OPENING LECTURE

Review of Fuse Modelling Methods

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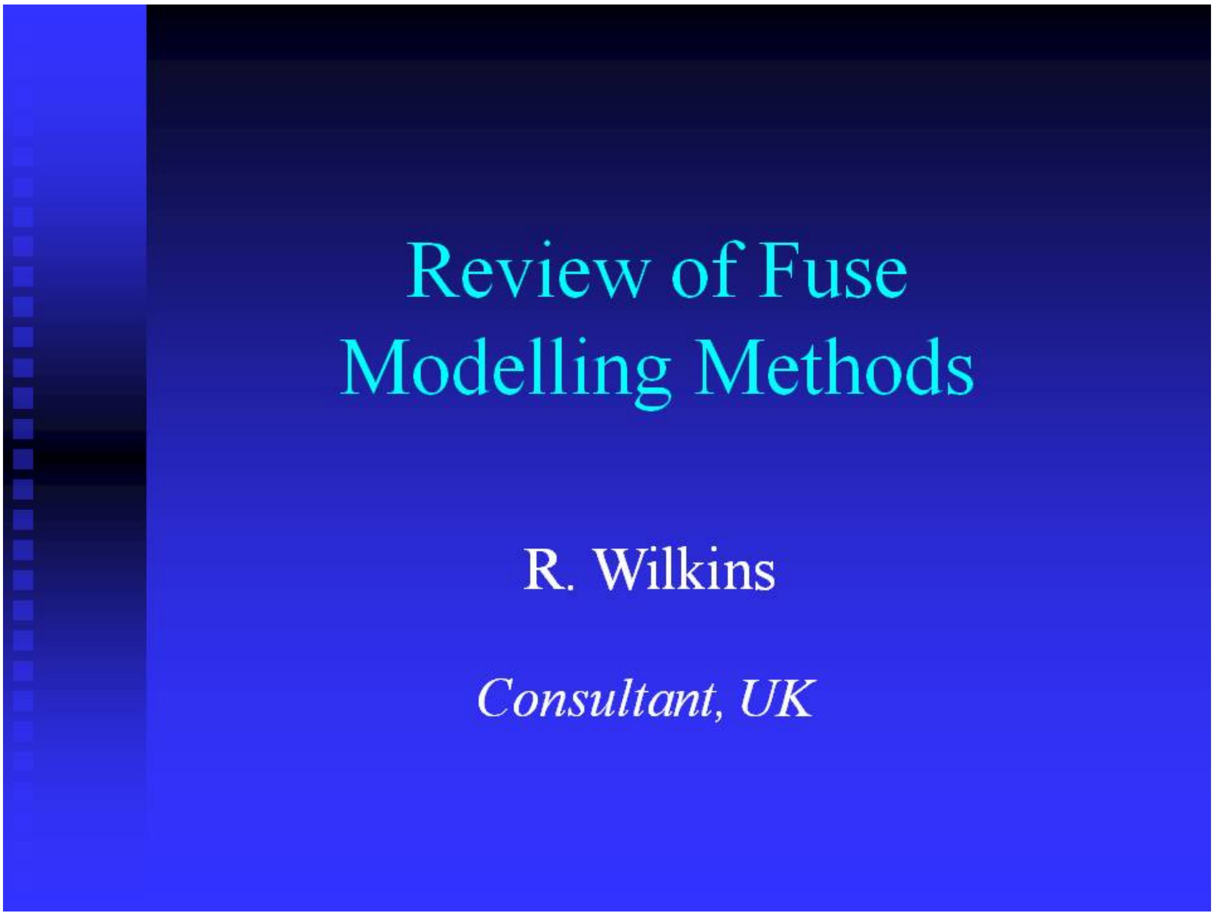
Abstract

Many people think that the fuse is a simple device. However this review shows that modelling fuse behaviour can be very complex, involving electrical circuits, electromagnetics, heat transfer, materials science, mechanical engineering, plasma physics and numerical methods. The review is restricted to those modelling methods which can be directly put to practical use in fuse design and applications. The key issues are highlighted, and significant progress is reported, when compared with the situation which existed at the time of the first ICEFA in 1976. A list of key reference is provided to accompany the review.

Keywords: electric fuses, modelling methods.



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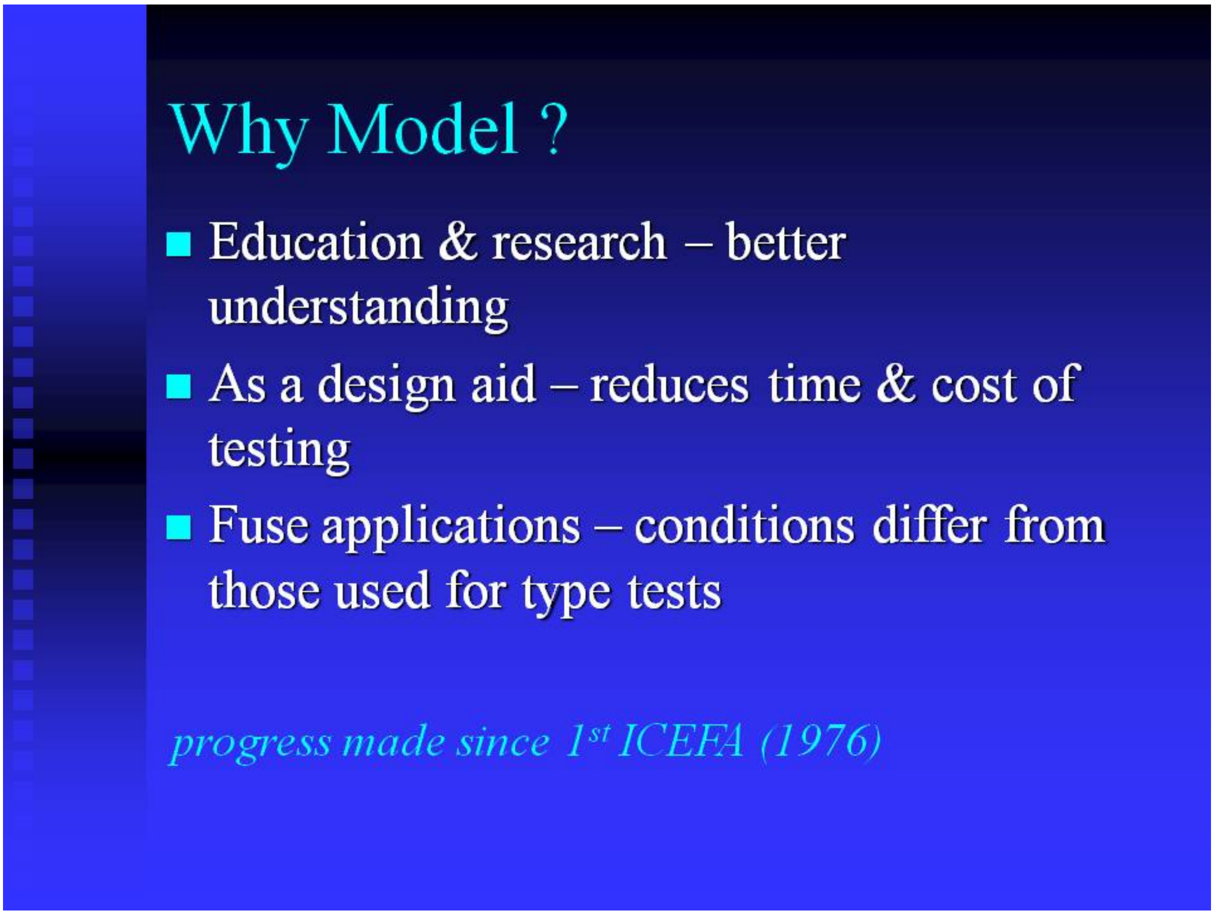
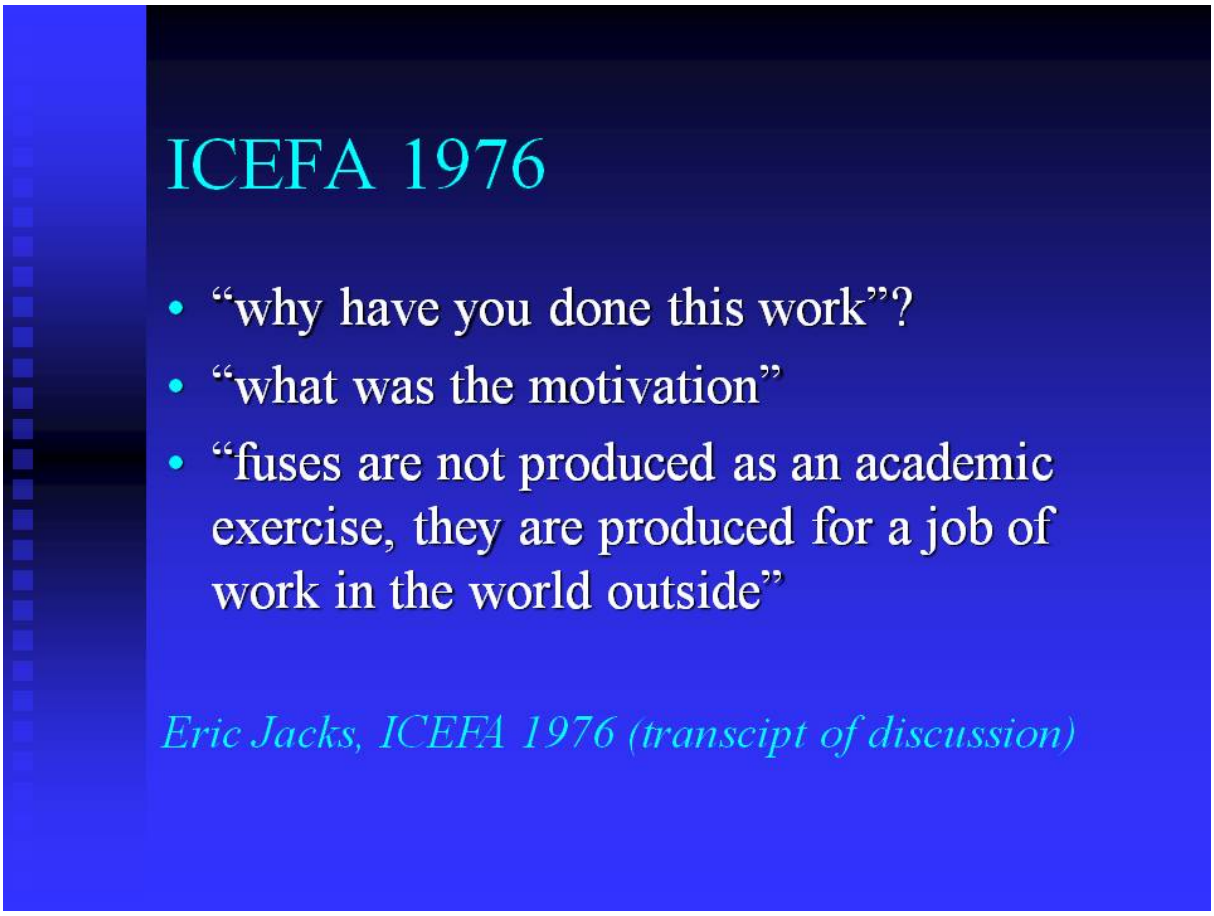


Why Model ?

