U.S. Department of Energy
Energy Efficiency and Renewable Energy

Energy Conservation Standards for Distribution Transformers

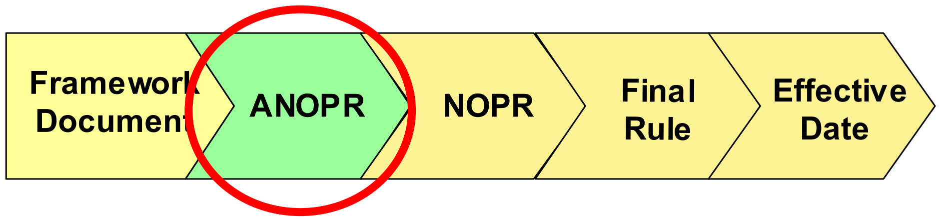
ANOPR Public Meeting

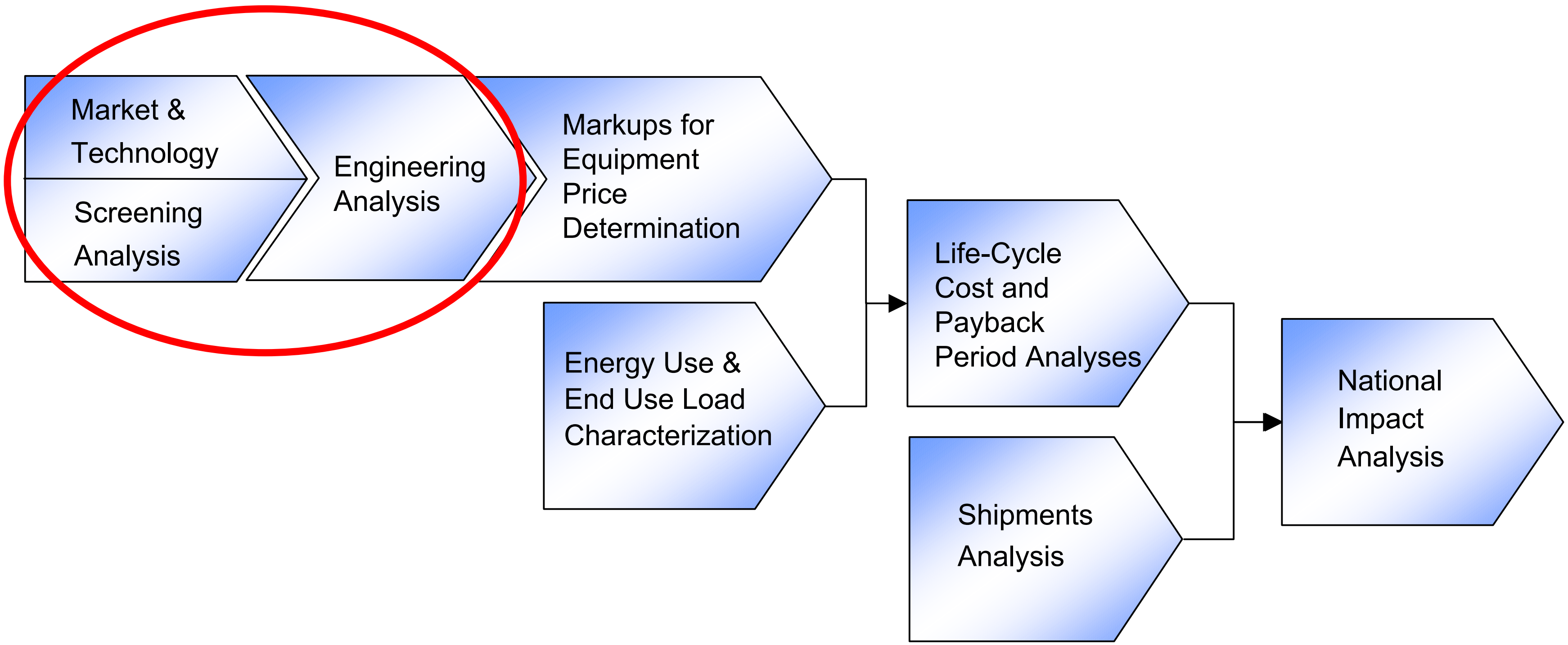
Engineering Analysis

Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

September 28, 2004

ANOPR Analyses Flow Diagram





Purpose

- **Market & Technology Assessment**
  - To characterize the distribution transformer market and determine product classes
- **Screening Analysis**
  - To identify design options that improve distribution transformer efficiency and determine which of these to evaluate and which to screen out
- **Engineering Analysis**
  - To characterize the manufacturer’s price-efficiency relationship for increasingly efficient distribution transformers

Issues for Public Comment

- Distribution Transformer Definition (ANOPR issue #1)
- Product Classes (ANOPR issue #2)
- Engineering Analysis Inputs (ANOPR issue #3)
- Design Option Combinations (ANOPR issue #4)
- The 0.75 Scaling Rule (ANOPR issue #5a)

Definition of a Distribution Transformer

"Distribution transformer means a transformer with a primary voltage of equal to or less than 35 kV, a secondary voltage equal to or less than 600 V, a frequency of 55-65 Hz, and a capacity of 10 kVA to 2500 kVA for liquid-immersed units and 15 kVA to 2500 kVA for dry-type units, and does not include the following types of transformers:

(1) autotransformer;
(2) drive (isolation) transformer;
(3) grounding transformer;
(4) harmonic mitigating transformer;
