

Transformer Overloading and Assessment of Loss-of-Life for Liquid-Filled Transformers

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Presentation Outline

- **Introduction and Motivations**
- **Remaining Transformer (Insulation) Life, Transformer Thermal Model, IEEE Loading Guides**
- **Modeling and Economic Evaluation**
- **Simulation and Results**
- **Conclusions**

Transformer Type and Nameplate Rating

• Oil-Filled Transformer

- 
- <500 kVA (distribution, OA)
 - 500 kVA - 100 MVA (distribution power) (OA, OA/FA, OA/FA/FA)
 - >100 MVA (transmission power) (OA/FA/FA and OA/FA/FOA)

- 65°C average winding temperature rise
(thermally-upgraded paper insulation)
- 55°C average winding temperature rise
(not thermally-upgraded paper, *kraft*)
- 30/40/50/**56** MVA @55° / 65° C TR (OA/FA/FA)

@55°C TR

Issues and Considerations

- **Thermal Model**

- Design Consideration (Losses & Cooling)
- Temperature (Top & Bottom Oil, Winding Hottest-Spot Temp.)
- Insulation Degradation
- Estimation of Transformer Remaining Life from Its Insulation

- **Economic Model**

- Total Owning Cost (TOC)
- Revenue Requirement
- Other Models!!

Thermal Model

- Design
- Temperature
- Insulation
- Life

Optimization

(Minimum Cost & Optimum Sizing)

- New Design
- Retrofit Design
 - Replace now
 - Replace later
 - Add a second transf.
 - ??

Economical Model

Revenue Requirement

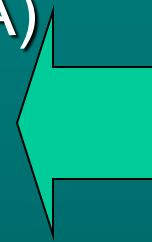
Uncertainties & Probability

Approach

- Future load growth projection
- Ambient temp.
- Transformer Failure

Loading Guide Standards

- IEEE Std. C57.91-1995 (USA)
 - Clause 7 (Classical Model)
 - Annex G (Detailed Model)
- IEC 354-1991 (EUROPE, CANADA and Others)
- IEEE & IEC Comparisons
 - IEC is somewhat similar to IEEE Clause 7



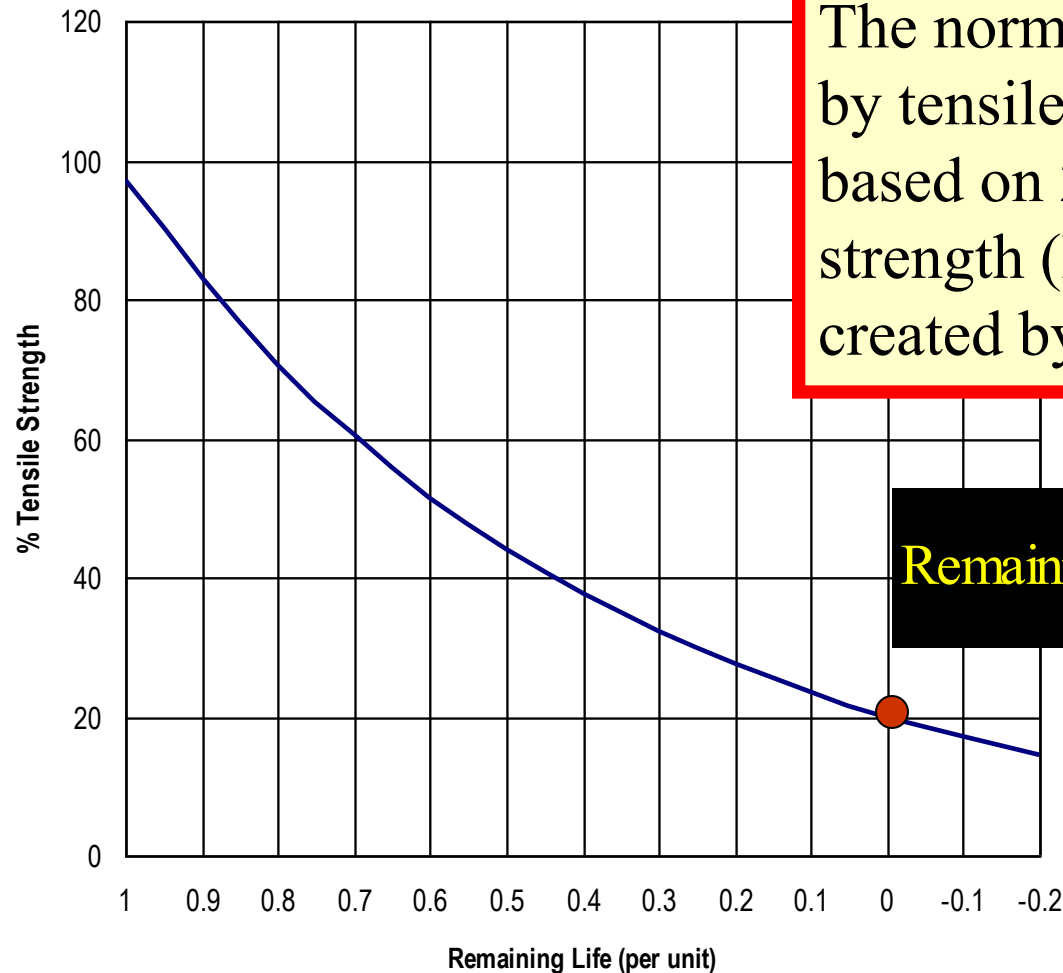
Transformer Failure Modes

- **Long-term Failure Mode**
 - Mechanical and chemical properties of insulation deterioration
 - Dielectric strength reduction (approx. 10% over the transformer life)
- **Short-term Failure Mode**
 - Bubble formation (gassing), temporally dielectric strength reduction (30% impulse strength reduction @ 180 °C)

Remaining Transformer (Insulation) Life

- The **Tensile Strength** (Mechanical) of cellulose insulation is used as a criteria for loss-of-life estimation.
- Recently, the **Degree of Polymerization (DP)** (Chemical) has also become a popular measurement of insulation life.
- If a sample of insulation near hot spot location is made available, the remaining life of the transformer could be approximately predicted based on specific criteria.

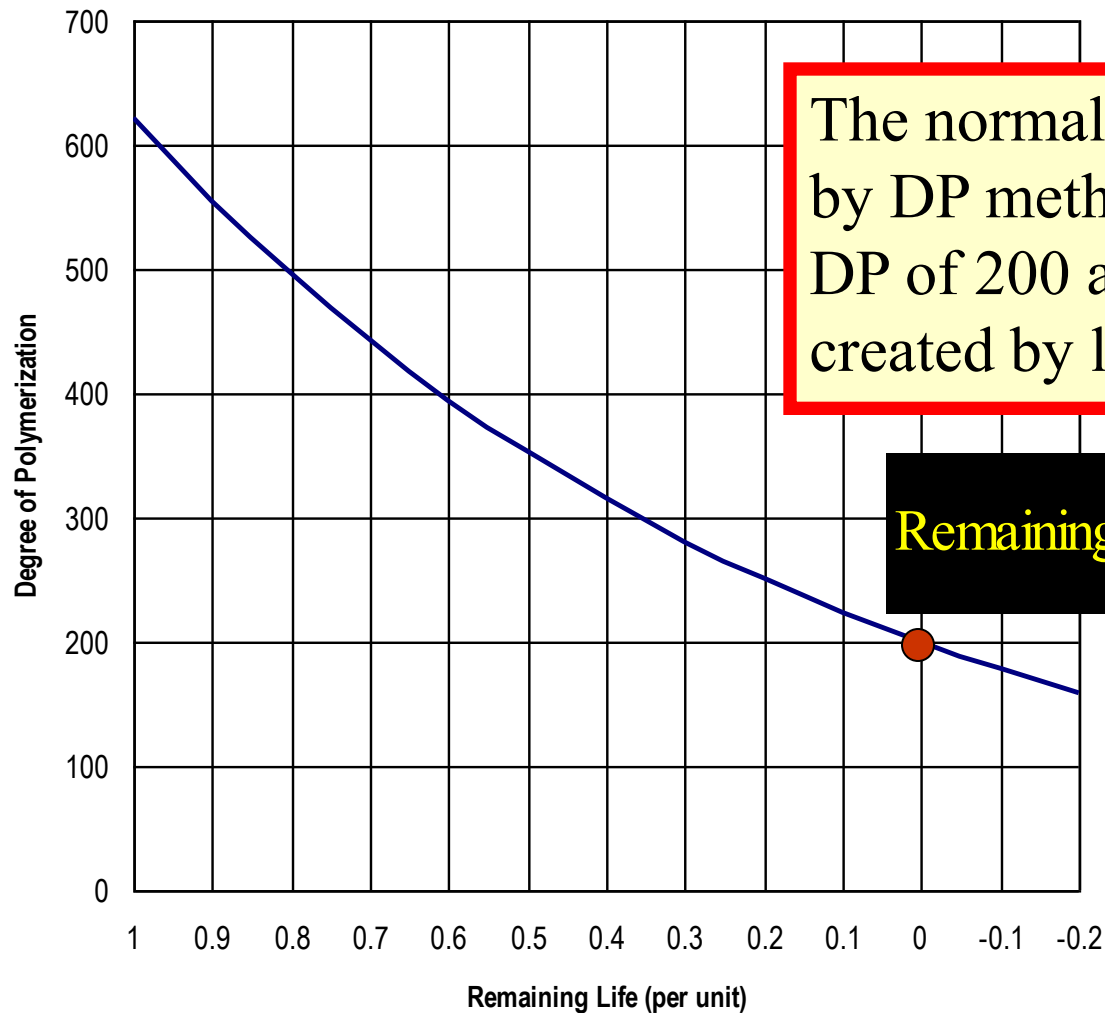
Remaining Life by Tensile Strength Method



