CHAPTER 5: ENGINEERING ANALYSIS

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LIST OF ACRONYMS AND ABBREVIATIONS

A	present value of future core losses ($/watt)
AL	aluminum
ANOPR	Advance Notice of Proposed Rulemaking
ANSI	American National Standards Institute
B	present value of future coil losses ($/watt)
BIL	basic impulse insulation level
CSA	Canadian Standards Association
CU	copper
DL	design line (followed by a number indicating which design line)
DOE	United States Department of Energy
H-O DR	laser-scribed M3 core steel
Hz	hertz
kV	kilovolt
kVA	kilovolt-ampere (transformer size rating)
M*	M2, M3, M4, M6 - thickness of core steel
NEMA	National Electrical Manufacturers Association
NCI	Navigant Consulting, Inc. (formerly Arthur D. Little, Inc.)
NL	no-load losses
NOPR	Notice of Proposed Rulemaking
OPS	Optimized Program Service, Inc.
ORNL	Oak Ridge National Laboratory
PC	product class
SA1	Metglas amorphous core material
SEC	Securities and Exchange Commission
TL	total losses
US	United States
V	volts
Y	wye-type transformer terminal connection
ZDMH	mechanically scribed, deep-domain refined core steel
Φ	phase

CHAPTER 5: ENGINEERING ANALYSIS

5.1 INTRODUCTION

This chapter provides the technical support documentation on the engineering analysis, evaluating both liquid-immersed and dry-type distribution transformers. The purpose of the engineering analysis is to estimate the relationship between the manufacturer's selling price of a transformer and its efficiency level. This relationship serves as the basis for the subsequent cost-benefit calculations for individual consumers, manufacturers, and the nation (see Chapter 8, Life-Cycle Cost and Payback Period Analyses). Determining the cost-efficiency relationship involves analysis of the options available to manufacturers for increasing the efficiency of a distribution transformer.

The Department selected a modified design-option approach for the engineering analysis. The design-option approach normally involves selecting technology and/or material options for transformer designs, and requesting that manufacturers provide estimated costs of transformers built with these options at various efficiency levels. The modification applied to the design-option approach involved using a third party to create the designs for the transformer design database and working with manufacturers to select appropriate design options and obtain correct costing information.

In planning the structure of the engineering analysis, the Department visited the facilities of nine distribution transformer manufacturers and one component supplier.[a] Together, representatives of these companies contributed more than 60 hours of presentations, technical information, and plant tours to the engineering analysis. Topics discussed at these meetings included the structure of the engineering analysis, product classifications, product design, materials handling, market dynamics, high-efficiency designs, and manufacturers' concerns relating to the rulemaking.

The Department recognizes that the results in this chapter are not the definitive answer to the question of the relationship between a manufacturer's cost and the efficiency of the transformer. These results assume an ideal situation, where manufacturers do not incur any increased retooling, redesign, marketing or special handling costs associated with changing materials or core/coil dimensions. The Department requests that reviewers, and particularly manufacturers, submit comments on what additional costs they may incur if minimum efficiency standards are introduced. Identification of additional costs will be important in subsequent stages of the rulemaking process (e.g., manufacturer impact analysis (MIA)).

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[a] During the first quarter of 2002, meetings were held with eight distribution transformer manufacturers, including ABB Power Technology Products Division USA (both liquid-immersed plant and a dry-type plant), Acme Electric Corporation, Cooper Power Industries, Federal Pacific Transformer Company, Howard Industries Inc., Jefferson Electric Inc., Kuhlman Electric Corporation, and Square-D Company. The Department also met with AK Steel, a core steel manufacturer.

5.2 STRUCTURING THE ENGINEERING ANALYSIS

As discussed in the market and technology assessment (Chapter 3), distribution transformers are classified by their insulation type (liquid-immersed or dry-type), the number of phases (single or three), the primary voltage (low-voltage or medium-voltage for dry-types) and the basic impulse insulation level (BIL) rating (for dry-types). Following this convention, the Department developed ten product classes, shown in Table 5.2.1. These product classes were adapted from National Electrical Manufacturers Association's (NEMA) TP 1 classification system, though they do not follow the classification system precisely. NEMA's TP 1 classifies medium-voltage, dry-type distribution transformers into two product classes, ≤60 kilovolt (kV) BIL and >60 kV BIL. Based on input from manufacturers, the Department elected to increase the differentiation of medium-voltage, dry-type transformers, and create three product classes of BIL ratings: 20-45 kV BIL, 46-95 kV BIL and ≥96kV BIL (see section 3.3).

Within each of these product classes, distribution transformers are further classified by their kVA rating. The range and number of kilovolt-amp (kVA) ratings varies by product class, as shown in Table 5.2.1. For NEMA's TP 1-2002, there are 99 kVA ratings across all the product classes (see section 3.7.1). For the Department, because of the greater degree of differentiation around the BIL rating, there are 115 kVA ratings across all the product classes. These kVA ratings are essentially size categories, indicating the power handling capacity of the transformers. Due to the physical principles of construction and material properties, efficiency levels vary by both product class and kVA rating.

Table 5.2.1 Product Classes and Number of kVA Ratings

Distribution Transformer Product Class	kVA Range	Number of kVA Ratings
1. Liquid-immersed, medium-voltage, single-phase	10-833	13
2. Liquid-immersed, medium-voltage, three-phase	15-2500	14
3. Dry-type, low-voltage, single-phase	15-333	9
4. Dry-type, low-voltage, three-phase	15-1000	11
5. Dry-type, medium-voltage, single-phase, 20-45 kV BIL	15-833	12
6. Dry-type, medium-voltage, three-phase, 20-45 kV BIL	15-2500	14
7. Dry-type, medium-voltage, single-phase, 46-95 kV BIL	15-833	12
8. Dry-type, medium-voltage, three-phase, 46-95 kV BIL	15-2500	14
9. Dry-type, medium-voltage, single-phase, ≥96 kV BIL	75-833	8
10. Dry-type, medium-voltage, three-phase, ≥96 kV BIL	225-2500	8
	Total	115

The Department recognized that it would be impractical to conduct a detailed engineering analysis of the cost-efficiency relationship on all 115 kVA ratings, so it sought to develop an approach that simplified the analysis while retaining reasonable levels of accuracy. The Department consulted with industry representatives and transformer design engineers, and developed an understanding of the construction principles for distribution transformers. It found that many of the units share similar designs and construction methods. Thus, the Department simplified the analysis by creating 13 engineering design lines, which group together kVA ratings based on similar principles of design and construction. These 13 design lines subdivide the product classes, to improve the accuracy of the engineering analysis. These 13 engineering design lines differentiate the transformers by insulation type (liquid-immersed or dry-type), number of phases (one or three), and primary insulation levels (three different BIL levels for medium voltage dry-types).

The Department then selected one unit from each of the engineering design lines for study in the engineering analysis and the LCC analysis (see Chapter 8). It then extrapolated the results of this analysis from the unit studied to the other kVA ratings in that engineering design line. This reduced the number of units for analysis from 115 to 13. The technique used to extrapolate the findings is referred to as "the 0.75 scaling rule." This rule states that, for similarly-designed transformers, costs of construction and losses scale to the ratio of kVA ratings raised to the 0.75 power. The relationship is valid where the optimum efficiency loading points of the two transformers being scaled are the same. An example of how this scaling can be applied appears in section 5.2.1 of this chapter. A technical discussion on the derivation of the 0.75 scaling rule appears in Appendix 5-B.

Table 5.2.2 presents the Department's 13 design lines and the representative units selected from each engineering design line for analysis. Descriptions of each of the design lines and the rationale behind the selection of the representative units follow Table 5.2.2.

Table 5.2.2 Engineering Design Lines (DL) and Representative Units for Analysis

PC*	DL	Type of Distribution Transformer	kVA Range	Voltage Taps	Secondary Voltages	Engineering Design Line Representative Unit
1	1	Liquid-immersed, medium-voltage, single-phase, rectangular tank	10-100	±2-2.5%	240/120 to 600V	50kVA, 65˚C, single-phase, 60Hz, 7200V primary, 240/120V secondary, rectangular tank
	2	Liquid-immersed, medium-voltage, single-phase, round tank	10-100	±2-2.5%	120/240 to 600V	25kVA, 65˚C, single-phase, 60Hz, 24940GrdY/14400V primary, 120/240V secondary, round tank
	3	Liquid-immersed, medium-voltage, single-phase	167-833	±2-2.5%	120/240 to 600V	500kVA, 65˚C, single-phase, 60Hz, 14400/24940YV primary, 277/480YV secondary
2	4	Liquid-immersed, medium-voltage, three-phase	15-500	±2-2.5%	208Y/120 to 600V	150kVA, 65˚C, three-phase, 60Hz, 12470Y/7200V primary, 208Y/120V secondary
	5	Liquid-immersed, medium-voltage, three-phase	750-2500	±2-2.5%	208Y/120 to 600Y/347V	1500kVA, 65˚C, three-phase, 60Hz, 24940GrdY/14400V primary, 480Y/277V secondary
3	6	Dry-type, low-voltage, single-phase	15-333	Universal**	120/240 to 600V	25kVA, 150˚C, single-phase, 60Hz, 480V primary, 120/240V secondary, 10kV BIL
4	7	Dry-type, low-voltage, three-phase	15-150	Universal**	208Y/120 to 600Y/347V	75kVA, 150˚C, three-phase, 60Hz, 480V primary, 208Y/120V secondary, 10kV BIL
	8	Dry-type, low-voltage, three-phase	225-1000	Universal**	208Y/120 to 600Y/347V	300kVA, 150˚C, three-phase, 60Hz, 480V Delta primary, 208Y/120V secondary, 10kV BIL
6	9	Dry-type, medium-voltage, three-phase, 20-45kV BIL	15-500	±2-2.5%	208Y/120 to 600Y/347V	300kVA, 150˚C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL
	10	Dry-type, medium-voltage, three-phase, 20-45kV BIL	750-2500	±2-2.5%	208Y/120 to 600Y/347V	1500kVA, 150˚C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL
8	11	Dry-type, medium-voltage, three-phase, 60-95kV BIL	15-500	±2-2.5%	208Y/120 to 600Y/347V	300kVA, 150˚C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
	12	Dry-type, medium-voltage, three-phase, 60-95kV BIL	750-2500	±2-2.5%	208Y/120 to 600Y/347V	1500kVA, 150˚C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
10	13	Dry-type, medium-voltage, three-phase, 110-150kV BIL	225-2500	±2-2.5%	208Y/120 to 600Y/347V	2000kVA, 150˚C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 125kV BIL

* PC means Product Class (see Chapter 3 of the TSD). PC5, PC7 and PC9 are based on their three-phase counterparts. They were not addressed in the detailed engineering analysis because of their low sales volume.
** Universal Taps are two above and four below 2.5 percent

Dry-type distribution transformers are broken into eight engineering design lines, primarily according to their BIL levels. The Department believes this level of disaggregation is necessary to capture important differences in the cost-efficiency relationship between units as the

BIL level varies. For example, a 300 kVA, three-phase, dry-type unit can appear in design lines 8, 9, 11, or 13 depending on whether the BIL level is 10 kV, 20-45 kV, 60-95 kV, or 110-150 kV.

For design lines 9 through 13, it should be noted that the representative units selected for some of the dry-type design lines may not be the standard BIL levels associated with a given primary voltage. The Department selected a slightly higher BIL level for the representative units from these design lines to ensure that any candidate minimum efficiency standard would not excessively penalize customers purchasing higher BIL levels. For example, a 300 kVA with a 4160V primary is called a "5kV class" transformer and would normally be built with a 30kV BIL level. However, customers also order a 5kV class 300 kVA with 45kV BIL or 60kV BIL. If the candidate minimum efficiency standard were set at 30kV BIL, it may be prohibitively difficult to achieve that same candidate standard level for customers ordering 60kV BIL. Thus, the Department elected to evaluate the middle BIL level (in this example, 45kV BIL), making it slightly easier for the lower BIL, and not too difficult for the higher BIL, to achieve compliance.

The remainder of this section discusses the engineering design lines, providing a description and explanation of the transformers covered.

Design Line 1. This is the basic, high-volume line for rectangular-tank, single-phase, liquid-immersed distribution transformers, ranging from 10 kVA to 100 kVA. The BIL level of the windings ranges between 30 kV and 150 kV, and the tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35 kV and the secondary voltage is less than or equal to 600 Volts (V).

The representative unit selected for design line 1 is a 50 kVA pad-mounted unit, as this is a high shipment volume rating, and is approximately the middle of the kVA range for this design line (10 kVA, 15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA and 100 kVA). Also, NEMA recommended a 50 kVA rating for the Department's analysis. Engineering design and manufacturing differences led to the omission of 167 kVA and higher rated units, which are considered part of design line 3.

Design Line 2. This is the basic, high-volume line for round-tank (pole mounted), single-phase, liquid-immersed distribution transformers, ranging from 10 kVA to 100 kVA. Although some manufacturers tend to employ the same basic core/coil design for design line 1 and design line 2, others may have design differences between pad-mounted and pole-mounted transformers. The Department decided to analyze these two types of distribution transformers separately for the engineering and Life Cycle Cost (LCC) analysis. The BIL level of the windings ranges between 30 kV and 150 kV, and the tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35 kV and the secondary voltage is less than or equal to 600 V.

The representative unit selected design line 2 is a 25 kVA pole-mounted unit, as this is a high-volume rating for round-tanks, and is approximately in the middle of the kVA range for this design line (10 kVA, 15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA and 100 kVA). Also, NEMA recommended that the Department consider a 25 kVA pole-mounted unit in its analysis. (NEMA, No. 7 at p. 5) Engineering design and manufacturing differences led to the omission of 167 kVA and higher rated units, which are considered part of design line 3.

Design Line 3. This design line groups together single-phase, round-tank, liquid-immersed distribution transformers, ranging from 167 kVA to 833 kVA. Together, design lines 1 through 3 cover all the single-phase, liquid-immersed units (there are no units produced between 100 and 167 kVA). The BIL level of the windings ranges between 30 kV and 150 kV, and the tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35kV and the secondary voltage is less than or equal to 600V.

The representative unit selected for design line 3 is a 500 kVA round-tank, as this is a common rating and occurs approximately in the middle of the kVA range for this design line (167 kVA, 250 kVA, 333 kVA, 500 kVA, 667 kVA, and 833 kVA). Although high currents result with 277/480Y Volt secondary at the larger kVA ratings, high-current bushings are available, and a market does exist for these transformers.

Design Line 4. Design line 4 represents rectangular tank, three-phase, liquid-immersed distribution transformers, ranging from 15 kVA to 500 kVA. The BIL level of the windings range between 30 kV and 150 kV, and the tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35 kV and the secondary voltage is less than or equal to 600 V.

The representative unit selected for design line 4 is a 150 kVA transformer, as this is a common rating and occurs approximately in the middle of the kVA range for this design line (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 300 kVA, and 500 kVA).

Design Line 5. Design line 5 represents rectangular tank, three-phase, liquid-immersed distribution transformers, ranging from 750 kVA to 2500 kVA. Design lines 4 and 5 cover all the three-phase, liquid-immersed units (there are no units produced between 500 and 750 kVA). The BIL level of the windings ranges between 95 kV and 150 kV, and the tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35 kV and the secondary voltage is less than or equal to 600 V.

The representative unit selected for this design line is a 1500 kVA transformer, as this is a common rating in this size range, and occurs in the middle of the kVA range for this design line (750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

Design Line 6. Design line 6 represents single-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 333 kVA. The BIL of the windings is 10 kV, and the tap arrangement is "universal," meaning six 2½ percent, two above and four below normal. The Department selected this tap arrangement based on recommendations from manufacturers who produce transformers at these ratings. The primary voltage is 600 V or below. The secondary voltage is less than 600 V.

The representative unit selected for design line 6 is 25 kVA, as this is a common rating in this size range, and occurs toward the low end of the kVA ratings for this design line (15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA, 100 kVA, 167 kVA, 250 kVA, 333 kVA).

Design Line 7. Design line 7 represents three-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 150 kVA. Because the kVA range of three-phase ratings is broad and construction techniques differ, the Department split the range of three-phase, low-voltage, dry-type transformers into design line 7 and design line 8, so the engineering differences in core-coil design and manufacturing would be more readily apparent. The primary windings are less than or equal to 600V, with a BIL of 10 kV. The secondary voltage is less than 600 V. The tap arrangement is universal, meaning six 2½ percent, two above and four below normal.

The representative unit selected for design line 7 is a 75 kVA transformer, as this is a common rating in this size range, occurs in the middle of the kVA ratings for this design line (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA), and NEMA recommended this rating for analysis.

Design Line 8. Design line 8 represents three-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 225 kVA to 1000 kVA. The primary windings are less than or equal to 600V, with a BIL of 10kV. The secondary voltage is less than 600V. The tap arrangement is universal, meaning six 2½ percent, two above and four below normal.

The representative unit selected for this design line is a 300 kVA transformer, as this is a common rating in this size range, and occurs toward the low end of the range of kVA ratings included in this design line (225 kVA, 300 kVA, 500 kVA, 750 kVA, and 1000 kVA).

Design Line 9. Design line 9 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 500 kVA. To accommodate the broad kVA range and to allow for engineering differences in construction principles and associated costs, the Department split the complete three-phase, medium-voltage, dry-type units into design lines 9 and 10. The primary voltage is less than or equal to 5 kV, and the BIL is between 20 kV and 45 kV. The secondary voltage is less than or equal to 600 V. The tap arrangement is four 2½ percent, two above and two below normal.

The representative unit selected for design line 9 is 300 kVA, as this is a common rating in this size range, and occurs near the high end of the kVA ratings for this design line (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 225 kVA, 300 kVA, and 500 kVA).

Design Line 10. Design line 10 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 750 kVA to 2500 kVA. The primary voltage is less than or equal to 5kV, and the BIL is between 20kV and 45kV. The secondary voltage is less than or equal to 600V. The tap arrangement is four 2½ percent, two above and two below normal.

The representative unit selected for this design line is a 1500 kVA transformer, as this is a common rating, and occurs in the middle of the kVA range for this design line (750kVA, 1000kVA, 1500kVA, 2000kVA, and 2500kVA).

Design Line 11. Design line 11 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 500 kVA. This design line parallels design line 9, with a higher primary insulation level, 60 kV to 95 kV BIL. Because dry-type transformer designs and, more importantly, the efficiency of those designs, is strongly influenced by changes in BIL, the Department considered these higher BIL ratings separately. The tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than or equal to 15 kV and the secondary voltage is less than or equal to 600 V.

