Bachelor Thesis



THE STUDY OF REMAINING OPERATIONAL LIFE OF POWER TRANSFORMERS

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The Study of Remaining Operational Life of Transformer

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ABSTRACT

Power transformers are critical and expensive components of electrical power networks. Their paper-oil insulation system degrades over time due to heat, moisture, and oxygen. Once the insulation fails, the transformer cannot be repaired on site, making accurate remaining life estimation essential for utility engineers deciding when to schedule maintenance or replacement. This bachelor thesis studies and applies the main engineering methods used to estimate the remaining useful life (RUL) of oil-immersed power transformers. Four calculation methods are studied and applied:

(1) the IEEE C57.91 and IEC 60076-7 thermal models, which calculate the hotspot temperature and the rate at which insulation life is consumed under a given load [7,8,16];

(2) the Arrhenius-based degree of polymerisation (DP) kinetic model, which predicts how quickly the cellulose paper insulation loses mechanical strength [17,18];

(3) chemical diagnostic methods including dissolved gas analysis (DGA) [6,12,23,24,25], furan compound analysis [30], and oil quality testing [9,32], which provide indirect evidence of insulation condition without opening the transformer;

(4) frequency domain spectroscopy (FDS) [11,15], which estimates the moisture content of the paper insulation.

All four methods are combined in a weighted health index (HI) formula that gives a single score for the overall transformer condition [3,10,19,20,21]. Full worked numerical examples are presented for each calculation step, and results are compared against published data from real 500 kV and 750 kV transformers [1]. The study confirms that neglecting moisture content leads to overestimates of remaining life by 20-40 % [3,4,22], highlighting the importance of including moisture measurement in any complete transformer condition assessment [3,4,11].

Keywords: remaining operational life; power transformer; insulation aging; hotspot temperature; degree of polymerisation; dissolved gas analysis; frequency domain spectroscopy; health index; Arrhenius kinetics; aging acceleration factor; moisture content.

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS

Symbol / Abbreviation	Definition	Units
θ_H	Hotspot (winding hottest-spot) temperature	°C
θ_A	Ambient temperature	°C
$\Delta\theta_{TO}$	Top-oil temperature rise above ambient	°C
$\Delta\theta_H$	Hotspot temperature rise above top oil	°C
$\Delta\theta_{TO,R}$	Rated top-oil rise	°C
$\Delta\theta_{H,R}$	Rated hotspot rise	°C
K	Per-unit load factor (load / rated load)	p.u.
R	Ratio of load loss to no-load loss at rated conditions	—
n	Oil thermal exponent	—
m	Winding thermal exponent	—
F_{AA}	Aging acceleration factor (relative to 98 °C reference)	—
F_{EQA}	Equivalent aging factor over a duty cycle	—
$\%LOL$	Percentage loss of insulation life	%
L_N	Normal insulation life at reference temperature	h
DP_0	Initial degree of polymerisation	—

DP_t	Degree of polymerisation at time t	—
DP_{end}	End-of-life DP threshold (typically 200)	—
η	Chain scission number	—
E_a	Activation energy of aging reaction	kJ/mol
A	Arrhenius pre-exponential factor	h^{-1}
$R\ (gas)$	Universal gas constant, 8.314 J mol^{-1} K^{-1}	$Jmol^{-1}K^{-1}$
T	Absolute hotspot temperature	K
k	Effective degradation rate constant	h^{-1}
$k(T)$	Temperature-dependent rate constant	h^{-1}
f_M	Moisture acceleration multiplier	—
M_c	Moisture content in cellulose paper	wt %
$DGAF$	Dissolved gas analysis factor (health index component)	—
OQF	Oil quality factor (health index component)	—
PIF	Paper insulation factor (health index component)	—
HI	Overall transformer health index	0–100

$2-FAL\ /\ 2FAL$	2-furfuraldehyde (furfural) concentration in oil	ppb or ppm
DP_{est}	Estimated DP derived from 2FAL measurement	—
BDV	Breakdown voltage of insulating oil	kV
IFT	Interfacial tension	mN/m
$tan\delta$	Dielectric loss tangent (dissipation factor)	—
$\varepsilon^{*}r$	Complex relative permittivity	—
$\varepsilon'r$	Real part of complex relative permittivity	—
$\varepsilon''r$	Imaginary part of complex relative permittivity	—
FDS	Frequency domain spectroscopy	—
PDC	Polarisation / depolarisation current method	—
DAR	Dielectric absorption ratio	—
PI	Polarisation index	—
$ANFIS$	Adaptive neuro-fuzzy inference system	—
DGA	Dissolved gas analysis	—
$TDCG$	Total dissolved combustible gas concentration	µL/L
$IEEE$	Institute of Electrical and Electronics Engineers	—

IEC	International Electrotechnical Commission	—
RUL	Remaining useful life	years or days

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

Power transformers are the single most expensive and irreplaceable items of plant in electrical transmission and distribution networks. A typical 500 kV autotransformer carries a replacement cost in excess of USD 3 million, requires a 12–24 month lead time for manufacture, and weighs up to 300 tons - making rapid substitution after failure effectively impossible. The consequences of an unplanned outage extend far beyond the direct asset cost; they include lost revenue, penalties for non-delivery of contracted energy, costs of emergency procurement, and in severe cases, cascading voltage collapses that endanger grid stability across entire interconnected systems.

The world's transformer fleet is aging. In developed economies, 40 % to 70 % of high-voltage transformers currently installed have already surpassed their nominal design life of 30 to 40 years. Mongolia's grid, in particular, has many Soviet-era transformers—commissioned in the 1970s and 1980s—that were designed for deterministic flat-load profiles, unlike the dynamic renewable-integrated dispatch regime seen today. Continued operation of these units, combined with the recent increase in peak loads during extreme winter events, places the insulation systems under stresses that were never envisaged at the time of design.

Cellulose paper insulation is the life-limiting component of an oil-immersed transformer. Unlike the mineral oil, which can be reclaimed, filtered, or replaced, the kraft-paper windings cannot be renewed without complete disassembly of the active part. Once the degree of polymerisation (DP) of the paper falls below approximately 200, corresponding to a loss of roughly 70 % of its original tensile strength, the insulation can no longer withstand normal electrodynamic or seismic mechanical stresses, and the transformer is considered to have reached end of life [1,17,18].

Accurate estimation of remaining useful life (RUL) therefore serves three strategic objectives: (1) it enables condition-based maintenance to replace time-based maintenance schedules, eliminating costly over-maintenance of healthy units and catastrophic under-maintenance of deteriorating ones; (2) it provides the quantitative basis for capital-expenditure planning and procurement lead-time management; and (3) it supports grid operators in making informed decisions about short-term overloading acceptability, load redistribution, and emergency contingency planning.

1.2 Why Studying Remaining Operational Life Matters

Despite several decades of research, the accurate quantification of transformer remaining life remains an unsolved problem in practice. Three fundamental challenges are identified in the literature surveyed for this thesis:

First, classical thermal models [7,8] were formulated under the assumption of constant or slowly varying load and ambient conditions, and they treat moisture content as a fixed parameter. [3] demonstrated rigorously that this static assumption leads to systematic overestimation of transformer lifetime by 20–60 % [3] when compared with a dynamic simulation that honours the actual hourly load profile and the slow autonomous increase in paper moisture content over service life.

Second, no single diagnostic indicator is sufficient. The degree of polymerisation measured from a paper sample is the most direct indicator of insulation condition, but it requires an invasive tank opening. Indirect indicators — furfural concentration, dissolved combustible gases, oil quality parameters, and dielectric response measurements each capture one projection of the insulation's multidimensional state. Integrating them into a single quantitative life estimate requires a mathematically coherent weighting and normalisation framework that the existing literature addresses only partially.

Third, the moisture content of the paper is both an output of the aging process (hydrolysis produces water as a byproduct) and an accelerant of it. This positive feedback loop means that a correct life assessment model must simultaneously estimate moisture from FDS [11,15] or PDC measurements, use that moisture estimate in the DP kinetic chain, and feed the resulting DP trajectory back into the health index, a circular dependency that is rarely handled consistently in the published literature.

1.3 Study Objectives

The specific objectives of this study on the remaining operational life of transformers are:

- To derive and implement the full IEEE C57.91/IEC 60076-7 thermal model in dynamic difference-equation form, computing hotspot temperature, aging acceleration factor, equivalent aging factor, and percentage loss of life for arbitrary load profiles.
- To formulate the Arrhenius-Emsley DP kinetic model with explicit decomposition into hydrolysis, oxidation, and pyrolysis pathways and to derive the remaining life expression as a closed-form function of current DP, hotspot temperature history, and moisture content.

- To develop a quantitative DGA scoring algorithm based on individual gas concentrations, delta values, and rate-of-change values, validated against the Duval Triangle method.
- To establish the mathematical relationship between FDS dielectric parameters and paper moisture content using the Clausius-Mossotti framework and temperature-corrected relaxation-time analysis.
- To synthesise all indicators into a composite health index with physically motivated weighting factors and to propagate uncertainty through the combined estimate.
- To validate the integrated framework against published case studies on transformers ranging from 20 MVA distribution units to 750 MVA bulk-power transformers.

1.4 Scope and Limitations

This study focuses on mineral-oil-immersed transformers with kraft or thermally-upgraded kraft (TUK) paper insulation. Dry-type, cast-resin, and ester-oil-filled units are outside the scope. The thermal model is limited to the top-oil / hotspot two-zone representation of IEEE C57.91 and IEC 60076-7; detailed finite-element thermal analysis is not undertaken. Statistical failure models (Weibull end-of-life distributions based on field populations) are discussed conceptually but are not the primary focus. Machine-learning accelerators such as ANFIS are reviewed for their predictive capability but the thesis does not develop new training datasets; instead, the analytical calculation methods are emphasised throughout.

1.5 Thesis Structure

Chapter 2 reviews the published literature across all relevant diagnostic and modelling domains. Chapter 4 derives the full thermal calculation chain. Chapter 5 develops the DP kinetic and remaining-life mathematics. Chapter 6 presents the chemical diagnostic quantification methods. Chapter 7 covers FDS-based moisture estimation. Chapter 8 assembles the integrated health index algorithm. Chapter 9 applies the framework to three published case studies and compares the results. Chapter 10 states conclusions and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 Transformer Insulation Aging Mechanisms

The aging of oil-paper insulation in power transformers is governed by three simultaneously acting chemical degradation pathways acting on the cellulose polymer chain [4,17,18]. Cellulose is a linear polysaccharide consisting of glucose rings linked by β (1→4) glycosidic bonds [17,18]. The average chain length — expressed as the degree of polymerisation DP — falls from a typical factory value of 1000–1250 for new kraft paper to a mechanical end-of-life threshold of approximately 200, at which point the paper has lost 70 % of its original tensile strength [1,3,4].

Thermal degradation (pyrolysis) is dominant at temperatures above 130 °C and involves direct thermal cleavage of glycosidic bonds [4,17,18]. Hydrolysis is driven by water — including the water generated as a byproduct of cellulose chain scission itself — and is the primary pathway at normal transformer operating temperatures (80–110 °C) [4,17,18]. Oxidation, catalysed by dissolved oxygen and transition-metal ions from copper windings and iron cores, proceeds most rapidly below 75 °C and produces carbonyl and carboxyl groups that further weaken the cellulose structure [4].

Moisture occupies a uniquely important position: it is both a reactant in hydrolysis and a product of the same reaction [4,17,18]. Through dynamic simulation that a realistic model must account for a 0.2 % per-year moisture growth rate in the paper, since ignoring this feedback leads to an overestimation of remaining life by up to 60 % [3]. The moisture multiplier f_M can increase the effective rate constant by a factor of 1.35–1.80 relative to a dry-paper baseline, compressing the predicted lifetime by 20–40 % [2].

2.2 Thermal Aging Models: IEEE C57.91 and IEC 60076-7

The first engineering standard to quantify the relationship between hotspot temperature and insulation life was the 1981 edition of IEEE C57.92, which established 110 °C as the reference hotspot temperature for a normal insulation life of 65,000 hours for non-upgraded insulation and 180,000 hours for thermally upgraded insulation [8]. The current standard, retains this framework while adding the alternate Annex G difference-equation thermal model that accounts for viscosity variation, multiple cooling modes, and transient load cycles [8].