The normalized remaining life by tensile strength method based on 20% remaining tensile strength (RTS) as end-of-life criteria, created by least square method

$$\text{Remaining Life} = 1 + 0.633 \ln \left(\frac{RTS}{97.05} \right)$$

Remaining Life by DP Method



The normalized remaining life by DP method based on remaining DP of 200 as end-of-life criteria, created by least square method

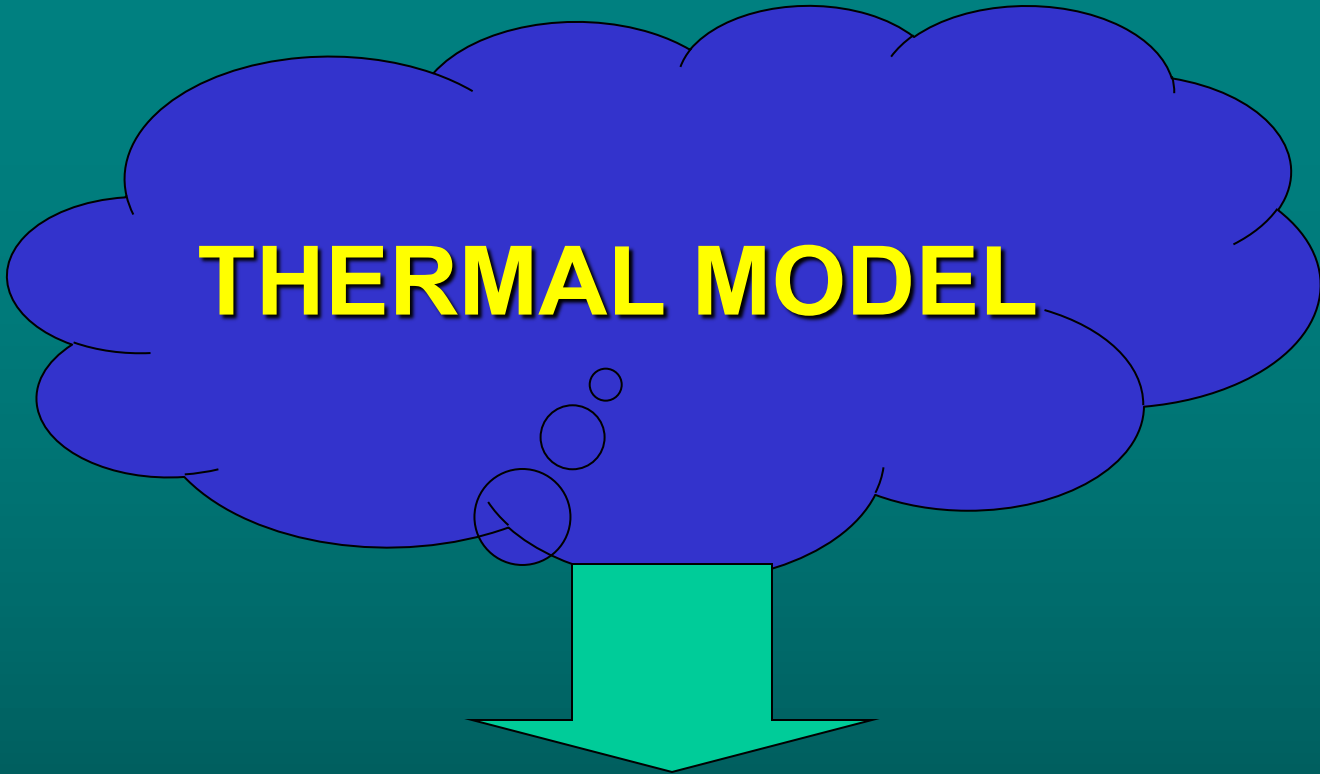
$$\text{Remaining Life} = 1 + 0.881 \ln \left(\frac{RDP}{622} \right)$$

IEEE Std. C 57.91-1995, Per-Unit Life

- Per-Unit Life
$$L = 9.80 \times 10^{-18} e^{\left[\frac{15,000}{T_{HS} + 273} \right]}$$
- Relative Aging Factor
$$F_{AA} = \frac{dL}{dt} = e^{\left[39.164 - \frac{15,000}{T_{HS} + 273} \right]}$$
- Equivalent Aging
$$F_{EQA} = \frac{1}{T} \int_0^T F_{AA} dt$$
- % Loss-of-Life
$$= \frac{F_{EQA} \times T}{\text{Normal Insulation Life}} \times 100$$

- Normal Insulation Life  (20-30 Yrs.)
- Hottest-Spot Temperature (T_{HS})

THERMAL MODEL



Hottest-Spot Temperature (T_{HS})

Hottest-spot temperature = ambient temperature (T_A)
+ top oil rise over ambient (ΔT_{TO})
+ hot spot rise over top oil (ΔT_G)

Thermal Model (IEEE Clause 7)

Steady-State Equations

$$T_{HS} = T_A + \Delta T_{TO} + \Delta T_G$$

$$\Delta T_{TO} = \Delta T_{TOR} \left(\frac{K^2 R + 1}{R + 1} \right)^n$$

$$\Delta T_G = \Delta T_{GR} \cdot (K^2)^m$$

K = Per-Unit Loading (Actual Load/Rated (max) Load)

R = Loss Ratio (Load Loss @ Rated Load/No-Load Loss)

Exponent „n“and „m“depends on “Cooling”

Thermal Model (IEEE Clause 7)

Transient Equations

Oil

$$\tau_{TO} \frac{d\Delta T_{TO}}{dt} = -\Delta T_{TO} + \Delta T_{TO,u}$$

$$\Delta T_{TO,u} = \Delta T_{TOR} \cdot \left(\frac{K^2 R + 1}{R + 1} \right)^n$$