The kVA ratings in design line 11 are 15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 300 kVA and 500 kVA. The shipments for this design line are concentrated in the 225 kVA through 500 kVA rating; therefore, the Department selected the 300 kVA rating as the representative unit for analysis.

Design Line 12. Design line 12 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 750 kVA to 2500 kVA. This design line parallels design line 10, with a higher primary insulation level, 60 kV to 95 kV BIL. The tap arrangement is four 2½ percent, 2 above and 2 below normal. The primary voltage is less than or equal to 15 kV and the secondary voltage is less than or equal to 600 V.

The representative unit selected for this design line is a 1500 kVA transformer, as it is a common rating in this size range and BIL rating, and it occurs in the middle of kVA range covered by this design line (750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

Design Line 13. As a further extension on the dry-type, three-phase, medium-voltage BIL ranges, the Department analyzed 110 kV to 150 kV BIL, in a design line ranging from 225 kVA to 2500 kVA. The 225 kVA rating is considered to be the lowest kVA rating where one would expect to see a unit with a BIL greater than 110 kV. The tap arrangement is four 2½ percent, two above and two below normal. The primary voltage is less than 35 kV and the secondary voltage is less than or equal to 600 V.

This third set of dry-type, three-phase, medium-voltage distribution transformers spans a smaller range of kVA ratings, 225 kVA to 2500 kVA. As most of the sales activity in this design line occurs in the higher kVA ratings, the representative unit selected for design line 13 is a 2000 kVA transformer. This unit is a common rating in this size range, occurs toward the high end of the range covered by this design line (225 kVA, 300 kVA, 500 kVA, 750 kVA, 1000 kVA, 1500 kVA, 2000 kVA and 2500 kVA), and NEMA recommended this rating for analysis.

In addition to the three product classes for dry-type, medium-voltage, three-phase distribution transformers (for which there are five engineering design lines) presented in Table 5.2.1, there are three product classes for single-phase, dry-type, medium-voltage units. As discussed in Chapter 3, the shipment volume for the single-phase, dry-type, medium voltage is very low, and thus it does not warrant the level of effort involved in conducting analysis on these specific units. The Department decided instead to scale the analysis findings from three-phase units to the single-phase units by dividing by three. In this way, the Department was able to concentrate resources and improve the accuracy in other, higher volume and more important distribution transformer product classes.

5.2.1 Scaling Relationships in Transformer Manufacturing

As discussed in the previous section, the Department simplified the engineering analysis by creating design lines, selecting representative units from these design lines, and scaling the results of the analysis on these representative units within their respective design lines. This section briefly introduces the scaling relationship the Department used to extrapolate the findings on the representative units to the other kVA ratings.

The scaling formulae are mathematical relationships that exist between the kVA ratings and the physical size, cost, and performance of transformers. The size-versus-performance relationships arise from fundamental equations describing a transformer's voltage and kVA rating. For example, when the kVA rating and voltage frequency is fixed, the product of the conductor current density, core flux density, core cross-sectional area, and total conductor cross-sectional area is constant.

To illustrate this point, consider a transformer with a fixed frequency, magnetic flux density, current density, and BIL rating. If one enlarges (or decreases) the kVA rating, then the only parameters free to vary are the core cross-section and the core window area through which the windings pass. Thus, to increase (or decrease) the kVA rating, the dimensions for height, width, and depth of the core/coil assembly are scaled equally in all directions. Analysis of this scaling relationship reveals that each of the linear dimensions vary as the ratio of kVA ratings to the ¼ power. Similarly, areas vary as the ratios of kVA ratings to the ½ power and volumes vary as the ratio of the kVA ratings to the ¾ or 0.75 power, hence the term "0.75 scaling rule" (see Appendix 5B). Table 5.2.3 depicts the most common scaling relationships in transformers.

Table 5.2.3 Common Scaling Relationships in Transformers

Parameter Being Scaled	Relationship to kVA Rating (varies with ratio of kVA^x)
Weight	$(kVA_1/kVA_0)^{3/4}$
Cost	$(kVA_1/kVA_0)^{3/4}$
Length	$(kVA_1/kVA_0)^{1/4}$
Width	$(kVA_1/kVA_0)^{1/4}$
Height	$(kVA_1/kVA_0)^{1/4}$
Total Losses	$(kVA_1/kVA_0)^{3/4}$
No-load Losses	$(kVA_1/kVA_0)^{3/4}$

The following three relationships are true as the kVA rating increases or decreases, if the type of transformer (distribution or power transformer, liquid-immersed or dry-type, single-phase or three-phase), the primary voltage, the core configuration, the core material, the core flux density, and the current density (amperes per square inch of conductor cross-section) in both the primary and secondary windings are all held constant:

1. The physical proportions are constant (same relative shape),
2. The eddy loss proportion is essentially constant, and
3. The insulation space factor (voltage or BIL) is constant.

In practical applications, it is rare to find that all of the above are constant over even limited ranges; however, over a range of one order of magnitude in both directions (e.g., from 50 kVA to 5 kVA or from 50 kVA to 500 kVA), the scaling rules shown in Table 5.2.3 can be used to establish reasonable estimates of performance, dimensions, costs, and losses. In practice, these rules can be applied over even wider ranges to estimate general performance levels.

To illustrate how the scaling laws are used, consider two transformers with kVA ratings of S_0 and S_1. The no-load losses (NL) and total losses (TL) of these two transformers would be depicted as NL_0 and TL_0, and NL_1 and TL_1. Then the relationships between the NL and TL of the two transformers could be shown as follows:

$$NL_1 = NL_0 \times (S_1 / S_0)^{0.75} \qquad \textbf{Eq. 5.1}$$

where:

NL_1 = no-load losses of transformer "1,"
NL_0 = no-load losses of transformer "0,"

S_1 = kVA rating of transformer "1," and
S_0 = kVA rating of transformer "0."

and

$$TL_1 = TL_0 \times (S_1 / S_0)^{0.75} \qquad \textbf{Eq. 5.2}$$

where:

TL_1 = total losses of transformer "1," and
TL_0 = total losses of transformer "0."

Equations 5.1 and 5.2 can be manipulated algebraically to show that the load loss also varies to the 0.75 power. Starting with the concept that total losses equals no-load losses plus load losses, we can derive the relationship for load loss (LL), and show that it also scales to the 0.75 power. Specifically:

$$LL_1 = TL_1 - NL_1 \qquad \textbf{Eq. 5.3}$$

where:

LL_1 = load losses of transformer "1"

Plugging the TL_1 and NL_1 terms into this equation, we find:

$$LL_1 = (TL_0 \times (S_1 / S_0)^{0.75}) - (NL_0 \times (S_1 / S_0)^{0.75}) \qquad \textbf{Eq. 5.4}$$

$$LL_1 = (TL_0 - NL_0) \times (S_1 / S_0)^{0.75} \qquad \textbf{Eq. 5.5}$$

$$LL_1 = (LL_0) \times (S_1 / S_0)^{0.75} \qquad \textbf{Eq. 5.6}$$

Where:

LL_0 = load losses of transformer "0."

Thus, the 0.75 scaling rule can be used to estimate the losses of a transformer, given the losses and kVA rating of a reference unit. However, in order for this rule to be applicable, the transformer type must be the same, and key parameters—such as the type of core material, core flux density, and conductor current density in the high and low voltage windings—must be fixed. For dditional information on the derivation of the 0.75 scaling rule, see Appendix 5B. The Department used the 0.75 scaling rule to scale the analysis findings on each of the representative units within the 13 design lines. It applied the scaling rule to the design lines in the national impact analysis (Chapter 10), where it scaled losses and other properties from the 13 units to the 102 kVA ratings it did not analyze.

5.3 TECHNICAL DESIGN INPUTS

For all the representative units, the engineering analysis explores the relationship between the manufacturing selling prices and corresponding transformer efficiencies. To study this relationship, the Department contracted a transformer design software company called Optimized Program Service, Inc. (OPS) to create a database of designs that span the range of efficiency levels for each of the units being analyzed. The Department learned during its visits to the nine distribution transformer manufacturing facilities in early 2002 that many companies developed and use their own, proprietary design software to develop new transformer designs for their customers.

The design software creates an optimized, practical transformer design, bill of materials and an electrical analysis report based on a set of input specifications and design parameters. The software produces information about the core and coil design that would enable a manufacturer to build this unit, such as core dimensions, high- and low-voltage windings, insulation, cooling ducts, and labor. The software generates an estimated cost of manufacturing materials and labor, which is then converted to a sales price by applying markups.

The electrical analysis report estimates the performance of the transformer design (including efficiency) at 25 percent, 35 percent, 50 percent, 65 percent, 75 percent, 100 percent, 125 percent, and 150 percent of nameplate load. The software output provides a clear understanding of the relationship between cost and efficiency because it provides detailed data on design variances, as well as a bill of materials, labor costs, and efficiency. The software does not capture retooling costs associated with changing production designs for a specific manufacturer. The Department will research these retooling costs in the MIA, following the ANOPR public workshop and when appropriate will incorporate these costs in future engineering analyses.

One of the inputs to the design software consisted of a range of what are known in the industry as A and B evaluation combinations (see section 3.6, Total Ownership Cost Evaluation). The combination of A and B values supplied to the design software mimics hundreds of distribution transformer purchase orders. The A parameter represents a customer's net present value of future losses in the transformer core (no-load losses) and the B represents a customer's net present value of future losses in the windings (load losses). These values take into account a range of factors depending on the customer. The B parameter is never larger than A, as this would mean a user was specifying a transformer whose average load would be more than 100 percent of nameplate load.

The A and B values are expressed in terms of dollars per watt of loss. The greater the values of A and B, the greater the importance a customer attaches to the value of future transformer losses. As A and B values increase, the customer places greater importance on reducing the watts of core and winding losses, and so the customer chooses a more efficient transformer.

For the engineering analysis, the Department used broad ranges of A and B evaluation values (presented in Table 5.3.1) resulting in a comprehensive range of efficiency levels for each design option combination of core steel and winding material. During the 2002 site visits, manufacturers helped develop the range of A and B values used in the analysis. These values result in the spectrum of efficiencies represented in transformer orders from customers, as well as a low first-cost design and a maximum technologically feasible ("max-tech") design. For the low first-cost design, the A and B evaluation values are both $0/watt, indicating that the customer does not attach any financial value to future losses in the core or coil of the transformer being bought. For the maximum technologically feasible design, the A and B evaluation values are sufficiently high to push the design to the highest efficiency achievable, and are different for the liquid-immersed and dry-type distribution transformers.

Table 5.3.1 A and B Combinations used by Software to Generate Design Database

Transformers	A values and increments	B values and increments	Resultant number of (A, B) combinations
Liquid-immersed DLs: 1 - 5	$0 to $8 by 0.5 steps $8 to $16 by 1.0 steps*	$0 to $3 by 0.25 steps $3 to $6 by 0.5 steps*	179 63*
Dry-type DLs: 6 - 13	$0 to $12 by 0.5 steps	$0 to $8 by 0.5 steps	289

*Note: The Department conducted extended analyses on the A and B values for the liquid-immersed units when it determined that max tech designs had not been captured with an $8 A and a $3 B. The Department applied the extended analysis only to certain core steels for a representative unit, as manufacturers would not build transformers with certain steels at such high evaluation conditions.

As an example of how the software used increments of A and B value combinations, consider design line 1. For one construction method of the 50-kVA liquid-immersed transformer, the software would be given A values starting at zero and increasing by 50-cent increments and B values starting at zero and increasing by 25-cent increments. Because B is never greater than A, the combinations of ($A, $B) designs for this design line were ($0.00, $0.00), ($0.50, $0.00), ($0.50, $0.25), ($0.50, $0.50), ($1.00, $0.00), ($1.00, $0.25), ($1.00, $0.50), and so on, totaling 179 different combinations of ($A, $B). The department carried out this evaluation for each core-coil combination considered in the analysis. Furthermore, if this core-coil combination studied under an extended analysis (to reach max tech), it would have ($A, $B) designs starting at ($8.00, $3.00) and increasing by $1 increments on the A and 50 cent increments on the B up to $16 and $6, respectively. Thus, the ($A, $B) combinations for those core-coil combinations to which an extended analysis was applied were ($8.00, $3.50), ($8.00, $4.00), ($8.00, $4.50) and so on, for an additional 63 designs.

Occasionally, the design software generated the same transformer design for two different $A and $B combinations, creating duplicate designs in the engineering analysis database. The Department removed these duplicate designs from the resultant database, as they might introduce some bias in the LCC analysis resulting from a greater prevalence of a particular design.

The Department understands that there are many ways to build a transformer, even with constant kVA and voltage ratings. For instance, manufacturers can vary the core steels (e.g., M2, M3, M6), the winding materials (aluminum or copper), and core configurations (shell or core-type). Within each of the design lines discussed in the sections starting at 5.3.1, the Department provides tables listing the design option combinations that it used to analyze each of the representative units. Depending on customer needs, the cost of materials, the capital equipment in their facility, and the skills of their labor force, manufacturers make decisions on how to manufacture a given transformer using different core configurations, core steels and winding materials. To capture this variation in designs, DOE analyzed each representative unit using five to eleven design option combinations of core type, core steel and winding material. As discussed in the technology assessment (see Chapter 3), core steel is produced in a range of qualities (from an efficiency perspective). M2 core steel is grain-oriented and has very thin laminations, and consequently has very low losses. M43 core steel is not grain-oriented and is rolled in much thicker laminations, thus contributing to higher core losses. Table 5.3.2 lists all the steel types used in the analysis, and properties associated with these steels, including nominal thickness and core losses per pound of steel. Note that the core losses per pound of steel are given as a function of the magnetic flux density, measured in Tesla.

Table 5.3.2 Core Steel Grades, Thicknesses and Associated Losses

Steel Grade	Nominal Thickness (inches)	Core Loss at 60 Hz (Watts per Pound at magnetic flux density)*	Notes / Remarks
M43	0.0185	2.10 Watts/lb at 1.5 T	Non-oriented grain silicon steel
M36	0.0185	2.00 Watts/lb at 1.5 T	Non-oriented grain silicon steel
M19	0.0185	1.65 Watts/lb at 1.5 T	Non-oriented grain silicon steel
M6	0.014	0.66 Watts/lb at 1.5 T 0.94 Watts/lb at 1.7 T	Grain-oriented silicon steel
M4	0.011	0.51 Watts/lb at 1.5 T 0.74 Watts/lb at 1.7 T	Grain-oriented silicon steel
M3	0.009	0.45 Watts/lb at 1.5 T 0.70 Watts/lb at 1.7 T	Grain-oriented silicon steel
M2	0.007	0.41 Watts/lb at 1.5 T	Grain-oriented silicon steel
H0	0.009	0.60 Watts/lb at 1.7 T	"High permeability" grade silicon steel
SA1	0.001	0.08 Watts/lb at 1.3 T	Amorphous core steel (silicon and boron); flux density limitation - testing at 1.3 T
ZDMH	0.009	0.34 Watts/lb at 1.5 T 0.46 Watts/lb at 1.7 T	Imported silicon steel, magnetic domain-refined by mechanical process

* Watts of loss per pound of core steel are only comparable at the same magnetic flux density (measured in Tesla)

In addition to selecting a core steel, the manufacturer's selection of a core design may also contribute to the overall efficiency of a transformer. A transformer facility may be optimized to work around one or two core configurations. Table 5.3.3 provides a list of all the core configurations used for each of the 13 design lines. The Department selected these configurations, in combinations with the range of core steels and winding materials, to represent the most common construction methods for these kVA ratings in the US market. Note that for design lines 6 and 7, the Department analyzed two different core configurations.

Table 5.3.3 Core Configurations Used in Each Design Line

Design Line	# Phases	Core Configuration
DL1	1	Shell-type, wound core - distributed gap
DL2	1	Shell-type, wound core - distributed gap
DL3	1	Shell-type, wound core - distributed gap
DL4	3	Wound core - distributed gap, 5-leg
DL5	3	Wound core - distributed gap, 5-leg
DL6	1	Shell-type and core-type, stacked, butt-lap
DL7	3	Stacked, butt-lap, 3-leg; or Evans wound core- distributed gap
DL8	3	Stacked, butt-lap, 3-leg
DL9	3	Stacked, butt-lap, 3-leg
DL10	3	Stacked, mitered joint, 3-leg
DL11	3	Stacked, mitered joint, 3-leg
DL12	3	Stacked, cruciform, mitered joint, 3-leg
DL13	3	Stacked, cruciform, mitered joint, 3-leg

For the single-phase representative units, the configuration is either core-type or shell-type. This applies whether the core consists of stacked or wound laminations of core steel. For the wound cores, manufacturers generally employ a technique known as 'distributed gap.' This means that each lamination of core steel wound around the form will have a start and finish point (the 'gap'), staggered with respect to the previous and the following lamination. The distributed gap is used to minimize the performance impact of the lamination joint gaps (reducing the exciting current) and, by locating inside the coil window, reduces the transformer's operating sound level.

Three-phase transformers can have three-legged, four-legged, five-legged or Evans cores. Of these, in the engineering analysis, the Department considered the 3-legged, the 5-legged and the Evans. A three-legged core is assembled from stacked laminations. The joints can be butt-lapped or mitered. Where there is an economic need to reduce core losses, particularly in keeping with the use of more efficient grades of core steel (M2 or M3), the mitered core tends to be selected. Also, for larger kVA ratings, design economics may cause the selection of a cruciform core section, consisting of multiple lamination widths in order to create a circular core form around which the windings are placed. By using a core configuration that better follows the contours of the windings, losses are again reduced, making a more efficient transformer. The use of the three-legged core usually depends on the primary winding being delta-connected. If the primary winding is wye-connected, as is frequently the case for pad-mounted transformers used in underground distribution, the core configuration needs to be four-legged or five-legged.

The five-legged core is assembled from four wound-core loops, and is the common configuration for liquid-filled three-phase distribution transformers having a wye-wye voltage connection. Again, this occurs for pad-mounted transformers used in underground distribution. The individual core loops have distributed gaps as explained for single-phase wound-core transformers.

The Evans core is sometimes employed for small dry-type transformers in the 600V class. It consists of two inner wound cores which link the three winding assemblies. Enveloping these two inner cores is a larger wound core which passes through the windows of the two outside windings.

