Industrial Advisory Group

Heat Transfer in Polymers

Chris Brown

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Introduction: why heat transfer in polymers?

- To help enhance productivity
  - Faster heat transfer means better equipment utilisation
  - Energy saving

- To help reduce scrap rates
  - Remove hot spots / degradation
  - Uniform cooling to avoid warpage

- To make better use of materials
  - With known thermal conductivities
- To ensure efficient heat transfers across interfaces
  - With known heat transfer coefficients

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Outline

- Heat transfer at surfaces & interfaces (the heat transfer coefficient)
- Thermal conductivity
- Simulation (shows how important good data are)
- Industrial demonstrations of the importance of heat transfer in polymers
- A Eureka project “Aimtech”
- NPL’s new building
- Summary

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Heat Transfer Coefficient

- It is the heat flux (q) across a surface from one material of temperature T_1 to another material of temperature T_2 :

$$h = q/(T_1 - T_2) \text{ units: } Wm^{-2}K^{-1}$$

- The main boundary condition for process simulation
- In injection moulding & compression moulding
  - Polymer to metal
- In extrusion & film blowing
  - Polymer to fluid (eg air or water)
- This project will build apparatus to measure heat transfer coefficient and investigate the significance of different interfaces to commercial processing

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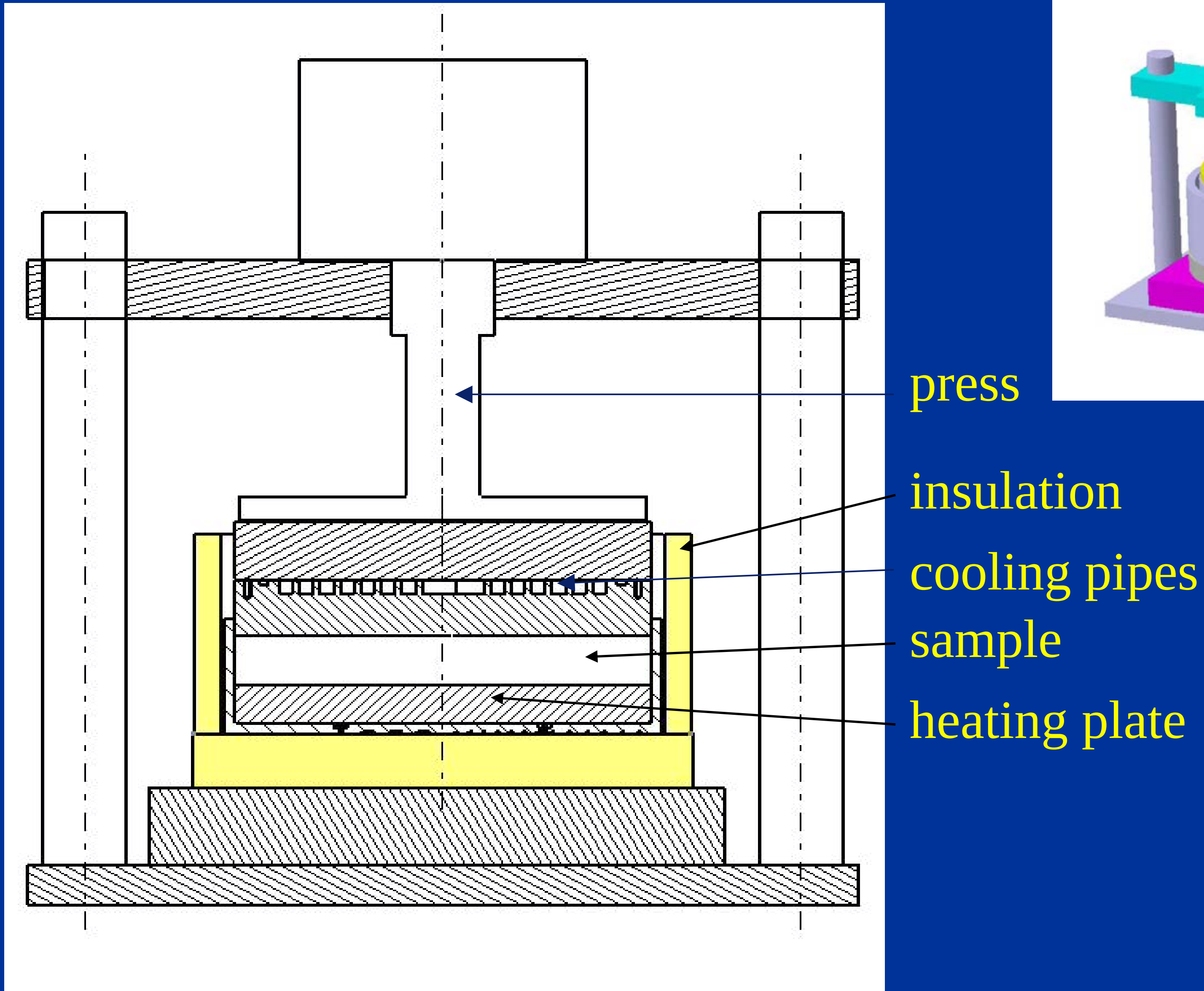
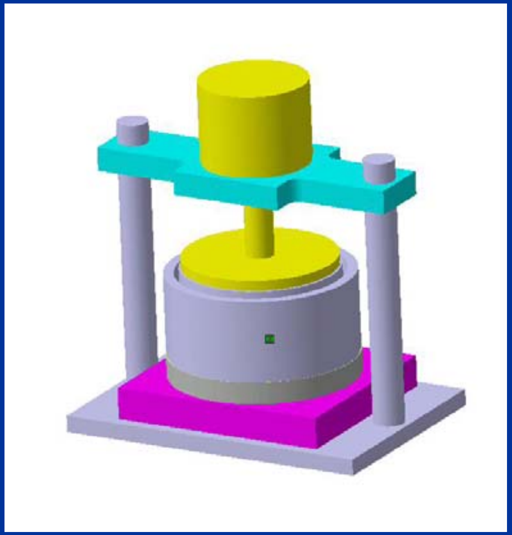
Heat transfer apparatus: general schematic





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Features of Apparatus

- Room temperature to 275C
- Pressure to at least 500 bar
- Polymer samples 2 to 25 mm thick
- Interchangable top plate to investigate
  - Different surface finishes
  - Effect of mould release agents
- Option to introduce a gap between polymer & top plate
  - Shrinkage, sink marks
- Mould samples in situ
- Instrumented with thermocouples, fibre optics, heat flux sensors and calorimeter

Aim to be able to simulate all aspects of commercial moulding

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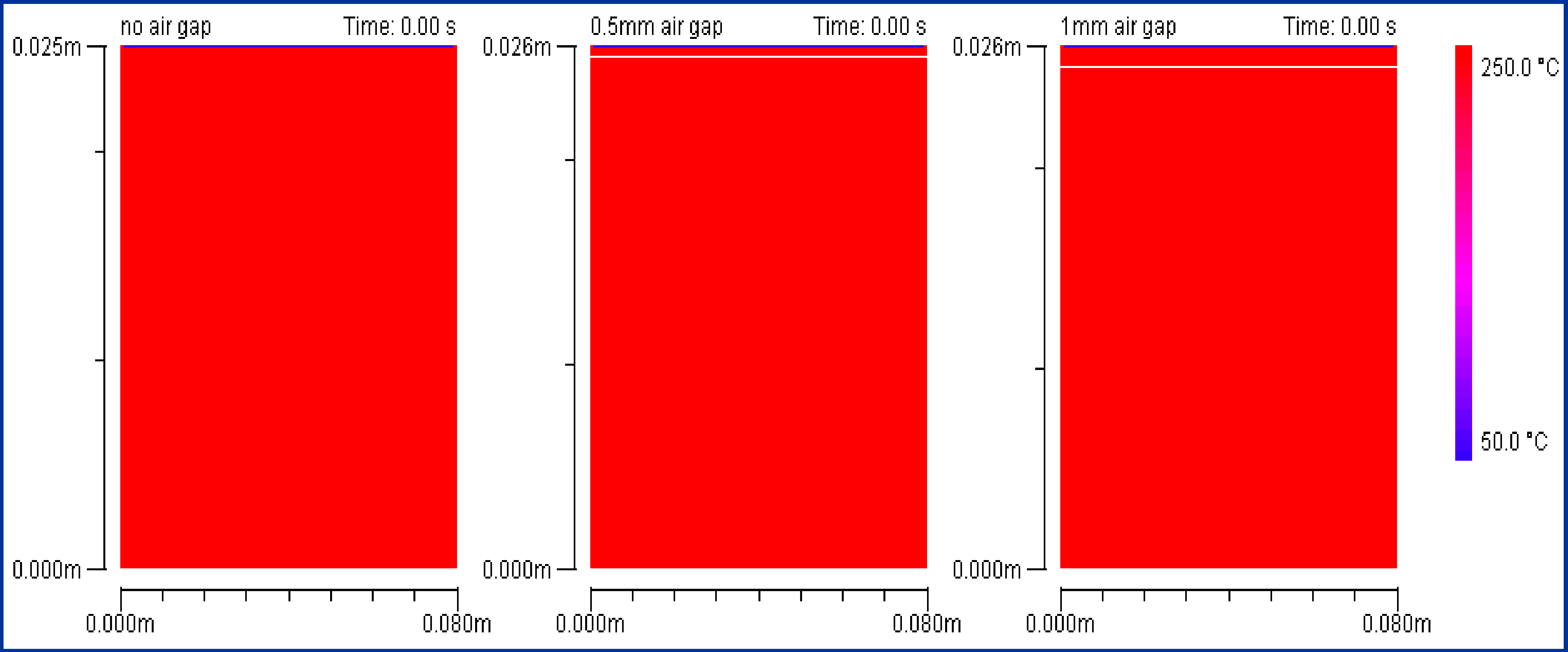
Modelling of key features

- Air gap
- Will a vertical thermocouple distort the heat flow significantly?

