Amorphous Metal Transformer: Next Steps

An EPRI White Paper

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Abstract

Amorphous Metal Transformer: Next Steps

Amorphous-metal transformers were developed through EPRI in the early 1980's. Over the next 15 years, US electric utilities bought and installed over 500,000 units and had satisfactory field experience. The demand for this product disappeared in North America late in the 1990's as deregulation set-in. Globally, this product has been in use, and its acceptance has been increasing. This paper describes the current state of amorphous transformer activities globally.

An analysis using US Department of Energy (DOE) data shows that amorphous transformers are slightly more expensive at the DOE ruling efficiency, but they are significantly lower in costs compared to conventional units as the efficiency of the transformer increases. If utilities consider the current outlook of energy and capacity costs along with reasonable cost of emissions in their transformer loss evaluation factors, amorphous transformers will provide significantly lower total owning costs.

To help jumpstart development and use of amorphous transformers, a series of new research projects is proposed. The primary objective of this work is to develop and commercialize third generation amorphous-core transformers that utilize newer materials and manufacturing processes to reduce cost, weight, and size of units while improving performance.

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Report Summary

Background

Amorphous metal transformers (AMTs) were developed in the United States under an Electric Power Research Institute (EPRI) program in early 1980 with General Electric Company (GE) [1, 2]. These novel and highly energy-efficient units were slightly more expensive but had significantly lower operating costs than conventional units, resulting in lower life-cycle (LC) or total ownership costs (TOC). During the next 15 years, over 500,000 units were installed in the United States with very satisfactory field experience [1, 2]. In the late 1990s, the demand for this product disappeared as restructuring (deregulation) set in, resulting in all manufacturers abandoning the production of these types of units in the United States. However, the product has been very active in Asian countries like India, China, Japan (in descending order of installations), and others.

On October 12, 2007, the U.S. Department of Energy (DOE) issued the Final Ruling on minimum efficiency for distribution transformers [9]. This ruling becomes effective January 1, 2010. As a result of this ruling, there is a renewed interest in the United States for AMTs.

Total Ownership Cost (TOC) and Band of Equivalency (BOE)

Utilities traditionally have used the concept of total ownership cost (TOC) when deciding to purchase distribution transformers (DT). In this methodology, both core (no load) loss and winding (load) loss are evaluated by assigning them economic values in equivalent first cost (a form of present worth). Factors used for such evaluation are called A and B in the industry, and TOC is calculated as follows:

TOC = Price + A x Core Loss + B x Winding Loss

Values of A/B factors are very dispersed nationally. They range from a low of A = $2/watt to a high of $13/watt. Generally speaking, low values seem to be associated with users that have not updated their numbers in many years. Users who have updated their numbers based on their current outlook of energy and capacity costs are deriving numbers in the upper end of a band in the range of $8-$12/watt for core loss factor (A). Typically, B factor is one third to one fourth the value of A factor. Among user groups, rural electric coops (RECs) and municipalities (munies) generally have slightly higher evaluation factors than investor-owned utilities (IOUs). The higher their evaluation factor numbers, the more efficient (lower losses) transformers can be justified economically. A higher ratio of A/B favors AMT.

However, there is another concept used in the industry called band of equivalency (BOE) that negates the purchase of the optimum (and most efficient) products. In the BOE concept, all bids within the band (typically 3%) of the lowest TOC are treated "equal," and the lowest-cost unit within this band is purchased.

Table 1, on the following page, illustrates the BOE methodology.

Table 1. BOE Methodology

BOE Methodology				
Evaluation Factors : A=$5, B=$1				
Unit	**AMT**	**S1**	**S2**	**S3**
Price	$1050	$850	$900	$800
Core Loss	15	65	66	80
Wind Loss	375	370	300	400
TOC	**$1500**	**$1545**	**$1530**	**$1600**

In this example, AMT offers the best TOC of $1500. For 3% BOE, the maximum TOC permitted for the second-round consideration is $1545. Thus, unit S3 is thrown out during the first round of evaluation because its TOC exceeds 3% over minimum. In the second round, the business is awarded to unit S1 because it offers the lowest price among three remaining units (AMT, S1, and S2). Thus, under the BOE methodology, AMT loses even though it offered the lowest TOC.

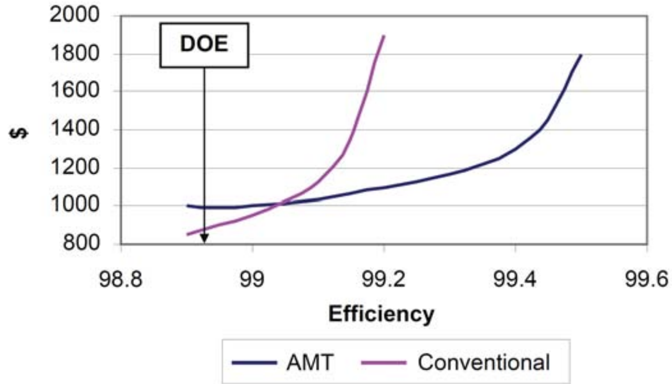
Under such purchase criteria, the supplier of the transformer does not have any incentive to bid the optimum unit, which offers lowest TOC. The supplier intentionally bids units that have higher losses but lower cost (and a higher TOC) to win the business. After a few such rounds of bidding, the utility generally ends up purchasing low-cost/high-loss units.

AMT Value Proposition

Before setting the ruling, DOE had done an extensive analysis of tradeoffs between energy savings vs. transformer costs with all available (but practical) material options, including amorphous metal [8].

Analysis shows that the value of AMT calculated as the amount of energy saved, generation deferred, and emissions reduced is three times the benefit that will be realized from the current ruling [8]. Thus, there is a huge potential in adopting this product.

Figure 1 shows cost vs efficiency of transformers using conventional (silicon) and amorphous material for one typical (25-kVA) rating [8]. Figure 1 shows that the cost of the transformer using conventional material increases dramatically beyond the current DOE (efficiency) ruling. In fact, it is impossible to increase the efficiency of the unit beyond a certain point (for example, 99.2% in Figure 1) with traditional material options. In contrast, AMT can achieve levels of efficiencies not possible with conventional materials at significantly lower costs. This relationship of cost of conventional materials vis-à-vis amorphous vs. efficiency holds true for the entire range of distribution transformer kVAs.



Source : DOE TDS [8]

Figure 1. 25 kVA, Cost vs. Efficiency 1Q 2005 Material Price

Thus, for the utility that wants to go beyond minimum efficiency requirements set by DOE, AMT becomes the product of choice.

The section on ***AMT Value Proposition*** describes how AMT starts to show benefit (lower TOC) at $4/watt of core loss evaluation factor. For higher values, one moves further up on the AMT efficiency curve thereby justifying higher efficiency economically.

If a utility uses the current-day outlook of energy and generating capacity costs and includes reasonable emission costs, A/B values will be in a range of A = $8-$10/watt and B = $2-$3/watt or higher. At these levels of loss evaluation, a very high efficiency AMT can be justified economically while yielding great benefits in energy savings, deferred generation, and reduced emissions.

Table 5 shows that, by switching to AMT, an additional energy savings potential (over the current DOE ruling) of more than 500 Gwhr/annually is possible.

