		<b>Transformer Products</b>	
ENGINEERING DEVELOPMENT REPORT			
Envirotemp® FR3™ Fluid Filled Transformer Extreme Cold Start (Gelled Fluid) Thermal Model			
Author: Stewart Durian		Approved: R. Marusinec	Project No. 04000002.0
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## **ABSTRACT**


A lumped parameter thermal model for transformer cold starting with gelled Envirotemp® FR3™ fluid has been developed to assist with evaluating startup loading effects on transformers and estimate the time required to melt the fluid in the main transformer tank. The model has been programmed into an Excel/VBA application for use by customers. The application uses readily available information about the transformer and assumes the remainder of the required design criteria (i.e. core and coil displacement, core and coil time constant, winding temperature gradient, etc.). The application analyzes the first 24 hours of operation. The application can accommodate a variable ambient and 3 load levels during the first 24 hours.

Limitations and assumptions in the model include:

- Transformer fluid is completely gelled upon startup.
- Coolers, radiators, and/or corrugate remain completely gelled throughout the first 24 hours of operation.
- Only the first 24 hours of operation is analyzed.
- The ambient temperature varies throughout a 24 hour period sinusoidally with the temperature maximum occurring at 1700 hours (5pm).
- During the gelled phase, the transformer and fluid respond as a single homogeneous entity (lumped parameter formulation).

Two primary thermal models for the fluid temperature are used; one for pre-melt and the other for post-melt. Additionally sinusoidal varying ambient model is employed along with proprietary tank wall dissipation and gradient thermal models. The pre-melt model is a standard formulation of the energy equation for a lumped parameter system and includes heat input (C&C losses), heat storage (increased temperature), melt energy, and heat dissipation. The post-melt model is the transient temperature model from the Loading Guide (ANSI C57.91-1995).

The model and application are theoretical and have not been confirmed against actual test data.

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## ***Model Description***

The cold start situation was broken up into 2 phases; pre-melt, and post-melt. Pre-melt is defined as the period of operation from start up up through the point at which sufficient energy has been input into the system to melt the entire mass of fluid. The pre-melt includes both the increase in the unit temperature from the initial non-energized temperature up to the initiation of large scale melting (bulk fluid temperature equal to the FR3 fluid melt temperature) through to complete melting of the fluid. Post-melt is defined as the period after all of the fluid has melted through stability.

Common to both periods are the models for tank wall dissipation to the environment, tank wall to fluid temperature gradient, winding to fluid temperature gradient, and ambient temperature.

The ambient temperature model was developed for this application. The model assumes the ambient varies between a maximum and minimum over a 24 hour period in a sinusoidal fashion, with the maximum occurring at 1700 hours. Complete derivation of the model is presented in Attachment 1. The final form of the ambient model is:

$$T_a(t) = T_{avg} + (T_{a\max} - T_{avg}) \cdot \frac{\sin\left(\frac{2\pi}{1440} \cdot t\right)}{\sin\left(\frac{2\pi}{1440} \cdot t_{a\max}\right)}$$

where

$T_a(t)$  ≡ Ambient temperature, °C, at time  $t$


$t$  ≡ Time from midnight, seconds

$$T_{avg} \equiv \frac{T_{a\max} + T_{a\min}}{2}$$

$T_{a\max}$  ≡ Daily maximum temperature, °C

$T_{a\min}$  ≡ Daily minimum temperature, °C

$t_{a\max}$  ≡ Time from midnight of  $T_{a\max}$ , seconds

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The winding to fluid temperature gradient model is based on the Loading Guide (ANSI C57.91-1995) and an assumed relationship between the average and hot spot winding gradient. The form of the model is:

$$AWT(t) = T(t) + AWG(t)$$

$$HST(t) = T(t) + HSG(t)$$

$$AWG(t) = (AWG_f - AWG_s) \cdot \left( 1 - e^{-\left(\frac{t-t_s}{\tau_{wdg}}\right)} \right) + AWG_s$$

$$AWG_f = AWG_0 \cdot K(t)^{1.6}$$

$$HSG(t) = (HSG_f - HSG_s) \cdot \left( 1 - e^{-\left(\frac{t-t_s}{\tau_{wdg}}\right)} \right) + HSG_s$$

$$HSG_f = AWG_f \cdot 1.6$$

$$HSG_0 = AWG_0 \cdot 1.6$$

where

$AWT(t)$  ≡ Average winding temperature, °C, at time t

$HST(t)$  ≡ Hot spot winding temperature, °C, at time t

$T(t)$  ≡ Average fluid temperature, °C, at time t

$AWG(t)$  ≡ Average winding gradient, °C, at time t

$HSG(t)$  ≡ Hot spot winding gradient, °C, at time t

$AWG_f$  ≡ Average winding gradient, °C, at stability for load K(t)

