Distribution Transformer Rulemaking

Engineering Analysis Update

(Draft for review only)

Report to
U.S. Department of Energy
Office of Building Technology, State, and Community Programs

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Table of Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

ADL	Arthur D. Little, Inc.
ANN	Air cooled, natural circulation
ANOPR	Advance Notice of Proposed Rulemaking
ANSI	American National Standards Institute
BIL	Basic lightning Impulse insulation Levels
CSA	Canadian Standards Association
DOE	United States Department of Energy
HO	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
NOPR	Notice of Proposed Rulemaking
ONAN	Oil filled, Natural convention cooling
OPS	Optimized Program Service
ORNL	Oak Ridge National Laboratory
SA1	Amorphous metal core material
SEC	Securities and Exchange Commission
US	United States
Y	Wye-type transformer terminal connection
Φ	Phase

Acknowledgments

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1. Setting the Context

On November 1st, 2000 the US Department of Energy held a public meeting in Washington DC where it circulated and discussed its Framework Document for Distribution Transformer Energy Conservation Standards Rulemaking. An electronic copy of this report is available on the Department's web site at http://www.eren.doe.gov/buildings/codes_standards/applbrf/dist_transformer.html

The Framework Document describes the procedural and analytical approaches the Department is using as it considers energy conservation standards for distribution transformers. The formal rulemaking process for developing energy conservation standards includes three Federal Register notices: the Advanced Notice of Proposed Rulemaking (ANOPR), the Notice of Proposed Rulemaking (NOPR) and the Notice of Final Rulemaking. At the publication of this interim report, the Department is in what is commonly called the "pre-ANOPR" stage, meaning the Department is presently conducting the analysis that will be published for the ANOPR meeting next year.

One of the key points highlighted in the Framework Document is the importance of stakeholder review and feedback in the rulemaking process. In the spirit of consultation, the Department elected to circulate this progress report on the Engineering Analysis.

This structure of this report is as follows:

- Chapter 2 discusses the methodology and structure of the Engineering Analysis;
- Chapter 3 discusses the software modeling process, including input values and assumptions;
- Chapter 4 presents the results from the software analysis on a 50kVA unit;
- Chapter 5 presents the design option combinations for the other liquid type units;
- Appendix A provides information on the 0.75 Scaling Law (Ben McConnell, ORNL); and
- Appendix B provides further information about OPS Inc. and the software used for this analysis.

The Department recognizes that the results in this report are not the definitive answer to the question of the relationship between cost and efficiency. These results assume an ideal situation, where manufacturers do not incur any retooling or special handling costs associated with changing materials or core/coil dimensions. An answer to this part of the question will be gathered directly through interviews with manufacturers.

The Department will be requesting meetings with manufacturers in the coming months to provide an opportunity to discuss the analytical methods, assumptions, and preliminary results presented in this report, as well as gather information about retooling and other special handling costs associated with more efficient designs. The Department is also interested in receiving written comments from all concerned parties about this analysis, to be entered into the docket. Please have these comments submitted by 4pm on January 4, 2002 to:

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2. Structuring the Engineering Analysis

The following is an excerpt from the Department of Energy's aforementioned Framework Document. These paragraphs discuss the fundamental purpose of the Engineering Analysis, i.e., to elucidate the cost-efficiency relationship for distribution transformers.

> *3.4 ENGINEERING ANALYSIS*
>
> *After the screening analysis, the Department performs an engineering analysis on the options or efficiency levels that were not eliminated. The purpose of the engineering analysis is to estimate the relationship between transformer cost and energy efficiency levels, referred to as a cost-efficiency schedule.*
>
> *In consultation with outside experts, the Department selects the specific engineering analysis tools to be used in the evaluation. There are three general approaches for developing cost-efficiency schedules: the "efficiency level approach," the "design option approach," and the "cost assessment approach" (see Sect. 4.4). The critical inputs to the engineering analysis are data from manufacturers and/or experts in designing and costing transformers. This includes the cost-efficiency information available through retail prices of transformers and their existing efficiencies. However, information is also required to estimate, for some products, cost-efficiency tradeoffs that may not be available from current market information. This type of information may be developed by manufacturers, from simulation models and/or by design experts.*
>
> *The cost-efficiency schedules for each product class from the engineering analysis are used in evaluations of life-cycle cost and the calculation of simple payback periods.*

The Department of Energy (the Department) considered three possible methods of conducting the engineering analysis, and decided on an approach that is a modified (and more transparent) efficiency level analysis. The Department has contracted an independent third-party which owns and operates a software product developed specifically for designing distribution transformers. The software is used to conduct literally thousands of design runs in order to explore the cost-efficiency relationship for the units being studied. These results are then circulated for public review and comment, and this report presents the results of the first analysis conducted.

This chapter starts by discussing how the engineering analysis was structured and simplified. It then discusses all the units that will be analyzed. And finally, the chapter closes with a discussion and information about the software product being used to create the design database.

2.1 Simplifying the number of units to Analyze

The National Electrical Manufacturers Association (NEMA) created 73 product classes (kVA ratings) in its TP-1 document, spanning the range of liquid and dry-type distribution transformers. The Department recognizes that it would be impractical to conduct a detailed analysis on the cost-efficiency relationship for each of these seventy-three units, and therefore it sought to create reasonable groupings of similar product classes. The Department solicited assistance from experts with transformer design experience, and developed a simplified, technically robust approach.

The consensus of expert opinion indicates that while holding constant the type (liquid or dry), the number of phases and the insulation (BIL) levels, certain kVA ratings could be grouped together as they shared similar design principles. The following two tables provide a breakdown of the standard BIL levels associated with typical distribution transformer primary voltages.

Table 1. Liquid-type: Primary voltages and corresponding BIL levels

Primary voltages	Voltage BIL (grounded - ungrounded)
35kV	150 - 200 kV BIL
25 kV	125 - 150 kV BIL
18 kV	125 kV BIL
15 kV	95 kV BIL
5 kV	60 kV BIL
480 V	30 kV BIL

Source: CSA C2-2001; ANSI C57.12.00-1993

Table 2. Dry-type: Primary voltages and corresponding BIL levels

Primary	Voltage BIL
35kV	150 kV BIL
25 kV	110-125 kV BIL
18 kV	95 kV BIL
15 kV	60 kV BIL
8.7 kV	45 kV BIL
5.0 kV	30 kV BIL
2.5 kV	20 kV BIL
1.2 kV	10 kV BIL

Source: CSA C9-2001; ANSI C57.12.01-1989

The groupings of kVA ratings that were developed by the DOE team are based on known similarities in engineering design and construction principles. For the purposes of this analysis, the Department has called these groupings "design lines". There were thirteen design lines that were created which represent the 73 product classes listed in TP-1. The table below presents the thirteen design lines and indicates the range of kVA ratings covered in each. Following the table, the rationale used to arrive at these thirteen design lines is discussed.

Table 3. Design Lines for simplifying the analysis

Design Line	Type	# of Phases	kVA Range	Primary BIL (kV)	Primary Taps, Full Capacity	Secondary Voltage
1	Liquid - Pad	1	25-167	≤95	±2-2.5%	240/120 through 600V
2	Liquid - Pole	1	10-167	≤95	±2-2.5%	120/240 through 600V
3	Liquid - Pad	1	25-167	125-150	±2-2.5%	240/120 through 600V
4	Liquid - Pole	1	10-167	125-150	±2-2.5%	120/240 through 600V
5	Liquid	1	250-833	≤95-150	±2-2.5%	250-333 kVA: 120/240 through 2400/4160YV 500-833 kVA: 277/480Y through 2400/4160YV
6	Liquid	3	10-225	≤95	±2-2.5%	208Y/120-600V
7	Liquid	3	300-2500	≤95-150	±2-2.5%	300-1000 kVA: 208Y/120 through 4160Y/2400V 1500-2500 kVA: 480Y/277 through 4160Y/2400V
8	Dry	1	15-333	10	No Taps	120/240V
9	Dry	1	15-833	20-60	±2-2.5%	15-333 kVA: 120/240V through 600V 500-833 kVA: 480 through 2400V
10	Dry	1	15-833	95-150	±2-2.5%	15-333 kVA: 120/240V through 600V 500-833 kVA: 480 through 2400V
11	Dry	3	15-1000	10	No Taps	208Y/120V
12	Dry	3	15-2500	20-60	±2-2.5%	45-1000 kVA: 208Y/120 through 600V 1500-2500kVA: 480Y/277 through 4160Y/2400V
13	Dry	3	15-2500	95-150	±2-2.5%	45-1000 kVA: 208Y/120 through 600V 1500-2500kVA: 480Y/277 through 4160Y/2400V

2.2 Rationale for selection of the Thirteen Design Lines

All transformers described above are for step-down applications. Therefore, the term "primary" refers to the high voltage winding, and "secondary" refers to the low voltage winding.

Design Lines 1 through 4
These lines represent the lower kVA ratings for liquid-type units, which are typically higher-volume production distribution transformers. These four design lines are distinguished from each other by whether the unit is being built for a pole or pad-mounted application, and by the BIL level.

Secondary voltage is set at a maximum of 600V in order to reject 2400V or higher, which in comparison with 600V has a significant impact on the sizes of windings and consequently the core window. Also the usage of such a secondary voltage in these design lines is minimal.

The dominant impulse range in the U.S. is ≤95 kV, whereas 125 kV tends to dominate in Canada. Because production volumes are high for both 95 kV and 125 kV, parallel product classes were created for 125 kV through 150 kV (Design Lines 3 and 4).

Standard primary taps are included in the table, even though many transformers in these classes will be without taps. Because a transformer with no taps will generally have approximately 5% less core/coil material than a transformer with standard taps, it is easier to include the no-taps design in a regulation developed around designs including taps than the other way around.

Impedance is influenced by the loss evaluation formula, particularly the load-loss coefficient or "B" value. Impedance tends to vary inversely with B. It is therefore appropriate to impose a minimum value of 1.5% impedance for ratings of 50 kVA; otherwise the transformer may not withstand short circuit forces resulting from a load-side fault. Generally, the impedance for these design lines is in the area of 2.0%-2.5%, but can be around 4% if the core/coil configuration is the "core type", that is one core loop and two coil assemblies. Core type cores tend to be found more often in pole-mounted rather than pad-mounted units.

Design Line 5

Larger core/coil assemblies and lower volume often cause manufacturing to be done in an area separate from that for Design Lines 1 through 4, where size and weight dictate different handling methods such as hoists instead of roller-conveyers.

BIL and graded insulation are not heavily influential in the design of the core/coil assembly as is the case in Design Lines 1 through 4. The 150 kV BIL has been selected to provide a convenient umbrella for the various primary voltages and BIL levels which can be included in the class represented by Design Line 5.

Minimum secondary voltage becomes an important control factor, without which the sizes of secondary leads and secondary bushings become large and costly. Also the stray load loss attributable to the secondary leads and bushings becomes inordinately high. The 2400V secondary voltage is shown as the top of the range because in Design Line 5 the larger kVA sizes accommodate this voltage level quite readily.

Impedance is generally an open consideration except for those transformers that have a secondary voltage of 2400/4160YV, in which case a minimum of 4% is commonly specified. Dual voltage is less common in this design line because massive upgrades of voltage levels within electric utilities usually do not affect ratings 250 kVA and above.

Design Lines 6 and 7

In Design Line 7, the BIL was set at 150 kV, judging that it would encompass a broad range of primary voltages appropriate for the 300-2500 kVA range, and that 200 kV is relatively rare for distribution transformers.

On the smaller ratings of Design Line 6, the secondary voltage range does not include 4160Y/2400V because of its impact on the design, causing the core/coils to be increased in size. An efficiency discounting factor is recommended for applications which require this voltage.

Impedance for transformers 750-2500 kVA should be set at 5.75% recognizing the ANSI pad-mounted and underground standards. As with Design Line 5, dual voltage is less common because massive upgrades of voltage levels within electric utilities usually do not affect ratings which fall into the classes represented by Design Lines 6 and 7.

<u>Design Lines 8-13</u>
The single phase kVA ranges were taken from NEMA TP-1. No taps were considered the appropriate choice for Design Lines 8 and 11 because of the infrequent need for changing taps at the low primary voltage. Also it is difficult to obtain adjustments such as 2.5%.

The secondary voltages for Design Lines 8 and 11 are listed as 120/240 and 208Y/120 respectively, resulting from the low primary voltage. However, 1:1 transformers could, in less frequent applications for the single phase transformer of Design Line 8, cause the secondary to be 480V or 600V.

The secondary voltages for Design Lines 9, 10, 12, and 13 are expressed in two groups by kVA range because there would be too low a voltage for a larger kVA size such as the 500 kVA single phase in Design Lines 9 and 10. The combination of 500 kVA with a secondary of 120/240V would cause a very high secondary current and a consequent high stray loss as explained for Design Line 5. And thus, a means of including 2400V for the larger kVA sizes is provided in the second group.

2.3 Selecting the representative unit

For each of the thirteen design lines created, one representative transformer was selected for analysis. This representative unit would be studied in detail to understand the cost-efficiency relationship for that particular model. This relationship would then be extrapolated to the other units within the same design line using the 0.75 scaling rule (see Appendix A). The scaling rule can be used to estimate manufacturing costs, and no-load and load losses. The Department was able to demonstrate the effectiveness of the 0.75 scaling rule by using it to extrapolate NEMA's TP-1 standard levels. The rationale for the selection of the representative models from the design lines follows Table 4.

Table 4. Summary table of the Design Lines and Representative Models for the analysis.

Design Line	Type	# of Phases	KVA Range	Primary BIL	Primary Taps, Full Capacity	Secondary Voltage	Selected unit to represent Design Line	Typical Owners and Applications
1	Liquid Pad	1	25-167	≤95 kV	±2-2.5%	240/120 through 600V	50kVA, 65°C, ONAN, 1Φ, 60Hz, 12470GrdY/7200 -240/120V, 95 kV BIL	Mainly Utility Owned or Influenced[1]; Residential and Small Commercial
2	Liquid Pole	1	10-167	≤95 kV	±2-2.5%	120/240 through 600V	25kVA, 65°C, ONAN, 1Φ, 60Hz, 12470GrdY/7200 -240/120V, 95 kV BIL	Mainly Utility Owned or Influenced; Residential and Small Commercial
3	Liquid Pad	1	25-167	125-150 kV	±2-2.5%	240/120 through 600V	50kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 -240/120V, 125 kV BIL	Mainly Utility Owned or Influenced; Residential and Small Commercial
4	Liquid Pole	1	10-167	125-150 kV	±2-2.5%	120/240 through 600V	25kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 -240/120V, 125 kV BIL	Mainly Utility Owned or Influenced; Residential and Small Commercial
5	Liquid	1	250-833	≤95-150 kV	±2-2.5%	250-333 kVA: 120/240 through 2400/4160YV; 500-833 kVA: 277/480Y through 2400/4160YV	333kVA, 65°C, ONAN, 1Φ, 60Hz, 14400/24940Y – 277/480YV, 150 kV BIL	Mainly Utility Owned or Influenced; Med and large C&I. Single phase overhead and industrial purposes, perhaps in a bank of 3.
6	Liquid	3	30-225	≤95 kV	±2-2.5%	208Y/120-600V	150kVA, 65°C, ONAN, 3Φ, 60Hz, 12470Y/7200-208Y/120V, 95 kV BIL	Mainly Utility Owned or Influenced; Residential apartments and small commercial buildings
7	Liquid	3	300-2500	≤95-150 kV	±2-2.5%	300-1000 kVA: 208Y/120 through 4160Y/2400V 1500-2500 kVA: 480Y/277 through 4160Y/2400V	1000kVA, 65°C, ONAN, 3Φ, 60Hz, 24940Δ-480Y/277V, 150 kV BIL	Electric Utility, Industrial or Commercial; Substations and Industrial applications, commercial buildings
8	Dry	1	15-333	10 kV	No Taps	120/240V	25kVA, 150°C, ANN, 1Φ, 60Hz, 480-120/240V, 10 kV BIL	Commercial or Industrial Facilities; C&I and multi-family residential, lighting, etc.
9	Dry	1	15-833	20-60 kV	±2-2.5%	15-333 kVA: 120/240V through 600V 500-833 kVA: 480 through 2400V	75kVA, 150°C, ANN, 1Φ, 60Hz, 2400-480V, 20 kV BIL	Comm. / Building Owners, Industrial Facilities; C&I and multi-family residential, lighting, etc.
10	Dry	1	15-833	95-150 kV	±2-2.5%	15-333 kVA: 120/240V through 600V 500-833 kVA: 480 through 2400V	500kVA, 150°C, ANN, 1Φ, 60Hz, 12470-480V, 95 kV BIL	Comm. / Building Owners, Industrial Facilities; C&I and multi-family residential, lighting, etc.

[1] Utility draws up the transformer specification for the owner.

11	Dry	3	45-1000	10 kV	No Taps	208Y/120V	75kVA, 150°C, ANN, 3Φ, 60Hz, 480-208Y120V, 10 kV BIL	Comm. / Building Owners, Industrial Facilities; C&I and multi-family residential, lighting, etc.
12	Dry	3	45-2500	20-60 kV	±2-2.5%	45-1000 kVA: 208Y/120 through 600V 1500-2500kVA: 480Y/277 through 4160Y/2400V	300kVA, 150°C, ANN, 3Φ, 60Hz, 4160-480Y/277V, 30 kV BIL	Comm. / Building Owners, Industrial Facilities; C&I and multi-family residential and industrial substations
13	Dry	3	45-2500	95-150 kV	±2-2.5%	45-1000 kVA: 208Y/120 through 600V 1500-2500kVA: 480Y/277 through 4160Y/2400V	2000kVA, 150°C, ANN, 3Φ, 60Hz, 12470-480Y/277V, 95 kV BIL	Comm. / Building Owners, Industrial Facilities; C&I and multi-family residential and industrial substations

Representative Units for Design Line 1 and 2
After considering a common grouping for pad-mounted and pole-mounted transformers, discussions with manufacturers revealed that many of the manufacturers employed different core-coil designs for the two applications. The shorter height of coil in the shell-type design seemed to be the choice for the pad-mounted transformers whereas, for pole-mounted ratings (25 kVA), the taller coils of a core-type design tended to be the choice. Consequently Design Line 1 was selected for pad-mounted transformers with 50 kVA as the representative rating, and Design Line 2 was selected for pole-mounted transformers with 25 kVA as the representative rating, matching NEMA's recommendation. The 240/120 V secondary in Line 1 reflects the pad-mounted application.

Note the ONAN designation, which is the new international designation for an oil-filled transformer with natural cooling. Reference to this change was made at the 2000 IEEE Transformer Committee meeting in Niagara Falls as addressed by the Working Group for Continuous Revisions to (ANSI) C57.12.00.

Representative Units for Design Lines 3 and 4
The above remarks apply, the only change for the selected units of these design lines being the higher primary voltage (corresponding to a 150kV BIL).

Representative Unit for Design Line 5
This single phase transformer will usually be part of a three phase bank, of which 1000 kVA is a prominent rating. Therefore 333 kVA becomes an appropriate choice for the single phase transformer.

Representative Units for Design Lines 6 and 7
These lines embrace overhead platform-mounted, pad-mounted, and distribution substation transformers. Recognizing the existence of the smaller overhead type combined with the pad-mounted type of design line 6, 150 kVA appears to be a logical choice for the representative transformer. Having made that choice, 1000 kVA then becomes a logical choice for the representative transformer of design line 7.

Representative Units for Design Line 8
For a primary voltage of 480V, 25 kVA is considered to be a common kVA rating, if not the most active, for small loads in commercial and industrial applications. For the dry-type units, the cooling method is changed to ANN.

Representative Units for Design Lines 9 and 10
Both of these lines represent relatively low volume activity where access for installation and maintenance of a three phase transformer could be awkward, (such as in a hospital or a tower structure), thereby causing a three phase bank of three single phase transformers to be used.

Representative Unit for Design Line 11
For a low primary voltage of 480V, the more commonly sold transformers will tend to be at the low end of the kVA range. NEMA had suggested that 75 kVA be considered as the unit of analysis, and that recommendation was accepted.

Representative Units for Design Lines 12 and 13
Relating the kVA values to the level of primary voltage, similarly as with the single phase ratings, the selections were 300 and 2000 kVA respectively.

2.4 Software Modeling

In order to understand what design modifications could lead to improvements in efficiency at what cost, a software product for designing distribution transformers was used. The Department selected software developed by Optimized Program Service (OPS) to create a database of different designs. Summary information about OPS and their software products can be found in Appendix B.

Given a range of inputs, the software provides an optimized, practical design for distribution transformers. The software output - a design specification report - includes information about the core and coil design that would enable a manufacturer to build this unit in their facility. The design report includes information about the core dimensions, high voltage and low voltage windings, insulation, cooling ducts, labor and other critical inputs necessary to build the unit. The software generates an estimated cost to manufacturer, which can then be converted to a manufacturer sales price assuming a certain mark-up.

The software also provides a comprehensive electrical analysis of the unit at part, full and over-load points. The electrical analysis includes the anticipated efficiency of the unit. With the bill of materials, the mark-up and the efficiency, a better understanding of relationship between cost and efficiency is realized. However, as stated in section 1, this approach does not capture retooling costs associated with changing production designs. Therefore, the preliminary results shown in section 4 underestimate manufacturer costs where retooling would be necessary. The Department intends to gather information about retooling costs when it starts its meetings with manufacturers, and include these in future analyses.

In order to create a database that incorporates transformer designs covering a broad spectrum of efficiencies, the Department decided to use an approach involving loss evaluation variables. Because the OPS software is structured to help manufacturers create designs to meet their client needs, it has a facility to specify the customer's valuation of no-load (A-value) and load (B-value) losses. These two terms - the A and B values - are expressed in dollars per watt, and essentially represent the present value of all the future core (A) and coil (B) losses that the transformer will experience in its lifetime. The Department developed a matrix of A and B values - which span A values from $0 to $8 and B values from $0 to $3. The A and B values were changed in increments as follows:

A ranging from $0 to $8 by 0.2 increments
B ranging from $0 to $3 by 0.1 increments

Because B is never greater than A, the complete matrix included 1031 combinations of A and B. These combinations were then used as inputs to the OPS software to create 1031 slightly different optimized designs, built to the matrix of A and B combinations. This range of designs is then used to study the cost/efficiency relationship for the representative unit being studied.

3. Set-up for the first Design Line

This chapter provides background information on the inputs used to set up the run for the first unit analyzed - the 50kVA single phase liquid-type pad mounted transformer. Specifically, this chapter discusses the typical construction methods used by industry to build a unit with this kVA rating, and some of the economics and price inputs used to do the runs on the evaluated unit.

3.1 Typical construction methods

The Department understands that there are several ways to build a transformer, even at the same kVA rating. For instance, manufacturers may vary selection of core steels (e.g., M2, M3, M4, M6), winding materials (aluminum or copper) and core configurations (shell or core-type) when building a given rating. For the unit evaluated in this report, twelve construction combinations were selected based on input from the DOE team of experts and consultation with manufacturers. The core/coil design type (shell vs. core-type) selected was shell-type because the application is for a pad-mount, and core-types will generally not be used for this installation. With the exception of the max tech / high efficiency designs[2], these design option combinations were selected to represent the most common construction practice for this representative unit.

During the manufacturer interview, the Department will solicit additional manufacturer input on typical construction practices for different efficiency levels. For example, the Department is interested in understanding which design option combinations are commonly used and the tooling costs and other implications of implanting more efficient designs.

Table 5 and the following criteria provide information concerning the 50 kVA single phase liquid type design option combination.[3] These are input assumptions used by the software to produce valid and relevant distribution transformer designs.

KVA: 50 (liquid type, pad mount)
Primary: 7200 Volts at 60 Hz
Secondary: 240/120V
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi-Lo
Core: Distributed Gap
Taps: Four 2½ % , 2 above and 2 below normal
Impedance Range: 1.5 - 3.5%

[2] As part of the analysis, the Department is charged with evaluating the "max tech", or the feasible technology that can achieve maximum efficiency, irrespective of cost. For this design line, the amorphous core metal with copper primary and secondary windings was selected as the max tech design option combination.
[3] This unit is the representative model for design line 1, and constitutes the unit analyzed and presented in this report.