Briefly, to justify AMTs economically, utilities need to do the following:

1. Update their A/B factors using current and projected costs of energy and generation capacity addition.
2. Include emission costs in calculating A/B factors.
3. Abandon use of the band of equivalency (BOE) methodology.

Under the current environment of high energy costs, concerns for climate change, and an increasingly carbon-constrained economy, AMT can be an effective solution for U.S. utilities working to improve distribution system efficiency, reduce their carbon footprint, and meet/exceed other environmental (SO2, NOx, and mercury reduction) goals.

EPRI Projects

Since AMTs have not been produced in this country for over a decade, both suppliers and users have lost institutional memory of it. The following EPRI projects will ensure that the United States regains its leadership in this important energy-efficient technology, re-commercializes the product, and creates green jobs.

1. ***Material Stability:*** Technically, amorphous is an unstable state of metal. Accelerated aging tests performed in the past on the composition used for transformers have shown that the stable "life" is over 500 years [1]. Testing 30-50 (AMT) units from different parts of the country that have been in service for around 20 years and confirming results against as-shipped factory data will validate such understanding.
2. ***Develop a Third-Generation AMT Product:*** Amorphous materials and production techniques have changed over the last 25 years. New improved material 2605HB1 offers great promise to reduce the size and weight of units with improved performance [3, 4, 5]. New manufacturing techniques can drive down the production cost. As operating characteristics of this material are very similar to current materials, this third-generation product development is expected to be centered around optimization and automation of manufacturing processes. Thus, it is not envisioned as being a major new development.
3. ***Establish a Pilot Production Facility:*** The project would purchase 1000-2000 units for EPRI members for field installation (0.1-0.2% of annual U.S. usage). This large purchase will incentivize suppliers to make the necessary investments to set up a pilot production facility. With 20+ years of satisfactory field experience for this product, there is no need for further extensive field evaluation. A pilot facility can then be scaled up to commercial production as demand for this product increases.
4. ***Green Circuit Field Trials with State-of-the-Art Monitoring Equipment:*** Currently, EPRI has an active Green Distribution Circuit project that helps understand and quantify performance improvements from various changes in operating practices [10]. By changing transformers in this circuit to AMTs and adding real-time monitoring, the value of this technology can be verified.
5. ***Transformer Modeling and Harmonic Testing:*** Consumers and industry are increasingly using nonlinear loads such as electronic devices with switching power supplies (for example, computers and fax machines), variable-speed drive devices (for example, central air conditioners and motor controls), and other devices. AMT is expected to perform better under such harmonic-generating conditions than conventional units [5, 6, 7]. A finite element analysis (FEA) model of the transformer needs to be constructed to understand and visualize electromagnetic phenomena under such load conditions. Actual testing under nonlinear load conditions needs to be carried out to confirm the benefits.

Introduction

Amorphous metal transformers (AMTs) were developed in the United States under an EPRI program with General Electric Company (GE) in early 1980 [1, 2]. These novel and highly efficient units were slightly more expensive than conventional units but had significantly lower operating costs, resulting in lower life-cycle or total operating costs (TOC). GE successfully commercialized this product over the next 15 years. However, the demand for this product disappeared in the late 1990s as restructuring (deregulation) set in, resulting in all manufacturers abandoning the production of this type of unit in the United States.

Asia is a different story. Due to relatively high energy costs and some encouragement from government, many Asian countries have adopted this energy-efficient (AMT) product. Currently, over ninety percent of global production and use of these types of units is occurring in Asia. It is interesting to note that both the amorphous metal and the transformers using it were invented in the United States, but nobody currently is producing AMTs in the United States.

Under the current environment of high energy costs, concerns for climate change, and an increasingly carbon-constrained economy, AMT can be an effective solution for U.S. utilities working to improve distribution system efficiency and reduce emissions. Since these types of products have not been produced in this country for over a decade, both suppliers and users have lost institutional memory of it.

This White Paper captures historical background, documents the current state of AMT product globally, explains the methodology behind the Department of Energy (DOE) ruling on minimum efficiency of distribution transformers, and discusses the AMT value proposition under the current environment. The paper also provides sufficient information to develop new EPRI projects that can result in:

- the United States regaining its leadership position in this important energy-saving technology,
- re-commercializing this product with newer material and newer production techniques, and
- creating new green jobs in the United States.

History

Amorphous Metals

Amorphous metals are a new class of material. Their atomic structure is random (hence, amorphous) unlike regular metals, which are crystalline. Typically, they are made by rapidly quenching liquid metal at a very high cooling rate of around one million K/s [1]. Due to their random atomic structure, they possess very unique properties. Iron-based amorphous metals are easy to magnetize, but because of their noncrystalline atomic structure, their physical characteristics are more like glass then metal.

Challenges in Making Transformers

Several properties of amorphous metal presented a formidable challenge to the designer of distribution transformers. The material is very thin, approximately 0.025mm (1 mil), almost 1/10th the thickness of conventional silicon iron material used to make cores in present-day transformers. It also is very hard, having a Vicker's hardness of about 1000, some four to five times harder than silicon iron. Traditional cutting/punching tools, even with carbide tips, would wear out in a very short period. The material also is very (mechanical) stress sensitive and requires annealing under a magnetic field to achieve optimum performance. Another drawback is that it has 20% lower magnetic saturation, resulting in increased core and, hence, transformer size. These were some of the engineering challenges in making transformers out of this material. Despite all these problems, the potential benefit of amorphous core transformers made the effort to develop them worthwhile [1].

Early Transformer Development

GE started their internal development work for making these types of units in the early 1980s. The world's first full size 25-kVA AMT unit was installed in the Duke Power system on April 13, 1982 [2]. Since material cutting issues were not solved yet, coils were wound into continuously wound uncut cores. This transformer was periodically tested in the field for core loss, and performance was stable [2].

Another design concept that was developed, again to get around the "cutting" issue, was "toroidal" design. In this construction, the core is continuously wound in a donut shape without any cuts. Coil is then wound around the core using a bobbin that passes through the core window once each turn [1]. Core performance of this design was excellent. However, coil winding was very complex and very labor intensive. One U.S. manufacturer even commercialized this product; however, the product offering was limited to only smaller sizes. Japanese manufacturers initially made AMTs using the same design concept [1]. Both U.S. and Japanese groups latter gave up this approach as cutting techniques were developed and switched to distributed-gap construction, developed under an EPRI project.

EPRI-ESSERCO-GE Project

In late 1982, Electric Power Research Institute (EPRI), the Empire State Electrical Energy Research Corporation (ESEERCO), and GE embarked on a $6.5 million project to comprehensively determine if an AM core distribution transformer could be a commercially viable product offering to electric utilities and, if so, accelerate its development [1, 2].

In addition to addressing the technical issues involved in the design and manufacture of AMTs, another EPRI goal was to establish a record of operating performance in the field. EPRI wanted data that would substantiate the laboratory findings that there is no degradation of the exceptionally good soft magnetic properties of amorphous metal under typical distribution system operating conditions [1, 2].

