Strongly Coupled Interaction in Multi-Physics problems

- Overview of CC-MPA – M Cross
- CC FSI in CA – A Svobodnik
- Coupled field analysis in ANSYS – D Ellis
- LUNCH
- Numerical Simulation of Aluminium Foundry Processes – M Chumenti
- CC-MP for FSI – A Slone
- Master-Class in CC-MP

RTD Thematic Area	Date
MultiPhysics & Analysis Technology	Sep-02

Characterising closely coupled MULTI-PHYSICS simulation

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What is multi-physics simulation?

- Most CAE analysis software tools based upon single discipline:
  - CFD (fluid flow, heat transfer, combustion)
  - CSM (structures, dynamics, contact, heat transfer)
  - CEM (electro-magnetics)
  - Acoustics
- What of their interactions?

  - mostly we cheat or ignore them

Challenge of multi-physics

- Multi-physics - closely coupled interactions amongst the physics
- CAE modelling and analysis software is essentially phenomena specific :

  - **CFD uses FV** techniques with segregated iterative solvers
  - **CSM uses FE** techniques with direct solvers
  - **CAA & CEM** uses **either FE/FV** techniques

plus the heritage software approaches that go with each.

- **Must ensure accurate filtering and mapping of data for volume source and boundary data**

Levels of physical coupling

- **Very Low** - 1 way

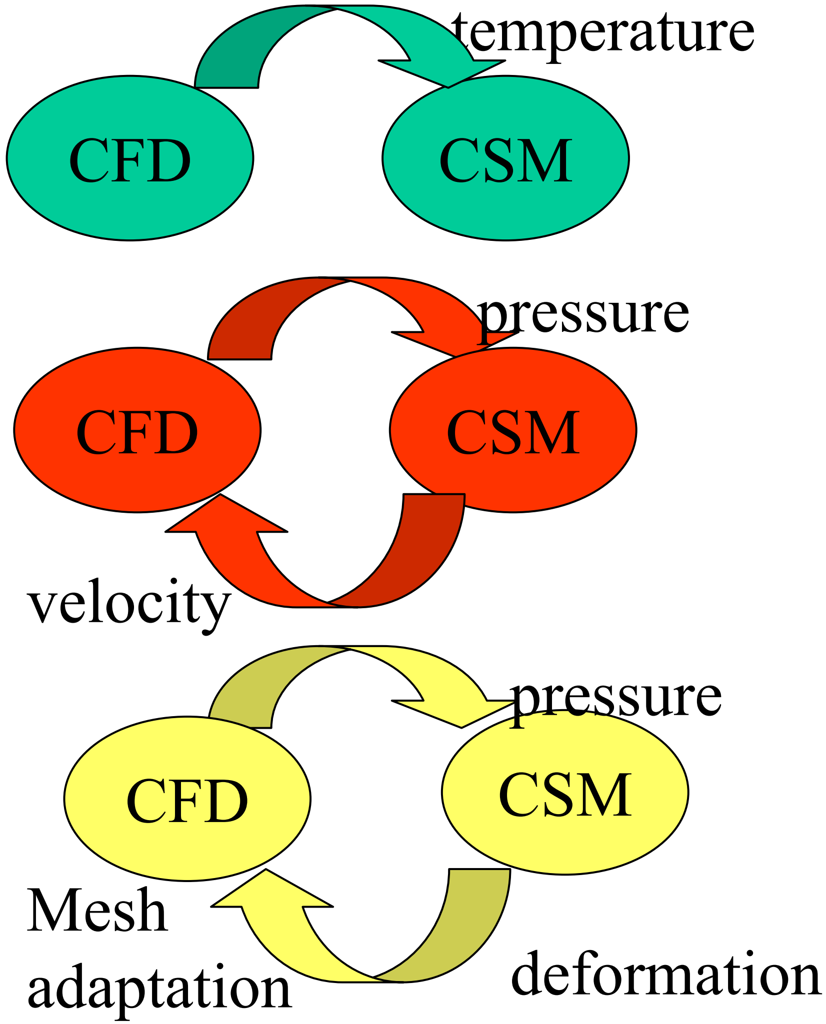
- simple via a file between codes

- **Medium** - 2 way

- much trickier, mesh compatibility & time step constraints

- **High**

- time & space accurate
- very challenging in every respect!



Coupled Solution

$$\underline{\mathbf{K}}\underline{\mathbf{a}} = \underline{\mathbf{f}}$$

$$\underline{\mathbf{K}} = \begin{bmatrix} \underline{\mathbf{K}}_f & \underline{\mathbf{K}}_{fs} & \underline{\mathbf{K}}_{ft} \\ \underline{\mathbf{K}}_{sf} & \underline{\mathbf{K}}_s & \underline{\mathbf{K}}_{st} \\ \underline{\mathbf{K}}_{tf} & \underline{\mathbf{K}}_{ts} & \underline{\mathbf{K}}_t \end{bmatrix}$$

$$\underline{\mathbf{f}} = \begin{bmatrix} \underline{\mathbf{f}}_f \\ \underline{\mathbf{f}}_s \\ \underline{\mathbf{f}}_t \end{bmatrix} \qquad \underline{\mathbf{a}} = \begin{bmatrix} \underline{\mathbf{a}}_f \\ \underline{\mathbf{a}}_s \\ \underline{\mathbf{a}}_t \end{bmatrix}$$

Multi-physics solver approach

Staggered Solution

$$\underline{K}_f^n \underline{a}_f^n = \underline{f}_f^n - \underline{g}_1(\underline{a}_s^{n-1}, \underline{a}_t^{n-1})$$

$$\underline{K}_s^n \underline{a}_s^n = \underline{f}_s^n - \underline{g}_2(\underline{a}_f^n, \underline{a}_t^{n-1})$$

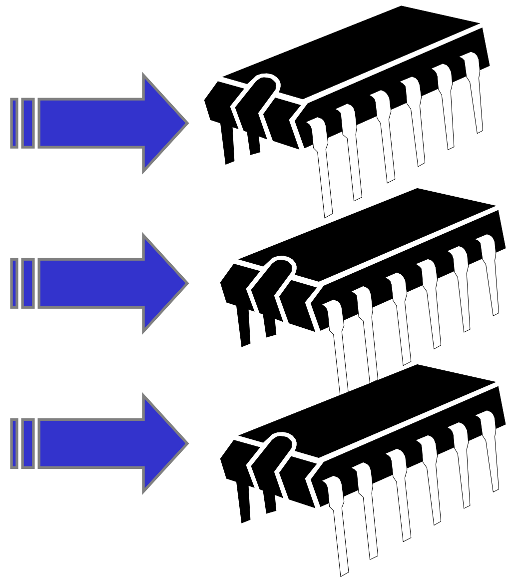
$$\underline{K}_t^n \underline{a}_t^n = \underline{f}_t^n - \underline{g}_3(\underline{a}_s^n, \underline{a}_t^n)$$

Parallel multi-physics solver strategy

$$\underline{\mathbf{K}}_f^n \underline{\mathbf{a}}_f^n = \underline{\mathbf{f}}_f^n - \underline{\mathbf{g}}(\underline{\mathbf{a}}_s^n, \underline{\mathbf{a}}_t^n)$$

$$\underline{\mathbf{K}}_s^n \underline{\mathbf{a}}_s^n = \underline{\mathbf{f}}_s^n - \underline{\mathbf{g}}_2(\underline{\mathbf{a}}_f^n, \underline{\mathbf{a}}_t^n)$$

$$\underline{\mathbf{K}}_t^n \underline{\mathbf{a}}_t^n = \underline{\mathbf{f}}_t^n - \underline{\mathbf{g}}_3(\underline{\mathbf{a}}_s^n, \underline{\mathbf{a}}_t^n)$$