IEC 60076-7:2018 provides the internationally harmonised equivalent. The Loading Guide Comparison study provides a side-by-side mapping of every major clause between the two standards [7,8], revealing that while the steady-state formulas are algebraically identical, the IEC difference equations use a 1-minute time step and slightly different viscosity corrections for the three permissible insulating liquids (mineral oil, silicone, and HTHC) [7].

[3] embedded the IEC 60076-7 [7] difference equations inside a dynamic Monte Carlo–style life estimation algorithm in which the load factor K and ambient temperature θ_A are sampled from real hourly operating data [3]. This contribution is particularly significant because it showed that the DP profile from a dynamic simulation contains 'ripples' corresponding to daily and seasonal load variation, and that the highest rate of DP degradation occurs during peak-load summer periods rather than uniformly throughout the year, a finding with direct implications for maintenance scheduling [3].

Genetic-programming approach is applied to derive hot-spot temperature prediction models for traction transformers in high-speed railway applications, demonstrating that data-driven corrections to the standard models can reduce prediction error to below 2 °C [16]. Similarly, FDS measurements at the transformer hotspot region can be used to back-calculate the local thermal aging state, providing an independent cross-check of the kinetic model [15].

2.3 Chemical Diagnostic Approaches

Dissolved gas analysis has been the primary in-service diagnostic technique for mineral oil transformers since the work of the UK Central Electricity Generating Board in the 1960s [6]. The technique is based on the observation that electrical and thermal faults in a transformer release characteristic gas that dissolve in the insulating oil at concentrations proportional to fault severity and duration [6]. [23] provides a comprehensive practical reference for DGA interpretation, acid number monitoring, and furan analysis as used by the United States Bureau of Reclamation.

The Duval Triangle method, based on the relative proportions of methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2), maps DGA results onto seven fault zones: partial discharge (PD), low-energy discharge (D1), high-energy discharge (D2), thermal fault T1 (<300 °C), T2 (300–700 °C), T3 (>700 °C), and a combined DT zone. The Duval Pentagon extends this to include hydrogen and ethane, improving the separation between thermal and electrical fault zones [10,12].

Furan compounds — principally 2-furfuraldehyde (2-FAL), 5-hydroxymethyl-2-furaldehyde (5-HMF), 2-furfurol (2-FOL), furoic acid, 2-acetylfuran (2-ACF), and 5-methyl-2-furaldehyde (5-MEF) — are released by thermal degradation of cellulose and migrate into the oil. Their total concentration in the oil provides an indirect measure of paper DP. Several empirical correlations between 2-FAL concentration and DP have been published; the one used by [2] for thermally upgraded paper is: $DP_{est} = [log(2FAL \times 0.88) - 4.51] / (-0.0035)$. This conversion formula is calibrated for PLN Indonesia transformers with TUK paper; different conversion equations apply for standard kraft paper, and the choice of equation can affect the estimated remaining life by 5–15 years [4,5].

ANFIS model trained on 108 Indonesian distribution transformers to predict DP from oil dielectric characteristics (acidity, IFT, color) and dissolved gas ratios (CO + CO_2) when furfural data were unavailable [5]. The model achieved 89.07 % training accuracy and 85.75 % test accuracy.

2.4 Dielectric Measurement Methods

Frequency domain spectroscopy measures the complex relative permittivity $\varepsilon^* r = \varepsilon' r - j\varepsilon'' r$ of the oil-paper insulation system as a function of excitation frequency, typically over the range 0.05 mHz to 5 kHz [11,15]. Because water is a strongly polar molecule, increasing moisture content raises both $\varepsilon' r$ and $\varepsilon'' r$ at low frequencies through enhanced dipolar polarisation and interfacial (Maxwell-Wagner) polarisation [11]. The Clausius-Mossotti equation links $\varepsilon' r$ to the number density of polar particles per unit volume, providing a thermodynamic basis for the empirical moisture correlations observed in measurements [11,15].

Temperature-correcting the FDS loss-angle-tangent curves to a reference temperature of 20 °C using the activation energy of the dominant relaxation process eliminates the temperature-dependent overlay on the frequency spectra, leaving only the moisture-dependent component. This enables consistent cross-comparison of FDS results taken at different ambient temperatures, which is particularly important for field measurements on live or recently de-energised transformers where the oil temperature may be anywhere between 20 °C and 80 °C [11].

The polarisation index ($PI = R_{600}s / R_{60}s$) and dielectric absorption ratio ($DAR = R_{60}s / R_{30}s$) are simpler time-domain dielectric indices derived from insulation resistance measurements. Both parameters are strongly temperature-dependent and therefore unreliable as stand-alone aging indicators unless corrected to a reference temperature using the Arrhenius relationship; however, the paper conductivity-based

correction using the same activation energy as the aging kinetics yields a stable, moisture-sensitive indicator [15].

2.5 Health Index Methodologies

The health index (HI) concept consolidates multiple diagnostic results into a single number on a 0–100 scale, where 100 denotes a new transformer and 0 denotes an immediately failing unit. [10] provide an exhaustive review of HI methodologies spanning scoring-weighting methods, Bayesian networks, fuzzy logic, neural networks, and hybrid approaches. The scoring-weighting approach pioneered by [19] and [20] assigns a score Si to each diagnostic parameter based on measured ranges and multiplies by a weighting factor Wi that reflects the parameter's importance to transformer health. The weighted sum is normalised to produce the HI.

[21] proposed a dynamic weighting scheme in which the weight factors are updated in real time as a function of the measured values themselves: for example, when acetylene is detected at high concentration, the DGA weight factor increases sharply to reflect the disproportionate hazard posed by a developing high-energy discharge. This adaptive approach prevents a high DGA reading from being masked by good results in other categories.

[12] proposed a Modified DGAF scoring method that includes delta values (absolute change between consecutive DGA tests) and rate-of-change values alongside absolute gas concentrations. This temporal dimension captures the speed of fault development, which is often more significant than the instantaneous concentration level. The method was validated against 36 DGA results from a single transformer monitored over approximately 10 years, and it identified a developing T1 + S (stray gassing combined with thermal fault below 300 °C) condition approximately 18 months before the conventional TDCG threshold was breached.

2.6 Machine-Learning and Hybrid Methods

[5] demonstrated that ANFIS, which combines a Takagi-Sugeno fuzzy inference system with a back-propagation neural network, can estimate DP from oil test data with accuracy comparable to direct measurement when four carefully selected input variables are used. The same ANFIS architecture was applied by [2] as part of a broader remaining-life pipeline.

2.7 Identified Gaps in the Existing Literature

The literature review identifies three specific gaps that motivate the methodology developed in this thesis. First, no published paper simultaneously couples the dynamic DP kinetic model of [3] with the FDS-derived moisture content from [11] and the modified DGAF scoring of [12] within a single consistent numerical framework. Second, the sensitivity of the remaining-life estimates to the choice of activation energy E_a, which varies from 94 kJ/mol to 111 kJ/mol across the published literature depending on moisture and degradation stage, has not been fully quantified through a structured parametric analysis. Third, the conversion equation between 2-FAL concentration and DP has been calibrated only for specific paper types and geographic fleets; its applicability to Mongolian transformers with mixed Russian/European insulation specifications requires explicit discussion.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Research Approach and Integrated Framework

This thesis uses an integrated four-stream analytical framework to estimate the remaining operational life of oil-immersed power transformers. The framework was designed to address three specific limitations identified in the literature review (Section 2.7): the over-reliance on thermal-only models that ignore moisture [3]; the inadequacy of single-indicator diagnostics [1,10]; and the absence of a complete, fully-coupled calculation chain in published single studies [3,11,12].

It merges the four separate measurement streams - thermal modelling, cellulose kinetics, chemical analysis, and dielectric response - into a weighted health index. This has the advantage that no one poor indicator can be overwhelmed by others showing good health, and all of the dominant modes of aging (thermal, hydrolytic, oxidative) can be measured concurrently.

Stream	**Derived in**	**Primary output**	**Connects to**
1 — Thermal	Chapter 4	Hotspot θ_H; F_{AA}; $\%LOL$	Stream 2 (via T); HI thermal sub-factor
2 — Kinetic	Chapter 5	Rate k_{eff}; remaining life RL	HI paper sub-factor (via RL and DP)
3 — Chemical	Chapter 6	DGAF; OQF; PIF; indirect DP	Health Index (all three sub-factors)
4 — Dielectric	Chapter 7	Paper moisture M_c	Stream 2 (via fM); OQF (via tanδ)
5 — Synthesis	Chapter 8	HI (0–100); combined RUL	Final remaining life estimate

Table 3.1. Five analytical streams and their connections in the integrated framework.

3.2 Calculation Flow and Inter-Stream Dependencies

The four streams interact in a defined sequence. The thermal model (Chapter 4) receives the transformer rated parameters and load profile, producing hotspot temperature θ_H. This temperature enters the kinetic model (Chapter 5) as the primary driver of the Arrhenius rate constant k(T).

The dielectric stream (Chapter 7) independently estimates paper moisture content M_c from frequency domain spectroscopy data [11,15]. M_c feeds into the moisture multiplier f_M, which amplifies k(T) to give the effective degradation rate k_{eff} (3,4). Together with the current DP — measured directly or estimated from oil 2-FAL concentration [30], k_{eff} yields the kinetic remaining life RL.

The chemical stream (Chapter 6) provides three sub-factors: the DGA factor (DGAF) from dissolved gas analysis, the oil quality factor (OQF) from physical oil tests, and the paper insulation factor (PIF) from furan analysis. These, combined with a normalised thermal aging score in the health index model (Chapter 8), produce the composite Health Index HI and the combined remaining life estimate $RUL_{combined}$.

This sequence means that moisture content is not an optional add-on it is a critical coupling variable between the dielectric and kinetic streams. Omitting it is equivalent to setting $f_M = 1.0$, which systematically overestimates remaining life as demonstrated by Ariannik et al. (2020) and confirmed in the case study of Chapter 9.

3.3 Data Requirements and Confidence Classification

The framework requires 35 input parameters. Since not all are measurable from a single oil sample or test report, each parameter is classified by its confidence status. This classification is applied explicitly in Chapter 9 so that readers can assess the reliability of each calculation output.

Code	Status	Definition

M	Directly Measured	Value physically measured and published in peer-reviewed source
S	Standard Default	Representative value from IEC 60076-7 or IEEE C57.91 standard tables
C	Calculated	Value derived from a measured value using a stated, traceable equation
A	Assumed	Engineering estimate used where source data is unavailable

Table 3.2. Input data confidence classification system used in Chapter 9.

This classification system does not imply that assumed values are unreliable. Engineering assumptions are standard practice in transformer condition assessment and are acceptable in an academic thesis provided they are explicitly disclosed. Chapters 4–8 define which class each parameter belongs to; Chapter 9 applies the classification to every input for Transformer T1.

3.4 Case Study Selection — Transformer T1

To apply and validate the framework, a real in-service transformer with published measured data was selected. Three selection criteria were applied: (1) the data source is a peer-reviewed journal paper independent of the 24 primary thesis references; (2) the measured dataset covers all major diagnostic parameter groups, DGA, oil quality, and furan analysis, in a single published table; (3) the source paper reports an independently calculated remaining life estimate against which this thesis can directly validate its results.

Transformer T1 from [1] satisfies all three criteria. It is a 25 MVA, 35/6.3 kV, three-phase ONAN transformer with kraft paper insulation serving an industrial cement factory. Table 14 of the source paper publishes all seven DGA gas concentrations, six oil quality parameters (BDV, water content, tanδ, IFT, acidity, colour), and a complete furan compound profile including 2-FAL, 5-HMF, 2-FOL, 2-ACF, and 5-MEF. The paper also reports an independently assessed health index of HI = 73 and a remaining life of approximately 15 years.

3.5 Structure of Chapters 4–9 and Equation Reference Map

Chapters 4 through 8 each cover one analytical stream. Every chapter presents the physical and mathematical derivation of its equations and explains the role of each parameter. No specific numerical values from Transformer T1 appear in those chapters. The purpose is to establish the complete theoretical framework before data is applied.

Chapter 9 is the only chapter where measured values are substituted into equations. Every calculation in Chapter 9 states the equation number from Chapters 4–8 that it applies. Table 3.3 provides the complete cross-reference map so that any reader can trace from a Chapter 9 result back to the equation derivation and forward to the corresponding result in Chapter 10 (Results).

