Metered Load Factors for Low-Voltage, Dry-Type Transformers in Commercial, Industrial, and Public Buildings

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EXECUTIVE SUMMARY

Purpose of the Study

This study was undertaken to determine the load factors, expressed as a percentage of nameplate rating, that are commonly experienced by low-voltage, dry-type transformers in commercial and industrial applications. Because the benefits of energy-efficient transformers vary depending on load factor, this information will be useful in evaluating the savings to be expected from Massachusetts s statutory requirement that such units be installed in all new construction.

Background

Industrial and commercial facilities that are served by 3-phase power from the utility typically use low-voltage, dry-type transformers to distribute power internally at 208/120 volts. Loads commonly served by such transformers include wall plugs, lights, fans, and equipment such as computers, printers, and small industrial machinery. This study focused on the size of the loads that such transformers serve.

Transformers are generally sold in three categories distinguished by the expected temperature rise of the winding surface over ambient conditions at their design load. Models specified as 80…C or 115…C temperature rise typically are manufactured with more efficient (more conductive) windings that heat up less than standard 150…C units. The vast majority of the transformers found in the survey were standard 150…C temperature-rise models (Figure ES-1).

In 1996 the National Electrical Manufacturers Association (NEMA), in its TP-1 standard, specified minimum recommended efficiencies for various sizes of transformers, including low-voltage ones.[1] The TP-1 standard calls for efficiencies of around 98 percent (depending on transformer size) at a load factor of 35 percent.[2] At that load factor, such efficiencies are achieved by reducing core losses, which as a percentage of total losses are highest at low load factors. The U.S. Environmental Protection Agency adopted this standard as a criterion for the ENERGY STAR¤ label for low-voltage transformers. In 1997, the Commonwealth of Massachusetts passed Act 164, Section 313 of which requires that all distribution transformers sold in the Commonwealth after December 31, 1999 meet the TP-1 standard.

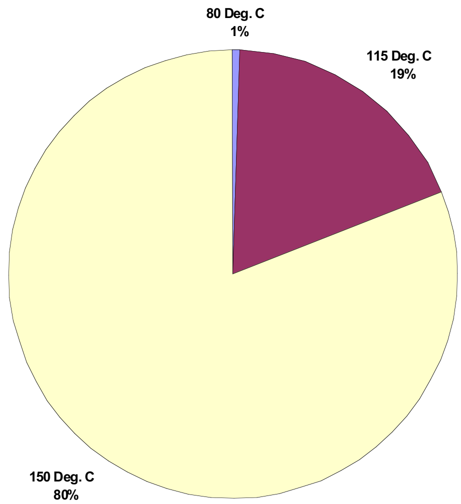
As shown in Figure ES-2, standard-model (150…C) transformers reach peak efficiencies of roughly 96 to 97 percent when the transformers are loaded at 30 to 50 percent of their nameplate capacity (depending on the model). This contrasts with the efficiency of roughly 98 percent achieved by TP-1 transformers at a 35 percent load factor. Also shown are the losses for conventional (non-TP-1) transformers rated at an 80…C temperature rise; these are more efficient than both TP-1 and 150…C transformers at high load factors, but not at low ones.

Figure ES-3 displays the same information as the preceding figure but in a different form. It shows that TP-1 models have lower losses than conventional (150…C) models at all loads, but higher losses than low-temperature-rise (e.g., 80…C) models at loads greater than 65 percent. The savings from using TP-1

[1] National Electrical Manufacturers Association, 1996. Guide for Determining Energy Efficiency for Distribution Transformers. NEMA Standards Publication TP 1-1996.
[2] A load factor of 35 percent means that the transformer is transforming electricity at a rate equal to 35 percent of its nameplate capacity. For example a 75 kVA transformer operating at 35 percent load factor is transforming 26.25 kVA (26,250 volt-amperes).

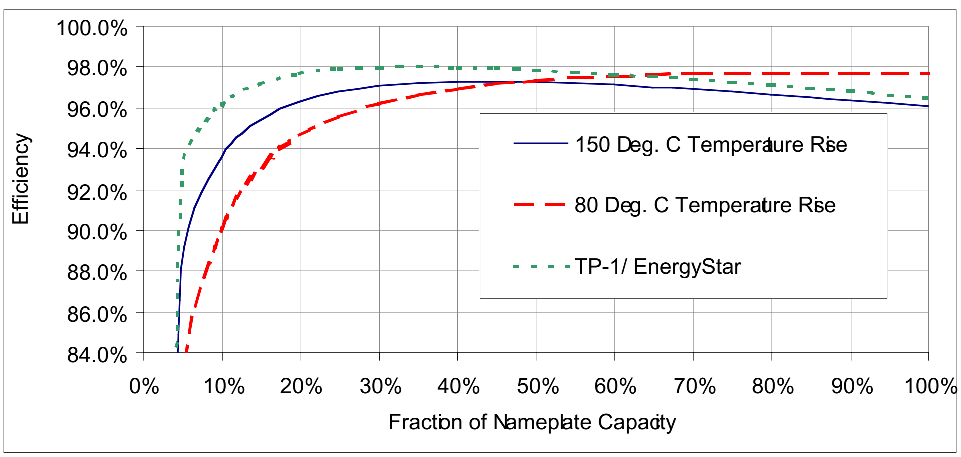
transformers are thus sensitive to the transformer load factor. Determining the load factor at which low-voltage transformers actually operate thus was a primary motivation for this study.

Figure ES-1
Frequency of Surveyed Transformers by Temperature Rise



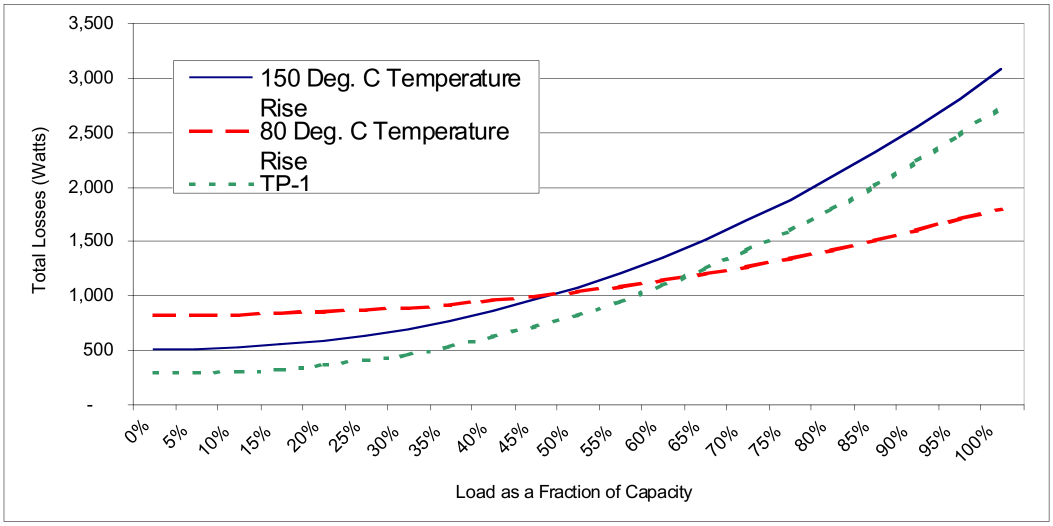
(Most of the 115°C rise transformers were K-4 rated.)

Figure ES-2
Efficiency versus Load for Three Representative 75kVA Transformer Models[3]



[3] Graph produced by the Transformer Efficiency Calculator (TEC) developed by The Cadmus Group, Inc. under contract to U.S. EPA, August 1999.

Figure ES-3
Total Losses versus Load for Three Representative 75kVA Transformer Models



Methodology

Cadmus designed this study as a random sample of transformers in the service areas of two Massachusetts utilities The NEES Companies and The Boston Edison Company. To provide adequate representation of five building types (office, manufacturing, health care, school and institutions, and retail) in the utilities service areas, the study was designed to monitor 86 transformers. From lists of the utilities commercial and industrial customers with 480-volt service, 43 buildings representing the five building types were randomly selected to participate in the study. At each building all of the dry-type transformers were surveyed and a subset were randomly chosen for monitoring. In developing their initial list of buildings, the participating utilities first screened buildings to include those that were either built or modified in the last 10 years. Transformers monitored were less than 15 years old and in most cases were less than 10 years old.

Using portable metering equipment, instantaneous measurements were collected for each phase (1) just prior to installation of recording current meters and (2) when the meters were removed 2 weeks later. Measurements included: voltage, current, power, power factor, total harmonic distortion as a percent of the fundamental frequency, and K Factor.

Current transducers (CTs) were sized for the expected current, attached to each of the 3 secondary phases and wired to a four-channel data recorder. The MicroDataLogger¤ was programmed to collect current measurements every 10 minutes continuously for 2 weeks (2,034 measurements per phase, up to 8,136 measurements per transformer if the neutral phase was also monitored).

Results: Loads of Monitored Transformers

The average load factor of each of the 89 transformers monitored was calculated using a root-mean-square (RMS) method to properly weight periods of high loads. By using this method, the average can be used directly to calculate transformer losses, which are proportional to the square of the load. Averaged over all transformers, the load factor was 15.9 percent of the transformers nameplate capacity (Table ES-1). Expressed in terms of confidence intervals, the estimated average load factors of dry-type transformers over the service areas of the two participating utilities were between 13 and 18 percent at a 95-percent confidence level. The confidence interval means that statistically there is a 95 percent chance that the average transformer load for all transformers in the utilities' service areas is between 13.3 and 18.5 percent. Not only was the average RMS load on the sampled transformers low, fewer than 4 percent of the transformers monitored had average loads greater than 50 percent. Only 14 percent had average loads greater than the 35-percent target load of the TP-1 standard.

Table ES-1
Summary Statistics for the 89 Transformer Loads Measured
(Percent of transformer capacity)

Average RMS load factor	15.9%
Upper estimate @ 95 percent confidence level	18.5%
Lower estimate @ 95 percent confidence level	13.3%
Median RMS load factor	12.7%
Observed maximum RMS load factor	62.4%
Observed minimum RMS load factor	0.0%
Standard deviation of average load factor	12.4%
Number of transformers	89

Results: Load by Building Type

To determine whether transformer loads varied among building types, 17 or 18 transformers were monitored in each of the following five building types:

- Universities
- Health care facilities
- Manufacturing facilities
- Office buildings
- Retail facilities

The average load factors were consistent across building types, varying only from 14.1 to 17.6 percent (Table ES-2). Figure ES-4 shows the average RMS load factors and the range of the 95-percent confidence limits of the average load factor for each building type. Even the upper bounds are well below the 35-percent load specified in TP-1 and in the ENERGY STAR label.

The RMS average transformer loads measured also differed little whether the building was on a one-, two-, or three-shift schedule. For the range of transformer sizes metered (15 to 300 kVA), loads varied somewhat but on average were below 25 percent for all sizes.

At an RMS average load of 15.9 percent, core losses dominate and winding losses are relatively unimportant, so TP-1 transformers, which have efficient cores, have large efficiency advantages. Because average transformer loads varied little across building types, ages, sizes, and operating schedules, TP-1 transformers appear to offer efficiency advantages across the population of commercial and industrial buildings in Massachusetts.