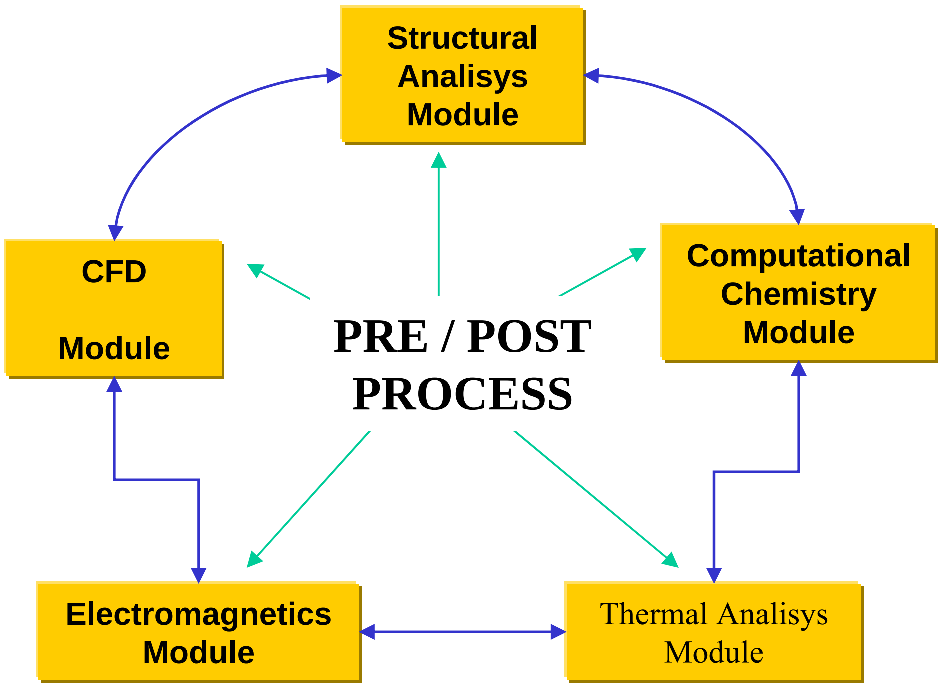


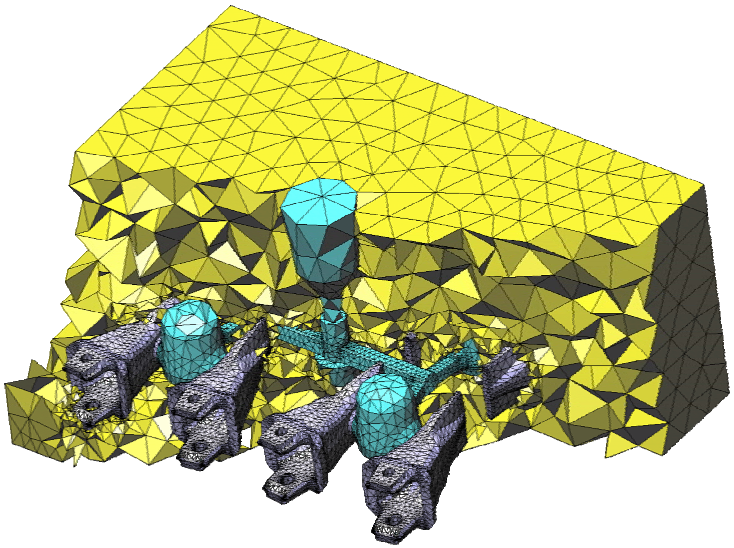
P1

P2

P3

Multi-Disciplinary Environment





Need for read and write data in different formats.

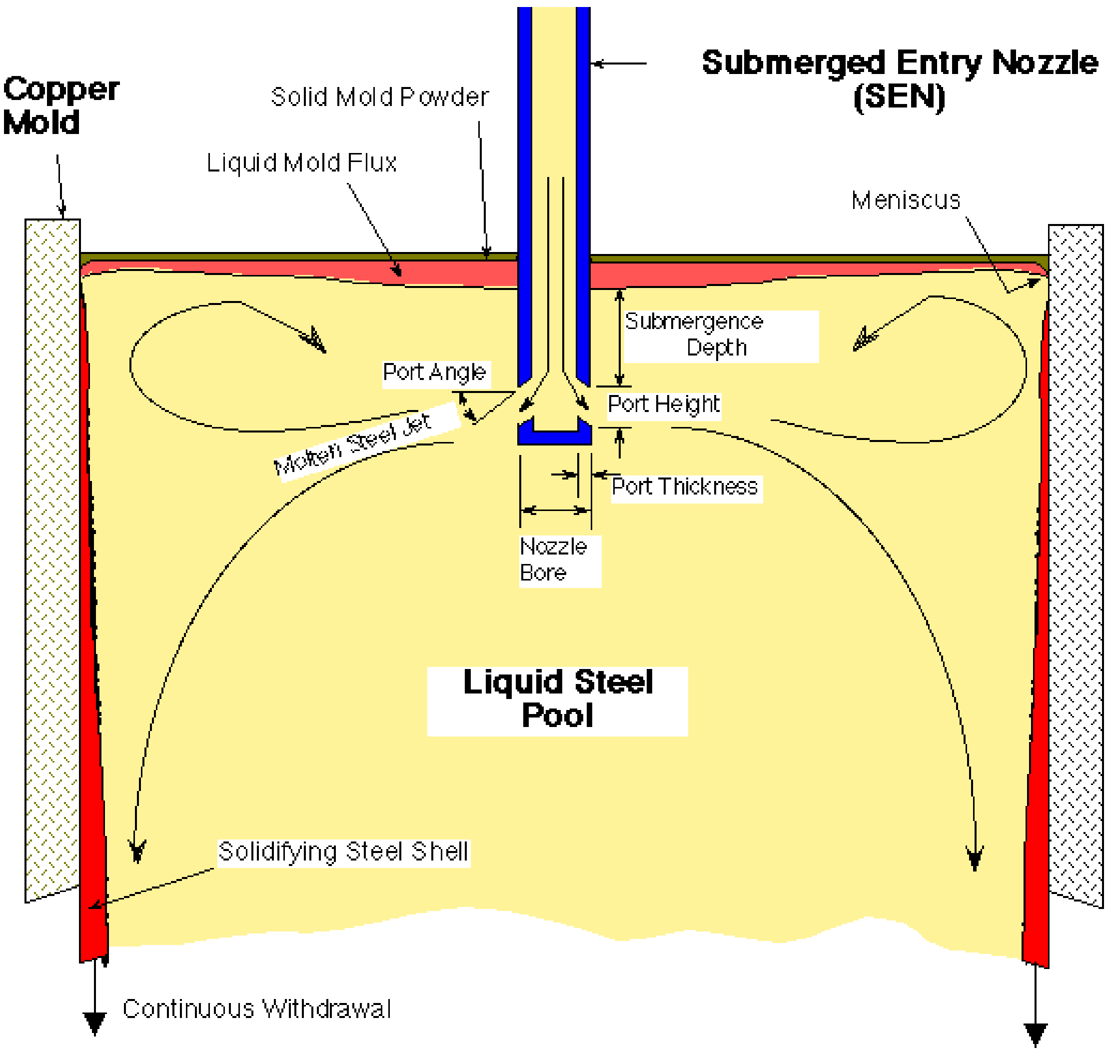
Multi-user environment for the development and application of different numerical simulation programs.

Classifying Multi-physics

- One way coupling – information only goes one way – loosely coupled
- Two way coupled – some problems can be addressed by exchanging data between codes if mesh is similar and mpCCI like tools can be used
- Else – closely coupled and problematic with phenomena specific codes
- ***Fluid-structure interaction (FSI) is always the key challenge in CC-multi-physics simulation***
- ***CFD capability is another key issue in FSI problems***

CFD in action:- Argon injection in continuous casting

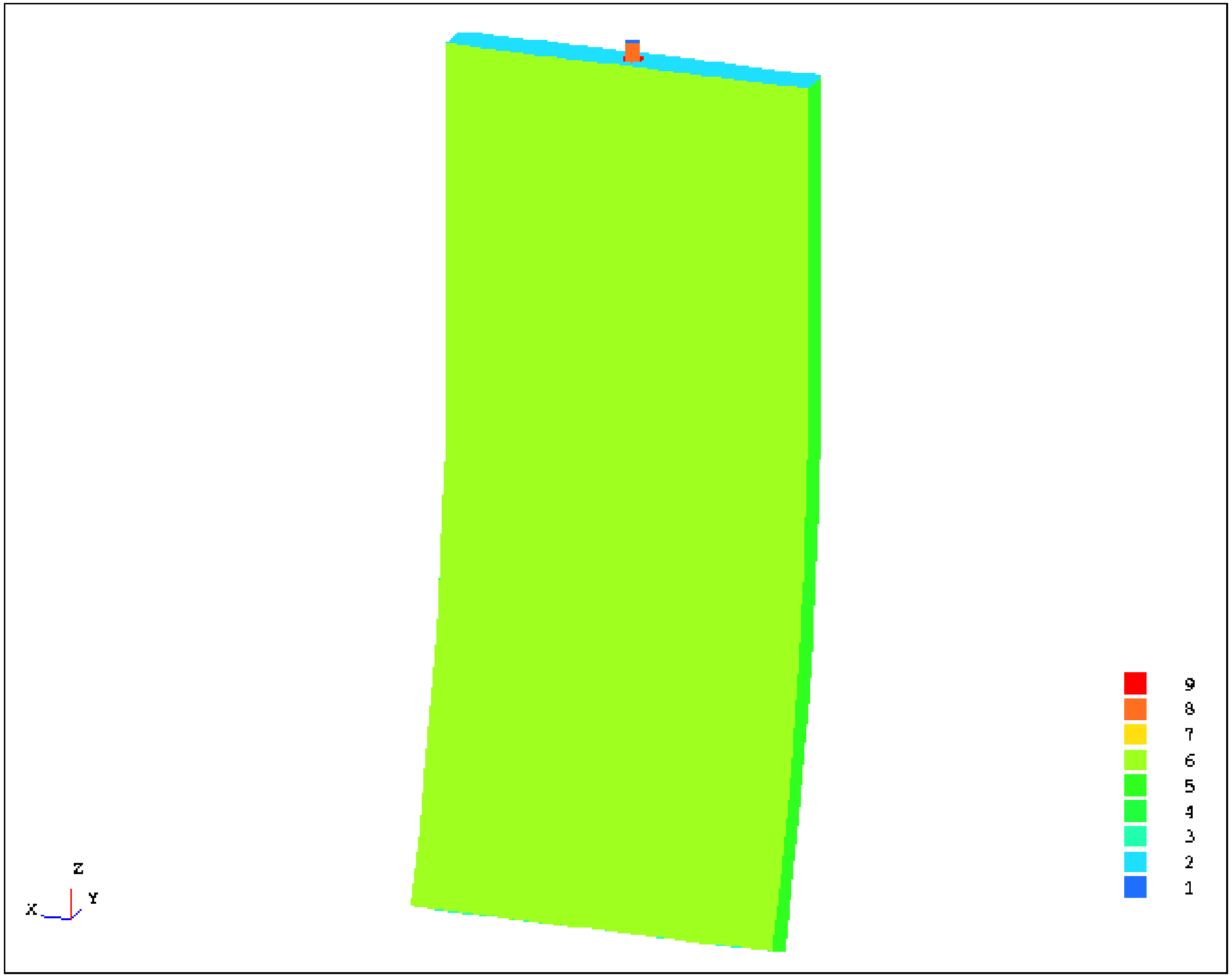
- Mould region of concast machine
- Main physical phenomena
- Complex multi-phase flow dynamics
- Role of argon injection in the process