Eq. ref.	**Derived in**	**Applied in Ch. 9**	**Produces**
Eq. 4.1	Ch.4 4.1	9.4	Hotspot temperature θ_H for T1 operating condition
Eq. 4.2	Ch.4 4.1	9.4	Top-oil temperature rise $\Delta\theta_{TO}$
Eq. 4.3	Ch.4 4.1	9.4	Hotspot rise above oil $\Delta\theta_H$
Eq. 4.12	Ch.4 4.3	9.4	Aging acceleration factor F_{AA}
Eq. 4.16	Ch.4 4.4	9.4	Cumulative loss of life %LOL
Eq. 5.3	Ch.5 5.2	9.5	Arrhenius rate constant k(T)

Eq. 5.12	Ch.5 5.4	9.5	Moisture multiplier f_M from measured M_c
Eq. 5.10	Ch.5 5.4	9.5	Effective rate constant k_{eff}
Eq. 5.6	Ch.5 5.5	9.5	Remaining life RL from T1 DP
Eq. 6.5b	Ch.6 6.4	9.5	Indirect DP from measured 2-FAL (kraft paper)
Eq. 6.1	Ch.6 6.1	9.6	Total dissolved combustible gas TDCG
Eq. 6.2	Ch.6 6.3	9.6	DGA factor DGAF from T1 gas concentrations
Eq. 6.7	Ch.6 6.5	9.7	Oil quality factor OQF from T1 oil tests
Eq. 6.9	Ch.6 6.6	9.8	Paper insulation factor PIF from T1 furan data
Eq. 7.7	Ch.7 7.4	9.9	FDS temperature correction shift factor α_T
Eq. 7.5	Ch.7 7.3	9.9	Moisture content Mc from FDS parameters
Eq. 8.1	Ch.8 8.1	9.10	Composite Health Index HI
Eq. 8.5	Ch.8 8.3	9.11	Combined remaining life $RUL_{combined}$

Table 3.3. Equation cross-reference map: theoretical derivation in Chapters 4–8 → numerical application in Chapter 9. All results in Chapter 9 cite their equation number from this map.

CHAPTER 4
THERMAL MODELLING AND HOTSPOT TEMPERATURE CALCULATION

4.1 IEEE C57.91 Steady-State Thermal Model

The hotspot temperature θ_H is the single most important variable in transformer life assessment because all aging models depend on it through an exponential (Arrhenius) relationship [7,8,17]. The basic IEEE C57.91 / IEC 60076-7 steady-state expression for θ_H is:

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \qquad (4.1)$$

where:

θ_A = ambient temperature (˚C)

$\Delta\theta_{TO}$ = top-oil temperature rise above ambient (˚C)

$\Delta\theta_H$ = hotspot temperature rise above top oil (˚C)

The steady-state rises depend on the load factor K (per-unit ratio of actual load current to rated load current) and the ratio R of load loss to no-load loss at rated conditions through the following power-law expressions [7,8]:

$$\Delta\theta_{TO} = \Delta\theta_{TO,R}\left(\frac{1+K^2R}{1+R}\right)^n \qquad (4.2)$$

$$\Delta\theta_H = \Delta\theta_{H,R}K^{2m} \qquad (4.3)$$

The exponents n and m are empirically determined constants that reflect the cooling mode and the nature of the oil circulation. IEEE C57.91-2011 Table 4 provides recommended values (7,8):

Cooling Mode	**n (oil exponent)**	**m (winding exponent)**
ONAN (natural oil / natural air)	0.80	1.60
ONAF (natural oil / forced air)	0.80	1.60
OFAF (forced oil / forced air)	1.00	1.00
ODAF (directed oil / forced air)	1.00	1.00

Table 4.1. Recommended thermal exponents from IEEE C57.91-2011 Table 4 and IEC 60076-7:2018 Table 4.

Substituting Equations (4.2) and (4.3) into (4.1) yields the complete steady-state hotspot temperature as an explicit function of load factor K for given rated thermal parameters and ambient temperature. This formulation is exact at steady state but cannot represent transient behaviour following a load step change. The dynamic model of Section 4.2 addresses this limitation [7,8].

4.2 IEC 60076-7 Dynamic Difference-Equation Model

For time-varying loads, Annex G of IEEE C57.91-2011 and the main body of IEC 60076-7:2018 provide a forward-marching finite-difference scheme. The scheme computes the oil and hotspot temperatures at each time step $t_2 = t_1 + \Delta t$ from the values at the previous step t_1. Because the IEC method uses a constraint that $\Delta t \leq \tau_{\min}/2$ and the minimum time constant is 2 minutes, the standard time step is set to Δt = 1 min [7,8].

The four governing difference equations are:

$$D\theta_o = \left(\Delta t/(k_{11}\tau_o)\right) \cdot [(1 + K^2R)/(1 + R)]^n \cdot \Delta\theta_{TO,R} - (\theta_o - \theta_A) \qquad (4.4)$$

$$\theta_o(n) = \theta_o(n-1) + D\theta_o(n) \qquad (4.5)$$

$$D\Delta\theta_{h1} = \left(\Delta t/(k_{22}\tau_w)\right) \cdot \left(k_{21} \cdot \Delta\theta_{H,R} \cdot K^{\mathrm{y}} - \Delta\theta_{h1}\right) \qquad (4.6)$$

$$D\Delta\theta_{h2} = \left(\Delta t/\left((1/k_{22})\tau_o\right)\right) \cdot \left((k_{21} - 1) \cdot \Delta\theta_{H,R} \cdot K^{\mathrm{y}} - \Delta\theta_{h2}\right) \qquad (4.7)$$

$$\Delta\theta_h(n) = \Delta\theta_{h1}(n) - \Delta\theta_{h2}(n) \qquad (4.8)$$

$$\theta_H(n) = \theta_o(n) + \Delta\theta_h(n) \qquad (4.9)$$

where the notation is:

$$\tau_o = oil\ thermal\ time\ constant \quad \text{min}$$

$$\tau_w = winding\ thermal\ time\ constant \quad \text{min}$$

$$k_{11} = ratio\ of\ load\ loss\ at\ maximum\ load\ to\ load\ loss\ at\ rated\ load$$

$$k_{21} = ratio\ of\ ultimate\ hotspot\ rise\ to\ rated\ hotspot\ rise$$

$$k_{22} = ratio\ of\ winding\ time\ constant\ to\ oil\ time\ constant$$

$$y = winding\ exponent\ (equals\ 2m\ for\ the\ ONAN\ model)$$

The variable $\Delta\theta_{h1}$ tracks the forced response of the hotspot rise driven by the current load, while $\Delta\theta_{h2}$ tracks a thermal correction term that accounts for the difference

between the winding and oil time constants. The complete winding hotspot rise above top oil is their difference (Eq. 3.8). This two-component representation was derived from thermal circuit analysis and improves accuracy over the single time-constant model by correctly reproducing the overshoot in winding temperature immediately after a load step [7,8].

For mineral oil at temperature T (°C), the viscosity correction factor fv applied to the thermal time constant is [7,8]:

$$f_v = [\nu(T)/\nu(T_{\text{ref}})]^{0.5} \qquad (4.10)$$

where ν(T) is the kinematic viscosity in mm²/s. For mineral oil:

$$\nu(T) = \nu_{ref} \cdot \exp\left[B_v\left(1/T_K - 1/T_{K,\text{ref}}\right)\right] \qquad (4.11)$$

with B_v ≈ 1800 K for mineral oil. IEC 60076-7 Table 5 tabulates ν_{ref} and B_v for mineral oil, silicone, and HTHC.

4.3 Aging Acceleration Factor and Loss-of-Life Calculation

The aging acceleration factor F_{AA} quantifies the rate of insulation aging at temperature θ_H relative to the aging rate at the reference hotspot temperature θ_{ref} =98°C (for thermally upgraded paper). The relationship is derived from the Arrhenius

Equation (17,18) for chemical reaction rate and has the form:

$$F_{AA} = \exp\left[(E_a/R) \cdot \left(1/\theta_{\text{ref},K} - 1/\theta_{H,K}\right)\right] \qquad (4.12a)$$

Substituting the IEEE C57.91 value of $\frac{E_a}{R}$ corresponding to a doubling of aging rate per 6 °C rise:

$$F_{AA} = \exp\left[15000 \cdot \left(1/383 - 1/(\theta_H + 273)\right)\right] \qquad (4.12b)$$

where θ_H is in °C and 383 K corresponds to the reference temperature of 110 °C (for non-upgraded insulation; the IEC reference is 98 °C = 371 K). Some publications use E_a = 111 kJ/mol specifically for ANFIS-based Indonesian transformer calculations [5]; the sensitivity of F_{AA} to this choice is quantified in Chapter 5.

The percentage loss of life during a time period t at approximately constant θH is:

$$\%LOL = 100 \cdot F_{AA} \cdot t/L_N \qquad (4.13)$$

where L_N is the normal insulation life at the reference temperature. IEEEC57.91 specifies L_N=65,000h for non-thermally-upgraded paper and 150,000h (or 180,000h) for

thermally upgraded paper (8). Table 3.2 lists the loss of life contribution per day for selected hotspot temperatures:

θ_H °C	F_{AA}	**% LOL per day (L_N = 150 000 h)**	**Equivalent normal days**
80	0.0527	0.00845	11.83
90	0.125	0.02	5.00
98 (ref)	1.000	0.1600	0.625
110	4.74	0.759	0.132
120	16.2	2.59	0.039
130	48.8	7.81	0.013
140	138	22.1	0.0045

Table 4.2. Loss-of-life rate as a function of hotspot temperature for thermally upgraded paper ($L_N = 150000h$).

4.4 Equivalent Aging Factor for Variable Load Profiles

In practice, a transformer experiences a continuously varying load profile [16,1]. The equivalent aging factor F_{EQA} represents the single constant value of F_{AA} that would produce the same cumulative aging over the time period N·Δt as the actual variable profile [7,8]:

$$F_{EQA} = \sum_i \left(F_{AA,i} \cdot \Delta t_i\right) / \sum_i \Delta\, t_i \qquad (4.14)$$

For a discrete load profile with n intervals each of duration $\Delta t = 1h$, and with the hotspot temperature in interval i detoned by $\theta_{H,i}$, the equivalent aging factor is calculated as follows [7,8]:

$$F_{EQA} = (1/N) \cdot \sum_{i} {}_{=1}{}^{\mathrm{N}} \exp\left[15000 \cdot \left(1/383 - 1/\left(\theta_{H,i} + 273\right)\right)\right] \qquad (4.15)$$

The total loss of life consumed over the period is then [7,8]:

$$\%LOL = 100 \cdot F_{EQA} \cdot N \cdot \Delta t / L_N \qquad (4.16)$$

The number of days of equivalent normal aging consumed per operating day at an average load profile is an important operational metric. For a daily load cycle with four

blocks, each block I has a duration Δt_i (hours) and load factor K_i , yielding hotspot temperature $\theta_{H,i} = \theta_A + \Delta\theta_{TO,i} + \Delta\theta_{H,i}$ where the two rise components are computed from Equations (4.2) and (4.3).The daily F_{EQA} is then given by Equation (4.14) with N=24. The average acceleration factor for a 500kV main transformer in 2010 with load data and an average hotspot of 38.963°C was $F_{EQA} = 0.409912$, meaning this transformer was aging at less than half the reference rate.

Note that F_{EQA} < 1 does not mean the transformer is aging more slowly than it would at the reference temperature; rather, it means the hotspot was frequently below 98 °C (or 110 °C). The total life consumed is still positive and accumulating [2]. The important implication for Mongolian grid conditions, where extreme winter ambient temperatures of −40 °C are common, is that winter operation significantly reduces F_{AA} [8] and partially offsets summer overload effects, but this cannot be relied upon as a permanent safety margin, since the hotspot temperature during summer peak loads can readily exceed 120 °C if loading is not managed [8].

Table 4.3. Generic worked example parameters and four-block daily load profile for equivalent aging factor calculation (Section 4.4).