- Education & research – better understanding
- As a design aid – reduces time & cost of testing
- Fuse applications – conditions differ from those used for type tests

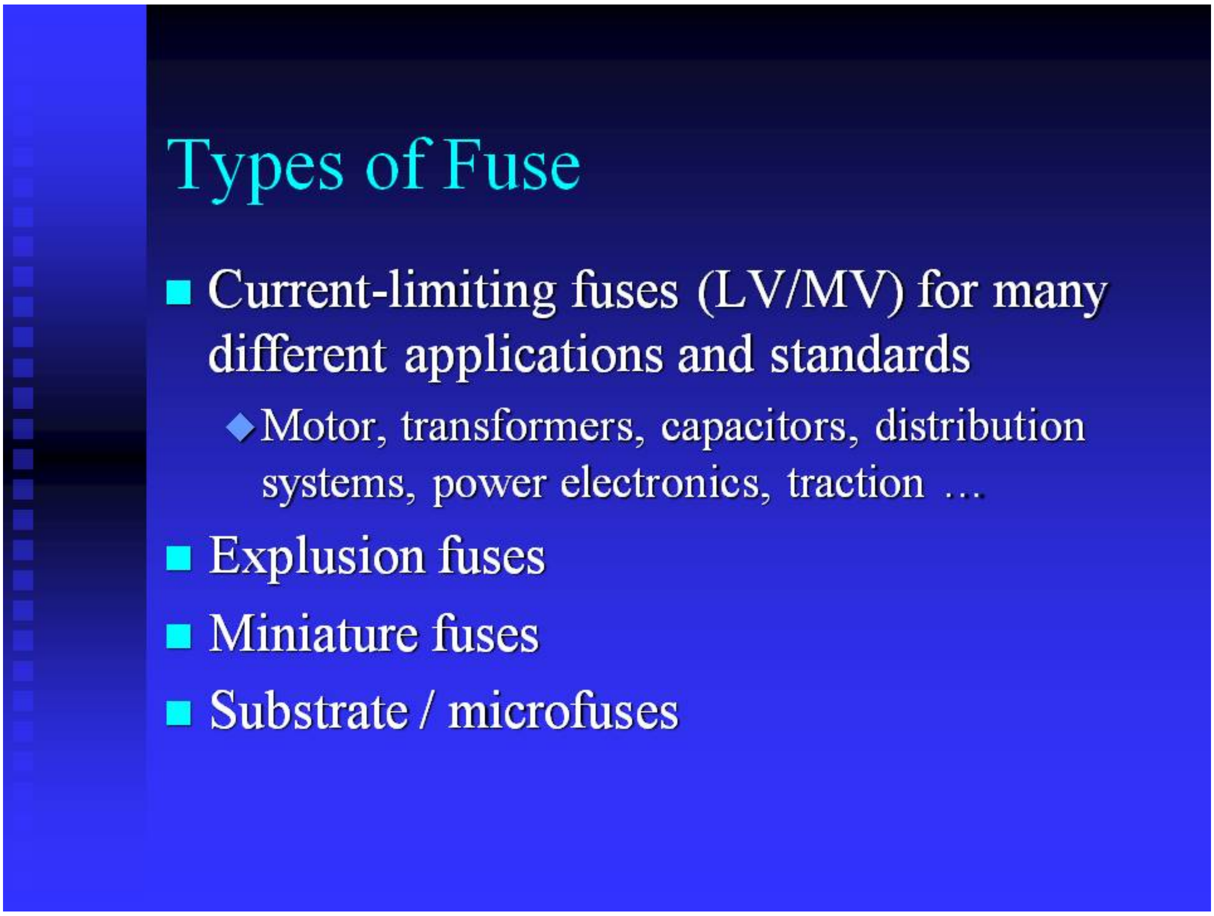
progress made since 1st ICEFA (1976)



ICEFA 1976

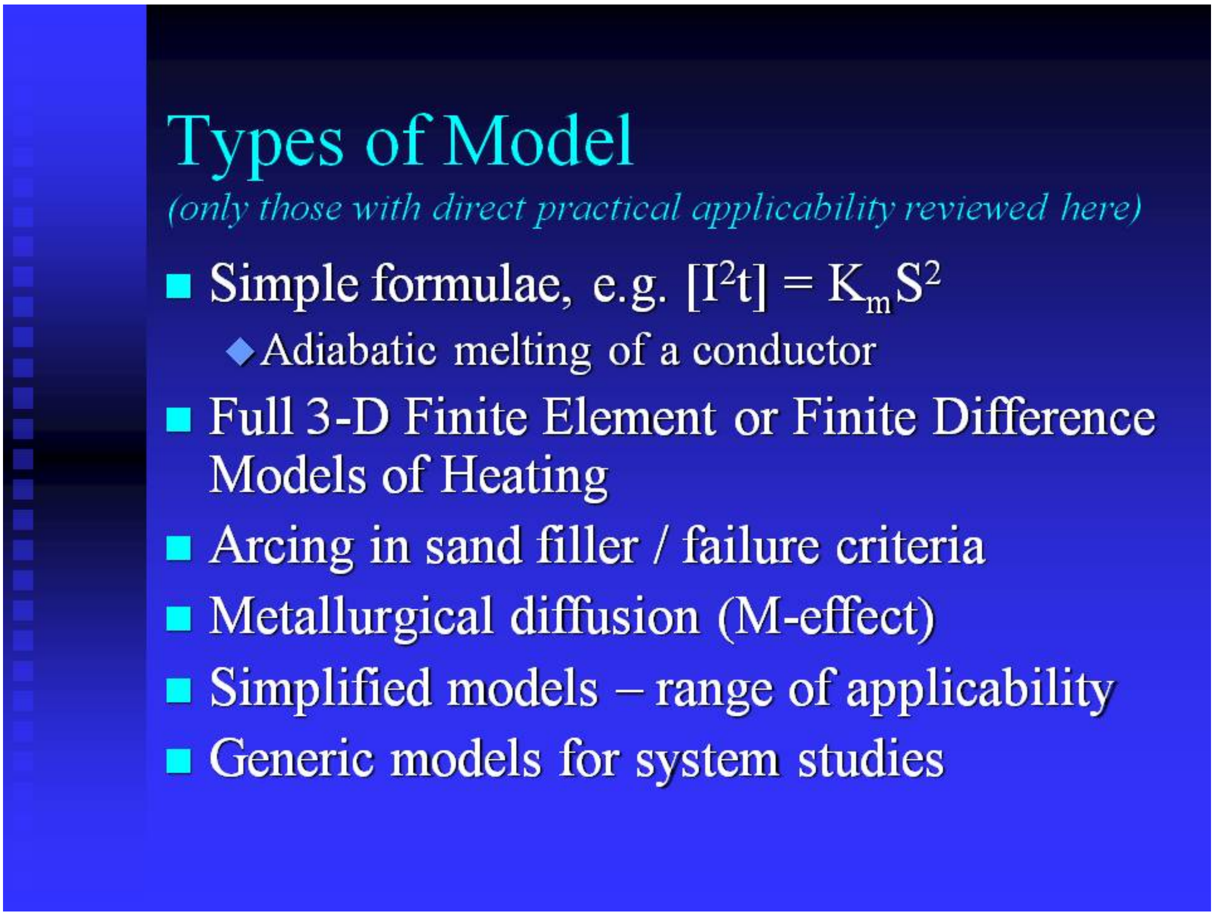
- “why have you done this work”?
- “what was the motivation”
- “fuses are not produced as an academic exercise, they are produced for a job of work in the world outside”

Eric Jacks, ICEFA 1976 (transcipt of discussion)



Types of Fuse

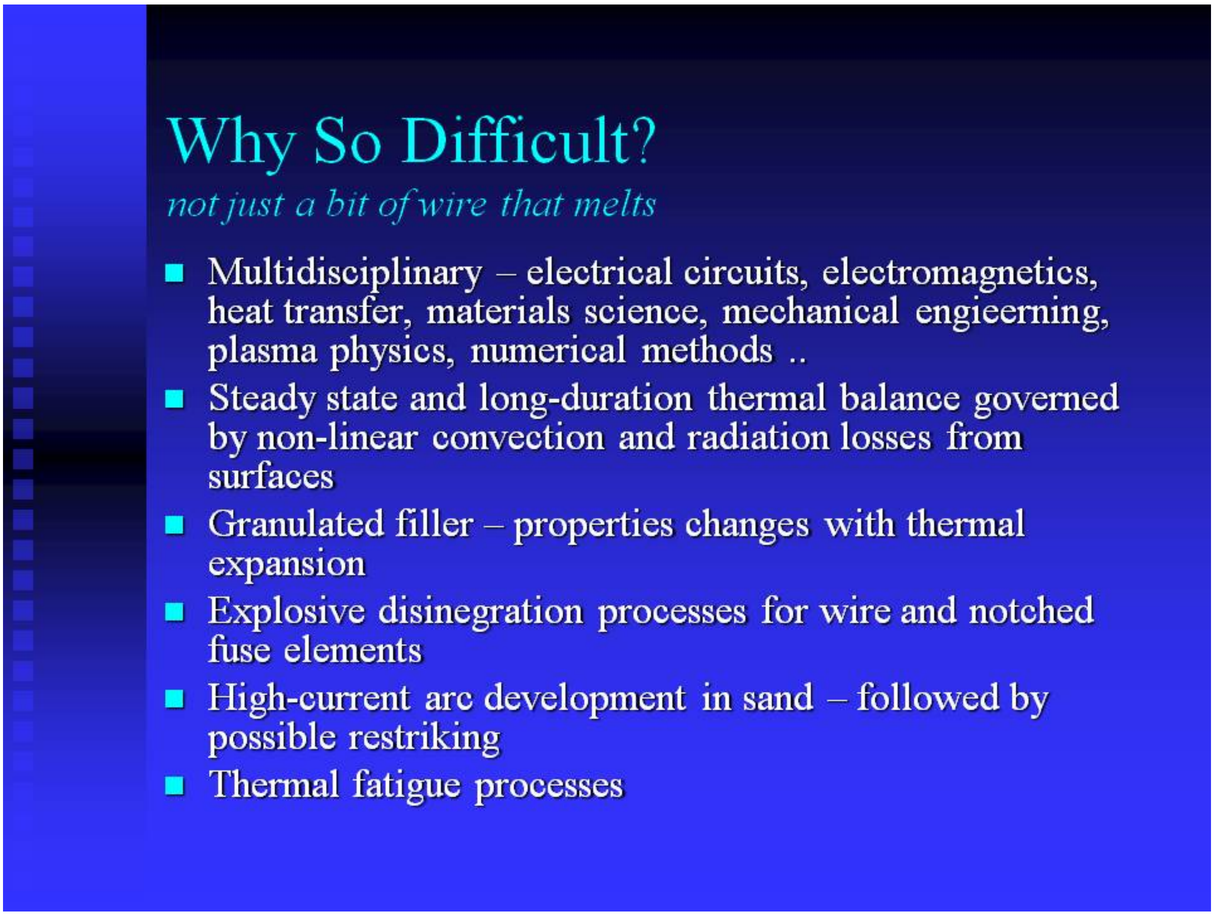
- Current-limiting fuses (LV/MV) for many different applications and standards
  - Motor, transformers, capacitors, distribution systems, power electronics, traction ….
- Explusion fuses
- Miniature fuses
- Substrate / microfuses



Types of Model

(only those with direct practical applicability reviewed here)