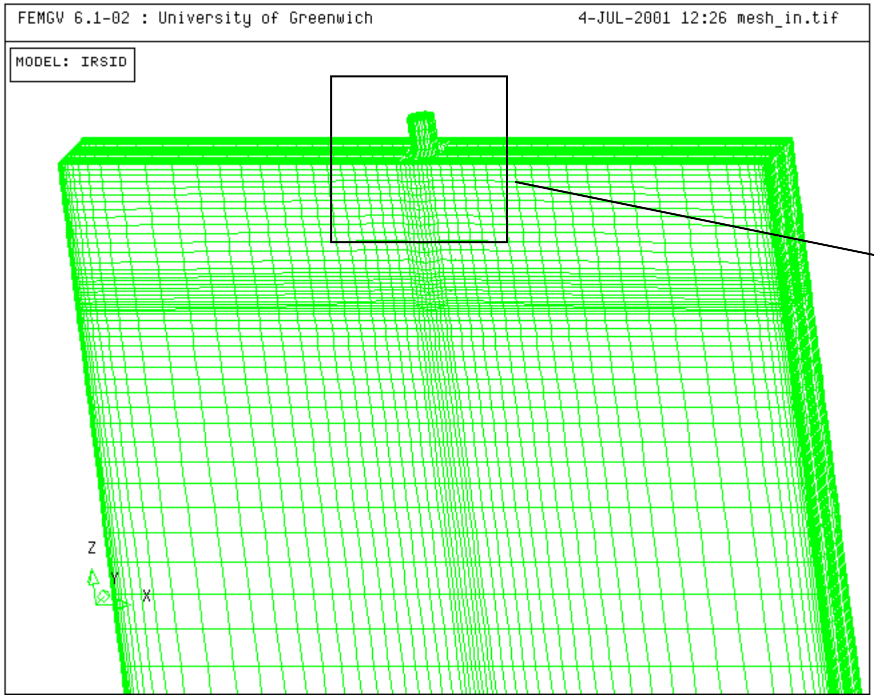
Computational model

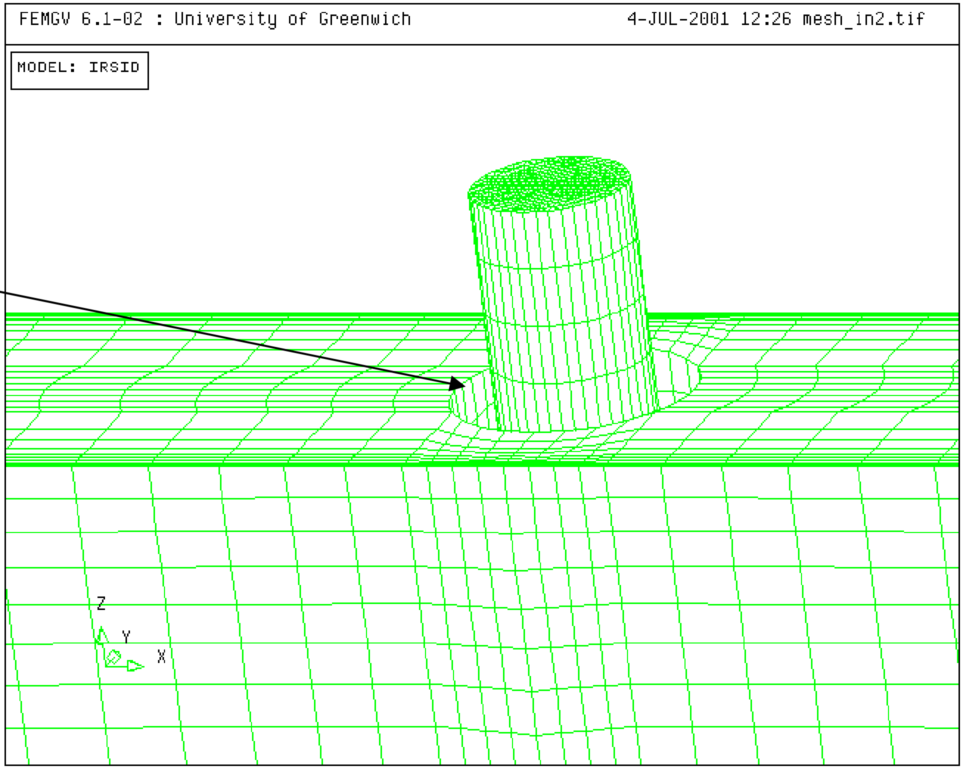
1. Time dependent, **turbulent free surface fluid flow and heat transfer** in the molten steel and flux regions
2. **Solidification** of the skin layer, under prescribed heat loss boundary conditions
3. Particle tracking **simulation of Argon bubbles** injected with the metal into the mould (many '000's of tracks used)
   - **Full coupling** between bubbles and liquid through buoyancy and interfacial forces
4. Full transient **simulation of flux-metal interface** behaviour under the influence of buoyancy and fluid inertial forces

