CHAPTER 4. SCREENING ANALYSIS

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4.1 INTRODUCTION

The purpose of the screening analysis is to identify design options that improve distribution transformer efficiency and to determine which options the Department will evaluate and which options will be screened out. The Department consults with industry, technical experts, and other interested parties in developing a list of design options for consideration. It then applies the following set of screening criteria to determine which design options are unsuitable for further consideration in the rulemaking (10 CFR Part 430, Subpart C, Appendix A at 4(a)(4) and 5(b):

(1) Technological feasibility. Technologies incorporated in commercial products or in working prototypes will be considered technologically feasible;

(2) Practicability to manufacture, install, and service. If mass production of a technology in commercial products and reliable installation and servicing of the technology could be achieved on the scale necessary to serve the relevant market at the time of the effective date of the standard, then that technology will be considered practicable to manufacture, install, and service.

(3) Adverse impacts on product utility or product availability. If a technology is determined to have significant adverse impact on the utility of the product to significant subgroups or consumers, or result in the unavailability of any covered product type with performance characteristics (including reliability), features, sizes, capacities, and volumes that are substantially the same as products generally available in the U.S. at the time, it will not be considered further.

(4) Adverse impacts on health or safety. If it is determined that a technology will have significant adverse impacts on health or safety, it will not be considered further.

This chapter discusses all the design options the Department considered for improving the energy efficiency of distribution transformers, and describes how the Department applied the screening criteria.

4.2 DISCUSSION OF DESIGN OPTIONS

There are several well-established engineering practices and techniques for improving the efficiency of a distribution transformer. A transformer design can be made more energy-efficient by improving the materials of construction (e.g., better quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies.

Core and winding losses are not independent variables of transformer design; they are linked to each other by the heat they generate and by the physical space they occupy. Transformers are designed for a certain temperature rise, resulting from the heat generated by transformer losses during operation. The upper boundary on the temperature rise is a design constraint, based on industry practice and standards (Institute of Electrical and Electronics Engineers IEEE C57.12.00 and C57.12.01). If this temperature limitation is exceeded, it will accelerate the aging process of the insulation and reduce the operating life of the transformer.

In addition to the core and winding assemblies, a transformer has other non-electromagnetic elements that may constrain the design of a transformer: the electrical insulation, insulating media (oil for liquid-immersed transformers and air for dry-type transformers), and the enclosure (the tank or case). Once the insulation requirements are set, a transformer design can vary both materials and geometry to reduce the losses.

Making a transformer more efficient (i.e., reducing electrical losses) is a design tradeoff between more expensive, lower-loss materials, and the value a customer attaches to those losses. For a given efficiency level, the core and winding losses are generally inversely related—reducing one usually increases the other. Additionally, at a given loading point and associated efficiency level, there can be several viable designs that achieve that efficiency level. The Department found that a wide range of designs and efficiencies are technologically feasible using common materials, engineering practices, and construction techniques (see Chapter 5).

Table 4.2.1 presents a general summary of the loss-reduction approaches from which transformer design engineers may choose to build more energy-efficient transformers. (This table was adapted from Table 2.2 in ORNL report number 6847 published July 1996.)[1] For most of these approaches, there are clear tradeoffs between no-load (core) losses, load (winding) losses, and price.

Some of the approaches presented in Table 4.2.1 refer to specific technologies (e.g., lower-loss core materials, lower-loss conductor materials), while other approaches refer to transformer geometry modifications (e.g., core or conductor cross-sectional area). This screening analysis considers the materials and technologies that may be used in transformer construction, but does not consider geometry or construction modifications such as a larger cross-sectional area or different core-stacking techniques. Construction methods and geometric modifications are inherent to the design and manufacturing process, and therefore are not a technology or design option considered in the screening analysis. These construction methods and geometric modifications are controlled by the transformer engineer and/or software design tool to improve the efficiency of resultant designs. Thus, they are applied to the designs prepared in the engineering analysis (see Chapter 5).

Table 4.2.1 General Loss-Reduction Interventions for Distribution Transformers

Loss-Reduction Interventions		No-Load Losses	Load Losses	Effect on Price
Decrease Core Losses	Use lower-loss core materials	Lower	No Change*	Higher
	Decrease flux density by increasing core cross-sectional area	Lower	Higher	Higher
	Decrease flux density by decreasing volts/turn	Lower	Higher	Higher
	Decrease flux path length by decreasing conductor cross-sectional area	Lower	Higher	Lower
Decrease Coil Losses	Use lower-loss conductor materials	No Change	Lower	Higher
	Decrease current density by increasing conductor cross-sectional area	Higher	Lower	Higher
	Decrease current path length by decreasing core cross-sectional area	Higher	Lower	Lower
	Decrease current path length by increasing volts/turn	Higher	Lower	Lower

*Amorphous-core materials would result in higher load losses because flux density drops, requiring a larger core volume.