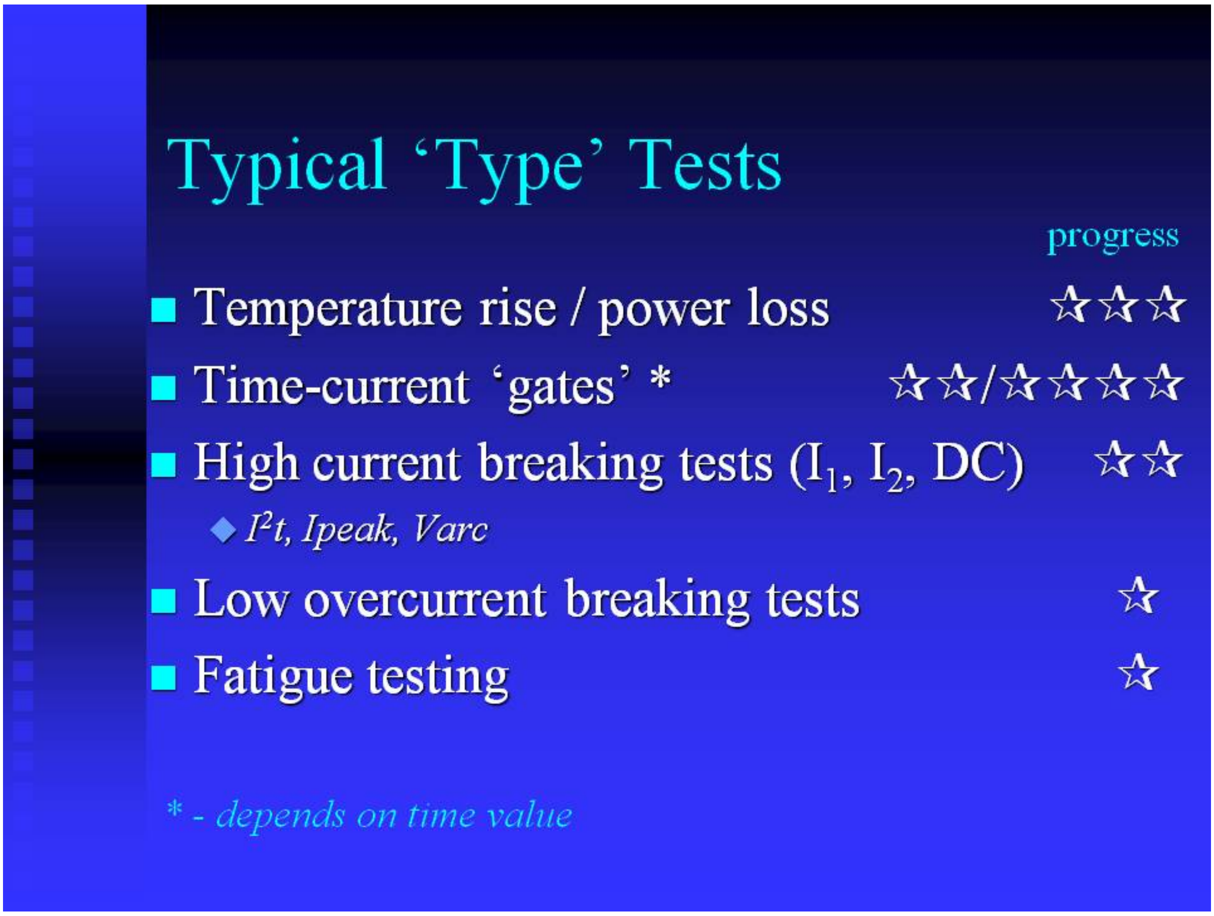
- Simple formulae, e.g. $[I^2t] = K_m S^2$
  - Adiabatic melting of a conductor
- Full 3-D Finite Element or Finite Difference Models of Heating
- Arcing in sand filler / failure criteria
- Metallurgical diffusion (M-effect)
- Simplified models – range of applicability
- Generic models for system studies



Why So Difficult?

not just a bit of wire that melts

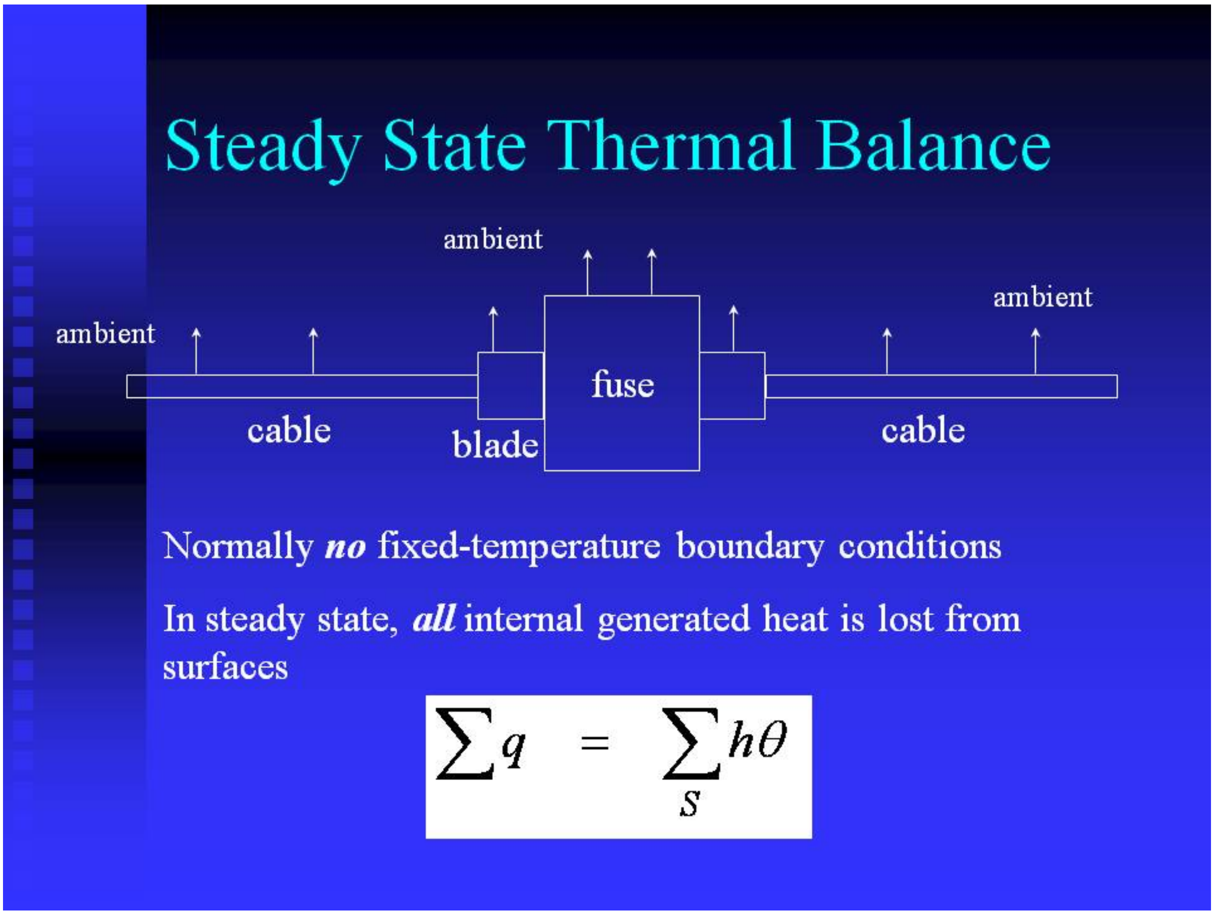
- Multidisciplinary – electrical circuits, electromagnetics, heat transfer, materials science, mechanical engieerning, plasma physics, numerical methods ..
- Steady state and long-duration thermal balance governed by non-linear convection and radiation losses from surfaces
- Granulated filler – properties changes with thermal expansion
- Explosive disinegration processes for wire and notched fuse elements
- High-current arc development in sand – followed by possible restriking
- Thermal fatigue processes



Typical 'Type' Tests

	progress
Temperature rise / power loss	☆☆☆
Time-current 'gates' *	☆☆/☆☆☆☆
High current breaking tests (I_1, I_2, DC) ◆ I^2t, *Ipeak, Varc*	☆☆
Low overcurrent breaking tests	☆
Fatigue testing	☆

** - depends on time value*

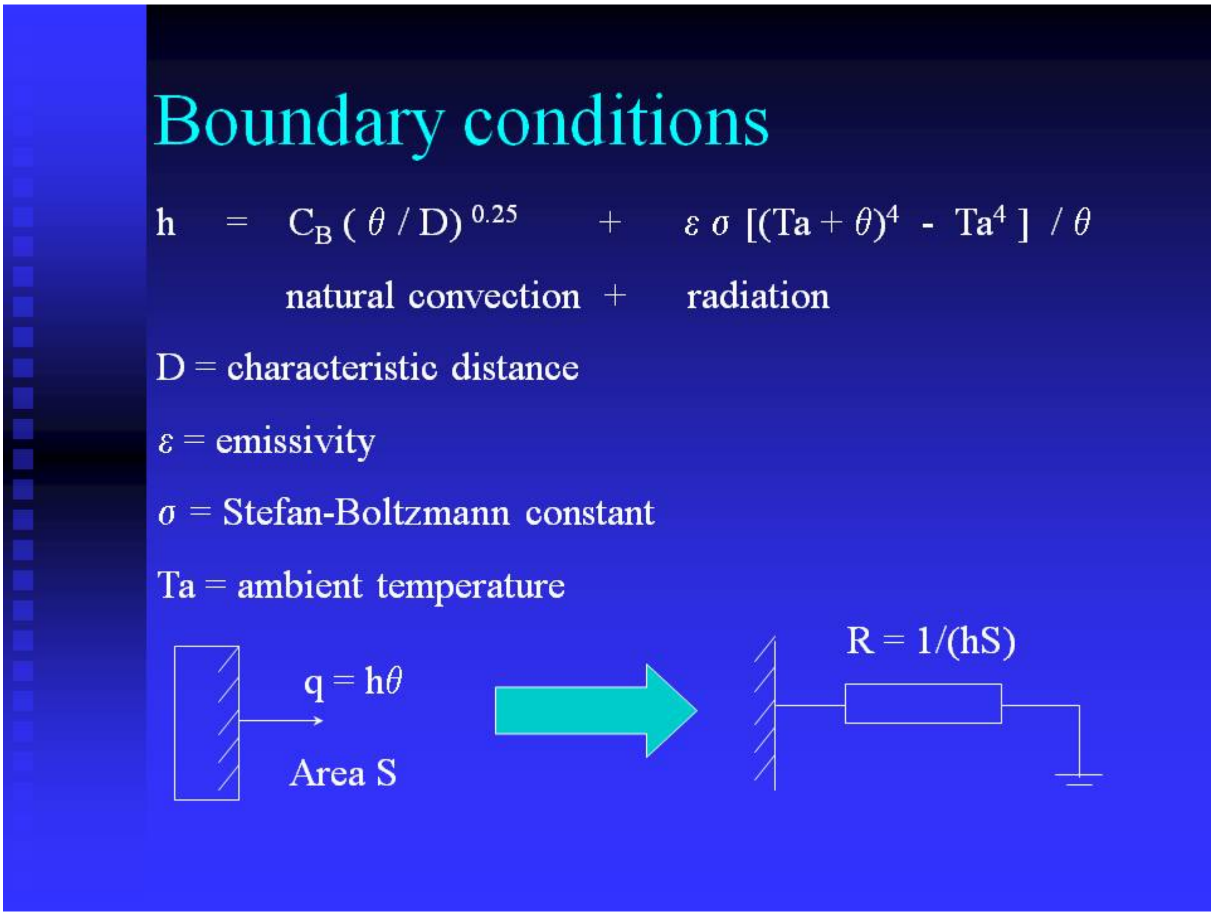


Steady State Thermal Balance

Normally ***no*** fixed-temperature boundary conditions

In steady state, ***all*** internal generated heat is lost from surfaces

$$\sum q = \sum_{S} h\theta$$



Boundary conditions

$h = C_B(\theta / D)^{0.25} + \varepsilon\sigma[(Ta + \theta)^4 - Ta^4] / \theta$