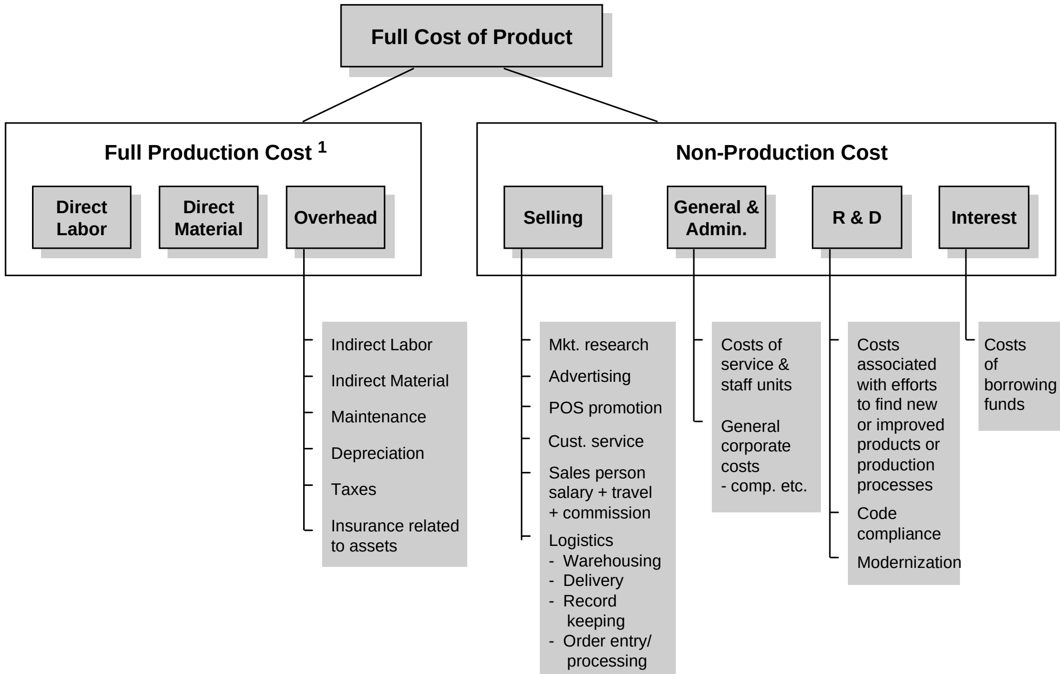
Table 5. Design Option Combinations for the 50kVA single phase liquid-type pad mount

50 kVA Design Option	Core Metal	Conductor High Voltage Metal	Conductor Low Voltage Metal	Core/Coil Design Type
1	HO (Laser Scribed)	Cu	Cu	Shell
2	M2	Al	Al	Shell
3	M2	Cu	Al	Shell
4	M2	Cu	Cu	Shell
5	M3	Al	Al	Shell
6	M3	Al	Cu	Shell
7	M3	Cu	Al	Shell
8	M3	Cu	Cu	Shell
9	M4	Cu	Al	Shell
10	M6	Al	Al	Shell
11	M6	Cu	Al	Shell
12	SA1 (Amorphous)	Cu	Cu	Shell

Each of the twelve design option combinations was run through the OPS software using the matrix of A and B values to create 1031 different designs. These designs, which include data about the manufacturing cost and performance of the units, are then used to study the cost-efficiency relationship for the engineering analysis. Thus, for the first design line, the engineering analysis is based on over twelve thousand transformer designs.

3.2 Inputs on materials and labor

The Department of Energy uses a standard method of cost accounting to determine the costs associated with manufacturing. This methodology is illustrated in Figure 1, where production costs and non-production costs are combined to determine the full cost of a product.



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

Figure 1. Standard method of cost accounting for DOE Rulemaking

Estimates of the costs listed in Figure 1 were derived from the US Industry Census Data reports for 1992 and 1997, SEC 10-K reports for Acme, Powell, Magnetek and Hammond, and industry representatives. Note that this method of analysis does not include the profit margin associated with the product, which is generally a mark-up applied to the full cost of product.

In consultation with OPS and manufacturers about the input costs of materials, the Department was informed that when the optimizer program is running, inputs should reflect the final marked-up sales price, not just the direct material cost of the materials or labor to the manufacturer. This means for example, that instead of having the input for M2 core steel be $1.15 per pound, it should be entered as $2.04 - a value that reflects the scrap and handling factor, factory overhead and non-production mark-up.

Table 6. Input materials to OPS software for the 50 kVA single phase liquid-type pad-mount

Type	Item	Description	Units	Direct Material		Factory Overhead[4]	Non-production Mark-up[5]	$ Input to OPS
				$ Cost[6]	Handling and Scrap[7]			
Variable Costs (change with design modifications)	Core Steel	M2 steel	lb	1.15	1.1	1.125	1.43	2.04
	Core Steel	M3 steel	lb	1.05	1.1	1.125	1.43	1.86
	Core Steel	M4 steel	lb	0.95	1.1	1.125	1.43	1.68
	Core Steel	M6 steel	lb	0.90	1.1	1.125	1.43	1.59
	Core Steel	HO (Laser-scribed M3 steel)	lb	1.15	1.1	1.125	1.43	2.04
	Core Steel	SA1 (Amorphous Metal)	lb	1.50	1.2	1.125	1.43	2.65
	Copper Wire	Enameled, semi-cured epoxy, round Sizes 10 to 12	lb	1.90	1.1	1.125	1.43	3.36
	Copper Wire	Enameled, semi-cured epoxy, round Sizes 13 to 15	lb	1.90	1.1	1.125	1.43	3.36
	Aluminum Wire		lb	2.25	1.1	1.125	1.43	3.98
	Copper Strip	Thickness Range .02 to .045	lb	2.40	1.1	1.125	1.43	4.25
	Aluminum Strip	Thickness Range .02 to .045	lb	1.30	1.1	1.125	1.43	2.30
	Kraft Paper	Thermally Up-Graded w/Diamond Adhesive	lb	1.54	1.1	1.125	1.43	2.73
	Oil	Mineral Oil	gal	1.50	1.1	1.125	1.43	2.65
Fixed Costs (constant across designs)	Lead Sleeving	Crepe Paper	ft	0.20	Quantity of these materials will not vary by design, thus there is no input to OPS software. However, we will be using these material costs to determine the full production cost when the optimized designs are created.			
	H.V. Bushing	Two universal bushing wells, 15 KV, 95 BIL, 7200V	ea.	7.00				
	L.V. Bushing	Three copper studs, 120/240V, 50 KVA	ea.	8.00				
	Fuse System	Bayonet fuse holder, fuse and isolation link	ea.	35.00				
	Core Clamp	For Shell-Type design (only considered design)	ea.	9.25				
	Internal Hardware		ea.	5.00				
	Tap Changer	Package of 40	ea.	20.00				
	Nameplate	Package of 24	ea.	13.25				
	Finished Tank	24 high x 34 wide x 35 deep (19" tank and 16" door)	ea.	250.00				

[4] Factory overhead includes all indirect costs associated with production, energy use, lightbulbs, 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.
[5] Material mark-up reflects non-production costs including sales and general administrative, R&D, interest payments and profit factor mark-ups. Source: US Industry Census Data for 1992 and 1997; SEC 10-K reports for Acme, Powell, Magnetek and Hammond.
[6] Purchasing price to manufacturers from suppliers of raw materials necessary for building a transformer. Note that unit costs of Core Steel include a 0.20 per pound conversion adder, which reflects the cost of assembling the steel into a finished core. Source: ADL, 2001.
[7] Handling and scrap is a multiplier factor for the handling of material (loading into assembly and winding equipment). Source: Paul Goethe, OPS.

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The prices of core steel used were obtained by OPS from a US steel manufacturer, given a standard quantity order.

A simplifying assumption was made concerning the tank, in that one size was used for all designs generated. The tank is large, and easily accommodates all the designs in the database. With the assumption of 21 inches of oil in the tank (3 inch air gap for expansion), typical core/coil combinations will have approximately 50 gallons of oil in the tank. In making this simplifying assumption, the cost estimate is catering to the lowest common denominator – a manufacturer who doesn't have several standard sizes available.

The hourly cost of labor to manufacturers was developed in a similar fashion, however mark-ups on labor are slightly different than mark-ups on material, thus they are shown in a separate table. These figures were developed after consulting with industry experts familiar with typical manufacturing facilities in the United States. As with the materials, the labor mark-ups had to be determined before the OPS software runs, because optimization programs require the final, mark-up price of labor as an input to the model. Table 7 presents the mark-ups followed in determining the input to OPS.

Table 7. Developing the labor cost input

Item description	Percent change	Hourly rate ($)
Labor cost per hour[8]		14.31
Indirect Production[9]	33%	19.03
Overhead[10]	30%	24.74
Fringe[11]	21%	29.93
Assembly Labor Up-time[12]	70%	42.77
Profit Factor	43%	61.16
Cost of Labor Input to OPS		61.16

Since the software generates a detailed bill of materials, retail prices can be generated after the design optimization is complete, using different mark-up assumptions. The Department will solicit additional input to the assumptions in Table 4 and Table 5 during the manufacturer interviews.

[8] 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.

[9] Indirect Production Labor (Production managers, quality control, etc.) as a percent of direct labor on a cost basis. ADL estimate.

[10] Overhead includes commissions, dismissal pay, bonuses, vacation, and sick leave, social security contributions. ADL estimate.

[11] 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).

[12] Assembly labor up-time - reflects number of hours workers are actively assembling product and/or reworking unsatisfactory units. ADL estimate. (Note: to calculate mark-up, multiply amount by the ratio of 100/70).

4. Results of Analysis on 50 kVA

4.1 Results for each of the 12 Design Option Combinations

This section of the report provides summary information on the database of designs developed for the Engineering Analysis, studying the relationship between price and efficiency. For each of the twelve design option combinations evaluated for a 50 kVA unit, scatter plots of the designs are provided showing the distribution of prices and efficiencies in the database. This chapter also provides a design specification, an electrical analysis report and a bill of materials for one model from each of the twelve design option combination databases. The unit selected from each of the databases is the optimized design for an A value of $3 and a B value of $1.

4.1.1 Results for HOCuCu

Figure 2 provides a scatter plot of cost and efficiency relationship for the 1031 designs[13] of laser-scribed M3 core steel with a copper primary and secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for nearly all of the designs in the database.

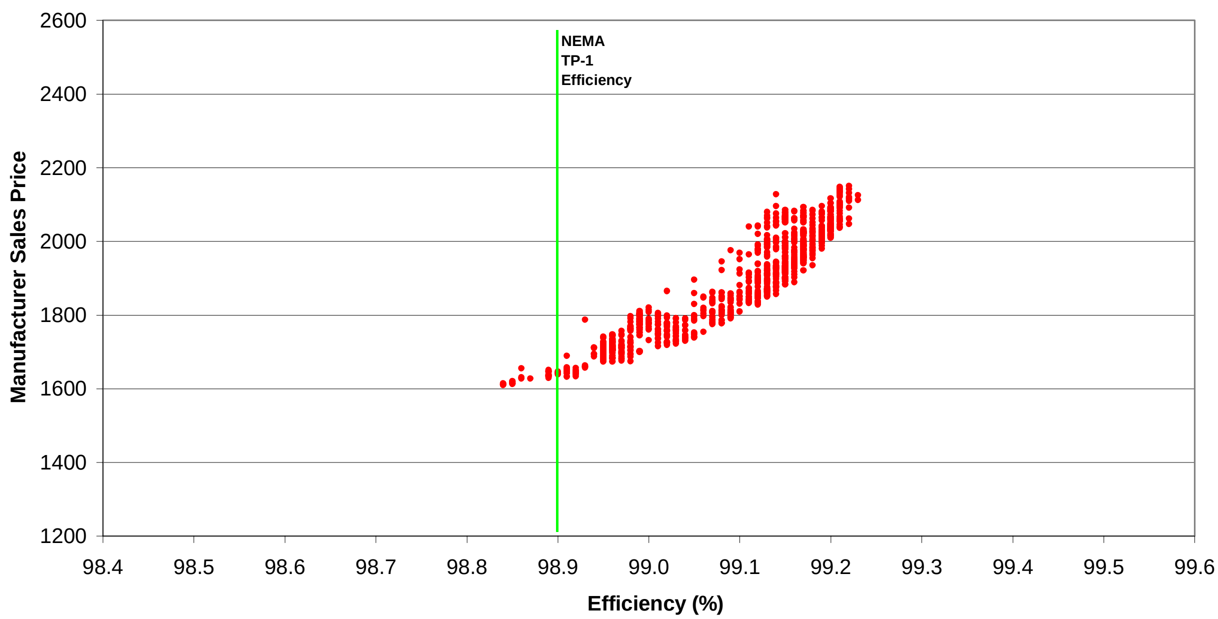

Figure 2. Manufacturer Sales Price vs. Efficiency for HOCuCu at 50% load

[13] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for HO (Laser Scribed) M3 core steel, copper primary, copper secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                          OPTIMIZED PROGRAM SERVICE

                      CLEVELAND OHIO            101800
                          2001-11-16    11:33:33
DG-CORE        SHELL   TYPE TRANSFORMER                50PHOCUCU

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE  DG-HO         M10                                THICKNESS .0090

  D: 9.139 E: 1.834 F: 3.115 G: 6.565  EFF. AREA  31.842 WEIGHT 218.412

WINDING FORM: INS. DIM.  9.389 X  4.042  THICKNESS  .030  LENGTH  6.315

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1          .0245X 5.4397   CU      31.22       28.82     .438     16.026
P1         1 #12.5 ROUND    CU    2569.81       37.65     .625     45.329
S2          .0245X 5.4397   CU      49.96       46.11     .438     25.644

NUMBER OF COILS  1               TOTAL BARE CONDUCTOR WEIGHT    87.000

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      13.0                 13      1.0  1(.00700)  1(.16800)     .403
P1     780.0   741.0   819.0 14     61.0  3(.00500)  1(.16800)    1.306
S2      13.0                 13      1.0  1(.00700)  1(.02100)     .403

                                                TOTAL BUILD(%)  87.18

                                                COIL CLEARANCE    .250
WNDG                  TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     760.5(  7020.00)   799.5(  7380.00)   819.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.035	4.57360	1537.	
S1	118.83			10.0	208.330	.00191	1564.	1.0
S2	118.53			10.0	208.330	.00305	1564.	1.2

	F.L.	N.L.		
FLUX DENS.	16.768	16.861	LEAKAGE INDUCTANCE MHYS	54.486
CORE LOSS	107.930	109.667	POWER FACTOR	1.0000
COIL LOSS	560.039	.003	IMPEDANCE %	2.27
EXCIT. VA	154.851	159.401	EFFICIENCY %	98.68
EXCIT. CURR.	.022	.022	TANK OIL GAL	20.26

AMBIENT TEMP.	20.00	NOMINAL LENGTH	13.57
TEMP.RISE	65.00	NOMINAL DEPTH	17.50
OPERATING TEMP.	85.00	NOMINAL HEIGHT	10.23

AVG. OIL RISE: 46.
TOP OIL RISE: 55.7

COND. I^2R LOSS =	541.1337
COND. EDDY CURRENT LOSS =	5.3774
OTHER STRAY LOSS =	13.5283
K VALUE =	1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.23	98.90	.223	.501	.548	29.745	16.6
35	.33	99.05	.316	.700	.768	58.946	20.1
50	.48	99.08	.463	1.000	1.102	123.442	27.6
65	.65	99.01	.624	1.300	1.442	216.068	37.7
75	.77	98.93	.741	1.502	1.674	295.846	45.9
100	1.11	98.68	1.053	2.007	2.267	560.039	65.0
125	1.40	98.45	1.319	2.515	2.840	877.135	65.0
150	1.69	98.20	1.588	3.025	3.416	1266.651	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, laser-scribed M3 core steel, with a copper primary and a copper secondary.

					$ values
Bill of Materials and Labor for 50 kVA Pad-mount				A$ Input	3.00
HOCuCu				B$ Input	1.00
(Laser-scribed M3)					
Material item	**Quantity**	**$ each**	**$ total**	**Labor item**	**hours**
Tube Ins *	1	$ 0.56	$ 0.62	P1 Labor	0.819
Weight Core *	218.41	$ 1.15	$ 276.29	S1 Labor	0.026
Weight P1 *	45.33	$ 1.90	$ 94.74	S2 Labor	0.026
Weight S1 *	16.03	$ 2.40	$ 42.32	Lead Dressing Labor	0.800
Weight S2 *	25.64	$ 2.40	$ 67.69	Banding Labor	0.050
Weight P1 Insulation *	1.83	$ 1.54	$ 3.10	Assembly Labor	0.500
Weight S1 Insulation *	0.96	$ 1.54	$ 1.63	Inspection Labor	0.100
Weight S2 Insulation *	0.62	$ 1.54	$ 1.05	Preliminary Test Labor	0.100
Tank Oil Gal	54.2	$ 1.50	$ 81.31	Final Test Labor	0.150
Fixed Tank	1	$ 250.00	$ 250.00	Packing Labor	0.500
HV Bushing	2	$ 7.00	$ 14.00	Marking Labor	0.100
LV Bushing	3	$ 8.00	$ 24.00	Miscellaneous Labor	0.250
Core Clamp	1	$ 9.25	$ 9.25	Total Labor	3.421
Fuse System	1	$ 35.00	$ 35.00		
Tap Changer	1	$ 20.00	$ 20.00	Hourly Rate	$ 42.77
Internal Hardware	1	$ 5.00	$ 5.00	Labor Cost $	$ 146.32
Name Plate	1	$ 13.25	$ 13.25		
Miscellaneous	1	$ 20.00	$ 20.00	Manufacturing Cost $	$ 1105.56
				Factory Overhead	1.125
Scrap Factor			1.1	Selling Factor	1.43
Total Material Cost $			$ 959.24	Selling Price $	$ 1778.57

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 3 provides a summary of the costs contributing to the total selling price of this particular transformer. From this illustration it becomes clear that approximately 54% of the final selling price of a laser scribed, copper primary and copper secondary, is direct material and scrap. Labor accounts for approximately 8% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

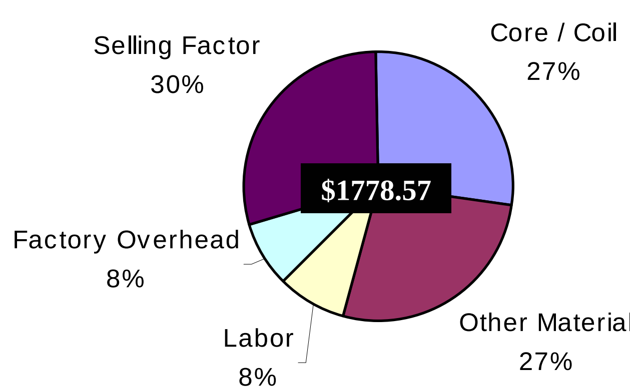

Figure 3. Selling Price Breakdown for HOCuCu

4.1.2 Results for M2AlAl

Figure 4 provides a scatter plot of cost and efficiency relationship for the 1031 designs[14] of M2 core steel with an aluminum primary and secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for about half of the designs in the database.

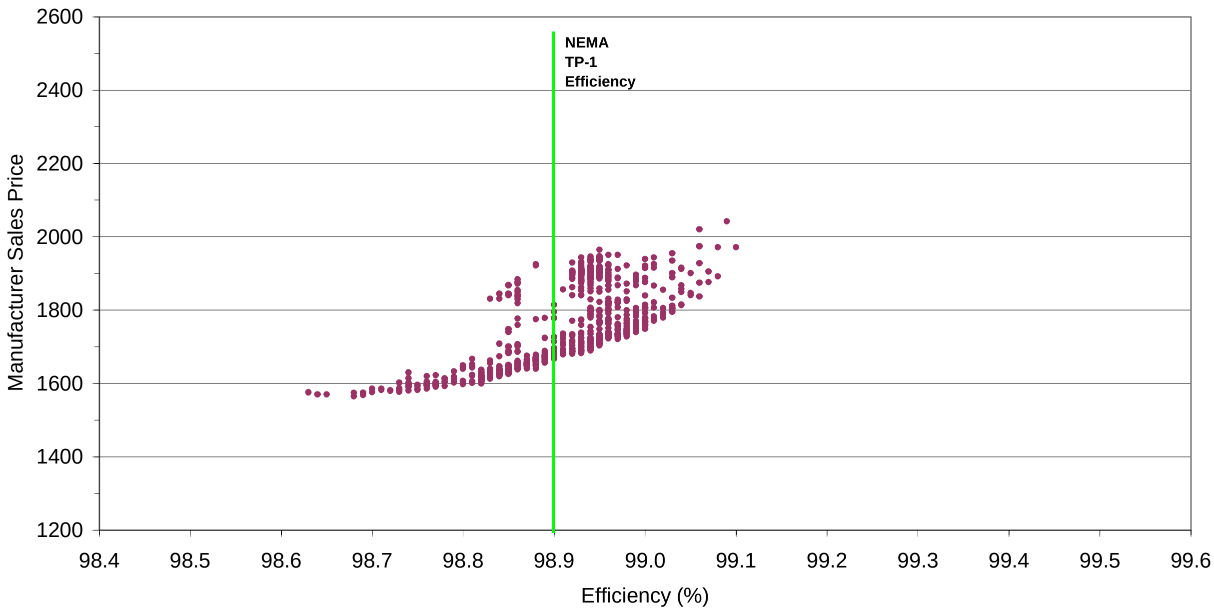

Figure 4. Manufacturer Sales Price vs. Efficiency for M2AlAl at 50% load

[14] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M2 core steel, aluminum primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-17    10:13:35
DG-CORE       SHELL   TYPE TRANSFORMER                54PM2ALAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M2          M 2                              THICKNESS .0070

  D: 7.421 E: 1.898 F: 4.098 G: 9.522  EFF. AREA  26.761 WEIGHT 245.230

WINDING FORM: INS. DIM.  7.671 X  4.171  THICKNESS  .030  LENGTH  9.272

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
-----------------------------------------------------------------------
S1        .0289X 8.3970   AL      34.94      26.21     .438      9.927
P1     1X 1 #10 ROUND    H AL    3095.60      36.85     .625     29.587
S2        .0289X 8.3970   AL      62.83      47.12     .438     17.850

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    57.364

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
-----------------------------------------------------------------------
S1     16.0                  16      1.0  1(.00700)  1(.16800)     .567
P1     960.0   912.0  1008.0 14     73.0  3(.00500)  1(.16800)    1.665
S2     16.0                  16      1.0  1(.00700)  1(.02100)     .567

                                                TOTAL BUILD(%)  82.82

                                                COIL CLEARANCE    .250
WNDG              TAPS: TURNS( VOLTS)
---------------------------------------------------------
P1     936.0(  7020.00)   984.0(  7380.00)  1008.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.047	5.07092	864.	
S1	118.74			10.0	208.330	.00193	859.	1.1
S2	118.33			10.0	208.330	.00346	859.	1.4

	F.L.	N.L.		
FLUX DENS.	16.199	16.300	LEAKAGE INDUCTANCE MHYS	58.833
CORE LOSS	133.943	136.360	POWER FACTOR	1.0000
COIL LOSS	617.585	.007	IMPEDANCE %	2.46
EXCIT. VA	230.628	246.622	EFFICIENCY %	98.52
EXCIT. CURR.	.032	.034	TANK OIL GAL	26.74

AMBIENT TEMP.	20.00	NOMINAL LENGTH	15.79
TEMP.RISE	64.58	NOMINAL DEPTH	17.74
OPERATING TEMP.	84.58	NOMINAL HEIGHT	13.32

AVG. OIL RISE: 49.
TOP OIL RISE: 58.9

COND. I^2R LOSS =	598.0432
COND. EDDY CURRENT LOSS =	4.5912
OTHER STRAY LOSS =	14.9511
K VALUE =	1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.25	98.67	.242	.542	.594	32.652	16.2
35	.36	98.87	.342	.757	.831	64.594	19.3
50	.53	98.93	.500	1.081	1.191	134.905	25.8
65	.71	98.87	.672	1.406	1.558	235.388	34.6
75	.84	98.80	.796	1.624	1.808	321.530	41.8
100	1.23	98.52	1.147	2.171	2.455	617.565	64.6
125	1.55	98.27	1.441	2.720	3.078	969.441	65.0
150	1.88	98.00	1.733	3.273	3.704	1399.867	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, M2 core steel, with an aluminum primary and secondary.

