		<b>Transformer Products</b>	
ENGINEERING DEVELOPMENT REPORT			
Overview of Transformer Life, Loading, and Thermal Operation			
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## ***Abstract***

Historically, ANSI has dealt only with mineral oil and thermally upgraded kraft paper insulation systems. This combination has resulted in the standard ONAN65 rating for transformers. The ONAN65 rating simply means that the transformer is guaranteed not to exceed a 65°C AWR at continuous nameplate kVA loading in a 30°C ambient. Several assumptions of transformer characteristics were made in establishing this rating, most important for this topic is that at 65°C AWR the hot spot will not exceed 80°C HSR. This rating and the associated assumptions are at best only valid with mineral oil and thermally upgraded kraft paper.

New insulation systems, including FR3 fluid and thermally upgraded kraft paper, have different thermal performance characteristics. Differences include thermal aging of the solid insulation, heat transfer efficiency, and heat storage capacity (thermal time constant). The exact effects of differing insulation systems depend strongly on the transformer design. Designs originally created for one insulation system will age differently, have different operating temperatures, and react differently to loads if built (or rebuilt) with a different insulation system.

The mineral oil and thermally upgraded kraft paper system covered in depth in the ANSI loading guide performs differently than the recently introduced FR3 fluid and thermally upgraded kraft paper system. In identical transformers and when compared to mineral oil and thermally upgraded kraft system the FR3 fluid and thermally upgraded kraft system will:


- Thermally age at a significantly slower rate or have higher loadability with the same life.
- Operate with slightly higher winding and hot spot rises under identical loading.

If, however, the transformer is designed for the insulation system and for the same thermal target (e.g. life, winding rise, hot spot rise, etc.) the unit performance can be expected to be the same. FR3 fluid and thermally upgraded kraft paper insulation systems can offer users significant benefits regarding transformer longevity and loading flexibility. This report provides a dissertation on general transformer thermal design and loading considerations. Although all information contained herein applies to any insulation system, specific references are made to the most common thermally upgraded kraft paper mineral oil and FR3 fluid systems.

## ***Introduction***

Transformers are thermally rated by the cooling class and the average temperature rise and/or the hot spot rise of the windings above the ambient temperature. The thermal ratings are intended to provide a normal transformer thermal life. For example, an ONAN65 rating means that at continuous full kVA operation the average temperature of the windings are guaranteed not to exceed 65°C over the ambient. The insulation system life, however, is determined by the hottest spot temperature, time at temperature (aging is a cumulative effect), the dielectric fluid, and the insulating materials used.

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It is well known that both ambient conditions and actual in-service loading are both cyclical and seasonal. The ambient temperature, the loading, pre-loading, and the time at load all determine the hot spot temperature and thus the insulation system aging. Transformers, however, are often purchased based on a single defining thermal rating (e.g. 65°C AWR or 80°C HSR<sup>1</sup>) yet are applied in a time continuum of variable loading and ambient temperatures.

Separate and independent from design, users develop in-house transformer loading rules in an effort to apply transformers in the most economical manner. Unfortunately, these application rules must be applied to all transformers in a system. The transformers in the system have variations in thermal performance based on manufacturer, nameplate kVA, loss evaluations/specifications, and even by purchase date. Other items such as oil levels, lead assemblies, internal connections, bushings, or other components may additionally limit safe overload levels and durations. In no applicable industry standards is a required level of overloadability or performance in a loading condition specified. The ANSI loading guide is directed at the user and provides methods for calculating temperatures and aging based on loading. Other ANSI standards specify minimum oil temperatures without expulsion and minimum component overload levels. Unless specified by the user, and incorporated into the design, there is no inherent level of continuous overloadability in a transformer.

### ***Thermal Operation***


The insulation systems in a transformer age at a normal rate and provide standard transformer life when they are operated at temperatures which are specific to the fluid and the insulating materials. ANSI C57.91 (the Loading Guide) and TP03-DR-009 show that for mineral oil and thermally upgraded kraft paper operation at 110°C results in normal thermal life. TP03-DR-009 shows that for FR3 fluid and thermally upgraded kraft paper operation at 131°C results in normal thermal life. Other insulation systems will have different characteristic temperatures for normal aging. Operation below the characteristic temperature will slow the degradation of the insulation, and operation above the characteristic temperature accelerates the aging.

From the physics of heat transfer the temperature of the oil inside of a transformer will not be higher than the temperature of the coil. Additionally, the tank wall temperature will not be higher than the oil. The actual temperature differences between coil and oil and oil and tank wall are strongly dependent upon the transformer design. The best that can be done is to refer back to ANSI and also provide a few rules of thumb. At continuous full load operation the average oil rise will be 10 to 20°C lower than the average winding rise. The average tank wall rise will be 5 to 10°C lower than the average oil rise. The hottest oil temperature will be the top oil and therefore the highest tank wall temperature will occur adjacent to the top oil. Again assuming continuous full load operation the top oil rise will be 15 to 20°C lower than the winding hot spot rise, and the adjacent tank wall rise will be another 5 to 10°C lower.