Comp model: solution domain

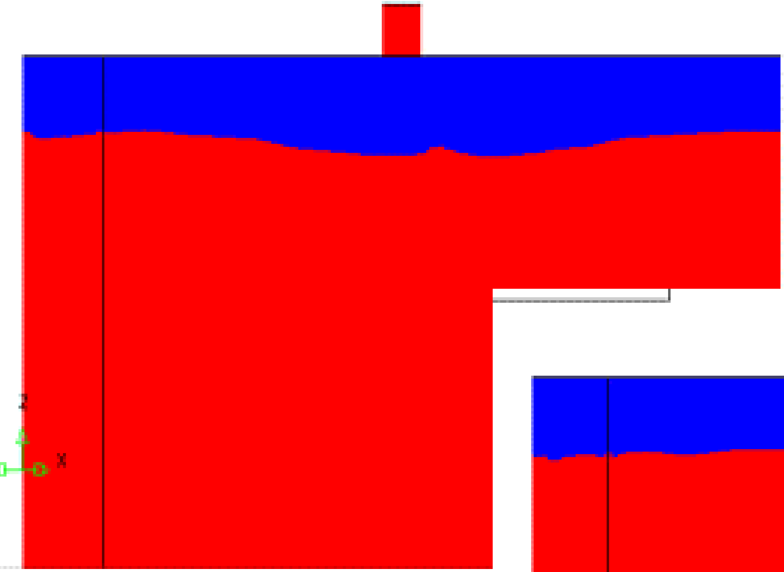


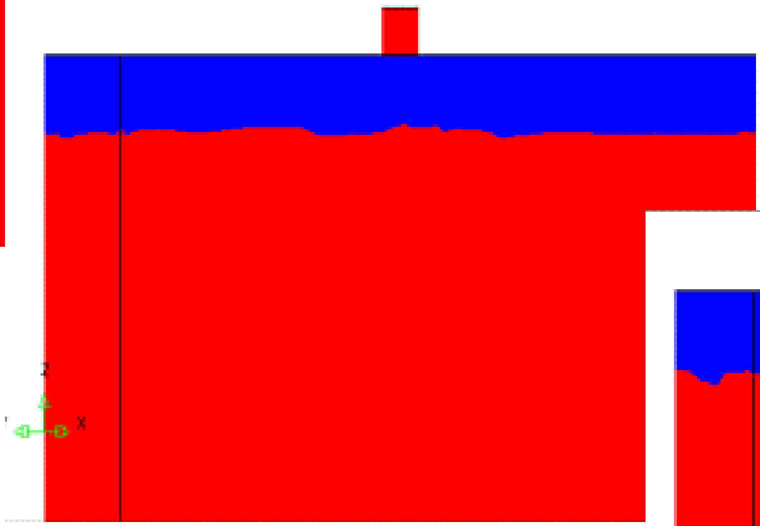
Mesh details

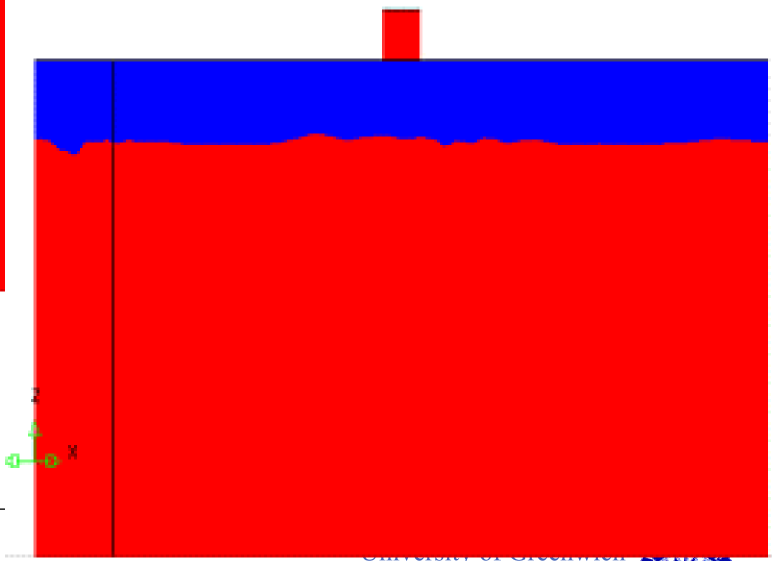




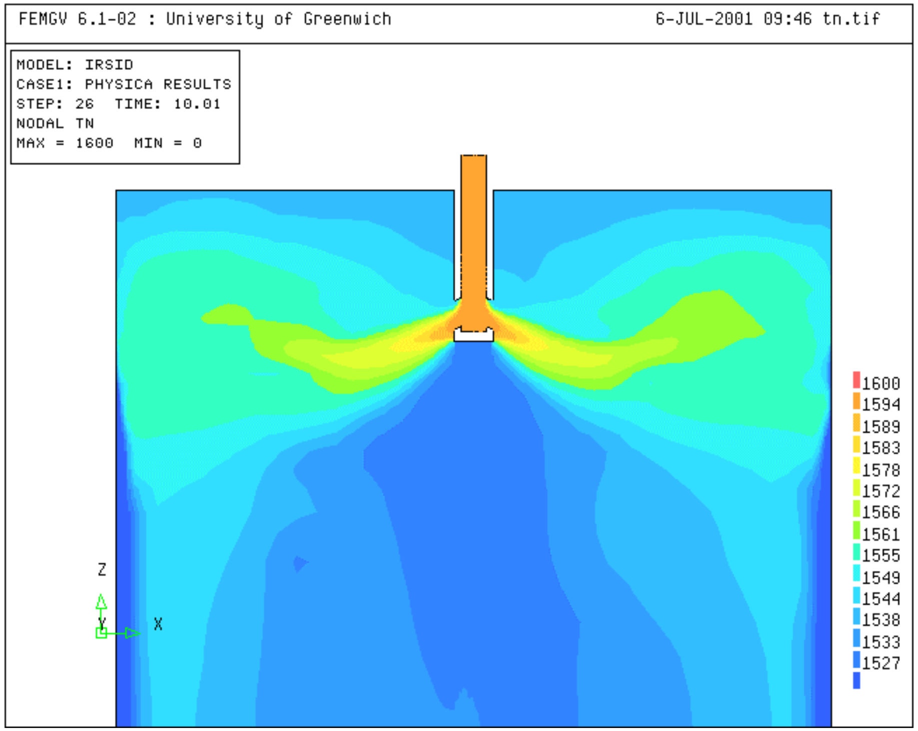
Frames from a free surface animation show evidence of various wavelengths

