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INTERNATIONALLY RECOGNIZED EXCELLENCE

Office of Naval Research

MODELING AND SIMULATION OF MOLD FILLING WITH LIMS

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UD-CCM

Report Documentation Page

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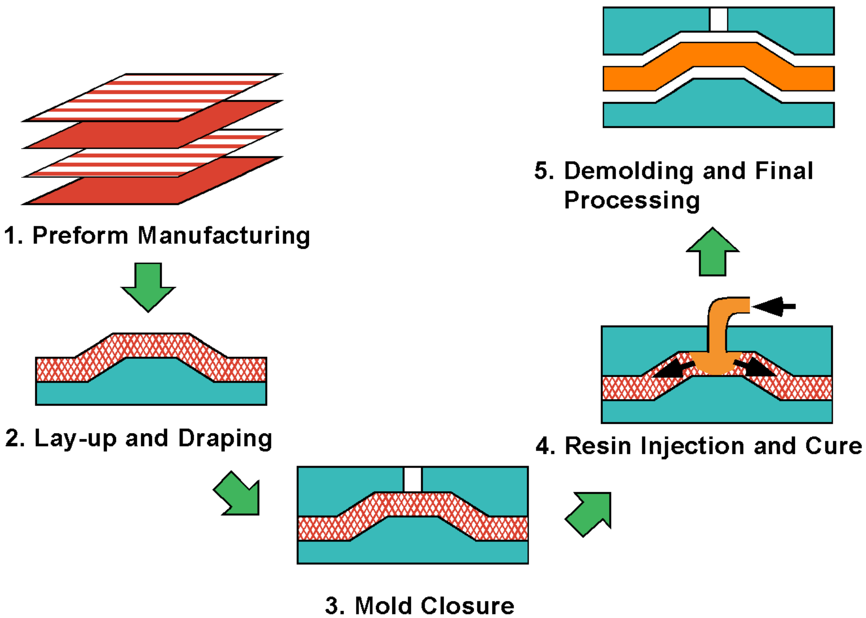
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Outline

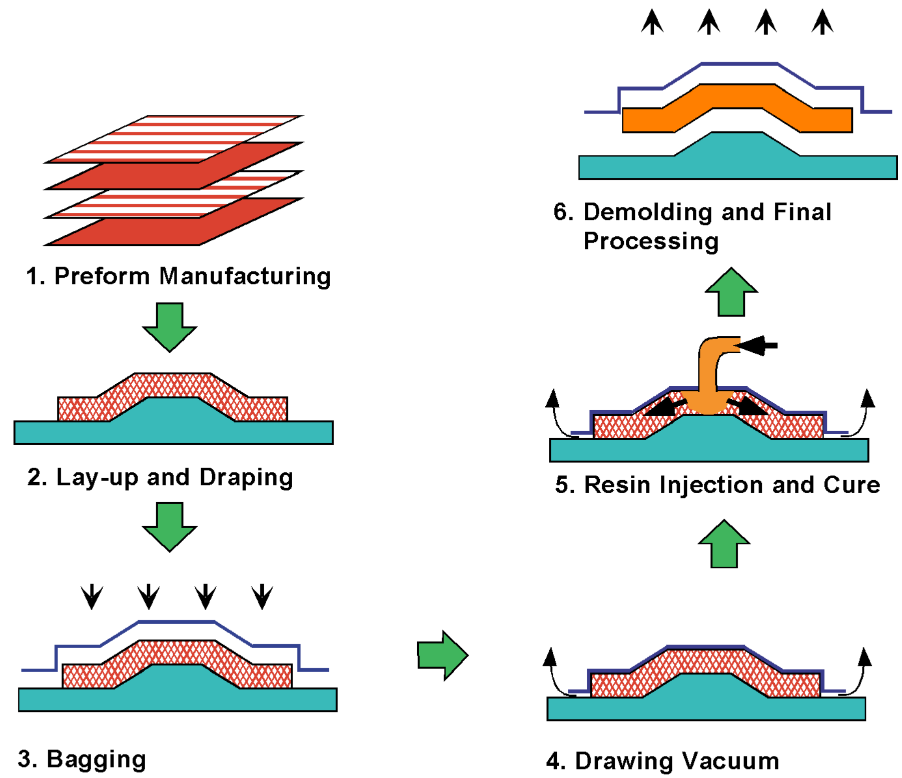
- What is the Computer Simulation (Modeling)
- Why Do We Need Simulation
- Computer Modeling - Basics:
  - Experimental Characterization
  - Process Modeling
    - Analytic
    - Numeric
- Computer Modeling - Advanced:
  - Control and Sensing
  - Optimization
- Putting the Whole Package Together or the Art of Integration
- Conclusions

RTM and VARTM Processes

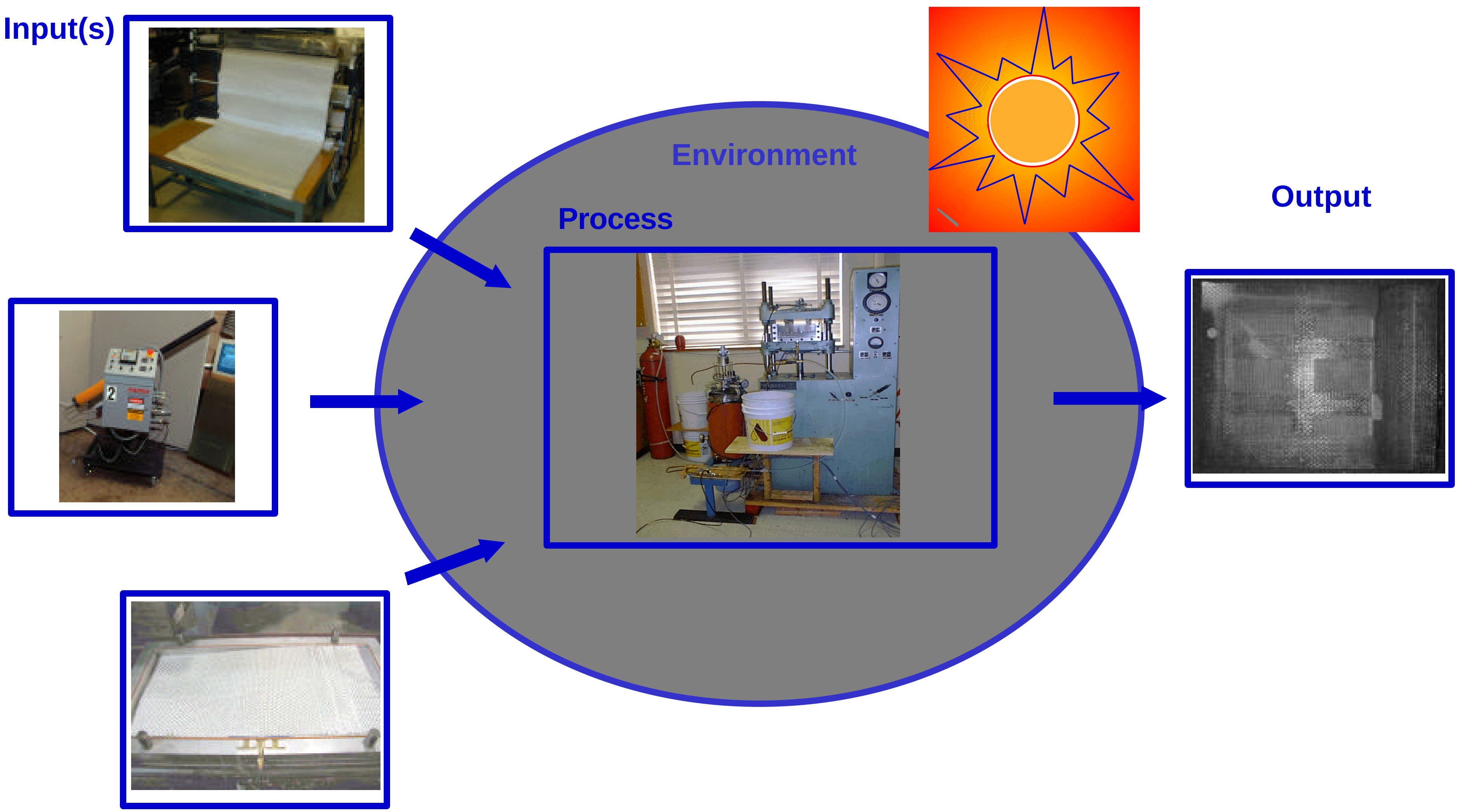
RTM



VARTM



What Is To Be Simulated?



The Model

Input(s)

Material Parameters

- Geometry
- Resin Viscosity
- Preform Porosity
- Permeability
- Environment
- Global Temperature

Process

Governing Equation(s)

Numerical Solution

Output

Process parameters

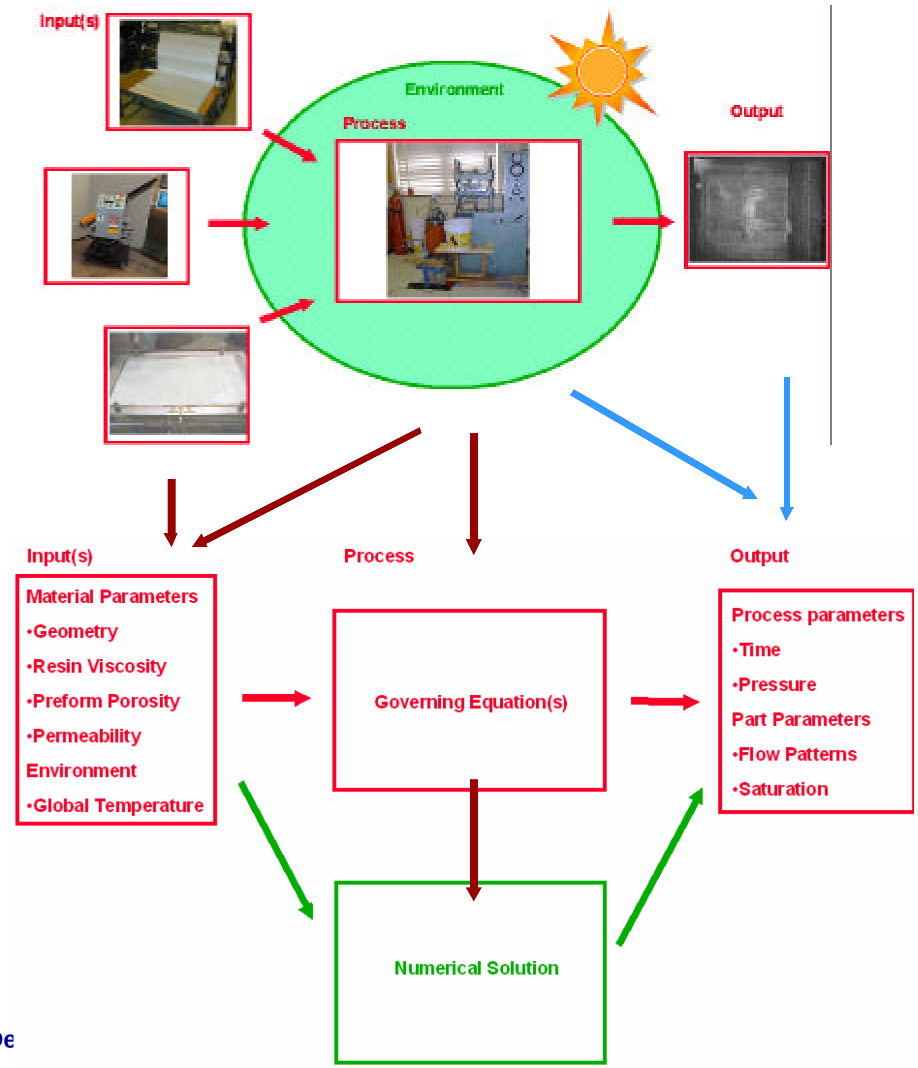
- Time
- Pressure

Part Parameters

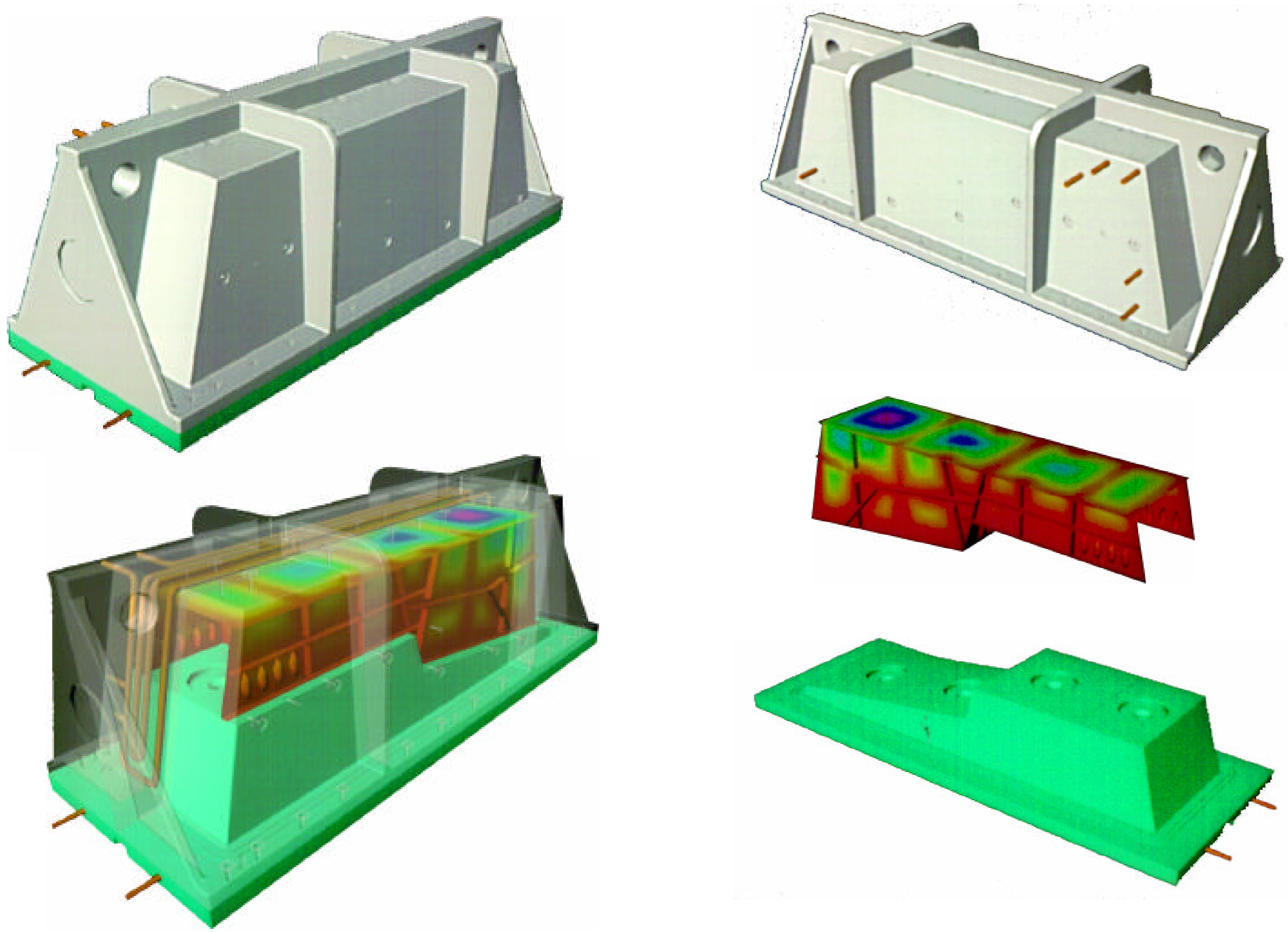
- Flow Patterns
- Saturation

Model Creation

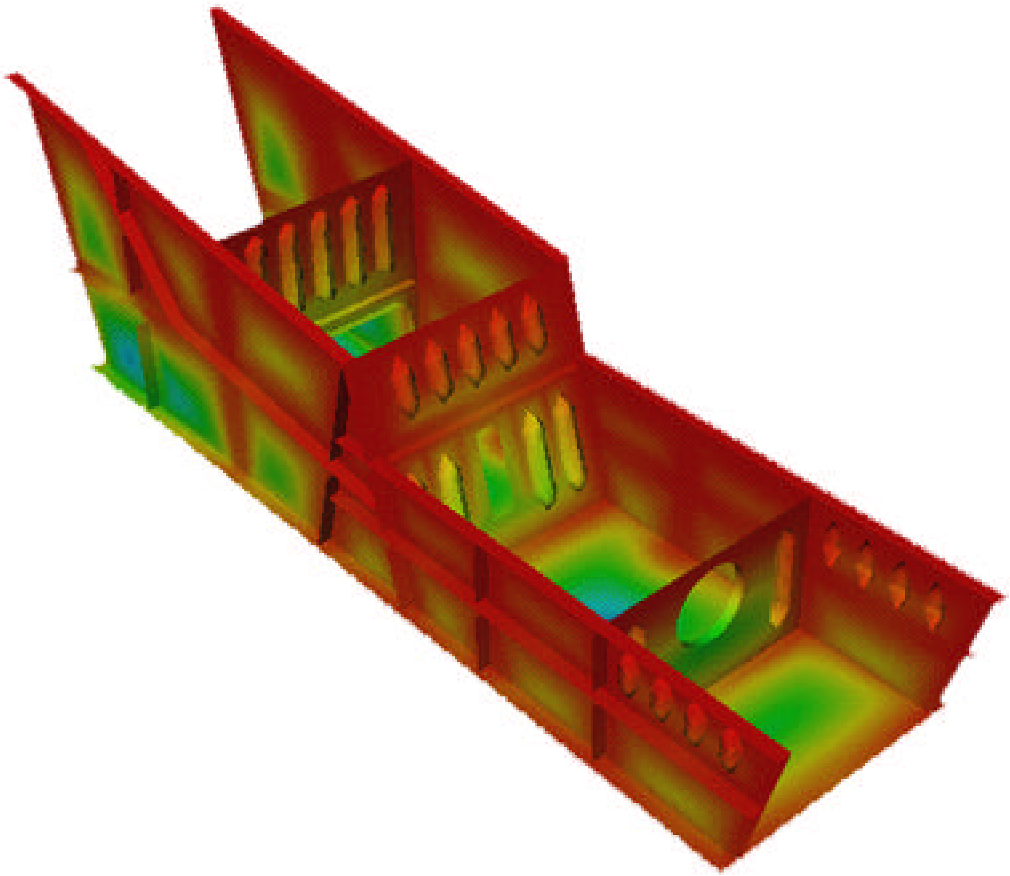
- Choose the output of interest
  - Decide the accuracy
- Figure out the governing equations
  - Decide of what is important
  - Decide of what input and environment parameters are considered
- Solve the equations
  - Numerical solution
- Number of Sources of Error
  - Mathematicians mislead!