Parameter	**Symbol**	**Value**	**Units**
Rated top-oil rise	$\Delta\theta_{TO,R}$	45	°C
Rated hotspot rise above top oil	$\Delta\theta_{H,R}$	15	°C
Load-loss to no-load-loss ratio	R	5.0	—
Oil exponent	n	0.80	—
Winding exponent	m	1.60	—
Oil thermal time constant	τ_o	180	min
Winding time constant	τ_w	10	min
Ambient temperature	θ_A	30	°C

Normal insulation life	L_N	150,000	h

Block	$Duration\ \Delta t_i$	$Load\ factor\ K_i$	$\Delta\theta_{TO,i}$ °C	$\Delta\theta_{H,i}$ °C	$\theta_{H,i}$ °C	$F_{AA,i}$
1 (off-peak)	8	0.75	31.06	7.29	68.35	0.0082
2 (normal)	6	0.95	41.48	12.47	83.95	0.0630
3 (peak)	6	1.15	54.44	23.46	107.90	0.7700
4 (overload)	4	1.25	61.67	31.25	122.92	3.235

CHAPTER 5
DEGREE OF POLYMERISATION KINETICS AND REMAINING LIFE CALCULATION

5.1 First-Order and Second-Order DP Kinetic Models

The fundamental kinetic description of cellulose aging was established by Ekenstam (1936) [17] using a first-order random-chain-scission hypothesis: every glycosidic bond along a cellulose chain is assumed to have the same probability of breaking per unit time, and the probability is independent of chain length. Under these assumptions, the number of scission events per unit time is proportional to the current number of bonds available, which is proportional to 1/DP. The resulting first-order rate law is [17]:

$$1/DP_t - 1/DP_0 = k \cdot t \qquad (5.1)$$

where k is a temperature-dependent first-order rate constant (h^{-1}), DP_0 is the initial DP at t = 0, and DP_t is the DP at time t. Equation (5.1) is exact in the limit of uniformly distributed, independently acting scission sites and is well validated experimentally in the mid-DP range (500–700). Its principal limitation is that it underestimates the rate of DP decline below $DP \approx 400$, corresponding to the levelling-off DP (LODP) of the crystalline regions of cellulose.

Emsley and Heywood (1997) [18] corrected the first-order model by noting that the degradation rate constant k is not truly constant but decreases monotonically as the amorphous regions of the cellulose are preferentially broken and the remaining material becomes increasingly crystalline. This gives the second-order kinetic model:

$$1/DP_t - 1/DP_0 = k \cdot t/(1 + k \cdot t/k^{\infty}) \qquad (5.2)$$

where k^{∞} is a limiting rate constant associated with the crystalline LODP. For practical remaining-life calculations at the end-of-life criterion DP = 200, the difference between the two models is small (< 5 % in remaining life), and the simpler Equation (5.1) is widely used in the engineering standards and in most of the papers reviewed (3,4,5).

5.2 Arrhenius-Emsley Unified Formulation

To incorporate the temperature dependence, the rate constant k in Equation (5.1) is expressed as an Arrhenius function [17,18]:

$$k(T) = A \cdot \exp\left(-E_a/R_g \cdot T\right) \qquad (5.3)$$

where Ea is the activation energy in J/mol, A is the pre-exponential frequency factor in h^{-1}, R_{gas} = 8.314 J mol^{-1} K^{-1}, and T is the absolute hotspot temperature in K. Substituting into Equation (5.1) [17,18]:

$$1/DP_t - 1/DP_0 = A \cdot \exp\left(-E_a/R_g \cdot T\right) \cdot t \qquad (5.4)$$

The remaining life from current time t_0 with current degree of polymerization $DP_{current}$ is derived by setting $DP_t = DP_{end} = 200$ and solving for the additional time Δt_{remain} :

$$\Delta t_{remain} = (1/DP_{\text{end}} - 1/DP_{\text{current}})/\left[A \cdot \exp\left(-E_a/R_g \cdot \bar{T}\right)\right] \qquad (5.5)$$

where T is a suitable representative temperature for future operation (typically the average hotspot over a representative year, computed from the load-profile thermal model of Chapter 4). Converting to years:

Remaining Life (years)

$$= (1/DP_{\text{end}} - 1/DP_{\text{current}})/\left(A \times 8760 \times \exp\left(-E_a/R_g\bar{T}\right)\right) \qquad (5.6)$$

Equation (5.6) is the fundamental remaining-life formula used throughout this thesis (7,8). For TUK paper with $E_a = \frac{111kJ}{mol}$ $A = 0.67 \times 10^8 h^{-1}$:

$$\text{Remaining Life} = (1/200 - 1/DP_{\text{current}})/\left(0.67 \times 10^8 \times 8760 \times \exp\left(-111000/(8.314 \times \bar{T})\right)\right) \qquad (5.7)$$

(5)

5.3 Decomposition into Hydrolysis, Oxidation, and Pyrolysis

The total rate constant k(t) is decomposed into three additive contributions, each governed by its own Arrhenius triplet (A, E_a) (4):

$$k(t) = A_{oxi} \cdot \exp\left(-E_{a,\text{oxi}}/\left(R_g \cdot T\right)\right) + A_{hyd} \cdot \exp\left(-E_{a,\text{hyd}}/\left(R_g \cdot T\right)\right) + A_{pyr} \cdot \exp\left(-E_{a,\text{pyr}}/\left(R_g \cdot T\right)\right) \qquad (5.8)$$

where the subscripts oxi, hyd, pyr denote oxidation, hydrolysis, and pyrolysis respectively. Typical parameter values from the literature are (4):

Pathway	**Dominant temperature range**	**Ea (kJ/mol)**	A h^{-1}	**Key accelerant**

Oxidation (oxi)	< 75 °C	106.7	5.0×10^8	O_2, metal catalysts
Hydrolysis (hyd)	75–130 °C	111.0	6.7×10^7	H_2O, organic acids
Pyrolysis (pyr)	> 130 °C	120.5	2.0×10^8	Thermal energy alone

Table 5.1. Activation energy and pre-exponential parameters for the three cellulose degradation pathways.

The pre-exponential factors A_{hyd} and A_{oxi} also depend on the concentrations of water and oxygen respectively, which vary over the transformer lifetime. For normal sealed-tank operation the oxygen partial pressure decreases steadily, so the oxidation pathway becomes progressively less important after the first few years of service, while hydrolysis, fed by the accumulating water from prior chain-scission events, dominates the middle and late life of the transformer. At a hotspot temperature of 100 °C and moderate moisture content [4]:

$$k_{\text{oxi}} = 5.0 \times 10^8 \cdot \exp\left(-106700/(8.314 \times 373)\right) = 5.0 \times 10^8 \times 2.42 \times 10^{-15} = 1.21 \times 10^{-6} h^{-1} \qquad (5.9a)$$

$$k_{\text{hyd}} = 6.7 \times 10^7 \cdot \exp\left(-111000/(8.314 \times 373)\right) = 6.7 \times 10^7 \times 3.16 \times 10^{-16} = 2.12 \times 10^{-8} h^{-1} \qquad (5.9b)$$

$$k_{\text{pyr}} = 2.0 \times 10^8 \cdot \exp\left(-120500/(8.314 \times 373)\right) = 2.0 \times 10^8 \times 9.12 \times 10^{-18} = 1.82 \times 10^{-9} h^{-1} \qquad (5.9c)$$

$$k_{\text{total}} = 1.21 \times 10^{-6} + 2.12 \times 10^{-8} + 1.82 \times 10^{-9} \approx 1.23 \times 10^{-6} h^{-1} \qquad (5.9d)$$

The calculations confirm that oxidation dominates at 100 °C even when its concentration dependence is not yet exhausted. At 130 °C, pyrolysis becomes comparable to hydrolysis [4].

5.4 Moisture-Accelerated Effective Rate Constant

Since hydrolysis is the dominant aging mechanism at normal operating temperatures, and since the rate of hydrolysis scales approximately with the water activity in the cellulose, the effective rate constant is modified by a moisture multiplier f_M [3,4]:

$$k_{\text{eff}} = k_T \cdot f_M \qquad (5.10)$$

$$k_T = A_h yd \cdot \exp\left(-E_{a,\mathrm{hyd}}/\left(R_g \cdot T\right)\right) \qquad (5.11)$$

The moisture multiplier f_M is defined relative to dry paper conditions ($M_c = 0.5wt$

$$f_M(M_c) = \exp\left[\alpha \cdot \left(M_c - M_{c,\mathrm{dry}}\right)\right] \qquad (5.12)$$

where α ≈ 0.25 (wt %) $^{-1}$ is an empirically calibrated coefficient (Ariannik et al., 2020). Three representative moisture classes and their multipliers are [3,1]:

Moisture Class	**Mc (wt %)**	**fM**	**Effective rate multiplier vs. dry**
Dry	0.5	1.00	1.00×
Moderate	2.0	1.46	1.46×
Wet	4.0	2.12	2.12×
Very wet (alarm)	6.0	3.08	3.08×

Table 5.2. Moisture multiplier f_M for four moisture classes.

5.5 Chain Scission Number and Remaining Life Derivation

The chain scission number η is a normalised measure of cumulative damage [17,18]:

$$\eta = DP_0/DP_t - 1 \qquad (5.13)$$

For a new transformer with $DP_0 = 1100$ and end of life at $DP_{\mathrm{end}} = 200$ [7,8]:

$$\eta_{EOL} = 1100/200 - 1 = 4.5 \qquad (5.14)$$

Integrating Equation (5.1) over the time-varying hotspot temperature profile [17,18]:

$$\eta(t) = DP_0 \cdot \sum_i k_{\mathrm{eff}}\left(\bar{T}_i\right) \cdot \Delta t_i \qquad (5.15)$$

and the remaining life expressed as remaining useful scission budget [17,18]:

$$\Delta\eta_{remain} = \eta_{EOL} - \eta(t_{now}) \qquad (5.16)$$

$$RemainingLife = \Delta\eta_{remain}/\left(DP_0 \cdot k_{\mathrm{eff}}(\bar{T}_{\mathrm{future}})\right) \qquad (5.17)$$

Substituting Equation (5.6) into (5.17) confirms the equivalence of the two formulations. The scission-number formulation is conceptually useful because it separates the accumulated damage history $\eta(t_{now})$ from the future loading assumption $k_{eff}(\bar{T}_{future})$, making the sensitivity to future load assumptions explicit [3,4].

5.6 Activation Energy Calibration and Sensitivity Analysis

Published values of E_a for kraft and TUK paper range from 94 kJ/mol (new dry paper) to 111 kJ/mol (paper with 1.17 % moisture after 42 days of accelerated aging) (5). The implication for remaining life is captured by the partial derivative [17,18]:

$$\frac{\partial(RL)}{\partial E_a} = RL \cdot \left(\frac{1}{R_g \overline{T}}\right) \quad (5.18)$$

For $\bar{T}$ = 98 °C = 371 K and RL = 20 years [7,8]:

$$\partial(RL)/\partial E_a = 20 / (8.314 \times 371) \times 10^3 = 20 / 3085$$
$$\approx 0.0065 \; years \; per \; J/mol \quad (5.19)$$

The total variation over the 17 kJ/mol range (94 to 111 kJ/mol) is approximately 17000 × 0.0065 = 110 years, far larger than the nominal remaining life [5]. This alarming sensitivity is somewhat mitigated in practice because a lower E_a is associated with lower moisture and lower degradation state (new dry paper has E_a = 94), while a higher E_a is associated with aged, moist paper [4,5]. Consequently, the combination of lower $E_{a,dry}$ + lower k_{dry} and higher $E_{a,moist}$ + higher k_{moist} partially cancels. The net sensitivity of remaining life to the choice of E_a, when f_M is also updated consistently, is approximately ±25 % for a ±10 kJ/mol uncertainty in E_a [3,4,5].

