INL/CON-14-32590
PREPRINT

IMPLEMENTATION OF REMAINING USEFUL LIFETIME TRANSFORMER MODELS IN THE FLEET-WIDE PROGNOSTICS AND HEALTH MANAGEMENT SUITE

9TH INTERNATIONAL CONFERENCE ON NUCLEAR PLANT INSTRUMENTATION, CONTROL & HUMAN–MACHINE INTERFACE TECHNOLOGIES (NPIC & HMIT 2015)

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February 2015

IMPLEMENTATION OF REMAINING USEFUL LIFETIME TRANSFORMER MODELS IN THE FLEET-WIDE PROGNOSTICS AND HEALTH MANAGEMENT SUITE

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ABSTRACT

Research and development efforts are required to address aging and reliability concerns of the existing fleet of nuclear power plants. As most plants continue to operate beyond their original 40 year license life, plant components are more likely to incur age-related degradation mechanisms. To assess and manage the health of aging plant assets across the nuclear industry, the Electric Power Research Institute has developed the Fleet-Wide Prognostic and Health Management (FW-PHM) Suite, a set of web-based diagnostic and prognostic tools and databases comprised of the Diagnostic Advisor, the Asset Fault Signature Database, the Remaining Useful Life Advisor, and the Remaining Useful Life Database, that serves as an integrated health monitoring architecture. The main focus of this paper is the implementation of prognostic models for generator step-up transformers in the FW-PHM Suite. One prognostic model discussed is based on the functional relationship between degree of polymerization, the most commonly used metric to assess the health of the winding insulation in a transformer, and furfural concentration in the insulating oil. The other model is based on thermally induced degradation of the transformer insulation. By utilizing transformer loading information, established thermal models are used to estimate the hot spot temperature inside the transformer winding. Both models are implemented in the Remaining Useful Life Database of the FW-PHM Suite. The Remaining Useful Life Advisor utilizes the implemented prognostic models to estimate the remaining useful life of the paper winding insulation in the transformer based on actual oil testing and operational data.

Key Words: prognostic models, generator step-up transformer, fleet-wide prognostic and health management suite, thermal model, degree of polymerization.

1 INTRODUCTION

More than two-thirds of the existing commercial nuclear power plants (NPPs) in the United States have received license extensions to 60 years from the original 40-year license. As the fleet of NPPs continues to age, it is important to understand the condition of their aging components and be proactive in maintenance and replacement. The current practice of periodic and condition-based maintenance at NPPs could result in high repairs costs, primarily due to unexpected component failure and forced outage. Implementation of advanced predictive online monitoring (OLM) would enable plant maintenance engineers to diagnose incipient faults and estimate the remaining useful life (RUL) of their assets. Knowledge of asset health gained from predictive OLM would help optimize maintenance activities, ultimately leading to maintenance cost reduction.

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) Program to develop the scientific basis for extending the operation of commercial light water reactors beyond the current 60-year license period. The program is operated in collaboration with the Electric Power Research Institute's (EPRI's) research and development (R&D) efforts in the Long-Term Operations (LTO) Program. The LTO Program is a separate technical program in the Plant Technology Department of the EPRI Nuclear Power Sector, which is guided by an industry advisory integration committee. Both the LWRS and LTO programs work closely with nuclear utilities to conduct R&D in technologies that can be used to ensure long-term reliability, productivity, safety, and security of aging light water reactors. Under the Advanced Instrumentation, Information, and Control Technologies Pathway of the LWRS Program, Idaho National Laboratory (INL) focuses on research, development, and implementation of diagnostic and prognostics models for generator step-up transformers (GSUs) and emergency diesel generators (only diagnostic models were developed for emergency diesel generators).

