Study of Conventional and Conformal Cooling Systems on 3D Printed Injection Mold Tooling

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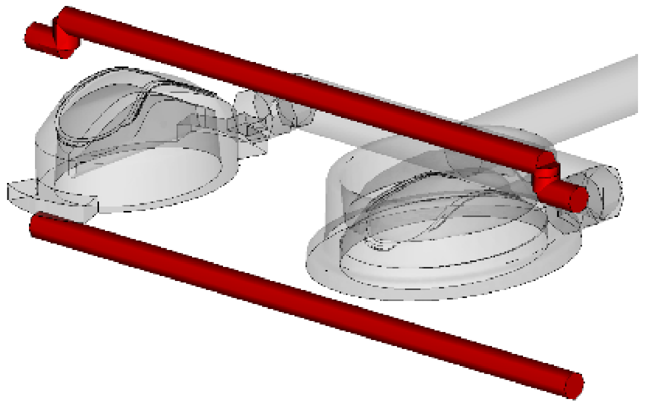
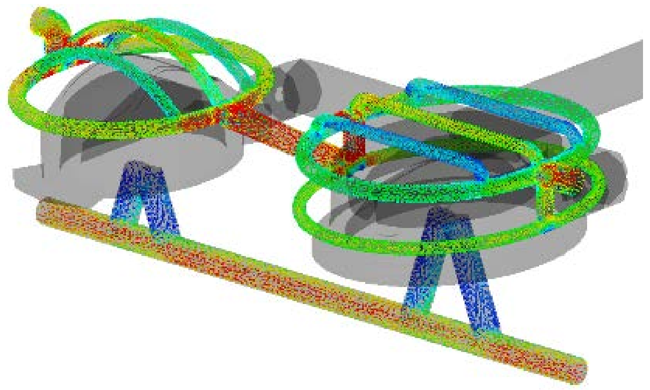
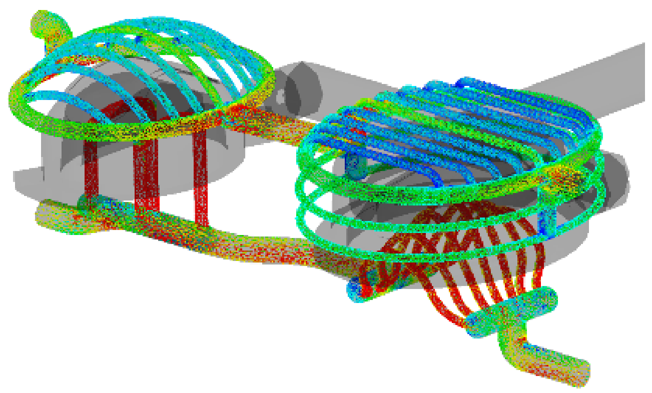
Class Summary

This class details how Autodesk Moldflow Insight software was used to evaluate and optimize conformal cooling designs within 3D-printed injection mold tooling. Three sets of 3D-printed tooling were manufactured using an ultraviolet-curable photopolymer via PolyJet printing. One set of tooling was cooled via cooling channels in the steel mold base; the second set was cooled via straight cooling channels in the mold inserts; and the last set was cooled via conformal cooling channels in the mold inserts. Moldflow simulations were performed to investigate the temperature gradients within the inserts, which were correlated with measured temperatures taken during molding trials. Results showed lower, more-uniform surface temperatures for the inserts with conformal channels. Optimal conformal cooling designs were then evaluated via Moldflow simulations, showing that further improvements are possible as the capabilities of 3D-printed technology continues to advance.







Key Learning Objectives

At the end of this class, you will be able to:

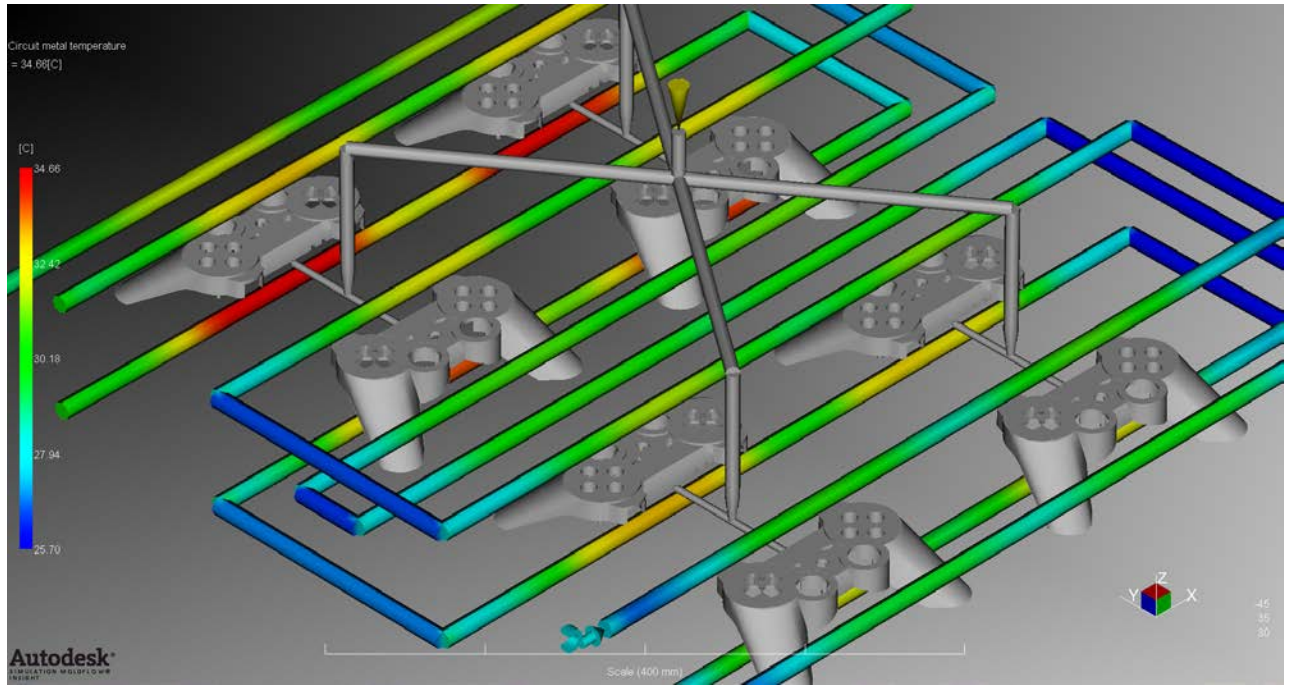
- Learn how to set up conformal cooling analyses
- Learn how to interpret conformal cooling results
- Discover how cooling results compare to actual molding trials
- Gain an understanding of the design flexibility and limitations of 3D printing for injection mold tooling

Cooling Analysis Options
Review of Past AU Results

Why is Cooling Optimization Important?

- Cycle time reduction
  - Cycle time is typically driven by cooling time

- Improved part quality
  - Warpage
  - Molded-in stresses
  - Surface finish
  - Crystallinity



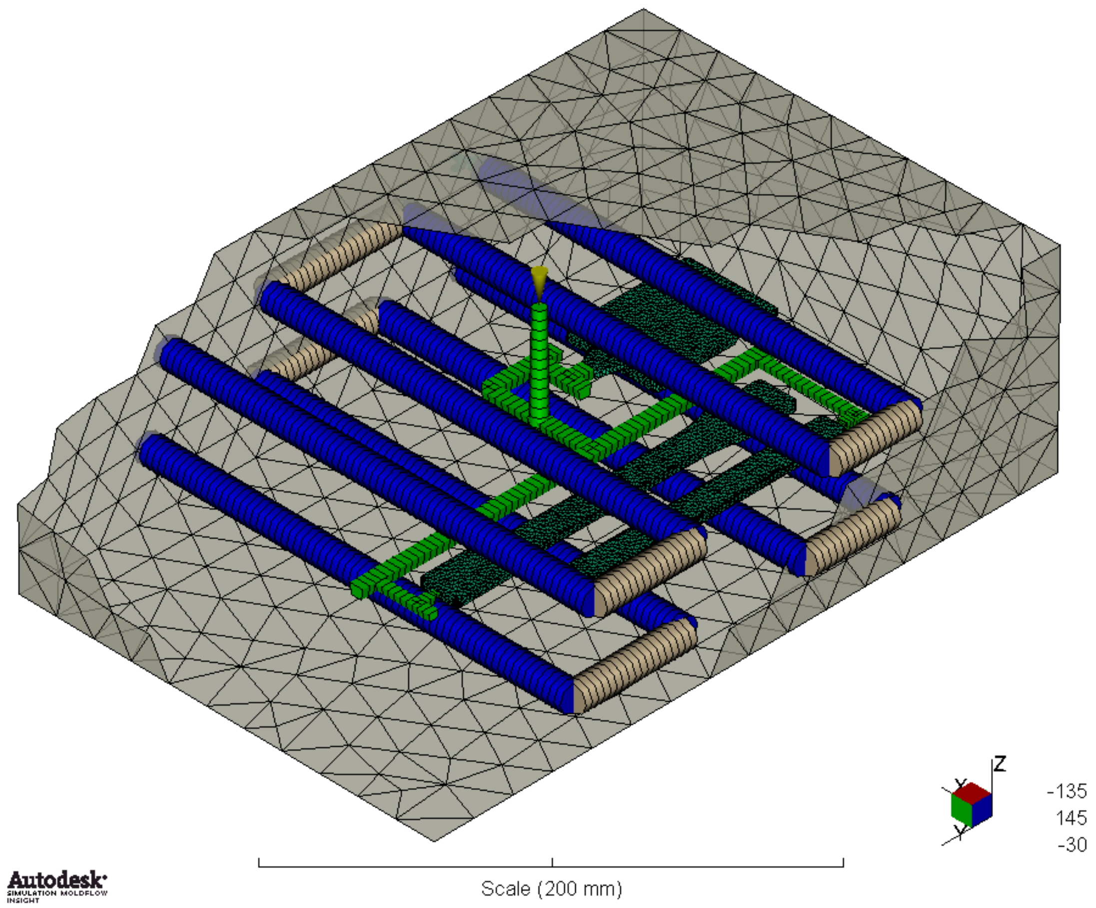
- Autodesk Moldflow analyses can reduce production costs and improve part quality

Types of Cooling Analysis

- Boundary Element Method (BEM)
  - Steady-state solution: No time dependency of mold temperature results
  - Results are averaged through the cycle
  - Fast analysis
  - Mold boundary mesh recommended but not required
  - Easy to setup

Types of Cooling Analysis

- Boundary Element Method (BEM)
  - Surface mesh of the mold boundary



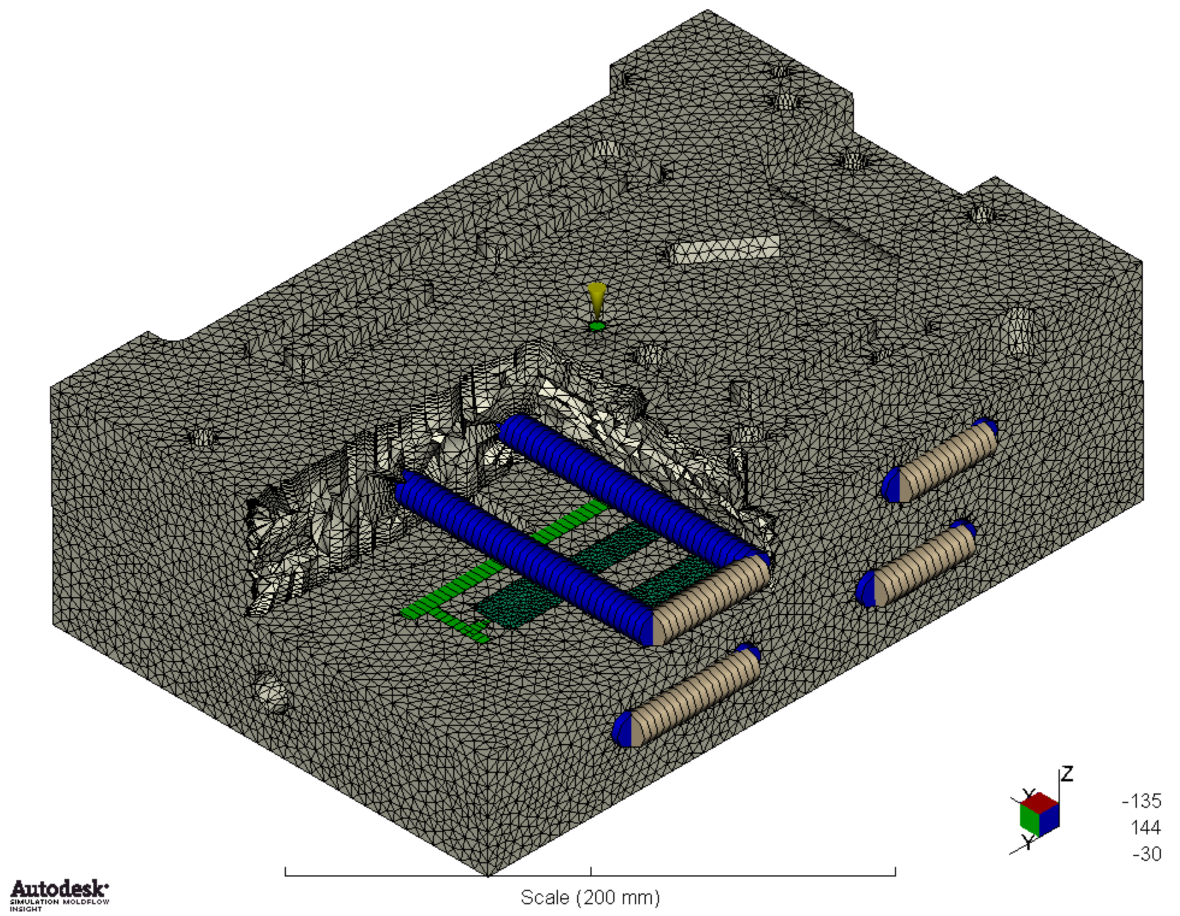
Types of Cooling Analysis

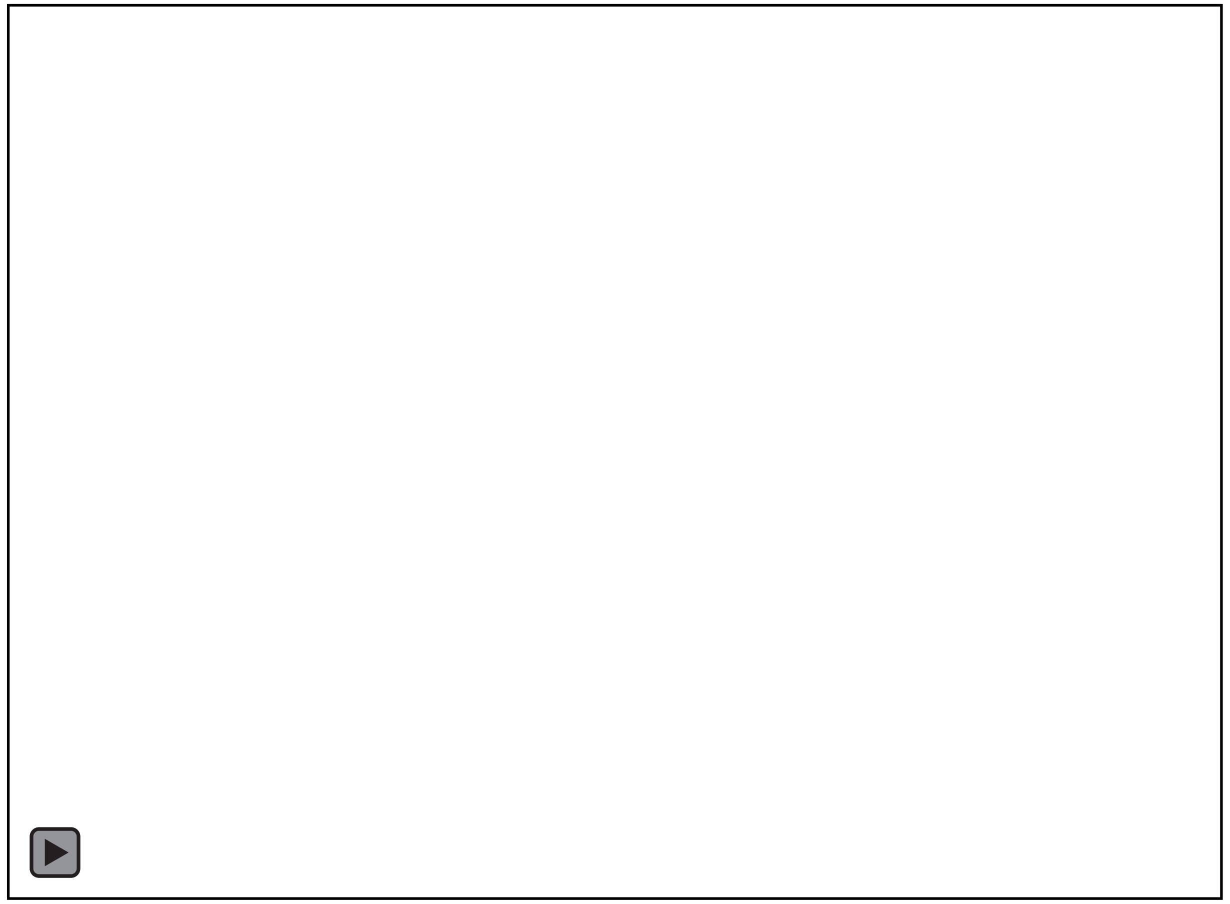
- Finite Element Method (FEM)
  - Average within cycle: Results are averaged through the cycle
  - Transient within cycle: Time dependent mold temperature
  - Transient from production startup: Multiple cycles analyzed

- Considerations when choosing cool FEM
  - Requires more time to solve
  - Must mesh mold geometry

Types of Cooling Analysis

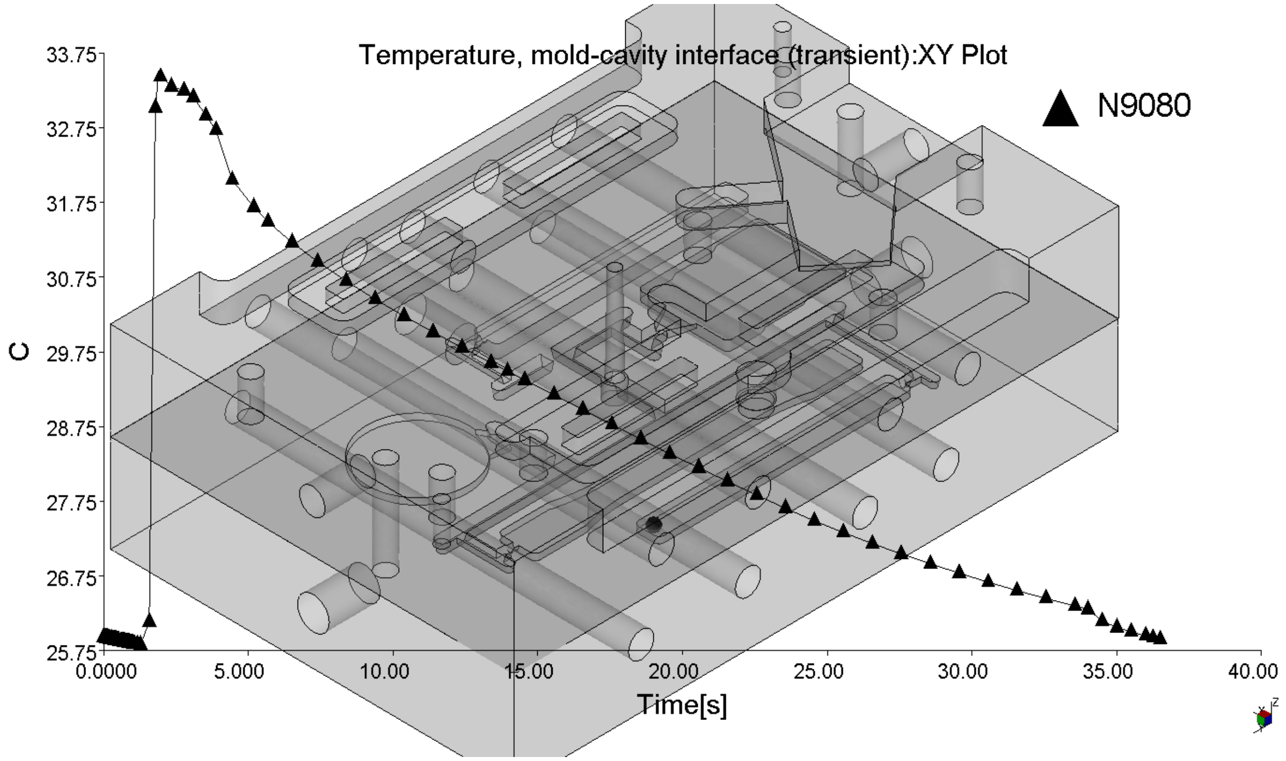
- Finite Element Method (FEM)
  - Mold Temperature options:
    - **Averaged within cycle**: Steady state calculation





