B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Emerging Technologies

Phase 1 report: High Efficiency Distribution Transformer Technology Assessment

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BPA's Emerging Technologies Initiative

April 7, 2020

Energy Program
Washington State University

Webinar Topics

- Definition of Transformer Efficiency
- Liquid-Immersed Transformer Efficiency Standards
- Transformer Losses
- Amorphous Core Transformer Construction
- High Efficiency Amorphous Core Transformer Performance Characteristics
- Transformer Sizing and Loading Considerations
- Utility Transformer Purchasing Practices (TCO)
- Potential Energy and Cost Savings
- “Early Adopter” Experiences

Transformer Facts

- Generally, electricity passes through 4 or 5 transformers as it travels from the powerplant to the customer.
- Liquid immersed utility distribution transformer losses account for 2% to 3% of U.S. generated electricity (losses are valued at $25 billion per year).
- No-load losses account for approximately 25% of these losses.

Don Hammerstrom, PNNL, “Distribution Transformer Data, Testing, and Control. 2017
UN Environment, “Accelerating the Global Adoption of Energy-Efficient Transformers”, 2017

Transformer Efficiency

- The efficiency of a distribution transformer is the power output at the secondary side divided by the input power on the supply side.
- Efficiency may also be expressed as: (Input – Losses) / Input
- A decrease in losses thus yields an increase in efficiency

Transformer Efficiency over Time

- Transformers generally have efficiencies over 98% with efficiency constantly improving over time due to the establishment of voluntary and mandatory minimum efficiency standards.
- NEMA TP-1 (1996, 1998, 2002) Voluntary
- Energy Star (at NEMA TP-1 levels) Voluntary
- EPACT 2005 (at NEMA TP-1 levels) Mandatory
- NEMA Premium (2010) Losses 30% less than TP-1 Voluntary
- DOE 2016 Approximately equivalent to NEMA Premium Mandatory

DOE 2016 Transformer Efficiency Standards

Current Transformer Mandatory Minimum Efficiency Standards

The efficiency of **a liquid-immersed distribution transformer** manufactured on or after **January 1, 2016**, shall be no less than that required for their kVA rating below.

Low Voltage Secondary, less than 600 V LIQUID – IMMERSED

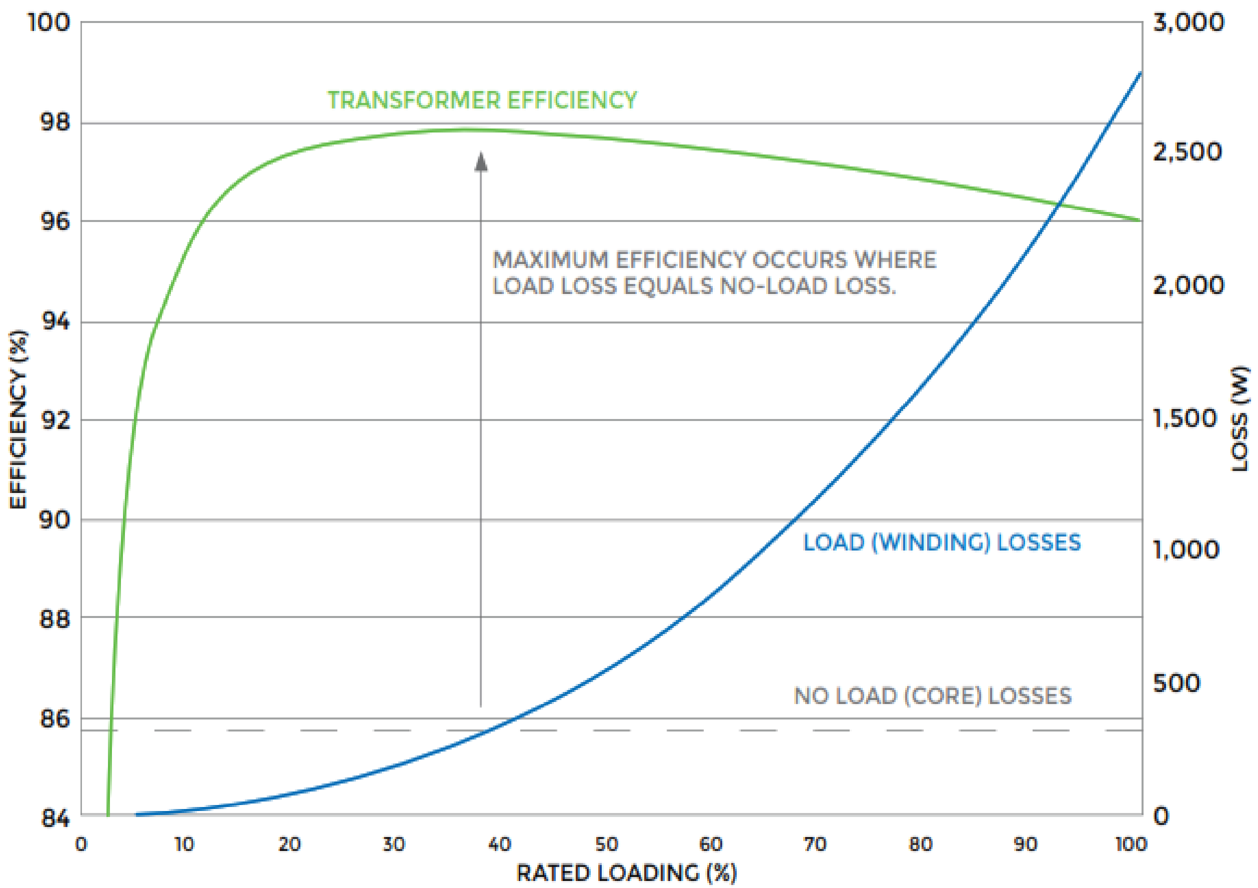
Single-phase		Three-phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	98.70	15	98.65
15	98.82	30	98.83
25	98.95	45	98.92
37.5	99.05	75	99.03
50	99.11	112.5	99.11
75	99.19	150	99.16
100	99.25	225	99.23
167	99.33	300	99.27
250	99.39	500	99.35
333	99.43	750	99.40
500	99.49	1000	99.43
667	99.52	1500	99.48
833	99.55	2000	99.51
		2500	99.53

Note: All efficiency values are at 50 percent of nameplate-rated load.