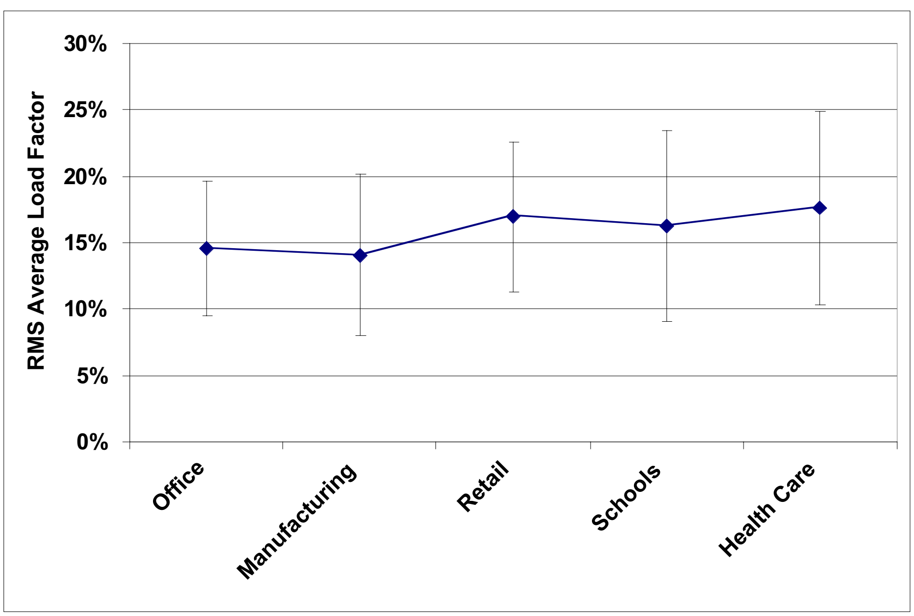
Projected Energy Savings

For the transformers surveyed in 43 facilities, nearly 800,000 kWh would have been saved annually had TP-1/ ENERGY STAR transformers been installed.[4] This amounts, on average, to annual savings of roughly 18,600 kWh per facility. The facilities in the study had an average floor area of roughly 100,000 square feet.

Table ES-2
Transformer RMS Average Loads by Building Type
(Percent of transformer capacity)

	Building Category				
RMS average load factor:	Universities	Health Care	Manufacturing	Office	Retail
Average RMS load factor	16.3%	17.6%	14.1%	14.6%	17.0%
Upper estimate @ 95 percent confidence level	23.4%	24.9%	20.2%	19.7%	22.6%
Lower estimate @ 95 percent confidence level	9.1%	10.4%	8.0%	9.5%	11.3%
Median RMS load factor	14.3%	12.7%	10.8%	13.6%	14.3%
Maximum RMS load factor	62.4%	50.0%	47.5%	33.7%	42.5%
Minimum RMS load factor	1.3%	1.3%	0.9%	0.0%	1.1%
Standard deviation of average load factor	14.5%	14.2%	12.3%	10.2%	11.4%
Number of transformers	18	17	18	18	18

Figure ES-4
RMS Average Transformer Loads by Building Type



(Bars indicate 95 percent confidence interval of each average load)

[4] Of the 353 transformers surveyed, 321 had information on both size and type available.

If TP-1/ENERGY STAR transformers were to make up 20 percent of sales, after five years roughly 350 million kWh would be saved annually nationwide. Interpolating this figure based on commercial and industrial electrical sales[5] this converts to a savings of 5.5 million kWh in Massachusetts. Interpolating based on population yields a savings figure of 8 million kWh. An ultra-low-loss transformer is now under development. Approximately 620 million kWh could be saved annually if it were rapidly brought to market.[6] Massachusetts' savings would range from 10 to 14 million kWh.

Because average transformer load factors above 65 percent, where 80…C-temperature rise transformers are most efficient, were not encountered in this study, TP-1 transformers will be more efficient than 80…C - temperature rise transformers in the vast majority of low-voltage transformers likely to be installed in the foreseeable future. Thus, energy consumption per facility and in the aggregate will decrease through adoption of the TP-1 standard.

[5] U.S. Census Bureau, 1998 Statistical abstract of the United States, Table 973.
[6] Savings were calculated by extrapolating study savings to the annual sales of transformers.

INTRODUCTION

This study examined low-voltage dry-type transformers and measured the load they carry in commercial and industrial facilities. Transformers change the voltage of alternating current (ac) electricity. They consist of a core made of a steel alloy around which primary and secondary sets of wire-like conductors are wound. The relative number of wraps of each of these sets of windings determines the change in the voltage provided by the transformer.

Electricity is commonly carried at 4,000 to 13,000 volts on distribution lines to an industrial or commercial facility. A medium-voltage transformer, often located outside of the facility, brings the voltage down to 480-volt 3-phase power. This service can be then used as 480-volt power often to power large motors, or as 277-volt single-phase power for lighting. For selected circuits, this power is further reduced to 208/120-volt service using low-voltage dry-type transformers. It is these transformers that are the focus of this study. The power that these transformers produce can be used as 208-volt 3-phase power for motors, or more typically to serve 120-volt single-phase loads. Common 120-volt loads are wall plugs, lights, refrigerators, computers, and printers. In some buildings exhaust fans and other HVAC equipment are also served by 120-volt electricity.

The transformers studied in this report are inherently efficient, delivering for low-voltage use between 90 and 98 percent of the power they receive. The remaining electricity is lost to vibration and heat. There are two components of losses: (1) core losses, which are relatively constant over time and independent of load, and (2) winding losses, which are proportional to roughly the square of the current in the windings at any given time.

As shown in Figure 1-1, standard-model transformers (150…C temperature rise) reach peak efficiencies of roughly 96 to 97 percent when the transformers are loaded at 35 percent of their nameplate capacity (depending on the particular transformer model). While the figure shows results for three particular models it is generally representative of most models. The National Electrical Manufacturers Association (NEMA) issued a standard describing minimum recommended efficiencies for various sizes of transformers termed TP-1 in 1996.[7] U.S. EPA adopted this standard as a criterion for the ENERGY STAR label for low voltage transformers (see Appendix A for a list of efficiencies listed under the label and under TP-1). Transformers meeting the TP-1 efficiency standard reach efficiencies of roughly 98 percent (this varies with transformer size) when loaded at 35 percent of their capacity. TP-1 transformers are efficient primarily because they are manufactured with more efficient cores. At loads in the region of 65 percent and higher, however, where winding losses dominate, the TP-1 standard does not require improvement in winding losses over conventional models. As shown in Figure 1-1, TP-1 models have almost the same losses as conventional (e.g., 150…C -rise) models at high loads and higher losses than low-temperature-rise models (e.g., 115…C- and 80…C-rise models). This is also shown in Figure 1-2 comparing total losses for three example transformers. The savings from using TP-1 transformers are thus sensitive to the transformer load factor. This was a primary motivation for this study: to determine the load regime in which these transformers operate.

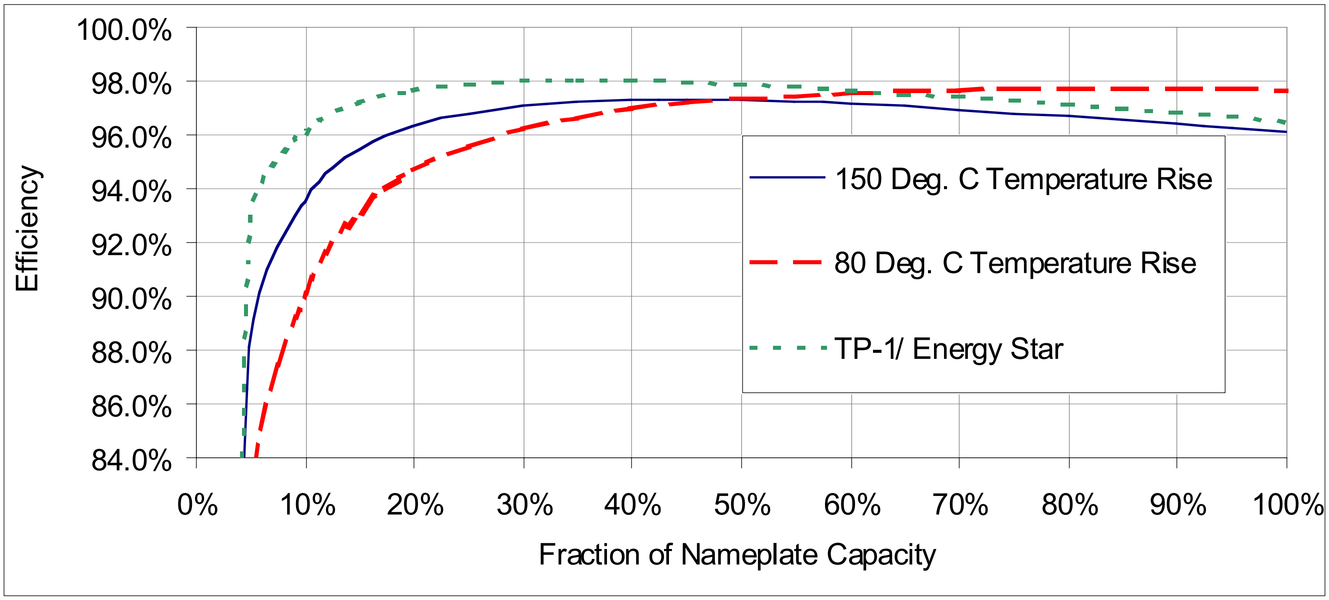
TP-1 and Recent Legislation

Section 313 of the Act passed in 1997 by the Commonwealth of Massachusetts to restructure the electric utility industry requires that all distribution transformers sold or first installed in the Commonwealth after December 31, 1999 meet the minimum efficiency levels contained in tables 4-1 and 4-2 of NEMA

[7] National Electrical Manufacturers Association, 1996. Guide for Determining Energy Efficiency for Distribution Transformers. NEMA Standards Publication TP 1-1996.

standard TP1-1996. The requirement applies to transformers designed for primary voltages up to 34.5kV and secondary voltages below 600 volts. The TP-1 tables list relatively high-energy efficiencies at a 35-percent load. Because winding losses are relatively low at a 35-percent load, these energy efficiencies are generally achieved by improving the design of the transformer core.

Figure 1-1
Efficiency versus Load for Three Representative 75kVA Transformer Models[8]



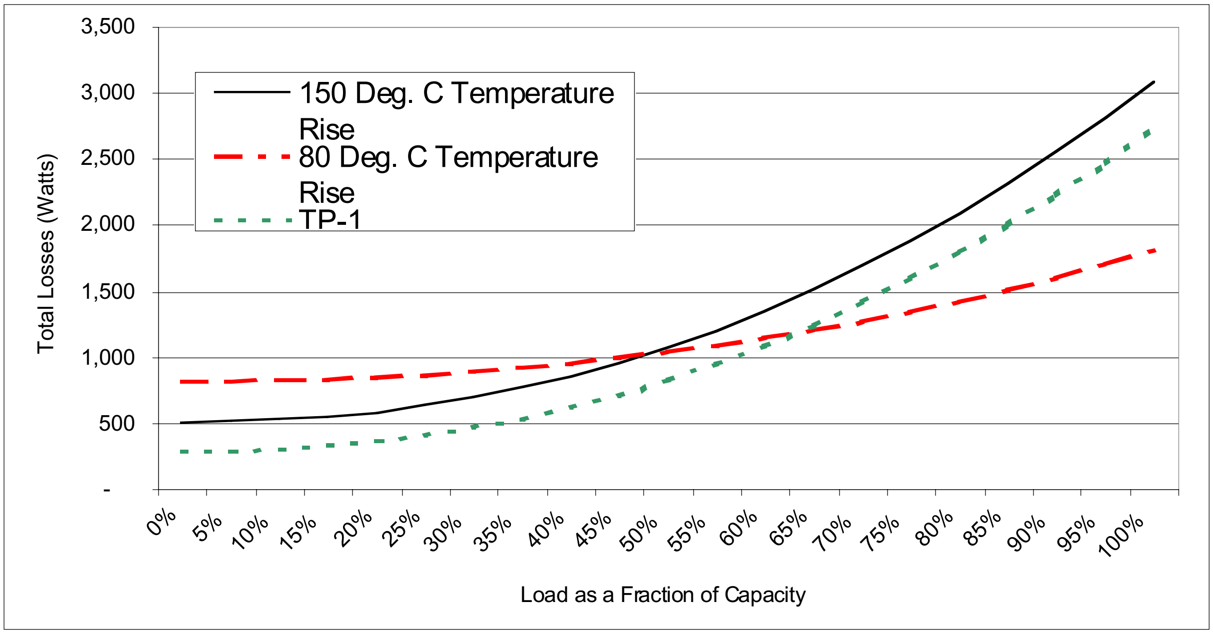
The Purpose of the Study

The higher efficiency of TP-1/ ENERGY STAR transformers is an opportunity for substantial savings, particularly if loads on dry-type transformers are 50 percent of their capacity or lower. Energy savings would not be as large as those available from low-temperature rise transformers loaded at 65 percent or more.