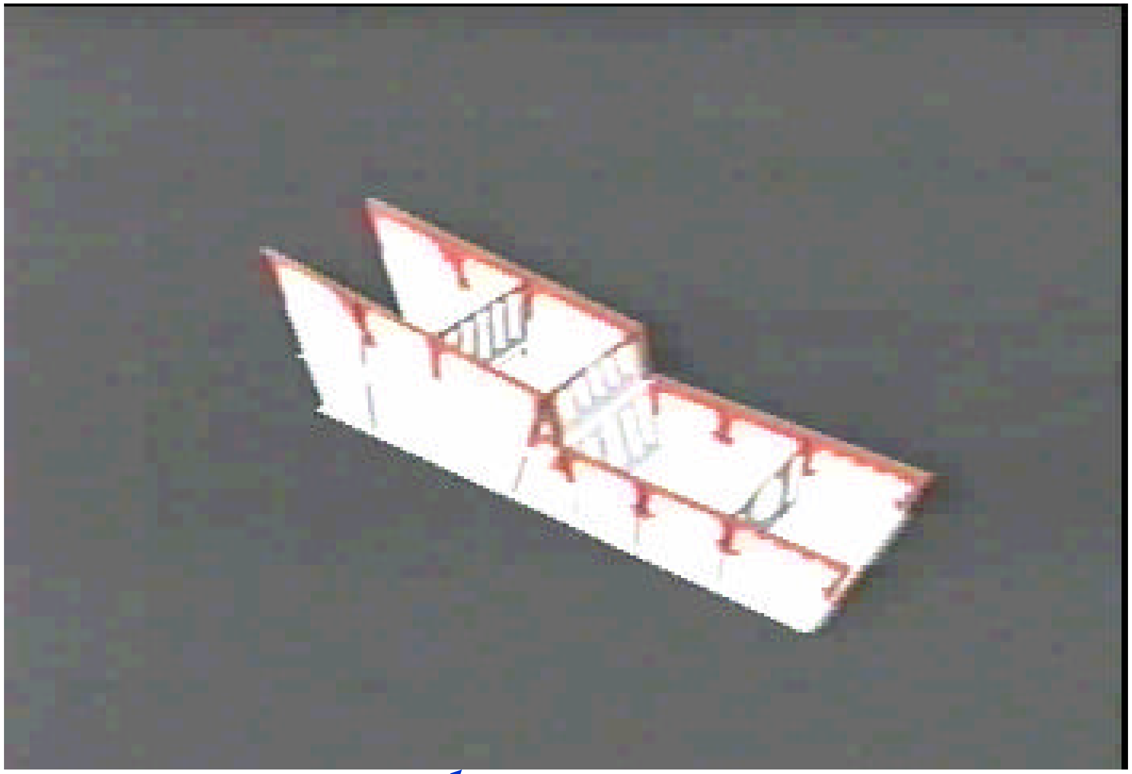
Keel Beam And Tooling



Flow Fronts in a 40-ft. Keel Beam



Flow Fronts in a 40 ft Keel Beam



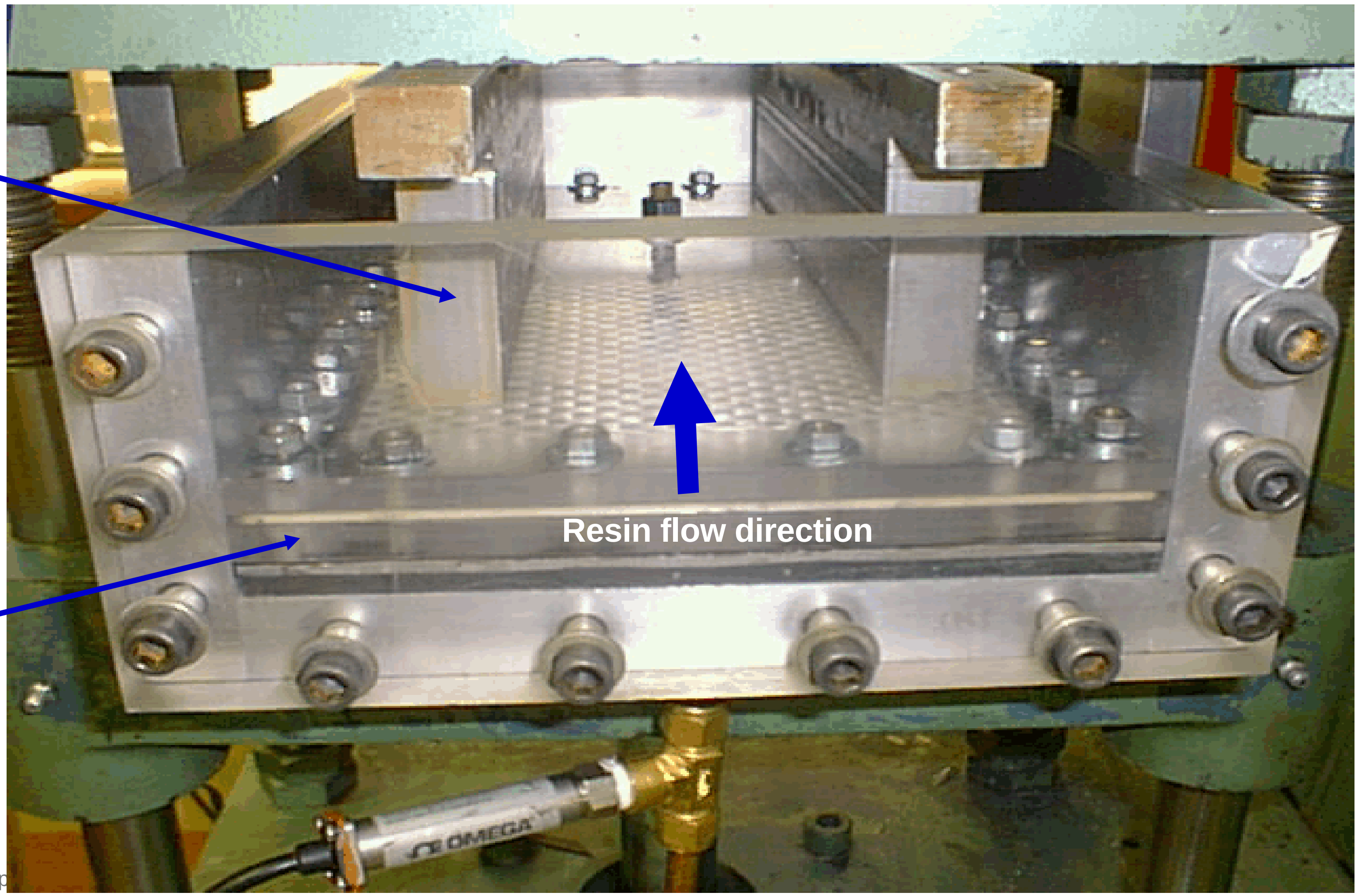
Why Do We Need Simulation Tools?

Can We See Into the Mold?

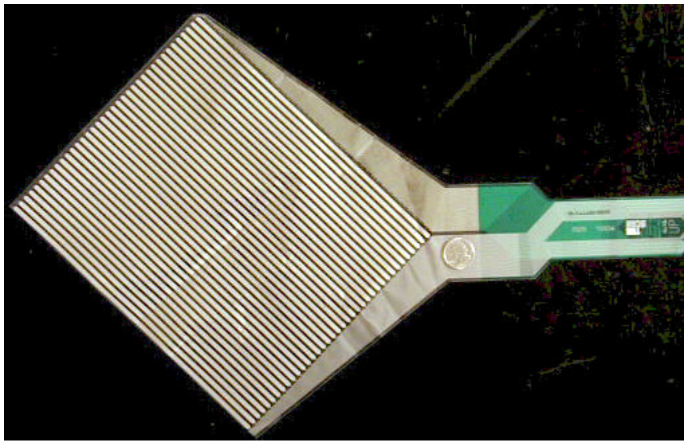
Can We Measure What is Happening?

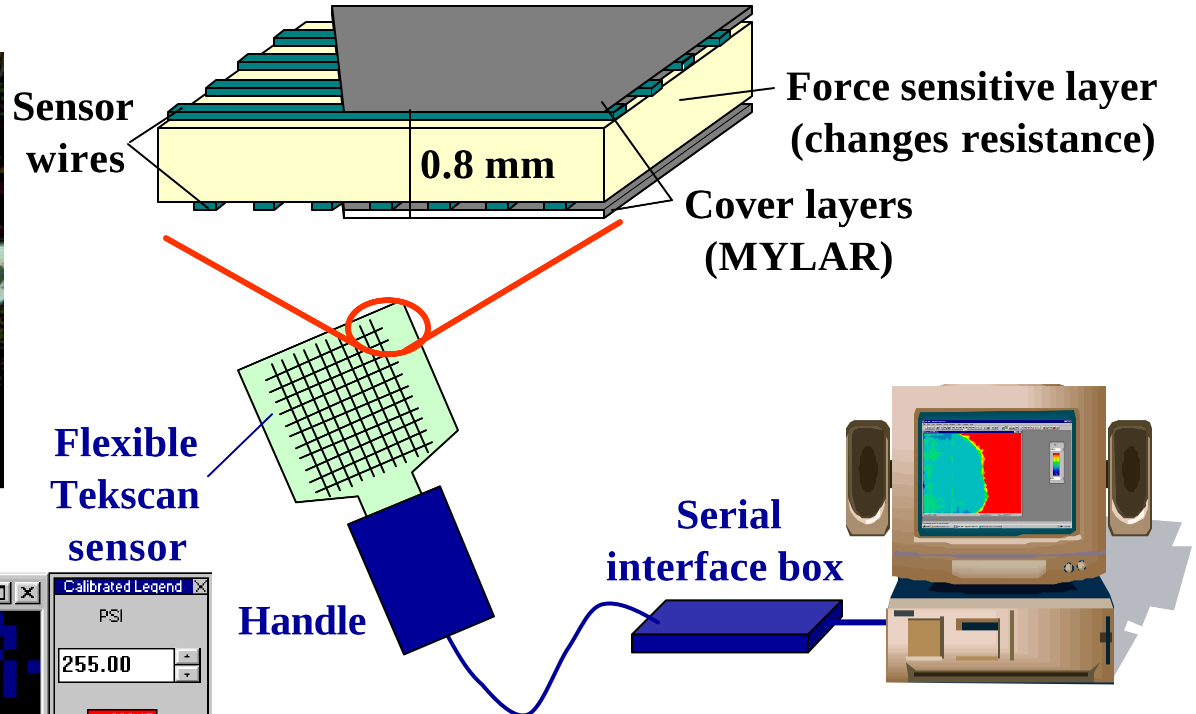
If We Could, How Much Good Can Come Out Of It?

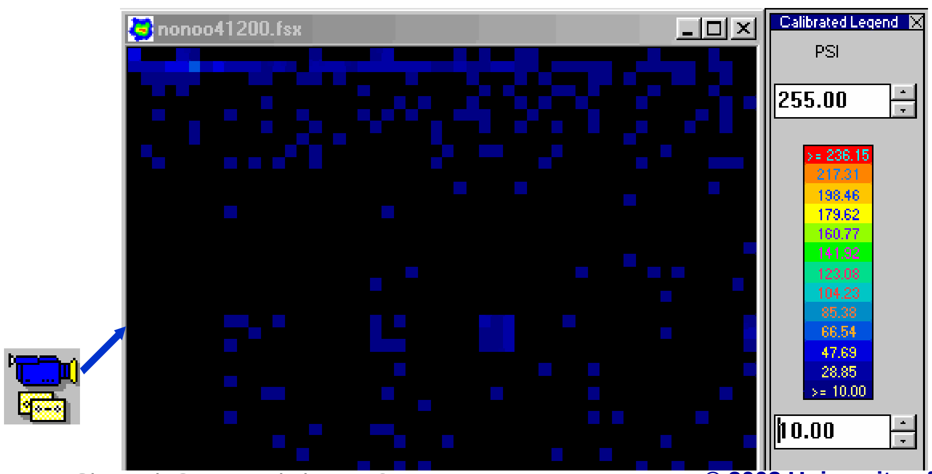
Can We See The Flowfront?



Can We ‘Measure’ it?

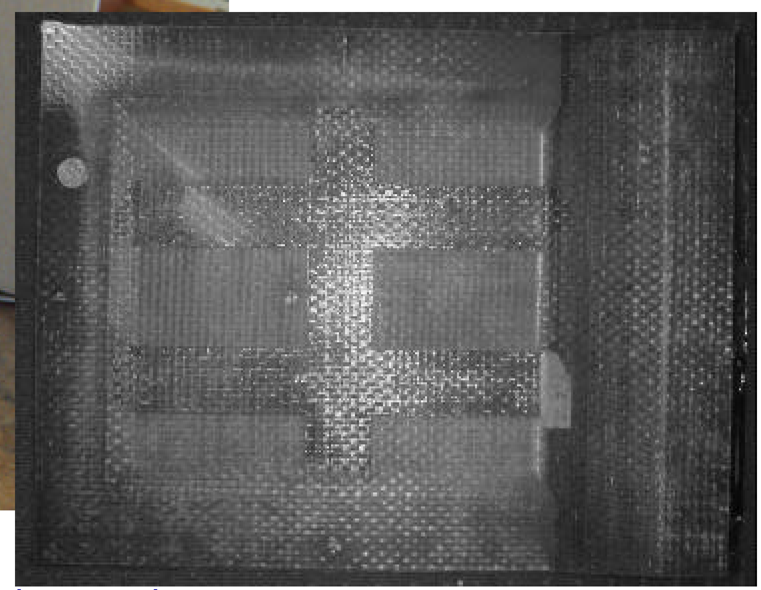






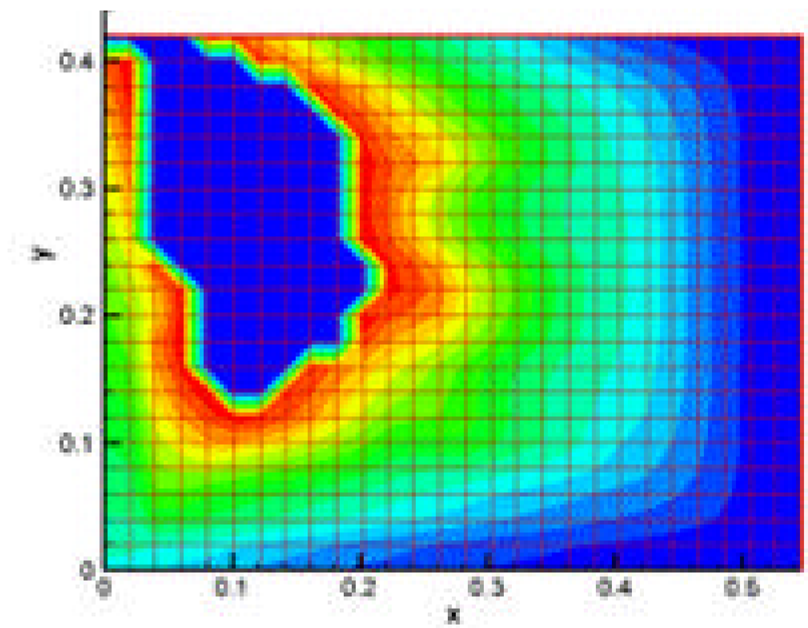
In Order to Obtain Visual Input, You Must Have:

To Get:



In Order to Obtain Input From Simulation, You Need:

To Get:



Why Do We Need Simulation Tools?

- **Can We See Into the Mold?**
  - **In RTM Manufacturing NO!**
  - **In VARTM or Laboratory A little**
- **Can We Measure What is Happening?**
  - **Yes, but at High Cost. On Top, the Used Technology is Immature.**
- **If We Could, How Much Good Can Come Out Of It?**
  - **Visual/Sensorial Examination Requires Mold and Part to Be Real**
  - **Errors -> Post Mortem Analysis -> New Trial**

- **PREDICTIVE CAPABILITY IS NEEDED!**

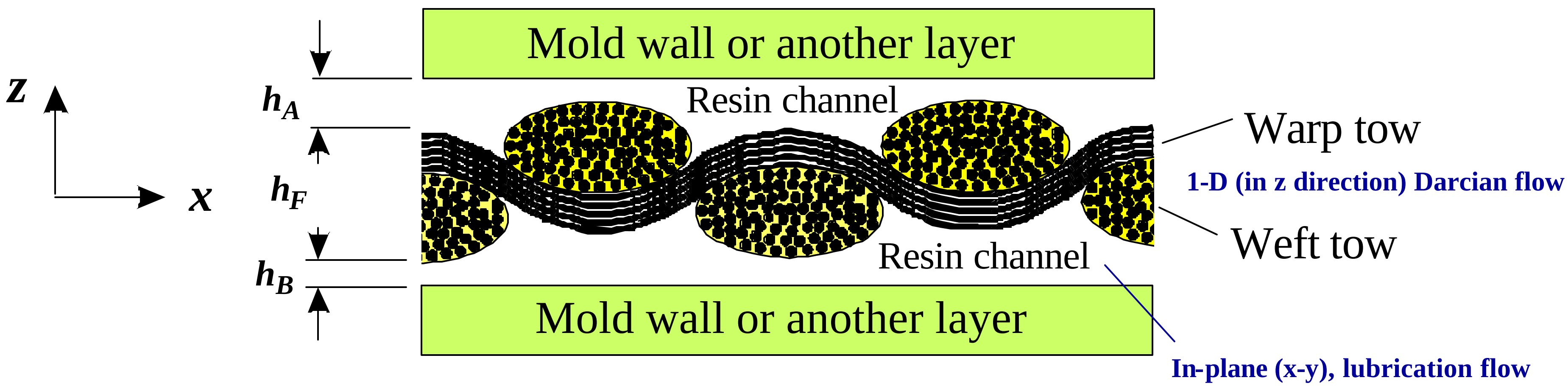
What Is Needed for Modeling

- **Computer Modeling Basics:**
  - **Experimental Characterization of Used Materials.**
  - **Process Modeling - Equations and Their Solution.**
    - Analytic.
    - Numeric.
  - **Tricks of the Trade.**
- **Computer Modeling Advanced:**
  - **Modeling Control and Sensing and "Intelligent" Manufacturing Processes.**
  - **Process Optimization.**

Lesson I. : Knowing the Material

- Characterization of Materials
  - Resins
  - Preforms
- Preform Data that Influence the Process
  - Permeability
  - Porosity
  - Thermal Characteristics
- Ways to Obtain Them
  - Computer Simulations (Hypothetic)
  - Experimental
- Other Uses of Experiment
  - Verification!