Transformer Losses versus Loading

Example of the relationship between transformer losses and efficiency

Transformer No-load and Load Losses versus Loading



Annual Energy Losses and Energy Savings Using 'Equivalent Hours' Methodology

Annual Transformer Energy Losses (kWh/year) = (No-load loss + Loss factor x Load loss at peak) x 8760 hours/year x kW/1000W

Where:

Annual Load Factor	=	average kVA / kVA at peak transformer load (or average power in kW/peak power in kW)
Loss Factor	=	0.85 x (annual load factor)^2 + 0.15 x (annual load factor)
Load loss (W)	=	Watts loss when transformer is fully loaded to its nameplate kVA rating
Load loss at peak	=	Nameplate load loss (W) x (kVA at peak transformer load / nameplate kVA rating)^2

Energy Savings (kWh/year) = Energy Losses from baseline transformer (kWh/year) - Energy Losses from higher efficiency unit (kWh/year)

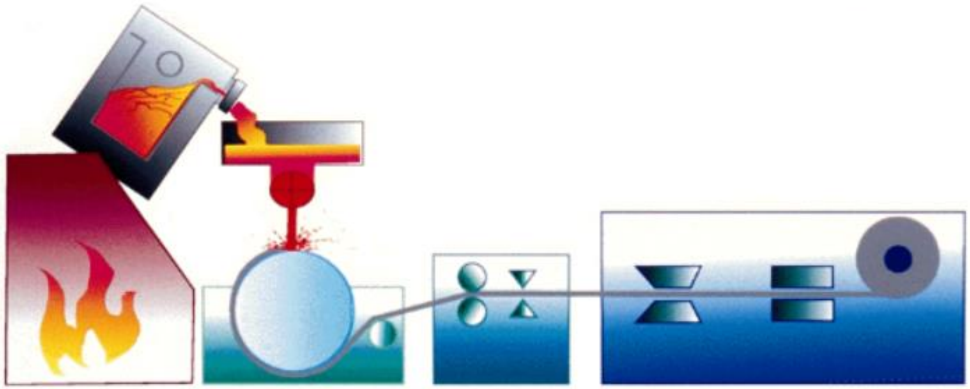
A High Efficiency Alternative: Amorphous Core Transformers

- Amorphous core transformers are a mature and proven technology---they have been available since the 80’s.
- Over 3 million units are in operation worldwide with over 40 manufacturers (Source: ABB).
- Amorphous Metal distribution transformers have mainly been used in China and India in single phase ratings below 250 kVA.
- All Canadian utilities, save Manitoba Hydro, have shifted to amorphous core transformer designs.

Amorphous Metal Manufacturing

Amorphous Metal Manufacturing

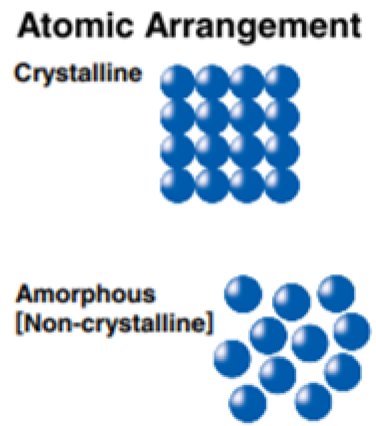
Creating the amorphous metal ribbon



Molten metal poured on super cooled wheel

Spinning at 100 km/hr

Cooling rate: 10^6 °C per second.



Continuous casting to the final thickness and width

- Thickness = .0254mm .001"
- Widths = 142mm, 170mm, 213mm
- No further rolling or slitting

Rapid solidification prevents the normal crystalline structure.

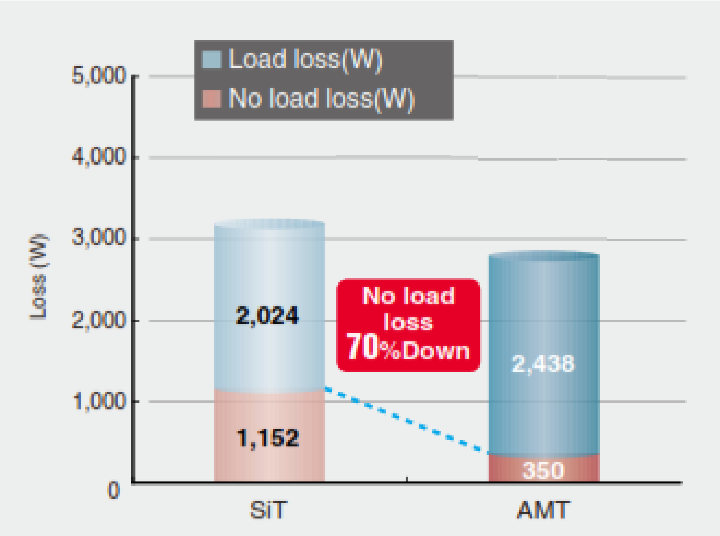
Thickness 25μm

(1/10 of conventional materials)

Ribbon thickness is 1/10 of Silicon Steel's
[Silicon Steel:0.23mm, Amorphous Alloy:0.025mm]

Sources: ABB, Amorphous core distribution transformers Hitachi, Amorphous Transformers

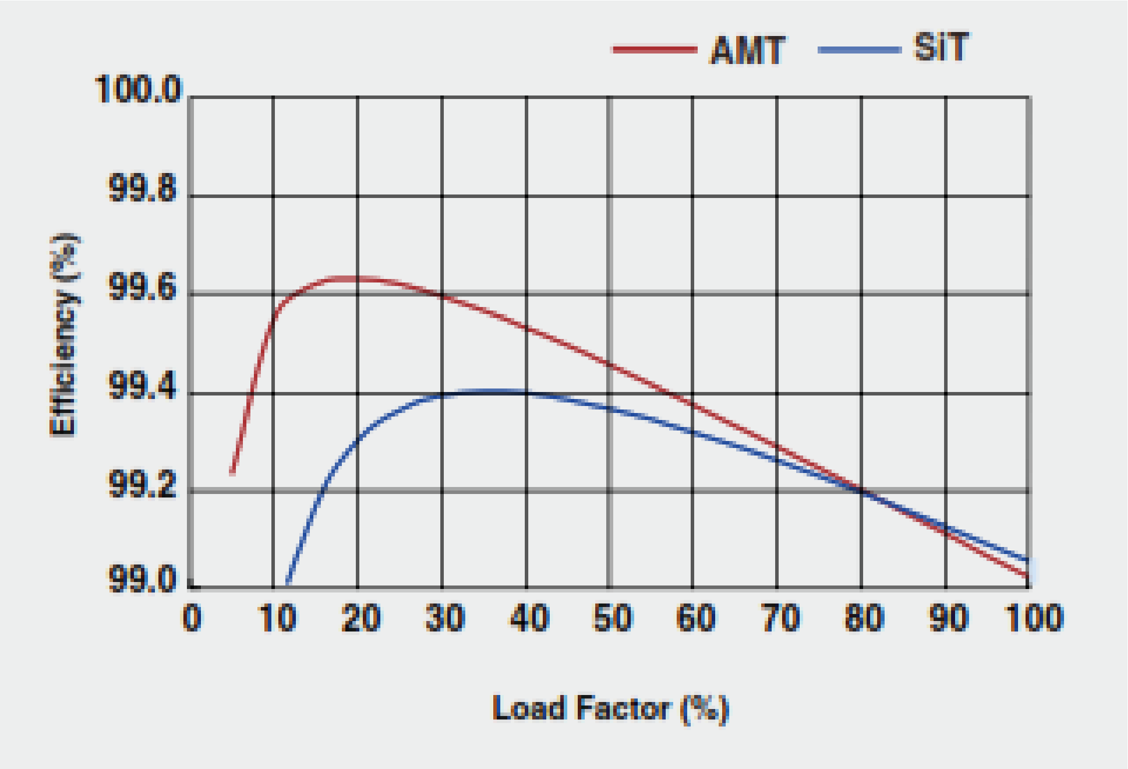
Amorphous Metal Reduction in Core Losses



