fractional HP	20	
Commercial, integral HP	74	
Commercial, fractional HP	16	
Motor Drive (HVAC)		122
Industrial	12	
Commercial	110	
Motor Drive (other sectors)		411
Municipal water works	116	
Electric utilities	147	
Mining and construction	28	
Residential	120	
All Other Electrical Consumption	602	602
Total U.S.	1,683	1,683
Total Motor Drive	1,081	1,081

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

In the commercial sector conversely, excluding HVAC and transportation equipment, electric drive motor consumption is predominately attributable to refrigeration compressors. As shown in Table ES-3, the 70 billion kW-hr consumed in these applications in 1972 were principally in central systems and unit coolers of the types employed in supermarkets.

Table ES-4 shows the distribution of consumptions by types of motors utilized in industry and commerce, and indicates that integral HP AC polyphase motors account for 75% of the consumption of the combined sectors. By comparison the consumption of other types of motors is minor.

Within the integral HP motor category, 1- to 125-HP motors consume 62% of the two sectors' consumption; over 125-HP motors consume 38%.

Additionally, as shown in Table ES-5, electric motor drive consumption in commerce and industry can principally be attributed to a few process industries. Five process industries – chemicals, primary metals, paper, food, and petroleum products – consume just 50% of all the motor drive electric power supplied to both sectors.

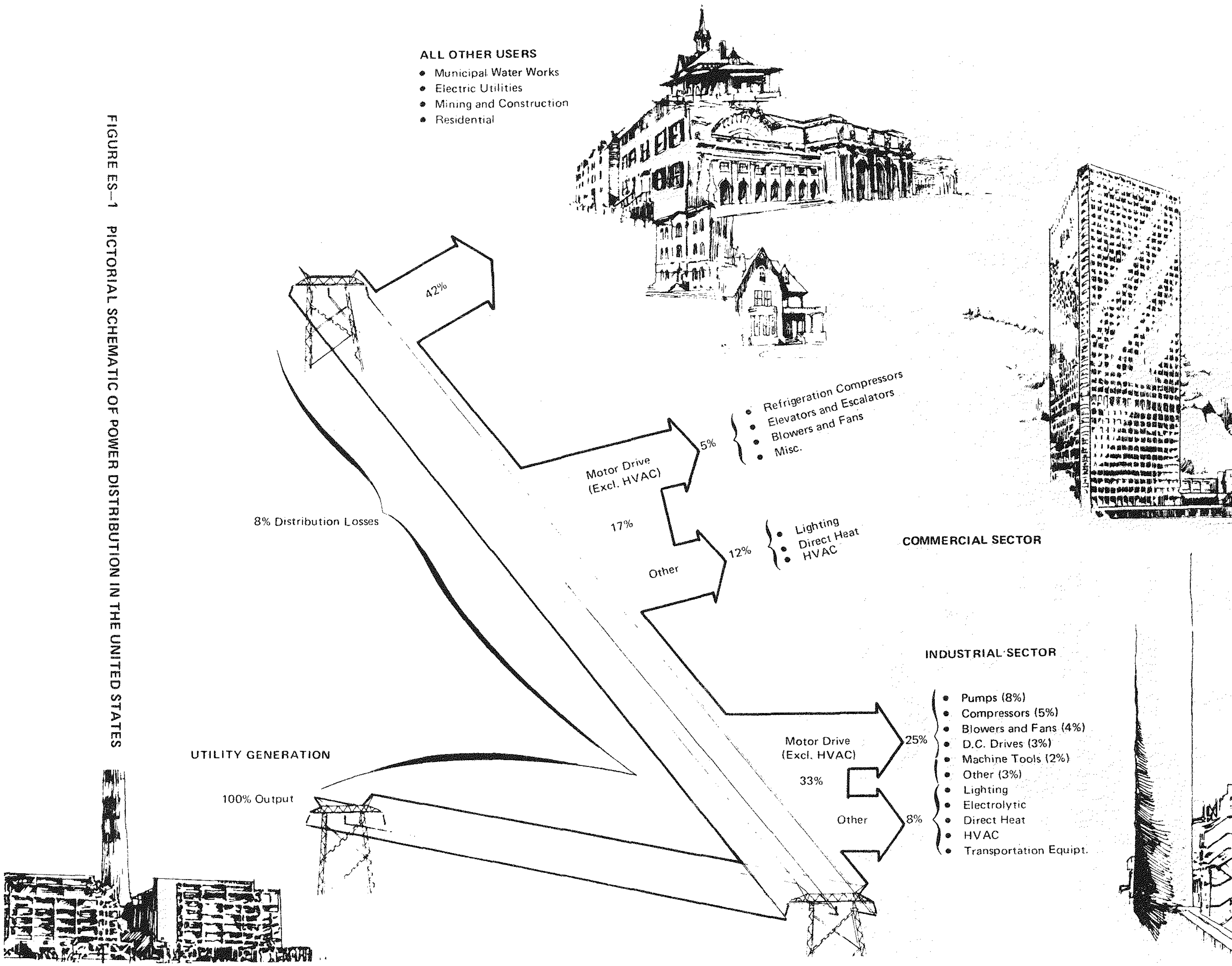


FIGURE ES–1 PICTORIAL SCHEMATIC OF POWER DISTRIBUTION IN THE UNITED STATES

TABLE ES-2

TOTAL INDUSTRIAL ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Industrial Motor Drive (except HVAC)		458
Pumps	143	
Compressors	83	
Blowers and fans	73	
Machine tools	40	
Other integral HP applications	52	
DC drives	47	
Fractional HP applications	20	
Other Industrial Electrical Usage		142
Electrolytic		
Direct Heat		
HVAC		
Lighting & Misc.		
Total Industrial		600

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE ES-3

TOTAL COMMERCIAL ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Commercial Motor Drive			200
Air conditioning		110	
Refrigeration compressors		70	
Central systems	32		
Unit coolers/display cases	27		
Beverage refrigeration	5		
Water coolers	3.5		
Ice makers	2.5		
Other Motor Applications		20	
Direct Heat and Light			120
Total Commercial			320

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE ES-4

TOTAL COMMERCIAL AND INDUSTRIAL MOTOR ELECTRICAL CONSUMPTION (1972)
(excluding HVAC) (billions kW-hr)

Integral HP, AC polyphase	413	75%
Integral HP, DC	36	7%
Inegral HP, AC single-phase	18	3%
Fractional HP	36	7%
Synchronous	45	8%
Total Industrial and Commercial (excl. HVAC)	548	100%

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE ES-5

POWER CONSUMPTION BY SPECIFIC INDUSTRIES (1972)
(billions kW-hr)

Industry (excluding HVAC)				458
Chemicals	(SIC 28)	81		
Primary Metals	(SIC 33)	76		
Paper	(SIC 26)	59		
Food	(SIC 20)	35		
Petroleum	(SIC 27)	29		
		280		
Commerce			51%	90
Total				548

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

C. VARIABILITY AND TRENDS IN MOTOR EFFICIENCIES

Motor inefficiencies have two dimensions, if one thinks of losses in economic terms. One is largely concerned with the power losses that occur within the motor itself, and these are commonly thought of as the only motor inefficiency. However, a second category of losses exists. It relates to the motor being more reactive (low power factor) than it need be. This characteristic causes some additional power losses to occur in the power generation and distribution system, and typically requires that this system be significantly larger and, of course, more costly than it ideally need be. The first category of losses (efficiency) is essentially uncorrectable; the second (power factor) can be corrected by additional investment in components (capacitors) added to the motor externally. However, these corrections are often not made.

In our study we were concerned with intrinsic inefficiency losses only. The analysis of power factor losses would require an entirely different focus – that of distribution rather than usage – and for this reason we considered this category outside the scope of our work.

Published motor efficiency data for a given size and type of motor are highly variable between manufacturers and often even between different models of the same manufacturer. These variations are quite dramatically displayed in Figure ES-2, which shows the efficiencies we identified by contacting local sales representatives of seven motor manufacturers and requesting technical information on their "standard" line of motors. For comparison we have also included the efficiencies of a newly announced high-efficiency line of motors.

The variations shown in Figure ES-2 may or may not be wholly real. We feel that substantial variations do exist. The variations are also caused in part because current specifications allow many alternate efficiency test methods of varying overall precision and opportunity for error. Additionally, however, there are no specifications or rules on the correlation between test and published data. Manufacturers may arbitrarily choose to be either conservative, precise, or, in some few cases perhaps, even cavalier about the data they publish. Moreover manufacturers often produce two or more lines of motors of varying price and efficiencies and the distinction between their various lines is often obscure.

The accuracy of currently published efficiency data then is obviously quite suspect. Knowledgeable people readily admit that substantial actual variability exists between comparable motors. Large purchasers may and often do request and receive test certifications. However, such procedures apply to only a small fraction, not the mainstream of integral horsepower motor sales. The average purchaser must rely on and should be insecure about published data.

Motor efficiencies in units under 15 HP have dropped significantly over the past 20 years, as shown in Figure ES-3. There is fairly good correlation of these attenuations with the drop in the cost of electric power over the same period. The connotation is, and intuitively we know it to be true, that efficiency simply became less important during the period of inexpensive power costs.

D. MOTOR PURCHASE PATTERNS

Historically, motors have been purchased predominantly pretty much as commodities with little consideration being given to characteristics other than enclosure requirements, price, and supply.

The industrial and commercial end-user is largely unaware of efficiency variations in commercially available motors, and thinks of them as being very similar. His purchasing habits reflect these attitudes as well as the desire to purchase the highest quality (largely translates to reliability) motor at the lowest possible price.

Motors are typically purchased by non-technical personnel from approved vendor lists which are largely compiled from past experience on price, reliability, and ready supply. The purchasing agent purchases the lowest priced, approved motor that has the desired HP rating, design type, and enclosure.

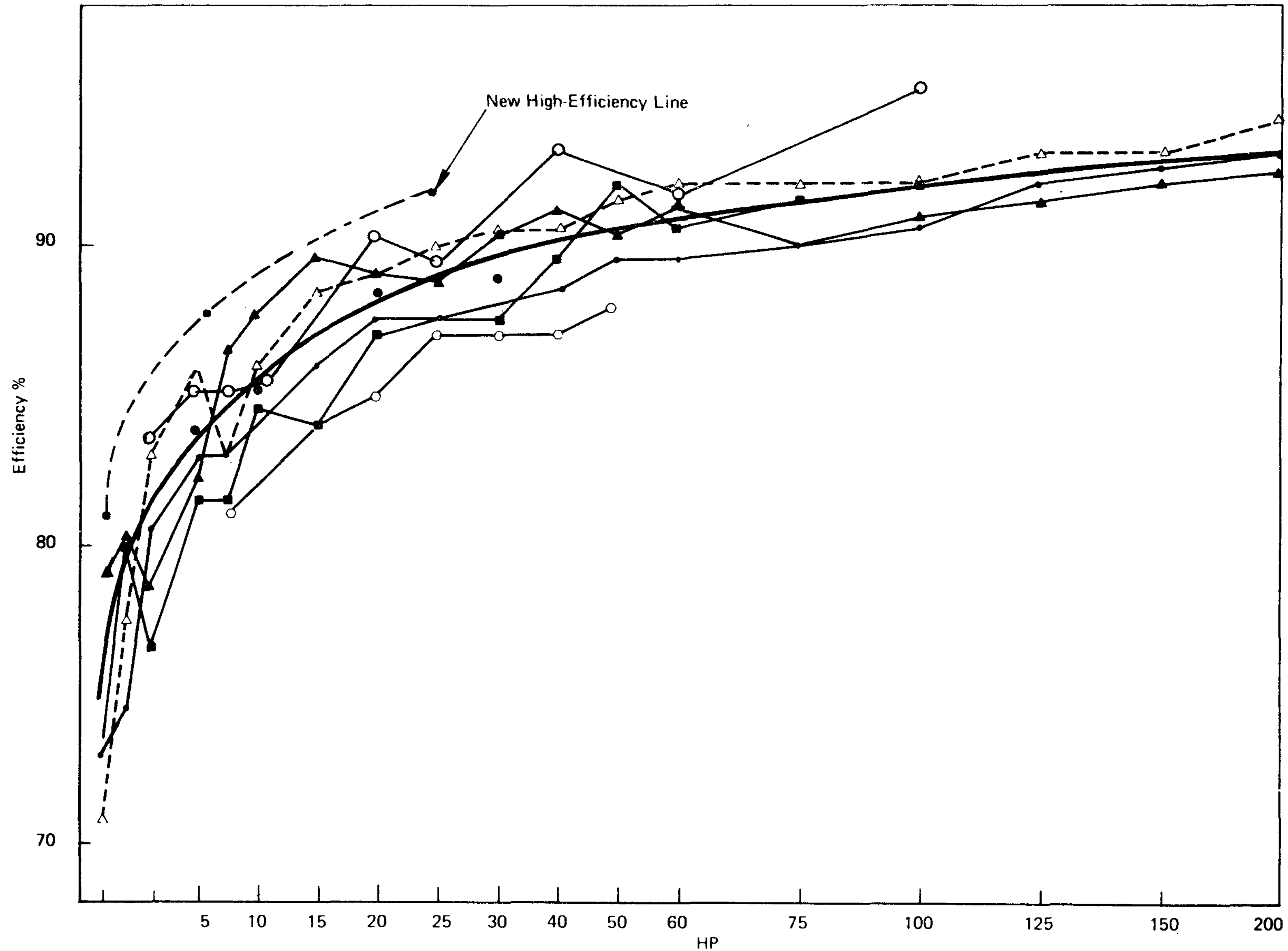


FIGURE ES-2 PUBLISHED MOTOR EFFICIENCIES OF PRINCIPAL MANUFACTURERS
(Open, Drip-Proof, 1800 RPM, NEMA Design B)

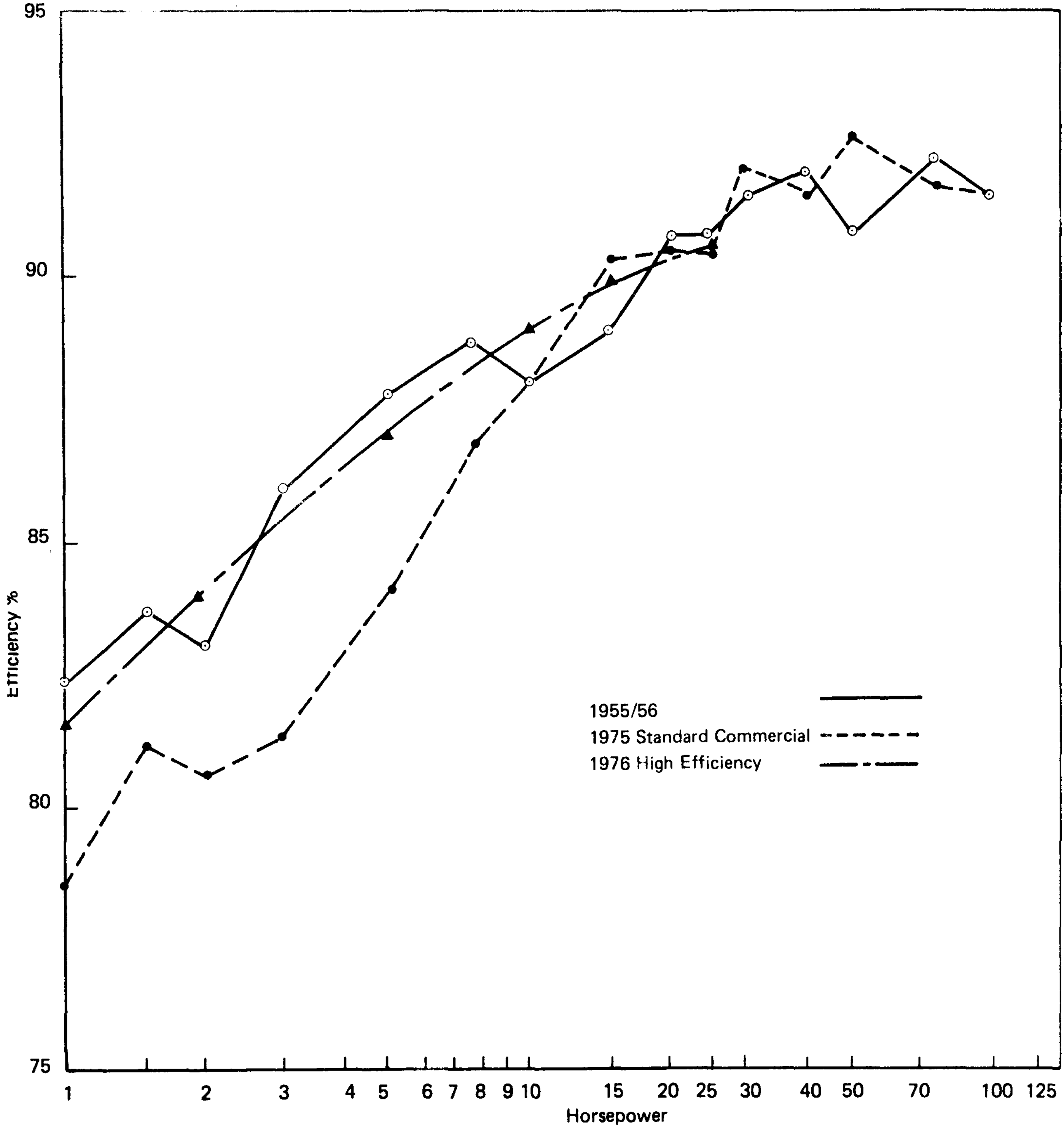


FIGURE ES–3 AVERAGE MOTOR EFFICIENCY 1955/56 VS. 1975, 1800 RPM CLASS B OPEN MOTORS

Approximately 50% of all motors sold are purchased by Original Equipment Manufacturers (OEM's) – manufacturers of pumps, blowers, machine tools, and a myriad of other equipment ultimately supplied to end-users complete with motors. An OEM quite obviously is not very interested in efficiency – he won't be paying the power bill. He is interested in reliability and durability as he must warrant his machinery. Additionally, the end-user almost universally will accept purchased equipment without questioning the characteristics of its motor(s).

While there is evidence that these viewpoints and habits are gradually changing, there obviously is a lot of inertia in the existing system. Change wholly in response to the changing economic pressures will undoubtedly come slowly.

E. POTENTIAL FOR INCREASED MOTOR DRIVE ECONOMY

The principal problem in interesting industrial end-users in electric motor economy has been that, in the past, such economies have been relatively unimportant. The average electric cost in industry in 1974 amounted to less than 1% of the value of total shipments. The maximum cost which occurred in the paper and allied products industry was 2.3%. Of this proportion, only a very small fraction obviously is potentially conservable through the use of motors of increased efficiency. Compared to other potential savings, such as reducing production line interruptions through higher reliability components, inventory management, and the like, motor efficiency has just not been a very visible economy issue.

Additionally for a motor with relatively infrequent usage, an inexpensive but inefficient motor can be economical. However, it would cost little for users to select an optimally efficient motor if the data were readily available and believable. The case of the economic analysis of premium-priced, high-efficiency motors becomes more complex. The intensity of intended usage, projected power costs, and the like, must be researched and taken into account. Thus the selection analysis of high-efficiency motors becomes so time-consuming that the typical user would probably wait to be sold by the motor manufacturer – let him provide the analysis – he wants to sell his motors, doesn't he?

From the motor manufacturer's standpoint, sales of AC polyphase integral horsepower motors, the largest consumers of electric drive energy, increased less than 2% over the 1967-72 period. These motors represent a stable low-growth segment of the market. Therefore, the manufacturers tend to reflect the stability and maturity of their market by being relatively conservative in both their advanced engineering and marketing approaches; i.e., they probably would not make such a proposal except for very large orders.

The economies associated with high-efficiency motors obviously would not be so readily attainable as would those from decreased lighting or heat. Motors of increased efficiency first have to supersede those of lesser economy. This dictates a gradual replacement process in areas where the economies of such replacement might prove attractive. Thus, practically all energy-management programs, to date, have ignored the electrical consumption of motors and concentrated on other more immediately achievable conservation potentials.

Nevertheless, significant conservation potential exists in electric motor drive consumption. Figure ES-4 depicts this potential by HP category, numbers in the population, and relative consumptions. It can be seen that, while the 1- to 5-HP category predominates in numbers, the greatest potential for conservation is in the 5- to 20-HP category. Over 20 HP, the potential for conservation progressively decreases as the horsepower increases.

Potential savings, as has been mentioned, are significant, peaking at about 5% of total electrical consumption by 1990 and continuing until about the year 2050.

F. GOVERNMENT POLICY CHANGES AND PROBABLE EFFECTS

Our basic premise – based on all considerations of Government policy changes and rulings (interventions) aimed at accelerating the utilization of higher efficiency motors – is that these changes will occur eventually anyway, because of existing market economic forces already at work as power costs increase.

Two types of Government policy interventions, however, are obviously possible to accelerate the usage of high-efficiency motors:

(1) those that would increase the "market pull" for them by users; and

(2) those that would stimulate manufacturers to both produce and promote them.

Of the two alternatives – influencing the users as opposed to influencing the manufacturers – the former can be demonstrated historically to be far more effective.

Thus, we found the most effective policy mechanisms to be better information/education for the user. These included:

- The limitation of test specifications for 1- to 125-HP polyphase motors to a perhaps reinforced version of IEEE – 112A test method B. This would ensure consistent results when comparable motors are tested by different manufacturers;

- The establishment of additional specifications dictating accurate correlations of tests with published data;

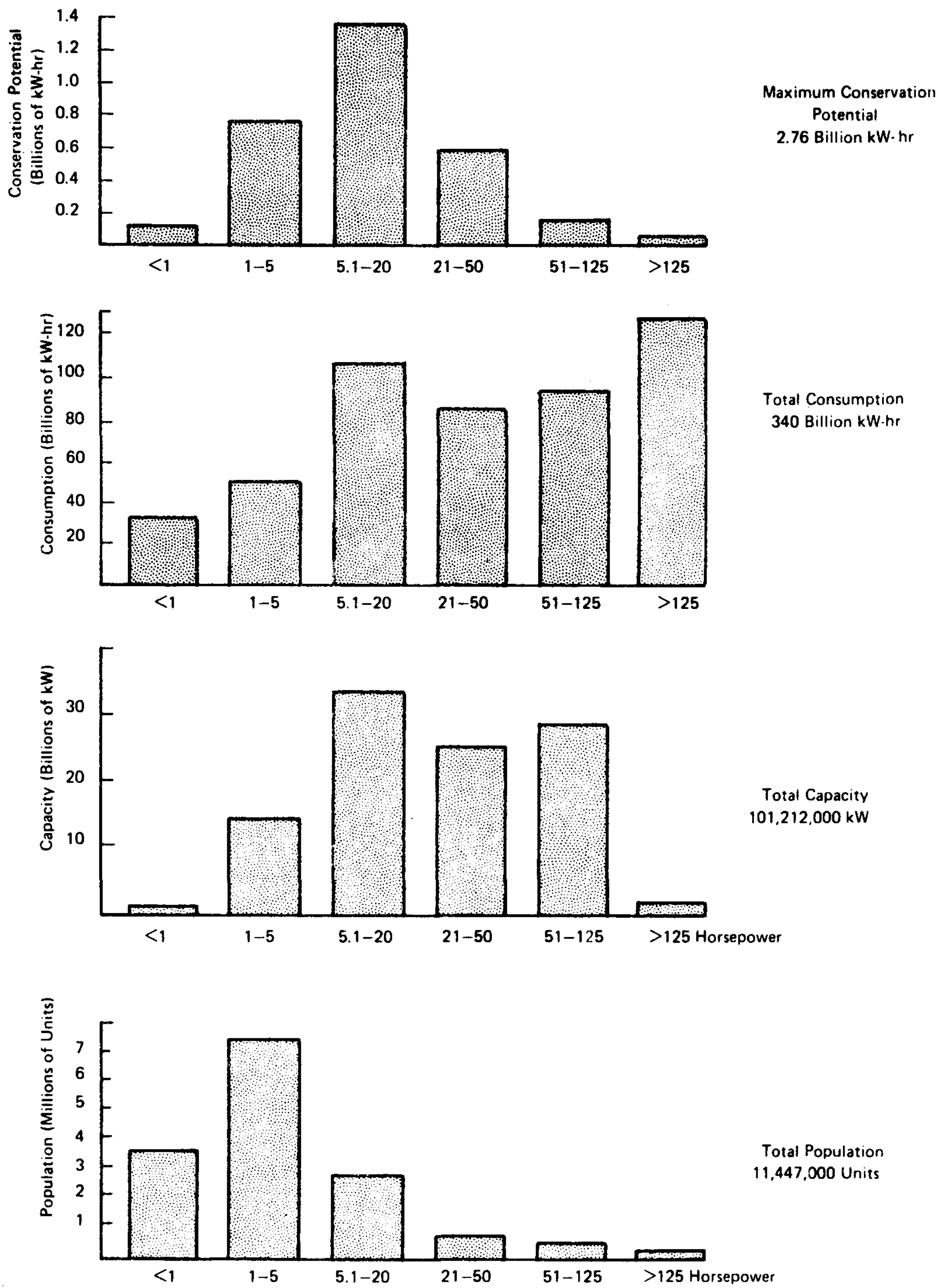


FIGURE ES–4 PROJECTIONS OF FRACTIONALS, 1- to 125-HP, AND > 125 HP POLYPHASE MOTOR USAGE IN INDUSTRY AND COMMERCE (1977) & EXCLUDING HVAC & TRANSPORTATION EQUIPMENT

- Mandatory nameplate labelling of efficiency and power factor data;* and

- Publication of comparative efficiency data as well as the methodology of calculating payback periods for more expensive, but higher efficiency motors.*

Capital investment credits and other fiscal incentives used to motivate the end-user were found to be too difficult to administer.

It is quite possible that Government intervention might only necessitate meeting with and soliciting commitments from the various concerned professional and trade associations. These associations now control various types of information to end-users as well as the specifications that apply. They are the ideal parties to effect change if they will do so voluntarily. However, in case the associations are not prepared to act expeditiously, the FEA, in our opinion, should be prepared to publish an act mandating the desired changes.

The cost effectiveness of Government intervention is shown in Figure ES-5. The figure shows estimated future conservation based on normal economic and marketing forces, as well as conservation with the Government intervention previously discussed. It will be seen that measurable conservation will, in any event, commence in 1977. We estimate the savings due to Government intervention (persuasion) from 1977 to 1990 amount to 91 billion kW-hr having a value of more than $4 billion (1975). Additionally the stream of savings would appear to persist until at least 2050, when we estimate normal market/economic forces would have, in any case, achieved about the same result as that resulting from Government intervention.

G. SUMMARY CONSIDERATIONS

In summary, there is clear evidence now that past patterns of power usage are gradually changing, with costs increasing and shortages being forecast. Industrial and commercial users are beginning to be sensitive to the potential of motors of increased efficiency. A couple of the industries we interviewed now include at least embryonic motor-efficiency considerations in their energy-management screening procedures, and motor manufacturers have told us they feel this trend is on the rise. Thus, the stage is set for accelerated realization of these economies. What obviously is needed are Government-sponsored (or encouraged) changes – in close cooperation with the professional and trade associations – to make increased motor efficiency feasible, visible, and economically attractive. Hopefully, the work reflected in this report will delineate and catalyze the required effort.

*We have been informed that NEMA has actively been working on these issues and is now prepared to cooperate with the FEA on their implementation.

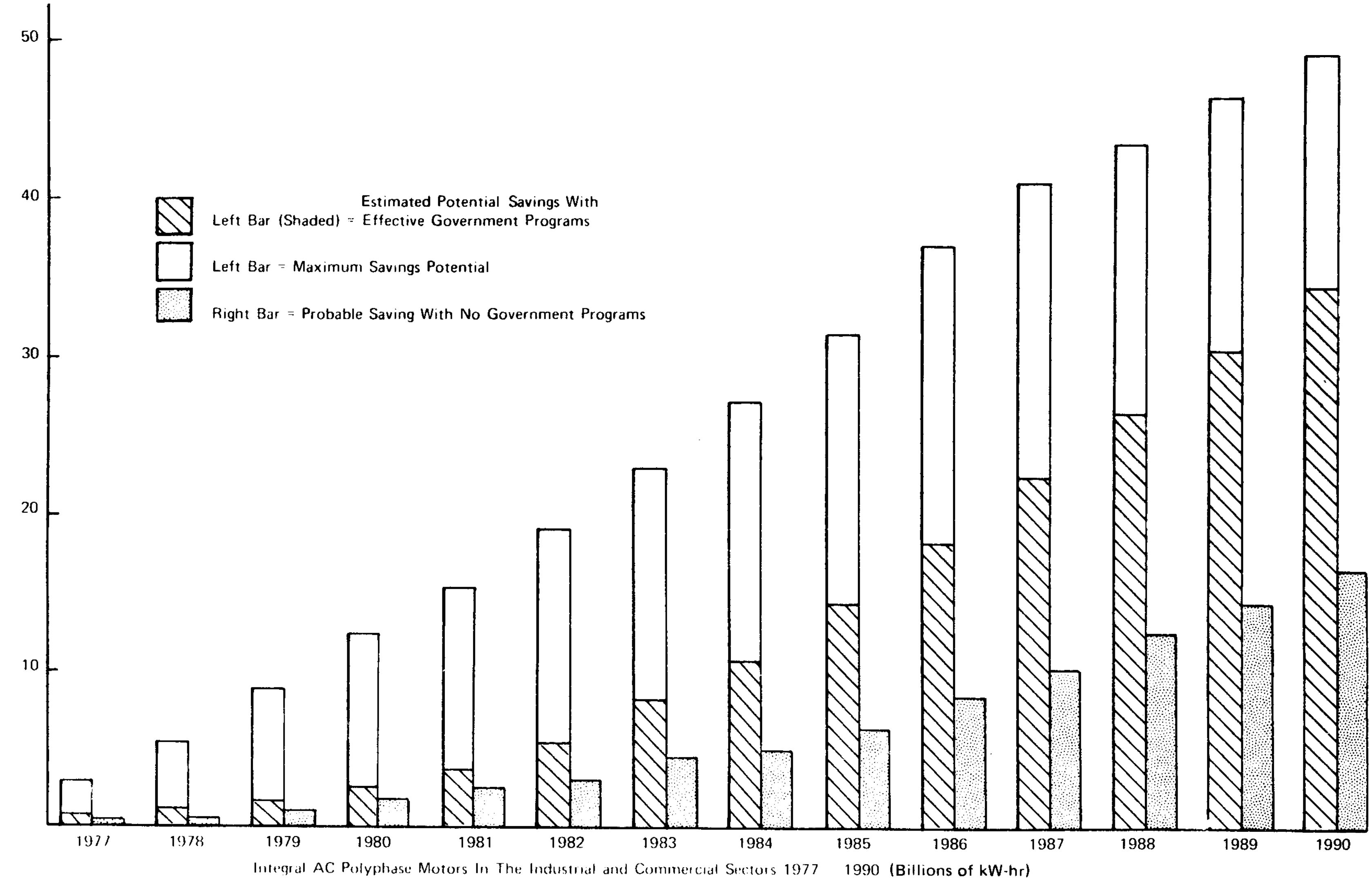


FIGURE ES–5 ESTIMATED POTENTIAL ELECTRICITY CONSUMPTION SAVINGS FROM THE USE OF MORE EFFICIENT ELECTRIC MOTORS

H. FINDINGS AND CONCLUSIONS

- Equipment/Consumption Characterization

  a) Significant conservation potential exists in electric motor drive consumption. The maximum (if every integral 1- to 125-HP motor requirement resulted in the selection of a high-efficiency model) potential exists for about 0.8% (2-3/4 billion kW-hr) savings in 1977, progressing to 6.8% (about 50 billion kW-hr) in 1990. The practical limit, however, is about 35 billion kW-hr or 5% of total U.S. electrical power consumption by that date.

  b) About 62% of total U.S. electric motor drive power consumption (about 55% of total U.S. consumption for all purposes) is utilized by the commerce and industry sectors in motor drive applications.

  c) Of the two sectors, industrial consumption overwhelms commercial, consuming 70% of their combined electric motor drive requirements.

  d) Most of the power used to drive motors ($\sim$ 88%) in industry is consumed by integral HP polyphase (design B and C) motors.

  e) The power consumed by industrial motors is predominantly (65%) associated with general-purpose rather than special industry machinery; i.e., pumps (31%), compressors (18%), and blowers and fans (16%).

  f) The average size of integral HP polyphase motors sold is about 15 HP; their average life is approximately 40,000 hours.

  g) While the numbers of integral HP polyphase motors amount to a negligible percentage of motors sold, they do account for about 47% of total U.S. electric motor drive power consumption.

  h) Commercial electric motor drive consumption is applied much narrower than its industrial counterpart, going predominantly to refrigeration compressors.

- Market Characterization

  a) The predominant basis of motor choice by the commercial and industrial end-user is lowest first cost for the highest quality.

b) The term quality in the end-user's mind is a complex of attributes which rank approximately as follows:

- reliability,
- availability,
- service/warranty,
- durability, and
- efficiency – infrequently, because even in energy-intensive industries, electric drive power consumption costs do not currently exceed 2% of gross sales.

c) The end-user frequently (perhaps as much as 50% of the time) has no voice in motor choice, as the motor is supplied integrally with a piece of equipment.

d) The manufacturer of this equipment (an OEM) typically has a very different basis of motor choice than the end-user – he usually just wants the motor to give reasonable service at the lowest possible price and is largely uninterested in any other of the motor's characteristics.

e) Both the end-user and OEM's frequently buy from a distributor who fulfills the role of a source of ready availability and service as outlined in (b) above.

f) The distributor logically selects a line of motors of broadest potential sales to the OEM's and end-users. Thus, he is interested in carrying the motors of a well known manufacturer who has a broad line that maximizes potential sales among the often divergent requirements of both OEM's and end-users.

- Trends

a) Electric power costs are projected to increase at an annual rate of 7% over the next 15 years.

b) The efficiencies of electric motors under 15 HP have degraded significantly over the past 12-20 years.

c) The efficiencies of motors above 15 HP, conversely, have remained relatively unchanged.

d) Electric motor costs are projected to increase only at an annual rate of about 3-1/2% over the next 15 years.

e) The net effect of the difference in a) and d) above will be to shorten the economic payback period for more efficient motors in the near future – making motor replacement more attractive.

f) The trend toward lower efficiencies appears to be reversing.

g) Without a Federal program, however, noticeable improvements in the efficiencies of industrial motors will require 3 to 7 years.

h) A Federal program could halve the above period.

i) Even with a Federal program, however, the full impact of higher efficiency industrial motors may not be felt until well into the 21st Century.

- Technical and Economic

a) About 8% of the motors used in commercial and industrial applications are the design D, high-slip type units of relatively low efficiency. However, their application to cyclic, high-inertial loads demands these precise characteristics.

b) About 85% of the remaining motors of interest are design A, B, and C, low-slip types which have relatively high efficiencies.

c) Nevertheless, based on manufacturers' published data, judicious selection of low-slip motors – using efficiency as the criterion – can provide significant gains in efficiency; e.g., up to 5-6 percentage points at 10 HP.

d) However, published efficiency data are not reliable because:

- a single standardized test method is not mandated; and
- no standards (in the U.S.) stipulate with what precision published data have to agree with test results; i.e., such data may be either optimistic or conservative.

e) Additionally, variations in efficiency values from motor to motor in production runs can be significant. These variations can be attributed to manufacturing tolerances and material differences, for example. Efficiency tolerances associated with manufacturing variations typically are 15% of the motor's nominal efficiency subtracted from unity. A 1-HP motor typically varies by ± 4%; 150-HP motors vary by ± 1%.

f) Improved efficiency can be obtained by:

- optimally increasing the amount of core steel;
- changing core steel material to non-oriented silicon steel;
- optimally increasing the amount of copper in the windings;
- optimizing the design for efficiency at each motor size – neglecting standardization of materials/components for cost reduction; and
- optimally reducing the air gap.

g) Where motors are being replaced or added in high-duty cycle applications, high-efficiency models at premium prices can usually be easily justified on a cost-savings basis. For instance, 50-HP models would have payback periods of 6000-8000 hours of use.

h) On a net-energy basis, additional energy invested in material increments is typically replaced within 1000 hours of use.

- Policy

a) There are several categories of potentially beneficial occurrences that public policy could address to reduce electric motor drive power consumption:

1. Accurate and comprehensive efficiency data;
2. Educational/promotional programs;
3. Rules, regulations, and orders;
4. Legislation; and
5. Legal pressure

b) Better information/education for users was found to be the most effective overall policy the Government could pursue.

c) Such policy, however, must be based on accurate and comprehensive efficiency data; current data are inadequate.

d) The professional and trade associations were found to be the best vehicle to implement the needed informational and data changes required.

e) However, the Government should be prepared to undertake some or all of the required tasks if the associations cannot or will not expeditiously develop specific test and publication standards, as well as a mandatory nameplate labelling policy.

f) Adjusted capital investment credits, as well as other fiscal incentives to the end-user, based on motor efficiency, were not found to be cost-effective Government policy.

g) Similarly, various possible Government programs involving motor manufacturers were not judged potentially effective.

h) Pump priming by concentrating public sector sales to high-efficiency motors, while helpful, would not significantly influence other sales with greater consumption potential.

I. RECOMMENDATIONS

We recommend that the Government, either by negotiation and/or ruling:

1. Insist that all 1- to 125-HP polyphase motors be tested on a statistically valid quality control schedule to IEEE-112A, test method B, to verify published efficiency.

2. Mandate that published efficiency data bear a specified and consistent relationship to test results, and include allowable manufacturing tolerance variations.

3. Demand that motor name plate data include efficiency and power factor* data.

4. Insist that more comprehensive and comparative motor selection, application,* and economic justification data covering efficiency be made available to the buying public.

*We have been informed that NEMA has actively been working on these issues and is now prepared to cooperate with the FEA on their implementation.

I. INTRODUCTION

A. BACKGROUND

The Edison Electric Institute and the Department of Commerce reported that in 1972 the commercial and industrial sectors of the U.S. economy consumed approximately 920 billion kW-hr of electrical energy. Of this amount, about 60% was used to power electric motors in industrial and commercial process equipment. This consumption, more than 548 billion kW-hr per year, accounted for nearly 33% of the U.S. electrical energy demand (9% of total energy demand).

Approximately 51 million motors are in use in the industrial and commercial sectors of our economy. Today they can be broken down as follows:

BREAKDOWN OF MOTOR POPULATION IN INDUSTRY AND COMMERCE

AC Integral HP Polyphase Motors	8,710,000
DC Motors	279,000
Synchronous Motors	30,000
Fractional (> 1/6 HP) Motors	36,000,000
Integral HP, Single-Phase Motors	6,000,000
Total	51,019,000

Despite the predominance of fractional HP motors, integral HP units consume about 93% of the electrical energy consumed by the two sectors.

Motors, in general, can range in efficiency between a low of 10% in small circulating fans to a high exceeding 90% in large, special-purpose industrial motors, with most of the commercial and industrial motors rated in the 50 to 70% range. The amount of energy which is not converted directly into useful motive power, as indicated by the efficiency rating, is termed an "energy loss," and their sum across the nation as a whole is considerable. Furthermore, the trend in the manufacture of commercially standardized electric motors over the last several decades has been to compromise higher efficiency ratings in favor of other factors, such as lower initial cost and conservation of materials.[13]

The efficiency rating is but one of many performance parameters to be considered in the selection of an electric motor and in many cases a low efficiency rating can be, and is, entirely justified. Nevertheless, the underlying hypothesis of this investigation is that efficiency ratings are not being given proper consideration in the selection and purchase of electric motors. Specifically, it is proposed that a "life cycle" cost analysis from the user's point of view (including first cost, operating and maintenance costs, salvage, etc.) may often dictate the selection of more efficient, albeit more expensive, models. Further, it is proposed that, for particular pieces of equipment, efficiency standards may be established in the name of energy conservation without unreasonably affecting equipment performance or cost. The motivating implication is that, since motors account for more than 658 billion kW-hr per year of energy consumption, even a small increase over time in the average efficiency of installed equipment, 3 to 5 percentage points, for example, would result in significant energy savings, on the order of 20 to 33 billion kW-hr per year by 1985.

With this background, we undertook the study as outlined by study objectives, scope, structure, and tasks in Section B.

B. STUDY OBJECTIVES, SCOPE, STRUCTURE, AND TASKS

1. Objectives

The objectives of this study were:

- To identify types of commercial and industrial equipment having the greatest potential for the reduction of electric power consumption nationally if they utilized more efficient drive motors;

- To assess and project the impact of technological developments and economic trends as they might relate to the attractiveness of these more efficient motors to end-users and, additionally, to assess the relative benefit of such usage nationally on a net energy basis; and

- To generate and test the efficacy of possible governmental strategies with the objective of encouraging and/or supporting the use of these more efficient motors, and estimate a reasonable energy conservation impact of a Federal program.

2. Scope

The study was structured around five principal tasks:

- **Task I – Equipment Characterization.** In this task we identified equipment and motor types and the sizes associated with them. Additionally, we identified motor sales by types and electric motor drive consumption by industry. Finally we characterized electric motor drive consumptions by industry and motor types; i.e., a motor/consumption profile.

- **Task II – Market Characterization.** In this task, we identified the basis of motor choice by users and intermediaries.

- **Task III – Project Future Efficiency Trends.** In this task, we traced the historical progression of motor efficiencies and projected future trends under various influences, such as Government programs and material shortages.

- **Task IV – Technical and Economical Evaluation.** In this task, we assessed the technological and economical constraints associated with motor design. Additionally, we assessed the impact of material shortages on motor efficiencies and costs, and conducted a net energy analysis of motor designs of increased efficiency.

- **Task V – Policy Analysis.** In this task, we developed policy option scenarios and assessed manufacturers' and users' reactions to their impact.

3. The Structure and Tasks of the Project

Figure 1 presents in block diagram form the interrelationships of the tasks and subtasks of the project which we began on July 1, 1975. Descrption of the work content of the subtasks follows.

a. Task I – Equipment Characterization

(1) Subtask A – Identify Equipment Types

We identified yearly sales and Census data on types (categories) of process equipment. From this base, we identified the equipment population by types as well as the rates at which they changed due to replacement and augmentation.

(2) Subtask B – Profile Usage

We analyzed and constructed profiles of usage by type. These profiles served to organize coherently the critical performance characteristics of various types of process equipment with respect to:

- starting torque,
- duty cycle,
- power demand, and
- efficiency.

(3) Subtask C – Characterize Energy Consumption

On the basis of the findings of the foregoing subtasks, we constructed a reasonable characterization of the electrical energy consumption and losses associated with each type of process equipment.