Implementation of predictive OLM of essential assets in the existing fleet of NPPs is consistent with the long-term objective of both the LWRS and LTO programs. Predictive (also known as proactive) maintenance requires predicting the future operating state of an asset based on the current state and history of operating conditions. For example, the consequence of running a transformer for an extended period with a high oil temperature is an unacceptable loss of dielectric strength of the insulating oil. Accurate estimation of a transformer's RUL accounting for high temperature operating conditions would help maintenance staff take appropriate actions to prevent costly unplanned outages. Taking the lead in predictive OLM research, EPRI has developed the Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software (currently at version 1.2.2) for predictive OLM of assets in the power industry. The FW-PHM Suite software is an integrated collection of web-based diagnostic and prognostic tools and databases, as shown in Figure 1, which enables maintenance staff to perform diagnosis and prognosis at different hierarchical levels, from the component level to the plant level, across a fleet of power units. FW-PHM Suite consists of four main modules: the Diagnostic Advisor, the Asset Fault Signature Database, the Remaining Useful Life Advisor, and the Remaining Useful Life Database. The tools and databases are described in detail in [1-5].

High-voltage power transformer conductor windings are insulated by a combination of cellulose paper and an insulating mineral oil, and are expected to operate reliably for up to 40 years. Cellulose is a natural polymer of glucose that degrades slowly as the polymer chains break down during service, releasing chemical byproducts that dissolve in the insulating oil. The factors and mechanisms that contribute to transformer winding insulation paper degradation are well studied in the literature, including cellulose reaction [6], degradation due to hydrolysis [7], and thermolysis [8]. Transformer winding paper insulation degradation rate is critical in determining the operational life span of a transformer. Therefore, this paper presents two prognostic models for transformer paper winding insulation degradation that were researched and implemented in the FW-PHM Suite. The Chendong model [9] estimates degree of polymerization of the transformer winding insulation based on the concentration level of 2-Furaldehyde (2FAL), measured by offline oil analysis. The IEEE thermal life consumption model [10] estimates the hot spot temperature in the insulation at a given transformer load and ambient temperature. Both of the

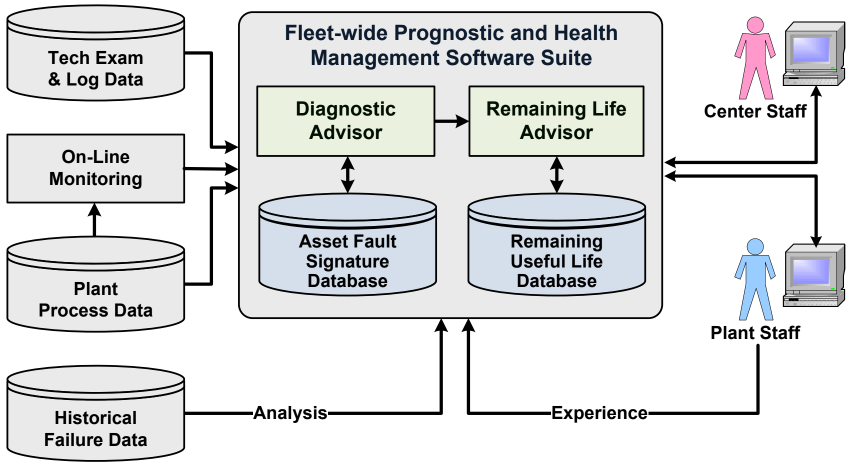

Figure 1. Data flow in the EPRI FW-PHM Suite [1].

models are implemented in the Remaining Useful Life Database of the FW-PHM Suite. The Remaining Useful Life Advisor evokes the implemented prognostic models to estimate the remaining useful life of transformer paper winding insulation based on the degree of polymerization (DP) or history of hot spot temperature.

The paper is organized as follows. The Chendong model used to estimate DP of the transformer winding insulation paper is presented in Section 2. Section 3 summarizes the IEEE thermal model used to estimate the hot spot temperature in the insulation at a given transformer load and ambient temperature. A brief discussion on the implementation of the models in the FW-PHM Suite's Remaining Useful Life Database is presented in Section 4. Section 5 presents results from the Remaining Useful Life Advisor. Finally, conclusions are drawn in Section 6.