(5) K-factor transformer;
(6) machine-tool (control) transformer;
(7) non-ventilated transformer;
(8) rectifier transformer;
(9) regulating transformer;
(10) sealed transformer;
(11) special-impedance transformer;
(12) testing transformer;
(13) transformer with tap range greater than 15%;
(14) uninterruptible power supply transformer; or
(15) welding transformer."

Distribution Transformer Definition (ANOPR Issue #1)

The definition will be finalized in the Test Procedure rulemaking process, where these issues were discussed in some detail yesterday.

The Department invites comment on its definition of a Distribution Transformer.

- Exclusion of 5 and 10 kVA dry-type units
- Exclusion of sealed and non-ventilated units
- Definition of special-impedance (normal impedance tables)
- Exclusion of K-factor transformers of K-13 or greater
- No exclusion for retrofit transformers

Product Classes

There are 115 discrete kVA ratings across the ten product classes (PC)

PC	Insulation	Phases	Voltage	BIL	kVA Ratings
1	Liquid-Immersed	Single	---	---	10-833 kVA
2	Liquid-Immersed	Three	---	---	15-2500 kVA
3	Dry-Type	Single	Low-Voltage	---	15-333 kVA
4	Dry-Type	Three	Low-Voltage	---	15-1000 kVA
5	Dry-Type	Single	Medium-Voltage	20-45 kV BIL	15-833 kVA
6	Dry-Type	Three	Medium-Voltage	20-45 kV BIL	15-2500 kVA
7	Dry-Type	Single	Medium-Voltage	46-95 kV BIL	15-833 kVA
8	Dry-Type	Three	Medium-Voltage	46-95 kV BIL	15-2500 kVA
9	Dry-Type	Single	Medium-Voltage	≥96 kV BIL	75-833 kVA
10	Dry-Type	Three	Medium-Voltage	≥96 kV BIL	225-2500 kVA

Product Classes (ANOPR Issue #2)