Field Evaluation

To obtain additional operating experience with AMTs, the first objective of the EPRI project was to manufacture and install an additional 25 units at different utilities throughout the country [1, 2]. These transformers were identical to the initial unit installed by Duke Power in 1982. These first-generation units were significantly larger and heavier compared to nonloss-evaluated (low first-cost) conventional units. Again, periodic testing of these units confirmed performance stability [1, 2].

1000 25-kVA AMTs

Through the design evaluation phase of the EPRI project, GE selected and recommended the distributed-gap design configuration for manufacturing 1000 AMTs. The reason for 1000 transformers was two fold. First, it was believed that manufacturing this number of transformers would demonstrate the feasibility of mass production. A second purpose was to conduct the most widespread field evaluation of AMT performance to-date [1, 2].

Typical performance of these AMTs compared to silicon iron transformers is shown in Table 2 [1, 2].

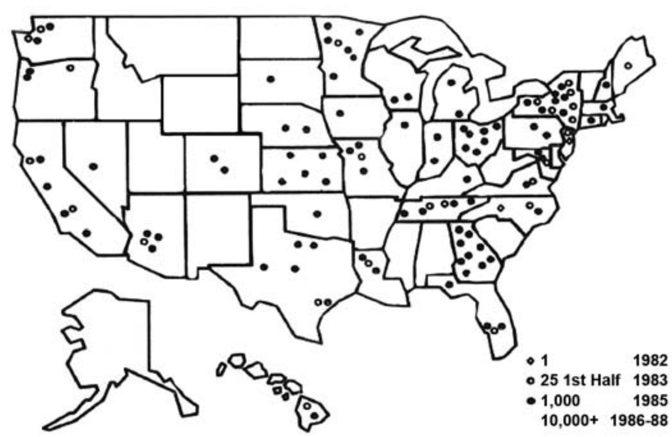
Table 2. 25-kVA AMT vs. Silicon Transformer

	Amorphous	Silicon Iron
Core Loss (w)	15.4	57
Load Loss (w)	328	314
Impedance (%)	2.45	2.45
Audible Noise (db)	33	40
Temperature Rise (OC)	48	57
Short Circuit Test (XN)	40	40
Inrush Current (XN) @ 0.01/0.1 sec	21/13	23/14
TIF @ 100/110% Exc. (IT/kVA)	2/10	5/25
Weight (Lbs)	441	406

Source: 1 and 2

Table 2 shows these second-generation units had significantly better core loss and were only slightly heavier than comparable silicon iron units.

Approximately 90 EPRI members participated in this two-year field evaluation of AMT performance. By the end of 1985, all 1000 units were shipped to participating utilities [1, 2]. Locations of utilities receiving these as well as 25 prototype units and the initial installation at Duke Power Company are shown in Figure 2 [1, 2].



Source: 2

Figure 2. AMT Installations in the United States

This evaluation program consisted of each utility testing all transformers received before they were installed and mailing test results to GE for comparison with the factory test. Subsequent tests were made by utilities with their own equipment on 10% of units after the first year of service and another test on a different 10% after the second year. These tests have confirmed performance stability in actual operating conditions in the field [1, 2].

Commercial AMT Production

With the success of the EPRI/ESEERCO project, GE started commercial production of AMTs in early 1986. A comparison of typical AMTs and low-loss silicon iron (SiFe) transformers is shown in Table 3. [1, 2].

GE shipped over 400,000 AMTs before abandoning production in the late 1990s along with all other suppliers due to lack of demand.

New Developments

New Developments Since 1990

The amorphous metal used to produce 1000 units for the EPRI project was MetGlas alloy no. 2605SA1. This material is still the workhorse of all current commercial production of AMTs globally. Over the last couple of decades, improvements in this material have come in the form of consistency in performance (lower variability) and much smoother surface conditions (better space factor) while the basic chemistry has stayed the same. These improvements have allowed transformer manufacturers to reduce the size and weight of the unit by making the material work "harder" without sacrificing performance. Thus, current AMTs are somewhat smaller and lighter than those produced under the EPRI project in the mid 1980s; however, they are still a bit heavier than conventional units.

Continued demand for reduced size, weight, cost, and audible noise of the transformer has led the major manufacturer of this material, MetGlas Inc., to develop a new composition. The new material is called 2605HB1 [3, 4, 5]. This material has slightly higher saturation induction and its hysteresis loop is "squarer" compared to 2605SA1 (see Figure 3 on the following page) [4].

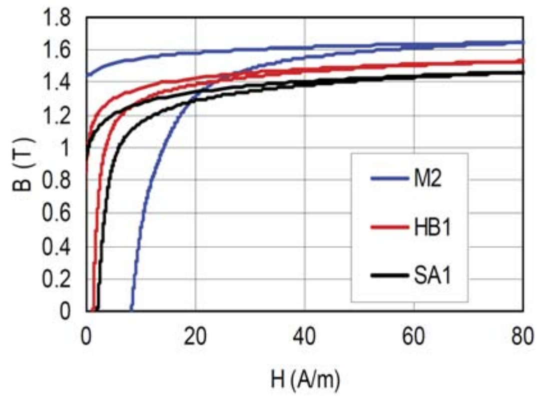
Both of these characteristics will allow transformer manufacturers to reduce size and weight of the unit further. Because of a squarer hysteresis loop, the audio noise level will reduce, too [4, 5]. This material is now available in small commercial quantity. It is expected that AMTs made with this new material should be approximately 10% lighter with a corresponding reduction in size [5].

It is envision that new EPRI projects will use AMTs made from this material (HB1) to assess its benefits and gather operating experience.

Table 3. Comparison of AMT vs. Silicon Transformers

Type	kVA	Amorphorous				Low Loss Silicon Iron			
		Core Loss	Wind Loss	% Imp	Weight	Core Loss	Wind Loss	% Imp	Weight
Single Phase	10	12	102	1.6	318	29	111	1.8	300
	15	16	141	1.9	422	41	143	1.9	321
	25	18	330	2.5	441	57	314	2.5	406
	50	29	455	2.7	719	87	462	3.2	709
	75	37	715	3.3	994	122	715	3.0	8231
	100	49	944	3.0	1131	162	933	2.6	961
Three Phase	75	51	925	4.0	2030	142	956	4.1	2000
	150	90	1397	3.9	2870	227	1429	3.5	2900
	300	165	1847	3.9	4360	435	2428	5.1	3600
	500	230	2383	4.8	6090	610	3589	4.6	4900
	750	327	4468	5.75	6600	713	5206	5.75	6800
	1000	419	5626	5.75	8200	1033	6839	5.75	7000

Source : 1 & 2



Source : 4

Figure 3. BH Curve for M2-Grade Silicon Steel, Conventional 2605SA1 and New 2605HB1 Amorphous Metal

Manufacturing Processes

As expected, several new manufacturing processes have been developed to reduce production costs while reducing variability.

One such development has been the use of "continuous annealing." Amorphous metal cores require annealing under a magnetic field to achieve best performance. Units produced in the United States had used the "batch annealing" process. As production volume builds up, use of continuous annealing will reduce manufacturing costs while improving performance consistency.

Similar opportunities exist for core-making processes due to improved electronic controls on machinery and other innovations.

Current Global Activities

Global Activities

As mentioned in the History section, AMTs were invented and first used in the United States. After several years of use in the United States, other countries became interested and adopted this product. The following section describes current AMT activities in different countries.