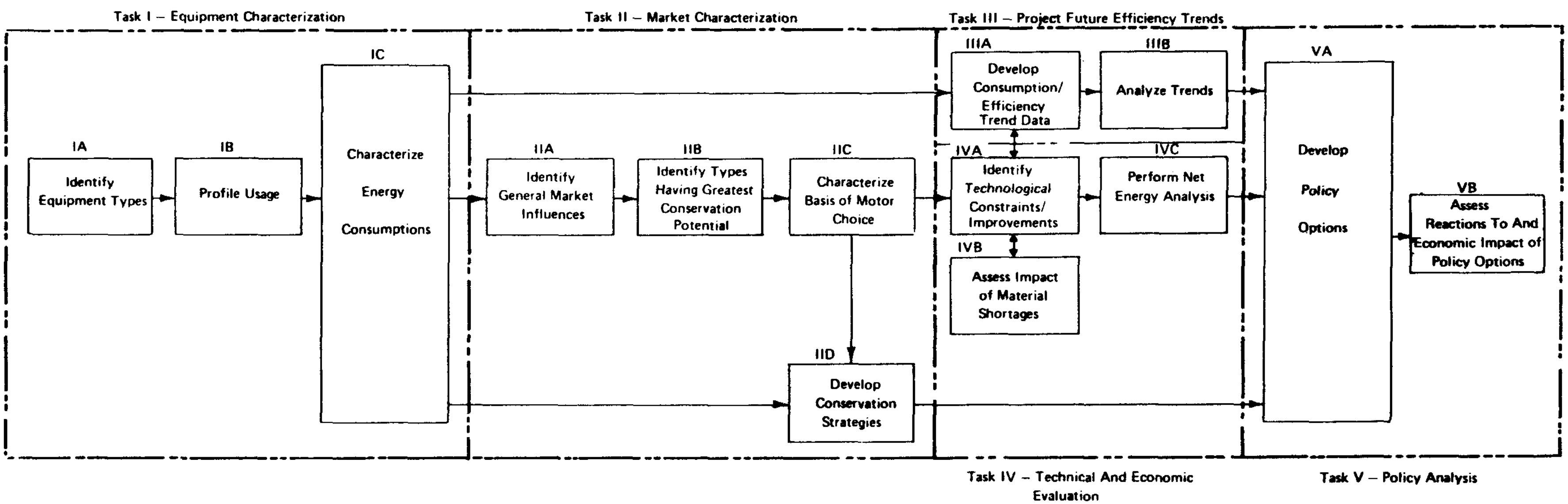


FIGURE 1 BLOCK DIAGRAM OF PROJECT

b. Task II – Market Characterization

(1) Subtask A – Identify General Market Influences

We investigated and described in detail current market forces which are influencing the design, manufacture, and sale of commercially standardized electric motors and process equipment in the United States today.

(2) Subtask B – Identify Types Having Greatest Conservation Potential

Working from the output of Subtask II-A, as well as that of Subtask I-C which characterizes electrical energy consumption, we identified the motor types having the greatest potential for conservation. We thereby narrowed the scope of our investigation considerably. The conservation parameter was viewed in two dimensions: (1) technical and (2) marketing/economic. Within the subtask we additionally projected changes in efficiencies and substantiated our findings by interviews with manufacturers and purchasers.

(3) Subtask C – Characterize Basis of Motor Choice

In this subtask, we characterized (constructed) a "motor-choice" decision matrix of several large categories of commercial and industrial buyers. Additionally, we analyzed and critiqued the hypothesis that the market is relatively sensitive to purchase price and relatively insensitive to life-cycle costs.

(4) Subtask D – Develop Conservation Strategies

In this subtask, we estimated the potential of various possible national conservation strategies.

c. Task III – Project Future Efficiency Trends

(1) Subtask A – Develop Consumption/Efficiency Trend Data

For critical (greatest conservation potential) types identified in Subtask II-B, we developed trend curves through the year 1990, focussing our analysis on power consumption and efficiencies on the basis of no Government programs. We based our analysis on several electricity cost-level assumptions, as well as several material availability and cost levels.

(2) Subtask B – Analyze Trends

We evaluated the foregoing trends analysis further by comparison with specifics of current usage identified in Subtask I-C. We thus related the significance of trends comprehensively to future energy demands.

d. Task IV – Technical and Economic Evaluation

(1) Subtask A – Identify Technological Constants/Improvements

In this subtask, we identified technical and economic factors influencing critical inefficiencies in electric motors, and we briefly, but comprehensively, described the kinds of losses which occur in equipment operation. Finally, we projected potential technological improvements in terms of energy savings and costs.

(2) Subtask B – Assess Impact of Material Shortages

We characterized the materials used to construct the electric motors of interest. We then determined the availability of these materials, projected their costs, and finally discussed the impacts of material shortages upon equipment design and energy losses.

(3) Subtask C – Perform Net Energy Analysis

We performed a net energy analysis on selected case studies involving increased usage of energy-intensive materials. We discussed related salvage technology and its impact on energy balance. Finally, we developed an algorithm for estimating and comparing life-cycle costs of competitive models.

e. Task V – Policy Analysis

(1) Subtask A – Develop Policy Options

In this subtask, we developed the conservation strategies used in Subtask II-D – in the light of subsequent findings – into policy scenarios.

(2) Subtask B – Assess Reactions to Policy Options

We surveyed at least five representative manufacturers of electric motors and process equipment and provided a summary of their assessments of options developed in the foregoing subtask.

C. THE COMMERCIAL AND INDUSTRIAL SECTORS DEFINED

The definition of the motors to be included in the industrial and commercial sectors was determined partially by the components which make up those sectors and partially by the definition provided in the scope of the study. Specifically, the scope of study excluded electric motors used for air-conditioning as well as transportation and traction motors.

The industrial sector is perhaps the easiest to define, since the standard industrial classification includes all manufacturing within 21 two-digit SIC codes.* This is substantially the same definition which Stanford Research Institute (SRI) used in its previous study on Patterns of Energy Consumption in the United States. The only difference is that the SRI study utilized 20 two-digit codes, omitting ordinances and accessories, whereas we used all of the 21 codes to include all manufacturing.

The commercial sector** is somewhat more difficult to define. We chose a relatively broad definition and included the following categories detailed in Appendix B.

1. Wholesale trade,
2. Retail trade,
3. Finance, insurance, and real estate,
4. Services, and
5. Public Administration.

Although, strictly speaking, the Government sector is not commercial, we believe that inclusion is reasonable, since a public administration office is equipped almost identically to one devoted to commerce.

Excluded then are those which did not fit in the above defined categories. These include agriculture, forestry and fishing, mining, construction, transportation, communications, electric, gas, and sanitary services. However, to make certain adjustments to the equipment populations, we found that we had to make rough estimates of electric motors utilized in the mining and construction field, the electric utility field, and the water supply and waste treatment area.

D. CHARACTERIZATION OF INDUCTION MOTORS

In our analysis we concerned ourselves with standard and built-in electric motors applied to commercial and industrial process equipment. We excluded motors used for heating, ventilation, transportation, and air conditioning equipment, as well as motors under one-sixth horsepower.

The types of motors we analyzed fell principally into the following categories:

A.C. Single Phase
- Squirrel-cage
- Wound-rotor
- Synchronous

*See Table B-1 in Appendix B.
**See Table B-2 in Appendix B.

A.C. Polyphase

- Squirrel-cage
- Wound-rotor
- Synchronous

D.C.

- Shunt-wound
- Series-wound
- Compound-wound

Universal (AC-DC)

Early in the project we narrowed the focus of our investigation to just AC polyphase motors in the 1- to 125-HP range. Of the vast majority of motors produced, we found 96% to be fractional HP types; their relative consumption of electrical power is insignificant. Conversely, we found the large polyphase (over 125 HP) and DC motors, although they consumed significant amounts of electrical power, to be already highly efficient. We also found their potential for efficiency increases at practical additional costs to be minimal. What then are the characteristics of the 1- to 125-HP polyphase motor? What are the elements of its inefficiencies that are candidates for improvement?

Figure 2 is a cut-away drawing of a large AC polyphase motor. These motors are probably the simplest and most rugged of all electric motors. They consist of two basic electrical elements – a wound stator and a rotor assembly. There is no electrical connection between the two. Alternating-current power applied to the stator windings causes a voltage to be induced in the rotor conductors – hence the name "induction" motor – and the combined electromagnetic effects of stator and rotor voltages produce the force to create rotation.

Mechanical parts consist simply of a frame to hold the stator, a shaft, and endshields with bearings and lubrication system (Figure 2). Considerable variation is possible in the basic components. Bearings may be sleeve, ball, or roller type, and oil or grease may be used for lubrication. The frame may be open drip-proof, totally enclosed, totally enclosed fan-cooled, force-ventilated, waterproof, vertical or horizontal. Frames can be made of cast iron, steel, aluminum, brass, or anything else with the strength and rigidity to hold alignment. Endshields may be equipped with a face or flange for mounting the motor on the driven machine, or mounting driven equipment on the motor. Shafts may be machined in any number of special ways and may be made of any suitable material. However, certain standards of dimensions and performance have been established which limit the possible variety of mechanical and electrical characteristics. (See Appendix A – NEMA frame size assignments for integral HP motors.)

Evolution and standardization in the industry have resulted in four fundamental types of induction motors, each having its own specific set of characteristics, i.e., starting torque,

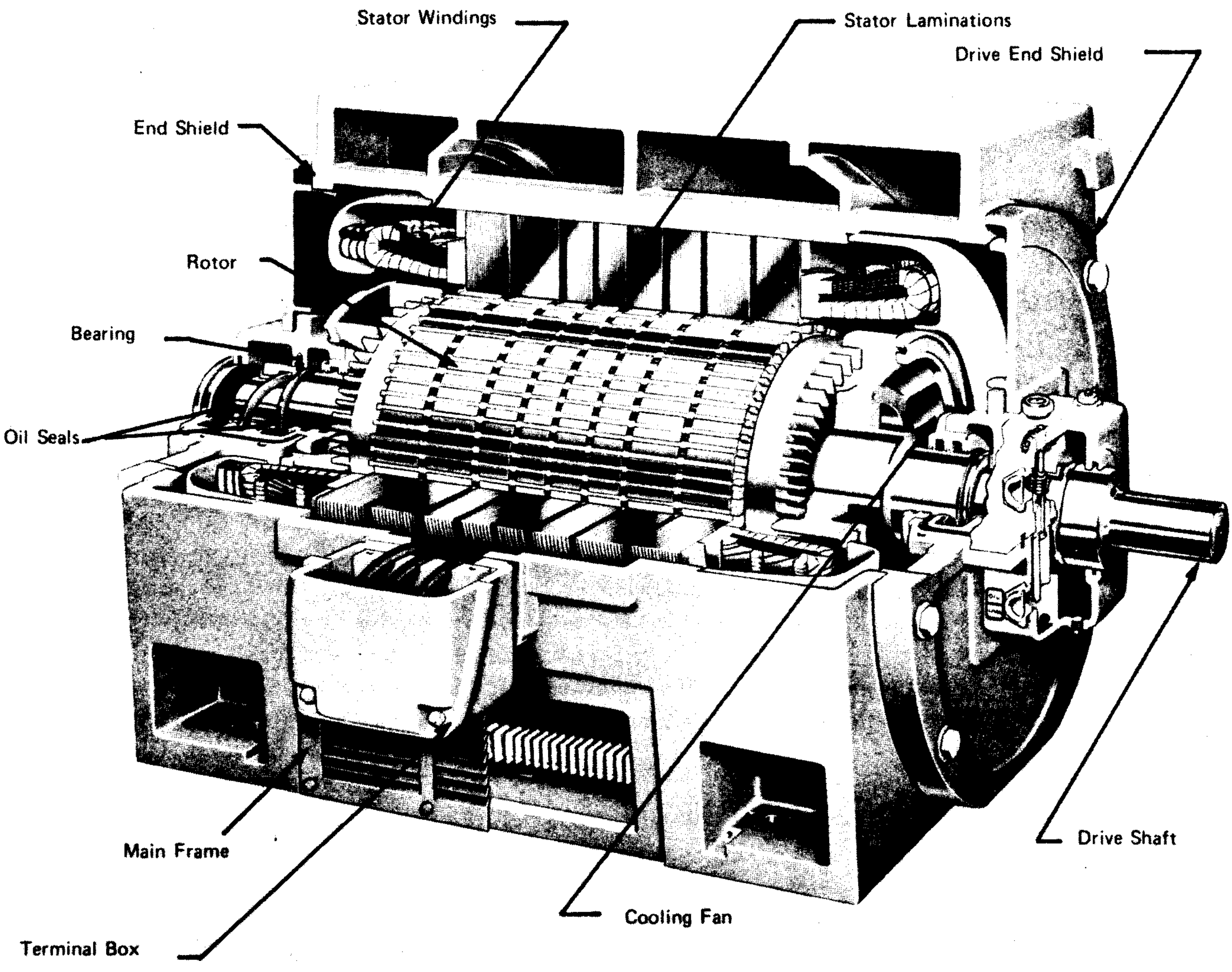


FIGURE 2 LARGE POLYPHASE AC INDUSTRIAL MOTOR

starting current, and efficiency. These four types whose characteristics are shown in Figures 3 and 4 are:

- **NEMA Designs A and B**: General-purpose motors with normal starting torque, normal starting current, and low slip. These motors represent a "standard" to which the characteristics of other designs are compared. About 78% of all AC polyphase motors are either Design A or B, overwhelmingly Design B.

- **NEMA Design C**: The Design C motor has a higher starting torque than a Design B motor, but still retains a reasonable starting current and low slip.

- **NEMA Design D**: A "high-slip" motor, characterized by very high starting torque, low starting current, and low full-load speed.

- **NEMA Design F**: A motor with low starting torque, low starting current, and low slip This design type is now obsolete, but it used to see some application in 50 and over horsepower motors.

Of particular interest, of course, are the intrinsic efficiencies associated with these types of motors. Figure 5 shows efficiency, power factor, and current vs. power output curves for an average sized (10 HP), AC polyphase motor. The figure shows that efficiency tends to reach an asymptote at or slightly before the motor's rated output. Moreover, it does not fall off badly until the load drops below 50% of the motor's full load rating. Conversely, the figure shows that the motor's power factor increases with load more slowly and linearly than its efficiency. Power factor is a measure of other potential losses in the supply system to the motor, but it is still a function of the motor's characteristics. These will be discussed in Section E – Additional System Losses Associated with Induction Motors (Power Factor).

Intrinsic induction-motor losses are the reason why efficiency is very low at light loads, but high near full load (Figure 6). Intrinsic motor losses by categories are defined below:

Friction and Windage: This is the input power required to make up bearing and fan windage losses. Since speed varies so little from no load to full load, this loss is constant, unaffected by load.

Core Loss: Core loss is made up primarily of hysteresis losses in rotor and stator iron caused by the 60-Hz magnetization of the core. This loss is also independent of load.

Load Loss: Load loss also occurs in the rotor and stator iron. This loss is roughly proportional to current (or load) squared, and is induced by leakage fluxes caused by load currents.

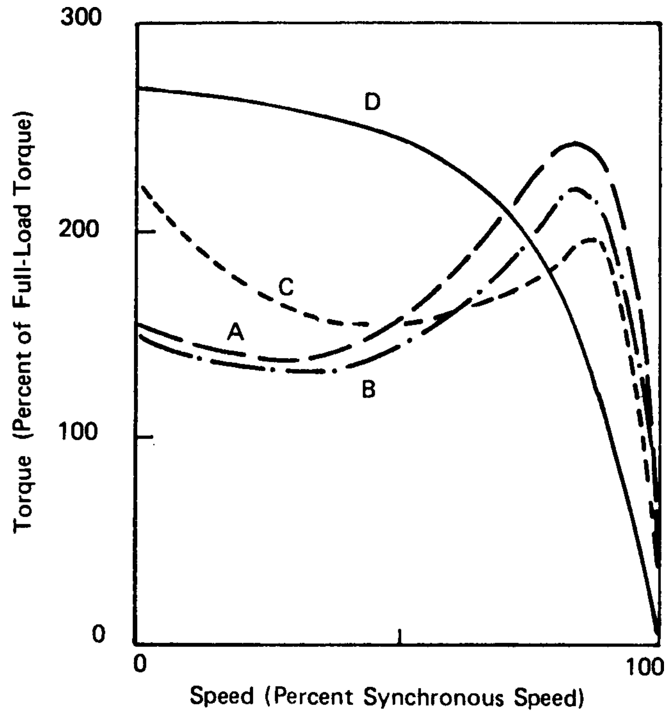


FIGURE 3 GENERAL SHAPE OF SPEED-TORQUE CURVES FOR MOTOR WITH NEMA DESIGN A, B, C, AND D

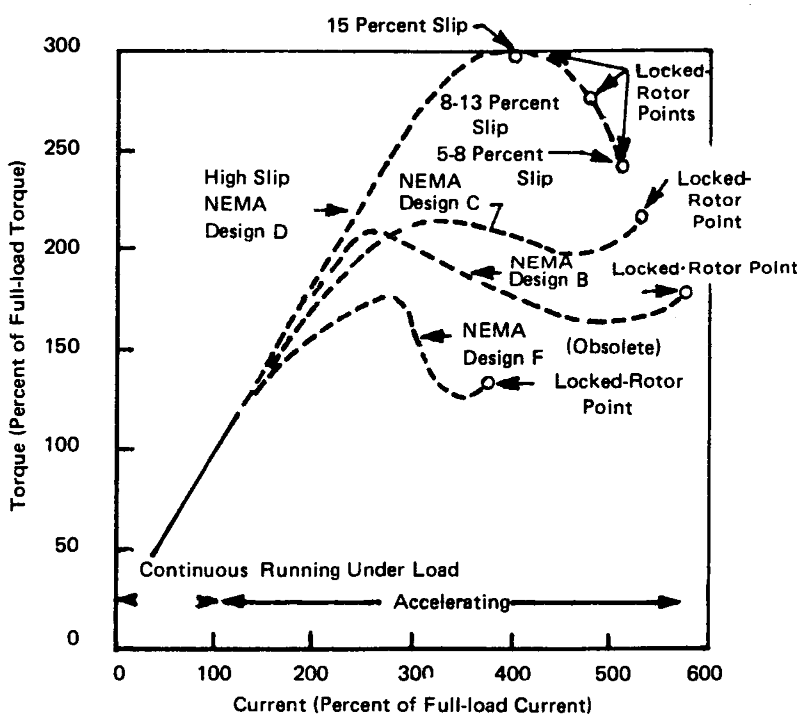


FIGURE 4 TORQUE AND CURRENT RELATIONSHIP FOR SQUIRREL-CAGE INDUCTION MOTORS WITH A RANGE OF 30 TO 75 HP

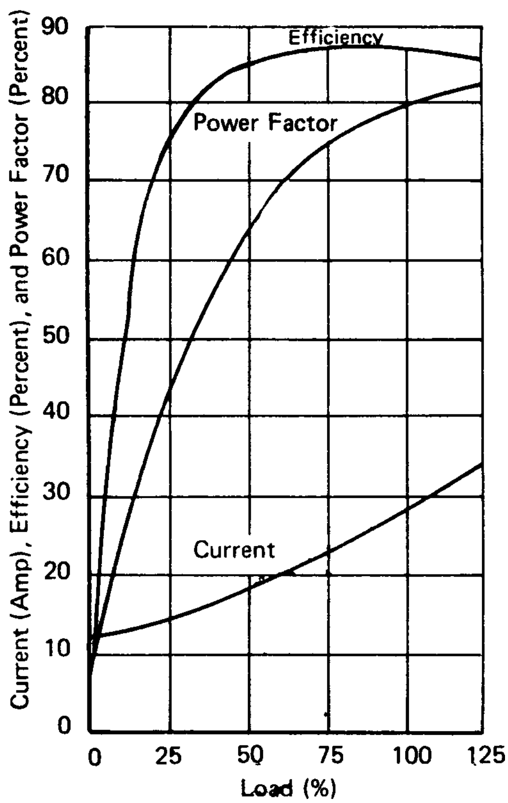


FIGURE 5 TYPICAL PERFORMANCE CURVES FOR DESIGN B, 10-HP, 1800RPM, 220-V, THREE-PHASE, 60-HZ INDUCTION MOTOR

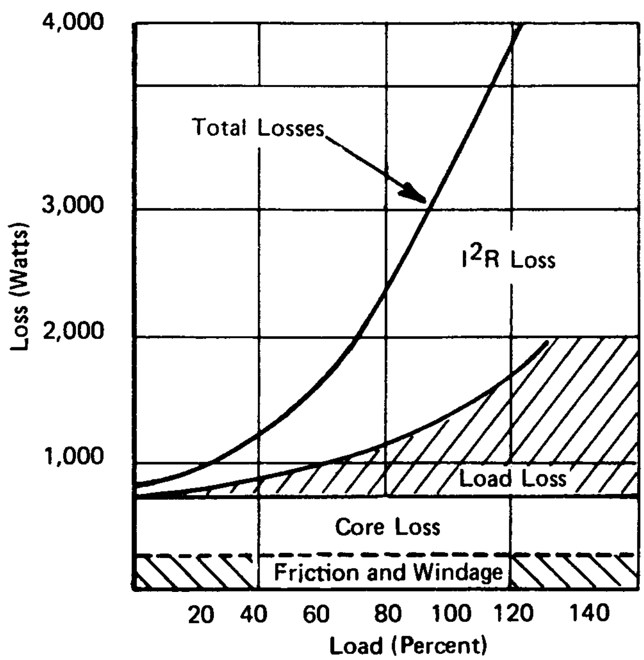


FIGURE 6 TYPICAL LOAD VS. LOSS CURVE FOR DESIGN B, 50-HP, 1800 RPM INDUCTION MOTOR

I^2R Losses: These are heating losses in rotor and stator conductors caused by the current flowing though the conductor resistance. Because it varies as the square of the current, it is generally small at no load but of major proportion at full load.

E. ADDITIONAL SYSTEM LOSSES ASSOCIATED WITH INDUCTION MOTORS (Power Factor)

Induction motors in common with other inductances in a total electric power system cause:

- More current to flow, thus requiring larger generating, transmission line, and transformation equipment than would be the case if the load were purely resistive;

- Greater I^2R losses in the transmission system.

Induction motor line current consists of two components: real and reactive.

- Real current produces power and does the work. Consumption is measured and customers billed on the basis of this real current. It more nearly approximates system energy input requirements than any summation of real and reactive currents.

- Reactive current, however, creates the magnetic field in the motor. Without it an induction motor obviously would cease to function; it has to be inductive.

The vector sum of real and reactive currents is the total current, and it is this total current that the supply and distribution system must handle and be sized for. The ratio of real current to total current is a motor's power factor. These relationships are shown in Figure 7.

A motor's power factor increases with load as was previously shown in Figure 5. Additionally, there is a substantial range of power factors in comparable, commercially available motors, and larger units have larger (better) power factors than their smaller counterparts as shown in Figure 8.

The capital investment requirements of utilities are roughly inversely proportional to the integrated power factors they experience in supplying a diverse group of users. Additionally, as has been mentioned, inductive loads increase total current and increase copper losses in the supply system. They also cause voltage drops which, in concert with these increased currents, result in nearly the same real power (energy input) requirements. Distribution losses overall normally average 7 to 9%. Of this figure, 1 to 2% can probably be attributed to the reactive component of the load.

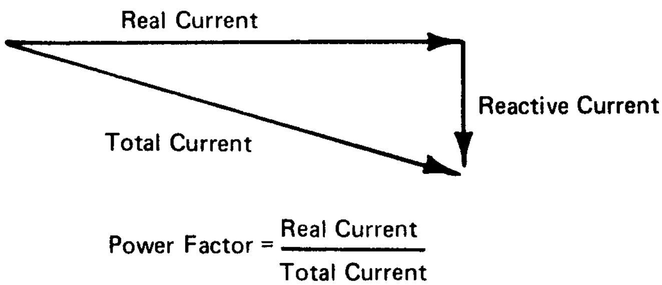
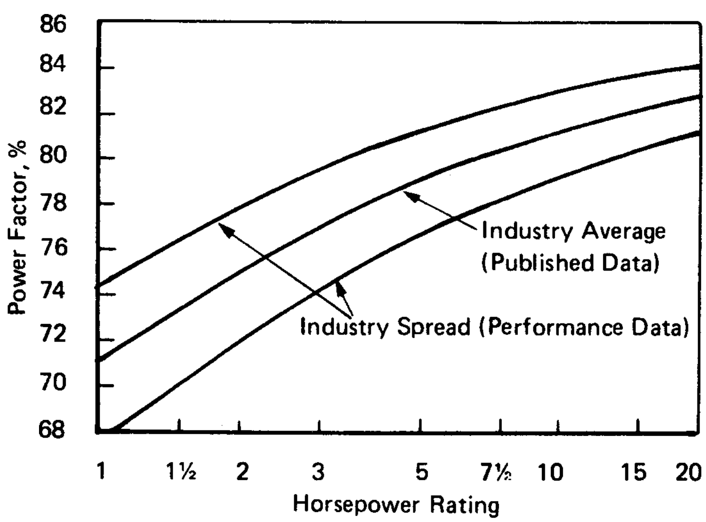


FIGURE 7 VECTOR RELATIONSHIPS OF CURRENT ON AN INDUCTIVE CIRCUIT



Source: Gould Inc., Century Electric Division.

FIGURE 8 POWER FACTOR VS. HORSEPOWER RELATIONSHIPS OF COMMERCIALLY AVAILABLE MOTORS

Utilities typically – and for obvious reasons – penalize industrial customers for low power factors. Conversely, they do not reward customers with high power factors. Users having power factors below 80 to 85% typically have surcharges added to their bills. These penalties, while they may amount to thousands of dollars a month for large industrial plants, are nevertheless a relatively small percentage of the cost of electrical power.

Unlike motor efficiency losses which are inexorable, the losses due to low power factors are largely correctable. Attaching a properly sized capacitor across an inductance in an AC circuit causes the resulting combination to behave as a pure resistance as far as the supply is concerned. In this way, then, power factor correction of motors can be quite directly realized by the simple application of capacitors.

A second method of power factor correction involves use of an overexcited synchronous motor in conjunction with an induction motor load. The synchronous motor acts as a capacitor. A large synchronous motor then has the capability of power factor correcting for many smaller induction motors.

Power factor, then, is an important dimension of electrical economy. However, quite obviously it is quite a separate economic issue from that of motor efficiency. The economic potential for different power factor correction practices is complex and should be the subject of a completely different study. We have therefore not made any attempt in our analysis to add the costs and losses associated with uncorrected power factors to those of intrinsic motor inefficiencies.

F. LIMITATIONS OF DATA ENCOUNTERED

Early in our analysis we found that there were serious limitations to the data needed to pursue our analysis. To our knowledge there have been no comprehensive market studies completed focusing on electric motor application. Motor manufacturers on the average sell 50% of their products to distributors and OEM's where the end-use is unknown to them. Even in the case of direct sales to end-users, the intended application is not always apparent to the motor manufacturers. The National Electrical Manufacturers Association (NEMA) conducts a survey of the end-use of motors by size and industry periodically. Nevertheless it is a fair statement that motor manufacturers do not have comprehensive market research data that could be used to identify sales by industry, motor size, application, duty cycles, life cycles, and the like. Similarily, end-users typically do not maintain good motor inventories. Additionally, of course, they do not have specific application references, including duty and life cycles.

Furthermore, we had a greal deal of difficulty reconciling basic Department of Commerce and Edison Research Institute consumption data with the results of past studies dealing with energy consumption. The problem seemed to be largely one of varying and unspecified definitions of various sectors of consumption. Nevertheless, we sometimes found ourselves unable to correlate well identified data points.

Given the foregoing, we had to piece together large numbers of small pieces of disparate data in an effort to structure a coherent whole. This necessitated changing the structure of our analysis somewhat over that originally proposed. We were forced to conduct many more interviews than originally planned. We accumulated, correlated, and often treated in parametric analysis small isolated pieces of data. While we cannot be completely confident of the results so achieved, we believe we have arrived at the best possible understanding of motor application in the United States, recognizing the limitations we faced.

II. EQUIPMENT ENERGY-CONSUMPTION CHARACTERIZATION

A. MOTOR POPULATION

1. Introduction

The data base used in this report was specifically generated during this project. Interviews with motor manufacturers, OEM's, trade associations, and searches of published literature indicated that no such data base had ever been constructed, since previously there had been neither demand nor use for such information. However, with the need to conserve energy, a corrolary need to identify major consumption modes developed, so that conservation estimates could be made and necessary programs developed.

The data base is somewhat complex and difficult to work with, because electricity consumption is an integration of three factors:

a. Number of units (n),
b. Size or capacity (kW), and
c. Usage (hr/yr).

Carrying out a census to determine these factors would be an overwhelming task. Consequently, we had to use available data, industry knowledge, and informed opinion to estimate the motor population, its applications, and its electricity consumption in the industrial and commercial sectors. Normally, one would expect to determine population and application, and then calculate electricity consumption based on these figures. However, the best data source in the industrial sector was the total electricity consumption figures gathered by the Department of Commerce. By making adjustments for non-motor consumption and air conditioning, we were able to derive figures on motor consumption and break them down by industry. This estimate provided the foundation for all others used in the industrial sector.

We then made a second estimate of the four major motor applications:

- pumps,
- compressors,
- blowers and fans, and
- machine tools.

This estimate, in turn, required major adjustments to correct for use of these types of machines outside of the industrial sector.

Finally, we estimated motor population from past sales of those classes which accounted for the overwhelming consumption of electricity in the industrial sector, and we keyed these estimates to the base data on total kW-hr consumption in the sector.

The commercial data base was somewhat simpler, since a preponderance of the electricity consumption was accounted for by refrigeration. The major refrigeration applications were well known and we were able to derive estimates for them. We estimated the remaining electricity consumption on the basis of per employee consumption. This miscellaneous category has a multitude of different applications, no one of which is particularly significant.

Throughout this section we will be dealing repeatedly with the following two numbers:

1971 motor consumption of electricity – industrial = 458.3 billion kW-hr.

1971 motor consumption of electricity – commercial = 90 billion kW-hr.

2. Industrial Sector

To estimate the population of electric motors in the industrial and commercial sectors we had to rely on a variety of techniques and data. Using different methods allowed us to cross-check estimates generated one way against those developed in a different manner. Moreover, in addition to coming up with estimates of the total population, we were also able to segment the motor population in terms of motor size, usage, and application. We used these estimates as follows:

1. To pinpoint those areas where the greatest electricity consumption was taking place so that attention could be focused on them;

2. To identify current motor efficiencies in the high electricity consumption areas; and

3. To estimate energy savings which might be expected through the use of more efficient motors in high-consumption applications.

We selected 1971 and 1972 as base years for all of our data, because they are the last ones covered by the Department of Commerce Census of Manufactures' statistics on electricity consumption in industry. These data on industry consumption of electricity provide the primary foundation for our estimates of motor population in the industrial sector. These data are shown in some detail in Appendix C.

However, before the data could be used as a base for estimating motor population, the electricity consumed for non-motor purposes had to be removed. Principal components of this non-electric drive consumption include electrolytic processes, direct heat (including welding), lighting and heating, ventilating, and air conditioning. These corrections are included in Table 1 and amount to a total of 142.2 billion kW-hr. When this volume is subtracted from the total consumption, we are left with 458.3 billion kW-hr, the amount used in electric mechanical drive.

TABLE 1

ELECTRIC ENERGY ALLOCATIONS FOR THE INDUSTRIAL SECTOR USED TO OBTAIN MOTOR DRIVE CONSUMPTION

	1971 Consumption (million kW-hr)	
Total Consumption – All Purposes		600,500
Allocations		
Electrolytic Processes (attributed to Industrial Chemicals and Primary Non-ferrous Metals)	91,100	
Direct Process Heat (attributed to Blast Furnace and Basic Steel, Iron and Steel Foundries)	14,000	
Other Direct Heat and Electrolytic Uses (miscellaneous Industry Groups)	4,000	
Lighting and Miscellaneous Services	33,100	
Total Allocations		142,200
Motor Drive Consumption		458,300

Table 2 shows the individual two-digit SIC codes after each one has been corrected for the non-electric drive component of electricity consumption. The top five industries which account for slightly over 60% of the industrial sector's total are essentially continuous process industries. Although food and kindred products might be viewed more as batch processes, many of the operations resemble continuous processing-type operations, particularly those where the product is being pumped and/or blown, or where it requires continuous refrigeration for production and storage.

To translate electricity consumption into electric motor population, we had to estimate the applications of the motors, the distribution of horsepower sizes, and their usage (hr/yr). The major motor manufacturers were most helpful in providing us with estimates of major applications and end-uses for their motors. However, they were careful to point out that they had no way of providing really accurate information, since about one-third to one-half of the motors they sell are delivered through distributors. Thus they do not know to which industries their motors are sold and for what applications. Another complicating factor is that those motors which do not go through distributors are sold in at least two different ways: direct to user, or to OEM equipment manufacturers. Figure 9 shows the major distribution routes for electric motors which help explain the difficulty which manufacturers have in keeping track of the sale and end-use of their products. Motor manufacturers indicated that about two-thirds of their products are sold for applications involving pumps, blowers, compressors, and fans.

TABLE 2

ELECTRIC ENERGY CONSUMED BY ELECTRIC MOTORS IN THE INDUSTRIAL SECTOR
(corrected for non-electric drive component)

SIC Code	Industry Group	1971 Rank	Electric Energy Consumed by Electric Motors (kW-hr x 10^9)	Percent of Total	Cumulative Percent of Total
28	Chemicals and Allied Products	1	80.9	18	18
33	Primary Metal Industries	2	76.1	17	35
26	Paper and Allied Products	3	59.1	13	48
20	Food and Kindred Products	4	34.9	8	56
29	Petroleum and Coal Products	5	28.8	6	62
32	Stone, Clay, and Glass Products	6	24.5	5	67
37	Transportation Equipment	7	24.2	5	72
22	Textile Mill Products	8	23.7	5	77
36	Electrical Equipment and Supplies	9	20.4	4	81
35	Machinery, except Electrical	10	19.2	4	85
34	Fabricated Metal Products	11	17.8	4	89
30	Rubber and Plastics Products	12	16.0	3	93
24	Lumber and Wood Products	13	9.3	2	95
27	Printing and Publishing	14	7.5	2	97
23 25,38,31 21,39 and 19	Remaining Industries	15-21	15.9	4	100
	Total		458.3	100%	

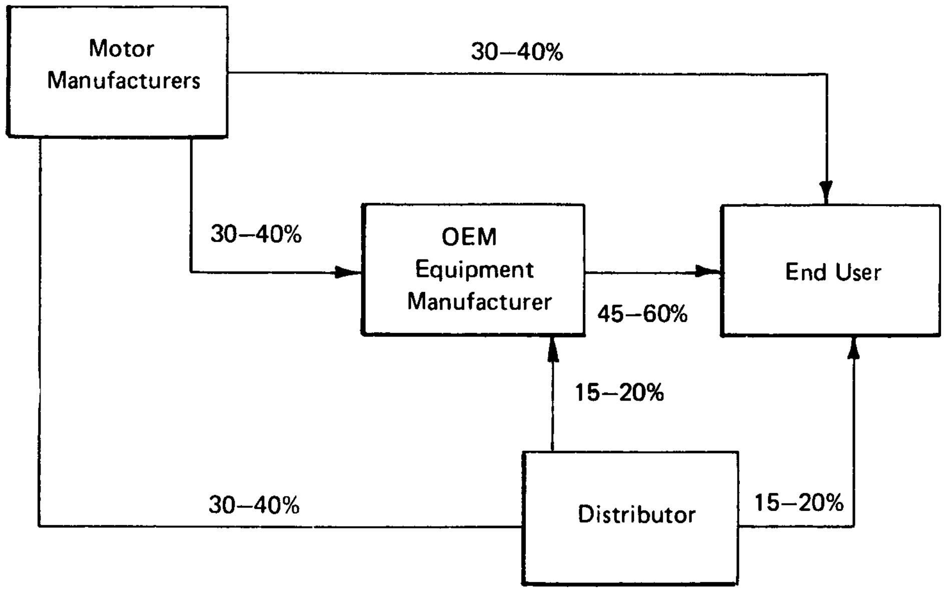


FIGURE 9 MAJOR DISTRIBUTION ROUTES FOR ELECTRIC MOTORS

For each of the three major categories of pumps, compressors, blowers, and fans, we estimated the population through shipments data reported by the Census of Manufactures. In most cases, we were able to estimate the approximate size of the driven unit by the descriptions of capacities of the various categories in the Census data.

The major problem in using this approach was that there were significant parts of the population of pumps, compressors, blowers, and fans which fell outside of the segments under consideration. Therefore, we had to make corrections for these other applications to determine the population in the identified sectors.

We estimated usage from our discussions with motor and equipment manufacturers, as well as with end-users in the process industries. Then, we combined the equipment populations and the usage for the major equipment populations to estimate electricity consumption within the three major equipment categories which comprise 65% of the industrial sector's electricity consumption by electric drives.

We added a fourth specific equipment category – machine tools – because it was an important identified equipment category. Inventory figures were available from a McGraw-Hill survey. The heavy electricity consumption of machine tools was due to their widespread use in industry and their very heavy application in the production of transportation equipment. We also estimated energy consumption by metal-cutting and metal-forming machines used in the transportation equipment industry and in all other industries, and we combined them to provide an overall estimate of the electricity consumed by electric drives on all machine tools.

The electric drives for these classes of equipment are largely comprised of integral horsepower AC motors. The use of fractional motors and DC motors is relatively small. The fractionals tend to be used in applications other than main drives. For example, they are used to drive control valves, for lubricating pumps, and in similar auxiliary drive-type applications. Furthermore, most AC industrial motors are of the polyphase induction type. Relatively few single-phase motors are used. Some synchronous motors are used in the larger sizes for driving pumps, compressors and blowers, and fans. However, such applications represent less than 10% of the total electricity consumption by motors in the industrial sector.

Table 3 shows the estimated population of machines, the estimated average drive motor size in kilowatts, and the average usage in hours per year. We built up the populations for the machines generally by taking past data from the Census of Manufactures and multiplying it by the number of years expected as the useful life for that type of equipment. We derived the average drive size from the Census of Manufactures' breakdowns of these types of equipment, together with estimates from the trade, if breakdowns were not available. The average usages represent an average of high-usage machines which sometimes operate 8000 plus hours per year as well as those with very light usage periods. The average figure tends to mask this very great difference in usage within the total population. For example, in the machine tool field, the transportation sector only employs about 14% of the population. However, we believe that the automotive industry has larger machines, uses them with a much higher usage level, and probably accounts for 40-50% of the total electricity consumed by metal-cutting machine tools.

3. Commercial Sector

The energy use and the equipment profile in the commercial sector is substantially different from that in the industrial sector. Other than electric drives associated with air conditioning (which are outside the scope of this study), the consumption of electricity in the commercial sector is very heavily oriented toward refrigeration. Refrigeration equipment is largely associated with food storage and handling in both wholesale and retail trade. Table 4 shows the major components of refrigeration in terms of the estimated population, the average kilowatt capacity per unit, the estimated usage, and the total annual estimated electricity consumption.

Table 4 also shows that unit coolers and display cases, together with central refrigeration systems, account for about 85% of the electricity used for refrigeration in the commercial sector. The beverage refrigerators and water coolers are considerably more numerous and the population is spread over a much wider range of commercial establishments. However, their unit capacity is relatively small and hence they are not very sizable consumers of electricity.

In addition to the 70 billion kW-hr of electricity consumed by refrigeration equipment in the commercial sector, an additional amount is used for a wide variety of other

TABLE 3

INDUSTRIAL EQUIPMENT USAGE PROFILE (1971)
(Integral HP Motor Drive Only)

Equipment Type	Estimated Population (000's)	Estimated Average Drive Size (kW)	Average Usage (hr/yr)	Estimated Electricity Consumption (kW-hr x 10^6)
Centrifugal Pumps	6,310	11.42	3,000	216,000
Rotary Pumps	3,934	7.55	3,000	89,000
Reciprocating Pumps	383	7.5	3,000	8,600
Turbine and Other Pumps	545.6	8.0	3,000	13,400
Subtotal – Pumps	11,172.6	–	–	327,000
Air Compressors	705	13.94	3,000	29,400
Refrigeration Compressors	50.3	175	4,000	35,200
Vacuum Pumps	1,256.0	3.75	4,000	18,900
Subtotal – Compressors	2,011.3	–	–	83,500
Centrifugal Blowers and Fans	1,808.0	20.0	2,500	90,400
Axial and Propeller Fans	2,352.0	11.16	2,500	65,600
Subtotal – Blowers and Fans	4,160.0	–	–	156,000
Metal-Cutting Machine Tools	2,362.0	9.0	1,000	21,300
Metal-Forming Machine Tools	703.0	26.25	1,000	18,500
Subtotal – Machine Tools	3,065.0	–	–	39,800
Subtotal	20,408.9			606,300
Adjustment for Usage in Other Sectors				(267,300)
				339,000
Other AC Integral HP				63,300
Fractional AC				20,000
DC Motors and Drives				36,000
Total				458,300

TABLE 4

COMMERCIAL EQUIPMENT USAGE PROFILE (1971)

Type Machinery	Average kW per Unit	Number of Units (x 10^6)	Usage (hr/yr)	Electricity Consumption (kW-hr x 10^6)
Unit Coolers & Display Cases	4	1.7	4,000	27,200
Beverage Refrigerator	0.3	3.9	4,000	4,700
Water Coolers	0.3	3.8	3,000	3,400
Ice Makers	0.5	1.3	4,000	2,600
Central Refrigeration Systems	40	0.2	4,000	32,000
Subtotal				69,900
Other				20,100
Total				90,000

applications. We estimate that these miscellaneous uses account for 20 billion kW-hr per year. Many of these electric drives are fractional HP motors, such as those used for office copiers and computer printer drives, and in similar applications. Some of the larger users in the integral HP class applications are elevators, moving stairways, electric door openers, vacuum cleaners, floor polishers, and laundry equipment.

Even though we were unable to develop a population in the same way as it was done for industrial equipment and commercial refrigeration, we were still able to describe some salient aspects of this miscellaneous motor-drive segment in the commercial sector. The first, and most obvious point, is that there is a myriad of different applications. However, motors are not much in evidence since, for the most part, they are small and have light usage periods. Moreover, unlike the industrial sector, the commercial sector almost always purchases its equipment with the motors already attached, and frequently they are hidden within some kind of housing. Therefore, the commercial sector purchaser often does not know who manufactured the motor, and he has little concern about efficiency, power factor, and similar characteristics.

B. MOTOR USAGE PROFILE

Comparing the industry usage of electricity for electric motor drives with the major equipment types which are the most important power consumers led to the conclusion that process equipment and the process industries are the major power consumers. We confirmed this conclusion by interviews with motor manufacturers who told us that the movement of fluids by the use of pumps, blowers, and compressors was by far the most significant application for electric motors in the industrial sector.

An almost endless variety of processes are used in industry today, and there is a legitimate question as to whether all of the process industries can be lumped together in terms of their motor requirements. Following interviews with motor manufacturers, OEM equipment suppliers, and process industry end-users, we concluded that most processes are sufficiently similar, so that their needs can usually be met by standard electric motors. In fact, a standard motor type has been developed which grew out of the particular needs of the process industry. These motors have different names associated with them when they are produced by different manufacturers, but generally they are known as "mill and chemical" motors. Typically such motors carry a 15% price premium over standard motors (totally enclosed fan-cooled), because they are designed to operate effectively in corrosive atmospheres. Furthermore, they have a 1.15 service factor which allows them to be slightly overloaded without overheating or failing.

Although such motors are, to some extent, especially designed for the process industry, they are not specifically oriented toward any particular process. Therefore, a given 5-HP process industry motor could be used on any of a number of different pumps which, in turn, might be employed in a wide variety of different process types.