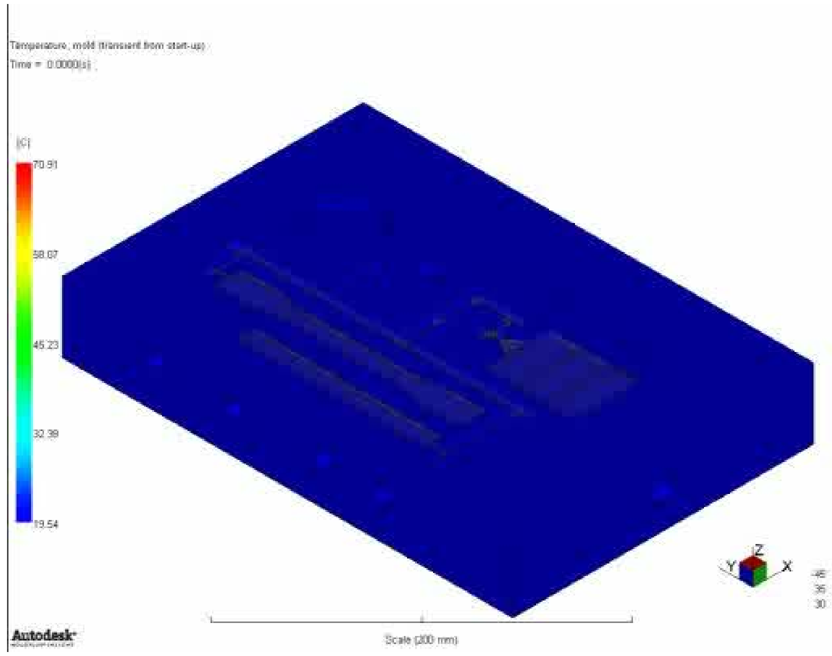
Types of Cooling Analysis

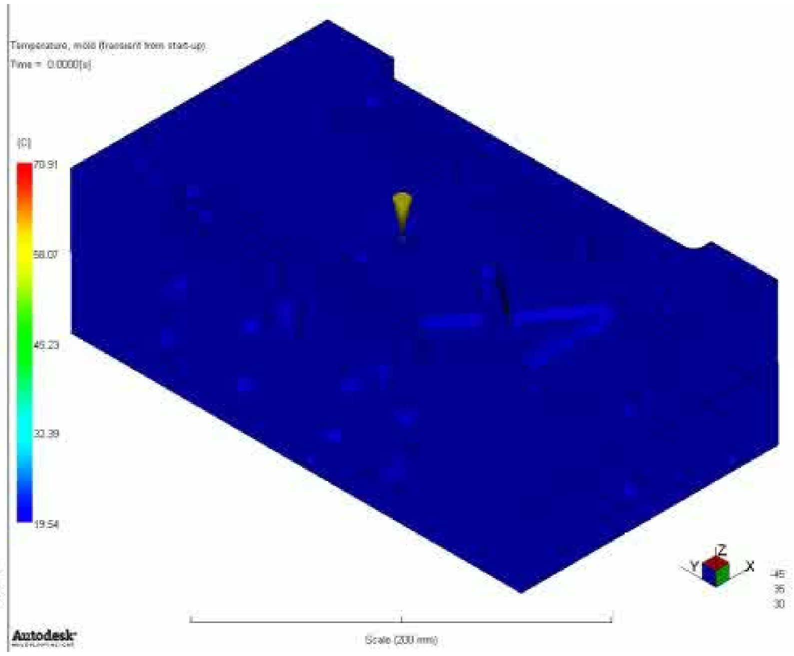
- Finite Element Method (FEM)
  - Mold Temperature options:
    - **Transient within cycle**: Shows temperature cycle in the mold as it transfers heat from molten plastic

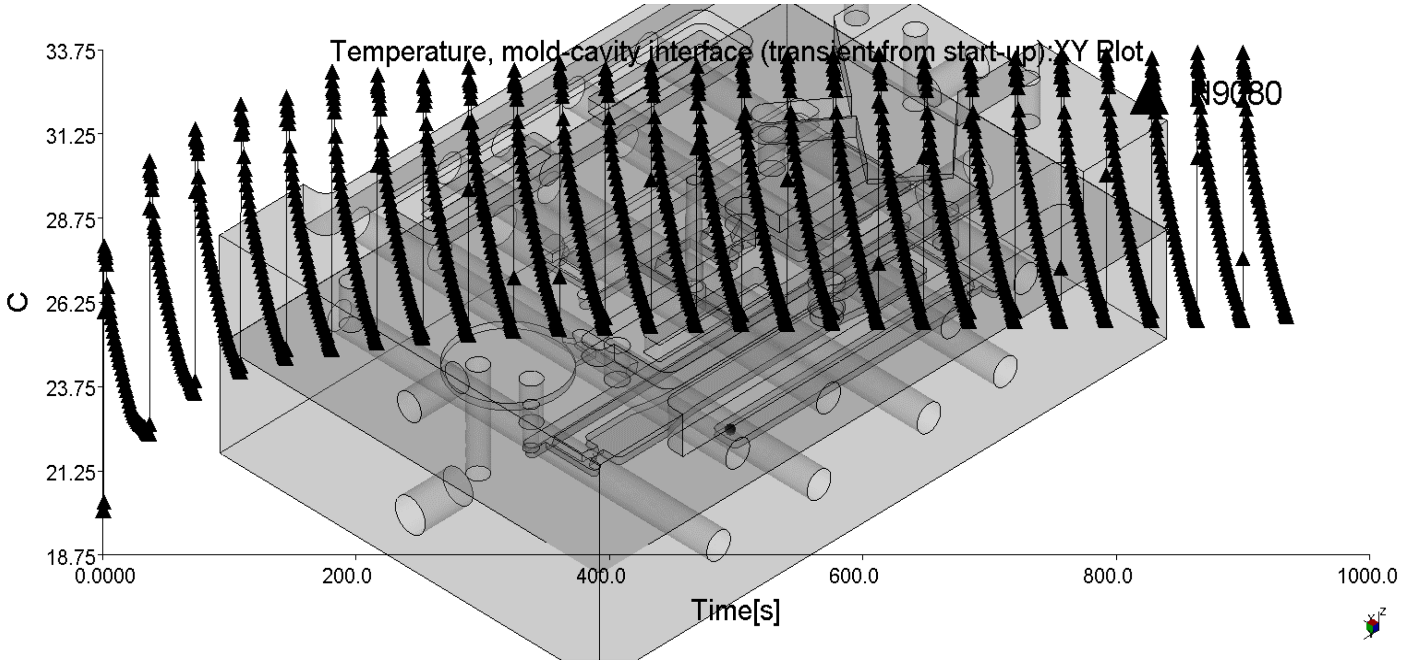


Types of Cooling Analysis

- Finite Element Method (FEM)
  - Mold Temperature options:
    - **Transient from production start-up**: Shows mold temperature cycle and heat accumulation until it reaches steady state.
      Temperature cycle at steady state reflects transient within cycle result
    - *AU 2013 (SM2868 – Transient Cooling)*



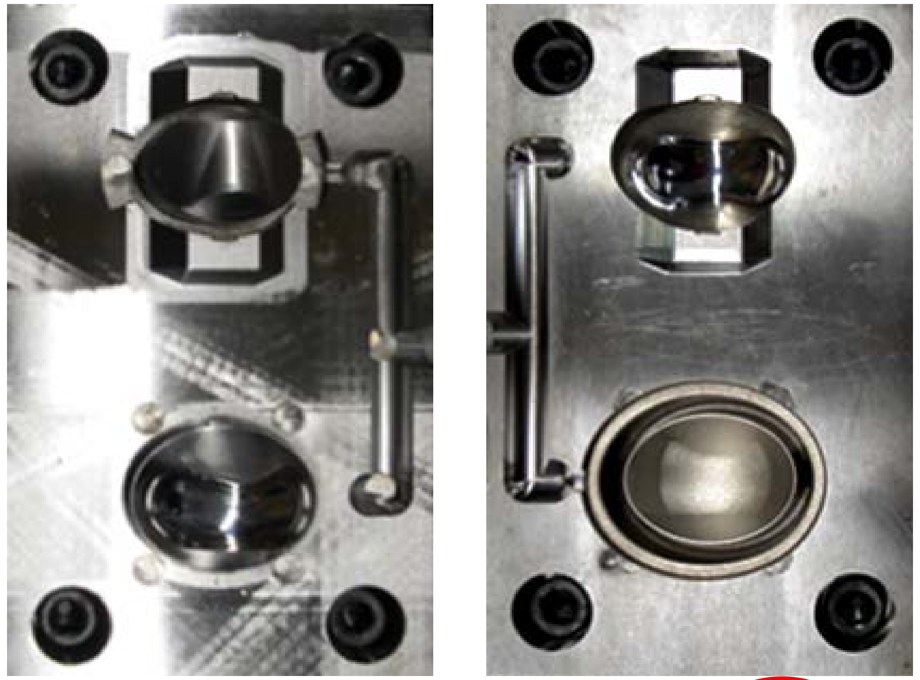


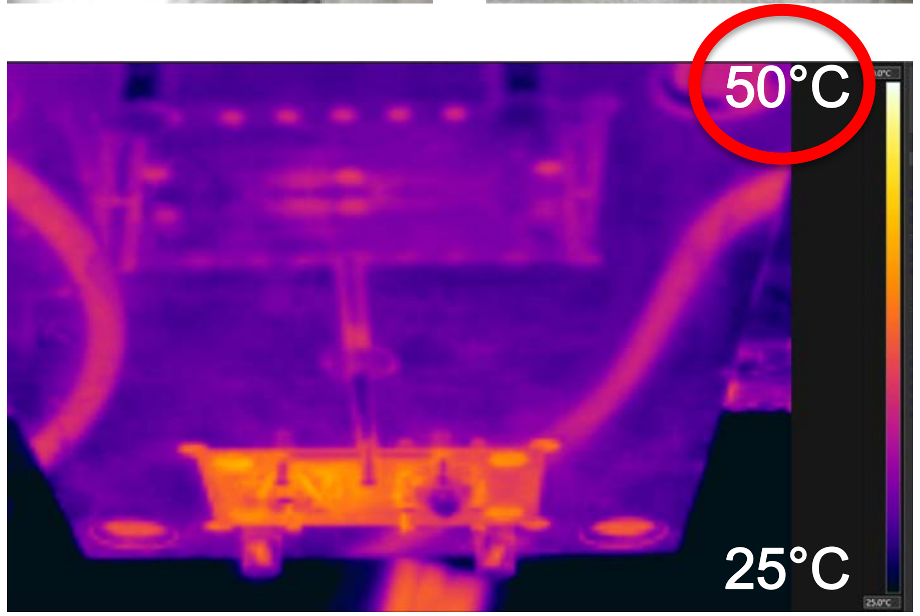


Summary of AU 2014 Experimentation (SM6859)

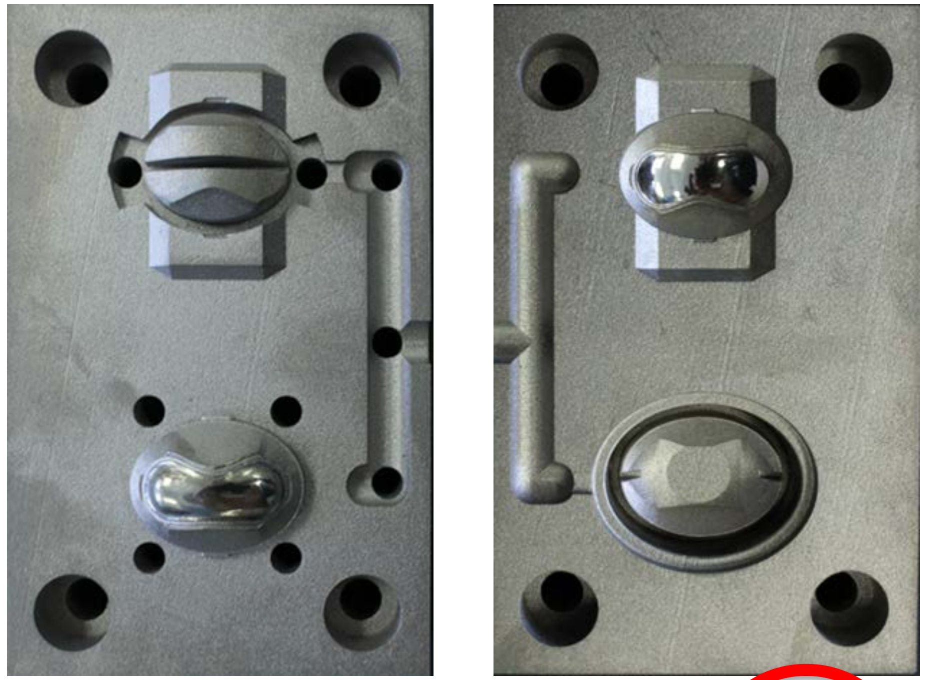
Comparison of Conventional and 3DP Mold Inserts