Bill of Materials and Labor for 50 kVA Pad-mount
M2AlAl

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	245.23	$ 1.15	$ 310.22
Weight P1 *	29.59	$ 2.25	$ 73.24
Weight S1 *	9.93	$ 1.30	$ 14.20
Weight S2 *	17.85	$ 1.30	$ 25.53
Weight P1 Insulation *	2.68	$ 1.54	$ 4.54
Weight S1 Insulation *	1.4	$ 1.54	$ 2.37
Weight S2 Insulation *	1.11	$ 1.54	$ 1.88
Tank Oil Gal	51.9	$ 1.50	$ 77.92
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 901.00

Labor item	hours
P1 Labor	1.008
S1 Labor	0.032
S2 Labor	0.032
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.622
Hourly Rate	$ 42.77
Labor Cost $	$ 154.91
Manufacturing Cost $	$ 1055.92
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1698.71

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 5 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M2, aluminum primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

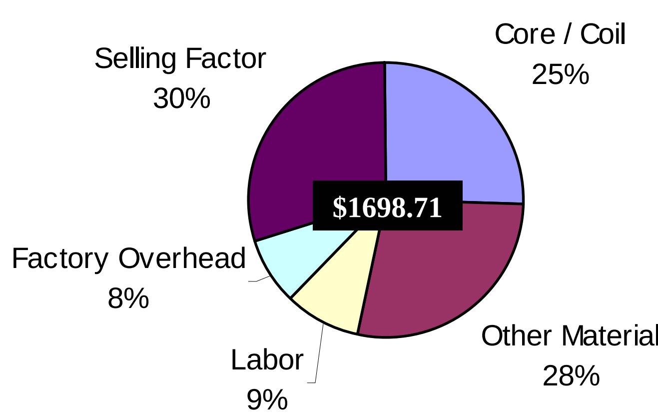

Figure 5. Selling Price Breakdown for M2AlAl

4.1.3 Results for M2CuAl

Figure 6 provides a scatter plot of cost and efficiency relationship for the 1031 designs[15] of M2 core steel with a copper primary and aluminum secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for about half of the designs in the database.

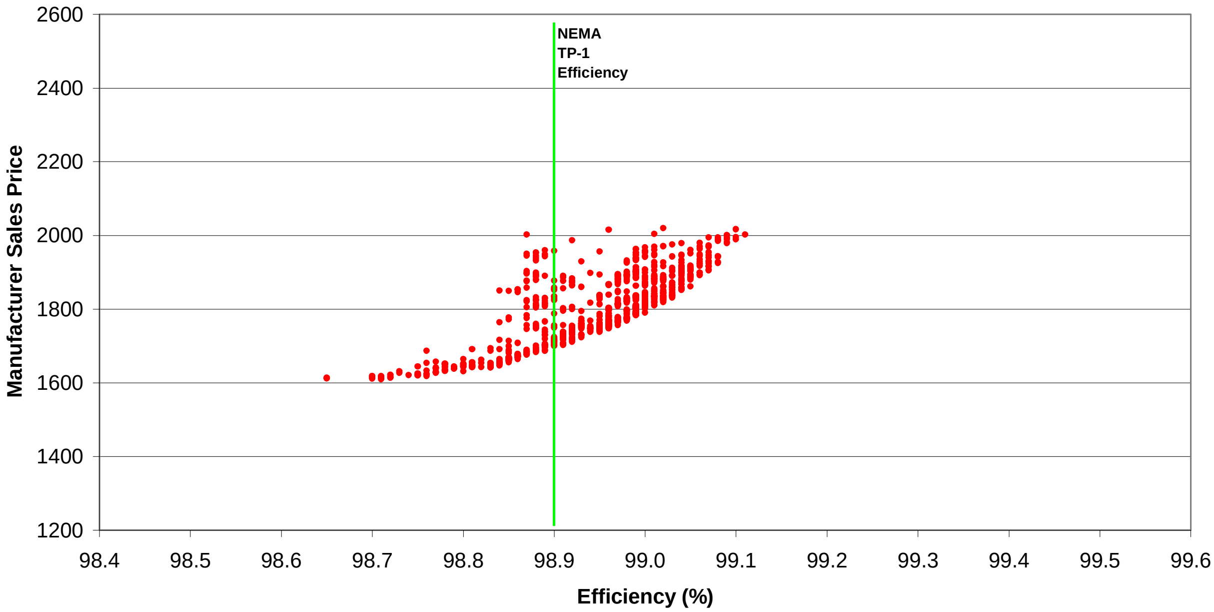

Figure 6. Manufacturer Sales Price vs. Efficiency for M2CuAl at 50% load

[15] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M2 core steel, copper primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-15    10:14:17
DG-CORE       SHELL   TYPE TRANSFORMER                 50PM2CUAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M2          M 2                                THICKNESS .0070

  D: 6.962 E: 2.003 F: 3.267 G: 9.611  EFF. AREA  26.488 WEIGHT 234.276

WINDING FORM: INS. DIM.  7.212 X  4.380  THICKNESS  .030  LENGTH  9.361

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1         .0245X 8.4805   AL      34.32      25.74     .438      8.313
P1     1X 1 #12 ROUND    H CU    2901.54      34.54     .625     57.448
S2         .0244X 8.4855   AL      56.92      42.69     .438     13.780

NUMBER OF COILS  1               TOTAL BARE CONDUCTOR WEIGHT    79.542

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     16.0                  16      1.0  1(.00700)  1(.16800)     .577
P1    960.0   912.0  1008.0 11      93.0  4(.00500)  1(.16800)    1.123
S2     16.0                  16      1.0  1(.00700)  1(.02100)     .495

                                                TOTAL BUILD(%)  85.54

                                                COIL CLEARANCE    .250
WNDG              TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     936.0(  7020.00)   984.0(  7380.00)  1008.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END        .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.046	4.60059	1372.	
S1	118.75			10.0	208.330	.00222	1008.	1.0
S2	118.36			10.0	208.330	.00368	1008.	1.4

	F.L.	N.L.
FLUX DENS.	16.378	16.469
CORE LOSS	132.063	134.183
COIL LOSS	615.212	.008
EXCIT. VA	248.504	264.987
EXCIT. CURR.	.035	.037

LEAKAGE INDUCTANCE MHYS	41.457
POWER FACTOR	1.0000
IMPEDANCE %	1.92
EFFICIENCY %	98.53
TANK OIL GAL	22.01

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.54
TEMP.RISE	65.00	NOMINAL DEPTH	15.62
OPERATING TEMP.	85.00	NOMINAL HEIGHT	13.62

AVG. OIL RISE: 49.
TOP OIL RISE: 58.8

COND. I^2 R LOSS = 597.0034
COND. EDDY CURRENT LOSS = 3.2837
OTHER STRAY LOSS = 14.9251
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.25	98.69	.245	.382	.454	32.650	17.3
35	.36	98.88	.346	.534	.636	64.649	20.6
50	.53	98.94	.507	.762	.915	135.218	27.6
65	.71	98.88	.682	.991	1.203	236.341	37.1
75	.84	98.80	.809	1.144	1.401	323.251	44.8
100	1.21	98.53	1.155	1.530	1.917	615.212	65.0
125	1.53	98.28	1.448	1.917	2.402	963.467	65.0
150	1.84	98.01	1.742	2.306	2.890	1390.826	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, M2 core steel, with a copper primary and aluminum secondary.

			$ values
Bill of Materials and Labor for 50 kVA Pad-mount		A$ Input	3.00
M2CuAl		B$ Input	1.00

Material item	**Quantity**	**$ each**	**$ total**
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	234.28	$ 1.15	$ 296.36
Weight P1 *	57.45	$ 1.90	$ 120.07
Weight S1 *	8.31	$ 1.30	$ 11.88
Weight S2 *	13.78	$ 1.30	$ 19.71
Weight P1 Insulation *	2.52	$ 1.54	$ 4.27
Weight S1 Insulation *	1.39	$ 1.54	$ 2.35
Weight S2 Insulation *	1.01	$ 1.54	$ 1.71
Tank Oil Gal	53.2	$ 1.50	$ 79.81
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 927.28

Labor item	**hours**
P1 Labor	1.008
S1 Labor	0.032
S2 Labor	0.032
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.622
Hourly Rate	$ 42.77
Labor Cost $	$ 154.91
Manufacturing Cost $	$ 1082.20
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1740.99

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 7 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M2, copper primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

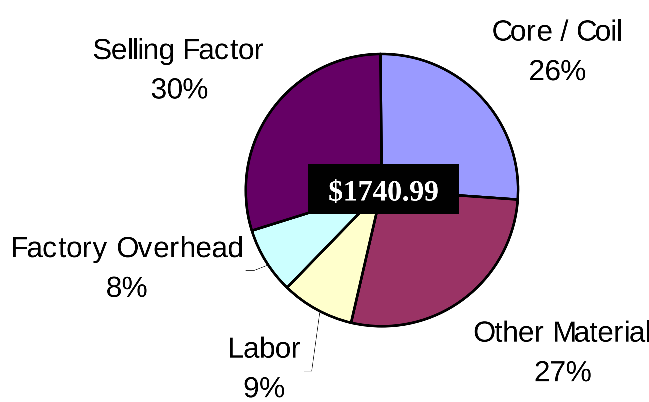

Figure 7. Selling Price Breakdown for M2CuAl

4.1.4 Results for M2CuCu

Figure 8 provides a scatter plot of cost and efficiency relationship for the 1031 designs[16] of M2 core steel with a copper primary and secondary (copper strip). These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for more than half of the designs in the database.

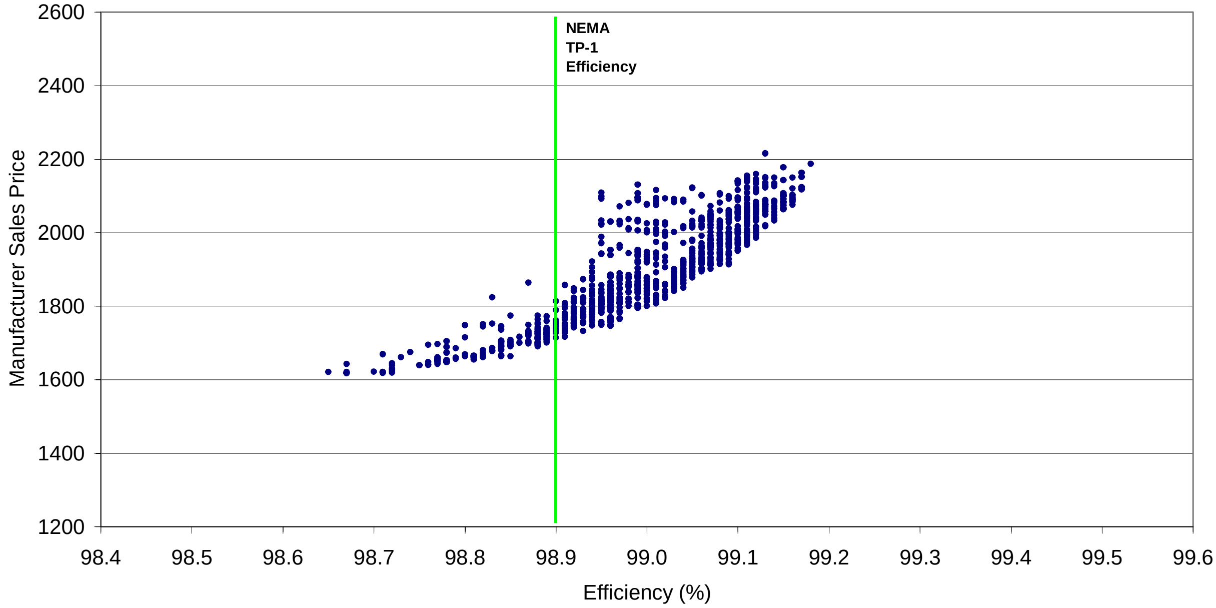

Figure 8. Manufacturer Sales Price vs. Efficiency for M2CuCu at 50% load

[16] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M2 core steel, copper primary, copper secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-15    19:12: 1
DG-CORE       SHELL   TYPE TRANSFORMER                 50PM2CUCU

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M2          M 2                                THICKNESS .0070

  D: 7.438 E: 1.969 F: 3.199 G: 7.446  EFF. AREA  27.822 WEIGHT 210.971

WINDING FORM: INS. DIM.  7.688 X  4.312  THICKNESS  .030  LENGTH  7.196

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1         .0220X 6.3206   CU      32.55      26.04     .438     17.425
P1        1 #12.5 ROUND    CU    2753.48      34.96     .625     48.569
S2         .0220X 6.3206   CU      54.39      43.51     .438     29.113

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    95.107

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     15.0                  15      1.0  1(.00700)  1(.16800)     .428
P1    900.0   855.0   945.0 14      72.0  3(.00500)  1(.16800)    1.306
S2     15.0                  15      1.0  1(.00700)  1(.02100)     .428

                                                TOTAL BUILD(%)  86.42

                                                COIL CLEARANCE    .250
WNDG                  TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     877.5(  7020.00)   922.5(  7380.00)   945.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.043	4.90049	1539.	
S1	118.77			10.0	208.330	.00191	1500.	1.0
S2	118.43			10.0	208.330	.00319	1500.	1.3

	F.L.	N.L.		
FLUX DENS.	16.623	16.723	LEAKAGE INDUCTANCE MHYS	59.618
CORE LOSS	132.314	134.705	POWER FACTOR	1.0000
COIL LOSS	588.102	.010	IMPEDANCE %	2.46
EXCIT. VA	268.004	290.040	EFFICIENCY %	98.58
EXCIT. CURR.	.037	.040	TANK OIL GAL	20.55

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.27
TEMP.RISE	65.00	NOMINAL DEPTH	15.96
OPERATING TEMP.	85.00	NOMINAL HEIGHT	11.38

AVG. OIL RISE: 46.
TOP OIL RISE: 54.6

COND. I^2R LOSS = 568.4301
COND. EDDY CURRENT LOSS = 5.4608
OTHER STRAY LOSS = 14.2108
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.24	98.69	.235	.549	.598	31.519	18.8
35	.35	98.89	.333	.767	.836	62.421	22.3
50	.51	98.95	.488	1.095	1.199	130.676	29.9
65	.69	98.90	.658	1.425	1.569	228.734	40.1
75	.82	98.82	.781	1.645	1.821	313.236	48.5
100	1.17	98.58	1.101	2.198	2.459	588.102	65.0
125	1.47	98.34	1.380	2.754	3.081	921.166	65.0
150	1.78	98.09	1.660	3.314	3.706	1330.459	65.1

This is the breakdown of costs, or the 'bill of materials', associated with this design, M2 core steel, with a copper primary and copper secondary.

Bill of Materials and Labor for 50 kVA Pad-mount
M2CuCu

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	**Quantity**	**$ each**	**$ total**
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	210.97	$ 1.15	$ 266.88
Weight P1 *	48.57	$ 1.90	$ 101.51
Weight S1 *	17.42	$ 2.40	$ 45.99
Weight S2 *	29.11	$ 2.40	$ 76.85
Weight P1 Insulation *	1.95	$ 1.54	$ 3.30
Weight S1 Insulation *	1.05	$ 1.54	$ 1.78
Weight S2 Insulation *	0.75	$ 1.54	$ 1.27
Tank Oil Gal	54.3	$ 1.50	$ 81.46
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 970.15

Labor item	**hours**
P1 Labor	0.945
S1 Labor	0.030
S2 Labor	0.030
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.555
Hourly Rate	$ 42.77
Labor Cost $	$ 152.05
Manufacturing Cost $	$ 1122.20
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1805.34

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 9 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M2, copper primary and copper secondary, is direct material and scrap. Labor accounts for approximately 8% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

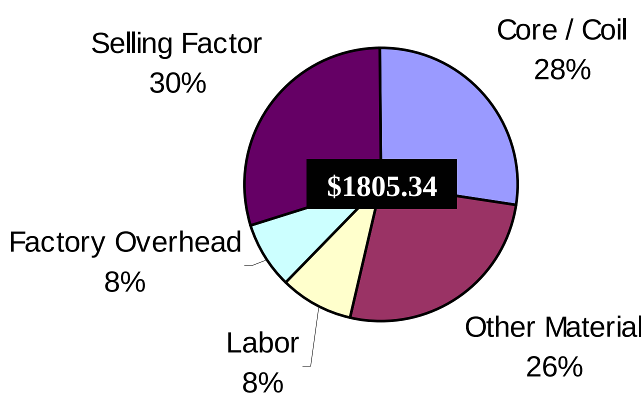

Figure 9. Selling Price Breakdown for M2CuCu

4.1.5 Results for M3AlAl

Figure 10 provides a scatter plot of cost and efficiency relationship for the 1031 designs[17] of M3 core steel with an aluminum primary and secondary (aluminum strip). These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for slightly less than half the designs in the database.

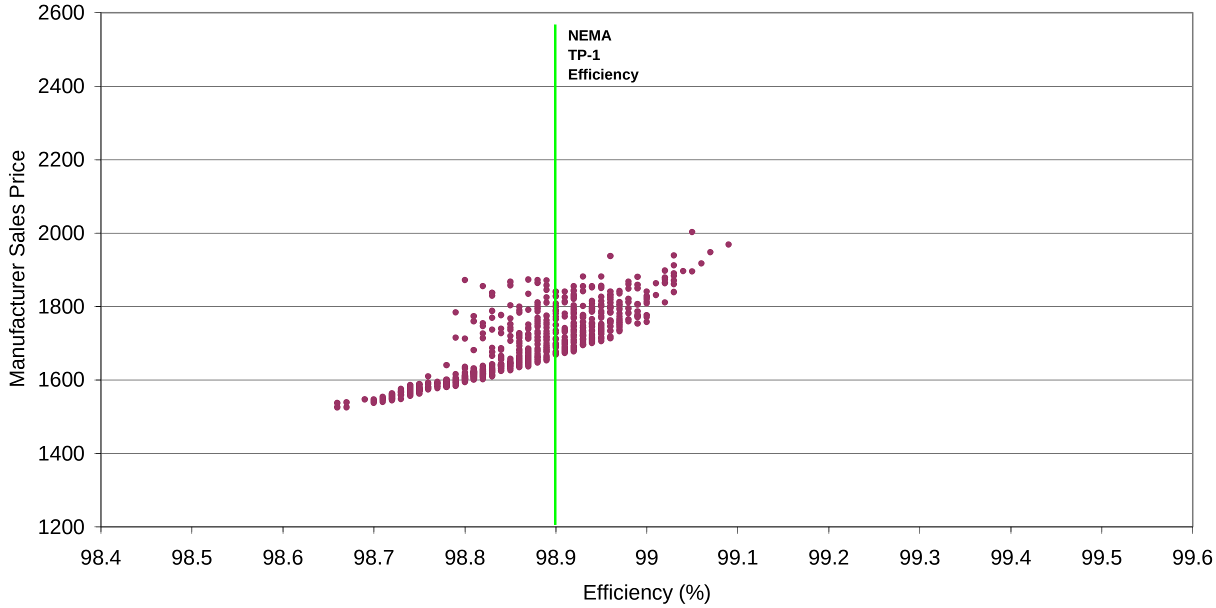

Figure 10. Manufacturer Sales Price vs. Efficiency for M3AlAl at 50% load

[17] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M3 core steel, aluminum primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO           101800
                       2001-11-20    19: 1:11
DG-CORE       SHELL   TYPE TRANSFORMER               50PM3ALAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M3          M 3                                THICKNESS .0090

  D: 7.099 E: 1.958 F: 4.130 G: 9.005  EFF. AREA  26.825 WEIGHT 238.045

WINDING FORM: INS. DIM.  7.349 X  4.291  THICKNESS  .030  LENGTH  8.755

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

WNDG            WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1        .0274X 7.8797   AL      34.30      25.72     .438      8.678
P1     1X 1 #10 ROUND    H AL    3082.82      36.70     .625     29.465
S2        .0274X 7.8797   AL      63.07      47.30     .438     15.959

NUMBER OF COILS  1               TOTAL BARE CONDUCTOR WEIGHT    54.102

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     16.0                  16      1.0  1(.00700)  1(.16800)     .544
P1     960.0   912.0  1008.0 15     69.0  3(.00500)  1(.16800)    1.785
S2     16.0                  16      1.0  1(.00700)  1(.02100)     .544

                                                TOTAL BUILD(%)  84.00

                                                COIL CLEARANCE    .250
WNDG                TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     936.0(  7020.00)   984.0(  7380.00)  1008.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                              .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.052	5.05000	865.	
S1	118.68			10.0	208.330	.00212	965.	1.1
S2	118.21			10.0	208.330	.00390	965.	1.5

	F.L.	N.L.		
FLUX DENS.	16.160	16.261	LEAKAGE INDUCTANCE MHYS	62.837
CORE LOSS	139.477	142.071	POWER FACTOR	1.0000
COIL LOSS	654.322	.005	IMPEDANCE %	2.62
EXCIT. VA	191.379	201.351	EFFICIENCY %	98.44
EXCIT. CURR.	.027	.028	TANK OIL GAL	18.65

AMBIENT TEMP.	20.00	NOMINAL LENGTH	16.09
TEMP.RISE	65.00	NOMINAL DEPTH	17.48
OPERATING TEMP.	85.00	NOMINAL HEIGHT	12.92

AVG. OIL RISE: 48.
TOP OIL RISE: 66.9

COND. I^2R LOSS = 633.4654
COND. EDDY CURRENT LOSS = 5.0200
OTHER STRAY LOSS = 15.8366
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.27	98.61	.260	.579	.635	35.210	21.6
35	.39	98.81	.368	.809	.889	69.899	25.6
50	.58	98.86	.542	1.155	1.276	147.031	34.3
65	.78	98.79	.735	1.503	1.673	258.923	46.0
75	.94	98.69	.877	1.736	1.945	356.229	55.6
100	1.30	98.44	1.209	2.320	2.617	654.322	65.0
125	1.64	98.17	1.516	2.908	3.279	1025.010	65.0
150	1.99	97.89	1.824	3.500	3.946	1480.197	65.0

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

Bill of Materials and Labor for 50 kVA Pad-mount
M3AlAl

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	238.05	$ 1.05	$ 274.95
Weight P1 *	29.47	$ 2.25	$ 72.94
Weight S1 *	8.68	$ 1.30	$ 12.41
Weight S2 *	15.96	$ 1.30	$ 22.82
Weight P1 Insulation *	2.63	$ 1.54	$ 4.46
Weight S1 Insulation *	1.3	$ 1.54	$ 2.20
Weight S2 Insulation *	1.05	$ 1.54	$ 1.78
Tank Oil Gal	52.9	$ 1.50	$ 79.32
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 862.00

Labor item	hours
P1 Labor	1.008
S1 Labor	0.032
S2 Labor	0.032
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.622
Hourly Rate	$ 42.77
Labor Cost $	$ 154.91
Manufacturing Cost $	$ 1016.91
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1635.96

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 11 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M3, aluminum primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

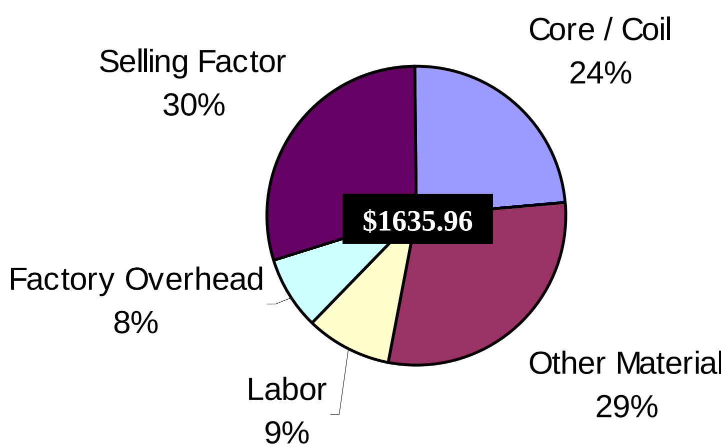

Figure 11. Selling Price Breakdown for M3AlAl

4.1.6 Results for M3AlCu

Figure 12 provides a scatter plot of cost and efficiency relationship for the 1031 designs[18] of M3 core steel with a aluminum primary and copper secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for more than half of the designs in the database.