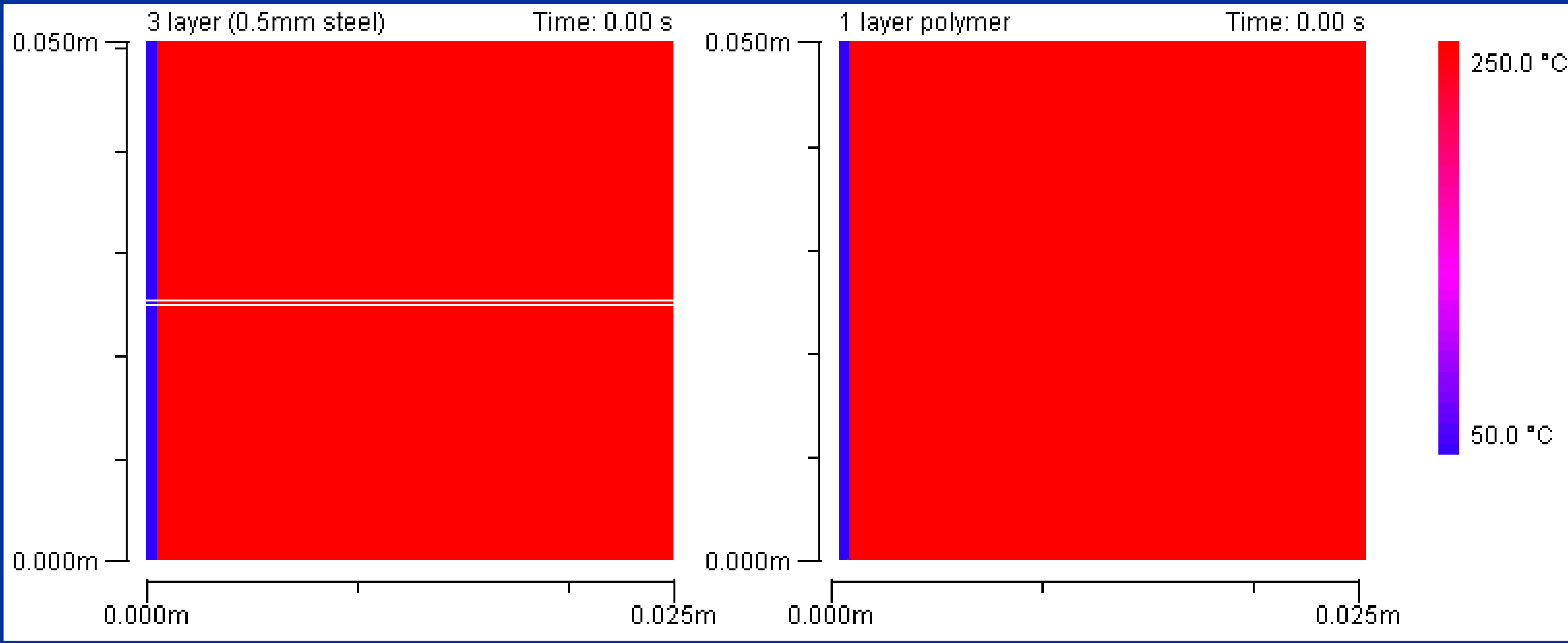
Air Gap

Mould at 50C with air gap of 0, 0.5 & 1 mm



Polymer at 250C

Effect of a thermocouple



Mould at 50C

Polymer at 250C

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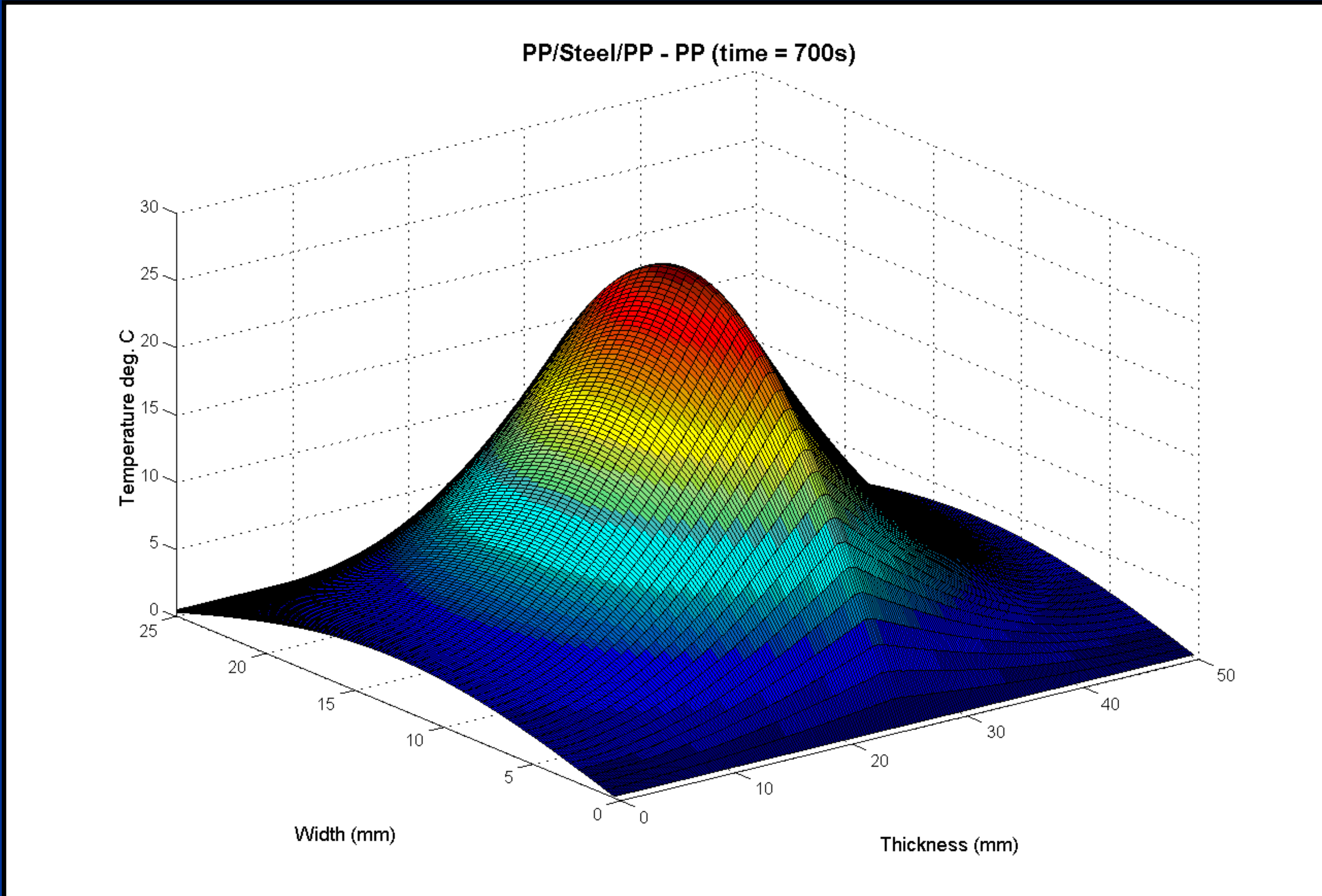
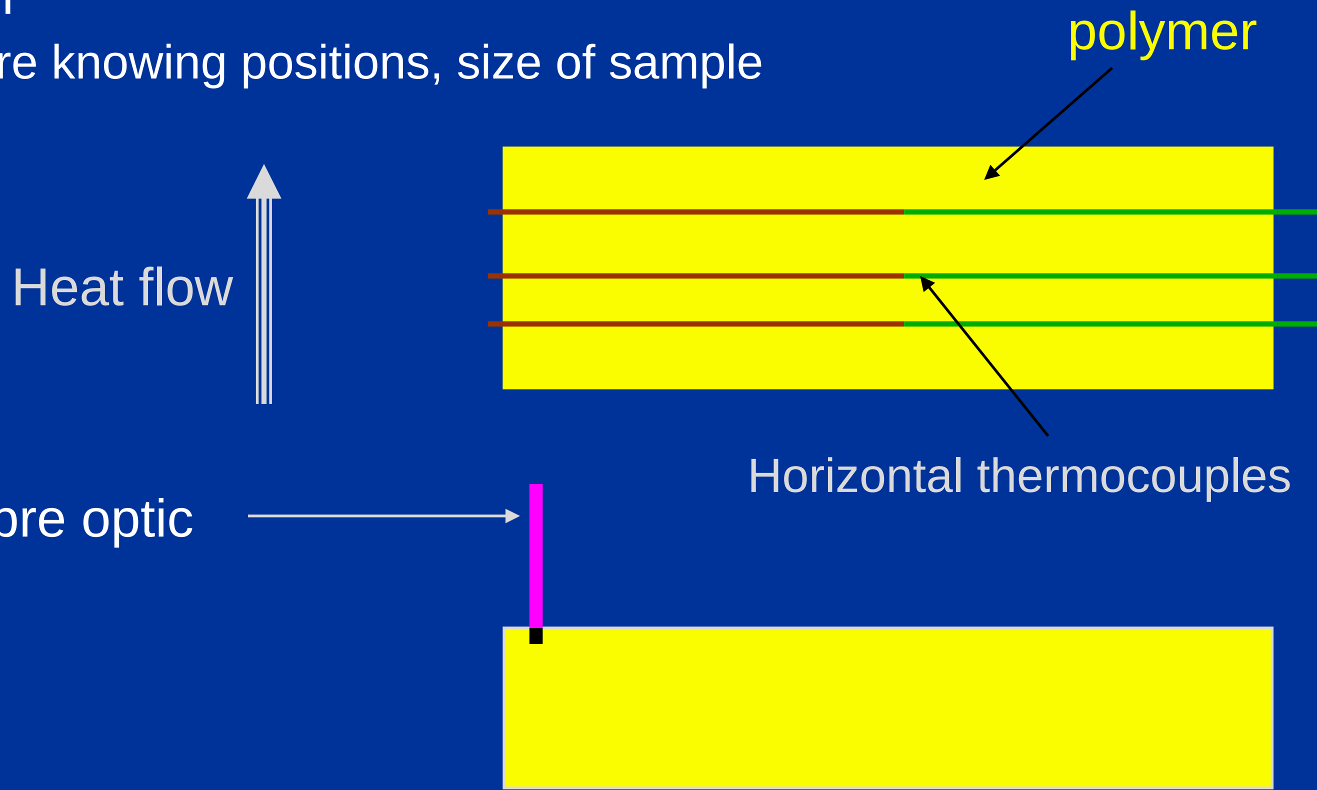

PP/Steel/PP - PP (time = 700s)
Temperature deg. C
30
25
20
15
10
5
0
25
20
15
10
5
0
Width (mm)
0
10
20
30
40
50
Thickness (mm)

Critical factors

- Temperature at polymer surface
  - By extrapolation
    - Challenges are knowing positions, size of sample



  - Measure with fibre optic
  - ………………

Thermal Conductivity

- How accurately can we measure thermal conductivity?
  …..of molten thermoplastics
- Previous project showed how important it is to measure at the correct *temperature* (and *pressure*)
- Extending the scope beyond thermoplastics
- Formal uncertainty analysis