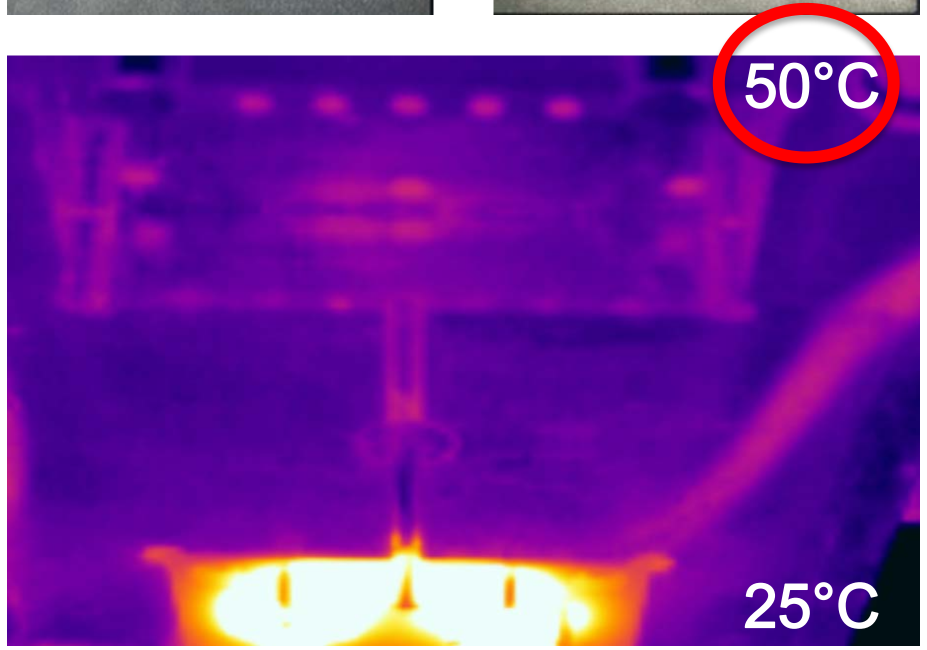
Machined Stainless Steel



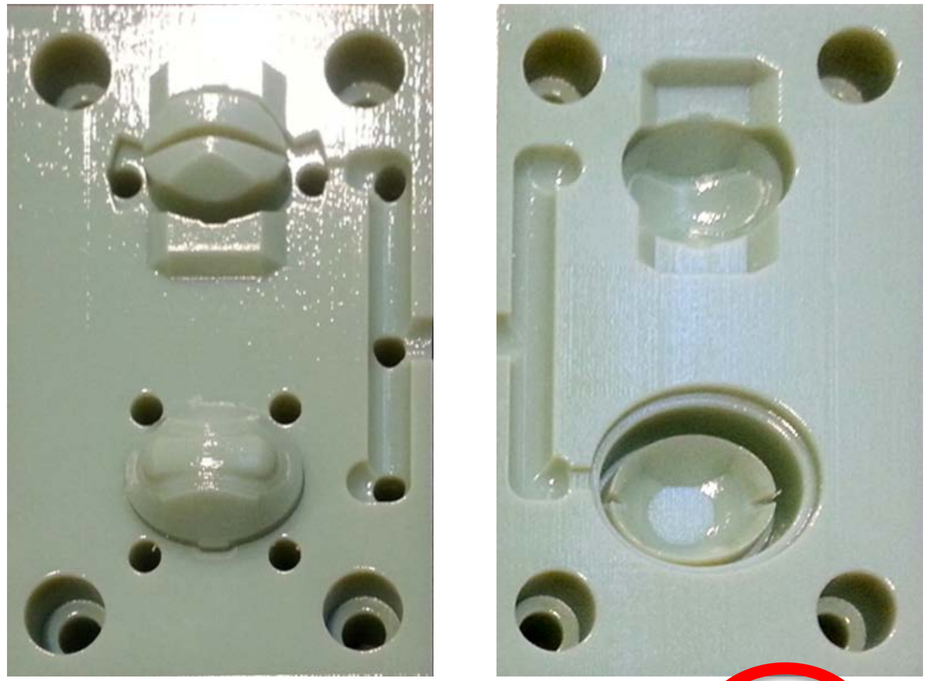


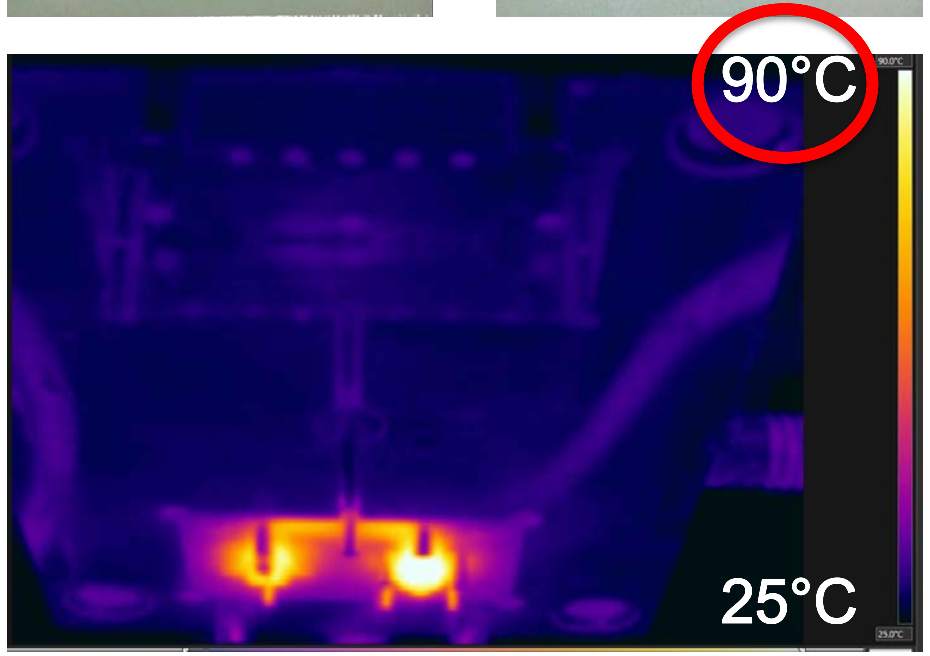
DMLS Bronze





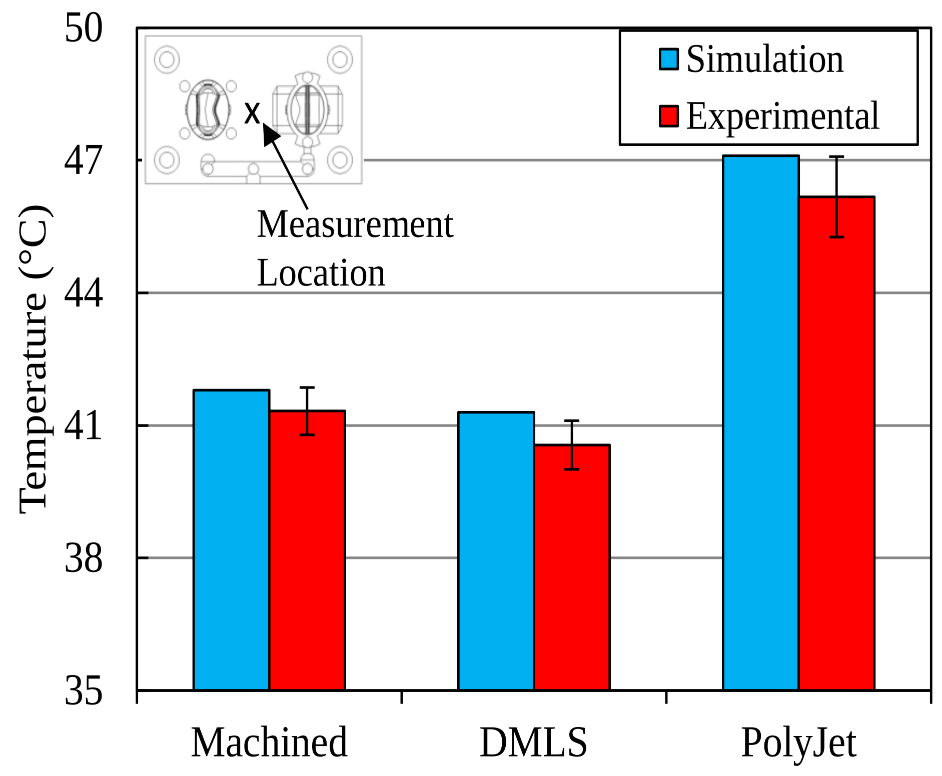
Digital ABS

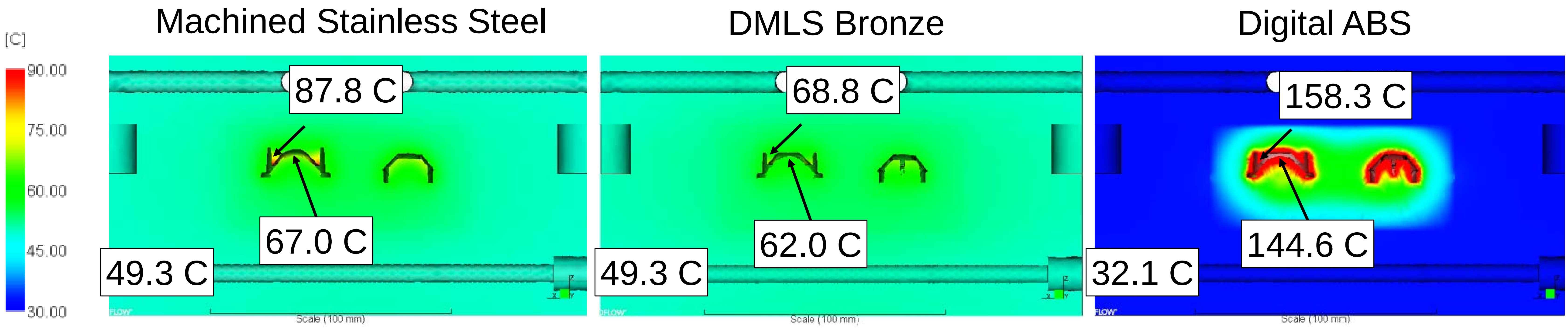




Summary of AU 2014 Results (SM 6859)

- Autodesk Moldflow simulations showed close agreement with experimental results
- Lowest cooling rate on Digital ABS inserts
  - Affected crystallinity and dimensions
- High temperatures compromised structural integrity
  - Strength dependency on temperature is unknown



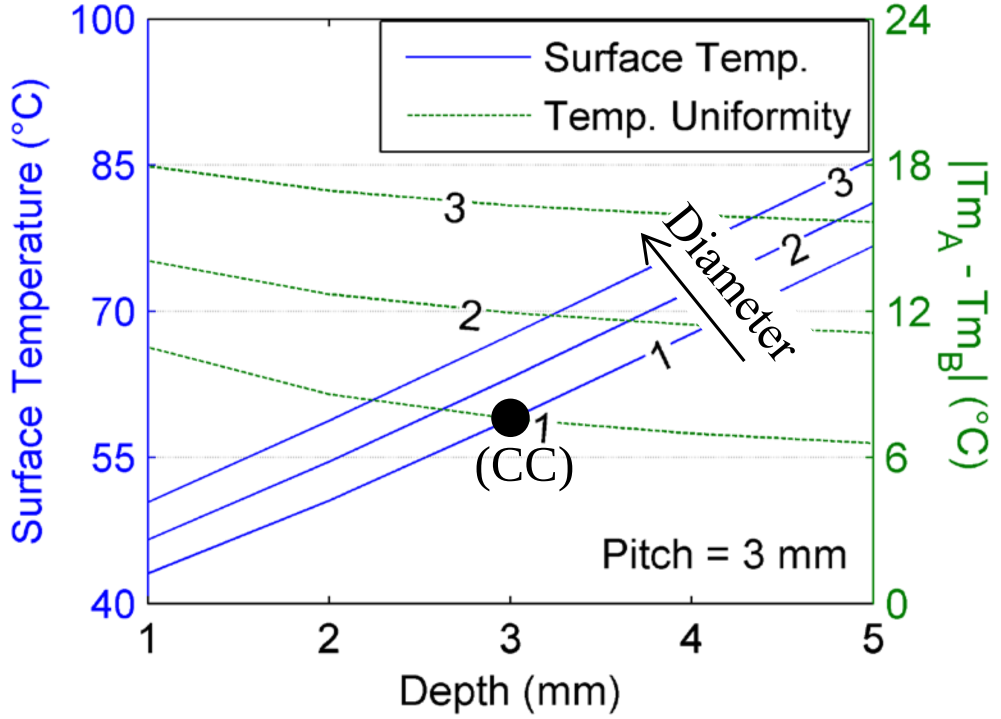


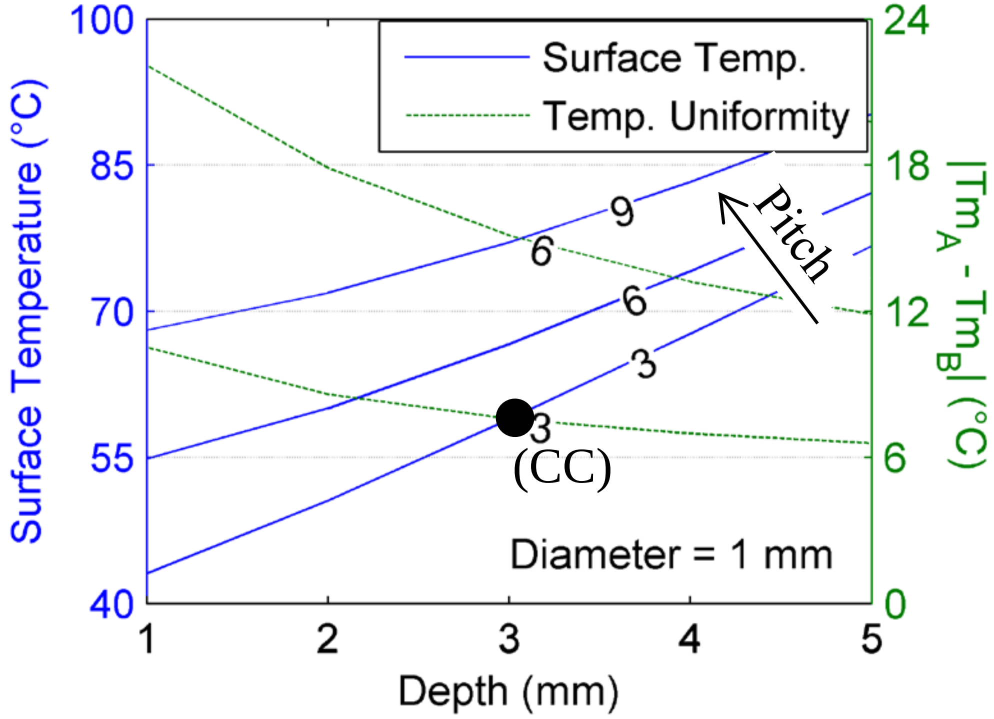
Conformal Cooling

- Advantages
  - Cycle time improvements
  - Improved temperature uniformity and part quality
  - Faster steady-state conditions

- Depth, pitch, & diameter effect cooling efficiency and structural integrity
  - Analytical solution[1]:

$$Tm_l = T_c + \frac{\rho_p c_p l_p (2K_m W + h\pi D l)(T_{melt} - T_{eject})}{h\pi D K_m t_{cycle}}$$

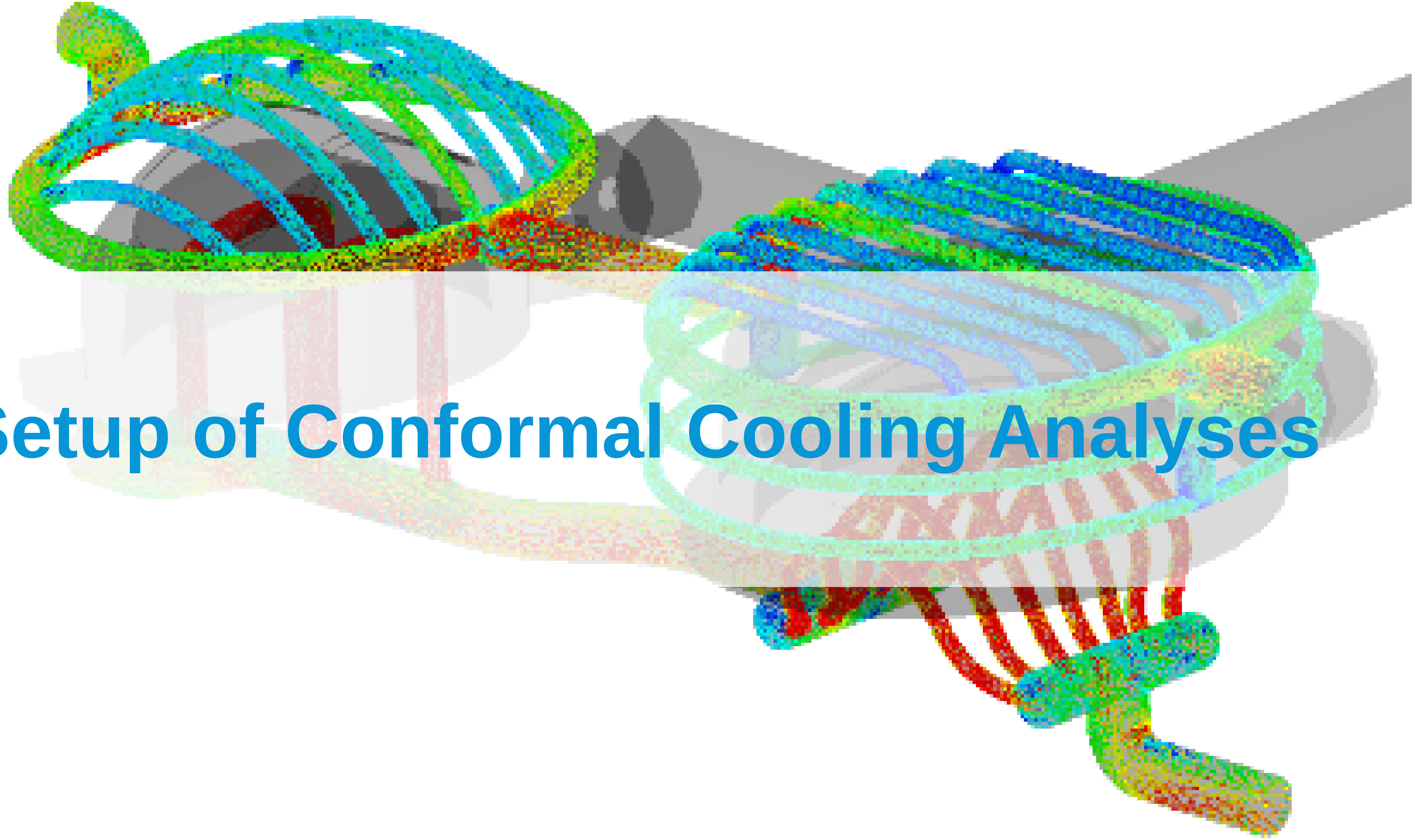




Definition of Terms

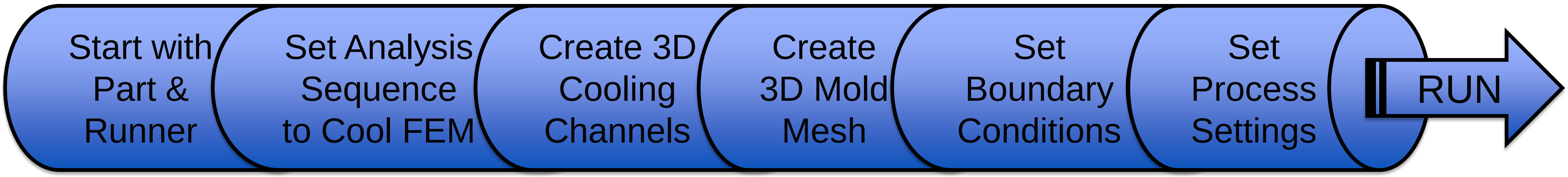
Tm_l – Mold temp. at distance l from channel
T_c - Coolant temperature
T_{melt} - Melt temperature
T_{eject} - Ejection temperature
ρ_p - Density of resin
c_p - Specific heat of resin
l_p - Half thickness of part
K_m - Thermal conductivity of mold
h - Heat transfer coeff.(~30,000 W/m^2°C)
W - Pitch
D - Diameter of channel
t_{cycle} - Cycle time

[1] X. Xu, E. Sachs, and S. Allen, "The Design of Conformal Cooling Channels in Injection Molding Tooling," *Polym. Eng. Sci.*, vol. 41, no. 7, pp. 1265–1279, Jul. 2001.



Setup of Conformal Cooling Analyses

Workflow for Cool FEM with Conformal Cooling



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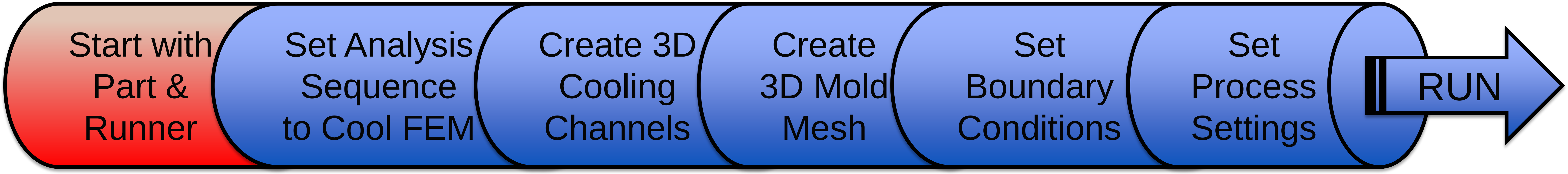