The primary purpose of the study was to better understand the loads on transformers and the resulting effect on transformer losses. This study complements work done by the U.S. EPA[9] and Cadmus to examine the impact of energy-efficient transformers. Field work performed during this study focused on determining the average transformer load for the service territories of the two participating utilities at a resolution that would allow differentiation between three load regimes: (1) low loads (0 to 30 percent), where core losses would be dominant; (2) moderate loads (30 to 65 percent), where core and winding losses would be important but where TP-1 transformers would still be a logical choice; and (3) high loads (65 to 100 percent), where winding losses would be increasingly important and where low-temperature-rise transformers would be advantageous choices. The study was designed so that results could reasonably be extrapolated to other regions.

[8] Graph produced by the Transformer Efficiency Calculator (TEC) developed by The Cadmus Group, Inc. under U.S. EPA contract 68-W6-0050, August 1999.
[9] Information on EPA s commercial and industrial ENERGY STAR program can be viewed at www.energystar.gov. The web site contains lists of models with an ENERGY STAR label and has several transformer evaluation tools available for downloading. For further information contact Steve Ryan at (202) 564 — 1254.

Figure 1-2
Total Losses versus Load for Three Representative 75kVA Transformer Models



The study monitored electrical circuit loads in commercial and industrial buildings to determine, with a reasonable level of statistical confidence, the load factors experienced by dry-type, low-voltage distribution transformers (which are typically rated at or below 600 kVA). This information was sought primarily to predict the average efficiencies of standard transformers in use and to assess the usefulness of the TP-1 standard. It is expected that this information will give utilities, specifiers, and designers a better basis for projecting the savings expected to accrue from the use of TP-1 transformers. Secondary benefits of this study will be to gain information on how transformer capacities relate to the expected and actual load, and include answering questions related to the type of transformer best suited for actual commercial and industrial loads.

This report shows the characteristics of the 353 transformers reviewed in the study and reports detailed findings from monitoring 89 of these transformers. Because the facilities and the transformers studied were chosen at random, the results can be extrapolated to the service territories of the New England Electric System Companies and Boston Edison Company. Although other service territories were not sampled, the results are representative of southern New England and New York State because climate, and therefore the mix of heating and cooling, is similar. To the extent that circuit design practices are similar nationally, many of the results are applicable because the bulk of the loads carried by the transformers are plug loads such as computers and task lighting, which are used in a similar manner throughout the country.

METHODOLOGY

Introduction

The primary purpose of the study was to determine the average transformer load factor for the service territories of the participating utilities at a resolution that would allow differentiation between three load regimes: 0 to 30 percent, 30 to 65 percent, and 65 to 100 percent.

A second goal was to examine several building types and determine whether loads vary appreciably among them. If loads were found to vary greatly between the building types, then the information would be important to designers specifying the type of transformer to be installed. Sample sizes were designed to provide a resolution of ±5 percent, at a 95-percent confidence level, based on initial estimates of population variation.

The study was intended to monitor circuits that were installed or modified in the last 10 years so that the results would represent recent design practices and so be useful to engineers now specifying transformers.

To accomplish the goals described above, buildings considered for the study were screened to meet each of the following conditions:

- Buildings had to be within the service areas of the participating utilities.
- Buildings had to be in one of five categories:
  - Universities
  - Health care facilities
  - Manufacturing facilities
  - Office buildings
  - Retail facilities
- Buildings had to be built or have had their electrical distribution system modified or renovated within the past 10 years.

Determination of Sample Size

The required sample size depends on the desired degree of confidence and the expected variance of the transformer loads measured. The calculation used to determine sample size is presented in Appendix B. It shows that, based on the expected variance in transformer load and a 95 percent confidence level, a confidence range of ±5 percent can be met with a sample of 14 circuits per building type. Cadmus sampled 17 or 18 circuits per building type to allow for contingencies that could otherwise jeopardize the confidence level:

- Underestimation of the variance in the population.

- Non-normality of the distribution of load factors (the formula for deriving sample size assumes normality).

- Problems with data acquisition or building operations that may occur during monitoring.

Facility Selection

The participating utilities supplied Cadmus with lists of large customers that had either renovated or built their facilities in the last 10 years. Between the utilities, roughly 250 facilities were identified in the 5 building types listed above. Cadmus organized the lists provided by the utilities into the 5 building types and used a random-number generator to select 12 buildings of each type; a total of 60. For each building type, Cadmus and the utilities made initial contacts and requested participation. Building managers refusing to cooperate and buildings that did not have 480-volt service were removed from consideration. After initial contacts, 43 buildings were qualified for participation in the study.

Circuit Selection

At each facility, the study field team first surveyed all dry-type transformers and noted the following information:

$ Transformer make, type (temperature rise), and model.
$ Transformer capacity.
$ Transformer impedance.
$ Primary and secondary voltages and, where listed, amperages.
$ Type of primary and secondary circuits (e.g., typically delta primary/wye secondary).

The field team then listed the transformers as candidates for measurement. They removed from consideration a few transformers that did not meet these requirements:

- They could not be accessed safely, or the load they served could not be at least generally determined.

- They were known to be older than 10 years. In developing their initial list of buildings, the participating utilities first screened buildings to include those that were either built or modified in the last 10 years. Cadmus then interviewed building operators in the field to determine the approximate ages of the transformers. In some cases the building operators did not precisely know transformer ages, and several transformers probably up to 15 years old were monitored.

Transformers remaining on the candidate list were randomly selected for monitoring using a random-number generator. This selection method was used for several reasons:

- It helped ensure that a representative selection of transformer sizes would be monitored. This was important because the ratio of core to winding losses varies by size and thus the relationship between load and efficiency also varies.

- It avoided a bias toward monitoring transformers that the field teams or the facility electricians found interesting. This avoided focusing on problem transformers or on particular brands or types.

Spot Measurements

Using portable metering equipment, including a Fluke¤ Model 41 power analyzer, [10] instantaneous measurements were collected for each phase (1) just prior to installation of recording current meters and (2) when the meters were removed 2 weeks later. Measurements included:

[10] Crowley Associates generously provided Fluke¤ equipment for use in the study.

- $ Voltage.
- $ Current in amperes (also measured in the neutral).
- $ Power (watts).
- $ Power factor (kW/kVA).

The current was also checked just after installation of the recording current meters to check the accuracy of the recording meter s readings.

In recent years, there has been concern that harmonics are being induced in commercial buildings primary from the use of variable speed drives and from the switched mode power supplies that are used in many computers and other electrical equipment. Spot measurements of the two harmonics metrics, total harmonic distortion as a percent of the fundamental frequency, and K Factor, were also collected to provide a general indication of how often the problem occurs. Because they were point-in-time measurements, they did not provide statistically significant values for these parameters.

Datalogging

Current transducers (CTs) were sized for the expected current and attached to each of the 3 secondary phases. CTs were also attached to the neutral wires of several circuits where high harmonics were measured. Each CT was connected to a channel of a MicroDataLogger¤ data recorder. The MicroDataLogger¤ was programmed to collect current measurements every 10 minutes continuously for 2 weeks (2,034 measurements per phase, up to 8,136 measurements per transformer).

Load Analysis

Measured current readings and nominal voltage values were used to calculate the transformer load in volt-amperes for each 10-minute measurement. The loss in transformer windings is proportional to the square of the current; therefore periods of high loading create much higher losses than periods of low loading. The average load of the monitored transformers for the time period was calculated using a root-mean-square (RMS) method to properly weight periods of high loads and calculate losses.

In the RMS method, the load for each time period is squared and the average of all the squared values is calculated. The square root of this average yields an RMS value. For a transformer with a relatively constant load, the RMS and arithmetic averages are nearly identical. For a transformer with wide variation in its load, the RMS will differ from the simple average.

RESULTS OF TRANSFORMER SURVEY

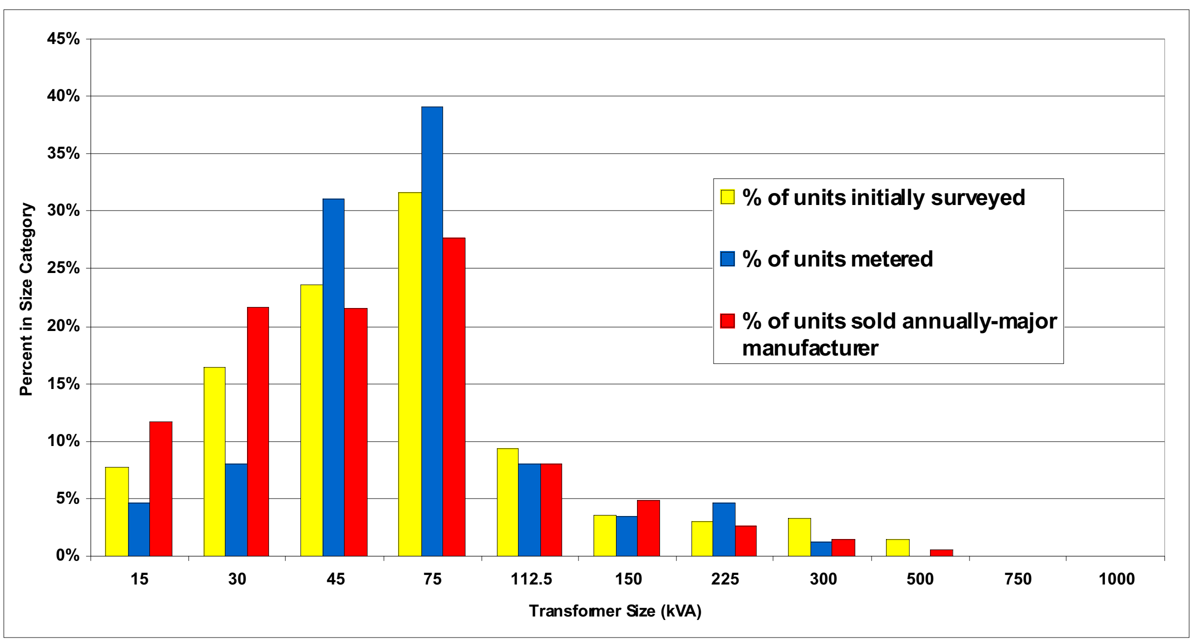
Cadmus initially surveyed all transformers in each of the 43 buildings studied, recording complete nameplate information on 335 transformers.[11] These transformers are listed in Appendix C. There was an average of 7.8 transformers per building with a total capacity of 628 kVA, resulting in a net average transformer size of 81 kVA.