natural convection + radiation

D = characteristic distance

ε = emissivity

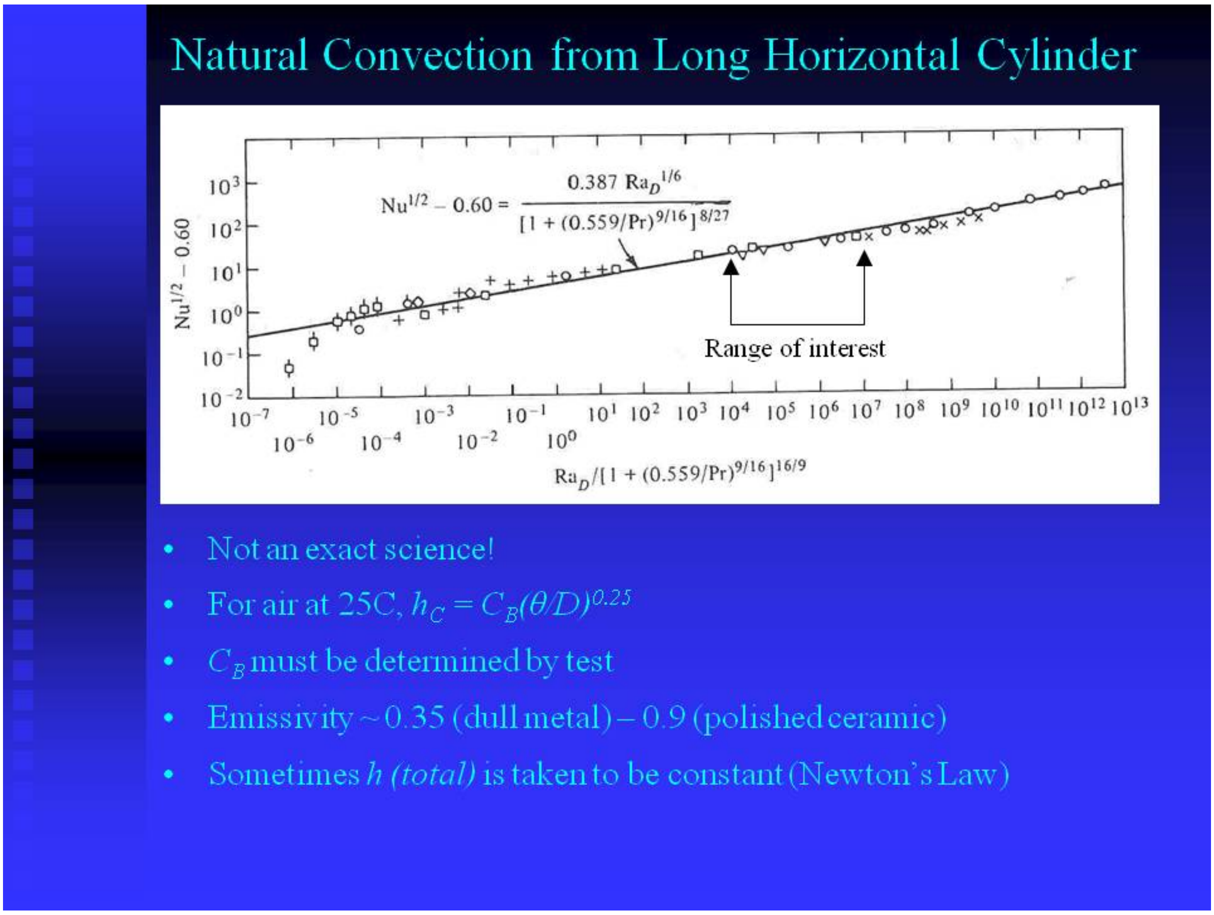
σ = Stefan-Boltzmann constant

Ta = ambient temperature

$q = h\theta$

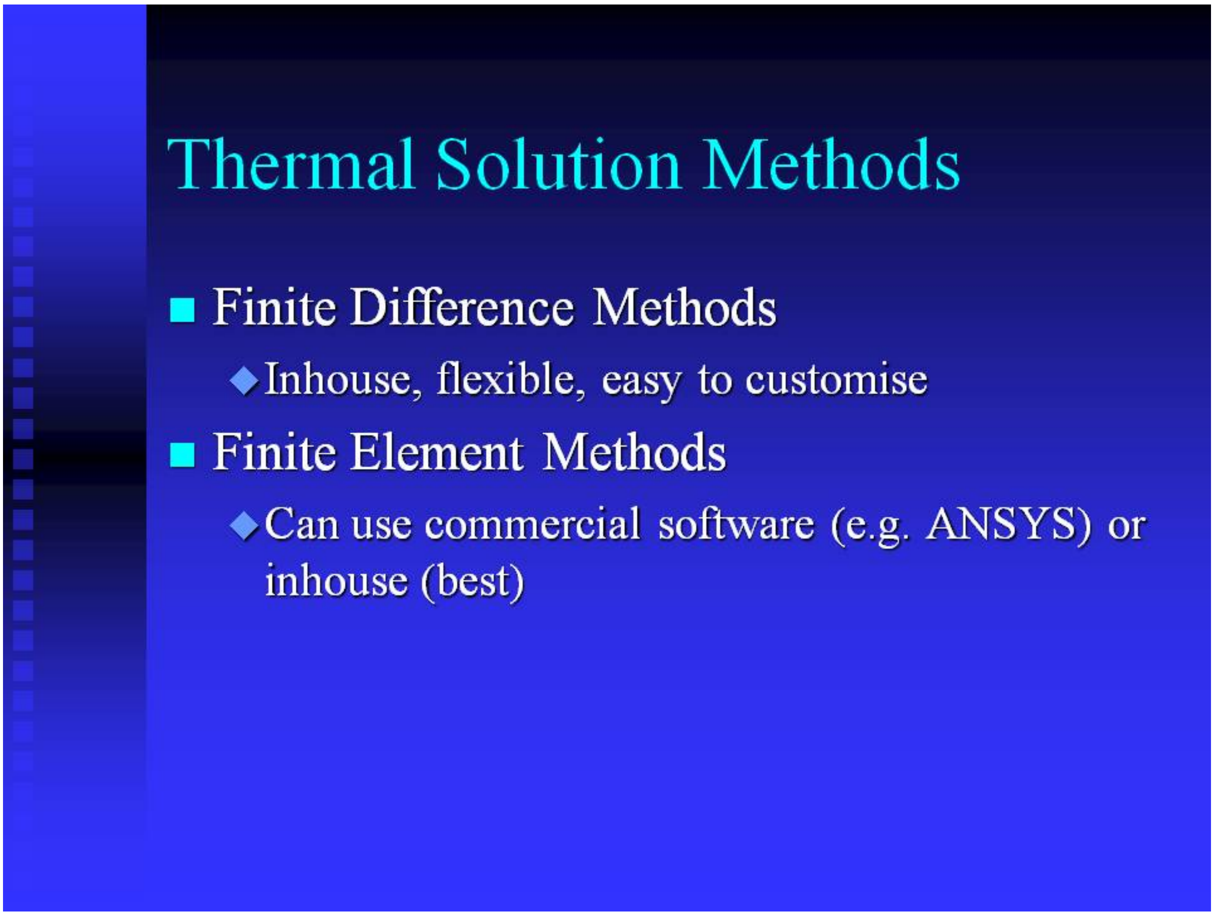
Area S

$R = 1/(hS)$



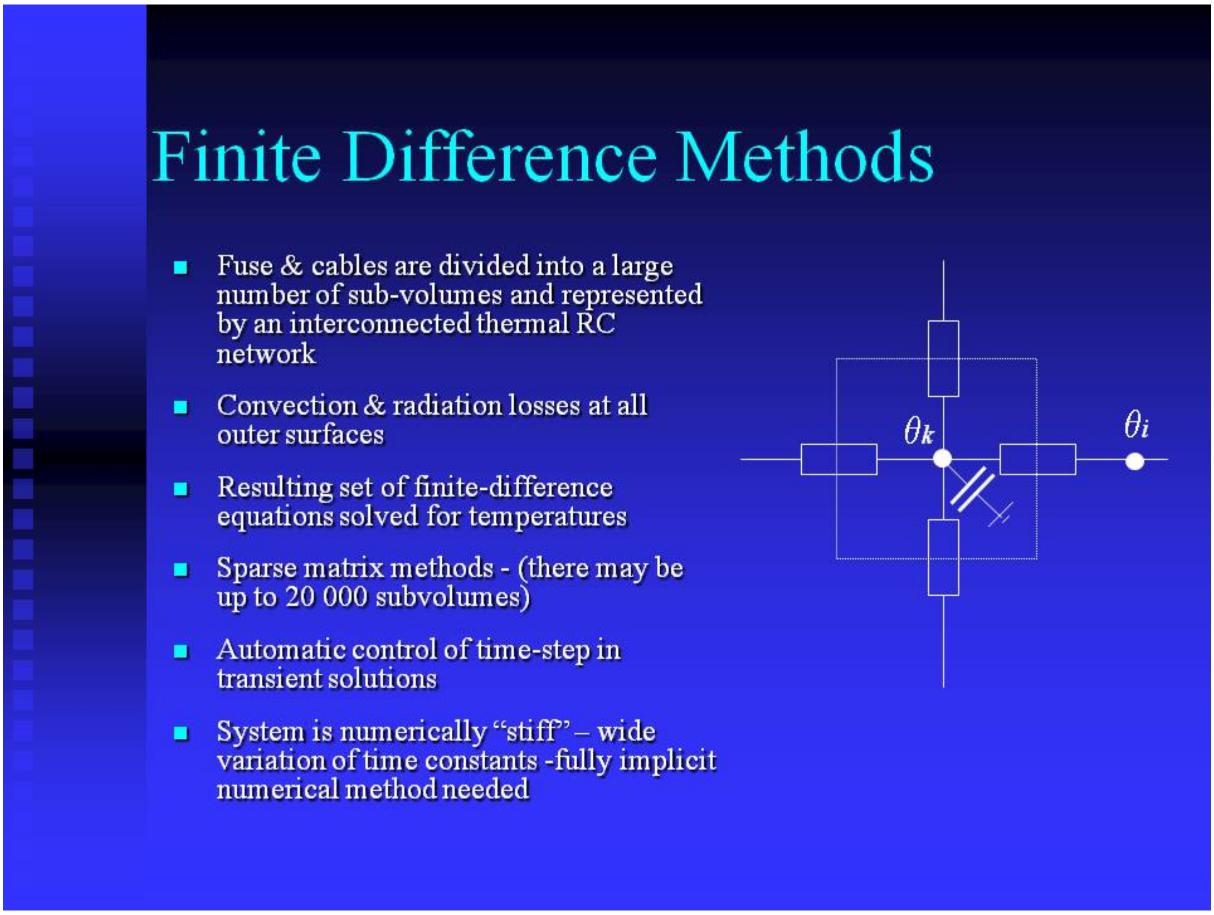
Natural Convection from Long Horizontal Cylinder

- Not an exact science!
- For air at 25C, $h_C = C_B(\theta/D)^{0.25}$
- C_B must be determined by test
- Emissivity ~ 0.35 (dull metal) – 0.9 (polished ceramic)
- Sometimes *h (total)* is taken to be constant (Newton's Law)



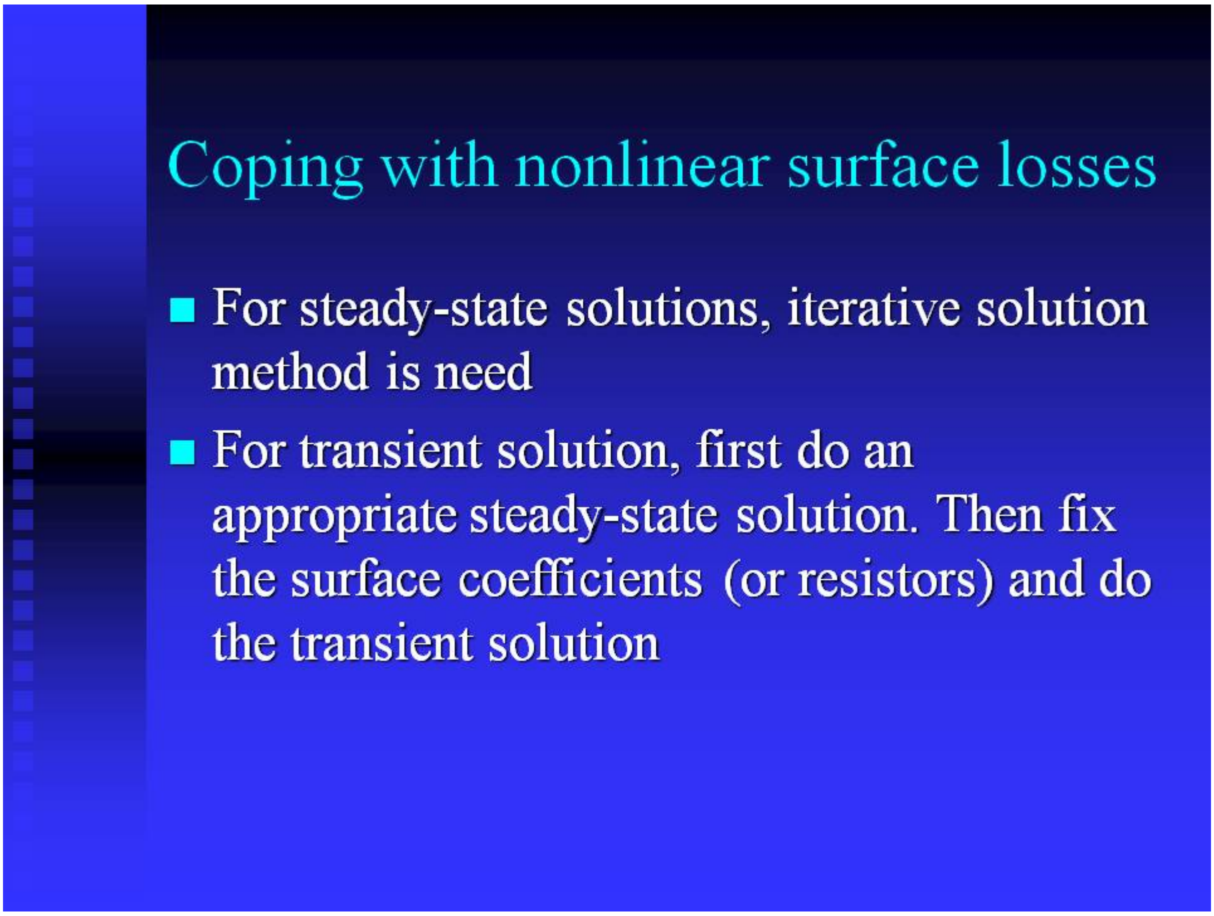
Thermal Solution Methods

- Finite Difference Methods
  - Inhouse, flexible, easy to customise
- Finite Element Methods
  - Can use commercial software (e.g. ANSYS) or inhouse (best)