Rating (kVA)	No-load losses (W) Regular Grain Oriented	No-load losses (W) Amorphous Metal	Loss reduction
100	145	65	55%
250	300	110	63%
400	430	170	60%
800	650	300	54%

Sources: ABB, Amorphous core distribution transformers   Hitachi, Amorphous Transformers

Amorphous Core Transformer Performance



Source: Hitachi, Amorphous Transformers

Gross and Net Savings from Amorphous Core

Amorphous Core Energy Savings Opportunity

Data Source: A major US transformer manufacturer

	Gross Core Savings	Winding * Negative Savings	Net Core Savings
Avg 1-phase	67%	30%	37%
Avg 3-phase	57%	27%	30%

* Winding losses evaluated at 50% load factor (29% loss factor), peak load at 50% of nameplate. This is a relatively high load assumption making the winding negative savings large thus the net core savings conservative.

Total Cost of Ownership Methodology

$$TCO = C_T + A \times P_{NL} + B \times P_{LL}$$ where:

TCO = Total Cost of Ownership ($)

C_T = Transformer purchase price

P_{NL} = No-load losses in W - This is a steady value when the transformer is energized.

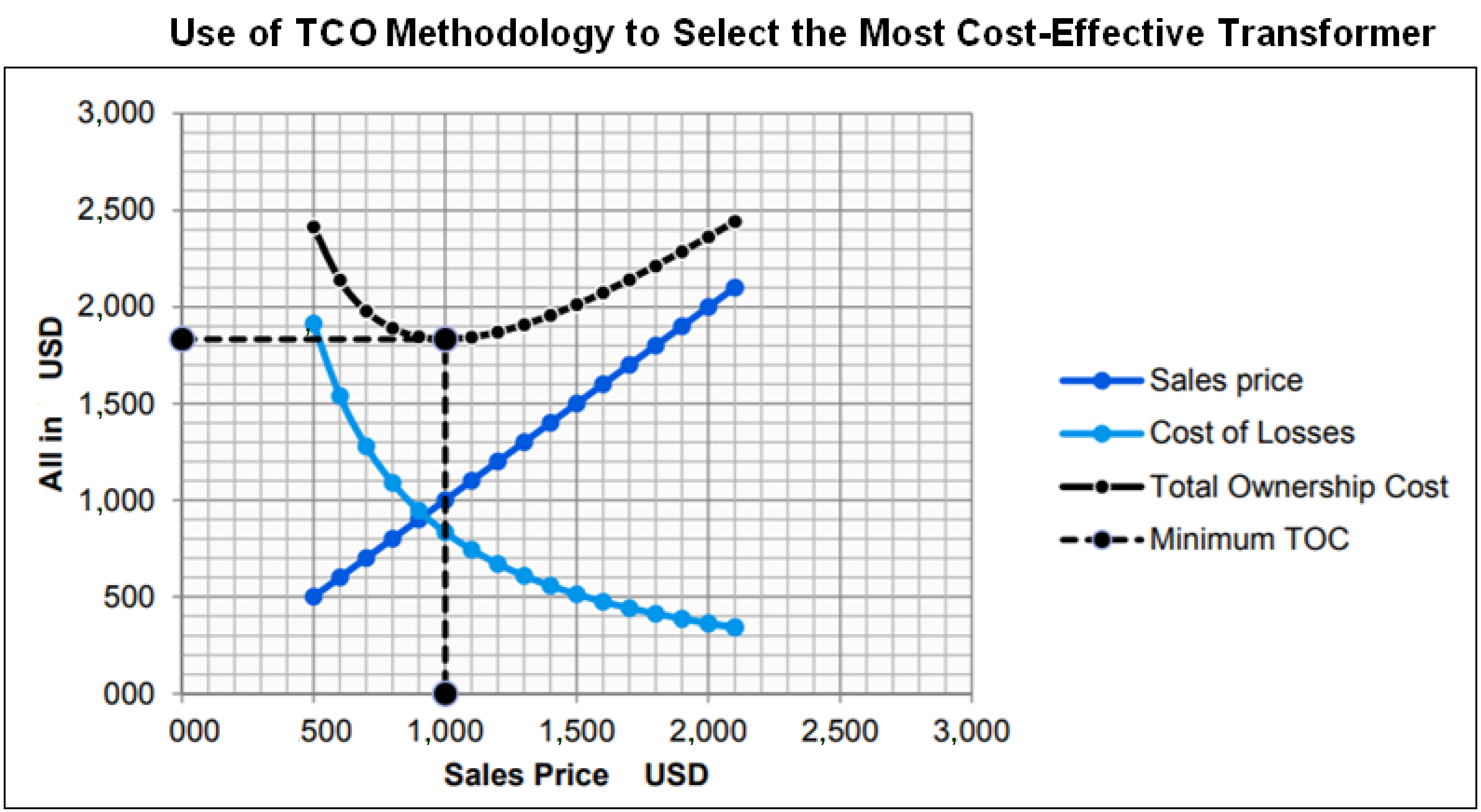
P_{LL} = Load-losses in W (given at full load and at a reference temperature).