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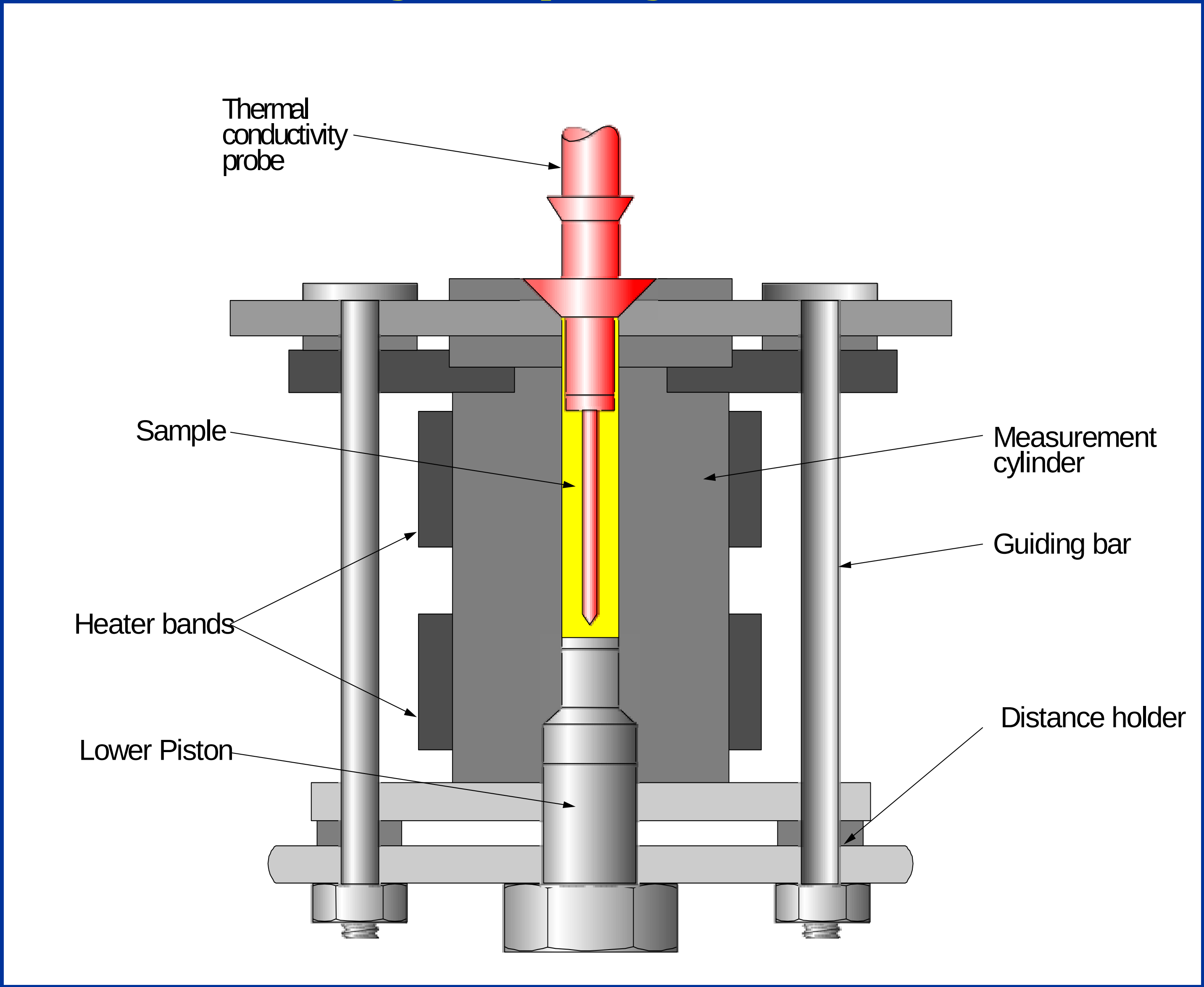
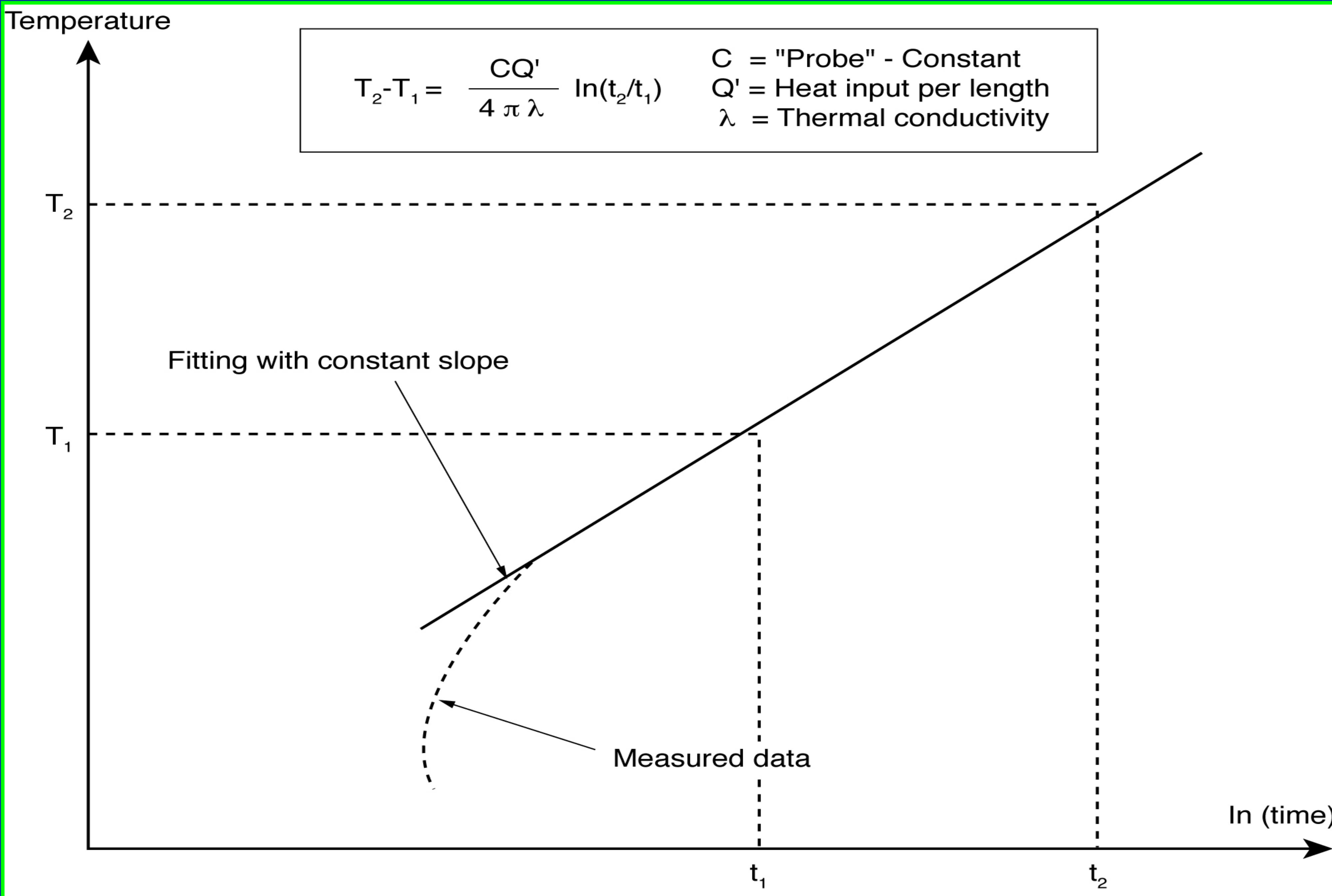
Line source probe apparatus for thermal conductivity of polymer melts




Temperature
$T_2 - T_1 = \frac{CQ'}{4 \pi \lambda} \ln(t_2/t_1)$
C = "Probe" - Constant
Q' = Heat input per length
λ = Thermal conductivity
T_2
T_1
Fitting with constant slope
Measured data
ln (time)
t_1
t_2

Thermal Conductivity: Extending the Scope

- Aim to extend the scope beyond thermoplastics

- Six materials to be studied in all

- From last meeting:
  - Two thermosets (from Railko)
  - One rubber (from Avon Rubber)
  - One powder (further offers or a rotational moulding PE grade)
  - Two commercial “nanoblends”
    - PolyOne PP based

Thermal Conductivity: reasons behind choices

- Avon rubber grade used in MPP7.7 & 7.4 too
  - Before and after vulcanisation, at temp. + compare with Avon

- Thermosets
  - Before and after cure, effect of fibres & fillers, phenolic and/or polyester

- HDPE Powder
  - Thermal conductivity difference between melt, powder & solid,

- Nano-material
  - Do very fine particles help or hinder heat transfer?
  - Can representative samples be prepared and measured easily?