Japan: Japan was the second country after the United States to use this highly energy efficient product. Early units used the "toroidal" design [1]. After making only a few hundred units of this type, the construction technique was abandoned in favor of distributed-gap construction, same as the one developed under the EPRI project. Currently, there are at least four Japanese manufacturers offering AMTs commercially. It is estimated that Japan has over several hundred thousand units installed in the field and operating satisfactorily for over 18 years.

Recently, several utilities removed 30 units from the field that were in service for 10 years or longer and conducted core performance tests. All showed stable performance. X-ray diffraction patterns did not show any crystallization activity, further confirming that the material had maintained amorphous status.

Hitachi Metals, the parent company of Metglas (the U.S. producer of the metal), has now started producing amorphous metal in Japan.

India: India was the third country to adopt this product and currently is the largest user. It installs as many AMTs annually as the rest of the world combined. Currently, it has the largest installed base, surpassing the United States. The Bureau of Energy Efficiency of the Ministry of Power of India has established a "5 star" efficiency scale for distribution transformers. AMT meets a 5-star rating. The Bureau also has proposed that state electric boards and industry specify 3 stars as a minimum requirement. However, the purchase decision is left to the state electric boards, and AMTs are justified on total ownership cost. There are three manufacturers of AMTs in India.

China: China was a latecomer in adopting this product, but now is purchasing in significant quantities. There are two amorphous metal (AM) core manufacturers who supply cores to transformer manufacturers. There are now many (8+) manufacturers of AMTs in China.

Taiwan: Tai Power started evaluation and purchase of AMTs in the mid 1990s. Tai Power is now a significant user of AMTs. There is an AM core manufacturer in Taiwan, and three manufacturers of transformers are AMT suppliers.

Bangladesh: Bangladesh has purchased AMTs and also has a significant installed base. Many of these are procured with aid money, and AMT has been justified based on units having lower total ownership costs. There is no manufacturer of AMT in Bangladesh.

Other Asian Countries: Several other Asian countries are using AMTs, and a few additional ones have started the evaluation process. Both KEPCO in Korea and PHELEC in the Philippines are now significant users of AMTs. Australia and Thailand have initiated adoption and are now purchasing small quantities of AMTs.

Europe: In Europe, distribution transformers use "stack core" construction where the core is formed by stacking laminations of steel. This manufacturing process doesn't lend itself to adopting AMTs because they require a "wound" construction. Thus, adoption of AMTs in Europe is somewhat slow. However, several utilities have evaluated AMTs, and now ENEL in Italy and ENDESA in Spain have stepped up AMT purchases.

South America: Brazil is the first South American country using AMTs. An Indian AMT company has started manufacturing AMTs in Brazil. In response to this market entry, an AM core manufacturer has emerged, supported primarily by other transformer manufacturers. Other transformer manufacturers will source AM cores from this core manufacturer and produce AMTs.

North America: As discussed in the History section, the United States has one of the largest installed bases and the longest operational experience. Currently, AMTs are neither produced in this country nor being installed in any significant quantity.

Canada has relatively high loss evaluation factors. Numbers are high enough to justify AMTs even at significantly higher first cost. Thus, several Canadian utilities have started evaluating this product. One AM core manufacturer has emerged, and it is expected that most transformer manufacturers will source AM cores and produce AMTs.

Recently, several transformer manufacturers in North America have initiated the production of AMTs in small quantities.

DOE Ruling on Distribution Transformer Efficiency

Background

The National Appliance Energy Conservation Act (NAECA) of 1987 gave the U.S. Department of Energy (DOE) specific authority to set national standards for certain residential and commercial appliances. The Energy Policy Act (EPACT) of 1992 expanded a number of products DOE could set standards for while requiring it to assess the feasibility of energy conservation standards for distribution transformers.

In response to this act, the National Electrical Manufacturers Association (NEMA) developed a voluntary guide called TP1 in 1996 and latter revised it in 2002. Even though a few states have made this standard a mandatory minimum requirement for dry-type transformers, for liquid-filled units meeting the standard is mostly done on a voluntary basis.

A mandated study conducted by DOE determined that a new standard could save energy and would result in life-cycle cost (LCC) savings. An Advanced Notice of Proposed Rulemaking (ANOPR) meeting was called in September 2004 to review results of their findings with stakeholders. After getting inputs from stakeholders, DOE issued Notice of Proposed Rulemaking (NOPR) documents in September 2005 and held another stakeholder meeting in September 2006. The Final Ruling was issued on October 12, 2007 [9].

The Final Ruling

The Final Ruling sets minimum efficiency standards for liquid-filled and medium-voltage dry-type transformers up to 2500 kVA and is effective January 1, 2010 (see Figure 4 and Figure 5 on the following page). The standard for low-voltage dry-type product was set at TP1 as a part of EPACT 2005, effective January 1, 2007 [9].

Engineering Analysis

Prior to setting these rulings, DOE had done an extensive engineering analysis of various ratings, considering all available material options, including amorphous metal, to arrive at a minimum life-cycle cost (LCC) under various operating conditions and energy costs. Following is an overview of the methodology used in that an analysis [8].

First, DOE classified product ranges into 10 product classes. Initially, product classes 3 and 4 were for low-voltage dry-type transformers. Since efficiencies of these products (low-voltage dry type) were incorporated into EPACT 2005, DOE dropped these product classes from further analysis; hence, they are missing from Figure 6 (on page 10).

Single-phase kVA	Single-phase Efficiency (%)	Three-phase kVA	Three-phase Efficiency (%)
10	98.62	15	98.36
15	98.76	30	98.62
25	98.91	45	98.76
37.5	99.01	75	98.91
50	99.08	112.5	99.01
75	99.17	150	99.08
100	99.23	225	99.17
167	99.25	300	99.23
250	99.32	500	99.25
333	99.36	750	99.32
500	99.42	1000	99.36
667	99.46	1500	99.42
833	99.49	2000	99.46
		2500	99.49

Note: All efficiency values are at 50 percent of nameplate-rated load, determined according to the DOE test procedure. 10 CFR Part 431, Subpart K, Appendix A.

Source : 9, Table I.1

Figure 4. Standard Levels for Liquid-Immersed Distribution Transformers

Single-phase				Three-phase			
BIL kVA	20–45 kV efficiency (%)	46–95 kV efficiency (%)	≥96 kV efficiency (%)	BIL kVA	20–45 kV efficiency (%)	46–95 kV efficiency (%)	≥96 kV efficiency (%)
15	98.10	97.86		15	97.50	97.18	
25	98.33	98.12		30	97.90	97.63	
37.5	98.49	98.30		45	98.10	97.86	
50	98.60	98.42		75	98.33	98.12	
75	98.73	98.57	98.53	112.5	98.49	98.30	
100	98.82	98.67	98.63	150	98.60	98.42	
167	98.96	98.83	98.80	225	98.73	98.57	98.53
250	99.07	98.95	98.91	300	98.82	98.67	98.63
333	99.14	99.03	98.99	500	98.96	98.83	98.80
500	99.22	99.12	99.09	750	99.07	98.95	98.91
667	99.27	99.18	99.15	1000	99.14	99.03	98.99
833	99.31	99.23	99.20	1500	99.22	99.12	99.09
				2000	99.27	99.18	99.15
				2500	99.31	99.23	99.20

Note: BIL means basic impulse insulation level.
Note: All efficiency values are at 50 percent of nameplate-rated load, determined according to the DOE test procedure. 10 CFR Part 431, Subpart K, Appendix A.