2 CHENDONG MODEL

Degree of polymerization has traditionally been used as the primary indicator of the condition of insulation paper in transformers. The paper insulation deteriorates with age due to stresses generated by thermal, mechanical, and electrical transients. A lowering of the DP corresponds to scission of cellulose chains, a chemical breakdown reaction reducing the mechanical strength of the paper. When the DP falls below approximately 250, the paper is weak and brittle (fresh paper has a DP of 1100-1200). Although examples of paper insulation with DP values as low as 150 have been found in operating transformers [11], DP values around 250 are generally considered to indicate imminent failure. Experimental studies suggest that the DP value varies along the length of the transformer winding. Therefore, it is important to consider an average DP value over the length of the transformer winding [11].

Use of DP for accurate life prediction requires that the rate of degradation be properly calibrated, accounting for type of paper, operating temperature (the rate of degradation increases with temperature), and moisture. In addition, a nonlinear functional relationship exists between tensile strength and DP. Despite these limiting factors, DP is commonly used to estimate insulation age. DP of transformer insulation can be inferred by non-intrusively measuring the concentration of dissolved byproducts such as furanic compounds in the insulating oil. 2FAL is the most predominant of the five furanic compounds that are generated due to cellulose paper aging [12]. The relationship between 2FAL and DP is seen in Figure 2. For further discussion on furanic compounds and other oil-soluble decomposition products, refer to [4].

Several mathematical models have been developed based on the observed relationship between DP value and the 2FAL concentration. One of the most widely used models is the Chendong model [9].

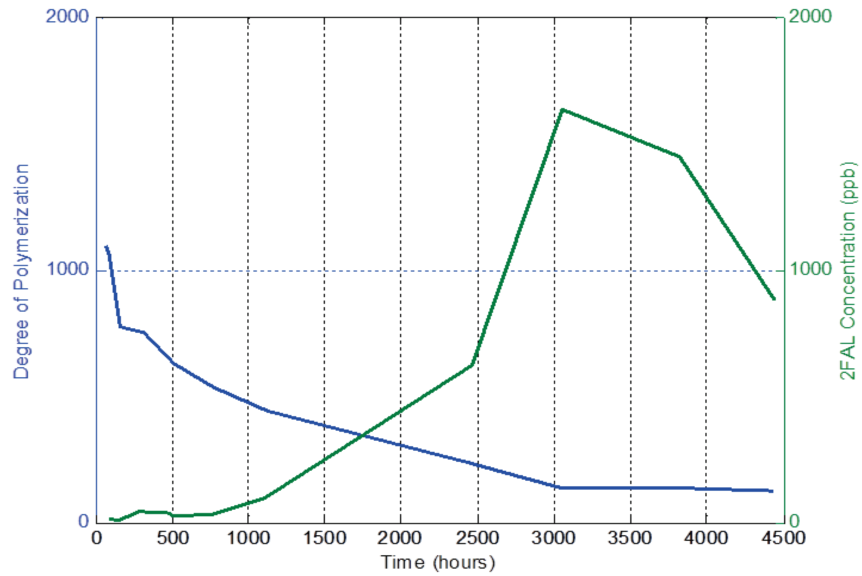

Figure 2. A functional relationship between 2FAL concentration in oil and degree of polymerization over time.

The model in Equation (1) is based on a series of data collected from transformers with normal Kraft insulation paper and a free-breathing conservator. The Chendong model exploits the release of furanic compounds, estimates DP based on 2FAL, and then predicts remaining useful life. In order to establish the relationship between 2FAL content and DP, Chendong performed a regression analysis on the collected data as following:

$$\log(2FAL) = 1.51 - 0.0035DP \quad (1)$$

The data support a linear dependence between the DP value and the logarithm of the 2FAL concentration level. The DP of insulating paper directly reflects the transformer insulation condition, as shown in Table I. Although the measurement of 2FAL concentration level from an oil sample is relatively simple, the differentiation of aging mechanisms effecting the formation of 2FAL compounds in the oil is complex. Nevertheless, Equation (1) can be applied to approximate the average DP of insulating paper and estimate the aging level for the transformer insulation winding.