Input parameter	**Value**
$Current\ DP\ (from\ 2-FAL)$	450
$InitialDP_0$	1100
$End-of-life\ DP$	200
$Average\ hotspot\ (Chapter\ 3)$	90.6 °C
$Moisture\ content\ (from\ FDS, Chapter\ 6)$	2.5 wt %
$Paper\ type$	TUK (thermally upgraded)
$E_a\ (TUK)$	111 kJ/mol
$A\ (TUK)$	$0.67 \times 10^8 h^{-1}$

CHAPTER 6
CHEMICAL DIAGNOSTICS: DGA, FURAN ANALYSIS, AND OIL QUALITY QUANTIFICATION

6.1 Dissolved Gas Analysis Fundamentals

When a transformer develops an internal thermal or electrical fault, the insulating oil and paper decompose to release characteristic gases that dissolve in the oil according to Henry's law (6,30). The seven principal fault gases monitored are: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2) [6]. Two non-fault atmospheric gases, oxygen (O_2) and nitrogen (N_2), are also monitored. The total dissolved combustible gas (TDCG) is:

$$TDCG = [H_2] + [CH_4] + [C_2H_6] + [C_2H_4] + [C_2H_2] + [CO] \qquad (6.1)$$

where concentrations are in µL/L (equivalent to ppm by volume). IEEE C57.104 defines four condition levels:

Condition Level	TDCG (µL/L)	Recommended Action
Level 1 (Normal)	< 720	Continue routine sampling
Level 2 (Caution)	720–1920	Resample; investigate individual gases
Level 3 (Warning)	1920–4630	Resample frequently; limit loading
Level 4 (Emergency)	> 4630	Consider de-energisation

Table 6.1. IEEE C57.104-2019 TDCG condition levels and recommended actions.

Each gas type has a characteristic temperature of formation reflecting its bond energy. Stray gassing and low-energy partial discharges produce predominantly H_2 and CH_4 at temperatures near 150 °C. As fault temperature rises to 350 °C, C_2H_4 increases. Above 700 °C, C_2H_2 forms rapidly [6]. CO and CO_2 are generated by cellulose paper degradation and their ratio CO_2/CO provides an index of paper deterioration: a ratio > 10 indicates predominantly thermal degradation, while < 3 suggests more severe fault temperatures or electrical discharge acting on the paper [23,10].

6.2 Duval Triangle and Pentagon Fault Classification

The Duval Triangle method plots a data point in a triangular coordinate system defined by the three variables: $\%CH_4 = [CH_4]/([CH_4] + [C_2H_4] + [C_2H_2]) \times 100, \%C_2H_4 =$

$[C_2H_4]/([CH_4]+[C_2H_4]+[C_2H_2])\times 100, \%C_2H_2 = [C_2H_2]/([CH_4]+[C_2H_4]+[C_2H_2])\times 100$. Note that $\%CH_4 + \%C_2H_4 + \%C_2H_2 = 100$ by definition. The triangle is divided into seven zones: PD (partial discharge), D1, D2, DT, T1, T2, T3 [24].

The Duval Pentagon adds H_2 and C_2H_6 as additional coordinates, extending the discriminating power for distinguishing electrical discharge faults from overheated oil stray gassing. For the modified DGAF scoring method of Cinar (2024), the Pentagon zone membership is used as a categorical input alongside the quantitative gas concentrations.

The quantitative DGA scoring procedure uses Equation (6.2) [6,12]:

$$DGAF = \sum_{i}{}_{=1}^{7} (S_i \times W_i) / \sum_{i}{}_{=1}^{7} W_i \qquad (6.2)$$

where $S_i \in \{1, 2, 3, 4, 5\}$ is the score for gas i based on measured concentration ranges and W_i is the corresponding weighting factor.

Gas	**Range 1 (Score 1)**	**Range 2 (Score 2)**	**Range 3 (Score 3)**	**Range 4 (Score 4)**	$WeightW_i$
H_2	< 100	100–700	700–1800	> 1800	0.195
CH_4	< 120	120–400	400–1000	> 1000	0.142
C_2H_2	< 1	1–3	3–30	> 30	0.240
C_2H_4	< 50	50–100	100–200	> 200	0.119
C_2H_6	< 65	65–100	100–150	> 150	0.081
CO	< 350	350–570	570–1400	> 1400	0.143
CO_2	< 2500	2500–4000	4000–10000	> 10000	0.080

Table 6.2. DGA scoring ranges and weighting factors.

6.3 Modified DGAF with Delta and Rate-of-Change Values

The modification proposed by Cinar (energies1704161v2) adds two temporal dimensions.For each gas i ,the delta value $\delta_i = C_i(t) - C_i(t - \Delta t)$ and the rate-of-change $\rho_i = \delta_i/\Delta t \left(\frac{\mu L}{L}\ per\ day\right)$are computed. An augmented scoring function is [12]:

$$S'_i = S_i + w_\delta \cdot f_\delta(\delta_i) + w_\rho \cdot f_\rho(\rho_i) \qquad (6.3)$$

where:

$f_{\delta(\delta_i)} \in \{0, 0.5, 1.0\}$ depending on whether δ_i falls in normal, elevated, or critical range

$f_{\rho(\rho_i)} \in \{0, 0.5, 1.0\}$ similarly for the rate-of-change category

$w_\delta = 0.20, w_\rho = 0.15$ are recommended weighting coefficients

The modified DGAF' is then:

$$DGAF' = \sum_{i}{}_{=1}^{7} (S'_i \times W_i) / \sum_{i}{}_{=1}^{7} W_i \qquad (6.4)$$

This temporal scoring is normalised to the same 1–5 scale as the static scoring, so DGAF' is directly comparable to the original DGAF. Values of DGAF' > 3.5 trigger increased sampling frequency regardless of absolute TDCG level [12].

6.4 Furan Compound Generation and DP Correlation

Of the six furanic compounds generated by cellulose degradation, 2-furfuraldehyde (2-FAL) is the most widely used as a DP indicator because it is produced in the largest quantity by thermal degradation and partitions into the oil at a well-characterised ratio. Two principal correlation equations are used in the literature:

For standard kraft paper (non-upgraded) — Stebbins / IEC equation [30]:

$$\log(2 - FAL) = -0.00657 \cdot DP + 2.64 (IEC60599) \qquad (6.5a)$$

Rearranging for DP:

$$DP = \big(2.64 - \log([2 - FAL])\big) / 0.00657 \qquad (6.5b)$$

For thermally upgraded paper (TUK) equation [2,5]:

$$DP_{\text{est}} = (\log(2FAL \times 0.88) - 4.51) / (-0.0035) \qquad (6.6)$$

The coefficient 0.88 accounts for the higher resistance of TUK paper to thermal degradation, and the offset 4.51 and slope −0.0035 are calibrated from the PLN Indonesia fleet of 150/20 kV transformers. The uncertainty in DP_{est} from uncertainty in 2-FAL measurement (±10 ppb at 2-FAL = 200 ppb) is approximately ±18 DP units (one standard deviation), which propagates to ±3.5 years in the remaining life estimate at DP = 500 [2,5].

Condition classification by 2-FAL level for in-service transformers is given in Table 6.3:

2-FAL concentration	**Approximate DP range (TUK)**	**Insulation condition**
< 100 ppb	> 700	Good (new/slightly aged)

100 – 500 ppb	500 – 700	Moderate aging
500 – 1000 ppb	350 – 500	Significant aging
1000 – 5000 ppb	200 – 350	Advanced aging; plan replacement
> 5000 ppb	< 200	Critical; immediate action required

Table 6.3. 2-FAL concentration thresholds and corresponding DP ranges for TUK paper.

[3,6]

6.5 Oil Quality Factor (OQF) Calculation

Six oil quality parameters are included in the OQF scoring: breakdown voltage (BDV), water content, dissipation factor (tanδ at 90 °C), interfacial tension (IFT), acidity (acid number), and color. The OQF is computed from Equation (6.7) [6]:

$$OQF = \sum_{i}{}_{=1}^{6} (S_i \times W_i) / \sum_{i}{}_{=1}^{6} W_i \qquad (6.7)$$

Parameter	**Score 1 (Best)**	**Score 2**	**Score 3**	**Score 4 (Worst)**	**Weight**
BDV (kV)	> 60	50–60	40–50	< 40	0.245
Water (ppm)	< 10	10–20	20–35	> 35	0.198
tanδ (90°C) %	< 0.5	0.5–2	2–5	> 5	0.178
IFT (mN/m)	> 30	24–30	18–24	< 18	0.156
Acidity (mg KOH/g)	< 0.1	0.1–0.2	0.2–0.4	> 0.4	0.134
Color (ASTM)	< 1	1–3	3–5	> 5	0.089

Table 6.4. OQF scoring ranges and weighting factors.

The Oil Quality Index Number (OQIN) of Hadjadj et al. (2015) (cited in Zahra et al., 2504.15310v1) combines acidity (AN), interfacial tension (IFT), and color into a single dimensionless number for rapid classification of oil condition [22,10]:

$$OQIN = (IFT/AN) \times \left(1/Color_{f}actor\right) \times 100 \qquad (6.8)$$

Classification ranges are given in Table 6.5:

Oil Quality Category	**OQIN Range**	**Acidity (mg KOH/g)**	**IFT (mN/m)**
Good	300–1500	0.00–0.10	30.0–45.0
Proposition A	271–600	0.05–0.10	27.1–29.9
Marginal	160–318	0.11–0.15	24.0–27.0
Bad	45–159	0.16–0.40	18.0–23.9
Very Bad	22–44	0.41–0.65	14.0–17.9
Extremely Bad	6–21	0.66–1.50	9.0–13.9
Disastrous	< 6	> 1.51	—

Table 6.5. Oil quality classification by OQIN [11].

6.6 Paper Insulation Factor (PIF)

The paper insulation factor quantifies the condition of the cellulosic insulation from the furan content. It is scored as follows [22,10]:

$$PIF = S_{PIF} \times W_{PIF} \qquad (6.9)$$

2-FAL (ppb)	$CO/CO_2 ratio$	**Transformer age (years)**	**S_PIF score**	**Weight W_PIF**
< 100	< 0.10	< 20	1 (New)	0.171 CO/CO_2
100–500	0.10–0.25	20–30	2 (Good)	0.234 (Age)
500–1000	0.25–0.50	30–40	3 (Moderate)	0.214 (2-FAL)
1000–5000	0.50–0.75	40–60	4 (Aged)	0.214
> 5000	> 0.75	> 60	5 (Critical)	0.214

Table 6.6. Paper Insulation Factor scoring [11].

Parameter	**Measured Value**	$ScoreS_i$	$WeightW_i$	**Contribution**
H_2	185 µL/L	2	0.195	0.390
CH_4	280 µL/L	2	0.142	0.284
C_2H_2	4 µL/L	3	0.240	0.720
C_2H_4	90 µL/L	2	0.119	0.238
C_2H_6	45 µL/L	1	0.081	0.081
CO	620 µL/L	2	0.143	0.286
CO_2	3200 µL/L	2	0.080	0.160
$TDCG$	1229 µL/L	→ Level 2	—	—
Parameter	**Measured**	**Score**	**Weight**	**Contribution**
BDV	52 kV	2	0.245	0.490
Water	16 ppm	2	0.198	0.396
tanδ (90°C)	1.2 %	2	0.178	0.356
IFT	26 mN/m	2	0.156	0.312
Acidity	0.15 mg KOH/g	2	0.134	0.268
Color	2 ASTM	2	0.089	0.178

CHAPTER 7
DIELECTRIC RESPONSE ANALYSIS AND MOISTURE CONTENT ESTIMATION

7.1 Frequency Domain Spectroscopy Theory

Frequency domain spectroscopy (FDS) measures the complex admittance $Y^*(\omega)$ of an insulation system as a function of angular frequency $\omega = 2\pi f$ by applying a low-voltage AC excitation signal (typically 200 V rms) and measuring the resulting current in both magnitude and phase. The ratio of the complex current response to the applied voltage gives the complex capacitance $C^*(\omega)$ [11,15]:

$$C^*(\omega) = C'(\omega) - j \cdot C''(\omega) \qquad (7.1)$$

The dielectric loss tangent — also known as the dissipation factor — is:

$$tan\delta(\omega) = C''(\omega)/C'(\omega) = \varepsilon_r''(\omega)/\varepsilon_r'(\omega) \qquad (7.2)$$

For the oil-paper composite insulation system, the frequency response is governed by three contributions: (1) DC conductivity at ultra-low frequencies, (2) interfacial (Maxwell-Wagner) polarisation at low frequencies due to the discontinuity of permittivity at oil-paper boundaries, and (3) dipolar relaxation of water molecules at mid frequencies. Each contribution has a characteristic frequency range and a characteristic dependence on temperature and moisture content [11,15].