Product classes parallel the structure of NEMA TP 1-2002

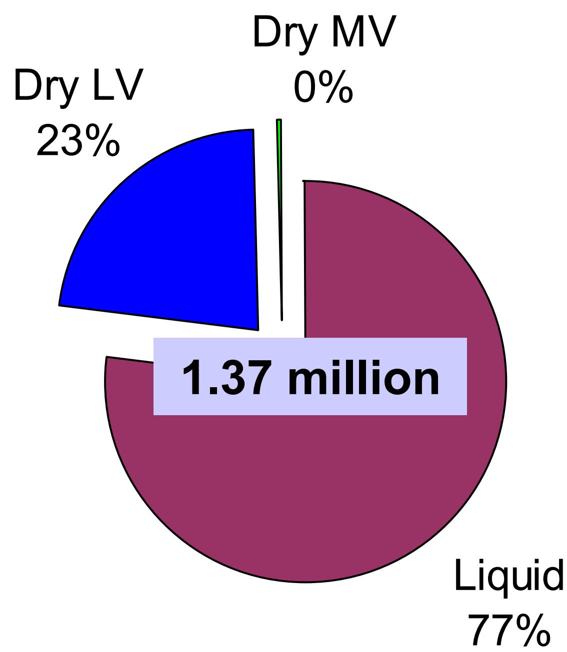
- Identical:
  - Liquid-immersed single-phase and three-phase
  - Dry-type low-voltage single-phase and three-phase
- Modified:
  - Dry-type medium-voltage single-phase and three-phase

Greater disaggregation by BIL rating for dry-type medium-voltage

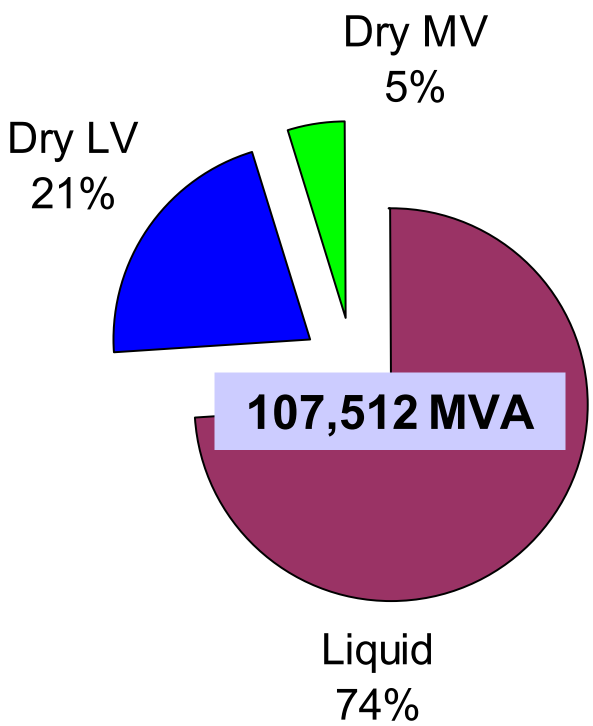
- NEMA TP 1-2002 has: $\leq$ 60kV BIL and > 60kV BIL
- DOE ANOPR has: 20-45kV BIL, 46-95kV BIL and $\geq$ 96kV BIL
- Facilitates compliance with standards for designs near the upper-limit of a BIL range

The Department invites comment on its product classes, including the disaggregation of MV Dry-type into three BIL groupings.

Distribution Transformer Shipments, 2001



Unit Shipments



MVA Capacity

Across the distribution transformer sector, liquid-immersed transformers outsell dry-types 3 to 1, and constitute about 75% of the annual MVA capacity sold.

Screening Analysis Method

- **Design options screened using the following criteria:**
  - Technological feasibility
  - Practicability to manufacture, install and service
  - Adverse impacts on product utility or product availability
  - Adverse impacts on health or safety

Design Options Selected For Further Consideration

- Varying conductor coil materials: aluminum and copper, wire and strip
- Varying core materials: non-oriented core steel (e.g., M36, M19), grain-oriented silicon steel (e.g., M6, M3); domain refined steels (e.g., H-O DR, ZDMH); and amorphous materials (wound core, SA1)
- Varying design dimensions and parameters: core magnetic flux density; conductor current density; volts / turn; voltage spacings; frame/coil dimensions; shape; cooling channels - number and location; insulating materials; shell or core form, stacked or wound
- Utilizing different construction techniques: core cutting; core stacking; core lapping or butting of joints; coil winding and LV-HV pattern