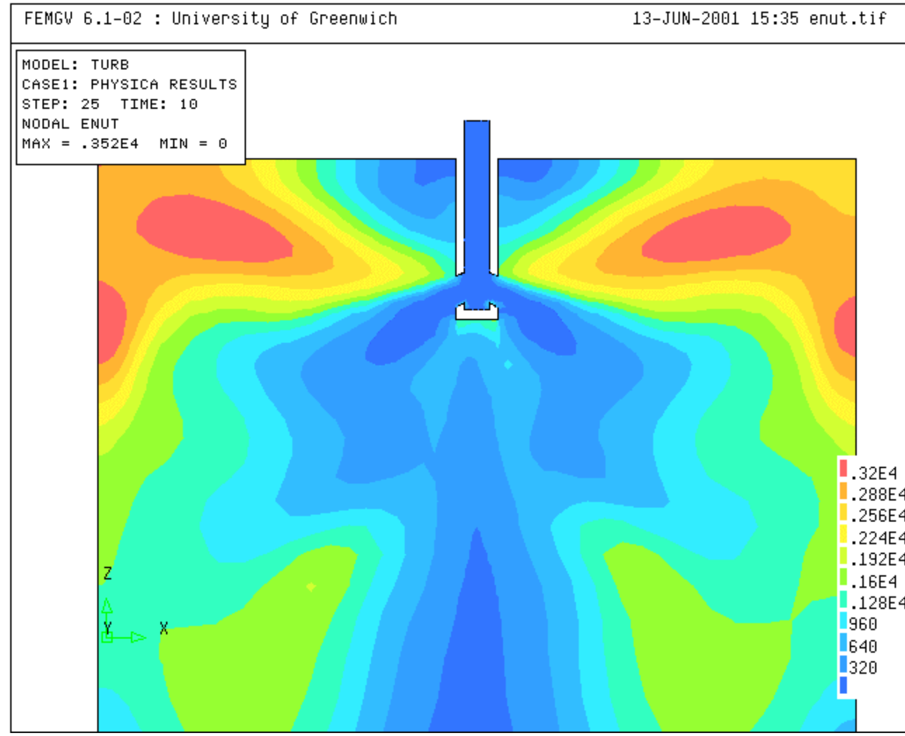






Simulation results

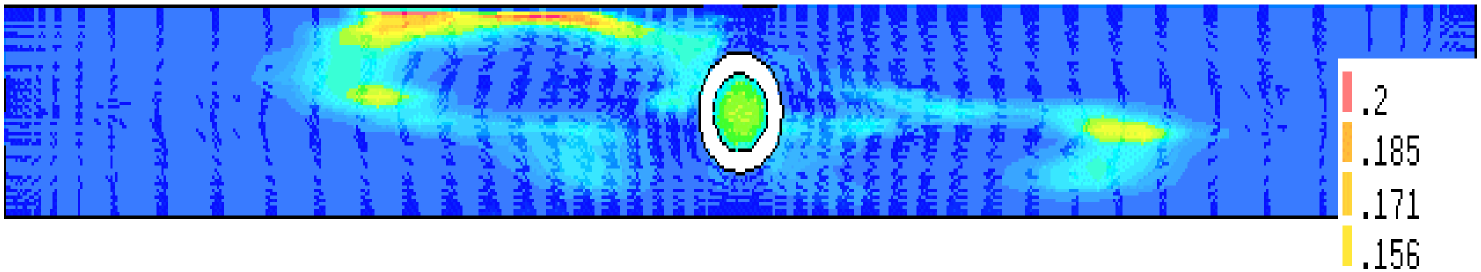


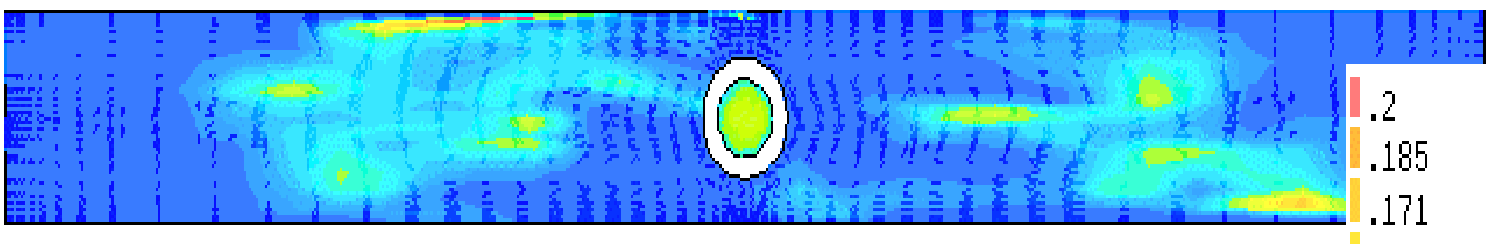


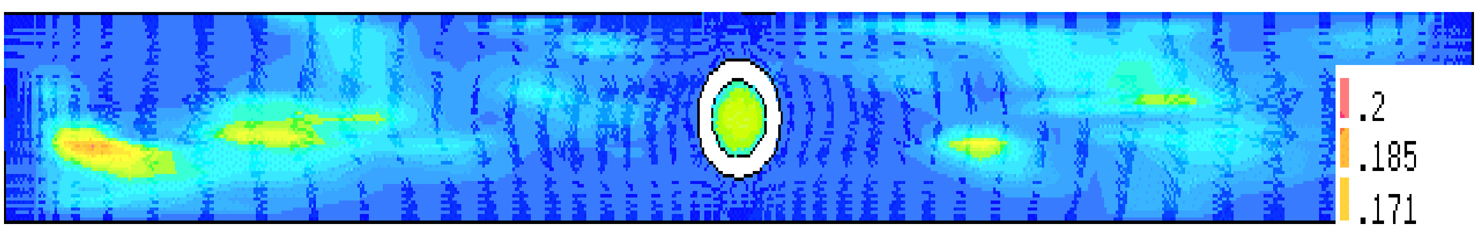
Thermal and solidification flow fields

Turbulence level (effective viscosity) distribution

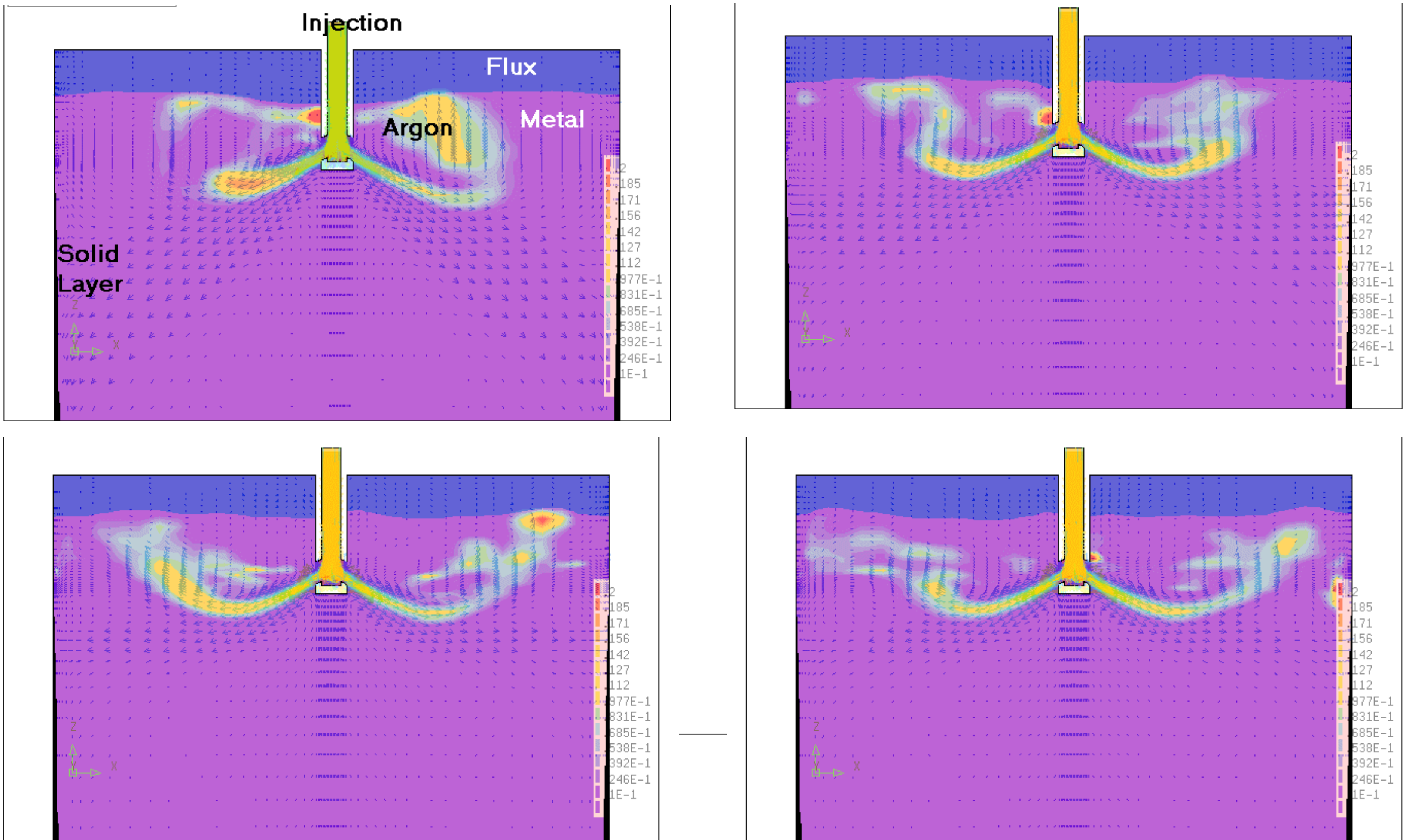
‘Bubble clusters’ arriving at mould surface







Bubble clusters



Existing CAE analysis technologies

- Carried out a web based **survey** of all the major and emerging suppliers of CAE analysis technology to identify capability in

  - multi-disciplinary (MDA)

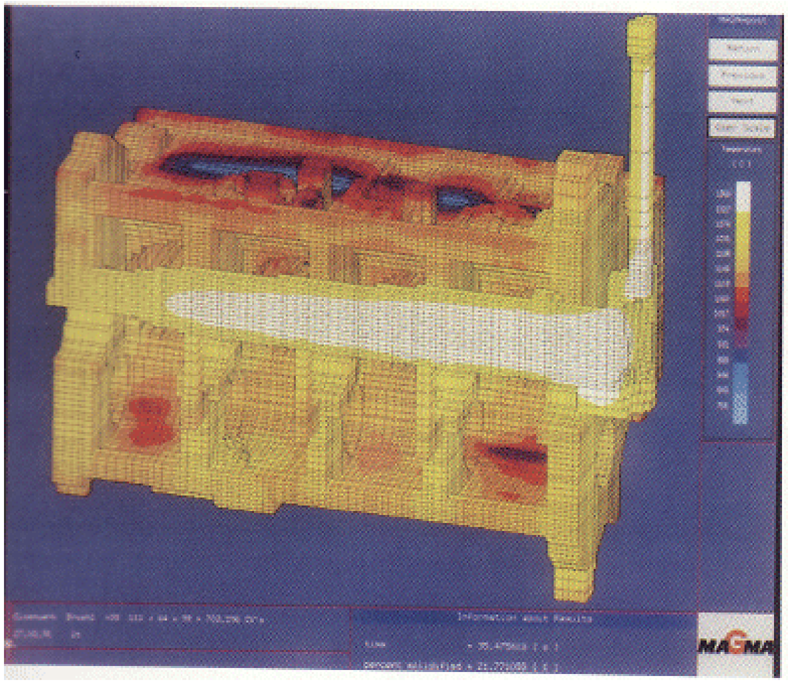
  - multi-physics (MPA)

  simulation analysis

- Key feature was flow AND structural capability and degree of coupling

Sector Specific 'multi-physics' Software

- Castings
  - **PROCAST**
  - **http://www.ues-software.com**
  - **MAGMASOFT**
  - **http://www.magmasoft.com**
- Forgings
  - **DEFORM**
  - **http://www.deform.com**
  - **SUPERFORGE**
  - **http://www.mscsoftware.com**
  - **FORGE3**
  - **http://www.transvalor.com**



Temperature Profiles – MAGMASoft: Hansen et-al Numerical Simulation of Casting Solidification in Automotive Applications, Pub TMS

Sector Specific 'multi-physics' Software

- Polymers

  C-Mold

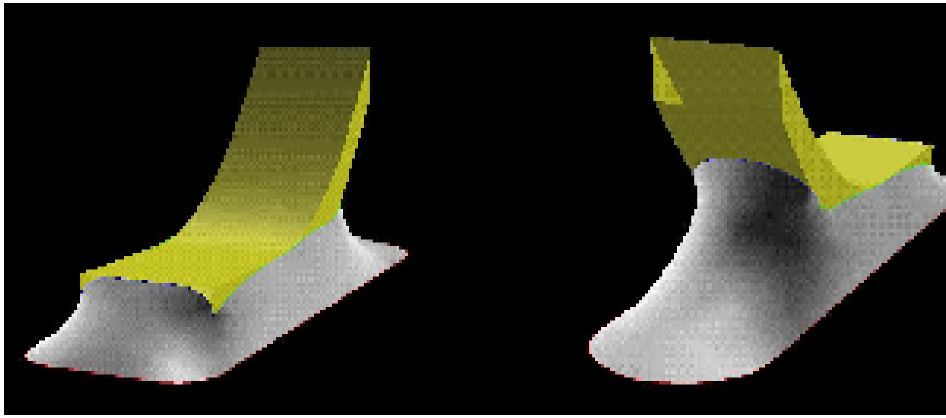
  http://www.moldflow.com
- Joining Processes