Distribution of Transformer Sizes Found

The size distribution of transformers surveyed and monitored is shown in Figure 3-1. The distributions are similar in shape. The smaller sizes (15 and 30 kVA) are somewhat underrepresented because some of the units encountered could not accept add-on monitoring equipment,[12] however the difference between the distribution of surveyed and monitored sizes was small and the 15- and 30-kVA transformers account for only 1 and 6 percent of the surveyed transformers capacity, respectively.

As a check, the size distributions were compared with the national sales figures of a major manufacturer for a recent year. The distribution of surveyed transformers matched the distribution of the sales figures closely, especially considering that the sales data were for the nation, and the survey was limited to two utility service areas. This close match supports the conclusion that the survey included a representative size distribution and that the size distribution in the surveyed area may well match the national transformer population. The distribution of sizes by capacity (kVA) is shown in Appendix D. It has a slightly different shape because larger transformers make up a larger fraction of the population than they do by count of units.

Figure 3-1
Transformer Size Distributions of Surveyed and Monitored Transformers



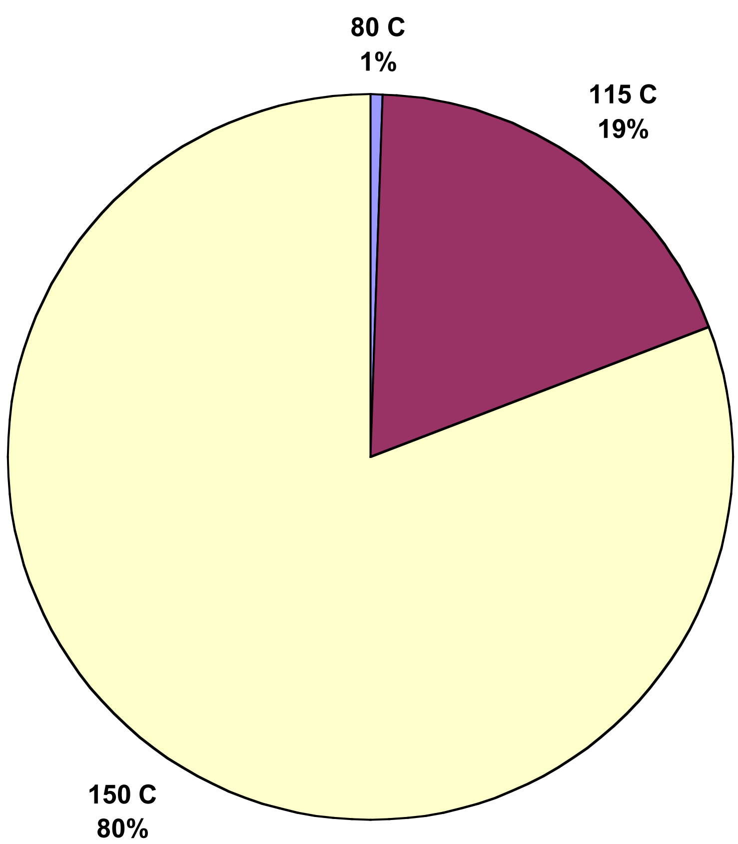
[11] While 353 transformers were initially observed, several had missing or inaccessible nameplates and were not included in this section.
[12] Some of the smaller transformers were two small internally to allow insertion of metering equipment and did not have heat vent positioned to allow low-voltage wires to run to an external installation.

Distribution of Transformers by Temperature Rise

Transformers are generally sold in three temperature-rise categories (80…C, 115…C, and 150…C) reflecting the design temperature rise of the winding surface over ambient conditions at their design load. Models with an 80…C or 115…C temperature rise typically are manufactured with more efficient (more conductive) windings that heat up less.

The vast majority of the transformers found in the survey were standard 150…C temperature-rise models (Figure 3-2). Few 80…C transformers were found. No TP-1/ ENERGY STAR transformers were encountered, probably because the population of transformers surveyed varied from 1 to more than 10 years old and TP-1 transformers have entered the market only recently.

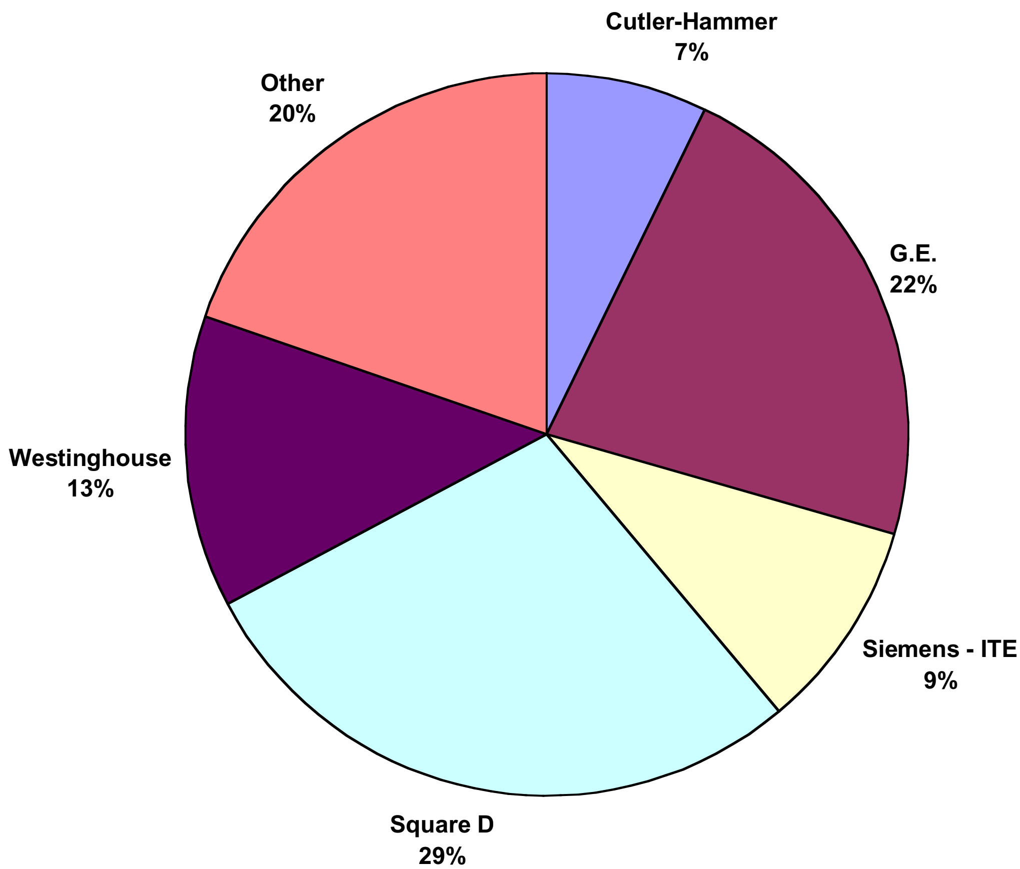
Figure 3-2
Frequency of Surveyed Transformers by Temperature Rise



Distribution of Transformers by Manufacturer

Figure 3-3 illustrates the distribution of surveyed transformers by manufacturer. Cutler-Hammer, GE, Siemens, and Square D account for 67 percent of these transformers. While Westinghouse-labeled transformers account for another 13 percent, these were older models no longer made. Of the four leading makers, Cutler-Hammer labels a portion of its transformers and manufactures the remainder, and Siemens labels transformers manufactured by other makers, so the distribution of transformers by maker may differ somewhat from the one based on labels in Figure 3-3.

Figure 3-3
Distribution of Transformers by Manufacturer



Loads Served by Low-Voltage Dry-Type Transformers.

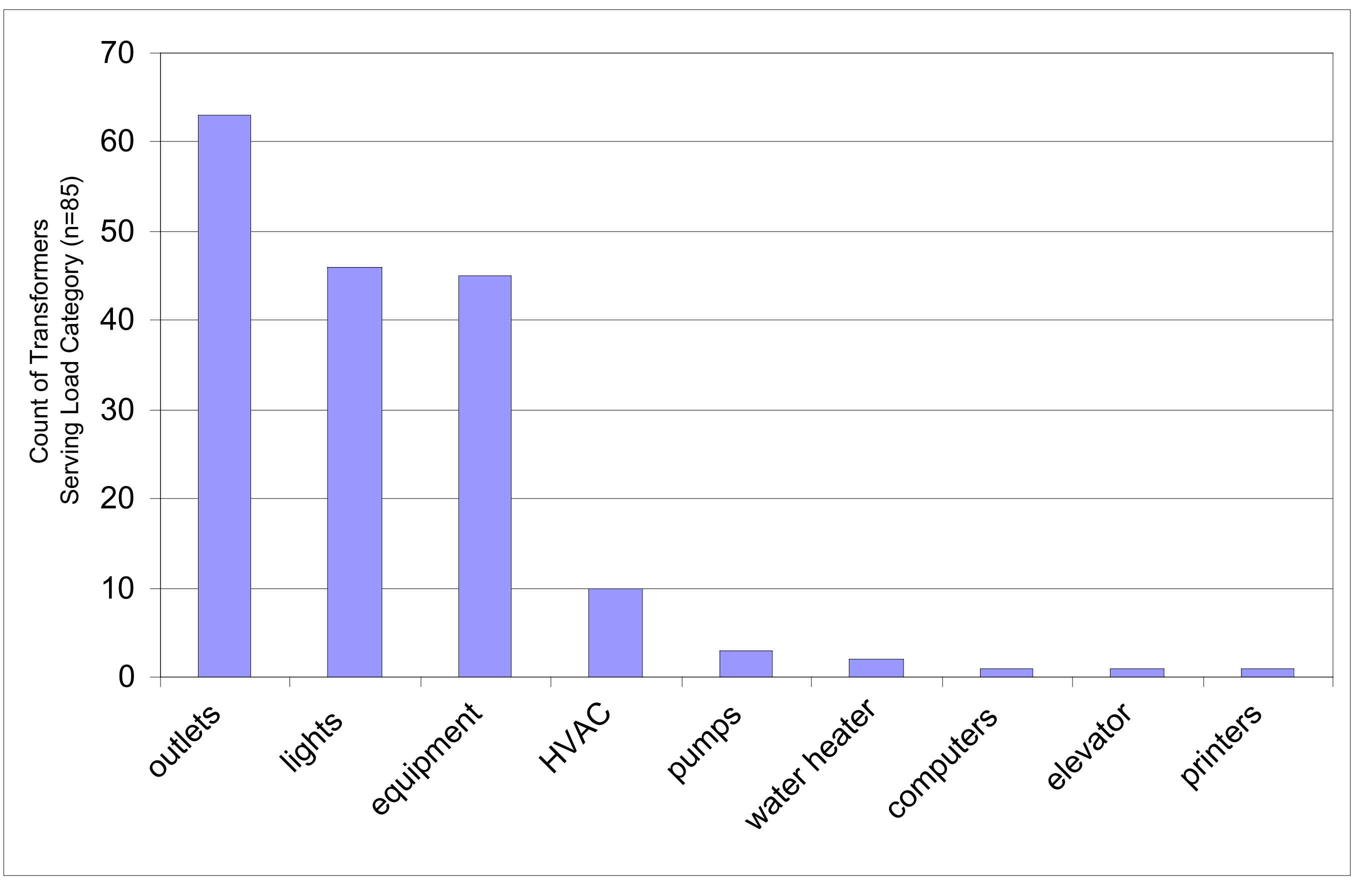
During the initial survey of a building s transformers, Cadmus noted the categories of loads served by each transformer and then reviewed the loading of the transformers chosen for metering in more detail. Listed loads for those transformers are presented in Figure 3-4. In general, transformers served the following loads:

- Plug loads (primarily office equipment and task lighting).
- General lighting loads.
- Various equipment including low-voltage manufacturing equipment.
- HVAC equipment including exhaust fans.
- Pumps.
- Small water heaters.