Design Options Screened Out

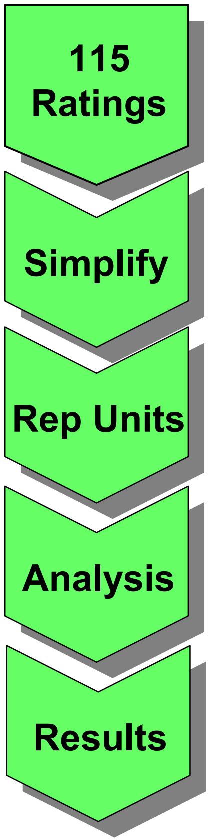
Design Option	Screening Criteria Not Met
Silver as a conductor material	Practicability to manufacture, install and service
High Temperature Superconductors	Technological feasibility
Amorphous Core Material in Stacked Core Configuration	Technological feasibility; Practicability to manufacture, install and service
Carbon Composite Materials for Heat Removal	Technological feasibility
High Temperature Insulating Material	Technological feasibility
Solid-State (power electronics) Technology	Technological feasibility

Design Option Combinations (ANOPR Issue #4)

Screening analysis - both technologies and materials that were included and those screened out from further consideration

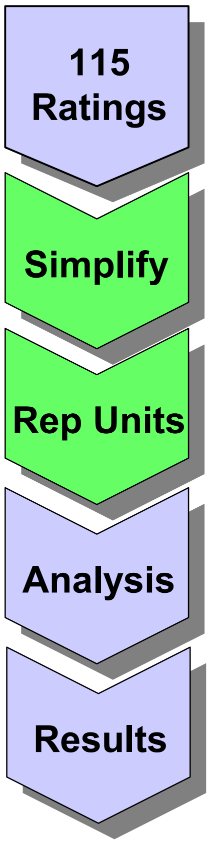
The Department invites comment on the Screening Analysis.

Engineering Analysis Overview



- Start with 10 product classes and 115 discrete kVA ratings
- Create Engineering Design Lines – 13 sub-groupings of the product classes
- Select 13 representative units – one from each design line
- Select design option combinations and use Optimized Program Service (OPS) software to prepare cost-efficiency curves
- Provide price-efficiency relationship for use in the Life-Cycle Cost Analysis

Engineering Design Lines and Representative Units



- **Subdivide product classes to create thirteen engineering design lines based on similar construction methods**
  - Five liquid-immersed
  - Three low-voltage dry-type
  - Five medium-voltage dry-type
- **Span a range of kVA ratings where the 0.75 scaling rule would provide accurate results**
- **Select one representative unit from each engineering design line**

Liquid-Immersed
Product Class to Design Line Mapping

115 Ratings
Simplify
Rep Units
Analysis
Results

Product Class 1

<table>
<tr><th colspan="3">Single Phase</th></tr>
<tr><th>kVA</th><th>Rectangular Tank</th><th>Round Tank</th></tr>
<tr><td>10</td><td rowspan="7">DL 1</td><td rowspan="7">DL 2</td></tr>
<tr><td>15</td></tr>
<tr><td>25</td></tr>
<tr><td>37.5</td></tr>
<tr><td>50</td></tr>
<tr><td>75</td></tr>
<tr><td>100</td></tr>
<tr><td>167</td><td colspan="2" rowspan="6">DL 3</td></tr>
<tr><td>250</td></tr>
<tr><td>333</td></tr>
<tr><td>500</td></tr>
<tr><td>667</td></tr>
<tr><td>833</td></tr>
</table>

Rep Unit: Rectangular Tank, 50 kVA (DL 1); Round Tank, 25 kVA (DL 2); 500 kVA (DL 3).