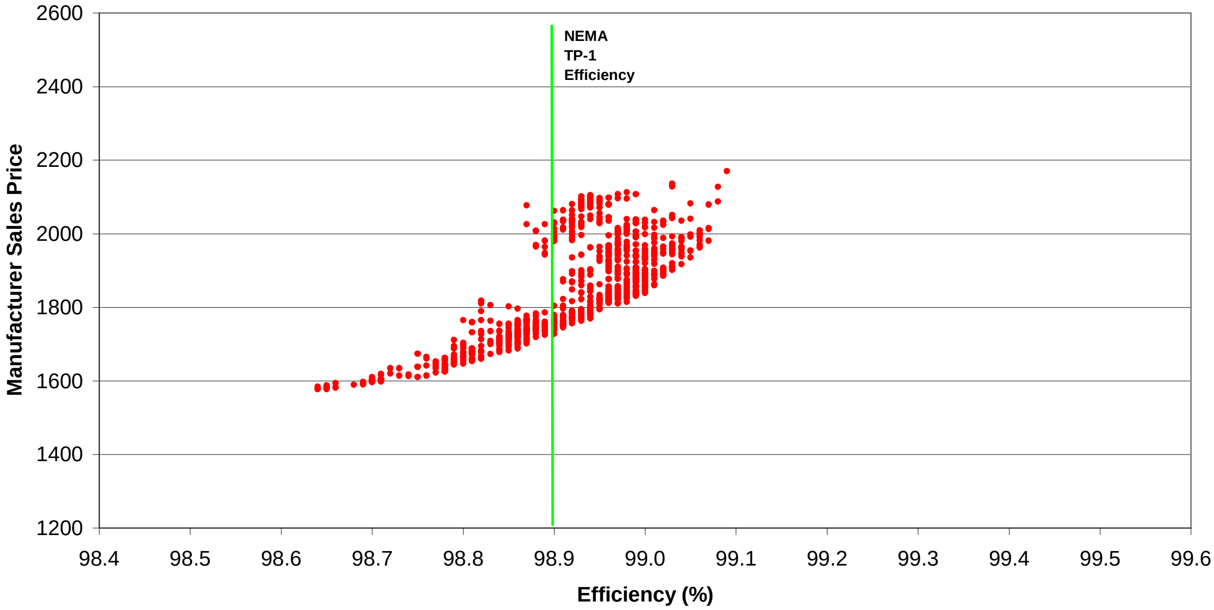

Figure 12. Manufacturer Sales Price vs. Efficiency for M3AlCu at 50% load

[18] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M3 core steel, aluminum primary, copper secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-18    15:56:30
DG-CORE       SHELL   TYPE TRANSFORMER               50PM3alcu

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M3          M 3                                THICKNESS .0090

  D: 7.212 E: 2.024 F: 3.890 G: 7.547  EFF. AREA  28.172 WEIGHT 225.206

WINDING FORM: INS. DIM.  7.462 X  4.423  THICKNESS  .030  LENGTH  7.297

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1         .0221X 6.4215   CU      32.27       25.82     .438    17.654
P1        1 #10.5 ROUND    AL    2905.60       36.90     .625    24.741
S2         .0221X 6.4215   CU      59.50       47.60     .438    32.548

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    74.943

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      15.0                 15      1.0  1(.00700)  1(.16800)     .430
P1     900.0   855.0   945.0 17     58.0  3(.00500)  1(.16800)    1.928
S2      15.0                 15      1.0  1(.00700)  1(.02100)     .430

                                                TOTAL BUILD(%)  87.21

                                                COIL CLEARANCE    .250
WNDG                TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     877.5(  7020.00)   922.5(  7380.00)   945.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.049	5.34257	970.	
S1	118.71			10.0	208.330	.00185	1468.	1.1
S2	118.30			10.0	208.330	.00341	1468.	1.4

	F.L.	N.L.		
FLUX DENS.	16.407	16.516	LEAKAGE INDUCTANCE MHYS	67.762
CORE LOSS	138.103	141.041	POWER FACTOR	1.0000
COIL LOSS	628.865	.006	IMPEDANCE %	2.76
EXCIT. VA	206.038	219.581	EFFICIENCY %	98.49
EXCIT. CURR.	.029	.030	TANK OIL GAL	24.14

AMBIENT TEMP.	20.00	NOMINAL LENGTH	15.88
TEMP.RISE	65.00	NOMINAL DEPTH	17.12
OPERATING TEMP.	85.00	NOMINAL HEIGHT	11.59

AVG. OIL RISE: 45.
TOP OIL RISE: 53.3

COND. I^2R LOSS = 606.8158
COND. EDDY CURRENT LOSS = 6.8784
OTHER STRAY LOSS = 15.1704
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.26	98.63	.247	.625	.672	33.545	18.2
35	.37	98.83	.349	.873	.940	66.438	21.7
50	.54	98.90	.513	1.246	1.347	139.135	29.2
65	.74	98.84	.691	1.620	1.761	243.693	39.4
75	.88	98.75	.821	1.871	2.043	333.910	47.8
100	1.25	98.49	1.162	2.501	2.758	628.865	65.0
125	1.58	98.24	1.456	3.134	3.456	985.295	65.0
150	1.92	97.96	1.752	3.771	4.158	1423.833	65.1

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

Bill of Materials and Labor for 50 kVA Pad-mount
M3AlCu

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	225.21	$ 1.05	$ 260.12
Weight P1 *	24.74	$ 2.25	$ 61.23
Weight S1 *	17.65	$ 2.40	$ 46.60
Weight S2 *	32.55	$ 2.40	$ 85.93
Weight P1 Insulation *	2.37	$ 1.54	$ 4.01
Weight S1 Insulation *	1.05	$ 1.54	$ 1.78
Weight S2 Insulation *	0.83	$ 1.54	$ 1.41
Tank Oil Gal	52.9	$ 1.50	$ 79.31
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 931.51

Labor item	hours
P1 Labor	0.945
S1 Labor	0.030
S2 Labor	0.030
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.555
Hourly Rate	$ 42.77
Labor Cost $	$ 152.05
Manufacturing Cost $	$ 1083.55
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1743.17

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 13 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M3, aluminum primary and copper secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

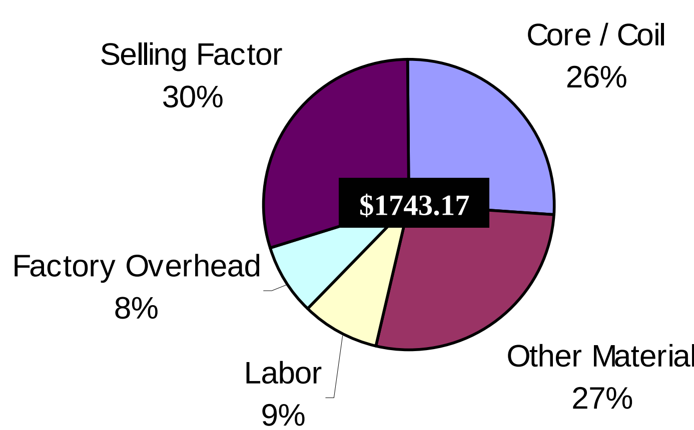

Figure 13. Selling Price Breakdown for M3AlCu

4.1.7 Results for M3CuAl

Figure 14 provides a scatter plot of cost and efficiency relationship for the 1031 designs[19] of M3 core steel with a copper primary and aluminum strip secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for more than half of the designs in the database.

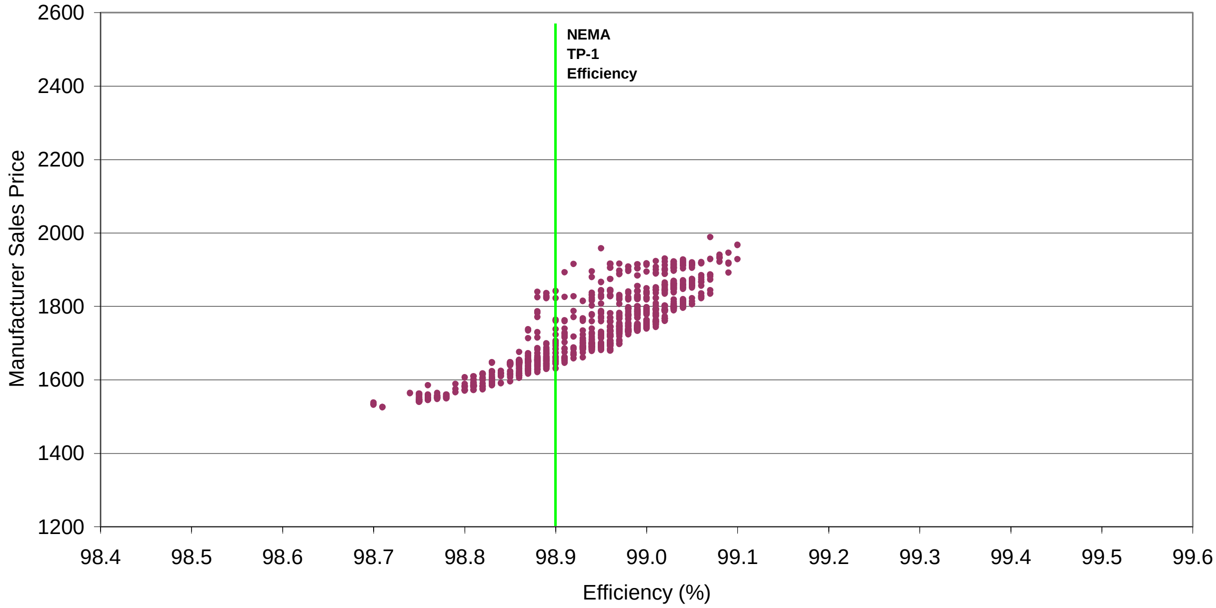

Figure 14. Manufacturer Sales Price vs. Efficiency for M3CuAl at 50% load

[19] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M3 core steel, copper primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO           101800
                       2001-11-13    20:41:44
DG-CORE       SHELL   TYPE TRANSFORMER                50PM3cual

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M3          M 3                             THICKNESS .0090

  D: 6.904 E: 1.895 F: 3.605 G: 8.851  EFF. AREA  25.251 WEIGHT 213.239

WINDING FORM: INS. DIM.  7.154 X  4.165  THICKNESS  .030  LENGTH  8.601

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

WNDG            WIRE           LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1         .0277X 7.7260   AL      35.73      25.22     .438     8.964
P1     1X 1 #12 ROUND    H CU    3084.08      34.56     .625    61.063
S2         .0277X 7.7260   AL      61.65      43.52     .438    15.468

NUMBER OF COILS  1             TOTAL BARE CONDUCTOR WEIGHT    85.494

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     17.0                  17      1.0  1(.00700)  1(.16800)     .583
P1   1020.0   969.0  1071.0 13      84.0  3(.00500)  1(.16800)    1.270
S2     17.0                  17      1.0  1(.00700)  1(.02100)     .583

                                                TOTAL BUILD(%)  84.19

                                                COIL CLEARANCE    .250
WNDG                  TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     994.5(  7020.00)  1045.5(  7380.00)  1071.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                              .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.049	4.89002	1372.	
S1	118.68			10.0	208.330	.00223	973.	1.1
S2	118.26			10.0	208.330	.00385	973.	1.5

	F.L.	N.L.		
FLUX DENS.	16.161	16.259	LEAKAGE INDUCTANCE MHYS	64.804
CORE LOSS	124.961	127.202	POWER FACTOR	1.0000
COIL LOSS	644.781	.004	IMPEDANCE %	2.68
EXCIT. VA	171.505	180.114	EFFICIENCY %	98.48
EXCIT. CURR.	.024	.025	TANK OIL GAL	22.59

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.79
TEMP.RISE	65.00	NOMINAL DEPTH	16.24
OPERATING TEMP.	85.00	NOMINAL HEIGHT	12.64

AVG. OIL RISE: 47.
TOP OIL RISE: 56.0

COND. I^2R LOSS = 624.1834
COND. EDDY CURRENT LOSS = 4.9926
OTHER STRAY LOSS = 15.6046
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.27	98.73	.254	.597	.649	34.190	17.1
35	.38	98.90	.360	.834	.908	67.773	20.7
50	.56	98.94	.528	1.191	1.303	142.045	28.2
65	.75	98.86	.713	1.549	1.705	248.915	38.5
75	.90	98.77	.847	1.789	1.979	341.135	46.8
100	1.29	98.48	1.202	2.392	2.677	644.781	65.0
125	1.62	98.22	1.506	2.998	3.355	1010.013	65.0
150	1.97	97.93	1.813	3.607	4.037	1458.450	65.0

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

Bill of Materials and Labor for 50 kVA Pad-mount
M3CuAl

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	213.24	$ 1.05	$ 246.29
Weight P1 *	61.06	$ 1.90	$ 127.62
Weight S1 *	8.96	$ 1.30	$ 12.81
Weight S2 *	15.47	$ 1.30	$ 22.12
Weight P1 Insulation *	2.21	$ 1.54	$ 3.74
Weight S1 Insulation *	1.29	$ 1.54	$ 2.19
Weight S2 Insulation *	1	$ 1.54	$ 1.69
Tank Oil Gal	53.5	$ 1.50	$ 80.27
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 887.85

Labor item	hours
P1 Labor	1.071
S1 Labor	0.034
S2 Labor	0.034
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.689
Hourly Rate	$ 42.77
Labor Cost $	$ 157.78
Manufacturing Cost $	$ 1045.63
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1682.16

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 15 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M3, copper primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

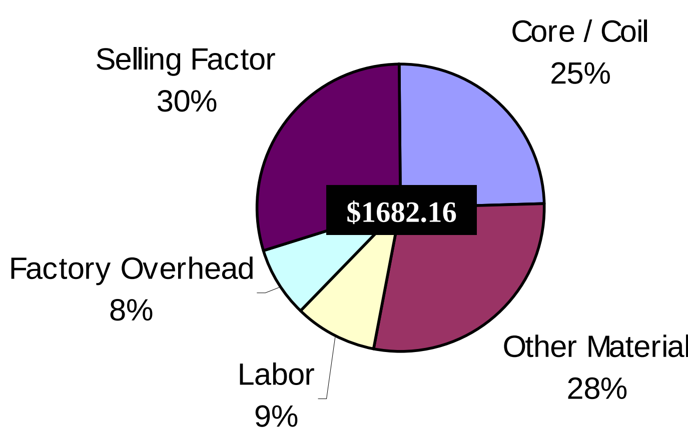

Figure 15. Selling Price Breakdown for M3CuAl

4.1.8 Results for M3CuCu

Figure 16 provides a scatter plot of cost and efficiency relationship for the 1031 designs[20] of M3 core steel with a copper primary and copper strip secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for more than half of the designs in the database.

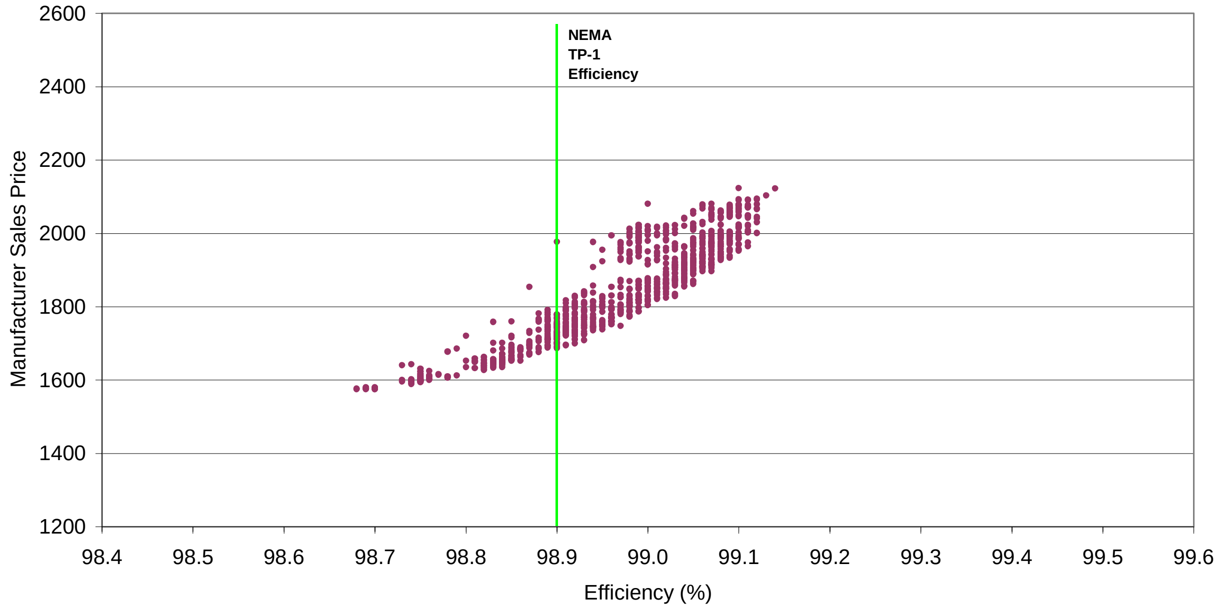

Figure 16. Manufacturer Sales Price vs. Efficiency for M3CuCu at 50% load

[20] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M3 core steel, copper primary, copper secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-13    10:32:30
DG-CORE       SHELL   TYPE TRANSFORMER                50PM3cucu

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M3          M 3                               THICKNESS .0090

  D: 8.251 E: 1.875 F: 3.200 G: 6.936  EFF. AREA  29.854 WEIGHT 213.345

WINDING FORM: INS. DIM.  8.501 X  4.124  THICKNESS  .030  LENGTH  6.686

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1          .0227X 5.8109   CU      31.76      27.23     .438     16.135
P1         1 #12.5 ROUND    CU    2652.10      36.08     .625     46.781
S2          .0227X 5.8109   CU      51.99      44.56     .438     26.409

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    89.324

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      14.0                 14      1.0  1(.00700)  1(.16800)     .409
P1     840.0   798.0   882.0 14     66.0  3(.00500)  1(.16800)    1.306
S2      14.0                 14      1.0  1(.00700)  1(.02100)     .409

                                                TOTAL BUILD(%)  85.10

                                                COIL CLEARANCE    .250
WNDG                TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     819.0(  7020.00)   861.0(  7380.00)   882.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.042	4.72005	1539.	
S1	118.79			10.0	208.330	.00196	1581.	1.0
S2	118.46			10.0	208.330	.00321	1581.	1.3

	F.L.	N.L.		
FLUX DENS.	16.603	16.699	LEAKAGE INDUCTANCE MHYS	57.160
CORE LOSS	135.943	138.612	POWER FACTOR	1.0000
COIL LOSS	581.401	.006	IMPEDANCE %	2.37
EXCIT. VA	219.542	233.620	EFFICIENCY %	98.59
EXCIT. CURR.	.030	.032	TANK OIL GAL	20.39

AMBIENT TEMP.	20.00	NOMINAL LENGTH	13.90
TEMP.RISE	65.00	NOMINAL DEPTH	16.78
OPERATING TEMP.	85.00	NOMINAL HEIGHT	10.69

AVG. OIL RISE: 46.
TOP OIL RISE: 54.6

COND. I^2R LOSS = 561.9081
COND. EDDY CURRENT LOSS = 5.4452
OTHER STRAY LOSS = 14.0477
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.24	98.66	.234	.527	.576	31.239	19.4
35	.34	98.87	.331	.736	.807	61.868	23.0
50	.51	98.94	.485	1.050	1.157	129.525	30.6
65	.68	98.89	.653	1.366	1.514	226.740	40.9
75	.81	98.82	.776	1.577	1.758	310.534	49.3
100	1.15	98.59	1.091	2.108	2.373	581.401	65.0
125	1.45	98.35	1.366	2.641	2.973	910.571	65.0
150	1.76	98.10	1.644	3.177	3.577	1315.084	65.1

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

Bill of Materials and Labor for 50 kVA Pad-mount						$ values
M3CuCu				A$ Input		3.00
				B$ Input		1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	213.34	$ 1.05	$ 246.41
Weight P1 *	46.78	$ 1.90	$ 97.77
Weight S1 *	16.14	$ 2.40	$ 42.61
Weight S2 *	26.41	$ 2.40	$ 69.72
Weight P1 Insulation *	1.86	$ 1.54	$ 3.15
Weight S1 Insulation *	0.99	$ 1.54	$ 1.68
Weight S2 Insulation *	0.67	$ 1.54	$ 1.13
Tank Oil Gal	54.4	$ 1.50	$ 81.53
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 935.12

Labor item	hours
P1 Labor	0.882
S1 Labor	0.028
S2 Labor	0.028
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.488
Hourly Rate	$ 42.77
Labor Cost $	$ 149.18
Manufacturing Cost $	$ 1084.30
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1744.36

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 17 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 54% of the copper selling price of an M3, copper primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 37%. For definitions of these categories, please see section 3.2 of this report.

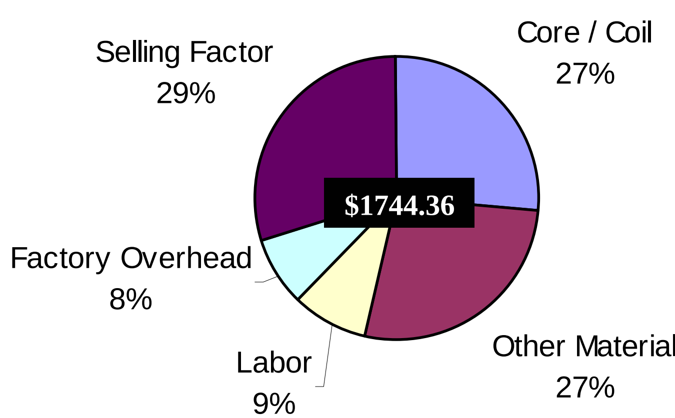

Figure 17. Selling Price Breakdown for M3CuCu

4.1.9 Results for M4CuAl

Figure 18 provides a scatter plot of cost and efficiency relationship for the 1031 designs[21] of laser-scribed M4 core steel with a copper primary and aluminum strip secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for less than half of the designs in the database.

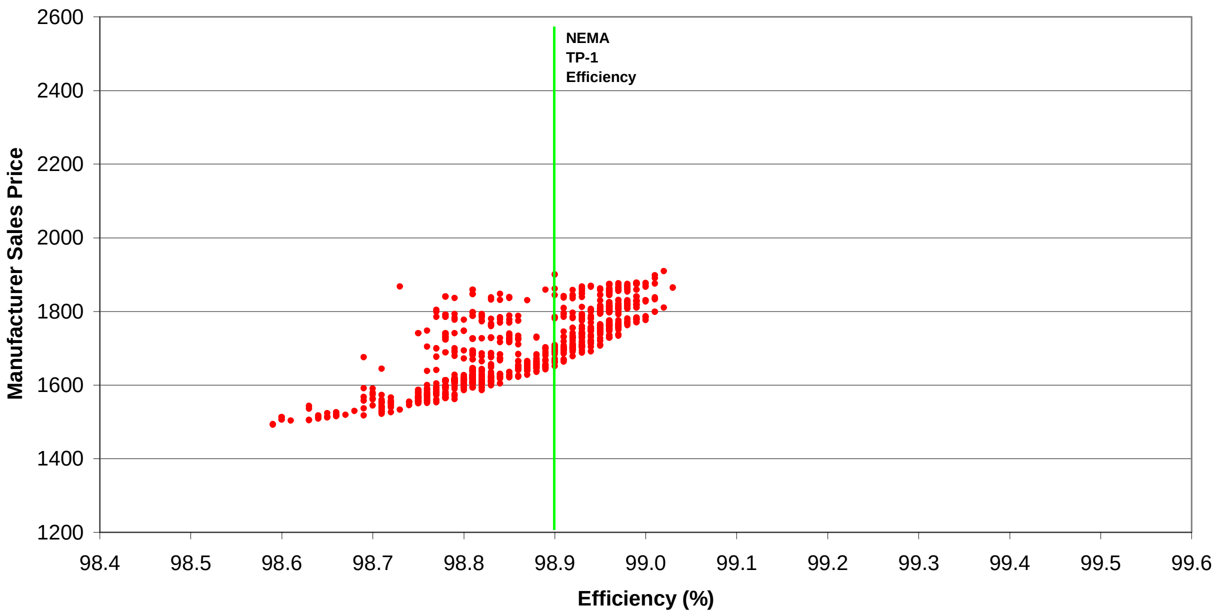

Figure 18. Manufacturer Sales Price vs. Efficiency for M4CuAl at 50% load

[21] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M4 core steel, copper primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-19    15:17:33
DG-CORE       SHELL   TYPE TRANSFORMER                50PM4CUAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M4          M 4                             THICKNESS .0110

  D: 7.507 E: 1.971 F: 3.389 G: 8.764  EFF. AREA  28.402 WEIGHT 236.954

WINDING FORM: INS. DIM.  7.757 X  4.316  THICKNESS  .030  LENGTH  8.514

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1          .0291X 7.6390   AL      33.19      26.55     .438      8.626
P1     1X 1 #12 ROUND    H CU    2786.00      35.38     .625     55.161
S2          .0291X 7.6390   AL      54.78      43.83     .438     14.237

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    78.023

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     15.0                  15      1.0  1(.00700)  1(.16800)     .534
P1     900.0   855.0   945.0 12     83.0  3(.00500)  1(.16800)    1.172
S2     15.0                  15      1.0  1(.00700)  1(.02100)     .534

                                                TOTAL BUILD(%)  83.67

                                                COIL CLEARANCE    .250
WNDG                  TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     877.5(  7020.00)   922.5(  7380.00)   945.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.043	4.41740	1371.	
S1	118.82			10.0	208.330	.00200	940.	1.0
S2	118.48			10.0	208.330	.00330	940.	1.3

	F.L.	N.L.		
FLUX DENS.	16.295	16.382	LEAKAGE INDUCTANCE MHYS	50.522
CORE LOSS	155.433	157.622	POWER FACTOR	1.0000
COIL LOSS	570.501	.007	IMPEDANCE %	2.15
EXCIT. VA	239.294	253.262	EFFICIENCY %	98.57
EXCIT. CURR.	.033	.035	TANK OIL GAL	15.61

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.66
TEMP.RISE	65.00	NOMINAL DEPTH	16.41
OPERATING TEMP.	85.00	NOMINAL HEIGHT	12.71

AVG. OIL RISE: 50.
TOP OIL RISE: 69.0

COND. I^2R LOSS = 553.0559
COND. EDDY CURRENT LOSS = 3.6187
OTHER STRAY LOSS = 13.8264
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.24	98.52	.233	.466	.521	31.130	24.3
35	.34	98.77	.330	.651	.730	61.678	28.1
50	.50	98.87	.485	.929	1.048	129.290	36.0
65	.68	98.84	.655	1.208	1.374	226.719	46.8
75	.82	98.77	.778	1.395	1.597	310.907	55.7
100	1.13	98.57	1.072	1.863	2.149	570.501	65.0
125	1.42	98.35	1.342	2.334	2.692	893.262	65.0
150	1.72	98.11	1.615	2.807	3.239	1289.257	65.0

This is the breakdown of costs, or the ‘bill of materials’, associated with this design, M4 core steel, with a copper primary and aluminum secondary.