4.3 DESIGN OPTIONS NOT SCREENED OUT OF THE ANALYSIS

The Department considers all distribution transformer design options currently in use by distribution transformer manufacturers to be viable. Viable design options include different conductor materials for coils and core materials.

4.3.1 Conductor Materials

Aluminum and copper are used in current distribution transformer designs and are available for use in standard wire sizes and foils. When the two materials are applied in exactly the same manner, copper has a higher electrical conductivity and about 40 percent lower resistive losses than aluminum. Compared to copper, aluminum is easier to form and work mechanically, and can be less expensive. By utilizing aluminum conductor material at a lower current density (i.e., larger conductor cross-sectional area), aluminum transformer windings can be built with essentially the same load losses as copper. However, aluminum conductors increase core losses due to their larger core frames, necessitated by the larger winding space (“core window”) through which the windings must pass. It is common for an efficient design option to have copper in the high-voltage (HV) windings and aluminum at a lower current density in the low-voltage (LV) windings. In these LV windings, aluminum can be used in the form of flat, rolled foils to reduce eddy current losses.

Considering the four screening criteria for this technology, the Department did not screen out aluminum and copper as conductor materials. These materials are in commercial use today, and DOE therefore found them to be technologically feasible. They are obviously practicable to manufacture, install, and service because they have been used in mass production for many years and are expected to continue to be the primary winding materials for the foreseeable future. There are no adverse impacts on consumer utility or reliability associated with the use of these conductor materials. Finally, there are no additional adverse impacts on health or safety associated with the use of these winding materials.

4.3.2 Core Materials

Transformer cores in the past had relatively high losses, since they were fabricated from thick laminates of non-oriented, low-silicon, magnetic steels. Modern cores are made with steels that incorporate silicon (approximately 2–3 percent) and trace amounts of other elements, are cold-rolled to thinner laminations, have improved laminar insulation, and may also be grain-oriented or domain-refined (i.e., laser or mechanically scribed steels).

Amorphous metal (or METGLAS[a]) material allows the construction of a low-loss core. Amorphous metal is extremely thin, has high electrical resistivity, and has little or no magnetic domain definition. Cores made from this material can exhibit 60–70 percent lower core losses than one made of conventional steels. However, amorphous metal material does have some drawbacks: It saturates at a lower flux level of 1.57 Tesla versus 2.08 Tesla for conventional materials, and it has higher excitation requirements. Amorphous metal material is also fragile and requires special handling during the construction process. Additionally, these designs cannot be "packed" as effectively into the winding window, causing the designs to have a space factor of 85 percent versus 95–98 percent for steel core materials, which increases losses. The net effect of the lower flux density and higher space factor is a larger core with greater winding (conductor) losses and higher production costs.

The core steels considered in this screening analysis are all those found in commercial use today. These include high-silicon electrical steels, both non-oriented hot-rolled and grain-oriented cold-rolled, domain-refined grain-oriented electrical steel, and amorphous material (wound core designs). The Department considered all of these core materials to be technologically feasible, as they are used commercially today (or in the past) by distribution transformer manufacturers at varying flux levels and lamination thicknesses. These commercially available high-silicon, cold-rolled transformer steels, nominally designated M2-M6, and domain-refined or laser-scribed steels are available for use in both stacked- and wound-core configurations. However, at present the application of amorphous material is only a viable design option in a wound core. Its manufacturers have not been successful in producing an

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[a] Registered trademark of Metglas, Inc., a wholly-owned subsidiary of Hitachi Metals, Ltd., Tokyo, Japan.

amorphous product that can be used in a stacked-core configuration (discussed in section 4.4.3 of this Chapter).

These core steels, high-silicon electrical steels, both non-oriented hot-rolled and grain-oriented cold-rolled, domain-refined grain-oriented, and amorphous material (wound core designs), are considered practicable to manufacture, install, and service, since they are core materials that are being used or that have been used by the distribution transformer industry. There are no known adverse impacts on consumer utility or reliability, and no known adverse impacts on health or safety associated with these core materials.

Table 4.3.1 summarizes the design options not screened out of the analysis.