A functional relationship between operating time and 2FAL concentration was established based on varying operating conditions of 77 step-up generator transformers [9], along with confidence bounds. The confidence intervals are a function of operating time (T) and are expressed as:

$$\log(2FAL_1) = -1.29 + 0.058T \quad (2)$$

$$\log(2FAL_2) = -2.37 + 0.058T \quad (3)$$

Given the DP estimate from equation (1), the empirical formulation in equation (4) can be used to calculate the elapsed insulation life of a transformer

$$\text{Elapsed life (in years)} = 20.5 \cdot \frac{DP_t}{DP_0} \quad (4)$$

where DP_0 is the degree of polymerization of a new (un-aged) transformer and DP_t is the degree of polymerization of the transformer at time t. In Equation (4), the value 20.5 is the required minimum normal insulation life expectancy of 180,000 hours (~20.55 years) per IEEE Std. C57.12.00-2010 [14].

Table I. DP and 2FAL correlation [13]

2FAL (ppm)	DP Value	Significance
0 – 0.1	1200 – 700	Healthy insulation
0.1 – 1.0	700 – 450	Moderate deterioration
1 – 10	450 – 250	Extensive deterioration
>10	<250	End-of-life criteria

3 IEEE THERMAL LIFE CONSUMPTION MODEL

The IEEE thermal life consumption model presented here has been developed for mineral-oil-immersed transformers and step-voltage regulators with insulation systems rated for a 65°C average winding temperature rise at rated load. A transformer's life span is determined mainly by the solid insulation system's mechanical resistance to withstand a short circuit. As a result, the transformer life is usually defined as the total time between the initial state with new insulation and the final state for which dielectric stress, short circuit stress, or mechanical movement could cause an electrical failure (likely a short circuit) for a given temperature of the transformer insulation.

The IEEE thermal life consumption model estimates the hot spot temperature in the insulation at given transformer load and ambient temperature, which in turn is used to estimate the transformer insulation life spent (or equivalent RUL).

IEEE standard C57.91-2011 presents two different models for calculation of hot spot temperatures. The model implemented here is a simplified model that calculates oil and winding temperatures for changes in load relative to the rated load. The alternate method is more exact, but requires an iterative solution of equations. If load, ambient temperature, and tap position can be determined accurately, the alternate method should provide more accurate results. Details can be found in [10].

The hot spot temperature (T_H) is given by:

$$T_H = T_A + \Delta T_{TO} + \Delta T_{H/TO} \tag{5}$$

where T_A is the ambient temperature, ΔT_{TO} is the top oil temperature rise over ambient, and $\Delta T_{H/TO}$ is the hot spot temperature rise over top oil. Given the ambient temperature and load, the two remaining terms of the hot-spot temperature are calculated per the procedure and equations described in [10]. Due to page limitations and the complexity of the formulation, the equations are not presented here.

The transformer insulation RUL can be calculated as

$$RUL = Normal\ insulation\ life - F_{EQA} \times t \tag{6}$$

where $F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA,n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n}$ is the equivalent aging factor at the reference hot-spot temperature in a given time period with varying load profile. Here F_{AA} is the aging acceleration factor for a given load resulting in corresponding hot spot temperature. The expression for F_{AA} is

$$\mathrm{F}_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{T_H + 273}\right]} \tag{7}$$

By substituting the T_H in equation (5) into equation (7), the transformer insulation RUL can be calculated using equation (6).

4 IMPLEMENTATION OF PROGNOSTIC MODELS IN THE FW-PHM SUITE

The procedure for implementing new prognostic models in FW-PHM is detailed in [5]. The implementation of each model in FW-PHM includes the following steps: programming the model and publishing it as a service; adding the model type to FW-PHM; defining the technical examinations required as model inputs; and creating a RUL signature for the asset in question, including parameter values. The RUL Advisor can then be used to estimate RUL.