A = Capitalization factor or system capital investment to supply the no-load losses, and

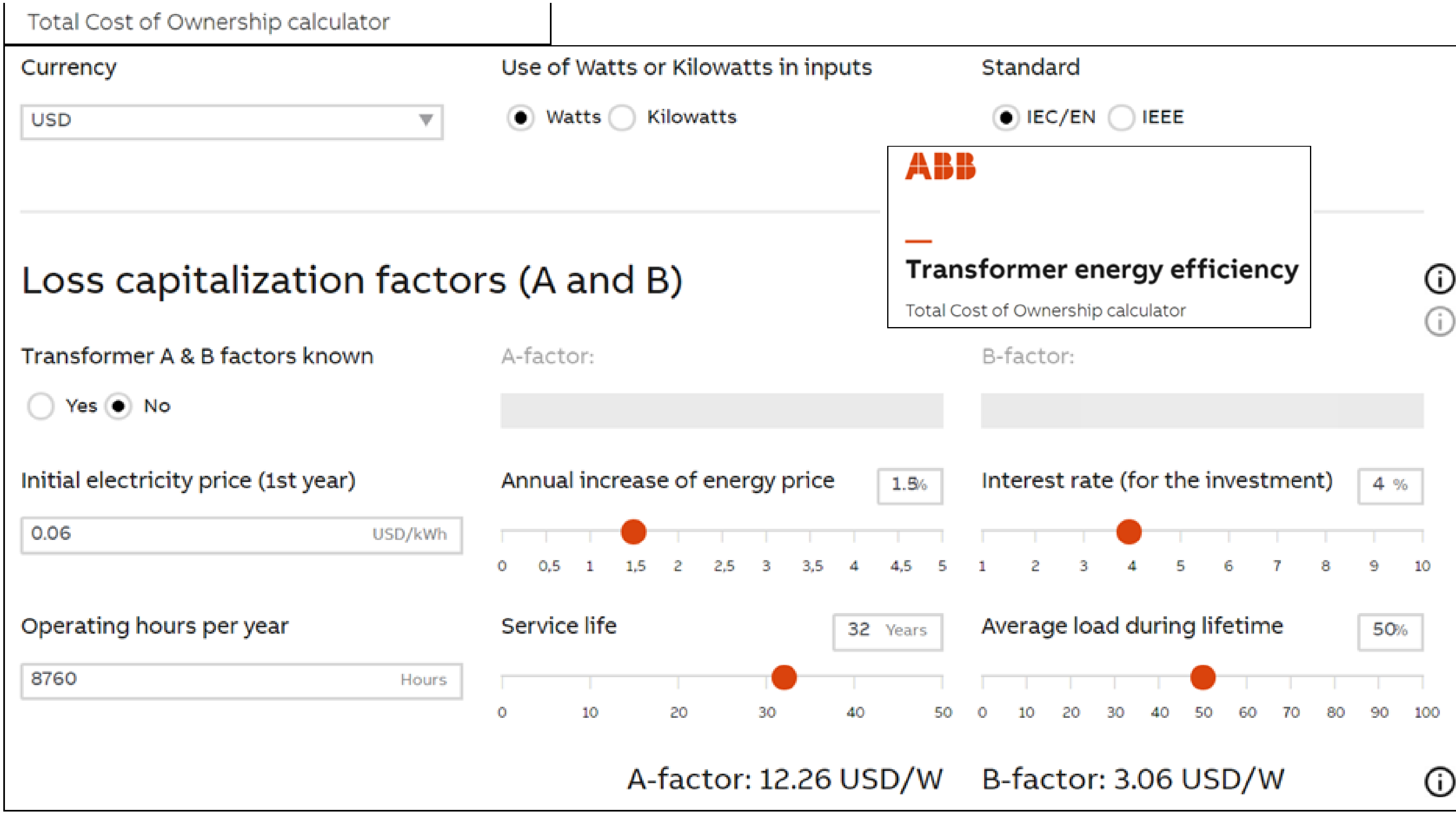
B = Capitalization factor for load-losses.

The multiplication factors A and B are dependent upon costs of new generation, transformer loading, operating hours, cost of capital, energy prices and market forecasts, and the expected transformer life (typically 32 years). Utility values for A and B and often in the range of $5/W to $10/W for P_{NL} and $1/W to $2/W for P_{LL}

Selecting the Most Cost-Effective Transformer



Determining Loss Valuation Multipliers



Loss Valuation Multipliers (A & B values) Reported by Various Northwest Utilities

Utility	"A" or no-load loss multiplier	"B" or load-loss multiplier
Utility #1	$5.47/W	$0.76/W
Utility #2	$4.93/W	$1.62/W
Utility #3	$7.50/W	$1.35/W
Utility #4	$3.96/W	$1.25/W
Utility #5	$3.75/W	$1.50/W
Utility #6	$4.11/W	$1.03/W
Average	$4.95/W	$1.25/W

Source: BPA survey of 20 Northwest Utilities

Approximate Amorphous core "tipping point": A = $7.00 to $8.00/W

Loss Valuation Factors used by "Early Adopters"

- Nashville Electric Service (NES):

  A = $12.90/W, B = $1.66/W Single-phase pole

- Los Angeles Dept of Water and Power (LADWP):

  A = $9.60/W, B = $2.00/W

- Canadian Utilities:

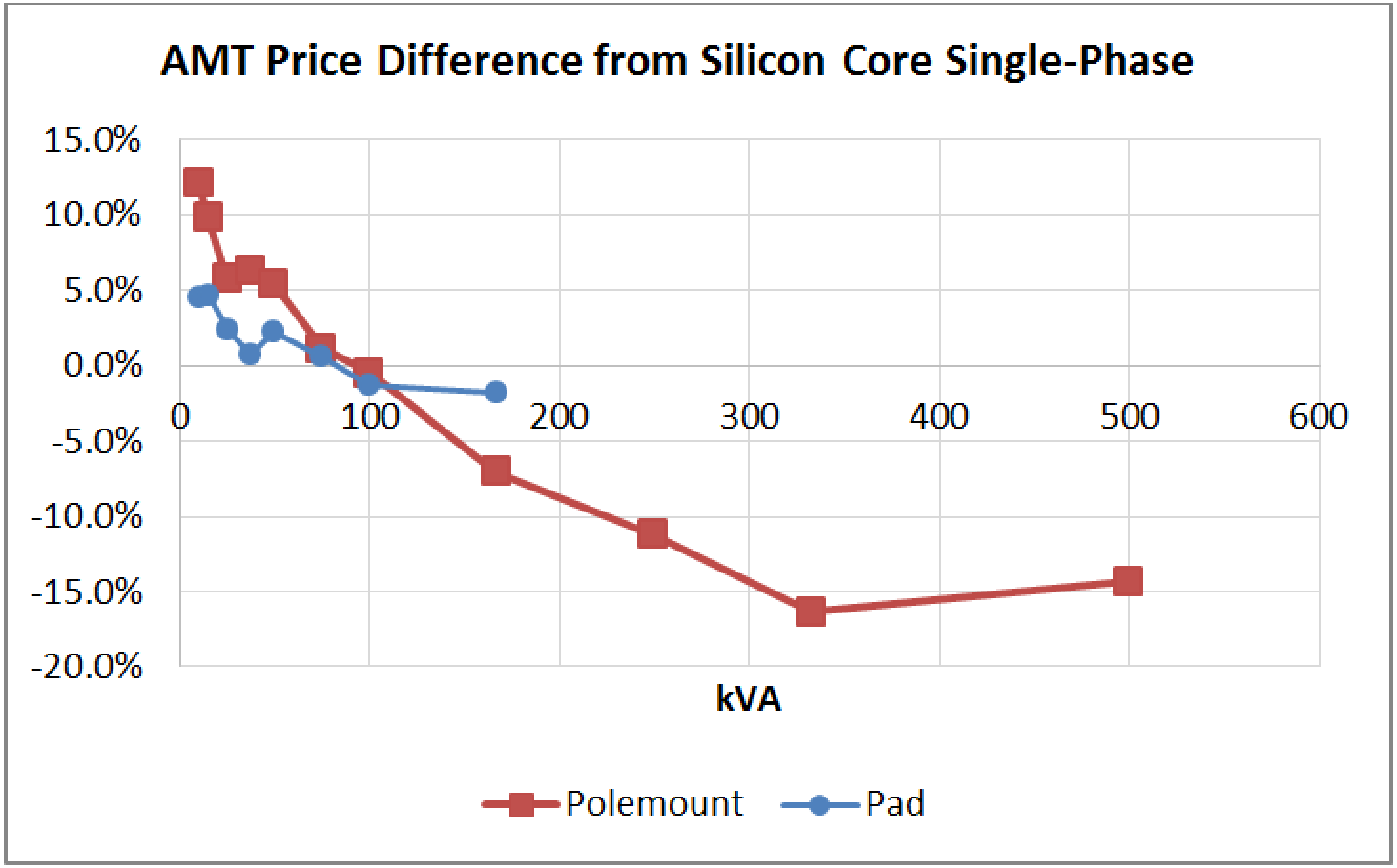
  A = $8.15 - $14.80/W, B = $0.75 - $3.70/W in USD