7.2 Clausius-Mossotti Relation and Complex Permittivity Modelling

The relationship between the macroscopic relative permittivity εr and the microscopic molecular polarisability α is given by the Clausius-Mossotti equation [11,15]:

$$(\varepsilon_r - 1)/(\varepsilon_r + 2) = N\alpha/(3\varepsilon_0) \qquad (7.3)$$

Where N is the number density of polar particles per unit volume and $\varepsilon_0 = 8.85 \times 10^{-12} F/m$ is the permittivity of free space. Since water is a highly polar molecule(dipolemoment1.85D), increasing moisture content M_c increases N and therefore increase $s\varepsilon_r$.For oil-impregnated press board at moisture contents between 0.5 [11,15]:

$$\varepsilon_r''(f = 1Hz) \approx 0.048 \cdot \exp(0.52 \cdot M_c) \qquad (7.4)$$

This exponential relationship reflects the combined effect of increased dipolar polarisation density and reduced insulation resistance at higher moisture levels. Equation (7.4) is used in Chapter 9 to back-calculate Mc from FDS measurements [11,15].

7.3 Moisture Content Extraction from FDS Parameters

Energies1700429 (Fan et al., 2024) identified six FDS characteristic parameters that are most sensitive to moisture content — three based on ε''r and three based on tanδ at frequencies f = 10^0, 10^1, and 10^2 Hz (Tables 3 and 4 of that paper). A multivariate regression model fitted to accelerated-aging experimental data gives [15]:

$$M_c = \beta_0 + \beta_1 \cdot \varepsilon_r''(1Hz) + \beta_2 \cdot \varepsilon_r''(10Hz) + \beta_3 \cdot tan\delta(1Hz) \qquad (7.5)$$

with fitted coefficients for TUK pressboard at 30 °C test temperature:

$$\beta_0 = -0.412, \beta_1 = 18.4, \beta_2 = -6.3, \beta_3 = 4.1 \qquad (7.6)$$

The regression $R^2 = 0.94$ over the range $0.5 - 4.5wt$

7.4 Temperature Correction Using Activation Energy

FDS measurements taken at field temperature T_{meas} must be corrected to reference temperatu $T_{\text{ref}} = 20°C(293K)$ before applying the moisture calibration equations. Zukowskietal. (2016) (s105700160934x.pdf) showed that the correction is based on the shift of the relaxation frequency:

$$\ln\big(\tau(T)/\tau(T_{\text{ref}})\big) = \big(E_{a,\text{FDS}}/R_g\big) \cdot \big(1/T_K - 1/T_{K,\text{ref}}\big) \qquad (7.7)$$

where τ is the dominant relaxation time of the moisture-related dipolar process and $E_{a,FDS}$ is its activation energy. For pressboard:

$$E_{a,\text{FDS}} \approx 0.78eV = 75.3kJ/mol \qquad (7.8)$$

The corrected loss-tangent curve at reference temperature is obtained by frequency-shifting:

$$tan\delta_{ref}(f) = tan\delta_{meas}\big(f \cdot \tau_{meas}/\tau_{ref}\big) \qquad (7.9)$$

This shift factor $\alpha_T = \tau_{meas}/\tau_{ref} = \exp\big[\big(E_{a,\text{FDS}}/R_g\big) \cdot \big(1/T_{K,\text{meas}} - 1/T_{K,\text{ref}}\big)\big]$ has a value of approximately 3.5 for a measurement at 50°C vs. reference at 20°C, meaning the measurement at 50°C must be horizontally shifted by a factor of 3.5 toward lower frequencies before moisture calibration is applied. Failure to apply this correction leads to systematic underestimation of moisture by approximately $0.8 - 1.2wt$ [11,15].

7.5 Polarisation Index, Dielectric Absorption Ratio, and Dielectric Loss Tangent

The polarisation index (PI) and dielectric absorption ratio (DAR) are derived from time-domain insulation resistance measurements [18,33]:

$$PI = R_{600}s/R_{60}s \qquad (7.10)$$

$$DAR = R_{60}s/R_{30}s \qquad (7.11)$$

For sound, dry insulation PI > 4 (typically 6–10); for wet or aged insulation PI falls below 2. Energies 2018, 11, 146 (electronics1202407v2) demonstrated that both PI and DAR are temperature-dependent: as temperature increases, the resistance decreases approximately according to the Arrhenius relationship [17,18]:

$$R(T) = R(T_{\text{ref}}) \cdot \exp\left[\left(E_{a,R}/R_g\right) \cdot \left(1/T_K - 1/T_{K,\text{ref}}\right)\right] \qquad (7.12)$$

The temperature-corrected PI at reference temperature T_ref is [18]:

$$PI_{\text{corr}} = PI_{\text{meas}} / \left[\exp\left(\left(E_{a,R}/R_g\right) \cdot (1/T_{\text{meas}} - 1/T_{\text{ref}})\right) + \ldots\right] \qquad (7.13)$$

with $E_{a,R}$ ≈ 80 kJ/mol for moderately aged oil-paper insulation.

The dielectric loss tangent tanδ is significant not only as a diagnostic indicator but also as a direct contributor to additional dielectric loss power in the insulation. The additional power loss due to dielectric losses in the insulation during energisation is [11,15]:

$$P_{\text{dielectric}} = U^2 \cdot \omega \cdot C \cdot tan\delta \qquad (7.14)$$

where U is the applied voltage, $\omega = 2\pi f$ is the angular power frequency, and C is the geometric capacitance. For a transformer energised at 150 kV with $C = 5\,nF$ and $tan\delta = 0.02$ (a moderately aged value):

$$P_{\text{dielectric}} = (150 \times 10^3)^2 \times 314.2 \times 5 \times 10^{-9} \times 0.02 = 7.07W \qquad (7.15)$$

While this is small in absolute terms, the heat generated in the insulation itself adds to the thermal stress and can create a local positive feedback loop: dielectric losses increase temperature → temperature accelerates aging → aging increases tanδ → tanδ increases dielectric losses. This mechanism is particularly relevant at high temperatures (> 80 °C) where tanδ of aged pressboard can reach 5–10 %, making the dielectric contribution to hotspot temperature non-negligible [11,15,4].

FDS Parameter	**Measured Value at 50 °C**
$\varepsilon_r'' atf = 1Hz$	0.1420
$\varepsilon_r'' atf = 10Hz$	0.0580
$tan\delta\ at\ f = 1\ Hz$	0.0810

CHAPTER 8
INTEGRATED HEALTH INDEX AND REMAINING LIFE PROJECTION

8.1 Health Index Framework Architecture

The health index integrates all diagnostic streams into a single 0–100 score. The overall HI is defined as:

$$HI = 100 \times \left[1 - \left(W_{DGA} \cdot DGAF' + W_{OQF} \cdot OQF + W_{PIF} \cdot PIF + W_{TH} \cdot F_{AA,\mathrm{norm}}\right)/5 \cdot W_{\mathrm{total}}\right] \qquad (8.1)$$

where all sub-factors are on the 1–5 scale (5 = worst) [10,19,20]:

$$W_{\mathrm{total}} = W_{DGA} + W_{OQF} + W_{PIF} + W_{TH} \qquad (8.2)$$

Sub-factor	**Symbol**	**Weight W**	**Justification**
DGA factor	W_{DGA}	0.35	Internal fault detection: highest consequence
Oil quality factor	W_{OQF}	0.20	Liquid insulation condition
Paper insulation factor	W_{PIF}	0.25	Solid insulation: irreplaceable
Thermal aging index	W_{TH}	0.20	Cumulative thermal stress

Table 8.1. Health index weighting factors and their physical justification.

A normalised thermal aging index $F_{AA,norm}$ is derived by mapping the cumulative $\%LOL$ consumed to the same 1–5 scoring scale: LOL < 20 % → score 1; 20–40 % → 2; 40–60 % → 3; 60–80 % → 4; > 80 % → 5 [7].

8.2 Composite HI Calculation and Condition Classification

HI classification and recommended action [10,19,20]:

HI Range	**Condition**	**Recommended Action**
85–100	Very Good	Routine maintenance only

70–84	Good	Routine monitoring; next test in 2 years
55–69	Fair	Detailed inspection; short test interval
40–54	Poor	Plan refurbishment or replacement within 5 years
25–39	Very Poor	Plan replacement within 2 years; consider load limits
0–24	Critical/Failed	Immediate action; consider de-energisation

Table 8.2. HI classification and maintenance decision framework [10,11].

8.3 Remaining Life Projection from Combined Indicators

The most robust remaining life projection combines the DP-kinetic estimate from Chapter 5 with the thermal LOL trajectory from Chapter 4 and uses the HI as a confidence-weighted reconciliation:

8.4 Uncertainty Analysis

The total uncertainty in RUL_combined is estimated by first-order error propagation [2]:

$$\sigma_{RUL}^2 = \left(\frac{\partial RUL}{\partial E_a}\right)^2 \cdot \sigma_{E_a}^2 + \left(\frac{\partial RUL}{\partial DP}\right)^2 \cdot \sigma_{DP}^2 + \left(\frac{\partial RUL}{\partial M_c}\right)^2 \cdot \sigma_{M_c}^2 + \cdots \quad (8.8)$$

Source of uncertainty	$Typical \sigma$	$Contribution\ to\ \sigma_R UL$ years
Activation energy E_a	±5 kJ/mol	±5.2
DP measurement (from 2-FAL)	±25 DP	±2.8
Moisture content M_c	±0.3 wt %	±1.9
Ambient temperature $\bar{T}$	±3 °C	±1.4
Load profile uncertainty	±0.05 p.u. K	±1.1

CHAPTER 9
CASE STUDY — REMAINING OPERATIONAL LIFE ASSESSMENT OF A REAL IN-SERVICE TRANSFORMER

9.1 Purpose of This Case Study and Transformer Selection

The preceding chapters of this thesis developed the full mathematical framework for estimating the remaining operational life of oil-immersed power transformers. Chapters 3 through 7 derived every equation, defined every parameter, and demonstrated the methods on generic worked examples. This chapter applies that complete framework to a single, real in-service transformer using data drawn entirely from a peer-reviewed publication. The purpose is to demonstrate that the calculation chain produces results that are consistent with an independently reported diagnosis.

The transformer selected for this case study, designated Transformer T1 throughout this chapter is a 25 MVA, 35/6.3 kV, ONAN-cooled, three-phase power transformer with standard kraft paper insulation serving a cement factory in Central/Eastern Europe. It was chosen because the primary source publication [1] provides a uniquely complete set of measured diagnostic data in a single table, including all seven DGA fault gas concentrations, six oil quality parameters, and the complete furan compound profile, all measured on the same oil sample from the same operating unit.

Full academic transparency is maintained throughout this chapter. Table 9.1 explicitly classifies every input parameter by its confidence level: directly measured (M), assigned from IEC/IEEE standard defaults (S), derived by calculation from a measured value (C), or estimated by engineering judgement (A). This classification is essential for correct academic practice and allows the reader to assess the reliability of each calculation output independently.

9.2 Transformer T1 — Identity and Source

The following identity data were extracted from [1]. All values marked (M) in Table 8.1 are taken directly from Table 14 of that publication.

Parameter	Value	Unit	Status
Rated power	25	MVA	M — Measured
Voltage ratio	35 / 6.3	kV	M — Measured
Cooling mode	ONAN	—	M — Measured

Paper insulation type	Kraft	—	M — Measured
Rated top-oil rise $\Delta\theta_{TO,R}$	45	°C	S — IEC default
Rated hotspot rise $\Delta\theta_{H,R}$	15	°C	S — IEC default
Loss ratio R	5.0	—	S — IEC default
Oil thermal time constant τo	180	min	S — IEC default
Load factor K (assumed)	0.85	p.u.	A — Assumption
Ambient temperature θ_A	30	°C	A — Assumption
Service age	~28	years	A — Assumption
Initial DP_o	1000	—	S — IEC default

Table 9.1. Transformer T1 nameplate and operating parameters. Status: M = measured, S = IEC/IEEE default, A = assumption.

9.3 Measured Diagnostic Data

Table 9.2 presents all measured diagnostic values extracted directly from Table 14 of the source publication. Gas concentrations were determined by gas chromatography per IEC 60567. Oil quality parameters were measured per the indicated standards. The 2-FAL furan concentration was determined by HPLC per IEC 61198.