Product Class 2

<table>
<tr><th colspan="2">Three Phase</th></tr>
<tr><th>kVA</th><th>Design Lines</th></tr>
<tr><td>15</td><td rowspan="9">DL 4</td></tr>
<tr><td>30</td></tr>
<tr><td>45</td></tr>
<tr><td>75</td></tr>
<tr><td>112.5</td></tr>
<tr><td>150</td></tr>
<tr><td>225</td></tr>
<tr><td>300</td></tr>
<tr><td>500</td></tr>
<tr><td>750</td><td rowspan="5">DL 5</td></tr>
<tr><td>1000</td></tr>
<tr><td>1500</td></tr>
<tr><td>2000</td></tr>
<tr><td>2500</td></tr>
</table>

Rep Unit: 150 kVA (DL 4); 2000 kVA (DL 5).

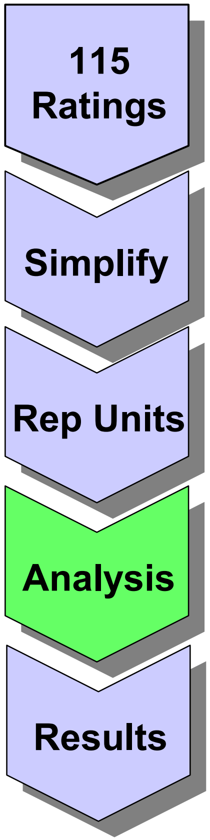
Design Option Combinations

115 Ratings
Simplify
Rep Units
Analysis
Results

- **Select representative unit design option combinations**
  - Vary core configurations, core steels & winding materials
  - Capture most common designs and max-tech
- **Example: Design Option Combinations for representative unit DL1: 50kVA liquid-immersed, single-phase, pad-mount**

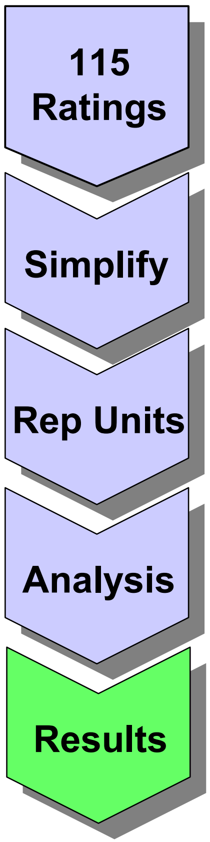
Design Option	Core Material	Conductor Primary	Conductor Secondary	Core/Coil Design Type
1	M2	Cu	Al	Shell
2	M2	Cu	Cu	Shell
3	M3	Al	Al	Shell
4	M3	Cu	Al	Shell
5	M3	Cu	Cu	Shell
6	M6	Al	Al	Shell
7	M6	Cu	Al	Shell
8	SA1 (Amorphous)	Cu	Cu	Core
9	ZDMH	Cu	Cu	Shell