Source : 9, Table I-2

Figure 5. Standard Levels for Medium-Voltage, Dry-Type Distribution Transformers

Because it would be impractical to analyze all kVA ratings in all voltage classes of these product classes, DOE set out to simplify the analysis. Product classes were further subcategorized by the shape of the tank used to make the product, resulting in 10 design lines. Recognizing that many ratings used essentially the same construction techniques, one representative rating was chosen from each design line for detailed analysis. Design lines and representative ratings are shown in Figure 7.

Graphically, Figure 7 can be depicted as follows in Figure 8, Figure 9, and Figure 10 (on page 11).

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

Source: 8, Table 5.2.1

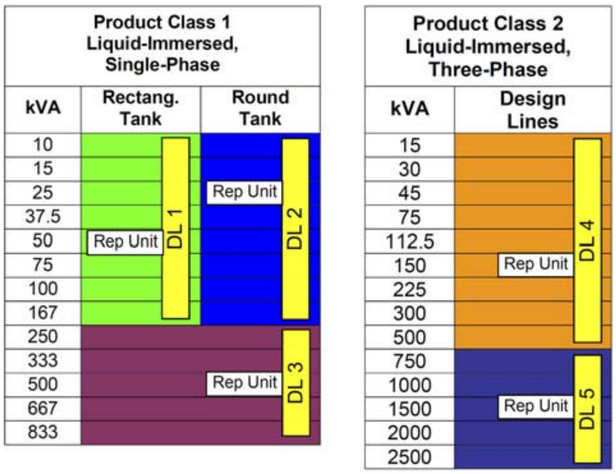
Figure 6. Product Classes and Number of kVA Ratings

PC*	DL	Type of Distribution Transformer	kVA Range	Representative Unit for this Engineering Design Line
1	1	Liquid-immersed, single-phase, rectangular tank	10–167	50 kVA, 65°C, single-phase, 60Hz, 14400V primary, 240/120V secondary, rectangular tank
	2	Liquid-immersed, single-phase, round tank	10–167	25 kVA, 65°C, single-phase, 60Hz, 14400V primary, 120/240V secondary, round tank
	3	Liquid-immersed, single-phase	250–833	500 kVA, 65°C, single-phase, 60Hz, 14400V primary, 277V secondary
2	4	Liquid-immersed, three-phase	15–500	150 kVA, 65°C, three-phase, 60Hz, 12470Y/7200V primary, 208Y/120V secondary
	5	Liquid-immersed, three-phase	750–2500	1500 kVA, 65°C, three-phase, 60Hz, 24940GrdY/14400V primary, 408Y/277V secondary
6	9	Dry-type, medium-voltage, three-phase, 20-45kV BIL	15–500	300 kVA, 150°C, three-phase, 60Hz, 4160V Delta primary, 480Y/277V secondary, 45kV BIL
	10	Dry-type, medium-voltage, three-phase, 20-45kV BIL	750–2500	1500 kVA, 150°C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL
8	11	Dry-type, medium-voltage, three-phase, 46-95kV BIL	15–500	300 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
	12	Dry-type, medium-voltage, three-phase, 46-95kV BIL	750–2500	1500 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
10	13	Dry-type, medium-voltage, three-phase, 96-150kV BIL	225–2500	2000 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 125kV BIL

* PC means product class (see Chapter 3 of the TSD). The Department calculated the analytical results for PC5, PC7, and PC9 based on the results for their three-phase counterparts. The Department did not select any representative units from the single-phase, medium-voltage product classes (PC5, PC7 and PC9) because of their low sales volume.

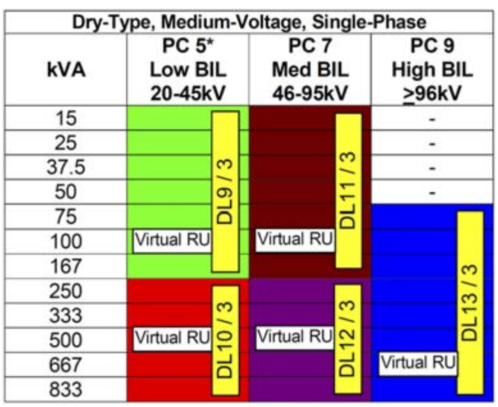
Source : 8, Table 5.2.2

Figure 7. Engineering Design Lines (DLs) and Representative Units for Analysis.



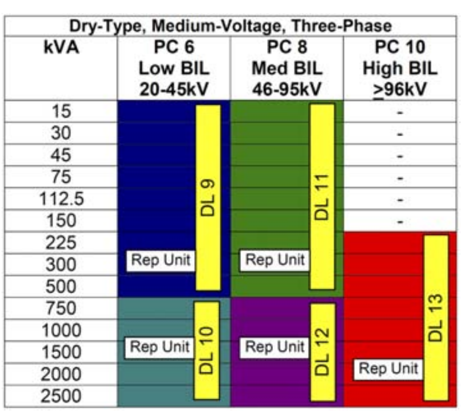
Source: 8, Tables 5.2.3

Figure 8. Liquid-Immersed Design Lines and Representative Units



Source: 8, Tables 5.2.4

Figure 9. Dry-Type, Medium-Voltage, Single-Phase Design Lines



Source: 8, Table 5.2.5

Figure 10. Dry-Type, Medium-Voltage, Three-Phase Design Lines

Scaling Relationship

Transformer design engineers know that there is a mathematical relationship that exists between the kVA rating and a transformer's physical size, cost, and performance. The size vs. performance relationship arises from fundamental equations describing a transformer's voltage and kVA rating [9]. DOE used this methodology to extrapolate cost and performance of the remaining ratings in the design lines.

Core Configuration

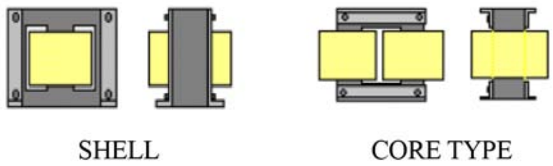
Industry has used different core configurations to make different design lines. Figure 11 describes what core configurations were used for which design lines.

Graphically, core constructions are shown in Figure 12 and Figure 13 on page 12.