$HSG_f$  ≡ Hot spot winding gradient, °C, at stability for load K(t)

$AWG_s$  ≡ Average winding gradient, °C, at start of load K(t), at time  $t_s$

$HSG_s$  ≡ Hot spot winding gradient, °C, at start of load K(t), at time  $t_s$

$K(t)$  ≡ Per unit load at time t


$t_s$  ≡ Time at start of load K(t)

$\tau_{wdg}$  ≡ Winding time constant

$AWG_0$  ≡ Design average winding gradient, °C, at 1.0 per unit load

$HSG_0$  ≡ Design hot spot winding gradient, °C, at 1.0 per unit load

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The tank wall to fluid gradient model is a combination of a proprietary empirical relationship developed for Cooper Power System's design programs and thermal conduction through the gelled fluid. The tank wall to average fluid temperature model uses a melted mass averaged combination of the two models:

$$T_w(t) = T(t) - dT_{wall}$$

$$dT_{wall} = \left(1 - \frac{M_{melt}(t)}{M}\right) \cdot dT_{cond} + \left(\frac{M_{melt}(t)}{M}\right) \cdot dT_{conv}$$

$$dT_{cond} = Q_{wall}(t) \cdot \left(\frac{x}{k \cdot A_{wall}}\right)$$

$$dT_{conv} = 7.8 \cdot \left(\frac{Q_{wall}(t)}{A_{wall}}\right)^{0.42}$$

where

$T_w(t)$  ≡ Average tank wall temperature, °C, at time t

$dT_{wall}$  ≡ Average tank wall to fluid temperature gradient, °C

$M_{melt}(t)$  ≡ Mass of fluid melted at time t

$M$  ≡ Total mass of fluid

$dT_{cond}$  ≡ Average tank wall to fluid temperature gradient in conduction through gel, °C


$dT_{conv}$  ≡ Average tank wall to fluid temperature gradient in convection, °C

$Q_{wall}(t)$  ≡ Total tank wall heat dissipation, W, at time t

$k$  ≡ Gelled fluid thermal conductivity

$x$  ≡ Conduction thermal path length in gelled fluid

$A_{wall}$  ≡ Base tank wetted wall surface area

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The tank wall heat dissipation to the environment model is a proprietary semi-empirical relationship developed for Cooper Power System's design programs:

$$Q_{wall}(t) = Q_{conv}(t) + Q_{rad}(t)$$

$$Q_{conv}(t) = C \cdot A_{wall} \cdot (T_w(t) - T_a(t))^z$$

$$Q_{rad}(t) = \sigma \cdot \varepsilon \cdot A_{wall} \cdot \left( (T_w(t) + 273)^4 - (T_a(t) + 273)^4 \right)$$

where

$T_w(t)$  ≡ Average tank wall temperature, °C, at time t

$T_a(t)$  ≡ Ambient temperature, °C, at time t

$Q_{wall}(t)$  ≡ Total tank wall heat dissipation, W, at time t

$Q_{conv}(t)$  ≡ Convective tank wall heat dissipation, W, at time t


$Q_{rad}(t)$  ≡ Radiative tank wall heat dissipation, W, at time t

$C$  ≡ Convective model constant

$z$  ≡ Convective model exponent

$\sigma$  ≡ Radiative emmissivity

$\varepsilon$  ≡ Boltzmann constant

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For the pre-melt model of the average fluid temperature an energy balance is used accounting for the heat input (losses), heat loss (tank wall dissipation), heat storage (temperature change), and phase change energy (melting):

$$Q_{losses}(t) = Cp \cdot M \cdot \frac{dT}{dt} + Q_{melt}(t) + Q_{wall}(t)$$

this can be re - arranged and discretized into

$$\frac{T(t) - T(t - \Delta t)}{\Delta t} = \left( \frac{1}{Cp \cdot M} \right) \cdot (Q_{losses}(t) - Q_{melt}(t) - Q_{wall}(t))$$

or

$$T(t) = \left( \frac{\Delta t}{Cp \cdot M} \right) \cdot (Q_{losses}(t) - Q_{melt}(t) - Q_{wall}(t)) + T(t - \Delta t)$$