Additional loads observed included forklift battery chargers in warehouses and sign lighting.

The majority of transformers serve receptacle and lighting loads. The remaining loads are various low-voltage equipment, some of which is listed in panel schedules and some that is plugged into outlets but not listed.

Figure 3-4
Listed Loads for Metered Transformers



(Each of the 85 transformers in the figure serve one or more load categories)

Transformer Capacity and Load per Square Foot of Facility

For the 24 buildings providing square-footage data at the writing of this report,[13] the installed transformer capacity in kVA/square foot of building space is illustrated in Figure 3-5. The 24 buildings cover roughly 2.7 million square feet. The transformer capacity per square foot varies widely from less than 1 VA for several retail facilities to a maximum of over 17 VA at a manufacturing facility, with an average of 6.0 VA per square foot. There are several reasons for the variation in design capacity:

- Safety factors incorporated by the design engineer vary across engineering firms and may vary over time (i.e., older practice may differ from current design practice).
- Lighting can account for 1.5 to 2 VA per square foot of actual and design load, more in older buildings. In many facilities lighting uses 277-volt single-phase primary power and does not use electricity transformed by the low-voltage transformer.
- Not every industrial facility has machinery using 208/120-volt electricity transformed by the low-voltage transformer.
- The four highest design capacities ranged from 12 to 17.5 VA per square foot. They were a manufacturing facility, a medical laboratory, a telecommunications installation, and a supermarket. The lowest design loads tended to be retail spaces.

In general, the lower design values were from retail facilities and the higher values were in industrial facilities.

Loading per Square Foot of Building Space

We estimated the loading per square foot based on the RMS load of 15.9 percent measured in this study and the design kVA data presented in Figure 3-5. The estimated loads vary from less than 0.25 VA/square foot to less than 2.5 VA, with a single estimate of 2.78 VA/square foot in an industrial facility. The average load per square foot is estimated at 0.8 VA.

[13] Of the 43 buildings surveyed 24 had reliable and available information on areas served.

Figure 3-5
Histogram of Transformer Capacity per Square foot of Building

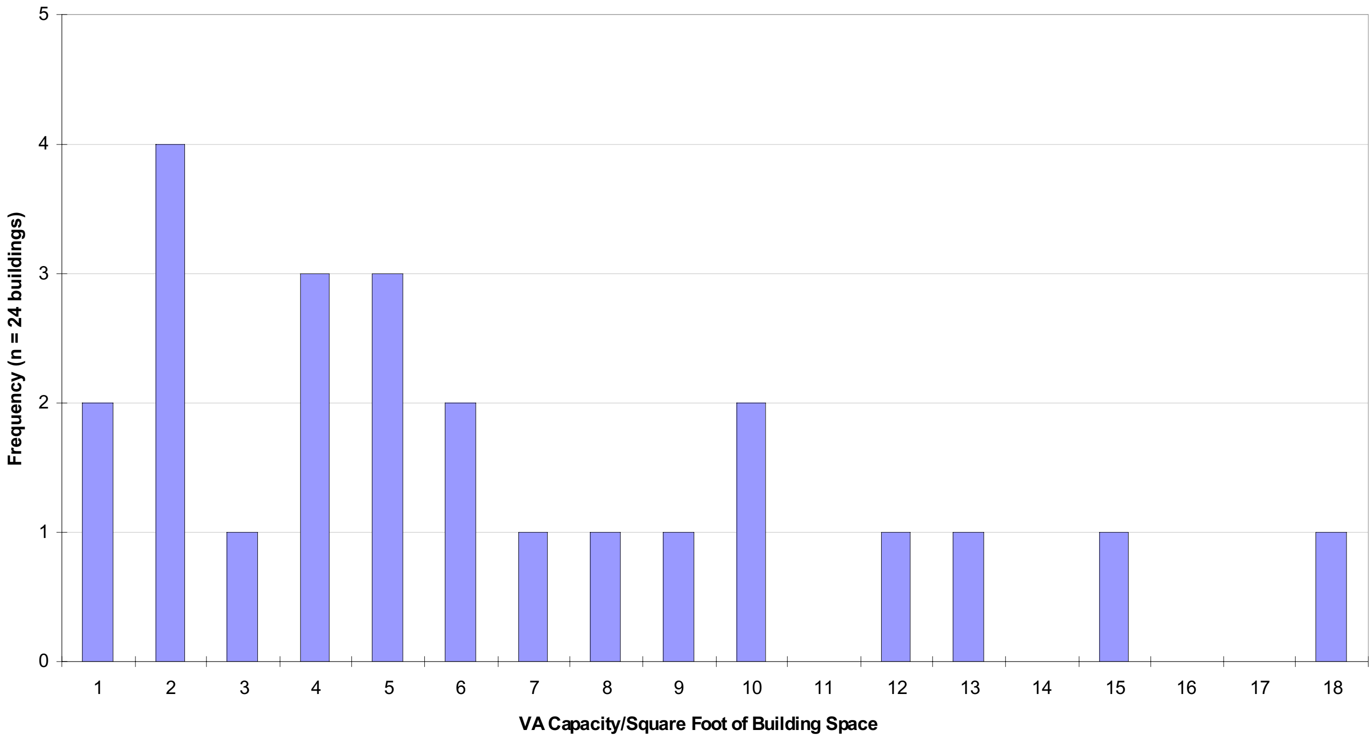
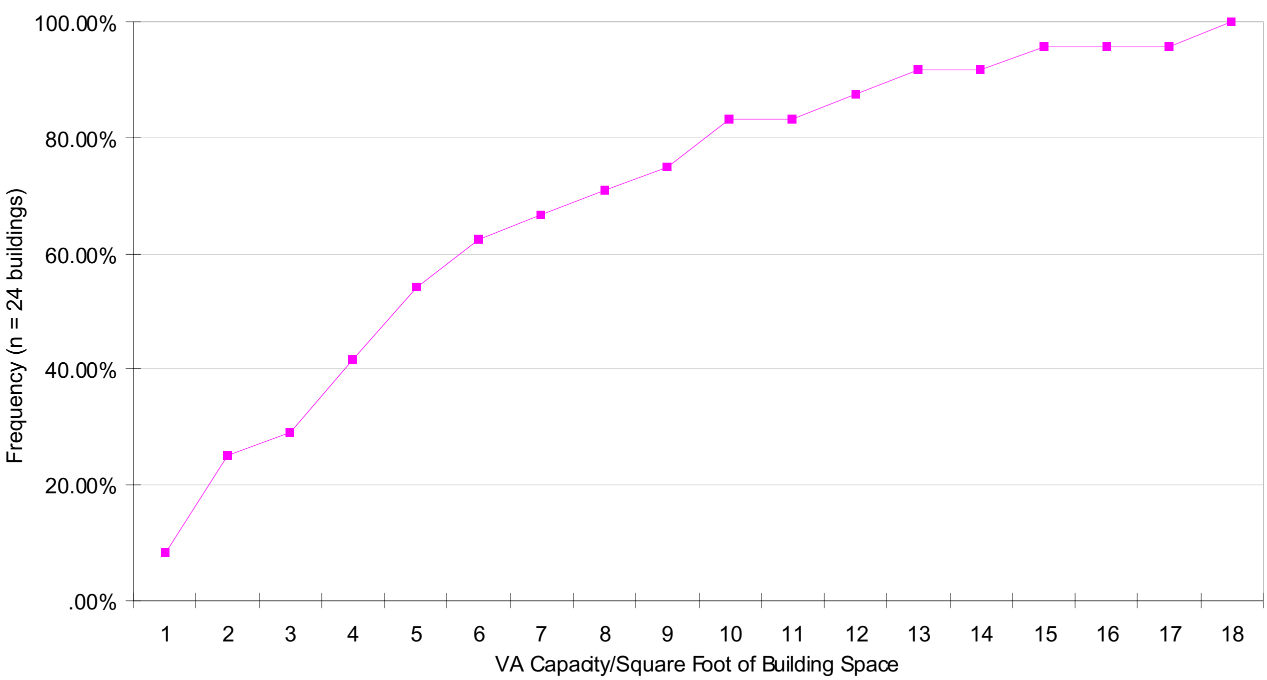


Figure 3-6
Cumulative Frequency of Transformer Capacity per Square foot of Building



TRANSFORMER LOADING

Loads for All Monitored Transformers

The average load factors of the 89 transformers monitored were calculated using a root-mean-square (RMS) method to properly weight periods of high loads. By using this method, the average can be used to directly calculate transformer losses. On average, the load was 15.9 percent of the transformers nameplate capacity in volt-amperes. Summary statistics for the 89 transformer loads are presented in Table 4-1. Based on the observed standard deviation, the estimated average load of dry-type transformers over the utility service areas was 13 to18 percent at a 95-percent confidence level.

The median load factor is well below the mean, reflecting the effect of using RMS averaging rather than a simple arithmetic mean, and the fact that several transformers loaded in 30 to 60 percent range will pull up the average load without appreciably raising the median. The minimum load of 0.0 percent reflects a single transformer serving an unused circuit. The fact that it was not used was not known prior to installing metering equipment. It was retained in the study because it was chosen randomly and metered and will reflect a portion of the larger transformer population. Removing the transformer from the study would have minimal effect on the statistics in Table 4-1 because of the large number of transformers metered.

Table 4-1
Summary Statistics for the 89 Transformer Loads Measured
(Percent of transformer capacity)