Most processes tend to be run continuously with shutdowns planned for periodic intervals for maintenance and/or to adjust output to demand. Therefore, process equipment drive motors tend to be used on continuous duty cycles which, in turn, accounts in part for their heavy consumption of electrical drive power. Another reason for shutting down a continuous process operation is unscheduled failure of some part of the total operation. Unscheduled shutdowns are frequently expensive. As a result, the design of the process and the selection of equipment for it reflect this difference from the usual discrete manufacturing type of operation in which the failure of a single unit frequently does not require the disruption of the entire operation.

The process designer can take certain steps to try to improve overall reliability of the process. He can put in redundant equipment at certain critical points, he can provide standby and spare equipment to reduce the length of the downtime, or he can buy premium quality equipment to achieve the highest degree of reliability in the system. It is this last point that provides the major market for the premium-priced process industry motor.

There continues to be a considerable amount of discussion in the industry about the oversizing of electrical motors and the potential increases in electricity consumption that are associated with such practices. It is certainly true that, in many instances, process industry designers use larger motors than are absolutely required by process design. However, in most cases this appears to be a conscious move on the part of the designer, and he explains his reasons for this in a number of ways. First of all, he would like to have a safety factor in case power requirements are greater than calculations indicated. A burned out motor that shuts down a process is a more serious occurrence than the slight oversizing of a motor which subsequently operates on a slightly uneconomic but satisfactory basis.

Another frequently mentioned factor is the potential for expanding the process output after it has been operating for some time at its designed capacity. In fact, there is not much of a penalty associated with oversizing motors, since the added cost is frequently moderate and the power consumption is relatively flat for most motors between 0.5 and 1.25 of rated capacity. In fact, it has been pointed out that, in some instances, going to the next larger horsepower size and running at a fraction of the load produces a higher efficiency than using a lower horsepower motor at full load.

Both motor manufacturers and end-users indicated that in the 1- to 125-HP range, AC induction motors tend to be viewed as commodities. There is a widespread belief that all motors are about the same, and that there is little from which to choose from one manufacturer to the other. Motor manufacturers themselves indicated that they tend to stress quality control, their excellent service, and their competitive price rather than technical characteristics of the motor itself. In most instances, process designers do not appear to get involved in considerations of efficiency, power factor, and similar matters. Frequently the only decision they make relates to the size and type of enclosure for the motor. The buying details are left to the purchasing department.

In some cases, the technical characteristics become a very significant part of the application, and the motor manufacturer and end-user work closely on the specifications. However, these applications are relatively few. The most frequently mentioned one was the need for high-slip motors in designing drive systems for presses with flywheels. Then too, very large motors get a high degree of attention from the end-user and the motor manufacturer. They are customarily designed specifically for the application in terms of mechanical and electrical characteristics as well as balancing first cost and operating costs on the basis of the power rates in the locations where the motors will be used.

C. ENERGY CONSUMPTION IN THE INDUSTRIAL AND COMMERCIAL SECTORS

1. Energy Consumption

Energy consumption in the industrial sector is broken down by equipment types in Table 5, and the commercial sector energy consumption is similarly shown in Table 6. The consumption in the two sectors in proportion to total U.S. consumption is shown in Table 7. We derived these estimates of energy consumption in the industrial and commercial sectors using estimates developed for the population of major pieces of driven equipment. Another way of deriving electricity consumption in these sectors is to estimate the motor populations in total and then correct for motor usage outside of the two sectors in question. Tables 8 through 11, respectively, detail the estimated motor population in terms of the number of units in use, as well as the installed capacity. This is shown separately on the tables for integral horsepower, AC-polyphase induction motors, integral horsepower, DC motors and generators, synchronous motors, fractional HP motors, and other single and polyphase integral motors.

TABLE 5

TOTAL INDUSTRIAL ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Industrial Motor Drive (except HVAC)		458
Pumps	143	
Compressors	83	
Blowers and fans	73	
Machine tools	40	
Other integral HP applications	52	
DC drives	47	
Fractional HP applications	20	
Other Industrial Electrical Usage		142
Electrolytic		
Direct heat		
HVAC		
Transportation		
Lighting		
Total Industrial		600

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE 6

TOTAL COMMERCIAL ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Commercial Motor Drive			200
Air conditioning		110	
Refrigeration compressors		70	
Central systems	32		
Unit coolers/display cases	27		
Beverage refrigeration	5		
Water coolers	3.5		
Ice makers	2.5		
Other Motor Applications		20	
Direct Heat and Light			120
Total Commercial			320

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE 7

TOTAL U.S. ELECTRICAL CONSUMPTION (1972)
(billions kW-hr)

Motor Drive (excluding HVAC)		548
Industrial, integral HP	438	
Industrial, fractional HP	20	
Commercial, integral HP	74	
Commercial, fractional HP	16	
Motor Drive (HVAC)		122
Industrial	12	
Commercial	110	
Motor Drive (other sectors)		411
Muncipal water works	116	
Electric utilities	147	
Mining and construction	28	
Residential	120	
All other electrical consumption	602	602
Total U.S.	1,683	1,683
Total Motor Drive	1,081	1,081

Source: Refs. 1, 3, and 4 and Arthur D. Little, Inc., estimates.

TABLE 8

ESTIMATED MOTOR POPULATION IN THE INDUSTRIAL AND COMMERCIAL SECTORS

Integral AC-Polyphase Induction-Motors

HP Range	Estimated Number in Active Use in 1972 (x 10^3)	Average kW	Active Installed Capacity (kW x 10^3)
1-5	9,645	2.0	19,290
5.1-20	3,650	12.0	43,800
21-50	975	32.0	31,200
51-125	623	60.0	37,380
126-200	176	120.0	21,120
201-500	68	260.0	17,680
> 500	27	1,500.0	40,500
Subtotal	15,164		210,970
Used in Air Conditioning and in Drives in Sectors Other Than Those Covered	6,454		89,789
Population and Capacity in Defined Sectors	8,710		121,181

TABLE 9

ESTIMATED MOTOR POPULATION IN THE INDUSTRIAL AND COMMERCIAL SECTORS

Integral HP DC Motors and Generators

HP Range	Estimated Number in Active Use in 1972 (x 10^3)	Average kW	Active Installed Capacity (kW x 10^3)
1-5	160	2.0	320
5.1-20	125	12.0	1,500
21-50	80	32.0	2,560
51-200	93	94.0	8,742
201-500	22	260.0	5,720
> 500	6	1,500.0	9,000
Subtotal	486		27,842
Used in Drives in Sectors Other Than Those Covered	207		11,850
Population & Capacity in Defined Sector	279		15,992
Less Generator			5,392
Total			10,600

TABLE 10

ESTIMATED MOTOR POPULATION IN THE INDUSTRIAL AND COMMERCIAL SECTORS

Synchronous Motors

Category	Estimated Number in Active Use in 1972 (x 10^3)	Average kW	Active Installed Capacity (kW x 10^3)
Synchronous	30	750	22,500
Motors used for Air Conditioning and in Sectors Other Than Those Covered			9,576
Capacity in the Defined Sectors			12,924

TABLE 11

ESTIMATED MOTOR POPULATION IN THE INDUSTRIAL AND COMMERCIAL SECTORS

Fractional HP Motors, Single-Phase Integral and Other Polyphase Integral Motors

Motor Classification	Estimated Number in Active Use in 1972 (kW x 10^3)	Average kW	Active Installed Capacity (kW x 10^3)
Fractional HP Motors – Single- and Polyphase > 1/6 HP	36,000	0.5	18,000
Single-Phase Integral and Other Integral Polyphase	6,000	1.5	9,000
Subtotal	42,000		27,000

Table 12 summarizes the electrical consumption in the industrial and commercial sectors by all of the various types of motors, and shows the total consumption to be 548 billion kW-hr. This sum consists of about 458 billion kW-hr in the industrial sector and about 90 billion kW-hr in the commercial sector. This total resulted after correcting the motor populations for applications outside of the two sectors and for work outside the scope of the program.

Table 13 shows the estimated electricity consumption by all integral HP electric motors compared to consumption in the defined areas. It shows further that there is a fairly sizable consumption of electricity in other sectors, particularly by municipal water and waste treatment plants and electric utilities.

TABLE 12

ESTIMATED INSTALLED MOTOR CAPACITY, DUTY CYCLE, AND ELECTRICITY CONSUMPTION IN THE INDUSTRIAL AND COMMERCIAL SECTORS – 1972

Category	Active Installed Capacity (kW x 10^3)	Estimated Usage (hr/yr)	Consumption (kW-hr)
Integral HP AC Polyphase	121,000	3,400	413,000,000
Integral HP DC Motors (excl. generators)	10,600	3,000	36,000,000
Single Phase Integral AC and Other Polyphase AC Motors	9,000	2,000	18,000,000
Fractional HP Motors	18,000	2,000	36,000,000
Synchronous Motors	12,900	3,500	45,000,000
Total			548,000,000

TABLE 13

ESTIMATED ELECTRICITY CONSUMPTION BY ALL INTEGRAL HP ELECTRIC MOTORS COMPARED TO CONSUMPTION IN THE DEFINED SECTORS (x 10^3) – 1972

	Total Electricity Consumption (kW-hr)	Electricity Consumed in Defined Sectors (kW-hr)
AC Integral HP Polyphase Induction Motors	738,000,000	413,000,000
Integral HP DC Motors (excl generators)	63,000,000	36,000,000
Single-Phase Integral AC Motors & Other Polyphase Integral Motors	33,000,000	18,000,000
Synchronous Motors	79,000,000	45,000,000
Subtotal	913,000,000	512,000,000

Difference Between Total and Defined Sector Consumption Made up as Follows:

Category	Consumption (kW-hr)
Commercial Air Conditioning	110,000,000
Municipal Water Works	116,000,000
Electric Utilities	147,000,000
Mining and Construction	28,000,000
Total	401,000,000

Table 14 shows the estimated electricity consumption by integral and fractional HP motors in both sectors. It also shows that there is a significant difference in proportion of fractionals in the two sectors. It is relatively insignificant in the industrial sector, but comprises almost a fifth of the total electricity consumption in the commercial sector.

TABLE 14

ESTIMATED ELECTRICITY CONSUMPTION BY FRACTIONAL AND INTEGRAL HP MOTORS IN THE INDUSTRIAL AND COMMERCIAL SECTORS – 1972
(kW-hr x 10^3)

Excluding Air Conditioning

	Industrial Sector	% of Sector Total	Commercial Sector	% of Sector Total
Fractional HP All Types > 1/6 HP	20,000,000	4	16,000,000	18
Integral HP Motors All Types	438,000,000	96	74,000,000	82
Total	458,000,000	100	90,000,000	100

2. Energy Conservation Potential

The major energy consumption is clearly in the integral HP AC-polyphase induction motor class. The largest application for these motors is for driving pumps, compressors, blowers and fans, and machine tools in the industrial sector and for driving refrigeration compressors in the commercial sector. The greatest concentration of pumps, compressors, blowers and fans in the industrial sector is in those industry groups which we call the process industries.

For the purposes of this report, electrical losses in industrial and commercial drive applications are a function of motor inefficiency, motor size, and usage. Table 15 lists the current and future motor efficiencies, indicates the worst and best motors available in various HP classes, together with the average of the best and worst, and estimates achievable efficiency within the state-of-the-art. There is a much greater spread between the best and the worst in the smaller HP categories; there is also a considerably larger area for improvement in the smaller motors. It may be possible to make minor efficiency improvements in large motors, but they are already designed for a very high efficiency. Most of our respondents felt that it was not a fruitful area for investigation.

Energy savings potential is commonly expressed in percentage points of improvement compared to the current standard. For instance, a motor manufacturer may talk about being able to achieve an eight or nine point efficiency improvement in his small integral HP motors, but having a limitation of maybe one or two points of improvement in the medium size motors, and virtually no room for improvement in the very large sizes. Table 16 shows

TABLE 15

ESTIMATED ELECTRICITY CONSUMPTION AND MAXIMUM SAVING POTENTIAL THROUGH MORE EFFICIENT MOTORS (1977-1990)

Integral AC Polyphase Motors — Industrial and Commercial Sectors

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Estimated Electricity Consumption with Normal Growth and No Change in Efficiency																			
1-5 HP	40.5	42.9	45.5	48.2	51.1	54.2	57.5	60.9	64.6	68.4	72.5	76.9	81.5	86.4	91.6	97.1	102.9	109.1	115.7
5.1-20 HP	85.5	90.6	96.1	101.8	107.9	114.4	121.3	128.6	136.3	144.5	153.1	162.3	172.3	182.4	193.3	204.9	217.2	230.3	244.1
21-50 HP	60.9	64.6	68.4	72.5	76.9	81.5	86.4	91.6	97.1	102.9	109.0	115.6	122.5	128.9	137.7	145.9	154.7	163.9	173.7
51-125 HP	67.2	71.2	75.5	80.0	84.8	89.9	95.3	101.0	107.1	113.5	113.5	127.6	135.2	143.3	151.9	161.0	170.7	180.9	191.8
Total	254.1			302.5	302.7	340.0	360.50	382.10	405.10	429.30	454.90	482.40	511.30	541.0	574.50	608.90	545.50	684.2	725.3
Estimated Capacity Available for Improvement (New Additions Plus Replacements)																			
1-5 HP						6.5	13.4	20.7	28.5	36.7	45.4	54.6	64.3	74.7	85.7	97.1	102.9	109.1	115.7
5.1-20 HP						13.7	28.3	43.7	60.1	77.4	95.8	115.3	136.0	157.9	181.1	204.9	217.2	230.3	244.1
21-50 HP						9.8	20.2	31.2	42.9	55.3	68.4	82.3	97.0	112.5	129.0	145.9	154.7	163.9	173.7
51-125 HP						8.09	16.67	25.76	35.40	45.62	56.45	67.93	80.10	93.0	106.67	121.16	136.52	152.80	170.1
Total						38.1	78.6	121.4	166.9	215.0	266.1	320.1	377.4	438.1	501.5	569.1	611.3	656.1	703.6
Estimated Efficiency Savings Potential in the Available Portion of the Population																			
1-5 HP						0.78	1.61	2.48	3.45	4.40	5.45	6.55	7.72	8.96	10.28	11.65	12.35	13.09	13.9
5.1-20 HP						1.23	2.55	3.93	5.41	6.97	8.62	10.38	12.24	14.21	16.30	18.44	19.55	20.73	22.0
21-50 HP						0.59	1.21	1.87	2.57	3.32	4.10	4.94	5.82	6.75	7.74	8.75	9.28	9.83	10.4
51-125 HP						0.16	0.33	0.52	0.71	0.91	1.13	1.36	1.60	1.86	2.13	2.42	2.73	3.06	3.4
Total						2.76	5.70	8.80	12.14	15.60	19.30	23.23	27.38	31.78	36.45	41.26	43.91	46.71	49.7

energy savings potential based on estimated percentage points of efficiency improvement for integral HP AC-polyphase motors. The total savings are expressed in kW/1000 hr of usage per year. On an overall basis, we estimate that the average usage for these motors is about 2500 hours per year. The larger motors generally tend to run higher usage periods; hence the savings as shown are slightly skewed in favor of the smaller motors. However, the percentage point savings are so small in the large motors that the adjustment is not significant.

TABLE 16

CURRENT AND FUTURE MOTOR EFFICIENCIES IN INTEGRAL AC-POLYPHASE MOTORS

HP Category	Avg. Efficiency Now	Potential Efficiency Next 2-10 Years	Potential Energy Saving
<1	65.0	75.0	0.15
1-5	76.5	85.5	0.12
5.1-20	82.5	89.5	0.09
21-50	87.5	92.5	0.06
51-125	91.0	93.0	0.02
$>$ 125	94.0	94.2	0.002

One further fact that should be noted about percentage point improvement is that it has a differentially greater effect in the lower efficiency range than it does in the higher one. For instance, improving efficiency 10 percentage points from 60% to 70% yields a net energy saving of about 14.3%. Improving the efficiency from 70% to 80%, on the other hand, would yield about a 12.5% improvement.

Before introducing higher efficiency motors into the industrial and commercial sectors, the question of population turnover must be addressed. We have discussed motor and equipment life with both manufacturers and end-users. The answers vary depending on the industry, the application, and the size of the motors. However, there appears to be a consensus that in the small- and medium-size motors and driven machines, the average useful life is in the range of 7 to 10 years. However, it appears that the process industries generally expect a somewhat lower life expectancy based on the adverse conditions under which the motors must operate and the rapidity of process obsolescence. It is not uncommon for motors and their associated driven equipment to become obsolete in 3 to 5 years in a fast-moving process industry. In some cases the motors are salvaged and put into a pool, but in a number of instances the entire package of machinery is scrapped.

This is definitely not the case for the larger motors. Any motor above 50 HP will probably be rewound. The very large motors "go on forever," as one respondent put it. For instance, the AEC has recently rewound some of its compressor motors which were installed originally in the 1940's. This is another strong reason for concentrating the effort on the smaller motors (which tend to be throw-away items) with higher population turnover rates.

Table 15 also shows our estimate of the electricity consumption by integral HP, AC polyphase motors in the industrial and commercial sectors from 1977 through 1990 It also shows the amount of that motor population which will be available to be replaced by more efficient motor models. This replacement availability segment has been calculated from a combination of new motor additions to the population, together with old motor replacements. These two figures added together equal the number of new motors which are being added to the population in any year. We believe that this is the only part of the population which will be susceptible to replacement by high-efficiency motors. It seems unlikely from our interviews and discussions that standard motors in good operating condition will be replaced by higher efficiency models.

The new growth factor is estimated at about 6% per year at a steady rate throughout the period under observation. The replacement rate has been calculated separately for the different size categories to reflect the longer life of the larger motors. The replacement factor has further been modified to reflect the fact that today's replacements are motors which were sold "n" years ago.

Table 15 shows the energy savings which could be achieved if all of the new and replacement motors were of the high-efficiency type. This is shown for each of the major size categories where any significant amount of energy saving can be accomplished. Table 17 shows the energy saving potential in the industrial sector for integral HP, AC polyphase motors.

TABLE 17

INDUSTRIAL SECTOR ENERGY SAVING POTENTIAL
INTEGRAL HP AC-POLYPHASE MOTORS

Motor Size Category HP	Average kW	kW Savings per 1000 Hours of Use (hr/yr)	Percent
1-5	2	2315	25.5
5.1-20	12	3942	43.4
21-50	32	1872	20.6
51-125	60	748	8.2
126-200	120	211	2.3
201-500	260	--	--
>500	1500	--	--
Total		9088	100.0

Figure 10 shows the estimated potential electricity consumption savings from the use of more efficient electric motors. It can be seen that the maximum savings available come to about 50 billion kW-hr by 1990. This maximum figure is derived from the efficiency savings which could be accomplished if all new and replacement motors were of the high-efficiency type. Since this does not seem reasonable under normal circumstances, we have added two

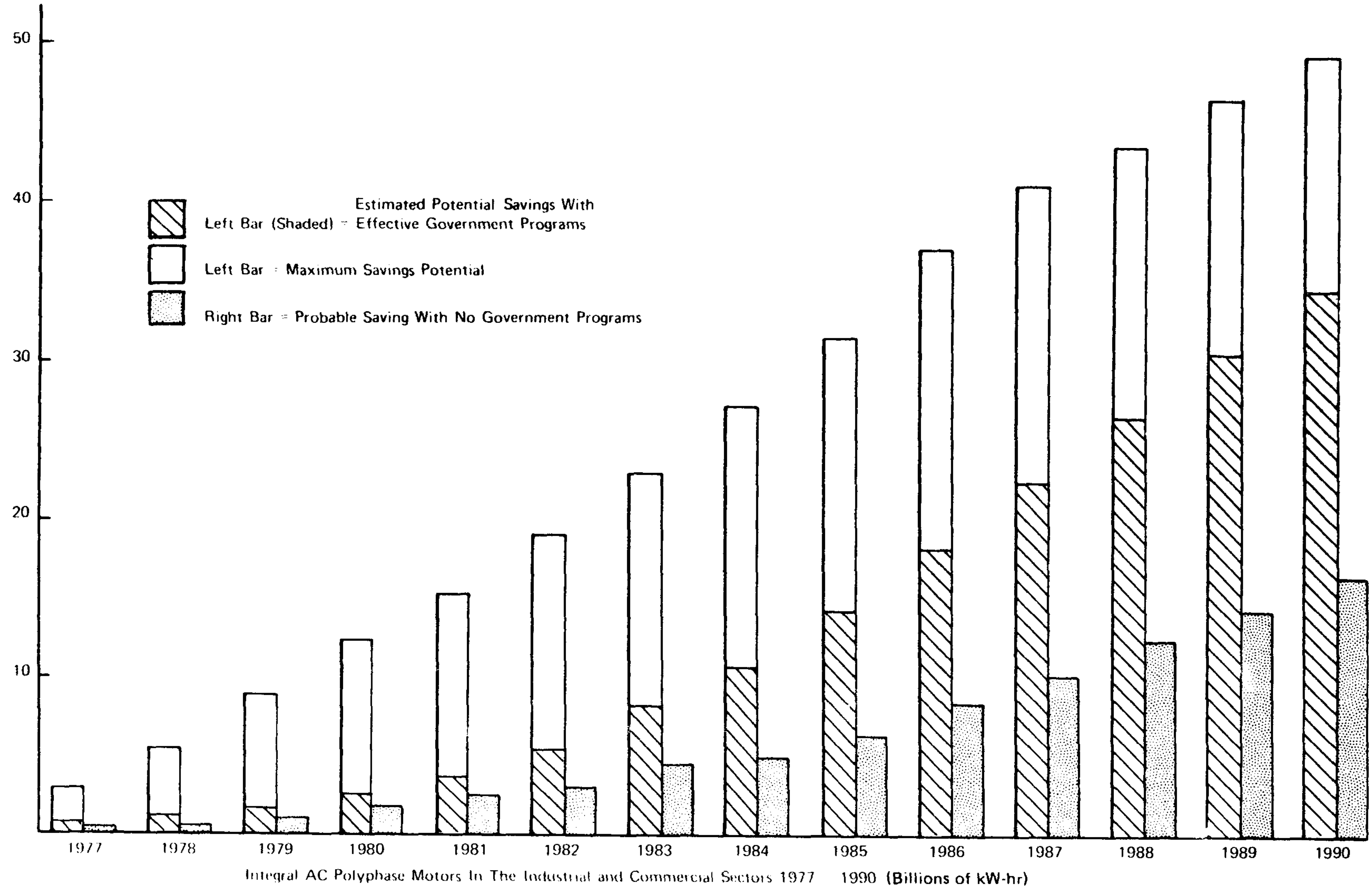


FIGURE 10 ESTIMATED POTENTIAL ELECTRICITY CONSUMPTION SAVINGS FROM THE USE OF MORE EFFICIENT ELECTRIC MOTORS

other displays to the histogram. The right bar indicates our estimate of the energy savings which would be accomplished if there were no government programs and encouragement for the use of high-efficiency motors. This figure comes out to about 17 billion kW-hr savings by 1990, or about one-third of the total maximum available.

The shaded portion of the left hand bar shows our estimate of the energy saving which could reasonably be expected if Government programs were instituted to encourage the use of more efficient motors in the industrial and commercial sector. This indicates a saving by 1990 of about 34.8 billion kW-hr per year in the industrial and commercial sector.

We derived the rationale for the estimate of energy saving potential from the specific information received from respondents during this study, as well as from more general observations of industry decision patterns in similar economic choice situations. First, it should be recognized that the maximum potential savings figure is not a realistic target. Rather, it was calculated to indicate the absolute maximum potential energy saving based on the number of new and replacement motors which would be added to the population on a year-to-year and cumulative basis. Some portion of these motors will be utilized in relatively light usage periods. As a consequence, they will not be able to show life cycle savings over conventional motors. Another portion will be used in medium usage periods where the pay-out may be considered marginal by many purchasers. We have assumed that end-users would not make economically irrational purchase decisions, and that they would not buy high-efficiency motors where both the first costs and the life cycle costs were greater than that for conventional motors.

We estimate that about 30% of the motor population will consist of motors with too low usage to provide a very attractive life-cycle cost comparison with conventional motors. Consequently, we estimate that 70% of the available energy consumption potential is economically favorable to high-efficiency motors and will offer a positive incentive for the end-user to purchase the high-efficiency models. We believe that a successful Government program could convince most of those who would be economically better off with high-efficiency motors to take action and purchase them when appropriate. Without Government action and information programs, however, we feel that the inertia and indifference will cause only about half of the realizable potential to actually occur.

There are many valid reasons why end-users are indifferent to these energy savings. Perhaps the most significant one is that the actual amount of energy and cost which can be saved is rather small for any given manufacturing operation. This is particularly true in relation to other cost components such as labor or purchased materials. It is not that the end-user is not interested in making savings in energy and cost; rather, his priorities are established so that the most important subjects get all the attention and those viewed as unimportant tend to be ignored. Moreover, there is a perceived cost and risk to going to new motor designs which have not been proven in years of field service. Finally, there is the cost of obtaining information about high efficiency motors; this is where a Government program could assist considerably in providing end users with information which would point out the benefits and provide the necessary facts and processes for making motor choices.

Finally, Figure 11 and Table 18 show the potential energy saving by motor size both with and without effective Government programs. Table 18 is derived from the information in Table 16. It is based on increasing awareness and purchases of high-efficiency motors as they become available and better known. Thus the "no Government program" series starts at about 10% of the annual potential in 1977 and goes to 34% of the potential annual replacements of standard motors by high-efficiency models in 1990. For the "effective Government program" series, the penetration starts at 20% in 1977 and goes to 70% in 1990.

TABLE 18

ESTIMATED POTENTIAL ENERGY CONSUMPTION SAVINGS
FROM THE USE OF MORE EFFICIENT ELECTRIC MOTORS
IN THE INDUSTRIAL AND COMMERCIAL SECTORS

	Estimated Savings if No Government Programs	Estimated Savings with Effective Government Programs
	(billions kW-hr)	
1977	.3	.6
1978	.6	1.1
1979	1.3	1.8
1980	1.8	2.4
1981	2.7	3.9
1982	3.3	5.8
1983	4.4	8.1
1984	5.2	11.0
1985	6.7	14.3
1986	8.4	18.2
1987	10.3	22.7
1988	12.3	26.3
1989	14.5	30.4
1990	16.9	34.8
Cumulative Total	88.7	181.4

D. CONCLUSIONS

We concluded that the major energy saving opportunities in the industrial and commercial sector can be identified by a number of different characteristics. First, by far, the majority of the energy consumed by electric motors in the industrial and commercial sector is consumed by integral HP, AC polyphase induction motors. We estimate that 75% of the power is consumed by such motors, and the rest is scattered among a variety of other types, no one of which is of much significance in the total picture. The largest part of the total energy consumed by electric motors is consumed by driving general-purpose machinery including pumps, compressors, blowers, and fans. The principal use for such general-purpose machinery is in the process industries, and these industries frequently purchase direct rather than through distributors or OEM's.

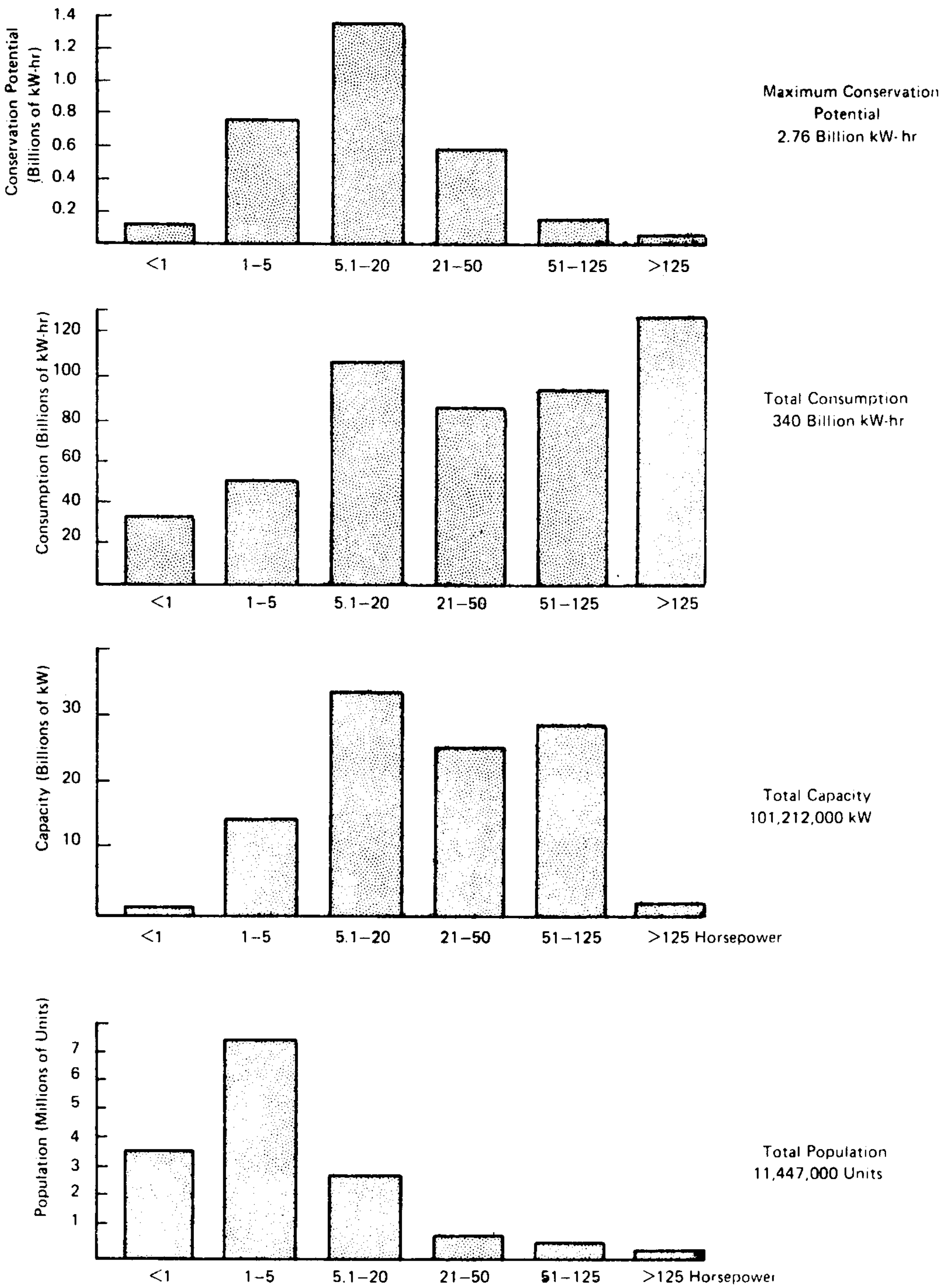


FIGURE 11 **PROJECTIONS OF FRACTIONALS, 1- to 125-HP, AND > 125 HP POLYPHASE MOTOR USAGE IN INDUSTRY AND COMMERCE (1977) & EXCLUDING HVAC & TRANSPORTATION EQUIPMENT**

There is a substantial opportunity for energy conservation through the use of more efficiently designed integral HP, AC polyphase motors. By increasing the core length and utilizing electrical steels, efficiencies can be improved by more than 10% in the smaller sizes. The efficiency improvement opportunity tails off at the over 125-HP size, since such motors are already virtually custom-designed and highly efficient.

The changing motor population provides an opportunity for the introduction of high-efficiency models from the new additions, together with the replacements. This is creating a change in the population sufficiently rapid so as to make it possible to obtain significant savings within a 10-year period. We estimate that in the integral HP, AC polyphase motor field, about 50 billion kW-hr represent the maximum potential saving by 1990. We estimate that 35 billion kW-hr appears reasonable, if Government programs are instituted. If no action is taken by the Government and industry is left to its own rate of change, then we estimate that efficiency savings by 1990 will probably not amount to much more than 17 billion kW-hr.

As we point out in the next Chapter (III-E, Electric Motor Design Influences), there is little current motivation to move aggressively to the use of more efficient electric motors. Under such a condition of weak motivation, there appears to be a need to provide some form of external information/stimulation to generate awareness and interest. Since we see no such force at work in the private sector, we believe that it is probably going to be necessary for Government programs to take on that mission, if the full energy conservation potential is to be realized.

III. MARKET CHARACTERIZATION

A. GENERAL MARKET INFLUENCES

To investigate the general market influences on motor choice, the market has to be segmented into its different purchasing components. Table 19 shows the three major sources of motors and motor-driven equipment for industrial customers and the typical purchasing patterns. Motor manufacturers estimate that about 50% of the unit volume goes through distributors, while the remaining 50% goes directly to end-users or to OEM's. On a dollar or HP basis, the share for distributors is closer to a third, since most of the large and expensive motors are sold direct.

TABLE 19

INDUSTRIAL PURCHASING PATTERNS FOR ELECTRICAL MOTORS

1. Purchase from Motor Manufacturer	2. Purchase from OEM's	3. Purchase from Distributors
Large User	Large User – New Plant	Medium and Small OEM's
Large User – Replacement	Large User – Replacement	Large Users – Replacement
Large and Medium OEM's	Medium and Small User – New Plant	Medium and Small Users – New Plant
Distributors and Dealers	Medium and Small User – Replacement	Medium and Small Users – Replacement
	Other OEM's	

There is a general tendency for the smaller motors and equipment to go through distributors and OEM's. In such cases, it is not uncommon for the end-user to be unaware of many of the motor's characteristics or even the manufacturer's name. In the case of an OEM supplier, the end-user looks to that company as having the total responsibility for the equipment. In fact, this is one reason why some very large manufacturers prefer to purchase their equipment from OEM's with the motor already installed, since then there is a single rather than dual responsibility, should the equipment fail.

The significant difference between OEM purchasers and direct end-user purchasers is that the OEM is not in the business of selling motors. He is selling a piece of equipment which is being purchased, to a large extent, on its price/performance characteristics in comparison with other similar equipment offered by other manufacturers. Therefore, his principal concern is in securing the lowest cost motor which will provide the reliability and performance he needs and which he is willing to back up with his warranty. In most instances, the OEM's customer is relatively unsophisticated concerning the technical characteristics of the motor.

The large end-user (who purchases direct), on the other hand, tends to be technically and economically more sophisticated. Frequently, the motor sizes are large and the end-user can afford to devote some engineering and financial analysis time to motor characteristics. Although his prime concern is usually reliability, he is generally conversant with and able to evaluate motor characteristics other than just cost and reliability.

The distributor market channel generally treats electric motors as commodities. Customers typically order them without specifying anything other than size, voltage, RPM, and enclosure type. These orders are frequently for replacement. The customer is often employed in a maintenance and repair department rather than in an engineering or purchasing area. His concern is usually speed of delivery, so that he can get the equipment back in operation. Thus, this would be one of the most difficult market segments to influence with increased efficiency policies.

Table 19 is a simplified description of the major routes by which electric motors get distributed to end-users, although there can be a number of additional hands through which the products pass in getting to the end-user. For instance, an end-user in the printing trade may buy a piece of equipment from a local printing equipment distributor. The distributor, in turn, may have purchased the equipment from an OEM manufacturer. The OEM manufacturer may have purchased the vacuum pump and motor assembly from another OEM. That OEM may have purchased his motor from a distributor who, in turn, may have purchased it from the motor manufacturer. This example illustrates the increasing difficulty one has in influencing motor choice the farther he gets from the direct route of motor manufacturer to end-user.

B. MOTOR TYPES OF GREATEST CONSERVATION POTENTIAL

In our study, we considered the technical as well as the marketing/economic considerations which govern motor choice and motor use. The most important single technical consideration is the amount of efficiency improvement which can be reasonably expected, given the present state of the art. From Table 20, we see that the potential for improved efficiency varies considerably, depending on the size of the motor. We have also shown that the population of motors decreases very rapidly as one goes larger than the 125-HP category. The combination of these two factors – low population and a relatively small amount of potential efficiency improvement – leads to the conclusion that an FEA energy conservation program should concentrate on the under 125-HP category in the integral AC-polyphase market segment.

The other AC motors used in the industrial and commercial sector include fractionals, single-phase integrals, and synchronous motors. The fractional HP motors and the single-phase integrals tend to be the smaller sizes running on lighter duty cycles. The amount of electricity they consume is relatively insignificant in the industrial sector.

TABLE 20

CURRENT AND FUTURE MOTOR EFFICIENCIES IN INTEGRAL HP AC-POLYPHASE MOTORS

	Current			Future
	Worst	Best	Average	Improved Efficiency Models
1 HP	68	78	73	85.5
5 HP	78	81.5	80	89
10 HP	81	88	85	90
50 HP	88.5	92.0	90	92.5
100 HP	90.5	92.5	91.5	93
200 HP	94	95	94.5	95

The synchronous motors are very specialized. They tend to be extremely efficient, generally more expensive than induction motors, and are typically produced only in the larger sizes. Synchronous motors commonly have efficiencies of 96-98%. Consequently, there are few opportunities for efficiency improvements. This category, therefore, offers little potential for energy conservation.

DC motors are another special case. They are used primarily for drives where precise speed control is required. The most common application for such drives can be found in operations in which webs of material are being handled and processed. Paper mills, plastic-extruding plants, and steel-rolling mills are typical users of DC motors. The DC motors are more expensive than the common polyphase induction AC motors, and they tend to be custom-made, or designed for specific drive characteristics. They constitute a relatively small opportunity for energy conservation.

In the commercial sector, the major potential for energy conservation exists in two major product categories: (1) unit coolers and display cases, and (2) large central refrigeration systems. Together, these two account for about 85% of the refrigeration drive in that sector and refrigeration drive accounts for about 78% of the sector's total electric motor drive (other than air conditioning). Unit coolers and display cases are usually sold as complete units. Most commonly they are sold with hermetically sealed motors. The purchaser, therefore, has little choice or influence on the selection of the motor. In fact, he cannot even see it since it is hermetically sealed in the refrigerator compressor housing. Therefore, since it is all OEM-controlled, the potential for changing buying patterns is relatively low compared to the higher visibility motors in the industrial sector.

The remaining miscellaneous electric drives in the commercial sector are made up of such diverse and low-power consumption devices as to have little conservation potential. Therefore, we concluded that the greatest potential for energy conservation was in the industrial sector. Moreover, it was predominantly in four identified equipment categories:

1. Pumps,
2. Compressors,
3. Blowers and fans, and
4. Machine tools.

Electric motor drives for these applications are overwhelmingly of the AC-polyphase induction type. They are almost all integral HP motors, and a significant quantity of them are purchased directly by end-users. Hence they have a degree of visibility that is not achieved when an OEM selects and installs them (often out of sight). In typical industrial applications, these types of equipment tend to have a relatively short life compared to some other types of motor-driven equipment. Process industries are particularly high in motor population turnover because of the adverse environment and the frequency of process change and process obsolescence. For instance, a high-usage process pump or blower might have a life expectancy of three to five years, but a hermetically sealed refrigeration unit would be expected to last at least 15 years and possibly double that.

Finally, Table 21 summarizes the major positive reasons for selecting the 1-125-HP AC-polyphase induction motor and the four major equipment classifications as most appropriate fields for concentration.

TABLE 21

MAJOR REASONS FOR SELECTION OF AREAS WITH GREATEST CONSERVATION POTENTIAL – MOTORS AND EQUIPMENT TYPES

1. Integral HP AC-polyphase induction – Motors account for 80% of drive electricity consumption in the industrial sector.

2. Pumps, compressors, blowers and fans, and machine tools use 80% of the AC motors in the industrial sector.

3. There is a substantial opportunity for improving the efficiency of AC-polyphase induction motors in the 1- to 125-HP range (95% of potential for all sizes).

4. There is a substantial amount of direct to user distribution in this sector.

5. There is a relatively high population turnover for this sector in the major applications.

C. BASIS OF MOTOR CHOICE

Major electric motor manufacturers, OEM equipment suppliers, and equipment end-users told us that current motor purchasing practices are relatively straightforward. There is general agreement that the characteristics of the motor choice selection are as follows:

1) Reliability is perhaps the single, most important factor and is a critical characteristic for the types of continuous processes in which a large number

of these motors are used. Therefore, the motor buyer generally has a list of approved vendors who have proven over the years that they can supply reliable electric motors.

2) Given approximately equal reliability from several approved vendors, the next basis of selection is price and ability to deliver the motors. At this stage in the decision process, the decisions are being made by the purchasing agent and for the medium- and small-size motors there is no participation by technical people.

3) Other than reliability, price, and availability, there are not many other factors used in motor selection for the vast majority of medium- and small-size motors. Motor manufacturers and OEM equipment suppliers told us that they very infrequently get questions about the motors they sell on such factors as power factor, efficiency, and electrical and mechanical characteristics of the motors. End-users appeared to be slightly embarrassed in telling us that they had never really considered efficiency in motor selection.

4) There is a general belief that all motors – medium and small size – are alike. They are not alleged to be identical, but that they are quite similar and are treated as a commodity. One brand can be readily intermixed with any other brand without any noticeable difference in results.

5) There is some evidence that a slight interest in motor efficiency is beginning to emerge. Although it is not strong at the present time, those in the trade expect that it will become more important as the price of electricity continues to increase.

On a more general basis, there was a frequently recurring theme of general attitudes in industrial companies as they relate to capital equipment purchases. Both motor manufacturers and motor users recounted this theme. Most companies make it somewhat difficult to obtain capital funds, but relatively easy to get operating funds. Industrial organizations are usually set up so that approvals are required at various levels and for various amounts for capital spending. For these reasons, technical and economic justifications are typically required for capital requests. The usual practice is to buy the least expensive equipment which will do the job in a satisfactory manner.

Operating expenses, on the other hand, are relatively easy to obtain, since they are required for production. Naturally, if they get way out of line, they are scrutinized and questions are asked, but under normal circumstances no justification is needed. Moreover, operating costs are paid with pretax dollars.

The purpose of the manufacturers in recounting this theme, or model, to us was to explain why industrial customers are relatively indifferent to the suggestion that they buy more expensive electric motors which will, in turn, save them money. Also, they used it to explain why much of the electric motor-operated equipment is old and has not been replaced by newer, more efficient machinery. This general model provided part of the explanation for the indifference to more efficient motors. However, it is also true that until recently the motor manufacturers themselves have been very reluctant to introduce efficiency as another point of competition in an already very competitive market.

Table 22 represents our suggestion for an economic motor choice decision matrix for individual purchasers. In this table we are comparing four different 10-HP motors, with different first costs and different efficiencies: a standard motor and three high-efficiency motors with increased efficiencies of 4.5%, 6.7%, and 7.6% compared to the standard. The OEM price is increased respectively by 24.4%, 40%, and 55% over that of the standard motor. The table shows that, at the assumed conditions, all three high-efficiency motors are cost-effective. The added costs over the standard motor are paid back in 0.89, 1.0 and 1.2 years with the three different models.

TABLE 22

MOTOR CHOICE DECISION MATRIX WITH EXAMPLE OF A 10-HP AC-POLYPHASE INDUCTION MOTOR

	Standard Motor	High-Efficiency Motors		
		A	B	C
1. First Cost	180	224	252	279
2. ÷ Life = Annual Cost	22.50	28.00	31.50	34.88
3. Electricity Required (kW)	8.93	8.52	8.33	8.24
4. Hr Use/yr	4,000	4,000	4,000	4,000
5. Efficiency	81.8	85.2	86.8	87.4
6. kW-hr/yr	35,720	34,080	33,320	32,960
7. Cost/kW-hr (Energy + Demand)	$ .03	$ .03	$ .03	$ .03
8. Annual Electric Cost	$ 1,071.60	$ 1,022.40	$ 999.60	$ 988.80
9. Difference in Elec. Cost	-0-	$ 49.20	$ 72.00	$ 82.80
10. Total Annual Cost	$ 1,094.10	$ 1,050.40	$ 1,031.10	$ 1,023.68
11. Payback – Yrs	– –	.89	1.0	1.2

Table 23 shows a motor choice decision matrix by classes of industrial buyers. In addition to weight-factoring motor characteristics as evidenced by various industrial purchasers, it also gives the questions that should be answered in choosing a particular type motor.