Design Line	# Phases	Core Configurations Used in the Engineering Analysis
DL 1	1	Wound core - distributed gap, shell-type
DL 2	1	Wound core - distributed gap, shell-type or core-type
DL 3	1	Wound core - distributed gap, shell-type or core-type
DL 4	3	Wound core - distributed gap, 5-leg
DL 5	3	Wound core - distributed gap, 5-leg
DL 9	3	Stacked, butt-lap or mitered joint, 3-leg
DL 10	3	Stacked, cruciform, mitered joint, 3-leg
DL 11	3	Stacked, mitered joint, 3-leg
DL 12	3	Stacked, cruciform, mitered joint, 3-leg
DL 13	3	Stacked, cruciform, mitered joint, 3-leg

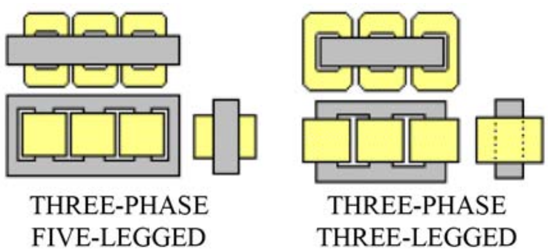
Source: 8, Table 5.3.4

Figure 11. Core Configurations Used in Each Design Line



Source: 8

Figure 12. Single-Phase Core Configurations



Source: 8

Figure 13. Three-Phase Core Configurations

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Al (wire)	Al (strip)	Shell - DG Wound Core
M6	Cu (wire)	Al (strip)	Shell - DG Wound Core
M4	Al (wire)	Al (strip)	Shell - DG Wound Core
M4	Cu (wire)	Al (strip)	Shell - DG Wound Core
M3	Cu (wire)	Al (strip)	Shell - DG Wound Core
M3	Cu (wire)	Cu (strip)	Shell - DG Wound Core
M2	Cu (wire)	Al (strip)	Shell - DG Wound Core
M2	Cu (wire)	Cu (strip)	Shell - DG Wound Core
ZDMH	Cu (wire)	Cu (strip)	Shell - DG Wound Core
SA1(Amorphous)	Cu (wire)	Cu (strip)	Core - DG Wound Core

Source: 8, Table 5.3.6

Figure 14. Design Option Combinations for the Representative Unit from Design Line 2

Materials Considered

Various combinations of materials were considered in the analysis. Figure 14, bottom left, shows sample materials considered for one design line.

Material and Labor Costs

DOE used a standard method of cost accounting to determine the cost associated with manufacturing. Figure 15, on page 13, illustrates this methodology, where production costs and non-production costs are combined to determine the manufacturer's selling price of the product.

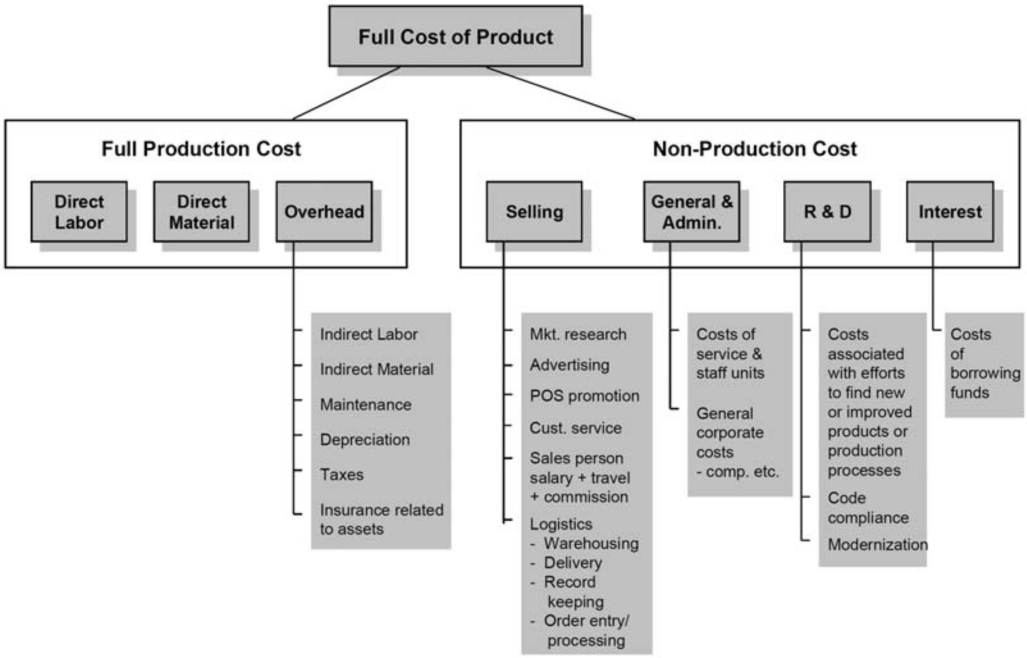
Design Database

All designs resulting from the above-mentioned combinations of materials were stored in a design database. This data set was then used to feed a life-cycle cost (LCC) model to arrive at the optimum solution for the nation as an aggregate. The design database can be depicted in a scattered plot showing the cost of each unit along with its efficiency for each combination of materials. Figure 16, on page 13, is one such scattered plot for one design line.

For reference, the DOE efficiency ruling is shown on this graph. The scatter plot clearly shows unit cost (and, hence, price) rising as efficiency increases. It also shows for each material combination a range of efficiency that can be achieved. In general, to achieve better efficiency, a better grade of steel and/or use of copper are necessary. For example, M3 or M2 core steel grades will be required to meet DOE efficiency costs effectively. Amorphous metal provides the best level of efficiency. In that respect, it is the best and only one in the class. In other words, it is not possible to achieve an efficiency much beyond the DOE ruling using conventional (silicon iron) materials. Thus, for users who want to go beyond (exceed) DOE minimum requirements, AMT becomes the material of choice.

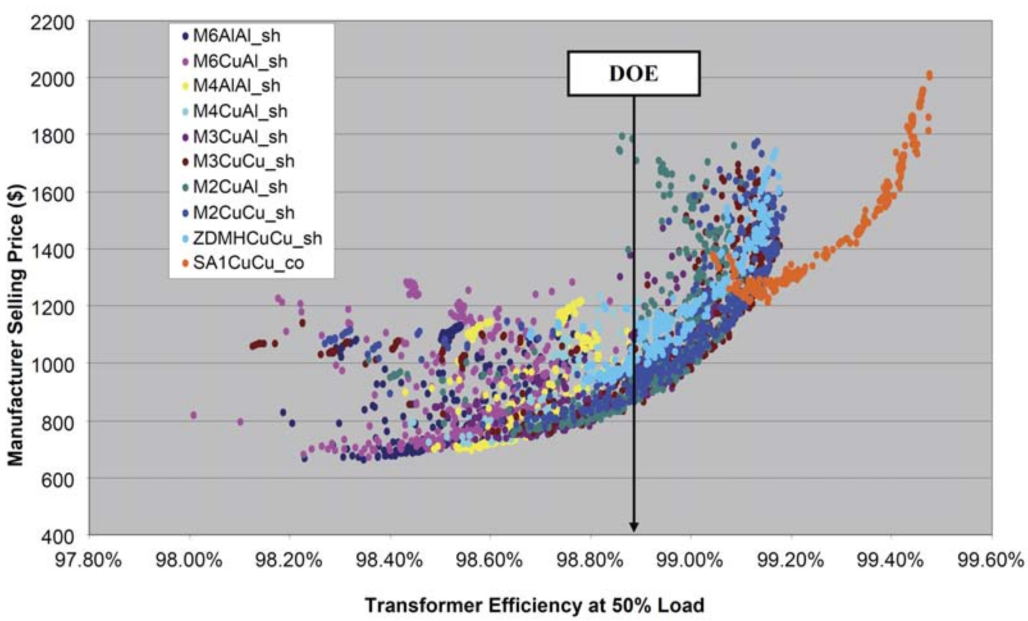
LCC Standard Levels

The output of the LCC model yielded the optimum efficiency for each design line. DOE called this level trial standard level 4 (TSL4). NEMA TP1 was called TSL1 because this was the voluntary standard prior to the ruling. Best in class amorphous



Source: 8

Figure 15. Full Cost of Product



Source: 8

Figure 16. Scatter Plot for One Design Line.

metal units were assigned TSL6. Other intermediate levels were equally spread among these three classes. As might be expected, such assignments resulted in some discontinuity and discrepancy of efficiency, not only among kVA ranges but also between single- and three-phase units within a given trial standard level.