Winding

$$\tau_G \frac{d\Delta T_G}{dt} = -\Delta T_G + \Delta T_{G,u}$$

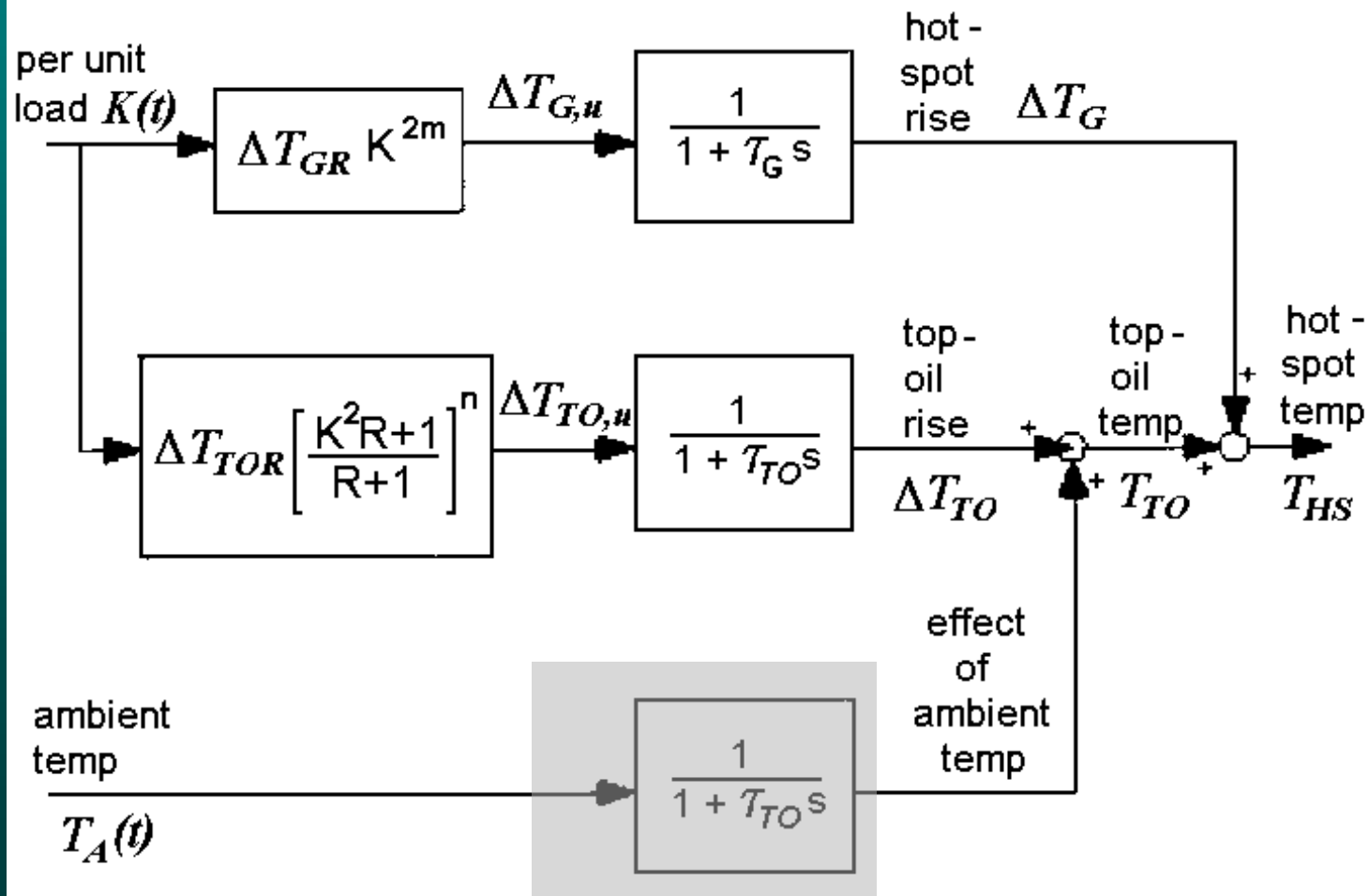
$$\Delta T_{G,u} = \Delta T_{GR} \cdot (K_u^2)^m$$

Modified Transient Equations

$$\tau_{TO} \frac{d\Delta T_{TO}}{dt} = -\Delta T_{TO} + \Delta T_{TO,u} + \Delta T_A$$

$$\Delta T_{TO}(s) = \frac{1}{1 + \tau_{TO}s} \cdot \Delta T_{TO,u}(s) + \frac{1}{1 + \tau_{TO}s} \cdot \Delta T_A(s)$$

Thermal Block Diagram (IEEE Clause 7)

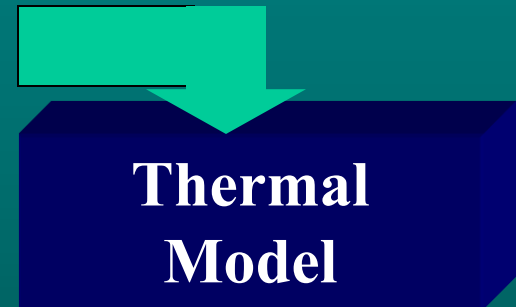


Aging Rate and % Loss-of-Life

- Loading cycle, Complex load growth
- Ambient temperature variation



$$\text{Aging Rate} = e^{\left(\frac{15,000}{383} - \frac{15,000}{T_{HS} + 273} \right)}$$



$$\% \text{loss of life} = \frac{e^{\left(\frac{15,000}{383} - \frac{15,000}{T_{HS} + 273} \right)} \Delta t * 100}{\text{Normal Life}}$$

Aging rate,
%Loss-of-life

IEEE “Clause 7” & “Annex G” Comparisons

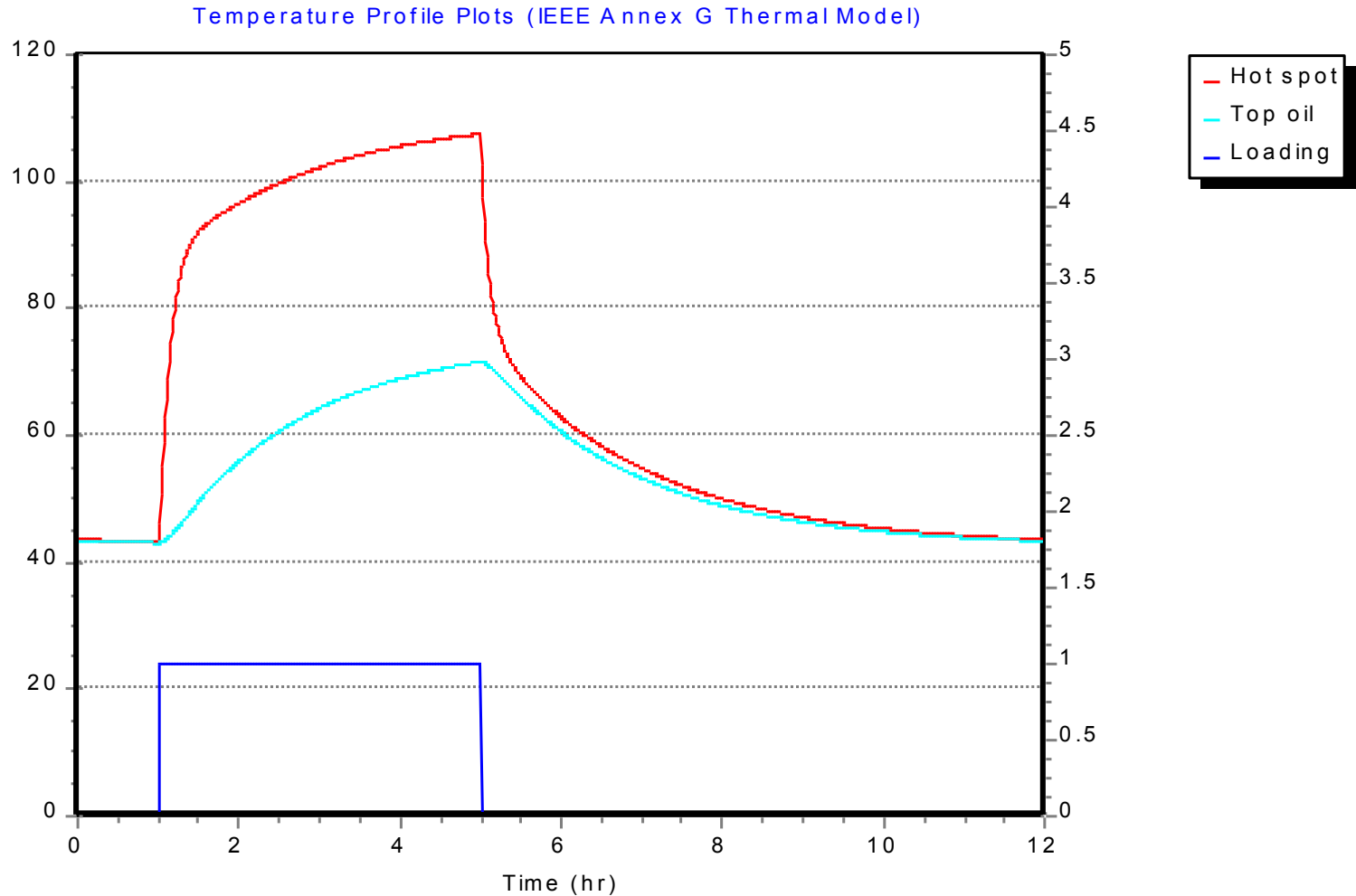
- “**Clause 7**” thermal model: Simple, Requires minimum information, uses top-oil temperature
- “**Annex G**” thermal model: More complex, Requires more information, Focus on duct oil temperature change, uses bottom-oil temperature