5.3.1 Design Line 1 Representative Unit

Design line 1 (DL1) represents rectangular-tank, liquid-immersed, single-phase distribution transformers, ranging from 10 kVA to 100 kVA. The representative unit selected for this design line is a 50kVA pad-mounted unit. The following are the technical specifications which constitute input parameters to the design software:

KVA: 50 (liquid-immersed, rectangular-tank)
Primary: 7200 Volts at 60 Hz
Secondary: 240/120V
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi-Lo
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 1.5–3.5 percent

For DL1, DOE selected ten construction combinations (called "design option combinations"), based on input from manufacturers and other technical experts. The core selected was shell-type, because the application is for a pad-mounted unit, and this shape is well suited to a rectangular tank. With the exception of the max tech/high efficiency designs, DOE selected ten design option combinations to represent the most common construction practices for this representative unit. It analyzed design option combinations 2, 8, 9 and 10 with both the normal range of A and B factors and the extended A and B factors to capture the maximum technologically feasible efficiency design.

Table 5.3.4 Design Option Combinations for the Representative Unit from DL1

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M2	Cu	Al	Shell
2*	M2	Cu	Cu	Shell
3	M3	Al	Al	Shell
4	M3	Cu	Al	Shell
5	M3	Cu	Cu	Shell
6	M6	Al	Al	Shell
7	M6	Cu	Al	Shell
8*,**	SA1 (Amorphous)	Cu	Cu	Core
9*,***	ZDMH - price 1	Cu	Cu	Shell
10*,***	ZDMH - price 2	Cu	Cu	Shell

* Design option combinations 2, 8, 9 and 10 were studied with the extended $A and $B analysis, as these are considered the likely core/coil combinations for high evaluation formulae. This extended analysis means that, in addition to the $0-8A and $0-3B, $8-16A and $3-6B were also analyzed.
** For amorphous metal cores, a magnetic flux density of 13.4 kilogauss and a 0.82 space factor were used.
*** ZDMH (mechanically scribed core steel) was analyzed at both a U.S. price and a Mexican/Canadian price, since Mexico and Canada do not apply a 31 percent import duty on ZDMH. See section 3.5.3.

The Department analyzed each of the ten design option combinations using the matrix of A and B values described in Table 5.3.1, creating 2,027 designs (after the removal of any duplicate designs).

5.3.2 Design Line 2 Representative Unit

Design line 2 (DL2) represents round-tank, liquid-immersed, single-phase distribution transformers, ranging from 10 kVA to 100 kVA. The representative unit selected for this design line is a 25kVA pole-mounted unit. The following are the technical specifications which constitute input parameters to the design software:

KVA: 25 (liquid-immersed, round-tank)
Primary: 24940GrdY/14400 Volts at 60 Hz (125 kV BIL)
Secondary: 120/240V
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi (Core-Type), Lo-Hi-Lo (Shell-Type)
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 1.0–3.5 percent

For DL2, DOE selected ten design option combinations, based on input from manufacturers and other technical experts. The Department selected shell-type core configuration because this is commonly used by manufacturers for a 25 kVA transformer. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practices for the representative unit. It analyzed design option combinations 1, 3, 8, 9 and 10 with both the normal range of A and B factors and the extended A and B factors to capture the maximum technologically feasible efficiency design.

Table 5.3.5 Design Option Combinations for the Representative Unit from DL2

Design Option **Combination**	**Core Material**	**High Voltage Conductor**	**Low Voltage Conductor**	**Core Design Type**
1*	M2	Cu	Al	Shell
2	M3	Cu	Al	Shell
3*	M3	Cu	Cu	Shell
4	M4	Al	Al	Shell
5	M4	Cu	Al	Shell
6	M6	Al	Al	Shell
7	M6	Cu	Al	Shell
8*,**	SA1 (Amorphous)	Cu	Cu	Core
9*,***	ZDMH - price 1	Cu	Cu	Shell
10*,***	ZDMH - price 2	Cu	Cu	Shell

* Design option combinations 1, 3, 8, 9 and 10 were studied with the extended $A and $B analysis, as these are considered the likely core/coil combinations for high evaluation formulae. This extended analysis means that, in addition to the $0-8A and $0-3B, $8-16A and $3-6B were also analyzed.
** For amorphous metal cores, a magnetic flux density of 13.4 kilogauss and a 0.82 space factor were used.
*** ZDMH (mechanically scribed core steel) was analyzed at both a U.S. price and a Mexican/Canadian price, since Mexico and Canada do not apply a 31 percent import duty on ZDMH. See section 3.5.3.

The Department analyzed each of the ten design option combinations using the matrix of A and B values described in Table 5.3.1, creating 2,100 designs (after removal of duplicate designs).

5.3.3 Design Line 3 Representative Unit

Design line 3 (DL3) represents round-tank, liquid-immersed, single-phase distribution transformers, ranging from 167 kVA to 833 kVA. The representative unit selected for this design line is a 500kVA round-tank. The following are the technical specifications which constitute input parameters to the design software:

KVA: 500 (liquid-immersed, round-tank)

Primary: 14400/24940Y Volts at 60 HZ (150kV BIL)
Secondary: 277/480Y Volts
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi (Shell-Type), Lo-Hi-Lo (Shell-Type)
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 2.5–5.75 percent

For DL3, the Department selected eight design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. The core selected was shell-type, because this is commonly used by industry for this rating. With the exception of the max tech/high-efficiency designs, DOE chose design option combinations to represent the most common construction practice for this representative unit. The Department analyzed design option combinations 5, 6, 7 and 8 with both the normal range of A and B factors and the extended A and B factors to capture the maximum technologically feasible efficiency design.

Table 5.3.6 Design Option Combinations for the Representative Unit from DL3

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	CU	AL	Shell
2	M4	AL	AL	Shell
3	M3	CU	AL	Shell
4	M2	CU	AL	Shell
5*	M2	CU	CU	Shell
6*,**	SA1 (Amorphous)	CU	CU	Shell
7*,***	ZDMH - price 1	CU	CU	Shell
8*,***	ZDMH - price 2	CU	CU	Shell

* Design option combinations 5, 6, 7, and 8 were studied with the extended $A and $B analysis, as these are considered the likely core/coil combinations for high evaluation formulae. This extended analysis means that, in addition to the $0-8A and $0-3B, $8-16A and $3-6B were also analyzed.
** For amorphous metal cores, a magnetic flux density of 13.4 kilogauss and a 0.82 space factor were used.
*** ZDMH (mechanically scribed core steel) was analyzed at both a U.S. price and a Mexican/Canadian price, since Mexico and Canada do not apply a 31 percent import duty on ZDMH. See section 3.5.3.

The Department analyzed each of the eight design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,674 designs (after removal of duplicate designs)

5.3.4 Design Line 4 Representative Unit

Design line 4 (DL4) represents rectangular tank, liquid-immersed, three-phase distribution transformers, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 150kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 150 (liquid-immersed, pad mount)
Primary: 12470Y/7200 Volts at 60 HZ (95kV BIL)
Secondary: 208Y/120 Volts
T Rise: 65˚C
Ambient: 20˚C
Terminal Configuration: ANSI/IEEE C57.12.26, Loop Feed
Winding Configuration: Lo-Hi or Lo-Hi-Lo
Core: Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 2.5–3.0 percent

For DL4, DOE selected nine design option combinations of core steel and winding types based on input from manufacturers and other technical experts. With the exception of the max tech/high efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit. It analyzed the design option combinations 3, 6, 7, 8 and 9 with both the normal range of A and B factors and the extended A and B factors to capture the maximum technologically feasible efficiency design.

Table 5.3.7 Design Option Combinations for the Representative Unit from DL4

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	AL	AL	5-Leg Core
2	M4	AL	AL	5-Leg Core
3*	M3	CU	AL	5-Leg Core
4	M3	CU	CU	5-Leg Core
5	M2	CU	AL	5-Leg Core
6*	M2	CU	CU	5-Leg Core
7*,**	SA1 (Amorphous)	CU	CU	5-Leg Core
8*,***	ZDMH-price 1	CU	CU	5-Leg Core
9*,***	ZDMH-price 2	CU	CU	5-Leg Core

* Design option combinations 3, 6, 7, 8, and 9 were studied with the extended $A and $B analysis, as these are considered the likely core/coil combinations for high evaluation formulae. This extended analysis means that, in addition to the $0-8A and $0-3B, $8-16A and $3-6B were also analyzed.
** For amorphous metal cores, a magnetic flux density of 13.4 kilogauss and a 0.82 space factor were used.
*** ZDMH (mechanically scribed core steel) was analyzed at both a U.S. price and a Mexican/Canadian price, since Mexico and Canada do not apply a 31 percent import duty on ZDMH. See section 3.5.3.

The Department analyzed each of the nine design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,906 designs (after removal of duplicate designs).

5.3.5 Design Line 5 Representative Unit

Design line 5 (DL5) represents rectangular tank, liquid-immersed, three-phase distribution transformers, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 1500 (liquid-immersed, pad mount)
Primary: 24940GrdY/14400 Volts (125kV BIL)
Secondary: 480Y/277 Volts
T Rise: 65˚C
Ambient: 20˚C
Terminal Configuration: ANSI/IEEE C57.12.26, Loop Feed
Winding Configuration: Lo-Hi
Core: Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 5.75 percent

For DL5, the Department selected eight design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practices for the representative unit. It analyzed design option combinations 4, 5, 6, 7, and 8 with both the normal range of A and B factors and the extended A and B factors to capture the maximum technologically feasible efficiency design.

Table 5.3.8 Design Option Combinations for the Representative Unit from DL5

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M4	AL	AL	5-Leg Core
2	M4	CU	AL	5-Leg Core
3	M3	AL	AL	5-Leg Core
4*	M3	CU	AL	5-Leg Core
5*	M2	CU	AL	5-Leg Core
6*,**	SA1 (Amorphous)	CU	CU	5-Leg Core
7*,***	ZDMH - price 1	CU	CU	5-Leg Core
8*,***	ZDMH - price 2	CU	CU	5-Leg Core

* Design option combinations 4, 5, 6, 7, and 8 were studied with the extended $A and $B analysis, as these are considered the likely core/coil combinations for high evaluation formulae. This extended analysis means that, in addition to the $0-8A and $0-3B, $8-16A and $3-6B were also analyzed.
** For amorphous metal cores, a magnetic flux density of 13.4 kilogauss and a 0.82 space factor were used.
*** ZDMH (mechanically scribed core steel) was analyzed at both a U.S. price and a Mexican/Canadian price, since Mexico and Canada do not apply a 31 percent import duty on ZDMH. See section 3.5.3.

The Department analyzed each of the eight design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,742 designs (after removal of duplicate designs).

5.3.6 Design Line 6 Representative Unit

Design line 6 (DL6) represents ventilated dry-type, single-phase, low-voltage distribution transformers, ranging from 15 kVA to 333 kVA. The representative unit selected for this design line is a 25 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 25 (dry-type)
Phases: Single
Primary: 480 Volts at 60 Hz (10 kV BIL)
Secondary: 120/240 Volts

T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi (For Core-Type) Lo-Lo-Hi (For Shell-Type)
Core: Stacked, butt-lap
Taps: Six 2½ percent, two above and four below normal
Impedance Range: 3.0–6.0 percent

For DL6, DOE selected ten design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.9 Design Option Combinations for the Representative Unit from DL6

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M43, 26 gauge	AL (wire)	AL (wire)	Core
2	M36, 26 gauge	AL (wire)	AL (wire)	Core
3	M19, 26 gauge	AL (wire)	AL (wire)	Core
4	M6	AL (wire)	AL (wire)	Core
5	M3	CU (wire)	AL (strip)	Core
6	H-O DR	CU (wire)	CU (strip)	Core
7	M6	AL (wire)	AL (wire)	Shell
8	M19	AL (wire)	AL (wire)	Shell
9	M3	CU (wire)	AL (strip)	Shell
10	H-O DR*	CU (wire)	CU (strip)	Shell

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the ten design option combinations using the matrix of A and B values described in Table 5.3.1, creating 2,597 designs (after removal of duplicate designs).

5.3.7 Design Line 7 Representative Unit

Design line 7 (DL7) represents ventilated dry-type, three-phase, low-voltage distribution transformers, ranging from 15 kVA to 150 kVA. The representative unit selected for this design line is a 75 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 75 (dry-type)

Phases: Three
Primary: 480 Volts at 60 Hz (10 kV BIL)
Secondary: 208Y/120 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, butt-lap; Evans Wound, DG
Taps: Six 2½ percent, two above and four below normal
Impedance Range: 3.0–6.0 percent

For DL7, DOE selected seven design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.10 Design Option Combinations for the Representative Unit from DL7

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M19, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
2	M36, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
3	M43, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
4	M6	AL (wire)	AL (wire)	3 - Leg Stacked
5	M6	AL (wire)	AL (wire)	3 - Leg Evans
6	M3	CU (wire)	AL (strip)	3 - Leg Evans
7	H-O DR*	CU (wire)	CU (strip)	3 - Leg Evans

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the seven design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,874 designs (after removal of duplicate designs).

5.3.8 Design Line 8 Representative Unit

Design line 8 (DL8) represents ventilated dry-type, three-phase, low-voltage distribution transformers, ranging from 225 kVA to 1000 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 300 (dry-type)
Phases: Three

Primary: 480V at 60 Hz (10 kV BIL) Delta Connected
Secondary: 208Y/120 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, butt-lap
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 3.0–6.0 percent

For DL8, the Department selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.11 Design Option Combinations for the Representative Unit from DL8

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M19, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
2	M6, 29 gauge	AL (wire)	AL (strip)	3 - Leg Stacked
3	M6, 29 gauge	CU (wire)	CU (strip)	3 - Leg Stacked
4	M3	CU (wire)	AL (strip)	3 - Leg Stacked
5	H-O DR*	CU (wire)	CU (strip)	3 - Leg Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,393 designs (after removal of duplicate designs).

5.3.9 Design Line 9 Representative Unit

Design line 9 (DL9) represents ventilated dry-type, three-phase, medium-voltage distribution transformers with a 20–45kV BIL, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 300 (dry-type)
Phases: Three
Primary: 4160V at 60 Hz (45 kV BIL) Delta Connected
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi

Core: Stacked, butt-lap
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 3.0–6.0 percent

For DL9, the Department selected six design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.12 Design Option Combinations for the Representative Unit from DL9

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M36, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
2	M19, 26 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
3	M6, 29 gauge	AL (wire)	AL (wire)	3 - Leg Stacked
4	M6, 29 gauge	CU (wire)	CU (wire)	3 - Leg Stacked
5	M3	CU (wire)	AL (strip)	3 - Leg Stacked
6	H-O DR*	CU (wire)	CU (strip)	3 - Leg Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the six design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,620 designs (after removal of duplicate designs).

5.3.10 Design Line 10 Representative Unit

Design line 10 (DL10) represents dry-type, three-phase, medium-voltage distribution transformers with a 20–45kV BIL, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 1500 (dry-type)
Phases: Three
Primary: 4160V at 60 Hz (45 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, Mitered
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 5.7 percent

For DL10, the Department selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.13 Design Option Combinations for the Representative Unit from DL10

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	AL (wire)	AL (strip)	Stacked
2	M6	CU (wire)	CU (strip)	Stacked
3	M4	CU (wire)	AL (strip)	Stacked
4	M3	CU (wire)	CU (strip)	Stacked
5	H-O DR*	CU (wire)	CU (strip)	Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,400 designs (after removal of duplicate designs).

5.3.11 Design Line 11 Representative Unit

Design line 11 (DL11) represents dry-type, three-phase, medium-voltage distribution transformers with a 46–95kV BIL, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 300 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (95 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, mitered joint
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 5.0–7.0 percent

For DL11, the Department selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.14 Design Option Combinations for the Representative Unit from DL11

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	AL (wire)	AL (strip)	Stacked
2	M6	CU (wire)	CU (strip)	Stacked
3	M4	CU (wire)	AL (strip)	Stacked
4	M3	CU (wire)	CU (strip)	Stacked
5	H-O DR*	CU (wire)	CU (strip)	Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,375 designs (after removal of duplicate designs).

5.3.12 Design Line 12 Representative Unit

Design line 12 (DL12) represents dry-type, three-phase, medium-voltage distribution transformers with a 46–95kV BIL, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 1500 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (95 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, cruciform, mitered joint
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 5.0–8.0 percent

For DL12, the Department selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.15 Design Option Combinations for the Representative Unit from DL12

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	AL (wire)	AL (strip)	Stacked
2	M6	CU (wire)	CU (strip)	Stacked
3	M4	CU (wire)	AL (strip)	Stacked
4	M3	CU (wire)	CU (strip)	Stacked
5	H-O DR*	CU (wire)	CU (strip)	Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,344 designs (after removal of duplicate designs).

5.3.13 Design Line 13 Representative Unit

Design line 13 (DL13) represents dry-type, three-phase, medium-voltage distribution transformers with a ≥96kV BIL, ranging from 225 kVA to 2500 kVA. The representative unit selected for this design line is a 2000 kVA transformer. The following are the technical specifications that constitute input parameters to the design software:

KVA: 2000 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (125 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, Cruciform, mitered joint
Taps: Four 2½ percent, two above and two below normal
Impedance Range: 5.0–8.0 percent

For DL13, the Department selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.16 Design Option Combinations for the Representative Unit from DL13

Design Option Combination	Core Material	High Voltage Conductor	Low Voltage Conductor	Core Design Type
1	M6	AL (wire)	AL (strip)	Stacked
2	M6	CU (wire)	CU (strip)	Stacked
3	M4	CU (wire)	AL (strip)	Stacked
4	M3	CU (wire)	CU (strip)	Stacked
5	H-O DR*	CU (wire)	CU (strip)	Stacked

* H-O DR is laser-scribed core steel, and represents the max tech for dry-type units.

The Department analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1, creating 1,335 designs (after removal of duplicate designs).

5.3.14 Summary of Design Line Coverage

The following four tables summarize the coverage of each of the design lines in relation to the various product classes and kVA ratings. The abbreviation DL stands for design line, and the row in the table where the phrase "Rep Unit" appears indicates the kVA rating of the representative unit from that design line. For example, DL1 stands for design line 1, spanning from 10 to 100kVA liquid-type, single-phase. The label "Rep Unit" appears in row 50kVA, indicating that the 50kVA is the representative unit for DL1. Similarly, the representative unit for DL2 is the 25kVA unit.