Amorphous Core Transformer Availability

Amorphous Core Transformer Manufacturers that Sell into the North American Market	
ABB	Central Maloney
Cooper Power Systems (Eaton)	Sanil (Korea)
Schneider Electric	CHERYONG (Korea)
Siemens	ERMCO
Howard Power Solutions	CAMTRAN (Canada)
GE Prolec	Hitachi (Japan)

Incremental Costs for AMTs: Single-Phase

Incremental Costs for Liquid-Immersed Single-Phase Pole and Pad-Mount Amorphous Metal Transformers (AMT) Relative to Standard Transformers

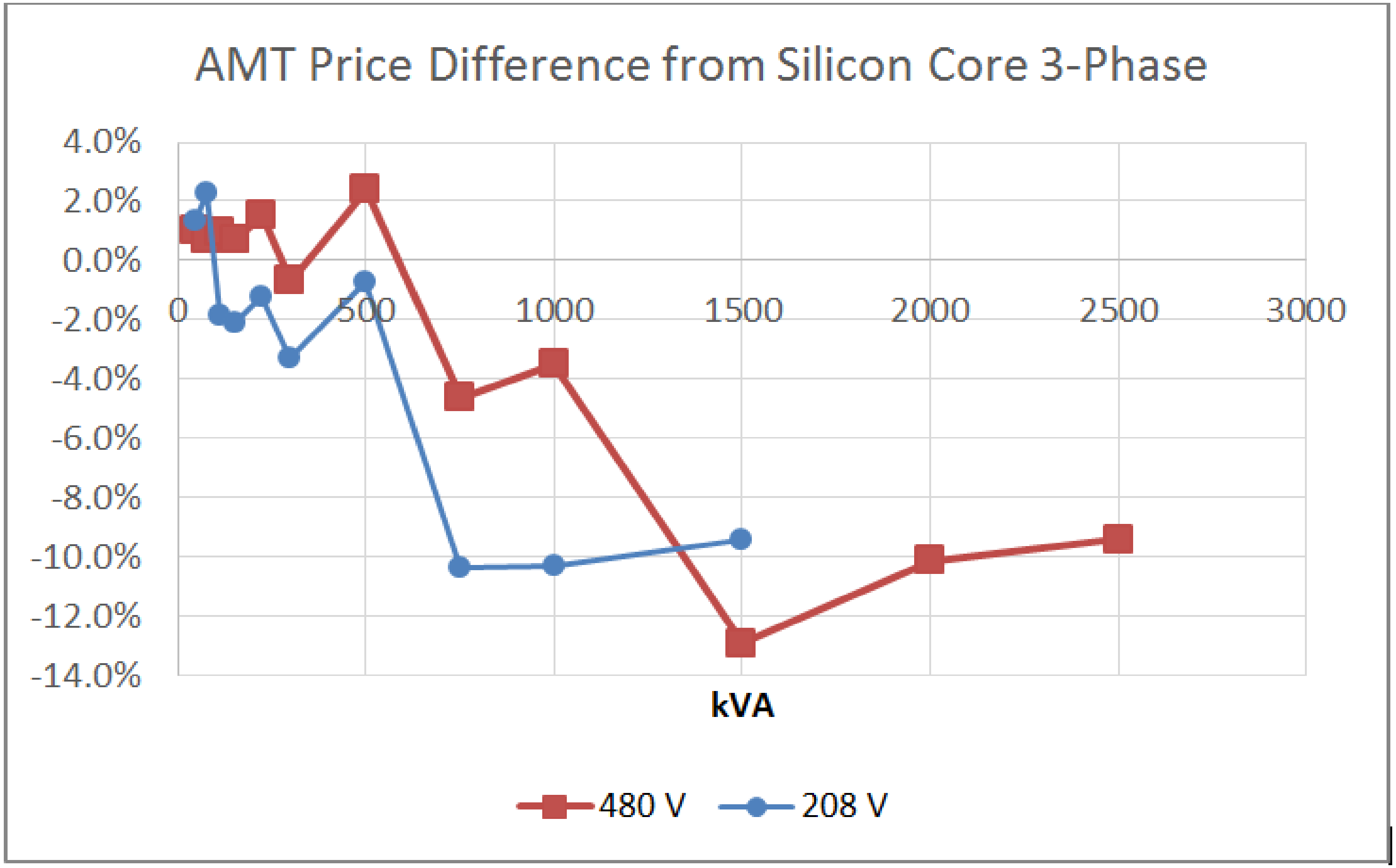


Cost and Performance Data from a major US Transformer Manufacturer

Cost differences are for Transformers that Just Meet the DOE 2016 Efficiency Standards

Incremental Costs for AMTs: Three-Phase

Incremental Costs for Liquid-Immersed Three-Phase Pad-Mount Amorphous Metal Transformers (AMT) Relative to Standard Transformers



Cost and Performance Data from a major US Transformer Manufacturer

Cost differences are for Transformers that Just Meet the DOE 2016 Efficiency Standards

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Annual Energy Savings from Purchase of AMT Transformer: Single-Phase