D. SUGGESTED CONSERVATION STRATEGIES

During our interviews with motor manufacturers, OEM equipment producers, and end-users, we discussed possible ways of encouraging the use of more efficient electric motors. Most of the motor manufacturers had recently tested the market demand for high-efficiency motors with some of their customers. They reported that, for the most part, they did not get much enthusiasm from customers for higher cost motors with higher efficiencies. Most motor manufacturers, therefore, were taking the attitude of "wait-and-see." Since Gould had announced its intention of bringing out a line of high-efficiency motors, most of the others felt that they could observe the Gould experience with their new line and see whether the volume would justify the addition of another line of high-efficiency motors.

Before discussing some of the specific conservation strategies, it is necessary to cover the essential element of accuracy and reliability of published efficiency numbers. At the present time, each motor manufacturer issues its own information on efficiency and power factor. However, within the motor manufacturing industry, there is a widely held belief that not all of the numbers are accurate reflections of the motors which are actually being shipped out of the factory. Part of the reason for this may be inaccurate test results or procedures, manufacturing design changes which have altered some of the electrical and mechanical characteristics, or normal production tolerances which cause products to differ from that of the machine tested. Before any conservation strategy can have much chance of impact, the end-user must be able to obtain efficiency information which is accurate and reliable. Conversely, no conservation program has much chance of success if it is widely believed that the published information is not a reasonably accurate reflection of the motors which are being sold.

On the positive side of energy conservation, it appears that high-efficiency motors will, in many instances, provide an economic advantage to the end-user. Moreover, even with conservative purchasing policies, it appears that high-efficiency motors can be paid back in relatively short periods of time.

There are some negative attitudes which must be overcome if high-efficiency motors are to be adopted in any major way. At the motor manufacturer level, the most significant objections were in the following categories:

1) *Don't rock the boat* – This objection runs along the lines that the motor manufacturers already compete on many fronts and that getting involved in an efficiency battle would just provide their customers with one more means to play them off against each other.

TABLE 23

MOTOR CHOICE DECISION MATRIX BY CLASSES OF INDUSTRIAL BUYERS

	Characteristics					
	Basic Characteristics	Efficiency	Other Special Characteristics	Manufacturer	Availability	Price
	• Speed-Torque • Enclosure	• High Efficiency • Low P.F.	• Low Noise • Mill and Chemical	• Reliability • Warranty • Permanence of availability	• Local Distributor	
Purchaser						
O.E.M.'s						
• Pumps	2	0	2	2	3	3
• Blowers	1	0	1	1	3	3
• Compressors	3	0	0	1	2	2
• Special Industry Equip.	2	0	1	0	1	2
Process Industry User						
• Chemicals	2	0	2	2	3	1
• Petroleum and Coal	2	1	2	2	3	1
• Paper	2	2	1	2	2	2
Manufacturer	1	0	1	2	3	0

Weighting Factors:

3 Essential
2 Very important
1 Important
0 Not important or not considered

TABLE 23 (Continued)

QUESTIONS TO BE ANSWERED IN MOTOR CHOICE:

Basic Characteristics

1. Does it have the basic speed torque and enclosure characteristics to meet the application?

2. Does it have *special characteristics* that would enhance its economy?

   - High efficiency
   - Low P.F.
   - Low noise
   - Chemical duty

Manufacturer/Quality

3. Do I have confidence in the manufacturer? That is, does he produce a reliable unit? Are his services and warranty dependable? Will a replacement be available should I need it some years from now?

4. Is the unit readily *available*?

5. Is it competitively *priced*?

2) *Don't split the line* – The argument here is that, if all the motor manufacturers brought out high-efficiency motor lines, this would divide the production for any given size category into standard efficiency and high efficiency. This would mean lower unit volumes in each of the lines and contribute to lower efficiency and higher manufacturing costs.

3) *Look at the whole system* – In this case, it is alleged that it is not proper to just look at motor efficiency, but rather one must take into account the efficiency of the whole system – the motor and its driven equipment.

4) *Market demand* – There is no market demand for the high-efficiency motors.

5) *Mandatory policies* – Mandatory policies are not looked upon favorably.

At the end-user level, the predominant attitude is one of indifference. In some cases there is an attitude of mild curiosity. In general, however, we found the end-users to be about as the motor manufacturers had described them to us – uninterested.

In between the motor manufacturers and the end-users are the OEM equipment manufacturers. In general, their attitude is that they do not want to increase the cost of their equipment relative to that of their competitors. Therefore, although they would be willing to add a high-efficiency line if the market demanded it, they have no interest in pioneering it.

Given these attitudes and conditions, it appears that the most susceptible people in the universe are the end-users – particularly those who buy their motors direct. The reasons for this are easy to see. First, the end-user is the one who benefits economically from reduced power consumption costs from a high-efficiency motor. Secondly, the direct buying end-user is already engaged in specifying and purchasing electric motors and he only has to add another specification for efficiency and power factor to obtain the benefits of conservation. Finally, the process industry, with its large-scale, direct-buying end-user tends to have high turnover motor populations because of adverse operating conditions and process obsolescence.

The suggested strategy then is to concentrate the promotional, educational, and incentive effort on large process industry customers to convince them that they should use high-efficiency electric motors to conserve energy and provide themselves with an economic benefit. Within this market segment, it appears that the most susceptible may be those companies which are planning to build new plants where an entire plant could be outfitted with high-efficiency motors and thereby reduce direct energy costs as well as demand factor costs.

We believe that the manufacturers of motors will come out with high-efficiency lines if they see the market demand developing. In the meantime, it appears important that the industry report efficiency and power factor ratings on a comparable, reliable, and accurate basis.

E. ELECTRIC MOTOR DESIGN INFLUENCES

The market forces which are influencing the design of electric motors and associated process equipment in the United States come from several sources. Motor manufacturers sell to three different classes of customers:

1. direct end-users;
2. OEM manufacturers; and
3. distributors.

Influences from these classes are differentiable, since each has different requirements and the motor manufacturer tries to arrive at a compromise to satisfy all with a single line of equipment.

1. The Direct End-User

The end-user who purchases motors directly from the motor manufacturer usually has two significant characteristics:

1. He is a large customer, and

2. He has a relatively sophisticated engineering organization (either captive or under contract).

The typical direct purchaser is a process industry manufacturing organization. Large buys typically occur when a new plant is being constructed.

The single most important characteristic which process designers require in a motor is reliability, which can be defined as a combination of factors relating to the ability of the motor to continue operating and not suffer random or premature breakdowns. It was in response to this reliability requirement which led the motor manufacturers to devise a line of motors specifically designed for the process industries. They built increased corrosion resistance and a service factor into these motors which they then marketed at a premium price. This is perhaps one of the clearest examples of the end-user influencing the design of electric motors. It is also an example of a customer group seeking a higher priced motor in order to achieve a higher degree of reliability.

Other than special process industry motors, however, the trend has been toward customers seeking lower priced motors. This, in turn, has been made possible by improved insulating materials and advances in metallurgy which have allowed the use of lower cost steel for lamination stampings. The new synthetic insulations have made it possible to run motors at higher temperatures without significantly lowering their service lives. Higher temperature capability has, in turn, made it possible to build motors smaller and with less material than was required with the older varnish-type insulations. These smaller motors, which run hotter, tend to be lower priced than their larger, cooler predecessors.

If we refer back to the end-user, we can portray the purchasing process in a typical process manufacturing company. The most common procedure is for Engineering to establish a list of approved vendors for different sizes and types of motors. This list is then turned over to the Purchasing Department which is responsible for actually buying the motors. The details include negotiating price, establishing delivery dates, and taking care of all the paper work.

The motors produced by the vendors on the approved list will all be of approximately equal quality and reliability. Both the motor manufacturers and the end-users consider them to be commodity items with few differentiating features from one manufacturer to the other. Purchasing, therefore, sees its responsibility as getting the best price for an undifferentiated product. Price competition, therefore, exerts a strong influence in the design and manufacture of standard motors.

The net effect of these purchasing procedures by direct end-users has been a reduction in the size of the motors, which resulted from taking advantage of better synthetic insulating materials. Then too, metallurgical advances have allowed the use of cheaper plain steels instead of electrical steels for the laminations. These two changes have produced smaller electric motors at lower cost with approximately the same degree of reliability as the older, larger, cooler running models. However, this has been done at the cost of some loss in efficiency over the decades (see Figure ES-3).

These purchasing procedures could readily be adapted to take into account efficiency and power factor – either by adding these specifications as requirements to get motors on the approved vendor list, or through a more sophisticated rating system. It should be noted, however, that even though the system could be readily adaptable to including efficiency and power factor in the purchasing decision, it is not being done at the present time. Therefore, there is a need for an educational program to point out the benefits of energy conservation through more efficient motors.

2. The OEM Manufacturer

The OEM equipment manufacturers have somewhat different attitudes toward the purchase of motors. In some ways their attitudes are similar to the end-users', but in other ways their motivations are quite different. The similarities are that they too have relatively sophisticated engineering available. They use this engineering to select motors which will be reliable and economical for their application. The motors are qualified to an approved vendor list and these vendors are dealt with directly by Purchasing which negotiates price and delivery.

To the OEM, the motor has two significant factors associated with it:

1. It is a potential source of failure and warranty problems with his total machine; and

2. It is an element of cost which must be reflected in the price of his equipment.

As a result of these two factors, the OEM equipment producer wishes to obtain a motor which has high reliability and which will, hopefully, not fail during the life of the equipment. It is most important that the motor not fail during the warranty period. It is equally important that the OEM obtain his motors at a competitive price. If he can get his motors at a lower cost than his competitors, then he will have a price advantage. His competitors, of course, will all try to do the same thing. Usually, the net result is that they all get approximately the same motors at about the same price (except for quantity discounts).

The major difference between the OEM motor purchaser and the direct buyer is that the OEM is not going to operate the machinery. He will be held accountable for its failure during the warranty period, but in most instances the end-user will be indifferent to minor differences in efficiency and the OEM manufacturer will have little concern for this factor.

The net result of all of these factors is that the OEM equipment manufacturer shows his major influence in design through his concern for reliability and low cost. His reaction to competition tends to lead him to the lowest cost motor which will provide him with the reliability which he feels he needs to satisfy his customers and to get by the warranty period. Efficiency is generally not of great significance to him or to his customer. Overall efficiency is the combined efficiency of the electric motor and the driven device. The OEM equipment manufacturer does not appear to be much interested in higher efficiency electric motors.

3. The Distributor

The distributor is the final category of customer for the electric motor manufacturers. Distributors typically stock anywhere from one to five lines of motors, usually in the smaller (less than 50 HP) sizes. The distributor functions as a local stocking source for the manufacturers whom he represents.

A typical motor distributor may have thousands of items in his catalogue. Most of the orders are telephoned in. Customers are typically small OEM manufacturers, as well as end-users.

The distributor is probably the least likely to be influenced by efficiency education. His business is handling standard components. His customer must be sufficiently knowledgeable so as to be able to specify the equipment he wants and order it over the telephone. The distributor has little or no influence on motor design.

We have noted that the process industries are the most significant electricity consumers for electric motor drives. Table 24 shows the ratio of electricity consumption by electric motors to the total value of industry shipments of the 14 largest consumers of electric drive energy and for all manufacturing as a whole. It can be seen why the process industries are important both as large electricity consumers and as major direct motor customers for the motor manufacturers. It is also easy to understand why the process industries have had such a significant influence on the design of electric motors.

TABLE 24

RATIO OF ELECTRICITY CONSUMPTION BY ELECTRIC MOTORS TO VALUE OF SHIPMENTS 1972

SIC Code	Industry Group	Value of Industry Shipments Billions of $	Electric-Motor Consumption Billions of kWh	Ratio of kwh per $ of Shipment
28	Chemicals and Allied Products	51.9	80.9	1.56
33	Primary Metal Industries	53.1	76.1	1.43
26	Paper and Allied Products	25.5	59.1	2.32
20	Food and Kindred Products	103.6	34.9	.34
29	Petroleum and Coal Products	26.9	28.8	1.07
32	Stone, Clay and Glass Products	18.5	24.5	1.32
37	Transportation Equipment	86.9	24.2	.28
22	Textile Mill Products	24.0	23.7	.99
36	Electrical Equipment and Supplies	49.2	20.4	.42
35	Machinery, except Electrical	55.6	19.2	.35
34	Fabricated Metal Products	42.0	17.8	.42
30	Rubber and Plastics Products	17.0	16.0	.94
24	Lumber and Wood Products	14.9	9.3	.62
27	Printing and Publishing	26.9	7.5	.28
All Manufacturing (SIC Codes 19-39 inclusive)		671	458	.68

F. CONCLUSIONS

From our discussions with major motor manufacturers, OEM equipment producers, and end-users, we found that there is little interest in high-efficiency motors at the present time. The end-users are not aware of the potential availability of high-efficiency motors, nor do they customarily consider efficiency in purchasing motors. Because energy has been cheap, and because it is a relatively small part of their total cost, and for the rare cases where conservation of electric motor drive power has been considered, the end-user has been reluctant to increase his capital outlay in order to achieve an overall lower life-cycle cost.

The motor manufacturers, on the other hand, are reluctant to add another point of competition. Moreover, they contend that their customers have not shown any interest in high-efficiency motors, and they cannot justify the engineering and manufacturing expense until there is a substantial market demand for such motors.

The OEM equipment manufacturers are in the middle. They have little interest in more efficient motors, because they do not sense that this would provide a selling point with their customers. They also point out that since they sell their product at a price competitive with others, a more efficient motor would make their unit more expensive than that of the competition, if the competition elected to stay with the less efficient motors.

IV. TECHNICAL AND ECONOMIC EVALUATION

A. TECHNOLOGICAL CONSIDERATIONS

1. Factors Affecting Efficiency

Motor efficiency, simply stated, is the ratio of output power to input power:

$$\% \text{ Efficiency } \eta = \frac{\text{output power}}{\text{input power}} \times 100 \qquad (1)$$

Output power can be restated as input power minus motor losses. Therefore, the equation for efficiency becomes

$$\% \text{ Efficiency } \eta = \frac{\text{input power} - \text{losses}}{\text{input power}} \times 100$$

$$= \left(1 - \frac{\text{losses}}{\text{input power}}\right) \times 100 \qquad (2)$$

Figure 12 shows the range of efficiencies currently available in typical commercially produced motors, according to published data. Eq. (2) clearly establishes that the less efficient units can be improved by reducing motor losses, which can be segregated into three basic elements. The following paragraphs contain brief definitions of the various loss elements shown in Table 26.

a. I^2R Losses (typically 55% to 60% of total losses)

I^2R losses are heating losses resulting from current passing through the stator and rotor conductors. Since this loss varies according to the square of the current, it is small at no load but increases to major proportions at full load.

b. Core Losses (typically 20-25% of total losses)

Core losses are those found in the stator and rotor magnetic steel due to hysteresis effects and eddy currents. The core losses (called no-load losses) are caused by 60-Hz magnetization of the core material and are independent of load.

c. Stray Load Losses (typically 11% to 14% of total losses)

These losses vary according to the square of the load current and are caused by leakage flux induced by load currents.

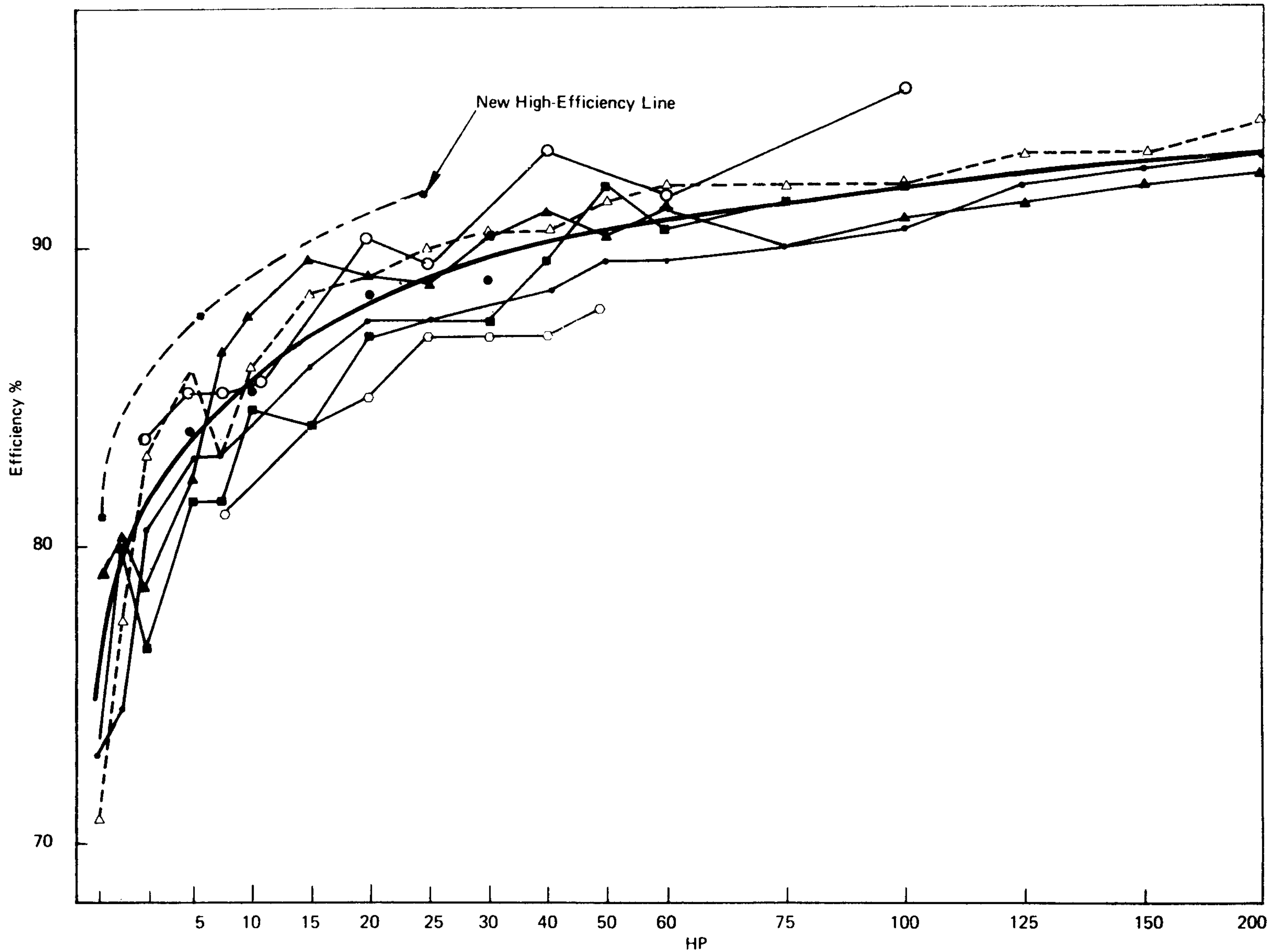


FIGURE 12 PUBLISHED MOTOR EFFICIENCIES OF PRINCIPAL MANUFACTURERS
(Open, Drip-Proof, 1800 RPM, NEMA Design B)

d. Friction and Windage Losses (typically 5% to 8% of total losses)

Friction and windage losses result from bearing friction, windage, and circulation of air through the motor, and they are essentially independent of motor load.

From the relationships we can draw the following conclusions with regard to magnetic circuits:

- A reduction in the length of an air gap in a magnetic circuit will reduce the mmf (F) required; therefore, the current I required will be reduced.
- For a constant value of flux ϕ, an increase in the cross-sectional area of the magnetic circuit will decrease the flux density B.
- A reduction in flux density B will reduce both eddy current and hysteresis losses in the magnetic core and the magnetizing portion of current.
- Eddy current losses P_e vary approximately as the square of the core lamination thickness τ. Therefore, reduction of lamination thickness can decrease eddy current losses.
- A reduction of the current I required will reduce I^2R losses in the motor windings.

Stator I^2R loss (also called copper loss) is due to line current in the stator winding conductors. This loss can be reduced by decreasing the winding resistance R, or the motor current. Conductor resistance varies inversely with cross-section and conductivity of the material. Therefore, by increasing conductor cross-section and/or utilizing high-conductivity material the winding resistance will be decreased. Reducing the motor current is most readily accomplished by decreasing the magnetizing component of current, which involves lowering the operating flux density and/or shortening the air gap.

Rotor I^2R losses are a function of the rotor conductors (usually aluminum) and the motor slip (synchronous speed minus operating speed). Utilizing copper conductors will reduce the winding resistance R. Motor operation closer to synchronous speed will also reduce rotor I^2R losses.

Eddy current losses caused by circulating currents within the core steel laminations can be reduced by using thinner gauge steel. This increases the effective resistance to circulating current, thereby reducing the magnetizing portion of motor current. Hysteresis losses, which are a function of flux density, can be reduced by utilizing steels with improved core loss characteristics, such as silicon steels. Reduction of these losses will decrease motor current and reduce I^2R losses.

From the preceding paragraphs, it is apparent that the changes required to improve motor efficiency can be categorized according to the following motor components:

- Core-related changes,
- Winding-related changes,
- Other changes, such as air gap and rotational.

Each of these is shown pictorially in Figure 13, and will be discussed in the following paragraphs.

2. Core-Related Changes

Modifying the core of a motor to reduce losses involves:

- increasing the cross-sectional area of the magnetic circuit to reduce operating flux density;

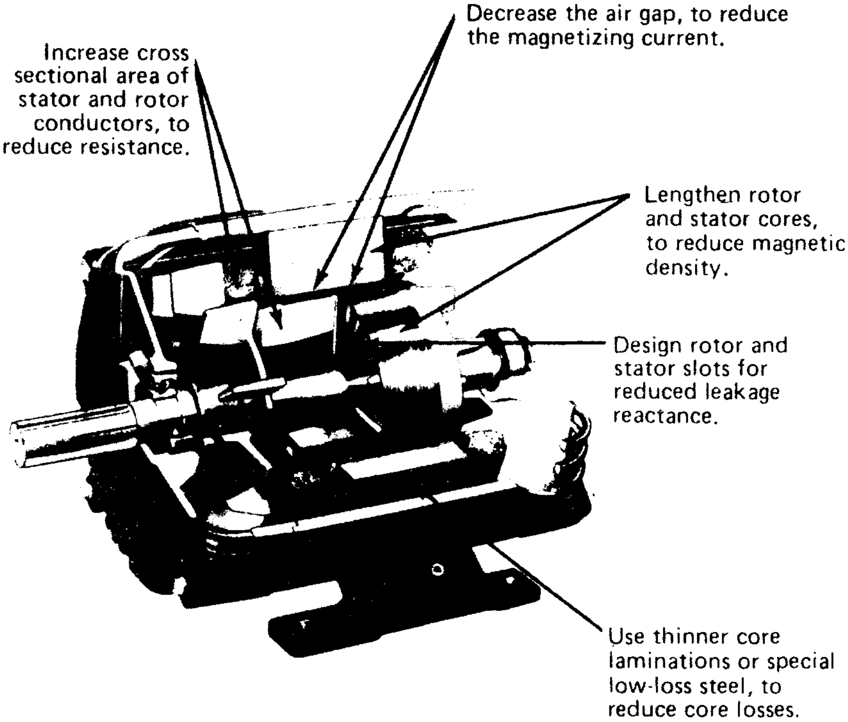
- utilization of thinner gauge core steel; or

- utilization of core steel with lower loss characteristics.

The magnetic circuit cross-sectional area can be increased by adding more core steel either radially or axially. Both of these alternatives require that dimensional changes to the motor be made. The National Electrical Manufacturers Association (NEMA) has established standardized motor frame sizes (and associated dimensional standards) for each motor size.* One of the dimensions established by these standards is the distance from the motor mounting surface to the center of the motor shaft – dimension D. An increase in the radial dimension of a motor requires that this dimension be increased. Such an increase may necessitate utilizing the next larger frame size to accommodate the larger core. There are no firmly established axial dimensions for the NEMA frame sizes. Therefore, increasing the axial length of the core can be accomplished without changing frame size, although there will be an increase in the overall length of the motor in most cases. Such an increase in the cross-sectional area of the magnetic circuit will result in an equivalent decrease in operating flux density.

Changes in core steel can also improve motor operating efficiency. By using thinner gauge steel (29 or 26 versus 24), losses due to eddy currents can be reduced. Eddy current losses – one component of core losses – vary directly with the square of both the lamination thickness and the flux density. Therefore, the effect of reductions in lamination thickness on eddy current losses is greater than the reduction itself.

*See Appendix A (Figures A-1, A-2, and Table A-3).



Source: Century Electric Div., Gould, Inc.

FIGURE 13 MODIFICATIONS TO IMPROVE EFFICIENCY AND POWER FACTOR OF ELECTRIC MOTORS

Hysteresis losses – a major component of core loss – can be reduced by utilizing silicon steels, which provide improved core loss characteristics when compared with carbon steels.

Carbon steels can be processed by the manufacturer to provide core loss characteristics of approximately 4.5 to 5.0 W/lb at 15 kilogausses (kG) for 24-gauge steel. By comparison, the lowest grade of silicon steel (M-45) has a core loss of 3.6 W/lb for 24-gauge at 15 kG. This represents a reduction of approximately 20 percent in core loss.

The potential impact of increasing core length can be illustrated by the following example. Assume a motor core constructed of 24-gauge carbon steel laminations with a core loss of 4.5 W/lb at 15 kG. Increasing the cross-sectional area of the core by 15% will reduce flux density to 12.75 kG, with a resulting decrease in core loss to approximately 3.1 W/lb, a reduction of approximately 31 percent. Giving effect to the increase in material weight, there is a potential reduction in core loss of approximately 21%. However, to maintain motor torque with the increased core length, the motor flux must be increased. This attenuates somewhat the reduction in core loss shown.

Table 25 illustrates the effect on core loss of various changes in type, grade, and amount of core steel. As the table shows, a significant reduction in core losses can be achieved through the use of silicon steels, thinner laminations, and more core material. Additionally, the increase in core length (cross-sectional area) results in a decrease in flux density of approximately equal proportions, which will reduce motor operating current and I^2R losses and improve the motor power factor.

TABLE 25

CORE LOSS LIMITS – NON-ORIENTED SILICON VERSUS CARBON STEEL (W/lb)

	24-Gauge		29-Gauge	
Type/Grade	Standard Core Length @ 10 kG	+15% Core Loss	Standard Core Length @ 10 kG	+15% Core Loss
Carbon C-1010*	1.65	1.27	1.15 (26)	0.84
Silicon M-43**	1.10	0.82	0.92	0.68
Silicon M-36**	1.00	0.77	0.74	0.58
Silicon M-22**	0.86	0.68	0.64	0.51

*Processed to provide core loss characteristics of approximately 4.5 W/lb at 15,000 kG.
**Cold reduced, fully processed, test procedure – as sheared ASTM A343.

The core loss limits in this and subsequent tables represent test values obtained from tests on small samples. Additional losses will occur in most equipment as a result of eddy currents in various parts of the magnetic path or in structural parts, stray flux in structural parts, or flux wave harmonics. Therefore, calculated efficiencies shown in the following sections are somewhat higher than would be found in actual experience.

3. Winding-Related Changes

Losses in the motor winding are a function of conductor resistance and motor current squared. Resistance is a function of conductor material, cross-section and length. Copper or aluminum are generally accepted winding materials, with copper exhibiting better conductivity for a given size conductor. Stator windings, where a major portion of the I^2R loss occurs, usually consist of copper, although some aluminum is now utilized. To reduce resistance (and I^2R losses), the cross-sectional area of the winding must be increased. This requires that a greater number of copper conductors (or larger conductors) be used in the winding. In turn, this involves increasing winding slot size and ultimately core size. For a given motor size (HP) and speed and a fixed lamination outside diameter, the relationships shown in Appendix D provide good average lamination designs for the stator and rotor. The equations indicate that changes in stator tooth width and/or slot depth to accommodate more winding copper will affect the stator inside diameter D. As the amount of copper increases, so too will slot dimensions and core diameter. The result may be an increase in the motor frame size to accommodate the additional copper and core steel. Increasing motor frame size would require more material to manufacture a given size motor in addition to the increased copper in the winding.

Increasing core steel to facilitate installation of the additional winding copper also has the effect of increasing the cross-sectional area of the magnetic path. As discussed in Section A-2, increasing the area will reduce flux density and the magnetizing component of current. As a result, stator I^2R losses will also be reduced.

The magnitude of loss reduction can be calculated as follows:

$$\begin{aligned} \%\Delta\ell &= 2n - .01(n)^2 \\ &= n\,(2 - .01n) \end{aligned} \tag{3}$$

where n equals the reduction in current in percent. For example, if current is reduced 10 percent the I^2R losses are reduced:

$$10\,[2 - .01\,(10)] = 10\,[1.9] = 19\% \tag{4}$$

Rotor winding losses are influenced by the material used for rotor conductors (aluminum is commonly used in induction machines), the conductor area, and the motor operating slip.* By changing from aluminum to copper, the resistance of the rotor conductors can be reduced by approximately 60 percent for equal cross-section. A further reduction is possible by increasing the amount of the conductor material used in the rotor. However, as with the stator, increasing winding conductor material will require a larger core and, therefore, a larger frame size for the motor. Perhaps the greatest effect on rotor I^2R losses can be obtained by changing motor slip. In squirrel-cage rotors, the rotor copper loss bears the

---

*(synchronous speed — operating speed)/(synchronous speed)

same relationship to total power transferred across the air gap as slip bears to synchronous speed. Therefore,

Rotor $I^2 R$ loss = Sx (power across air gap) where S = slip.

As can be seen from this relationship, rotor $I^2 R$ loss depends on the motor operating slip, increasing as slip increases.

4. Other Changes

Other modifications which can result in reducing motor losses are a reduction in motor gap length and a reduction in motor rotational losses (friction and windage).

a. Gap Length

In magnetic circuits containing an air gap, the required magnetomotive force is determined primarily by the gap length due to the relative permeability of air versus magnetic steels. The relation can be expressed as follows:

$$B = \mu_o \frac{NI}{g} \tag{5}$$

and

$$B \cdot g = \mu_o N \cdot I \tag{6}$$

where
g = gap length
N = number of coil turns
I = current
μ_o = permeability of free air.

As this equation suggests, a reduction in the air gap length will reduce current and therefore $I^2 R$ losses. However, the selection of air gap length for a given motor size is based on several factors, including motor noise levels, manufacturing tolerances, losses, and mechanical/thermal stresses as well as air gap flux density. Changes in power factor and the air gap may adversely affect any of these factors as well as motor reliability, which is an important consideration in the purchase decision of the end-user. For these reasons, this alternative was not considered as a possible means of reducing motor losses.

b. Rotational Losses

Friction and windage losses, which constitute a relatively fixed component of total motor losses, represent the energy required to overcome the inherent motor friction and wind resistance. Additionally, the resistance of internal cooling fans is included as a portion of these losses. At full load, friction/windage loss represents a small portion of total loss for large motors and increases to a larger portion for small motors. These losses can be minimized through proper maintenance of bearings, but otherwise there is relatively little that can be done to further reduce the friction/windage loss componen'.

Based on the foregoing discussions, and recognizing that there is a complex set of interrelated design parameters that must be considered in the modification of motors to achieve improved efficiency, we have evaluated the following areas of improvements in motor efficiency versus costs (see Figure 13):

a. Increased core length (steel),
b. Improved core steel (silicon),
c. Thinner laminations, and

We analyzed each individually in terms of impact on efficiency and cost. In addition, we analyzed the combined impact of two or three of them to determine total potential efficiency gain where possible.

B. EFFICIENCY IMPROVEMENTS

To assess the potential improvement in motor efficiency resulting from various modifications to the motor, we established three categories of analysis, as follows:

1. Increase core length by 15% and 30%;
2 Change core steel from carbon to silicon; and
3. Change in core steel thickness.

We made our final analysis, assuming a change in core steel type and thickness and an increase in core length. The results of these analyses are presented in the following paragraphs.

1. Base Data

We carried out our calculations for all motors of interest, including those for a 5-HP and a 50-HP motor presented here. Typical data relative to these motors are shown in Table 26.

2. Change in Motor Core Length

The effect on motor efficiency of changing core length is shown in Table 27. For these calculations, we assumed increases of 15 and 30 percent in original core length.

TABLE 26

TYPICAL MOTOR DATA FOR 5-HP and 50-HP, 1800-RPM, OPEN DRIP-PROOF INDUCTION MOTORS

	5-HP	% of Total Loss	50-HP	% of Total Loss
I^2R Loss (watts)	420	55.3	2567	58.6
Load Loss (watts)	180	23.7	895	20.4
Core Loss (watts)	100	13.2	592	13.5
Friction/Windage Loss	60	7.8	330	7.5
Total Losses	760	100%	4384	100%
Power Input (watts)	4490		41684	
Efficiency	.831		.895	
Power Factor, p.f	.815		.87	

TABLE 27

EFFECT ON EFFICIENCY BY CHANGING CORE LENGTHS

	5-HP			50-HP		
	Base	+15%	+30%	Base	+15%	+30%
Losses (watts)						
I^2R*	420	420	420	2567	2567	2567
Stray Load	180	180	180	895	895	895
Core	100	79	59	592	469	346
Friction/Wind	60	60	60	330	330	330
Total	760	739	719	4384	4261	4138
Power (watts)	4490	4469	4449	41684	41561	41438
Efficiency	.8307	.8346	.8384	.8950	.8975	.9000
Power Factor	.815			.87		

*Effects of reduced core losses on current ignored in these calculations.

3. Change in Motor Core Steel

In our second analysis we considered the effect of using core steel with improved core loss characteristics, such as silicon steels. As was suggested earlier, core losses can be reduced by utilizing such steels. Table 28 illustrates the potential core loss reduction possible by changing core steel.

TABLE 28

CORE STEEL – MAXIMUM CORE LOSS
(W/lb)

24-Gauge

	10 kG		15 kG	
	(W/lb)	% of Carbon Loss	(W/lb)	% of Carbon Loss
Carbon C-1010	1.65	––	3.50	––
Silicon M-43	1.25	.7576	2.36	.6750
Silicon M-36	1.10	.6667	2.10	.6000
Silicon M-22	0.95	.5758	1.90	.5450

The effect on efficiency of using 24-gauge M-36 silicon steel for the 5-HP and 50-HP motors is shown in Table 29.

TABLE 29

MOTOR EFFICIENCY IMPROVEMENTS BY CHANGING CORE STEEL
(Based on 24-Gauge M-36 Silicon Steel)

	5-HP		50-HP	
Loss (watts)	Base	Si Steel	Base	Si Steel
I^2R*	420	420	2567	2567
Stray Load	180	108	895	537
Core	100	60	592	355
Friction/Wind	60	60	330	330
Total	760	648	4384	3789
Power (watts)	4490	4378	41684	41089
Efficiency	.8307	.8520	.8950	.9078
Power Factor	.815		.870	
Efficiency Gain		.0213		.0128

*Effects of reduced core losses on current ignored in these calculations.

4. Change in Lamination Thickness

We based our third analysis on the use of thinner gauge electrical steels to further decrease core loss by reducing eddy current losses. The effect of reducing lamination thickness on core loss characteristics is shown in Table 30.

TABLE 30

CORE STEEL – MAX CORE LOSS
(W/lb – 15 kG)

	24-Gauge		26-Gauge		29-Gauge	
	(W/lb)	(% of 1010)	(W/lb)	(% of 1010)	(W/lb)	(% of 1010)
Carbon C-1010	3.50	–	–	–	–	–
Silicon M-43	2.36	.6750	2.01	.5750	–	–
M-36	2.10	.6000	1.80	.5125	1.66	.4750
M-22	1.90	.5450	1.62	.4625	1.47	.4200

The results of recalculating efficiency for the 5- and 50-HP motors for each type and gauge of steel are presented in Table 31.

TABLE 31

EFFICIENCY* OF 5- AND 50-HP MOTORS
Silicon Steel versus Carbon Steel

	24-Gauge		26-Gauge		29-Gauge	
	5	50	5	50	5	50
Carbon C-1010	.8307	.8950	–	–	–	–
Silicon M-43	.8477	.9053	.8532	.9086	NA	NA
Silicon M-36	.8520	.9078	.8569	.9107	.8587	.9119
Silicon M-22	.8549	.9096	.8596	.9123	.8618	.9137

*Effects of reduced core losses on current ignored in these calculations.

As this tabulation illustrates, significant improvements can be achieved by changing both the type and gauge of core steel. For the 5-HP motor, the efficiency can be improved by as much as 3.1 percentage points or 3.7 percent. Similarly for the 50-HP motor, efficiency is improved by 1.9 percentage points or 2.1 percent.

Table 31 also clearly shows that the incremental gains in efficiency achieved by using type M-22 silicon steel rather than type M-36 are relatively small. Similarly, there is no significant additional gain in efficiency by using 29-gauge steel over the 26-gauge steel. The major benefit is found in changing to the M-36 grade, 26-gauge silicon steel.

5. Change in Core Steel and Length

By combining a change of core steel with an increase in axial core length, greater improvement in motor efficiency can be achieved. To evaluate the potential improvement, we made the following assumptions:

- Core steel: silicon, M-36 grade, 26-gauge

- Core length increase: 15% and 30%

- Motor data – 5-HP: efficiency = .83, p.f. = .815
  Motor data – 50-HP: efficiency = .895, p.f. = .87

Under the assumed conditions, the efficiency and power factor of the 5-HP and 50-HP motors will be as shown in Table 32.

TABLE 32

EFFICIENCY AND POWER FACTOR OF 5- AND 50-HP MOTORS
UNDER ASSUMED CONDITIONS

	5-HP			50-HP		
Loss (watts)/core length increase	0	+15	+30	0	+15	+30
I^2R	378	385	398	2397	2489	2601
Stray Load	92	78	70	459	390	349
Core	51	44	39	303	258	231
Friction/Wind	60	60	60	330	330	330
Total	581	567	567	3489	3467	3511
Power (watts)	4311	4297	4297	40789	40767	40811
Efficiency	.8652	.8680	.8680	.9145	.9150	.9140
Power Factor	.8592	.8821	.8973	.9002	.9161	.9268

The results of similar calculations for the range of motors of concern are shown in Figures 14 and 15, and illustrate the range of potential improvements for the assumed core modifications. Figure 16* shows the incremental improvement in efficiency as a result of increasing core length.

The net effect on motor efficiency of utilizing type M-36, 26 gauge silicon steel and varying core length is illustrated in Table 32. Efficiency levels at 15% core increase suggest that additicnal core length is unwarranted. The most significant gain in efficiency results from the use of silicon steel.

C. COSTS

As with our efficiency analysis, we developed cost impacts according to the three categories described in Section B. Our final cost impact analysis was based on changing core steel type and thickness and increasing core length.

1. Base Data

Data from manufacturers relative to material breakdown suggest that the distribution of materials and costs is reasonably constant over the range of motors being considered; viz.,

*Figure 16 appears in Section C ahead.

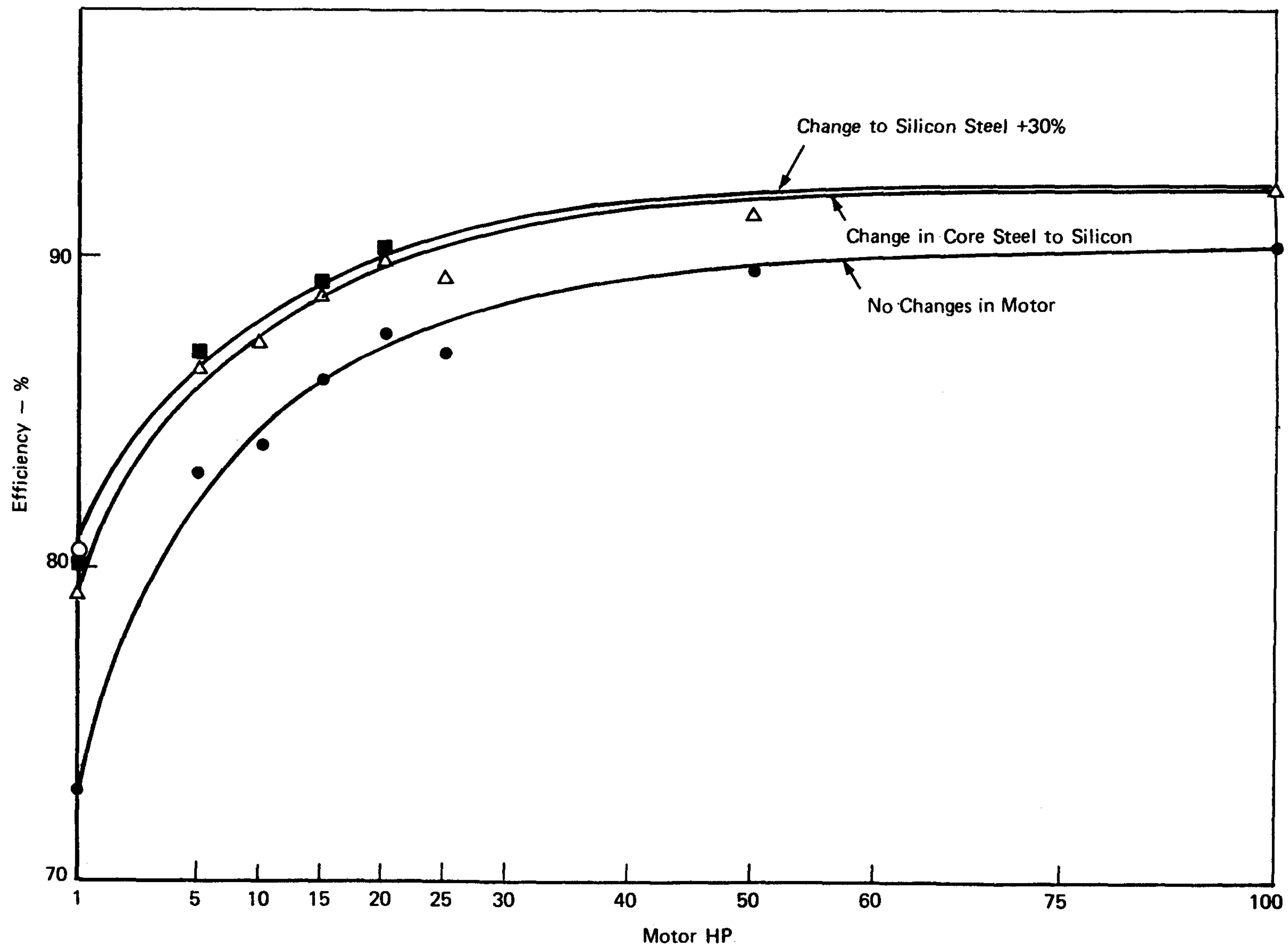


FIGURE 14 EFFECT OF ASSUMED MOTOR CHANGES ON EFFICIENCY

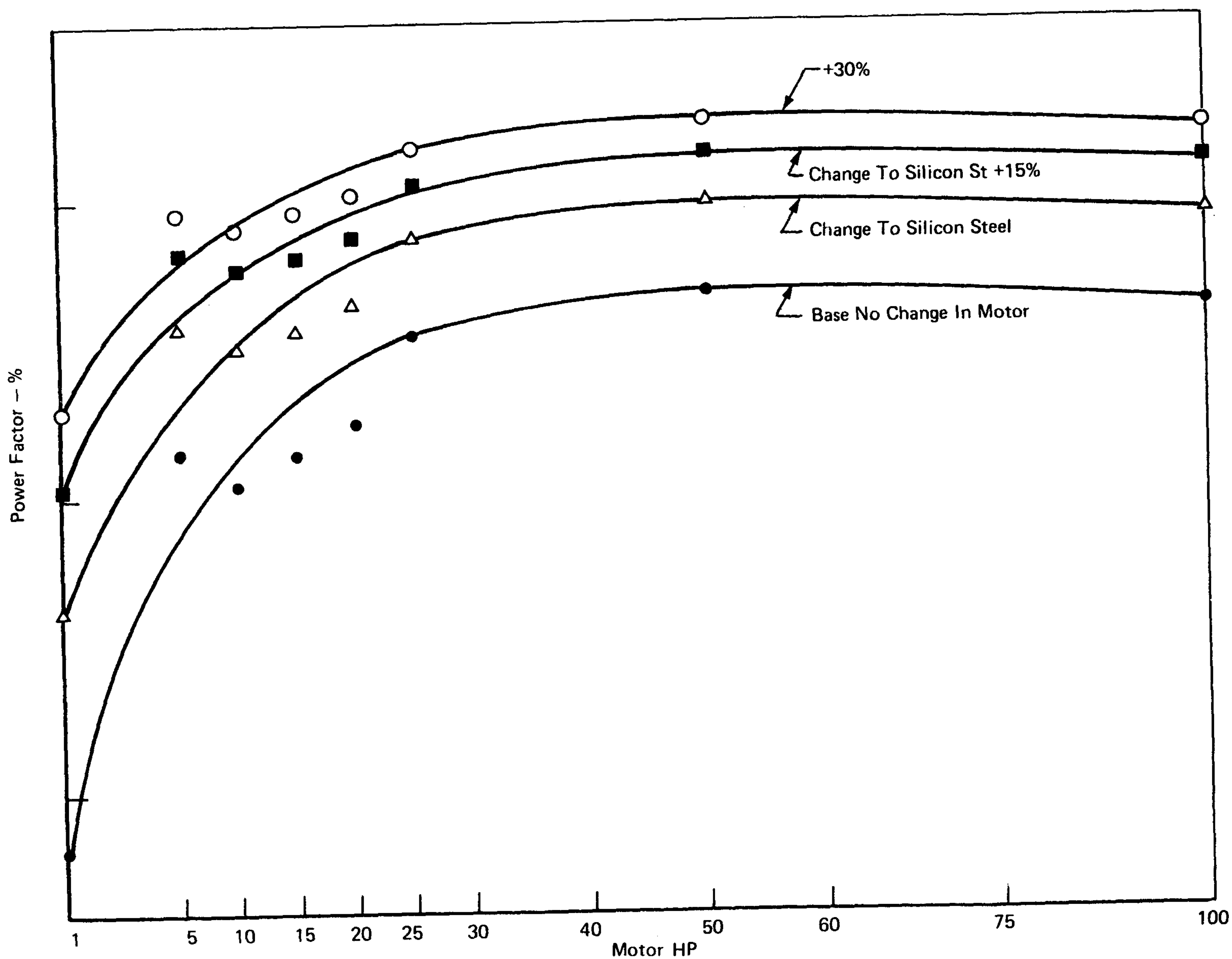


FIGURE 15 EFFECTS OF ASSUMED MOTOR CHANGES ON POWER FACTOR

1 to 125 HP. Additionally, we found the list to net price multipliers (shown in Table 33) exist for OEM sales by three large manufacturers and assumed they were constant across the motor industry.