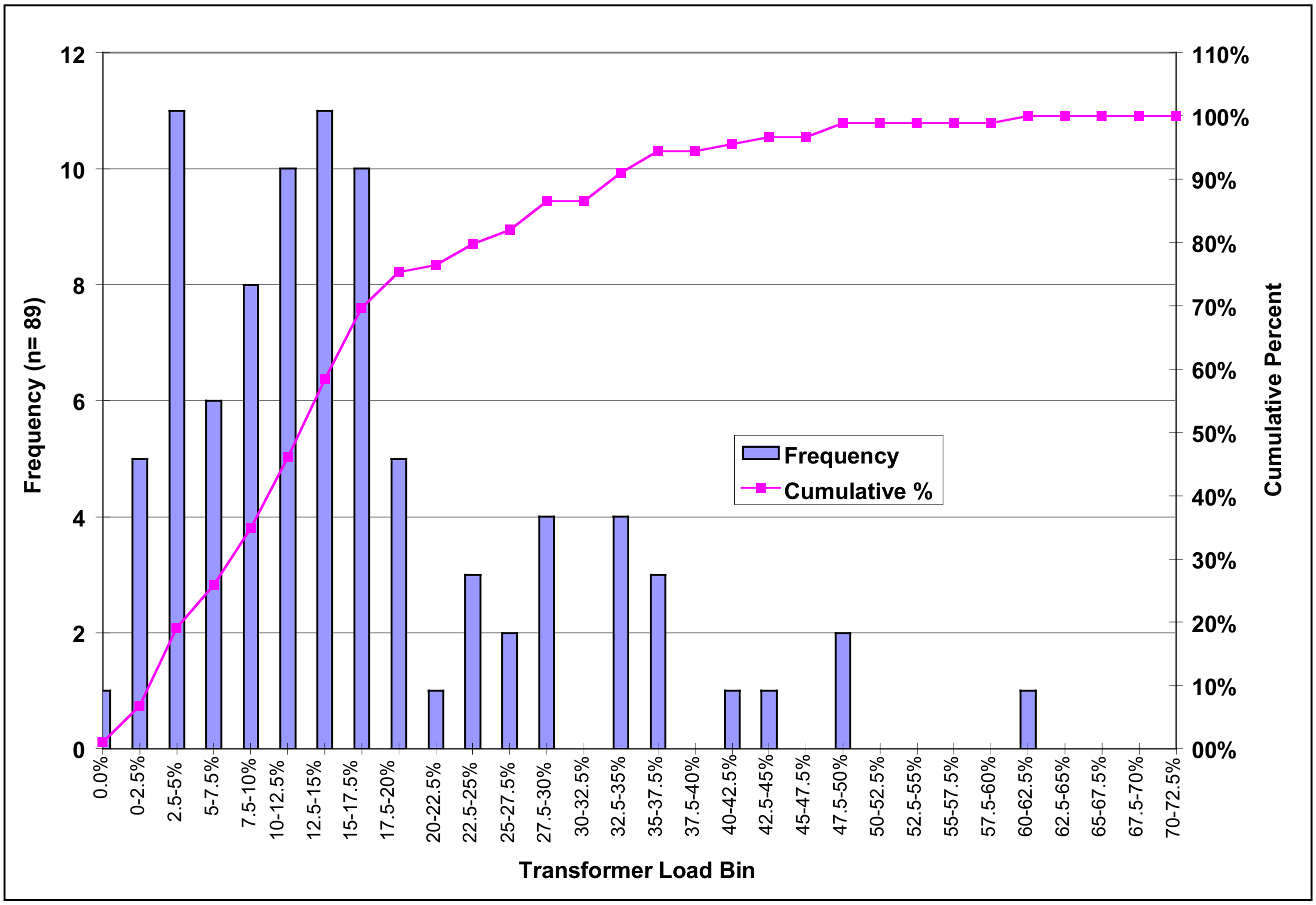
RMS average load	15.9%
Upper estimate @ 95 percent confidence	18.5%
Lower estimate @ 95 percent confidence	13.3%
Median RMS load	12.7%
Observed maximum RMS load	62.4%
Observed minimum RMS load	0.0%
Standard deviation of average loads	12.4%
Number of transformers	89

Not only was the average RMS load on transformers low, fewer than 4 percent of transformers monitored had average loads greater than 50 percent (see Figure 4-1). Only 14 percent had average loads greater than the 35-percent target load of the TP-1 standard.

The reason for the average load to be well below the transformer s capacity is two-fold. First, the average load is naturally lower than the peak load because of variations in loads that the transformer serves and the schedule of those loads. Advances in power management allow office equipment to sleep when not in use, effectively decreasing the average load relative to peak loads. Second, the peak load is below the transformer s capacity because transformers are specified based on their expected peak load plus some margin of safety and room for future expansion in demand. Considering the two ratios together, the peak relative to transformer capacity and the ratio of the peak to average load, it is understandable that the average load on a transformer is low.

The *peak* load of each transformer as measured by logged current readings collected every 10 minutes was determined for each of the 89 transformers, then averaged. The average peak load was 33 percent. This does not necessarily mean that the average margin of safety was precisely 3.0. Other considerations, including the balance of loads across the transformer s three phases, may reduce the margin somewhat, but the margin of safety is, nonetheless, substantial. The average ratio of average to peak loads for the monitored transformers was 52 percent, reflecting varying load schedules and the fact that modern office equipment draws little current when not in use.

Figure 4-1
Histogram of RMS Average Transformer Loads



Loads by Building Type

To determine whether there was variation in transformer loads between building types, 17 or 18 transformers were monitored in each of the following five building types:

- Universities.
- Health care facilities.
- Manufacturing facilities.
- Office buildings.
- Retail facilities.

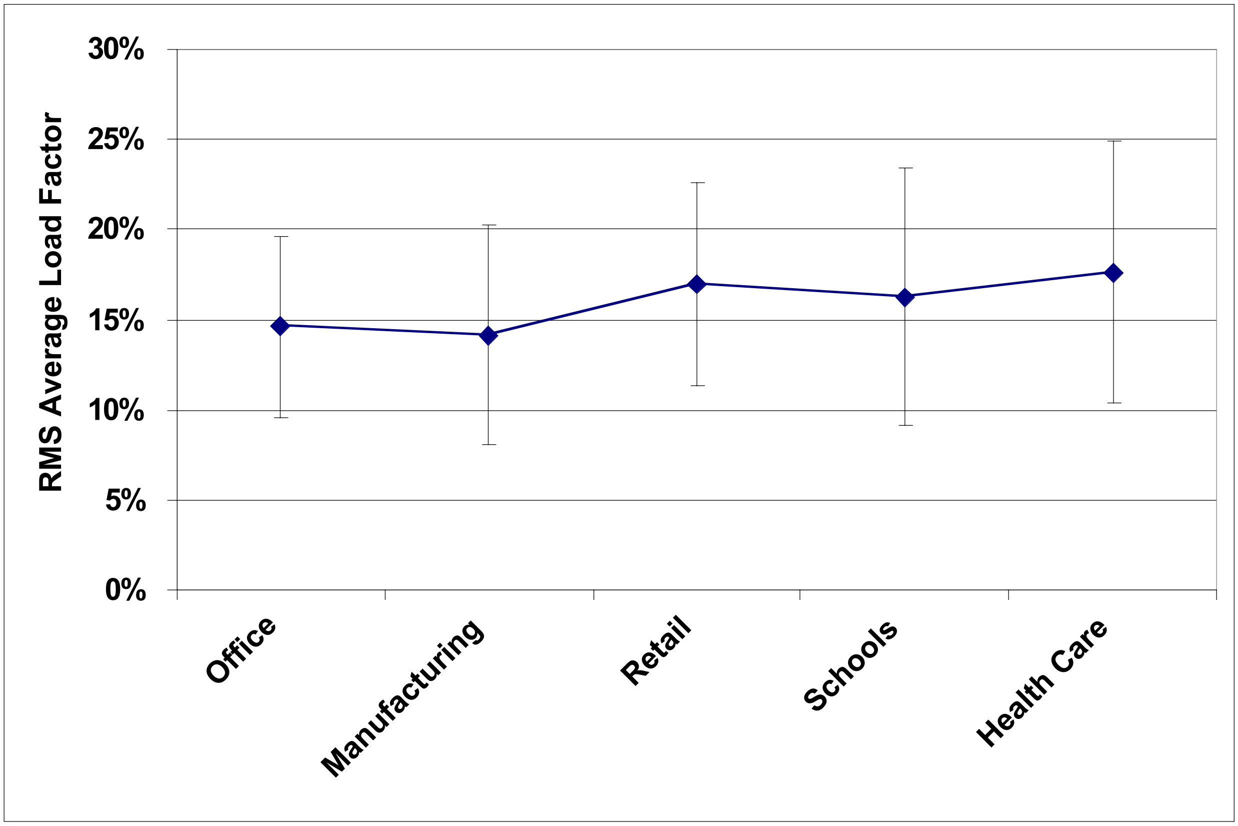
Summary statistics are presented in Table 4-2 for each building type. The average loads were consistent across building types, varying from only 14.1 to 17.6 percent. Figure 4-2 shows the average RMS loads and the range of the 95-percent confidence limits of the average load for each building type. The confidence interval is larger for each building type than for all building types together because fewer samples were collected for each building type. Even the upper bounds, however, are well below the 35-percent load at which transformer efficiencies are listed in TP-1 and in the ENERGY STAR label.

Table 4-2
Transformer RMS Average Load Factors by Building Type
(Percent of transformer capacity)

	Building Category				
RMS average load factor:	Universities	Health Care	Manufacturing	Office	Retail
Average	16.3%	17.6%	14.1%	14.6%	17.0%
Upper estimate @ 95 percent confidence level	23.4%	24.9%	20.2%	19.7%	22.6%
Lower estimate @ 95 percent confidence level	9.1%	10.4%	8.0%	9.5%	11.3%
Median	14.3%	12.7%	10.8%	13.6%	14.3%
Maximum	62.4%	50.0%	47.5%	33.7%	42.5%
Minimum	1.3%	1.3%	0.9%	0.0%	1.1%
Standard deviation of average loads	14.5%	14.2%	12.3%	10.2%	11.4%
Quantity	18	17	18	18	18

Prior to the study, it was expected that average loads would differ among building types because of varying schedules, varying equipment, and the possibility of different design practices. As measured, however, the average loading varied little in part because the transformers serve similar equipment, typically computers and lighting, across building categories. Loads particular to a building type, manufacturing equipment for example, are often served by 480-volt power upstream, on the primary side of the studied transformers. Histograms of average loads by building type are presented in Appendix E.

Figure 4-2
RMS Average Transformer Load Factors by Building Type



(Bars indicate 95 percent confidence interval of each average load)

Load by Building Schedule

There was little statistical difference between circuits in buildings with three-shift schedules and those with single-shift schedules. The primary reason is that transformers often serve a mixture of circuits with varying schedules, which do not necessarily correspond well with overall building schedules. For example, transformers in a single-shift office building may serve refrigerators and other loads that are not shut off at night. A portion of the loads in three-shift buildings may cycle off repeatedly and result in low average loads or, like task lighting, may be shut off during second and third shifts. This result is for the study-wide population of transformers. For an individual transformer, however, there are certainly cases where a three-shift building's transformer carries a higher average RMS load than one in a single shift building.

Table 4-3
Transformer RMS Average Load Factors by Building Schedule
(Percent of transformer capacity)

	Operating Schedule	
RMS average load factor	0 - 12 Hours/day	12 - 24 Hours/day
Average	15.2%	17.3%
Upper estimate @ 95 percent confidence	18.2%	22.5%
Lower estimate @ 95 percent confidence	12.2%	12.1%
Median	13.3%	12.6%
Maximum	62.4%	50.0%
Minimum	0.0%	0.9%
Standard deviation of average loads	11.8%	13.7%
Quantity	60	29

Load By Transformer Size

We examined loading by transformer size to see whether the size of a transformer was correlated with a high or low load. While the average loads varied, the variation was not statistically significant because of the large standard deviation and small sample size. While the load of 15 and 30 kVA transformers was relatively high, these transformers account for only 7 percent of the capacity of the dry-type transformer market.