As Table 5.3.17 shows, both design line 1 and design line 2 span the single-phase liquid-immersed units from 10 kVA to 100 kVA.

Table 5.3.17 Liquid-Immersed Design Lines and Representative Units

Product Class 1 Liquid-Immersed, Single-Phase		
kVa	Rectang. Tank	Round Tank
10		
15		
25		Rep Unit
37.5	DL 1	DL 2
50	Rep Unit	
75		
100		
167		
250		
333		
500		Rep Unit DL 3
667		
833		

Product Class 2 Liquid-Immersed, Three-Phase	
kVa	Design Lines
15	
30	
45	
75	
112.5	Rep Unit DL 4
150	
225	
300	
500	
750	
1000	
1500	Rep Unit DL 5
2000	
2500	

Table 5.3.18 presents the low-voltage, dry-type design lines and the product classes they cover. For single-phase units, one design line spans all nine kVA ratings while, for the three-phase units, two design lines cover the 11 kVA ratings in that product class. There is no overlap of design lines for these two product classes.

Table 5.3.18 Dry-Type, Low-Voltage Design Lines and Representative Units

<table>
<tr><th colspan="3">Product Class 3
Dry-Type, Low-Voltage
Single-Phase</th></tr>
<tr><th>kVa</th><th colspan="2">Design Lines</th></tr>
<tr><td>15</td><td></td><td rowspan="9">DL 6</td></tr>
<tr><td>25</td><td>Rep Unit</td></tr>
<tr><td>37.5</td><td></td></tr>
<tr><td>50</td><td></td></tr>
<tr><td>75</td><td></td></tr>
<tr><td>100</td><td></td></tr>
<tr><td>167</td><td></td></tr>
<tr><td>250</td><td></td></tr>
<tr><td>333</td><td></td></tr>
</table>

<table>
<tr><th colspan="3">Product Class 4
Dry-Type, Low-Voltage
Three-Phase</th></tr>
<tr><th>kVa</th><th colspan="2">Design Lines</th></tr>
<tr><td>15</td><td></td><td rowspan="6">DL 7</td></tr>
<tr><td>30</td><td></td></tr>
<tr><td>45</td><td></td></tr>
<tr><td>75</td><td>Rep Unit</td></tr>
<tr><td>112.5</td><td></td></tr>
<tr><td>150</td><td></td></tr>
<tr><td>225</td><td></td><td rowspan="5">DL 8</td></tr>
<tr><td>300</td><td>Rep Unit</td></tr>
<tr><td>500</td><td></td></tr>
<tr><td>750</td><td></td></tr>
<tr><td>1000</td><td></td></tr>
</table>

Table 5.3.19 presents product classes (abbreviated “PC” in this table) for medium-voltage, single-phase, dry-type units. As discussed in section 3.4, National Shipment Estimate, these units have an extremely low shipment volume. All three product classes shown in Table 5.3.18 together represent less than one-third of one percent of dry-type shipments on both a per-unit and an MVA-capacity basis. Thus, the Department did not consider it appropriate to conduct three design lines of analysis for each of the BIL ratings shown.

As an alternative to investing time and resources analyzing these low-volume units, the Department used the results from the medium voltage three-phase dry-type units (presented in Table 5.3.19) and divided those findings by three, creating virtual (calculated) representative units (labeled as “Virtual RU” in the table) for these three product classes. The Department used the representative units from design lines 9, 10, 11, 12 and 13. These virtual representative units are shown in their respective rows, following the application of the quotient. For example, in the single phase (20–45kV BIL) column, the representative unit from DL9 is a three-phase 300 kVA unit, so it scales to a single-phase, 100 kVA unit in Table 5.3.19.

Table 5.3.19 Dry-Type, Medium-Voltage, Single-Phase Design Lines

Dry-Type, Medium-Voltage, Single-Phase			
kVa	PC 5* Low BIL 20-45 kV	PC 7 Med BIL 46-95 kV	PC 9 High BIL ≥96 kV
10			-
25			-
37.5			-
50	DL 9 / 3	DL 11 / 3	-
75	Virtual RU	Virtual RU	
100			
167			
250			
333			DL 13 / 3
500	Virtual RU DL 10 / 3	Virtual RU DL 12 / 3	
667			Virtual RU
833			

*PC is an abbreviation for Product Class

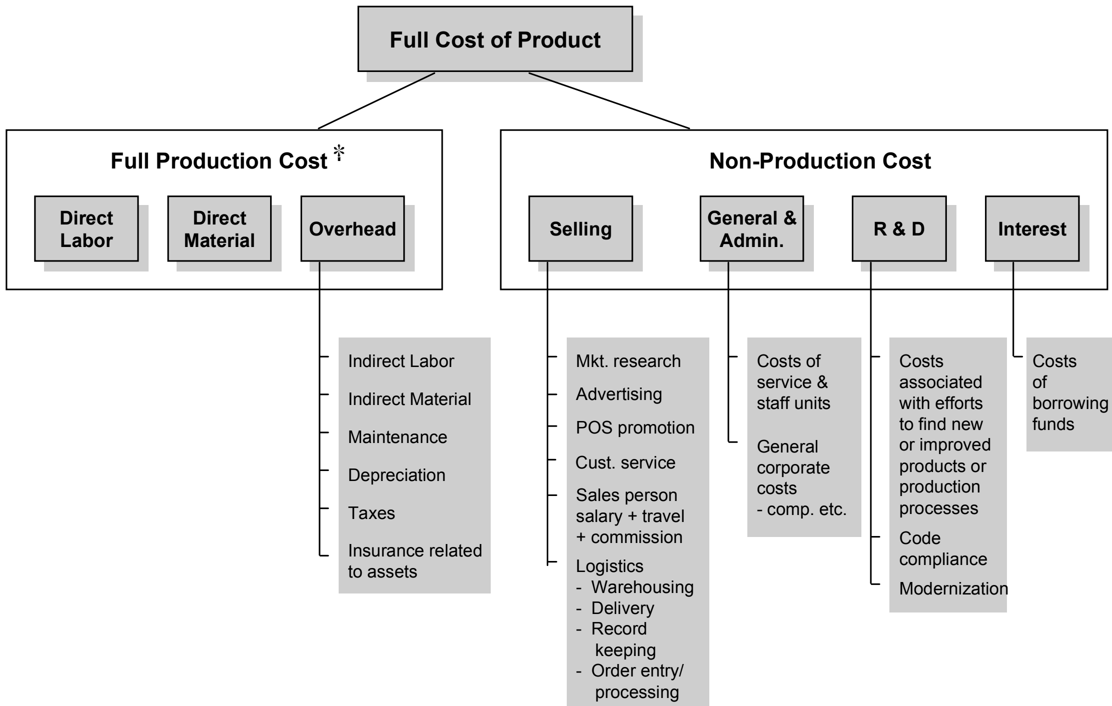
Table 5.3.20 presents the product classes (abbreviated "PC" in this table) for the medium-voltage, three-phase, dry-type distribution transformers and each of the design lines and respective representative units. For the higher volume and larger range of kVA ratings, the Department used two separate design lines for each, to maintain accuracy. However, for the very high BIL levels (≥96kV BIL), one design line (DL13) covers all the ratings from 225kVA to 2500kVA. As stated earlier, it is extremely unlikely that a three-phase, dry-type transformer with a BIL ≥96kV and a power rating less than 150kVA would be built.

Table 5.3.20 Dry-Type, Medium-Voltage, Three-Phase Design Lines

Dry-Type, Medium-Voltage, Three-Phase			
kVa	PC 6 Low BIL 20-45 kV	PC 8 Med BIL 46-95 kV	PC 10 High BIL ≥96 kV
15			-
30			-
45			-
75			-
112.5	DL 9	DL 11	-
150			-
225			
300	Rep Unit	Rep Unit	
500			
750			
1000			DL 13
1500	Rep Unit DL 10	Rep Unit DL 12	
2000			Rep Unit
2500			

5.4 MATERIAL AND LABOR INPUTS

The Department uses a standard method of cost accounting to determine the costs associated with manufacturing. This methodology is illustrated in Figure 5.4.1, where production costs and non-production costs are combined to determine the full cost of a product.



* Tax Reform Act of 1986, essentially, requires companies to measure cost of goods sold as the full production cost of the goods sold.

Figure 5.4.1 Standard Method of Cost Accounting for Standards Rulemaking

The Department developed estimates of the costs listed in Figure 5.4.1 from the U.S. *Industry Census Data Reports* for 1992 and 1997, manufacturer interviews, and SEC 10-K reports for ACME Electric Corporation, Powell Industries, Inc., Magnetek, Inc., and Hammond Manufacturing Company Limited. Together, the full production cost and the non-production cost equal the full cost of the product. Full production cost is a combination of direct labor, direct materials, and overhead. The overhead contributing to full production cost includes indirect labor, indirect material, maintenance, depreciation, taxes, and insurance related to company assets. Non-production cost includes the cost of selling (market research, advertising, sales representatives, logistics), general and administrative costs, research and development, interest payments and profit factor (not shown).

For the purposes of the rulemaking, the Department estimated manufacturer internal markups from U.S. Industry Census Data for 1992 and 1997; and SEC 10-K reports for Acme, Powell, Magnetek and Hammond. The Department then vetted these estimated markups with manufacturers during a series of consultative meetings held in early 2002. The following markups resulted:

- Scrap factor: 2.5 percent markup. This markup applies to variable materials (e.g., core steel, windings, insulation). It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished transformer (e.g., lengths of wire too short to wind, trimmed core steel).
- Factory overhead: 12.5 percent markup. Factory overhead includes all the indirect costs associated with production, indirect materials and energy use, taxes, and insurance. The Department only applies factory overhead to the direct material production costs.
- Non-production: 25 percent markup. This markup reflects costs including sales and general administrative, R&D, interest payments, and profit factor. The Department applies the non-production markup to the sum of the direct material production, the direct labor, and the factory overhead.

The following example shows how the Department applied the markups to the materials, and how it determined the total production cost. Consider a 300kVA 45kV BIL three-phase dry-type transformer designed for a $1.50 A and a $0.50 B. This design has $2,902 of materials, including M6 core steel, copper primary and secondary windings, and all the transformer hardware. There are approximately 12.5 hours of labor involved in manufacturing this design, resulting in a labor cost of $532. The factory overhead on this design is $362, as it is only applied to the material cost (i.e., 12.5 percent of $2902). The non-production cost is $949, as the 25 percent is applied to the material, labor, and factory overhead costs (i.e., 25 percent of $2902 + $532 + $362). Thus, in total, DOE estimates this 300kVA three-phase transformer to have a manufacturer selling price of $4,747.

5.4.1 Material Inputs to the Design Software - Liquid-Immersed

In addition to the design parameters described in section 5.3, the other critical inputs to the design software are material costs. As the price of one material increases or decreases relative to the other materials, the design software will adjust the design to increase or decrease the content of that material. The design software uses the final marked-up cost of materials as input to the optimization process. In other words, rather than use the raw material cost of $1.00 per pound of core steel, the software uses $1.44 per pound, to reflect a small handling and scrap factor (2.5 percent), the factory overhead (12.5 percent), and the non-production markup (25 percent). During its manufacturer site visits in early 2002, the Department found this approach to be consistent with that of several manufacturers who operate their own, proprietary design software.

The following pages describe all the material prices entered into the design software for liquid-immersed distribution transformers. As shown in these tables, the Department marked up the material prices before entering them into the design software.

Table 5.4.1 Variable Material Inputs for Liquid-Immersed Units

Item and Description	Material Cost*	Scrap and Handling**	Factory Overhead***	Non-production****	Input to design software
M2 core steel	$1.05	1.025	1.125	1.25	$1.51
M3 core steel	$0.95	1.025	1.125	1.25	$1.37
M4 core steel	$0.85	1.025	1.125	1.25	$1.23
M6 core steel	$0.80	1.025	1.125	1.25	$1.15
ZDMH (mechanically-scribed core steel), non-US price	$1.40	1.025	1.125	1.25	$2.02
ZDMH (mechanically-scribed core steel), US price with import tariff	$1.83	1.025	1.125	1.25	$2.64
SA1 (amorphous material) - finished core, priced at volume production	$1.70	1.1	1.125	1.25	$2.62
Copper wire, formvar, round #10-20 (DL1,2,4)	$1.30	1.025	1.125	1.25	$1.87
Copper wire, enameled, round #7-10 flattened (DL3,5)	$1.30	1.025	1.125	1.25	$1.87
Copper wire, enameled, rectangular sizes (DL3)	$1.50	1.025	1.125	1.25	$2.16
Aluminum wire, formvar, round #9-17 (DL1,2,4)	$1.36	1.025	1.125	1.25	$1.96
Aluminum wire, formvar, round #7-10 (DL3,5)	$1.36	1.025	1.125	1.25	$1.96
Copper strip, thickness range 0.02-0.045 (DL1,2,4)	$2.40	1.025	1.125	1.25	$3.46
Copper strip, thickness range 0.030-0.060 (DL3,5)	$2.40	1.025	1.125	1.25	$3.46
Aluminum strip, thickness range 0.02-0.045 (DL1,2,4)	$1.30	1.025	1.125	1.25	$1.87
Aluminum strip, thickness range 0.045-0.080 (DL3,5)	$1.30	1.025	1.125	1.25	$1.87
Kraft insulating paper with diamond adhesive	$1.54	1.025	1.125	1.25	$2.22
Mineral oil	$1.52	1.025	1.125	1.25	$2.19

* Purchasing price to manufacturers from suppliers of raw materials necessary for building a transformer. Source: Paul Goethe, OPS, 2001; Manufacturer interviews, 2002.

** Handling and scrap is a multiplier factor that applies to variable materials (e.g., core steel, windings, insulation). It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished transformer (e.g., lengths of wire too short to wind, trimmed core steel). Source: Paul Goethe, OPS; Manufacturer interviews, 2002.

*** Factory overhead includes all indirect costs associated with production, energy use (e.g., furnace), light bulbs, insurance on factory and equipment, etc. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond; Manufacturer interviews, 2002.

**** Material markup reflects non-production costs, including sales and general administrative, R&D, interest payments, and profit factor markups. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond; Manufacturer interviews, 2002.

The Department obtained prices of all core steels used in the analysis for a standard quantity order from a major U.S. core steel manufacturer. Due to a U.S. policy to apply an import tariff to core steels from Japan and Italy, the Department considered a dual-price point for a special Japanese core steel called 'ZDMH' in this analysis, to understand how significant changes in the cost of core steel may impact the rulemaking process. Given a recent administrative decision to remove steel import tariffs, DOE will review the need for this dual-price point in the Notice of Proposed Rulemaking (NOPR) analysis.

ZDMH is a mechanically-scribed core steel that has beneficial low-loss properties that can survive the high-temperature stress-relief annealing process conducted on wound cores during manufacture. However, this high-efficiency technology option is only available from one supplier in Japan. Thus, as discussed in section 3.5.3, two prices are necessary because finished transformers imported from Mexico and Canada would not be subject to the tariff. The Department analyzed designs at both price points, to ensure that the standard would not result in a competitive advantage to non-US manufacturers due to the import duty on ZDMH core steel. The wire and strip prices shown in Table 5.4.1 were obtained from a major U.S. wire manufacturer.

In addition to these variable materials which the design software considers when preparing its optimized designs, there are other materials that are fixed and do not influence the design of the product. These include materials like the transformer cabinet, the high- and low-voltage bushings, and the core clamps. Table 5.4.3, on the next page, outlines all the estimated fixed material costs for each of the five liquid-immersed design lines.

For design line 1, a 50kVA single-phase pad-mounted unit, the high-voltage bushings are two universal bushing wells, 15 kV, 95 BIL, 7200V, costing $7 for the set. The low-voltage bushings are three copper studs, 240/120V, 50 kVA, at $8 for the set. The fuse system specified is a bayonet fuse holder, fuse and isolation link, costing $35. The internal hardware includes a core clamp, tap changer, nameplate, and other miscellaneous hardware costing $28.65. The Department varied the finished tank sizes for design line 1, ranging in price from $210 for the smallest size to $250 for the largest. Table 5.4.2 shows the five tank sizes used in design line 1. The Department based tank-size selections on the dimensions of the core-coil assembly, and based the oil used in the design on the core-coil assembly displacement of the tank volume.

Table 5.4.2 Variable Tank Sizes for Design Line 1

Tanks	Length	Height	Depth	Volume (cubic inches)*	Volume (gal)*	Price ($)	Weight (lbs)
A	32	24	13	8,320	36.0	$210	167
B	32	24	15	9,600	41.6	$220	174
C	32	24	17	10,880	47.1	$230	181
D	32	24	19	12,160	52.6	$240	188
E	32	24	21	13,440	58.2	$250	195

* Note that the volume calculation is less a four inch air-gap in the height of the tank.

For design line 2, a 25kVA single-phase pole-mounted unit, the high-voltage terminals are two porcelain bushing assemblies, 15 kV, 125 BIL, costing $12.00 for the set. The low-voltage terminals are three porcelain bushings, 120/240V, 25 kVA, at $8.00 for the set. The Department specified no fuse system for this representative unit. The internal hardware includes a core clamp, tap changer, nameplate, and other miscellaneous hardware, costing $28.65. The finished tank sizes are determined by the design software. Rather than use five discrete sizes as in design line 1, the software calculates tank size based on core/coil clearances and oil requirements. The price for a 25kVA pole-mounted tank is held constant at $120.

For design line 3, a 500kVA single-phase unit, the high-voltage connectors are two porcelain bushings, 25 kV, 125 BIL, costing $20 for the set. The low-voltage bushings are two polymer 500kVA, 277V, costing $40 for the set. The internal hardware includes a core clamp ($30), tap changer ($15), and nameplate and miscellaneous hardware ($20), totaling $65. As with design line 2, the software was allowed to vary the tank size. The finished round tank has a diameter of 26" to 30" with external cooling, and has a fixed cost of $500.

For design line 4, a 150kVA three-phase, pad-mounted unit, the high-voltage bushings are six universal bushing wells, 8.3/14.4 kV, 95 BIL, costing $21 each. The low-voltage bushings are four copper studs at $12 each. The fuse system installed is a bayonet fuse holder, fuse, and isolation link, costing $105. The internal hardware includes core clamps ($45), tap changer ($40), and nameplate and miscellaneous hardware ($45), totaling $130. The finished tank sizes were determined by the design software, measuring 48 inches high and 54 inches wide, and varying the depth. The finished rectangular welded tank costs $650.