“Clause 7” and “Annex G”

Data Requirements

IEEE Classical Model (Clause 7)	IEEE Detailed Model (Annex G)
1. Top oil temperature rise at rated load 2. Hot spot temperature rise over top oil at rated load 3. Loss ratio at rated load 4. Winding time constant 5. Oil time constant or 6. Type of cooling system	1 Top oil temperature rise at rated load 2 Hot spot temperature rise at rated load 3 Average winding temperature rise at rated load 4 Bottom oil temperature rise at rated load 5 Losses data from test report 6. Weight of Core & coil 7. Weight of tank & fittings 8. Gallons of fluid 9. Type of cooling system 10. Type of cooling fluid 11. Type of winding material 12. Winding time constant 13. Location of hot spot 14. Per unit eddy current losses at hot spot location

IEEE Annex G & Clause 7 Thermal Model (Step Load Response)



Loading (Per unit)

Economic Evaluation

(Total Owning Cost)

Buying a New Transformer

Simplified Practice,

$$\text{TOC} = \text{IPP} + A * \text{NLL} + B * \text{LL}$$

Owner Specifies:

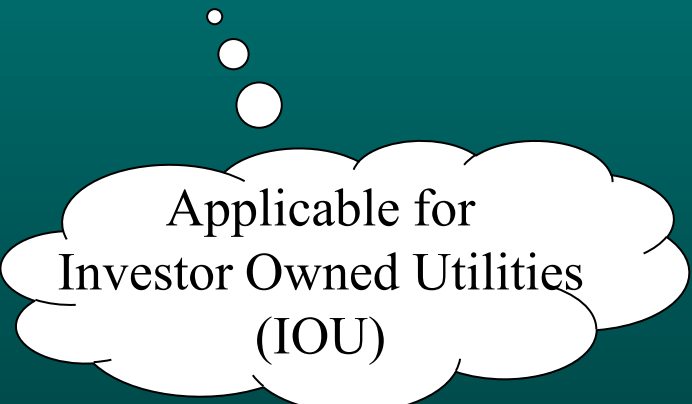
- Size (MVA)
- A & B Factors

Manufacturer Specifies:

- Initial purchase price (IPP)
- Losses (Winding & Core)

Economic Evaluation (Revenue Requirement)

Revenue Requirement



Applicable for
Investor Owned Utilities
(IOU)

- Daily load curves
- Daily ambient temp. variations
- Overloading & end-of-life
- Accurate energy loss
- Transformer replacement
- Refined & flexible method
- Detailed economic analysis

**THERMAL
MODEL**

```
graph TD; TM[THERMAL MODEL] --> O[OPTIMIZATION]; EM[ECONOMIC MODEL] --> O; O --- L["• NEW DESIGN<br/>• RETROFIT APPLICATIONS"]
```

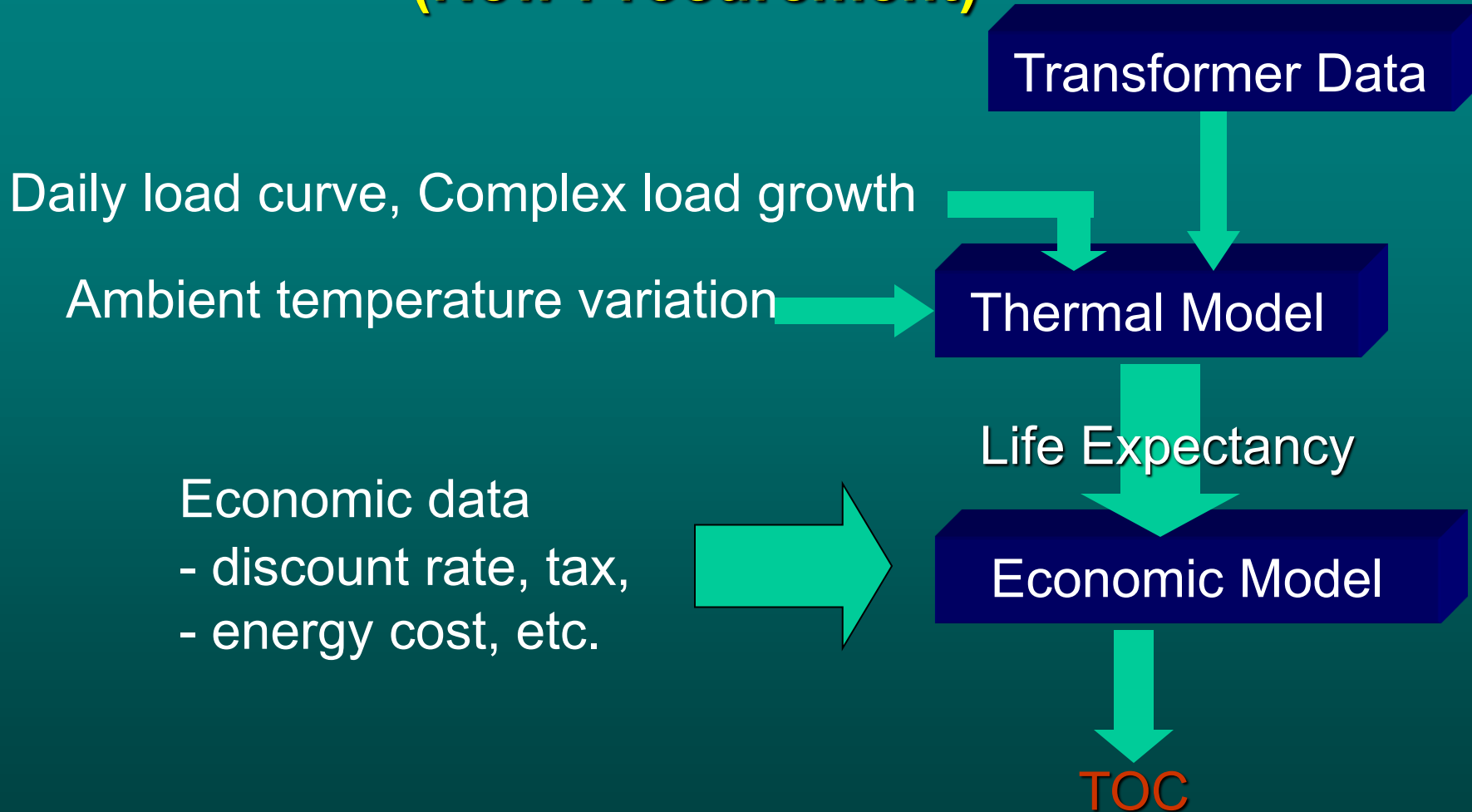
The diagram features a dark teal background. At the top left, a blue cloud contains the text 'THERMAL MODEL' in white. At the top right, a yellow cloud contains the text 'ECONOMIC MODEL' in black. Two large green arrows point from these clouds towards a central white cloud at the bottom. The white cloud contains the word 'OPTIMIZATION' in black, underlined, and a list of two items in pink: '• NEW DESIGN' and '• RETROFIT APPLICATIONS'.