$$Q_{melt}(t) = dM_{melt}(t) \cdot \frac{h_{melt}}{\Delta t}$$

$$dM_{melt}(t) \approx \frac{(Q_{losses}(t - \Delta t) - Q_{wall}(t - \Delta t)) \cdot \Delta t}{h_{melt}}$$

$$Q_{losses}(t) = NLL + LL \cdot (K(t))^2 \cdot \left( \frac{AWT(t - \Delta t) + T_{ref}}{T_{loss} + T_{ref}} \right)$$

where

$Q_{losses}(t) \equiv$  Total core and coil losses, W, at time t

$Cp \equiv$  Fluid specific heat

$\Delta t \equiv$  Discretization time increment

$Q_{melt}(t) \equiv$  Total energy to melt the incremental mass  $dM_{melt}(t)$

$dM_{melt}(t) \equiv$  Incremental fluid mass melted in time interval  $\Delta t$  at time t


$h_{melt} \equiv$  Latent heat of melting

$NLL \equiv$  Total no load losses, W

$LL \equiv$  Rated total load losses, W

$T_{loss} \equiv$  Temperature at which design losses are calculated

$T_{ref} \equiv$  Reference temperature for losses based on conductor material type

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For the post-melt period, the fluid temperature model is based on the transient fluid model found in the ANSI Loading Guide (C57.91-1995):

$$T(t) = (T_f - T_s) \cdot \left( 1 - e^{\left( \frac{t-t_s}{\tau_{oil}} \right)} \right) + T_a(t)$$

$$T_f = T_0 \cdot \left( \frac{(K(t))^2 \cdot R + 1}{R + 1} \right)^{0.8}$$

where

$T(t)$  ≡ Average fluid temperature, °C, at time  $t$

$T_f$  ≡ Average oil temperature, °C, at stability for load  $K(t)$

$T_0$  ≡ Design average oil temperature, °C, at stability for 1.0 per unit load

$T_s$  ≡ Average oil temperature, °C, at start of post - melt condition, at time  $t_s$

$t_s$  ≡ Time at start of post - melt condition

$\tau_{oil}$  ≡ Oil/Transformer time constant


$R$  ≡ Ratio of load to no - load losses

Model development notes are also provided in Attachment 2.

### ***Application Development***

The above cold start model has been developed into an application using Excel as a user interface and pre-calculator. The actual model is programmed into and solved using Visual Basic for Applications (VBA) in Excel. The VBA code for the main body of the calculations is included in Attachment 4.

The pre-melt discretized model is semi-stable and requires checks when programmed to ensure that temperatures remain in bounds when calculations are started and whenever the per unit load is changed. At the switchover from the pre-melt to the post-melt fluid temperature models, the models are subject to oscillating instability. Checks are required to ensure that the tank wall temperature continues to increase from the value at the end of the melt. Additionally, due to the variable ambient and the potential for the ambient to be above the tank wall temperature at the end of the melt a smoothing function is required for the fluid temperature to transition from pre-melt to post-melt without a step function change in the temperature.

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User inputs and a final report are handled on one sheet of the Excel application. For the input section, continuity checking is provided with live feedback. The application provides live checking for changes in inputs and analyzes the need for model re-calculation. If re-calculation is required on screen notification is provided. Additionally, the report print function is blocked if the model requires re-calculation.

The results reporting provides critical cold start thermal performance information as well as a graph of important temperatures during the first 24 hours of operation. A sample report output is provided in Attachment 3.

### **Conclusion**

Existing ANSI and proprietary thermal models have been combined with a discretized lumped parameter energy balance to provide a model for an FR3 fluid filled transformer being started with fully gelled fluid. The models do not consider active tank cooling devices (coolers/radiators/corrugate), nor do they predict the thawing of gelled fluid in cooling devices.

The process of changing the phase of the fluid from solid/gel to liquid is iso-thermal. The phase of a material normally requires a considerable amount of energy input. Because of the large amount of energy absorbed during the phase change, temperatures attained by the windings are mitigated during the startup, and helps during the period when tank cooling devices are inactive due to gelled fluid.

The low ambient temperatures required to be concerned with gelled fluid during startup assist in allowing a transformer to operate under load with inactive tank cooling devices. Transformer loadability is a function of hot spot and fluid temperatures. Since the temperature rise over ambient is dependent upon the load and tank cooling surface area, if the ambient is low enough the resultant temperatures will still be low enough as to not damage the transformer.