For design line 5, a 1500kVA three-phase, pad-mounted unit, the high-voltage bushings are six universal bushing wells, 15.2/26.3 kV, 125kV BIL, costing $42 for the set. The low-voltage bushings are four copper studs, costing $12 each. The fuse system installed is a bayonet fuse holder, fuse, and isolation link costing $105. The internal hardware includes core clamps ($45), tap changer ($40), and nameplate and miscellaneous hardware ($45), totaling $130. The finished tank sizes were determined by the design software, measuring 60 inches high and 57 inches wide, and varying the depth. The finished rectangular welded tank costs $800.

Table 5.4.3 Summary Table of Fixed Material Costs for Liquid-Immersed Units

Item	DL1	DL2	DL3	DL4	DL5
High voltage bushings	$7	$12	$20	$21	$42
Low voltage bushings	$8	$8	$40	$12	$12
Fuse system	$35	none	none	$105	$105
Core clamp, tap changer, misc. hardware	$28.65	$28.65	$65	$130	$130
Transformer tank	$210-250	$120	$500	$650	$800

5.4.2 Material Inputs to the Design Software - Dry-type

On the following pages, all the material costs entered into the design software for dry-type distribution transformers are given. As shown in these tables, the Department marked up the material costs before being entering them into the design software.

Table 5.4.4 Variable Material Inputs for Dry-Type Units

Item and Description	Material Cost*	Scrap and Handling**	Factory Overhead***	Non-production****	Input to design software
H-O DR core steel (laser-scribed)	$1.15	1.025	1.125	1.25	$1.66
M3 core steel	$0.95	1.025	1.125	1.25	$1.37
M4 core steel	$0.85	1.025	1.125	1.25	$1.23
M6 core steel	$0.80	1.025	1.125	1.25	$1.15
M19 core steel (26 gauge)	$0.70	1.025	1.125	1.25	$1.01
M36 core steel (26 gauge)	$0.46	1.025	1.125	1.25	$0.66
M43 core steel (26 gauge)	$0.39	1.025	1.125	1.25	$0.56
Copper wire, rectangular 0.1 x 0.2, Nomex wrapped	$1.60	1.025	1.125	1.25	$2.31
Aluminum wire, rectangular 0.1 x 0.2, Nomex wrapped	$2.00	1.025	1.125	1.25	$2.88
Copper strip, thickness range .02-.045	$2.40	1.025	1.125	1.25	$3.46
Aluminum strip, thickness range .02-.045	$1.30	1.025	1.125	1.25	$1.87
Nomex insulation (per pound)	$17.50	1.025	1.125	1.25	$25.22
Impregnation (per gallon)	$18.00	1.025	1.125	1.25	$25.95
Winding Combs (per pound)	$10.00	1.025	1.125	1.25	$14.41

* Purchasing price to manufacturers from suppliers of raw materials necessary for building a transformer. Source: Paul Goethe, OPS, 2001; Manufacturer interviews, 2002.
** Handling and scrap is a multiplier factor that applies to variable materials (e.g., core steel, windings, insulation). It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished transformer (e.g., lengths of wire too short to wind, trimmed core steel). Source: Paul Goethe, OPS; Manufacturer interviews, 2002.
*** Factory overhead includes all indirect costs associated with production, energy use (e.g., furnace), light bulbs, insurance on factory and equipment, etc. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond; Manufacturer interviews, 2002.
**** Material mark up reflects non-production costs, including sales and general administrative, R&D, interest payments, and profit factor markups. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond; Manufacturer interviews, 2002.

In addition to the variable inputs presented in Table 5.4.4, there is one input material that varied for each of the design lines: the dog-bone cooling duct spacer. The number and placement of cooling ducts is determined by the design software during the design process; however, the size (height) of the duct is defined as a design input. In addition to presenting some of the fixed material costs, Table 5.4.5 presents the input costs per foot for the duct-spacers used.

For design line 6, a 25kVA single-phase, low-voltage, dry-type, the fixed hardware costs are $4 for the low-voltage and high-voltage terminals. The mounting frame for attaching the core/coil assembly to the transformer enclosure costs $9.25. The fiberglass dog-bone duct-spacers used for this design line cost $0.24 per foot. The miscellaneous hardware costs were set at $4.50. The enclosure itself, a 14-gauge steel enclosure, base, and mounting feet cost $100. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 7, a 75kVA three-phase, low-voltage, dry-type, the fixed hardware costs are $6 for the low-voltage and high-voltage terminals. The low voltage bus-bar is estimated to be six feet at $1.50 per foot, or $9. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $19. The fiberglass dog-bone duct-spacers used for this design line cost $0.32 per foot. The miscellaneous hardware costs were estimated at $6. The enclosure itself, a 14-gauge steel enclosure, base, and mounting feet cost $125. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 8, a 300 kVA three-phase, low-voltage, dry-type, the low-voltage and high-voltage terminal set costs $19. The low-voltage bus-bar is estimated to be nine feet at $2.50 per foot, or $22.50. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $36. The fiberglass dog-bone duct-spacers used for this design line cost $0.42 per foot. The miscellaneous hardware costs were estimated at $12. The enclosure itself, a 14-gauge steel enclosure, base, and mounting feet cost $175. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 9, a 300 kVA three-phase medium-voltage dry-type at 45kV BIL, the low-voltage and high-voltage terminal set costs $75. The low-voltage bus-bar is estimated to be nine feet at $6 per foot, or $54. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $36. The fiberglass dog-bone duct-spacers used for this design line cost $0.24 per foot. The miscellaneous hardware costs were estimated at $25. The enclosure itself, a 14-gauge steel enclosure, base, and mounting feet cost $175. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 10, a 1500 kVA three-phase medium-voltage dry-type at 45kV BIL, the low-voltage and high-voltage terminal set costs $120. The low voltage bus-bar is estimated to be ten feet at $14 per foot, or $140. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $120. The fiberglass dog-bone duct-spacers used for this design line cost $0.52 per foot. The miscellaneous hardware costs were estimated at $42. The enclosure itself, a 12-gauge steel enclosure, base, and mounting feet cost $500. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 11, a 300 kVA three-phase medium-voltage dry-type at 95kV BIL, the low-voltage and high-voltage terminal set costs $75. The low-voltage bus-bar is estimated to be ten feet at $8 per foot, or $80. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $42. The fiberglass dog-bone duct-spacers used for this design line cost $0.24 per foot. The miscellaneous hardware costs were estimated at $32. The enclosure itself, a 14-gauge steel enclosure, base and mounting feet cost $200. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 12, a 1500 kVA three-phase medium-voltage dry-type at 95kV BIL, the low-voltage and high-voltage terminal set costs $120. The low-voltage bus-bar is estimated to be fourteen feet at $12 per foot, or $168. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $125. The fiberglass dog-bone duct-spacers used for this design line cost $0.56 per foot. The miscellaneous hardware costs were estimated at $42. The enclosure itself, a 12-gauge steel enclosure, base and mounting feet cost $600. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

For design line 13, a 2000 kVA three-phase medium-voltage dry-type at 125kV BIL, the low-voltage and high-voltage terminal set costs $150. The low-voltage bus-bar is estimated to be eighteen feet at $15 per foot, or $270. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $175. The fiberglass dog-bone duct-spacers used for this design line cost $0.60 per foot. The miscellaneous hardware costs were estimated at $56. The enclosure itself, a 12-gauge steel enclosure, base and mounting feet cost $750. The cost of the enclosure was held constant while the actual dimensions were allowed to vary with the core-coil assembly size.

Table 5.4.5 Summary Table of Fixed Material Costs for Dry-Type Units

Item	**DL6**	**DL7**	**DL8**	**DL9**	**DL10**	**DL11**	**DL12**	**DL13**
LV and HV terminals (set)	$4	$6	$19	$75	$120	$75	$120	$150
LV bus-bar	n/a	$9	$22.50	$54	$140	$80	$168	$270
Core/coil mounting frame	$9.25	$19	$36	$36	$120	$42	$125	$175
Dog-bone duct-spacer (ft.)	$0.24	$0.32	$0.42	$0.24	$0.52	$0.24	$0.56	$0.60
Misc. hardware	$4.50	$6	$12	$25	$42	$32	$42	$56
Enclosure (12, 14 gauge)	$100	$125	$175	$175	$500	$200	$600	$750

5.4.3 Labor Cost Inputs to the Design Software

Labor costs constitute a critical aspect of the cost of manufacturing a distribution transformer. As an input to the design software, the Department used the same hourly labor cost for both liquid and dry-type distribution transformers. The Department developed the hourly cost of labor using a similar approach to the development of the cost of materials; however, it used different markups except for the non-production markup. The Department developed the markups shown in Table 5.4.6 after reviewing publicly available information and consulting with industry experts familiar with transformer manufacturing in the U.S.

Table 5.4.6 Labor Markups for Liquid-Immersed and Dry-Type Manufacturers

Item description	Markup percentage	Rate per hour
Labor cost per hour*		$ 14.31
Indirect Production**	33%	$ 19.03
Overhead***	30%	$ 24.74
Fringe†	21%	$ 29.93
Assembly Labor Up-time††	43%	$ 42.77
Non-Production Mark-up†††	25%	$ 53.46
Cost of Labor Input to Software		**$ 53.46**

* Cost per hour is from U.S. Census Bureau, *1997 Economic Census of Industry*, published September 1999, Table 5, page 9. Data for NAICS code 3353111 "Power and distribution transformers, except parts" Production workers hours and wages.

** Indirect Production Labor (Production managers, quality control, etc.) as a percent of direct labor on a cost basis. Navigant Consulting, Inc. (NCI) estimate.

*** Overhead includes commissions, dismissal pay, bonuses, vacation, sick leave, and social security contributions. NCI estimate.

† Fringe includes pension contributions, group insurance premiums, workers compensation. Source: U.S. Census Bureau, *1997 Economic Census of Industry*, published September 1999, Table 3, page 8. Data for NAICS code 335311 "Power, Distribution and Specialty Transformer Manufacturing," Total fringe benefits as a percent of total compensation for all employees (not just production workers).

†† Assembly labor up-time is a factor applied to account for the time that workers are not assembling product and/or reworking unsatisfactory units. The markup of 42 percent represents a 70 percent utilization (multiplying by 100/70). NCI estimate.

††† Non-production markup reflects non-production costs, including sales and general administrative, R&D, interest payments, and profit factor markups. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond; Manufacturer interviews, 2002.

5.5 RESULTS OF THE ANALYSIS ON EACH DESIGN LINE

This section provides a visual representation of the results of the engineering analysis. The scatter plots in this section show the cost and efficiency relationships for each of the 13 design lines. Each dot on the plots represents one unique design created by the software at a given manufacturer selling price and efficiency level. The placement of each dot (and the uniqueness of each design) is dictated by the design option combinations (core steel and windings), core shape, and A/B combination. In Appendix 5A, additional scatter plots for the engineering analysis results for the 13 representative units are presented, including watts of core and coil loss by price and the weight by price. On the Department's website, the actual values behind these plots are available in two Microsoft Excel® workbooks, one for liquid-immersed and one for dry-type units. See:
http://www.eere.energy.gov/buildings/appliance_standards/commercial/dist_transformers.html

Figure 5.5.1 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 1. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- Designs achieving the highest efficiencies at the lowest costs are based on M2 and M3 steel cores. Of these cores, the M3CuAl offers the least-cost option for improving efficiency, but is limited to an efficiency of 99.3 percent.
- The all-copper windings available with the M2CuCu and M3CuCu options allow for somewhat higher efficiencies, but the costs escalate rapidly above 99.3 percent efficiency.
- The ZDUS (ZDMH core steel) has higher costs associated with increasing efficiency than do other cores.
- The amorphous metal (SA1) core dramatically extends the available efficiency for the transformers beyond 99.6 percent, but at a significant cost.

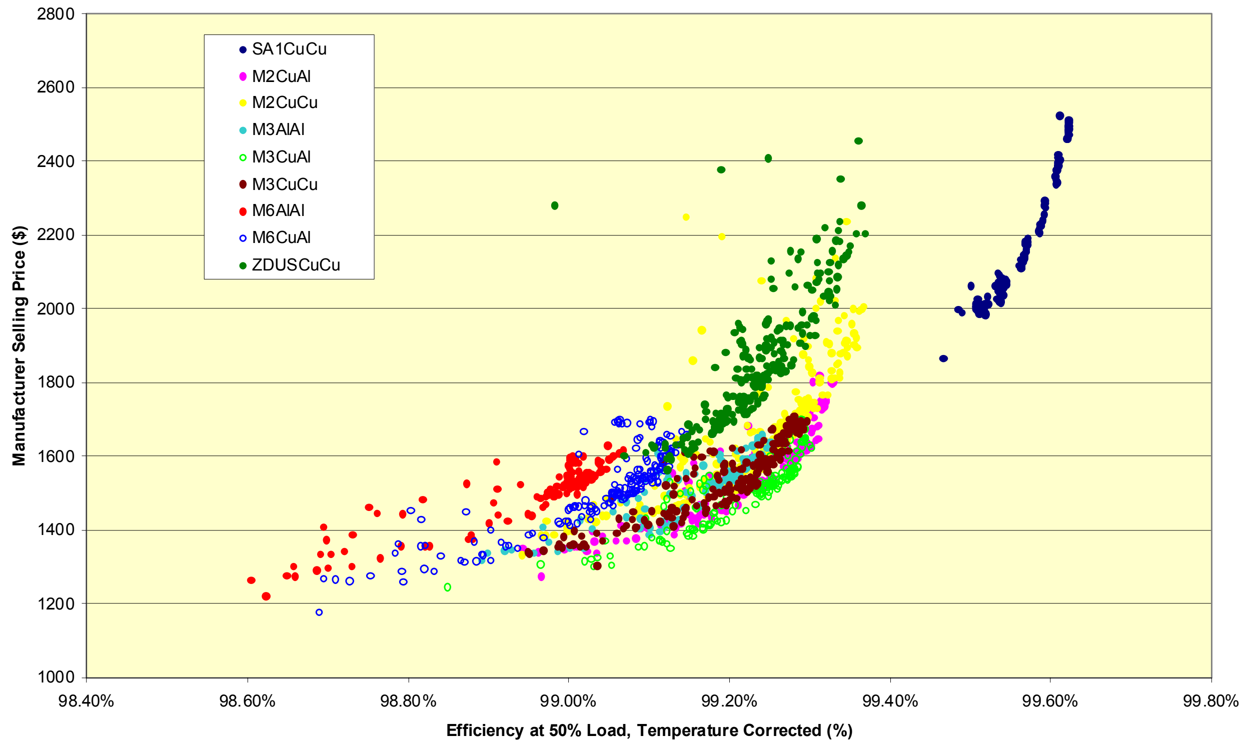


Figure 5.5.1 Scatter Plot of Manufacturer Selling Price and Efficiency for DL1

Figure 5.5.2 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 2. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The TP-1 standard of 98.7 percent can be achieved with several design option combinations, including M6AlAl and M4AlAl.
- The ZDUS core has higher costs associated with increasing efficiency relative to the other design option combinations.
- In most cases, the maximum efficiency available with conventional core steels is approximately 99.2 percent. However, the amorphous metal (SA1) provides efficiencies up to about 99.5 percent.
- For this kVA rating, the SA1 core has a very steep cost curve associated with increasing efficiency.

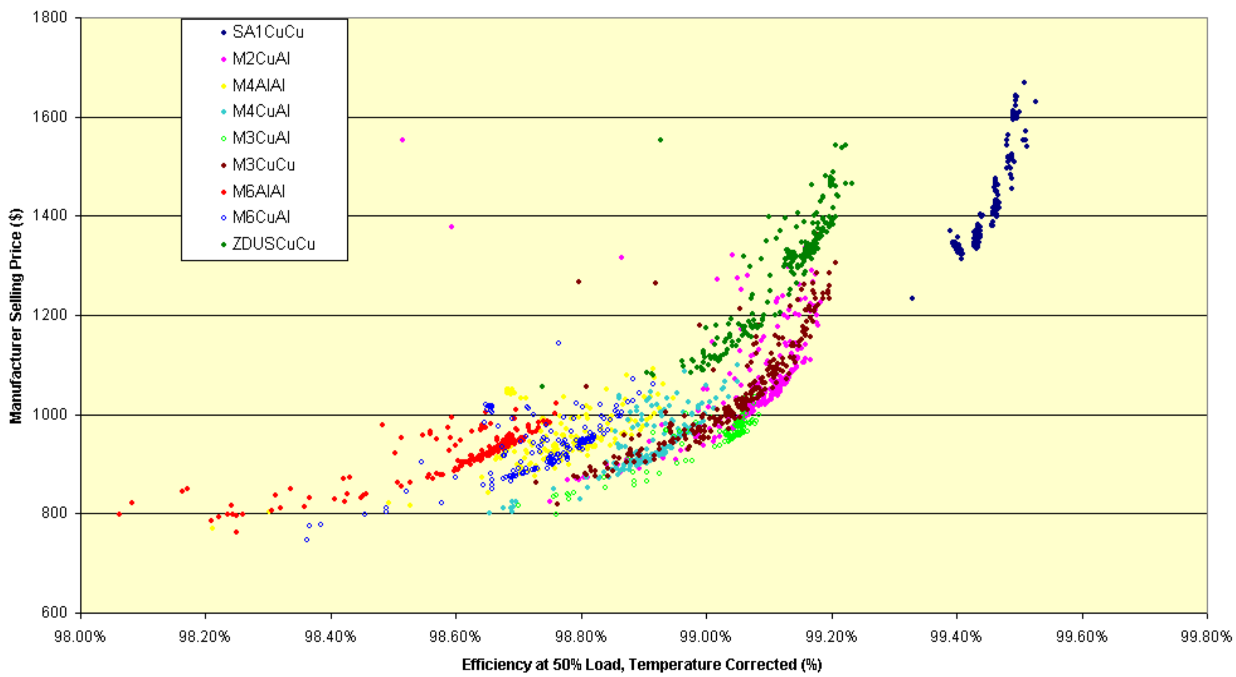


Figure 5.5.2 Scatter Plot of Manufacturer Selling Price and Efficiency for DL2

Figure 5.5.3 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 3. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The Japanese deep-domain refined core steel (ZDMH) design option combination, ZDUSCuCu, has higher costs associated with increasing efficiency relative to the other design options.
- In most cases, the maximum efficiency available is limited to approximately 99.6 percent. However, the amorphous metal design option combination provides efficiencies up to about 99.8 percent, with an available range from about 99.5 percent to nearly 99.8 percent.
- Beyond the efficiencies available with other cores, the amorphous core has a flat cost with increasing efficiency up to about 99.6 percent. Beyond that, the costs begin to rise exponentially.