- Scheduled to start this month

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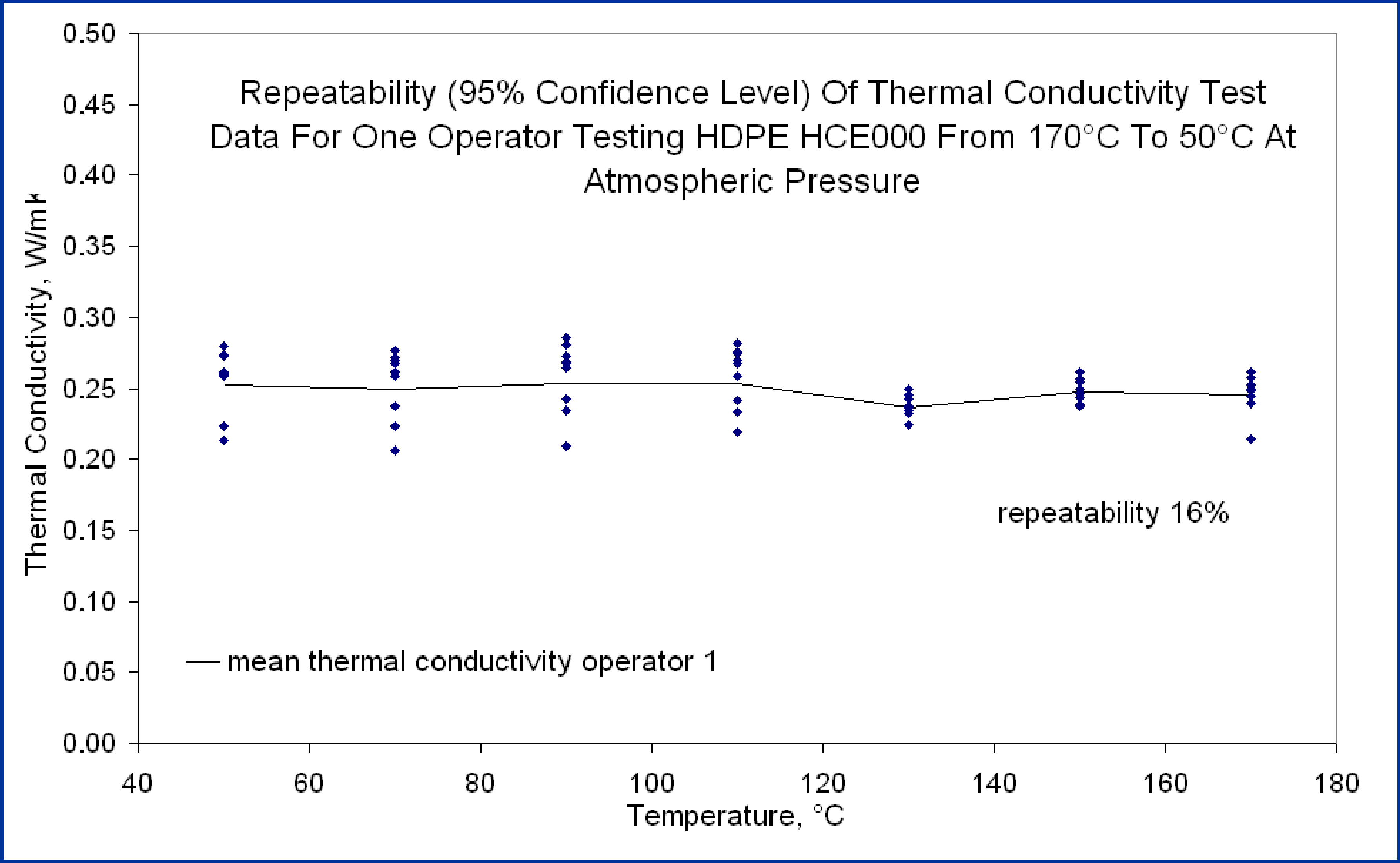
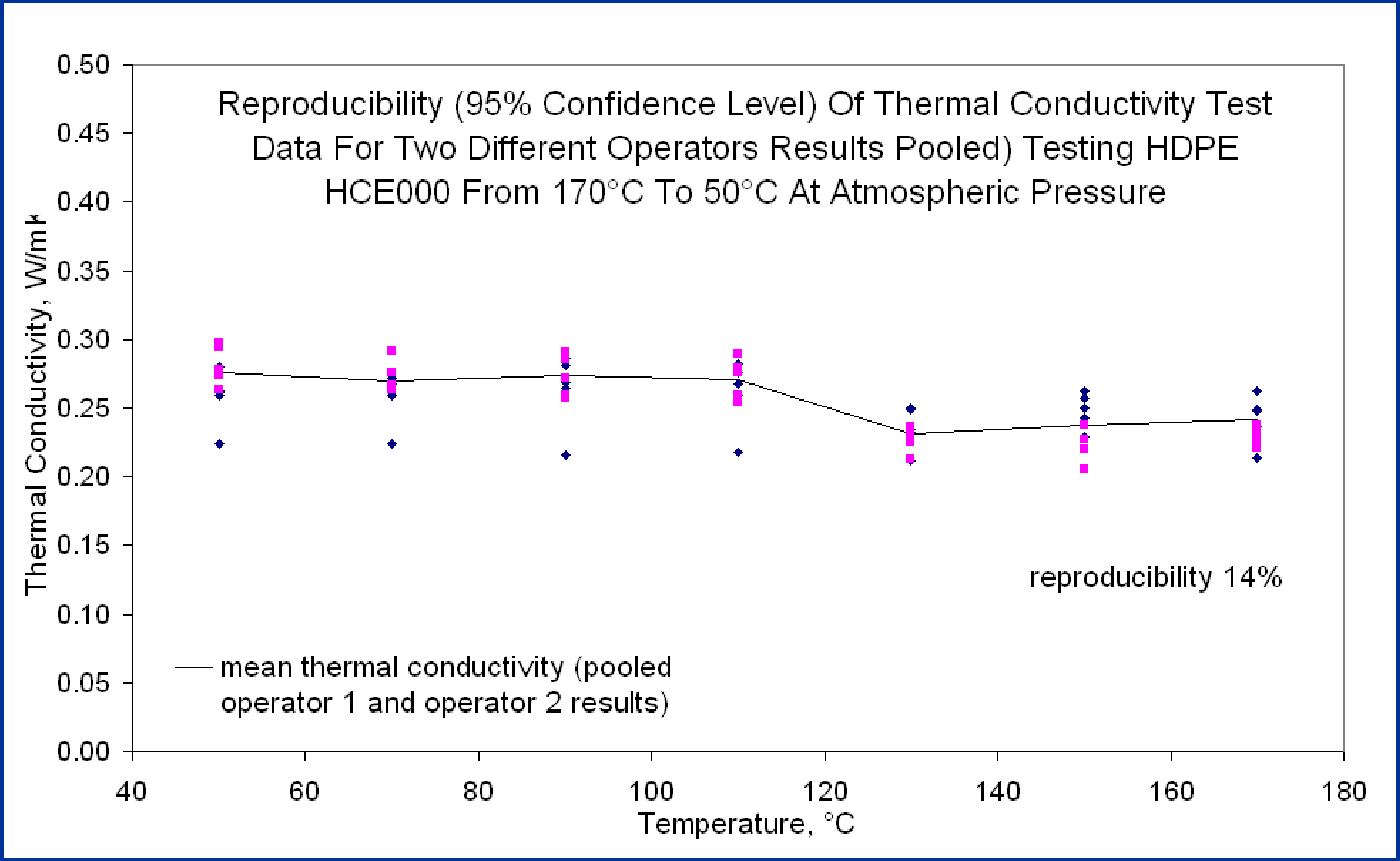
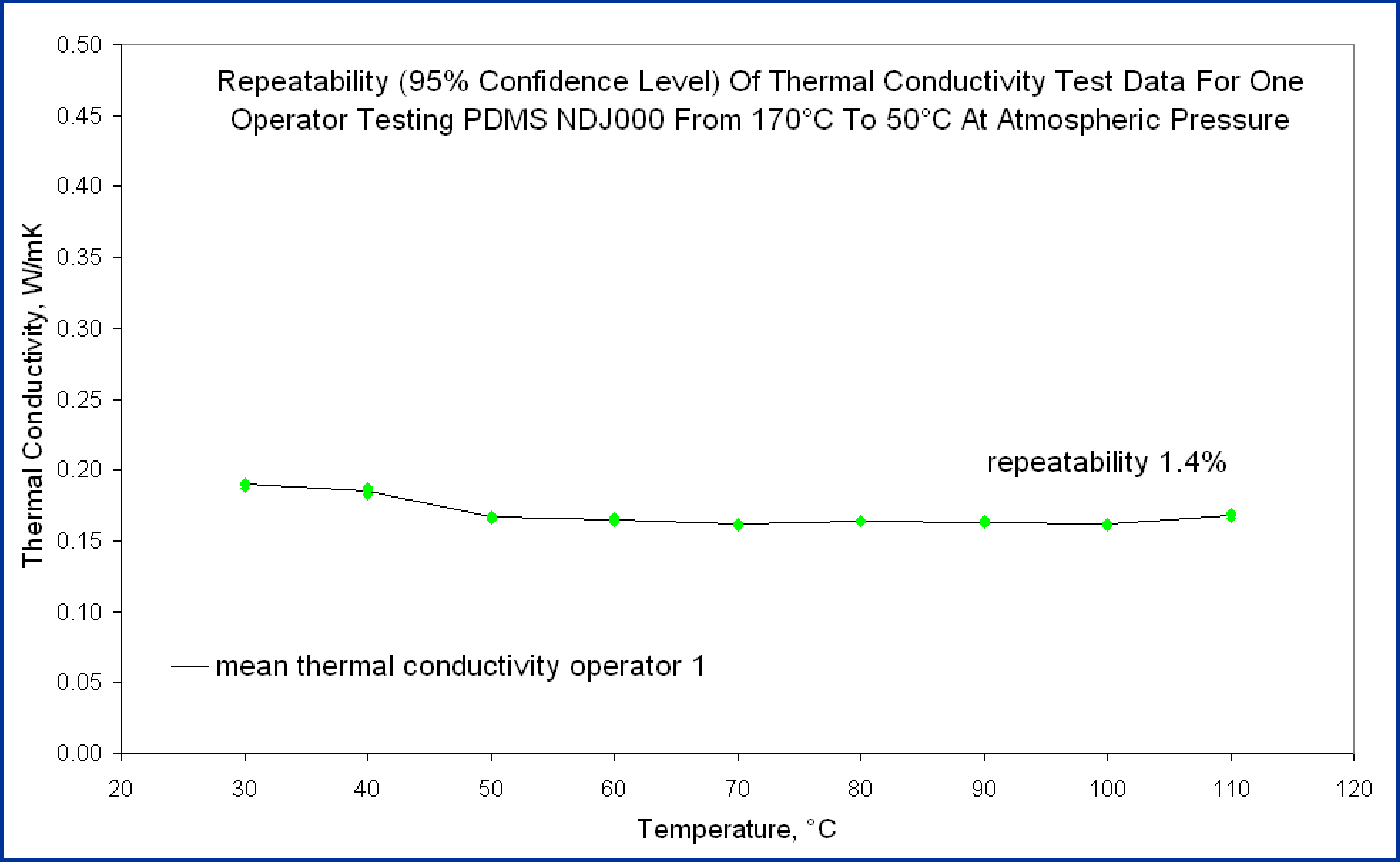
Results of Uncertainty Analysis



Thermal Conductivity Uncertainty 2



Thermal Conductivity PDMS



Thermal Conductivity Uncertainty Analysis Summary

- Picking data from literature – expect +/- 50%
- Measurement of a typical thermoplastic at atmospheric pressure – expect +/- 15% *(reproducability)*
- Measurement of lower viscosity PDMS +/- 1.5%
- Conclusion: Should be able to improve on +/- 15%
- Action:
  - Investigate uncertainty at elevated pressure
  - Increase measurements from 5 to 11 and ignore the first
- What is the commercial significance of this?
  - Illustrated by Moldflow simulation

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Process Simulation

Aim to establish the *commercial implications* of uncertainties in thermal conductivity data and heat transfer coefficients

On time to freeze, cycle times and thus productivity

On hot spots and thus scrap rates

On shrinkage & warpage, thus scrap rates

On energy bills.

- Moldflow simulations of an industrial product (pipe T piece)
- Effect of geometry on relative importance of the data (simple disc, & T)
  - Eg thin products v thick