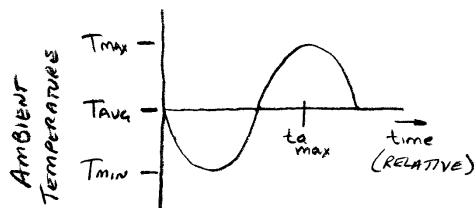
Just like the phase change from solid to liquid, the change from liquid to solid is iso-thermal and typically requires a large energy transfer. To attain the condition of fully gelled fluid the transformer needs to be exposed to temperatures below the gel point for sufficient time to extract all of the heat of solidification. The time required to actually completely gel the fluid is dependent upon how far below the ambient is below the gel temperature and the mass of fluid involved.

Tank cooling devices will be the first to gel and the last to melt. This is due to the large surface area to fluid mass ratio, and the remoteness from the heat source. Cooling device thawing could be assisted with thermal blankets set up over the device(s) and open to the tank wall to contain the heat dissipating from the tank wall adjacent to the cooling device. Likewise such thermal blankets could delay the onset of gelling in the cooling device(s).

**Attachment 1: Ambient Temperature Model**

SINUSOIDAL Ambient Model

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$$T_a(t) = A + B \sin(Ct)$$

- ASSUMPTIONS:
- 1)  $t = 0$   $T_a = T_{avg} = (T_{max} + T_{min})/2$
  - 2)  $t = 1440 \text{ min (24 hrs)}$   $T_a = T_{avg}$
  - 3)  $t = t_{max}$   $T_a = T_{max}$
  - 4)  $t_{max} = 1080 \text{ min (18 hrs)}$

$$t = 0: T_{avg} = A + B \sin(C \cdot 0)$$

$$A = T_{avg}$$

$$t = 1440: T_{avg} = T_{avg} + B \sin(1440C)$$

$$0 = B \sin(1440C) \quad \therefore B \neq 0$$

$$0 = \sin(1440C)$$

$$1440C = I\pi$$

$$C = I\pi/1440 \quad \text{LET } I = 2$$

$$C = 2\pi/1440$$

$$t = t_{max}: T_{max} = T_{avg} + B \sin\left(\frac{2\pi}{1440} \cdot t_{max}\right)$$

$$T_{max} - T_{avg} = B \sin\left(\frac{2\pi}{1440} \cdot t_{max}\right)$$

$$B = (T_{max} - T_{avg}) / \sin\left(\frac{2\pi}{1440} \cdot t_{max}\right)$$

So

$$T_a(t) = T_{avg} + \left[ \frac{T_{max} - T_{avg}}{\sin\left(\frac{2\pi}{1440} \cdot t_{max}\right)} \right] \sin\left[\frac{2\pi}{1440} \cdot t\right]$$

**Attachment 2: Pre-Melt Thermal Model**

## • PRIMARY MODEL

$$Q_i = \left[ m C_{p,li} \frac{T_i - T_{i-1}}{t_i - t_{i-1}} \right] + \left[ h_{melt} \frac{\Delta m_{melt}}{t_i - t_{i-1}} \right] \alpha$$

$$\left[ h A_T (T_{w,li} - T_{a,li}) + \epsilon \sigma A_T ((T_{w,li} + 273)^4 - (T_{a,li} + 273)^4) \right]$$

$Q_i$  ≡ HEAT INPUT FROM C&C AT  $t = t_i$  (Watts)  
 $m$  ≡ FLUID MASS (kg)  
 $C_{p,li}$  ≡ FLUID SPECIFIC HEAT AT  $t = t_i$  (Ws/kg°C)  
 $T_i$  ≡ FLUID BULK TEMPERATURE AT  $t = t_i$  (°C)  
 $T_{i-1}$  ≡ FLUID BULK TEMPERATURE AT  $t = t_{i-1}$  (°C)  
 $h_{melt}$  ≡ FLUID LATENT HEAT OF MELTING (Ws/kg)  
 $h$  ≡ TANK WALL EXTERNAL CONVECTION COEFFICIENT (W/m²°C)  
 $\epsilon$  ≡ BOLZEMANN CONSTANT =  $5.67 \times 10^{-8}$   
 $\sigma$  ≡ TANK WALL RADIATIVE EMISSIVITY  
 $A_T$  ≡ TANK WALL SURFACE AREA (m²)  
 $\alpha$  ≡ TERM ONLY VALID FOR  $T_i = T_{melt}$  AND  $\Delta m_{melt} \leq m$

## • ASSUMPTIONS:

- 1) LUMPED CAPACITY SYSTEM
- 2) RADIATORS/COOLERS/CORRUGATE NON-FUNCTIONAL
- 3) SYSTEMS INITIAL CONDITION IS FULLY GELLED AT A UNIFORM TEMPERATURE
- 4) TIME STEPS SUFFICIENTLY SMALL