Technically, the Final Ruling set at TSL4 would have theoretically resulted in the optimum condition for the nation. However, because of discontinuity in the efficiencies, the Final Ruling was set between TSL3 and TSL5 for single-phase ratings and between TSL2 and TSL3 for three-phase ratings. Such adjustments permitted a smooth transition from one kVA to the next kVA and permitted harmonization of efficiencies between single- and three-phase units.

Benefit of the Ruling

DOE estimates the standards will save approximately 2.74 quads (quadrillion [10^{15}]) British Thermal Units (BTU)) of energy over 29 years (2010-2038). This is equivalent to all energy consumed by 27 million American households in a single year [8, 9].

By 2038, DOE expects the energy savings from the standards to eliminate six 400-MW power plants (2400 MW) and 238 million tons of carbon dioxide (CO2). Using a 3% discount rate, the cost of the standards is $460 million per year in increased equipment and installation costs while annualized benefits are $904 million per year in reduced operating costs [8, 9].

Had AMT been the standard, energy savings would have been 7.37 quads, a CO2 reduction of 674 million tons, and generation elimination of 7200 MW—triple the benefit compared to the current ruling.

AMT Value Proposition

Background

In the United States, close to one million distribution transformers (DT) are purchased annually. DT purchases are a very significant portion of a utility's distribution budget. Transformers can always be made cheaper by using less active materials (core and coil). However, doing so increases losses and, hence, operating cost. In the early 1960s, the concept of total ownership cost (TOC) emerged where future operating costs of the unit are brought into present-day dollars and added to the purchase price to arrive at the TOC. This methodology permitted utilities to economically justify paying a higher price for units having lower losses (higher efficiency) and, hence, lower operating costs that resulted in lower TOC.

Total Ownership Cost (TOC)

Even though TOC sounds simple in concept, the supporting math is complicated. A transformer has two types of losses, core (no load) loss and winding (load) loss. Core loss is present as long as a transformer is connected to the system while winding loss is present only when the transformer is providing load. Also, load loss increases as a square function of load. Thus, to calculate energy consumed in the winding, the unit's "load profile" must be known. In addition, load profile is very likely season dependant. Generally, in this TOC methodology, each transformer loss component (core and winding) is assigned a monetary value ($/watt) in equivalent first cost. These values in the industry are known as the A/B factor. Thus, TOC is calculated as:

$$\text{TOC} = \text{Price} + \text{A} \times \text{Core Loss} + \text{B} \times \text{Winding Loss}$$

Almost all utilities use the TOC methodology in their purchase decisions. However, the evaluation factors (A/B) utilities use are widely dispersed nationally. They range from a low of A = $2/watt to a high of $13/watt. Generally speaking, low values seem to be associated with users who have not updated their numbers in many years. Users who have updated their numbers based on their current outlook for energy and capacity costs are deriving numbers in the upper end of the band in the range of $8-$12/watt for the core loss factor. Typically, B factor is one third to one fourth the value of A factor. Among user groups, rural electric coops (RECs) and municipalities (munies) generally have slightly higher evaluation factors than investor-owned utilities (IOUs). The higher their evaluation factor numbers, more efficient (lower losses) transformers can be justified economically. A higher ratio of A/B favors AMT.

AMTs in the 1990s were justified using this methodology.

Band of Equivalency (BOE)

In the late 1990s, a new concept developed in the purchase decision for distribution transformers (DT). This concept is called band of equivalency (BOE). In this concept, utilities list all bids in ascending order of TOC. Then, during the first round of bid evaluations, all bids exceeding some predetermined value (for example, 3% over minimum TOC) are thrown out. In the second round of evaluation, the business is awarded to the lowest first-cost supplier from this list, treating all bids within this range (band) as having equivalent TOC. The justification was that there are many assumptions made about future operating costs when calculating TOC, and each input has a range of probability (TOC is not an exact number). Thus, BOE permitted utilities to purchase low first-cost units that were "close enough" to the optimized loss-evaluated unit, thereby containing the budgeted expenditure. Table 4 illustrates the BOE methodology.

Table 4. BOE Methodology

BOE Methodology				
Evaluation Factors : A=$5, B=$1				
Unit	**AMT**	**S1**	**S2**	**S3**
Price	$1050	$850	$900	$800
Core Loss	15	65	66	80
Wind Loss	375	370	300	400
TOC	**$1500**	**$1545**	**$1530**	**$1600**

In this example, AMT offers a best TOC of $1500. For 3% BOE, the maximum TOC permitted for a second-round consideration is $1545. Thus, unit S3 is thrown out during the first round of evaluation because its TOC exceeds 3% over minimum. In the second round, the business is awarded to unit S1 because it offers the lowest price among the three remaining units (AMT, S1, and S2). Thus, under BOE methodology, AMT loses even though it offered the lowest TOC.

Under such an evaluation methodology (BOE), a smart supplier would intentionally bid designs that have higher TOC (than optimum) with higher losses but lower costs to win the business. After a few rounds of such game playing, the purchased unit would be an essentially low first-cost product but with a much higher operating cost. AMTs, which always had higher first costs but significantly lower losses and, hence, lower operating costs, lost under this methodology.

Since the winning bid under the BOE methodology always has a higher TOC, higher losses, and a lower price, it is like purchasing a unit at lower evaluation factors (BOE dilutes the economic value of A/B factors). It is estimated that use of just 3% BOE effectively reduces the value of A/B factors by 50%.

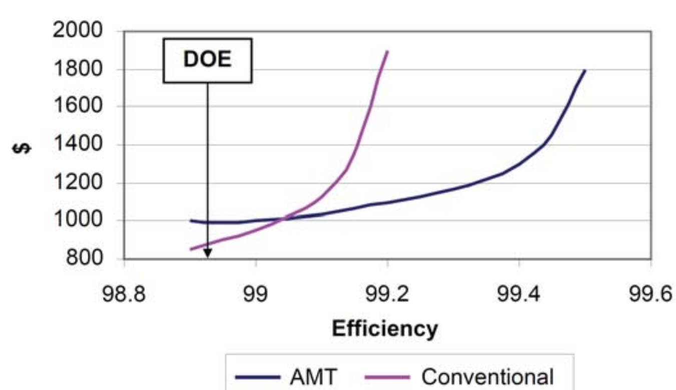
AMT Value Proposition

An analysis performed by DOE has shown that the value of AMT calculated as the amount of energy saved, generation deferred, and CO2 emissions reduced is three times the benefit realized from the current ruling. Thus, there is a huge potential in adopting this technology.