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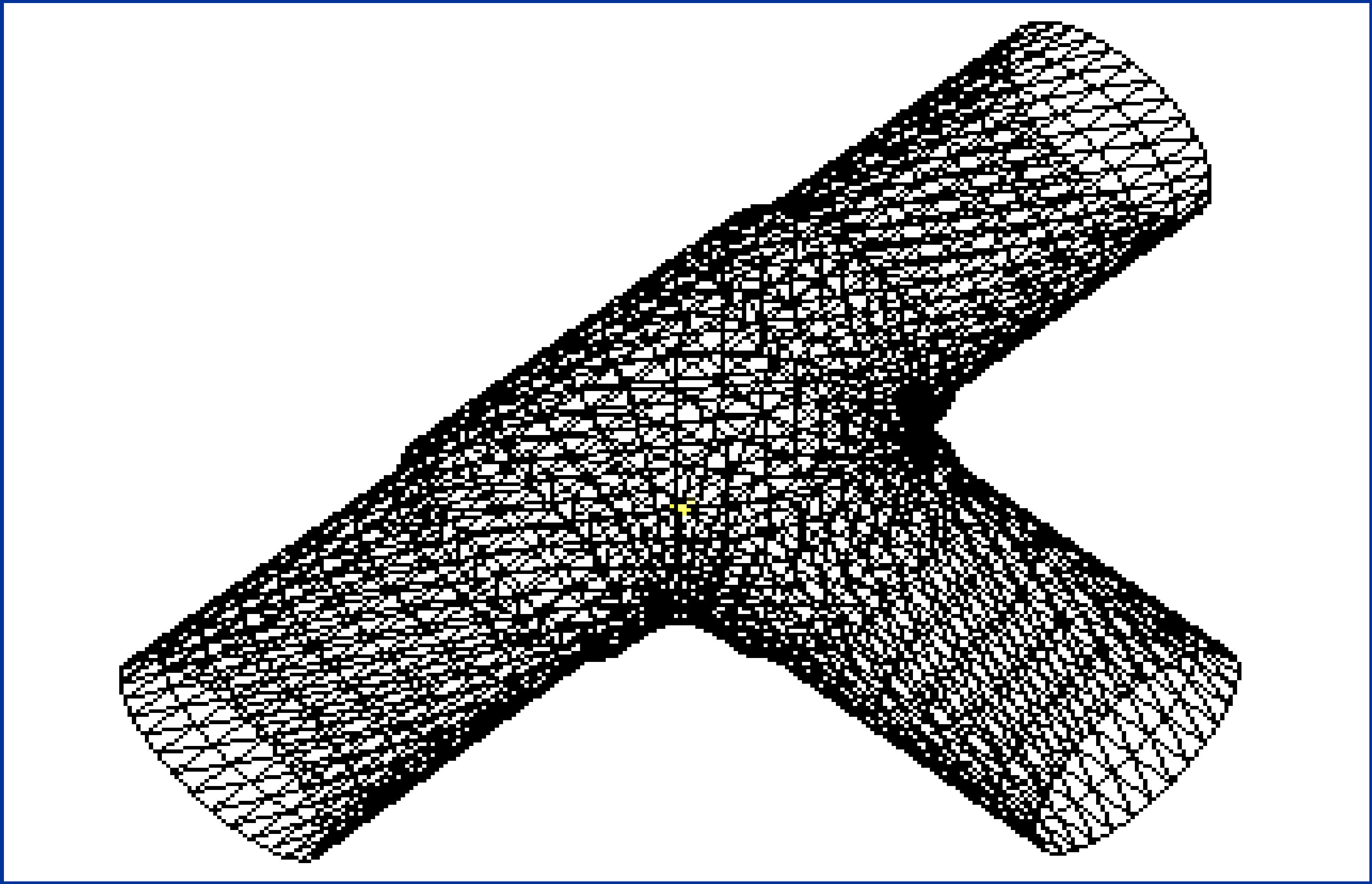
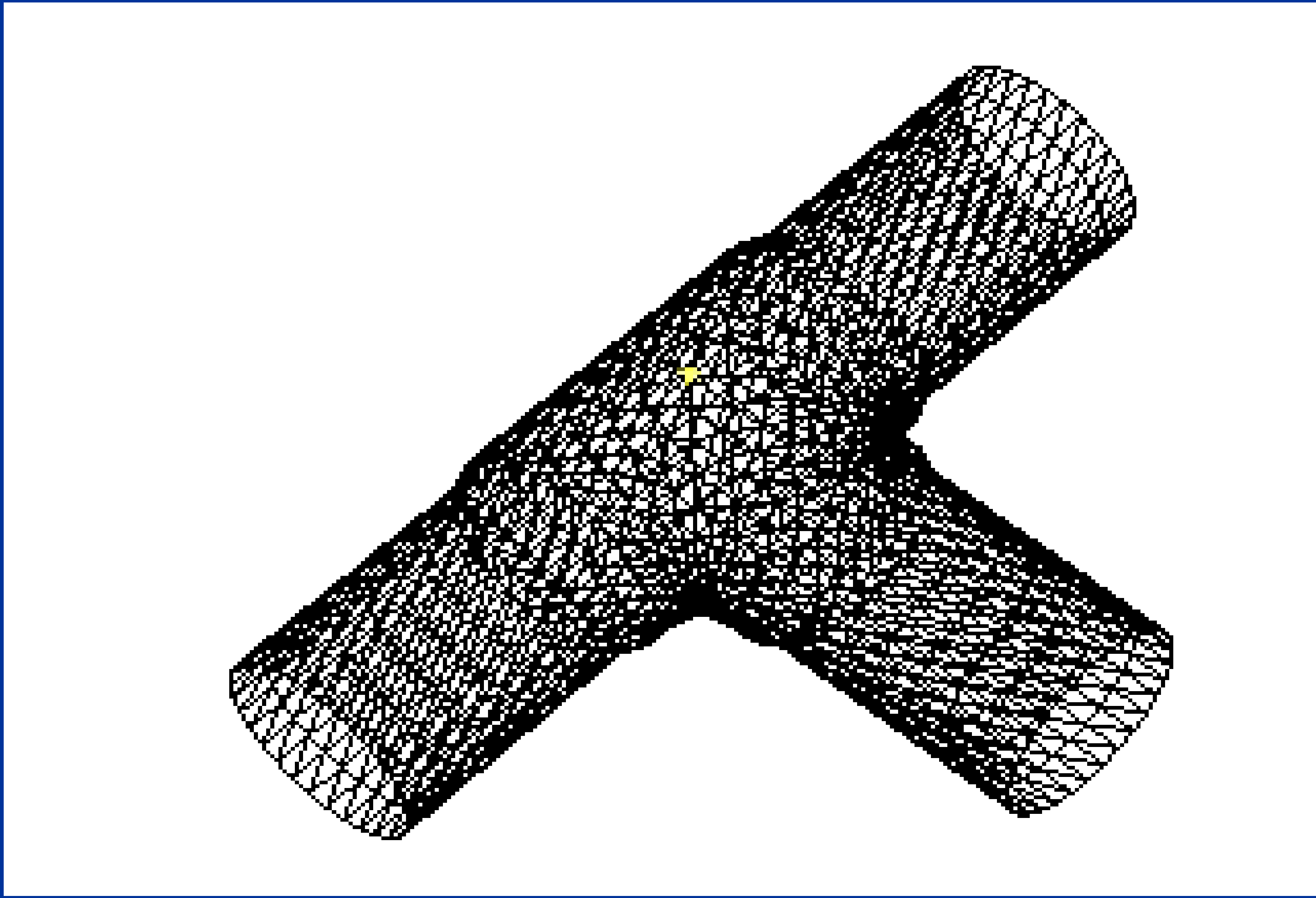
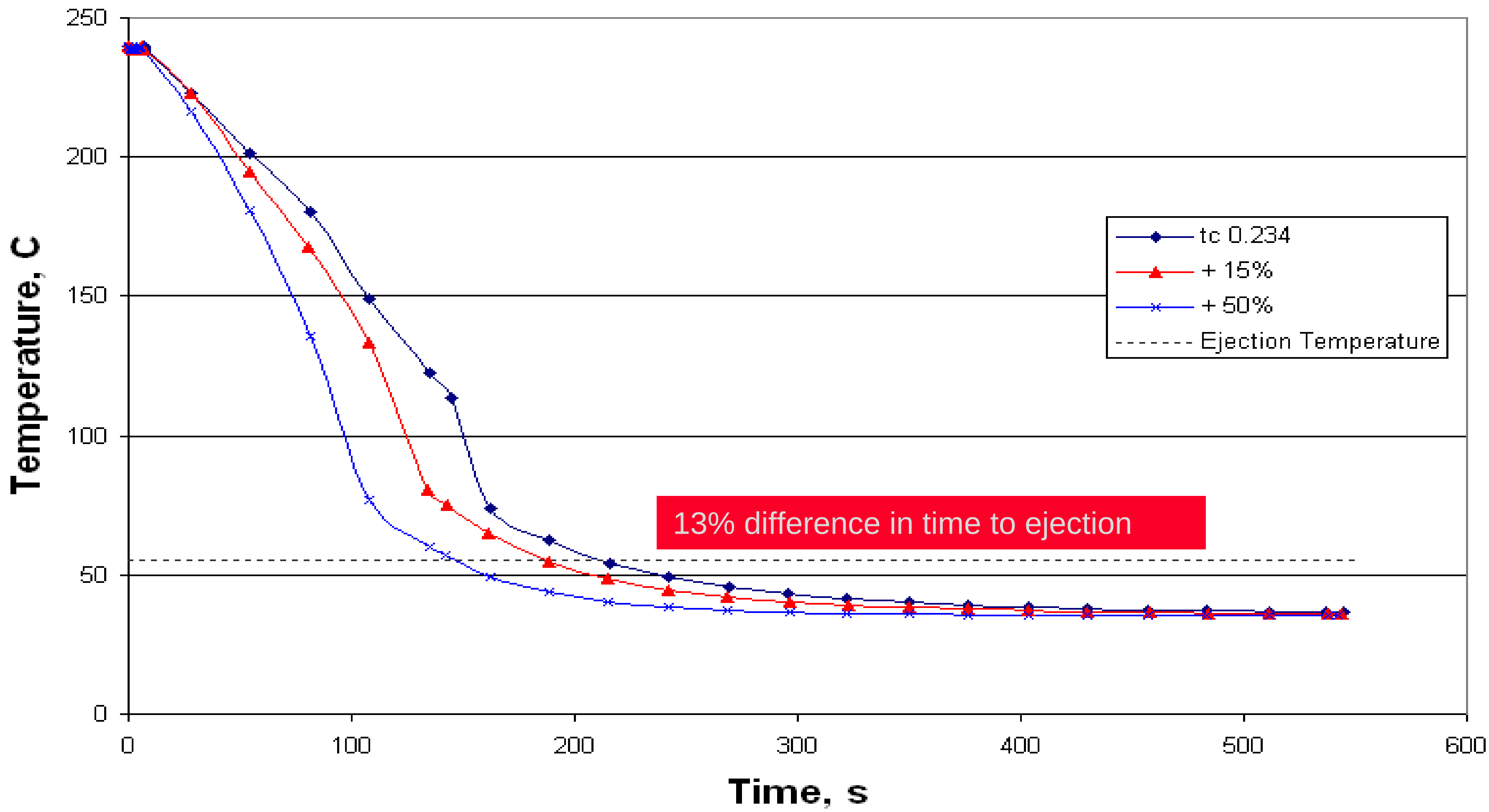
Moldflow simulation of fill



Temperature change during cooling

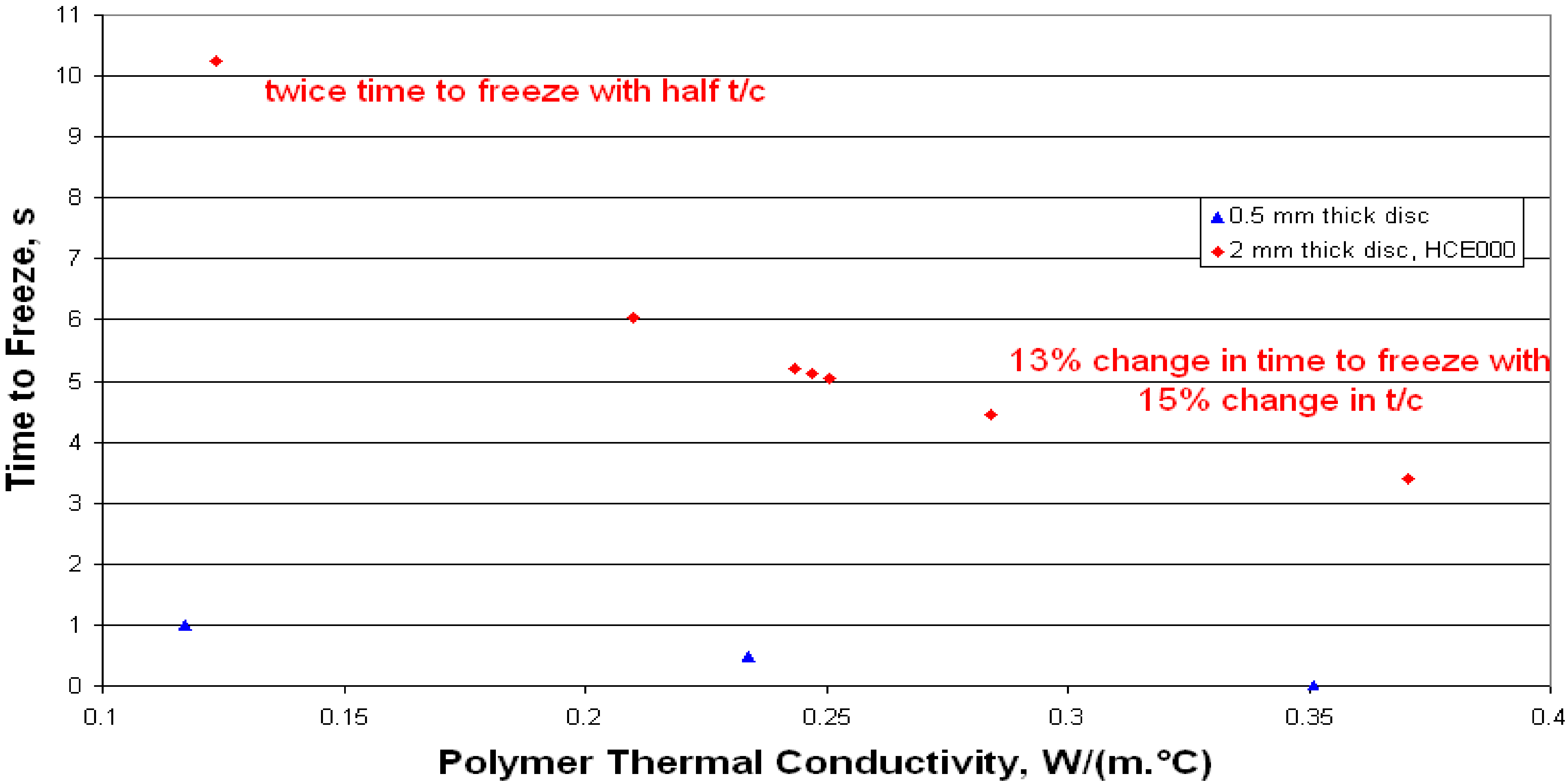


The Change in Temperature Over Time For A Given Location (T1717) on the T-Pipe For Analyses With Different Polymer Thermal Conductivity



The Effect of Polymer Termal Conductivity Upon Time to Freeze Part.

(Discs with central injection location, packed at 50 MPa for 10 s, cooling time 3000 s.)