Conducting the Engineering Analysis



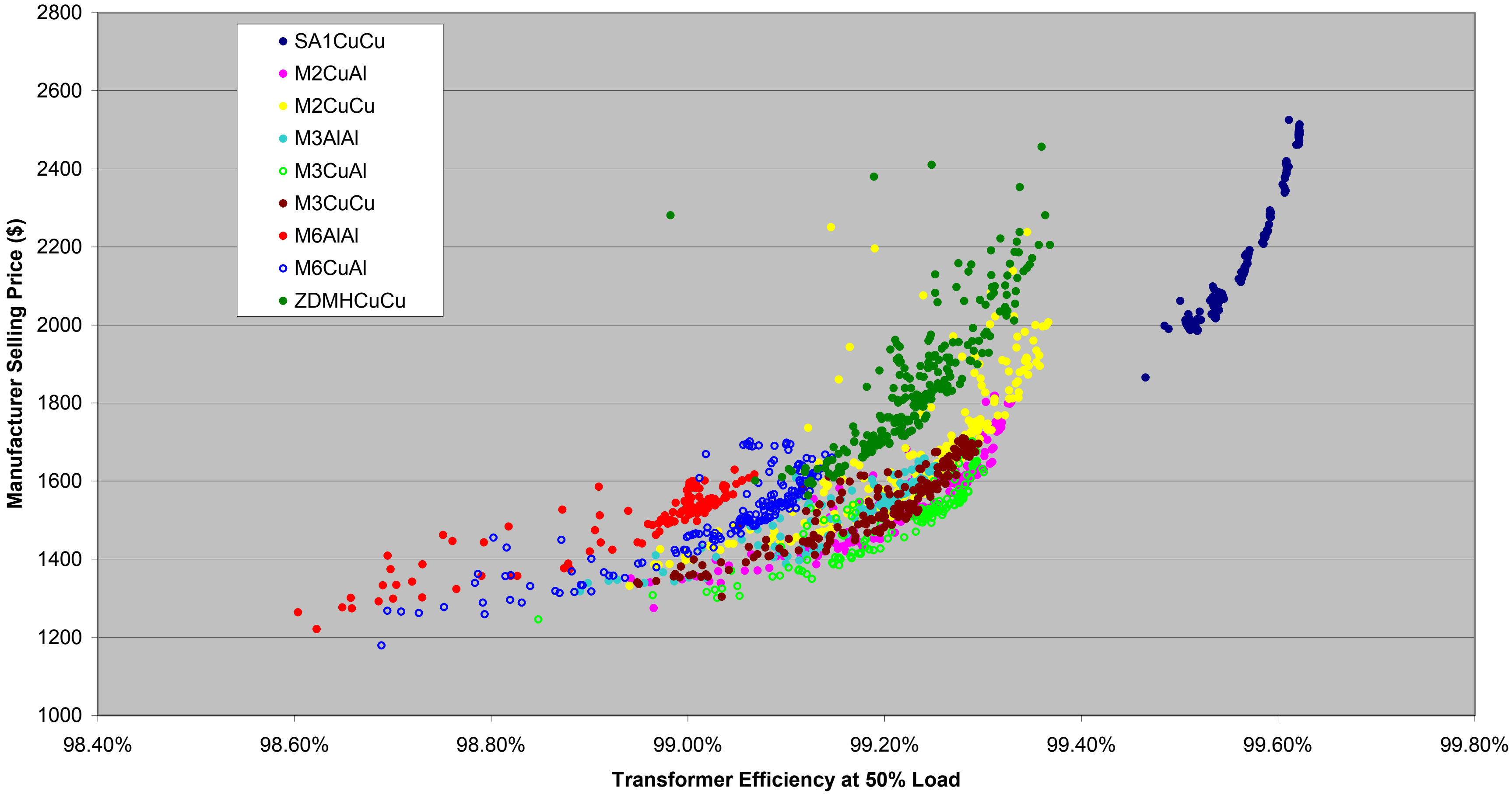
- Optimized Program Service software conducts design runs
- As an input to the OPS software, economic parameters (A and B values) are varied to simulate a range of customer orders, creating a database of transformer designs
- Approximately 2,000 unique designs for each of the thirteen representative units within each of the thirteen design lines

Engineering Analysis Results



- **OPS design software output includes:**
  - Construction and winding instructions for the core and coil, e.g., core dimensions, high- and low-voltage windings, tap locations, insulation, cooling ducts, and labor
  - Bill of materials and electrical analysis report
- **Material, labor costs and markups are combined to determine the manufacturer's selling price**
  - 2.5% markup on scrap
  - 12.5% factory overhead
  - 25% non-production
- **Efficiency determined from OPS software electrical analysis report**

Example Results: Representative Unit from DL1: 50 kVA Liquid-immersed Single-phase Pad-mounted



Engineering Analysis Inputs (ANOPR Issue #3)

The Department will be re-running the Engineering Analysis for the NOPR

Review of software inputs used in the Engineering Analysis conducted on each of the thirteen representative units

- Cross-cutting inputs impacting all the representative units
  - Material prices
  - Labor prices ($53.46 / hour fully burdened)
- Design line-specific inputs for each of the thirteen representative units
  - Voltages of primary and secondary
  - Winding configuration
  - Core configuration
  - Taps – number and location
  - Impedance range

The Department invites comments on the engineering analysis inputs discussed in detail in TSD Chapter 5.