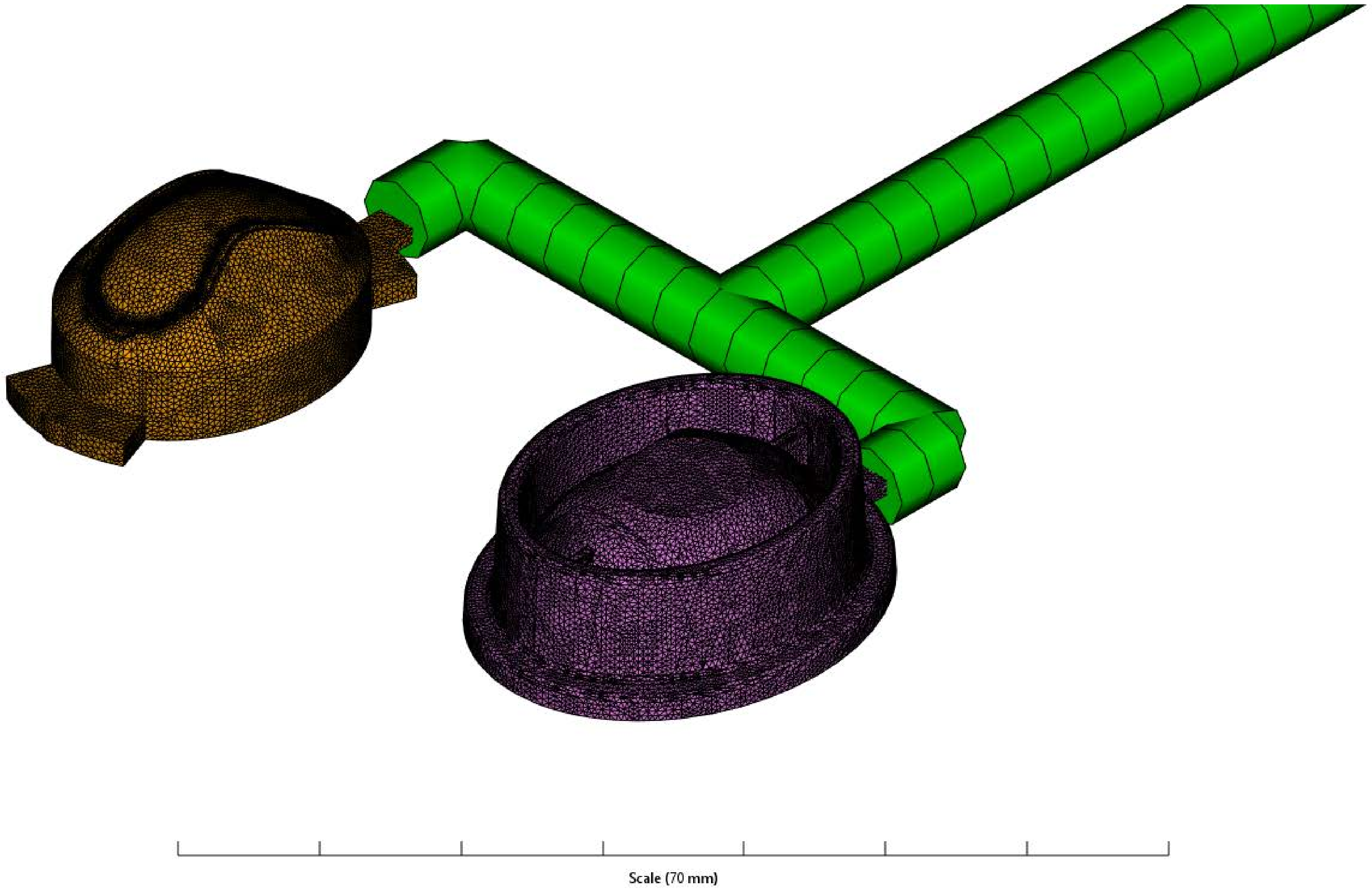

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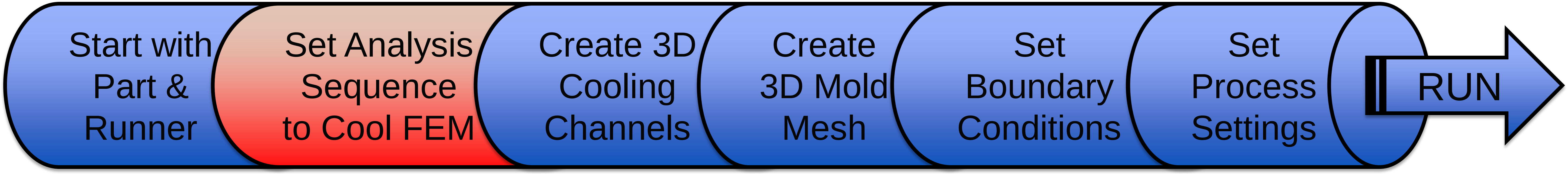
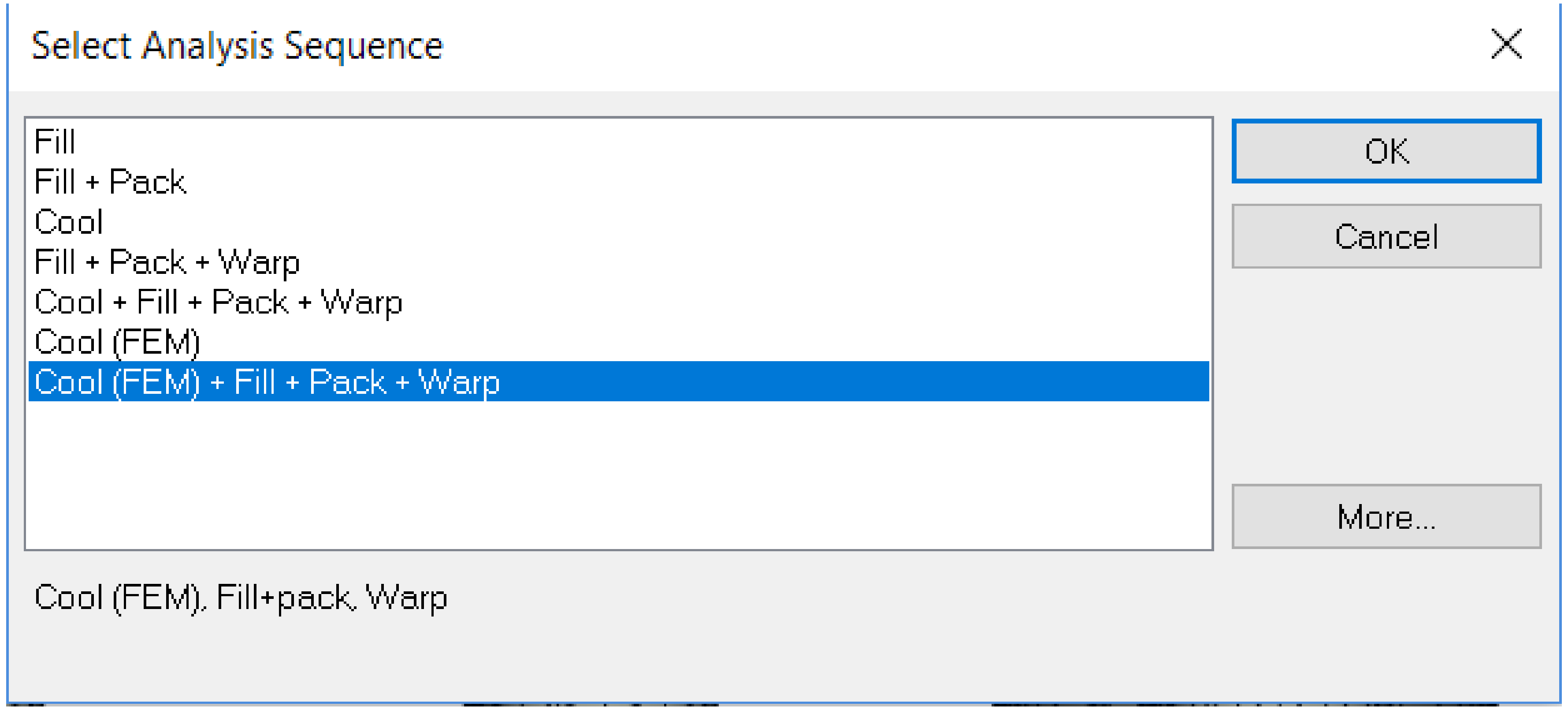
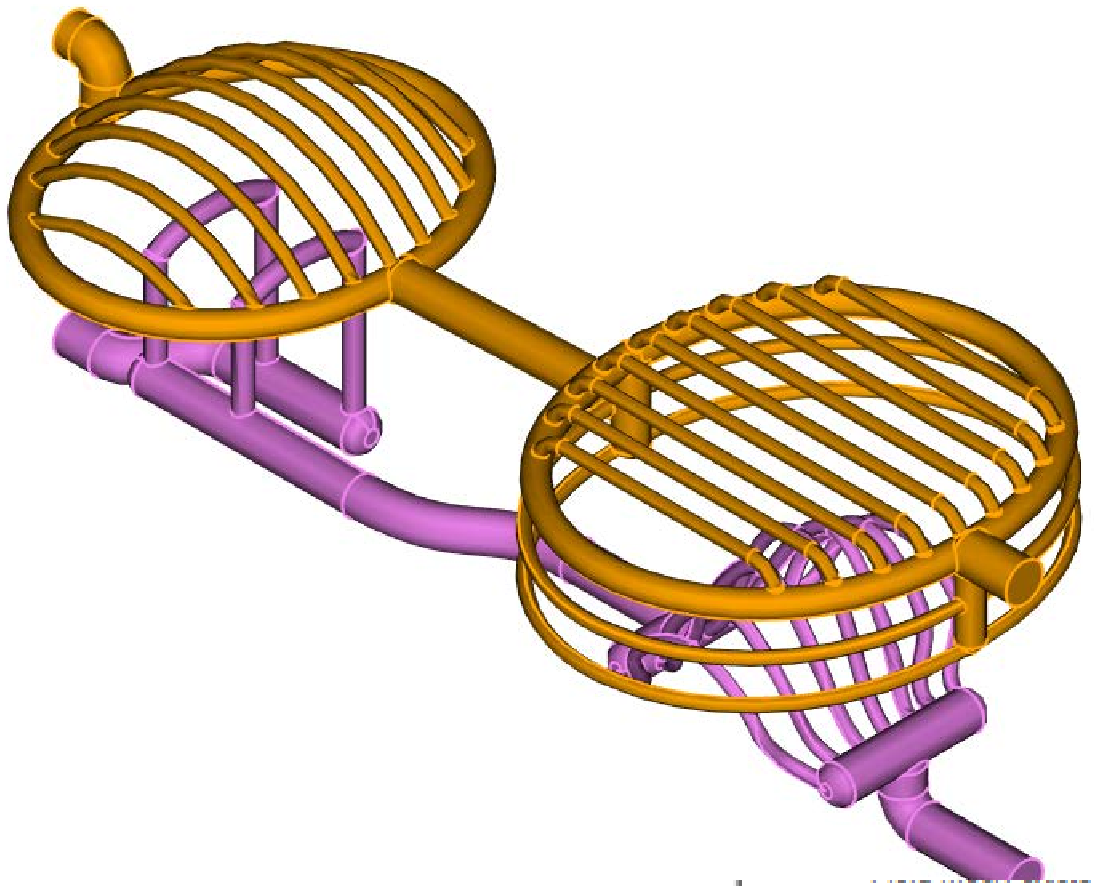
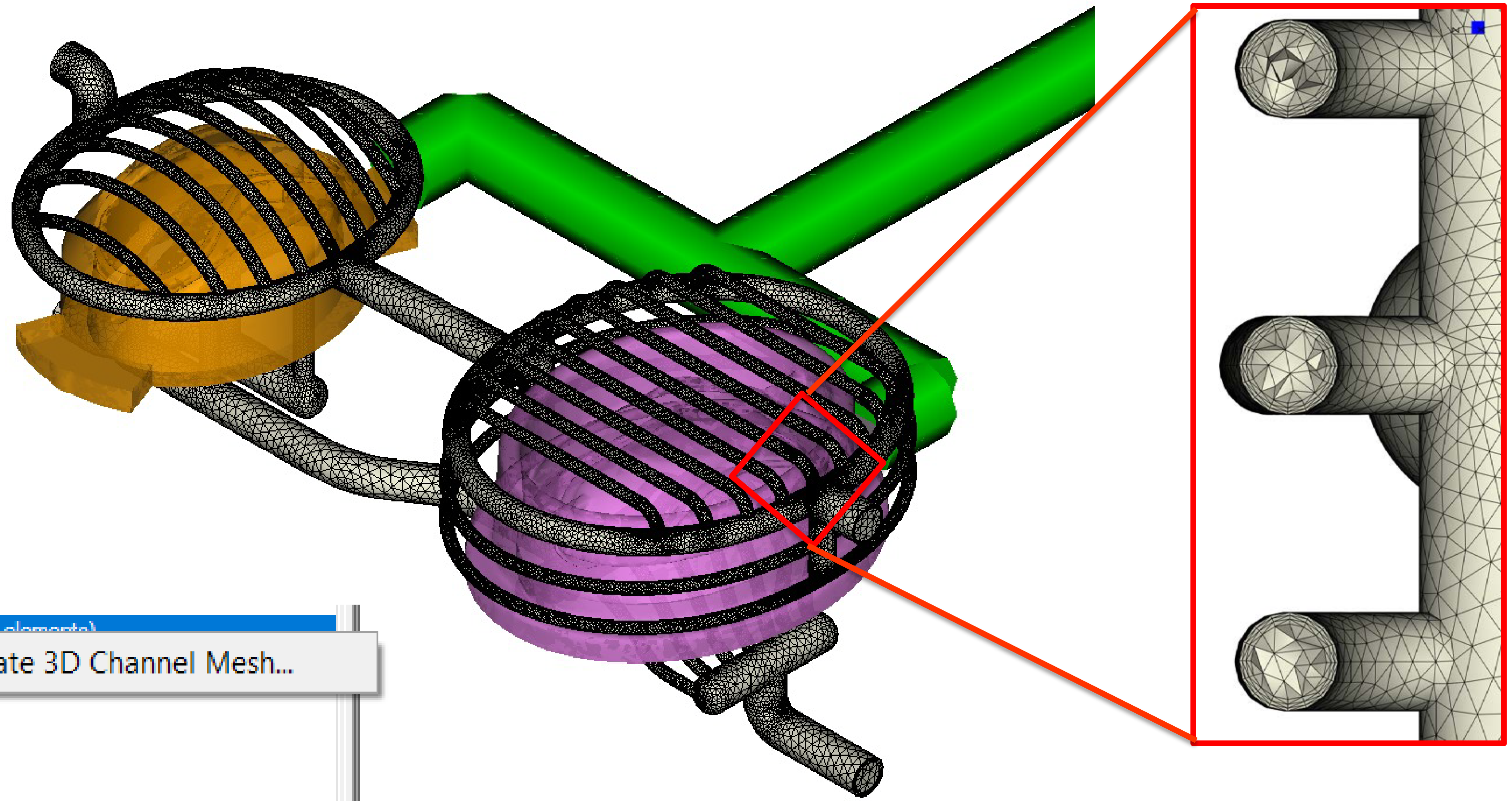


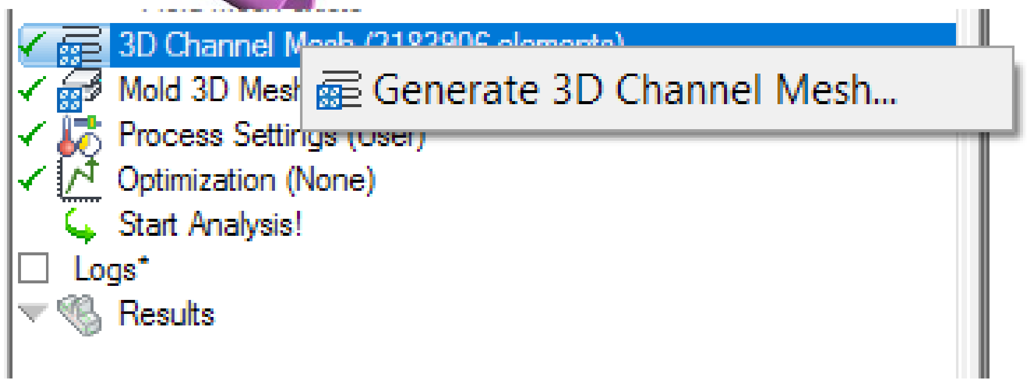


Workflow for Cool FEM with Conformal Cooling

Start with Part & Runner → Set Analysis Sequence to Cool FEM → Create 3D Cooling Channels → Create 3D Mold Mesh → Set Boundary Conditions → Set Process Settings → RUN







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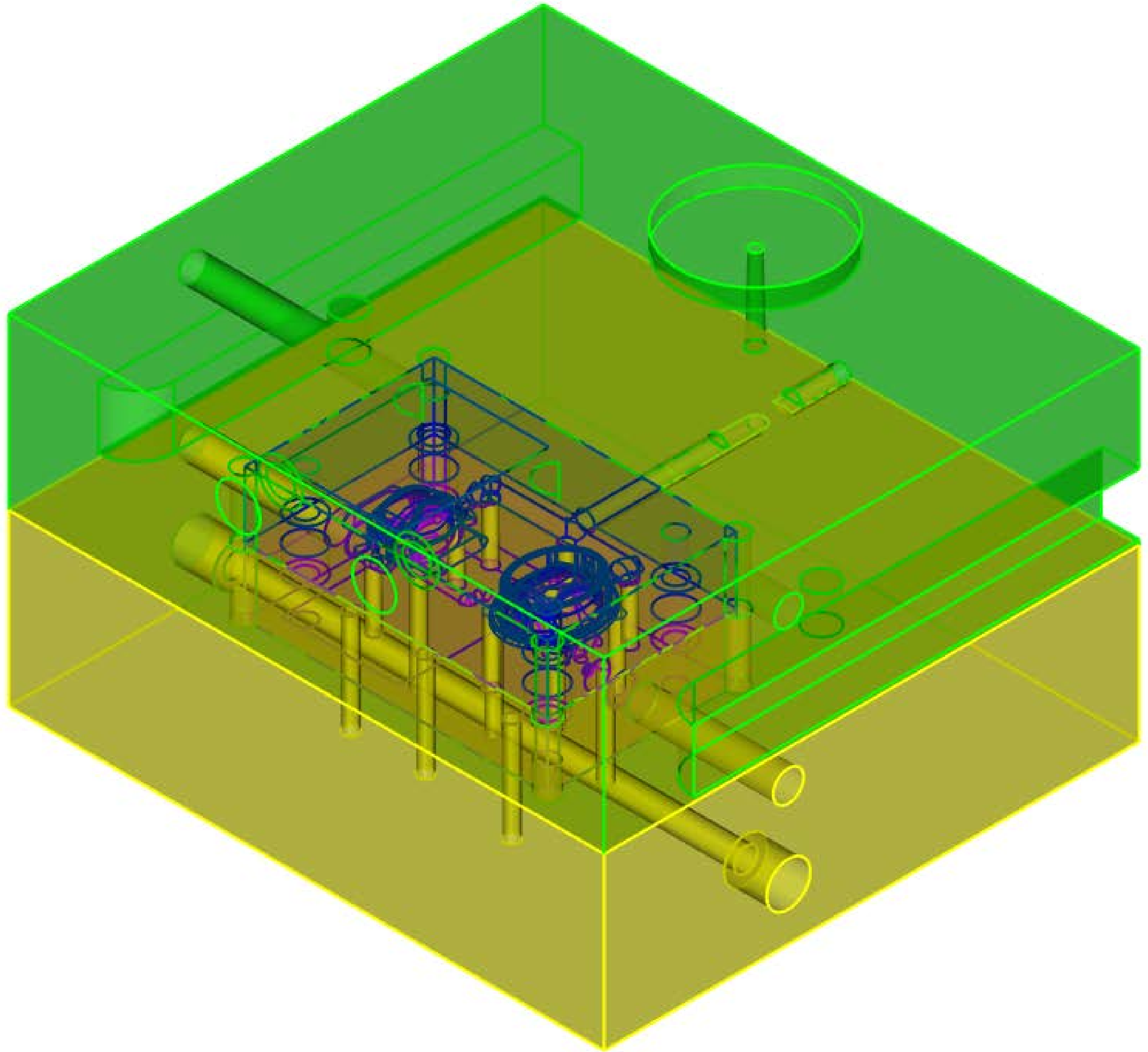