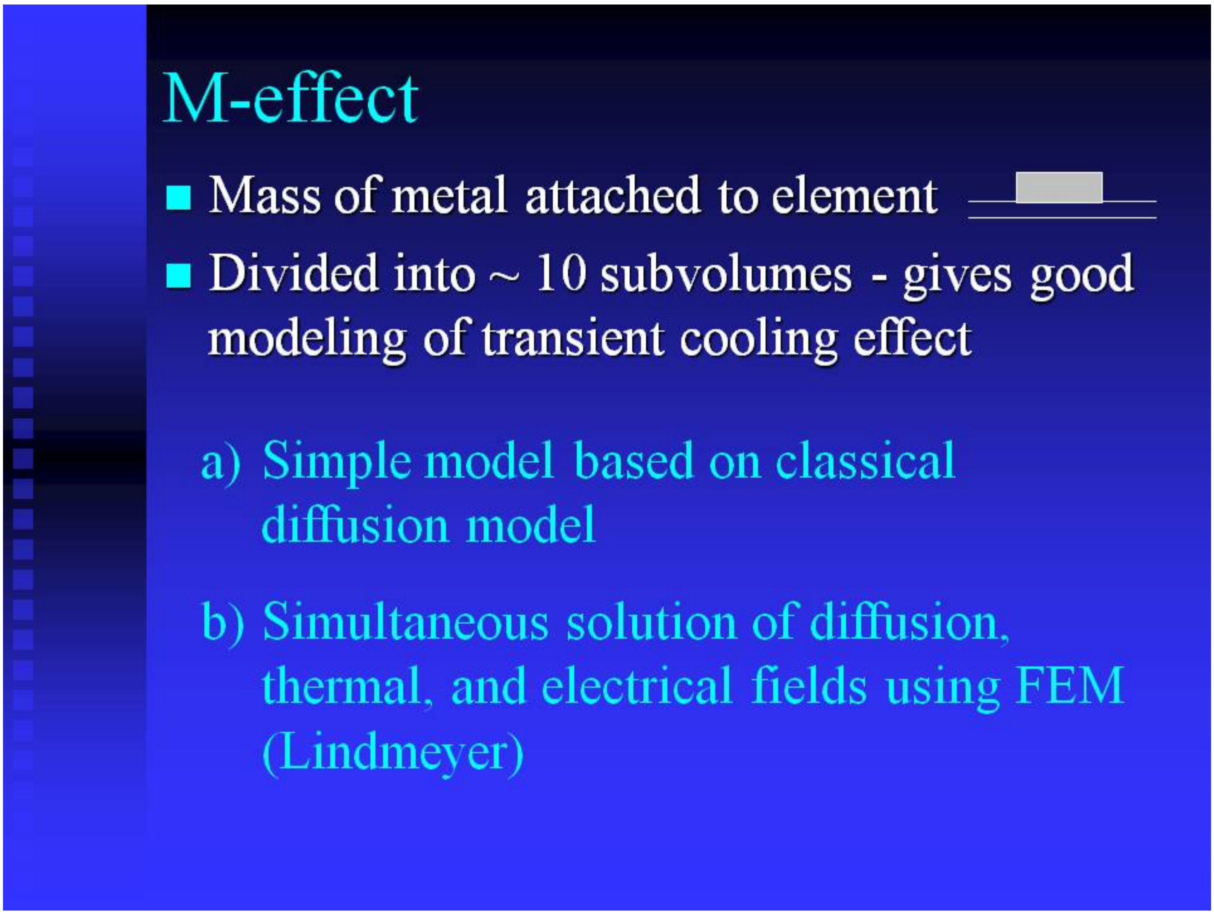
Finite Difference Methods

- Fuse & cables are divided into a large number of sub-volumes and represented by an interconnected thermal RC network
- Convection & radiation losses at all outer surfaces
- Resulting set of finite-difference equations solved for temperatures
- Sparse matrix methods - (there may be up to 20 000 subvolumes)
- Automatic control of time-step in transient solutions
- System is numerically “stiff” – wide variation of time constants -fully implicit numerical method needed



Coping with nonlinear surface losses

- For steady-state solutions, iterative solution method is need
- For transient solution, first do an appropriate steady-state solution. Then fix the surface coefficients (or resistors) and do the transient solution

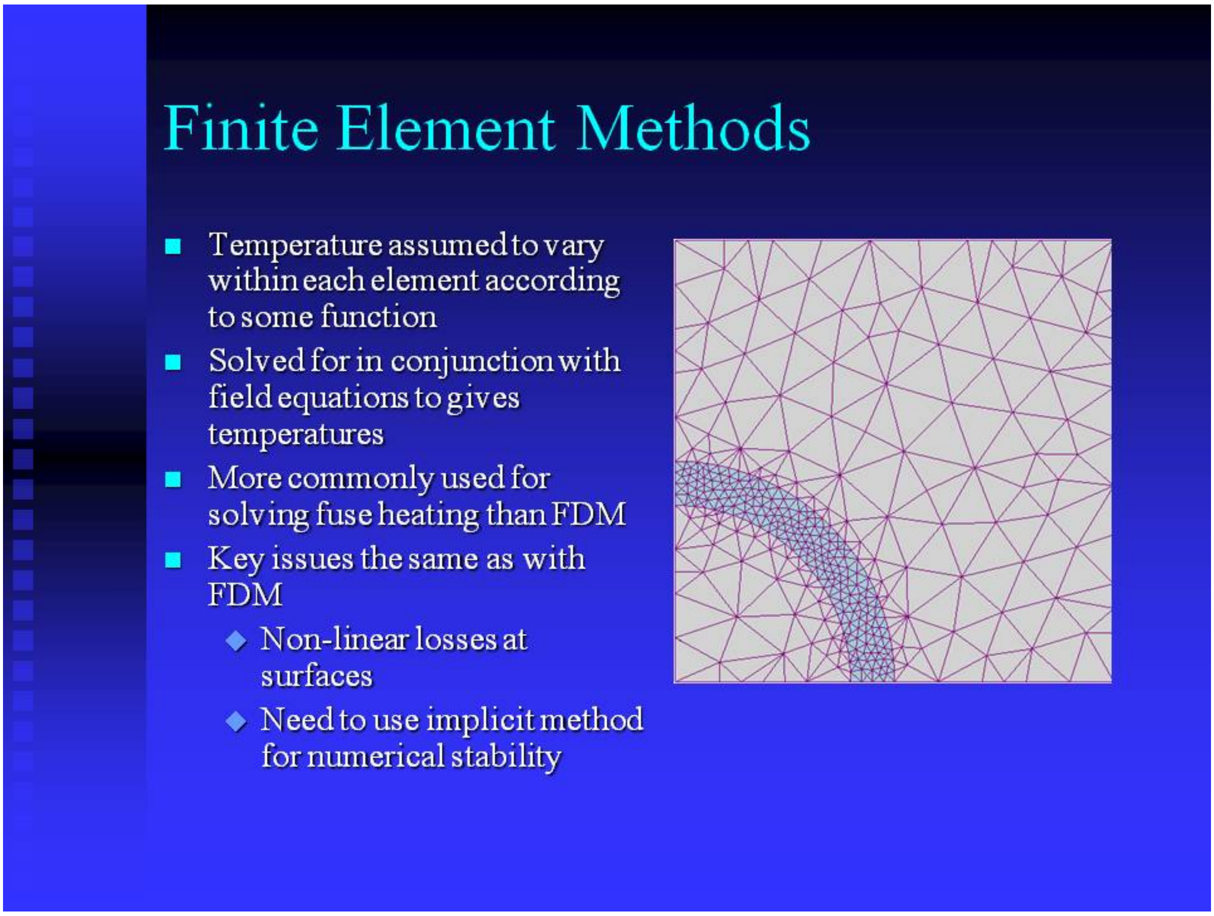


M-effect

- Mass of metal attached to element
- Divided into ~ 10 subvolumes - gives good modeling of transient cooling effect

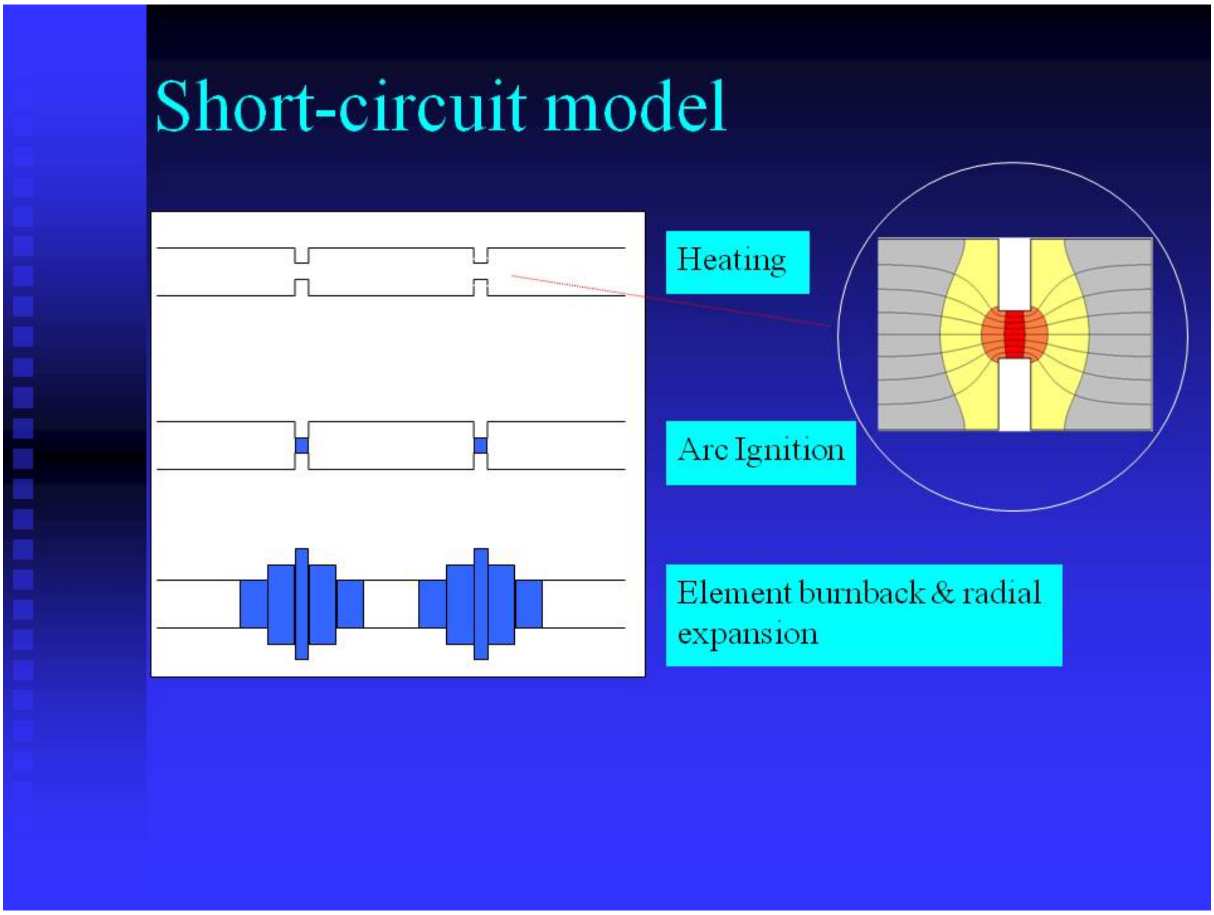
a) Simple model based on classical diffusion model

b) Simultaneous solution of diffusion, thermal, and electrical fields using FEM (Lindmeyer)