					$ values
Bill of Materials and Labor for 50 kVA Pad-mount				A$ Input	3.00
M4CuAl				B$ Input	1.00
Material item	**Quantity**	**$ each**	**$ total**	**Labor item**	**hours**
Tube Ins *	1	$ 0.56	$ 0.62	P1 Labor	0.945
Weight Core *	236.95	$ 0.95	$ 247.61	S1 Labor	0.030
Weight P1 *	55.16	$ 1.90	$ 115.28	S2 Labor	0.030
Weight S1 *	8.63	$ 1.30	$ 12.34	Lead Dressing Labor	0.800
Weight S2 *	14.24	$ 1.30	$ 20.36	Banding Labor	0.050
Weight P1 Insulation *	2.14	$ 1.54	$ 3.63	Assembly Labor	0.500
Weight S1 Insulation *	1.27	$ 1.54	$ 2.15	Inspection Labor	0.100
Weight S2 Insulation *	0.89	$ 1.54	$ 1.51	Preliminary Test Labor	0.100
Tank Oil Gal	53.5	$ 1.50	$ 80.20	Final Test Labor	0.150
Fixed Tank	1	$ 250.00	$ 250.00	Packing Labor	0.500
HV Bushing	2	$ 7.00	$ 14.00	Marking Labor	0.100
LV Bushing	3	$ 8.00	$ 24.00	Miscellaneous Labor	0.250
Core Clamp	1	$ 9.25	$ 9.25	Total Labor	3.555
Fuse System	1	$ 35.00	$ 35.00		
Tap Changer	1	$ 20.00	$ 20.00	Hourly Rate	$ 42.77
Internal Hardware	1	$ 5.00	$ 5.00	Labor Cost $	$ 152.05
Name Plate	1	$ 13.25	$ 13.25		
Miscellaneous	1	$ 20.00	$ 20.00	Manufacturing Cost $	$ 1026.25
				Factory Overhead	1.125
Scrap Factor			1.1	Selling Factor	1.43
Total Material Cost $			$ 874.21	Selling Price $	$ 1650.98

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 19 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M4, copper primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 9% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

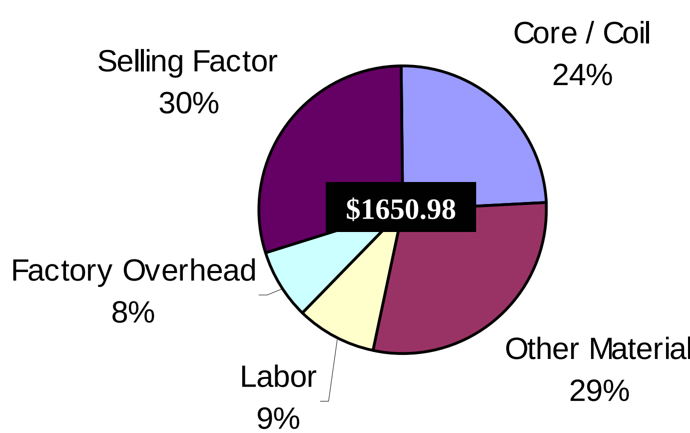

Figure 19. Selling Price Breakdown for M4CuAl

4.1.10 Results for M6AlAl

Figure 20 provides a scatter plot of cost and efficiency relationship for the 1031 designs[22] of M6 core steel with a aluminum primary and aluminum strip secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination fails to achieve TP-1 for any design in the database.

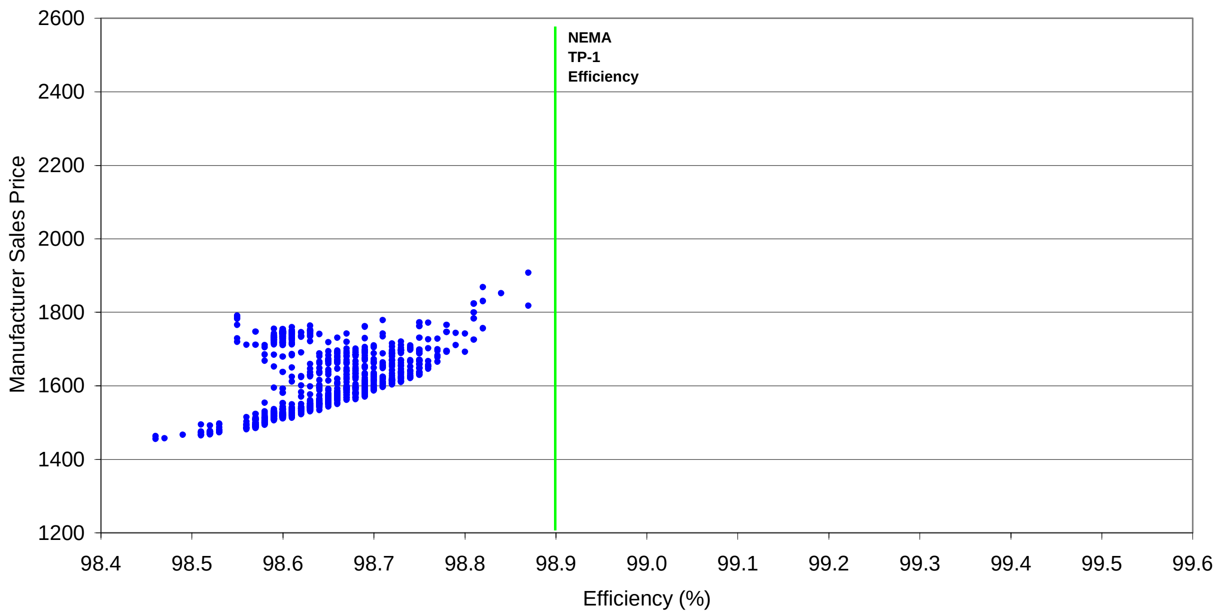

Figure 20. Manufacturer Sales Price vs. Efficiency for M6AlAl at 50% load

[22] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M6 core steel, aluminum primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-19    21:19: 1
DG-CORE       SHELL   TYPE TRANSFORMER                53PM6ALAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M4          M 6                                THICKNESS .0140

  D: 7.498 E: 1.746 F: 3.891 G:10.335  EFF. AREA  25.272 WEIGHT 234.850

WINDING FORM: INS. DIM.  7.748 X  3.868  THICKNESS  .030  LENGTH 10.085

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1          .0253X 9.2100   AL      36.36      25.67      .438      9.908
P1     1X 1 #10 ROUND    H AL    3232.79      36.22      .625     30.898
S2          .0253X 9.2100   AL      65.74      46.40      .438     17.913

NUMBER OF COILS  1              TOTAL BARE CONDUCTOR WEIGHT    58.719

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      17.0                 17      1.0  1(.00700)  1(.16800)     .541
P1    1020.0   969.0  1071.0 14     81.0  3(.00500)  1(.16800)    1.665
S2      17.0                 17      1.0  1(.00700)  1(.02100)     .541

                                                TOTAL BUILD(%)  86.10

                                                COIL CLEARANCE    .250
WNDG                  TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     994.5(  7020.00)  1045.5(  7380.00)  1071.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END          .188 X  .188 IN.  END
S2                                  .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.059	5.29565	866.	
S1	118.66			10.0	208.330	.00209	896.	1.1
S2	118.21			10.0	208.330	.00378	896.	1.5

	F.L.	N.L.		
FLUX DENS.	16.140	16.245	LEAKAGE INDUCTANCE MHYS	58.680
CORE LOSS	183.972	186.372	POWER FACTOR	1.0000
COIL LOSS	660.413	.009	IMPEDANCE %	2.49
EXCIT. VA	251.933	273.932	EFFICIENCY %	98.34
EXCIT. CURR.	.035	.038	TANK OIL GAL	17.52

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.77
TEMP.RISE	65.00	NOMINAL DEPTH	17.40
OPERATING TEMP.	85.00	NOMINAL HEIGHT	13.83

AVG. OIL RISE: 50.
TOP OIL RISE: 73.3

COND. I^2R LOSS	=	640.1154
COND. EDDY CURRENT LOSS	=	4.2947
OTHER STRAY LOSS	=	16.0029
K VALUE	=	1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.28	98.25	.268	.543	.606	36.179	25.8
35	.40	98.55	.380	.758	.848	71.691	29.7
50	.59	98.67	.558	1.081	1.217	150.459	38.1
65	.80	98.64	.755	1.406	1.596	264.370	49.4
75	.95	98.56	.899	1.623	1.856	363.155	58.6
100	1.31	98.34	1.226	2.169	2.492	660.413	65.0
125	1.65	98.09	1.537	2.718	3.122	1034.485	65.0
150	2.00	97.81	1.849	3.271	3.757	1493.829	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, M6 core steel, with a aluminum primary and aluminum secondary.

Bill of Materials and Labor for 50 kVA Pad-mount
M6AlAl

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	**Quantity**	**$ each**	**$ total**
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	234.85	$ 0.90	$ 232.50
Weight P1 *	30.9	$ 2.25	$ 76.48
Weight S1 *	9.91	$ 1.30	$ 14.17
Weight S2 *	17.91	$ 1.30	$ 25.61
Weight P1 Insulation *	2.87	$ 1.54	$ 4.86
Weight S1 Insulation *	1.53	$ 1.54	$ 2.59
Weight S2 Insulation *	1.25	$ 1.54	$ 2.12
Tank Oil Gal	52.8	$ 1.50	$ 79.16
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 828.61

Labor item	**hours**
P1 Labor	1.071
S1 Labor	0.034
S2 Labor	0.034
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.689
Hourly Rate	$ 42.77
Labor Cost $	$ 157.78
Manufacturing Cost $	$ 986.39
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1586.85

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 21 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 52% of the final selling price of an M6, aluminum primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 10% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

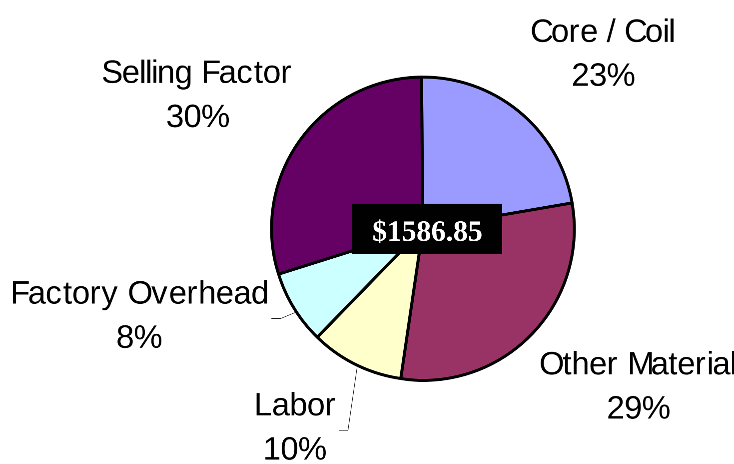

Figure 21. Selling Price Breakdown for M6AlAl

4.1.11 Results for M6CuAl

Figure 22 provides a scatter plot of cost and efficiency relationship for the 1031 designs[23] of M6 core steel with a copper primary and aluminum strip secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that virtually all designs the database for this design option combination fails to achieve TP-1.

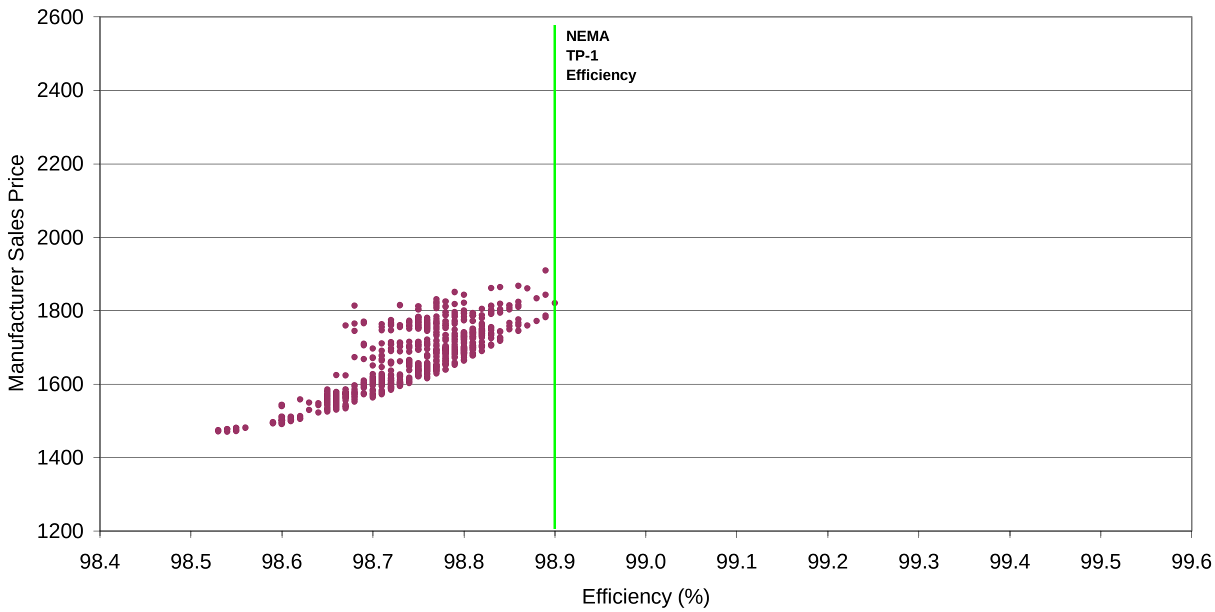

Figure 22. Manufacturer Sales Price vs. Efficiency for M6CuAl at 50% load

[23] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for M6 core steel, copper primary, aluminum secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-19    22:53:15
DG-CORE       SHELL   TYPE TRANSFORMER                 50PM6CUAL

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-M6          M 6                               THICKNESS .0140

  D: 6.771 E: 1.916 F: 3.488 G: 9.494  EFF. AREA  25.036 WEIGHT 219.138

WINDING FORM: INS. DIM.  7.021 X  4.207  THICKNESS  .030  LENGTH  9.244

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1         .0278X 8.3690   AL      35.47       25.04     .438     9.662
P1     1X 1 #12 ROUND    H CU    3037.86       34.04     .625    60.148
S2         .0278X 8.3690   AL      60.44       42.66     .438    16.462

NUMBER OF COILS  1             TOTAL BARE CONDUCTOR WEIGHT    86.272

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1      17.0                 17      1.0  1(.00700)  1(.16800)     .584
P1    1020.0   969.0  1071.0 12     92.0  3(.00500)  1(.16800)    1.172
S2      17.0                 17      1.0  1(.00700)  1(.02100)     .584

                                                TOTAL BUILD(%)  84.24

                                                COIL CLEARANCE    .250
WNDG                TAPS: TURNS( VOLTS)
----------------------------------------------------------
P1     994.5(  7020.00)  1045.5(  7380.00)  1071.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END         .188 X  .188 IN.  END
S2                                 .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.051	4.81674	1373.	
S1	118.74			10.0	208.330	.00204	896.	1.0
S2	118.37			10.0	208.330	.00347	896.	1.4

	F.L.	N.L.		
FLUX DENS.	16.302	16.398	LEAKAGE INDUCTANCE MHYS	58.052
CORE LOSS	175.118	177.182	POWER FACTOR	1.0000
COIL LOSS	607.904	.009	IMPEDANCE %	2.43
EXCIT. VA	267.364	288.381	EFFICIENCY %	98.46
EXCIT. CURR.	.037	.040	TANK OIL GAL	15.67

AMBIENT TEMP.	20.00	NOMINAL LENGTH	14.64
TEMP.RISE	65.00	NOMINAL DEPTH	15.87
OPERATING TEMP.	85.00	NOMINAL HEIGHT	13.33

AVG. OIL RISE: 49.
TOP OIL RISE: 70.2

COND. I^2R LOSS =	589.0457
COND. EDDY CURRENT LOSS =	4.1320
OTHER STRAY LOSS =	14.7261
K VALUE =	1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.26	98.35	.250	.537	.592	33.439	26.3
35	.37	98.63	.353	.749	.828	66.252	30.2
50	.54	98.75	.519	1.069	1.188	138.970	38.5
65	.74	98.72	.702	1.390	1.557	243.980	49.8
75	.88	98.66	.835	1.604	1.809	334.914	59.0
100	1.21	98.46	1.137	2.143	2.426	607.904	65.0
125	1.52	98.23	1.425	2.685	3.040	951.980	65.0
150	1.84	97.98	1.714	3.230	3.657	1374.303	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, M6 core steel, with a copper primary and aluminum secondary.

Bill of Materials and Labor for 50 kVA Pad-mount
M6CuAl

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	**Quantity**	**$ each**	**$ total**
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core *	219.14	$ 0.90	$ 216.95
Weight P1 *	60.15	$ 1.90	$ 125.71
Weight S1 *	9.66	$ 1.30	$ 13.81
Weight S2 *	16.46	$ 1.30	$ 23.54
Weight P1 Insulation *	2.24	$ 1.54	$ 3.79
Weight S1 Insulation *	1.38	$ 1.54	$ 2.34
Weight S2 Insulation *	1.06	$ 1.54	$ 1.80
Tank Oil Gal	53.7	$ 1.50	$ 80.60
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 859.66

Labor item	**hours**
P1 Labor	1.071
S1 Labor	0.034
S2 Labor	0.034
Lead Dressing Labor	0.800
Banding Labor	0.050
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.689
Hourly Rate	$ 42.77
Labor Cost $	$ 157.78
Manufacturing Cost $	$ 1017.44
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 1636.80

** indicates those items which had a scrap factor calculated in the $ total column = (Quantity * $ each * Scrap Factor)*

Figure 23 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 53% of the final selling price of an M6, copper primary and aluminum secondary, is direct material and scrap. Labor accounts for approximately 10% of the price, and overheads account for about 37%. For definitions of these categories, please see section 3.2 of this report.

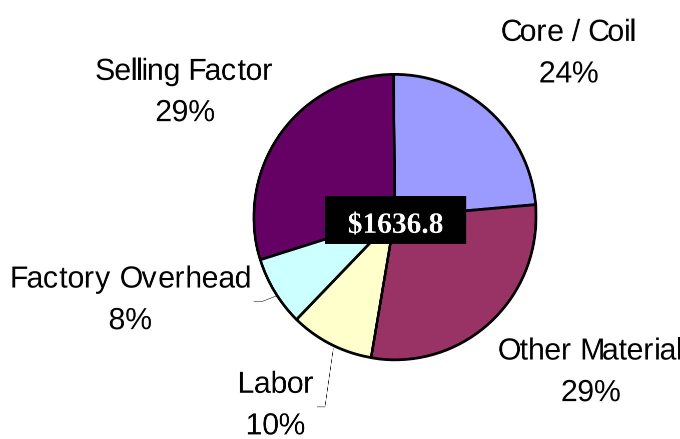

Figure 23. Selling Price Breakdown for M6CuAl

4.1.12 Results for SA1 (Amorphous) CuCu

Figure 24 provides a scatter plot of cost and efficiency relationship for the 1031 designs[24] of amorphous core (SA1) steel with a copper primary and secondary. These efficiency points are measured at 50% of nameplate load, the NEMA assumption for loading of this type of distribution transformer. Note that this design option combination achieves TP-1 for all of the designs in the database. Also note that the Manufacturer Sales Price axis has increased its range from a maximum of $2600 to $2800 to accommodate the more expensive designs in this design option combination.

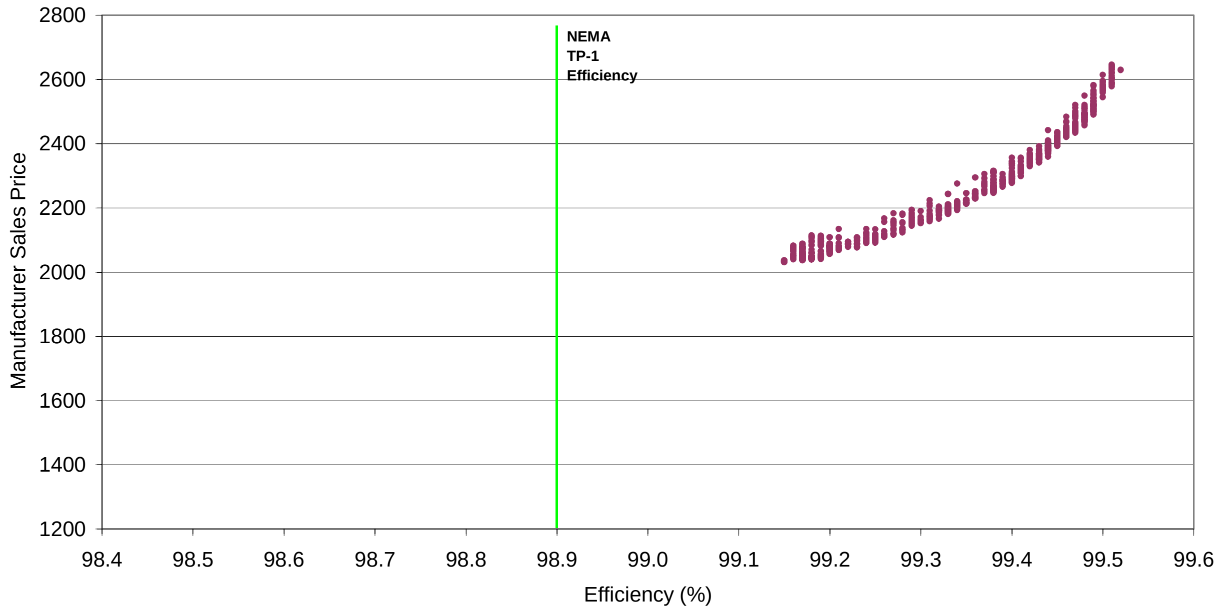

Figure 24. Manufacturer Sales Price vs. Efficiency for SA1CuCu at 50% load

[24] Note that the database of designs was generated by running the matrix of A and B values through the OPS design software, as discussed in Section 2.4.