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<sup>1</sup> AWR = Average Winding Rise                      HSR = Hot Spot Rise

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An issue arises in that real world operation seldom is at continuous full load. Most times transformers are subjected to cyclic loads that vary from day to day. During a cyclic load the transformer can be subjected to short duration overloads that cause the hot spot rise to exceed the rated characteristic temperature. During under-loaded periods in the load cycle the winding rises will fall below the characteristic temperature. During cyclic loading “normal” aging of the transformer will be obtained if there are sufficient periods of under-loading to balance the effects of the overload periods. The equations and theory of this can be found in ANSI C57.91. It should be noted that the aging rate is exponential with temperature, so that a small increase in paper temperature above the characteristic temperature results in large increase in the aging rate. During cyclic loading it is almost impossible to measure a temperature at an instant and determine if the transformer is aging at a normal rate. The one thing that can be done through temperature observations is to ensure that at the times of peak loads the temperatures do not reach dangerous levels. ANSI provides recommendations for temperature and loading limits for short time periods in C57.91 section 8.2.2 for mineral oil. No equivalent recommendations for FR3 fluid have been developed at the time of this writing. Generally standard mineral has a flash point of ~140-150°C, and FR3 fluid is above 300°C. Operation above the flash point is never recommended.


Based on thermal testing, it does not appear that the thermal performance of a transformer is greatly affected by it’s age. Polemount units have been load cycle thermal tested with accelerated aging until the units failed electrically, and no change in thermal performance (temperatures) was seen during the testing.

### ***Thermal and Loading Characteristics***

The temperature versus loading characteristics of a transformer are unique to each design. How a unit reacts to a cycling load is dependent upon the windings, the various time constants of the unit, and the full load operating temperatures. The thermal effects of continuous overloads are dependent upon the design and the rated load performance. In general transformers are very sensitive to overloads. The transformer losses increase with the square of the per unit load, and the characteristic temperatures increase with the per unit load raised to ~0.8 to 2.0 power. The actual power is dependent upon the transformer design. ANSI C57.91 provides models for calculating the temperatures based on transformer loading and ambient conditions.

### ***Design Considerations***

Manufacturers have the capability to design and provide transformers which will provide a specified thermal life in a varying load and ambient application. Models for calculating the thermal life are given in ANSI C57.91-1995 and TP03-DR-009. In order to accomplish this the customer would need to provide their loading and economic life specifications, and the manufacturer would return a design with their lowest total owning cost that meets or exceeds the loading criteria.

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The thermal life of a transformer is a function of the degradation of the cellulose insulation material. Currently ANSI defines the standard thermal life for mineral oil and thermally upgraded kraft paper systems when the insulation hottest spot is operated at 110°C. Per TP03-DR-009, standard thermal life for FR3 fluid and thermally upgraded kraft paper systems when the insulation hottest spot is operated at 131°C. Measuring and verifying the hot spot temperature is not always easy nor feasible. Because of this, often an average winding rise rating is used instead with calculations or assumptions used to estimate the hot spot rise. The average winding rise is a relatively easy measurement to make during thermal testing without resorting to special instrumentation or special prototypes.

Improved modeling techniques combined with the power of computers now lets a manufacturer calculate, with relative accuracy, the operating temperatures of a transformer (including the hot spot). Improvements in measuring techniques allows for the validation of these models.

Armed with this information it is now possible to calculate the thermal performance of a transformer in a time varying load situation.


In order to design and optimize transformers for thermal life at specified loading conditions, the manufacturer needs:

- The load profile for the transformer application, preferably normalized against the profile peak. Alternatively several load profiles could be specified corresponding to distinct periods throughout a year (e.g. summer, fall, winter, and spring). If multiple profiles are provided for the year, all should be normalized against the maximum yearly peak load.
- A 24 hour average ambient temperature profile. Alternatively several average ambient temperature profiles could be specified corresponding to distinct periods throughout a year (e.g. summer, fall, winter, and spring).
- The maximum peak load in kVA corresponding to the target thermal life.
- The target thermal life of the transformer in the above loading conditions.

The load profile(s) need to be established by the customer based upon their experience, data, and installation guidelines. The profile should represent a nominal situation for the application. If the customer expects distinctly different loading conditions throughout the year, due for example to heating or air conditioning, seasonal profiles could improve the calculation accuracy.