As described in ***DOE Ruling on Distribution Transformer Efficiency***, DOE has performed an extensive analysis of transformer cost vs. efficiency with many different material options. To understand the various tradeoffs between these options cost vs efficiency of these options can be plotted. Figure 17 is one such plot for 25 kVA, which represents one family of designs (design line 2).

Several observations can be made from Figure 17:

- The cost of the transformer using conventional material increases dramatically beyond the current DOE efficiency ruling.
- Even though AMTs are more expensive at the DOE efficiency level, they are lower in costs for efficiencies greater than 99.0%.



Source: DOE TDS [8]

Figure 17. 25 kVA, Cost vs. Efficiency, 1Q 2005 Material Price

- It is impossible to increase the efficiency of a unit using conventional material beyond a certain point (for example, 99.2% in Figure 17).
- In contrast, AMT can achieve levels of efficiencies not possible with conventional materials at significantly lower cost.

This relationship of cost of conventional materials vis-à-vis amorphous vs. efficiency holds true for the entire range of (DT) kVAs.

For the utility that wants to go beyond minimum efficiency requirements set by DOE, AMT becomes the product of choice.

Since utilities use the TOC methodology when purchasing transformers, the higher the value for evaluation factors, the higher the efficiency that can be justified.

If utilities use the current-day outlook for energy and generating capacity costs and include reasonable emission costs, A/B values will be in a range of A = \$8-\$10 and B = \$2-\$3 or higher. At these levels of loss evaluation, a very high efficiency AMT can be justified economically while yielding great benefits in energy savings, deferred generation, and reduced emissions.

TOC Example

To illustrate how a utility can justify a high-efficiency AMT on a TOC basis, first convert DOE efficiency data from Figure 17 into transformer loss data. Table 5 shows values of two different AMTs having different efficiencies (99.1% and 99.4%) at two different evaluation factors (\$5/\$1 and \$10/\$2.5 per watt of core loss and load loss, respectively). The table compares these with a DOE efficiency-compliant silicon (conventional) unit. Table 5 also depicts AMT value in terms of energy saved over the current DOE ruling.

Table 5 shows that for moderate values of evaluation factors (\$5/\$1), a high-efficiency (99.1%) AMT-2 can be justified on a TOC basis even though its first cost is 14% higher than a conventional (silicon) DOE-compliant unit. Similarly, if evaluation factors are \$10/\$2.5, a very high efficiency (99.4%) AMT-1 unit can be justified on a TOC basis even though its first cost is over 42% higher than a conventional (silicon) DOE-compliant unit. Energy savings and green house gas (GHG) reductions of such units also are very significant over the life of the units (30 years).

Since one million distribution transformers are added every year to the distribution system in the United States, an additional energy savings (over the current DOE ruling) of over 500 Gwhr/annually can be achieved by switching to AMT.

Briefly, to justify using AMTs economically, utilities need to do the following:

- Update their A/B factors using current and projected costs of energy and generation capacity addition.
- Include cost of emission in calculating A/B factors.
- Abandon use of the band of equivalency (BOE) methodology.

Table 5. TOC and Energy Savings 25 kVA, AMT vs. Silicon

	Amorphous-1	Amorphous-2	Silicon
% Efficiency	99.4	99.1	98.91
Core Loss (w)	15	14.5	70
Load Loss(w)	267	438	294
Price	\$1300	\$1035	\$910
TOC @ \$5/\$1	1642	1546	1554
TOC @ \$10/\$2.5	2118	2275	2345
Unit Annual Energy Consumed(kwhr)	657	986	1194
Unit Annual Energy Saved(kwhr)	537	208	–
Fleet* Annual Energy Savings (Gwhr)	537	208	–

* Fleet = Annual purchase of one million units

Under the current environment of high energy costs, concerns for climate change, and an increasingly carbon-constrained economy, AMT can be a very effective solution for U.S. utilities working to improve distribution system efficiency while reducing emissions.

Potential EPRI Projects

Introduction

As discussed earlier, under the current environment of high energy costs, concerns for climate change, and an increasingly carbon-constrained economy, AMT can be a very effective solution for U.S. utilities working to improve distribution system efficiency while reducing emissions. Since AMT products have not been produced in this country for over a decade, both suppliers and users have lost institutional memory of AMT.

This chapter describes potential EPRI projects designed to help:

- the United States regain its leadership position in this important energy-saving technology,
- re-commercialize this product with newer materials and newer production techniques, and
- create new green jobs in the United States.

EPRI Projects

1. ***Determine Material Stability:*** Technically, at a given temperature, an amorphous metal is stable up to a certain time, after which local structural and magnetic states start to change. This incubation period decreases as the operating temperature increases. The rated operating temperature of oil-filled distribution transformers is 105°C. In their daily use, they are routinely overloaded for a short period of time, and it is not uncommon for them to reach 140°C or higher. During the AMT development phase, accelerated aging tests were performed and it was determined that alloy 2605SA1 had an estimated life of 500 years at 150°C [1]. The material should be stable during the operating life of the transformer, but this needs to be confirmed.

   This first project needs to retrieve 30-50 AMT units from different parts of the country that have been in service for 15+ years, test them for core performance, and compare the results with factory data to validate stability.

2. ***Develop Third-Generation AMT Products:*** Material and production techniques have changed over the last 25 years. Newer material 2605HB1 offers great promise to reduce the size and weight of the unit and increase performance.

   This second project would develop AMT using 2605HB1with better core manufacturing techniques to drive down production costs while maintaining or improving performance.

3. ***Establish a Pilot Production Facility:*** Once the product is developed, the industry needs to commercialize it.

   This project would involve EPRI member companies in the purchase of several thousand units of this third-generation product. This level of purchase is needed to incentivize suppliers to make the necessary investment to establish a pilot production facility. This facility can then be scaled up to support commercial production.

4. ***Begin Green Circuit Field Trials:*** Because industry has over 25 years of trouble-free operating experience with the product in the United States, another extensive field trial with the third-generation product is not needed. However, EPRI has an active “green distribution circuit” project to quantify operating characteristics of distribution circuits under various operating conditions [10].

   This project would establish distribution system losses with traditional units under various loading and operating conditions, then replace traditional DTs with AMTs and establish performance gain and system efficiency. To accomplish this, the green circuit will have a state-of-the-art monitoring system to gather system performance data on an ongoing basis.

5. ***Power Quality Benefits:*** Research work and testing performed in India and Japan have shown that core loss of the transformer increases when it is supplying nonlinear loads. Under such current harmonic conditions, core loss of a silicon unit increases several times more than an amorphous core unit [6, 7]. Both of these referenced reports were merely reporting results of testing performed under such conditions, and no theoretical explanation was given (the phenomenon behind this observation is not fully understood).

To gain theoretical understanding, it will be necessary to create an electromagnetic model of the transformer and perform finite element analysis (FEA) under varying degrees of harmonics in a load current. Flux plots should provide visual understanding of the cause for increased core loss. The model can then be tuned for both kinds of core steel (silicon and amorphous) to predict loss increases in each case. This theoretical model then needs to be verified with actual tests under nonlinear load conditions. The lab will need nonlinear loads that can be varied to create different levels of harmonics. Loss measurement will have to be very precise and will have to use "differential" methods to maintain accuracy.

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