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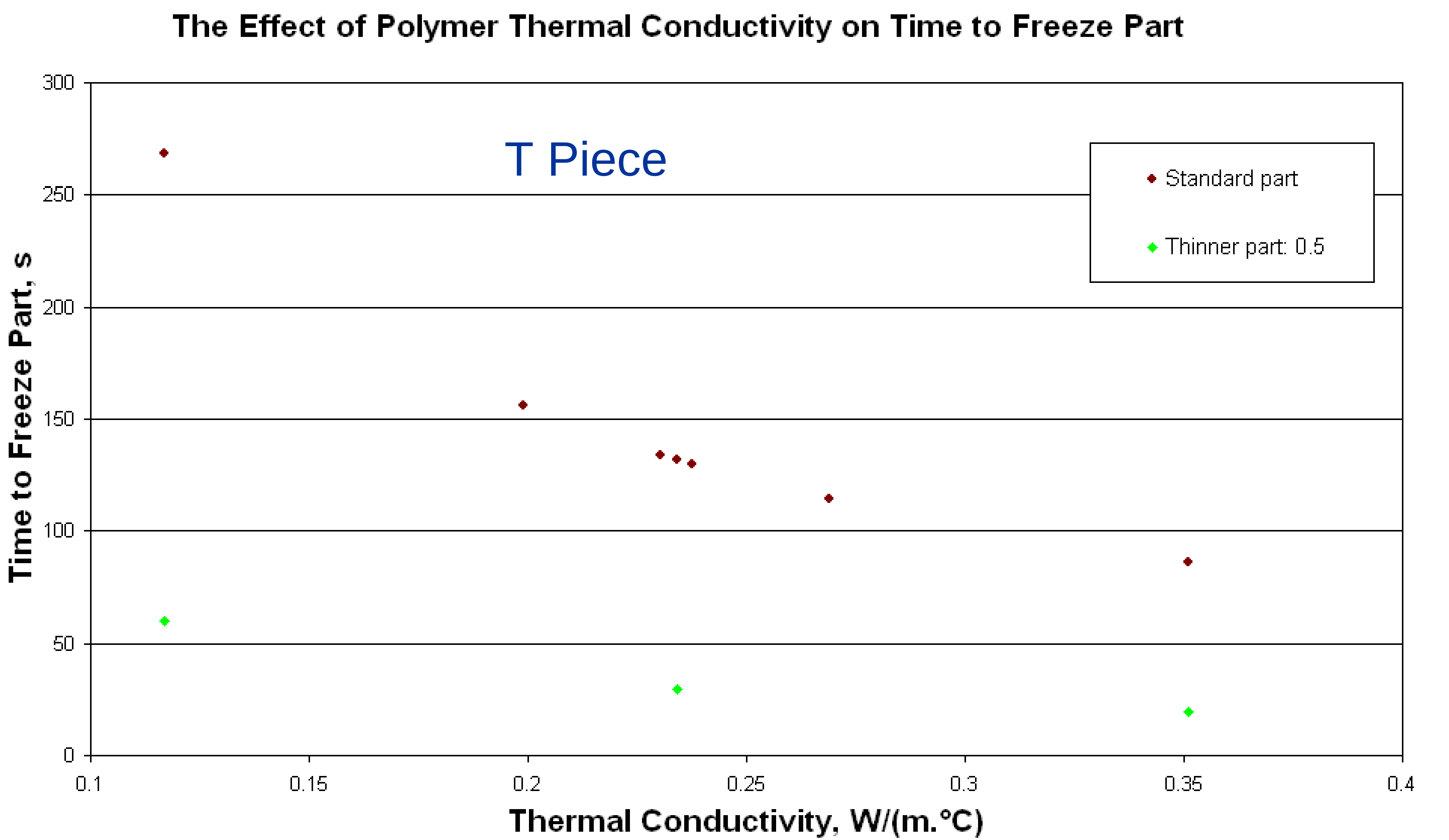
The Effect of Polymer Thermal Conductivity on Time to Freeze Part
T Piece
Standard part
Thinner part: 0.5
Time to Freeze Part, s
300
250
200
150
100
50
0
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Thermal Conductivity, W/(m.°C)

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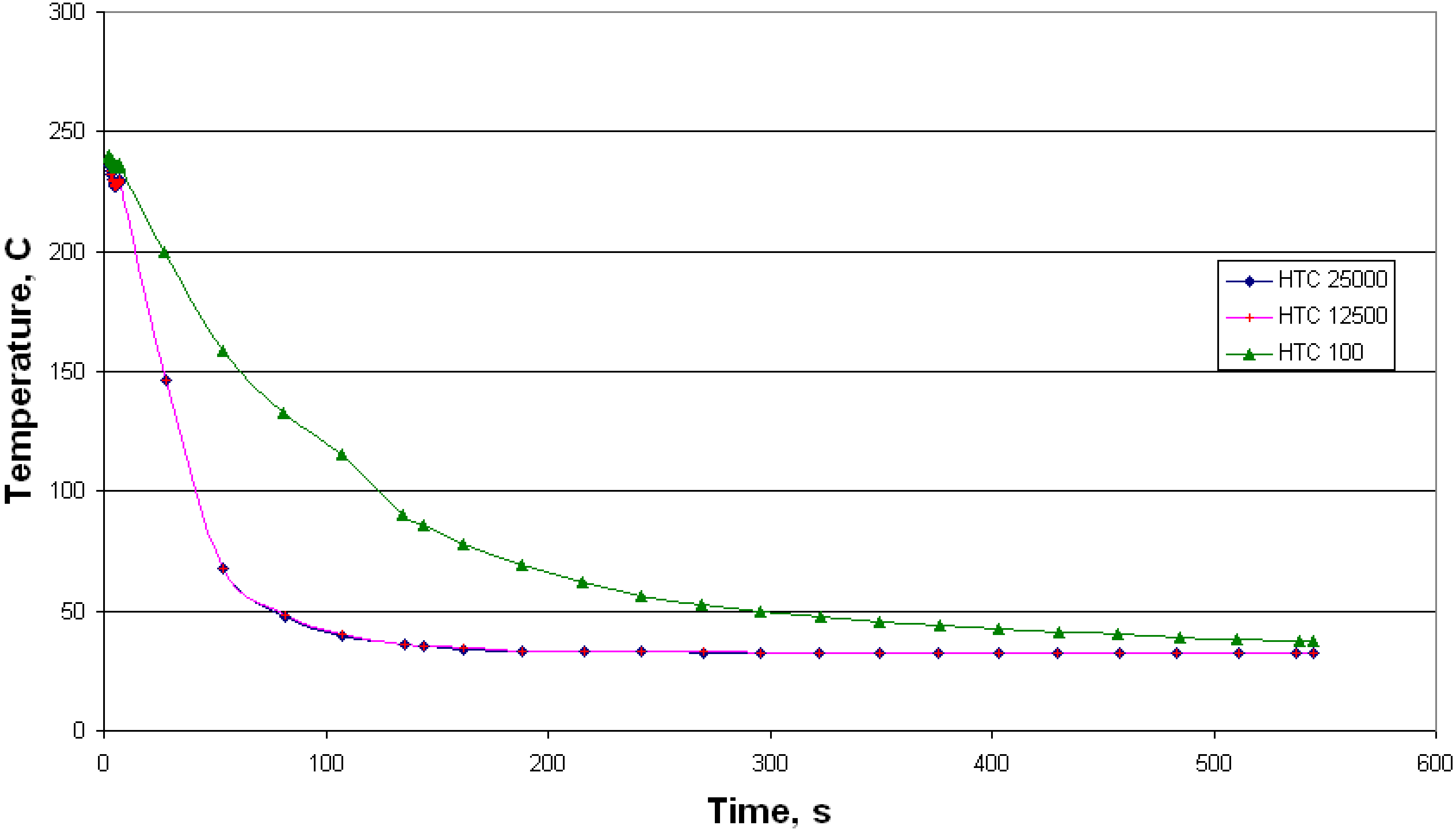
The Change in Temperature Over Time For A Given Location (T1149) on the T-Pipe For Analyses With Different Heat Transfer Coefficient



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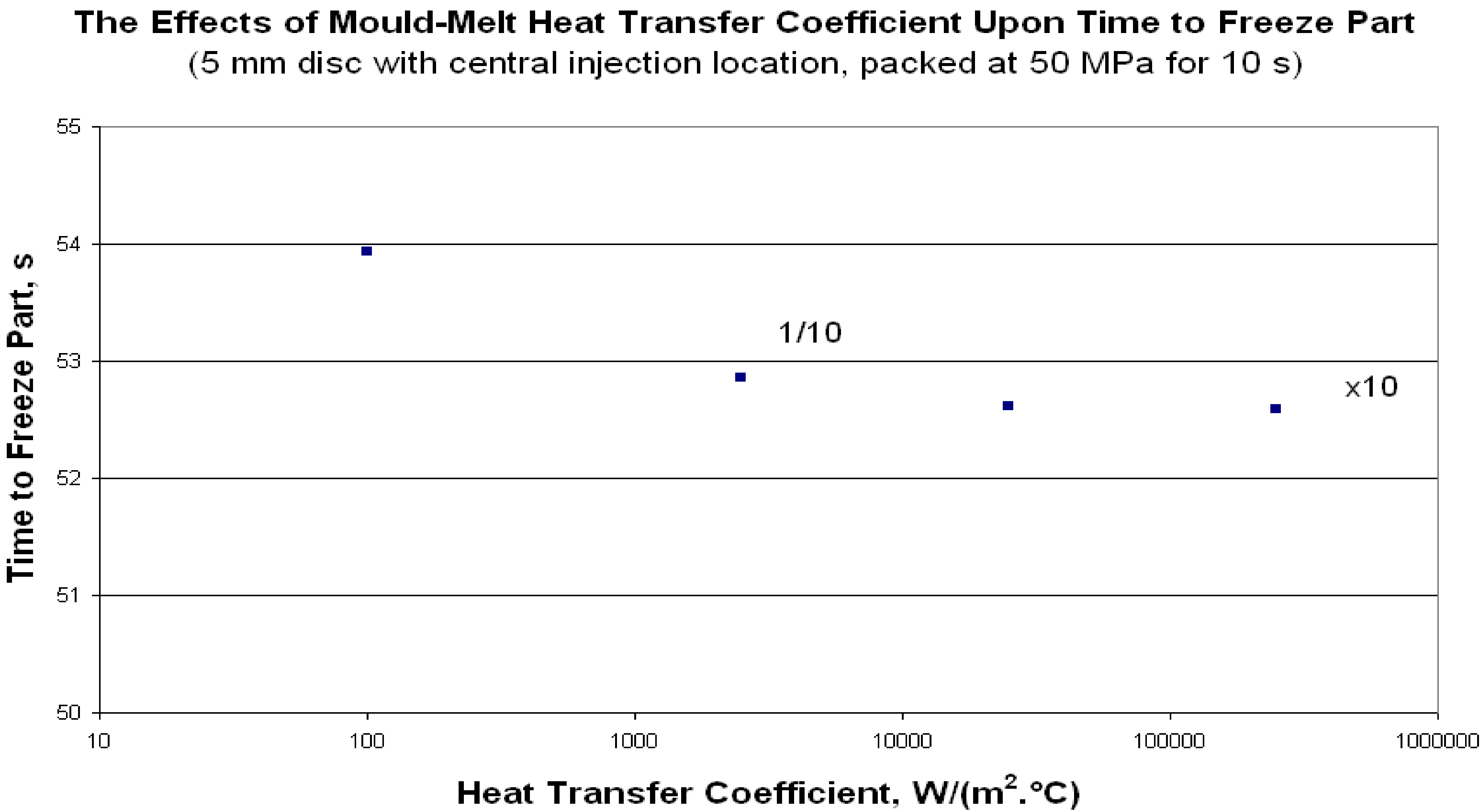
The Effects of Mould-Melt Heat Transfer Coefficient Upon Time to Freeze Part
(5 mm disc with central injection location, packed at 50 MPa for 10 s)
Time to Freeze Part, s
55
54
53
52
51
50
1/10
x10
10
100
1000
10000
100000
1000000
Heat Transfer Coefficient, W/(m2.°C)