Numerical Permeability Prediction



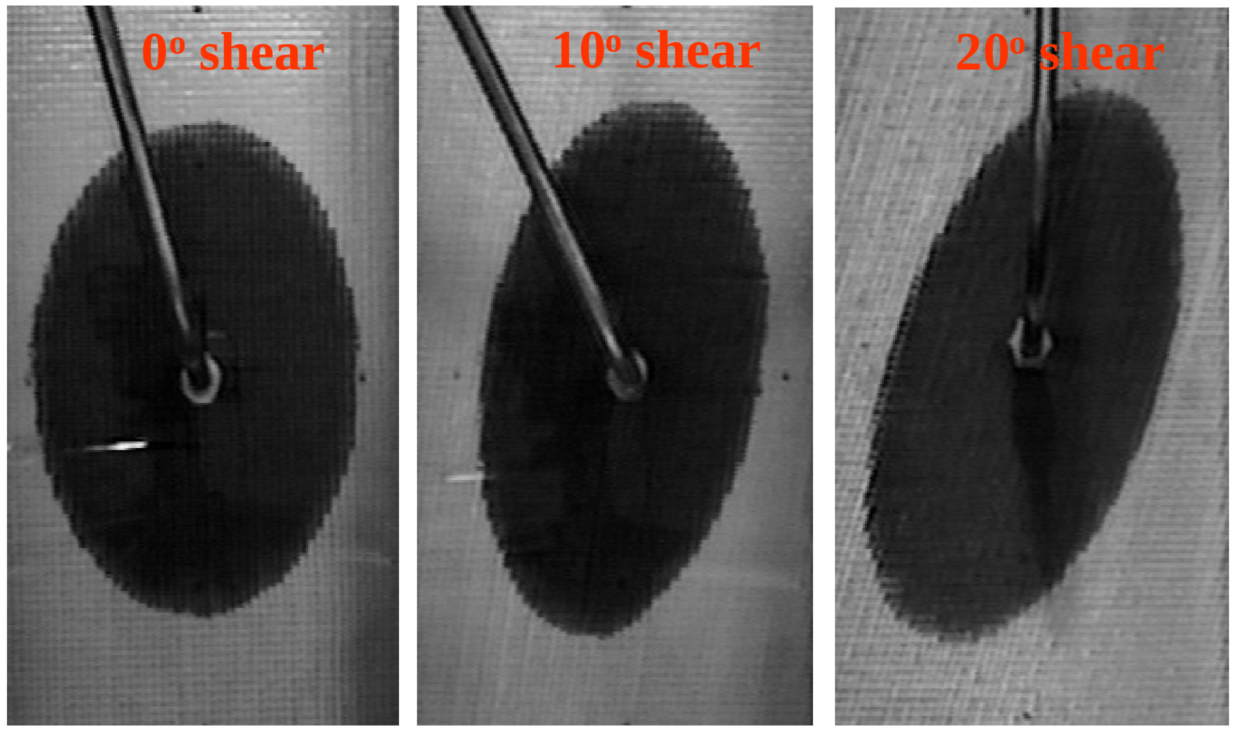
$$-\frac{K_{zz}(p^B - p^A)}{h\, h^F} - \frac{1}{6h}\left(\frac{\partial\left((h^A)^3 \partial p^A/\partial x\right)}{\partial x} + \frac{\partial\left((h^A)^3 \partial p^A/\partial y\right)}{\partial y}\right) = 0$$

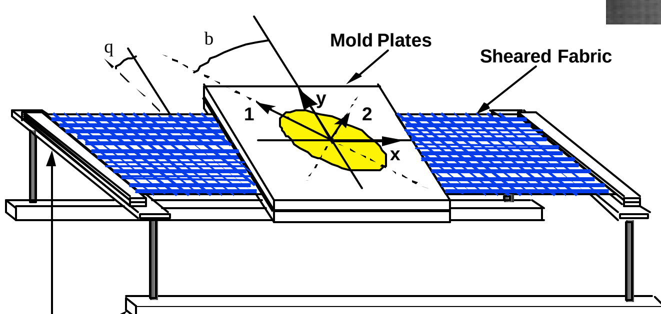
$$\frac{K_{zz}(p^B - p^A)}{h\, h^F} - \frac{1}{6h}\left(\frac{\partial\left((h^B)^3 \partial p^B/\partial x\right)}{\partial x} + \frac{\partial\left((h^B)^3 \partial p^B/\partial y\right)}{\partial y}\right) = 0$$

Input to model: **geometry:** $h_A(x,y), h_F(x,y), h_B(x,y)$ **Output:** K_{xx}, K_{yy}, K_{xy}

transverse permeability: K_{zz}

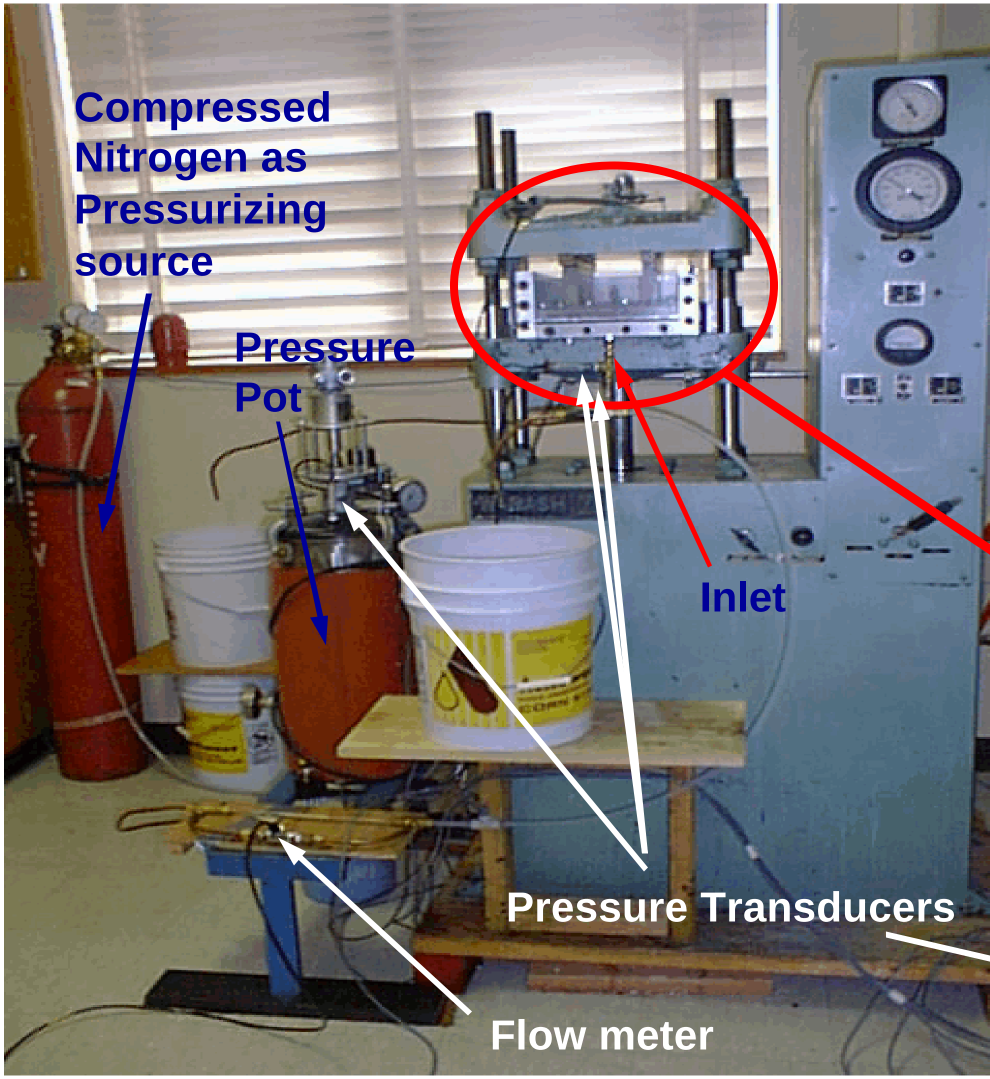
Experimental Permeability Prediction

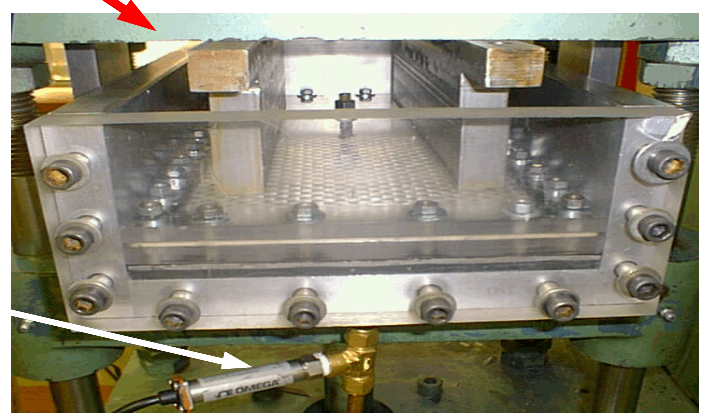




Problem: Many Experiments

Permeability vs. Vf Measurement



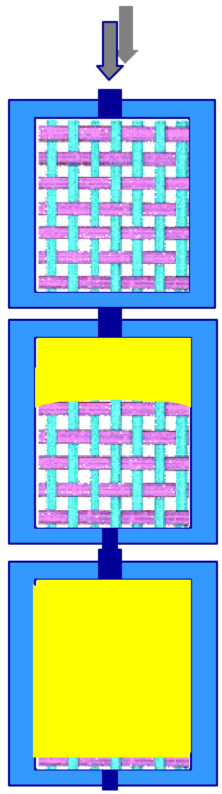


- Detailed measurements of permeability vs. V_f by changing the compaction load
- Steady state 1-D flow

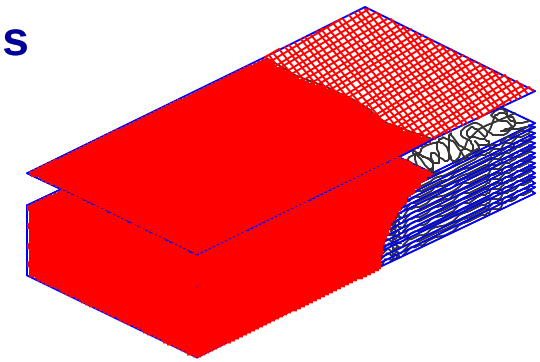
Experiments were performed by Mats Erninger

VARTM Specific Measurement : Distribution Media

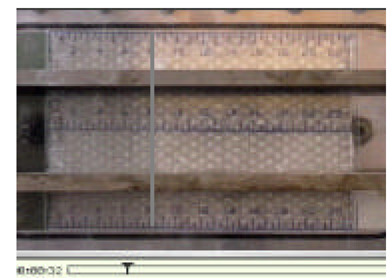
Direct (1D)