Finite Element Methods

- Temperature assumed to vary within each element according to some function
- Solved for in conjunction with field equations to gives temperatures
- More commonly used for solving fuse heating than FDM
- Key issues the same as with FDM
  - Non-linear losses at surfaces
  - Need to use implicit method for numerical stability

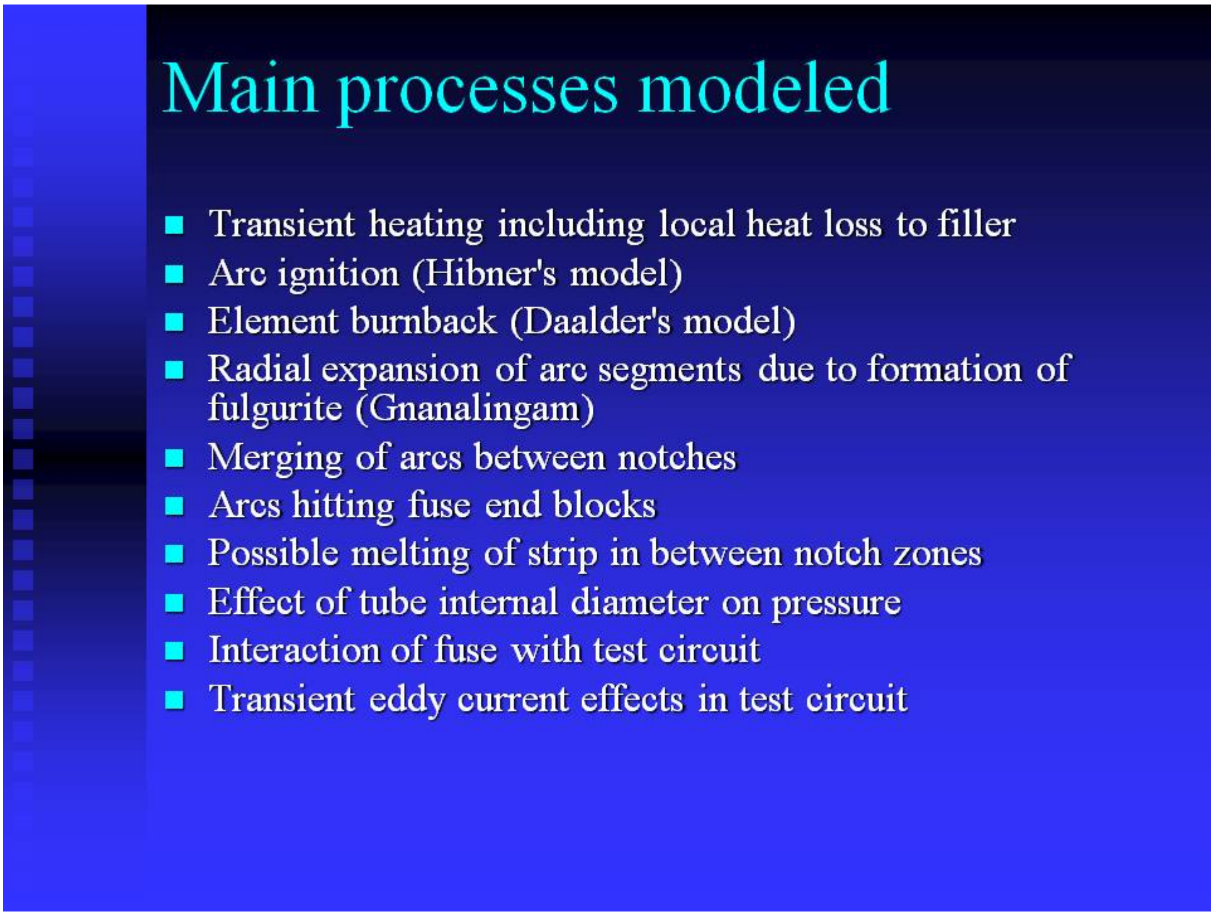


Short-circuit model

Heating

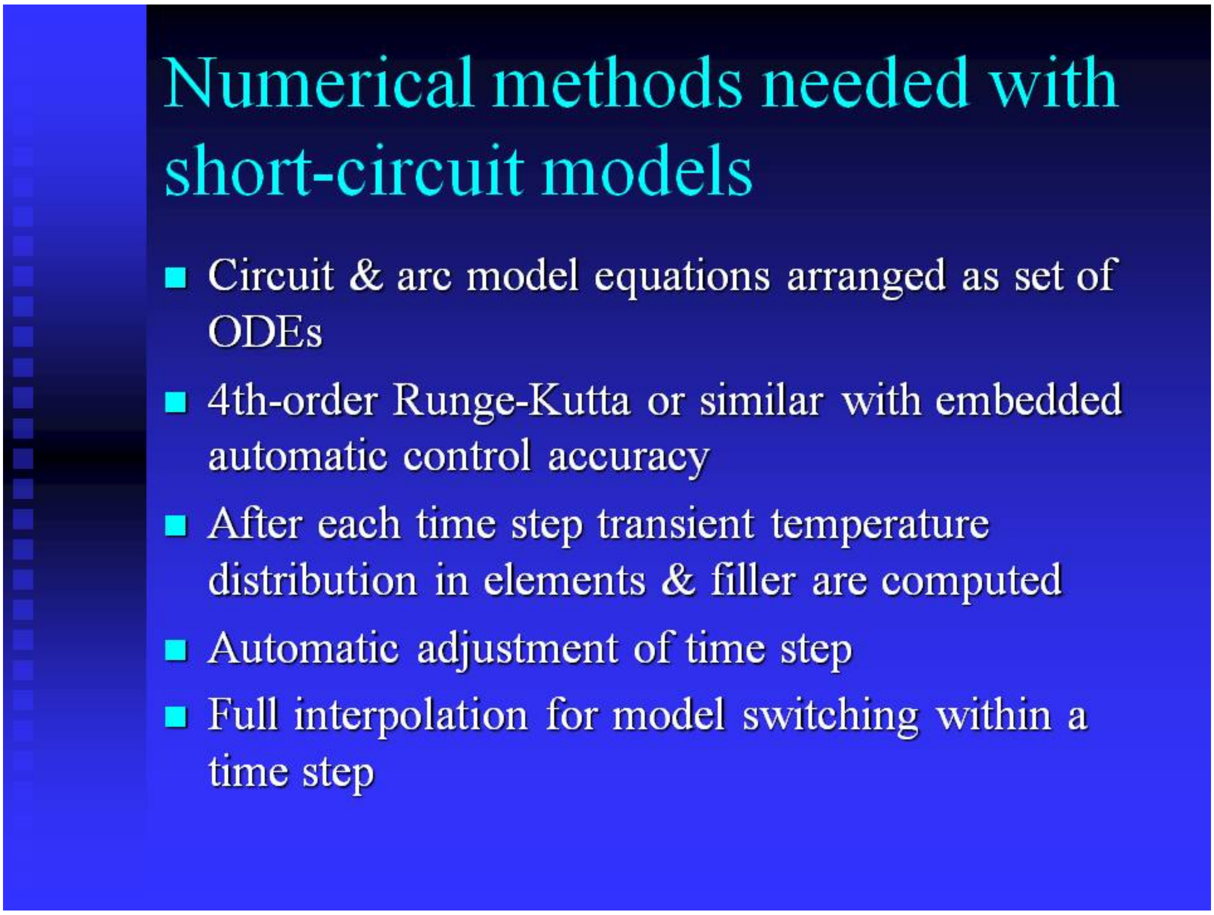
Arc Ignition

Element burnback & radial expansion



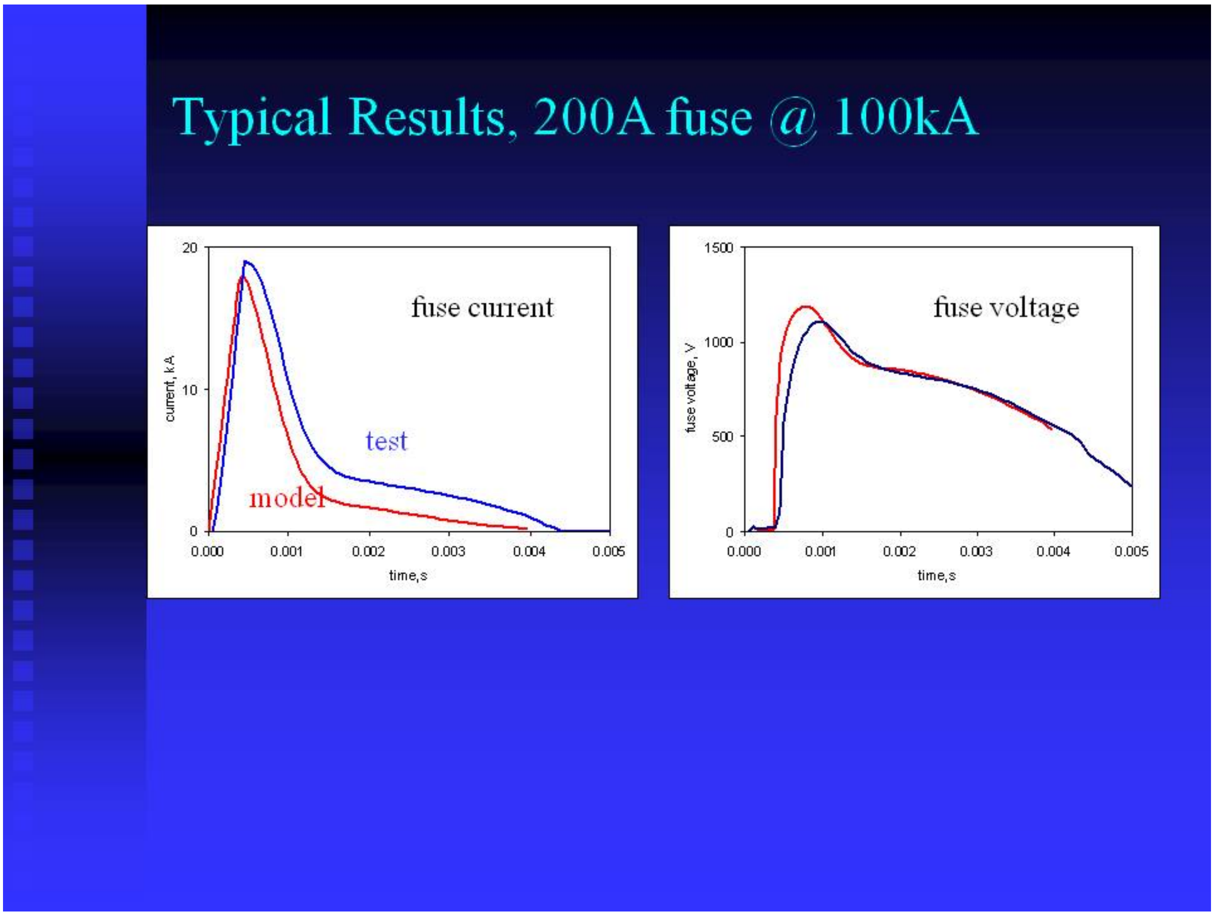
Main processes modeled

- Transient heating including local heat loss to filler
- Arc ignition (Hibner's model)
- Element burnback (Daalder's model)
- Radial expansion of arc segments due to formation of fulgurite (Gnanalingam)
- Merging of arcs between notches
- Arcs hitting fuse end blocks
- Possible melting of strip in between notch zones
- Effect of tube internal diameter on pressure
- Interaction of fuse with test circuit
- Transient eddy current effects in test circuit