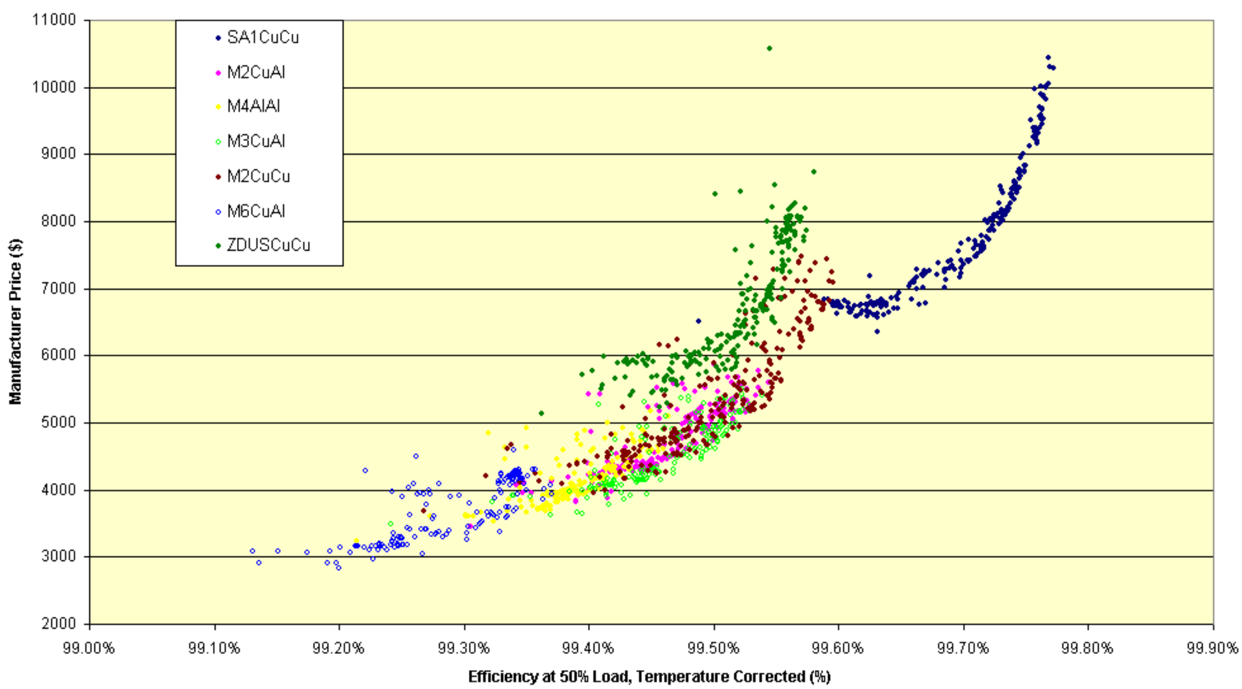


Figure 5.5.3 Scatter Plot of Manufacturer Selling Price and Efficiency for DL3

Figure 5.5.4 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 4. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- At the lower efficiencies, the M6 and M4 steel cores offer a low-cost option for increasing efficiency.
- Between 99.0 percent and 99.4 percent, the M2 and M3 steel cores are a cost-efficient option for increasing efficiency. For these cores there is no significant difference between the all-copper and copper-aluminum windings.
- The ZDUS core has a higher cost associated with increasing efficiency relative to the other steel core offerings.
- The amorphous metal design option combination extends the available efficiency for the transformers up to 99.6 percent, but at a significant cost.

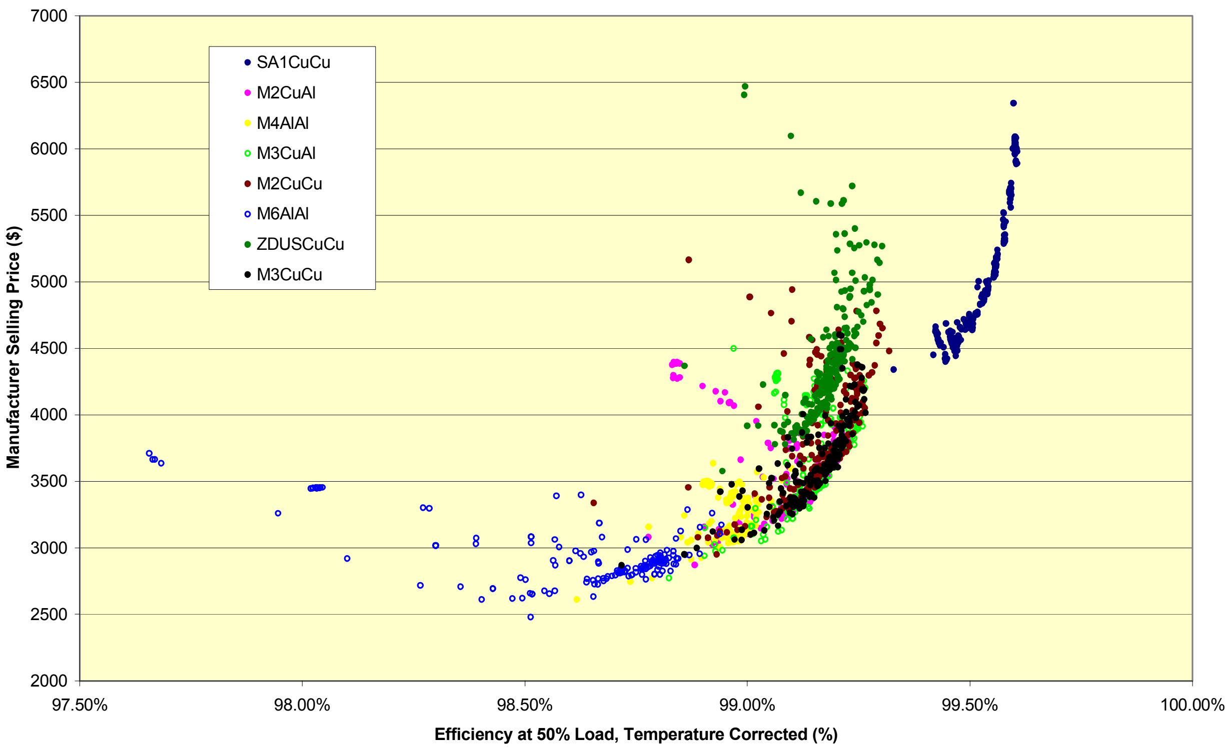


Figure 5.5.4 Scatter Plot of Manufacturing Selling Price and Efficiency for DL4

Figure 5.5.5 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 5. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load. Several observations can be made about this scatter plot:

- All the cores, except for the ZDUS, provide a low-cost option for increased efficiency between 99.2 percent and 99.5 percent. However, the optimal core and winding combination at a given efficiency rating vary.
- Beyond 99.5 percent, the SA1 core provides additional efficiency with increased cost. However, the units with the lowest manufacturer selling prices follow a similar general trend displayed by the other cores.
- From the least expensive to the most expensive, there is more than a three-fold difference in the manufacturer's sales price.

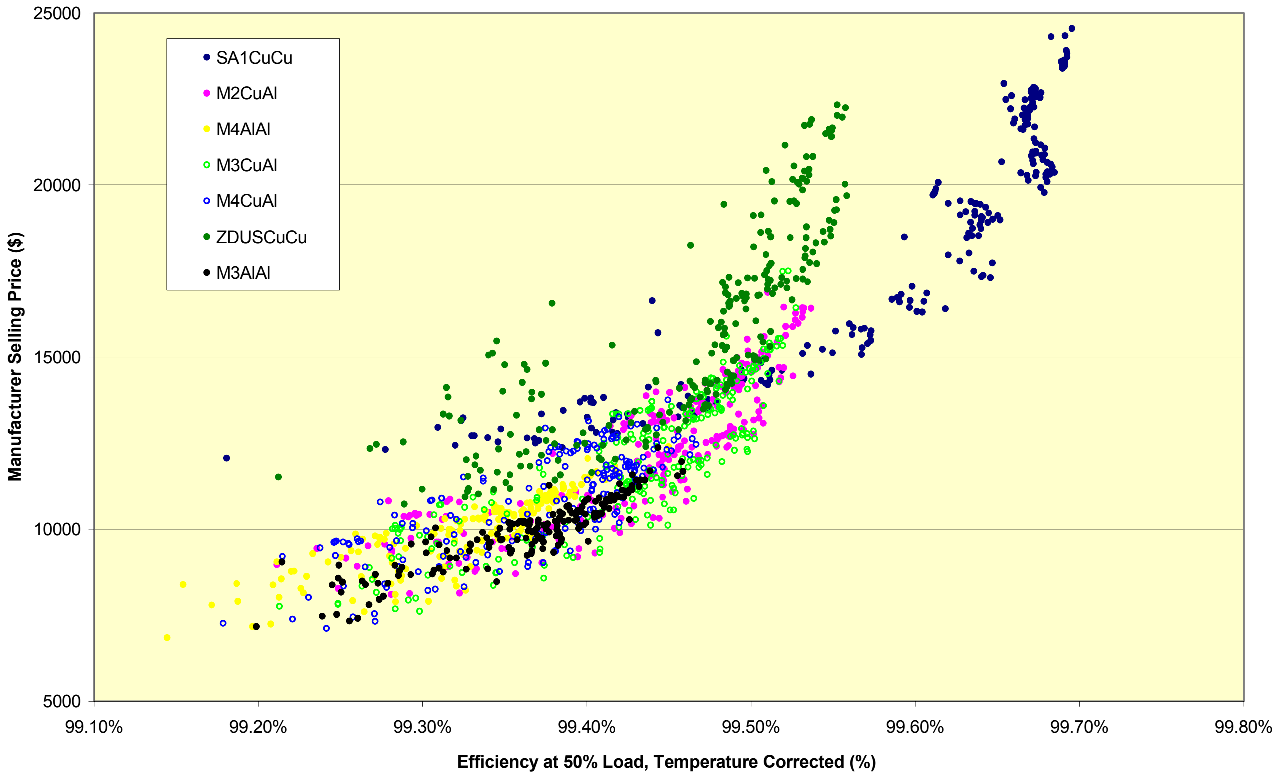


Figure 5.5.5 Scatter Plot of Manufacturing Selling Price and Efficiency for DL5

Figure 5.5.6 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 6. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. Some observations can be made about this scatter plot:

- The least-expensive cores, M43, M36, and M19, do not meet the minimum efficiency level for NEMA's TP 1-2002 for a 25kVA low-voltage, dry-type, single-phase of 98.0 percent.
- The H-O DR steel cores provide the highest efficiency but are limited to about 99.0 percent efficiency. At these higher efficiency levels, the cost of the transformers continues to rise with little or no gain in efficiency.
- The M3 and M6 cores provide the least-cost option, from 97.5 percent to 98.5 percent, for increasing efficiency.

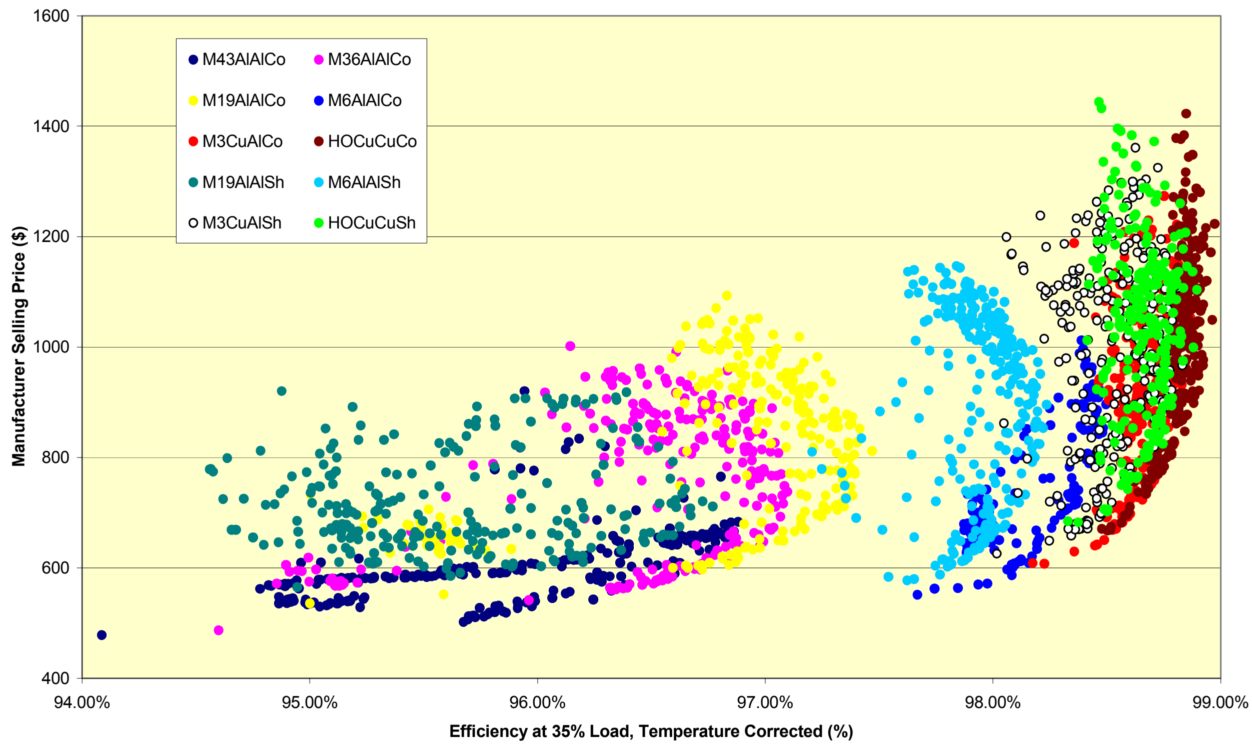


Figure 5.5.6 Scatter Plot of Manufacturing Selling Price and Efficiency for DL6

Figure 5.5.7 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 7. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The M3CuAlEv (Evans core) transformer has essentially the same costs and efficiency gains as the HOCuCuEv transformer. However, the H-O DR transformer provides a slightly higher efficiency than the M3 transformer.
- At the higher efficiency levels, the cost of the transformers continues to rise with little or no gain in efficiency.
- The M19 and M43 cores do not achieve the minimum efficiency rating of 98.0 percent under NEMA's TP 1-2002 for a 75kVA three-phase LV dry-type transformer.

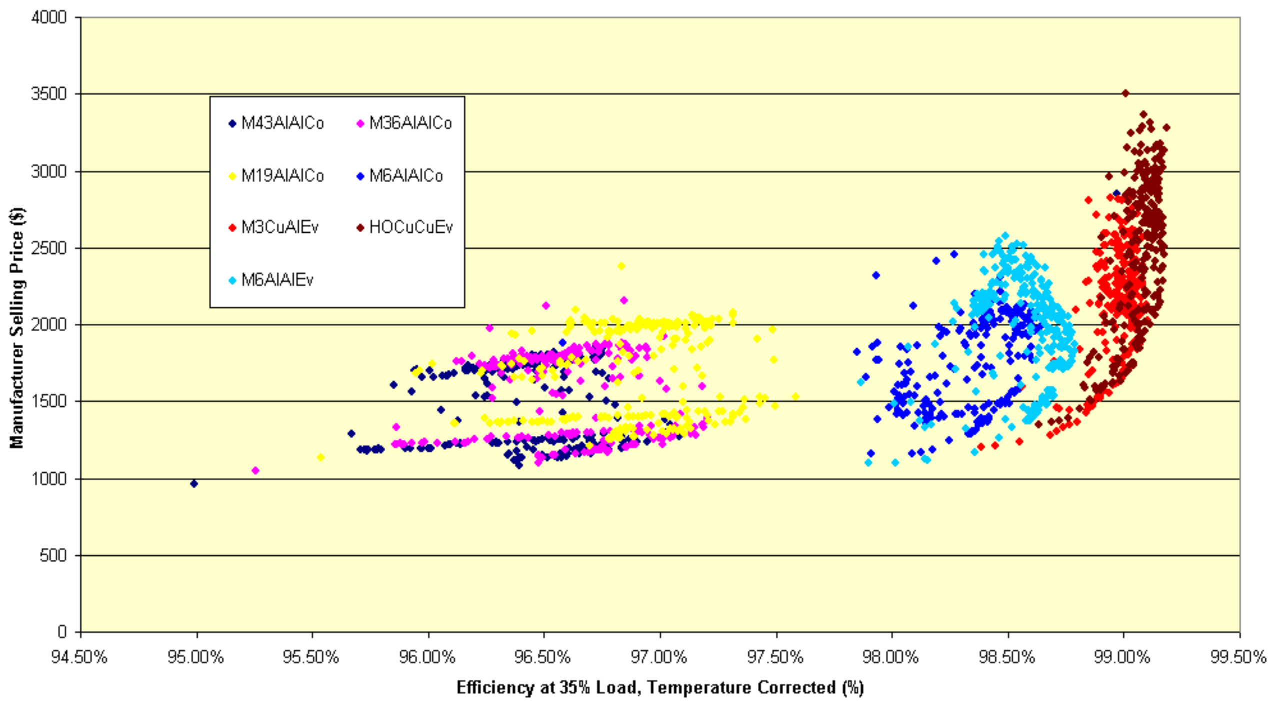


Figure 5.5.7 Scatter Plot of Manufacturing Selling Price and Efficiency for DL7

Figure 5.5.8 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 8. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The HOCuCu transformer does not appear to have any cost benefit over the M3CuAl transformer. At 99.0 percent efficiency, a transformer with the M3 steel core offers the least cost and at higher efficiencies has costs equal to those of the H-O DR core steel.
- At the higher efficiency levels, the cost of the transformers continues to rise with little or no gain in efficiency.
- The M19 core steel does not provide the minimum efficiency of 98.6 percent under NEMA's TP 1-2002.