## • AUXILIARY MODELS

$$T_i = T_{w,i} + \Delta T_i \Rightarrow T_{w,i} = T_i - \Delta T_i \equiv \text{TANK WALL TEMPERATURE (°C)}$$

SOLID FORM ( $T_i \leq T_{melt}$ )

$$\Delta T_i = (Q_{wall,i} \times x) / (k_i A_T)$$

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$$Q_{wall_i} \equiv \text{TANK WALL HEAT LOSS AT } t = t_i \quad (W)$$

$$Q_{wall_i} \approx h A_T (T_{w_{i-1}} - T_{a_{i-1}}) + \epsilon \sigma A_T ((T_{w_{i-1}} + 273)^4 - (T_{a_{i-1}} + 273)^4)$$

$$X \equiv \text{HEAT CONDUCTION DISTANCE} \quad (m)$$

LIQUID FORM ( $T_i > T_{MELT}$ )

$$\Delta T_i \approx (0.6)(13) \left[ \frac{Q_{wall_i}}{A_T (29.37)^2} \right]^{0.42} \leftarrow \text{CPS PROPRIETARY MODEL}$$

$$h \approx (2.17) (T_{w_{i-1}} - T_{a_{i-1}})^{0.25} \leftarrow \text{CPS PROPRIETARY MODEL}$$

$$\epsilon \approx 0.90$$

• WINDING RISE MODELS

$$AWR_i = T_i + AWG_i$$

$$AWG_i = AWG_0 K_i^{1.6}$$

$$AWR_i \equiv \text{AVERAGE WINDING RISE AT } t = t_i \quad (^\circ C)$$

$$AWG_i \equiv \text{AVERAGE WINDING GRADIENT AT } t = t_i \quad (^\circ C)$$

$$AWG_0 \equiv \text{AVERAGE WINDING GRADIENT AT } K=1.0 \quad (^\circ C)$$

$$K_i \equiv \text{PER UNIT LOAD AT } t = t_i$$

$$HSR_i \approx T_i + (1.6)(AWG_i)$$

$$HSR_i \equiv \text{WINDING HOT SPOT RISE AT } t = t_i \quad (^\circ C)$$

$$AWT_i = AWR_i + T_{a_i}$$

$$HST_i = HSR_i + T_{a_i}$$

$$AWT_i \equiv \text{AVERAGE WINDING TEMPERATURE AT } t = t_i \quad (^\circ C)$$

$$HST_i \equiv \text{WINDING HOT SPOT TEMPERATURE AT } t = t_i \quad (^\circ C)$$

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• MELT MASS MODEL

$$\Delta M_{\text{MELT}_i} = (Q_{i-1} - Q_{\text{WALL}_i}) (t_i - t_{i-1}) / h_{\text{MELT}}$$

$$M_{\text{MELT}_i} = \sum_{t=t_0}^{t_i} \Delta M_{\text{MELT}_i}$$

$$M_{\text{MELT}_i} = \text{MASS OF FLUID MELTED AT } t = t_i \quad (\text{kg})$$

• AMBIENT TEMPERATURE MODEL

$$T_{a_i} = \left( \frac{T_{\text{MAX}} + T_{\text{MIN}}}{2} \right) + \left( \frac{T_{\text{MAX}} - T_{\text{MIN}}}{2} \right) \sin \left[ 2\pi \left( \frac{t_i - t_{\text{MAX}}}{1440} \right) \right]$$

$$T_{a_i} = \text{AMBIENT TEMPERATURE AT } t = t_i \quad (^\circ\text{C})$$

$$T_{\text{MAX}} = \text{MAXIMUM DAILY TEMPERATURE AT } t = t_{\text{MAX}} \quad (^\circ\text{C})$$

$$T_{\text{MIN}} = \text{MINIMUM DAILY TEMPERATURE AT } t = t_{\text{MAX}} - 12 \text{ HRS} \quad (^\circ\text{C})$$

$$t_i = \text{time} \quad (\text{min})$$

ASSUMPTIONS:

5) AMBIENT TEMPERATURE PROFILE IS SINUSOIDAL

6) MAXIMUM AND MINIMUM TEMPERATURES ARE 12 HRS APART

• LOSS MODEL

$$Q_i = Q_{\text{LL}_i} + Q_{\text{WL}_i} = Q_{\text{NL}} + Q_{\text{LO}} (K_i^2) \left[ \frac{A_{\text{WT}_i} + T_{\text{REF}}}{A_{\text{WT}_0} + T_{\text{REF}}} \right]$$


$$Q_{\text{NL}} = \text{NO-LOAD (CORE) LOSSES} \quad (\text{W})$$

$$Q_{\text{LO}} = \text{RATED LOAD LOSSES AT } T = A_{\text{WT}_0} \quad (\text{W})$$

$$T_{\text{REF}} = \text{WINDING MATERIAL REFERENCE TEMPERATURE} \approx 229.75 \quad (^\circ\text{C})$$

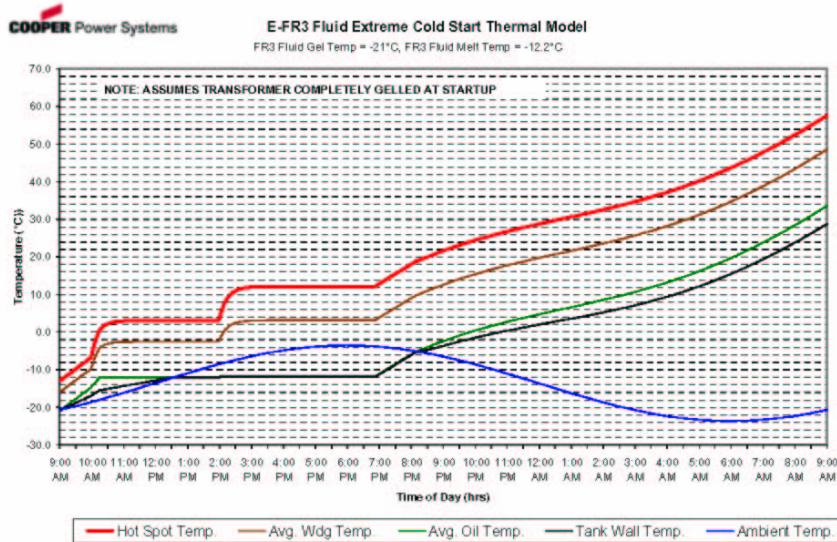
$$A_{\text{WT}_0} = \text{RATED AVERAGE WINDING TEMPERATURE} \quad (^\circ\text{C})$$


### Attachment 3: Sample Program Report

<b>E-FR3 Fluid Extreme Cold Transformer Startup Thermal Model</b>		02-Dec-2003	
Prototype V02 R00 M00b			
Transformer Main Tank Height (inches) =	72		
Main Tank Width or Diameter (inches) =	64		
Main Tank Depth (inches, leave blank if Round Tank) =	32		
Load Losses at Full Load (Watts, leave blank if unknown) =	15000		
No-Load Losses (Watts, leave blank if unknown) =	3000		
Base Level Nameplate kVA =	2000		
Rated Rise at Base Level kVA =	65		
Startup Time of Day =	09:00:00		
Startup Load (Per Unit) =	0.50	for	1.0 Hours
Second Applied Load (Per Unit) =	0.75	for	4.0 Hours
Third Applied Load (Per Unit) =	1.00	for	19.0 Hours
Bulk Transformer Temperature at Startup (*F, Max -5.8) =	-5.8		-21.0 °C
Daily Minimum Ambient Temperature (*F) =	-10.0		-23.3 °C
Daily Maximum Ambient Temperature (*F) =	25.0		-3.9 °C

**Results With all Coolers/Radiators Blocked with Gelled FR3 Fluid**

Equivalent RMS Per Unit Load for first 24 hours =	0.80	PUL
Est. Maximum Winding Hot Spot Temperature @ Stability (Max. 200°C Short Term) =	189.3	°C @ 1.00 PUL (Load @ 24hrs)
Est. Maximum Top Oil Temperature @ Stability (Max. 120°C Short Term) =	165.3	°C @ 1.00 PUL (Load @ 24hrs)
Est. Maximum Tank Wall Temperature @ Stability =	156.8	°C @ 1.00 PUL (Load @ 24hrs)
Estimated Time to Complete Main Tank E-FR3 Fluid Melting =	9.9	hrs @ 0.80 RMS PUL
Estimated Maximum Allowable Per Unit Load with No Excess Loss of Life =	0.79	@ -13.6°C/7.5°F Ambient
Est. Time Required to Completely Gel Transformer after Shutdown (continuous ambient)=	465 hrs	@ -26.0°C/-14.8°F Ambient