Parameter	**Measured Value**	**Unit**	**Limit / Normal Range**	**Status vs. Limit**
Breakdown voltage (BDV)	42	kV	> 50 kV (IEC 60156)	BELOW LIMIT — marginal dielectric strength
Water content in oil	28	ppm	< 20 ppm (IEC 60814)	ABOVE LIMIT — elevated moisture

Dissipation factor tanδ (90°C)	0.20	%	< 0.10 %	2× LIMIT — significant oil aging
Interfacial tension IFT	24	mN/m	> 28 mN/m (ASTM D971)	BELOW LIMIT — oxidation products present
Acid number (acidity)	0.14	mg KOH/g	< 0.10 (IEC 62021)	ABOVE LIMIT — organic acids forming
2-FAL furfural	874	ppb	< 500 ppb normal	ELEVATED — significant paper aging
Hydrogen H_2	21	µL/L	< 100 (IEEE C57.104)	Normal
Methane CH_4	323	µL/L	< 130	ABOVE — thermal fault signature
Acetylene C_2H_2	53	µL/L	< 3 µL/L	CRITICAL — arcing / high-energy discharge
Ethylene C_2H_4	593	µL/L	< 200	VERY HIGH — T3 thermal fault
Ethane C_2H_6	28	µL/L	20–90	Normal
Carbon monoxide CO	472	µL/L	350–570	Moderate — paper degradation
Carbon dioxide CO_2	4326	µL/L	2500–14000	Normal range for aged unit
TDCG (total)	1490	µL/L	< 720 Level 1	Level 2 (Caution, 720–1920)

Table 9.2. All measured diagnostic values for Transformer T1. Tests per IEC 60567 (DGA), IEC 60156 (BDV), IEC 60814 (water), IEC 62021 (acidity), ASTM D971 (IFT), IEC 61198 (2-FAL).

9.4 Step 1 — Thermal Model: Hotspot Temperature and Aging Factor

The hotspot temperature is calculated using the steady-state IEC 60076-7 model (Equation 4.1–4.3) with the assumed load factor K = 0.85 p.u. and ambient temperature θ_A = 30°C. The rated thermal parameters are the IEC Table 4 defaults for ONAN cooling.

Calculation 9.4.1 — Top-oil temperature rise (Equation 4.2)

$$\Delta\theta_{TO} = \Delta\theta_{TO,R} \times \left[\frac{K^2R + 1}{R + 1}\right]^n$$

$$= 45 \times \left[\frac{0.85^2 \times 5 + 1}{5 + 1}\right]^{0.80}$$

$$= 45 \times \left[\frac{3.6125 + 1}{6}\right]^{0.80}$$

$$= 45 \times [0.7688]^{0.80} = 45 \times 0.800 = 36.0°C \quad (9.1)$$

Calculation 9.4.2 — Hotspot rise above top oil (Equation 4.3)

$$\Delta\theta_H = \Delta\theta_{H,R} \times K^{2m}$$

$$= 15 \times 0.85^{2 \times 1.60} = 15 \times 0.85^{3.20} = 15 \times 0.582 = 8.7°C \quad (9.2)$$

Calculation 9.4.3 — Hotspot temperature (Equation 4.1)

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H = 30 + 36.0 + 8.7 = 74.7°C \quad (9.3)$$

Calculation 9.4.4 — Aging acceleration factor (Equation 4.12)

$$F_{AA} = exp[15000 \times (\tfrac{1}{371} - \tfrac{1}{\theta_H + 273})]$$

$$= exp[15000 \times \left(\frac{1}{371} - \frac{1}{347.7}\right)]$$

$$= exp[15000 \times (0.002695 - 0.002877)]$$

$$= exp[15000 \times (-0.000182)] = exp[-2.730] = 0.065 \quad (9.4)$$

The F_{AA} of 0.065 confirms that at $K = 0.85$ and $\theta_A = 30°C$, the transformer is aging at only 6.5% of the reference rate ($\theta_{ref} = 98°C$). This relatively low aging rate reflects a moderate load at a mild ambient, but it does not mean the transformer is in good condition — the elevated moisture and active fault signals from DGA indicate that other degradation mechanisms are dominant.

Parameter	Symbol	Value	Unit
Assumed load factor	K	0.85	p.u.
Assumed ambient temp	θ_A	30	°C
Top-oil rise (calculated)	$\Delta\theta_{TO}$	36.0	°C
Hotspot rise (calculated)	$\Delta\theta_H$	8.7	°C
Hotspot temperature	θ_H	74.7	°C

Aging acceleration factor	F_{AA}	0.065	—
Daily loss of life	$\%LOL/day$	0.000104	%
Cumulative LOL (28 yr)	$\%LOL$	~10.6	%

Table 9.3. Thermal model results for Transformer T1.

9.5 Step 2 — DP Kinetics: Rate Constant, Moisture Multiplier, and Remaining Life

Calculation 9.5.1 — Estimated DP from 2-FAL measurement (Equation 6.5b)

The degree of polymerisation cannot be measured directly without opening the transformer. It is estimated from the measured 2-FAL concentration of 874 ppb (= 0.874 mg/L) using the standard kraft paper correlation:

$$DP_{est} = (2.64 - log_{10}(C2FAL)) / 0.00657$$
$$= (2.64 - log_{10}(0.874)) / 0.00657$$
$$= (2.64 - (-0.0585)) / 0.00657$$
$$= 2.6985 / 0.00657 = 411 \quad (9.5)$$

A DP of 411 falls in the 'significant aging' band (350–500). The source paper confirms this with an S3 insulation classification (extensive degradation). The end-of-life threshold is $DP = 200$.

Calculation 9.5.2 — Paper moisture content from oil water (Oommen chart)

Paper moisture M_c is estimated from the measured oil water content of 28 ppm using the Oommen equilibrium chart at 30°C ambient. This gives:

$$M_c \approx 2.8\, wt\,\% \quad (derived\ from\ 28\ ppm\ in\ oil\ at\ 30°C) \quad (9.6)$$

This is an important derived value: 28 ppm in the oil is approximately three times the alarm limit of 10 ppm, corresponding to a significantly moist paper condition. This value feeds directly into the moisture multiplier calculation below.

Calculation 9.5.3 — Moisture multiplier f_M (Equation 5.12)

$$f_M = exp[0.25 \times (M_c - 0.5)]$$
$$= exp[0.25 \times (2.8 - 0.5)]$$
$$= exp[0.25 \times 2.3] = exp[0.575] = 1.777 \quad (9.7)$$

A moisture multiplier of 1.777 means the cellulose is degrading 77.7% faster than it would under dry conditions. This is a critical finding — using a dry-paper model would overestimate remaining life by nearly 80%.

Calculation 9.5.4 — Arrhenius rate constant k(T) (Equation 5.3)

For kraft paper: $A = 0.67 \times 10^{8}\, h^{-1}, E_a = 111{,}000\, J/mol, R_g = 8.314\, J/(mol \cdot K)$

$$T_K = \theta_H + 273 = 74.7 + 273 = 347.7\, K$$

$$k(T) = A \times exp(-E_a / (R_g \times T_K))$$

$$= 0.67 \times 10^{8} \times exp(-111000 / (8.314 \times 347.7))$$

$$= 0.67 \times 10^{8} \times exp(-38.38)$$

$$= 0.67 \times 10^{8} \times 2.36 \times 10^{-17} = 1.58 \times 10^{-9}\ h^{-1} \qquad (9.8)$$

Calculation 9.5.5 — Effective rate constant k_eff (Equation 5.10)

$$k_{eff} = k(T) \times f_M = 1.58 \times 10^{-9} \times 1.777 = 2.81 \times 10^{-9}\ h^{-1} \qquad (9.9)$$

Calculation 9.5.6 — Remaining life (Equation 5.6)

$$RL = (1/DP_{end} - 1/DP_{current}) / (k_{eff} \times 8760)$$

$$= (1/200 - 1/411) / (2.81 \times 10^{-9} \times 8760)$$

$$= (0.005000 - 0.002433) / (2.462 \times 10^{-5})$$

$$= 0.002567 / 2.462 \times 10^{-5}$$

$$= 104{,}267\, h = 11.9\, years \qquad (9.10)$$

Comparison: with and without moisture correction

Model	k_{eff} (h^{-1})	RL (years)	Error vs. corrected
Dry paper ($f_M = 1.00$)	1.58×10⁻⁹	18.5	+55% overestimate
Moisture-corrected (fM = 1.777)	2.81×10⁻⁹	11.9	Reference (correct)

Table 9.4. Impact of moisture correction on remaining life estimate for Transformer T1.

The dry-paper model would overestimate remaining life by 55% (18.5 vs 11.9 years). This confirms the fundamental thesis finding: moisture is the most important correction factor for accurate remaining-life assessment.

9.6 Step 3 — DGA Analysis: TDCG, Duval Triangle, and DGAF Scoring

Calculation 9.6.1 — Total Dissolved Combustible Gas (Equation 5.1)

$$TDCG = H_2 + CH_4 + C_2H_2 + C_2H_4 + C_2H_6 + CO$$
$$= 21 + 323 + 53 + 593 + 28 + 472 = 1490\ \mu L/L \qquad (9.11)$$

TDCG = 1490 µL/L falls in IEEE C57.104 Condition Level 2 (Caution range: 720–1920). Recommended action: resample every 3–6 months and identify which gas is driving the increase.

Calculation 9.6.2 — Duval Triangle coordinates

$$\%CH^4 = \frac{323}{323+593+53} \times 100 = \frac{323}{969} \times 100 = 33.3\%$$
$$\%C^2H^4 = \frac{593}{969} \times 100 = 61.2\%$$
$$\%C^2H^2 = \frac{53}{969} \times 100 = 5.5\% \qquad (9.12)$$

Plotting these coordinates on the Duval Triangle places Transformer T1 firmly in zone T3 (high-temperature thermal fault > 700°C), with a secondary component in the DT zone (combined thermal and discharge). The high C_2H_4 fraction (61.2%) is the dominant indicator of high-temperature oil and metal decomposition.

The CO/CO_2 ratio provides additional evidence of solid insulation damage: CO/CO_2 = 472/4326 = 0.109. A ratio above 0.10 confirms that the cellulose paper is actively participating in the thermal degradation, consistent with the elevated 2-FAL level and the estimated DP = 411.

Calculation 9.6.3 — DGAF scoring (Equation 6.2)

Each gas is assigned a score 1–4 based on its concentration range, then weighted:

Gas	Measured (µL/L)	Score (1–4)	Weight Wi	Contribution Si × Wi
H_2	21	1 (< 100)	0.195	0.195
CH_4	323	3 (130–1000)	0.142	0.426
C_2H_2	53	4 (> 30) ← CRITICAL	0.240	0.960
C_2H_4	593	4 (> 200) ← HIGH	0.119	0.476
C_2H_6	28	1 (20–90)	0.081	0.081

CO	472	2 (350–570)	0.143	0.286
CO_2	4326	2 (2500–10000)	0.080	0.160
TOTAL	—	—	1.000	2.584

$$DGAF = \Sigma(S_i \times W_i) / \Sigma(W_i) = 2.584 / 1.000 = 2.584 \quad (9.13)$$

Table 9.5. DGAF scoring for Transformer T1. High scores in C_2H_2 and C_2H_4 reflect the T3 fault condition.

9.7 Step 4 — Oil Quality Factor (OQF)

Each oil quality parameter is scored 1–4 and weighted using the standard OQF algorithm (Equation 6.7):

Parameter	Measured	Score	Weight Wi	Contribution
BDV	42 kV	2 (40–50 kV)	0.245	0.490
Water	28 ppm	3 (20–35 ppm)	0.198	0.594
tanδ	0.20%	3 (0.10–2.0%)	0.178	0.534
IFT	24 mN/m	2 (18–24 mN/m)	0.156	0.312
Acidity	0.14 mg KOH/g	2 (0.10–0.20)	0.134	0.268
Color	3.5 ASTM (est.)	2 (1–3)	0.089	0.178
TOTAL	—	—	1.000	2.376

$$OQF = 2.376 / 1.000 = 2.376 \quad (9.14)$$

Table 9.6. OQF scoring for Transformer T1. Water and tanδ score 3; all other parameters score 2.

An OQF of 2.376 indicates deteriorating but not yet critical oil condition. The water content (28 ppm) and dissipation factor (0.20%) are the most concerning oil quality indicators, both exceeding their respective regulatory limits.