**ECONOMIC
MODEL**

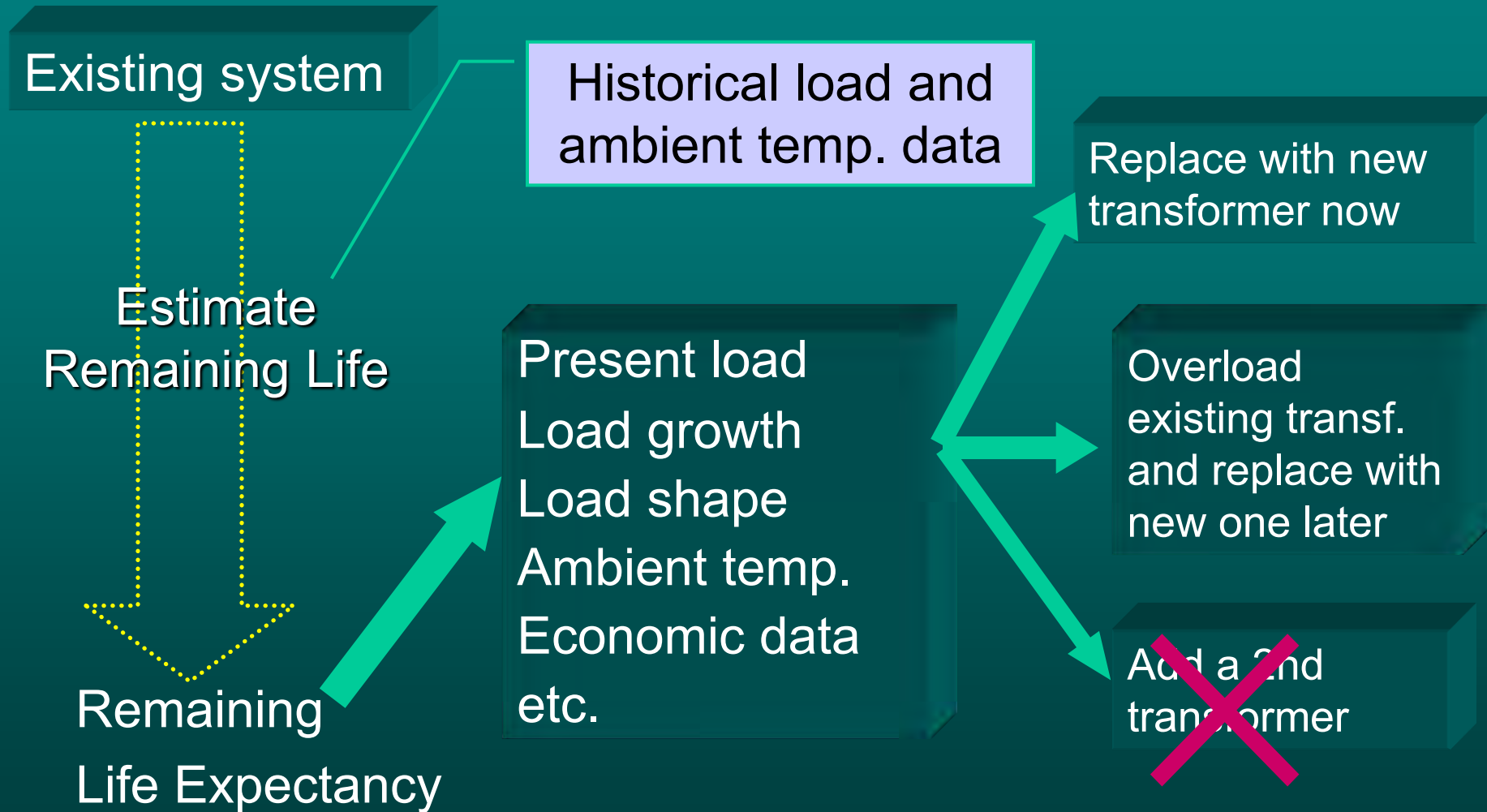
OPTIMIZATION

- **NEW DESIGN**
- **RETROFIT APPLICATIONS**

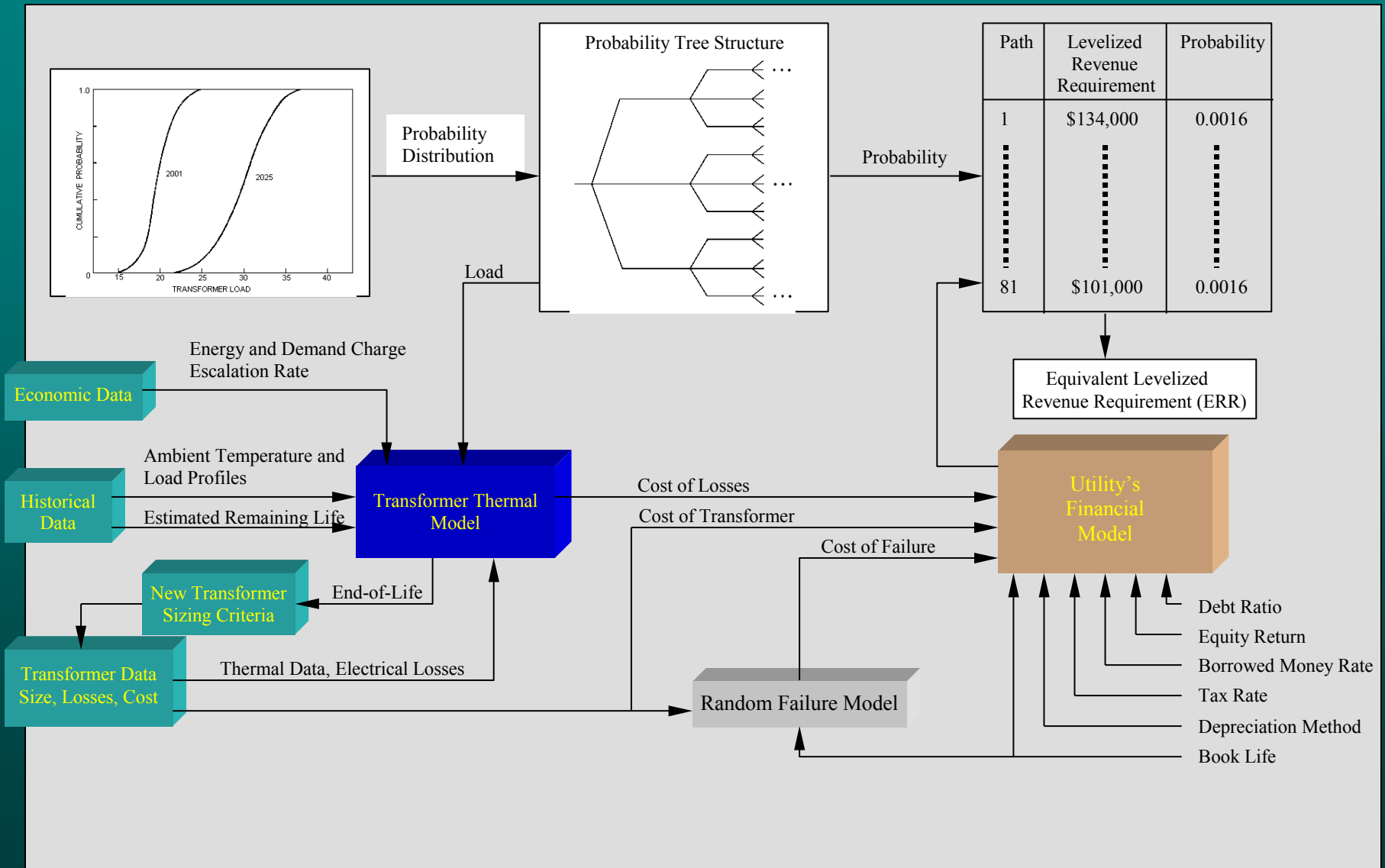
Optimization (New Procurement)