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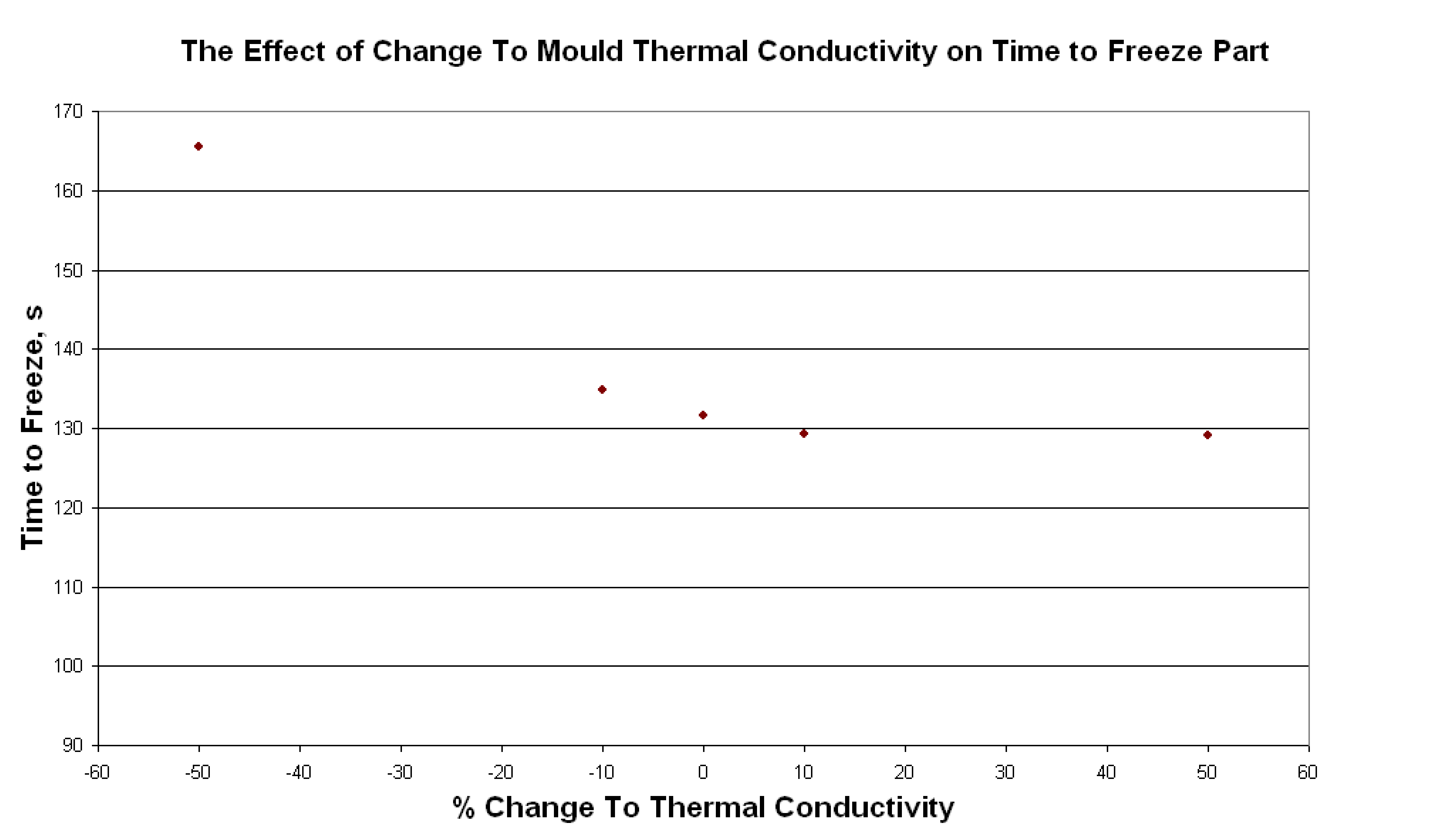
The Effect of Change To Mould Thermal Conductivity on Time to Freeze Part
Time to Freeze, s
170
160
150
140
130
120
110
100
90
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
% Change To Thermal Conductivity

Summary of Moldflow results

- Uncertainties in melt thermal conductivity lead to similar uncertainties in time to freeze & thus to productivity
  - 13% uncertainty in cycle time predictions typical
  - Any improvements to uncertainties in thermal conductivity data will result directly in improvements in cycle time predictions
  - 5% is probably achievable in the future

- Heat transfer coefficients do not alter Moldflow predictions except at very low values (100W/(m^2.C))
  - Good contact assumed

- Increasing mould thermal conductivity has little effect
- Decreasing mould thermal conductivity does have a big effect

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Industrial Demonstrations

- Aim is to demonstrate practical benefits of heat transfer measurements and modelling
- Zotefoams
  - Heat transfer during cooling of polyolefin foam
- Corus
  - Thermal conductivity of plastisol coated steel before and after solidification

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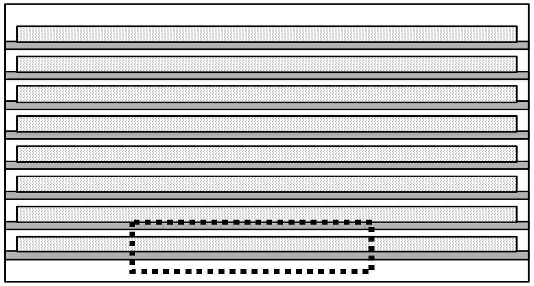
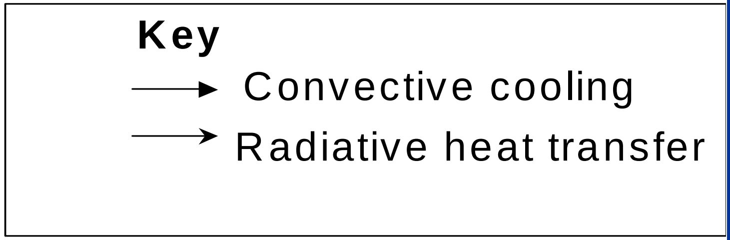
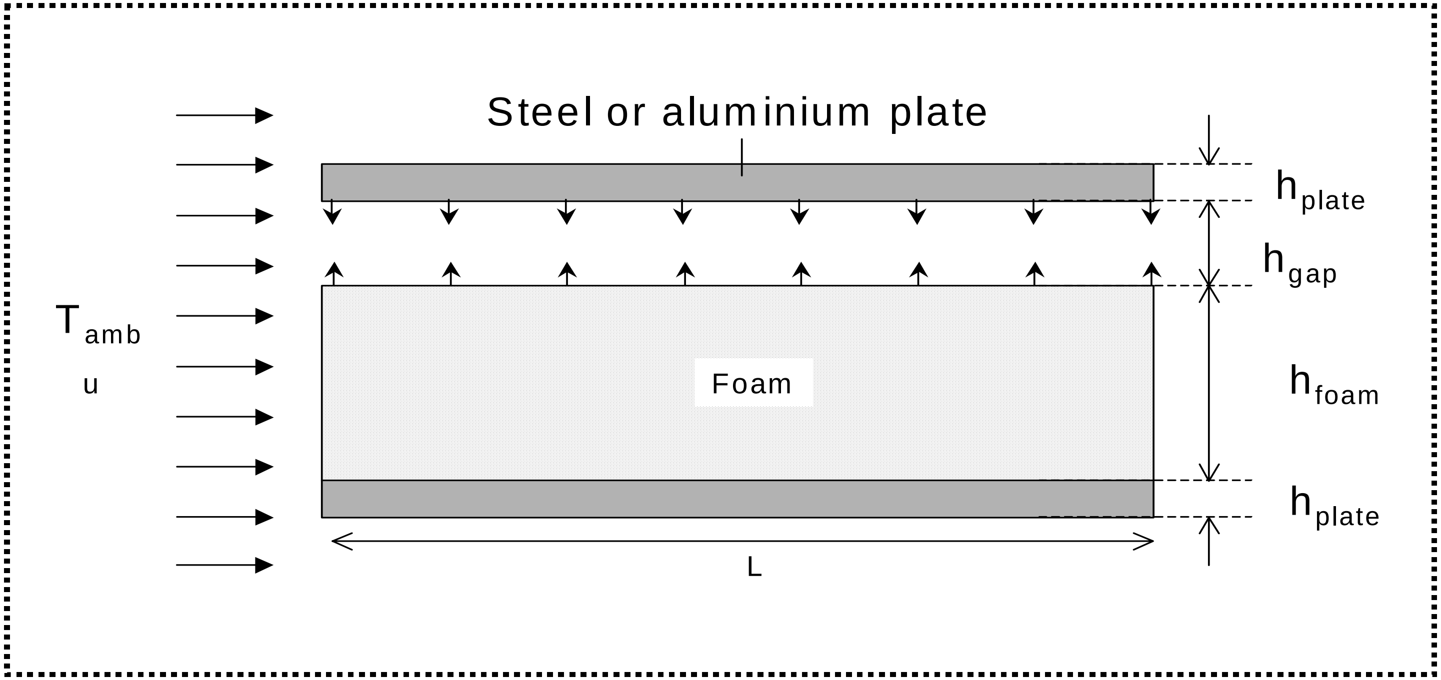
Zotefoams