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#### Attachment 4: VBA Code

```
Dim Q(2000), Qwall(2000), AWT(2000), HST(2000), Qmelt(2000), K(2000)
Dim T(2000), Cp(2000), tme(2000), dMmelt(2000), Tw(2000), Ta(2000),
Mmelt(2000)
```

```
Sub calc()
```

```
    i = 0
    dMmelt(i) = 0
    Mmelt(i) = 0
    Qwall(i) = 0
    Qmelt(i) = 0
    tmemelt = 0
    tmx = 0
    zzttop = 0
    tmeldchg = 0
    Ts = 0
    AWGs = 0
    HSGs = 0
    imelt = 0
    Range("io!a3") = "RE-CALCULATION IN PROGRESS"
```

```
    ' Constants
```

```
    tstrt = Range("precalc!g1")
    tend = Range("precalc!g2")
    deltat = Range("precalc!b1") * 60
    T(i) = Range("precalc!b2")
    Tf = Range("precalc!g38")
    tau = Range("precalc!d11") / 60
    tauwdg = Range("precalc!g11")
    NLL = Range("precalc!b36")
    LL0 = Range("precalc!b35")
    Tref = Range("precalc!b31")
    Tloss = Range("precalc!b30")
    tamax = Range("precalc!b43")
    Cps = Range("precalc!d14")
    Cpl = Range("precalc!g14")
    Tmelt = Range("precalc!b32")
    Tgell = Range("precalc!b33")
    hmelt = Range("precalc!b16")
    convec = Range("precalc!b25")
    radiate = Range("precalc!b26")
    conduct = Range("precalc!b28")
    Mass = Range("precalc!b10")
    At = Range("precalc!b8")
    AWG0 = Range("precalc!b19")
    K1 = Range("io!b14")
    K2 = Range("io!b15")
    If (K2 = 0) Then
        K2 = K1
    End If
    K3 = Range("io!b16")
```

## ENGINEERING DEVELOPMENT REPORT

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```
If (K3 = 0) Then
  K3 = K2
End If
tmeK1 = Range("io!d14") * 60 + tstrt
tmeK2 = Range("io!d15") * 60 + tmeK1
tmeK3 = Range("io!d16") * 60 + tmeK2

' Initialization
tme(i) = tstrt
imax = (tend - tme(i)) / (deltat / 60)
Q(i) = NLL + LL0 * (K(i) ^ 2) * ((T(i) + Tref) / (Tloss + Tref))
ATa = Range("precalc!b41")
Cta = 2 * 3.14159 / (24 * 60)
BTa = Range("precalc!b42") / Sin(2 * 3.14159 * tamax / (24 * 60))
Ta(i) = ATa + BTa * Sin(Cta * tme(i))
HST(i) = T(i)
AWT(i) = T(i)
Tw(i) = T(i)
Cp(i) = Cps

rowloc = Trim(Str(i + 3))
Range("results!a" + rowloc) = tme(i)
Range("results!b" + rowloc) = K(i)
Range("results!c" + rowloc) = Ta(i)
Range("results!d" + rowloc) = T(i)
Range("results!e" + rowloc) = Tw(i)
Range("results!f" + rowloc) = AWT(i)
Range("results!g" + rowloc) = HST(i)
Range("results!h" + rowloc) = dMmelt(i)
Range("results!i" + rowloc) = Mmelt(i)
Range("results!j" + rowloc) = Q(i)
Range("results!k" + rowloc) = Qwall(i)
Range("results!l" + rowloc) = Qmelt(i)

Do While (i <= imax)

  i = i + 1
  Range("io!a3") = "RE-CALCULATION IN PROGRESS " + Str(Int(i / imax *
    1000) / 10) + "%"

  ' Time
  tme(i) = tme(i - 1) + deltat / 60
  ' Load
  If (tme(i) <= tmeK1) Then
    K(i) = K1
  ElseIf (tme(i) <= tmeK2) Then
    K(i) = K2
  Else
    K(i) = K3
  End If
  If (tme(i) = tmeK1) Then
    AWGs = AWG
    HSGs = HSG
    tmeldchg = tme(i)
```