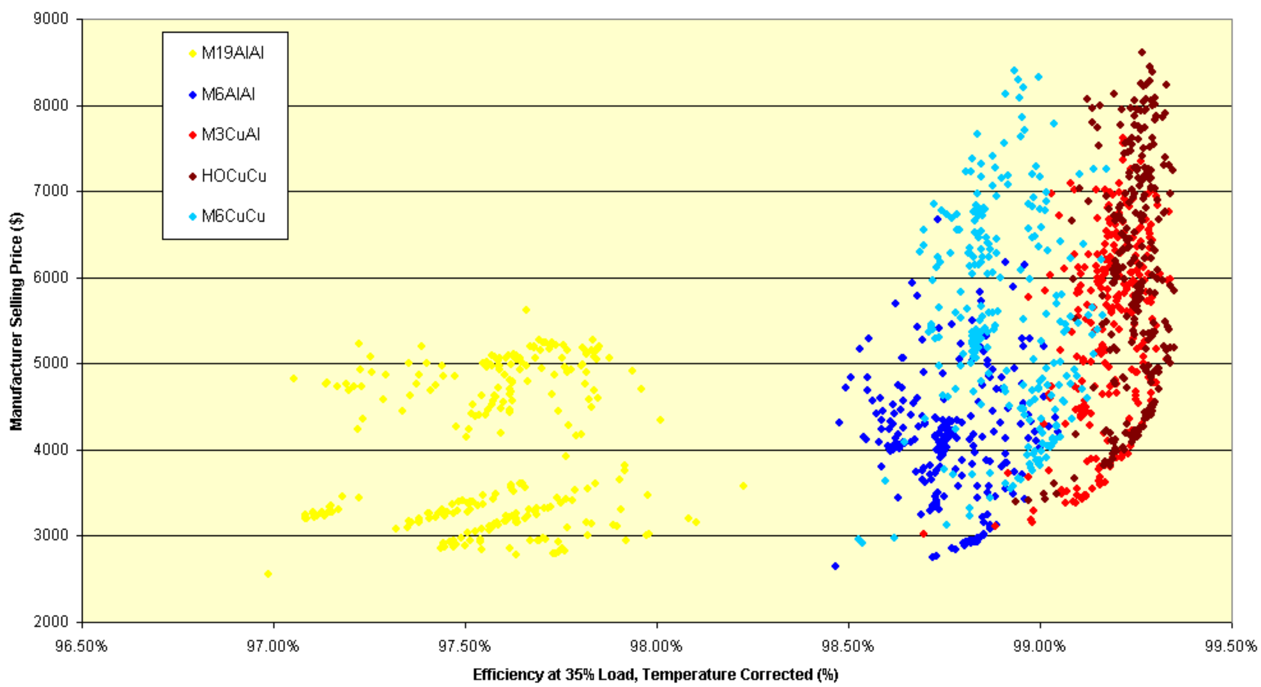


Figure 5.5.8 Scatter Plot of Manufacturing Selling Price and Efficiency for DL8

Figure 5.5.9 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 9. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The least-expensive units employ the least-expensive core steels, M36 and M19.
- Even though extremely high evaluation formulas are being applied to M36 and M19 steels (i.e., \$12A and \$8B), the efficiencies are unable to improve beyond 98 percent.
- NEMA's TP 1-2002 efficiency level for this unit is 98.6 percent efficient. This level cannot be achieved using the less expensive M36 and M19 core steels. This level can be achieved by using M6 or better core steels.
- Rapid increase in price is realized in the M3 and H-O DR core steels, as the efficiency level increases. For example, moving a fraction of an efficiency level (e.g., from 99.00 percent to 99.25 percent) can double the price.
- The increased performance and higher price of all-copper windings is shown when the M6AlAl design option combination is compared with the M6CuCu, although, at several efficiency points, M3CuAl appears to be a lower-cost option than M6CuCu.

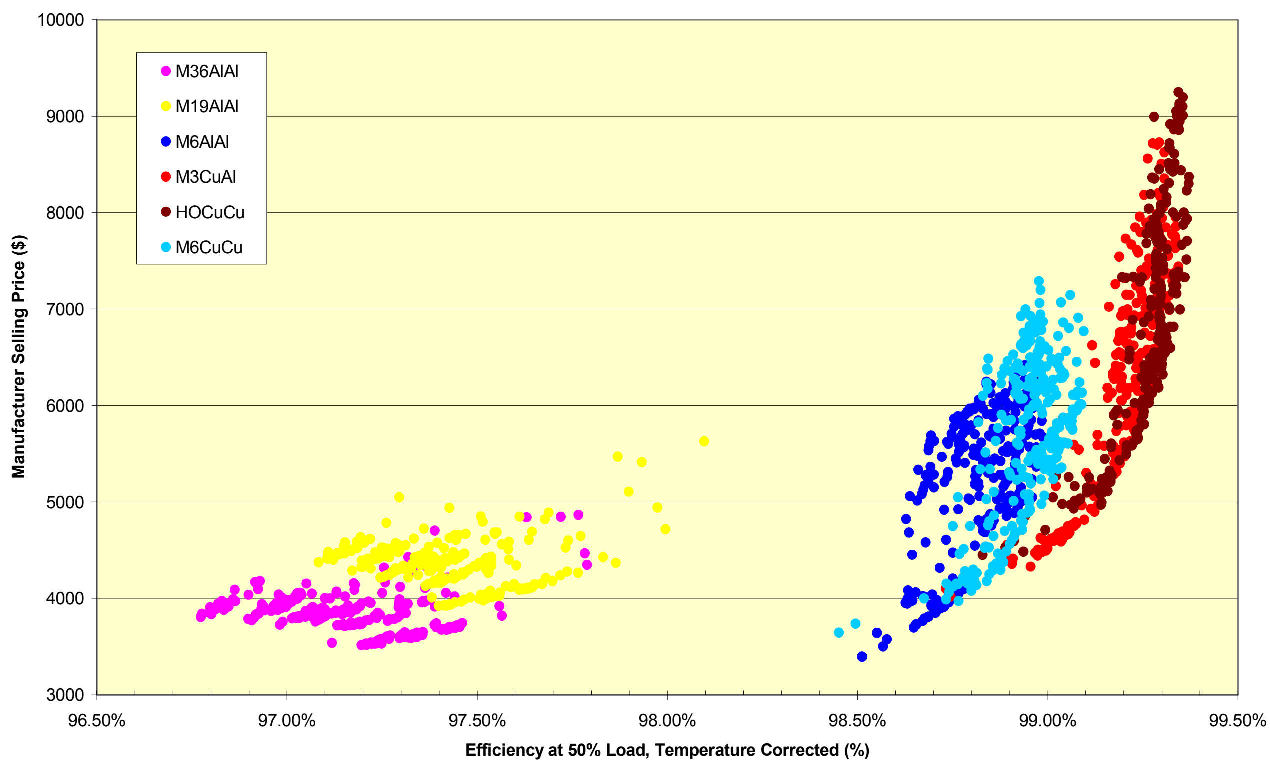


Figure 5.5.9 Scatter Plot of Manufacturing Selling Price and Efficiency for DL9

Figure 5.5.10 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 10. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The M4 core steel combined with the copper-aluminum windings (M4CuAl) offers a more cost-effective design option than the all-copper or all-aluminum windings available with the M6 cores.
- As the efficiency increases, the laser-scribed (H-O DR) and M3 steel cores have similar costs.

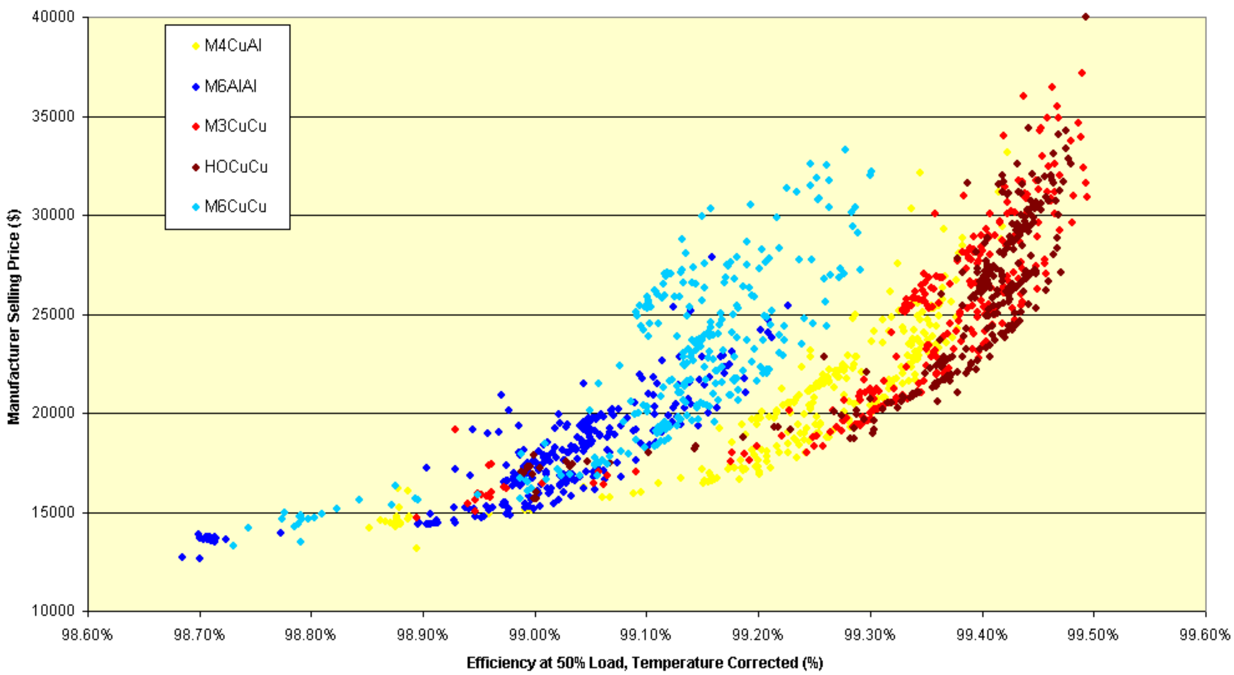


Figure 5.5.10 Scatter Plot of Manufacturing Selling Price and Efficiency for DL10

Figure 5.5.11 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the design line 11. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load. Several observations can be made about this scatter plot:

- The least-cost high-efficiency design path at 50 percent load varies between the M3, M4, and H-O DR cores steel design option combinations.
- The M6 cores offer the least-cost options only at the lowest efficiency levels. In general, the transformers that use the M6 core steel are not the most cost-effective option available.
- Many design option combinations are possible that comply with the NEMA TP 1-2002 efficiency level of 98.5 percent for this 300kVA, three-phase medium-voltage dry-type unit at 95kV BIL.

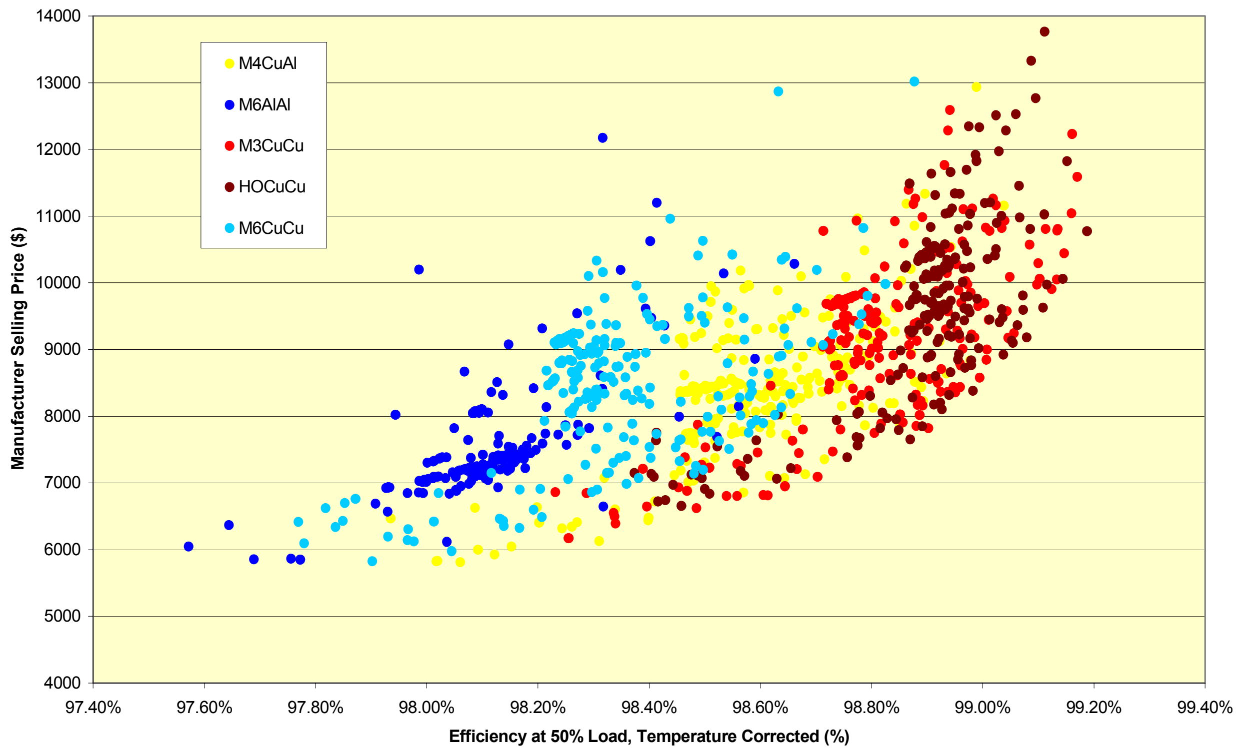


Figure 5.5.11 Scatter Plot of Manufacturing Selling Price and Efficiency for DL11

Figure 5.5.12 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 12. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load. Several observations can be made about this scatter plot:

- The M4 core steel combined with the copper-aluminum windings (M4CuAl) offers a more cost-effective design option than the all-copper or all-aluminum windings available with the M6 cores.
- Above 99.3 percent efficiency, the H-O DR steel design option combination has a slight cost advantage over the M3 core. Both provide a maximum efficiency of about 99.5 percent with similar costs.
- In general, the transformers that use the M6 core steel are not the most cost-effective option available.

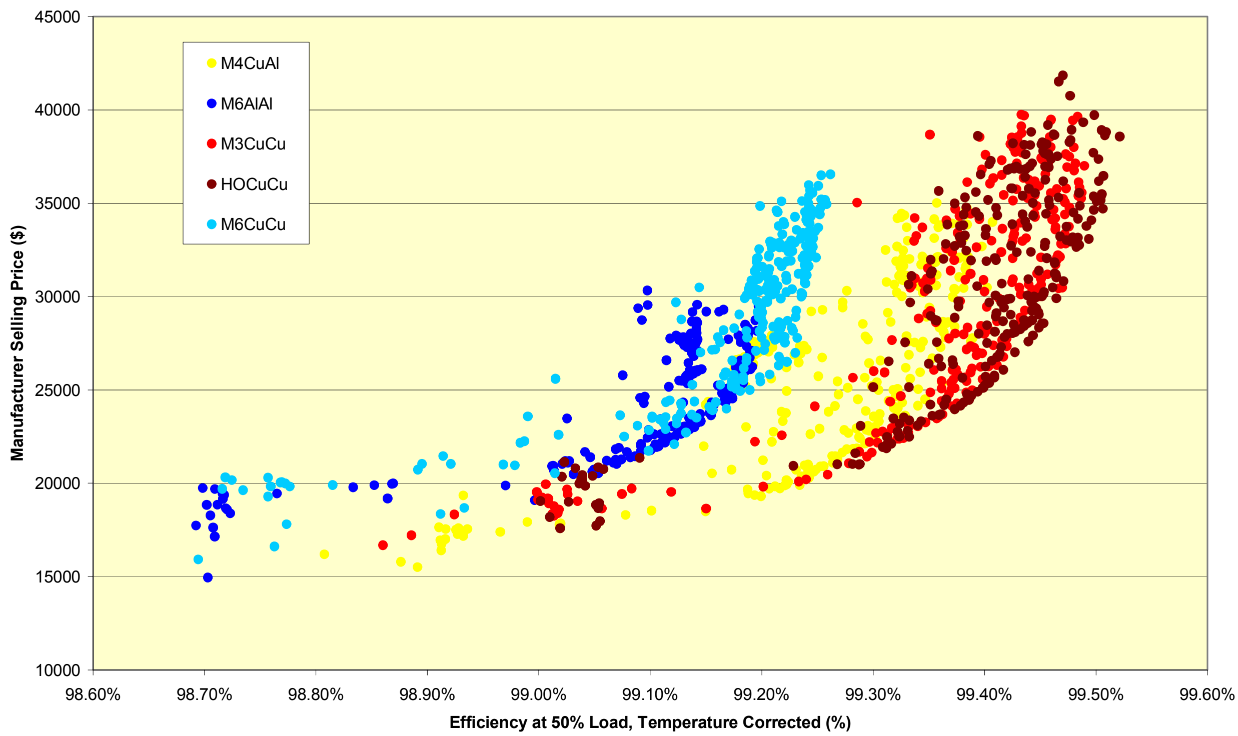


Figure 5.5.12 Scatter Plot of Manufacturing Selling Price and Efficiency for DL12

Figure 5.5.13 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from design line 13. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. Several observations can be made about this scatter plot:

- The M3CuCu transformer offers the least-cost option over an extended range of efficiencies, from slightly less than 99.0 percent up to nearly 99.5 percent.
- The HOCuCu transformer does not appear to yield any cost reduction relative to the M3CuCu transformer. At efficiency levels of 99.2 percent and above, the M3 steel core and H-O DR steel cores have similar costs and efficiency gains.
- The transformers that use the M6 steel are limited to an efficiency of about 99.25 percent and are only cost-effective up to about 99.0 percent.