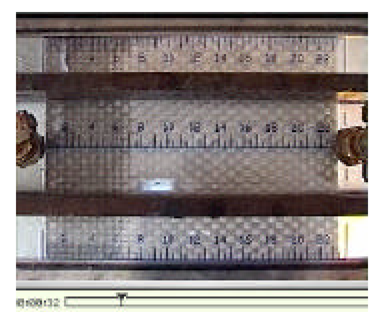
Heterogenous Porous Media Approach



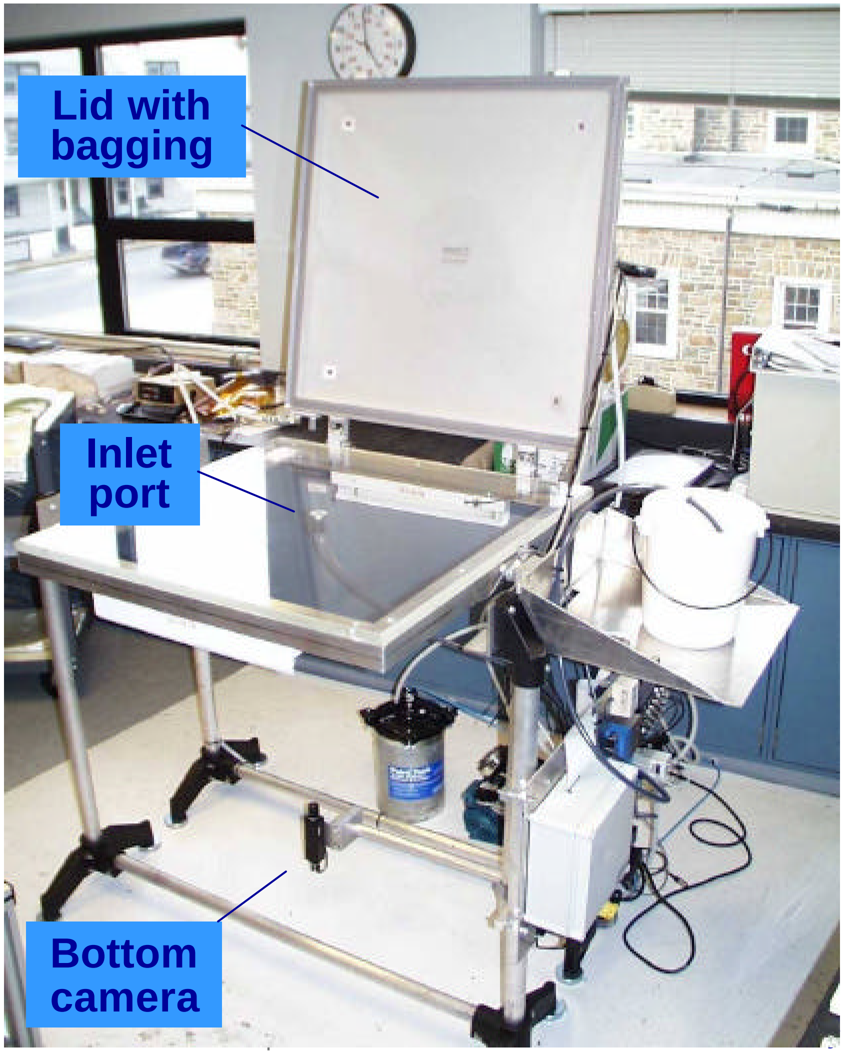
Distribution Media

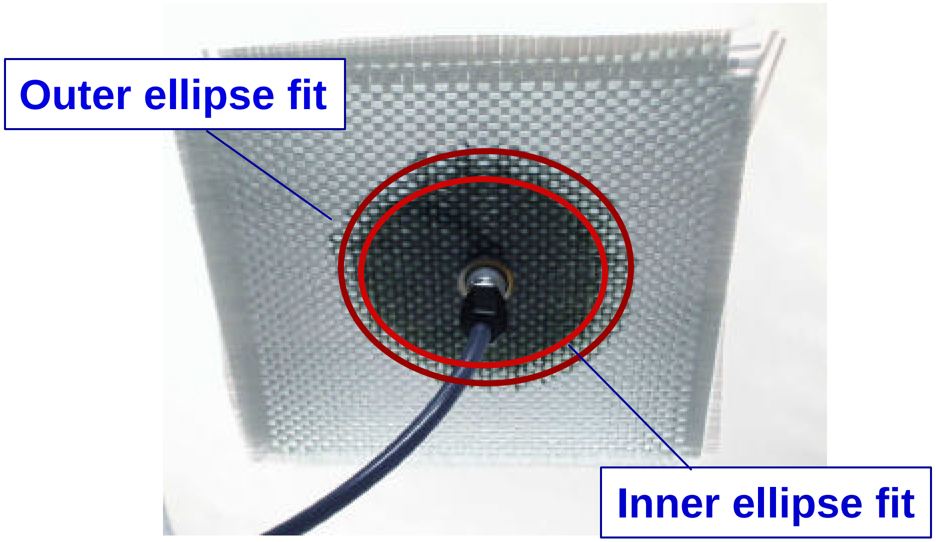


Structural layer



VARTM Specific Measurement : Transverse Permeability





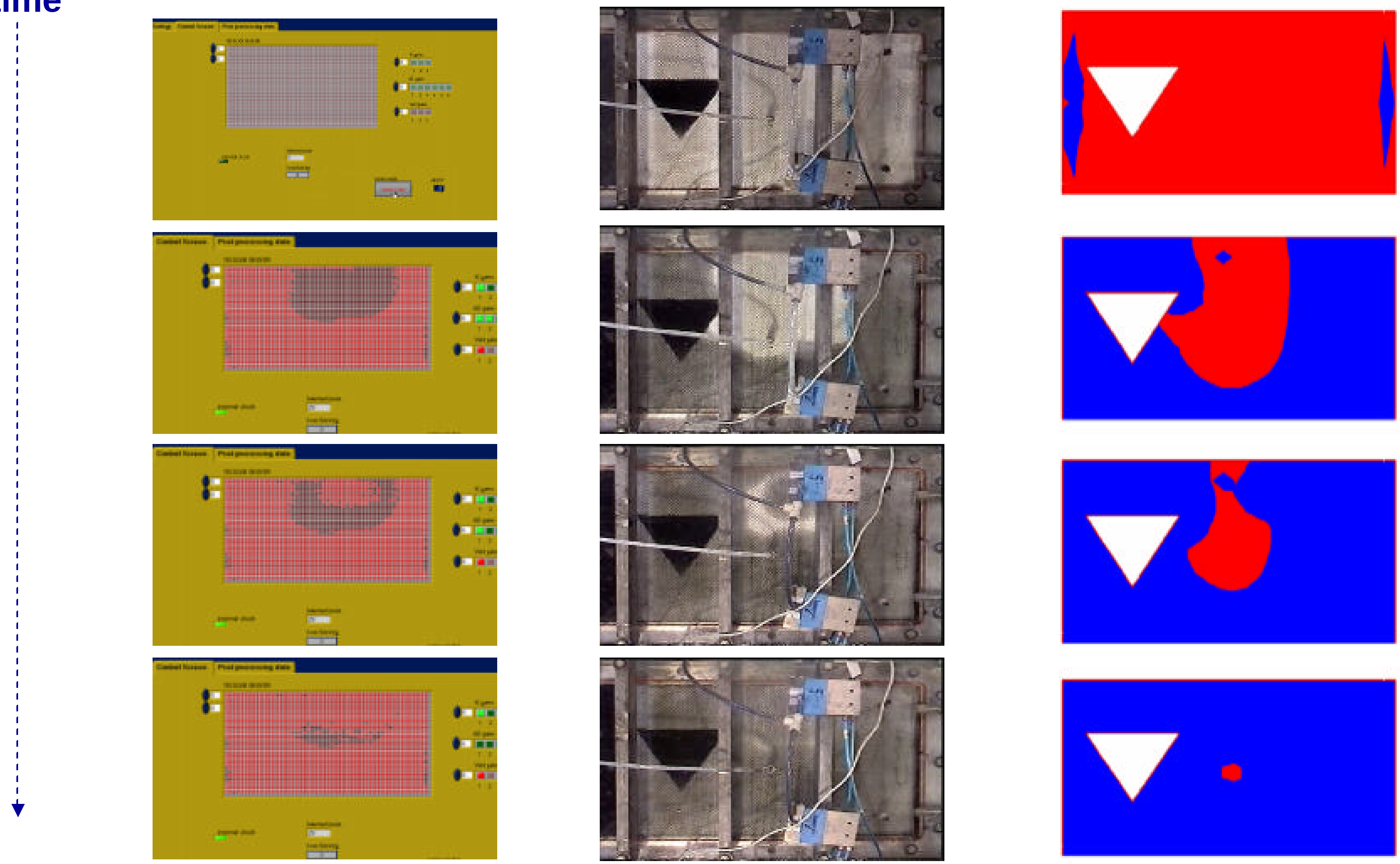
Top: Bottom view of point injection into dry preform, with blackened corn syrup

Left: PERMSTAT set-up

Experimental Validation of TekScan Sensor and Flow

Auto_RTM | Experiment | Simulation selected

time



Lesson II. : Describe and Model the Process

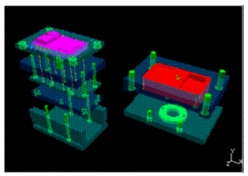
- Equations Dependent on Measured (or Predicted) Data
  - Darcy's Equation

$$\langle \mathbf{v} \rangle = -\frac{\mathbf{K}}{h} \cdot \nabla p$$

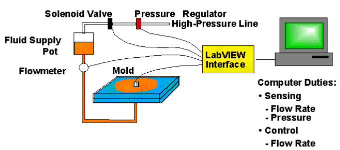
  - Continuity Equation
- Boundary Conditions (More Data)
  - Pressure at Inlet
- Solution
  - Analytic (Closed Form…)
  - Resorting to Computers
- Post-processing
  - Trying to Make Sense of the Results

LIMS GUI and Using LIMS

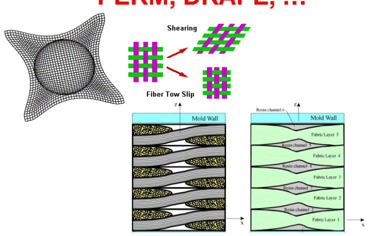
Part Design/Meshing
CAD Software



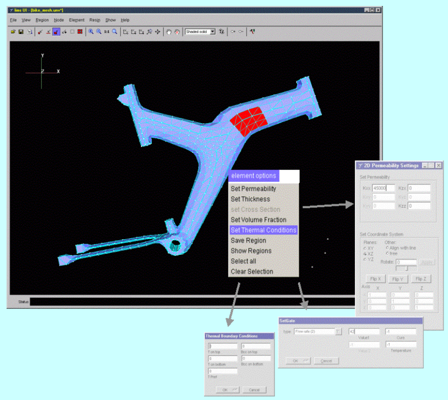
Permeability Measurement



Permeability and Preform Properties Computation
PERM, DRAPE, …



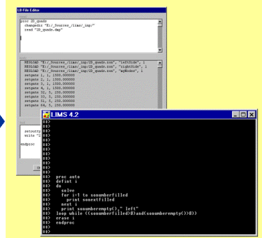
Preparing Data for Simulation
LIMS UI (User Interface)



- Converting Input Data
- Setting Material Properties
- Creating Gates and Vents
- Creating and Editing Control LBASICFiles

Running Simulation
LIMS or LIMSSLV

Directly From LIMS UI

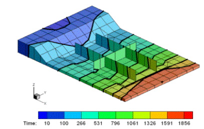


From Command Line

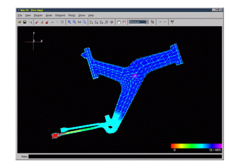
- Simulating Filling Procedure
- Executing Control Operations
- Writing Desired Output

Post-processing Results
LIMS UI, TECPLOT, …

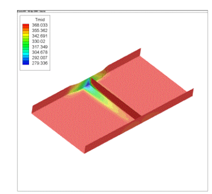
Flow Patterns



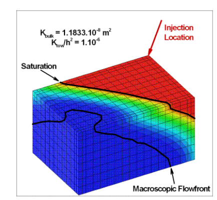
Pressure



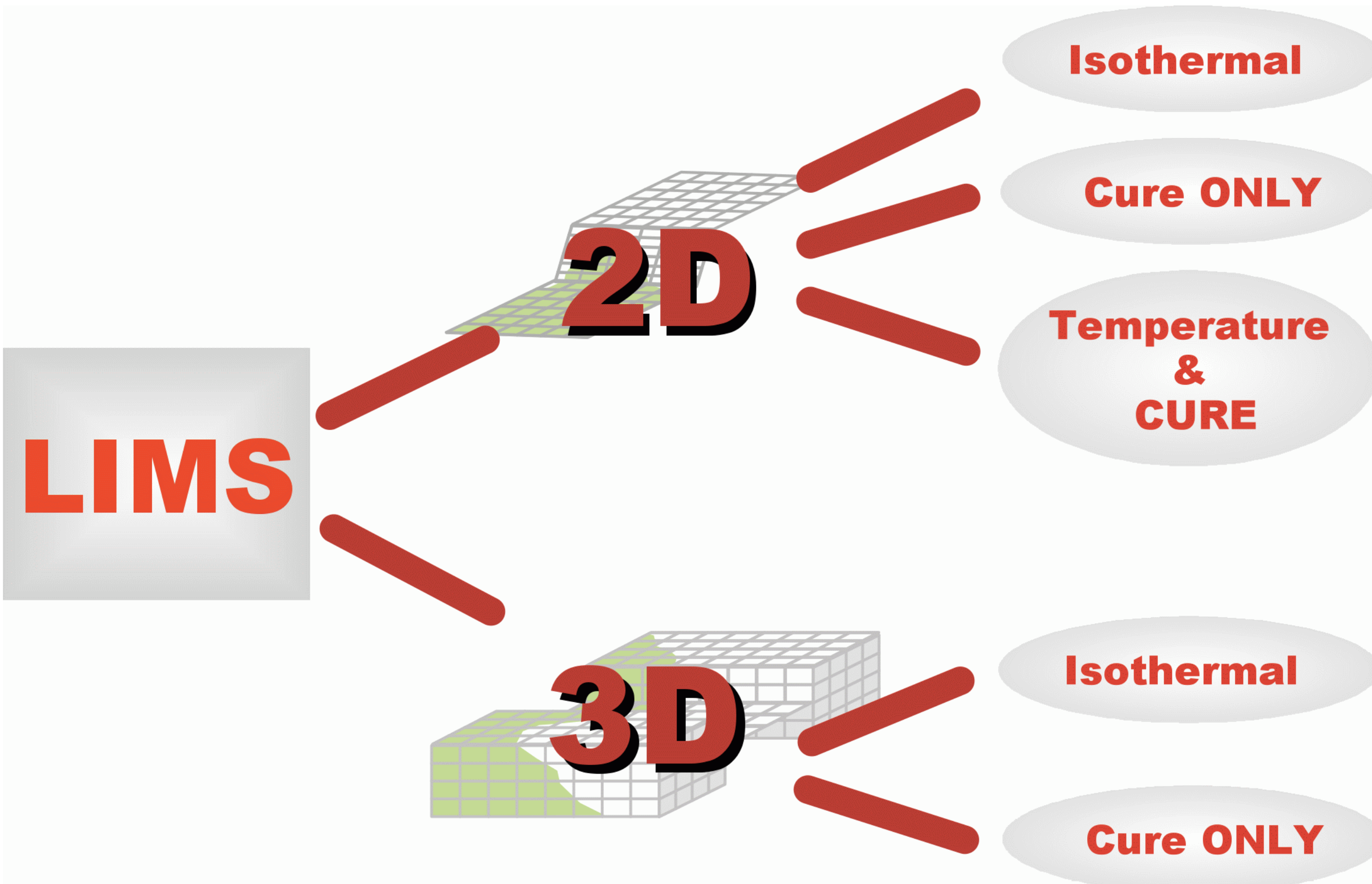
Mid-plane Temperature



Saturation

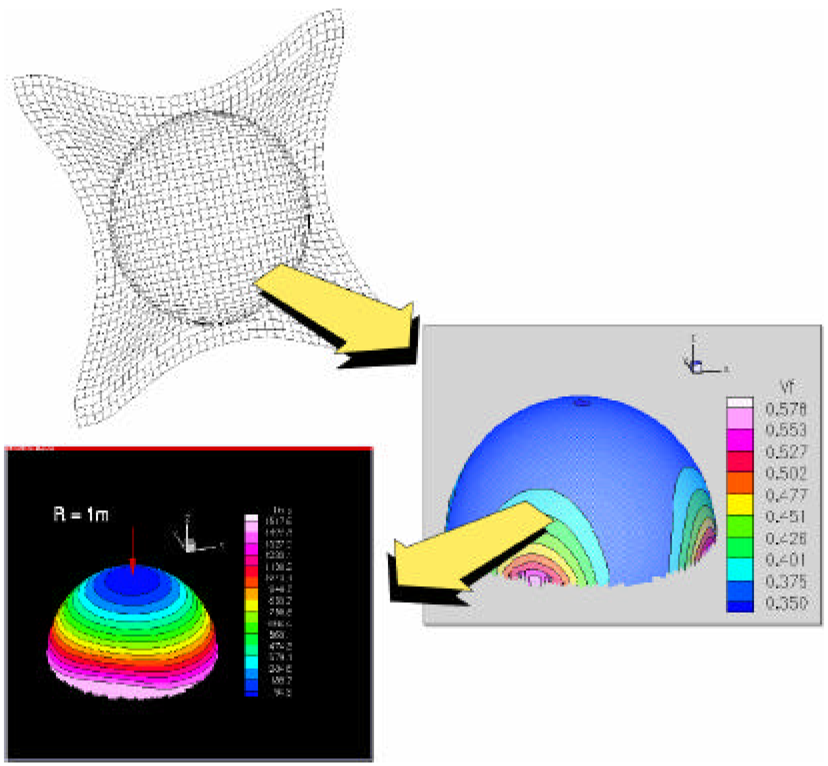


Simulation Capabilities I

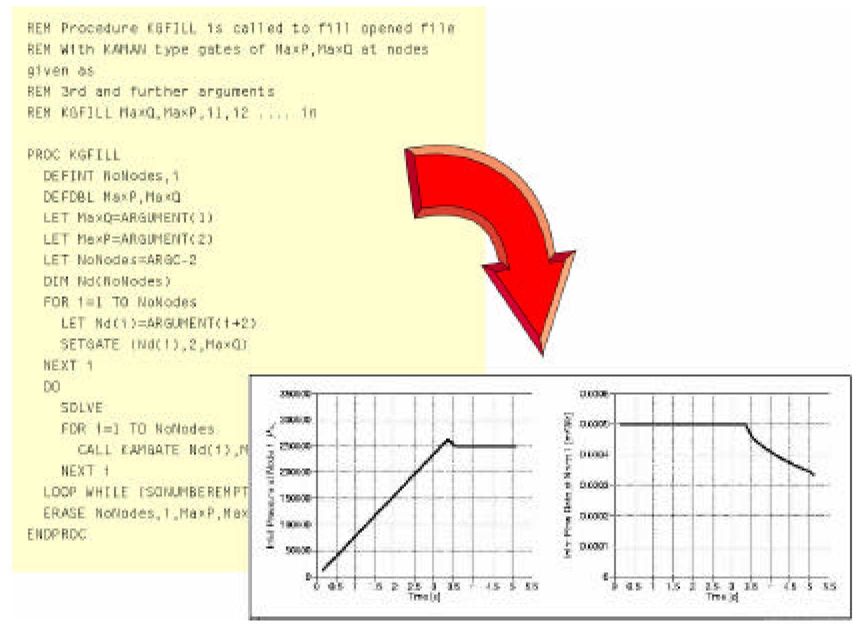


Simulation Capabilities II

Preform Deformation (Draping)