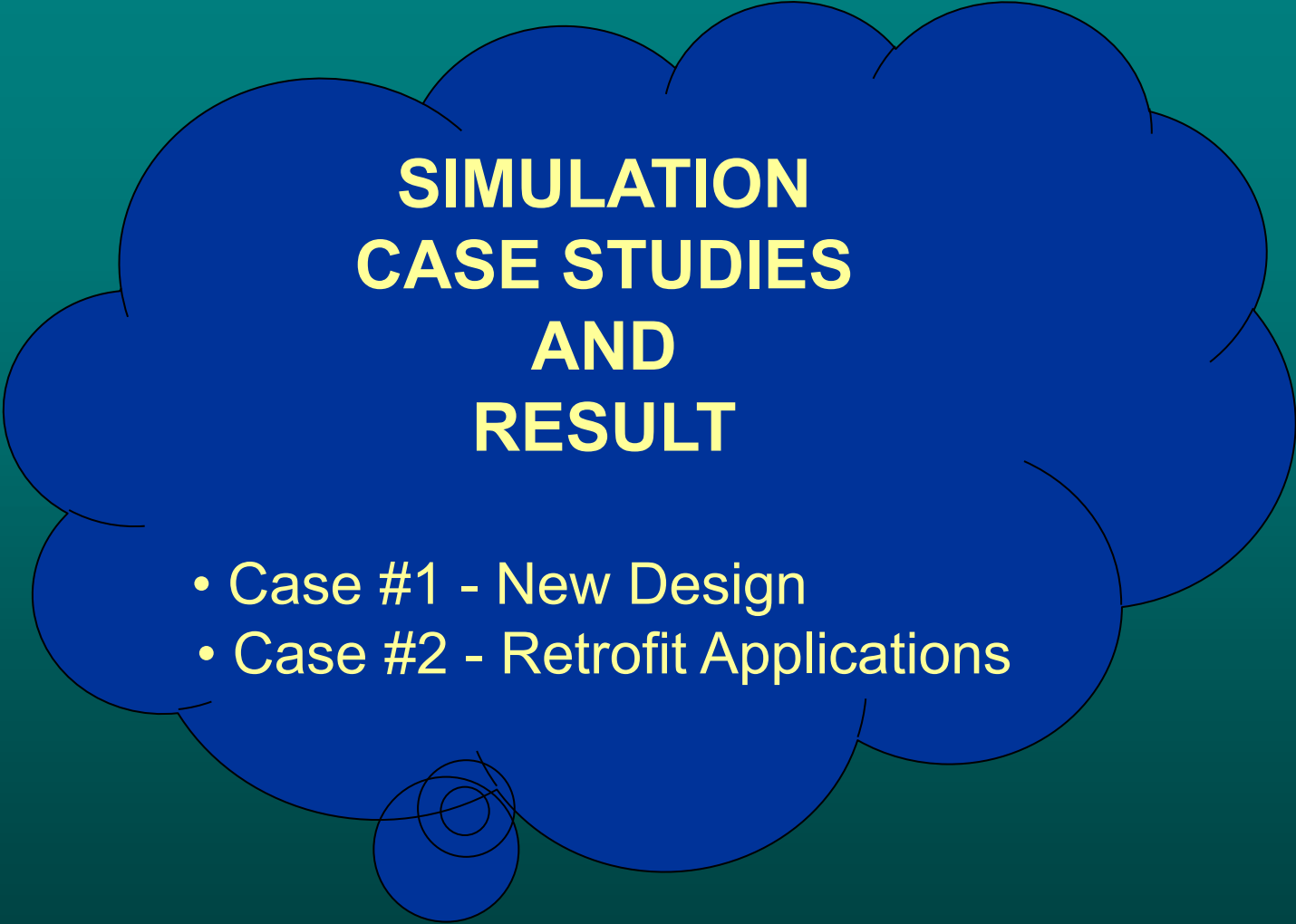


Optimization (Retrofit Design)



Complete Method Block Diagram





SIMULATION CASE STUDIES AND RESULT

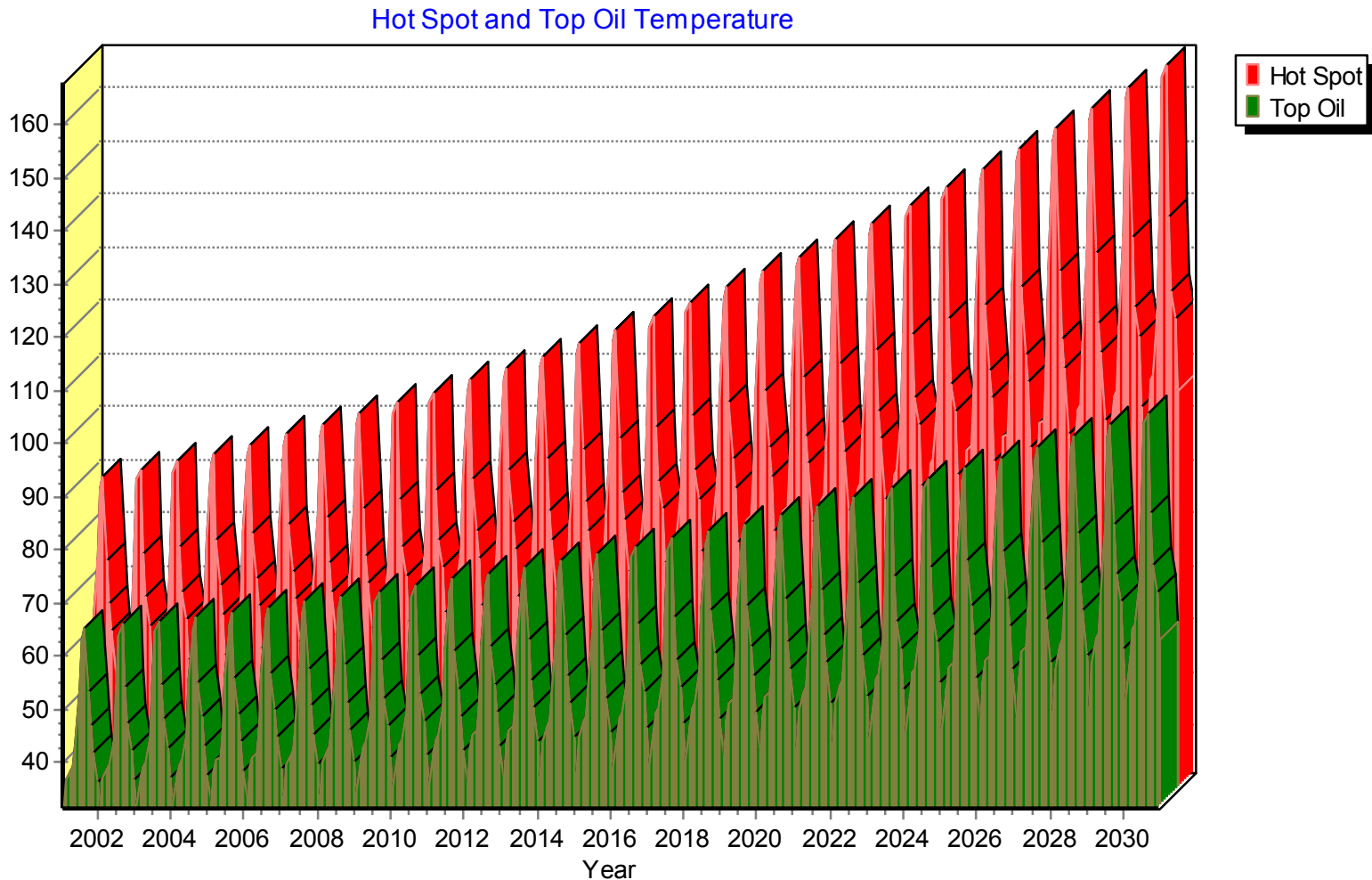
- Case #1 - New Design
- Case #2 - Retrofit Applications

Case #1: New Design

Example Data

- Buy new transformer for a new project
- Initial peak load = 20 MVA
- Load growth in first 4 years (Probability)
 - High growth = 2.00%
 - Moderate growth = 1.75%
 - Low growth = 1.00%
- Load growth after the 4th year is 2.00%

Case #1: Hot-Spot & Top-Oil Temperature Plots



Case #2: Retrofit Design

Example Data

- Existing transformer rating = 18 MVA
- In service for 25 years
- Estimated remaining life = 0.25 pu.
- Initial peak load = 20 MVA
- Load growth in first 4 year (Probability)
 - High growth = 2.00%
 - Moderate growth = 1.75%
 - Low growth = 1.00%
- Load growth after 4th year is 2.00%
- **Replace with new unit now or continue overload
..and replace later ?**

Windows Based Computer Program

- Graphic interface, Load, Save, Print, and Copy
- Transient Loading Analysis (Daily load)
- Life Cycle Study (with load growth from table)
- Optimize Transformer Size
- Delay Replacement or Replace now Analysis

Screen Shot (1), Main Menu



Screen Shot (2), Annex G Input

IEEE Annex G Input

Rating Losses Data Other Data Initial Temp.