TABLE 33

TYPICAL RANGE OF OEM MULTIPLIERS BY FRAME SIZE
(1 – 125 HP)

Frame	HP	Multiplier
143 to 184T	1 – 5	0.50
213 to 215T	5 – 10	0.53
215 to 405T	10 – 125	0.58

Utilizing the material cost/weight breakdown, the OEM multiplier information, and manufacturers' list prices for the motors concerned, we developed the distribution of costs as a percentage of OEM selling price shown in Table 34.

TABLE 34

COST BREAKDOWNS FOR POLYPHASE MOTORS
(1- to 125-HP Open Frame)

	Costs (% of total selling price)		
Component	Material	Labor*	Total
Front-End Plate Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.7	0.2	0.9
Laminations	7.8	6.4	14.2
Shaft	1.6	0.3	1.9
Bearings & Hardware	3.7	0.7	4.4
	13.8	7.6	21.4
Frame Assembly			
Frame Castings	8.8	0.6	9.4
Laminations	7.9	6.5	14.4
Windings	7.2	3.0	10.2
Insulation & Misc.	1.9	1.0	2.9
	25.8	11.1	36.9
Assembly	0.9	0.5	1.4
Packing	1.0	0.5	1.5
Overhead and Profit			30.0
Total Selling Price (based on list price times OEM multipliers)			100.0

* Based on labor costs of $12,000 per 1680-hour work-year.

2. Change in Motor Core Length

The data presented in Table 34 became the baseline for our analysis of costs. We measured the changes in the amount and type of materials used against this base cost to evaluate the impact on cost. Table 35 contains an analysis of costs assuming an increase in the core length of 15 percent, but without changing type of core steel employed. As can be seen, a 15 percent increase in core length will increase selling price (OEM) by approximately 11 percent. Similarly, a 30 percent increase in core length would raise the selling price by nearly 22 percent.

TABLE 35

COST BREAKDOWNS FOR POLYPHASE MOTORS – EFFECT OF 15% INCREASE IN CORE MATERIAL
(1- to 125-HP Open Frame)

Component	Costs (% of total selling price)		
	Material	Labor*	Total
Front-End Plate Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.8	0.2	1.0
Laminations	9.0	7.4	16.4
Shaft	1.8	0.3	2.1
Bearings & Hardware	3.7	0.7	4.4
	15.3	8.6	23.9
Frame Assembly			
Frame Castings	10.1	0.7	10.8
Laminations	9.0	7.4	16.4
Windings	8.3	3.2	11.5
Insulation & Misc.	2.2	1.0	3.2
	29.6	12.3	41.9
Assembly	0.9	0.5	1.4
Packing	1.2	0.5	1.7
Subtotal – Material and Labor			77.7
Overhead and Profit			33.3
Total Selling Price (based on list price times OEM multipliers)			111.0

*Labor increase approximately 6%.

3. Change in Motor Core Steel

Changing the motor core steel from carbon to silicon (non-oriented) results in a significant increase in the base cost of the material per pound. The relative cost of several types of silicon steel versus carbon steel is shown in Table 36.

TABLE 36

RELATIVE COST OF CORE STEEL (%)

24-Gauge

Carbon	C-1010	100.00
Silicon	M-43	201.09
	M-36	209.45
	M-22	225.86

Comparison of the information Table 36 with that in Table 28 indicates that using silicon steels will result in substantial core loss reductions at somewhat less substantial increases in cost depending upon the type of silicon steel used.

Table 37 shows the effect on motor selling price of using M-36 silicon steel for the motor core material. As illustrated, the OEM selling price would be increased by approximately 24.4 percent. In a similar manner, the OEM selling price using other grades of silicon steel would increase as follows:

M-43	22.7%
M-22	28.2%

4. Change in Lamination Thickness

We next evaluated the effect on motor cost of using a thinner gauge steel in the core to reduce eddy current loss. The effect on cost per pound versus carbon steel is shown in Table 38.

The effect on motor selling price of using thinner laminations is shown in Table 39, using the percentage distribution of costs found in Table 34 as baseline. As can be seen, using 26-gauge M-36 silicon steel will result in a 25.4 percent increase in OEM selling price. In similar fashion, the OEM selling price using other gauge steels would increase as shown in Table 40.

5. Change in Core Steel and Length

Based on the assumptions listed in Chapter V, Section B, the effect on motor OEM price can be determined. The results are shown in Tables 41 and 42.

Figure 16 is a plot of motor efficiency increase versus motor OEM selling price increase for the 5- and 50-HP motors. As can be seen from this figure, maximum benefits (maximum slope) occur at approximately 25% price increase, which represents a change in core steel to M-36 grade, 26-gauge silicon steel.

TABLE 37

COST BREAKDOWNS FOR POLYPHASE MOTORS SHOWING EFFECT OF UTILIZING M-36 GRADE SILICON STEEL (1- to 125-HP Open Frame)

Component	Costs (% of total selling price)		
	Material	Labor	Total
Front-End Plate Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.7	0.2	0.9
Laminations	16.3	6.4	22.7
Shaft	1.6	0.3	1.9
Bearings & Hardware	3.7	0.7	4.4
	22.3	7.6	29.9
Frame Assembly			
Frame Castings	8.8	0.6	9.4
Laminations	16.5	6.5	23.0
Windings	7.2	3.0	10.2
Insulation & Misc.	1.9	1.0	2.9
	34.4	11.1	45.5
Assembly	0.9	0.5	1.4
Packing	1.0	0.5	1.5
Total Material and Labor			87.1
Overhead and Profit			37.3
Total Selling Price (based on list price times OEM multipliers)			124.4

TABLE 38

RELATIVE COSTS OF CORE STEEL (%)

	Gauge		
	24	26	29
Carbon C-1010	100.00		
Silicon M-43	201.09	205.09	
M-36	209.45	213.45	218.91
M-22	225.86	229.82	235.27

TABLE 39

EFFECT ON MOTOR SELLING PRICE OF USING THINNER GAUGE SILICON STEEL
Example: M-36, 26-Gauge
(% of OEM Selling Price)

	Material	Labor	Total
Front-End Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.7	0.2	0.9
Laminations	16.6	6.4	23.0
Shaft	1.6	0.3	1.9
Bearings & Hardware	3.7	0.7	4.4
			30.2
Frame Assembly			
Frame Casting	8.8	0.6	9.4
Laminations	16.9	6.5	23.4
Windings	7.2	3.0	10.2
Insulation & Misc.	1.9	1.0	2.9
			45.9
Assembly	0.9	0.5	1.4
Packing	1.0	0.5	1.5
			87.8
Overhead and Profit			37.6
Total Selling Price (based on list price times OEM multipliers)			125.4

TABLE 40

INCREASE IN OEM SELLING PRICE DUE TO CHANGE IN MOTOR CORE STEEL

	Increase in Selling Price (%)		
	24-Gauge	26-Gauge	29-Gauge
Carbon C-1010	base	–	–
Silicon M-43	22.7	23.6	–
M-36	24.6	25.4	26.7
M-22	28.2	29.1	30.3

TABLE 41

COST BREAKDOWNS FOR POLYPHASE MOTORS – EFFECT OF ASSUMED CORE CHANGES ON SELLING PRICE
(1- to 125-HP Open Frame)
(+15% increase in core length and change to M-36, 26-gauge steel)

Component	Costs (% of total selling price)		
	Material*	Labor**	Total
Front-End Plate Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.8	0.2	1.0
Laminations	19.2	7.4	26.6
Shaft	1.8	0.3	2.1
Bearings & Hardware	3.7	0.7	4.4
	25.5	8.6	34.1
Frame Assembly			
Frame Castings	10.1	0.7	10.8
Laminations	19.2	7.4	26.6
Windings	8.3	3.2	11.5
Insulation & Misc	2.2	1.0	3.2
	39.8	12.3	52.1
Assembly	0.9	0.5	1.4
Packing	1.2	0.5	1.7
Subtotal Material & Labor			98.1
Overhead and Profit			42.0
Total Selling Price (based on list price times OEM multipliers)			140.1

* 15% increase in core material, change to M-36 Si steel.
** Labor increase approximately 6%.

TABLE 42

COST BREAKDOWNS FOR POLYPHASE MOTORS – EFFECT OF ASSUMED CORE CHANGES ON SELLING PRICE
(1- to 125-HP Open Frame)
(+30% increase in core length and change to M-36, 26-gauge steel)

Component	Costs (% of total selling price) Material*	Labor**	Total
Front-End Plate Assy	4.1	0.3	4.4
Pulley-End Plate Assy	4.1	0.3	4.4
Rotor Assembly			
Aluminum Casting	0.9	0.2	1.1
Laminations	21.6	8.3	29.9
Shaft	2.0	0.4	2.4
Bearings & Hardware	3.7	0.7	4.4
	28.2	9.6	37.8
Frame Assembly			
Frame Castings	11.4	0.7	12.1
Laminations	21.9	8.3	30.2
Windings	9.4	3.2	12.6
Insulation & Misc	2.5	1.1	3.6
	45.2	13.3	58.5
Assembly	0.9	0.5	1.4
Packing	1.3	0.5	1.8
Subtotal Material & Labor			108.3
Overhead and Profit			46.4
Total Selling Price (based on list price times OEM multipliers)			154.7

*30% increase in core material, change to M-36 Si Steel.
**Labor increase approximately 9%.

D. NET ENERGY ANALYSIS AND ECONOMIC PAYBACK

Based on the preceding calculations of efficiency improvement and corresponding cost increases, the economic payback and net energy impact for each motor size can be determined. For our analyses, we have used the measures described below.

1. *Economic Payback Period* – The length of time required to recover the incremental cost of higher efficiency motors through energy cost savings can be calculated as follows:

$$\text{EP (years)} = \frac{\text{Incremental Motor Cost (\$)}}{\text{Reduced Losses (kW) x operating hours/year x electricity cost (\$/kW-hr)}}$$

2. *Energy Recovery Period* – The motor running time required to recover the additional energy required to produce the higher efficiency motor:

$$\text{ER (hours)} = \frac{\text{Incremental Energy to Produce High-Efficiency Motor (kW-hr)}}{\text{Reduced Losses (kW)}}$$

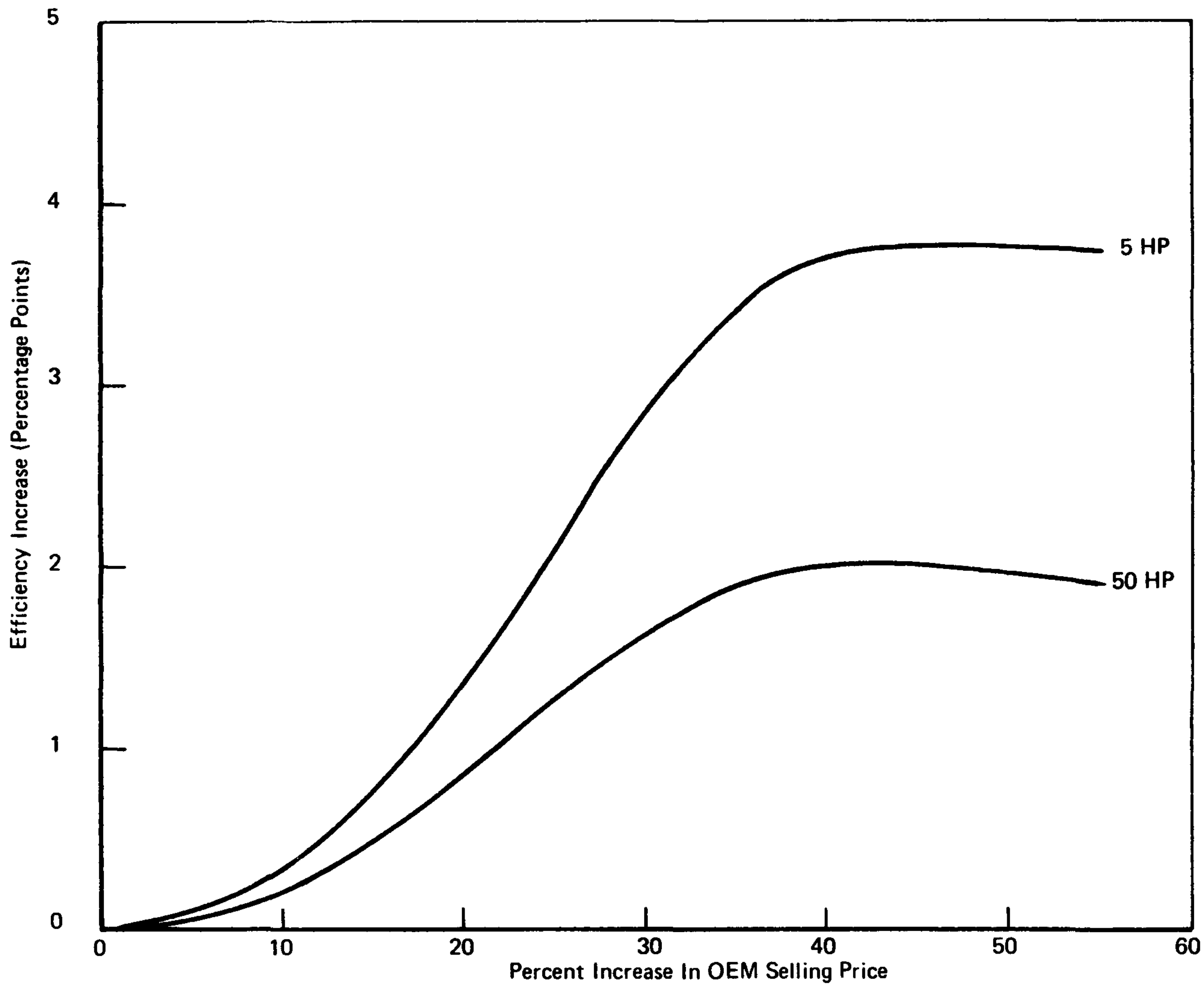


FIGURE 16 EFFICIENCY INCREASE VS. % INCREASE IN OEM SELLING PRICE FOR 5-HP AND 50-HP MOTORS

For the 5-HP and 50-HP motors, the EP and ER are computed as shown in the following example for a 15% increase in core length:

1. Economic Payback	5-HP	50-HP
OEM motor price (base)	$ 88	$ 636
High-efficiency price adder	$ 35.29	$ 255
Reduction in losses (watts)	193	918
Operating hours/year	4000	4000
Electricity cost (avg)/kW-hr	$ 0.03	$ 0.03

$$5\text{ HP: } EP = \frac{\$35.29}{.193 \times 4000 \times .03} = \frac{\$35.29}{\$23.16/\text{year}} = 1.5237 \text{ years}$$

$$50\text{ HP: } EP = \frac{\$255}{.918 \times 4000 \times .03} = \frac{\$255.04}{\$110.16/\text{year}} = 2.3152 \text{ years}$$

2. Energy Recovery	5-HP	50-HP
Incremental energy required (kW-hr)*	55.97	452.66
Reduction in losses (watts)	179	918

$$5\text{ HP: } ER = \frac{55.97}{.179} = 312.68 \text{ hours}$$

$$50\text{ HP: } ER = \frac{452.66}{.918} = 493.09 \text{ hours}$$

The results of these calculations for the 5-HP and 50-HP motors and all the assumed motor core modifications are shown graphically in Figure 17. Inspection of the figures reveals that the economic payback curve levels at approximately a 30 percent core length increase, then increases rapidly as core length is increased beyond 30 percent. The energy recovery curve shows the same reversal between 40 and 50 percent additional core length. Table 43 contains a summary of the EP and ER calculations for all motors concerned in our analysis. The calculations indicate an economic payback period of between 1.5 and 3.6 years at $0.03/kW-hr electricity costs.

The effects of various electricity costs on economic payback based on current OEM prices are shown in Figure 18 for a 15 percent increase in core length. As the figure illustrates, the economic payback for a 1-HP motor is greater than for a 5-HP or a 20-HP motor. Reference to Table 43 reveals that this is generally true when compared with all but

*Based on 5.5 kW-hr/lb for steel; 15.2 kW-hr/lb for copper; and 36.6 kW-hr/lb for aluminum.

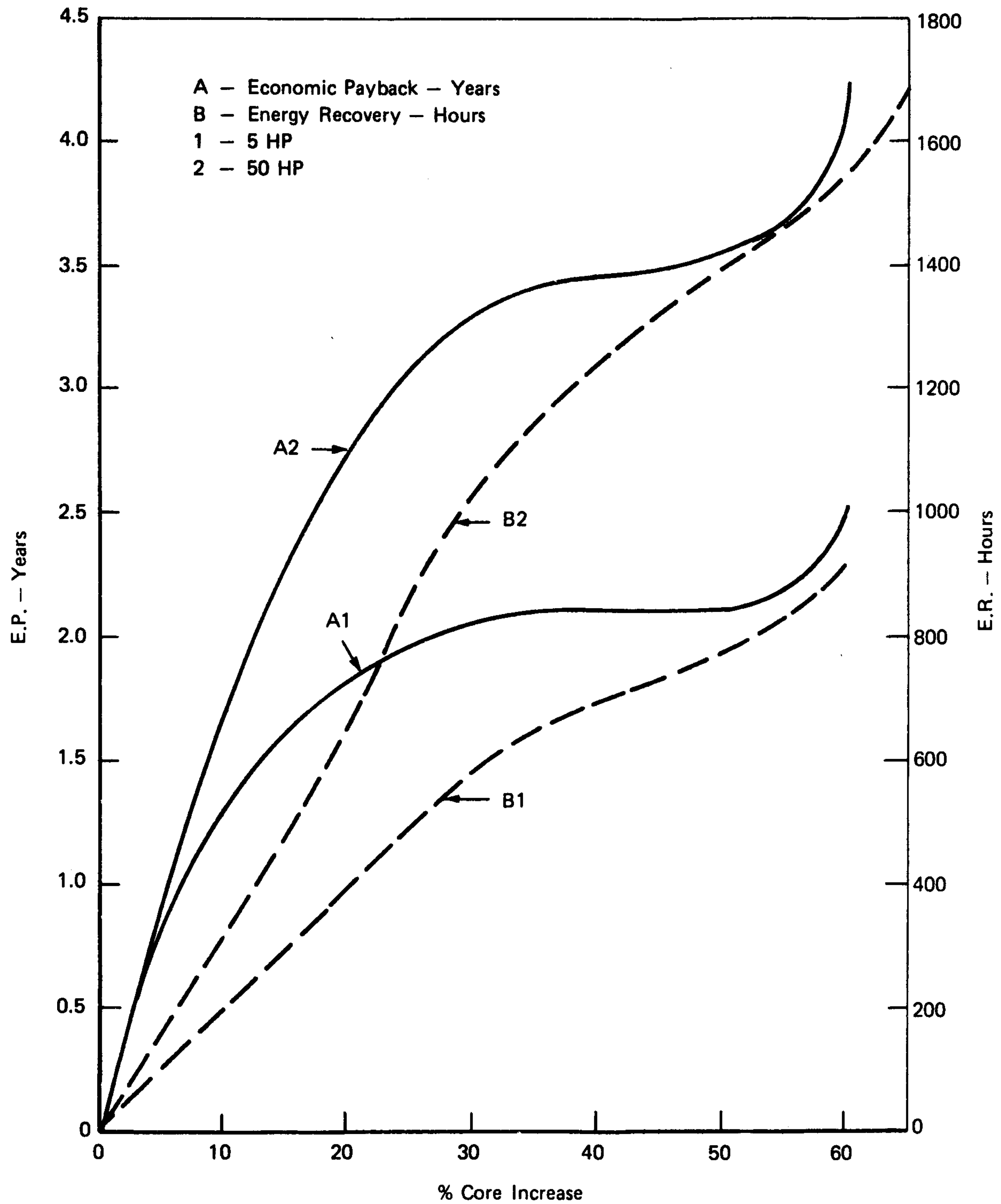


FIGURE 17 ECONOMIC PAYBACK AND ENERGY RECOVERY VS. % CORE LENGTH INCREASE — 5-HP AND 50-HP MOTOR

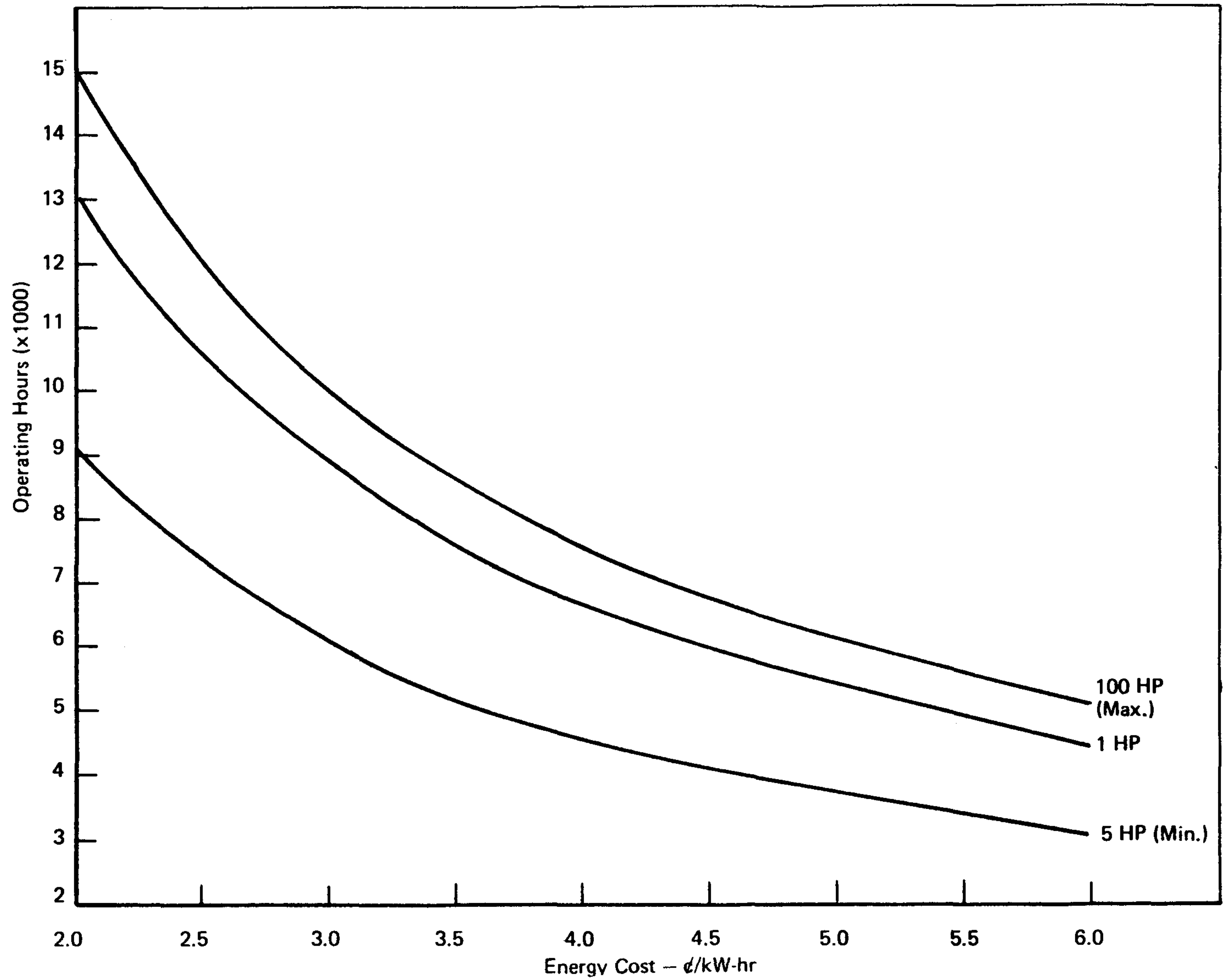


FIGURE 18 ECONOMIC PAYBACK VS. ENERGY COST FOR A 15% INCREASE IN CORE LENGTH

the larger motor sizes. The reasons for this relate to the fact that the value of energy saved does not offset the increased costs necessary to improve motor efficiency. However, at the assumed energy cost of $0.03/kW-hr and 4000 annual operating hours, all motors of concern show economic payback periods of 3.6 years or less.

TABLE 43

ECONOMIC PAYBACK AND ENERGY RECOVERY
(based on 4000 hr/yr and $0.03/kW-hr)

Motor	Change in Core Length			
	+15%		+30%	
Size (HP)	E.P.*	E.R.	E.P.*	E.R.
1	8,910	375	11,535	705
5	6,095	290	8,315	580
10	6,310	270	6,660	550
15	8,560	400	11,825	815
20	8,045	325	11,175	780
25	7,835	465	11,125	975
50	9,260	495	13,285	1,035
100	10,130	430	14,465	905

*Based on electricity costs of $0.03/kW-hr.

E. CONCLUSIONS

Based on the preceding discussion, we conclude that motor efficiencies can be improved significantly through utilization of silicon steels. Increasing the length of the motor core can also provide a small increase in motor efficiency. However, the major benefit is derived primarily through use of silicon steels. These changes will result in higher motor prices to the end user. However, increasing power costs will result in payback periods of less than 2.5 operating years in most cases, based on 4000 operating hours per year. Similarly, between 270 and 500 hours are necessary to recover the additional energy input requirements for materials to produce higher efficiency motors. This represents approximately 1 month of motor operation at the improved efficiency level. As a result, the national benefit in terms of energy conservation is essentially immediate.

V. TRENDS

A. COST OF ELECTRICITY

Although it is now only beginning to become an economic factor, a substantial future market influence is sure to be the rising cost of electric power. Moreover, the uneven distribution of power costs geographically will increasingly influence new plant locations as well as conservation programs. The cost of power to all consumers rose on the average from 1.9 to 2.3¢/kW-hr (21.05%) between the years 1973 and 1974. If this rate of increase were to continue, power costs would about double in four years and increase by five-fold in 10 years. These increases, however, were primarily the result of rapid increases in the cost of fuels used by utilities between 1972 to 1974. These costs stabilized during 1975, and are not expected to cause similar extreme increases in the future. Capital expenditures for new plants will become the dominant factor in future power cost increases. We anticipate that power costs will increase at a rate equal to the general inflation rate plus 2 percent. For purposes of our analyses, we have assumed a 5 percent inflation rate resulting in a growth rate of 7 percent for power costs.

Of interest is the variation in power costs between the various consuming sectors and geographically. Tables 44 and 45, which display this information, show that small industries and commercial establishments in New England and the Middle Atlantic States will be most affected by increased power costs. The latter is a large consumer of electrical power and, if one were to institute a trial program, it should be most successful in this area.

Applying our assumed inflation rate to the power costs shown in Table 44 yields the projected cost of power in 1980, 1985, and 1990 (Table 46).

As Table 46 shows, power costs will approximately triple by 1990 at the assumed inflation rate. Figure 19 illustrates the historical and projected cost of power in the United States for the period 1955 to 1990.

TABLE 44

COST OF ELECTRICAL POWER BY CONSUMING SECTOR (cents/kW-hr)

Year	Residential	Commercial & Small	Industrial Large	Street & Highways	Other Public	Railroads	Inter-Departmental	Average
1974	2.8	2.9	1.5	4.3	1.9	3.4	1.0	2.3
1973	2.4	2.3	1.2	3.8	1.5	2.2	0.8	1.9

Source: Statistical Yearbook of the Electric Utility Industry, Edison Electric Institute.

TABLE 45

GEOGRAPHICAL AND COST DISTRIBUTION OF ELECTRICAL POWER (1974)

Geographical Location	Percent of Total Power Consumed	Average Cost per kW-hr (cents)
New England	4	3.65
Middle Atlantic	13	3.44
East North Central	19	2.27
West North Central	6	2.28
South Atlantic	16	2.41
East South Central	10	1.49
West South Central	12	1.82
Mountain	5	1.86
Pacific	13	1.84
Alaska & Hawaii	$\geq$1	2.94
Total	~98	2.30

Source: Statistical Year Book of the Electric Utility Industry, Edison Electric Institute.

TABLE 46

PROJECTED POWER COSTS IN COMMERCIAL/INDUSTRIAL SECTORS (cents/kW-hr)

	Total	Commercial	Industrial
1974*	2.02	2.9	1.5
1980	3.03	4.4	2.3
1985	4.25	6.1	3.2
1990	5.97	8.6	4.4

***Source:** Statistical Year Book of the Electric Utility Industry, Edison Electric Institute.

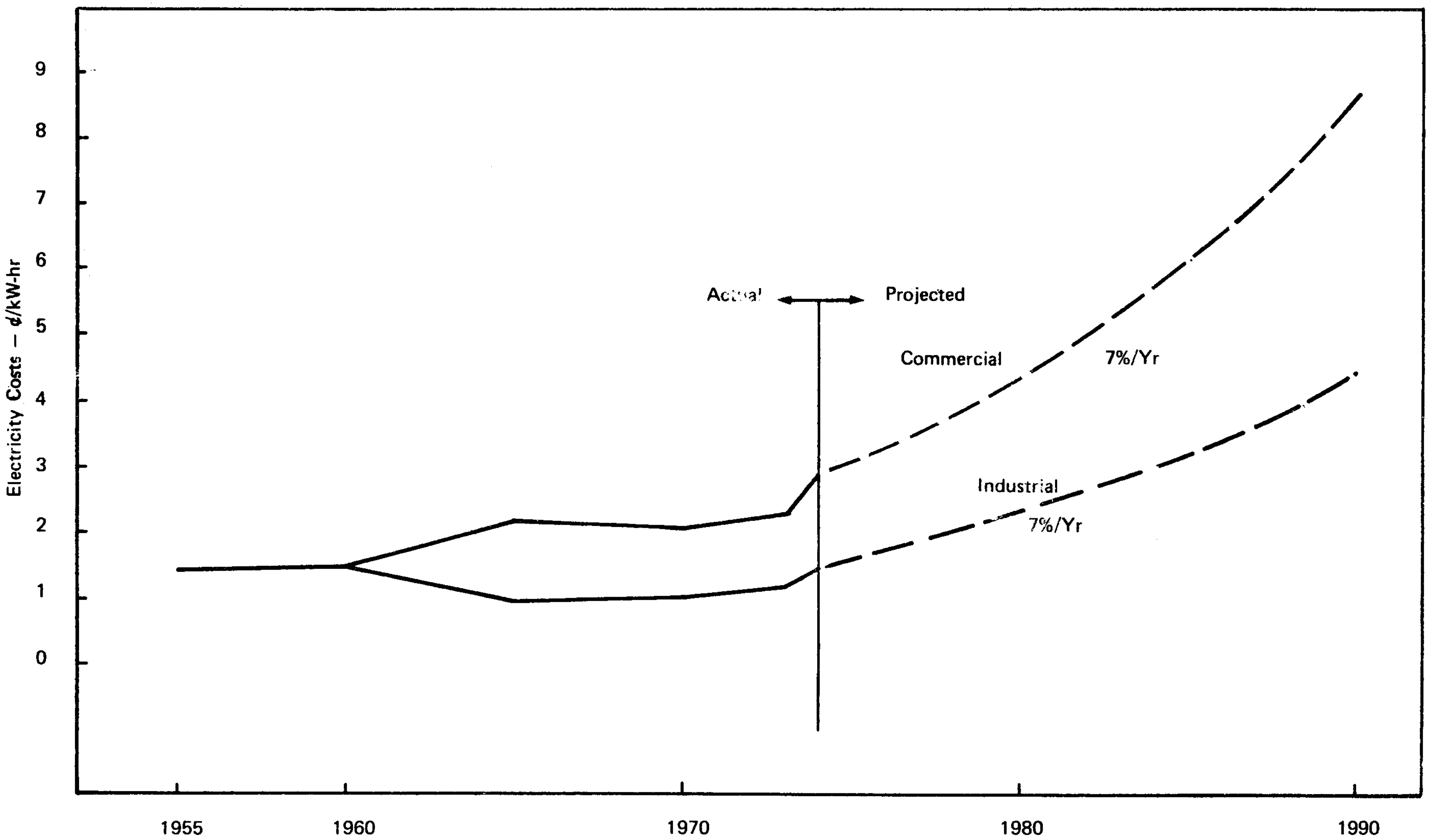


FIGURE 19 HISTORICAL AND PROJECTED COST OF ELECTRICITY, 1955–1990 COMMERCIAL AND INDUSTRIAL SECTORS IN THE UNITED STATES

B. MOTOR EFFICIENCY

Between 1955 and 1975, there has been a downward trend in motor efficiency most apparent in the smaller (1- to 10-HP) motor sizes. To illustrate this trend, we developed the average efficiency data for the years 1955 and 1975 shown in Figure 20. In the range from 1 to 10 HP, efficiencies for these motors fall between 2.0 and 4.7 percentage points (2.25 and 5.5%) lower in 1975 than in 1955. Above 15 HP, efficiencies have remained essentially the same.

Using power costs as a measure, we found that the average cost of electricity for various sectors for the years 1955, 1960, 1965, and 1970 was as shown in Table 47. Between 1955 and 1970, there was a 3.45 percent decrease in the average cost per kW-hr for commercial and industrial uses, which fairly approximates the decrease in motor efficiency for smaller motors.

TABLE 47

AVERAGE COST OF ELECTRICITY
(cents/kW-hr)

<table>
<tr><th></th><th>Total</th><th>Commercial</th><th>Industrial</th></tr>
<tr><td>1955</td><td>1.450</td><td colspan="2">1.450*</td></tr>
<tr><td>1960</td><td>1.490</td><td colspan="2">1.490*</td></tr>
<tr><td>1965</td><td>1.400</td><td>2.185</td><td>0.996</td></tr>
<tr><td>1970</td><td>1.403</td><td>2.081</td><td>1.017</td></tr>
</table>

*Separate statistics not available.

Source: FPC, "Statistics of Privately Owned Electric Utilities in the United States," FPC S-226.

The downward trend in efficiency during a period of similar decline in power costs suggests that motor users were not concerned about lower efficiency as long as power costs were low, a fact confirmed during conversations at many companies.

By comparing the figures in Table 47 with those of Table 44, it is apparent that there has been a dramatic reversal in the trend of power costs since 1970. For the total commercial/industrial sector, the average cost/kW-hr was 1.588 cents in 1973 and 2.021 cents in 1974, an increase of 27.2%. The increased interest in higher efficiency occurring as costs increase suggests that there will be a direct, if lagging, relation between power cost and motor efficiency. The introduction of a new line of higher efficiency motors by Gould, Inc., is an indication of the reaction to increased electricity costs. In fact, published data for the new line confirm that the efficiencies are essentially the same as those of 1955 (as shown on

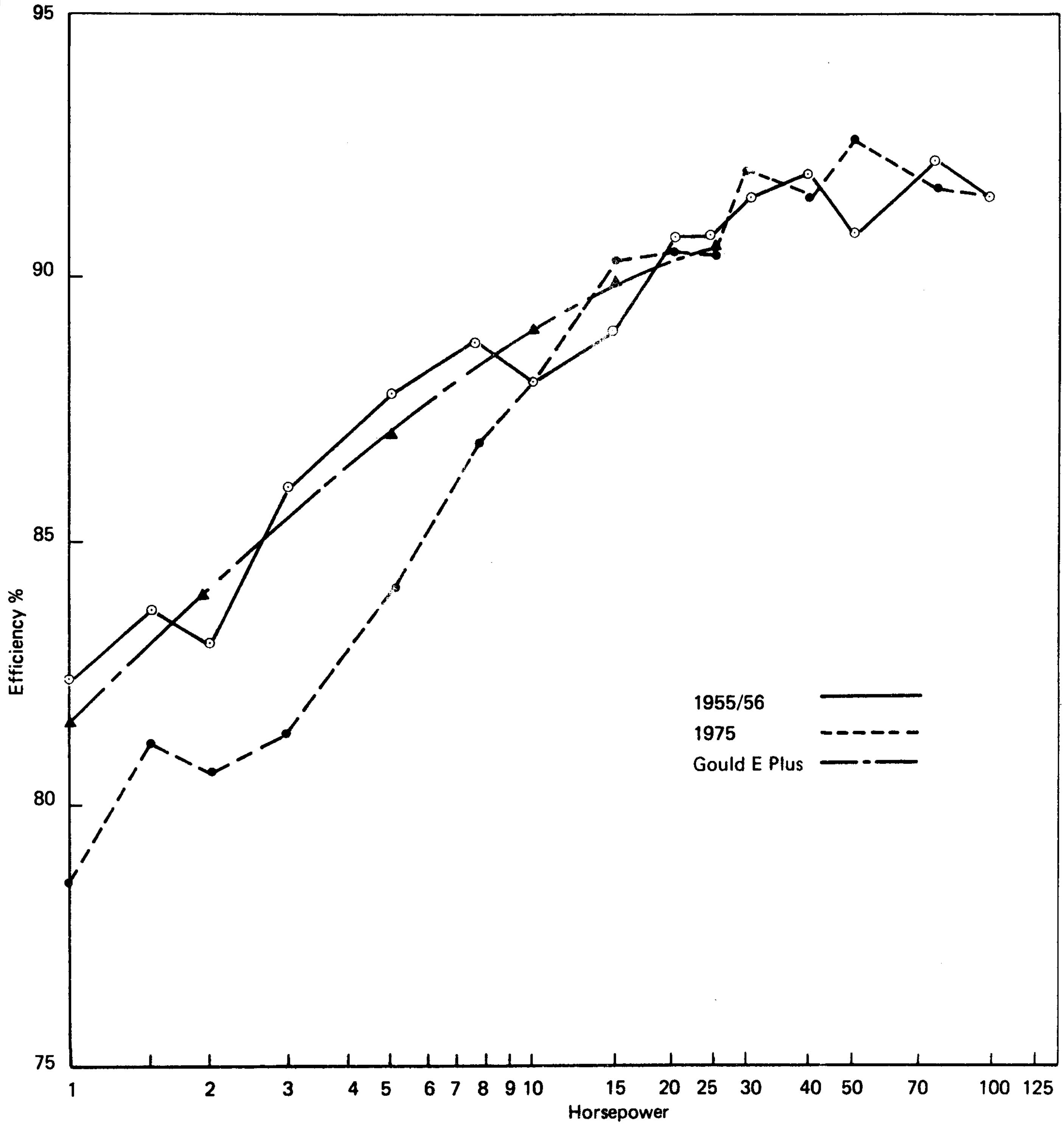


FIGURE 20 **AVERAGE MOTOR EFFICIENCY 1955/56 VS. 1975, 1800 RPM, DESIGN TYPE B, OPEN AC, POLYPHASE MOTORS**

Figure 20). It is reasonable to expect that additional gains in efficiency will be made as power costs increase further. As power costs continue to increase, the interest in higher efficiency motors should reverse the downward trend. We expect that motor efficiency will return to or exceed 1955 levels industry-wide.

As was demonstrated in Chapter IV, significant gains in efficiency are possible through utilization of silicon steels. Additional gains can be made by increasing motor core length (see Figure 21). The efficiencies published by Gould for the new E + line of motors compare favorably with those calculated for a change in core steel as shown in Figure 21. Certainly, the industry is capable of designing motors with higher efficiencies than are currently available, as demonstrated by Gould. Materials are available which can assist in accomplishing this objective. The motivating force, according to manufacturers, will have to be external; i.e., user demand or some other equally persuasive factor.