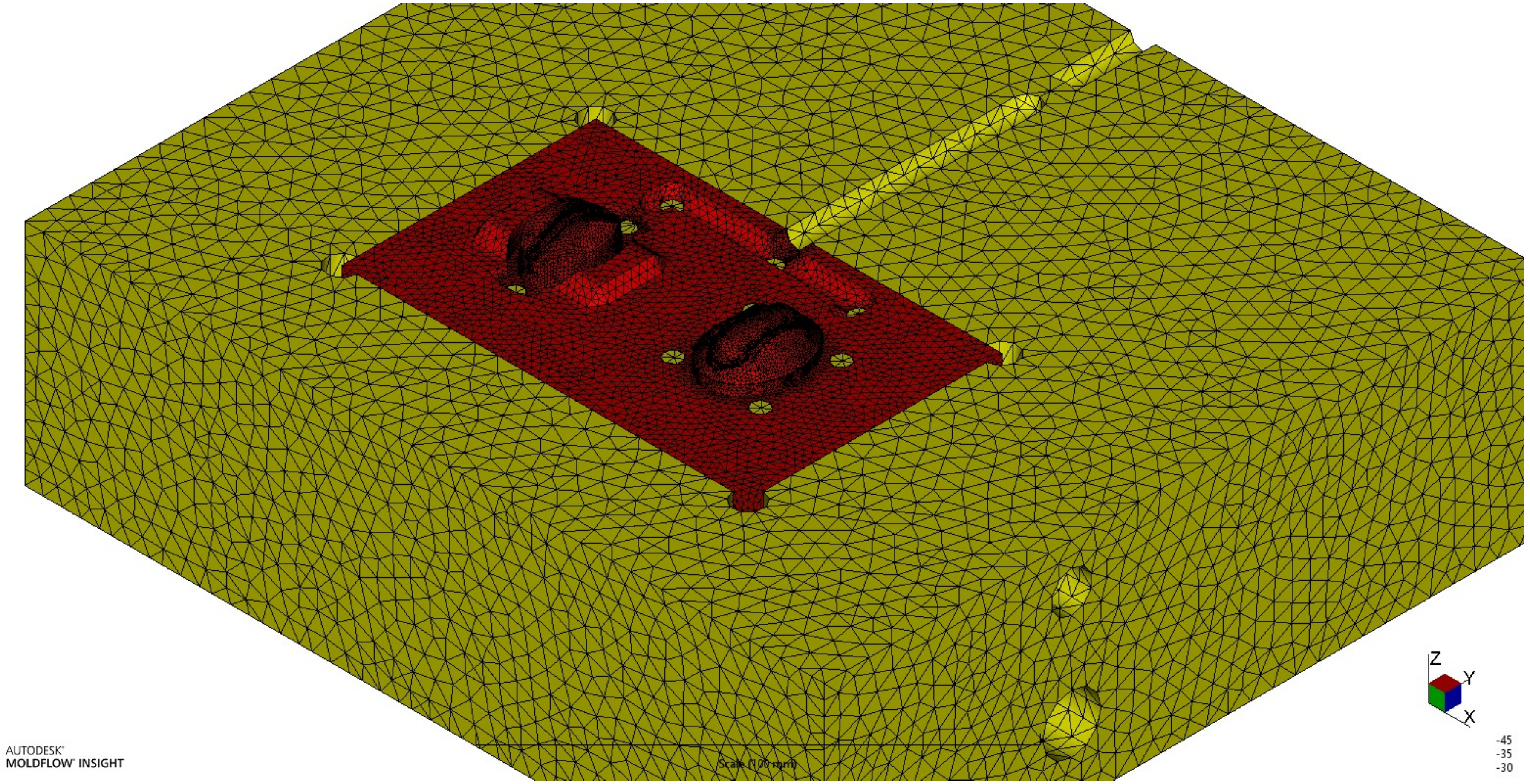

Workflow for Cool FEM with Conformal Cooling

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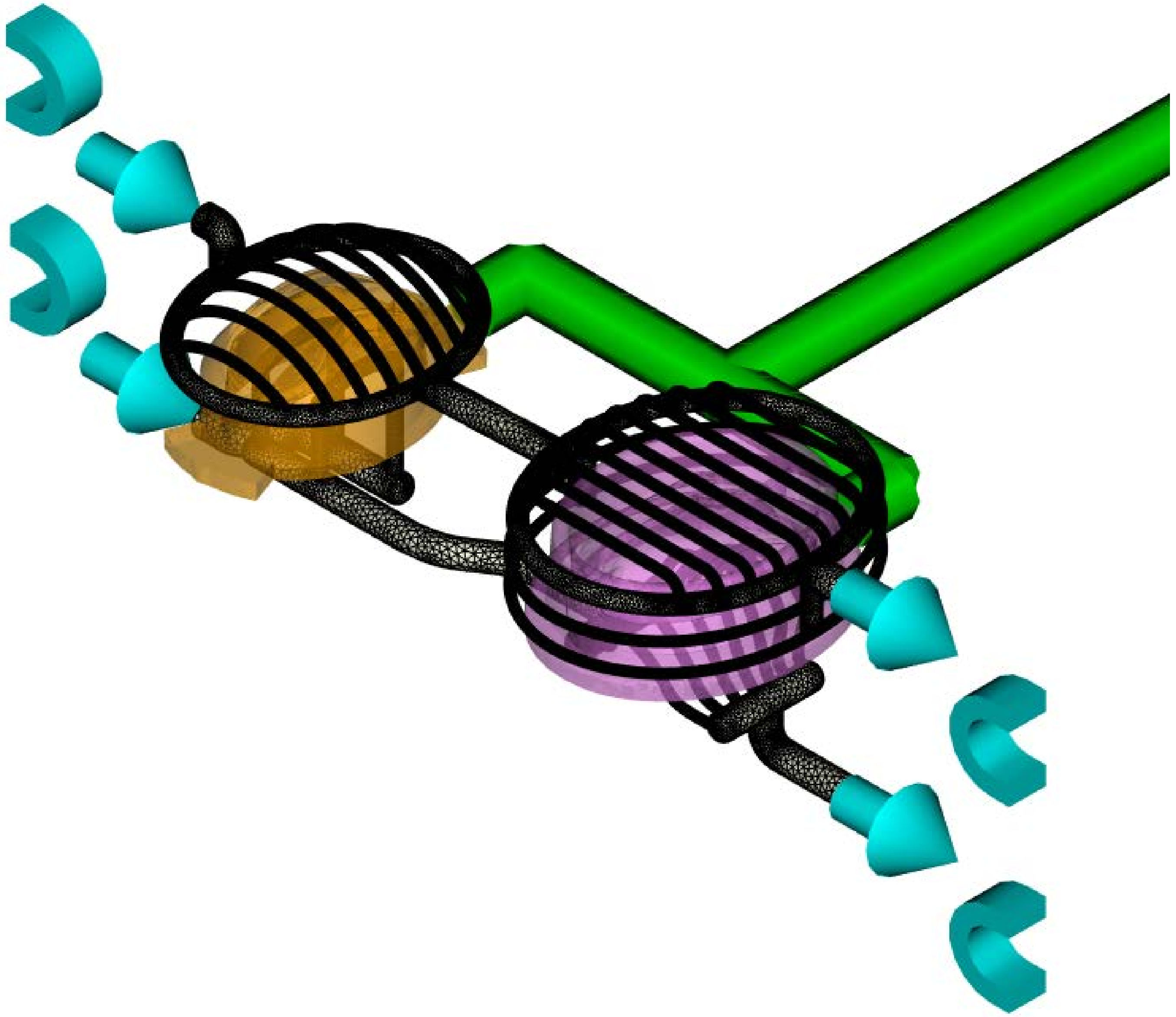

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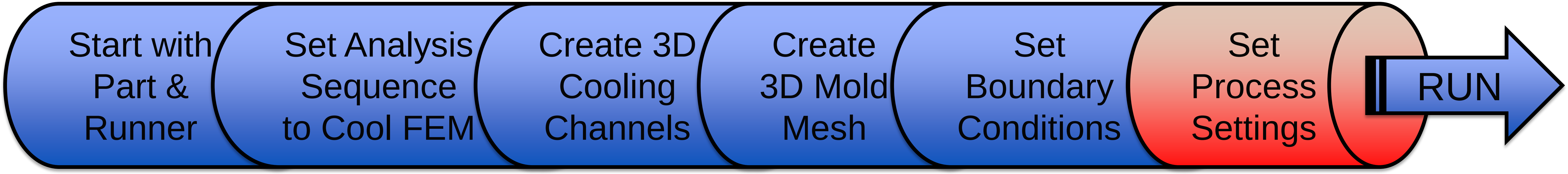
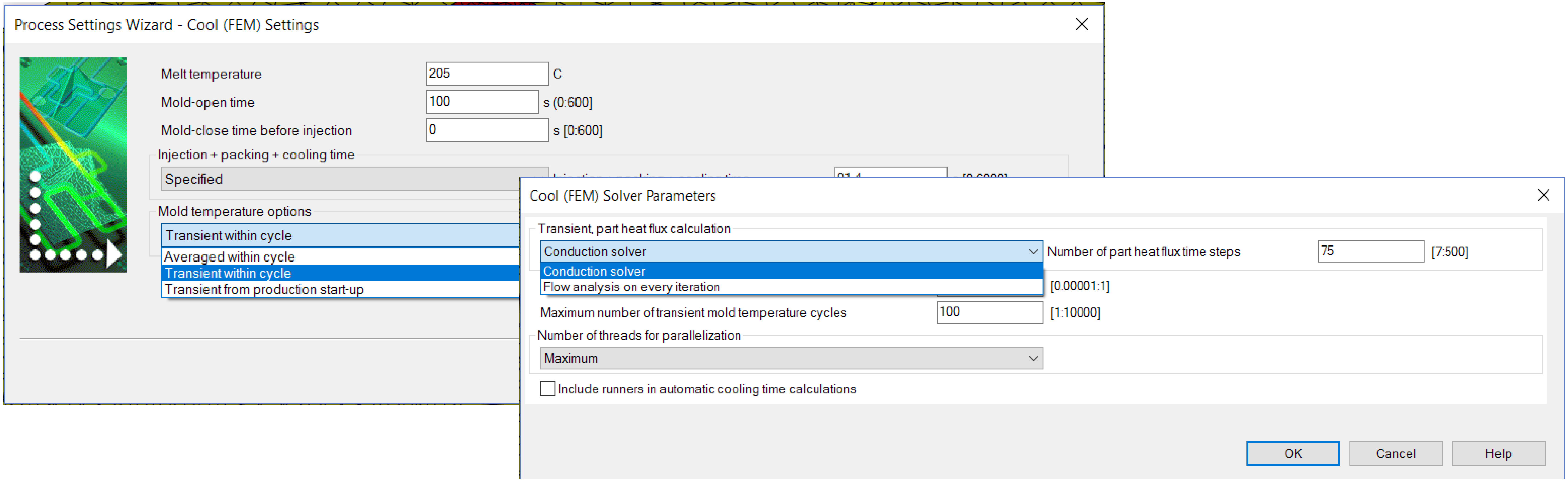
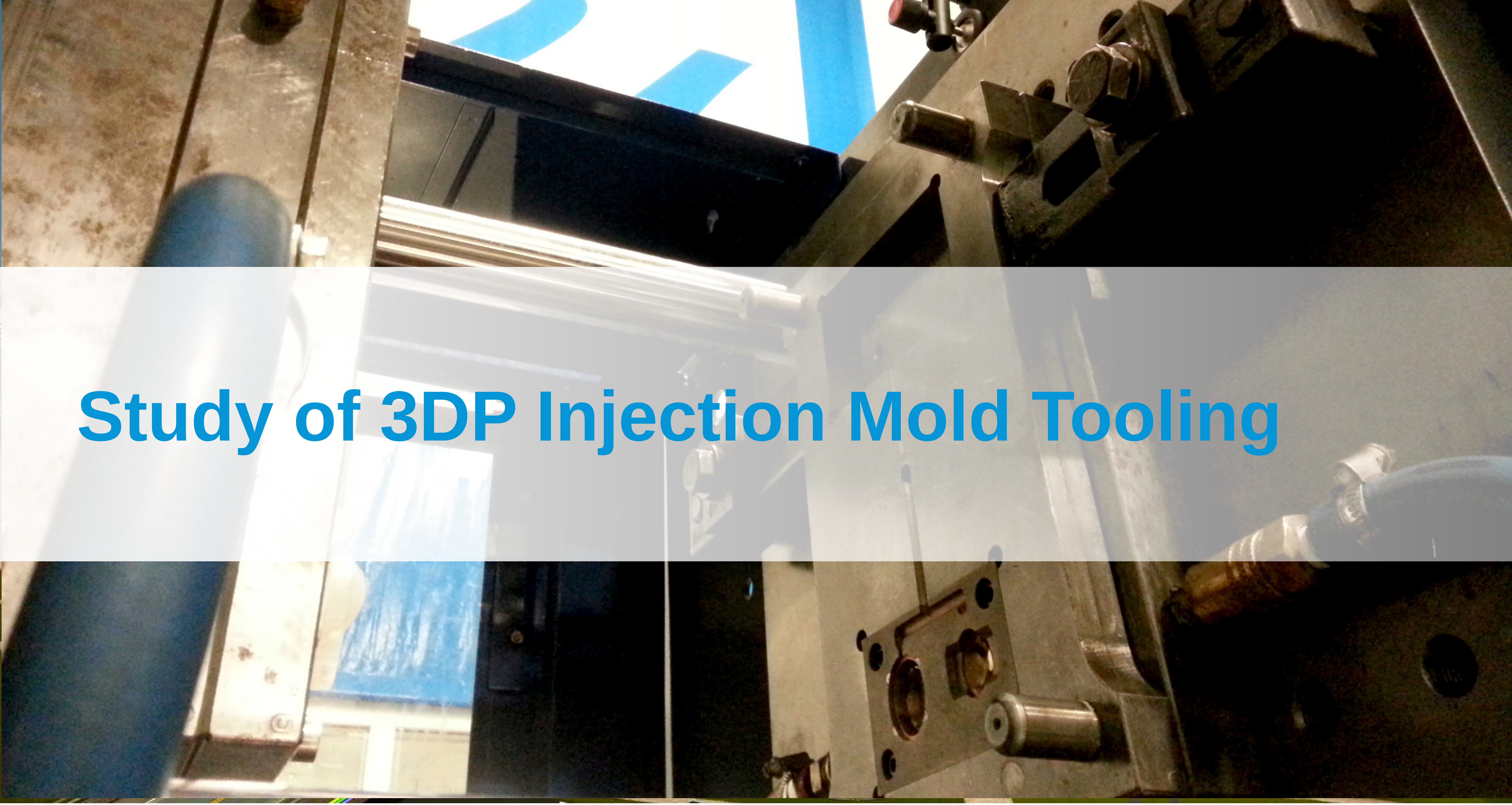


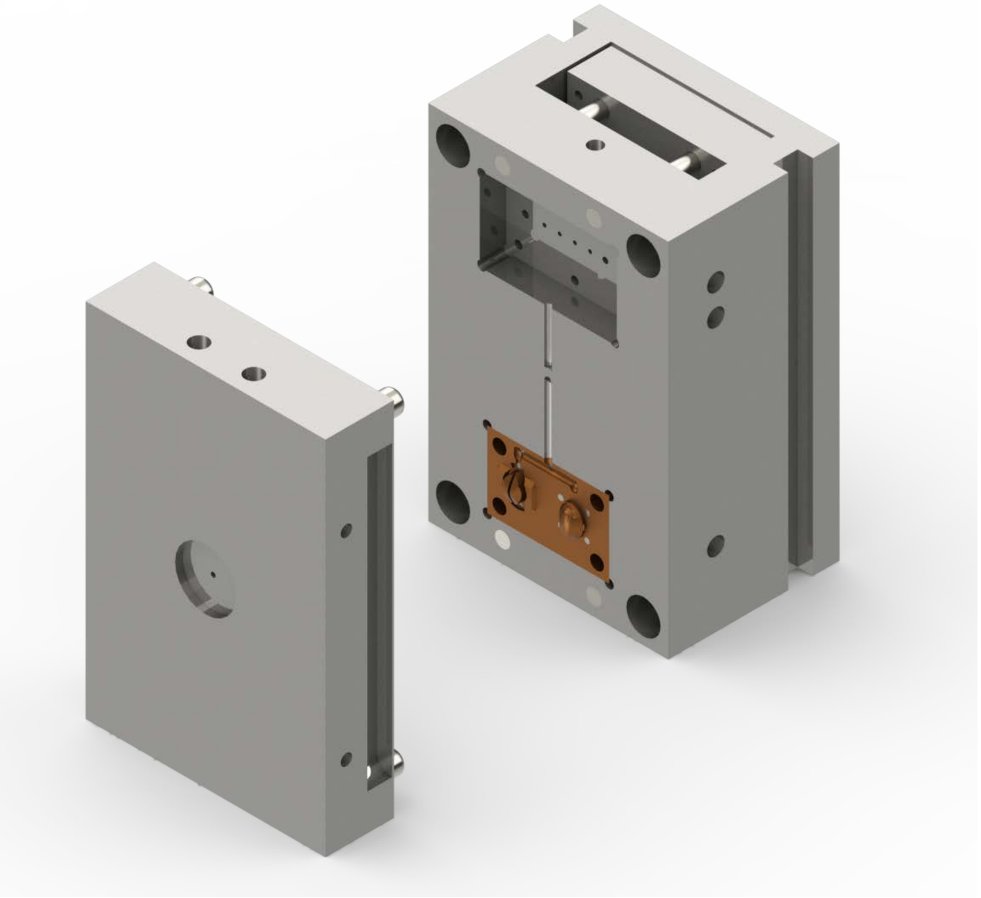


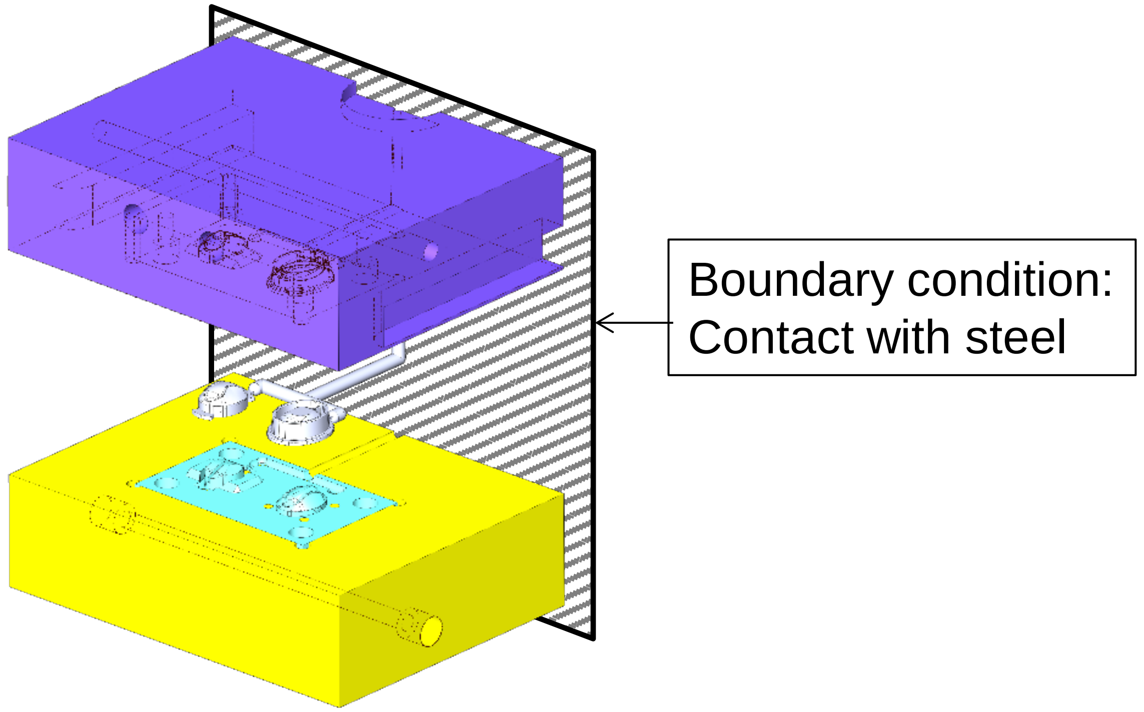


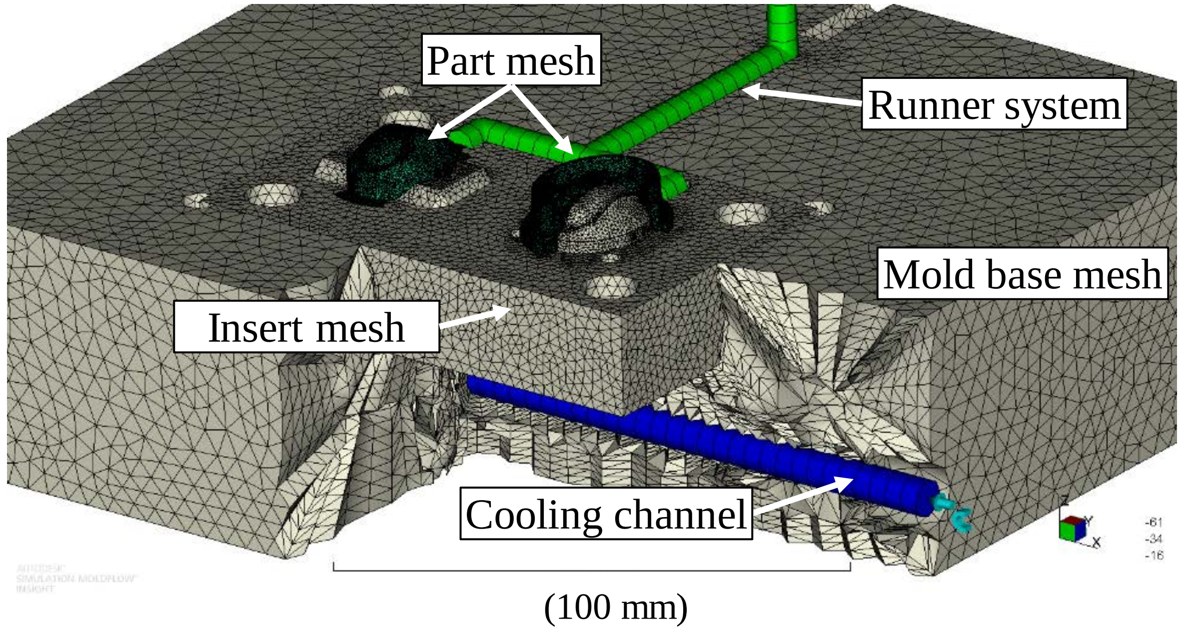
Study of 3DP Injection Mold Tooling

Methodology – Mold Geometry

- Full 3D mesh of the part geometry, insert, and mold
  - Simplified section of the mold without inserts and cooling