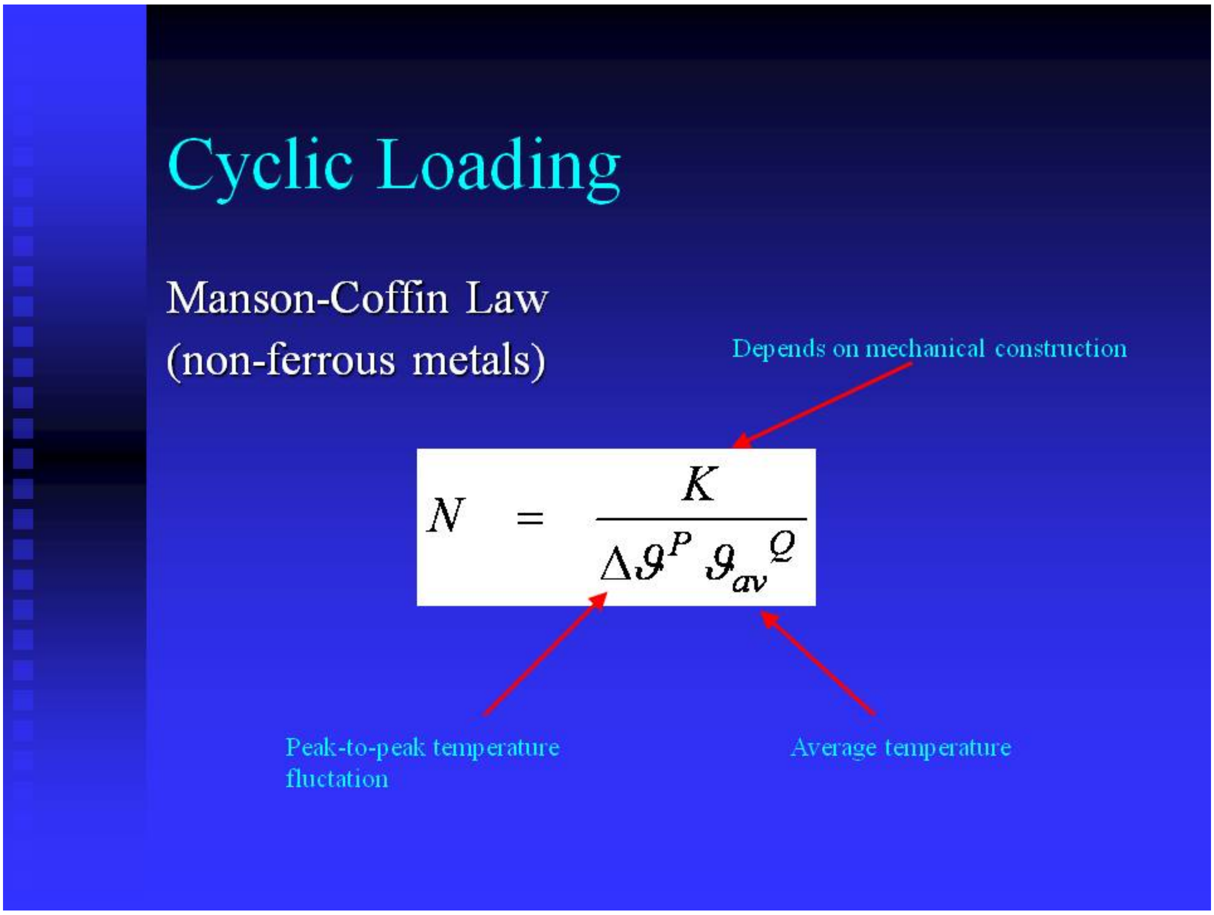


Numerical methods needed with short-circuit models

- Circuit & arc model equations arranged as set of ODEs
- 4th-order Runge-Kutta or similar with embedded automatic control accuracy
- After each time step transient temperature distribution in elements & filler are computed
- Automatic adjustment of time step
- Full interpolation for model switching within a time step



Typical Results, 200A fuse @ 100kA



Cyclic Loading

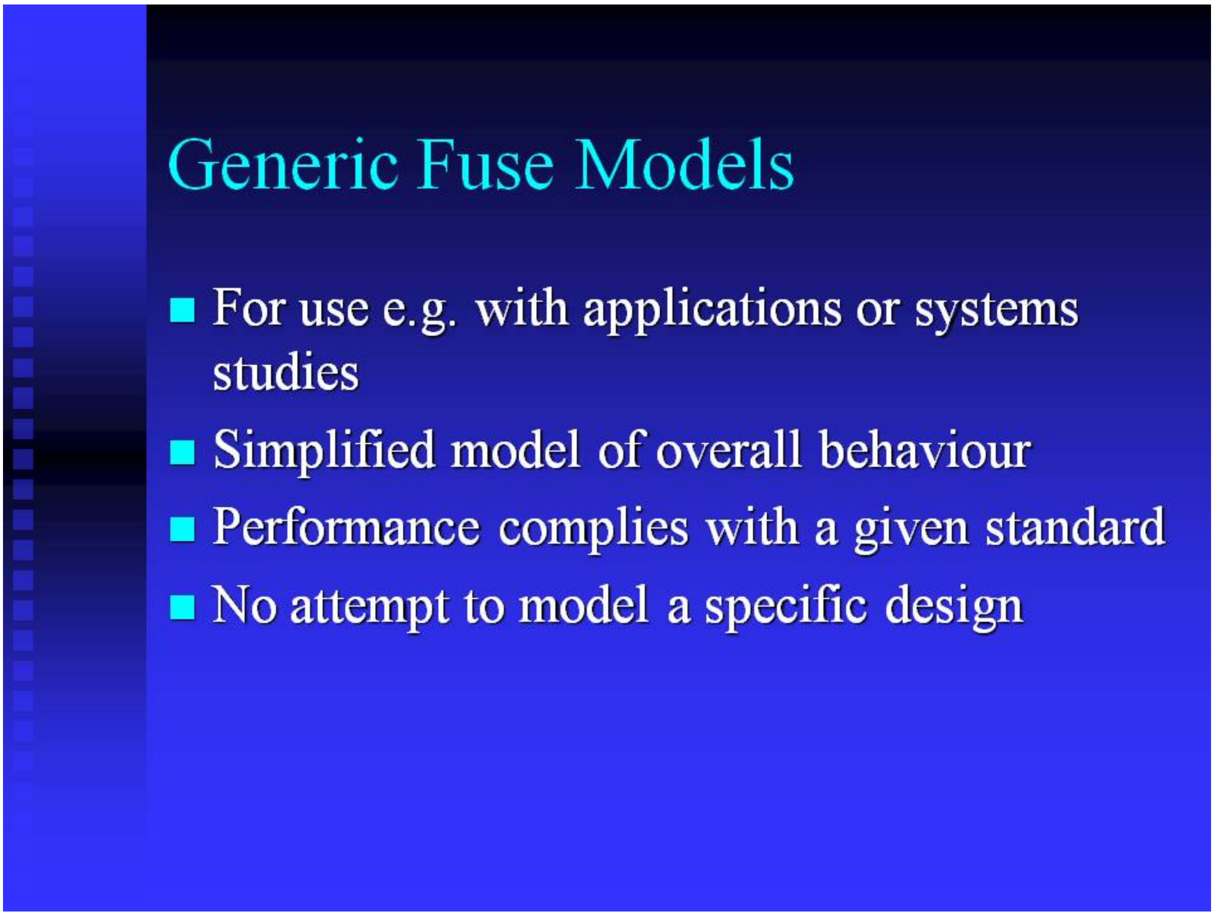
Manson-Coffin Law
(non-ferrous metals)

Depends on mechanical construction

$$N = \frac{K}{\Delta\vartheta^{P}\,\vartheta_{av}{}^{Q}}$$

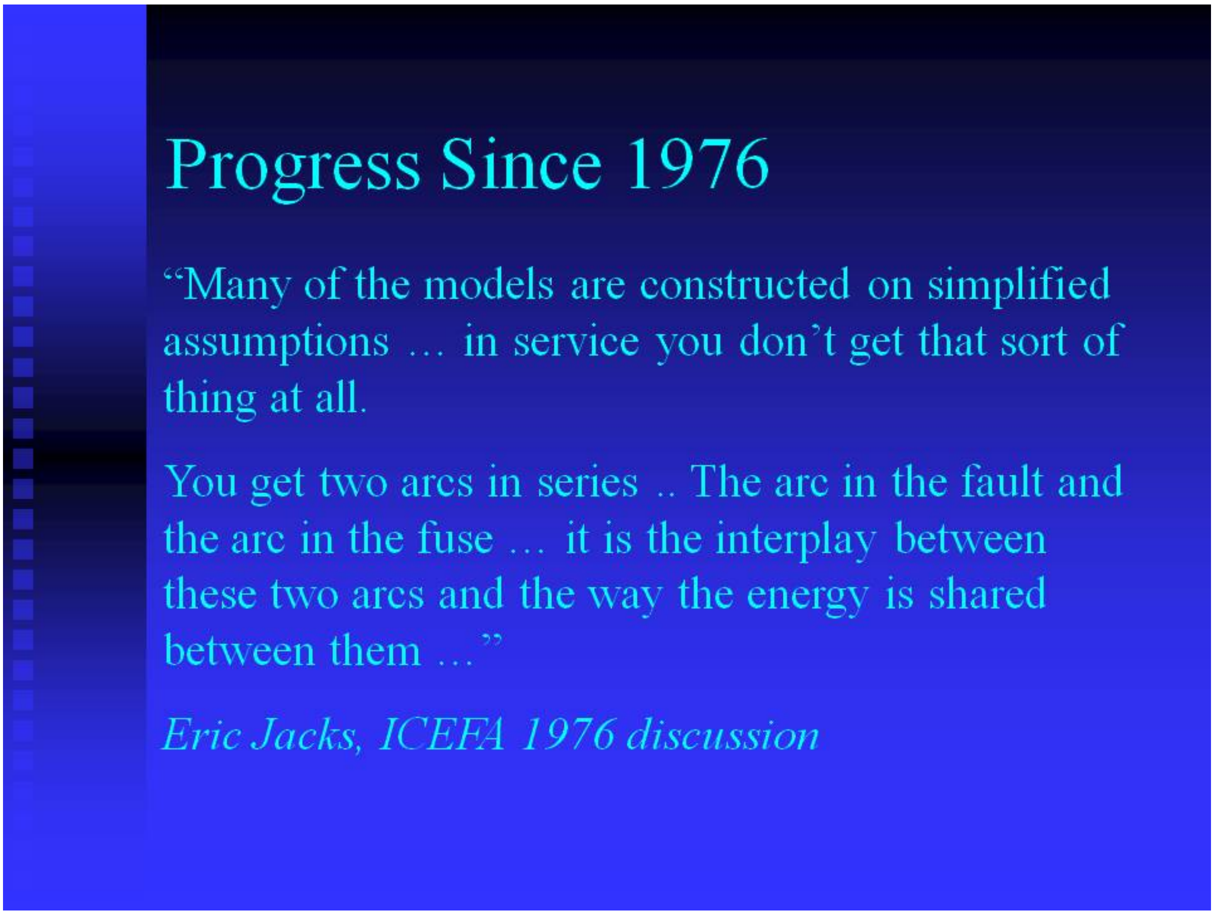
Peak-to-peak temperature fluctation

Average temperature



Generic Fuse Models

- For use e.g. with applications or systems studies
- Simplified model of overall behaviour
- Performance complies with a given standard
- No attempt to model a specific design