Table 4.3.1 Design Options Not Screened Out of the Analysis

Design Issue	Material
Conductor Materials for Coils	Aluminum (wire and sheet)
	Copper (wire and sheet)
Core Materials	Cold-Rolled High Silicon (CRHiSi) Steel
	CRHiSi Domain-Refined Steels
	Amorphous Materials in Wound Core

4.4 DESIGN OPTIONS SCREENED OUT OF THE ANALYSIS

The Department screened out the following design options from further consideration because they do not meet the screening criteria:

1. silver as a conductor material
2. high-temperature superconductors
3. amorphous core material in stacked core configuration
4. carbon composite materials for heat removal
5. high-temperature insulating material
6. solid-state (power electronics) technology

4.4.1 Silver as a Conductor Material

The electrical conductivity of silver exceeds that of copper, aluminum, and other normal metals at room temperature (25° Celsius). However, silver has a lower melting point, a lower tensile strength, and limited availability. The Department found that the use of silver as a conductor is technologically feasible, since distribution transformers with silver windings were built during World War II because of a war-time shortage of copper. The Department believes the use of silver as a conductor would not have any adverse impacts on consumer utility or reliability, as it can readily replace copper or aluminum in this application. The Department is also not aware of any adverse health or safety impacts associated with the use of this conductor material.

However, the Department screened out silver as a conductor material because it is impracticable to manufacture, install, and service. Silver conductor designs are constrained by lower operating temperatures (adding to manufacturing complexity) and lower tensile strength (material can easily break during manufacturing process). In addition, due to limited availability, silver is not feasible to use for mass production on the scale necessary to serve the U.S. distribution transformer manufacturing industry.

Thus, the Department screened silver out from further consideration as a conductor material in the analysis due to its impracticability to manufacture, install, and service (criterion 2).

4.4.2 High-Temperature Superconductors

A new class of high-temperature superconducting (HTS) materials was discovered in 1987. These new materials become superconducting at temperatures close to that of liquid nitrogen, a readily available coolant that is considerably less expensive than liquid helium, the coolant for the previous generation of superconducting materials. After the discovery of these materials, research programs were launched worldwide to explore the use of superconducting material in power transformers. However, the use of superconductors, both low- and high-temperature, in transformer manufacturing has proven to be an elusive goal. Low-temperature superconductors (liquid helium-cooled) are physically possible but not feasible for commercial use, since these units are often unable to return to the superconducting state following a high fault current condition. For HTS (liquid nitrogen-cooled), a few demonstration power transformers have been built, but a prototype distribution transformer has not been constructed. Design constraints include unique conductors, unacceptable alternating current variation losses, and complex cryogenic support components. Research to overcome these barriers is being conducted, some of which is funded by the Department.

HTS materials were screened out of further consideration in this analysis because they fail on two of the four screening criteria. First, the Department does not consider HTS materials to be technologically feasible because a HTS distribution transformer has never been built. Additionally, due to technical issues associated with HTS power transformers, the Department does not consider HTS technology a viable loss-reduction technology for distribution transformers now or in the foreseeable future. Second, the Department does not consider HTS materials to be practicable to manufacture because they are extremely brittle (built of ceramic composites), are orders of magnitude more expensive than conventional conductor material, and are not mass-produced in a manner that would meet the demands of today's distribution transformer market. Furthermore, they are not reliable in service because they require continuous active cooling or they cease to function. With regard to the third screening criterion, the Department is not aware of any adverse impacts on customer utility associated with these materials. Similarly, the Department is not aware of any adverse impacts on health and safety originating from the use of HTS materials.

Thus, DOE screened HTS materials out of the analysis because of technological infeasibility (criterion 1) and impracticability to manufacture, install, and service (criterion 2).

4.4.3 Amorphous Core Material in Stacked Core Configuration

As discussed in section 4.3.2, amorphous material is considered a viable core material in a wound-core configuration. However, stacked amorphous core material is not presently a viable design option for distribution transformers, and has not been demonstrated in a working design by a manufacturer.

The Department screened out stacked core amorphous core material from further consideration in the analysis. First, the Department is not aware of any working prototypes that use amorphous core material in a stacked core configuration. Thus, the technological feasibility of this material has not been demonstrated. Second, the material has not demonstrated its practicability with respect to manufacturing, and therefore cannot be assessed as to its ability to meet the demand of mass production nor demonstrate its reliability in service. Considering the third criterion, the Department is not aware of any adverse impacts on utility or availability to consumers associated with this material. Similarly, for the fourth criterion, the Department is not aware of any adverse impacts on health and safety from the use of amorphous core material in stacked core configuration.