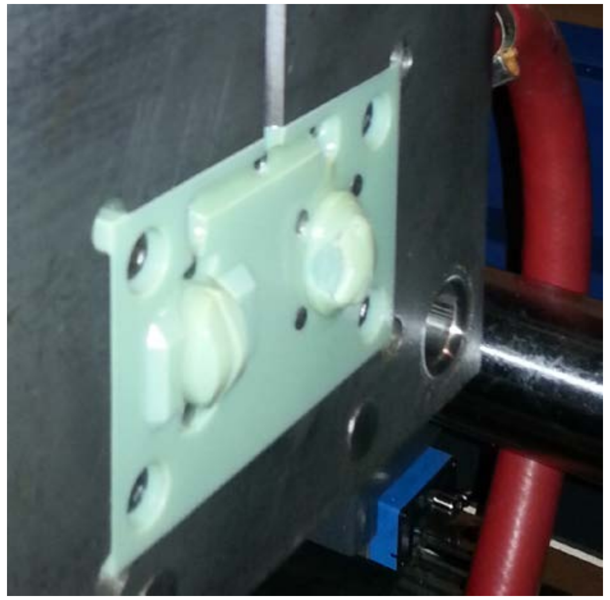


Methodology – Jetted Photopolymer Tooling

- PolyJet process overview
  - Inkjet printing of liquid acrylate photopolymer
  - UV lamp cures material
- Inserts originally printed on Objet Connex 500
  - Digital ABS – blend of two cartridge materials
  - Retains strength at higher temperatures
  - Recommended for prototype injection mold tooling
  - Support material washed away with water
- Conformal cooling designs rely on efficient support removal

Stratasys
FOR A 3D WORLD™

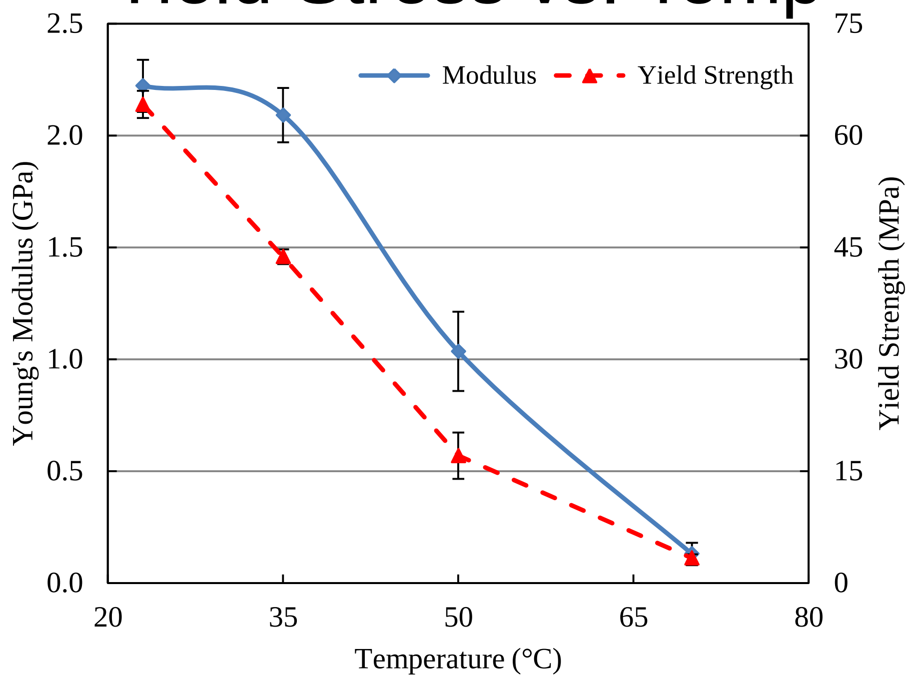
Digital ABS



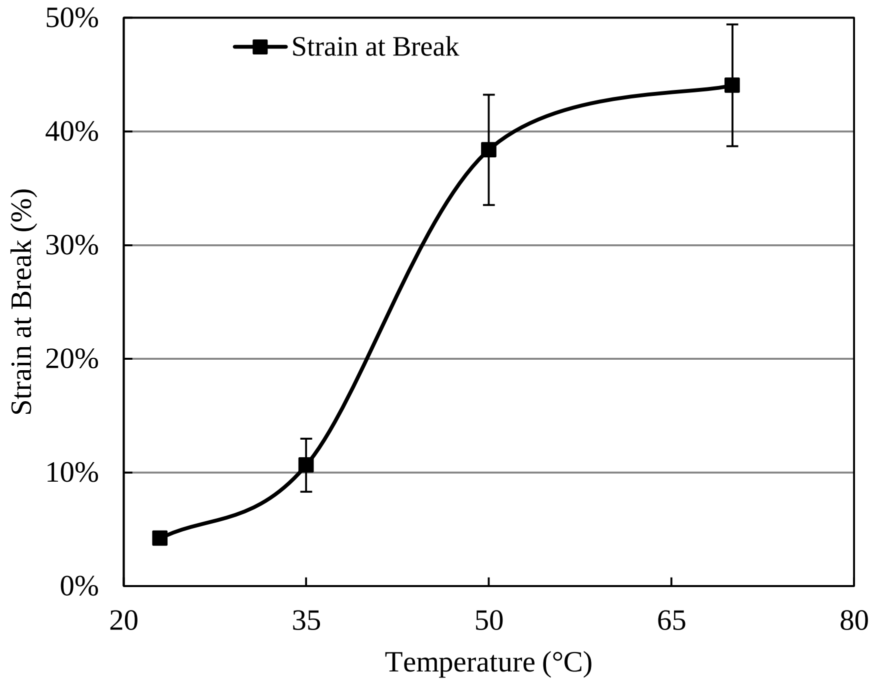
Methodology – Jetted Photopolymer Tooling

- Printed inserts on Stratasys Eden 260V
  - Vero-Gray (printed at UML) & Vero-White Plus (printed at Stratasys)
- Vero-White Plus & Vero-Gray
  - Single cartridge materials
  - Soluble support technology necessary for conformal cooling
  - Lower strength and temperature capabilities
  - Both materials reported to have the same properties[2]

Modulus vs. Temp
Yield Stress vs. Temp



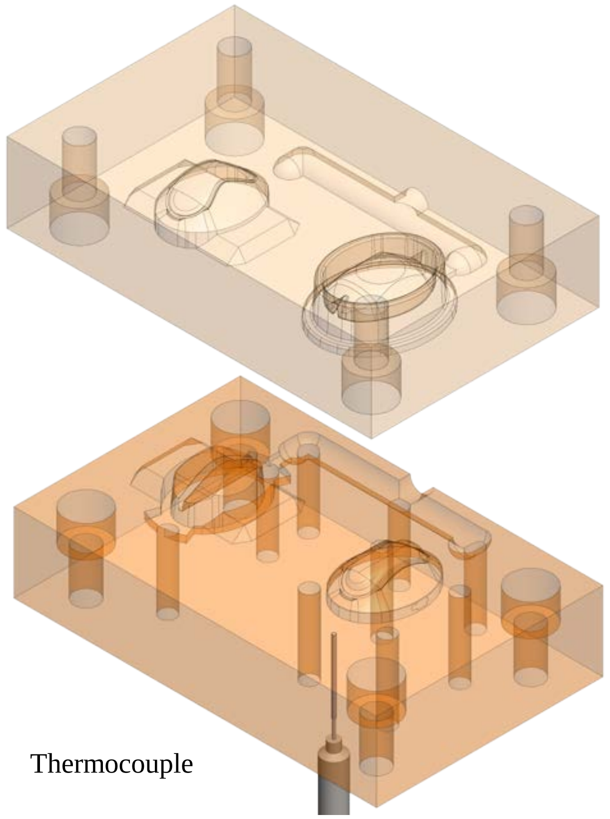
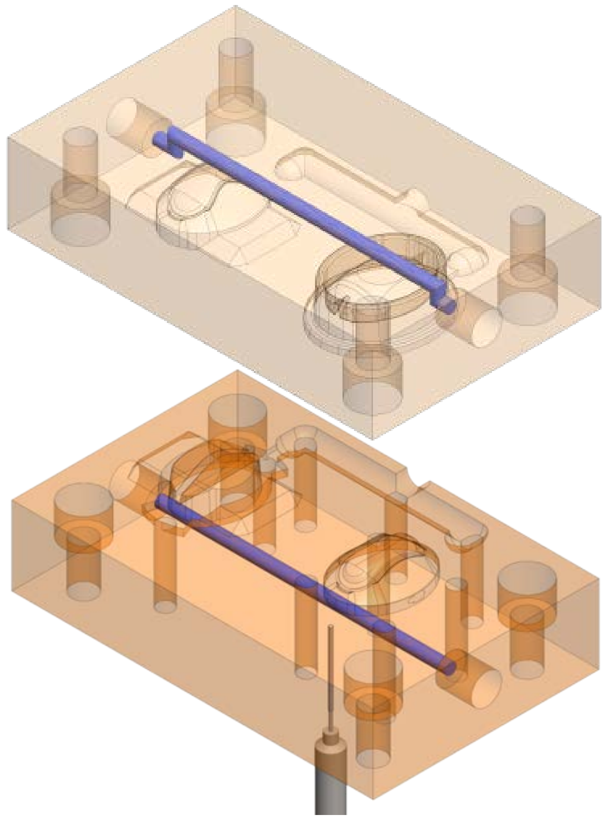
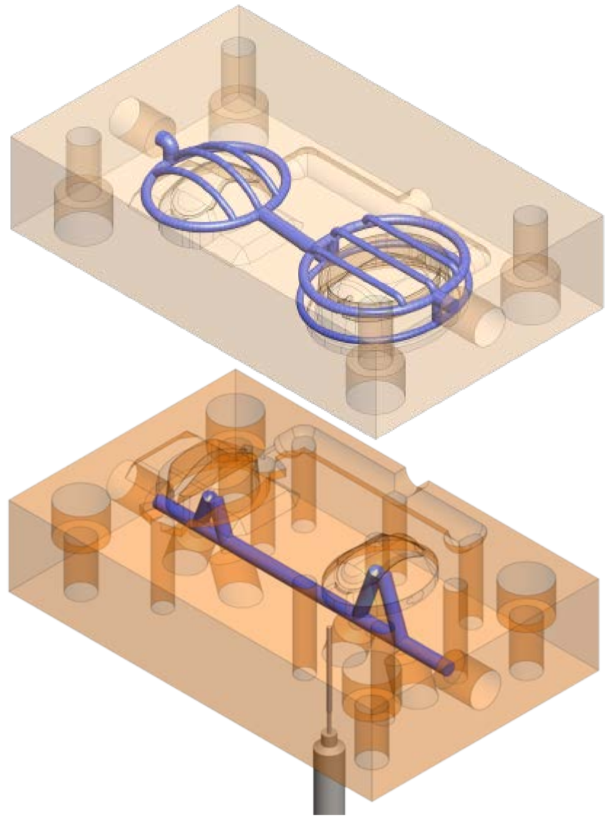
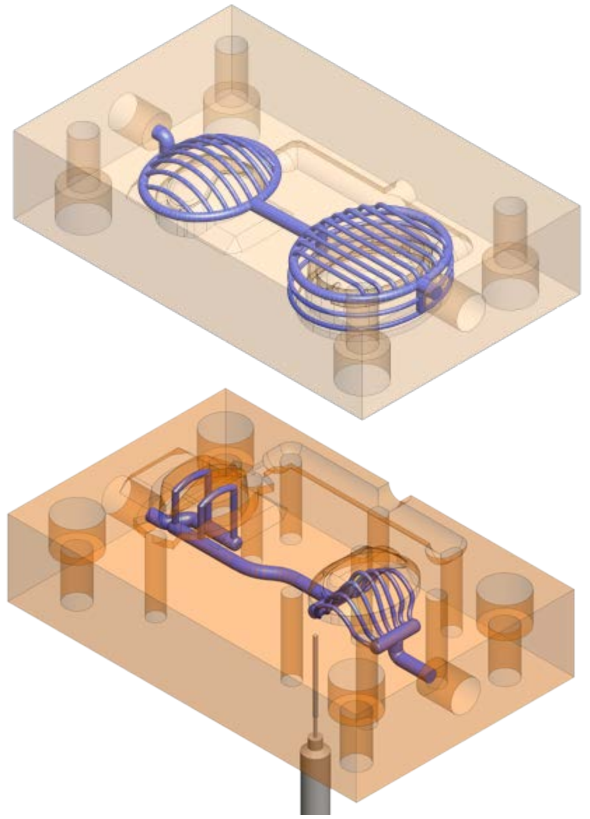
Strain at Break vs. Temp.



Vero White

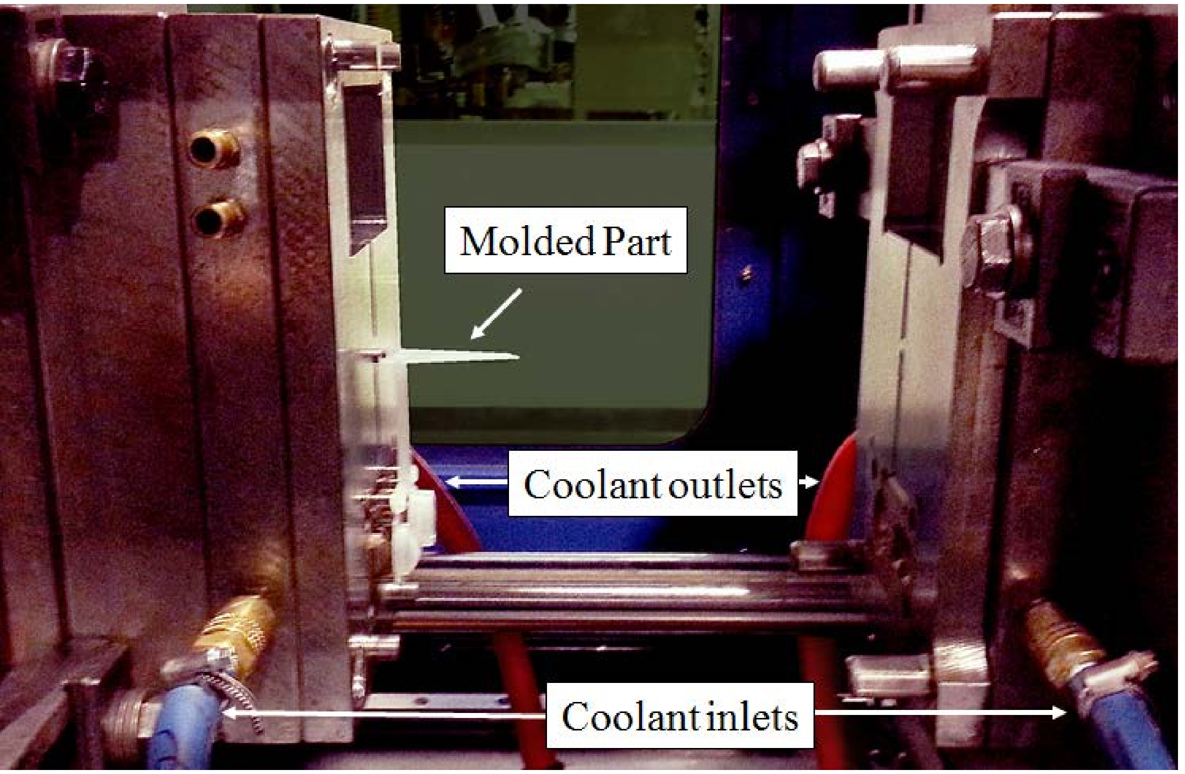
[2] "PolyJet Materials Data Sheet," *Stratasys, Ltd.* [Online]. Available: http://www.stratasys.com/materials/polyjet/digital-materials. [Accessed: 01-Jan-2015].

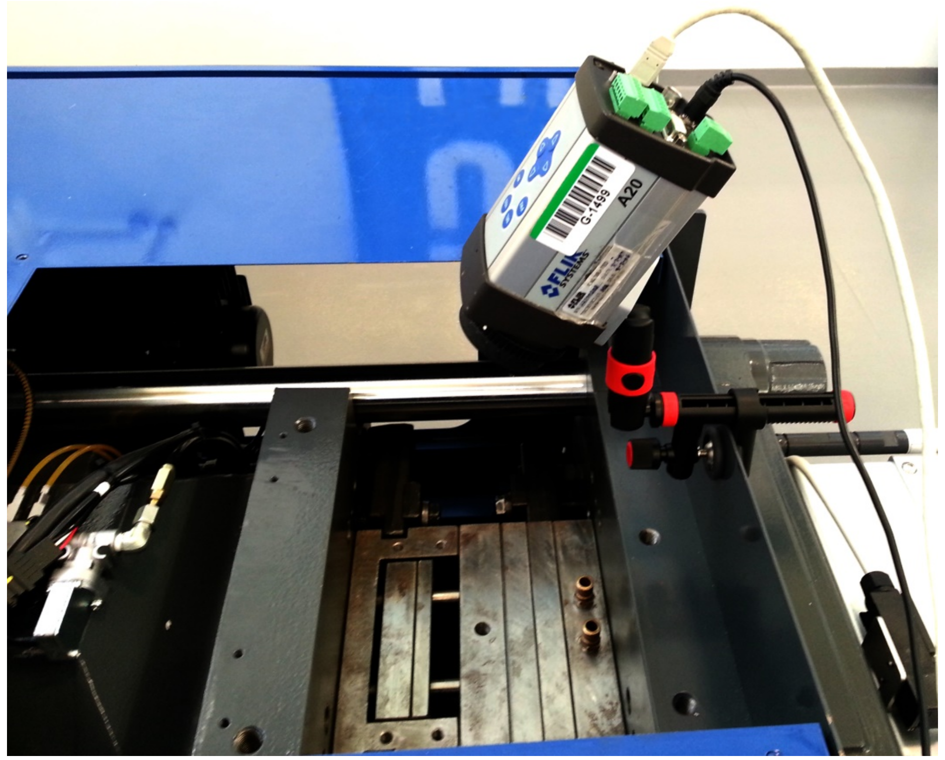
Methodology – Cooling System Designs

No Cooling (NC)	Straight Cooling (SC)	Interm. Conformal (SC/CC)	Conformal Cooling (CC)
No cooling channels **Vero-Gray RGD850** **Stratasys Eden 260V**	**Straight cooling channels** Ø = 3.2 mm **Vero-White Plus RGD835** **Stratasys Objet 500 Connex 2**	**A-Insert: Conformal channels** Ø = 1.5 mm Pitch= 6.2 mm Depth= 3 mm **B-Insert: Drilled channels** Ø = 3.2 mm **Vero-Gray RGD850** **Stratasys Eden 260V**	**Conformal Channels** Ø = 1 mm Pitch= 3 mm Depth= 3 mm **Impossible to Manufacture**
			

Methodology – Molding Trials

- Polyjet inserts fit into standard mold frame
  - Cooling supplied to individual inserts
- 75 ton electric injection molding machine
  - Sumitomo SE75 DUZ
- Polypropylene – A. Schulman Inc., PP1901-01