A design specification sheet for SA1 core steel, copper primary, copper secondary, optimized for the design points of A=$3 and B=$1 follows. The bill of materials and associated breakdown of costs for this design is also reported, after the design and electrical analysis reports.

```
                       OPTIMIZED PROGRAM SERVICE

                   CLEVELAND OHIO            101800
                       2001-11-18    17:40:47
DG-CORE       SHELL   TYPE TRANSFORMER                50PSA1CUCU

FREQUENCY    60.0            KVA RATING     50.00 @ 100.00% DUTY CYCLE

CORE DG-SA1                          2605-SA1        THICKNESS .0010

  D: 8.913 E: 2.564 F: 3.273 G: 6.869  EFF. AREA  36.564 WEIGHT 270.223

WINDING FORM: INS. DIM.  9.163 X  5.503  THICKNESS  .030  LENGTH  6.619

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

WNDG             WIRE            LENGTH   MEAN TURNS  MARGIN      WT
----------------------------------------------------------------------
S1          .0245X 5.7435   CU      36.63      31.40     .438     19.871
P1         1 #12.5 ROUND    CU    2965.04      40.34     .625     52.301
S2          .0245X 5.7435   CU      57.06      48.91     .438     30.955

NUMBER OF COILS  1             TOTAL BARE CONDUCTOR WEIGHT   103.127

WNDG  TURNS  LO TAP  HI TAP  LAYRS   T/L   LAYR INS   SEC. INS    BUILD
----------------------------------------------------------------------
S1     14.0                  14      1.0  1(.00700)  1(.16800)     .434
P1    840.0   798.0   882.0 14     65.0  3(.00500)  1(.16800)    1.306
S2     14.0                  14      1.0  1(.00700)  1(.02100)     .434

                                                TOTAL BUILD(%)  84.75

                                                COIL CLEARANCE    .250
WNDG                TAPS: TURNS( VOLTS)
-----------------------------------------------------------
P1     819.0(  7020.00)   861.0(  7380.00)   882.0(  7560.00)


WNDG    INTERNAL DUCTS(100.00) %EFF  EXTERNAL DUCTS(100.00) %EFF
----------------------------------------------------------------
S1      1  .188 X  .188 IN.  END
P1      2  .188 X  .188 IN.  END          .188 X  .188 IN.  END
S2                                  .188 X  .188 IN.  END
```

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	7200.00	6840.00	7560.00	34.5	7.035	5.27700	1537.	
S1	118.64			10.0	208.330	.00212	1480.	1.1
S2	118.33			10.0	208.330	.00330	1480.	1.4

	F.L.	N.L.		
FLUX DENS.	13.544	13.632	LEAKAGE INDUCTANCE MHYS	66.184
CORE LOSS	34.872	35.381	POWER FACTOR	.9999
COIL LOSS	629.248	.035	IMPEDANCE %	2.71
EXCIT. VA	523.086	530.720	EFFICIENCY %	98.69
EXCIT. CURR.	.073	.074	TANK OIL GAL	19.71

AMBIENT TEMP.	20.00	NOMINAL LENGTH	16.80
TEMP.RISE	65.00	NOMINAL DEPTH	17.58
OPERATING TEMP.	85.00	NOMINAL HEIGHT	12.64

AVG. OIL RISE: 47.
TOP OIL RISE: 61.6

COND. I^2R LOSS = 607.6531
COND. EDDY CURRENT LOSS = 6.4036
OTHER STRAY LOSS = 15.1913
K VALUE = 1.0000

%LOAD	%REG	%EFF	%IR	%IX	%IZ	COIL LOSS	TEMP. RISE
25	.25	99.46	.244	.605	.653	32.438	9.7
35	.36	99.43	.347	.847	.916	64.586	14.1
50	.53	99.32	.512	1.212	1.316	136.269	23.1
65	.73	99.16	.696	1.577	1.724	240.477	35.3
75	.87	99.03	.832	1.822	2.003	331.198	45.1
100	1.25	98.69	1.187	2.438	2.711	629.248	65.0
125	1.58	98.39	1.487	3.056	3.399	986.244	65.0
150	1.92	98.09	1.791	3.678	4.091	1425.146	65.0

This is the breakdown of costs, or the 'bill of materials', associated with this design, SA1 core steel (amorphous metal), with a copper primary and copper secondary.

Bill of Materials and Labor for 50 kVA Pad-mount
SA1CuCu
(Amorphous metal core)

	$ values
A$ Input	3.00
B$ Input	1.00

Material item	Quantity	$ each	$ total
Tube Ins *	1	$ 0.56	$ 0.62
Weight Core **	270.22	$ 1.50	$ 486.40
Weight P1 *	52.3	$ 1.90	$ 109.31
Weight S1 *	19.87	$ 2.40	$ 52.46
Weight S2 *	30.95	$ 2.40	$ 81.71
Weight P1 Insulation *	2.05	$ 1.54	$ 3.47
Weight S1 Insulation *	1.12	$ 1.54	$ 1.90
Weight S2 Insulation *	0.73	$ 1.54	$ 1.24
Tank Oil Gal	52.9	$ 1.50	$ 79.32
Fixed Tank	1	$ 250.00	$ 250.00
HV Bushing	2	$ 7.00	$ 14.00
LV Bushing	3	$ 8.00	$ 24.00
Core Clamp	1	$ 9.25	$ 9.25
Fuse System	1	$ 35.00	$ 35.00
Tap Changer	1	$ 20.00	$ 20.00
Internal Hardware	1	$ 5.00	$ 5.00
Name Plate	1	$ 13.25	$ 13.25
Miscellaneous	1	$ 20.00	$ 20.00
Scrap Factor			1.1
Total Material Cost $			$ 1206.91

Labor item	hours
P1 Labor	0.882
S1 Labor	0.028
S2 Labor	0.028
Lead Dressing Labor	0.800
Banding Labor	0.150
Assembly Labor	0.500
Inspection Labor	0.100
Preliminary Test Labor	0.100
Final Test Labor	0.150
Packing Labor	0.500
Marking Labor	0.100
Miscellaneous Labor	0.250
Total Labor	3.588
Hourly Rate	$ 42.77
Labor Cost $	$ 153.46
Manufacturing Cost $	$ 1360.37
Factory Overhead	1.125
Selling Factor	1.43
Selling Price $	$ 2188.49

** indicates those items which had a scrap factor calculated*
*in the $ total column = (Quantity * $ each * Scrap Factor)*
*** for amorphous core, a scrap factor of 1.2 was used to reflect*
greater handling and processing problems associated with SA1

Figure 25 provides a summary of the costs contributing to the total selling price of this transformer. From this illustration it becomes clear that approximately 55% of the final selling price of an SA1 (Amorphous metal), copper primary and copper secondary, is direct material and scrap. Labor accounts for approximately 7% of the price, and overheads account for about 38%. For definitions of these categories, please see section 3.2 of this report.

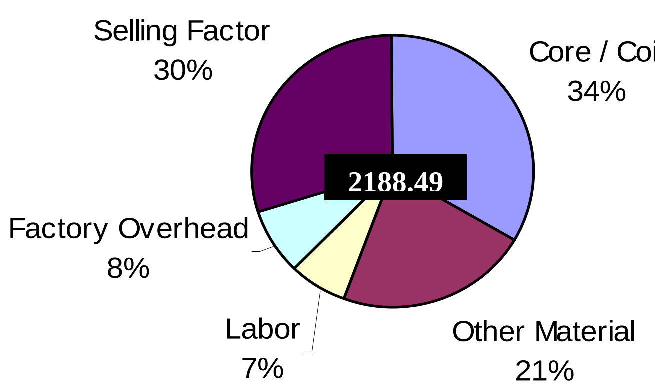

Figure 25. Selling Price Breakdown for SA1CuCu

4.2 Cross-cutting results

This section of the report provides limited analysis on the cost - efficiency attributes across the twelve design option combinations. In this section, a histogram of designs is presented; along with average cost-efficiency scatter plots and lowest cost-efficiency scatter plots.

The reader should bear in mind that the design databases were compiled using a range of A and B values ($0 to $8 for A by 0.2 increments and $0 to $3 for B by 0.1 increments). This range was selected based on available data from manufacturers on A and B values, consultation with transformer experts and study of the IEEE C57.12.33 draft standard on Total Ownership Cost. The database of designs presented here would have a different appearance if a larger or smaller range of A and B's was used.

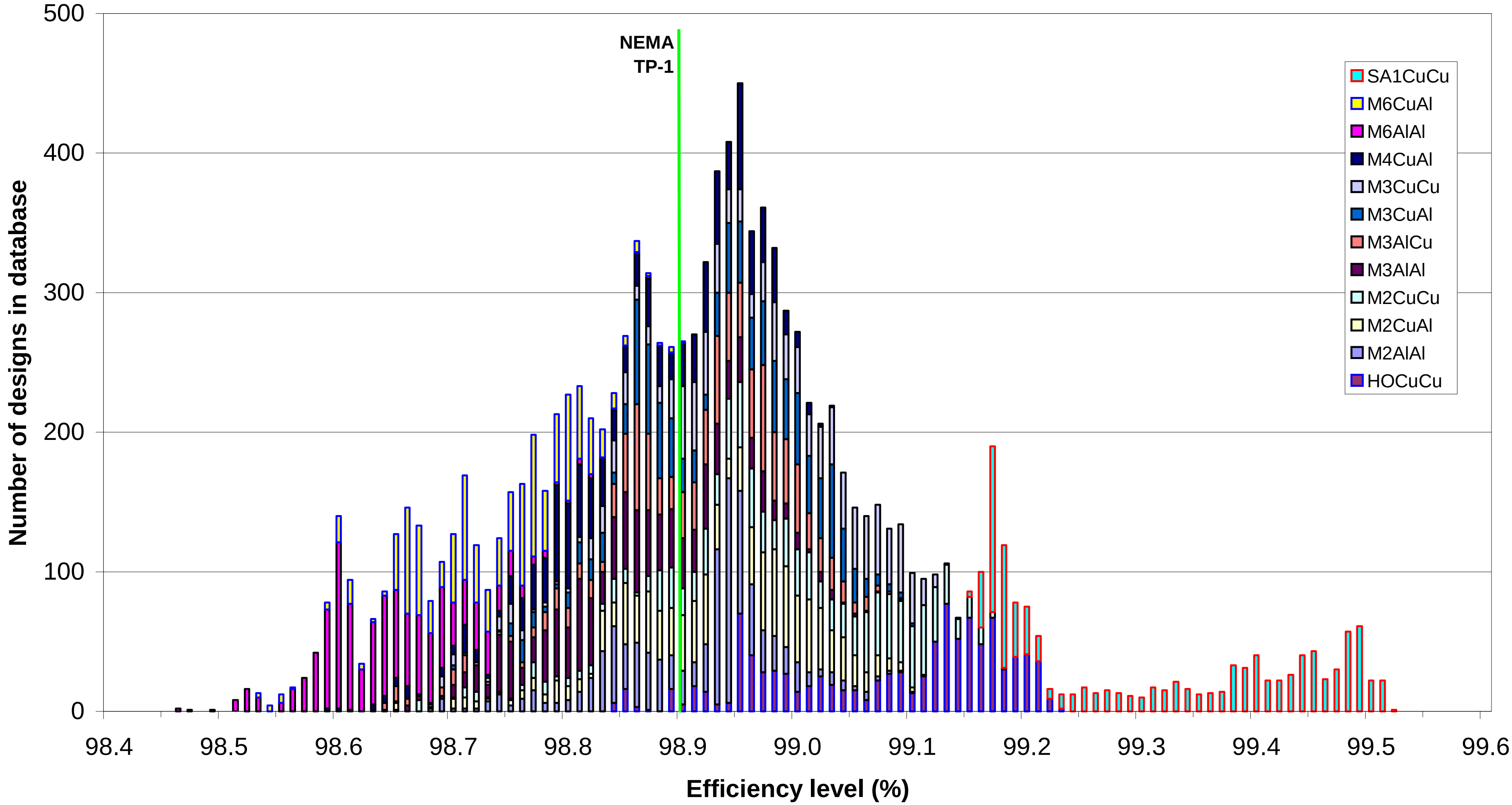

Figure 26. Histogram of plots by efficiency level in the database of designs

This figure illustrates the number of designs at each efficiency level generated by the OPS software for the range of A and B values used. The bar chart is cumulative, meaning different design option combinations will compound the number of designs at a given efficiency point. The various design option combinations can be identified by the legend to the right of the figure.

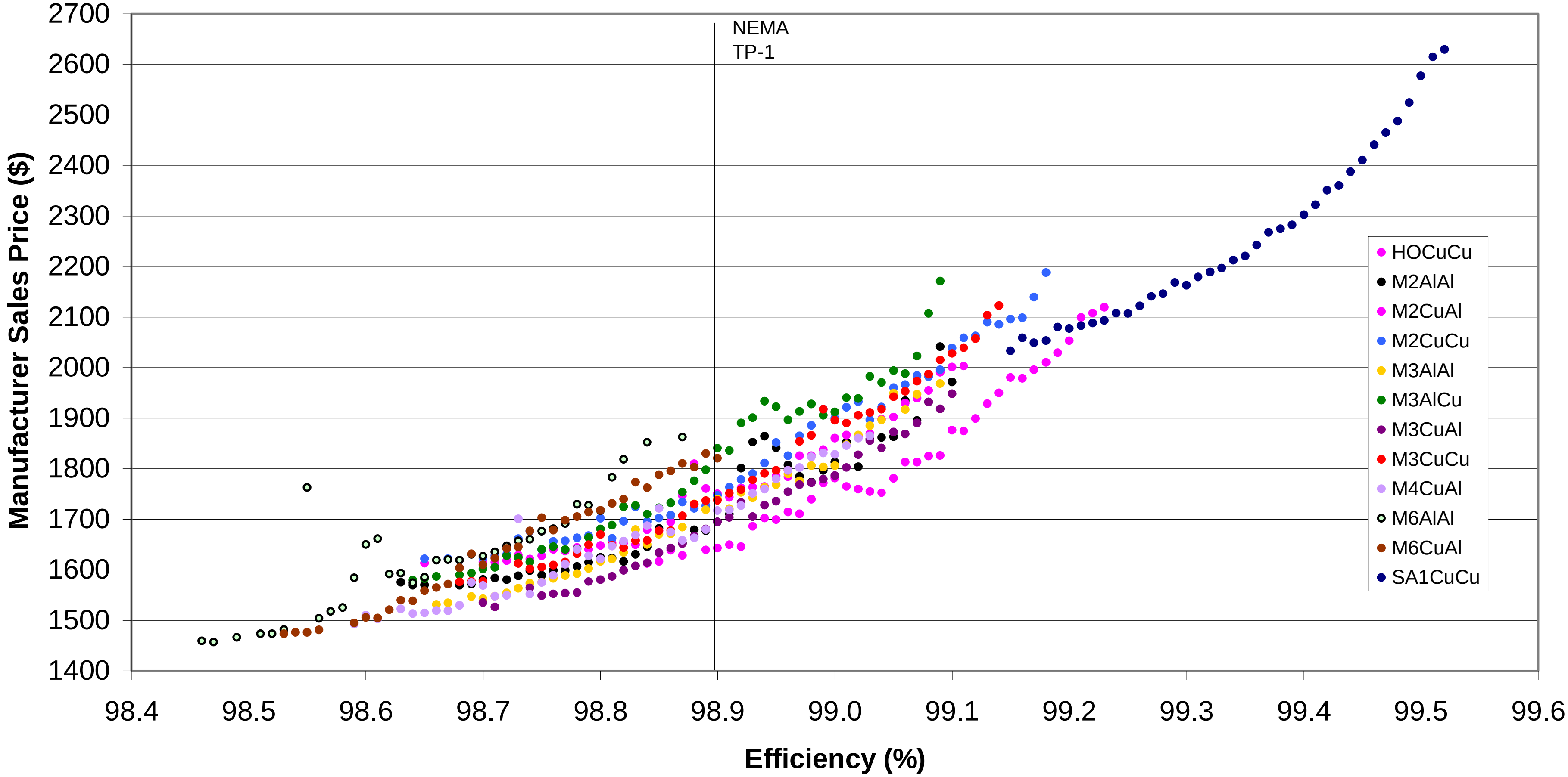

Figure 27. Average Prices of Design Option Combinations

This graph plots the average prices of the transformer designs in each of the twelve design option combination databases by efficiency point. The efficiency point increment selected was 0.01. Prices were averaged within each design option combination – i.e., as shown in the scatter plots throughout section 4.1, most efficiency points have several compliant designs at different prices. These prices would then be averaged together to establish one price for the design option combination at that efficiency point.

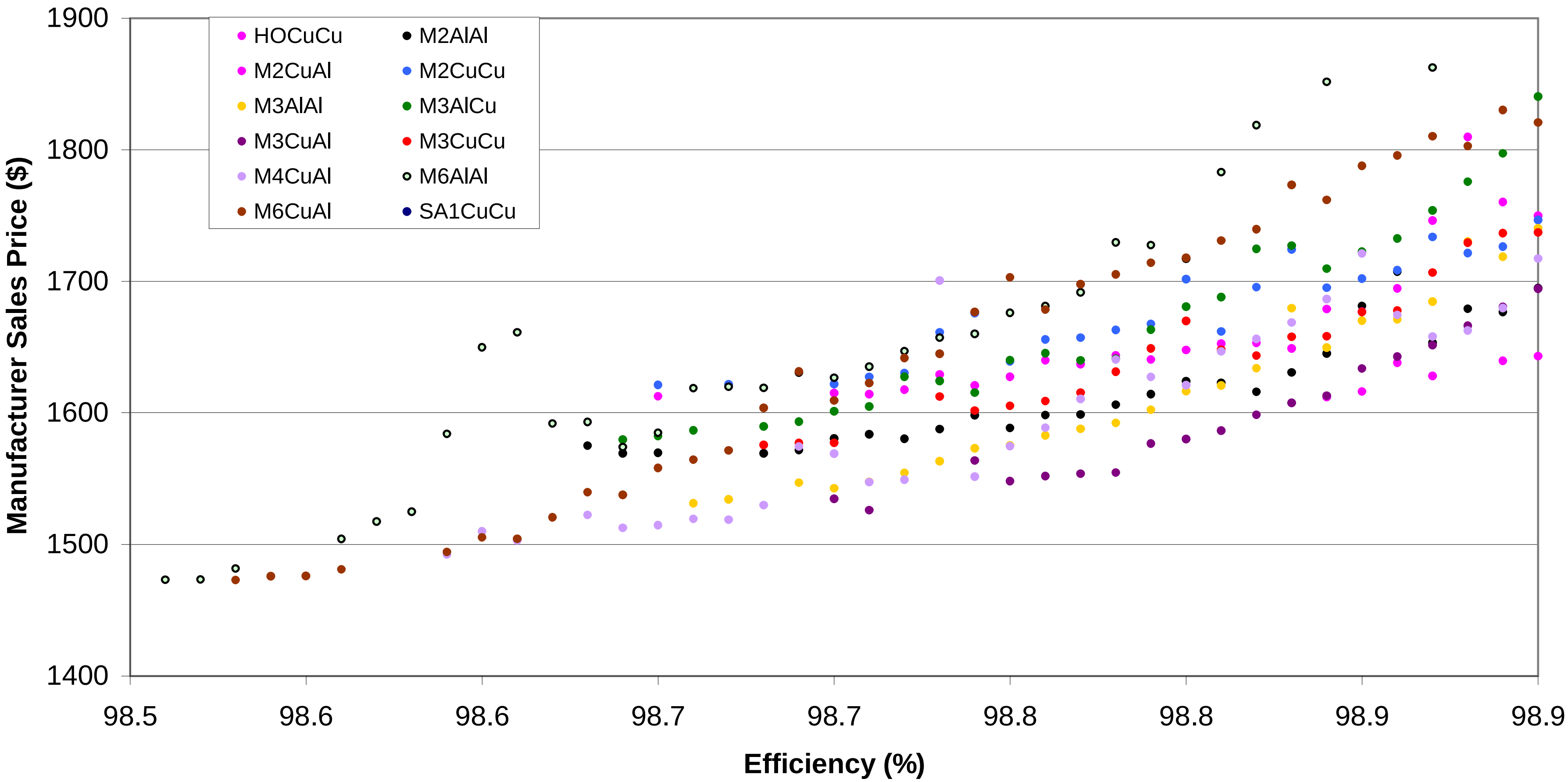

Figure 28. Average Prices of Design Option Combinations below TP-1

This graph zooms in on part of Figure 27, the efficiency levels below TP-1 (98.9%). From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices were averaged within each design option combination – i.e., as shown in the scatter plots throughout section 4.1, most efficiency points have several compliant designs at different prices. These prices would then be averaged together to establish one price for the design option combination at that efficiency point.

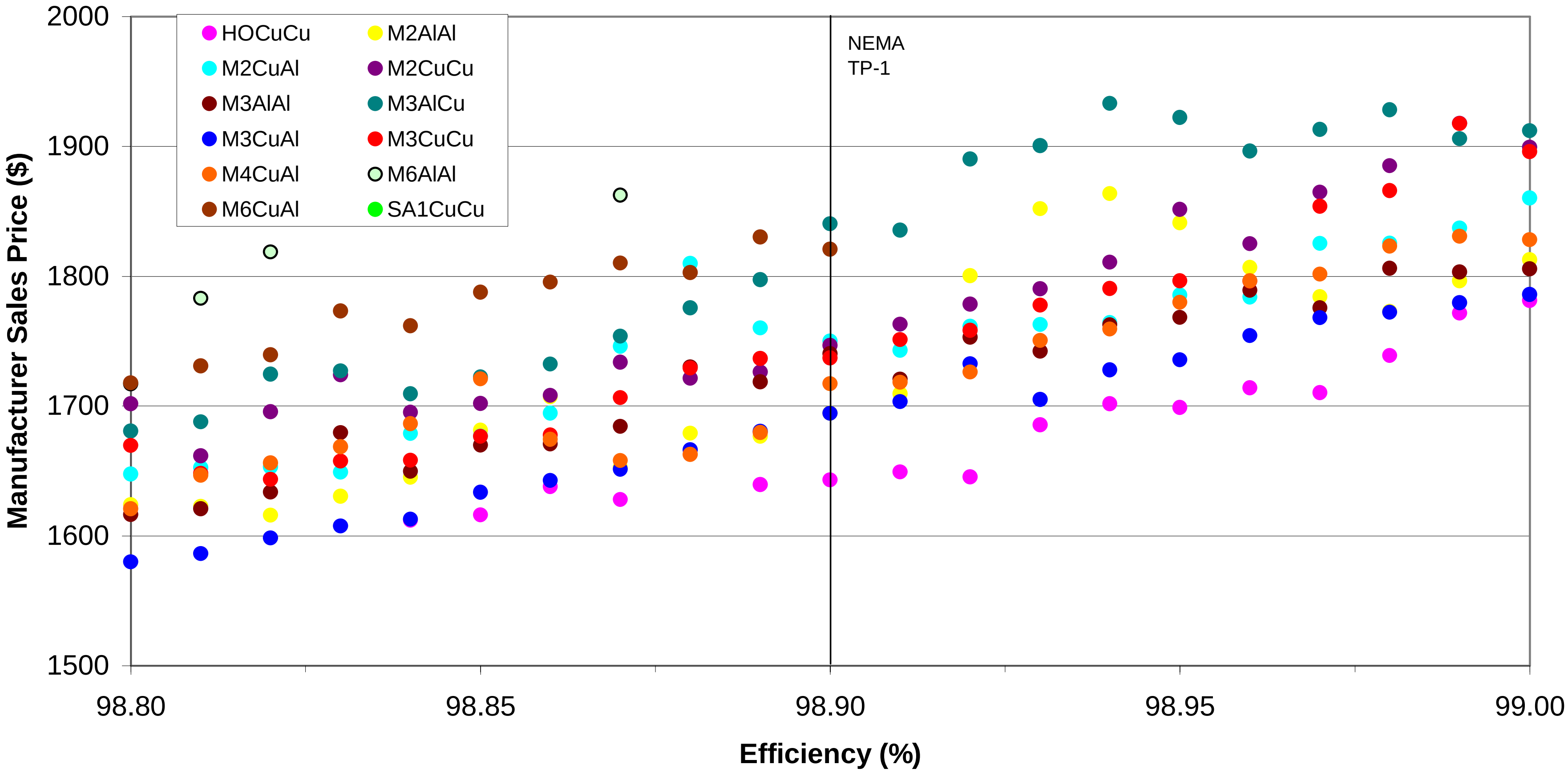

Figure 29. Average Prices of Design Option Combinations around TP-1

This graph zooms in on a different part of Figure 27, the efficiency levels around TP-1. From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices were averaged within each design option combination – i.e., as shown in the scatter plots throughout section 4.1, most efficiency points have several compliant designs at different prices. These prices would then be averaged together to establish one price for the design option combination at that efficiency point.