  SYSWELD (Welding software)

  http://www.esi-group.com
- Electronic cooling

  Flotherm

  http://www.flomerics.com



Tools claiming multi-physics capabilities:

- **ANSYS/Multi-physics** - http://www.ansys.com/
- **ADINA** - http://www.adina.com
- **PHYSICA+** - http://www.multi-physics.com
- **COMET** - http://www.iccm.de
- **FEMLAB** - http://www.femlab.com/
- **ALGOR** - http://www.algor.com

COMET

- FV approach - 3D
- ICCM, out of TU Hamburg, Germany
- Claims flow, heat transfer and solid mechanics including fluid-structure interaction
- Good flow and heat transfer web examples
- No web examples of solid mechanics or FSI
- Is it actually MDA or MP?
- BOUGHT OUT BY STAR-CD COMPANY & WITHDRAWN FROM MARKET

FEMLAB

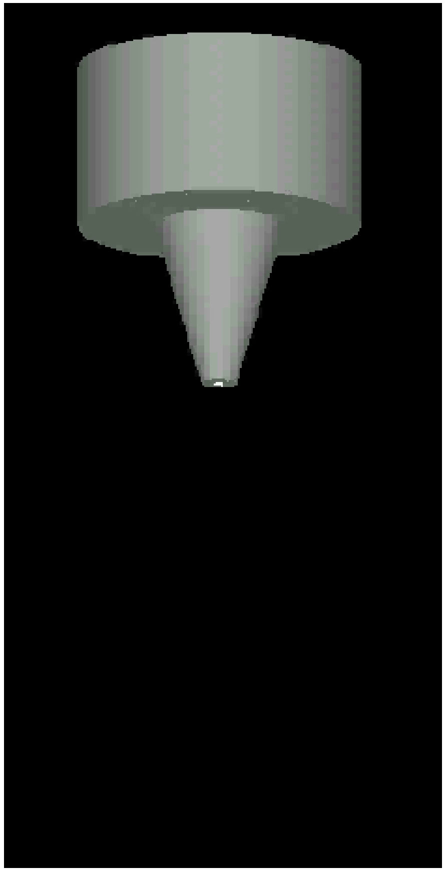
- Built upon MATLAB
- Uses FE methods
- Heat transfer
- Solid mechanics
- Electro-magnetics
- Flow (Potential only? Not competitive with commercial CFD codes)
- Some coupling claimed - no examples on web
- Definitely multi-disciplinary but not CC-MP?

ALGOR

- FE approach 3D
- Claims:
  - CFD
  - Heat transfer
  - Solid mechanics
- Examples of simple multi-physics on web but cannot be easily viewed!
- One way coupling from flow/heat transfer to solid mechanics - loosely coupled in reality

ANSYS - FLOTRAN

- Inkjet printer nozzle
- FE, well established toolkit
- Good on solid mechanics, heat transfer and electro-magnetics
- Examples of coupled electric-thermal-structural field calcs, but not on the web!
- **FLOTRAN is CFD tool**
- Limited capability - eg free surface is 2D/ axisymmetric
- **Definitely MDA, but MP limited ?**

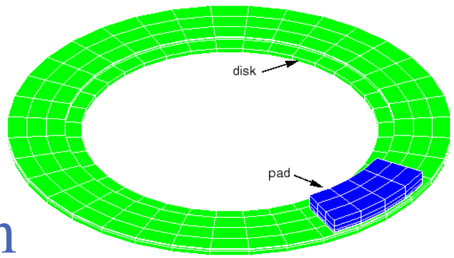


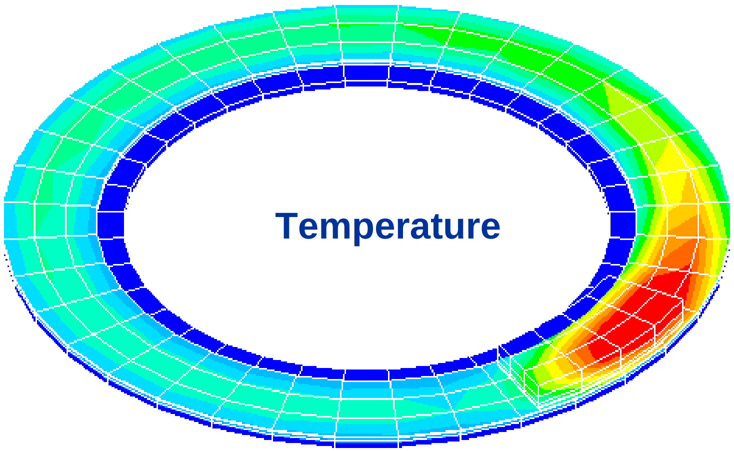
MSC- NASTRAN et al

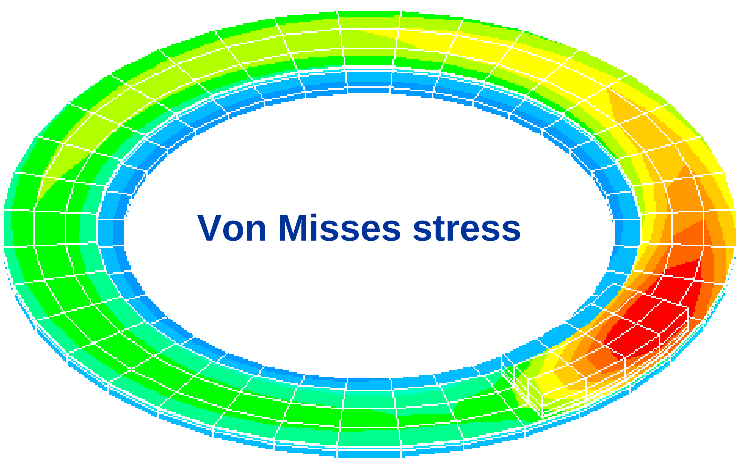
- Air Launched Cruise Missile showcase MP example!
  - Subject to engulfing fuel fire (temp 1273 K)
  - Finite element model ~ MSC Patran
  - Radiantly heated -MSC Patran Thermal
- Loosely Coupled
- Interface MSC Patran EXODUS PCL
- External Sandia software
  - Coyote (Thermo-Chemical-Fire)
  - Pronto (Dynamic)
  - Jaq (Structural)
  - Toro (Electro-magnetic)
- **Definitely MDA, but MP?**

ABAQUS

- **Very strong on non-linear solid mechanics analysis**
- Coupled problems
- Thermo - mechanical
  - sequentially or fully coupled
  - Disc Brake – fully coupled
- Thermo-electrical
- Pore fluid flow-mech
- Stress - mass diffusion
  - sequentially coupled
- Piezoelectric (linear only)
- Acoustic - mechanical (linear only)
- **Some MDA, not MP!**

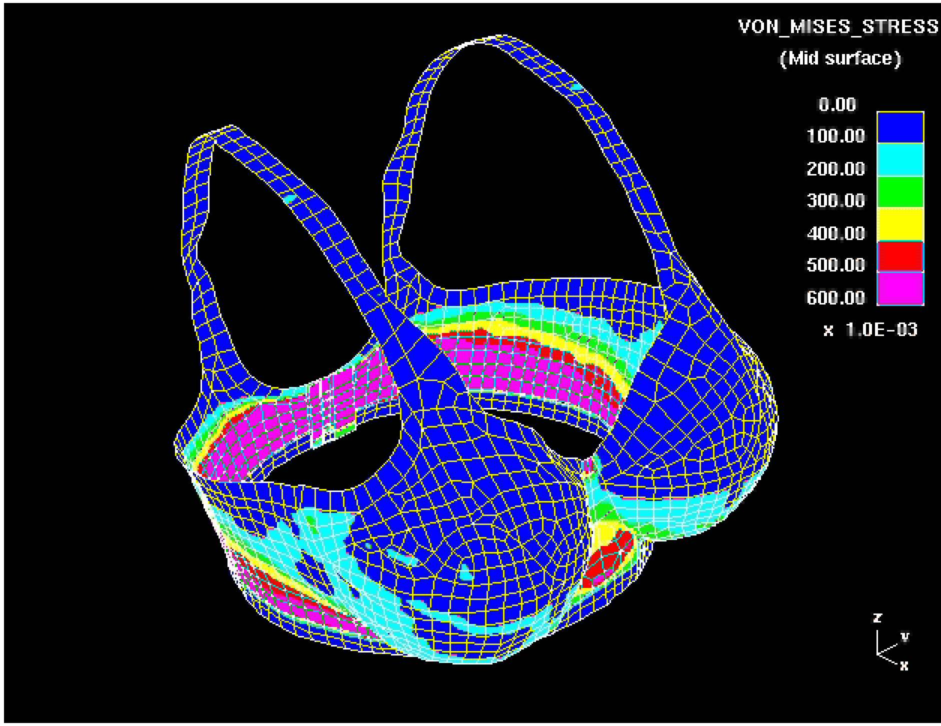






LS-DYNA

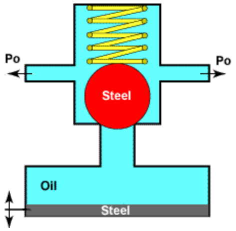
- **Human-clothing interaction**
- Dynamic non-linear FE
  - Contact interaction with the body
  - Large displacements
- Associated techniques
  - airbags and seatbelts in cars
- Stresses ~ bra cups and straps
- Jogging - Heat transfer?
- Human tissue
  - Solid mechanics or
  - Non-Newtonian fluid?
- **Dynamic, but is it MDA or MPA?**