Annual Energy Savings Due to Procurement of Amorphous Core versus Baseline Single-Phase Pole and Pad-Mount Transformers

1pole			Total
kVA	Core Savings	Conductor Savings	kWh
10	210	-66	144
15	254	-80	174
25	359	-106	253
37.5	491	-147	344
50	692	-220	472
75	946	-292	654
100	1086	-336	750
167	1594	-474	1120
250	1770	-515	1254
333	2129	-632	1497
500	2155	-640	1515

1pad			Total
kVA	Core Savings	Conductor Savings	kWh
10	184	-56	128
15	237	-73	163
25	377	-115	261
37.5	491	-154	337
50	578	-167	411
75	920	-284	636
100	1261	-396	865
167	1375	-409	966

Both Transformers Meet the 2016 Federal Efficiency Standards

These are non-evaluated loss values, TCO values are A = $0 B = $0

Cost and Performance Data from a major US Transformer Manufacturer

Conductor loss savings evaluated at 50% load factor (29% loss factor), peak load at 50% of nameplate

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Annual Energy Savings from Purchase of AMT Transformer Three-Phase

Annual Energy Savings Due to Procurement of Liquid-Immersed Amorphous Core versus Baseline Three-Phase Pad-Mount Transformers with a Secondary of 480 V or 208 V

3p480			Total
kVA	Core Savings	Conductor Savings	kWh
45	403	-130	273
75	990	-213	776
112.5	1086	-167	919
150	2006	-474	1532
225	1927	-385	1542
300	2961	-670	2291
500	4564	-1453	3111
750	6263	-2002	4261
1000	7192	-2139	5053
1500	8839	-2632	6207
2000	8480	-2578	5901
2500	11808	-2066	9743

3p208			Total
kVA	Core Savings	Conductor Savings	kWh
45	666	-145	521
75	990	-195	795
112.5	780	-237	543
150	1358	-424	933
225	1726	-520	1206
300	3189	-1096	2092
500	3119	-925	2194
750	4143	-1266	2878
1000	4844	-1514	3330
1500	6018	-1774	4244

Both Transformers Meet the 2016 Federal Efficiency Standards

These are non-evaluated loss values, TCO values are A = $0 B = $0

Cost and Performance Data from a major US Transformer Manufacturer

Conductor loss savings evaluated at 50% load factor (29% loss factor), peak load at 50% of nameplate

Transformer Purchases

- The DOE reports that 683,726 medium voltage liquid-filled single phase pole and pad transformers were sold nationwide in 2009.
- An additional 49,739 liquid-filled three-phase transformers were sold nationwide.

Responses to a BPA survey yield an estimate of 17,132 liquid immersed distribution transformers purchased by BPA customers per year.

Transformer Sales by kVA Rating (2009)

Liquid-Immersed Distribution Transformer Shipments by kVA Rating
(2009 Data)

Single-Phase		Three-Phase	
Capacity kVA	Units Shipped	Capacity kVA	Units Shipped
10	58,090	15	–
15	169,083	30	–
25	243,583	45	1,635
37.5	41,755	75	4,269
50	119,455	112.5	898
75	26,338	150	8,445
100	18,679	225	2,239
167	4,357	300	8,347
250	1,905	500	7,563
333	238	750	3,982
500	238	1,000	3,606
667	5	1,500	3,345
833	–	2,000	2,839
–	–	2,500	2,571
Total Units	**683,726**	**Total Units**	**49,739**
Total MVA	**21,994**	**Total MVA**	**32,266**

99% of single-phase transformers purchased were rated at <= 100 kVA

Energy Savings Analyzed for Two Scenarios

- BPA regional savings potential from customer utilities
- Assumes 50% load factor (29% loss factor, and peak load of 50% of nameplate
- Scenario #1: 30% purchase of amorphous core transformers **that just meet the DOE 2016 minimum efficiency standards, with no loss valuation, A = $0/W and B = $0/W.**
- Scenario #2: 30% purchase of “enhanced efficiency” amorphous transformers---Designed for loss valuation factors of A = $20/W and B = $5/W

Regional Annual Energy Savings: A = $0 B = $0

Annual Energy Savings due to Purchase of Liquid-Immersed Amorphous Core Distribution Transformers by BPA Customer Utilities when Assuming a 30% Market Penetration

Potential Regional Total Energy Savings			Sum Total	2,066,946	kWh
Single-phase Transformer			Three-phase Transformer		
	Total kWh			Total kWh	
kVA	Pole	Pad	kVA	Pad	
10	12,183	10,813	15	-	
15	108,609	101,999	30	-	
25	254,369	262,476	45	4,875	
37.5	102,700	100,632	75	42,389	
50	137,078	119,352	112.5	7,060	
75	52,645	51,188	150	63,511	
100	30,190	34,835	225	17,142	
167	13,527	11,666	300	174,678	
250	2,020	-	500	109,439	
333	-	-	750	35,202	
500	-	-	1000	53,990	
667	-	-	1500	67,311	
833	-	-	2000	38,007	
Total	**713,320**	**692,960**	2500	47,060	
			Total	**660,666**	

Both Transformers Meet the 2016 Federal Minimum Efficiency Standards

These are non-evaluated loss values, TCO values are A = $0 B = $0

The Total Annual Energy Savings Estimate is 2,066 MWh/year or 0.235 aMW/year per year of incentive program operation. Energy savings would double if the penetration rate reached 60%.

Enhanced Efficiency Transformers: A = $20 B = $5

Annual Energy Savings due to Purchase of Enhanced Efficiency Liquid-Immersed Amorphous Core Distribution Transformers by BPA Customer Utilities When Assuming a 30% Market Penetration