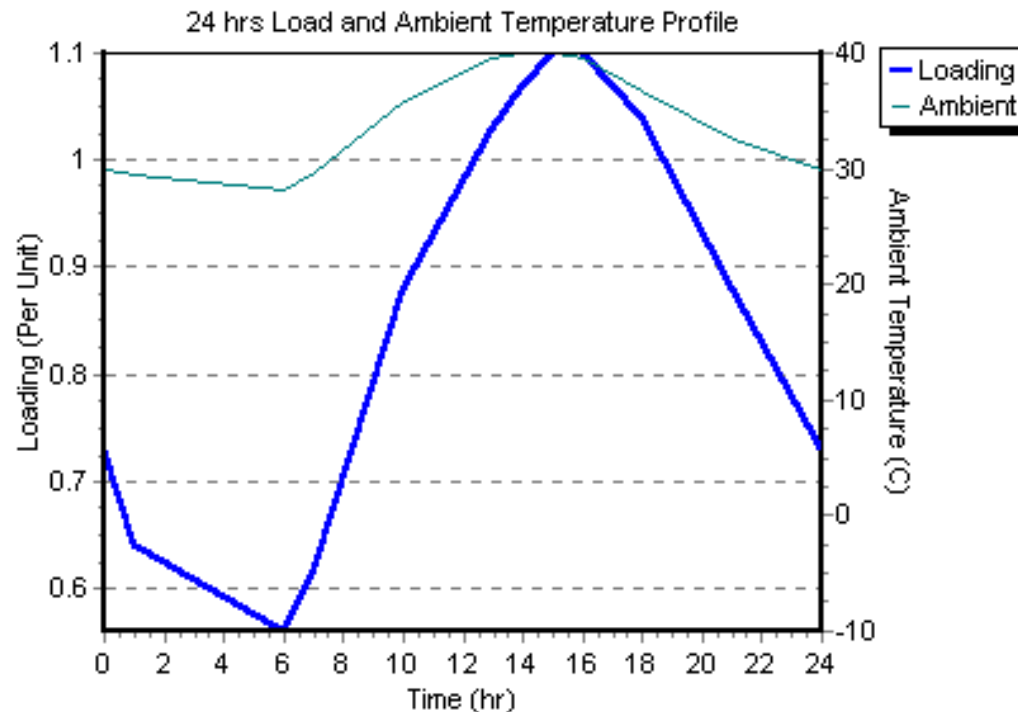
Test Data		Losses at one per unit loading
kVA Base for Testing	28000 kVA	52267 kva
Winding Temperature	75.0 C	95.0 C
I ² R loss	51690 watts	191752 watts
Winding Eddy Losses	0 watts	0 watts
Stray Losses	21078 watts	68988 watts
Core lossse	36986 watts	36986 watts
Total Losses		297726 watts

Update

Exit

Screen Shot (3), Load Profile Input

24hrs Load Profile Editor



Time Per unit Ambient
No. hrs. Loading Temp.

1	0:00	0.73	30.0
2	1:00	0.64	29.5
3	6:00	0.56	28.2
4	7:00	0.62	29.8
5	10:00	0.88	35.9
6	13:00	1.03	39.6
7	14:00	1.07	40.0
8	15:00	1.10	40.0
9	16:00	1.10	39.6
10	18:00	1.04	36.8
11	21:00	0.88	32.5
12	24:00	0.73	30.0
13			
14			
15			
16			