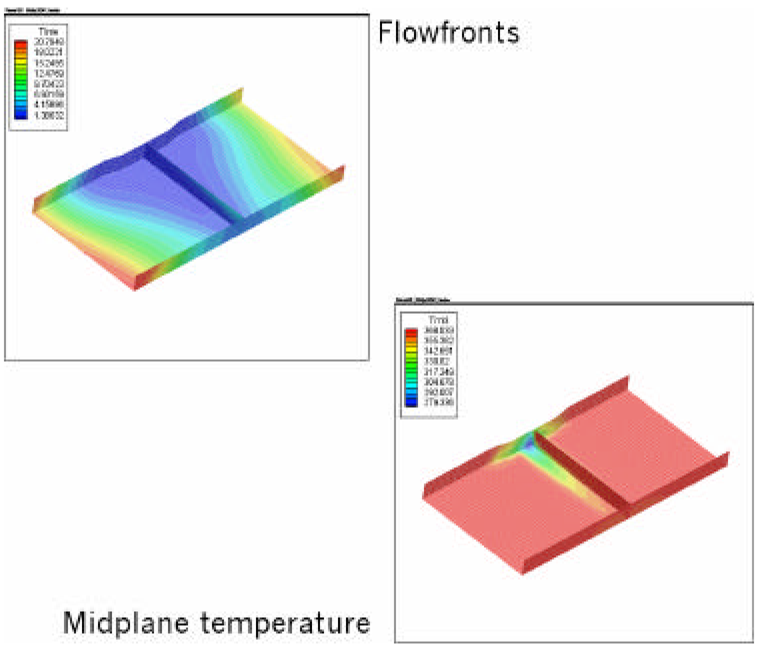


Scripting Control

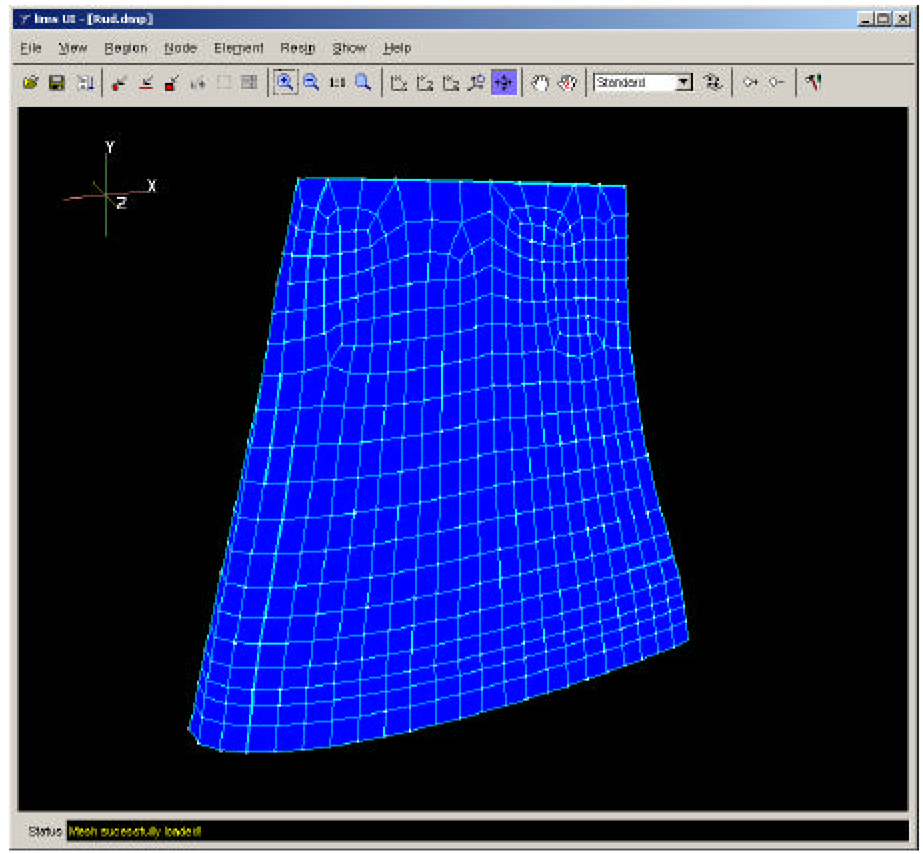


Simulation Capabilities III

Non-Isotropic Problems

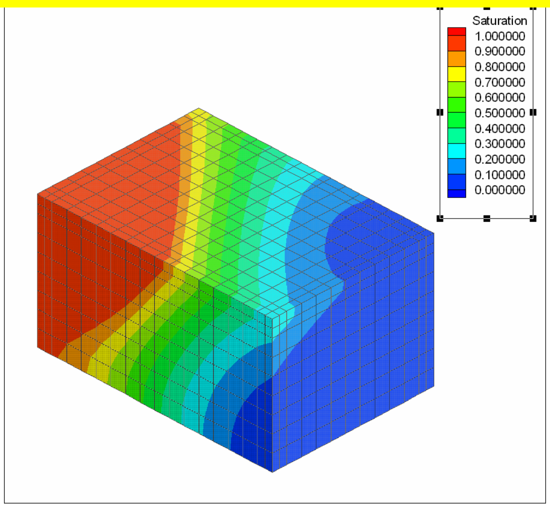


Graphical User Interface

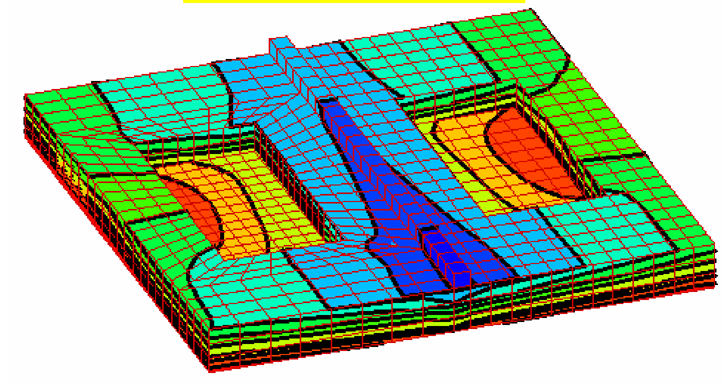


Simulation Capabilities Examples

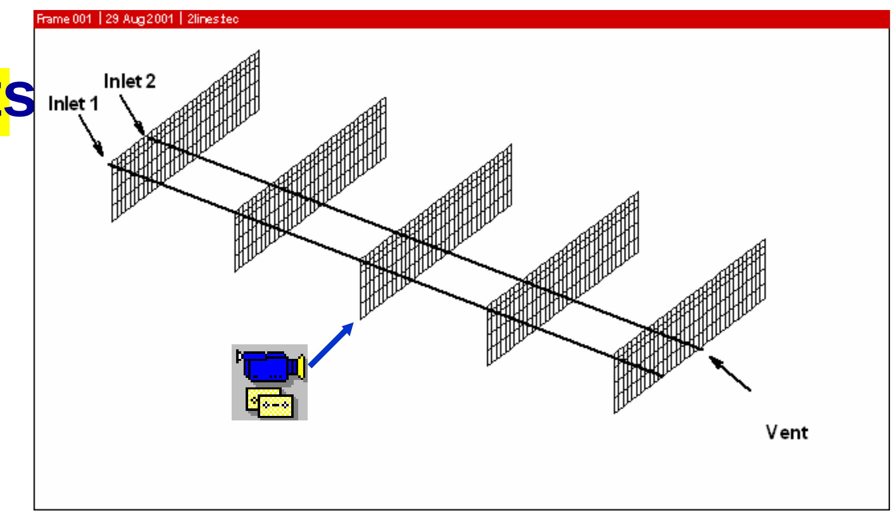
Saturation of Tows



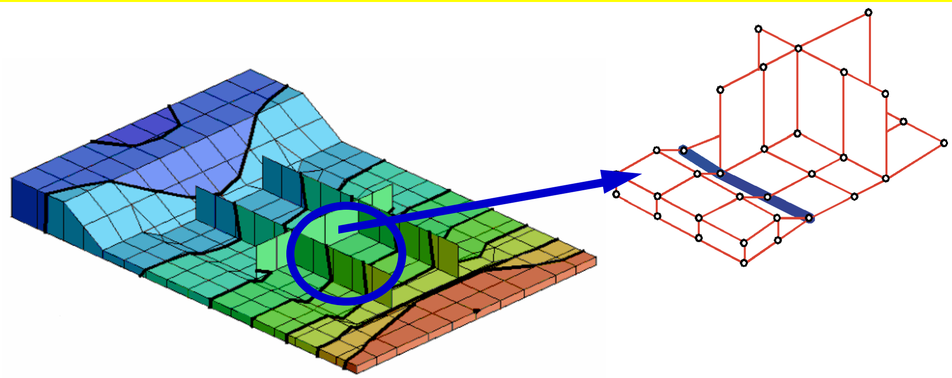
FASTRAC



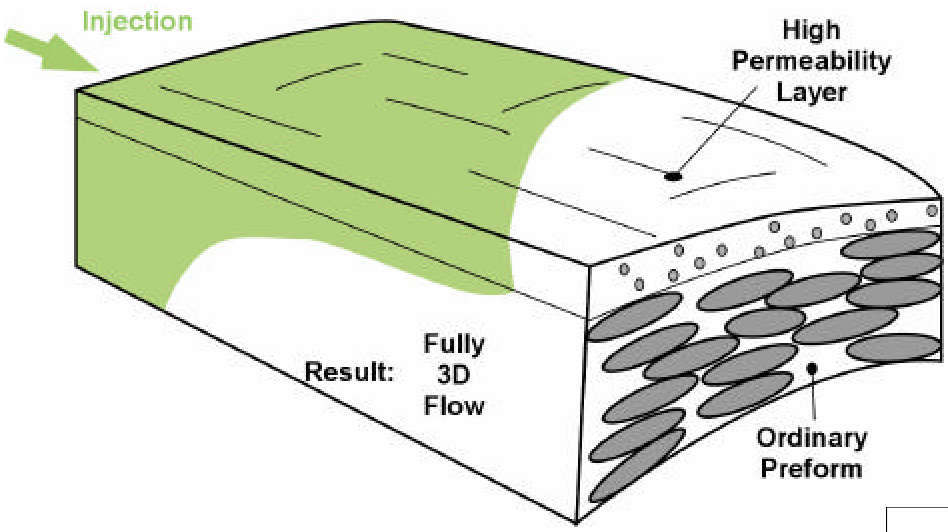
Sequential VARTM Injection

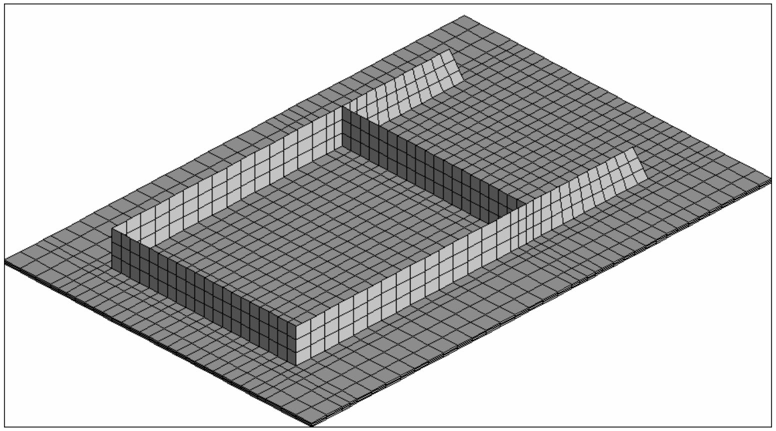


Integration of 2D and 3D elements

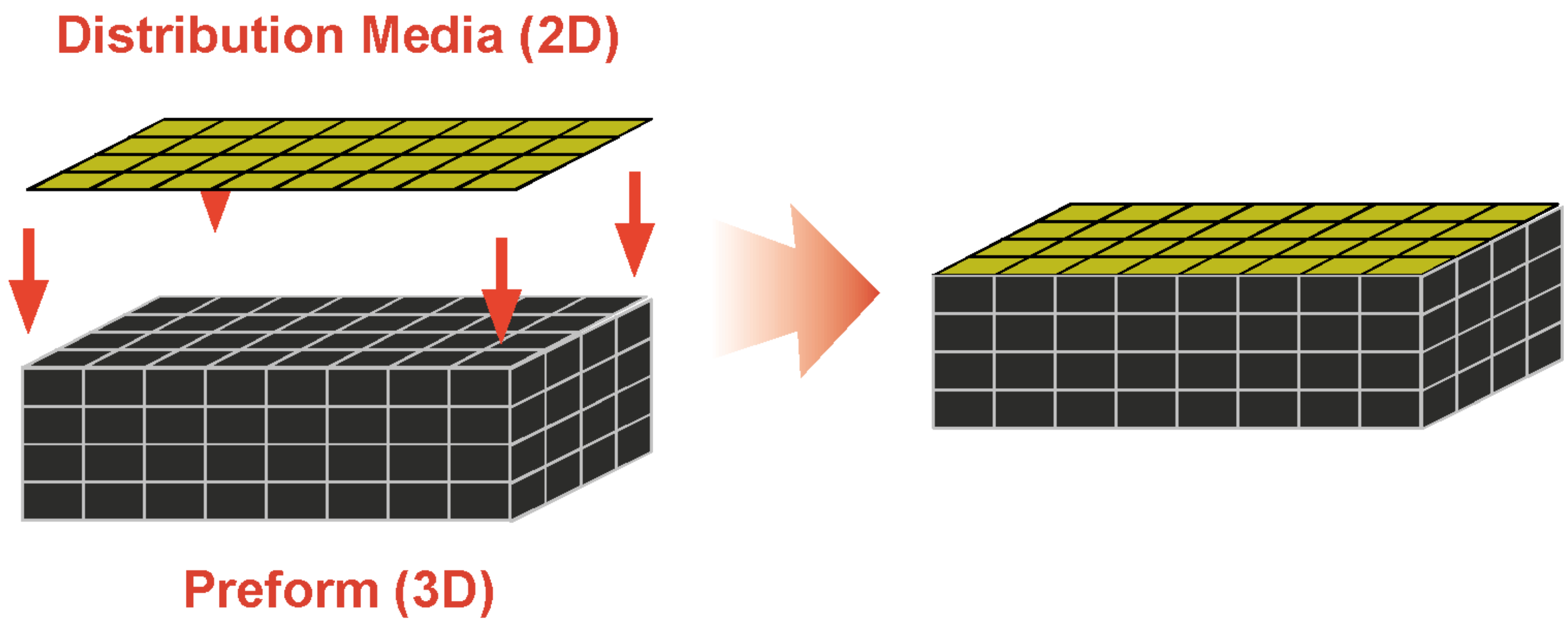


Distribution Media Modeling

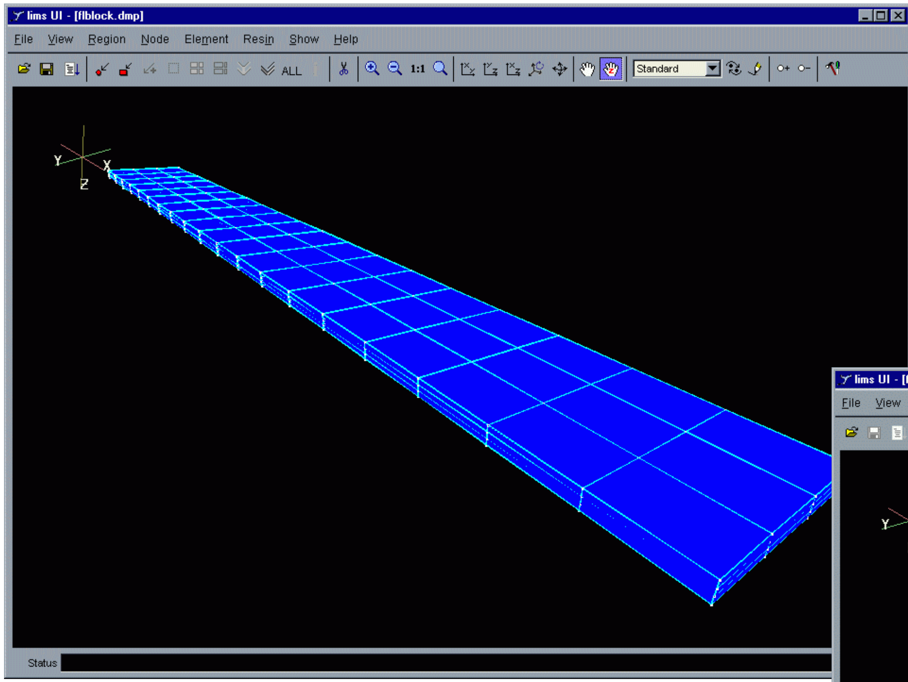




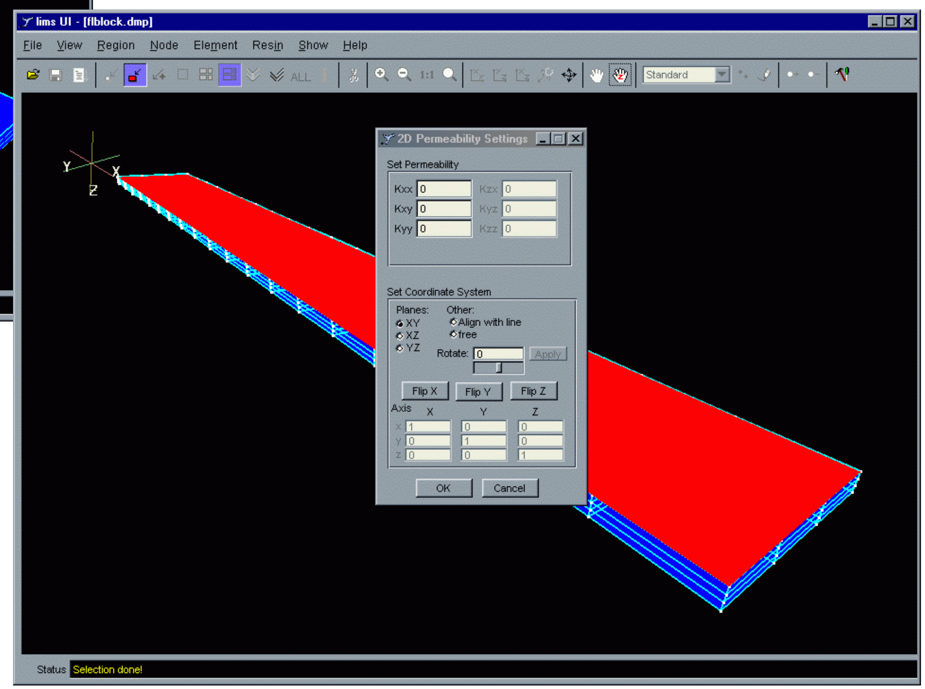
Distribution Media Modeling I.



Distribution Media Modeling II.



A few clicks later...



Lesson III. : Sensing and Control

- **Is What Was Predicted Really Happening?**
  - **Not Sure! There May Be Various Disturbances**
- **Let's Check**
  - **Common Sense Feedback**
  - **Sensors and Sensing**
    - Flowfront Position
    - Pressure and Flowrate
    - Temperature
- **Never Test For an Error Condition You Cannot Handle: The Control**
  - **Multiple Injection Gates and Vents**
  - **Taking Control Action**

Disturbances I

Where Do the Disturbances Come From ?

Preform Deformation

Inaccurate Preform Cutting

Inaccurate Material Properties

How Do We Detect Disturbances ?

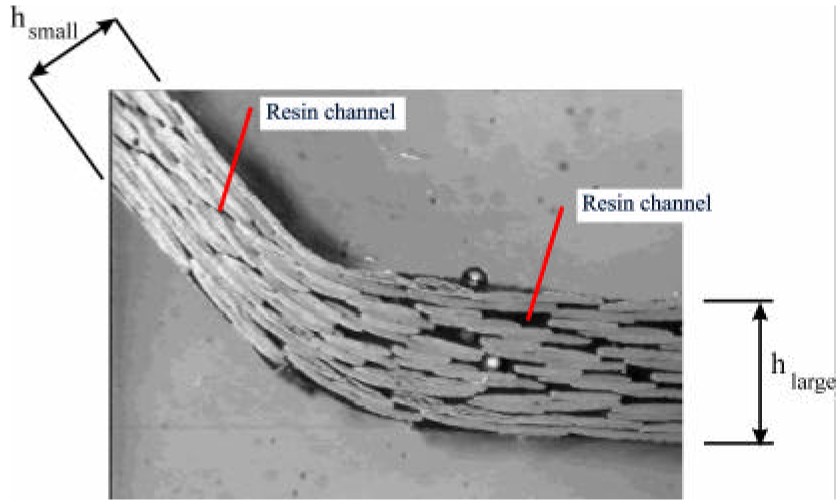
When Process Fails

When Part does not Pass Quality Control

Disturbances II

How To Predict Possible Disturbances ?