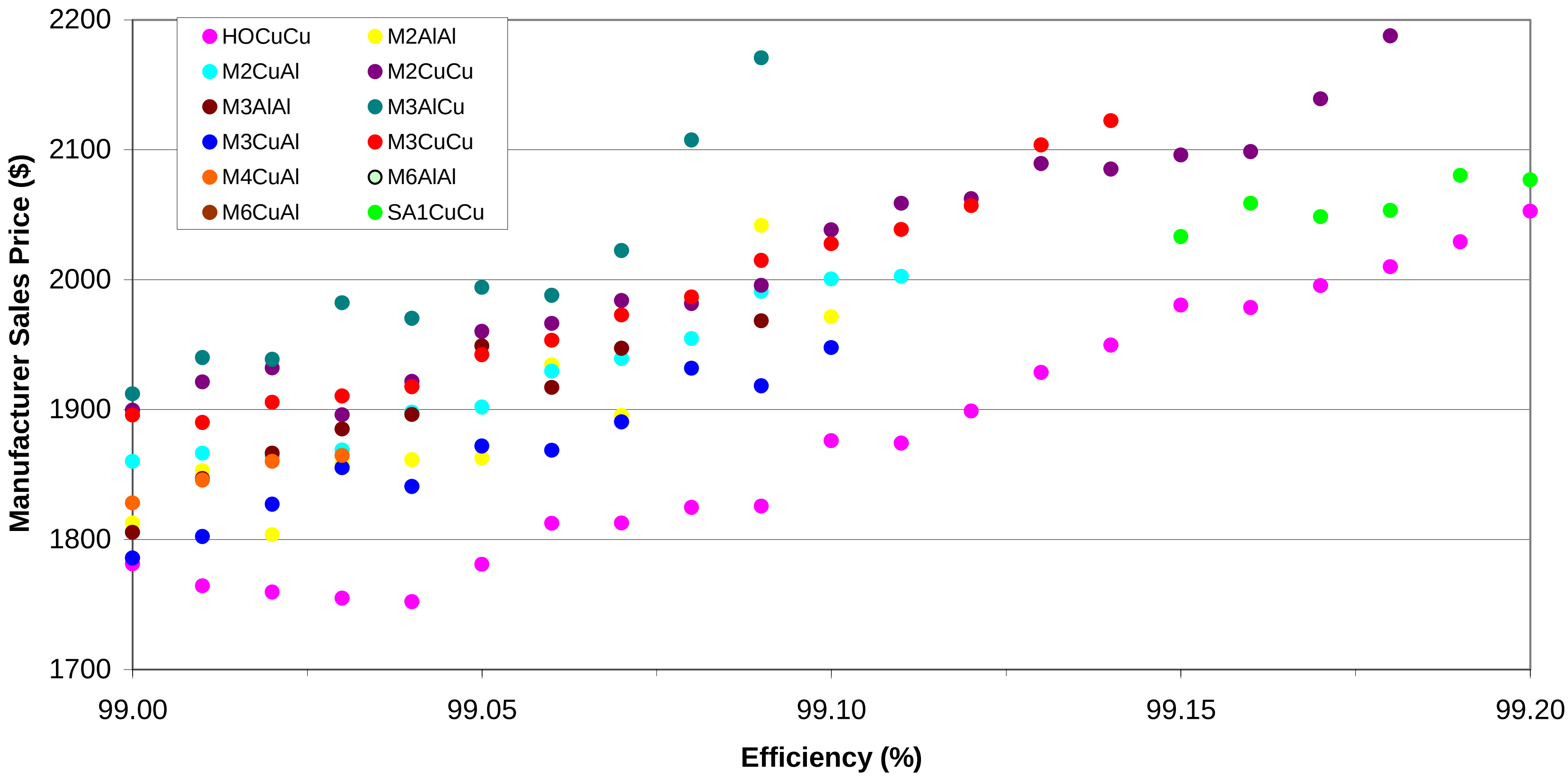

Figure 30. Average Prices of Design Option Combinations above TP-1

This graph zooms in on a different part of Figure 27, the efficiency levels above TP-1 (98.9%). From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices were averaged within each design option combination – i.e., as shown in the scatter plots throughout section 4.1, most efficiency points have several compliant designs at different prices. These prices would then be averaged together to establish one price for the design option combination at that efficiency point. In this figure, the laser scribed design option combination appears the most cost effective.

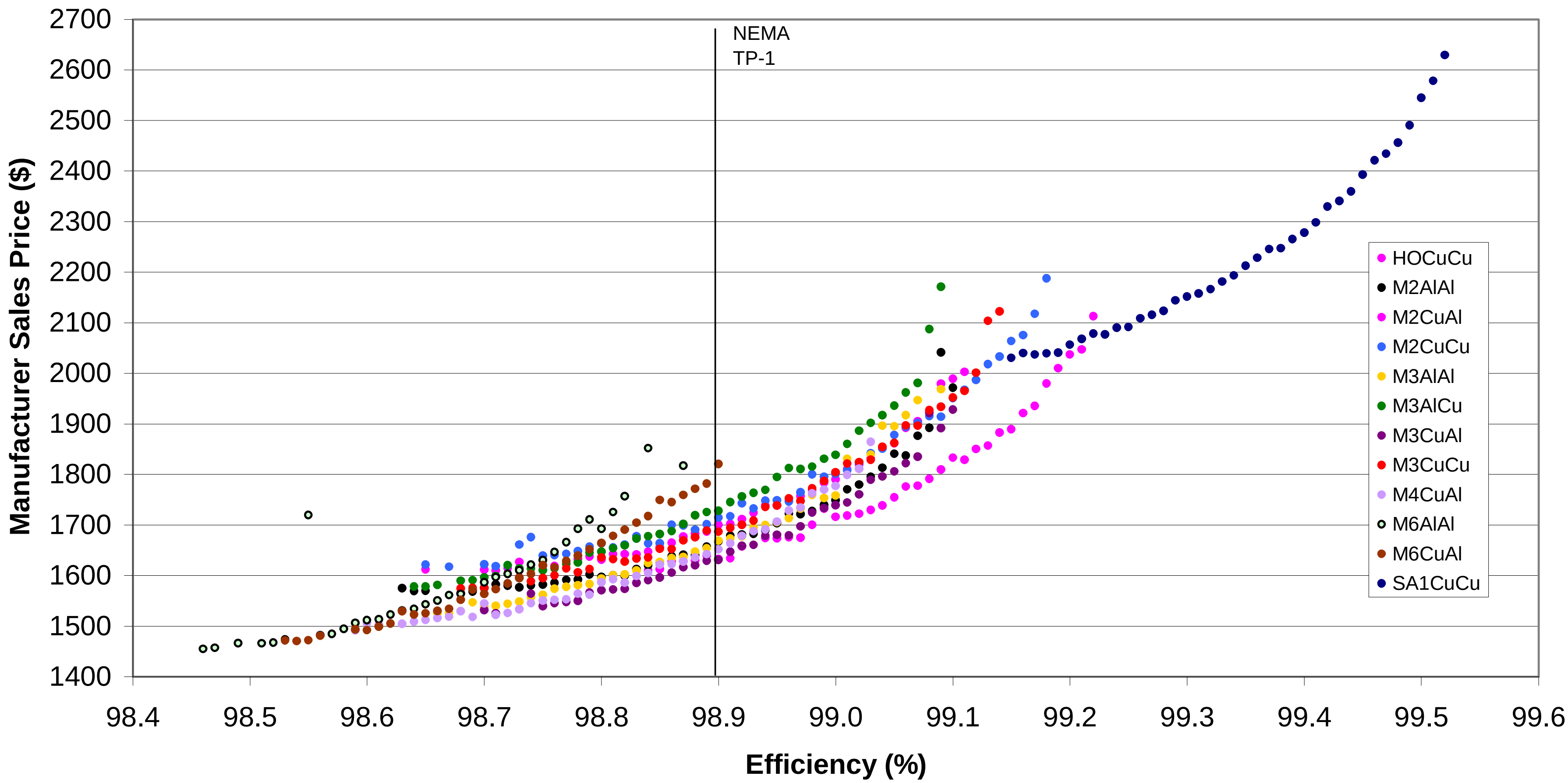

Figure 31. Minimum Prices of Design Option Combinations

This graph presents the minimum manufacturer sales price in the design database for each of the design option combinations at each of the efficiency points. Unlike the previous set of slides which averaged prices together for the compliant designs at a given efficiency point, this plot illustrates the least expensive design at that efficiency point for each design option.

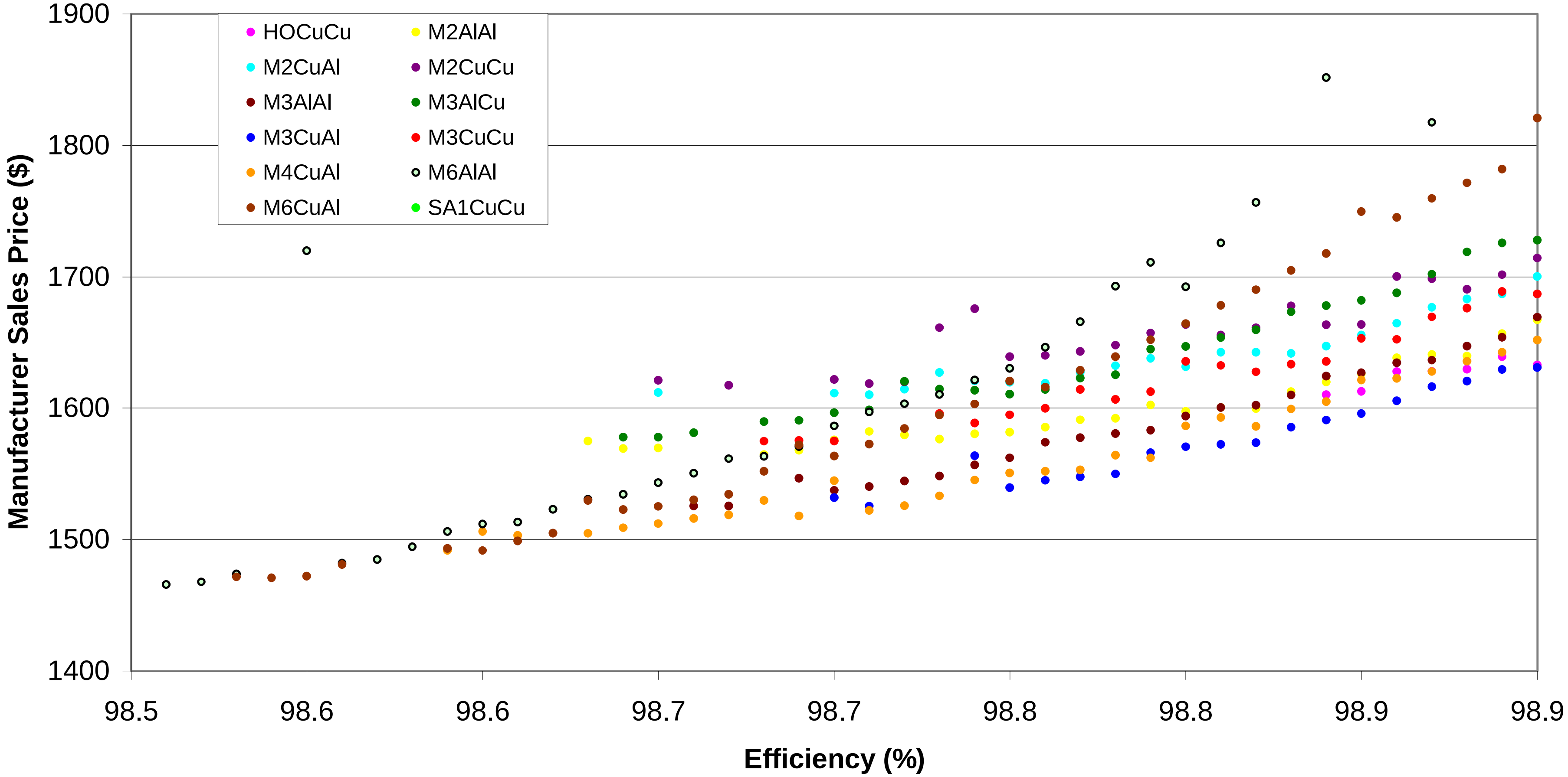

Figure 32. Minimum Prices of Design Option Combinations below TP-1

This graph zooms in on part of Figure 31, the efficiency levels below TP-1 (98.9%). From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices shown here are the lowest cost within each design option combination.

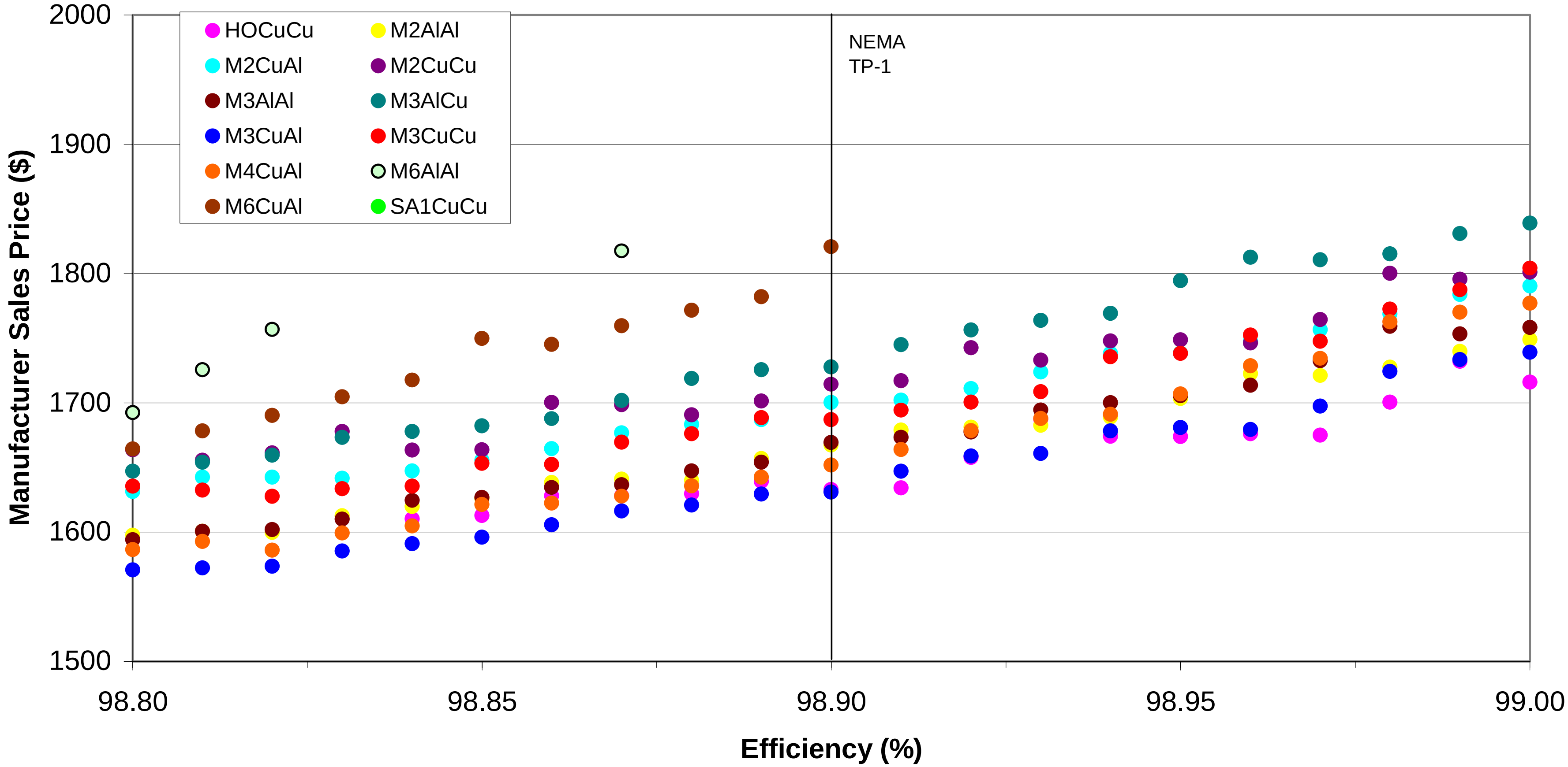

Figure 33. Minimum Prices of Design Option Combinations around TP-1

This graph zooms in on part of Figure 31, the efficiency levels around TP-1 (98.9%). From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices shown here are the lowest cost within each design option combination. At the NEMA TP-1 level, M3CuAl and HOCuCu appear to be the most cost effective design option combinations for achieving that efficiency point.

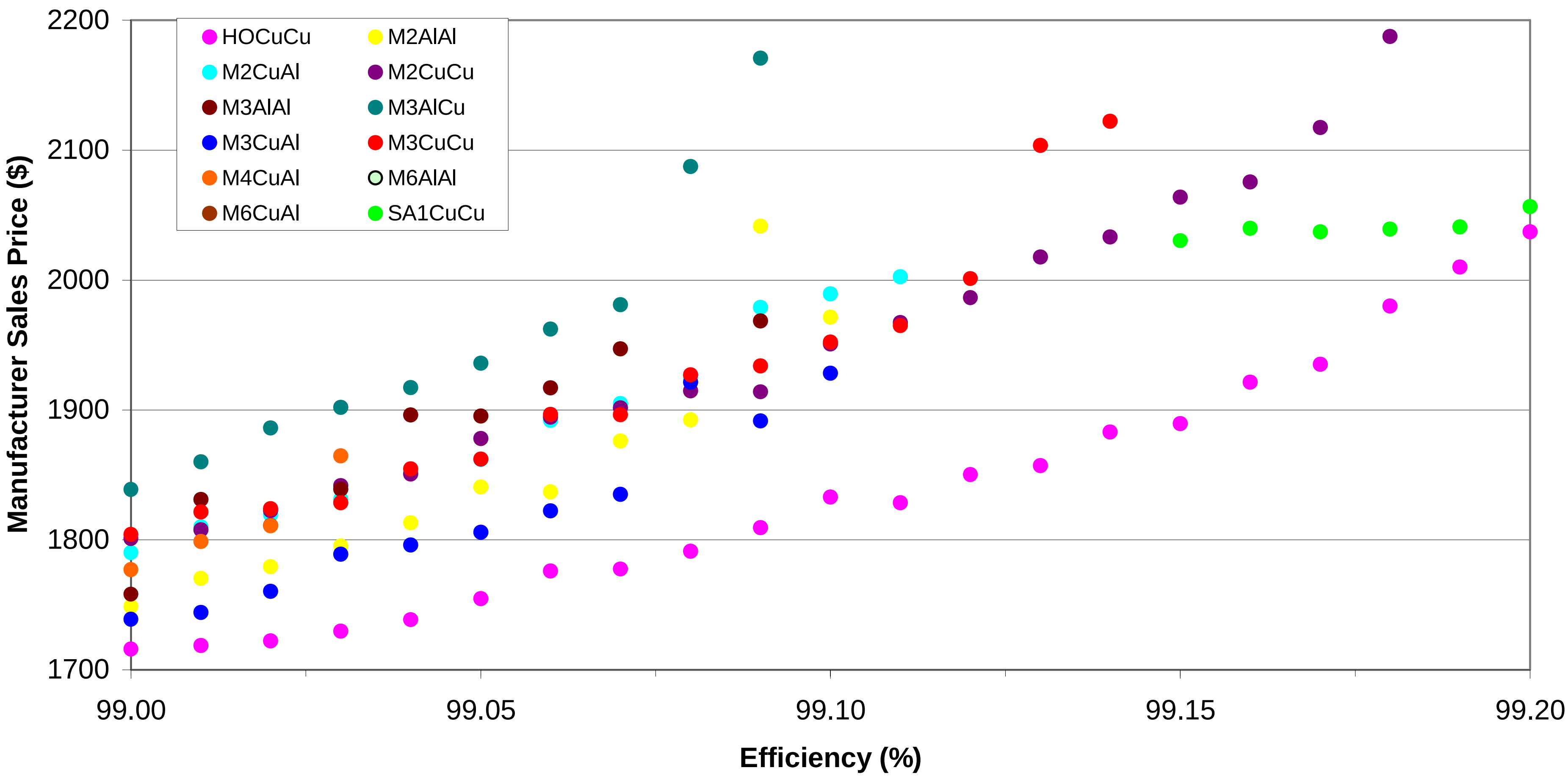

Figure 34. Minimum Prices of Design Option Combinations above TP-1

This graph zooms in on part of Figure 31, the efficiency levels above TP-1 (98.9%). From this plot it is possible to see which design option combinations are more competitive than others at achieving a certain efficiency level. Again, prices shown here are the lowest cost within each design option combination. In this plot, laser scribed (HOCuCu) appears the most cost effective across all design option combinations.

5. Remaining Liquid-Type Representative Models

The design option combinations – or most typical ways of building a representative model – are presented for the remaining liquid type units in this chapter. In section 3.1 of this report, the methods of building the 50 kVA unit representing design line 1 are provided. The following pages present the proposed methods of building representative units for design lines 2 through 7. The Department invites stakeholders to comment on these tables, proposed for study in the Engineering Analysis.

Table 8. Partial listing of design lines – only liquid-type units

Design Line	Type	# of Phases	KVA Range	Primary BIL	Primary Taps, Full Capacity	Secondary Voltage	Selected unit to represent Design Line
1	Liquid Pad	1	25-167	≤95 kV	±2-2.5%	240/120 through 600V	50kVA, 65°C, ONAN, 1Φ, 60Hz, 12470GrdY/7200 -240/120V, 95 kV BIL
2	Liquid Pole	1	10-167	≤95 kV	±2-2.5%	120/240 through 600V	25kVA, 65°C, ONAN, 1Φ, 60Hz, 12470GrdY/7200 -240/120V, 95 kV BIL
3	Liquid Pad	1	25-167	125-150 kV	±2-2.5%	240/120 through 600V	50kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 -240/120V, 125 kV BIL
4	Liquid Pole	1	10-167	125-150 kV	±2-2.5%	120/240 through 600V	25kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 -240/120V, 125 kV BIL
5	Liquid	1	250-833	≤95-150 kV	±2-2.5%	250-333 kVA: 120/240 through 2400/4160YV; 500-833 kVA: 277/480Y through 2400/4160YV	333kVA, 65°C, ONAN, 1Φ, 60Hz, 14400/24940Y – 277/480YV, 150 kV BIL
6	Liquid	3	30-225	≤95 kV	±2-2.5%	208Y/120-600V	150kVA, 65°C, ONAN, 3Φ, 60Hz, 12470Y/7200-208Y/120V, 95 kV BIL
7	Liquid	3	300-2500	≤95-150 kV	±2-2.5%	300-1000 kVA: 208Y/120 through 4160Y/2400V 1500-2500 kVA: 480Y/277 through 4160Y/2400V	1000kVA, 65°C, ONAN, 3Φ, 60Hz, 24940Δ-480Y/277V, 150 kV BIL

5.1 Design Line 2 – 25 kVA pole mount ≤95 kV BIL

Design Line 2 incorporates pole-mounted, single-phase, liquid-type transformers, from 10 through 167 kVA, with a BIL ≤95 kV, standard taps of 2 $\pm$ 2 ½ %, secondary voltages of 120/240 through 600V.

Representative model: 25kVA, 65°C, ONAN, 1Φ, 60Hz, 12470GrdY/7200 -120/240V, 95 kV BIL

KVA: 25 (liquid type, pole mount)
Primary: 7200 Volts at 60 HZ
Secondary: 120/240V
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi (Core-Type), Lo-Hi-Lo (Shell-Type)
Cores: DG
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range: 1.0 – 3.5%

Table 9. Design Option combinations for DL 2 - 25 kVA Pole-mount Transformer

25 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M6	AL	AL	Core-Type
2	M6	CU	AL	Core-Type
3	M4	AL	AL	Core-Type
4	M4	CU	AL	Core-Type
5	M3	AL	AL	Core-Type
6	M3	CU	AL	Core-Type
7	M2	CU	CU	Core-Type
8	Laser Scribed M3	CU	CU	Core-Type
9	Amorphous[25]	CU	CU	Core-Type
10	M6	AL	AL	Shell-Type
11	M6	CU	AL	Shell-Type
12	M4	AL	AL	Shell-Type
13	M4	CU	AL	Shell-Type
14	M3	AL	AL	Shell-Type
15	M3	CU	AL	Shell-Type

[25] For Amorphous metal cores, the design point magnetic flux density will be limited to 1.35 Tesla and a space factor of 0.80.