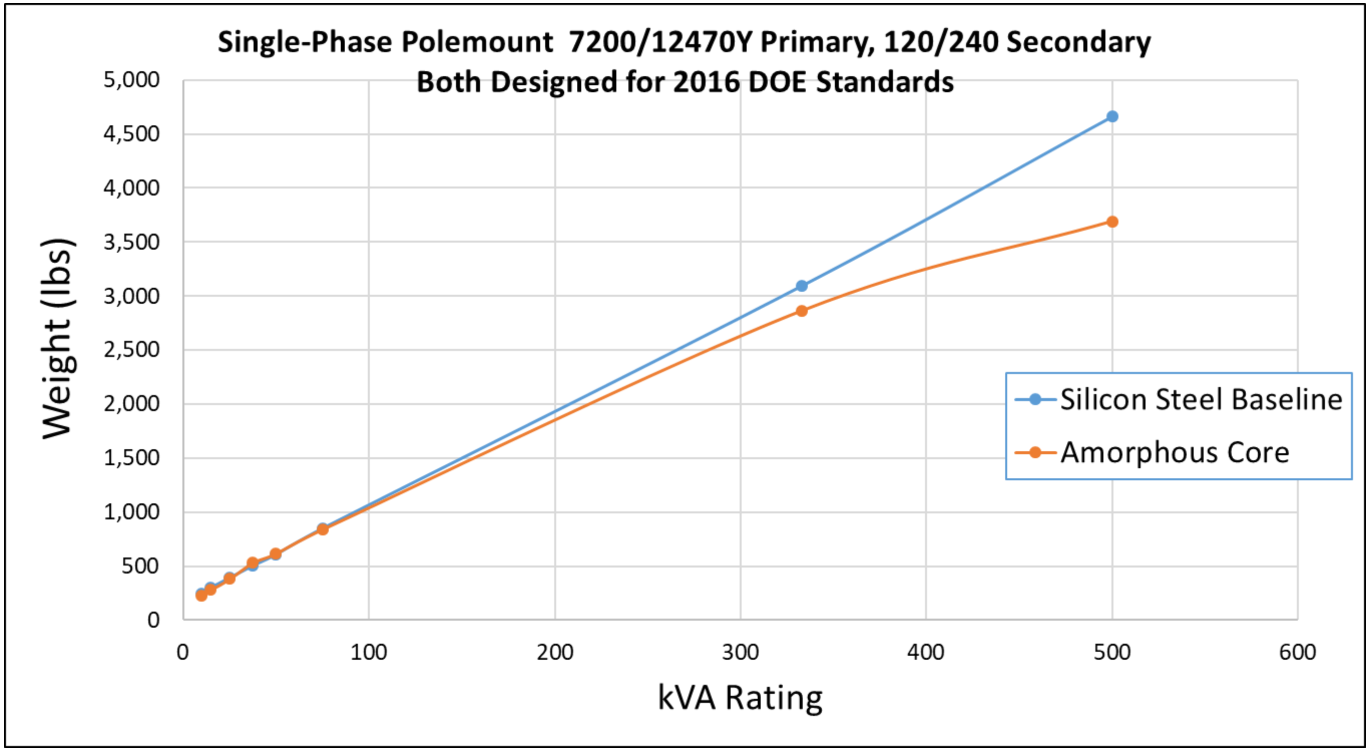
Potential Regional Total Energy Savings				Sum Total	2,852,401	kWh
Single-phase Transformer				Three-phase Transformer		
	Total kWh				Total kWh	
kVA	Pole	Pad		kVA	Pad	
10	17,156	13,507		15	-	
15	148,592	134,911		30	-	
25	339,836	355,198		45	8,555	
37.5	147,685	136,525		75	56,695	
50	193,325	149,123		112.5	11,801	
75	72,375	71,353		150	91,029	
100	42,522	47,405		225	23,906	
167	18,086	17,349		300	240,621	
250	2,843	-		500	169,835	
333	-	-		750	56,522	
500	-	-		1000	86,306	
667	-	-		1500	86,888	
833	-	-		2000	55,245	
Total	**982,420**	**925,371**		2500	57,207	
				Total	**944,610**	

These are evaluated with TCO values of: A = $20 B = $5

A = $20/W; B = $5/W. The Technical Potential Total Annual Energy Savings Estimate is 2,852 MWh/year or 0.325 aMW/year per year of incentive program operation. Energy savings increase by 38% over the baseline scenario".

Comparison of Amorphous Core Transformers

When first introduced in the 1980's, amorphous core transformers were bigger and weighed about 20% more than conventional units. Weight and cost penalties have decreased as the weight of conventional transformers designed to meet the DOE 2016 efficiency standards has increased and manufacturers have improved "steel-to-air gap" ratios for their amorphous core designs. As a result, weights are now equivalent.



Comparison of Amorphous Core Transformers (cont'd)

- The sound level may be a little higher, but easily meets established ANSI and CSA standards.
- No difference in aging characteristics.
- No difference in dielectric strength as coil and insulation design is the same as for grain-oriented cores
- No difference in reliability or load-ability.
- Footprint may be slightly bigger.

Source: ABB Transformer Training

Phase 2

High Efficiency Distribution Transformer Technology Assessment

Work to be performed
January – September 2020

Emerging Technologies

Research Intent

- Liquid Immersed Transformers
  - Gather actual Amorphous core market data (vendor quotes to utilities)
  - Need no-load and nameplate loss data and cost from Amorphous units
  - Use data to calculate energy savings and potential BPA incentive
  - BPA Incentive: Create a UES measure or possible calculator measure
  - Explore impact of losses on distribution transformers from harmonic voltage and harmonic currents
  - Address ferroresonance performance
- Dry Type Transformers
  - Amorphous core units not readily available
  - BPA / Utility rebates are not practical to administer for new construction
  - Explore possible market transformation effort with NEEA for new construction
  - Explore early replacement for lightly loaded transformer

Utility Participation

- Liquid Immersed Transformers
  - Are you willing to assist by including Amorphous core units in your on-going transformer bids? You need to ensure some Amorphous vendors are included in the bid request.
  - BPA will aggregate this data, not showing utility names and share general results.
  - Give input to potential BPA Incentive design, what works, what does not work.