Common Sense

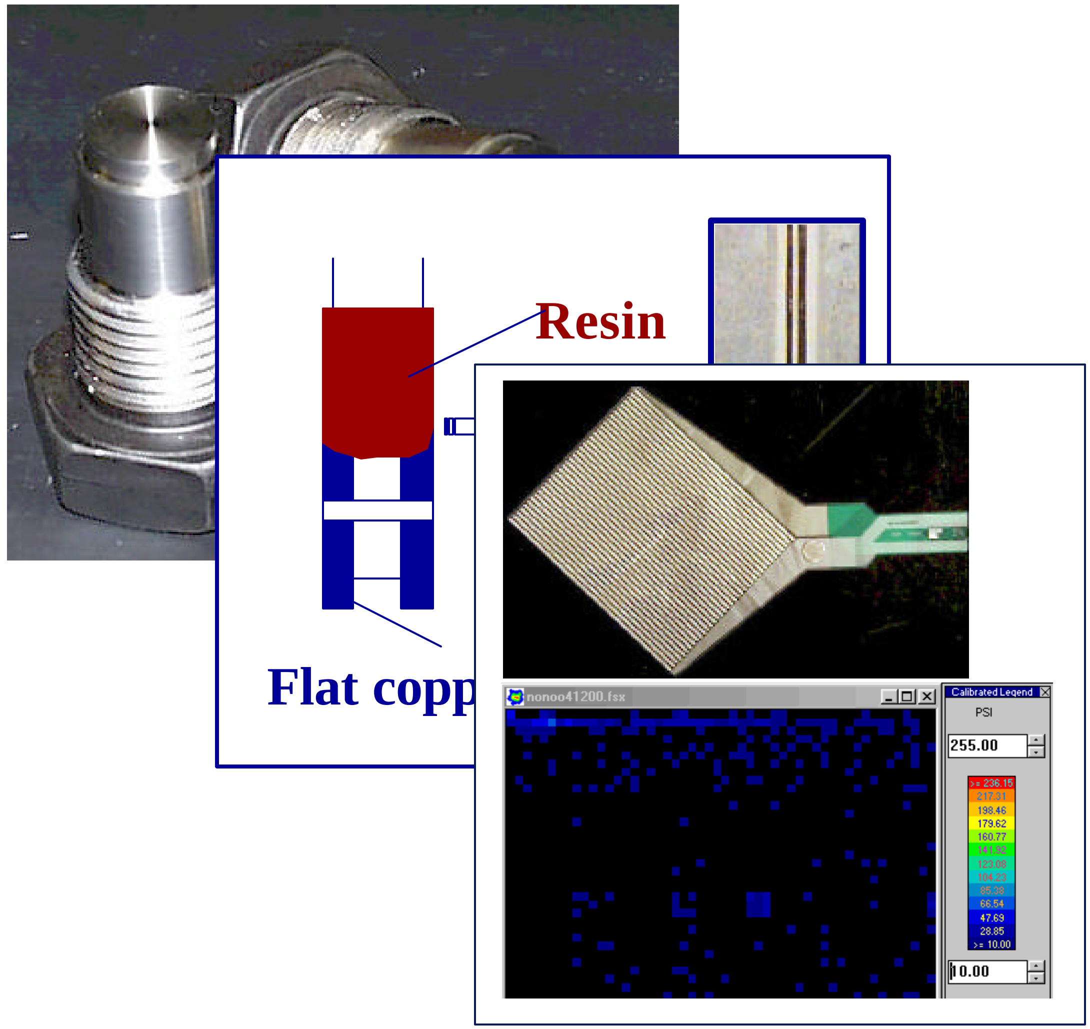


Experience

Rules of Thumb

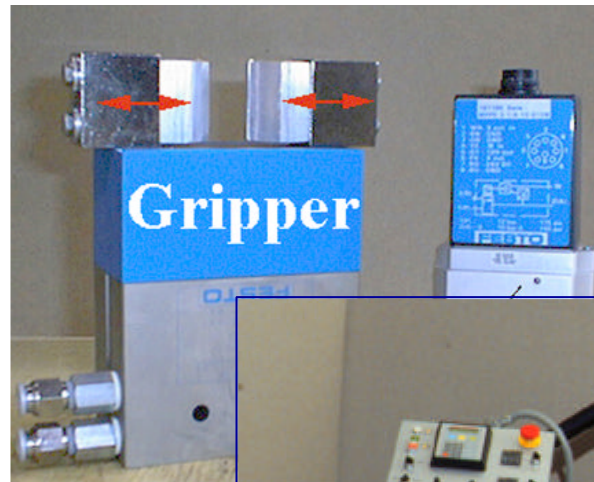
- Very Rare

- **Pointwise**
- **Lineal**
  - Electrical
  - Optical
- **Visual Input**
  - Smartweave™
  - Tekscan™
  - Visual (Camera)



Control Possibilities

- **Possible:**
  - **Open/Close Gates**
  - **Close Vents**
  - **Control Pressure or Flow-Rate in Existing Gates**
  - **Tinker with Injected Resin**
- **Barely Possible:**
  - **Control Distribution Media**
  - **Control Compaction**
- **Not Possible**
  - **Tinker with Preform and Distribution Media Locations**

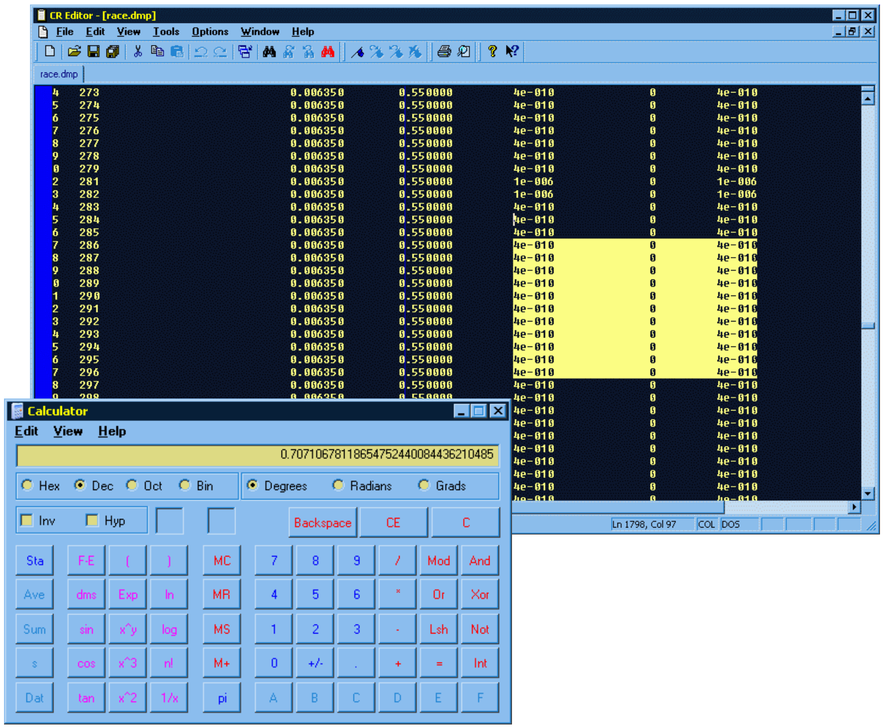


Can We Model the Disturbances and Sensors?

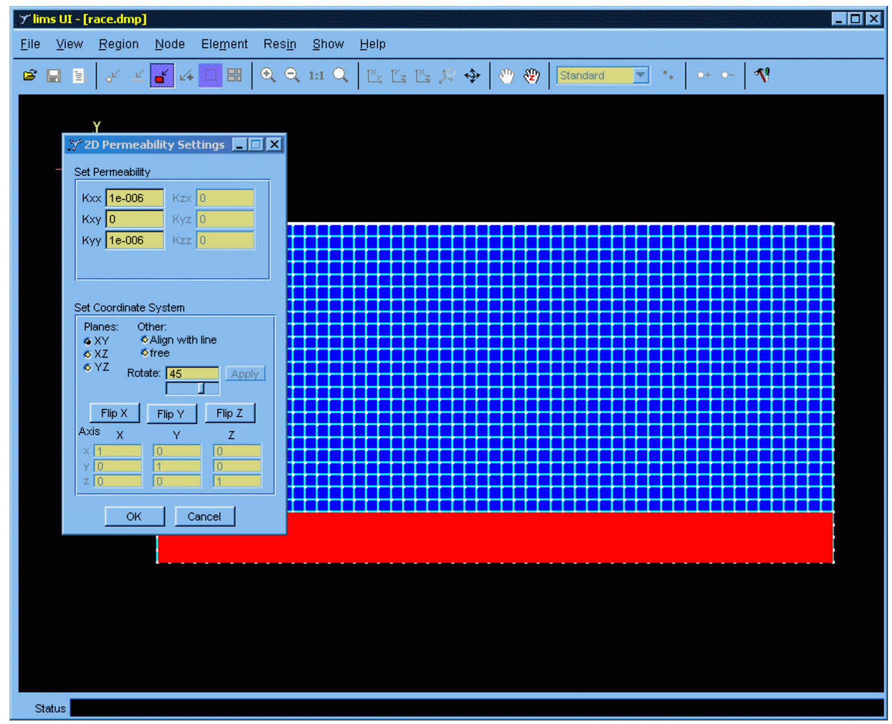
- **Variations in Resin Viscosity?**
  - **Yes, Primary Input Value**
- **Variations in Preform Permeability and Porosity?**
  - **As Above**
- **Racetracking Channels?**
  - **Multiple Options:**
    - High Permeability
    - 1D Elements
- **Sensor and Control Modeling**
  - **In LIMS One Can Access All the Data During Simulation and Change Settings Accordingly**

LIMS UI - Changing Permeability

LIMS Alone



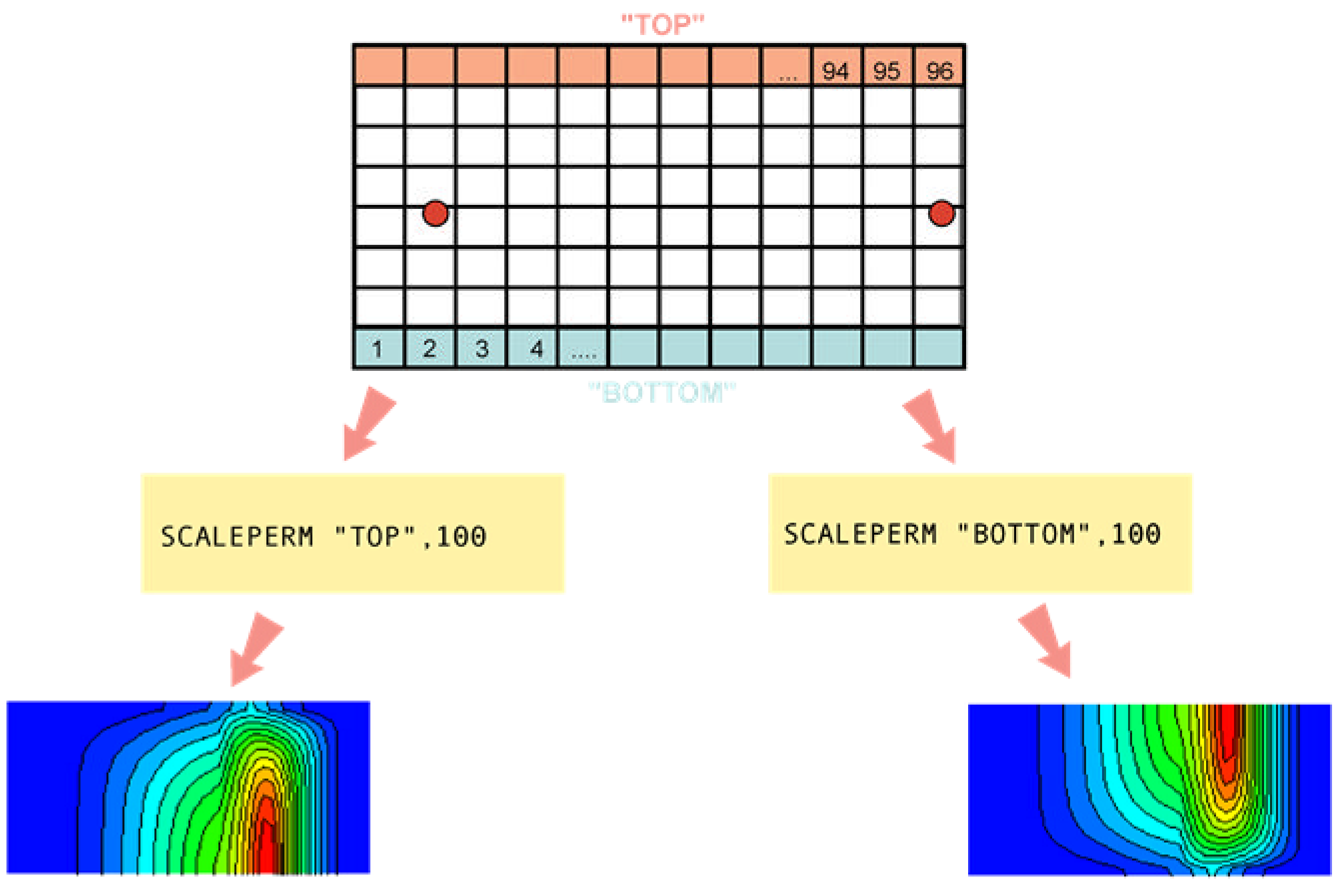
LIMS UI



Hope you remember element numbers….

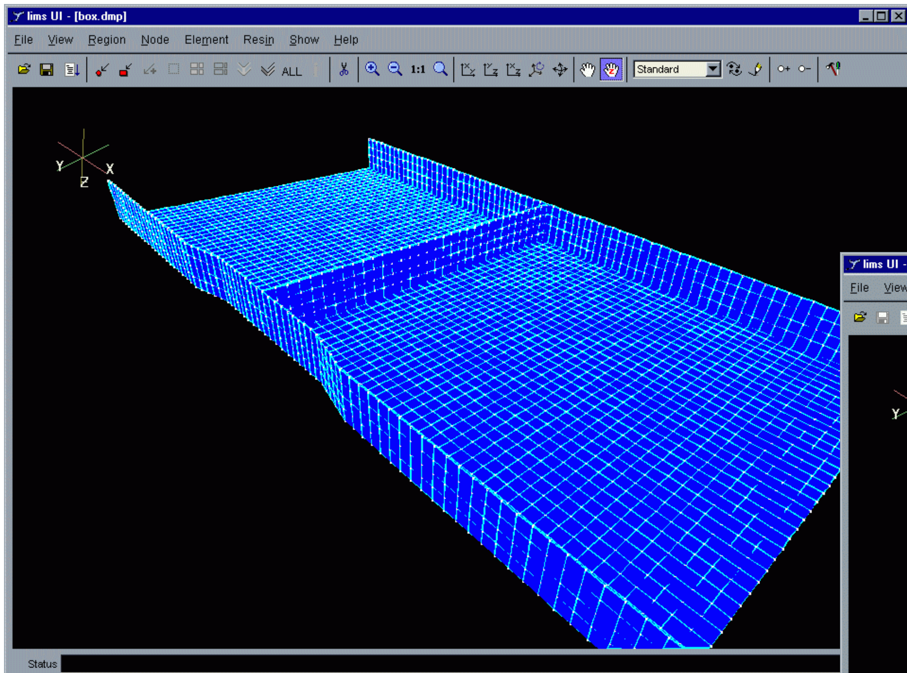
Modeling Racetracking Channel I.

Raise Permeability in Edge Elements!

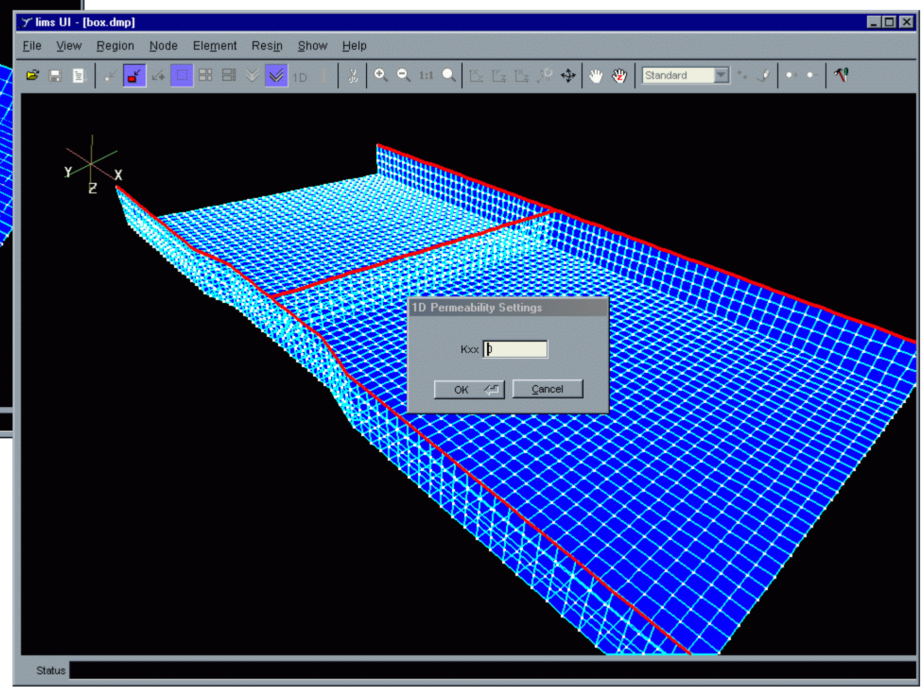


Modeling Racetracking Channel II.