Engineering Analysis Inputs (continued)
Material for Liquid-Immersed

Material for Liquid Immersed	2004 (draft)	2001 (ANOPR)	Change
M2 core steel	$1.05	$1.05	0%
M3 core steel	$0.90	$0.95	-5%
M4 core steel	$0.85	$0.85	0%
M6 core steel	$0.79	$0.80	-1%
ZDMH (mechanically-scribed core steel)	$1.50	$1.40	7%
SA1 (amorphous) - finished core, volume production	$1.89	$1.70	11%
Copper wire, formvar, round #10-20	$2.33	$1.30	79%
Copper wire, enameled, round #7-10 flattened	$2.28	$1.30	75%
Copper wire, enameled, rectangular sizes	$2.72	$1.50	81%
Aluminum wire, formvar, round #9-17	$1.53	$1.36	13%
Aluminum wire, formvar, round #7-10	$1.54	$1.36	13%
Copper strip, thickness range 0.02-0.045	$2.50	$2.40	4%
Copper strip, thickness range 0.030-0.060	$2.50	$2.40	4%
Aluminum strip, thickness range 0.02-0.045	$1.36	$1.30	5%
Aluminum strip, thickness range 0.045-0.080	$1.36	$1.30	5%
Kraft insulating paper with diamond adhesive	$1.56	$1.54	1%
Mineral oil	$1.80	$1.52	18%

Engineering Analysis Inputs (continued)
Material for Dry-type

Material for Dry-type	2004 (draft)	2001 (ANOPR)	Change
H-O DR core steel (laser-scribed)	$1.10	$1.15	-4%
M3 core steel	$0.90	$0.95	-5%
M4 core steel	$0.85	$0.85	0%
M5 core steel	$0.83	-	-
M6 core steel	$0.79	$0.80	-1%
M19 core steel (26 gauge)	$0.65	$0.70	-7%
M36 core steel (29 gauge)	$0.63	$0.46	37%
M36 core steel (26 gauge)	$0.59	-	-
M43 core steel (26 gauge)	$0.55	$0.39	41%
Copper wire, rectangular 0.1 x 0.2, Nomex wrapped	$2.72	$1.60	70%
Aluminum wire, rectangular 0.1 x 0.2, Nomex wrapped	$2.04	$2.00	2%
Copper strip, thickness range 0.02-0.045	$2.50	$2.40	4%
Aluminum strip, thickness range 0.02-0.045	$1.36	$1.30	5%
Nomex insulation (per pound)	$17.00	$17.50	-3%
Cequin insulation (per pound)	$12.00	-	-
Impregnation (per gallon)	$15.00	$18.00	-17%
Winding Combs (per pound)	$10.00	$10.00	0%

Engineering Analysis Inputs (continued)
Example Design Specifications DL1

Design Specification:

KVA: 50 (liquid-immersed pad mount)
Primary: 7200 Volts at 60 Hz
Secondary: 240/120 Volts
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%

Design Option Combinations (ANOPR Issue #4)

Review the design option combinations of materials and core designs selected for representative units

Combinations were meant to represent:

- Lowest first-cost
- Most common combination (high volume)
- Maximum technologically feasible

The Department invites comment on whether the correct design option combinations were used.

The 0.75 Scaling Rule (ANOPR Issue #5a)

Used to scale total losses (TL) from a representative unit to other kVA ratings (S) within an engineering design line

$$TL_1 = TL_0 \times (S_1 / S_0)^{0.75}$$

Scaling rule is valid when design parameters are held constant, including frequency, magnetic flux density, current density and insulation level

Industry uses scaling rule, and appears consistent with NEMA TP 1 tables

The Department invites comment on the use of the 0.75 Scaling Rule to reduce 115 discrete kVA ratings to 13 units for the analysis.

Other Issues

The Department seeks comments and recommendations from stakeholders on any other aspects related to the Engineering Analysis.