```
ElseIf (tme(i) = tmeK2) Then
  AWGs = AWG
  HSGs = HSG
  tmeldchg = tme(i)
ElseIf (tme(i) = tmeK3) Then
  AWGs = AWG
  HSGs = HSG
  tmeldchg = tme(i)
End If
' Ambient Temperature
Ta(i) = ATa + BTa * Sin(Cta * tme(i))
' Losses
Q(i) = NLL + LL0 * (K(i) ^ 2) * ((AWT(i - 1) + Tref) / (Tloss + Tref))
' Melt Heat
If (T(i - 1) >= Tmelt And Mmelt(i - 1) < Mass) Then
  dMmelt(i) = (Q(i - 1) - Qwall(i - 1)) * deltat / hmelt
  Mmelt(i) = Mmelt(i - 1) + dMmelt(i)
  Qmelt(i) = dMmelt(i) * hmelt / deltat
Else
  Qmelt(i) = 0
  Mmelt(i) = Mmelt(i - 1)
  dMmelt(i) = 0
End If
' Tank Wall Temperature
dTcond = MAX(0, Qwall(i - 1)) * conduct
dTconv = 0.6 * 13 * (MAX(0, Qwall(i - 1)) / (At * 39.37 ^ 2)) ^ 0.42
dTwall = (1 - Mmelt(i) / Mass) * dTcond + (Mmelt(i) / Mass) * dTconv
If (Mmelt(i - 1) < Mass) Then
  Tw(i) = MAX(Tw(i - 1), (T(i - 1) - dTwall))
Else
  If (tmemelt = 0) Then
    tmemelt = tme(i - 1)
    imelt = i - 1
    Ts = T(imelt)
  End If
  Tw(i) = (T(i - 1) - dTwall)
  Tw(i) = MAX(Tw(i), Tmelt)
End If
' Tank Wall Dissipation
Qconv = convec * (Tw(i) - Ta(i)) * Abs(Tw(i) - Ta(i)) ^ 0.25
Qrad = radiate * ((Tw(i) + 273) ^ 4 - (Ta(i) + 273) ^ 4)
Qwall(i) = Qconv + Qrad
' Temperature Change Heat
Qdt = Q(i) - Qwall(i) - Qmelt(i)
' Specific Heat
Cp(i) = (1 - Mmelt(i) / Mass) * Cps + (Mmelt(i) / Mass) * Cpl
' Bulk Temperature
If (Mmelt(i - 1) <= Mass) Then
  ' Solid model: Cp(dT/dt)=.....
  T(i) = T(i - 1) + Qdt * deltat / (Mass * Cp(i))
Else
  ' Liquid Model: Standard transformer transient model from ANSI C57.91
  If (Tw(i) < Ta(i) And zztop = 0) Then
    Tx = Ts
```

```
        tmx = tmemelt
    Else
        Tx = Ta(i)
        If (zztop = 0) Then
            zztop = 1
            tmx = tme(i)
            Ts = Tx
        End If
    End If
    T(i) = (Tf - Ts) * (1 - Exp(-1 * (tme(i) - tmx) / tau)) + Tx
    T(i) = MAX(T(i), Tmelt)
End If
' Winding Temperatures
AWGf = AWG0 * K(i) ^ 1.6
HSGf = AWGf * 1.6
AWG = (AWGf - AWGs) * (1 - Exp(-1 * (tme(i) - tmeldchg) / tauwdg)) +
      AWGs
HSG = (HSGf - HSGs) * (1 - Exp(-1 * (tme(i) - tmeldchg) / tauwdg)) +
      HSGs
AWT(i) = T(i) + AWG
HST(i) = T(i) + HSG
' Printing to Results
rowloc = Trim(Str(i + 3))
Range("results!a" + rowloc) = tme(i)
Range("results!b" + rowloc) = K(i)
Range("results!c" + rowloc) = Ta(i)
Range("results!d" + rowloc) = T(i)
Range("results!e" + rowloc) = Tw(i)
Range("results!f" + rowloc) = AWT(i)
Range("results!g" + rowloc) = HST(i)
Range("results!h" + rowloc) = dMmelt(i)
Range("results!i" + rowloc) = Mmelt(i)
Range("results!j" + rowloc) = Q(i)
Range("results!k" + rowloc) = Qwall(i)
Range("results!l" + rowloc) = Qmelt(i)


Loop

Calculate
beep
Range("precalc!g40") = tmemelt - tstrt
Range("io!a3") = ""
Call DataCpy

End Sub
Function MAX(a, b)

    If (a >= b) Then
        MAX = a
    Else
        MAX = b
    End If

End If
```

		<b>Transformer Products</b>	
ENGINEERING DEVELOPMENT REPORT			
Envirotemp <sup>®</sup> FR3 <sup>™</sup> Fluid Filled Transformer Extreme Cold Start (Gelled Fluid) Thermal Model			
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```
End Function
Function MIN(a, b)

  If (a <= b) Then
    MIN = a
  Else
    MIN = b
  End If
```

```
End Function
```