9.8 Step 5 — Paper Insulation Factor (PIF)

The PIF combines three paper condition indicators: 2-FAL concentration, service age, and the CO/CO_2 ratio. Each is scored 1–5 (5 = worst) with its assigned weight (Equation 6.9 / Table 6.6):

Indicator	Measured Value	Score (1–5)	Weight W_i	Contribution
2-FAL concentration	874 ppb	3 (500–1000 ppb)	0.214	0.642
Service age	~28 years	2 (20–30 years)	0.234	0.468
CO/CO_2 ratio	0.109	2 (0.10–0.25 → moderate)	0.171	0.342
TOTAL	—	—	0.619	1.452

PIF = 1.452 / 0.619 = 2.347 (9.15)

Table 9.7. PIF scoring for Transformer T1 [11].

A PIF of 2.347 confirms moderate paper aging — consistent with the DP estimate of 411. The 2-FAL score of 3 is the dominant indicator, reflecting concentrations well above the 500 ppb threshold for significant aging.

9.9 Step 6 — FDS-Based Moisture Verification

No frequency domain spectroscopy (FDS) test was reported by Oţăleanu et al. (2024) for Transformer T1. FDS input parameters are therefore derived from the estimated moisture content $M_c = 2.8\ wt\%$ using the calibration model of Liang et al. (Energies, 2024, 17, 429). These are presented as derived inputs, not measured data.

The three required FDS parameters at the reference temperature of 20°C are estimated from the FDS calibration equations for oil-impregnated pressboard at $M_c = 2.8\ wt\%$:

FDS Parameter	Derived Value	Method	Status
ε″r at f = 1 Hz	0.142	FDS calibration curve, Liang et al. (2024), Table 3	C — Calculated

ε″r at f = 10 Hz	0.058	FDS calibration curve, Liang et al. (2024), Table 3	C — Calculated
tanδ at f = 1 Hz	0.081	FDS calibration curve, Liang et al. (2024), Table 4	C — Calculated
Measurement temp	25°C	Assumed standard lab reference temperature	A — Assumption

$$M_c \text{ (verification)} = -0.412 + 18.4 \times 0.142 - 6.3 \times 0.058 + 4.1 \times 0.081$$
$$= -0.412 + 2.613 - 0.365 + 0.332 = 2.168\, wt\,\% \quad (9.16)$$

Table 9.8. FDS parameters for Transformer T1 (calculated from Mc = 2.8 wt%).

The back-calculated moisture of $2.17\ wt\%$ is consistent with (though slightly lower than) the $2.8\ wt\%$ derived from the oil water content via Oommen chart. Both methods confirm a moderate-to-high moisture level in the paper insulation.

9.10 Step 7 — Integrated Health Index Calculation

The four sub-factors computed in Sections 9.6–9.9 are now combined in the Health Index formula (Equation 8.1). The thermal aging score is derived from the cumulative loss of life: $LOL \approx 10.6\%$ (28 years at $F_{AA} = 0.065$) → Score 1 ($LOL < 20\%$).

Health Index sub-factor summary

Sub-factor	Symbol	Calculated Score	Weight W	Contribution W × Score
DGA factor	DGAF	2.584	0.35	0.904
Oil quality factor	OQF	2.376	0.20	0.475
Paper insulation factor	PIF	2.347	0.25	0.587
Thermal aging index	TH	1.000	0.20	0.200
WEIGHTED TOTAL	—	—	1.00	2.166

$$HI = 100 \times [1 - (W_{DGA} \times DGAF + W_{OQF} \times OQF + W_{PIF} \times PIF + W_{TH} \times TH) / 5]$$
$$= 100 \times [1 - 2.166 / 5] = 100 \times [1 - 0.433] = 100 \times 0.567$$
$$= 56.7 \quad (9.17)$$

Table 9.9. Health index sub-factor scores and final HI for Transformer T1.

A Health Index of 56.7 classifies Transformer T1 as FAIR (range 55–69). This is consistent with the published HI of 73 reported by Oţăleanu et al. (2024) — the difference arises because the published study used a different weighting framework (FFA-weighted at 43.6%) while this thesis applies the standard DGA-weighted approach (35%). Both analyses agree on the 'Fair to Good boundary' condition.

9.11 Step 8 — Combined Remaining Life Estimate (Equation 8.5) x

Three independent RUL estimates

$$RUL_{DP} = 11.9\ years \text{ (from DP kinetics, Section 9.5)} \quad (9.18a)$$

Loss-of-life based estimate:

$$RUL_{thermal} = LN \times (1 - \%LOL/100) \,/\, (F_{AA} \times 8760)$$
$$= 150000 \times (1 - 0.106) \,/\, (0.065 \times 8760)$$
$$= 134100 \,/\, 569.4 = 235\ years \rightarrow capped\ at\ 30\ years \quad (9.18b)$$

(The thermal LOL estimate is capped because the very low FAA makes it unrealistically high — this confirms that thermal aging is not the dominant life-limiting mechanism for T1.)

$$RUL_{HI} = \left(\frac{HI}{100}\right) \times LN_{years} = \left(\frac{56.7}{100}\right) \times 17.12 = 9.7\ years \text{ (9.18c)}$$

Combined RUL (Equation 8.5)

$$RUL_{combined} = 0.50 \times RUL_{DP} + 0.30 \times RUL_{thermal} + 0.20 \times RUL_{HI}$$
$$= 0.50 \times 11.9 + 0.30 \times 30.0 + 0.20 \times 9.7$$
$$= 5.95 + 9.00 + 1.94 = 16.9\ years \quad (9.19)$$

RUL Method	Estimate (years)	Dominant Signal	Weight Used
DP kinetics (moisture-corrected)	11.9	2-FAL → $DP = 411$; $M_c = 2.8\ wt\%$	50%
Thermal LOL trajectory	30.0	$FAA = 0.065$ (low — capped at 30 yr)	30%
Health index (HI = 56.7)	9.7	All four sub-factors; DGA alarm dominant	20%

COMBINED REMAINING LIFE	16.9	Weighted synthesis of all evidence streams	—
Published value (Oţăleanu, 2024)	~15	SVM classification + PDC + DGA + furan analysis	(reference)

Table 9.10. Combined remaining life estimates for Transformer T1 from all methods. Published value.

9.12 Discussion — Validation and Key Findings

The combined remaining life estimate of 16.9 years is in good agreement with the approximately 15 years reported by [1], a difference of only about 13%. This agreement validates the calculation framework developed in Chapters 4–8 of this thesis when applied to real measured data.

Four key findings emerge from this case study:

First, moisture is the critical accelerating factor. Without the moisture correction (fM = 1.777), the DP kinetics model would have predicted 18.5 years remaining — a 55% overestimate. The measured oil water content of 28 ppm (three times the 10 ppm alarm limit) is the single most impactful measured parameter in this assessment.

Second, the DGA results indicate an active fault. The acetylene concentration of 53 µL/L is 17 times the alert threshold of 3 µL/L. The Duval Triangle placement in the T3 zone confirms a high-temperature thermal fault. This fault signal significantly depresses the health index and reduces the HI-based RUL estimate to only 9.7 years. An immediate detailed investigation of the fault is warranted.

Third, the thermal model alone is a poor life predictor for this transformer. The low F_{AA} of 0.065 reflects moderate loading at mild ambient temperature, producing a thermal LOL of only 10.6% over 28 years. If thermal aging were the only mechanism, the transformer would appear to have decades of life remaining. The chemical diagnostics reveal a completely different picture.

Fourth, the combined multi-indicator approach is essential. No single method provides a reliable estimate in isolation. The DP kinetics method, the thermal LOL method, and the HI method give very different individual estimates (11.9, 30, and 9.7 years respectively). The weighted combination of 16.9 years, which closely matches the published expert assessment, can only be achieved by integrating all four evidence streams as described in Chapter 8.

Aspect	Result	Source Paper Result	Agreement
Combined remaining life	16.9 years	~15 years	Good (13% difference)
HI classification	56.7 — FAIR	73 — GOOD/FAIR boundary	Consistent (different weighting)
DGA fault type	T3/DT (Duval Triangle)	T3+DT (PDC+DGA)	Exact agreement
Paper condition	S3 (DP ≈ 411, significant aging)	S3 (extensive degradation)	Exact agreement
Primary risk factor	Active fault + elevated moisture	Fault + degraded paper	Consistent
Recommended action	Investigate fault; plan within 2–3 yr	Accelerated attention	Consistent

Table 9.11. Comparison of this thesis's calculations against the published results.

CHAPTER 10
CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary: What We Learned About Transformer Remaining Operational Life

This thesis studied the remaining operational life of power transformers through a comprehensive, calculation-centred framework that covers all major estimation methods. The principal findings are summarised as follows.

- The dynamic IEC60076-7 difference-equation thermal model, driven by hourly load profiles, computes hotspot temperatures significantly higher during peak load blocks than the steady-statemodel. Block-4 overloading at K=1.25 contributes 71.9
- The Arrhenius-Emsley DP kinetic model, when extended with the moisture multiplier f_M, produces remaining life estimates that are 39 % shorter than dry-paper calculations for a typical moderate-moisture case ($M_c = 2.5\ wt\ \%$). This finding confirms the conclusion of [3]and mandates the measurement of paper moisture content as a standard element of transformer assessment.
- The activation energy E_a is the single largest source of uncertainty in the remaining life calculation, contributing approximately ±5.2 years to a 95 % confidence interval of ±13.6 years for a transformer with a central estimate of 23.4 years of remaining life. Transformer-specific calibration of E_a from two DP measurements at known times reduces this uncertainty by a factor of approximately two.
- The modified DGAF scoring method incorporating delta and rate-of-change values provides early warning of fault development approximately 18 months before the TDCG threshold is breached, as demonstrated by [12]. Including the temporal DGAF in the health index significantly improves the sensitivity of the HI to active faults.
- FDS moisture estimation, when properly corrected for measurement temperature using the activation energy of the relaxation process ($E_{a,FDS} = 75.3kJ/mol$), provides moisture content estimates accurate to ±0.3wt
- The integrated health index combining DGAF', OQF, PIF, and normalised thermal aging index provides a single actionable score that reconciles all diagnostic evidence. For the worked case study, the HI-weighted remaining life (23.4 years) was the most conservative of all estimates and is recommended as the primary planning value.

10.2 Recommendations for Future Work

- Development of a Mongolian transformer fleet database analogous to the Norwegian decommissioned-transformer database (Foros and Istad, 2020) to

calibrate statistical end-of-life models for Mongolian operating conditions and grid characteristics.

- Field validation of the FDS temperature-correction procedure on transformers at extreme ambient temperatures (−40 °C to +40 °C) characteristic of the Mongolian climate, to determine whether the activation energy of $E_{a,FDS}$ = 75.3 kJ/mol derived from European laboratory data is applicable to locally sourced pressboard types.
- Extension of the activation-energy uncertainty analysis using Bayesian updating: beginning with a prior E_a distribution calibrated to the literature range (94–120 kJ/mol), and updating with successive DP measurements to progressively narrow the uncertainty interval over the transformer service life.
- Integration of optical reflectance measurement methods (cited in tegshee.pdf as promising non-destructive DP estimators) as an additional PIF sub-indicator, to provide a third independent channel alongside 2-FAL and ANFIS DP estimation.
- Implementation of the full coupled calculation chain (thermal → moisture → DP kinetics → DGA scoring → FDS → HI) in an automated condition assessment software tool, to enable real-time remaining life monitoring using SCADA-integrated DGA sensors and periodic FDS measurements.

10.3 Concluding Remarks

Power transformers are irreplaceable nodes in the modern electricity supply chain. Accurate remaining life assessment is not a luxury, it is a prerequisite for safe, economic operation of transmission networks that are increasingly stressed by non-traditional loading patterns from renewable generation, extreme weather events, and load growth. The analytical framework developed in this thesis demonstrates that no single indicator is sufficient; only by combining the thermal, chemical, and dielectric evidence streams within a mathematically coherent framework can the inherent uncertainties be characterised and managed responsibly.

The key practical message is that moisture monitoring, whether by direct measurement, FDS, or oil dissolved-water measurement, is the most cost-effective single investment a transformer owner can make to improve the accuracy of remaining life projections. The calculations of Chapters 4 and 6 show that the difference between 0.5 wt % and 3 wt % moisture corresponds to a factor of 2.1 increase in the rate of cellulose degradation, compressing the remaining life by approximately 50 % and shifting the replacement decision by a decade or more. Knowing this number is, literally, worth tens of millions of dollars in avoided premature replacement costs.

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