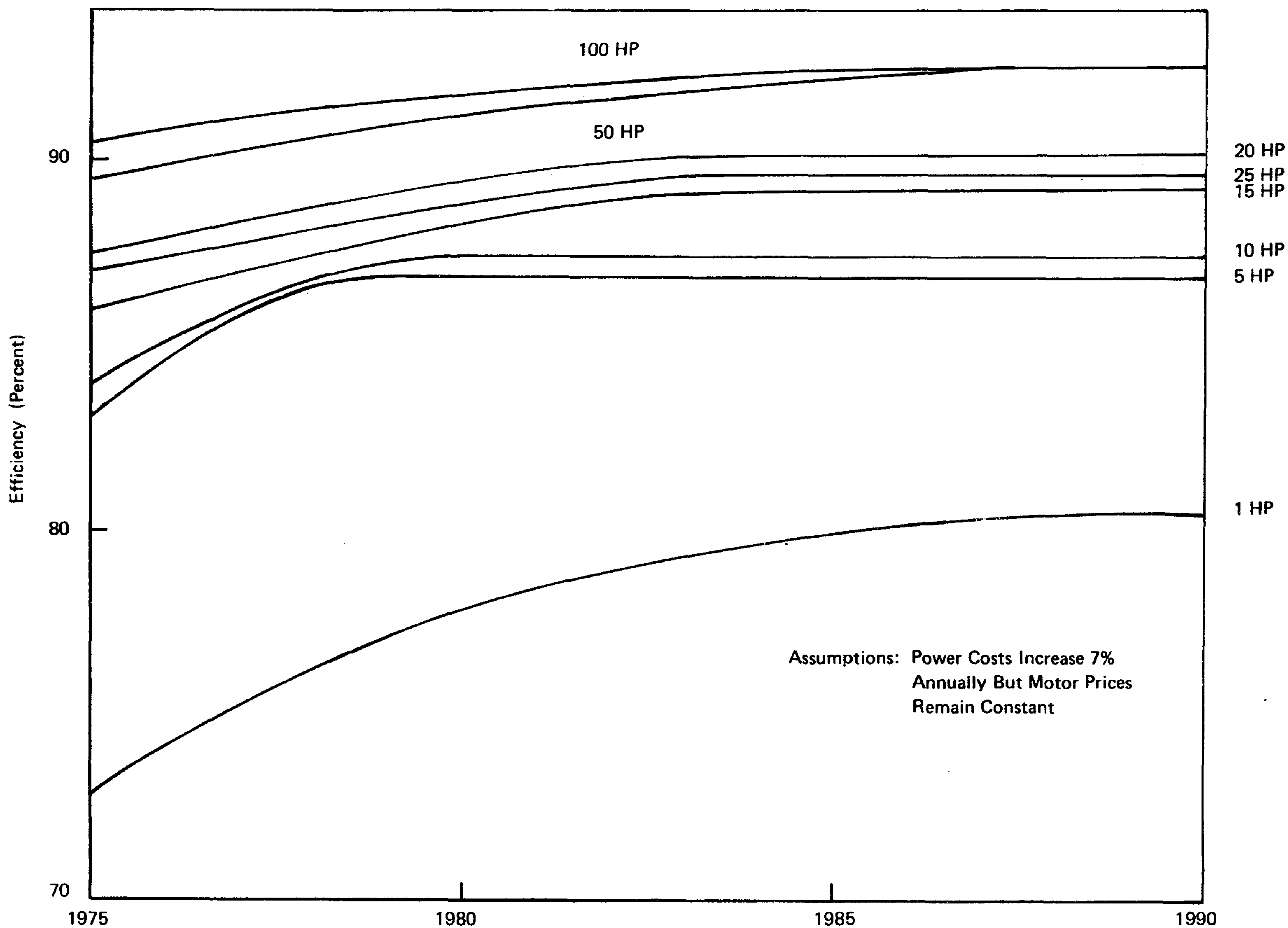
According to the Gould data, the energy savings resulting from the improved efficiency result in economic payback periods ranging from 0.9 year (3600 hours) to 1.75 years (7000 hours) at 2.0¢/kW-hr and 4000 annual operating hours, depending on motor size. Assuming a desired payback period of 1-3/4 operating years (7000 hours), by reference to Figure 25, it is possible to conclude that a 15% increase in core length using silicon steel will be justified as power costs approach 2.5¢/kW-hr in 1975 dollars (selectively by motor size at higher costs). Similarly, a 30% increase is justified at 5.0¢/kW-hr. If motor prices were to remain constant and power costs were to increase at the assumed rate of 7 percent annually, we can postulate that the efficiency levels represented by the curves in Figure 21 would be achieved by approximately 1983.

Based on the assumptions that:

- motor prices remain constant,
- power costs increase at 7 percent annually,
- users require a 7000-hour economic payback, and
- efficiency increases as power costs increase, but lag by a fixed period of time,

it is possible to develop a set of curves for the motors involved showing anticipated efficiency levels versus power cost (or year). For the purposes of this study, we have adopted a 2-year lag time in developing these curves, shown in Figure 21.

A sample calculation for the 5-HP motor follows:



Source: Arthur D. Little, Inc., estimates.

FIGURE 21 PROJECTED EFFICIENCY TRENDS FOR INTEGRAL HP POLYPHASE AC MOTORS

Efficiency Level: 86.52 (+0% core): $P = \dfrac{\$21.49}{.179 \times 4000 \times 1.75} = 1.72¢$

86.80 (+15% core) $P = \dfrac{\$35.29}{.193 \times 4000 \times 1.75} = 2.61¢$

86.80 (+30% core) $P = \dfrac{\$48.14}{.193 \times 4000 \times 1.75} = 3.56¢$

At the projected rate of increases, power costs will reach 2.6¢ by approximately 1978 and 3.66¢ by 1983. Therefore, we can postulate, based on our assumptions, that the efficiency of the 5-HP motor should be approximately 87 percent by 1978. These represent the earliest potential dates if natural pressures are allowed to operate.

C. EFFECT OF INFLATION

It is erroneous, of course, to assume that motor costs will be unaffected by inflation, while power costs increase at a rate greater than the general inflation rate. Motor prices will increase as a result of inflationary pressures.

Inflation will affect the economic payback period and the point at which implementation of motor modifications will be justified. Rising material and labor costs will increase motor prices and energy costs both, changing the economic payback for each motor size. For example, by 1980 the cost of material is expected to rise as shown in Table 48.

TABLE 48

ANTICIPATED PERCENT INCREASE IN MATERIAL COSTS
(1974-1980)
(100% = 1967)

	1974	Est. 1980	Total	Increase % Annual
Steel Laminations	147.2	170.0	16.7	2.61
Iron Castings	144.5	170.0	17.7	2.75
Aluminum Ingot	135.5	191.8	41.6	5.97
Copper Wire	102.0	118.4	16.1	2.52

Source: Arthur D. Little, Inc., estimates.

At the indicated rates of increase for material and a net 6% annual rate for labor cost, by 1980, the OEM selling price of motors will increase as shown in Table 49. Projected material and labor costs increases are shown in Figure 22.

TABLE 49

EFFECT OF INFLATION ON OEM SELLING PRICE

Increase in Core Length	1975 Price Level*	Est. 1980 Price Level*	% Increase (1975-1980) Total	Annual
Basic Core	100.0	118.6	18.6	3.47
+15%	140.1	166.1	18.6	3.47
+30%	154.7	183.3	18.5	3.45

*% of 1975 base motor OEM selling price.

These figures suggest that motor costs will increase at approximately one-half the rate at which power costs will increase. The effect will be to shorten the economic payback period in future years and delay the point at which higher efficiencies would be dictated. As an example, in 1980 the impact of inflation at these rates will reduce the economic payback by approximately 18 percent. For any year, the EP can be determined by the following relation:

$$EP_n = \left[\frac{(100 + MP)}{(100 + PC)}\right]^n EP_B$$

where

n = number of years from 1975 to the year in question,

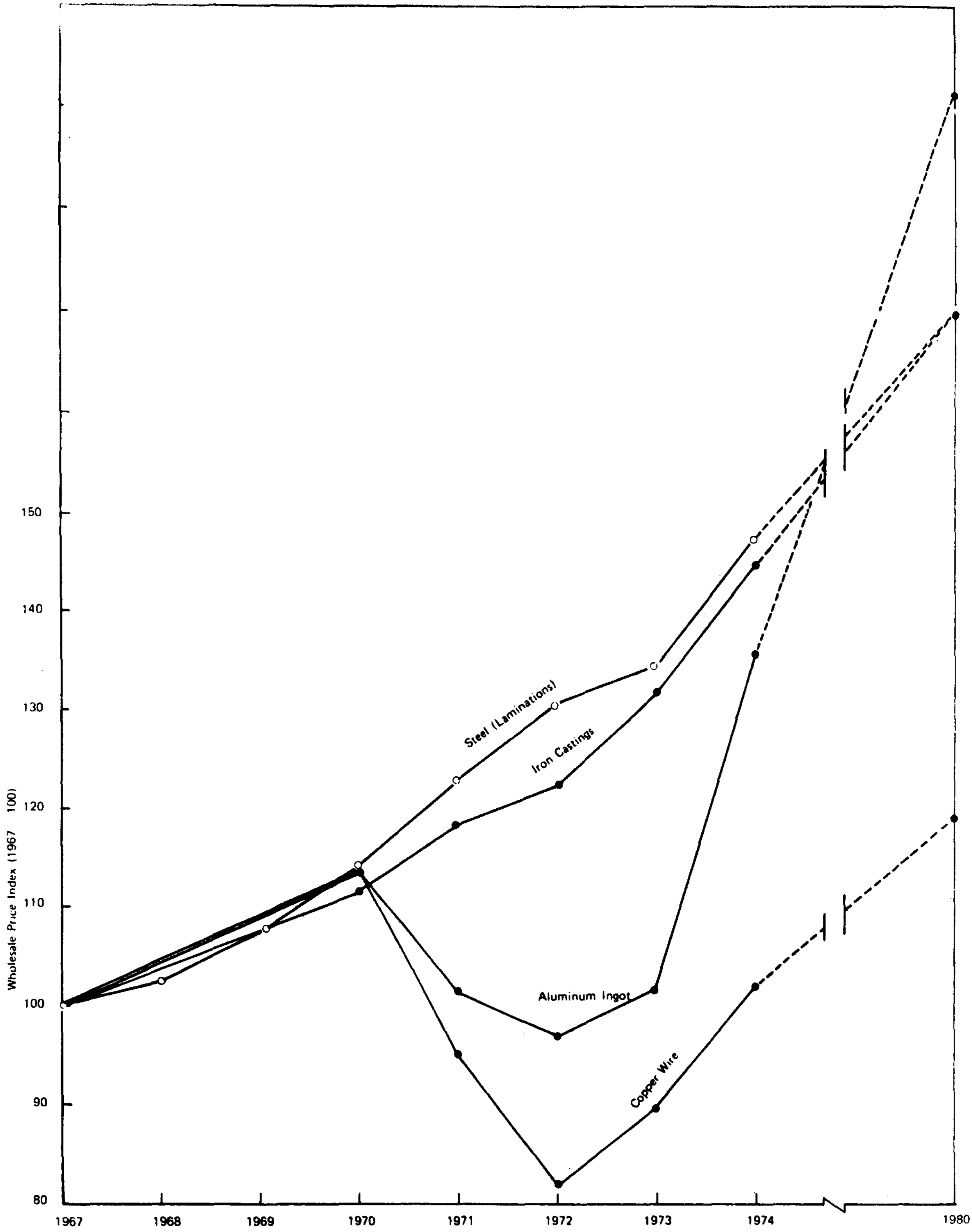
MP = annual increase in motor OEM selling price (%),

PC = annual increase in power cost (%), and

EP_B = 1975 economic payback period for motor.

Figure 23 illustrates the 1980 economic payback curves for the 5-HP motor, assuming a 15% increase in core length and a 3.5% annual increase in OEM selling price. If this curve is compared with the 1975 economic payback curve, it is apparent that the payback period has increased for given power cost levels. However, over the same period of time power costs will also increase, resulting in a decrease in the actual payback period. To illustrate, if power costs in 1975 are 3¢/kW-hr, the EP for a 5-HP motor is 6095 hours. At a 7 percent rate of increase, average power costs will increase to 4.2¢/kW-hr, yielding an economic payback of 4350 hours. Calculation of the 1980 EP by formula yields:

$$EP = 6095 \left[\frac{103.5}{107.0}\right]^5 = 5161 \text{ hours.}$$



Source: U.S. Industrial 1975 Index, U.S. Department of Commerce
and Arthur D. Little, Inc., estimates.

FIGURE 22 PRICE INDEX HISTORIES AND PROJECTIONS

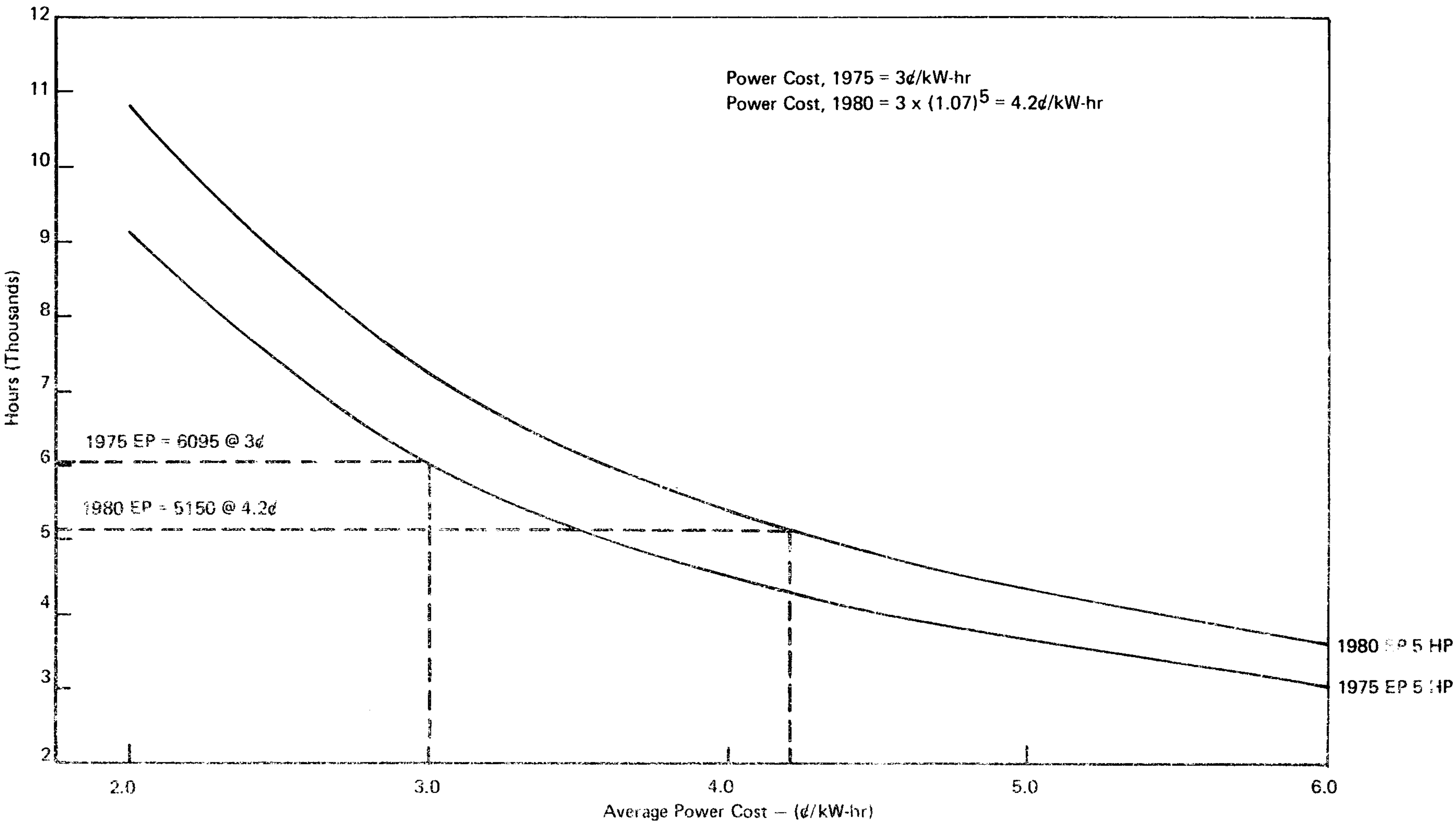


FIGURE 23 ECONOMIC PAYBACK AND ENERGY RECOVERY VS. % CORE LENGTH INCREASE – 5 HP AND 50 HP MOTOR

Using the payback formula, one can determine the approximate timing of future efficiency levels for particular payback periods by calculating the number of years required to achieve the desired payback period.

The formula employed to make these calculations is as follows:

$$n = \frac{\ln\left[\dfrac{EP_D}{EP_B}\right]}{\ln\left[\dfrac{100 + MP}{100 + PC}\right]}$$

where

EP_D = desired economic payback

EP_B = base year (1975) payback at energy cost of 2¢.

To illustrate the calculation for the 5-HP motor, the following data were used:

EP_B = 9145 hours (15% core length increase)
EP_D = 7000 hours
MP = 3.5%
PC = 7.0%

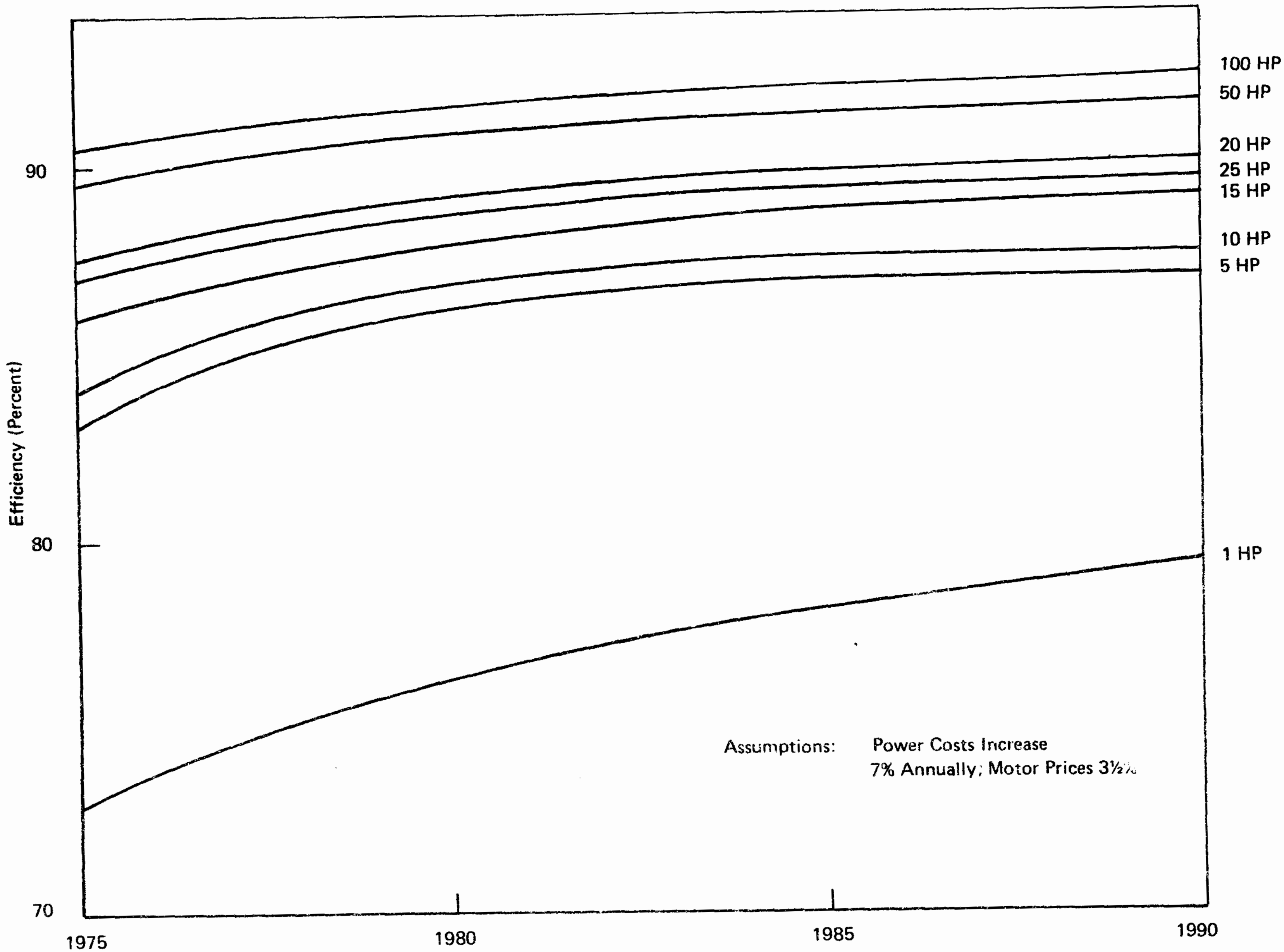
Thus:

$$n = \frac{\ln\left[\dfrac{7000}{9145}\right]}{\ln\left[\dfrac{100 + 3.5}{100 + 7.0}\right]} = \frac{\ln .7654}{\ln .9673} = \frac{-0.2673}{-0.0333} = 8.03 \text{ yr}$$

The interpretation of this result is that in 1983 (1975 + 8.0) increased motor costs to increase efficiency to 87% will be justified by the energy cost savings at 1983 power cost levels. A similar calculation for the 50-HP motor results in a value of n = 13.27 years to reach an efficiency level of 91.5%. Similar calculations for all motor sizes yield the curves shown in Figure 24.

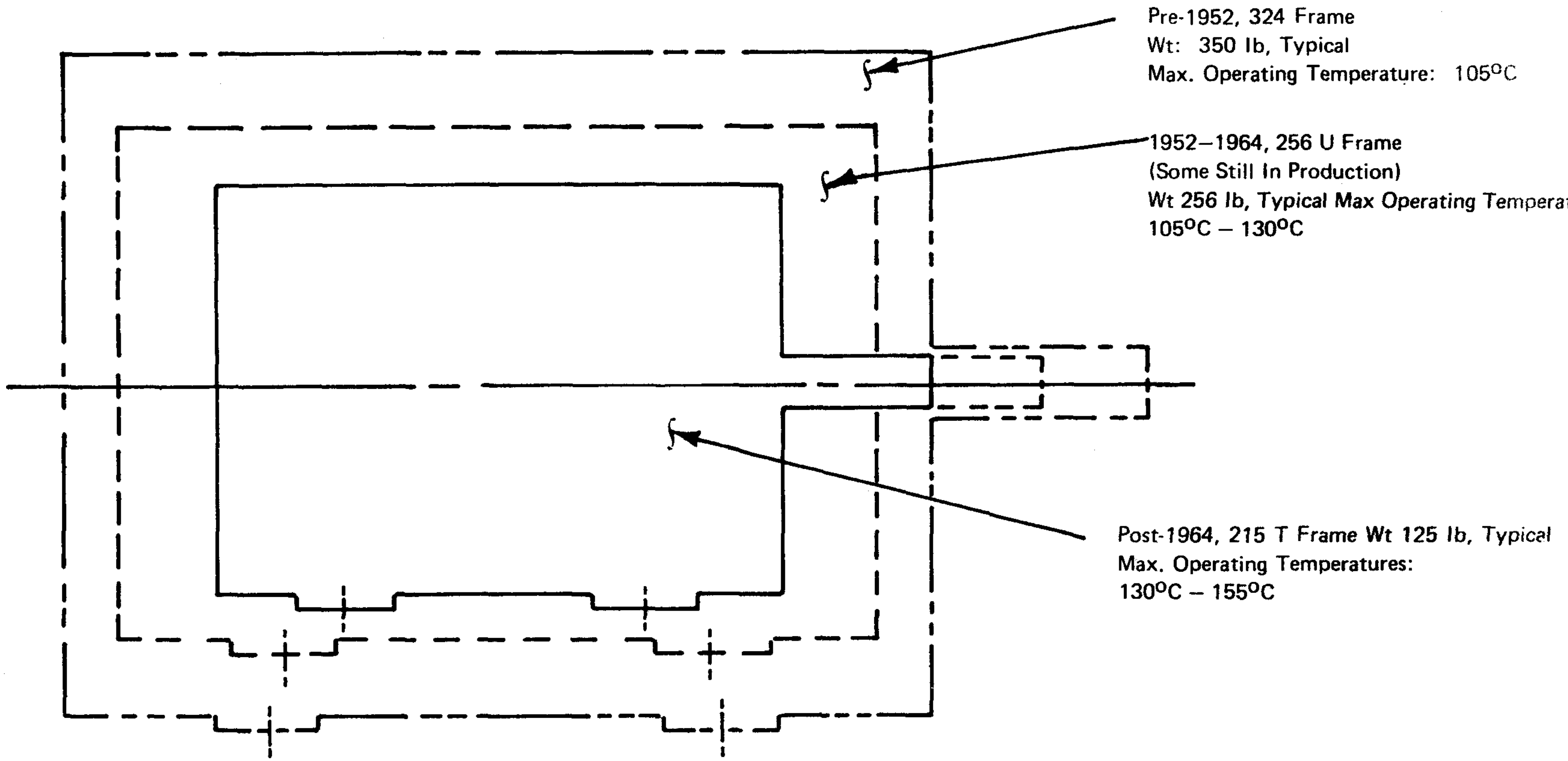
D. SIZE AND WEIGHT

Figure 25 shows the size, weight, and temperature rise history in the development of a 10-HP, AC polyphase motor. It shows that over the 12-year period from 1952 to 1964 the weight of the motor has been reduced almost two-thirds from 350 to 125 pounds. There



Source: Arthur D. Little, Inc., estimates.

FIGURE 24 PROJECTED EFFICIENCY TRENDS FOR INTEGRAL HP POLYPHASE AC MOTORS



Source: Electrical Apparatus Service Assoc.

FIGURE 25 HISTORICAL DEVELOPMENT OF 10-HP, POLYPHASE AC MOTOR WITH OPEN DRIP-PROOF ENCLOSURE

was, of course, a comparable reduction in size. More importantly, as a probable (but not absolute) measure of inefficiency, the motor's operating temperature increased substantially.

Conversely, if one investigates the size/weight history in the development of a 50-HP motor of the same type, it will be found that the weight reduction over the same period was far less. For the 50-HP motor, the weight reduction was in the order of 44% as opposed to 64% for the 10-HP unit.

These findings, in view of the data presented in Figure 20, lead us to believe the smaller motors have been size/weight-reduced to an extent that has significantly affected their efficiencies. While the larger motors have been significantly size/weight-reduced, better insulation systems appear to have allowed these changes without affecting their efficiencies.

E. CONCLUSIONS

Based on our investigations, power costs are projected to increase at approximately 7% annually for the period covered by this study (to 1990) as shown in Figure 19. For the same period of time, we expect that OEM motor prices will increase at an annual rate of only approximately 3.5%, based on material and cost increases illustrated in Figure 22. As a result of these factors, we anticipate that motor efficiency will increase at approximately the rates illustrated in Figure 24.

We conclude that the smaller (under 15 HP) AC polyphase motors have been size/weight-reduced over the past 15 years to an extent that their efficiencies have been significantly attenuated. The stage now seems to be set for a reversal of this trend.

VI. POLICY SCENARIOS

A. INTRODUCTION

We have divided this section in two main parts:

1. Possible means of increasing user demand, i.e., to increase the "market pull" for higher efficiency motors; and

2. Means of stimulating manufacturers' interest in supplying higher efficiency motors.

From experience in similar situations, we postulated that the first category, viz., increasing market demand, would likely be the more effective. We found in our interviews with both manufacturers and users that, indeed, both groups concur with this postulate. Manufacturers said unanimously and unequivocally that they know how to build more efficient motors and would do so, provided that sufficient demand existed for them. Users were divided on their likely demand for higher efficiency motors. This demand would depend on the type of application they had in mind and therefore, broadly speaking, on the kind of industry that they represented.

Both users and manufacturers were unanimous in hoping that a minimum of Government intervention in the free market would be necessary. They felt that the move to higher efficiency motors would occur "automatically" as electricity rates went up and the costs of operating electromechanical drives began to assume a significant portion of the total manufacturing costs. However, with an estimated motor population of 15 million integral HP, AC polyphase motors and an average useful life of the smaller (< 50 HP) units of 7-10 years, for new motors, approximately one and 2/3 million of which are produced in this horsepower range, the replacement of industrial motors now in use amounts to only about 10 percent per year with another smaller percentage of principally larger motors being repaired locally for further useful life. In short, the "automatic" trend toward higher efficiency – though it may come about – will not decrease the total electricity consumption for electromechanical drives appreciably per annum, for many years – it will take a very long time before a majority of motors in use are indeed operating at the higher possible efficiencies. Both users and manufacturers, therefore, are sympathetic to the to the notion that some Government measures may be needed to speed up the trend toward higher efficiency motors.

Broadly speaking, users are most interested in reliability and are only quite recently beginning to become interested in efficiency. There is now increasing evidence that many will consider installing higher efficiency motors in new plants, or in replacing existing motors, provided that the rate of return is adequate. In the pulp and paper industry, one of the major users of electromechanical drives, a payback period of no more than four years must be assured, if the higher capital costs of the high-efficiency motors are to be incurred.

This kind of risk calculus has to be demonstrated to the board of directors or the particular executive in the corporation who authorizes the total plant expenditure, and it is that group of senior executive personnel that needs to be better informed about the technical and economic features of high-efficiency motors. Once financial authorization has been made for new plants (including new motors), it is generally difficult to initiate changes downstream and at lower levels of authority, even though some of the plant design engineers may subsequently see the advantage of high-efficiency motors but find themselves without adequate funds to order them. There is little inclination on their part to go back to higher quarters to try and obtain additional funding.

B. INCREASE IN USER DEMAND FOR HIGHER EFFICIENCY MOTORS

1. Better Information/Education for User

a. Urge the Federated Voluntary Standards System (under the leadership of the American National Standards Institute) to have its cognizant member institutions, the Institution of Electrical and Electronic Engineers (IEEE), and/or the National Electric Manufacturers Association (NEMA) develop integrated test and publication specifications that would result in a more accurate portrayal of efficiencies and power factors in the literature, particularly for polyphase motors in the 1- to 125-HP range. Appendix E excerpts the current test specifications showing accommodation of test methods of varying accuracy and accommodation of error. Published data should accurately portray normal characteristics as well as manufacturing tolerances. Attempts should be made to make test methods consistent with the ones used in Europe under I.E.C. rules (to improve export sales of motors).

   Ensure a continuance of the policies that would ascertain that the IEEE and/or NEMA standards panel is not dominated by manufacturers and that relevant user groups and Government agencies are active members, so that resultant standard test methods will provide the information that the *user* needs.

   Provide Federal financial or technical assistance to expedite development of standard test methods.

b. Have NEMA take the lead in assuring that suitable test methods* are used (ensure that only dynamometer testing would be used on 1- to 125-HP polyphase motors).

c. If (b) is not effective, issue Federal regulation making standard test methods mandatory.

* * * * *

*Such procedures/policies have been used with success for years by various associations; for instance, the Air Moving and Conditioning Association (AMCA).

Industry Comments (on items 1a, b, c, above):

Manufacturers tell us that appropriate test methods are available now. The NEMA MG1 12.30 test procedures call for the IEEE standard 112A, Method B (under ANSI Standard C.50.2). This is a dynamometer test which provides meaningful information on efficiency (user needs were implicitly recognized in drawing up this standard). Importantly, this standard test method requires a minimum of elaborate test equipment. It is therefore a test which can be carried out by any manufacturer, large or small, without burdening the latter with the cost of expensive instrumentation that could be considered to be "in restraint of trade." One of the large manufacturers we talked to considered this test procedure more sophisticated than the European IEC rules, because IEC methods make assumptions on some efficiency losses without testing them and those assumptions are said to be conservative. American manufacturers have found that the actual efficiency measured by the above-mentioned American standard shows European motors to be significantly less efficient than quoted by IEC because of these assumptions.

Manufacturers believe that voluntary agreement can be reached to use such a test method as a standard throughout industry and that Federal regulations making use of such a method are not necessary.

* * * * *

d. Have NEMA publish efficiency data on every motor – grouped by horsepower rating – showing efficiency and power factors of motors manufactured by principal sellers. This will enable the user to pick the most efficient motor out of currently available competitive models.

e. If NEMA, or other private industry organizations, will not voluntarily publish comparative tables (as in d. above), issue Federal regulation making publication mandatory.

* * * * *

Industry Comment (on items 1d and e above):

NEMA considers these approaches impractical. They say: "To single out for separate publication one motor performance parameter from the many parameters that the user requires in applying the motor would not seem to best serve user needs. The work involved to create and maintain such a directory would not be commensurate with resultant energy conservation or user benefit."

There is also concern among some manufacturers about the publication of efficiency data in the manner suggested above, i.e., a comparative table showing *efficiencies by motor size and for different manufacturers. They believe that NEMA cannot do this because it is likely to be considered "in restraint of trade." (This needs to be checked with the Justice Department.) We are told, however, that in the 1920's NEMA did publish recommended minimum efficiency and power factor data, but the publication of such information was dropped in the early 1930's due to alleged apathy and lack of interest, presumably not unrelated to the then prevailing depression. The smaller manufacturers, some of whom have recently made special efforts in pushing high-efficiency motors, seem quite happy about the suggestion for this comparative type of publication of efficiency data, while the larger ones are less so. Both groups agree that the users should be better informed, but they believe that this information is available through their corporate trade literature and that, though it may be burdensome and time-consuming, the user can get it, provided he takes the trouble to do so. Our point is that the assembly of information in one place for ready comparative reference (and with frequent updating) would be of greater help to the consumer in making a wise, energy-sensitive choice.*

In the context of publication of efficiency data, manufacturers expressed varying opinions on the desirability of such data being stated on the motor nameplate. Some (again the smaller ones) believe this to be a most useful means of exposing the user to efficiency consciousness, while others believe that efficiency data so displayed would be understated for fear that it constituted a warranty as nameplate data usually does.

There is some obvious anxiety among manufacturers that publication of efficiency data in the manner suggested by us could lead to a "race for efficiency" with considerable disruption in the industry. It was suggested that some compromise may be better, such as agreeing upon minimum standards for what would be classed as 'high-efficiency motors.' This would result in two classes of motors, the high-efficiency ones and the normal ones. Industry believes that this could be done through voluntary action by the industry, with likely some FEA encouragement but without Federal regulation.

* * * * *

f. In conjunction with a comparative efficiency table for every motor size, publish methodology of calculating payback period for extra cost of higher efficiency motor depending on electricity costs, duty cycle, and the like.

   Give example of calculation based on present electric power rates in different regions, and anticipated increases (decreases) in electric power consumption.

g. Have the FEA commission preparation of a simple handbook on "how to choose best motor for specific applications" (incorporating or referring to data published as in d. and f. above), and distribute to principal groups of end-users and OEM's for polyphase motors in the 1- to 125-HP range.

Extent this "educational" effort by regional seminars of users and manufacturers of motors (under FEA sponsorship).

* * * * *

Industry Comments (on items 1f and g):

We are told that NEMA has an Energy Management Task Force at work which is addressing itself to items (f) and (g) above. The work is not yet completed, and we need to look into the quality of the proposed output before making a judgment on whether we believe it will be of real value to the user in making good motor choices. It is difficult to provide a simple uniform method for calculating payback because of complexities due to varying load conditions (particularly, for instance, cyclical loads as in punch presses and well-pumping installations).

The problem of mismatching the motor and its load (i.e., whatever it drives) often accounts for considerable losses and thus for greater inefficiency of the total system than simply the inefficiency in the motor itself.

There is a familiar story – one which we have not addressed in this study and were not asked to. But it is obvious that, though the move to higher efficiency motors itself is a good one, equal attention must be paid to the device the motor is driving and whether the two are properly matched to each other. We were told of cases in which 76 percent efficient motors were driving 20 percent efficient pumps: an increase in pump efficiency would be far more important in this case than any further increase in motor efficiency. Choosing motors with too big a power rating, which is prevalent practice, and then underloading them in actual use is also detrimental to power factor. In other words, choice of motor requires considerable sophistication with regard to the application for which it is intended and should not only depend upon the efficiency rating of the motor itself.

Seminars could be useful in clarifying these issues, and some manufacturers are undertaking such "educational" (promotional) efforts themselves, and with their distributors.

Original equipment manufacturers (OEM's) are allegedly one of the principal causes of decreased motor efficiencies over recent decades. In particular, the machine tool industry is blamed for continually pressing for smaller and lighter motors for any given power rating. Motor manufacturers have had to respond to this pressure, and motor efficiency has accordingly suffered.

Motors were rerated by the industry in 1952 and again in 1964. The trend has been to smaller frame sizes for a given horsepower rating. There is no talk yet in the industry of rerating in 1976 (if a 12-year cycle of rerating were to be sustained). Uncertainties about prospective metrification and about desired efficiency trends may be the most significant reasons for delay. By the same token, the next rerating (encouraged by FEA) could be used to focus on higher efficiency.

* * * * *

2. Incentives for User to Purchase a Higher Efficiency Motor

a. Adjust capital investment credit to users by:

- keeping credit at current level if "best *currently available* efficiency" motor is installed (if user can demonstrate selection derived from calculations based on Section 1);
- decreasing credit if motors of less than "best *currently available* efficiency" are installed (if user cannot demonstrate any particular efficiency-sensitive selection method);
- increasing credit if motors of "practical *maximum* efficiency" are installed (if user can demonstrate that manufacturer exceeded best *currently available* efficiency because of user's demand).

b. Problems of inspection and policing are formidable, except for large plants with well-documented engineering data. Availability of plant design information to Government likely to be resisted by industry, suspicious of industrial spying, and confidentiality of Federal records under "freedom of information" principles.

c. Nonetheless, this fiscal incentive – or any variation on subsidies of this kind – can exert significant inducements not only to use "best *currently available* motors," but also to stimulate both users/manufacturers to opt for motors with "practical *maximum* efficiency."

* * * * *

Industry Comments (on items 2(a) and (b) above):

Both users and manufacturers see some possible virtue in a financial incentive of the kind suggested above, but also agree that it is likely to be extremely difficult to police. One of the earlier suggestions made by one of our respondents was that *two classes of motors be established, the one for "normal" efficiency (i.e., current) and one for "higher" efficiency (the latter one to be agreed upon voluntarily by industry). If that suggestion were to be carried out, then policing of a fiscal incentive might be simplified, for the prospective purchaser would need only to show evidence that he had purchased higher efficiency motors as defined under the above standard setting in order to obtain either some increased tax credit, or (possibly as an alternative) increased amortization allowances. This or any other form of financial incentive clearly is of importance, considering the users' single-minded concern about rate-of-return.*

* * * * *

d. Fiscal incentive may be important, because most of the major motor users are not now concerned with motor efficiency, since power consumption for electromechanical drives amounts to only, at most, 2% of the selling price of final product (therefore, 10% increase in motor efficiency reduces product price by only 0.2%).

   By the same token, however, user resistance to extra capital costs of higher efficiency motors *should* not be great, and fiscal incentives should only be applied if "information/education" measures, as in Section 1 above, should fail.

e. The fundamental problem with any incentive designed to affect purchasing decision of motor buyer/user is how to balance the cost of providing and applying incentive against the net electric power saving – both measured on a national scale. This must be done considering the geographic differences in electric power rates and the low concern for motor efficiency by most motor users, to each of whom the electric power saving is relatively inconsequential in terms of the selling price of his product.

   The role of electric utilities which could apply a surcharge to customers using inefficient motors is a possibility, but the problem of policing – let alone establishing such a system on a reasonably equitable basis for a variety of users – is formidable. Changes in utility rate structures are notoriously slow to come about, and the State Power Commissions are not generally disposed toward permitting this form of "persuasion."

* * * * *

Industry Comments (on item 2(e) above):

Industry believes that the rate of increase in electricity rates will be the determining factor in its decisions to switch to higher efficiency motors and the possibilities for imposing surcharges on plants using inefficient equipment (though *the State Utility Commissions may find it difficult to make appropriate rate changes related to the efficiency of installed equipment). This question of providing incentives through appropriate changes in electricity rates is a generic energy conservation issue not specifically applicable to motors only, and we believe it should be considered in a much larger context than this study has allowed us to do. There is no question that this is probably the single most important motivating force behind any change toward high-efficiency equipment.*

We were told, for instance, that in the gasline pumping business high-efficiency motors are now the standard. The reason is that these motors are driving pumps in remote locations where the cost of providing electricity, either by long distance transmission or by local diesel-powered generators, raises the electricity cost to such high levels that the gasline pumping industry has asked for high-efficiency motors for many years now and does only buy such models.

* * * * *

C. STIMULATION OF MOTOR MANUFACTURERS' INTEREST IN BUILDING MORE EFFICIENT MOTORS

1. The measures suggested under Section B.1 above would also provide some stimulus to the manufacturers. We find that *different* manufacturers head the list of "currently highest efficiency" motor, depending on the specific horsepower rating. Since successful manufacturing and market dynamics of major manufacturers require that *each* carry a *full* line of all principal horsepower ratings, *competitive* pressure (in response to more efficiency-sensitive buying by the user – encouraged as in Section A.1 above) should drive manufacturers to improve efficiency of *all* of their motor sizes. They cannot afford to be "tops" in one or two sizes only, since each aims at selling all motors needed in, say, a new plant.

* * * * *

Industry Comments (on item B.1 above):

Our supposition that competitive forces will drive manufacturers toward the higher efficiency line when they see that the comparative ratings (available to users) identify them as being "lower on the totem pole" may, in fact, not work well. This is because motor sizes in relation to horsepower generally go in steps of motor frames and related diameters laid down by NEMA, and the only variation is in length which provides somewhat limited leverage on efficiency. There is some argument, therefore, which is rather technical in nature. One or two of the large manufacturers claim it would be unlikely that any one company would find it easy to capture consistently the highest efficiency rating for all power ratings without considerable dislocation of its current manufacturing practices.*

*See Appendix A.

* * * * *

2. There are no outright fiscal incentives that we can conceive of as being effective and politically acceptable and enforceable that would stimulate manufacturers.

3. We do not see the need to assist the manufacturer through Federal R&D funding. The technology to achieve higher efficiency is known; e.g., more and/or better core steel, increased axial length, more copper in windings, reduction of air gap. It is simply a question of market demand for higher efficiency motors.

* * * * *

Industry Comment (on items 2 and 3 above):

Industry agrees with item number 2 above.

As regards item 3, Federal R&D funding, the larger manufacturers tended to see no great virtue in this, but the smaller ones do. The technical developments that need to be made are mainly improvements in material properties (for instance, better steel laminates). One large manufacturer said that no single motor manufacturer could afford the expense of experimentation in composition, rolling, and treatment techniques to gain substantial improvement in loss and permeability properties of steel laminations. He thought the potential energy savings from this area alone could significantly exceed that of design changes with present materials.

In the motor industry, propreitary rights, i.e., patent protection, seem to be of relatively little concern. The firms with which we talked, particularly the smaller ones, therefore, said that Federal R&D funding would be desirable, and the fact that proprietary rights may be made available to all competitors did not seem to them to be a serious handicap.

* * * * *

4. Stimulating private sector market demand to, in turn, stimulate motor manufacturers is discussed in Section B above. In addition, the public sector market demand (Federal, state, local) could exert a significant stimulus on the manufacturers. It is possible to *aggregate* public sector demand and, for this total market, to specify *performance* of the motor in all respects, including efficiency.

The resultant demand-pull for higher efficiency motors could constitute a useful "pump-priming" for the manufacturers. It might even incorporate a "hidden" subsidy, in that some of the higher costs of higher efficiency motors, i.e., principally the costs of engineering development and motor-manufacturing plant modifications, could be "charged off" against public sector sales, thereby reducing the selling price of similar motors for private customers. The General Accounting Office (GAO), the General Services Administration (GSA), and the Department of Defense (DOD) – the principals involved in such a scheme – would need to agree on a deliberate policy under the guidance of the Federal Energy Administration (FEA).