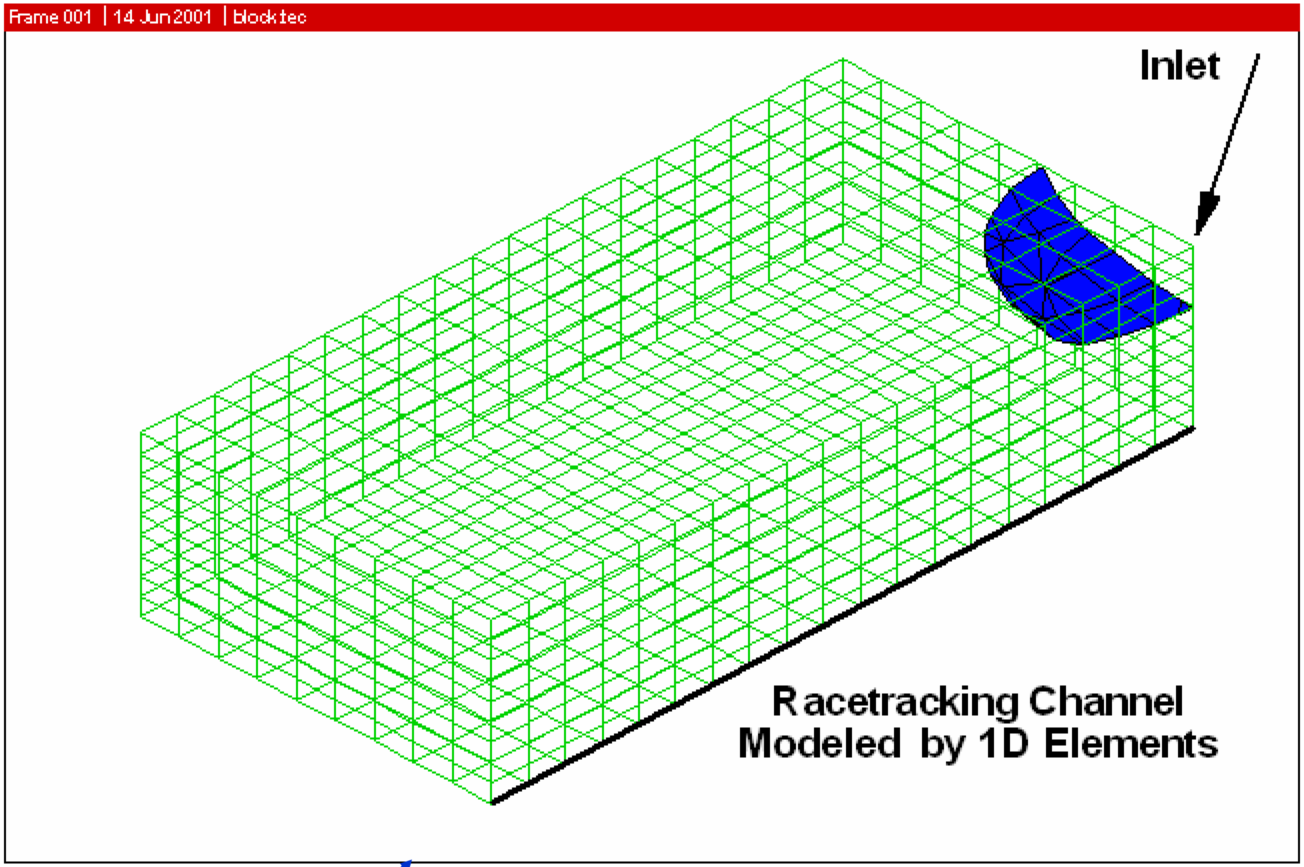
Add 1D Elements!



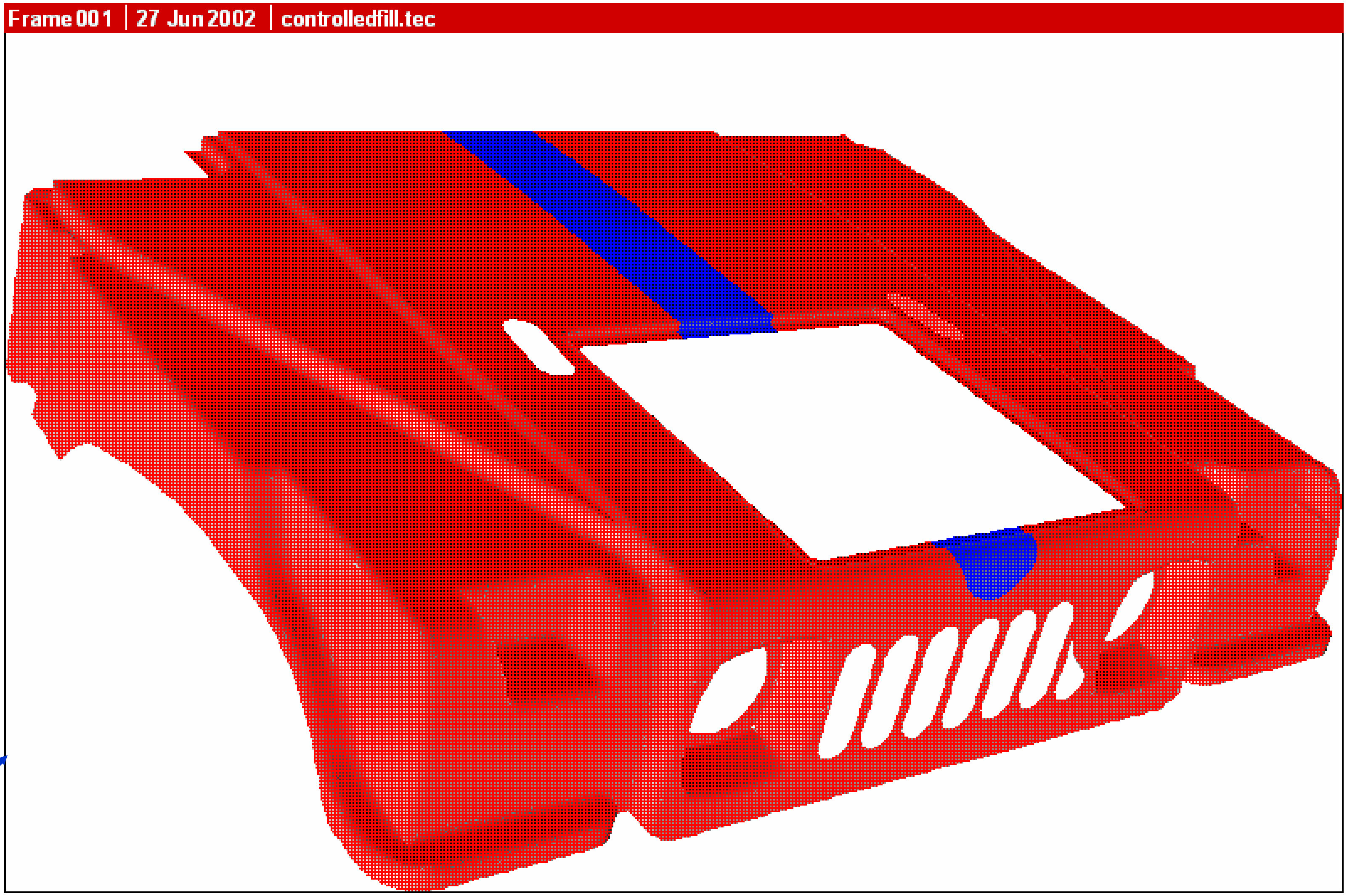
A few clicks later...



1D Elements for Racetracking



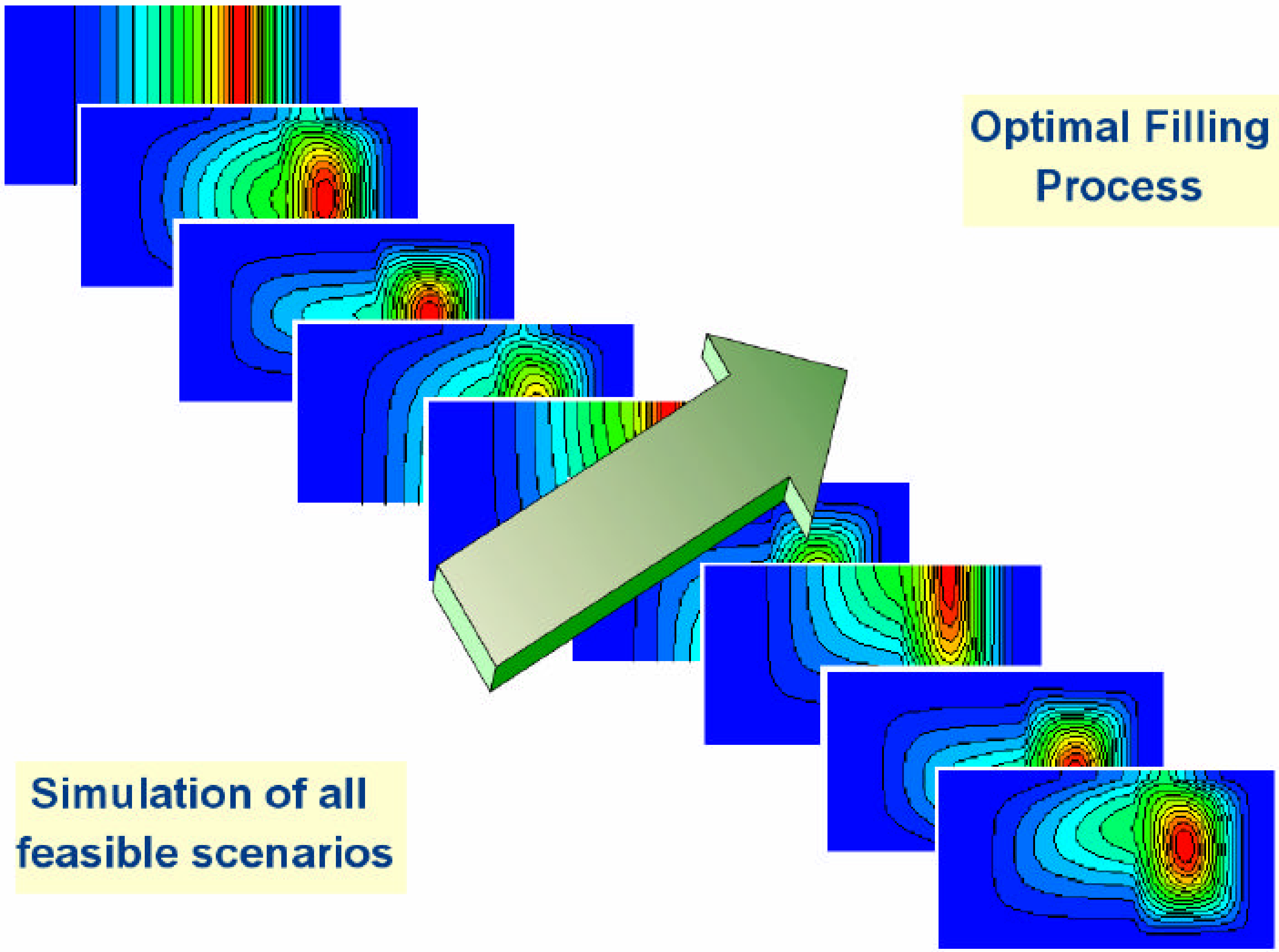
Simple Adaptive Filling: Sensor Model



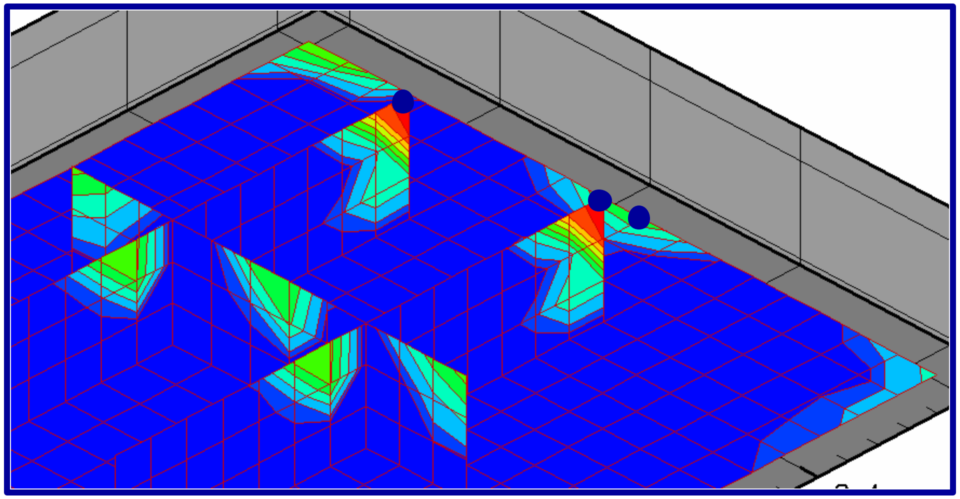
Optimization

- So Far We Just Tried to Make It
- The Real Challenge: How to make it Better
- What does Constitute "Better" (Cost Function) ?
  - Faster or Cheaper
  - Stronger or Better-Quality
  - Compromise between those Two
- What Can we Modify (Parameters)?
  - Part Design (Off-limits for Processing Only)
  - Material
  - Tooling and Process Parameters
  - Distribution Media
- How to Relate the Parameters to the Cost Function
  - !!! Efficiently !!!

Simple Optimization



Optimal Auxiliary Vent Locations



Cost Function:

Weighted average dry area size per each scenario

Nominal case: 24.10

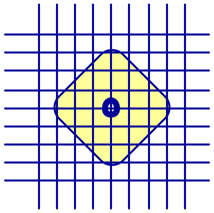
Optimization Problem:

Given the number of auxiliary vents, find the vent configuration that will minimize the cost function.

Tolerances:

A dry spot which include 3 or less nodes is ignored.

An area of radius 3 nodes around a vent is considered safe



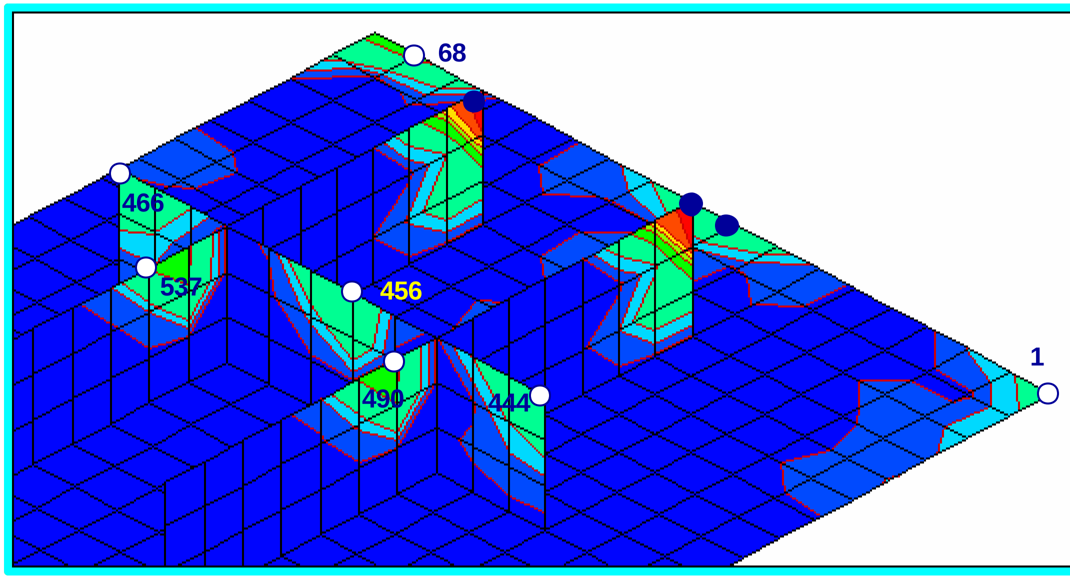
Optimal Auxiliary Vent Locations

Given:
- **Vend Candidate Pool**
- **Number of Auxiliary Vents**

Permutate Nodes in the Pool to obtain Vent Configurations

Apply Scenario Space to Each Vent Configuration and Estimate Cost Function

Output:
- **Optimal Vent Configurations**



Exhaustive Search
- 551 nodes in the candidate pool
- 151,525 possibilities for 2 auxiliary vents

Exhaustive Search II:
- 104 nodes in the candidate pool
- 5,356 possibilities for 2 auxiliary vents

Exhaustive Search III:
- 7 nodes in the candidate pool
- 21 possibilities for 2 auxiliary vents

Results, 2-Vent Configurations

Exhaustive Search II

5,356 vent configurations

Best Aux. Vent Configuration
Vents @ nodes [1 72]