The Chendong model (i.e., RUL Signature) was implemented at a component level for the main transformer primary winding insulation. The model uses two calibration parameters, one for the minimum life expectancy of transformer winding insulation (in years) and the second for the initial degree of polymerization when the transformer was placed in service. The single input to the model is the measured 2FAL concentration in ppm. The RUL Signature definition is seen in Figure 3. The RUL estimation units are restricted to the technical exam units, and thus are listed in PPM. The actual RUL estimation units for this example are years.

The IEEE Life Consumption model is also implemented at a component level for the main transformer primary winding insulation. The model uses nine calibration parameters, and requires one single input value and two time-series input values for load and ambient temperature. The RUL signature implementation is seen in Figure 4.

4.1 RUL Estimation

Test scenarios were developed to demonstrate the performance and robustness of the implemented models in the FW-PHM's Remaining Useful Life Database. In the case of Chendong model, a 2FAL concentration of 0.6 ppm (parts-per-million) and an initial $DP_0 = 1150$ were assumed. Using equation (1), the estimated DP was 494.8, resulting in an elapsed life estimate of 17.3 years (equation 4). The mean RUL estimate is 3.2 years given the life expectancy of 20.5 years, as seen in Figure 5. For the purposes of demonstration, the upper and lower bounds on RUL were calculated simply as 1.05 and 0.95 times the average RUL, respectively.

For the IEEE thermal model, a data set was fabricated using average ambient temperature from Idaho Falls, Idaho between June 1, 2013 and August 1, 2014. The load and ambient temperature profiles are shown in Figure 6. The left (blue) axis is the ratio of actual load to rated load, and the right (green) axis is ambient temperature. The model input parameters are described in Table 2.

Figure 7 shows the RUL estimate based on this data in the PHM prognostic advisor. The load ratios are generally higher than rated load for this data set, thus the usage estimate shows 1.35 years of life were consumed during this one-year period. The mean RUL estimate is given by the expected insulation life minus the sum of the life spent (the input usage value of 17.2 years) and the estimated usage: 20.5 – (17.2 + 1.35) = 1.95 years. Again, in this case, the upper and lower bounds on RUL are simply calculated to be 1.05 and 0.95 times the mean RUL.

5 CONCLUSIONS

The paper presented two life consumption prognostic models, the Chendong and IEEE thermal models, used to estimate the RUL of transformer paper winding insulation. Implementation of the models in the FW-PHM's Remaining Useful Life Database was discussed and some initial results were presented. The primary purpose of this work was to demonstrate use of predictive models that are relevant to the power industry and the prognostic capacity of the FW-PHM Suite. Future work should expand to the calibration of the approach for application to actual operating assets at NPPs. Development of methods for calculating upper and lower bounds for the RUL should also be studied.

6-PAPER INSULATION DEGRADATION: THERMAL- Chendong Model	NUCLEAR STEAM TURBINE	PRESSURIZED WATER REACTOR	GENERATOR VOLTAGE ELECTRICAL	TRANSFORMER: MAIN	PRIMARY WINDING INSULATION

Source/Description	Model Type	Model Inputs
INL Chendong RUL Estimation Units : PPM	**Chendong Model** **Model Calibration Parameters** <ElapsedLifeLineCoeff> <Avg_Tr_Life> 20.5 </Avg_Tr_Life> <DP_initial> 1150 </DP_initial> </ElapsedLifeLineCoeff>	

Name	Exam	Exam Units	Exam Location
FAL	INSULATING OIL ANALYSIS:2-FAL	PPM	INSULATING OIL

Figure 3. RUL signature for the Chendong Model in the Remaining Useful Life Database of the FW-PHM Suite.