Thus, DOE screened amorphous core materials in stacked core configuration out of the analysis due to technological infeasibility (criterion 1) and impracticability to manufacture, install, and service (criterion 2).

4.4.4 Carbon Composite Materials for Heat Removal

A new technology that may prove effective in future transformer designs is the use of carbon fiber composites for heat removal. These materials offer good heat conduction and electrical insulation performance. The U.S. Naval Research Laboratory built small (less than 1 kVA), high-frequency transformers with this technology and demonstrated a 35 percent size and core loss reduction (see U.S. Patent 6,259,347 B1). While these results are impressive, a larger-scale prototype distribution transformer has not been demonstrated, and if it were technologically feasible, it would still be several years away from commercialization.

The Department assessed carbon composite materials for heat removal from distribution transformers, and found the material failed the first screening criterion. These materials for heat removal failed the first screening criterion because there are no commercial products or working prototypes that incorporate this technology. The Department was not able to assess whether the material meets or fails any of the other three screening criteria. Specifically, the Department cannot determine whether transformers would be practicable to manufacture, install, and service with this new material, since the application of the technology in a distribution transformer design has not been determined. Similarly, any potential adverse impacts on consumer utility or availability cannot be assessed, and any adverse impacts on health and safety cannot be determined at this time.

Thus, DOE screened carbon composite materials for heat removal out of the analysis due to technological infeasibility (criterion 1).

4.4.5 High-Temperature Insulating Material

The transformer industry conducts research and development on insulating materials. While potentially improving dielectric performance, industry studies this technology to create an electrical insulation that can withstand higher operating temperatures, and to create an electrical insulation that conducts heat more effectively out of the core-coil assembly. Increasing electrical insulation performance would result in smaller effective core and coil volumes, and therefore reduce operating losses.

The Department assessed high-temperature insulating materials, and found that the material failed on the first screening criterion. The Department is not aware of any practical high-temperature insulating or composite heat removal material, either in prototype form or in commercial products. The Department was not able to assess whether the material meets or fails any of the other three screening criteria. Transformers are built today with standard grades of insulation (up to 220° Celsius); however, it is uncertain whether higher temperature materials may have certain issues that make them impracticable to manufacture, install, or service. Similarly, the Department is unable to assess whether there would be any adverse impacts on consumer utility or availability due to the lack of a working prototype. Finally, the Department is unable to assess whether there would be any adverse impacts on health and safety aspects of a distribution transformer because of this material.

Thus, DOE screened high-temperature insulating materials out of the analysis due to technological infeasibility (criterion 1).

4.4.6 Solid-State (Power Electronics) Technology

The application of solid-state (power electronics) technology to transformers is in the early stages of research. A small test transformer was built at Purdue University as a modeling exercise, but no distribution transformer prototype has ever been manufactured using this technology.

The Department assessed the feasibility of solid-state (power electronics) technology, and found that this technology failed on the first screening criterion. The Department is not aware of any solid-state distribution transformer, either in prototype form or in a commercial product. The Department was not able to assess whether solid-state transformer technology meets or fails any of the remaining screening criteria. Due to the lack of a working prototype, the Department is uncertain whether this technology may have certain issues that make them impracticable to manufacture, install or service. Similarly, the Department is unable to assess whether there would be any adverse impacts on consumer utility or availability associated with this technology. Finally, the Department is unable to assess whether there would be any adverse impacts on health and safety aspects of a distribution transformer.

Thus, DOE screened solid-state power electronics transformer technology out of the analysis due to technological infeasibility (criterion 1).

4.5 SUMMARY OF DESIGN OPTIONS SCREENED OUT

Those design options that DOE screened out from further consideration are listed below in Table 4.5.1. The design options that DOE did not screen out of the analysis are listed in Table 4.3.1.

Table 4.5.1 Design Options Screened Out of the Analysis

Design Option Excluded	Screening Criteria
Silver as a Conductor Material	Practicability to manufacture, install, and service
High-Temperature Superconductors	Technological feasibility; Practicability to manufacture, install, and service
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

REFERENCES

1. ORNL, 1996. Oak Ridge National Laboratory, Determination Analysis of Energy Conservation Standards for Distribution Transformers, P.R. Barnes, J.W. Van Dyke, B.W. McConnell, S. Das, ORNL report number 6847, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Published July 1996. Available online at: www.eere.energy.gov/buildings/appliance_standards/ commercial/dist_transformers.html