Table 4-4
Transformer Load Factor by Transformer Size
(Percent of transformer capacity)

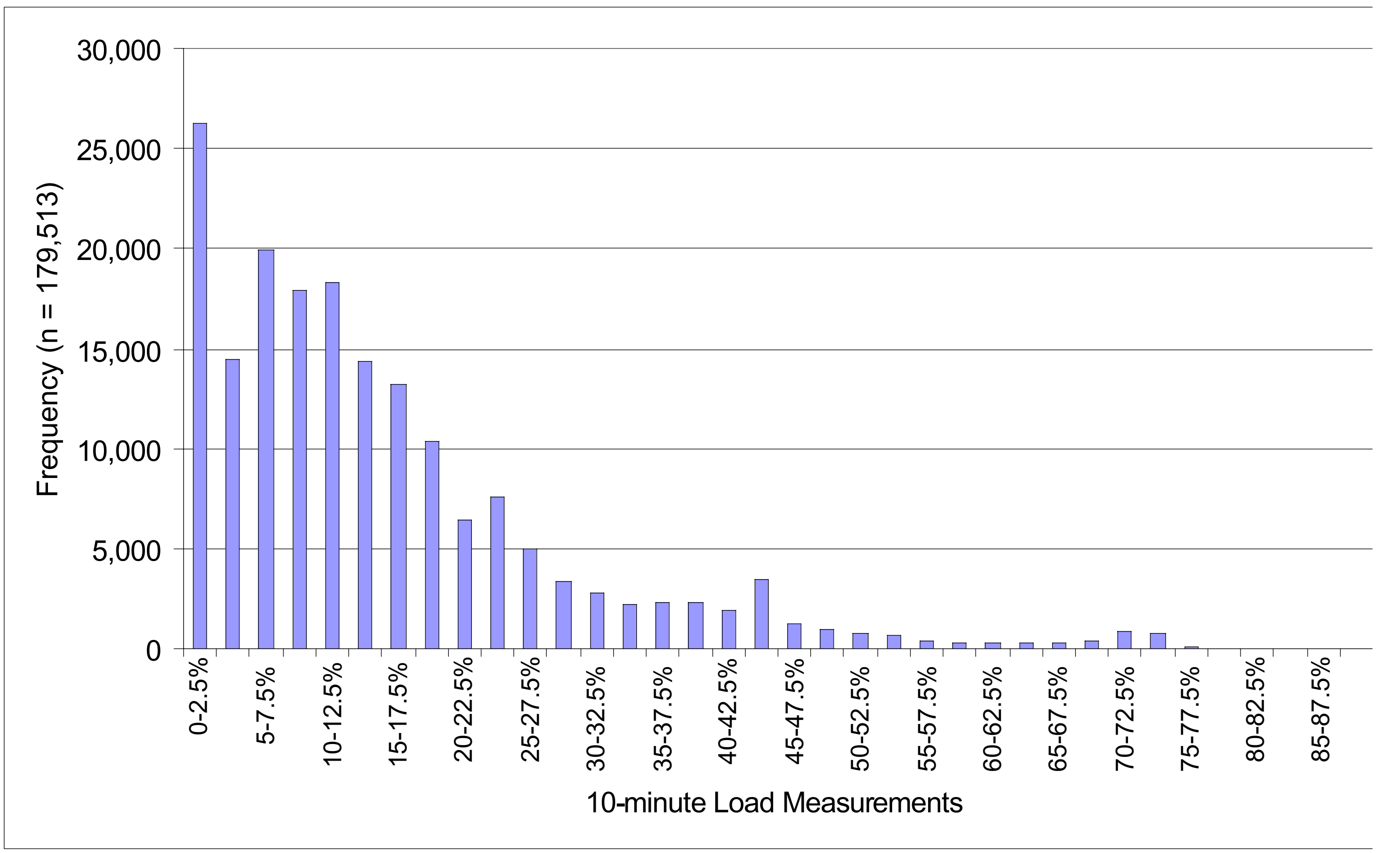
RMS average load factor	15 - 30 kVA	45 kVA	75 kVA	112.5 - 150 kVA	225 - 300 kVA
Average	23.4%	15.6%	14.0%	12.3%	19.9%
Upper estimate @ 95 percent confidence	34.1%	20.6%	17.6%	19.4%	31.7%
Lower estimate @ 95 percent confidence	12.6%	10.7%	10.3%	5.2%	8.1%
Median	18.4%	12.7%	11.3%	10.4%	16.4%
Maximum	62.4%	50.0%	40.2%	34.3%	35.6%
Minimum	1.3%	1.1%	0.9%	0.0%	11.0%
Standard deviation of average loads	16.9%	12.8%	10.4%	9.9%	10.2%
Quantity	12	28	34	10	5

Loads Observed in the Monitored Transformers

Histograms of 10-minute load measurements for each monitored transformer are presented in Appendix F, and a time series of the load measurements is presented in Appendix G. Figure 4-3 combines the 179,000 load measurements of all 89 transformers to illustrate the portion of time that the transformer population occupies a particular load regime. Not only are the average loads low, but the loads for all periods are relatively low. Loads exceeded 50 percent of design capacity during only about 3 percent of all measured time periods. The cumulative frequency of the loads is shown in Figure 4-4.

If transformers were reduced an average of one-third in size (equivalent to installing a 30-kVA model instead of a 45-kVA unit), roughly 1 percent of measurements would have been at or slightly above capacity, with most transformers well within their capacity for all time periods.

Figure 4-3
Histogram of Transformer Load Factor Measurements
For All Study Time Periods and All Transformers



Harmonics and Power Factor

The K factor, total harmonic distortion, and power factor were measured for each phase of monitored transformers when meters were installed and then again when meters were removed. The K factor is a number developed to take into account the effect of harmonics on transformer loading and losses.[14] It is

[14] Kennedy, Barry, W. 1998. *Energy Efficient Transformers.* McGraw Hill. ISBN# 0-07-034439-6.

calculated by summing the product of the square of the harmonic current and the square of the harmonic order divided by the square of the harmonic current. The histogram of K factor measurements is shown in Figure 4-5. The vast majority of spot readings were equal to or less than 4.0 and nearly all readings were less than 10.0. The average K factor was 2.7, with a median value of 1.4. Several manufacturers produce transformers with K ratings of 13 to serve circuits with high anticipated K factors.

The total harmonic distortion of current is the ratio of the total harmonic current to the fundamental frequency current. The average value of the total harmonic distortion was 21 percent, and the median value was12 percent.

The power factor is the ratio of useful power (kW) to apparent power (kVA). The average power factor for all metered transformers was 0.87 with a median value 0.91.

Figure 4-4
Cumulative Frequency of Transformer Load Factor Measurements
For All Study Time Periods and All Transformers

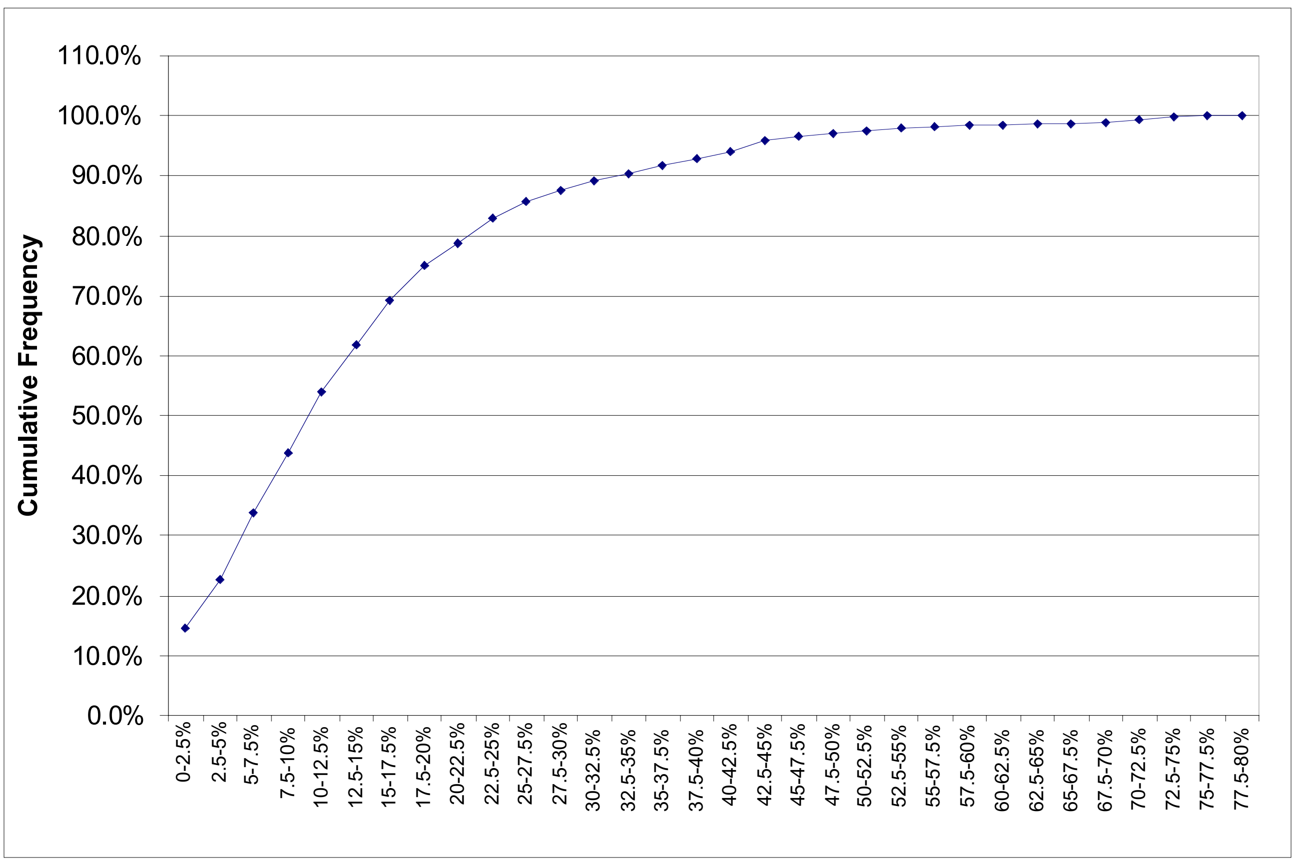
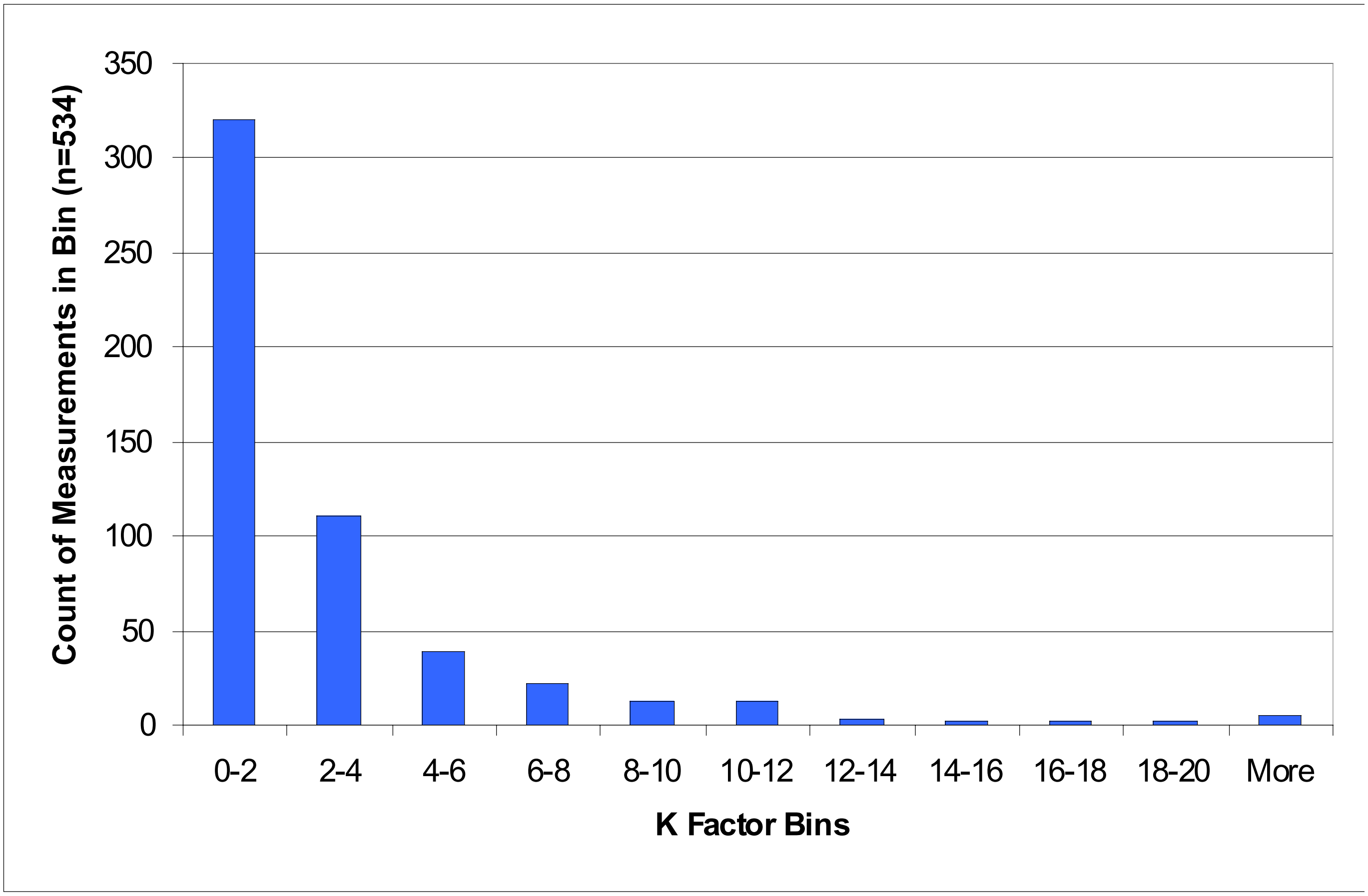