Cost function: 16.4

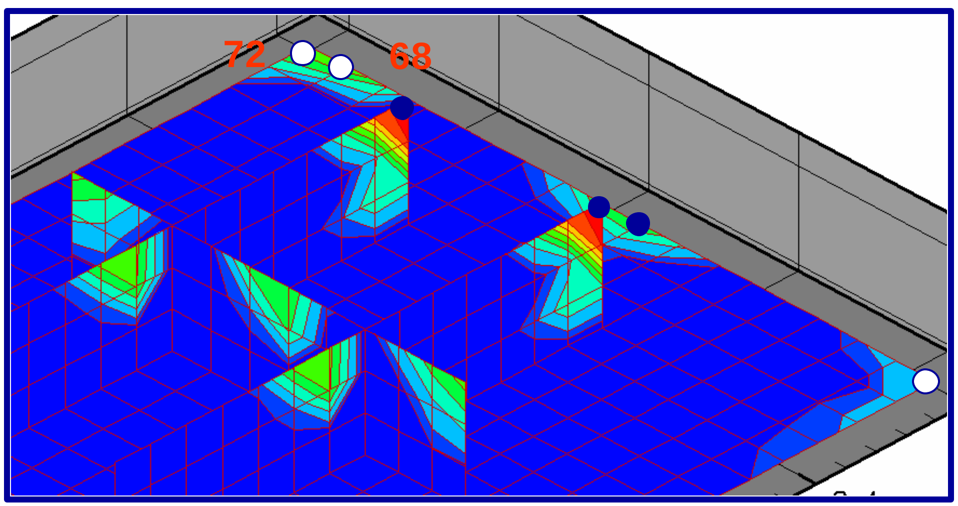
Exhaustive Search III

21 vent configurations

Best Aux. Vent Configuration
[68 1] *numbered nodes*

Cost function: 17.4

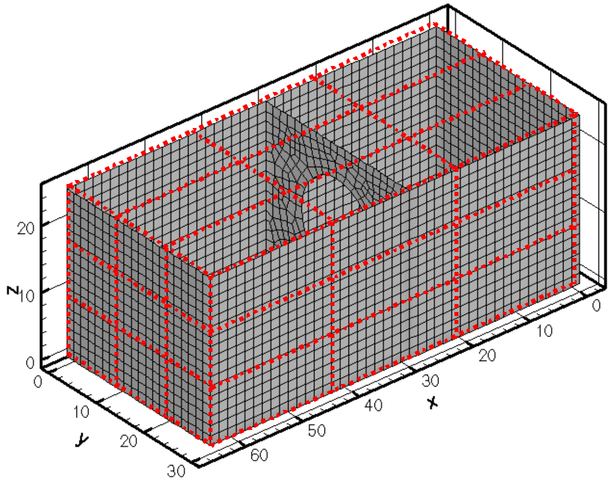
neighbors

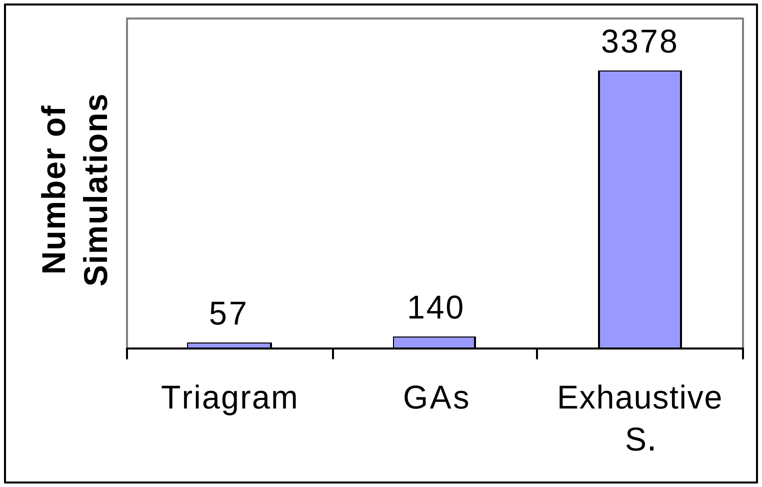


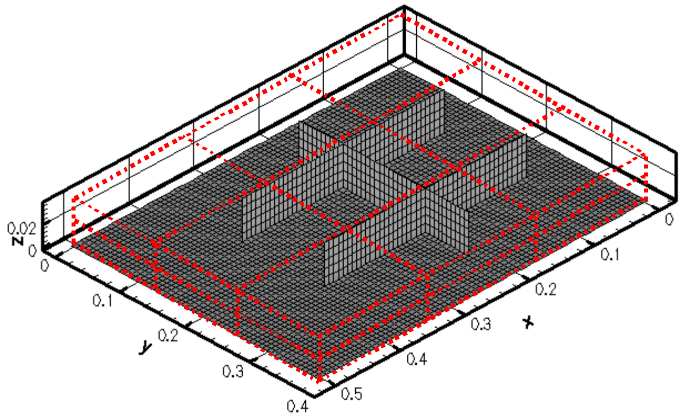
Accuracy loss: 6.1 %

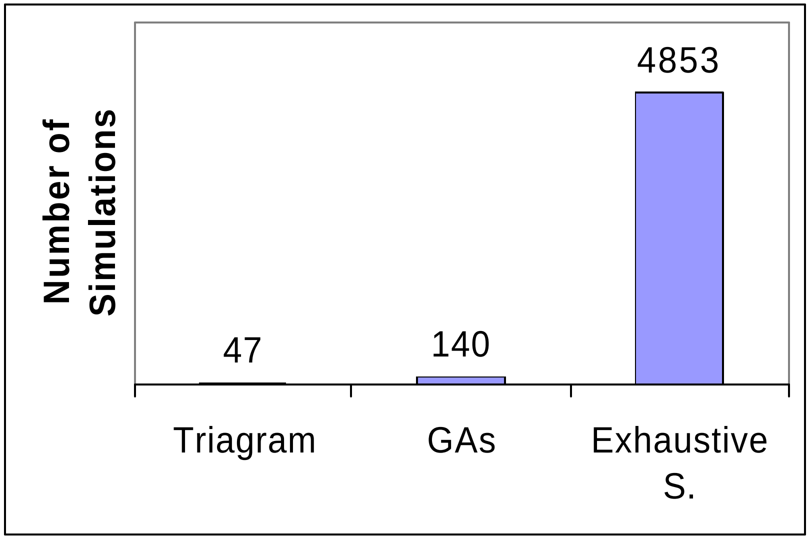
Computational Savings: 99.6 %

Optimization of Fill Time: The Quest for Effectiveness



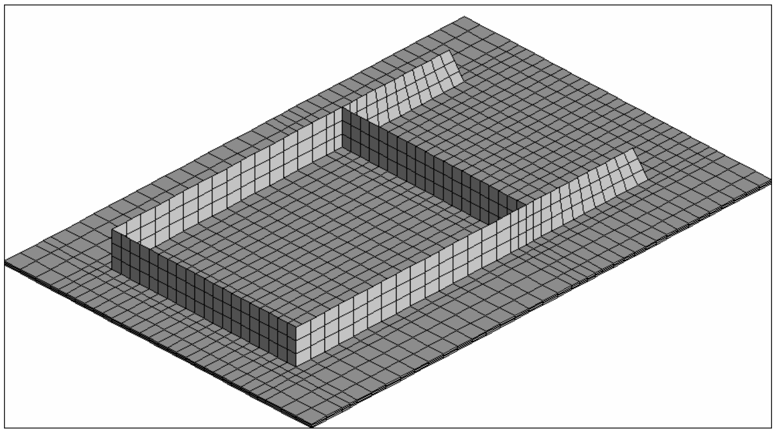






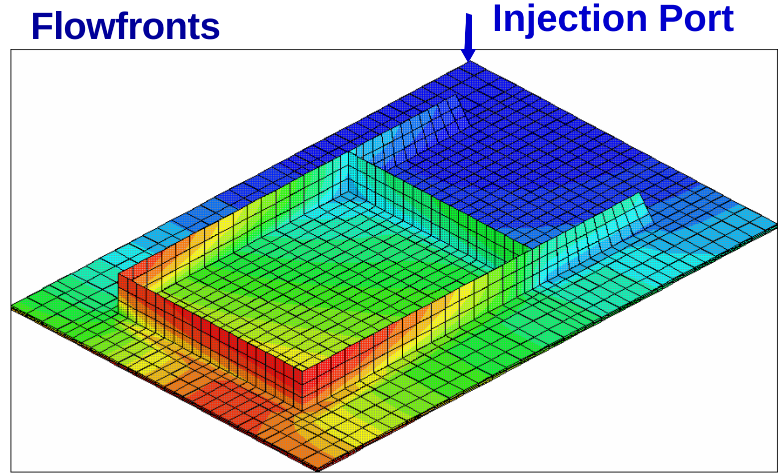
Optimization: “Distribution” of Distribution Media

Part

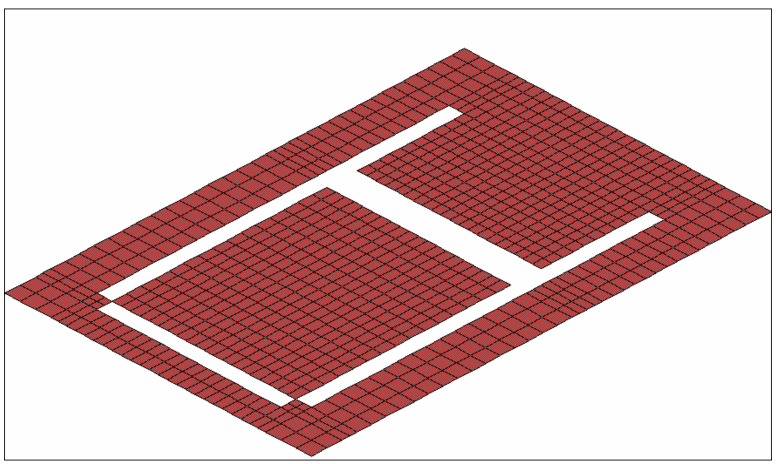


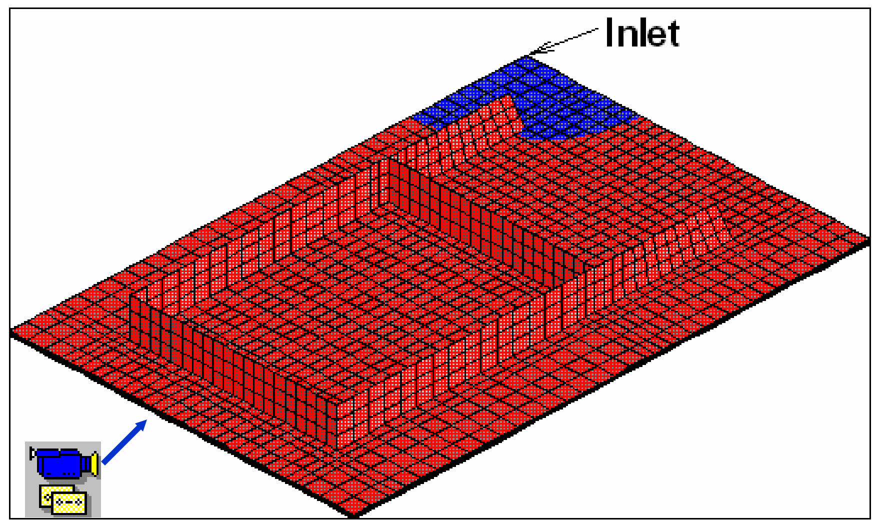
Flowfronts

Injection Port

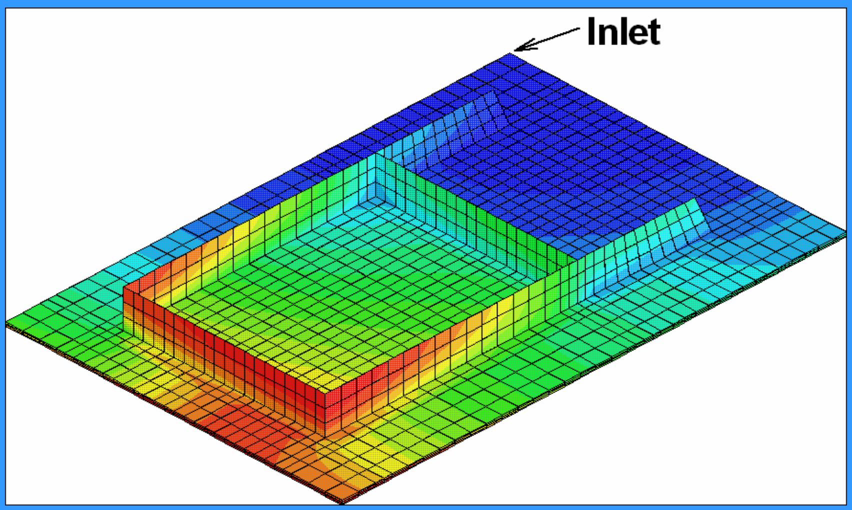


Distribution Media





Can We Expect Any Problems?



Original Preform Permeability

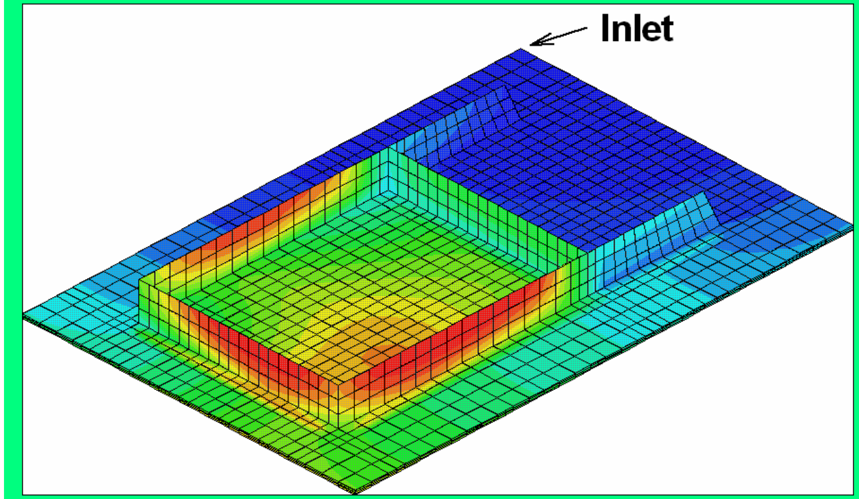
$K_{bulk} = 1.10^{-10}$

$K_{DM}=1.10^{-8}$

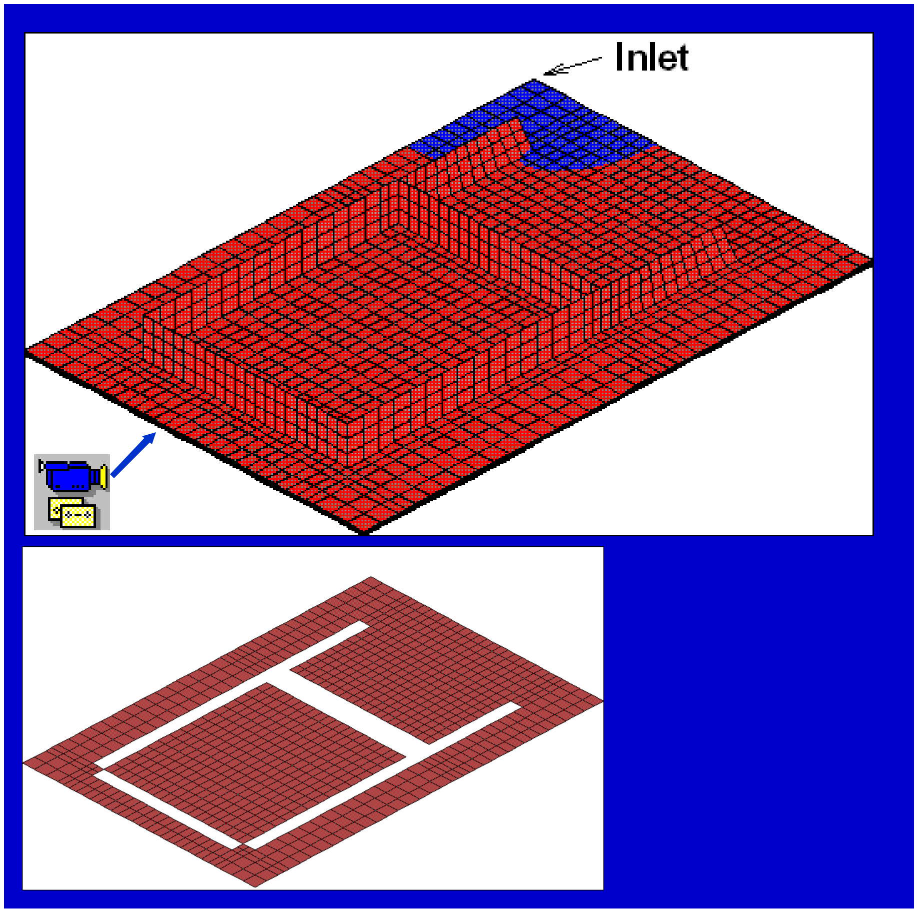
Reduced Preform Permeability

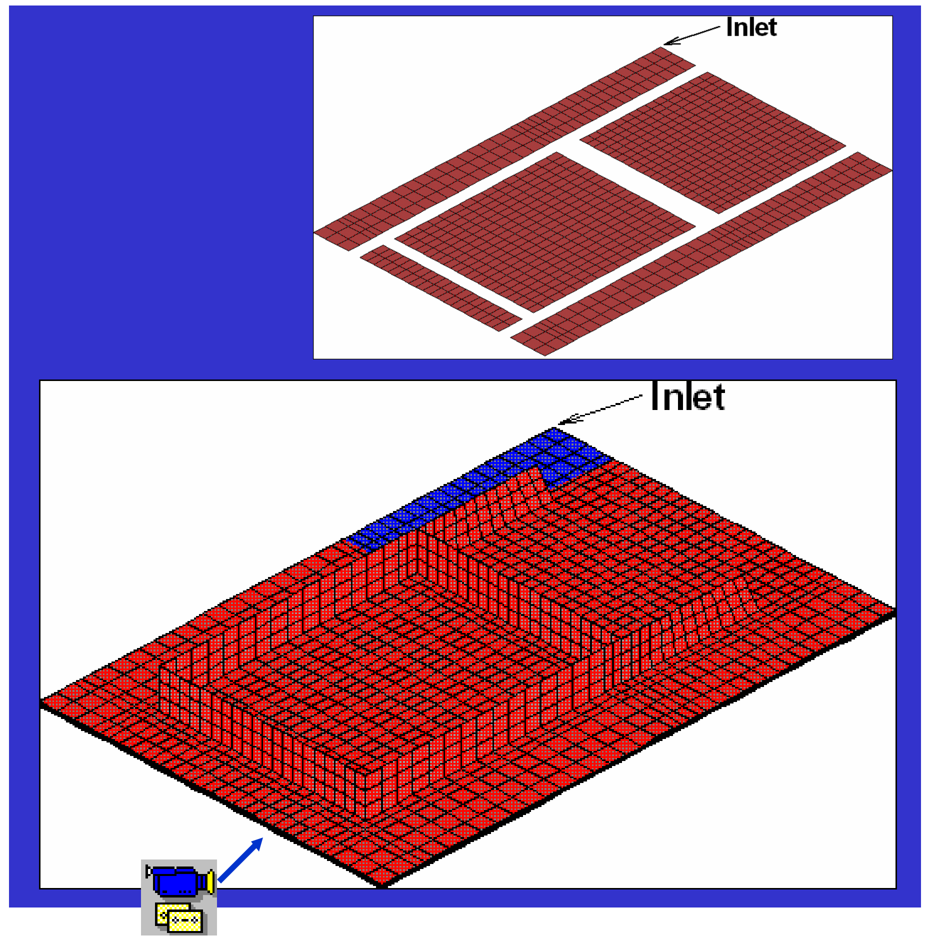
$K_{bulk} = 1.10^{-11}$

$K_{DM}=1.10^{-8}$



Can We Help It?





Conclusions I.

- Filling Process Can Be Accurately Simulated
- Tools Are Readily Available
- Simulation Allows Design of Process without Expensive Trial-and-Error Stage.
- Process Control and Optimization Require Flexible Simulation Tools
  - Repetitive Virtual Processes are Required
- It Is Possible to Deal with Process Disturbances via Automated Control
  - Simulation is Necessary for Design of Non-trivial Process Control
- It is Possible to Optimize Process Design With Respect to Various Cost Functions
  - Simulation is Necessary for Non-trivial Cases

Conclusions II.

- Simulation Tools Depend on Experimental Methods (or Additional Simulation) for Input Data
  - Permeability Components
  - Also Resin Data, Porosity, etc.
- Simulation, Optimization and Control Require Occasional Experimental Verification
- User Expertise Is Still Important
  - Building Part Model(s)
  - Prediction of Possible Disturbances
  - Dealing with Cost Functions

Credits

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Christof Ledermann
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Ali Gokce
Hubert Stadfeld
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Swen Elpelt
Angelika Geyer
Yeshwanth Rao
Ben Lenhard
And others….