16-PAPER INSULATION DEGRADATION: THERMAL-IEEE Life Consumption Model	NUCLEAR STEAM TURBINE	PRESSURIZED WATER REACTOR	GENERATOR VOLTAGE ELECTRICAL	TRANSFORMER: MAIN	PRIMARY WINDING INSULATION

Source/Description	Model Type	Model Inputs
IEEE Thermal Degradation Model (INL) IEEE Thermal Degradation MOdel RUL Estimation Units : YEARS	**IEEE Life Consumption Model** **Model Calibration Parameters** <IEEELCParams> <R> 4.87 </R> <dT_TOR> 36 </dT_TOR> <dT_HSTOR> 28.6 </dT_HSTOR> <dT_HSAR> 80 </dT_HSAR> <t_TOR> 3.5 </t_TOR> <t_W> 0.083 </t_W> <Rated_Load> 1200 </Rated_Load> <Life_Expectancy> 20.5 </Life_Expectancy> <Cooling_Type> ODAF </Cooling_Type> </IEEELCParams>	

Name	Exam	Exam Units	Exam Location
Load	ELECTRICAL VOLTAGE:VALUE	MVA	TRANSFORMER: MAIN
AmbientTemp	TEMPERATURE:VALUE	DEGC	TRANSFORMER: MAIN
PreviousUsage	USAGE:VALUE	YEARS	TRANSFORMER: MAIN

Figure 4. IEEE life consumption model implemented in the Remaining Useful Life Database of the FW-PHM Suite.

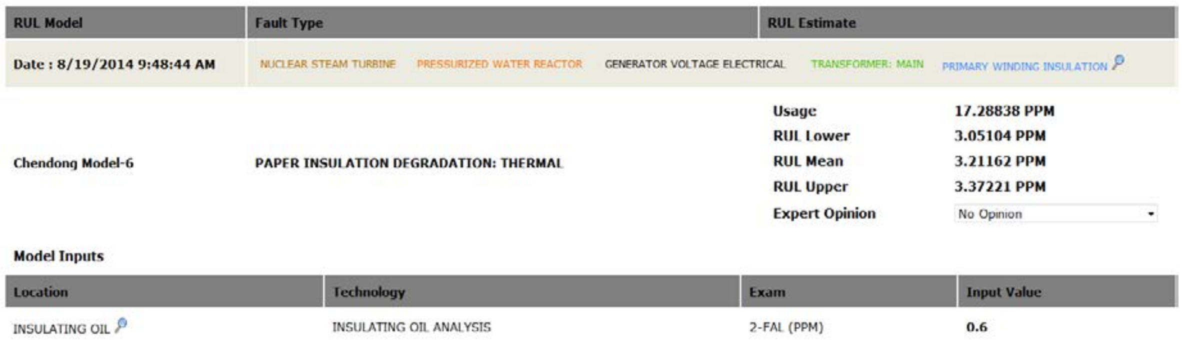

Figure 5. RUL estimate for the GSU transformer based on the Chendong Model.

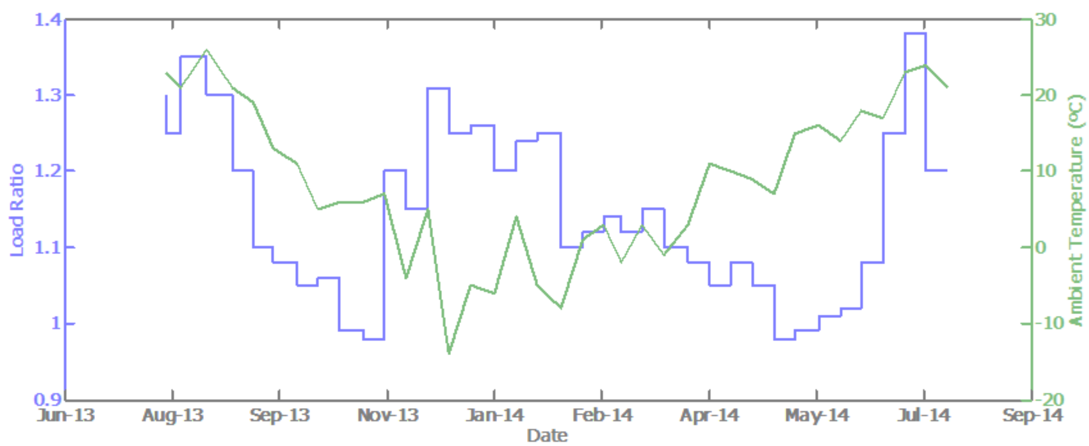

Figure 6. Load ratio and ambient temperature profile.