If willing to provide Amorphous quote, please email
Tony Koch jakoch@bpa.gov

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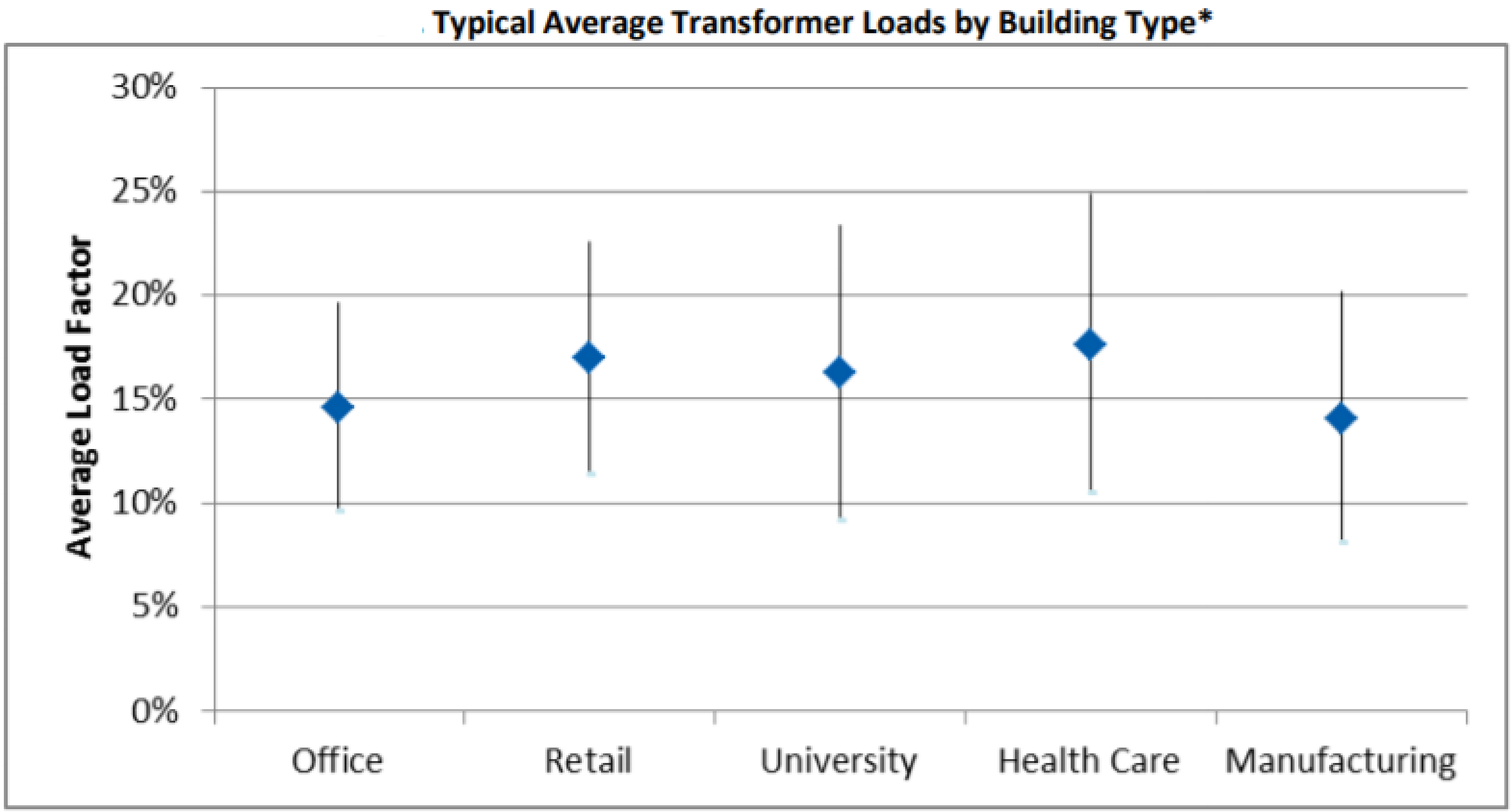
THANK YOU!

Tony Koch jakoch@bpa.gov

View the Phase1 report at:

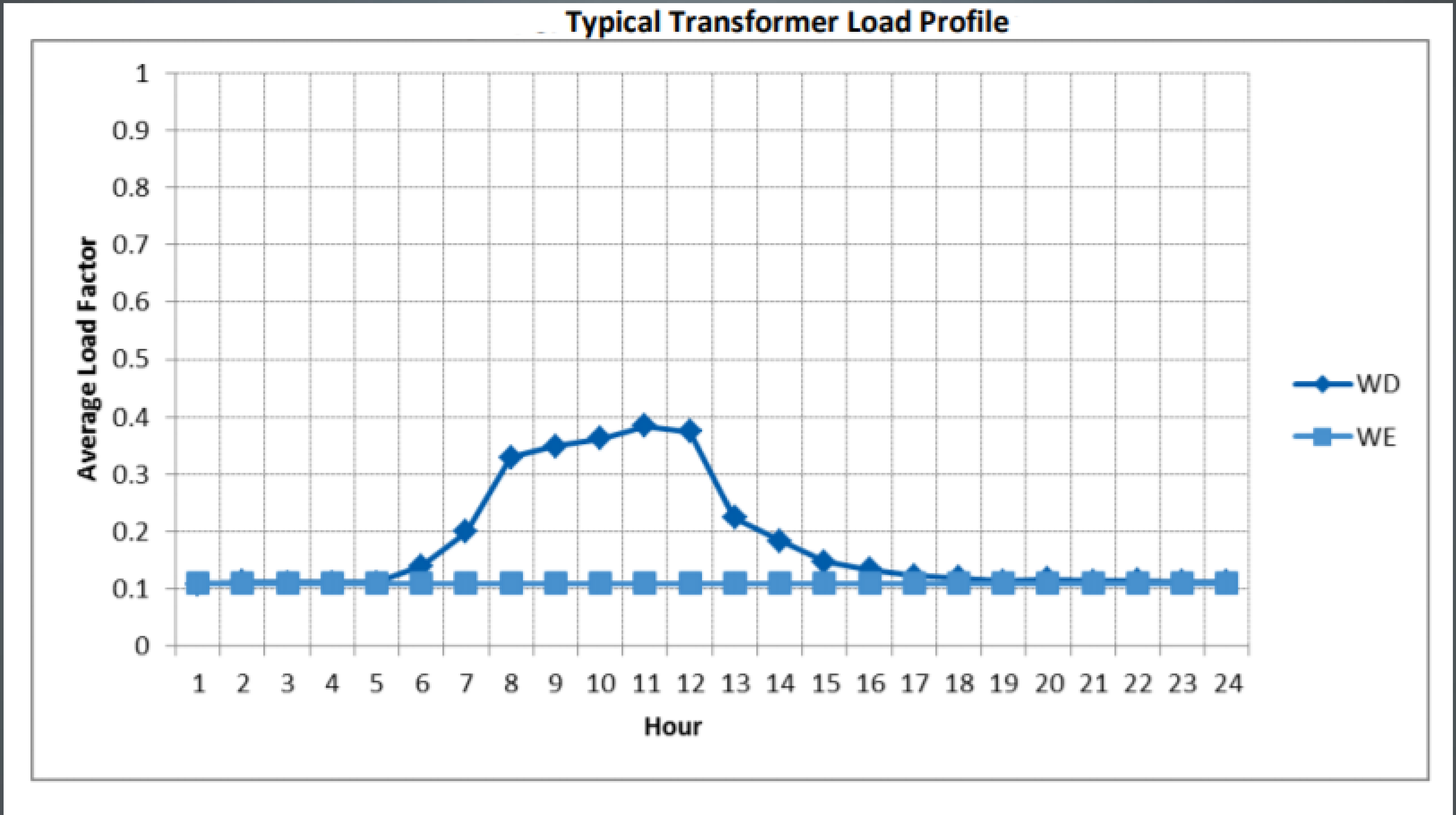
https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/Liquid%20Immersed%20Amorphous%20Core%20Distribution%20Transformers_2020-03-31%20FINAL.pdf

Transformer Loading



*The Cadmus Group, Inc. 1999. *Low-Voltage Transformer Loads in Commercial, Industrial, and Public Buildings. Prepared for Northeast Energy Efficiency Partnerships.*

Transformer Hourly Load Profile



Source: National Grid "Transformer Replacement Program for Low-Voltage Dry-Type Transformers". April, 2013