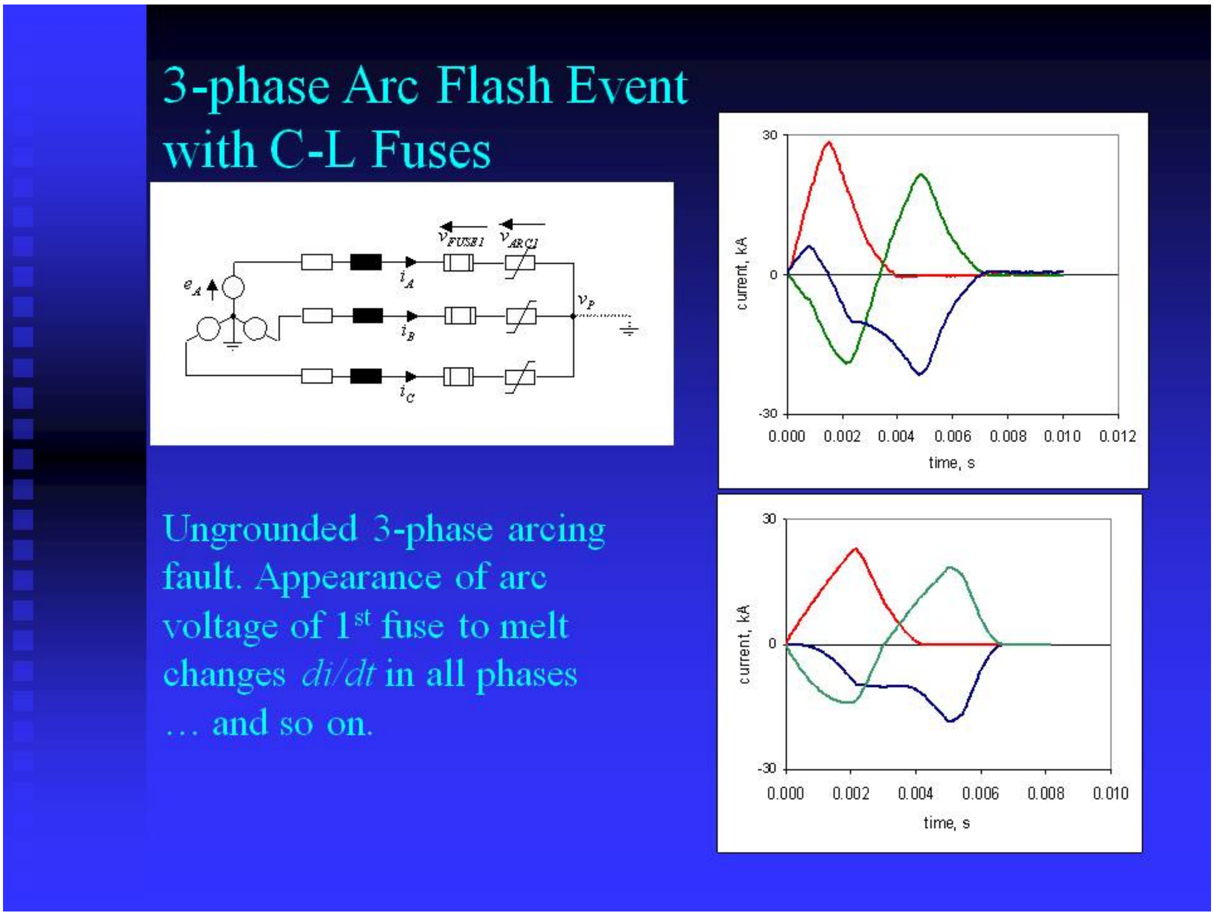


Progress Since 1976

"Many of the models are constructed on simplified assumptions … in service you don't get that sort of thing at all.

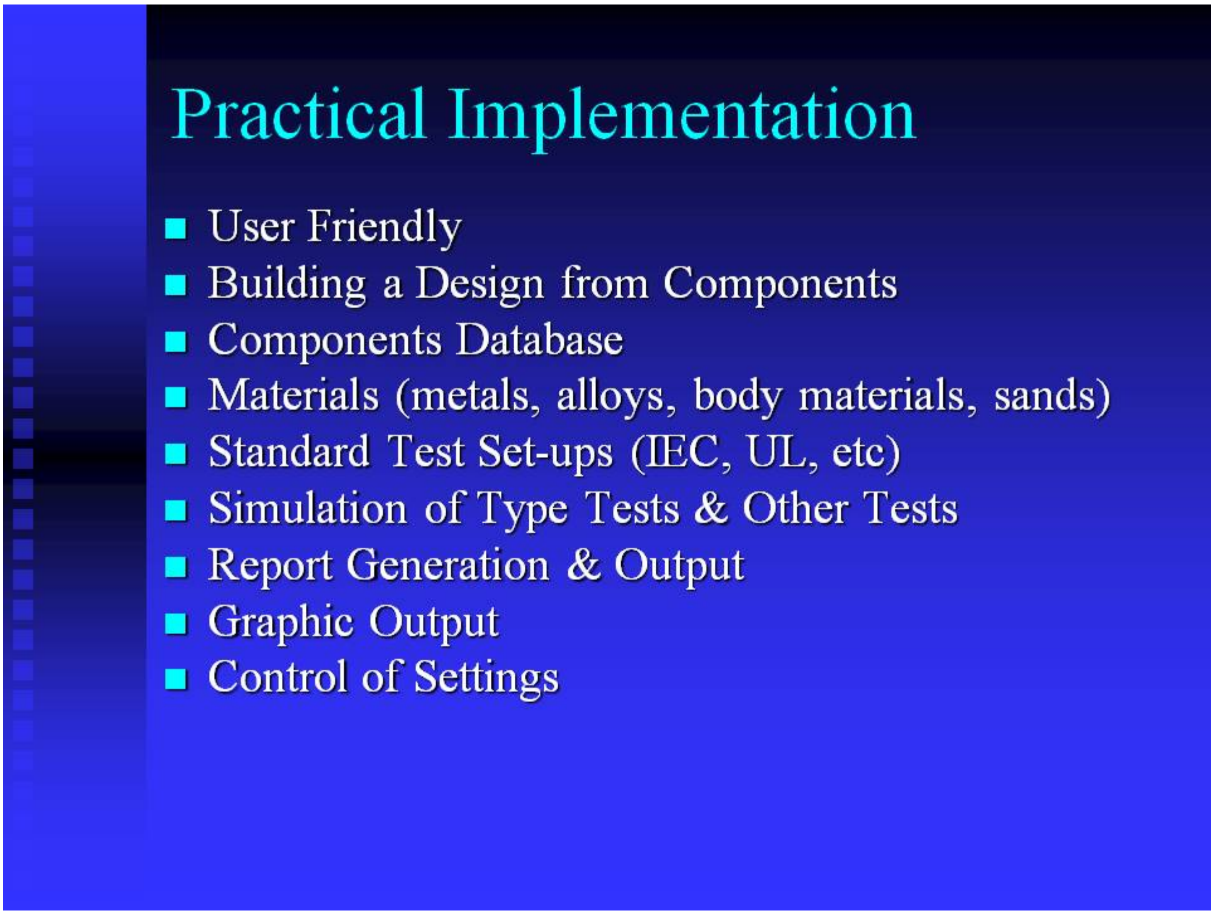
You get two arcs in series .. The arc in the fault and the arc in the fuse … it is the interplay between these two arcs and the way the energy is shared between them …"

Eric Jacks, ICEFA 1976 discussion



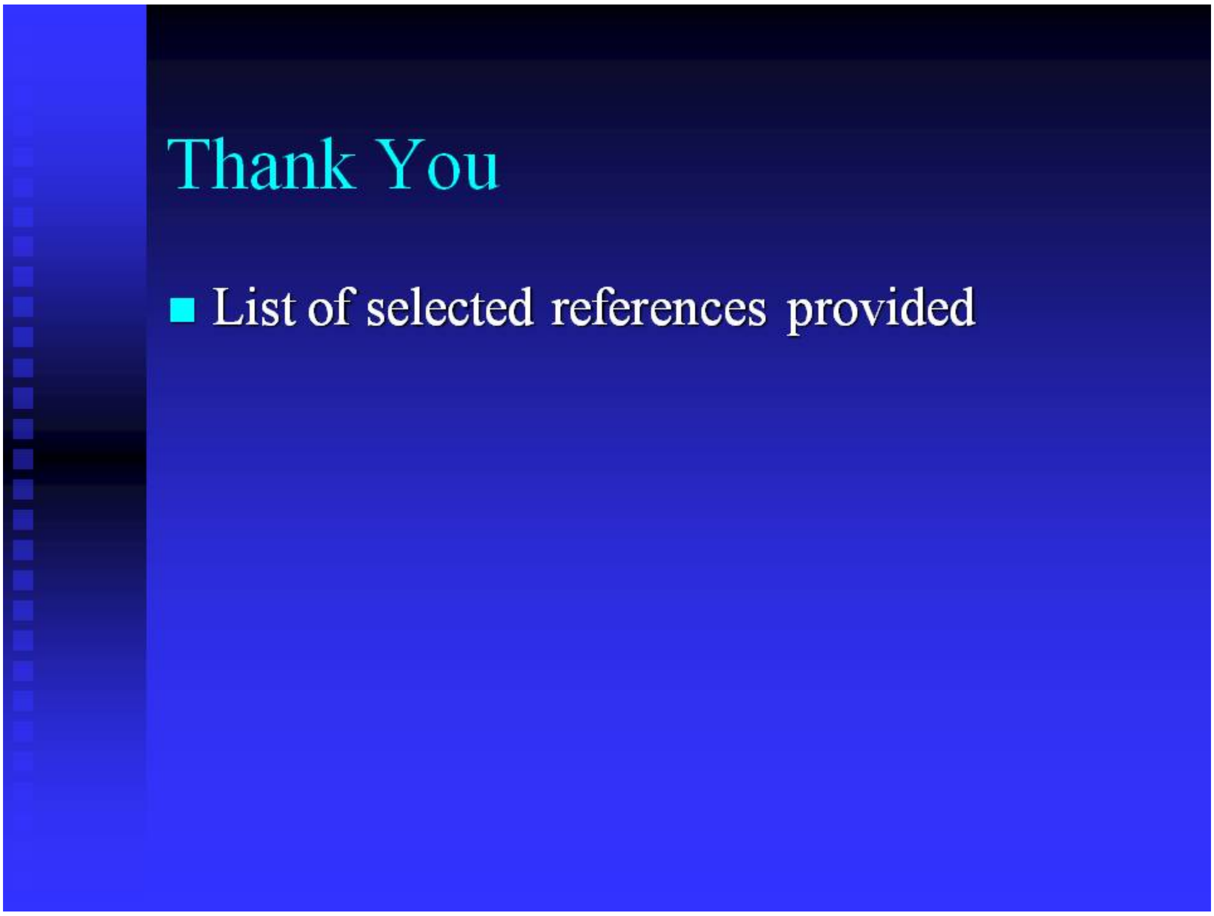
3-phase Arc Flash Event with C-L Fuses

Ungrounded 3-phase arcing fault. Appearance of arc voltage of 1st fuse to melt changes *di/dt* in all phases … and so on.



Practical Implementation

- User Friendly
- Building a Design from Components
- Components Database
- Materials (metals, alloys, body materials, sands)
- Standard Test Set-ups (IEC, UL, etc)
- Simulation of Type Tests & Other Tests
- Report Generation & Output
- Graphic Output
- Control of Settings



Thank You

- List of selected references provided

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ICEFA 2011

9th INTERNATIONAL CONFERENCE ON ELECTRICAL FUSES AND THEIR APPLICATIONS

LABVIEW APPLICATION TO CONTROL A NEW TYPE OF HIGH BREAKING CAPACITY FUSE

Adrian Plesca