Methodology – Molding Trials

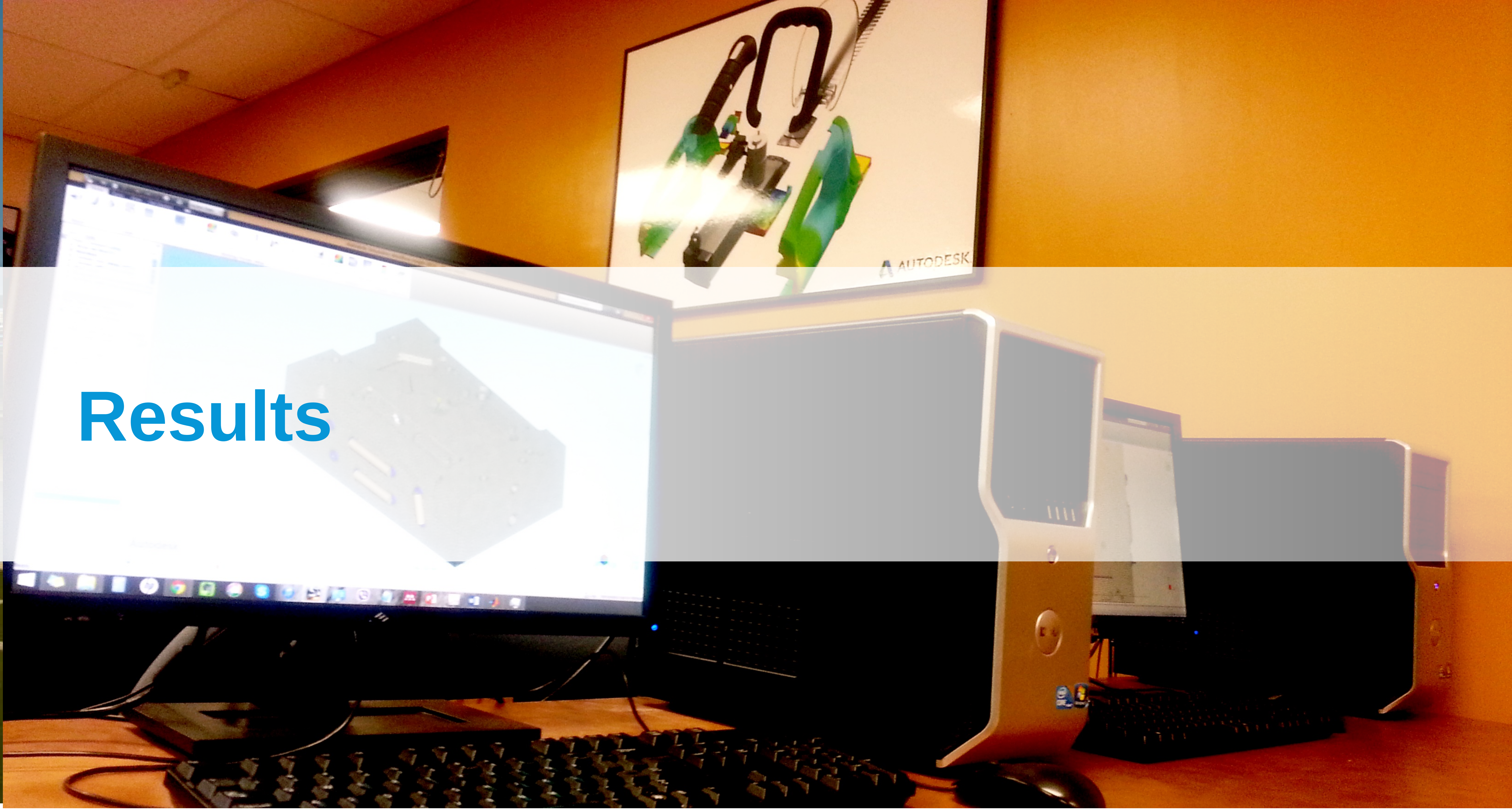
- Same processing conditions for all inserts
- Temperature measurements
  - In-mold thermocouple 1.7 mm from mold surface
  - IR Camera FLIR A20 and IR pyrometer
- Flow rate measured on the inlet of each cooling line
  - Artificially restricted to ensure flow
- Pressure drop measured on B-insert
  - SC: 39 Pa; SC/CC: 83 Pa

Process Settings

Process Parameter	Unit	Value
Melt temperature	°C	205
Coolant temperature	°C	23
Injection speed	mm/s	15
Holding pressure	MPa	8.5
Holding time	s	45
Cooling time	s	45
Mold open time	s	100
Cycle time	s	190

Insert	Thermolator 1: Top Clamp Plate	Thermolator 1: A-Insert	Thermolator 2: B-Insert	Thermolator 2: Support Plate	Total (l/min)
NC	10.4	-	-	10.4	20.8
SC	7.6	2.6	2.6	7.6	20.4
SC/CC	6.8	1.3	1.3	6.8	16.2

Flow Rates Monitored

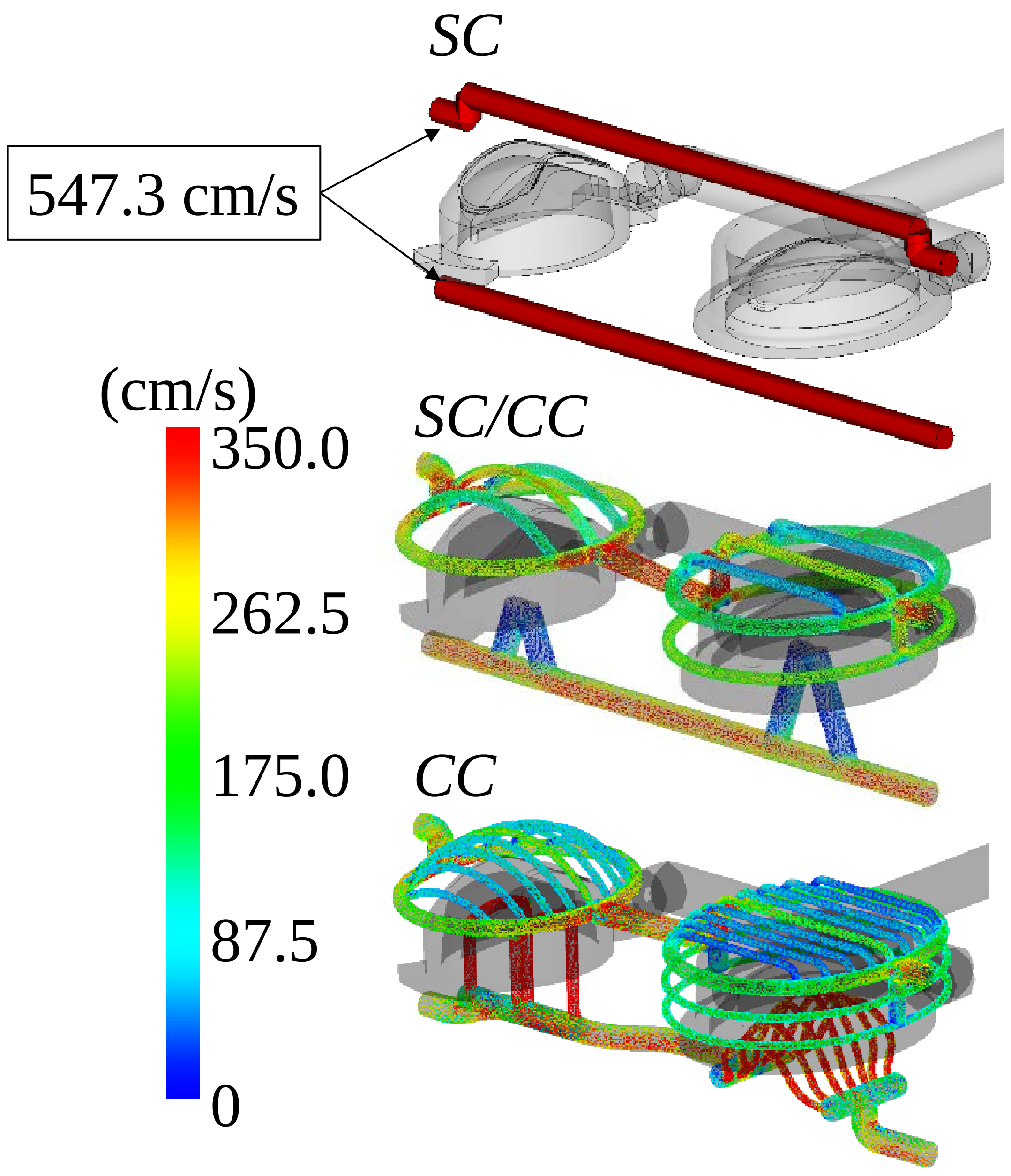


Results

Simulation Results

- Moldflow simulations show flow through all conformal cooling channels of at least 100 cm/s
- Threshold for laminar and turbulent flow conditions:

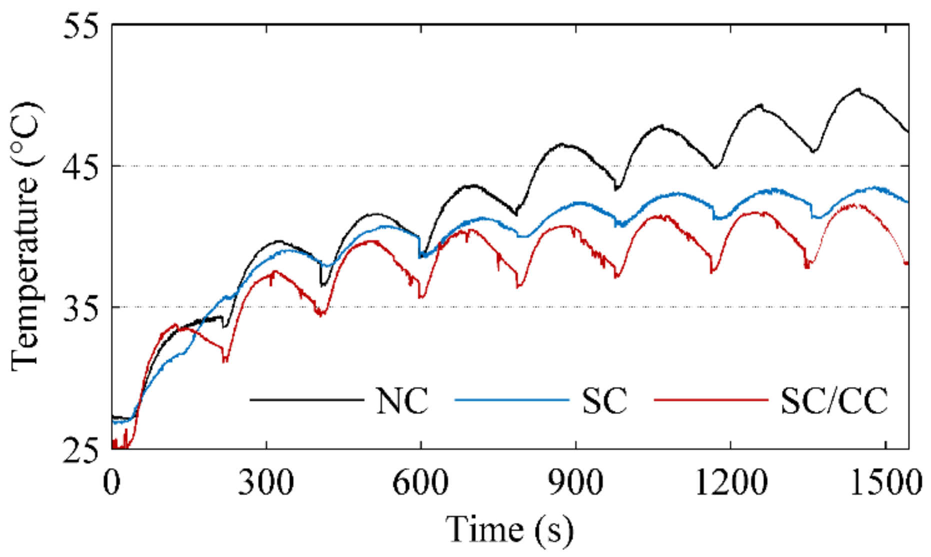
Diameter	Velocity threshold for Laminar flow (Re<2300)	Velocity threshold for Turbulent flow (Re>4000)
1.0 mm	< 205 cm/s	> 347 cm/s
1.5 mm	< 137 cm/s	> 238 cm/s
2.0 mm	< 103 cm/s	> 179 cm/s
3.2 mm	< 64 cm/s	> 112 cm/s

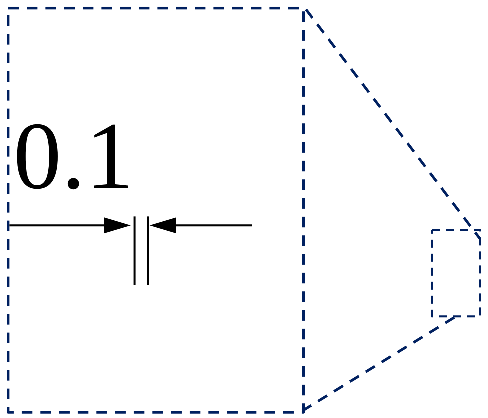


Results - Insert Temperature

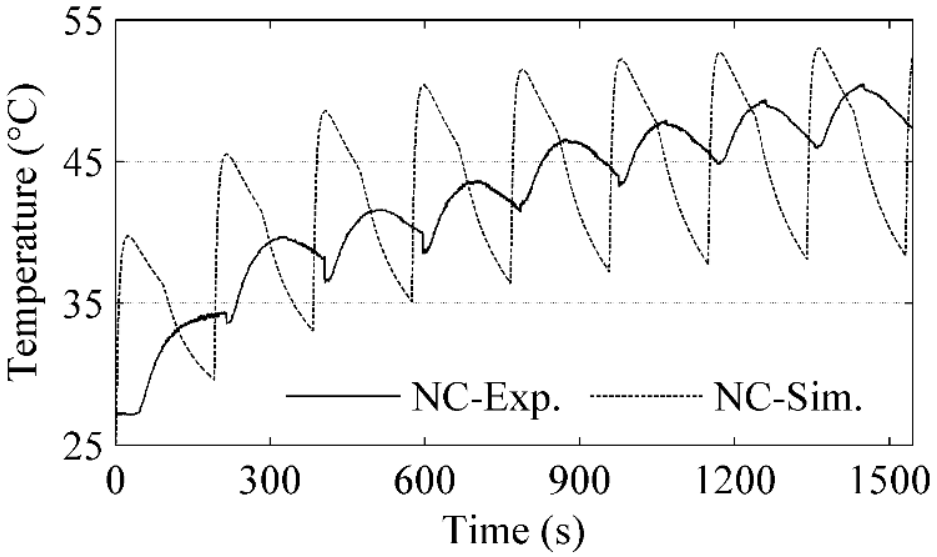
- Steady state reached faster for SC/CC inserts (1°C criteria)
  - NC: 8 cycles, SC: 6 cycles, SC/CC: 4 cycles
- Cooling reduced temperatures compared to NC inserts
  - SC: 5°C, and SC/CC: 8°C lower
- Simulated temperatures correlate with actual values
- Larger amplitude in the simulated data
  - Clearance between thermocouple not modeled in the simulation
    - Damping not represented in prediction
    - Could model air gap using 3D elements
    - Out of the scope of the work

Exp. Temperature

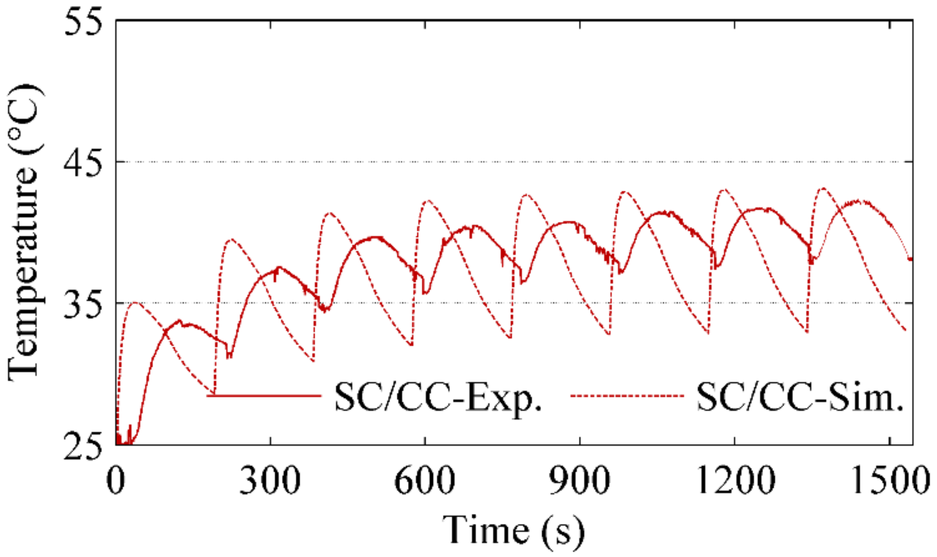




NC Simulated Temp.



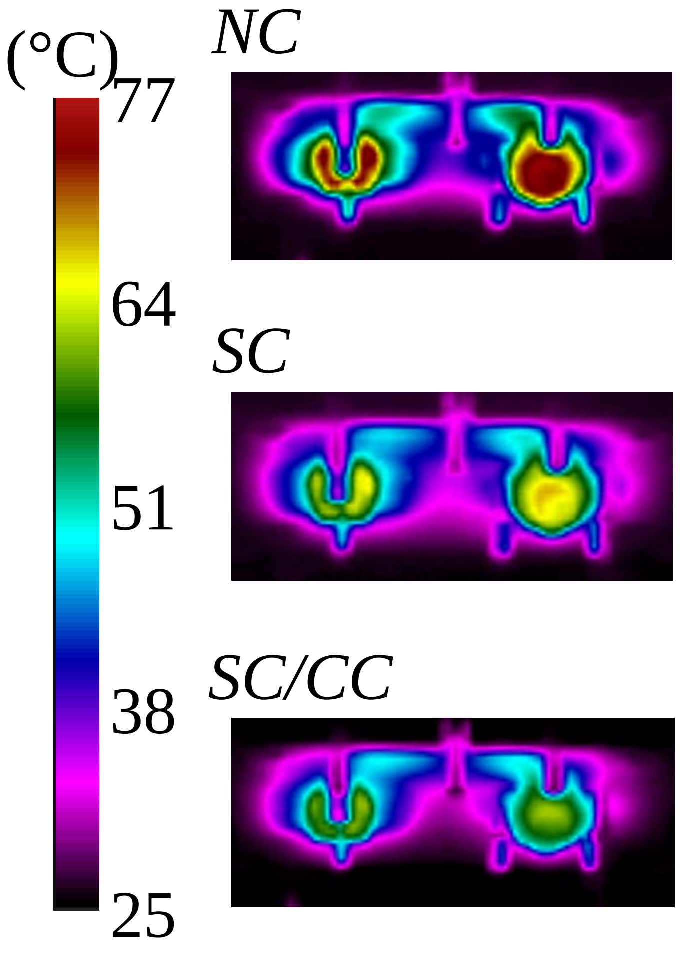
SC/CC Simulated Temp.