Table 2. Numeric parameter inputs to the IEEE thermal model as implemented in FW-PHM.

Parameter Name	Parameter Value (Unit)	Description
R	4.87	Ratio of load loss at rated load to no-load loss
dT_TOR	36.0 °C	Top oil temperature rise over ambient at rated load (ºC)
dT_HSTOR	28.6 °C	Winding hot spot temperature rise over top oil temperature at rated load (ºC)
dT_HSAR	80 °C	Winding hot spot rise over ambient at rated load (ºC)
T_TOR	3.5 h	Oil thermal time constant for rated load (hours)
T_W	0.083	Winding time constant for moderate overload (hours)
Rated_Load	1200 MVA	Rated load of the transformer
Life_Expectancy	20.5 years	Expected life of the transformer (years)

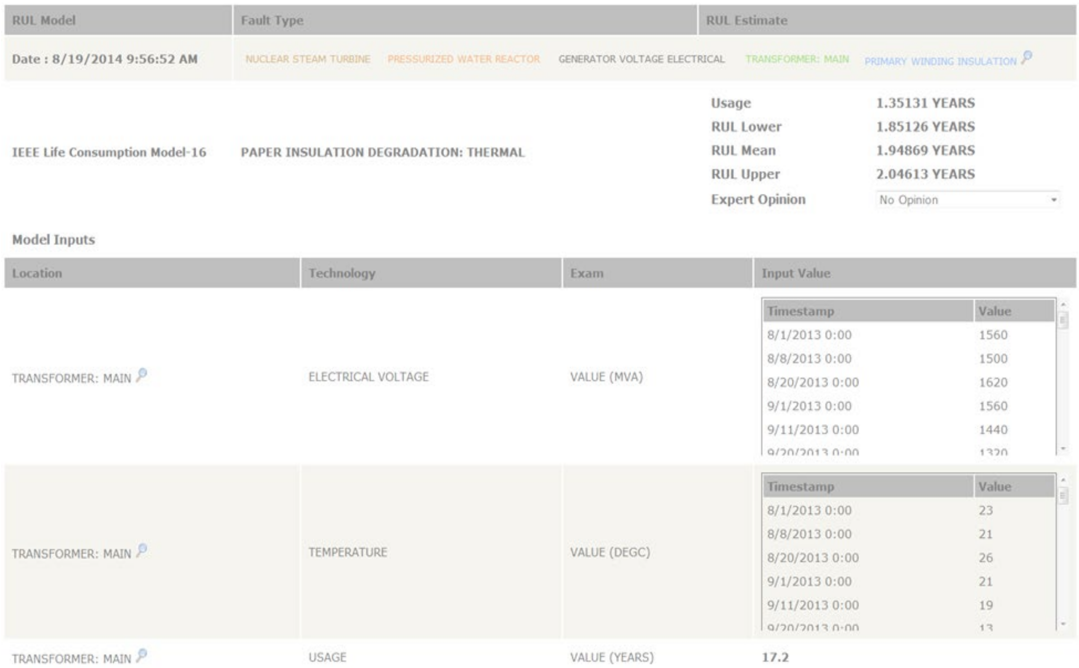

Figure 7. RUL estimate for the GSU transformer based on the IEEE thermal life consumption model.

6 ACKNOWLEDGMENTS

The authors would like to thank Kirk Fitzgerald (INL) and Rahul Palnitkar (Expert Microsystems) for their substantial support. The research work was supported by the Light Water Reactor Sustainability Program at Idaho National Laboratory, funded by the U.S. Department of Energy under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

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