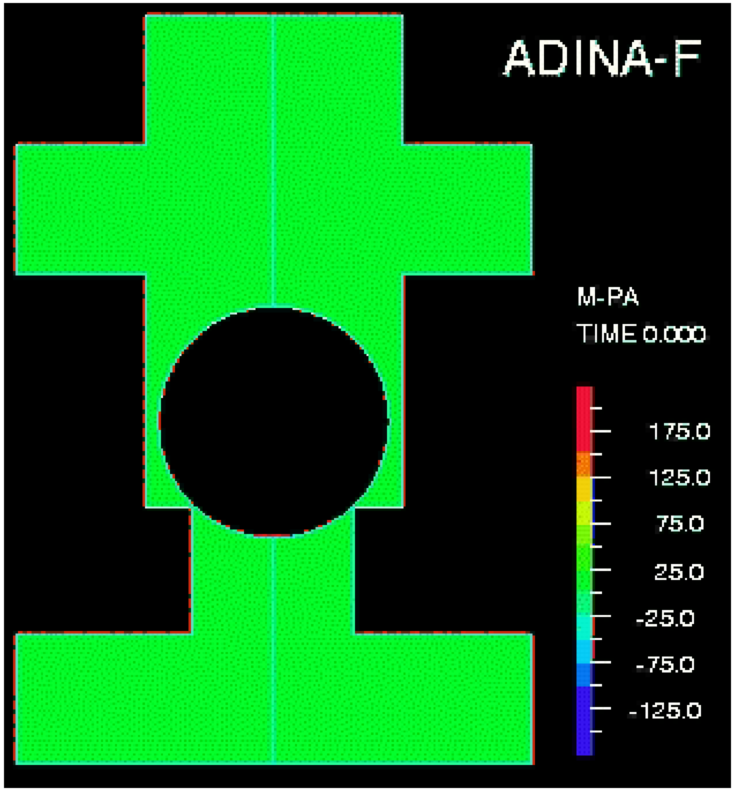


ADINA

- Anti-locking Brake System (ABS)
- Large structural motion.
- Fluid
  - Various turbulence models
  - Incompressible, slightly/fully compressible
- Different meshes for fluid & structure
- Variables of interest
  - Fluid pressure
  - Flow characteristics of brake fluid
  - Stresses in steel ball.
- Contact at the top? – Spring?
- **Claims MP,**

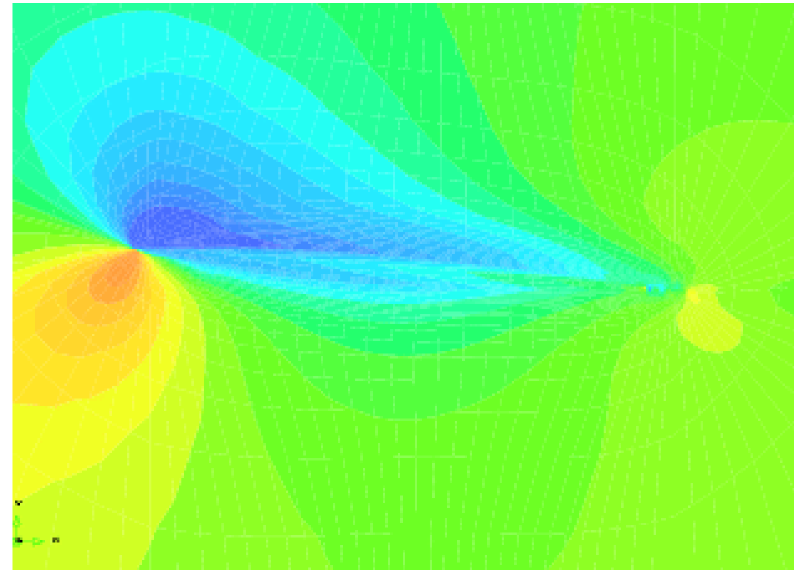
  but no real examples

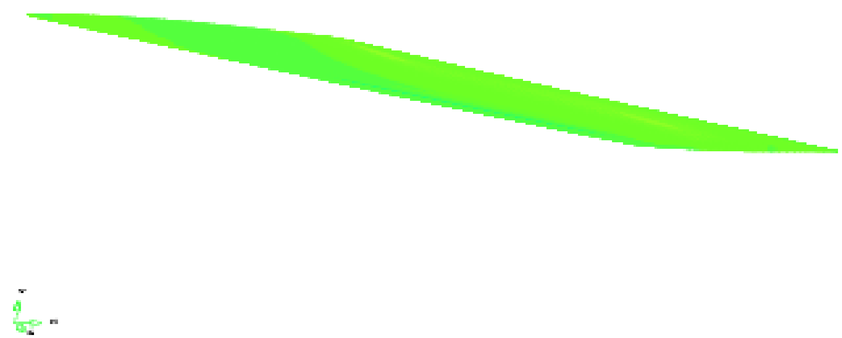




PHYSICA+

- Spin off from University of Greenwich
- Uses FV-UM methods
- Claims:
  - NS flows
  - Heat transfer
  - Solid mechanics
  - Electro-magnetics
  - All in parallel
- Website demonstrates genuine MP in parallel

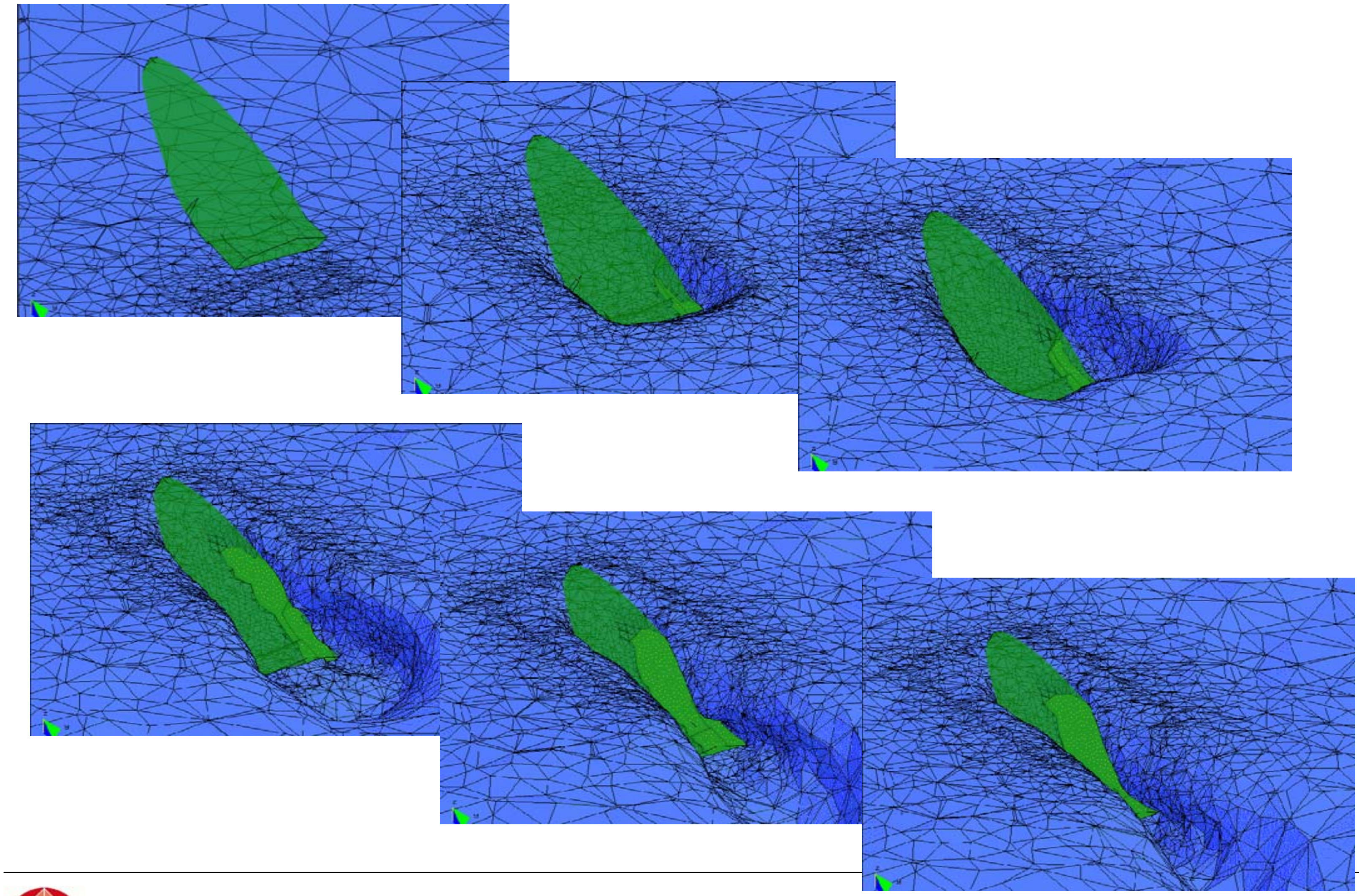




Some multi-physics apps

- Sea landing of space vehicle
- Welding
- Semi-levitation melting
- Granular flow
- Projectiles colliding into structures
- Casting/solidification processing