* * * * *

Industry Comments (on item 4 above):

This argument for providing a "hidden" subsidy through sales to the public sector market at premium prices does not seem to be workable as stated. That is to say, the supposition that the costs of engineering development and motor-manufacturing plant modifications are the principal costs to be incurred for higher efficiency motors does not hold true. The items that most contribute to the higher costs of high-efficiency motors are higher material costs. Aggregation of public sector markets, therefore, would not help in the sense that the higher material costs would be chargeable not only to those markets, but also to the private sector market as well. In only one sense might this option be useful, and that is if the public sector markets (all using similar performance specifications for efficiency) were to be aggregated. Then the volume of sales for higher efficiency motors might become sufficiently large soon enough to bring about a reduction in the cost of materials, which could, of course, be reflected in a lower sales price to the private sector market.

One manufacturer said that the difference between ordinary electrical steel at $360/ton and silicon steel at $580/ton – both used for laminations (low-efficiency vs. high-efficiency) in the motor – seem to him an exorbitant difference and one which he attributed to the low volume of silicon steel production. If the volume of production by specialty steel producers were to be raised, then he expects that the price of silicon steel would fall and, therefore, the price of higher efficiency motors using those steels for laminations would also fall. This kind of argument, however, was contested by another manufacturer who felt that using quite ordinary carbon steels for higher efficiency motors could be done quite successfully. He suggested that the argument of lower cost materials, because of higher volume sales for the public sector, was not in itself likely to be a viable incentive.

* * * * *

5. As a last resort – if resultant electric power savings are considered significant enough on a national scale – FEA could consider prohibiting (through Federal regulation) the sale of motors with less than specified efficiency, varying with horsepower rating.

   This, however, may lead to some inequities, in that motor users situated in high power-cost areas would stand to benefit proportionately more than those situated in low power-cost areas. Additionally, it would be difficult to deal with the issue of intended duty cycles, i.e., an inefficient motor in a low-duty cycle application may, on a net energy basis, be efficient.

* * * * *

Industry Comment (on item 5 above):

This option is disliked both by users as well as the manufacturers. There is a great deal of conviction that Government intervention should not take the form of outright prohibition of sales of certain types of motors and that the forces of the free market should be encouraged to take care of the issues involved in this study.

* * * * *

D. SUMMARY

To repeat, there seems to be a prevailing feeling in industry that the problem of providing incentives for the use of higher efficiency motors is only one of many issues concerning energy conservation. The assumption is that the rising costs of electricity will "automatically" take care of correcting the situation. However, if the speedup of this corrective process is to be achieved, then the most likely useful measures would address themselves to:

- More specific (thus more accurate) test specifications;
- Additional specifications dictating correlations of test to published data;
- Mandatory nameplate labeling of efficiency and power factor data; and
- Publication of comparative efficiency data, as well as the methodology of calculating payback periods for more expensive but higher efficiency motors.

Figure 26 shows our estimates of maximum possible theoretical conservation potential as well as those influenced and uninfluenced by Government programs. The potential savings from 1977-90 due to Government programs over those savings that would occur naturally are estimated at 91 billion kW-hr, having a probable cost to consumers of about $4 billion. The stream of savings would persist well into the 21st Century, although Government programs largely would not be required to persist that long. Indeed it might very well turn out that the various associations might volunteer to expeditiously execute the needed changes with little active effort on the part of the Government. At any rate publicity and minor educational programs probably would become unnecessary after conservation programs attained sufficient momentum which would probably occur after 5 to 7 years.

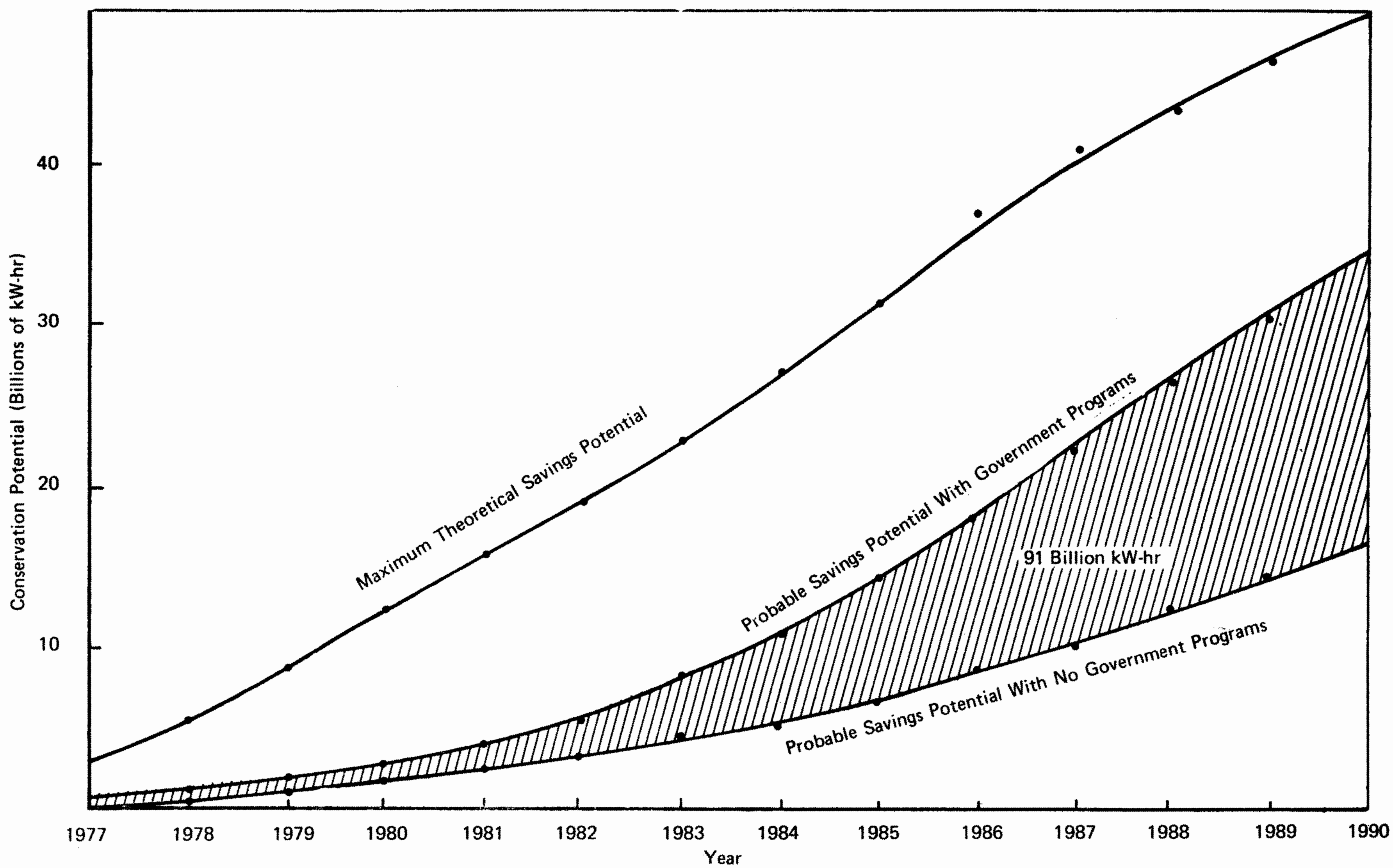


FIGURE 26 COMPARISON OF CONSERVATION POTENTIALS UNDER DIFFERING CIRCUMSTANCES

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APPENDIX A

NEMA FRAME SIZE ASSIGNMENTS FOR INTEGRAL HP MOTORS

Source: National Electrical Manufacturers Association. Reprinted by permission.

TABLE A-1

MG 13-1.02 FRAME DESIGNATIONS FOR POLYPHASE, SQUIRREL-CAGE, DESIGNS A AND B, HORIZONTAL AND VERTICAL MOTORS, 60 Hz, CLASS B INSULATION SYSTEM, OPEN TYPE, 1.15 SERVICE FACTOR, 575 VOLTS AND LESS*

HP	Speed, rpm 3600	1800	1200	900
½	...	...	...	143T
¾	...	...	143T	145T
1	...	143T	145T	182T
1½	143T	145T	182T	184T
2	145T	145T	184T	213T
3	145T	182T	213T	215T
5	182T	184T	215T	254T
7½	184T	213T	254T	256T
10	213T	215T	256T	284T
15	215T	254T	284T	286T
20	254T	256T	286T	324T
25	256T	284T	324T	326T
30	284TS	286T	326T	364T
40	286TS	324T	364T	365T
50	324TS	326T	365T	404T
60	326TS	364TS†	404T	405T
75	364TS	365TS†	405T	444T
100	365TS	404TS†	444T	445T
125	404TS	405TS†	445T	...
150	405TS	444TS†	...	...
200	444TS	445TS†	...	...
250 ‡	445TS	...	...	...

* The voltage rating of 115 volts applies only to motors rated 15 HP and smaller.

† When motors are to be used with V-belt or chain drives, the correct frame size is the frame size shown but with the suffix letter S omitted. For the corresponding shaft extension dimensions, see MG 1-11.31 in NEMA Publication No. MG 1.

‡ The 250-HP rating at the 3600 rpm speed has a 1.0 service factor.

NOTE—See MG 1-11.31 in NEMA Publication No. MG 1 for the dimensions of the frame designations.

Suggested Standard for Future Design 1-21-1964, revised 11-12-1964; 7-7-1965; 11-11-1965; 8-20-1966, NEMA Standard 7-16-1969, revised 1-17-1974.

Source: National Electrical Manufacturers Association, 1974.

TABLE A-2

MG 13-1.03 FRAME DESIGNATIONS FOR POLYPHASE, SQUIRREL-CAGE, DESIGNS A AND B, HORIZONTAL AND VERTICAL MOTORS, 60-Hz, CLASS B INSULATION SYSTEM, TOTALLY-ENCLOSED FAN-COOLED TYPE, 1.00 SERVICE FACTOR, 575 VOLTS AND LESS*

HP	Speed, rpm			
	3600	1800	1200	900
½	...	...	...	143T
¾	...	...	143T	145T
1	...	143T	145T	182T
1½	143T	145T	182T	184T
2	145T	145T	184T	213T
3	182T	182T	213T	215T
5	184T	184T	215T	254T
7½	213T	213T	254T	256T
10	215T	215T	256T	284T
15	254T	254T	284T	286T
20	256T	256T	286T	324T
25	284TS	284T	324T	326T
30	286TS	286T	326T	364T
40	324TS	324T	364T	365T
50	326TS	326T	365T	404T
60	364TS	364TS†	404T	405T
75	365TS	365TS†	405T	444T
100	405TS	405TS†	444T	445T
125	444TS	444TS†	445T	...
150	445TS	445TS†	...	...
200	...	...	...	...
250	...	...	...	...

* The voltage rating of 115 volts applies only to motors rated 15 horsepower and smaller.

† When motors are to be used with V-belt or chain drives, the correct frame size is the frame size shown but with the suffix letter S omitted. For the corresponding shaft extension dimensions, see MG 1-11.31 in NEMA Publication No. MG 1.

NOTE—See MG 1-11.31 in NEMA Publication No. MG 1 for the dimensions of the frame designations.

Suggested Standard for Future Design 1-21-1964, revised 11-12-1964; 7-7-1965, 11-11-1965, NEMA Standard 7-16-1969, revised 1-17-1974.

Source: National Electrical Manufacturers Association, 1974.

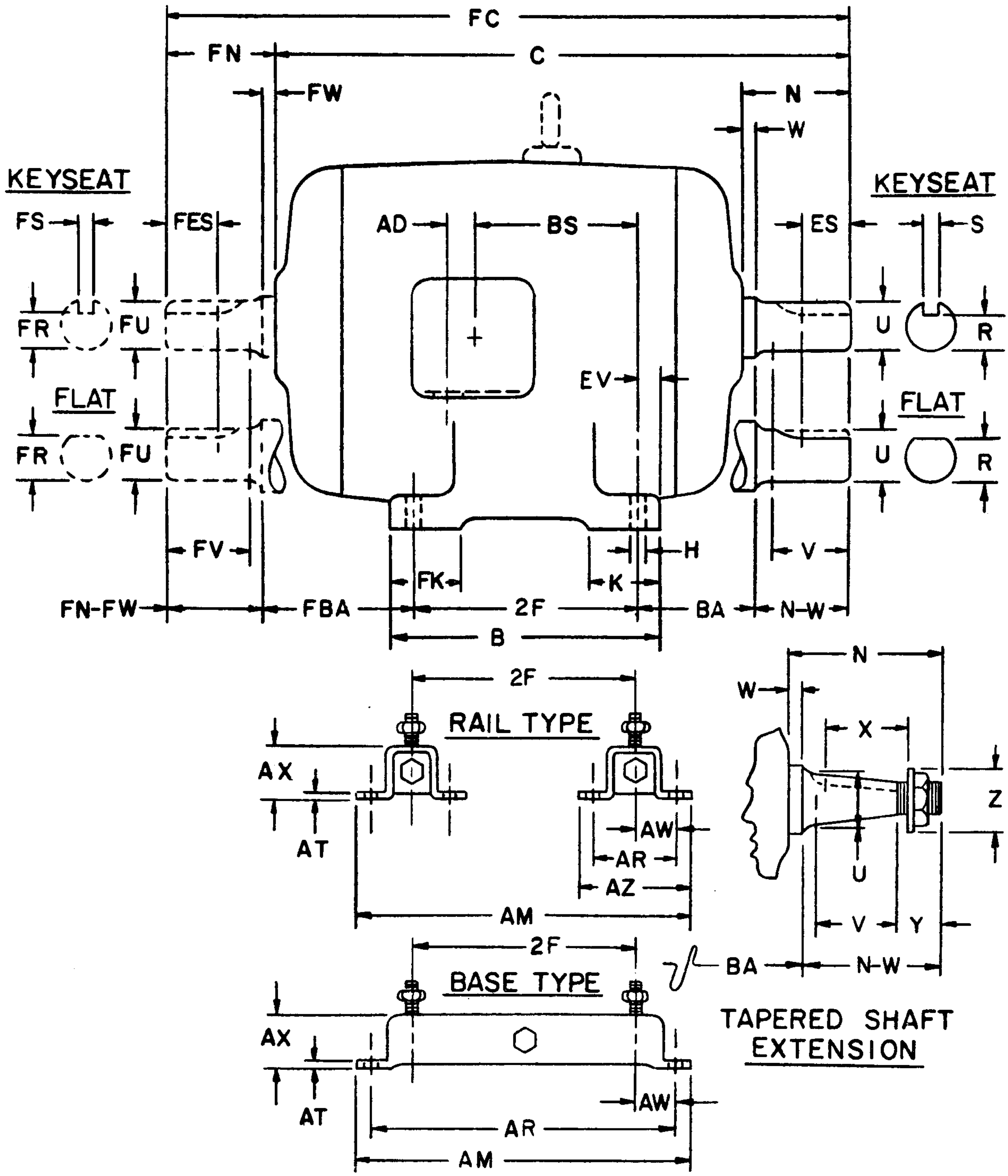


FIGURE A-1 LETTERING OF DIMENSION SHEETS FOR FOOT-MOUNTED MACHINES — SIDE VIEW

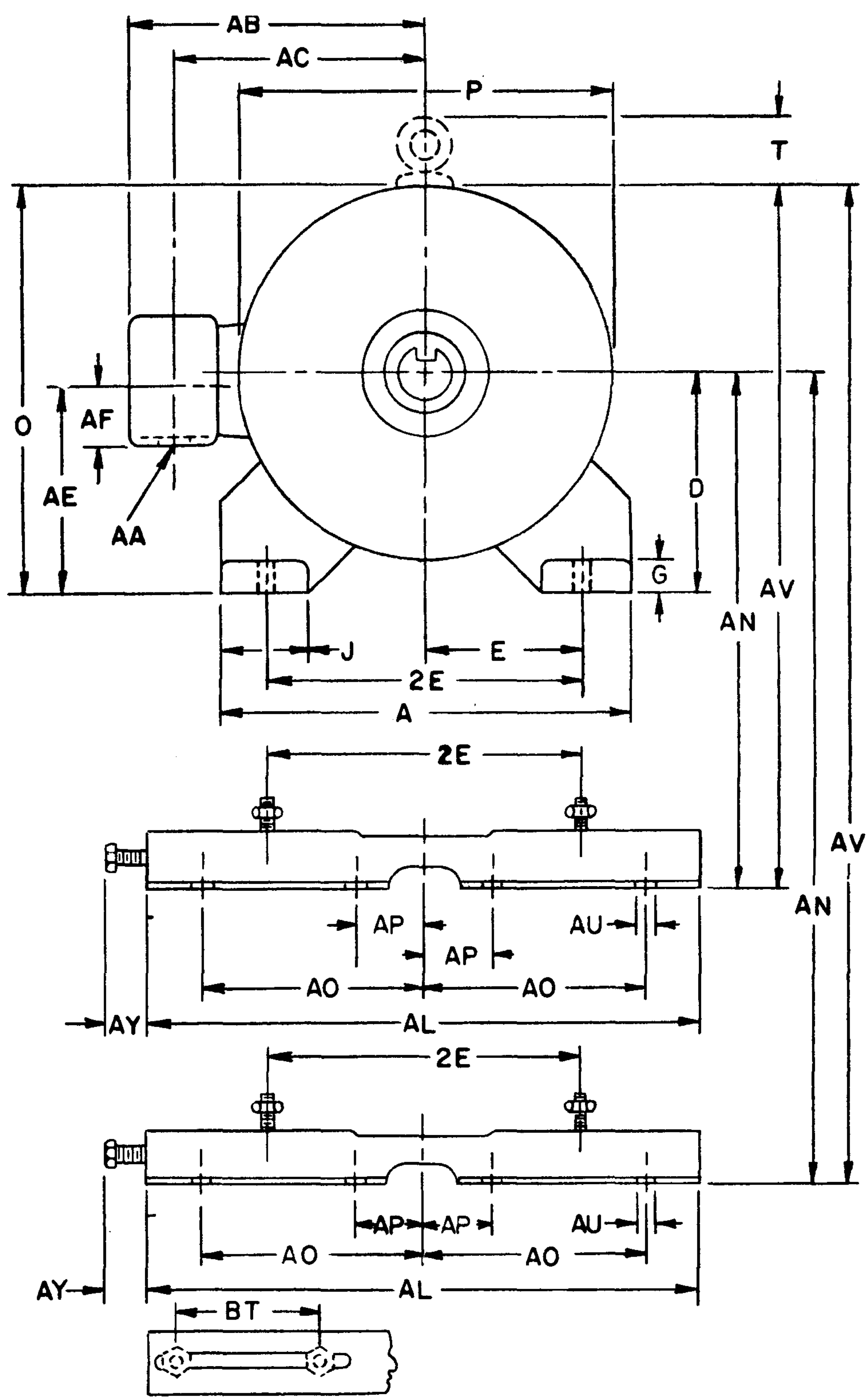


FIGURE A-2 LETTERING OF DIMENSION SHEETS FOR FOOT-MOUNTED MACHINES – DRIVE END VIEW

TABLE A-3

DIMENSIONS FOR ALTERNATING-CURRENT FOOT-MOUNTED MOTORS AND GENERATORS WITH SINGLE STRAIGHT-SHAFT EXTENSION

Frame Designation	A Max	B Max	D*	E†	2F†	BA	H†	U	N-W	V Min	Keyseat R	Keyseat ES Min	Keyseat S	AA‡
42	...	...	2.62	1.75	1.69	2.06	0.28 slot	0.3750	1.12	...	0.328–0.313 flat	...	...	...
48	...	...	3.00	2.12	2.75	2.50	0.34 slot	0.5000	1.50	...	0.453–0.438 flat	...	...	...
48H	...	...	3.00	2.12	4.75	2.50	0.34 slot	0.5000	1.50	...	0.453–0.438 flat	...	...	...
56	...	...	3.50	2.44	3.00	2.75	0.34 slot	0.6250	1.88	...	0.517–0.502	1.41	0.190–0.188	...
56H	...	...	3.50	2.44	5.00	2.75	0.34 slot	0.6250	1.88	...	0.517–0.502	1.41	0.190–0.188	...
143T	7.0	6.0	3.50	2.75	4.00	2.25	0.34 hole	0.8750	2.25	2.00	0.771–0.756	1.41	0.190–0.188	¾
145T	7.0	6.0	3.50	2.75	5.00	2.25	0.34 hole	0.8750	2.25	2.00	0.771–0.756	1.41	0.190–0.188	¾
182T	9.0	6.5	4.50	3.75	4.50	2.75	0.41 hole	1.1250	2.75	2.50	0.986–0.971	1.78	0.252–0.250	¾
184T	9.0	7.5	4.50	3.75	5.50	2.75	0.41 hole	1.1250	2.75	2.50	0.986–0.971	1.78	0.252–0.250	¾
213T	10.5	7.5	5.25	4.25	5.50	3.50	0.41 hole	1.3750	3.38	3.12	1.201–1.186	2.41	0.314–0.312	1
215T	10.5	9.0	5.25	4.25	7.00	3.50	0.41 hole	1.3750	3.38	3.12	1.201–1.186	2.41	0.314–0.312	1
254T	12.5	10.8	6.25	5.00	8.25	4.25	0.53 hole	1.625	4.00	3.75	1.416–1.401	2.91	0.377–0.375	1¼
256T	12.5	12.5	6.25	5.00	10.00	4.25	0.53 hole	1.625	4.00	3.75	1.416–1.401	2.91	0.377–0.375	1¼
284T	14.0	12.5	7.00	5.50	9.50	4.75	0.53 hole	1.875	4.62	4.38	1.591–1.576	3.28	0.502–0.500	1½
284TS	14.0	12.5	7.00	5.50	9.50	4.75	0.53 hole	1.625	3.25	3.00	1.416–1.401	1.91	0.377–0.375	1½
286T	14.0	14.0	7.00	5.50	11.00	4.75	0.53 hole	1.875	4.62	4.38	1.591–1.576	3.28	0.502–0.500	1½
286TS	14.0	14.0	7.00	5.50	11.00	4.75	0.53 hole	1.625	3.25	3.00	1.416–1.401	1.91	0.377–0.375	1½
324T	16.0	14.0	8.00	6.25	10.50	5.25	0.66 hole	2.125	5.25	5.00	1.845–1.830	3.91	0.502–0.500	2
324TS	16.0	14.0	8.00	6.25	10.50	5.25	0.66 hole	1.875	3.75	3.50	1.591–1.576	2.03	0.502–0.500	2
326T	16.0	15.5	8.00	6.25	12.00	5.25	0.66 hole	2.125	5.25	5.00	1.845–1.830	3.91	0.502–0.500	2
326TS	16.0	15.5	8.00	6.25	12.00	5.25	0.66 hole	1.875	3.75	3.50	1.591–1.576	2.03	0.502–0.500	2
364T	18.0	15.2	9.00	7.00	11.25	5.88	0.66 hole	2.375	5.88	5.62	2.021–2.006	4.28	0.627–0.625	3
364TS	18.0	15.2	9.00	7.00	11.25	5.88	0.66 hole	1.875	3.75	3.50	1.591–1.576	2.03	0.502–0.500	3
365T	18.0	16.2	9.00	7.00	12.25	5.88	0.66 hole	2.375	5.88	5.62	2.021–2.006	4.28	0.627–0.625	3
365TS	18.0	16.2	9.00	7.00	12.25	5.88	0.66 hole	1.875	3.75	3.50	1.591–1.576	2.03	0.502–0.500	3
404T	20.0	16.2	10.00	8.00	12.25	6.62	0.81 hole	2.875	7.25	7.00	2.450–2.435	5.65	0.752–0.750	3
404TS	20.0	16.2	10.00	8.00	12.25	6.62	0.81 hole	2.125	4.25	4.00	1.845–1.830	2.78	0.502–0.500	3
405T	20.0	17.8	10.00	8.00	13.75	6.62	0.81 hole	2.875	7.25	7.00	2.450–2.435	5.65	0.752–0.750	3
405TS	20.0	17.8	10.00	8.00	13.75	6.62	0.81 hole	2.125	4.25	4.00	1.845–1.830	2.78	0.502–0.500	3
444T	22.0	18.5	11.00	9.00	14.50	7.50	0.81 hole	3.375	8.50	8.25	2.880–2.865	6.91	0.878–0.875	3
444TS	22.0	18.5	11.00	9.00	14.50	7.50	0.81 hole	2.375	4.75	4.50	2.021–2.006	3.03	0.627–0.625	3
445T	22.0	20.5	11.00	9.00	16.50	7.50	0.81 hole	3.375	8.50	8.25	2.880–2.865	6.91	0.878–0.875	3
445TS	22.0	20.5	11.00	9.00	16.50	7.50	0.81 hole	2.375	4.75	4.50	2.021–2.006	3.03	0.627–0.625	3

All dimensions in inches.

* Dimension D will never be greater than the above values for rigid-base motors. However, it may be less, so that shims are usually required for coupled or geared machines. When the exact dimension is required, shims up to 0.03 inch may be necessary on frame sizes whose D dimension is 8.00 inches or less; on larger frames, shims up to 0.06 inch may be necessary. No tolerances have been established for the D dimension of resilient mounted motors.

† Frames 42, 48, 48H, 56 and 56H—The tolerance for the 2F dimension shall be ±0.03 inch and for the H dimension (width of slot) shall be +0.02 inch, −0 inch.
Frames 143T to 445T, inclusive—The tolerance for the 2E and 2F dimensions shall be ±0.03 inch and for the H dimension shall be +0.05 inch, −0 inch.

‡ For dimensions of clearance holes, see MG 1-11.07.

NOTE I—For the meaning of the letter dimensions, see MG 1-11.02 and Fig. 11-1 and 11-2.

NOTE II—For additional tolerances on shaft extension diameters and keyseats, see MG 1-11.08.

NOTE III—It is recommended that all machines with keyseats cut in the shaft extension for pulley, coupling, pinion, etc., be furnished with a key unless otherwise specified by the purchaser.

NOTE IV—Frames 42, 48, 48H, 56, 56H—If the shaft extension length of the motor is not suitable for the application, it is recommended that deviations from this length be in 0.25-inch increments.

Suggested Standard for Future Design 1-21-1964, revised 8-19-1964; 11-12-1964; 7-7-1965; 11-11-1965; 7-13-1967, NEMA Standard 7-16-1969, revised 11-13-1969; 11-12-1970; 7-14-1971.

● Title and BA dimensions revised editorially.

APPENDIX B

INDUSTRIAL AND COMMERCIAL SIC CATEGORIES

TABLE B-1

INDUSTRIAL CLASSIFICATIONS

Division D – Manufacturing

Major Group	
19	Ordnances and accessories
20	Food and kindred products
21	Tobacco manufactures
22	Textile mill products
23	Apparel and other finished products made from fabrics and similar materials
24	Lumber and wood products, except furniture
25	Furniture and fixtures
26	Paper and allied products
27	Printing, publishing, and allied industries
28	Chemicals and allied products
29	Petroleum refining and related industries
30	Rubber and miscellaneous plastics products
31	Leather and leather products
32	Stone, clay, glass, and concrete products
33	Primary metal industries
34	Fabricated metal products, except machinery and transportation equipment
35	Machinery, except electrical
36	Electrical and electronic machinery, equipment, and supplies
37	Transportation equipment
38	Measuring, analyzing, and controlling instruments: photographic, medical and optical goods; watches and clocks
39	Miscellaneous manufacturing industries

Source: Department of Commerce Industrial Index.

TABLE B-2

COMMERCIAL CLASSIFICATIONS

Division F – Wholesale Trade

Major Group	
50	Wholesale trade – durable goods
51	Wholesale trade – nondurable goods
	Division G – Retail Trade
52	Building materials, hardware, garden supply, and mobile home dealers
53	General merchandise stores
54	Food stores
55	Automotive dealers and gasoline service stations
56	Apparel and accessory stores
57	Furniture, home furnishings, and equipment stores
58	Eating and drinking places
59	Miscellaneous retail
	Division H – Finance, Insurance, and Real Estate
60	Banking
61	Credit agencies other than banks
62	Security and commodity brokers, dealers, exchanges, and services
63	Insurance
64	Insurance agents, brokers, and service
65	Real estate
66	Combinations of real estate, insurance, loans, law offices
67	Holding and other investment offices
	Division I – Services
70	Hotels, rooming houses, camps, and other lodging places
72	Personal services
73	Business services
75	Automotive repair, services, and garages
76	Miscellaneous repair services
78	Motion pictures
79	Amusement and recreation services, except motion pictures
80	Health services
81	Legal services
82	Educational services
83	Social services
84	Museums, art galleries, botanical and zoological gardens
86	Membership organizations
89	Miscellaneous services
	Division J – Public Administration
91	Executive, legislative, and general government, except finance
92	Justice, public order, and safety
93	Public finance, taxation, and monetary policy
94	Administration of human resources programs
95	Administration of environmental quality and housing programs
96	Administration of economic programs
97	National security and international affairs

Source: Department of Commerce Industrial Index

APPENDIX C

ELECTRICAL ENERGY CONSUMPTION BY INDUSTRY

TABLE C-1

ELECTRIC ENERGY CONSUMPTION AS A PERCENT OF TOTAL ENERGY CONSUMPTION (1954-1971)
(1972 Census of Manufactures, Department of Commerce)

	Total Purchased Fuels and Electric Energy (kW-hr equiv. x 10^6)	Electric Energy Purchased and Generated (kW-hr x 10^6)	Percent of Total
1954	2,220,212.0	247,787.0	11.16
1958	2,417,309.0	319,759.0	13.23
1962	2,875,291.0	388,222.0	13.50
1967	3,461,407.3	505,820.9	14.61
1971	3,850,180.4	600,530.5	15.60

TABLE C-2

ELECTRIC ENERGY PURCHASED AND GENERATED
BY INDUSTRY (1954-1971)
(1972 Census of Manufactures, Department of Commerce)

	Quantity Purchased (million kW-hr)	Generated Less Sold (million kW-hr)	Total Consumption (million kW-hr)
1954	187,148.0	60,639.0	247,787.0
1958	252,909.0	66,850.0	319,759.0
1959	281,301.0	69,291.0	350,592.0
1960	291,949.0	70,016.0	361,965.0
1961	298,325.0	68,533.0	366,858.0
1962	313,961.0	74,261.0	388,222.0
1963	333,512.0	72,949.0	406,461.0
1964	357,292.0	79,740.0	437,032.0
1965	373,428.0	80,453.0	453,881.0
1966	399,390.0	80,500.0	479,890.0
1967	427,465.1	78,355.8	505,820.9
1968	458,908.4	82,752.2	541,660.6
1969	497,015.7	83,351.7	580,367.4
1970	500,768.7	83,327.3	584,096.0
1971	517,780.4	82,750.1	600,530.5

TABLE C-3

ELECTRIC ENERGY CONSUMPTION BY 2-DIGIT SIC INDUSTRY GROUPS AS A PERCENT OF TOTAL FOR 1971*

SIC Code	Industry Group	1971 Rank	Electric Energy Quantity Purchased (million kW-hr)	Electric Energy Generated Less Sold (million kW-hr)	SIC Total (million kW-hr)	% of Total** Electric Energy	Cumulative % of Total
33	Primary Metal Industries	1	122,406.4	24,613.3	147,019.7	24.45	24.45
28	Chemicals and Allied Products	2	99,632.2	19,563.4	119,195.6	19.85	44.30
26	Paper and Allied Products	3	34,999.4	25,384.3	60,383.7	10.06	54.36
20	Food and Kindred Products	4	35,449.7	2,636.5	38,086.2	6.34	60.70
29	Petroleum and Coal Products	5	23,690.3	5,429.1	29,119.4	4.85	65.55
37	Transportation Equipment	6	27,474.9	(s)	27,474.9	4.58	70.13
32	Stone, Clay, and Glass Products	7	24,850.6	894.2	25,744.8	4.29	74.42
22	Textile Mill Products	8	24,952.2	506.5	25,458.7	4.24	78.66
36	Electrical Equipment and Supplies	9	23,569.2	183.0	23,752.2	3.96	82.62
35	Machinery, except Electrical	10	22,322.7	373.1	22,695.8	3.78	86.40
34	Fabricated Metal Products	11	20,308.2	126.2	20,434.4	3.40	89.80
30	Rubber and Plastics Products	12	16,396.6	668.3	17,064.9	2.84	92.64
24	Lumber and Wood Products	13	9,314.6	1,087.0	10,401.6	1.73	94.37
27	Printing and Publishing	14	9,595.6	31.5	9,627.1	1.60	95.97
23, 25, 38, 31, 21, 39 and 19	Remaining Industries	15-21	–	–	23,073.1	4.03	100.00
						100.00	

*1972 Census of Manufactures, Department of Commerce

**600,530.5 million kW-hr

(s) = not published

TABLE C-4

ELECTRIC ENERGY CONSUMPTION BY 3-DIGIT SIC INDUSTRY GROUPS AS A PERCENT OF TOTAL FOR 1971*

SIC Code	Industry Group	1971 Rank	Electric Energy Quantity Purchased (million kW-hr)	Electric Energy Generated Less Sold (million kW-hr)	SIC Total (million kW-hr)	% of Total** Electric Energy	Cumulative % of Total
281	Industrial Chemicals	1	75,200	15,800	91,000	15.2	15.2
331	Blast Furnace and Basic Steel Products	2	50,000	12,300	62,300	10.4	25.6
333	Primary Nonferrous Metals	3	49,900	12,200	62,100	10.3	35.9
262	Papermills, except Building Paper	4	16,800	12,500	29,300	4.9	40.8
291	Petroleum Refining	5	22,600	5,400	28,000	4.7	45.5
263	Paperboard Mills	6	6,700	10,400	17,100	2.8	48.3
282	Plastics Materials and Synthetics	7	13,700	3,200	16,900	2.8	51.1
371	Motor Vehicles and Equipment	8	15,800	(s)	15,800	2.6	53.7
335	Nonferrous Rolling and Drawing	9	9,900	100	10,000	1.7	55.4
307	Miscellaneous Plastic Products	10	9,200	(s)	9,200	1.5	56.9
324	Cement, Hydraulic	11	8,500	600	9,100	1.5	58.4
372	Aircraft and Parts	12	8,500	(s)	8,500	1.4	59.8
332	Iron and Steel Foundries	13	7,900	(s)	7,900	1.3	61.1
201	Meat Products	14	6,000	200	6,200	1.0	62.1
204	Grain Mill Products	15	5,300	800	6,100	1.0	63.1
222	Weaving and Finishing Mills, Wool	16	5,600	100	5,700	0.95	64.05
221	Weaving Mills, Cotton	17	5,400	200	5,600	0.93	64.98
209	Miscellaneous Food and Kindred Products	18	5,500	(s)	5,500	0.92	65.90
228	Yarn and Thread Mills	19	5,500	(s)	5,500	0.92	66.82
203	Canned, Cured, and Frozen Food	20	5,400	(s)	5,400	0.90	67.72
367	Electronic Components and Accessories	21	5,200	(s)	5,200	0.87	68.59
322	Glass and Glassware, Pressed or Blown	22	5,000	(s)	5,000	0.83	69.42

*1972 Census of Manufactures, Department of Commerce

**600,530.5 million kW-hr

(s) not published

TABLE C-5

ELECTRIC ENERGY CONSUMPTION BY 4-DIGIT SIC INDUSTRY GROUPS FOR 1967 AND 1971†

SIC Code	Industry Group	1971 Rank*	1971 Electric Energy Quantity Purchased (million kW-hr)	1971 Electric Energy Generated Less Sold (million kW-hr)	1971 Estimated Total Consumption**	1971 % of Total Electric Energy	1967 Electric Energy Quantity Purchased (million kW-hr)	1967 Electric Energy Generated Less Sold (million kW-hr)
3334	Primary Aluminum	1	42,711.6	10,976.3	53,687.9	8.9	41,956.9	11,648.0
3312	Blast Furnaces & Steel Mills	2	40,258.9	(D)	49,258.9	8.2	34,704.8	6,332.4
2819	Industrial Inorganic Chemicals, n.e.c.	3	33,460.7	(D)	35,460.7	5.9	45,924.8	2,693.4
2911	Petroleum Refining	4	22,524.1	5,565.1	28,089.2	4.7	17,474.0	4,088.0
2818	Industrial Organic Chemicals, n.e.c.	5	19,700.8	(D)	30,700.8	5.1	13,378.0	11,385.6
2621	Papermills, except Building Paper	6	16,955.4	12,515.9	29,471.3	4.9	12,776.9	11,770.1
2812	Alkalies and Chlorine	7	9,142.6	(D)	12,142.6	2.0	9,298.0	3,021.0
3714	Motor Vehicle Parts and Accessories	8	8,805.9	(D)	8,805.9	1.5	6,733.6	87.0
2813	Industrial Gases	9	8,548.6	(D)	8,548.6	1.4	6,776.4	274.0
3241	Cement, Hydraulic	10	8,514.6	607.1	9,121.7	1.5	7,495.2	923.0
3079	Miscellaneous Plastic Products	11	8,171.8	(D)	8,171.8	1.4	4,826.8	3.8
3313	Electrometallurgical Products	12	7,688.8	(D)	10,988.8	1.8	7,852.0	3,353.7
2631	Paperboard Mills	13	6,740.1	10,384.6	17,124.7	2.9	5,294.3	9,507.8
3711	Motor Vehicles	14	6,676.5	(D)	6,676.5	1.1	***	87.0
2821	Plastic Materials and Resins	15	6,358.4	(D)	6,358.4	1.1	4,367.6	439.0
						52.4		

(D) Withheld to avoid disclosing figures for individual companies

* Ranked on the basis of purchased electrical energy only

** Derived from Purchased and Generated kW-hr; where 1971 values for Generated are (D), an estimate is made based on 1967 data

*** 3711 and 3712 reported as one figure 5,714.2

† 1972 Census of Manufactures, Department of Commerce

TABLE C-6

ELECTRIC ENERGY ALLOCATIONS FOR THE INDUSTRIAL SECTOR TO OBTAIN MOTOR DRIVE CONSUMPTION

	1971 Consumption (million kW-hr)	
Total Consumption — All Purposes		600,500
Allocations		
Electrolytic Processes (attributed to industrial chemicals and primary nonferrous metals)	91,100	
Direct Process Heat (attributed to blast furnace and basic steel, and iron and steel foundries)	14,000	
Other Direct Heat and Electrolytic Uses (miscellaneous industry groups)	4,000	
Lighting and Miscellaneous Services	33,100	
Total Allocations		142,200
Motor Drive Consumption		458,300

TABLE C-7

ELECTRIC ENERGY CONSUMPTION FOR MOTOR DRIVE PURPOSES BY PRINCIPAL INDUSTRY USERS (1971)

SIC Code	Industry Group	1971 Rank*	Motor Drive Consumption** (million kW-hr)	% of Total Motor Drive Consumption***
281	Industrial Chemicals	1	54,200	11.8
331	Blast Furnace and Basic Steel Products	2	50,700	11.1
262	Papermills, except Building Paper	3	29,300	6.4
291	Petroleum Refining	4	27,900	6.1
263	Paperboard Mills	5	17,000	3.7
282	Plastics Materials & Synthetics	6	16,600	3.6
371	Motor Vehicles & Equipment	7	14,600	3.2
335	Nonferrous Rolling & Drawing	8	9,700	2.1
324	Cement, Hydraulic	9	9,000	2.0
307	Miscellaneous Plastics Products	10	7,700	1.7
372	Aircraft & Parts	11	7,600	1.7
333	Primary Nonferrous Metals	12	6,600	1.4
204	Grain Mill Products	13	5,900	1.3
201	Meat Products	14	5,600	1.2
222	Weaving & Finishing Mills, Wool	15	5,400	1.2
221	Weaving Mills, Cotton	16	5,400	1.2
209	Miscellaneous Food & Kindred Products	17	5,300	1.2
228	Yarn & Thread Mills	18	5,300	1.2
				62.1

*Ranked according to motor drive consumption

**Consumption by industry after electrolytic, direct heat, lighting, heating/AC, and miscellaneous allocations are subtracted

***Total motor drive consumption is 458,300 million kW-hr

TABLE C-8

ENERGY ALLOCATIONS FOR 3- AND 4-DIGIT SIC INDUSTRY GROUPS TO OBTAIN MOTOR DRIVE CONSUMPTION ESTIMATES (1971 consumption in million kW-hr from 1972 Census of Manufactures)

SIC Code	Industry Group	Electric Energy Quantity Purchased	Electric Energy Generated Less Sold	(A) Estimated Total Consumption	(B) Major Electrolytic Processes	Remarks	(C) Direct Process Heat	(D) Lighting HVAC and Misc.	(E) Subtotal (A-B-C)	(E-D) Estimated Motor Drive Consumption	Reranked By Motor Drive Consumption
281	Industrial Chemicals	75,356.4	15,838.9	91,200	36,600			436	54,600	54,200	1
2812	Alkalies and Chlorine	9,142.6	3,000*	12,100	12,000	Chlorine/Caustic			100		
2813	Industrial Gases	8,548.6		8,500					8,500		
2818	Industrial Organic Chemicals, n.e.c.	19,700.8	11,000*	30,700	16,300	Chlorine/Caustic			14,400		
2819	Industrial Inorganic Chemicals, n.e.c.	33,460.7	2,000*	35,400	8,300	Elemental Phosphorus			27,100		
2815, 16	Remainder	4,503.8		4,500					4,500		
331	Blast Furnace & Basic Steel	49,931.5	12,291.6	62,200			10,500	1,001	51,700	50,700	2
3312	Blast Furnaces & Steel Mills	40,258.9	9,000*	49,300			10,500		38,800		
3313	Electrometallurgical Products	7,688.8	3,300*	11,000					11,000		
333	Primary Nonferrous Metals	49,022.3	12,165.3	61,200	54,500			107	6,700	6,600	12
3331	Primary Copper	1,355.1	200*	1,600	400				1,200		
3333	Primary Zinc	1,547.1	900*	2,400	1,300				1,100		
3334	Primary Aluminum	42,711.6	10,976.3	53,700	51,000				2,700		
3339	Primary Nonferrous Metals, n.e.c.	3,195.9		3,200	1,800	Magnesium			1,400		
262	Papermills, except Building Paper	16,955.4	12,515.9	29,500				238	29,500	29,300	3
2621											
291	Petroleum Refining	22,524.1	5,565.1	28,100				193	28,100	27,900	4
2911											
263	Paperboard Mills	6,740.1	10,384.6	17,100				119	17,100	17,100	5
2631											
282	Plastics Materials & Synthetics	13,659.0	3,243.0	16,900				325	16,900	16,600	6
2821	Plastics Materials & Resins	6,358.4		6,400					6,400		
2822	Synthetic Rubber	1,946.5		1,900					1,900		
2823	Cellulosic Manmade Fibers	510.9	1,700*	2,200					2,200		
2824	Organic Fibers, Noncellulosic	4,843.1	1,000*	5,800					5,800		
371	Motor Vehicles & Equipment	16,017.6		16,000				1,405	16,000	14,600	7
3711	Motor Vehicles	6,676.5		6,700					6,700		
3714	Motor Vehicle Parts & Accessories	8,805.9		8,800					8,800		
335	Nonferrous Rolling & Drawing	9,910.8	122.4	10,000				333	10,000	9,700	8
307	Miscellaneous Plastics Products	8,171.8		8,200				508	8,200	7,700	10
3079											
324	Cement Hydraulic	8,514.6	607.1	9,100				52	9,100	9,000	9
3241											
372	Aircraft and Parts	8,541.7	(D)	8,500				928	8,500	7,600	11
332	Iron & Steel Foundries	7,872.1	46.8	7,900			3,500	381	4,400	4,000	

*Estimate derived from 1967 Census, for 4 digit classification, 1971 shown as (D)

TABLE C-9

INTEGRAL HORSEPOWER MOTORS AND GENERATORS PURCHASED BY SELECTED INDUSTRIES (1967)

SIC Code	Industry Group	Number of Units
3585	Refrigeration Machinery	4,240,000
3561	Pumps and Compressors	366,600
3522	Farm Machinery	133,700
3564	Blowers and Fans	128,900
3541	Machine Tools, Metal-cutting	110,800
3519	Internal Combustion Engines, n.e.c.	98,600
3559	Special Industry Machines, n.e.c.	95,800
3553	Woodworking Machinery	73,200
3634	Electric Housewares and Fans	64,400
3574	Calculating and Accounting Machines	57,600
3551	Food Products Machinery	53,200
3589	Service Industry Machines, n.e.c.	52,700
3433	Heating Equipment, except Electric	42,500
3621	Transformers	38,300
3537	Hoists, Cranes, and Monorails	33,500
3542	Machine Tools, Metal-forming	26,200
3582	Commercial Laundry Equipment	25,200
3535	Conveyors and Conveying Equipment	25,100
3569	General Industrial Machinery, n.e.c.	23,900
3554	Paper Industries Machinery	20,600
3721	Aircraft	13,300
3555	Printing Trades Machinery	13,100
3639	Household Appliances, n.e.c.	10,600
3532	Mining Machinery	8,500
3534	Elevators and Moving Stairways	7,700
3731	Ship Building and Repairing	3,200
3544	Special Dies, Tools, Jigs, and Fixtures	2,400
3722	Boat Building and Repairing	1,000
	All other industries, including Steam Engines & Turbines, Typewriters, Electronic Computing Machines, Automatic Merchandising Machines, Household Cooking Equipment, Household Refrigerators and Freezers, Household Vacuum Cleaners, Aircraft Equipment, Locomotives and Parts, Guided Missiles, and Aircraft Engines and Parts	16,400
		5,787,000

TABLE C-10

FRACTIONAL HORSEPOWER MOTORS PURCHASED BY SELECTED INDUSTRIES (1967)
(other than timing motors, synchronous, and subsynchronous)

SIC Code	Industry Group	Number of Units
3941	Games and Toys	28,940,200
3632	Household Refrigerators and Freezers	12,555,000
3585	Refrigeration Machinery	9,979,000
3633	Household Laundry Equipment	5,368,300
3714	Motor Vehicle Parts and Accessories	2,521,600
3639	Household Appliances	2,151,000
3561	Pumps and Compressors	1,617,000
3631	Household Cooking Equipment	1,345,600
3433	Heating Equipment, except Electric	1,201,100
3635	Household Vacuum Cleaners	914,600
	All Other Industries	1,813,300
		68,406,700

APPENDIX D

TECHNICAL AND ECONOMIC ANALYSIS

A. RELATIONSHIPS IN MOTOR MAGNETIC CIRCUITS

Following is a general discussion of the various relationships existing in magnetic circuits and the manner in which they may be changed to influence motor efficiencies.

a. Definitions

(1) Magnetomotive force F – the force required to drive magnetic flux around a magnetic circuit;

(2) Magnetic flux ϕ – magnetic lines induced in a magnetic core material by current in a surrounding electrical conductor;

(3) Magnetic intensity H – the strength of a magnetic field induced by current in a surrounding electrical conductor;

(4) Magnetic flux density **B** – magnetic flux per unit area of magnetic circuit; and

(5) Permeability μ – the ratio of magnetic induction and magnetizing force.

b. Basic Relationships – Three-Phase Machines

$$\text{Magnetomotive force } F = 2.7 \frac{N_p}{p} I \text{ ampere-turns per pole.} \quad (1)$$

In magnetic circuits containing an air gap, the mmf (F) required is determined essentially by the air gap length due to the lower permeability of air as compared to metal cores. In this case:

$$F \doteq \frac{Bg}{\mu_o} = 4 \times 10^{-7}/\text{amp.m} \quad (2)$$

where g = air gap length

μ_o = permeability of free space

$$\text{Magnetic flux density } \mathbf{B} = \frac{\mu_o}{g} \times 2.7 \frac{N_p}{p} I \quad (3)$$

$$\text{Magnetic flux } \phi = \mathbf{B} \times A \quad (4)$$

where A = cross-sectional area of magnetic circuit normal to the lines of flux.