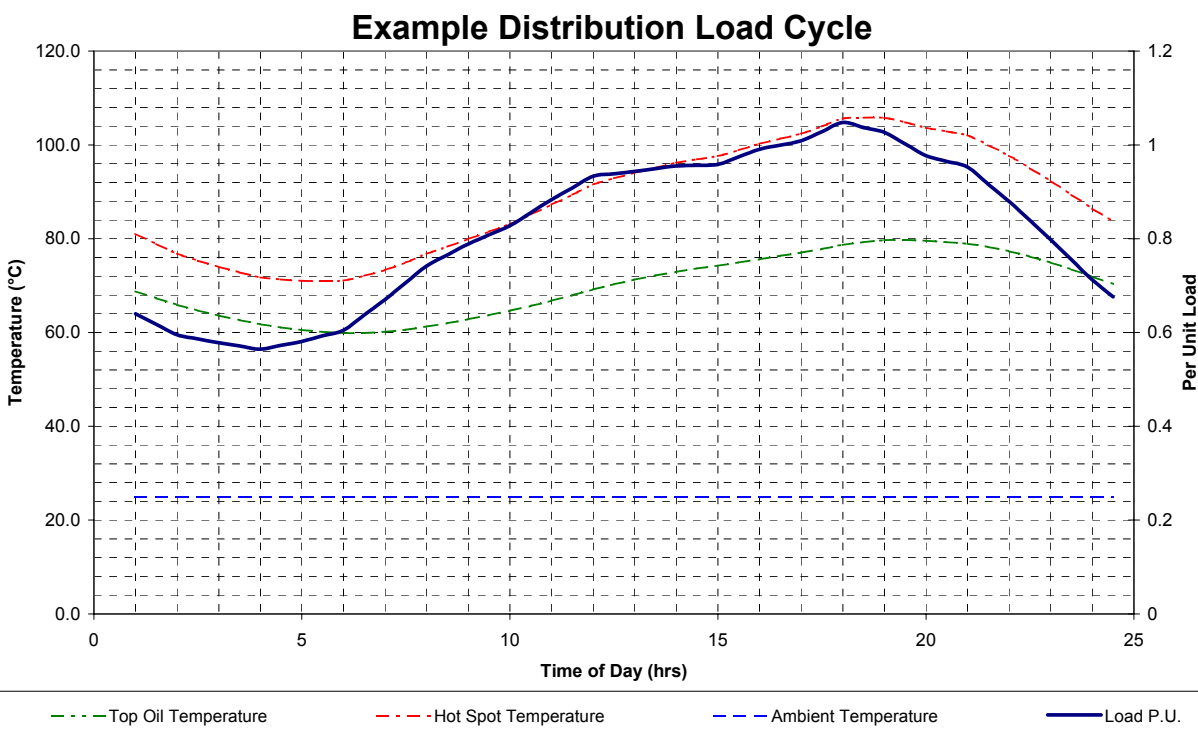
Ambient temperature profiles can be established either from actual data or by accessing the appropriate information from the National Weather Service.

Additional information that could be used to further increase the calculation accuracy would involve wind profiles (any wind or breeze blowing across the transformer can substantially increase the thermal life), and “sunshine” profiles for calculating solar heating (which can decrease thermal life).

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### Specification Considerations

In order to support the process of purchasing optimized transformers designed to function with a specified thermal life in the loading application, the user needs to be able to develop characteristic load profiles for their system. It is conceivable that several characteristic profiles could be needed to cover differing applications (e.g. residential, commercial, industrial, and etc.). Also, it is conceivable that for each application several profiles could be needed to cover differing loading conditions throughout the year (e.g. winter, spring, summer, fall).



The thermal life of a transformer is a function of the hot spot temperature (the load), the length of time the unit is operated at the temperature (the cycle), and the insulation system. The aging effects are cumulative. So both the past and future operation and environment affect the life of the unit. Two examples of problematic specification that are routinely encountered are:

- “xxx% peak load for n hours; yyy°C maximum top oil rise; zzz°C maximum hot spot temperature” - The major problem with this specification is that the manufacturer has no information concerning the pre- and post- peak operating conditions. The transformer temperatures after “n” hours at “xxx” load will vary greatly depending upon if the unit was at 100% prior to the peak, 50% prior to the peak, or started cold at the peak.

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- “xxx% peak load for n hours with no excess loss of life” - This one is problematic not only for the reasons above but also it is not known if the peak is a one time event or happens every day.

If complete information is not supplied the manufacturer must assume the rest, and depending upon whether the assumptions are conservative or aggressive two completely different and cost transformers are designed.

### ***Performance Verification Testing***

In order to use the ANSI thermal life models for design, the following is needed:

- Steady state rated load top oil rise, average winding rise, and hot spot rise.
- The top oil and hot spot rise exponent (ANSI C57.91-1995 section 7).
- The oil time constant (ANSI C57.91-1995 section 7).
- The hot spot time constant.
- The aging A & B factors for the insulation system.

For design purposes the manufacturer should be able to calculate all of the above based on models derived for the purpose. Some of the models will be proprietary, and others could be extracted directly from the appropriate ANSI standard.

In order to experimentally verify the thermal performance and applicability of a design, it is not necessary to perform load cycle testing. The information required to feed back into the ANSI life models can easily be established by performing a series of steady state thermal tests at differing load levels. Recommended load levels would be 80, 100, and 120% of nominal rating. From the tests the following can be determined:

- Oil time constant - By performing the 100% run first and logging oil temperature data from cold through steady state, the oil time constant can be determined.
- Steady state rated load top oil rise and average winding rise - Measurements performed during the 100% thermal test directly provide this information.
- Hot spot rise - The hot spot rise can either be measured directly at the multiple load levels by appropriately placed instrumentation, or can be estimated based on the design models and measured average winding gradients above the oil.
- Hot spot time constant - The hot spot time constant can be determined from the cool down resistance curves.
- The top oil and hot spot rise exponent - The exponents can be back calculated from the multi-level test data using the ANSI models.