5.2 Design Line 3 – 50 kVA pad mount 125 – 150 kV BIL

Design Line 3 incorporates pad-mounted, single-phase, liquid-type transformers, from 25 through 167 kVA, with a BIL of 125-150 kV, standard taps of 2 ± 2 ½ %, secondary voltages of 240/120 through 600V.

Representative model: 50kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 -240/120V, 125 kV BIL

KVA: 50 (liquid type, pad mount)
Primary: 24940GrdY/14400 Volts at 60 HZ
Secondary: 240/120V
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi-Lo
Cores: DG
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range: 1.5 – 3.5%

Table 10. Design Option combinations for DL 3 - 50 kVA Pad-mount Transformer

50 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M6	AL	AL	Shell
2	M6	CU	AL	Shell
3	M4	CU	AL	Shell
4	M3	AL	AL	Shell
5	M3	AL	CU	Shell
6	M3	CU	AL	Shell
7	M3	CU	CU	Shell
8	M2	AL	AL	Shell
9	M2	CU	AL	Shell
10	M2	CU	CU	Shell
11	Laser Scribed M3	CU	CU	Shell
12	Amorphous	CU	CU	Shell

5.3 Design Line 4 – 25 kVA pole mount 125 – 150 kV BIL

Design Line 4 incorporates pole-mounted, single-phase, liquid-type transformers, from 10 through 167 kVA, with a BIL was 125-150 kV, standard taps of 2 ± 2 ½ %, secondary voltages of 120/240 through 600V.

Representative model: 25kVA, 65°C, ONAN, 1Φ, 60Hz, 24940GrdY/14400 - 120/240V, 125 kV BIL

KVA: 25 (liquid type, pole mount)
Primary: 24940GrdY/14400 Volts at 60 HZ
Secondary: 120/240V
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi (Core-Type), Lo-Hi-Lo (Shell Type)
Cores: DG
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range: 1.0 – 3.5%

Table 11. Design Option combinations for DL 4 – 25 kVA Pole-mount Transformer

25 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M6	AL	AL	Core-Type
2	M6	CU	AL	Core-Type
3	M4	AL	AL	Core-Type
4	M4	CU	AL	Core-Type
5	M3	AL	AL	Core-Type
6	M3	CU	AL	Core-Type
7	M2	CU	CU	Core-Type
8	Laser Scribed M3	CU	CU	Core-Type
9	Amorphous[26]	CU	CU	Core-Type
10	M6	AL	AL	Shell-Type
11	M6	CU	AL	Shell-Type
12	M4	AL	AL	Shell-Type
13	M4	CU	AL	Shell-Type
14	M3	AL	AL	Shell-Type
15	M3	CU	AL	Shell-Type

[26] For Amorphous metal cores, the design point magnetic flux density will be limited to 1.35 Tesla and a space factor of 0.80.

5.4 Design Line 5 – 333 kVA pad mount ≤95 – 150 kV BIL

Design Line 5 incorporates pad-mounted, single-phase, liquid-type transformers, from 250 through 833 kVA, with a BIL of ≤95-150 kV, standard taps of 2 ± 2 ½ %, secondary voltages of 120/240 through 2400/4160YV.

Representative model: 333kVA, 65°C, ONAN, 1Φ, 60Hz, 14400/24940Y – 277/480YV, 150 kV BIL

KVA: 333 (liquid type, pad mount)
Primary: 14400/24940Y Volts at 60 HZ
Secondary: 277/480Y Volts
T Rise: 65°C
Ambient: 20°C
Winding Configuration): Lo-Hi-Lo (Shell Type)**,** Lo-Hi (Core-Type)
Cores: DG
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range: 2.5 – 5.75%

Table 12. Design Option combinations for DL 5 - 333 kVA Pad-mount Transformer

333 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M4	AL	AL	Shell
2	M3	CU	AL	Shell
3	M2	CU	AL	Shell
4	M2	CU	CU	Shell
5	Laser Scribed M3	CU	CU	Shell
6	Amorphous	CU	CU	Shell
7	M4	AL	AL	Core
8	M2	CU	AL	Core

5.5 Design Line 6 – 150 kVA pad mount ≤95 kV BIL

Design Line 6 incorporates pad-mounted and platform-mounted, three-phase, liquid-type transformers, from 30 through 225 kVA, with a BIL ≤95 kV, standard taps of 2 ± 2 ½ %, secondary voltages of 208Y/120 through 600V.

Representative model: 150kVA, 65°C, ONAN, 3Φ, 60Hz, 12470Y/7200-208Y/120V, 95 kV BIL

KVA: 150 (liquid type, pad mount)
Primary: 12470Y/7200 Volts at 60 HZ
Secondary: 208Y/120 Volts
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi
Cores: DG
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range:

Table 13. Design Option combinations for DL 6 – 150 kVA Pad-mount transformer

150 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M4	AL	AL	5-Leg Core
2	M3	CU	AL	5-Leg Core
3	M3	CU	CU	5-Leg Core
4	M2	CU	AL	5-Leg Core
5	M2	CU	CU	5-Leg Core
6	Laser-Scribed M3	CU	AL	5-Leg Core
7	Laser-Scribed M3	CU	CU	5-Leg Core

5.6 Design Line 7 – 1000 kVA pad mount ≤95 - 150 kV BIL

Design Line 7 incorporates pad-mounted, three-phase, liquid-type transformers, from 300 through 2500 kVA, with a BIL of ≤95 to 150 kV, standard taps of 2 ± 2 ½ %, secondary voltages of 208Y/120 through 4160Y/2400V.

Representative model: 1000kVA, 65°C, ONAN, 3Φ, 60Hz, 24940Δ-480Y/277V, 150 kV BIL

KVA: 1000 (liquid type, pad mount)
Primary: 24940 Delta Volts at 60 HZ
Secondary: 480Y/277V Volts
T Rise: 65°C
Ambient: 20°C
Winding Configuration: Lo-Hi
Cores: DG or Stacked-Mitered (3-Leg)
Taps: Four 2½ %, 2 above and 2 below normal
Impedance Range: 5.75%

Table 14. Design Option combinations for DL 7 - 1000 kVA Pad-mount Transformer

1000 kVA Design Option #	Core Material	Conductor HV	Conductor LV	Design Type
1	M4	AL	AL	5-Leg Core
2	M4	AL	AL	3-Leg Core
3	M3	CU	AL	5-Leg Core
4	M3	CU	AL	3-Leg Core
5	M2	CU	CU	5-Leg Core
6	M2	CU	CU	3-Leg Core
7	Laser-Scribed M3	CU	AL	5-Leg Core
8	Laser-Scribed M3	CU	AL	3-Leg Core

Appendix A. 0.75 Scaling Rule

Scaling or Size-Performance Relations in Transformers

Ben McConnell
Oak Ridge National Laboratory
June 8, 2001

There exist certain fundamental relations between the ratings in kVA of transformers and their physical size and performance. A rather obvious such relationship is the fact that large transformers of the same voltage have "inherently" less percentage loss than small units; i.e., are more efficient. These size performance relationships arise from the fundamental equations describing the transformers voltage and ratings. For example, for a fixed rating and frequency, the product of the current density, flux density, core cross-section, and total conductor cross-section is constant.

To illustrate this point, consider a transformer with fixed frequency, magnetic flux and current densities, and fixed BIL. If one enlarges (decreases) the rating, then the only free parameters are the core or iron cross section and the core window area through which the windings pass. Thus, to increase (decrease) the kVA rating, the frame dimensions are scaled equally in all dimensions. Careful examination revels that linear dimensions vary as the ratio of kVA's to the ¼ power. Similarly, areas vary as the ratios of kVA's to the ½ power and volumes vary as the ration of the kVA's to the ¾ or 0.75 power. Hence the term 0.75 rule.

If we limit or discussion to a particular type of transformer; i.e., single phase or three phases, low or medium voltage, a defined core construction, liquid or dry, distribution or power, then the following elements are essentially true as the kVA is varied:

1. The physical proportions are constant (same relative shape),
2. The flux density and core material type are constant,
3. The current density in the conductor and the conductor material are constant,
4. The eddy loss proportion is essentially constant, and finally,
5. 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 0.5 orders of magnitude (say 50-500 kVA) in both directions, the scaling rules shown in Table A.1 can be used to establish reasonable estimates of performance, dimensions, cost and losses. In practice, these rules are applied over even wider ranges to estimate general performance levels. The same quantities are depicted graphically in Figure A.1 for reference.

To illustrate how the scaling laws are used consider two transformers of kVA rations, S_0 and S_1. Given the no load (NL_0) or core loss in transformer S_0 and scaling this design to S_1 then $NL_1 = NL_0 \text{ x } (S_1/S_0)^{3/4}$. The relationships can be carefully manipulated algebraically; e.g., knowing that NL and total loss (TL) scale to the ¾ power, we find that load loss (LL) also scales to the ¾ power. Specifically:

$$LL_1 = TL_1 – NL_1$$
$$= TL_0 \text{ x } (S_1/S_0)^{3/4} – NL_0 \text{ x } (S_1/S_0)^{3/4} = (TL_0 – NL_0) \text{ x } (S_1/S_0)^{3/4}$$
$$= LL_0 \text{ x } (S_1/S_0)^{3/4}.$$

Table A.1 – Common scaling ratios in transformers

Quantity	Relative to kVA	Relative to a reference dimension, l
Rating	kVA	l^4
Weight	K $kVA^{3/4}$	K l^3
Cost	K $kVA^{3/4}$	K $(\% \text{ Total Loss})^{-3}$
Length	K $kVA^{1/4}$	K l
Width	K $kVA^{1/4}$	K l
Height	K $kVA^{1/4}$	K l
Total Losses	K $kVA^{3/4}$	K l^3
No-load losses	K $kVA^{3/4}$	K l^3
Exciting Current	K $kVA^{3/4}$	K l^3
% Total loss	K $kVA^{-1/4}$	K l^{-1}
% No-load loss	K $kVA^{-1/4}$	K l^{-1}
% Exciting Current	K $kVA^{-1/4}$	K l^{-1}
% R	K $kVA^{-1/4}$	K l^{-1}
%X	K $kVA^{1/4}$	K l
Volts/turn	K $kVA^{1/2}$	K l^2

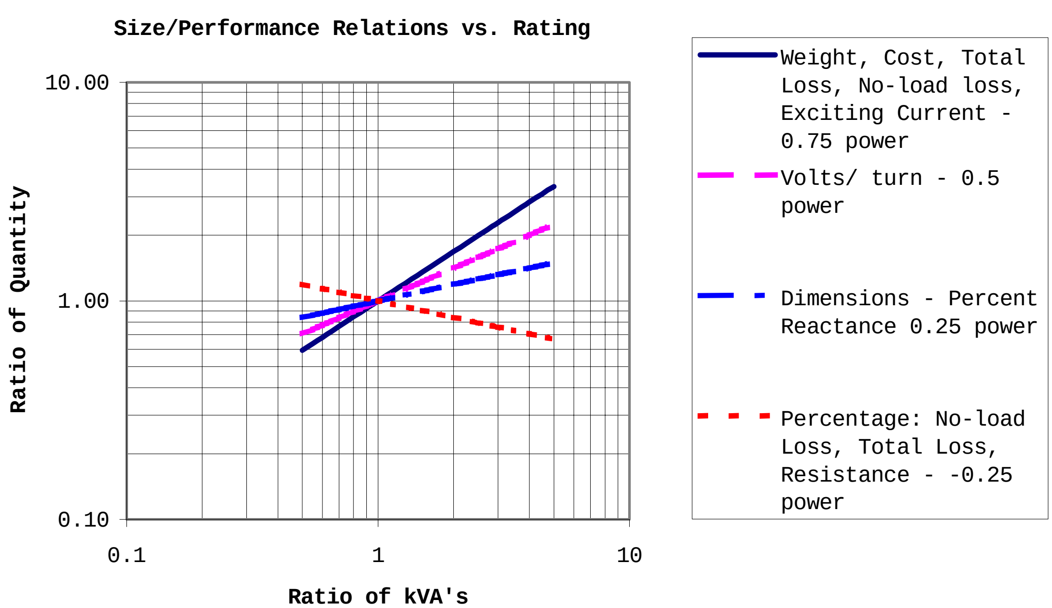

Figure A.1 – Graphical presentation of scaling rules

Theory and Basis for Scaling Rules

In order to understand the origins of winding and output coefficients and related scaling laws, it is necessary to review some basic equations and definitions. Most are lifted freely or derived from similar material in the text, **Modern Power Transformer Practice**, Wiley 1979, edited by R. Feinberg. This material is rather mathematical in nature and is included for completeness for those willing to "wade through" the mathematics. No mathematics beyond elementary algebra is required but there is a good deal of implied physics and electrical engineering required to fully appreciate these derivations.

Power and Voltage Equations

The machine equation relates the induced volts V (per phase) to the number of turns (N) the frequency (f) in Hertz, the peak core flux density B_m in Tesla, and the cross-sectional area of the core steel (A_{Fe}) in square meters. The units are mixed to simplify the basic equations, a common practice in transformer design texts. Since the insulation performance and quantity are key to machine dimensions, it is customary to express this in volts per turn:

$$V/N = 4.44\ f\ B_m\ A_{Fe}. \qquad (1)$$

The voltage and turns may apply to either winding and for the ideal transformer with no losses and no leakage flux, $V_1/V_2 = N_1/N_2 = n = I_2/I_1$. The quantity n is referred to as the turn ratio. This allows us to express the output or transformer capacity (S) in MVA/phase as

$$S = 4.44\ f\ B_m\ A_{Fe}\ N\ I = 2.22\ f\ B_m\ J\ A_{Fe}\ A_{Cu} = 1.11\ f\ B_m\ J\ A_{Fe}\ k_w\ A_w. \qquad (2)$$

Here the current (I) is in amps and current density (J) is in A/mm^2. The conductor cross-section in square meters, $A_{Cu} = (N_1a_1 + N_2a_2) \times 10^{-6}$ and assuming equal current density in each winding, $A_{Cu} = 2 \times 10^{-6}$ Na where 'a' is the conductor cross-section in mm^2 referred to the winding with N turns. As long as the winding current densities are equal either winding may be used as reference, just be consistent. A_w is the core window area in square meters, and $k_w = 2\ A_{Cu}\ /A_w$ is the window space factor. This fraction is indicative of the insulation and coolant channel requirements. For distribution transformers k_w is found to be about 0.3-0.4 for nominal 12 kV systems. Note that for a given rating and specified flux and current density, the product of conductor and core cross-section is constant and inversely related; i.e., $A_{Fe} = 1/A_{Cu}$.

Losses

Ideally, if the energy loss per unit mass (p_{Fe}, p_{Cu} in W/kg) of the materials constituting the core and windings are known, the total core and load losses (P_{Fe}, P_{Cu}) can be obtained by multiplying by the core and conductor masses (or their volumes x material density). We use the convention that lower case corresponds to per unit quantities and upper case corresponds to total or to total per phase quantities. Conductor losses consist of resistive (p_R) and eddy (p_i) components. Expressions can be derived that express each in terms of the conductor properties and geometry. The fraction of eddy losses plays an important role and can be expressed as $\%\ P_i = 100\ P_i/P_R$. Ignoring stray loss, total conductor losses, $P_l = 3P_{Cu}$, and assuming the same eddy loss fraction in each winding, $P_{Cu}=(1+\%\ P_i\ /100)\ P_R = k_i\ P_R$. We can express %R in terms of P_l in watts and S in MVA as $\%R = 10^{-4}\ P_l\ /3S$. Thus, an expression of %R is equivalent to indicating the transformer's load loss.

From equation (2), it is evident that once the core flux density and current density are set, the transformer rating is dependent upon the core cross-section and window area. At this point there is nothing to tell us about the window shape. In a detailed discussion of the reactance, the electrical characteristics depend upon the ratios h/s of winding height (h) to the mean winding circumference ($s = (s_1 + s_2)/2$) and A_{Fe}/A_{Cu}. These ratios together with the necessary space factors for insulation and cooling clearances establish the relative volumes of the core and conductor. Consequently, if fixed values for the specific loadings and therefore specific losses for core and conductor can be assumed, the ratios of total conductor and core loss are established.

It is a rather tedious but straightforward application the simple expression of $P_{Cu} = (1+\% P_i /100) P_R = k_i P_R$, an expression relating the flux and current density can be derived. Specifically,

$$J = C (f B_m / k_i) (A_{Fe}/s) \%P_{Cu}, \qquad (3)$$

Where J is in A/mm^2, C = 1040 for Cu and 655 for Al windings. The expression assumes equal J in both windings and that both windings are made of the same materials. The losses are expressed at operating temperature.

Hence, if J and B_m are chosen independently, the transformer will have a natural value of conductor loss depending upon the ratio A_{Fe}/s. Conversely, if losses are specified, the choice of J is determined by B_m and A_{Fe}/s. Note that this relationship gives no information about the other transformer dimensions. The impedance, voltage, and other space requirements provide the majority of this information.

Output and Winding Coefficients

By careful manipulation of the output or power equation (2), we are able to write

$$A_{Fe} = \{(1/2.22\, f B_m J) (A_{Fe}/A_{Cu})\}^{1/2} S^{1/2} = K_{AS} S^{1/2}. \qquad (4)$$

The expression K_{AS} is essentially constant for a wide range of transformer classes and is called the output coefficient. For three-phase liquid filled distribution transformers at 60 Hz, the value of K_{AS} ranges from 0.050-0.055 with a nominal median value of 0.052. For single phase, wound core, liquid filled units at 60 Hz the median value is about 0.040.

In a similar fashion making use of equation (4), we can restate equation (1) as

$$V/N = \{(8.88\, f B_m /J) (A_{Fe}/A_{Cu})\}^{1/2} S^{1/2} = K_{VS} S^{1/2}. \qquad (5)$$

The expression K_{VS} is also essentially constant for a wide range of transformer classes and is called the winding coefficient. We can also express K_{VS} in terms of K_{AS}

$$K_{VS} = 4.44\, f B_m K_{AS}. \qquad (6)$$

For 60 Hz systems this may be rewritten as $K_{VS} = 266.4 B_m K_{AS}$. Thus the median values for K_{VS} become 21.5 for three-phase and 17.0 for single-phase wound core distribution transformers at 60 Hz with Bm = 1.55 Tesla. Equations (4)-(6) provide initial estimates for transformer dimensions in studies. They are the starting basis for the scaling laws used to scale designs and performance. Typical values are given in Table A.2 for core type, liquid filled, 60 Hz distribution transformers at 12 kV, 95 kV BIL.

Table A.2 Nominal 60 Hz, core type liquid filled 12 kV distribution transformers

Class of Dist XFRM	$J(A/mm^2)$		B_m(Tesla)	A_{Fe}/A_{Cu}		K_{AS}		K_{VS}	%X
	Range	Nominal	Nominal	Range	Nominal	Range	Nominal		
3-Phase	2.4-3.2	2.7	1.55	1.4-2.8	1.6	0.050-0.055	0.052	21.5	4.75
1-Phase	2.0-2.5	2.3	1.55	0.65-0.85	0.8	0.038-0.043	0.041	17.0	4.75

Scaling Laws

Having established the output and winding coefficients, it is instructive to examine the origin of the 0.75 rules for scaling transformer losses. To illustrate, we consider the load losses, P_{Cu} (in kW/phase):

$$P_{Cu} = I^2R/1000 = (S/V)^2 R/1000 = 4.28 \times 10^{-17} S^2 s/ A_{Cu} (V/N)^2 = K S^{1/2} s = K` S^{0.75} \qquad (7)$$

In arriving at this expression, we use the relationships $V/N = K_{VS} S^{1/2}$, $A_{Cu} = K_{CS} S^{1/2}$, $A_{Fe} = K_{AS} S^{1/2}$, and $s \sim A_{Fe}^{1/2} + b_w/4 \sim S^{1/4}$. The shape of the window is set by voltage and the ratio h/s, which is essentially constant for a given voltage and size thus setting b_w. The expression for K_{CS} is easily derived from K_{AS} and the inverse relationship between the iron and conductor areas. Refer to Figure A.2 for dimensional definitions.

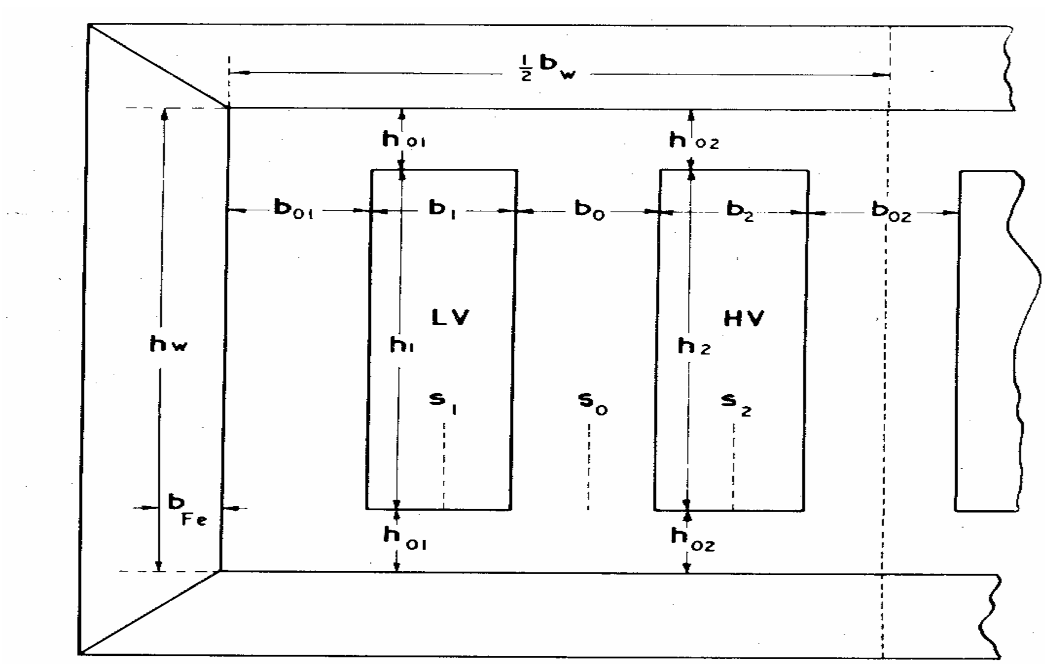

Figure A.2 Basic three-phase transformer dimensions, showing 1 leg and half the window

Appendix B. Optimized Program Service, Inc.

Optimized Program Service was retained to conduct the computer modeling runs on the representative models from each of the design lines. This section provides some background on the company and their design software.

Company profile

Optimized Program Service (OPS), Inc. began in 1969 to provide comprehensive design tools for the transformer industry. OPS blends magnetic design theory with practical manufacturing experience, resulting in a series of innovative software products that provide accurate and reliable designs.

The OPS programming staff has over one-hundred years of combined experience in transformer design and manufacturing. The programs are fast, accurate and easy to use, and have been proven in use throughout the world for over thirty years. Present and past clientele include large and small transformer manufacturers, designers and specifiers all over the world - from small one-man companies to large international blue-chip corporations.

How the software works

Design requirements are submitted to the program, which directs the user through the entire design process, asking for all data necessary to develop a design that meets the specific requirements of the application. Multiple-choice questions and on-screen illustrations show alternatives that are available for each condition and provide a graphical representation of the selections. The designer can use preprogrammed default values or change the data to meet any special requirements of the design.

Design data are then submitted to the programs that will develop a practical design. Using modular architecture, specific routines are called in to achieve different levels of functionality. The programs can automatically select cores, wires or insulation, or the user can enter their own.

The format of the program's output includes physical characteristics, dimensions, material requirements, and mechanical clearances, as well as a complete and very comprehensive electrical analysis of the final design.

Software used for the Engineering Analysis

Two OPS programs were used to generate the design database for the engineering analysis. These included 2TRANS and TOPT. The 2TRANS is a comprehensive design program used to design a wide range of linear transformers. For small linear transformers 2TRANS will design a broad range of single or three-phase transformers with or without rectified outputs. For large transformers, 2TRANS will handle ratings upwards of 5000 kVA. Standard industry winding schemes such as barrel, disk & section winding are accommodated. Cooling methods available are air, forced-air and oil-filled. 2TRANS is used to design a range of transformers, including distribution transformers.

TOPT is a transformer design optimization program, which uses sophisticated mathematical routines to develop the best combination of materials to minimize cost, weight or size of a transformer. It is used when the designer has complete freedom to change core dimensions. TOPT works in tandem with 2TRANS to produce practical designs close to the true optimum.

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