Update

Insert Row

Delete Row

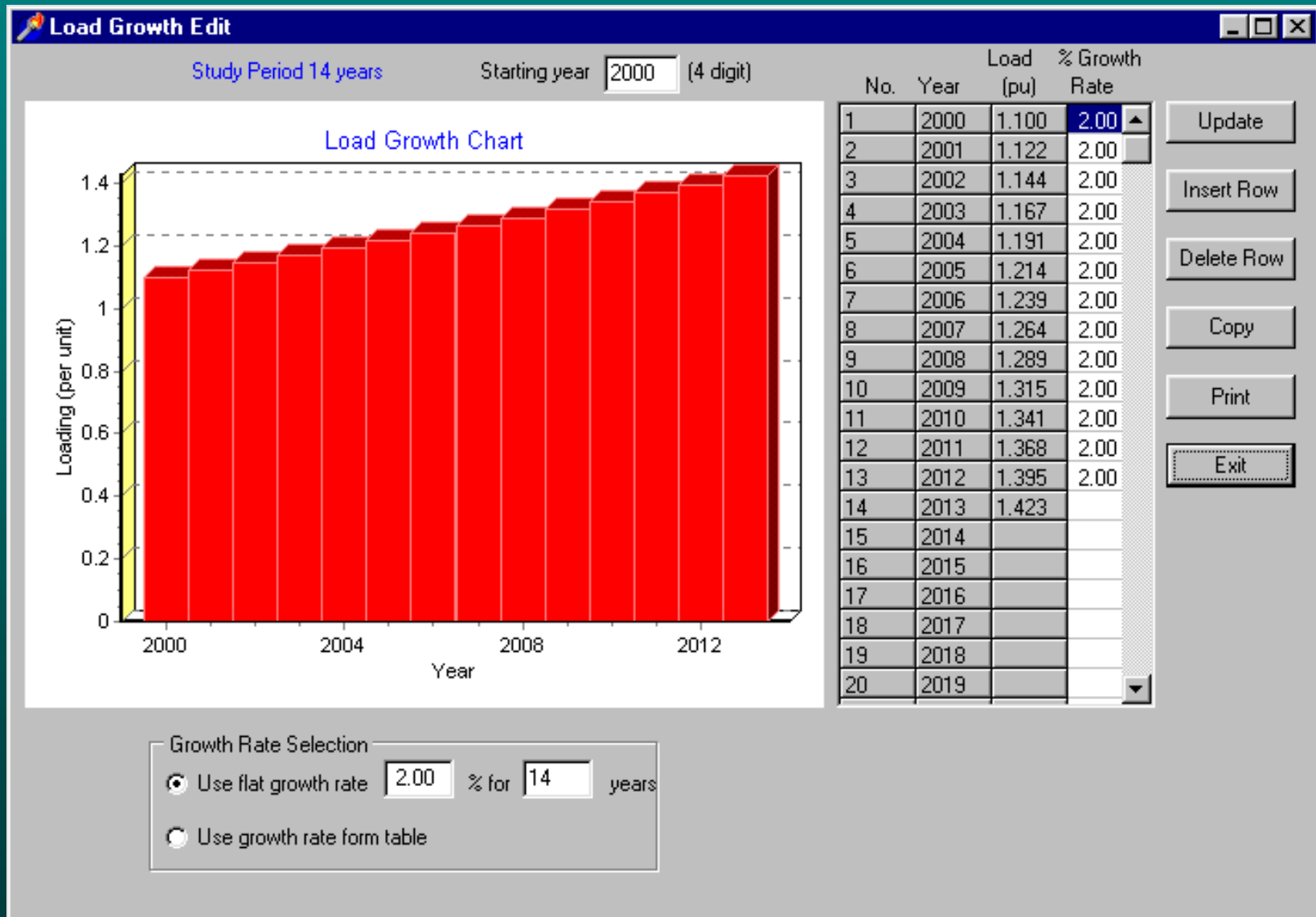
Copy Chart

Print

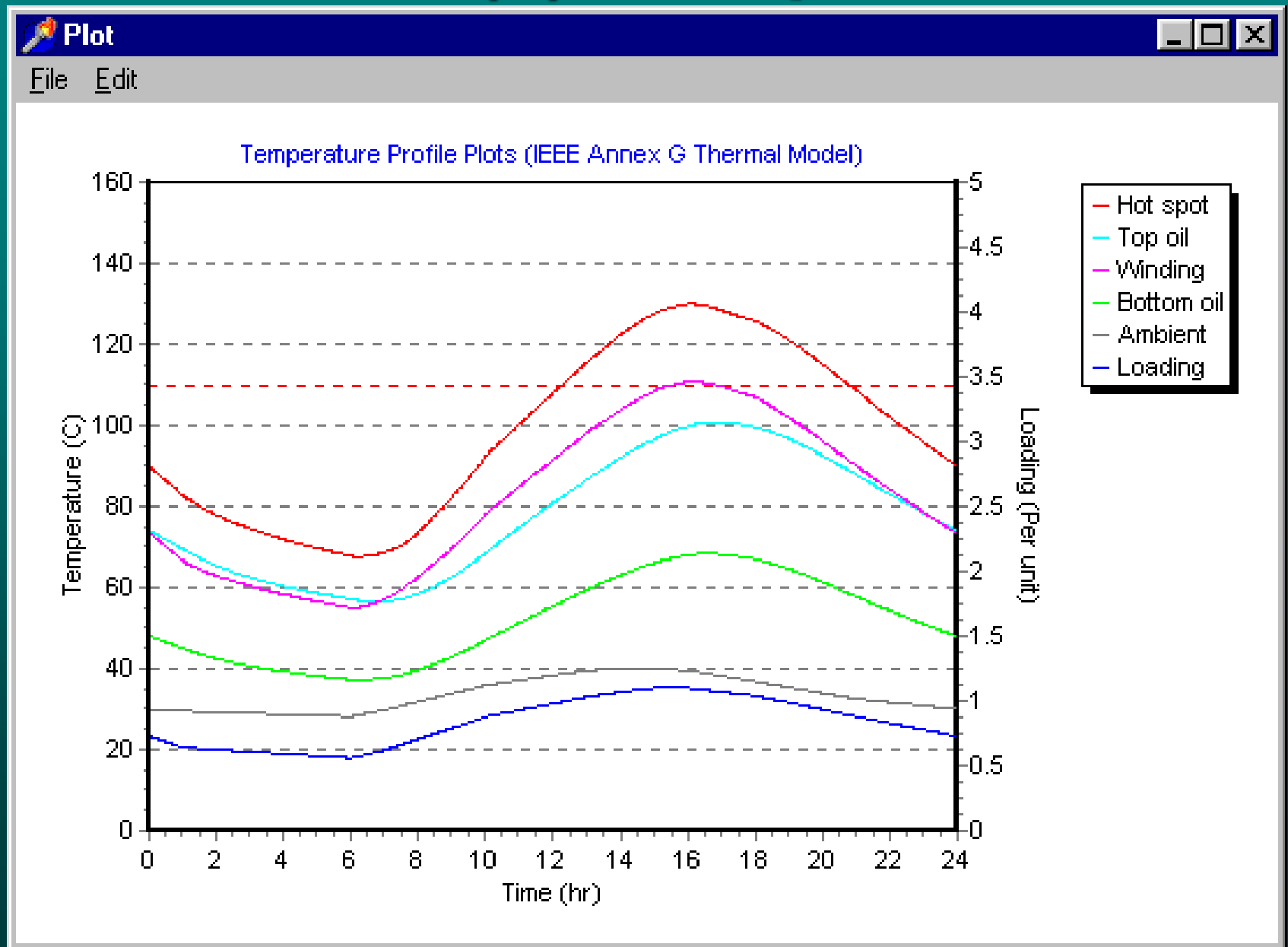
Exit

Note: To delete a row and the following rows,
enter "0" or BLANK in Time column and
press Update button

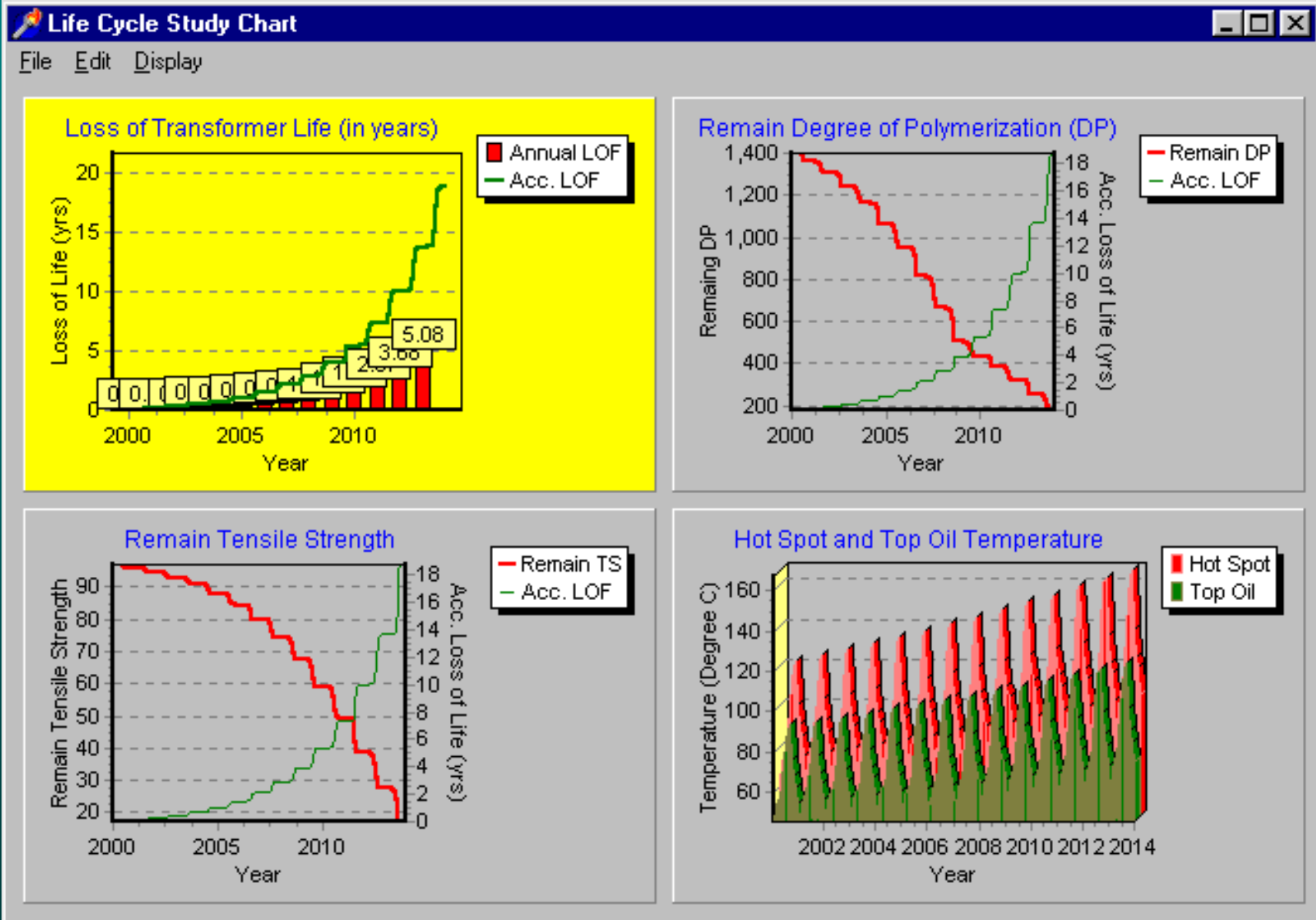
Screen Shot (4), Load Growth Input



Screen Shot (5), Temperatures Plot



Screen Shot (6), Life Cycle Charts



Screen Shot (8), Economic Data Input

Utilities Financial Data & Energy Cost Input

Minimum Transformer Size	20.0	MVA	Energy Price	0.035	\$/kwh															
Maximum Transformer Size	40.0	MVA	Energy Escalation Rate	2.00	%															
Load Growth Rate after 4th year	2.00	%	Demand Charge	120	\$/kw															
Return on Equity Rate	16.00	%	Demand Charge Escalation Rate	2.00	%															
Borrowed Money Rate	5.00	%	Peak Responsibility Factor	0.80																
Debt Ratio	0.50		Random Failure Rate	0.50	%															
Tax Rate	50.00	%	Existing Transformer <table><tbody><tr><td>Size</td><td> 18.00 </td><td>MVA</td></tr><tr><td>Years in Service</td><td> 25 </td><td>years</td></tr><tr><td>Remaining Life</td><td> 0.25 </td><td>per unit</td></tr><tr><td>Transformer Price</td><td> 340000 </td><td>\$</td></tr><tr><td>Market Value Rate</td><td> 10.00 </td><td>%</td></tr></tbody></table>			Size	18.00	MVA	Years in Service	25	years	Remaining Life	0.25	per unit	Transformer Price	340000	\$	Market Value Rate	10.00	%
Size	18.00	MVA																		
Years in Service	25	years																		
Remaining Life	0.25	per unit																		
Transformer Price	340000	\$																		
Market Value Rate	10.00	%																		
Market Value Rate	10.00	%																		
Inflation Rate	0.00	%																		
Book Life	30	years																		

Conclusions

- **Developed an Optimization Model for the “Best Utilization” of a transformer:**
 - Transformer replacement strategy (retrofit design)
 - Optimum transformer sizing (new design)
- **Computer program is written to facilitate long and complex calculations**
- **Windows based computer program**
- **Asset management tools**

Future Work

- New programming is required for faster optimization computation
- The different depreciation method (economic model) shall be explored
- Loss-of-life and hottest-spot calculation shall be updated when more real data is made available
- Other financial model shall be explored
- Sensitivity analysis on Loss Ratio (R)

**Now publicly available
on the PSERC Website**

**PSERC Project Report:
Transformer Overloading and
Assessment of Loss-of-Life
for Liquid-Filled Transformers**

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