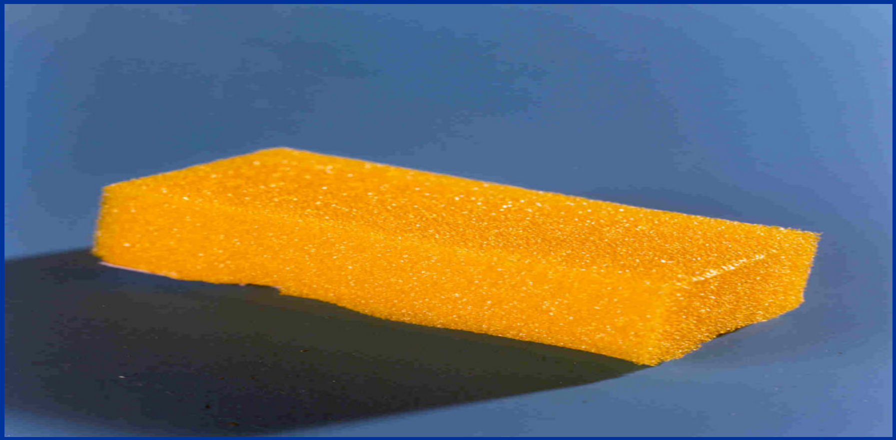



Key
Convective cooling
Radiative heat transfer


Steel or aluminium plate
h_{plate}
h_{gap}
T_{amb}
u
Foam
h_{foam}
h_{plate}
L

Zotefoams

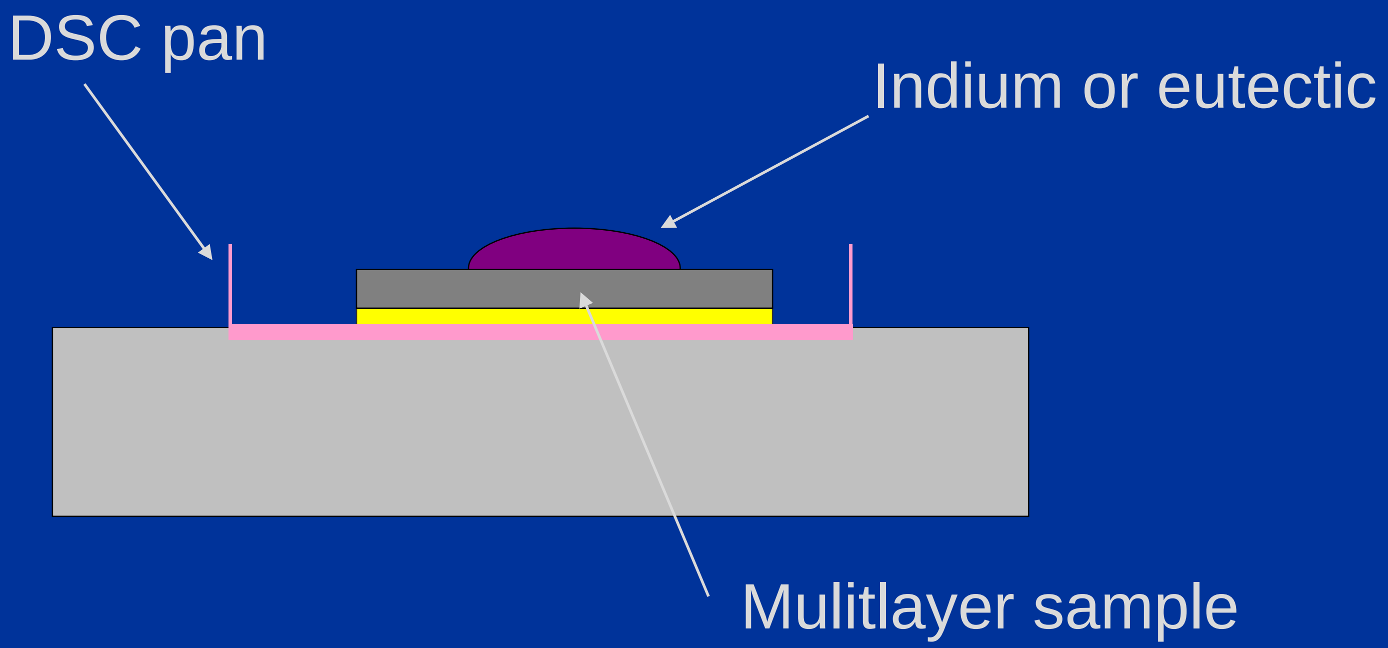
- Model heat transfer
- Measure (T, heat flux)t
- Model/measure shrinkage
- Calculate internal stresses
- Use bending theory to predict curvature

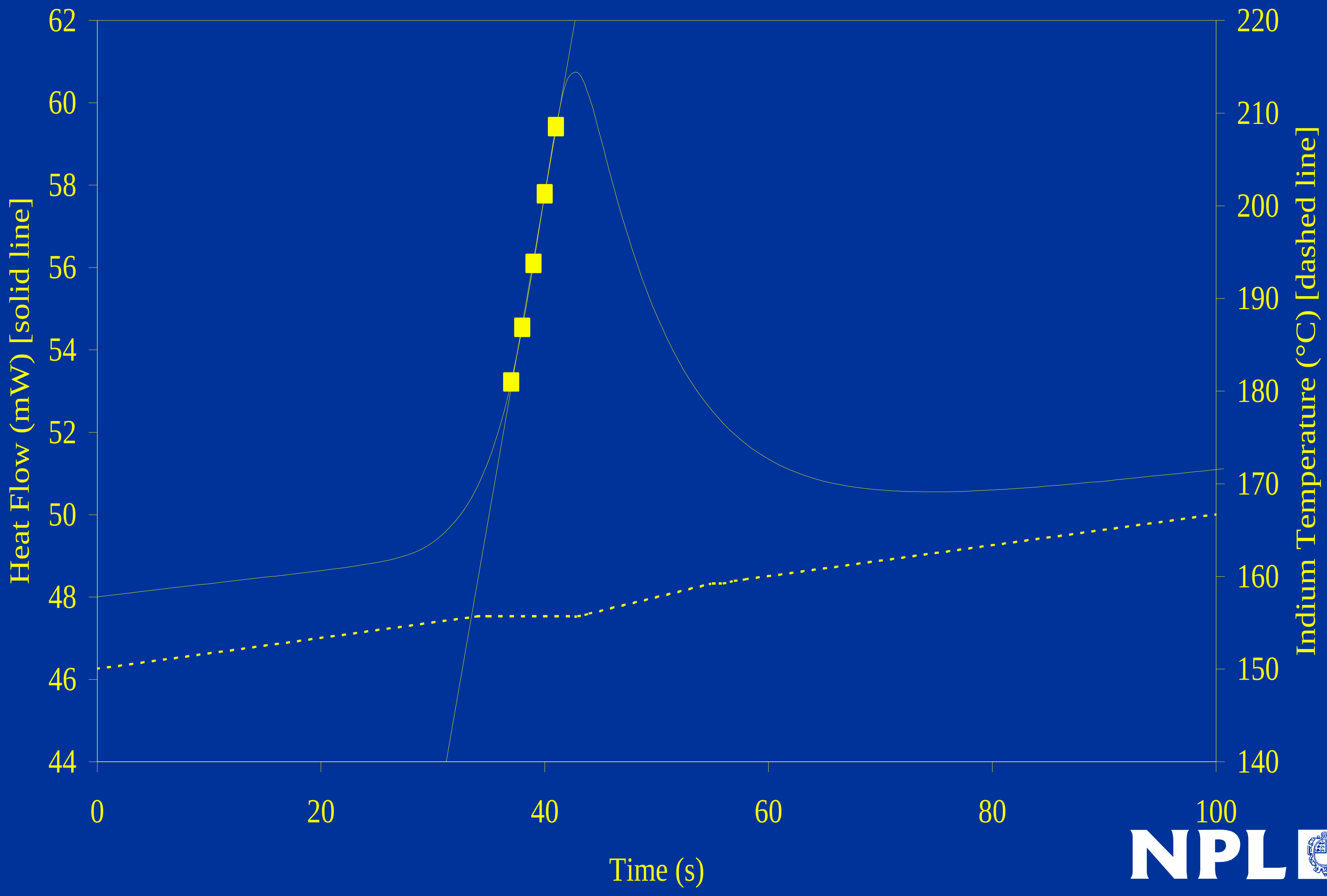


Corus

- Use DSC method to measure thermal conductivity of bilayer Plastisol/steel
- Measure before and after solidification
- Data useful in predicting optimum line speeds
  - Earlier work had shown that the polymer layer was significant in terms of heat transfer

DSC method for thermal conductivity




Heat Flow (mW) [solid line]
62
60
58
56
54
52
50
48
46
44
Indium Temperature (°C) [dashed line]
220
210
200
190
180
170
160
150
140
0
20
40
60
80
100
Time (s)
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We have moved into our new building

- Visit new labs at next IAG
- Cost of moving (decomissioning, recommissioning, packing…)

DTI decided would come from cutting science milestones:

Cut Milestone 7 (Comparability Studies) & d13.3 (workshop) + less money for M10 (industrial demonstration 2) -6.8%

Postpone all deliverables by 3 months

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Eureka Project

- An associated Eureka project (AIMTECH) has started.
- Its aim is to improve productivity of injection moulding
  - Main focus is on the moulds
  - NPL's role is the mould/polymer interface + the melt
- It will use measurement methods from this project
- Six UK companies involved
- NPL will measure some of their materials & do simple modelling
- £25k co-funding contribution

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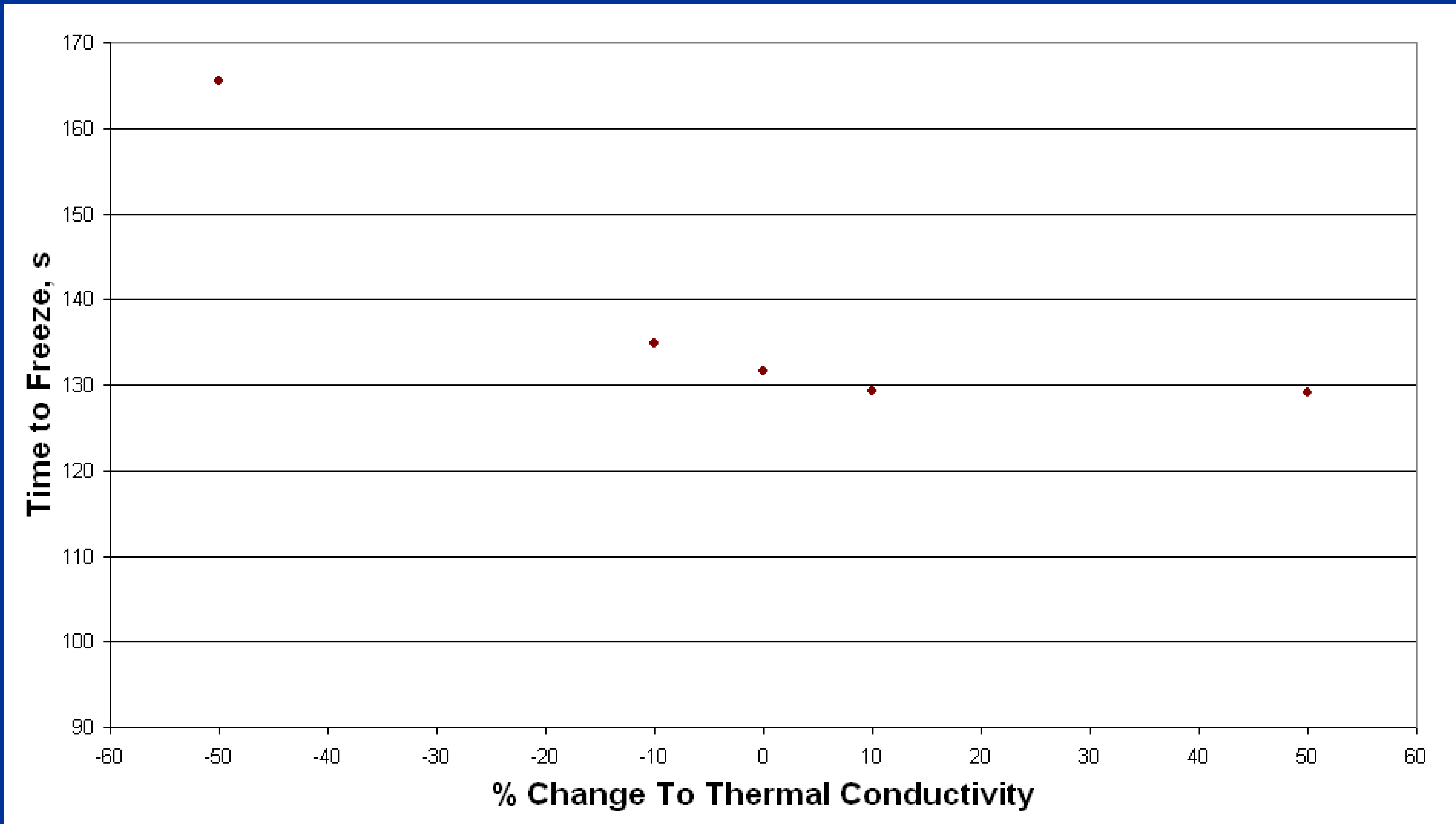
Moldflow simulation of effect of different mould materials on time to freeze (T piece)



Summary

- Heat transfer coefficient apparatus designed
  - Assisted by modelling studies
- Melt thermal conductivity uncertainties assessed
  - Potential to improve from +/-15% to at least +/-5%
- Moldflow simulations demonstrated:
  - Link between melt thermal conductivity and time to freeze
  - Apparent low sensitivity to heat transfer coefficient
  - Result of changes to mould conductivity
- Next Steps
  - Thermal conductivity measurements under pressure
  - Extending the scope of thermal conductivity measurements
  - Build heat transfer coefficient apparatus
  - Start industrial demonstrations

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