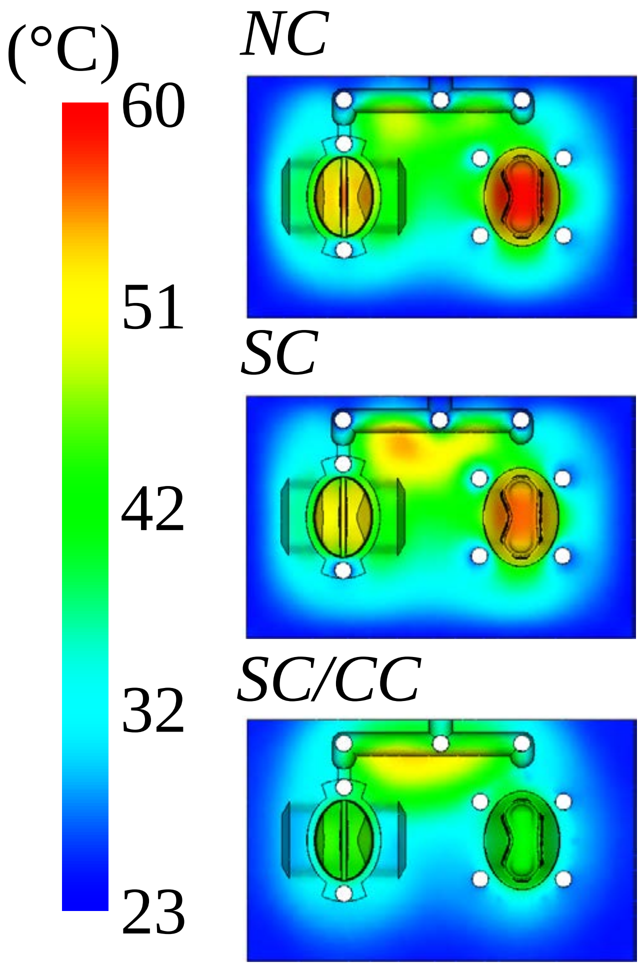
Results - Temperature Gradient at Mold Closing

- IR thermal images gradients correlate with simulated results
- Temperature gradients reduced from 50°C (NC) to 35°C (SC) and 25°C (SC/CC) with addition of cooling

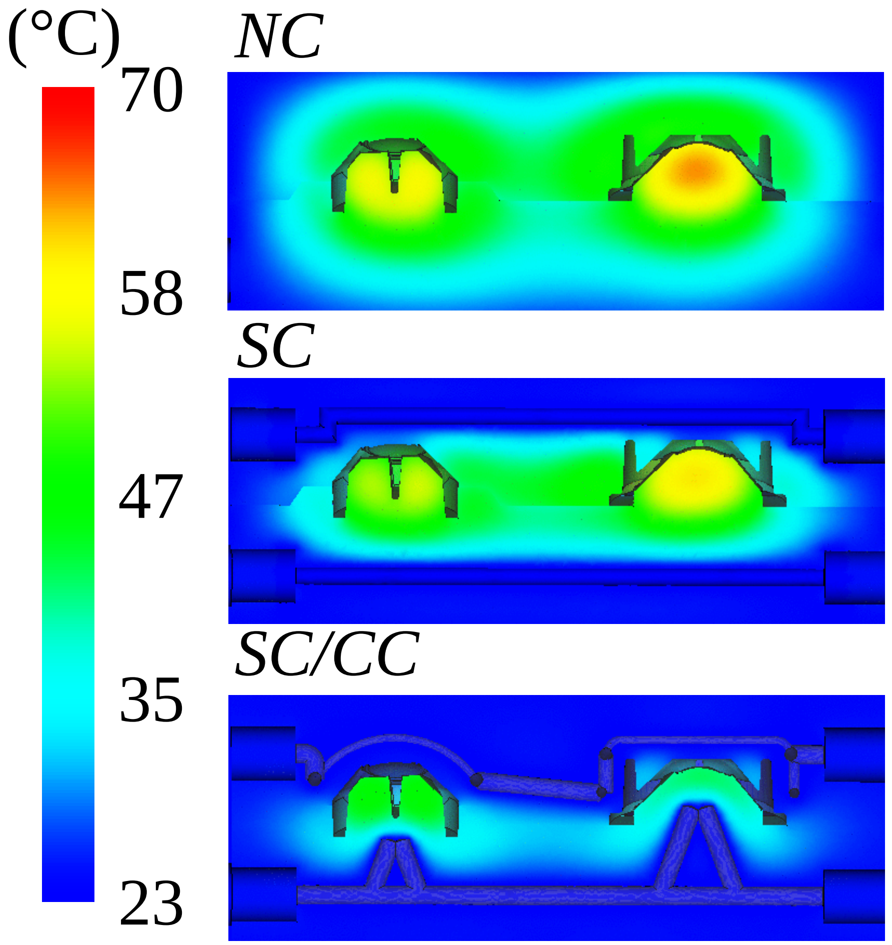
IR Thermal Images



Simulation (B-side)

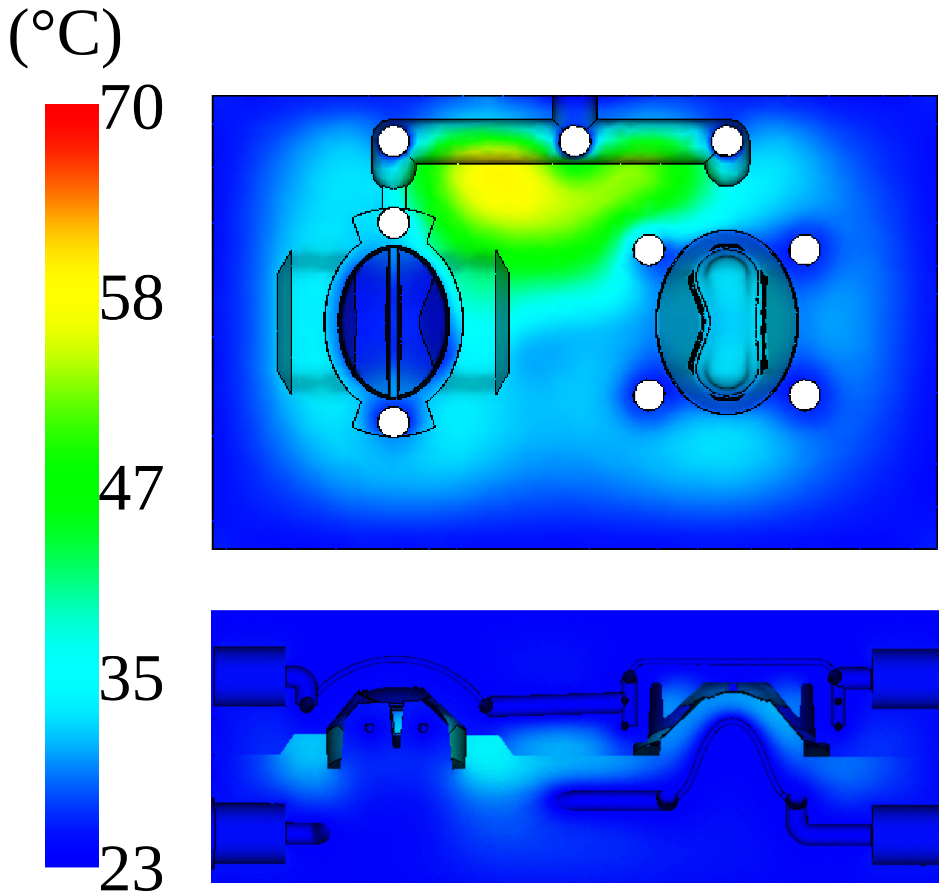


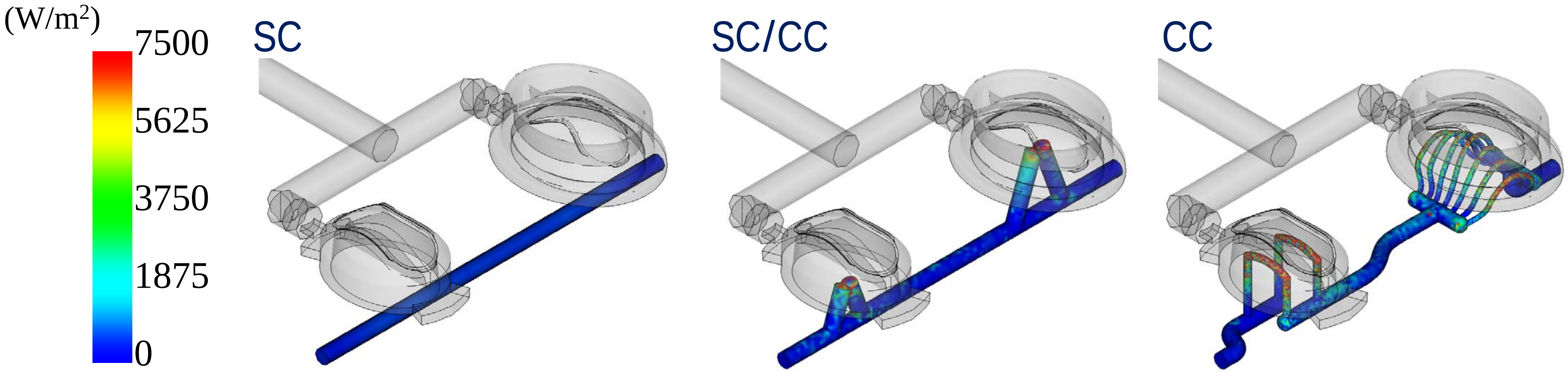
Simulation (cross section)



Results - “CC” Insert Design

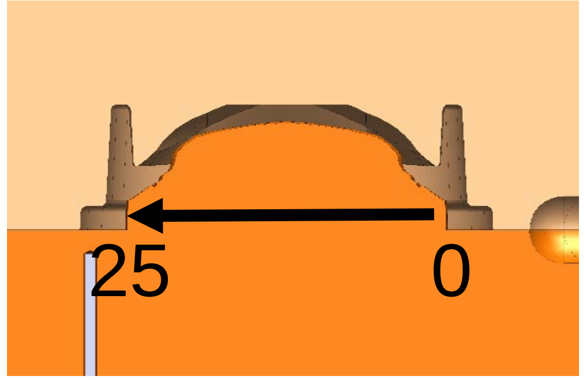
- Significantly lower thermal gradients
  - Besides area near runners, temperature gradients are within 12°C
- Simulated heat flux results show that CC design is more efficient
  - Higher heat flux and surface area
- Could not be manufactured due to support material removal limitations

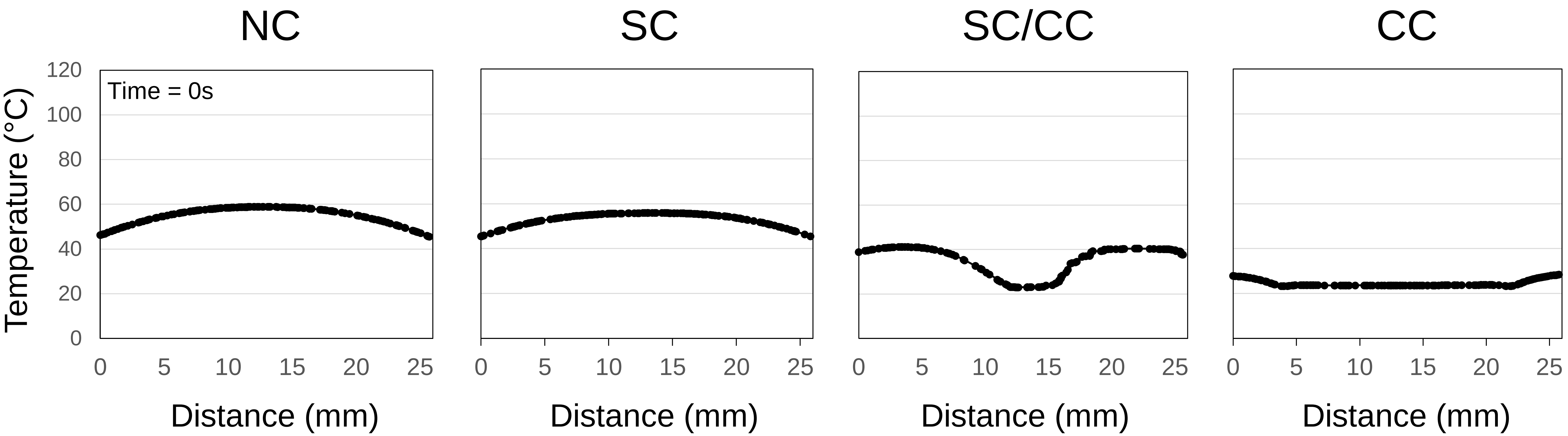




Internal Core Temperature (Probe plot)

- Probe plot through core at multiple time steps
  - Lower and more uniform temperature seen for conformal cooling inserts

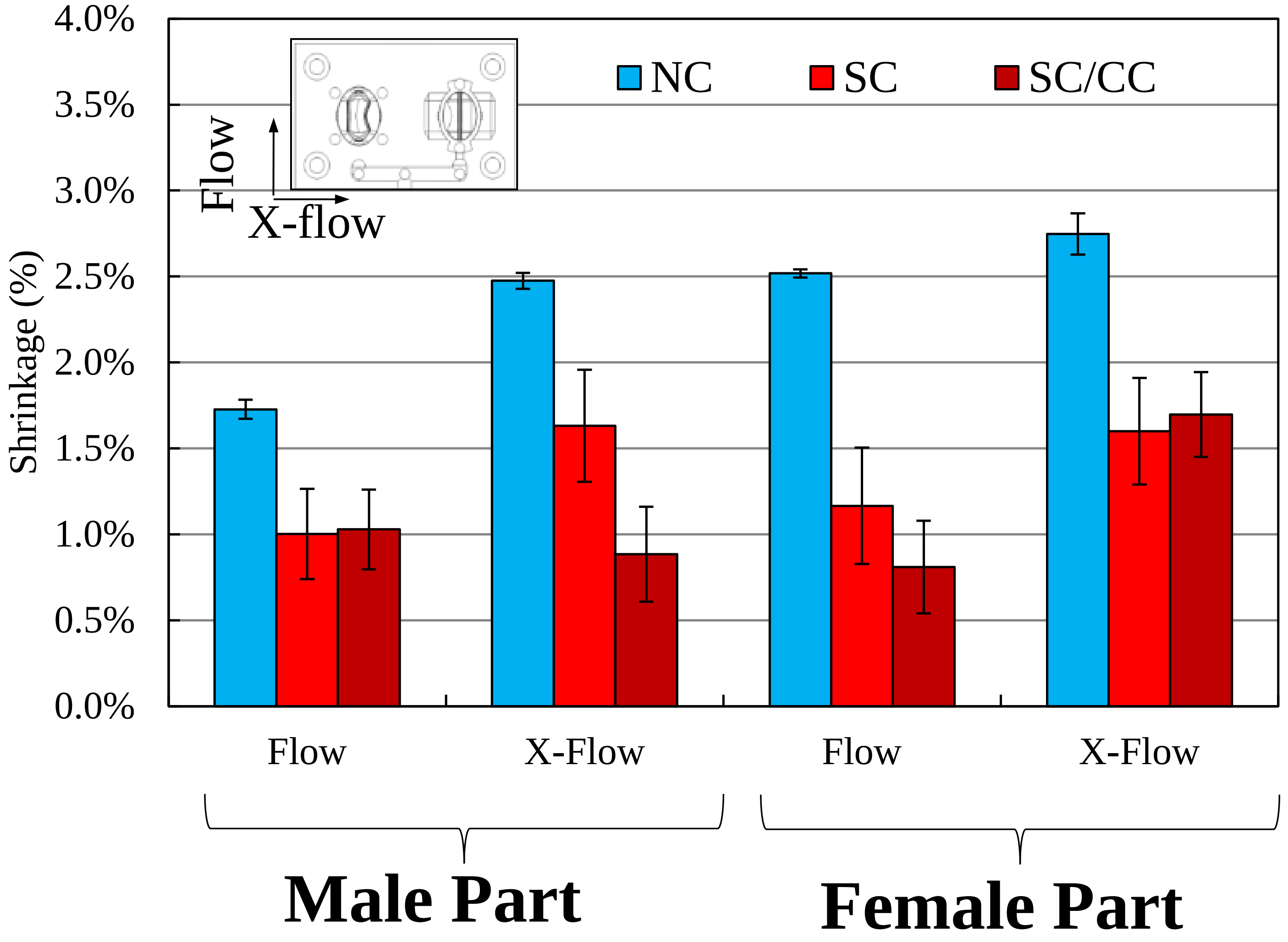




Replay Animation

Results - Shrinkage

- Shrinkage of the parts molded in NC inserts is significantly higher than other inserts.
  - Lower mold temperatures, faster cooling, lower crystallinity

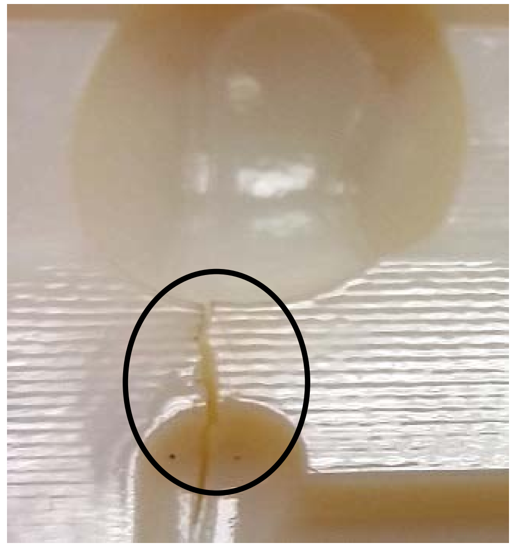


Results - Longevity

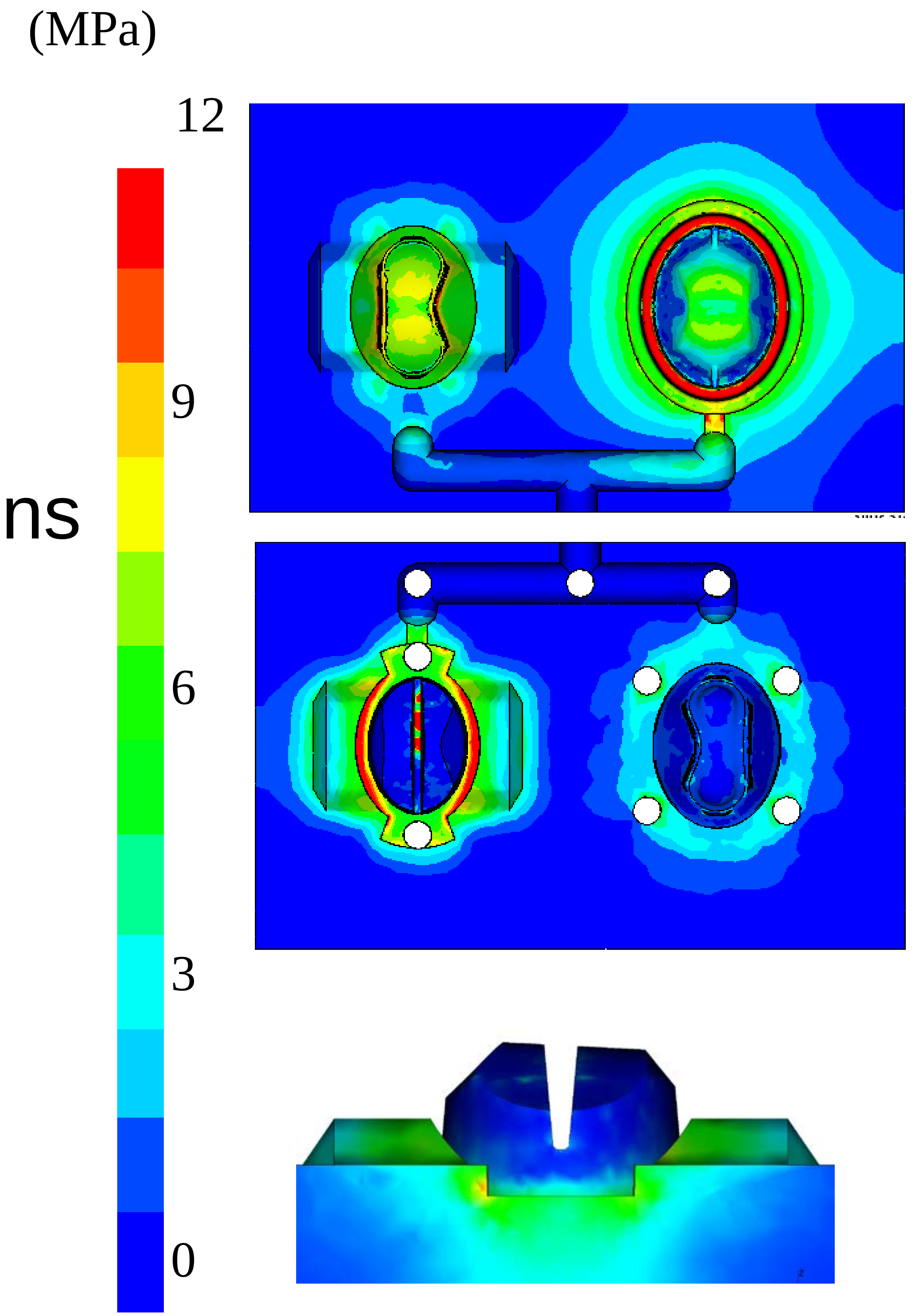
- Failure
  - NC: 50 cycles; SC: 64 cycles, SC/CC : 52 cycles
- NC and SC/CC inserts failed at the same location
  - Crack at the core of the male part
- SC inserts failed at the gate location on the A-Insert
- Structural analysis showed similar results for all designs

NC (Vero Gray)

SC (Vero White)



SC/CC (Vero Gray)



Conclusions

- Moldflow simulations accurately predicted improved cooling efficiency with conformal cooling designs
- Addition of conformal cooling channels to PolyJet printed mold inserts provided lower temperatures and better temperature uniformity
  - Reduced part shrinkage
  - Could have reduced cooling time
- Optimal CC design could not be manufactured with current printing technology due to support removal limitations
  - Simulation shows best results for designs with large number of small channels
- Further studies could investigate effect of mold temperature on the mechanical properties of the molded parts

Acknowledgements

- Autodesk
  - Sponsorship of Autodesk Simulation Lab at UMass Lowell
  - Moldflow Team – Support with software & questions
- Stratasys – 3D printed inserts
- Vista Scientific – Tooling designs

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