Figure 4-5
Histogram of Spot Measurements of K Factor



ENERGY SAVINGS POTENTIAL

As shown in Figure 5-1, the efficiency of a 75 kVA TP-1/ ENERGY STAR transformer peaks at 98 percent at 35 percent load while the efficiency of a conventional transformer peaks at a load of 40 to 50 percent. At the average RMS study load of 16 percent, a TP-1 transformer is roughly 1.7 percent more efficient than a conventional model, or stated another way, uses roughly 40 percent less energy than a conventional model.

A 75-kVA TP-1 transformer has a core loss of less than 300 watts, a saving of 200 to 250 watts over a standard unit (Table 5-1). Through the use of more-efficient core materials, lower core losses ultimately may be economically feasible. If amorphous cores prove practical for dry-type transformers, losses as low as 50 watts may be possible, an order of magnitude improvement over standard models. The winding losses for a typical 75-kVA transformer at 16-percent load are roughly 50 watts (roughly 2 percent of their full load losses). The winding losses are only slightly lower for other high-efficiency models, primarily because at low loads the winding losses are low and thus little improvement is possible.

Table 5-1
Losses in Various Types of 75 kVA Transformers

		Winding Loss (watts)		
75kVA Transformer Models	Core Loss (watts)	@ 100% Load	@16% *RMS* Average Load	Total Loss @16% *RMS* Average Load
Standard Model	500-550	2,500-3000	45-54	545-604
Major Manufacturer s TP-1	288	2,480	45	333
Major Manufacturer s 80…C	819	984	18	837
Custom model	190	910	16	208
Amorphous core (predicted)[15]	50	3,000	54	104

As shown in Figure 5-1, a typical 80…C model is designed to reach peak efficiency at a load of roughly 75 to 80 percent. In this graph using the RMS average load yields the average transformer efficiency. The 80…C model transformer would be a poor choice at the RMS load shown in this study. In fact, this model would have roughly 2.5 times the losses of a TP-1/ ENERGY STAR transformer. There may, however, be other reasons for specifying an 80…C model including the large margin of capacity it provides, and the lower heat rise which may be desired in confined spaces where heat buildup is a concern.

Energy Savings Available in the Surveyed Transformers

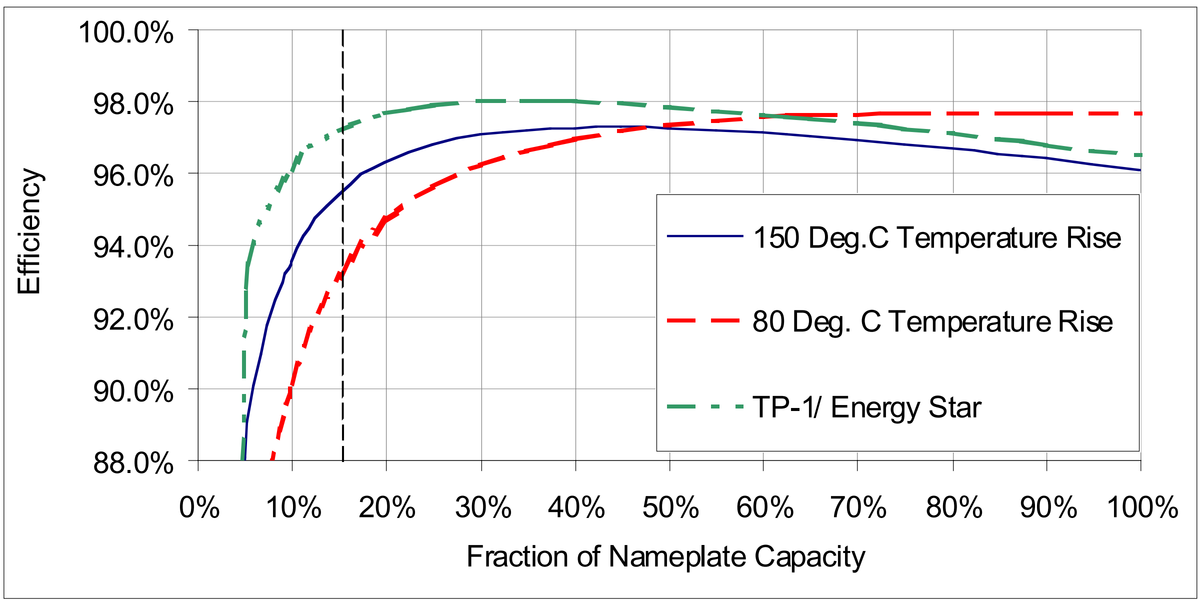
For the 321[16] three-phase transformers surveyed (26.5 MVA) for which full information was available and verifiable, roughly 790,000 kWh would have been saved annually had TP-1/ ENERGY STAR transformers been installed instead.[17] Extrapolating to the annual dry-type transformer market of roughly 12,000 MVA[18]

[15] Conversation with Allied Signal, Amorphous metals division, October 1999.
[16] Of the 353 transformers surveyed, 321 had information on both size and type available.
[17] Energy savings were calculated using a major manufacturer's TP-1 line and the average energy use of major manufacturers' standard transformer models. Savings were calculated for the sizes of the 321 transformers surveyed. The study average load of 15.9 percent RMS load was used to calculate losses.
[18] ORNL, Supplement to the Determination Analysis (ORNL-6847) and Analysis of the NEMA Efficiency Standard for Distribution Transformers, ORNL-6925, September 1997.

and using the size distribution found in this study, roughly 350 million kWh would be saved per year nationally assuming 20 percent market penetration for five years of sales.[19] Interpolating this figure based on commercial and industrial electrical sales[20] this converts to a savings of 5.5 million kWh in Massachusetts. Interpolating based on population yields a savings figure of 8 million kWh.

If an ultra-low-loss transformer were rapidly brought to market, the possible savings would be on the order of 620 million kWh, assuming the same level of market penetration. Massachusetts' savings would range from 10 to 14 million kWh.

Figure 5-1
Efficiency of a 150…C, and 80…C, and a TP-1 75 kVA transformer[21]



(The vertical dashed line indicates the average load factor of 15.9 percent determined in this study.)

[19] Savings were calculated by extrapolating study savings to the annual sales of transformers.
[20] U.S. Census Bureau, 1998 Statistical abstract of the United States, Table 973.
[21] Graph produced by the Transformer Efficiency Calculator (TEC) developed by The Cadmus Group, Inc. under U.S. EPA contract 68-W6-0050, August 1999.

CONCLUSIONS

This study found that dry-type low-voltage transformers are lightly loaded across building types, building schedules, and transformer sizes, with an RMS average load factor of 16 percent. This load is in the range in which most losses are attributable to the transformer core and where an efficient-core transformer design such as TP-1/ ENERGY STAR is advantageous. The study also found that loads on the monitored transformers were low for most time periods, exceeding 50 percent of capacity for only 3 percent of measurements. This means that most transformers do not approach 50-percent loading even during their peak load.

Transformers are lightly loaded: peak loads even at the individual phase level averaged 33 percent of capacity for transformers monitored. The low peak loads in the transformers indicate that sizing procedures for these types of transformers may be worth examining. While not all transformers are over-sized, the majority of those metered were lightly loaded during the study even at their peak loads. If it were possible to reduce the size of a portion of the transformers installed, the incremental cost of the smaller TP-1 transformer over the larger standard unit would be much lower then buying a TP-1 model of equal size.

At the loads measured in this study, nearly all of the transformer losses are from the core; losses from windings are minor. Because the windings are operating at such low loads, even major improvements in their efficiency would produce a relatively small benefit, not just on average but for nearly every transformer measured. Therefore, TP-1/ ENERGY STAR transformers and other models with high-efficiency cores are good choices for the loads measured in this study. For the transformers metered, an 80°C temperature rise model would have been a poor choice. In general because the types of transformers metered are lightly loaded, low temperature rise transformers would cost more *and* require more energy than standard models.[22] Similarly 115°C temperature rise models would use more energy than TP-1 models for nearly all of the average RMS loads measured.

The pending TP-1 requirement will reduce energy consumption over standard models for transformers operating at any load fraction. In addition, because no transformers metered had RMS average loads greater than 63 percent, TP-1 transformers would use less energy than a typical 80°C temperature rise for all metered installations.

For the transformers surveyed in 43 facilities, nearly 800,000 kWh would have been saved annually had TP-1/ ENERGY STAR transformers been installed instead.[23] This savings of roughly 18,600 kWh per facility per year could be achieved by a new building specifying ENERGY STAR transformers. For context, the study buildings were large commercial and industrial buildings with an average area of roughly 100,000 square feet.

Extrapolating to the annual dry-type transformer market of roughly 12,000 MVA, roughly 350 million kWh would be saved per year nationally, assuming 20 percent market penetration of TP-1/ ENERGY STAR for five years of transformer sales, and 620 million kWh could be saved annually if an ultra-low-loss transformer were rapidly brought to market.

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[22] There are some models available that combine low temperature windings with an energy efficient core that would be efficient at both low and high loads. The problem with these models is that the purchaser pays a premium for high efficiency windings but receives little benefit from them.

[23] Energy savings were calculated using a major manufacturer's TP-1 line and the average energy use of major manufacturers' standard transformer models. Savings were calculated for the sizes of the 321 transformers surveyed. The study average load of 15.9 percent RMS load was used to calculate losses.

Interpolating these savings figures to Massachusetts, 5.5 million to 8 million kWh could be saved by TP-1 and 10 million to 14 million kWh by the ultra-low-loss transformer.

The pending TP-1 standard will provide energy savings over the traditional use of standard models for any load fraction that transformers experience. Transformers with an 80…C temperature rise were rarely encountered in this study and nationally are not commonly used for dry-type, low-voltage applications. While they can provide higher energy efficiency than even TP-1 models at very high loads, such loads were not observed in metered transformers and are anticipated to occur rarely, if ever, in the transformer population. Thus, energy consumption per facility and in the aggregate will decrease through adoption of the TP-1 standard.