Motor losses

Core loss = eddy current loss + hysteresis loss

Eddy current loss, $P_e = k_e f^2\ B^2\ \tau^2$ (5)

where

k_e = a constant of the core material

τ = lamination thickness.

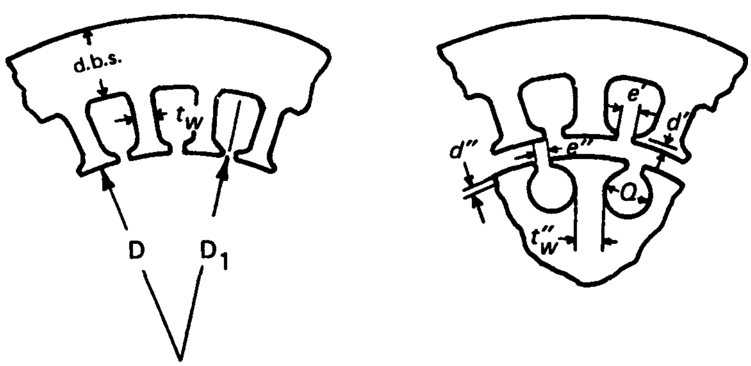
Hysteresis loss $P_h \propto k_h fB^n$ (6)

where n (Steinmetz exponent) varies between 1.5 and 2.5, commonly taken as 1.6

$I^2 R$ losses = stator copper loss + rotor "copper" loss

Stator copper loss = $I_1^2 R$

Rotor copper loss = S x (power across air gap)



LAMINATION DIMENSIONS

Stator:

Inside diameter, $D = \dfrac{OD - 0.647}{1.175 + (1.03/p)}$ p = number of poles

Diameter to slot bottoms: $D_1 = 1.175D + 0.647$

Tooth width: $T_w = \dfrac{1.35D}{S_1}$ S_1 = number of stator slots

Air gap radial length: $\Delta = 0.0016D + 0.001L + 0.0072$

L = axial length of core

Rotor:

Slot openings

$$e'' = 0.01D + 0.045$$

$$d'' = 0.00677D + 0.0304$$

Rotor slot diameter

$$Q = \frac{1.95D - 0.236}{S_2 + \pi} \qquad S_2 = \text{number of rotor slots}$$

Rotor tooth width

$$T_w'' = 1.15 \frac{D}{S_2}$$

B. EFFECT OF REDUCING FLUX DENSITY B

Flux density B affects several aspects of motor performance, including no-load core losses (eddy current and hysteresis), magnetic intensity, and magnetomotive force (and thereby a portion of current). Each will be discussed briefly in the following paragraphs relative to the effect of reducing flux density.

1. No-Load Core Losses

Both eddy current (P_e) and hysteresis losses (P_h) vary exponentially with flux density; P_e as the square of B and P_h, according to the Steinmetz exponent (n) which ranges between 1.5 and 2.5. If we assume all other factors remain constant, then

$$P_e = K_e B^2$$

and

$$P_h = K_h B^n$$

Since flux density $B = \phi/A$, an increase in axial core length l will increase the cross-sectional area A of the magnetic circuit. For constant flux ϕ, the flux density B will be reduced.

As an example, if core length l is increased by 15% (reducing B by 15%), P_e and P_h will vary as follows:

$$P_{e1} \propto B_1^2 \text{ and } P_{e2} \propto (.85B_1)^2$$
$$\propto .7225 B_1^2$$

Therefore, a 15% reduction in B results in a 27.75% decrease in P_e

$P_h \alpha B^n$ where n varies between 1.5 and 2.5.

(a) N = 1.5 $\quad P_{h1} \alpha (B_1)^{1.5}$

$$P_{hz} \alpha (.85B_1)^{1.5}$$

$$\alpha (.7837)\, B_1{}^{1.5}$$

(b) N = 2.5 $\quad P_{h2} \alpha (.85B_1)^{2.5}$

$$\alpha (.6661B_1)^{2.5}$$

Therefore, a 15% reduction in flux density B will reduce P_h between 21.6% and 33.4%, depending upon the value of n (Steinmetz exponent). The usual value of n is 1.6 which results in a 22.9% decrease.

Core loss can be reduced between 21.6% and 33.4%, depending upon the relative magnitude of P_e and P_h as components of core loss.

2. Magnetomotive Force (mmf) – *F*

In a magnetic circuit containing an air gap, the following relationships for mmf can be established:

$$B = \mu \frac{Ni}{l} + \mu_o \frac{Ni}{g}$$

$$= \mu_o Ni \left[\frac{\mu_o}{l} + \frac{1}{g} \right]$$

If permeability, air gap length, and coil turns are constant, a reduction in flux density will reduce the required current. The actual relationship between B and the exciting force is non-linear, because of the saturation property of magnetic material. Therefore, the reduction in current I will be proportional to the reduction in B, the proportionality being determined by the relative permeability of the magnetic material.

APPENDIX E

EXCERPTS FROM TEST PROCEDURE FOR POLYPHASE INDUCTION MOTORS AND GENERATORS

Source: The Institute of Electrical and Electronics Engineers, In
(No. 112A, Sept. 1964). Reprinted by permission.

4. PERFORMANCE DETERMINATION

4.1 (All) **Temperature.**

4.2 (All) **Efficiency.** Efficiency is the ratio of output to input. The electric power is measured directly; the mechanical power may be measured directly or obtained by adding the losses to or subtracting them from the electric ower for generating or motoring action. Unless otherwise pecified, the efficiency shall be determined for rated voltge and frequency.

4.2.1 (All) **Measurement of Input and Output.** Direct measurements of input and output are always made on fractional-horsepower machines and generally on small machines, but such measurements become increasingly difficult with the equipment usually available as the size of the machine increases.

4.2.1.1 In general, the brake or dynamometer method is used on fractional-horsepower machines and the dynamometer method on machines up to about 200 horsepower. The pump-back method may be used with advantage on larger machines whenever duplicate machines are available. For large machines, the segregated-loss method is used. In all of these methods the precautions listed in paragraphs 3.1 to 3.6 shall be observed.

4.2.2 (A-B-C) **Direct Measurement Methods.** In all direct measurement method tests the electric and mechanical power are measured directly. The difference between the various methods lies in the manner of measuring mechanical power.

4.2.2.1 **Measurements.** Readings of watts, current, voltage, frequency, slip, torque, ambient temperature, and stator-coil end-winding temperature, or resistance, shall be obtained for six load points substantially equally spaced from one-quarter to one and one-half times rated load.

4.2.2.2 **Determination of Motor Performance.** The motor performance shall be determined as outlined in either Form B or Form E.

4.2.2.3 (A) METHOD A: **Brake.** Care shall be exercised in the construction and use of the brake and brake pulley. The "tare," if present, shall be carefully determined and compensated for. Performance of a machine shall be calculated as shown on Form B.

4.2.2.4 (B) METHOD B: **Dynamometer.** One method of measuring mechanical power of an induction machine is the dynamometer method. The power in watts is obtained from the following formula:

$$\text{Watts} = \frac{2\pi \times T \times \text{rpm} \times 746}{33{,}000} = 0.1420\, T \times \text{rpm}$$

where T is the torque of the dynamometer in pound-feet.

To obtain accurate results* the dynamometer rating shall not exceed three times the machine rating, and it shall be sensitive to a torque of 0.25 percent of the rated torque. Dynamometer correction shall be made as outlined in Form B.

4.2.2.5 (C) METHOD C: **Duplicate Machines.** This method of determining efficiency may be used when duplicate machines are available. The two machines are coupled together and electrically connected to two sources of power, the frequency of one being adjustable. One machine is operated as a motor at rated voltage and frequency, and the other is driven as a generator at rated voltage, but at lower frequency, to produce the desired load.

4.2.2.5.1 Readings shall be taken of the electric input and output, winding temperature, and slip of each machine. The test shall be repeated with the direction of power flow reversed. The frequency of the first machine remains unchanged while that of the second is raised to produce the desired load. The location of the instruments and instrument transformers shall not be changed.

4.2.2.5.2 By this reversal of power flow ordinary calibration errors of all instruments are minimized. Phase-angle errors of the instrument transformers are cumulative for motoring and generating tests. It is important to make accurate corrections for these phase-angle errors, since they will make the losses appear smaller than the true value. See paragraph 3.2.

4.2.2.5.3 The motor efficiency is obtained as follows:

(*a*) The stator I^2R loss at the temperature of test is calculated for each machine, using the observed currents.

(*b*) The motor rotor I^2R loss** is:
Motor Slip × (Motor Input—Stator I^2R Loss) where slip is expressed as a decimal and corrected for temperature in accordance with paragraph 4.4.1.

(*c*) The generator rotor I^2R loss** is:
Generator Slip × (Generator Output + Stator I^2R Loss)

(*d*) The combined stray-load loss is determined

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* Bearing friction in the dynamometer may cause scale readings to differ for the same value of electric power, depending upon whether the load is increasing or decreasing prior to reading. In that case the average of two sets of readings shall be taken. The first set shall be taken while gradually increasing the load, the second set while decreasing load, care being taken in each case not to overrun the points to be read. Curves of torque versus electric power shall be plotted for each set of readings, and the average of the curves shall be used.

It may be desirable to make a check test by operating the machine as a generator and the dynamometer as a motor. Errors in scales or instruments will occur in opposite directions during the two tests, but the errors will tend to cancel in the average, even though the individual errors may be large. The total losses will be equal to the mechanical input minus the electric output for generating action, or they will be equal to the electric input minus the mechanical output for motoring action. The stray-load losses shall be separately calculated for each case by subtracting from the total losses the stator I^2R loss at the temperature of test, the core loss, friction and windage loss, and rotor I^2R loss corresponding to the measured value of slip. The stray-load losses shall be calculated from data obtained at several load points and plotted against rotor I^2R loss. The stray-load-loss value shall be taken from the average of the motoring and generating curves. Adding this stray-load loss to the I^2R losses, corrected to the measured rated-load stator-winding temperature rise plus 25C, and the core loss and friction and windage loss gives the total losses. Refer to Form E.

The accuracy can also be increased by plotting the apparent stray-load losses against torque squared. A straight line is drawn as near as possible to all values of apparent stray-load losses. A straight line drawn through the origin and parallel to this line gives the values of stray-load losses to be used in performance determinations.

** See explanatory note in paragraph 4.3.2.1.

by subtracting from the total measured loss (the difference between input and output) the sum of the stator I^2R losses, rotor I^2R losses, core losses, and friction and windage losses of the two machines.

(*e*) The stray-load losses are assumed to be proportional to the square of the rotor current. The stray-load losses are taken as:

Motor Stray-Load Loss =

$$\left(\frac{\text{Motor Rotor } I^2R \text{ Loss}}{\text{Motor Rotor } I^2R \text{ Loss} + \text{Generator Rotor } I^2R \text{ Loss}}\right) \times \text{Combined Stray-Load Loss}$$

Generator Stray-Load Loss =

Combined Stray-Load Loss — Motor Stray-Load Loss

The average of the results obtained with the two directions of power flow shall be taken as the correct value of stray-load loss.

(*f*) The efficiency is then taken as:

Motor Efficiency =

$$\frac{\text{Electric Input} - \text{Total Motor Losses}}{\text{Electric Input}}$$

Refer to Form E for detailed work-up of results.

Generator Efficiency =

$$\frac{\text{Electric Output}}{\text{Electric Output} + \text{Total Generator Losses}}$$

Total losses equal the sum of the stator and rotor I^2R losses corrected to 25C ambient, core loss, friction and windage losses, and stray-load loss.

4.2.2.6 (D) METHOD D: **Calibrated Machines.** The method for determination of efficiency by use of a calibrated machine included in American Institute of Electrical Engineers Standard No. 500, Test Code for Polyphase Induction Machines, August, 1937, is no longer recognized.

4.2.3 (E-F) **Segregated-Loss Methods.** The input shall be measured as outlined in Method E or calculated as described in Method F. The output shall be determined by subtracting the losses from the input. The losses of an induction machine are:

Type of Loss	*Description*
(*a*) Friction and windage	Mechanical loss due to bearing (and brush) friction and windage
(*b*) Core	Loss in iron at no load
(*c*) Stator I^2R	I^2R loss in stator windings
(*d*) Rotor I^2R	I^2R loss in rotor windings (and brush-contact loss of wound-rotor machines)
(*e*) Stray load	Stray loss in iron and eddy-current losses in conductors
(*f*) Ventilating	Mechanical power required to propel separately driven fans where used to circulate the cooling gas through the machine

4.2.3.1 (E) METHOD E: **Input Measurements.** To obtain the required data, it is necessary to couple, belt, or gear the machine to a variable load. The same setup as used for the temperature test may be employed.

The required data are:

Stator resistance	*Watts input
No-load current and no-load losses	*Line current
*Rotor slip	Stray-load loss
*Temperature of stator coil end	

Form E is recommended for tabulating and calculating the performance. All necessary explanatory notes are included in this Form.

4.2.3.2 (F) METHOD F: **Equivalent Circuit Calculations.** When tests under load cannot be made, operating characteristics (efficiency, power factor, etc.) are calculated from the no-load and impedance data by the equivalent circuit. See Figure 1. Required constants are calculated using formulas on Form F-1 and are recorded on Form F-2. Form F-3 is a work sheet upon which the circuit calculations are made.

4.2.3.2.1 Values of constants determined from the foregoing formulas and test data may be entered on Form F-2.

4.2.3.2.2 The results of the calculations on Form F-3 shall be plotted in curve form from which the Summary of Characteristics on Form F-2 can be determined.

4.2.3.2.3 Accurate prediction of machine characteristics by the equivalent circuit will depend upon the closeness by which R_2 represents the actual rotor resistance to currents of low frequency. Most careful procedure during the low-frequency impedance test is imperative.

4.2.3.2.4 Form F-1 is arranged on the basis of X_1 and X_2 remaining constant throughout the range of operation of the machine. Should the impedance curve of current versus volts depart from a straight line in the range of currents under consideration, each column of calculations in Form F-3 shall use values of reactance obtained from this curve for the value of I_1 calculated in the column.

4.2.3.2.5 When a slip-ampere curve under load with stator-winding temperature of t_s is available, but input-power readings are not, Method F may be used to determine machine characteristics.

* These values shall be obtained for six load points ranging from one-quarter to one and one-half times full load.

In such cases R_2 is not determined from the low-frequency impedance test. The following procedure is used:

Use Form F-3 but start with line 2 with assumed value of $\frac{R_2}{S}$.

After reaching line 10, refer to slip-ampere curve and obtain value of S. R_2, if desired, is obtained by multiplication of assumed value of $\frac{R_2}{S}$ by this value of S. Determination of R_2 is not, however, necessary for the remainder of the calculation.

4.2.3.2.6 Maximum or breakdown torque as a motor is determined from Form F-3 using slip value

$$S = \frac{R_2}{\sqrt{R_1^2 + (X_1 + X_2)^2}}$$

APPENDIX F

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Partial Reproduction of
Rotating Electrical Machines

NOTE: **This extract from IEC Publication 34-2 is reproduced by permission of the International Electrotechnical Commission.**

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RECOMMANDATION DE LA CEI

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC RECOMMENDATION

Publication 34-2

Troisième édition — Third edition

1972

Machines électriques tournantes

Deuxième partie: Méthodes pour la détermination des pertes et du rendement des machines électriques tournantes à partir d'essais (à l'exclusion des machines pour véhicules de traction)

Rotating electrical machines

Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles)

Bureau Central de la Commission Electrotechnique Internationale

1, rue de Varembé

Genève, Suisse

ROTATING ELECTRICAL MACHINES

Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles)

SECTION ONE — GENERAL

1. Scope

This Recommendation applies to d.c. machines and to a.c. synchronous and induction machines of all sizes within the scope of IEC Publication 34-1. The principles can, however, be applied to other types of machines such as rotary convertors, a.c. commutator motors and single-phase induction motors for which other methods of determining losses are generally used.

2. Object

This Recommendation is intended to establish methods of determining efficiencies from tests, and also to specify methods of obtaining particular losses when these are required for other purposes.

3. General

Tests shall be conducted on a completely sound machine with all covers fitted in the manner required for normal service, with any devices for automatic voltage regulation not a composite part of the machine itself being made inoperative, unless otherwise agreed.

Measuring instruments and their accessories, such as measuring transformers, shunts and bridges used during the tests, unless otherwise specified, shall have an accuracy class not above 1.0 (IEC Publication 51, Recommendations for Indicating Electrical Measuring Instruments and their Accessories). Instruments for determining d.c. resistance shall be to accuracy class not above 0.5.

Instruments shall be selected to give readings over the effective range such that a fraction of a division is a small percentage of the actual reading and can be easily estimated.

On machines with adjustable brushes, the brushes shall be placed in the position corresponding to the specified rating. For measurements on no-load, the brushes may be placed on the neutral axis.

Speed of rotation may be measured by a stroboscopic method, digital counter or tachometer. When measuring slip, the synchronous speed should be determined from the supply frequency during the test.

When the over-all efficiency or the absorbed power is measured for a group of machines comprising two electrical machines, or a machine and a transformer, or a generator and its driving machine, or a motor and its driven machine, there is no need to indicate the individual efficiencies. If, however, these are given separately, they should be regarded as approximate.

3.1 *List of symbols*

A list of symbols used in the draft, with the general meanings attributed to each one, is given below:

I = current
I_l = load current at rated voltage
I_{lr} = main primary current at reduced voltage
I_o = no-load current at rated voltage
I_{or} = no-load current at reduced voltage
J = moment of inertia
n = rated speed, in revolutions per minute
P_l = power absorbed at rated voltage
P_{lr} = power absorbed by main primary winding at reduced voltage
s = slip
U = excitation voltage across terminals of main rheostat
U_e = total excitation voltage
U_n = rated voltage
U_r = reduced voltage for load test
φ = load phase angle at rated voltage
φ_r = load phase angle at reduced voltage
φ_o = no-load phase angle at rated voltage
φ_{or} = no-load phase angle at reduced voltage

4. **Definitions**

For definitions of general terms used in this Recommendation, reference should be made to the International Electrotechnical Vocabulary [IEC Publication 50].

For the purpose of this Recommendation, the following definitions apply:

4.1 *Efficiency*

The ratio of output to input expressed in the same units and usually given as a percentage.

4.2 *Total loss*

The difference between the input and the output.

4.3 *Braking test*

A test in which the mechanical power output of a machine acting as a motor is determined by the measurement of the shaft torque, by means of a brake or dynamometer, together with the rotational speed. Alternatively, a test performed on a machine acting as a generator, by means of a dynamometer to determine the mechanical power input.

4.4 *Calibrated driving machine test*

A test in which the mechanical input or output of an electrical machine is calculated from the electrical output or input of a calibrated machine mechanically coupled to the machine on test.

4.5 *Mechanical back-to-back test*

A test in which two identical machines are mechanically coupled together, and the total losses of both machines are calculated from the difference between the electrical input to one machine and the electrical output of the other machine (see Figure 1, page 54).

4.6 *Electrical back-to-back test*

A test in which two identical machines are mechanically coupled together, and they are both connected electrically to a power system. The total losses of both machines are taken as the power input drawn from the system (see Figure 2, page 54).

4.7 *Retardation test*

A test in which the losses in a machine are deduced from the rate of deceleration of the machine when only these losses are present.

4.8 *Calorimetric test*

A test in which the losses in a machine are deduced from the heat produced by them. The losses are calculated from the product of the amount of coolant and its temperature rise, and the heat dissipated in the surrounding media.

4.9 *No-load test*

A test in which the machine is run as a motor providing no useful mechanical output from the shaft.

4.10 *Open-circuit test*

A test in which a machine is run as a generator with its terminals open-circuited.

4.11 *Sustained short-circuit test*

A test in which a machine is run as a generator with its terminals short-circuited.

4.12 *Zero power factor test*

A no-load test on a synchronous machine which is over-excited and operates at a power factor very close to zero.

5. **Reference temperature**

Unless otherwise specified, all I^2R losses shall be corrected to one of the temperatures given below:

Classes A, E and B: 75 °C
Classes F and H: 115 °C

Note. — The reference temperature need not necessarily correspond with the limits of temperature rise permitted for the actual class of insulation used for a particular part of the machine.

SECTION TWO — D.C. MACHINES

6. **Losses to be included**

The total losses may be taken as the sum of the following component losses:

6.1 *Excitation circuit losses*

a) I^2R losses in shunt or separately excited windings and in the excitation rheostats.

b) Exciter losses.

All the losses in an exciter mechanically driven from the main shaft, which forms part of the complete unit and is used solely for exciting the machine, together with losses in the rheostat in the excitation circuit of such an exciter, but with the exception of friction and windage losses.

In the case of a separate excitation supply such as battery, rectifier or motor generator set, no allowance is made for the losses in the excitation source or in the connections between the source and the brushes.

Note. — When the losses in a separate excitation system are required, these should be listed separately and can be taken as the difference between the excitation power divided by the efficiency of the excitation system, and the excitation power.

6.2 *Constant losses*

a) Losses in active iron, and additional no-load losses in other metal parts.

b) Losses due to friction (bearings and brushes) not including any losses in a separate lubricating system. Losses in common bearings shall be stated separately, whether or not such bearings are supplied with the machine.

Note. — When the losses in a separate lubricating system are required, these should be listed separately.

7.2.3 *Mechanical back-to-back test*

When identical machines are run at essentially the same rated conditions, the losses are assumed to be equally distributed, and the efficiency is calculated from half the total losses and the electrical input (in the case of a motor) or electrical output (in the case of a generator).

The test shall be made as nearly as possible at the temperature attained in operation at the end of the time specified in the rating. No winding temperature correction shall be made.

7.2.4 *Electrical back-to-back test* (see Clause 16)

When identical machines are run at essentially the same rated conditions, the losses supplied from the electrical system are assumed to be equally distributed and the efficiency is calculated as in Sub-clause 7.2.3.

The test shall be made as nearly as possible at the temperature attained in operation at the end of the time specified in the rating. No winding temperature correction shall be made.

SECTION THREE — POLYPHASE INDUCTION MACHINES

8. Losses to be included

The total losses may be taken as the sum of the following component losses:

8.1 *Constant losses*

a) Losses in active iron, and additional no-load losses in other metal parts.

b) Losses due to friction (bearings and brushes, if not lifted during operation) not including any losses in a separate lubricating system. Losses in common bearings shall be stated separately whether or not such bearings are supplied with the machine.

Note. — When the losses in a separate lubricating system are required these should be listed separately.

c) The total windage loss in the machine, including power absorbed in integral fans, and in auxiliary machines, if any, forming an integral part of the machine. The losses in auxiliary machines such as external fans, water and oil pumps not forming an integral part of the machine, but provided exclusively for the machine in question, shall be included only by agreement.

Note. — When the losses in a separate ventilating system are required they should be listed separately.

8.2 *Load losses*

a) I^2R losses in primary windings.

b) I^2R losses in secondary windings.

c) Electrical losses in brushes (if any).

8 3 *Additional load losses*

a) Losses introduced by load in active iron and other metal parts other than the conductors.

b) Eddy current losses in primary or secondary winding conductors caused by current dependent flux pulsation.

Notes 1. — Losses, Sub-clause 8.3 *a)* and *b)*, are sometimes called additional losses, but they do not include the additional no-load losses in Sub-clause 8.1 *a)*.

2\. — In the case of auxiliary machines such as phase advancers driven mechanically from the main shaft, the losses should be included in the same way as the exciter losses are included for synchronous machines. Losses in separately driven phase advancers or regulating equipment should be given separately for rated operating conditions of the main machine. These losses should be determined by the standard method for the types of apparatus involved.

9. Determination of efficiency

9.1 *Summation of losses*

The efficiency can be calculated from the total losses which are assumed to be the summation of the losses obtained in the following manner:

9.1.1 *Constant losses*

9.1.1.1 *No-load test at rated voltage*

The sum of the constant losses, Sub-clause 8.1 *a)*, *b)* and *c)*, is determined by running the machine as a motor on no-load. The machine is fed at its rated voltage and frequency. The power absorbed, decreased by the I^2R losses in the primary winding, gives the total of the constant losses. The I^2R losses in the secondary winding may be neglected.

9.1.1.2 *Calibrated machine test* (see Clause 13)

The constant losses may be determined separately by driving the machine, disconnected from the network, at its rated speed by means of a calibrated motor (see Sub-clause 9.2.2). With the brushes, if any, in place, the power absorbed at the shaft of the machine, which may be deduced from the electrical power absorbed by the calibrated motor, gives the sum of the losses in Sub-clause 8.1 *b)* and 8.1 *c)*. With the brushes, if any, lifted the sum of the bearing friction losses and the total windage losses is obtained in the same manner. The losses described in Sub-clause 8.1 *a)* may be obtained from the test described in Sub-clause 9.1.1.1 by subtraction.

9.1.1.3 *No-load test at variable voltage*

The losses described in Sub-clause 8.1 *a)* and the sum of the losses described in Sub-clause 8.1 *b)* and *c)* may alternatively be separated by running the machine as a motor at rated frequency but at different voltages. The power absorbed, less the I^2R losses in the primary winding, is plotted against the square of the voltage. This, at low values of saturation, will give a straight line which can be extrapolated to zero voltage to give the sum of the losses, Sub-clause 8.1 *b)* and *c)*.

It should be borne in mind that at very low voltages, losses plotted on the diagram may be high because of the increased secondary winding losses with increased slip. When plotting the straight line, those values should not be taken into account.

If the motor is started with a short-circuited secondary winding and the brushes are lifted (which is possible if the supply generator is started at the same time as the motor) the bearing friction and total windage losses are obtained at zero voltage by extrapolation as above.

Note. — For wound rotor motors a synchronous no-load test can be carried out as for synchronous machines with d.c. excitation in two rotor phases (or three if desired).

9.1.2 *Load losses*

9.1.2.1 *Load test*

The losses described in Sub-clause 8.2 *a)* are calculated from the resistance of the primary windings measured using direct current and corrected to the reference temperature, and from the current corresponding to the load at which the losses are being calculated.

To determine the losses in Sub-clause 8.2 *b)* when an on-load test is made, the secondary winding losses are taken to be equal to the product of the slip and the total power transmitted to the secondary winding, i.e. the power absorbed, decreased by the core losses in Sub-clause 8.1 *a)* and the I^2R losses in the primary winding in Sub-clause 8.2 *a)*. This method gives directly the sum of the losses in Sub-clauses 8.2 *b)* and 8.2 *c)* for wound rotor machines, and the losses in Sub-clause 8.2 *b)* for cage machines. For this latter type of machine, this is the only applicable method as it is not possible to measure the resistance and current of the secondary winding directly. When use is made of this method, the slip may be measured by a stroboscopic method or by counting the beats of a permanent-magnet millivoltmeter connected between two rings (for motors with wound secondary windings) or the terminals of an auxiliary coil (for motors with short-circuited secondary windings) or between the ends of the shaft.

9.1.2.2 *Calculated values*

For wound rotor motors, the losses in Sub-clause 8.2 *b)* may be calculated from the resistance measured by direct current and corrected to the reference temperature, and from the secondary current calculated from a circle diagram or equivalent circuit, account being taken of the true transformation ratio of the machine. The type of circle diagram to be used should be agreed between manufacturer and purchaser.

To make an on-load test, the losses in Sub-clause 8.2 *c)* in the brushes cannot be measured directly and these losses shall be taken as the product of the current flowing in the brushes and a fixed voltage drop. The voltage drop in all brushes of the same phase shall be taken as 1.0 V for carbon or graphite brushes, and 0.3 V for metal-carbon brushes.

9.1.2.3 *Load test at reduced voltage*

This method is also applicable to cage rotor machines.

When the voltage is reduced, while keeping the rotational speed of the machine constant, the currents diminish approximately in proportion to the voltage, and the power approximately in proportion to the square of the voltage. When the voltage is down to half its rated value, the currents will then be reduced to about one half, and the power to about one quarter, of their values at the rated voltage.

When a load is applied to an induction motor at a reduced voltage U_r, the power absorbed P_{lr}, the main primary current I_{lr} and the slip s are measured, as well as the no-load current I_{or} at the same reduced voltage U_r, and the no-load current I_o at the rated voltage U_n.

The current vector I_l of the load at rated voltage is obtained by constructing a vector diagram (Figure 3, page 55) in the following manner:

To the current vector I_{lr}, multiplied by the ratio

$$\frac{\text{rated voltage}}{\text{reduced voltage}} = \frac{U_n}{U_r}$$

add the vector:

$$\triangle I_o = I_o \sin \varphi_o - I_{or} \left(\frac{U_n}{U_r}\right) \sin \varphi_{or}$$

The resultant vector represents the current which would flow at the rated voltage U_n for the following absorbed power:

$$P_l = P_{lr} \left(\frac{U_n}{U_r}\right)^2$$

By means of the values I_l, P_l, thus determined, and with the slip s measured at reduced voltage, it is then possible to calculate the on-load losses, as indicated in Sub-clause 9.1.2.1.

9.1.3 *Additional load losses*

Unless otherwise specified, it is assumed that the losses specified in Sub-clauses 8.3 *a)* and 8.3 *b)* vary as the square of the primary current and that their total value at full load is equal to 0.5% of the rated input for motors and 0.5% of the rated output for generators.

Note. — For some designs of small machines these losses might be higher than 0.5% of the rated input. If, for a particular case, the value is of importance, the loss should be determined by the direct method of efficiency measurement.

9.2 *Total loss measurement*

9.2.1 *Braking test*

When the machine is run at rated conditions of speed, voltage and current, the efficiency is taken as the ratio of output to input.

11.2.5 *Zero power factor test* (see Clause 14)

When the machine is run at rated conditions of speed, voltage and current, the total losses are equivalent to the absorbed power during the test, corrected for the difference between actual and the full-load exciting current losses.

SECTION FIVE — METHODS OF TEST

12. General

Tests can be grouped in one of the three following categories:

a) Input-output measurement on a single machine. This usually involves the measurement of mechanical power into, or out of a machine.

b) Input and output measurement on two machines connected back-to-back, e.g. two identical machines or a test machine coupled to a calibrated machine. This is done to eliminate the measurement of mechanical power into or out of the machine.

c) Measurement of the actual loss in a machine under a particular condition.

This is not usually the total loss, but comprises certain component losses. The method may, however, be used to calculate the total loss or to calculate a component loss.

The choice of test to be made depends on the information required, the accuracy required, and the type and size of the machine involved. Where alternative methods are available for a particular type of machine, the preferred method is indicated (see Clause 18).

A distinction is made between direct and indirect efficiency measurement.

The direct measurement of efficiency is made by measuring directly the power supplied by the machine and the power absorbed by it.

The indirect measurement of efficiency is made by measuring the losses of the machine. Those losses are added to the power supplied by the machine, thus giving the absorbed power.

The indirect measurement may be carried out by the following methods:

(i) determination of separate losses for summation;
(ii) determination of total losses.

Note. — The methods for determining the efficiency of machines are based on a number of assumptions; it is therefore not possible to make a comparison between the losses obtained by the direct method of measurement and those obtained by the measurement of the separate losses.

Unless otherwise specified, the guaranteed efficiency of a machine is that which is based on the determination of separate losses, but when there is a choice of method, the evaluation of efficiency should be based on the accuracy obtainable from the method, the efficiency and the type of machine involved.*

When the efficiency or total loss is derived from the measured input and output power, any inaccuracy in these measurements appears as a direct error in the efficiency (e.g. with an

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**Note.* — In some countries 90% efficiency is accepted as a basis for using the indirect method whereas some other countries prefer a lower value, e.g. 70%.

accuracy of power measurement not better than 1%, the efficiency can be 2% in error or the total losses can be in error by 2% of the total input power). On small machines or machines with relatively low efficiencies (say below 90%),* this method may be quite acceptable and gives a convenient form of test for such machines. On these and other machines efficiency can be obtained with high accuracy by the calculation of losses from direct measurements.

13. **Calibrated machine test**

The machine of which the losses are to be measured is separated from the network, uncoupled from its driving motor if necessary, and driven at its rated speed by a calibrated motor, that is by an electric motor of which the losses have been previously determined with great accuracy, such that it is possible to determine the mechanical power which it furnishes at its shaft, knowing the electric power which it absorbs and its speed of rotation. The mechanical power transmitted by the calibrated motor to the shaft of the machine under test is a measure of the losses of this latter machine for the working conditions under which the test is made. In this method, the machine tested may be on no-load, excited or not excited, with or without brushes or short-circuited, which enables categories of losses to be separated.

As an alternative, the calibrated motor may be replaced by a dynamometer or by any other motor driving the machine under test through an appropriate torsionmeter, which enables the torque transmitted to the machine under test to be known, and hence the mechanical power absorbed by this latter machine.

When use is made of this alternative, the speed of rotation, which comes directly into the calculation of the power, must be measured with extreme care.

14. **Zero power factor test**

The machine operates as a motor at no-load and at rated speed, with a power factor in the neighbourhood of zero, while the excitation current is adjusted so that the machine carries its rated primary current.

The supply voltage is such that the magnetic losses have the same value as in no-load operation at rated voltage. The supply voltage is usually equal to the rated voltage unless this would give an active iron loss appreciably greater than that at full load. In principle, the reactive power should be positive, i.e. over-excited, but when this is impossible because the exciter voltage is not sufficient, the test can be made with absorption of the reactive power (i.e. under-excited).

Note. — The accuracy of this method is dependent upon the accuracy at low power factor of the wattmeters used.

15. **Retardation method**

This method is particularly applicable to large synchronous machines with considerable inertia. The method may also be used for a.c. induction machines and d.c. machines, using the appropriate losses for such machines. It consists of measuring the retardation time when the

**Note.* — In some countries 90% efficiency is accepted as a basis for using the indirect method whereas some other countries prefer a lower value, e.g. 70%.

machine is slowing down under different conditions between two predetermined speeds, say from 110% to 90% or from 105% to 95% of the rated speed. This time will vary inversely with the average losses during the same time.

The method permits the measurement of the mechanical loss (friction losses and total windage loss), core loss at different excitation and load loss on short-circuit under different excitation.

During the test, the machine is run as a motor at no-load fed from a generator for a sufficient time for the temperature of the bearings to be stabilized. If the bearing losses are guaranteed at a certain temperature of the bearing, the amount of cooling water to the bearing cooling system should be adjusted so that the agreed temperature will be obtained.

The machine on test is accelerated to a speed sufficiently above the speed from which the retardation time is measured. The test machine is then disconnected from its feeding machine and the required value of excitation, and primary winding connections, are established. This should be done with sufficient rapidity for the required steady electrical test conditions to have been reached before the speed of the machine, which is decreasing constantly during this interval, passes through the upper limit from which the retardation time is measured.

In the open-circuit retardation tests, the excitation and the stator voltage are measured as the machine passes through the rated speed. In the short-circuit retardation tests, the excitation current and the stator current are measured at this same instant. The test should be carried out for several values of excitation, with open-circuited and short-circuited connections respectively.

The time between the two limits of speed should be measured within an accuracy of 2%. The interval between the two limits chosen depends on the accuracy of measurement. A permanent magnet generator or an exciter may be used as a tachometer, or measurement may be made with electronic devices.

To obtain the absolute value of the losses, which are present in the machine during the corresponding open-circuit retardation test at the moment of passing through the rated speed, measurements are made with the machine running as a motor at no-load, normal speed and unity power factor, and at the same voltage as used in one of the retardation tests, preferably at normal voltage. The input, i.e. the losses, should be measured with great accuracy.

When the inertia of the machine is not known with sufficient precision, it may be determined by a retardation test with known losses, measured by another method.

The measurement is repeated several times and the average value calculated. Instead of measuring several times at the same voltage, several points can be measured at different voltages in the range of 95% to 105% to obtain a curve of losses *versus* voltage around the rated voltage. Retardation measurements should have been made in the same voltage range. The relation between losses P and retardation time is now established.

The losses at any condition (e.g., at no-load, at short-circuit, etc.) can be calculated as the input value P measured in the above test multiplied by the ratio between the retardation time in the above test and the retardation time in the actual test.

The mechanical loss is obtained from a retardation test without excitation, the core loss from the open-circuit tests with the mechanical loss subtracted, and the short-circuit loss from a retardation test on short-circuit with the mechanical loss subtracted.

The moment of inertia can be calculated from the retardation test with the equation:

$$J \simeq \frac{45600\,Pt}{\delta n^2}$$

where:

$$45600 = \frac{60^2 \times 10^3}{8\pi^2}$$

The retardation is measured from the speed $n(1+\delta)$ to the speed $n(1-\delta)$ where n is the rated speed in revolutions per minute. If P is expressed in kilowatts, inertia J is obtained in kgm², t being the time in seconds between the two instants where the speed is $n(1+\delta)$ and $n(1-\delta)$ respectively.

During the retardation test, the excitation on the tested machine should preferably be from a separate source. A directly coupled exciter can, however, be used, if the change in speed during retardation is small, e.g. 105% to 95%. An appropriate correction for the loss in the excitation circuit must then be made taking into account also that the excitation current in the retardation test, and the no-load tests, may be a little different, although the voltage is the same. Separate excitation of the exciter is, however, necessary.

Instead of using the no-load method for obtaining the absolute value of the losses, the calibrated motor method can be used.

16. **Electrical back-to-back test**

This method is applicable when two identical machines are available. The machines are coupled mechanically and electrically so as to operate at rated speed, one as a motor and the other as a generator. The actual temperature at which the measurements are carried out should be as close as possible to the working temperature and no further correction should be made. The losses of the assembled machines are supplied either by a network to which they are connected, or by a calibrated driving motor, or by a booster, or else by a combination of these various means.

The average value of the armature currents is adjusted to the rated value, the average of the voltage of the two armatures is above or below the rated voltage by an amount equal to the voltage drop, depending on whether the d. c. machines are intended to be used respectively as generators or as motors.

Where two induction machines are electrically connected, they should be mechanically coupled with a speed adjusting device, such as a gear box, to ensure the correct circulation of power. The magnitude of power circulated depends upon the difference in speed. The electrical system supplying the losses to the two machines will be required to provide magnetizing kvar to both machines.

When two synchronous machines are electrically connected, they should be mechanically coupled with a correct angular phase relationship. The magnitude of the power circulated depends upon the difference in phase angle between them.

17. **Calorimetric test**

Under consideration.

18. **Schedule of preferred tests**

18.1 *D.C. machines*

The preferred test for d.c. machines is in accordance with Sub-clause 7.1 and the preferred method of calculating the efficiency is in accordance with Sub-clause 7.1.2.

18.2 *Polyphase induction machines*

The preferred test for polyphase induction machines is in accordance with Sub-clause 9.1 and the preferred method of determining the constant losses is in accordance with Sub-clause 9.1.1.1.

18.3 *Synchronous machines*

The preferred test for synchronous machines is in accordance with Sub-clause 11.1 and the preferred method of determining the constant losses is in accordance with Sub-clause 11.1.2.1.

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