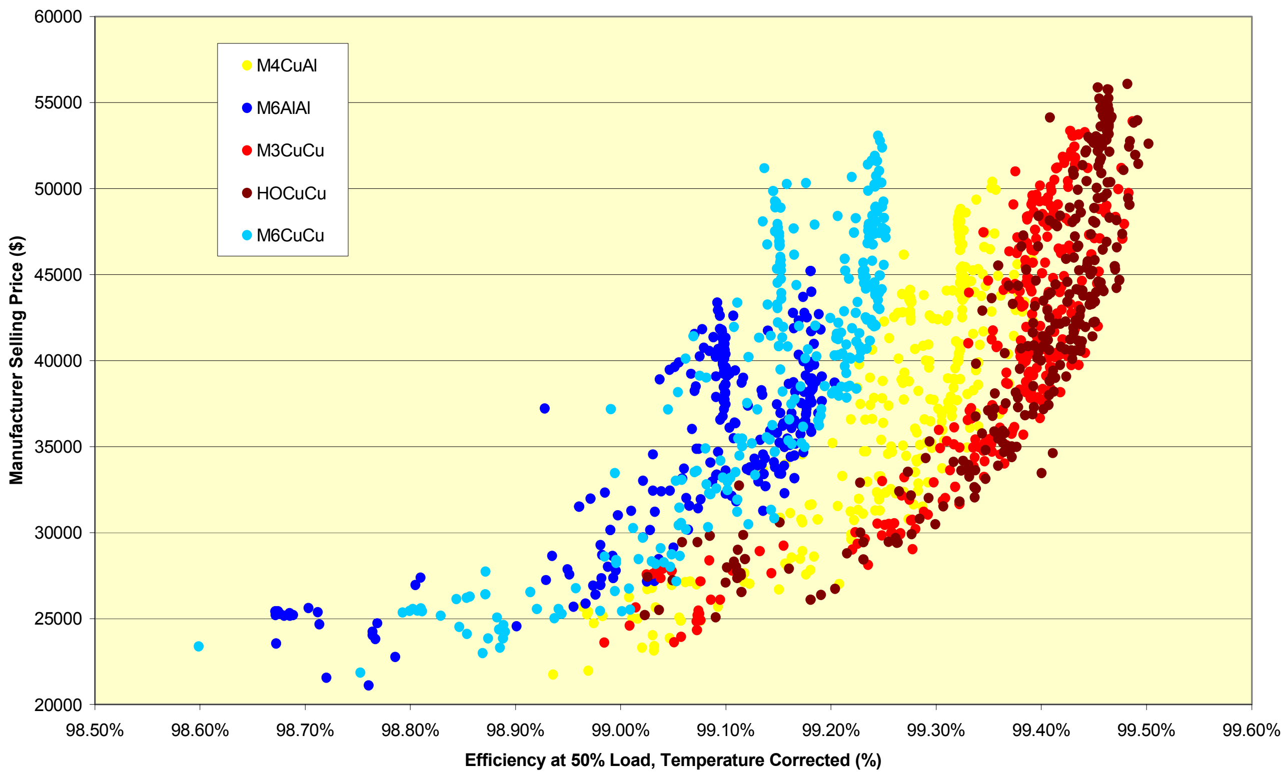


Figure 5.5.13 Scatter Plot of Manufacturing Selling Price and Efficiency for DL13

5.6 TWO EXAMPLE TRANSFORMER DESIGNS AND COST BREAKDOWNS

To provide some detail and establish credibility with its engineering analysis cost-efficiency database developed by the design software, the Department selected two designs from its database of over 20,000 to present in this section. Transformer engineers can review the design reports, and assess the quality of the designs. The two distribution transformers presented are the cost-optimized designs for two units, one each from design line 3 and design line 12. Across all the design lines, the complete database of designs contains 22,387 distribution transformer specification and winding sheets, bills of materials, and performance reports. This database is the output from the engineering analysis that is used in the LCC analysis.

Design Line 3: 500 kVA single-phase, liquid-immersed, M6 core steel with an copper primary and an aluminum secondary (M6CuAl) at a $3.00 A and a $1.00 B evaluation formula.

Design Line 12: 1500 kVA three-phase, medium-voltage dry-type, M3 core steel with primary and secondary copper windings (M3CuCu) at a $3.00 A and a $1.00 B evaluation formula.

For both designs presented, the design detail report is followed by a bill of materials showing the cost calculation, and a pie chart providing a breakdown of the final selling price.

5.6.1 Results for DL3 Transformer, M6CuAl at $3 A and $1 B

A design specification report for a 500kVA single-phase liquid-immersed transformer appears below. This design incorporates M6 core steel, with a copper primary and aluminum secondary. The evaluation factors for this design are $3.00 A and $1.00 B. The bill of materials and associated breakdown of costs for this design are also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2002- 3-22     9: 2:45
DG-CORE       SHELL   TYPE TRANSFORMER                L3SM6CUAL

FREQUENCY    60.0            KVA RATING    499.85 @ 100.00% DUTY CYCLE

CORE DG-M6          M 6                                 THICKNESS .0140

  D: 9.680 E: 4.083 F: 4.315 G:21.577  EFF. AREA  76.285 WEIGHT1354.749

WINDING FORM: INS. DIM. 10.180 X  8.541  THICKNESS  .122  LENGTH 21.265
```

COIL SPECIFICATIONS

WNDG	WIRE		LENGTH	MEAN TURNS	MARGIN	WT
S1	2X 1(.0512X20.5148)	AL	48.50	44.77	.375	119.358
P1	.1269X .2614	CU	3552.43	60.06	.750	442.697

NUMBER OF COILS 1 TOTAL BARE CONDUCTOR WEIGHT 562.055

WNDG	TURNS	LO TAP	HI TAP	LAYRS	T/L	LAYR INS	SEC. INS	BUILD
S1	13.0			13	1.0	1(.02000)	1(.15000)	1.571
P1	676.0	642.2	709.8	10	71.0	6(.00500)	1(.15000)	1.589

TOTAL BUILD(%) 87.37

WNDG	TAPS: TURNS(VOLTS)		
P1	659.1(14040.00)	692.9(14760.00)	709.8(15120.00)

WNDG	INTERNAL DUCTS(100.00) %EFF	EXTERNAL DUCTS(100.00) %EFF
S1	3 .188 X .188 IN. END	
P1	3 .188 X .188 IN. END	.188 X .188 IN. FULL

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	14400.00	13680.00	15120.00	34.5	34.977	.89491	1082.	
S1	275.04			10.0	1805.000	.00031	860.	.7

	F.L.	N.L.		
FLUX DENS.	16.175	16.240	LEAKAGE INDUCTANCE MHYS	56.817
CORE LOSS	987.255	999.001	POWER FACTOR	1.0000
COIL LOSS	2908.687	.011	IMPEDANCE %	5.23
EXCIT. VA	1328.606	1364.913	EFFICIENCY %	99.23
EXCIT. CURR.	.092	.095	TANK OIL GAL	69.04

AMBIENT TEMP.	20.00	NOMINAL LENGTH	24.96
TEMP.RISE	65.00	NOMINAL DEPTH	21.06
OPERATING TEMP.	85.00	NOMINAL HEIGHT	29.74

AVG. OIL RISE: 50.
TOP OIL RISE: 76.6

TANK DIMENSIONS

LENGTH = 25.963
DEPTH = 22.061
OIL HEIGHT = 41.743

2

```
COND. I R LOSS          =   2662.5920
COND. EDDY CURRENT LOSS =    166.2170
OTHER STRAY LOSS        =     79.8778
K VALUE                 =      1.0000
```

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.13	99.08	.123	1.303	1.309	168.913	39.1
35	.19	99.24	.174	1.821	1.829	335.370	44.1
50	.29	99.32	.258	2.599	2.612	705.026	54.7
65	.41	99.32	.346	3.379	3.396	1226.960	65.0
75	.48	99.30	.399	3.899	3.920	1633.676	65.0
100	.67	99.23	.533	5.203	5.230	2908.687	65.0
125	.89	99.12	.666	6.510	6.544	4553.014	65.0
150	1.12	99.00	.801	7.821	7.862	6569.333	65.0

Following is the breakdown of costs, or the 'bill of materials,' associated with this design, M3 core steel, with an aluminum primary and copper secondary.

Table 5.6.1 Bill of Materials for Example Design from DL3 Database

Bill of Materials and Labor for 1 phase, 500kVA liquid-type round-tank

	A$ Input	$3.00
	B$ Input	$1.00

Material item	Type	Quantity	$ each	$ total
Core Steel* (lb)	M6	1355	$ 0.64	$ 867.04
Primary winding* (lb)	Copper	443	$ 1.30	$ 575.51
Secondary windings* (lb)	Aluminum	119	$ 1.30	$ 155.17
Winding form & insulation* (lb)	Kraft Paper	25	$ 1.54	$ 39.18
Oil (gal)	-	70	$ 1.50	$ 104.94
Tank	round	1	$ 506.35	$ 506.35
Core Clamp	-	1	$ 30.00	$ 30.00
Tap Changer	-	1	$ 15.00	$ 15.00
Bushings	HV & LV	1	$ 60.00	$ 60.00
Misc. Hardware	-	1	$ 20.65	$ 20.65
Handling and Scrap Factor		2.5%		$ 40.92
Total Material Cost				$ 2,414.76

Labor item	hours	rate	$ total
Setup & wind primary	1.42	42.77	$ 60.72
Setup & wind secondary	0.90	42.77	$ 38.29
Banding core metal	0.50	43.77	$ 21.89
Assembly (coils, yoke & clamping)	0.75	42.77	$ 32.08
Lead dressing	0.35	42.77	$ 14.97
Inspection	0.10	42.77	$ 4.28
Preliminary and Final Test	0.25	42.77	$ 10.69
Shipment Packing and Marking	0.55	42.77	$ 23.52
Miscellaneous (incl. VPI)	0.30	42.77	$ 12.83
Total Labor	5.115	42.77	$ 218.76
Manufacturing Cost (Material + Labor)			$ 2,633.52
Factory Overhead (Materials only)	12.5%		$ 301.84
Selling Factor	25.0%		$ 733.84
Manufacturer Selling Price			$ 3,669.21

* indicates those items to which the handling and scrap factor (2.5%) is applied

Figure 5.6.1 provides a summary of the costs contributing to the total selling price of the DL3 representative unit. For this design, approximately 66 percent of the final manufacturer selling price of an M3, aluminum primary and copper secondary, is direct material and scrap. Labor accounts for 6 percent of the price, and overheads account for 28 percent.

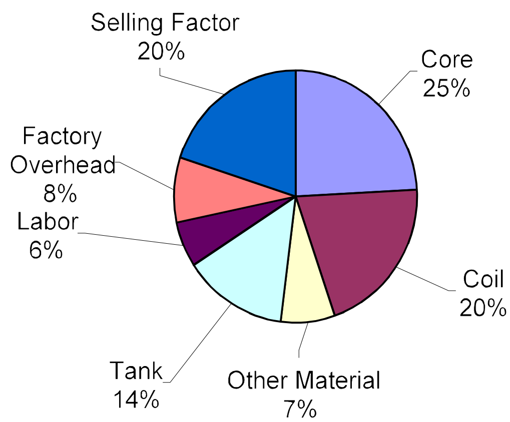


Figure 5.6.1 Cost Breakdown for DL3 M6CuAl Design at $3A, $1B

5.6.2 Results for DL12 Transformer, M3CuCu at $3A and $1B

The following design report provides information on one of several designs prepared to study the representative unit from design line 12. This is a 1500kVA, three-phase, medium-voltage, dry-type unit at 95kV BIL. The design shown here (out of the 1,344 designs in the database) is for M3 core steel with a copper primary and secondary, and a $3.00A and $1.00B.

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                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2002- 8- 9    11:35: 2
STRIP CRUC    3-PHASE TYPE TRANSFORMER                L12M3CUCU
FREQUENCY    60.0            MVA RATING      1.50 @ 100.00% DUTY CYCLE
CORE 10.063" CRUC  STACK 10.063             GRADE M 3    THICKNESS .0090
WINDOW:  15.241 X 47.372     EFF. AREA   76.894    WEIGHT  5591.294
WINDING FORM:INS. DIM. 10.598 X 10.598  THICKNESS  .156  LENGTH 45.372

                         COIL SPECIFICATIONS
                         -------------------

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1     3X 1(.0124X37.3721)   CU      51.62     44.24   4.000    276.774
P1         .1190X  .3225   CU    3850.89      69.86   5.750    557.192

NUMBER OF COILS  3              TOTAL BARE CONDUCTOR WEIGHT  2501.897

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      14.0                 14      1.0  1(.00700)  1(.20000)    3.112
P1     630.0   598.5   661.5 14      1.0  1(.00001)  1(.00001)    1.890

                                                 TOTAL BUILD(%)  90.23

WNDG              TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     614.3( 12158.25)   645.8( 12781.75)   661.5( 13093.50)


                        DISK  INFORMATION
                        -----------------

WNDG   DISK  WIDTH   VOLTS/DISK  BREAK  TAPS   SPACE
-------------------------------------------------------
P1     48    .338      272.781   .375  2(.38) 44( .375)


WNDG    INTERNAL DUCTS( 95.00) %EFF  EXTERNAL DUCTS( 95.00) %EFF
----------------------------------------------------------------
S1      4  .625 X  .625 IN.  FULL
P1                            2    .625 X  .625 IN.  FULL
```

WNDG	INT. DUCT AREA	EXT. DUCT AREA	TOTAL DUCT AREA
S1	9931.7920	1671.3810	11603.1700
P1	.0000	2278.9760	5815.4850

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	12470.00 D	11846.50	13093.50	18.0	40.431	.83551	1077.	
S1	274.72 W			4.0	1804.300	.00030	1297.	.9

	F.L.	N.L.		
FLUX DENS.	14.882	14.971	LEAKAGE INDUCTANCE MHYS	58.391
CORE LOSS	2794.702	2841.611	POWER FACTOR	1.0000
COIL LOSS	10076.760	.039	IMPEDANCE %	7.16
EXCIT. VA	3808.522	3899.871	EFFICIENCY %	99.15
EXCIT. CURR.	.102	.104	OPEN ALT. DUCT 3	.00

AMBIENT TEMP.	20.00	NOMINAL LENGTH	75.91
TEMP.RISE	76.58	NOMINAL DEPTH	24.32
OPERATING TEMP.	96.58	NOMINAL HEIGHT	67.50

WINDING:	S1	P1
TEMP RISE:	77.	63.

COND. I^2R LOSS = 8916.1750
COND. EDDY CURRENT LOSS = 803.9380
OTHER STRAY LOSS = 356.6469
K VALUE = 1.0000

WNDG	WIRE WRAP PER COIL THICKNESS	WEIGHT
P1	.00800	9.64374

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.15	99.10	.128	1.786	1.790	554.804	30.5
35	.21	99.26	.181	2.496	2.502	1096.539	33.9
50	.33	99.32	.264	3.563	3.573	2281.396	40.9
65	.47	99.31	.354	4.632	4.646	3953.208	49.7
75	.57	99.28	.418	5.346	5.363	5365.097	56.5
100	.86	99.15	.594	7.137	7.162	10076.760	76.6
125	1.21	98.97	.797	8.937	8.973	16764.860	100.6
150	1.64	98.74	1.033	10.748	10.798	25853.470	128.2

Table 5.6.2 provides a breakdown of costs, or the "bill of materials," associated with this design, 1500kVA three-phase medium-voltage (95kV BIL) dry-type with M3 core steel and copper primary and secondary windings. The evaluation factors for this design are $3.00 A and $1.00 B.

Table 5.6.2 Bill of Materials for Example Design from DL12 Database

Bill of Materials and Labor for 3 phase, 1500kVA dry-type, 95kV BIL				
	A$ Input	$3.00		
	B$ Input	$1.00		
Material item	**Type**	**Quantity**	**$ each**	**$ total**
Winding Form* (lb)	Nomex	29.71	$ 17.50	$ 519.84
Core Steel* (lb)	M3	5591	$ 0.95	$ 5,311.73
Primary winding* (lb)	Copper - Wire	1672	$ 1.60	$ 2,674.52
Secondary winding* (lb)	Copper - Strip	830	$ 2.40	$ 1,992.77
Winding Insulation* (lb)	Nomex	71	$ 17.50	$ 1,245.05
Winding Comb* (lb)		91	$ 10.00	$ 908.77
Duct Spacer* (ft)	Dog-bone	1553	$ 0.56	$ 869.73
Enclosure	14 gauge	1	$ 600.00	$ 600.00
Mounting Frame	-	1	$ 125.00	$ 125.00
Buss-bar (ft)	-	14	$ 12.00	$ 168.00
Start & finish terminals	HV & LV	15	$ 8.00	$ 120.00
Varnish impregnation (gal)		27	$ 18.00	$ 485.43
Misc. Hardware	-	1	$ 42.00	$ 42.00
Handling and Scrap Factor		2.5%		$ 338.06
Total Material Cost				$ 15,400.90
Labor item		**hours**	**rate**	**$ total**
Setup & wind primary (3 phase)		4.96	42.77	$ 212.19
Setup & wind secondary (3 phase)		2.85	42.77	$ 122.05
Stacking core metal		8.05	42.77	$ 344.32
Assembly (coils, yoke & clamping)		6.00	42.77	$ 256.62
Lead dressing (3 phase)		1.00	42.77	$ 42.77
Inspection		0.25	42.77	$ 10.69
Preliminary and Final Test		1.25	42.77	$ 53.46
Shipment Packing and Marking		2.20	42.77	$ 94.09
Miscellaneous (incl. VPI)		2.00	42.77	$ 85.54
Total Labor		28.565	42.77	$ 1,221.74
Manufacturing Cost (Material + Labor)				$ 16,622.64
Factory Overhead (Materials only)		12.5%		$ 1,925.11
Selling Factor		25.0%		$ 4,636.94
Manufacturer Selling Price				$ 23,184.69

* indicates those items to which the handling and scrap factor (2.5%) is applied

Figure 5.6.2 provides a summary of the costs contributing to the total selling price of the transformer detailed above. Approximately 67 percent of the final selling price is material-based: core, coil, insulation, and other materials. Labor accounts for approximately 5 percent of the price, and overheads account for about 28 percent.

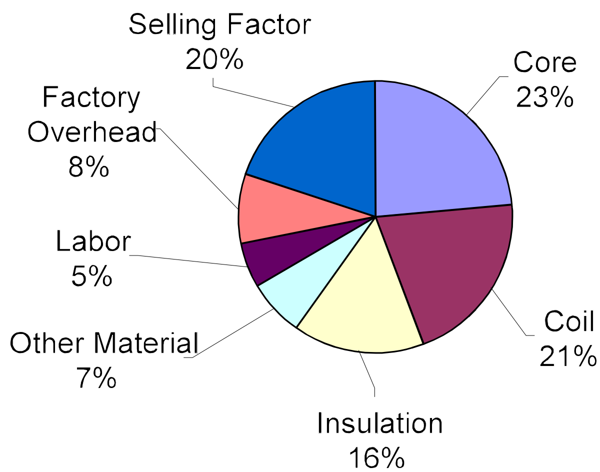

Figure 5.6.2 Cost Breakdown for DL12, M3CuCu Design at \$3A, \$1B.