Sea landing of space vehicle



High quality cheats

- Fix the mesh around the vessel
- Assume the vessel is rigid
- Transform the flow equations to capture the impact of the vessel movement
- Equivalent of moving mesh effects in CFD equations
- Still need to calculate the effective movement of the vessel (subject to the load on it)
- SO NASTY PROBLEM BUT CAN BE DONE BY A CFD CODE AND SOME HELP (see CFX website for an example with a commercial code)

Welding - natural multi-physics

- Processes involve:
  - free surface flow
  - electromagnetic forces
  - heat transfer with solidification/melting
  - development of non-linear stress
- Ideal candidate for multi-physics modelling

T-Junction arc weld

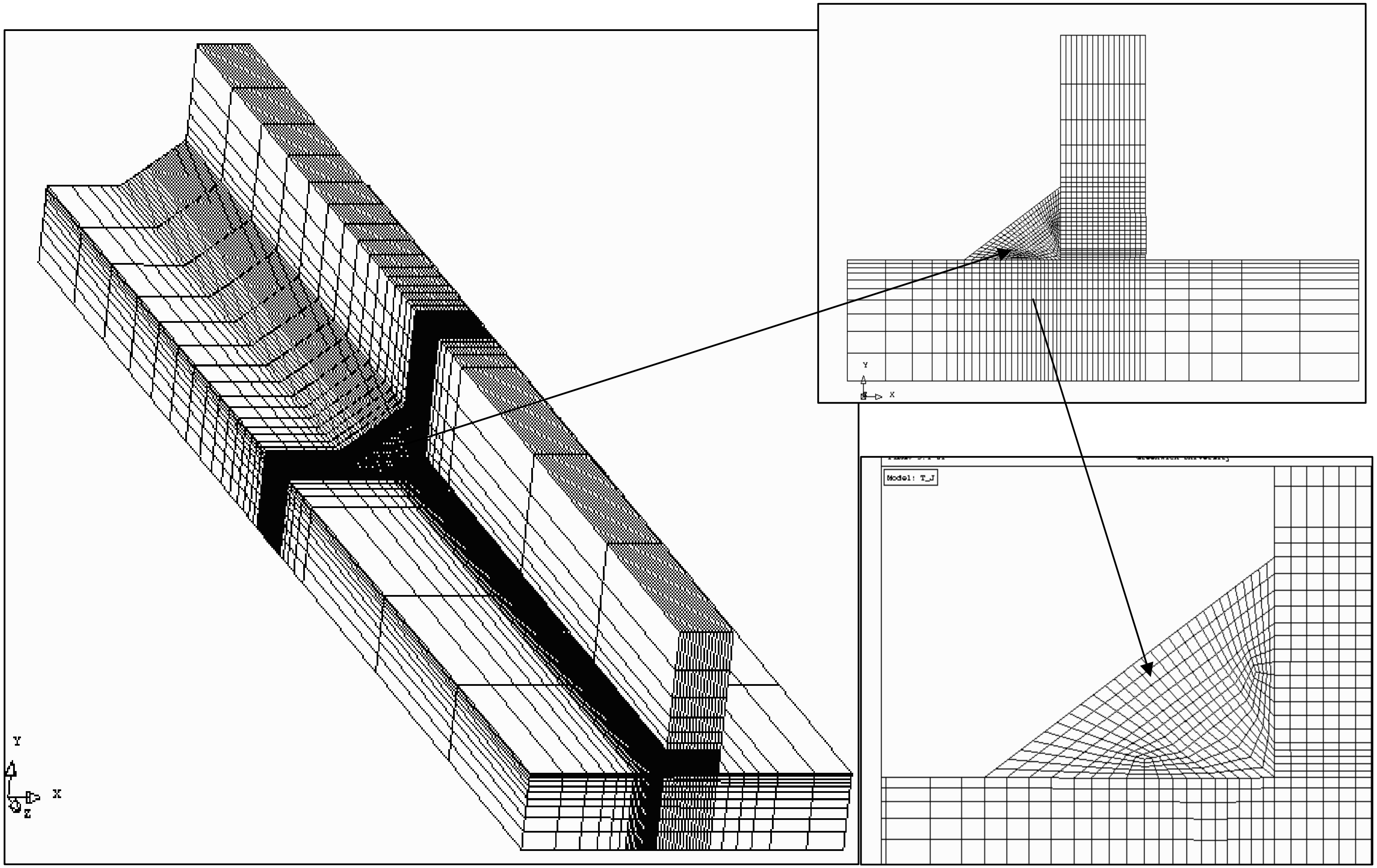
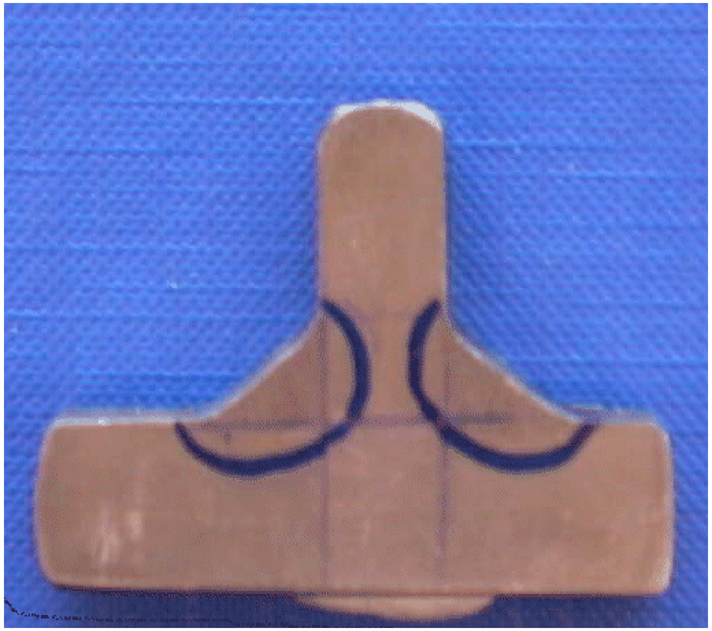


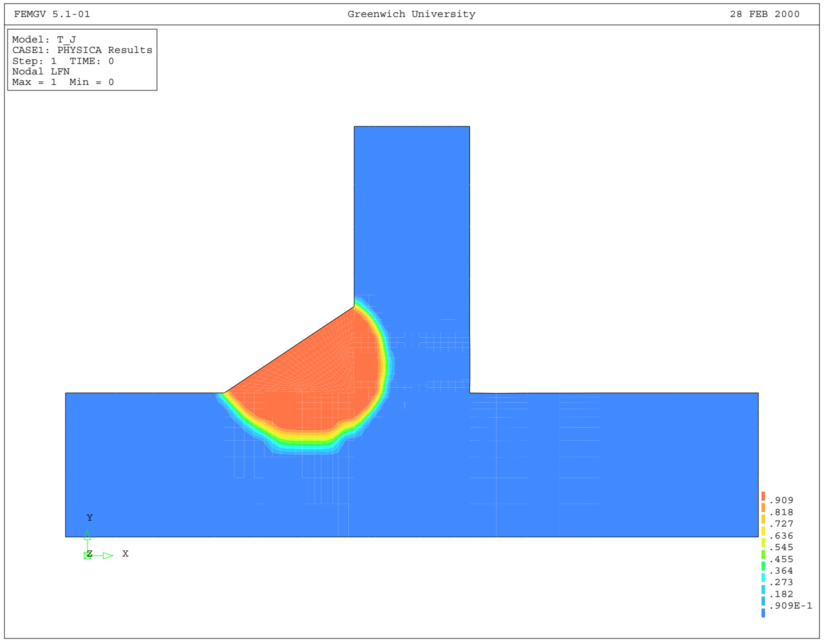
Figure 7: FV unstructured mesh used for weld-pool simulation

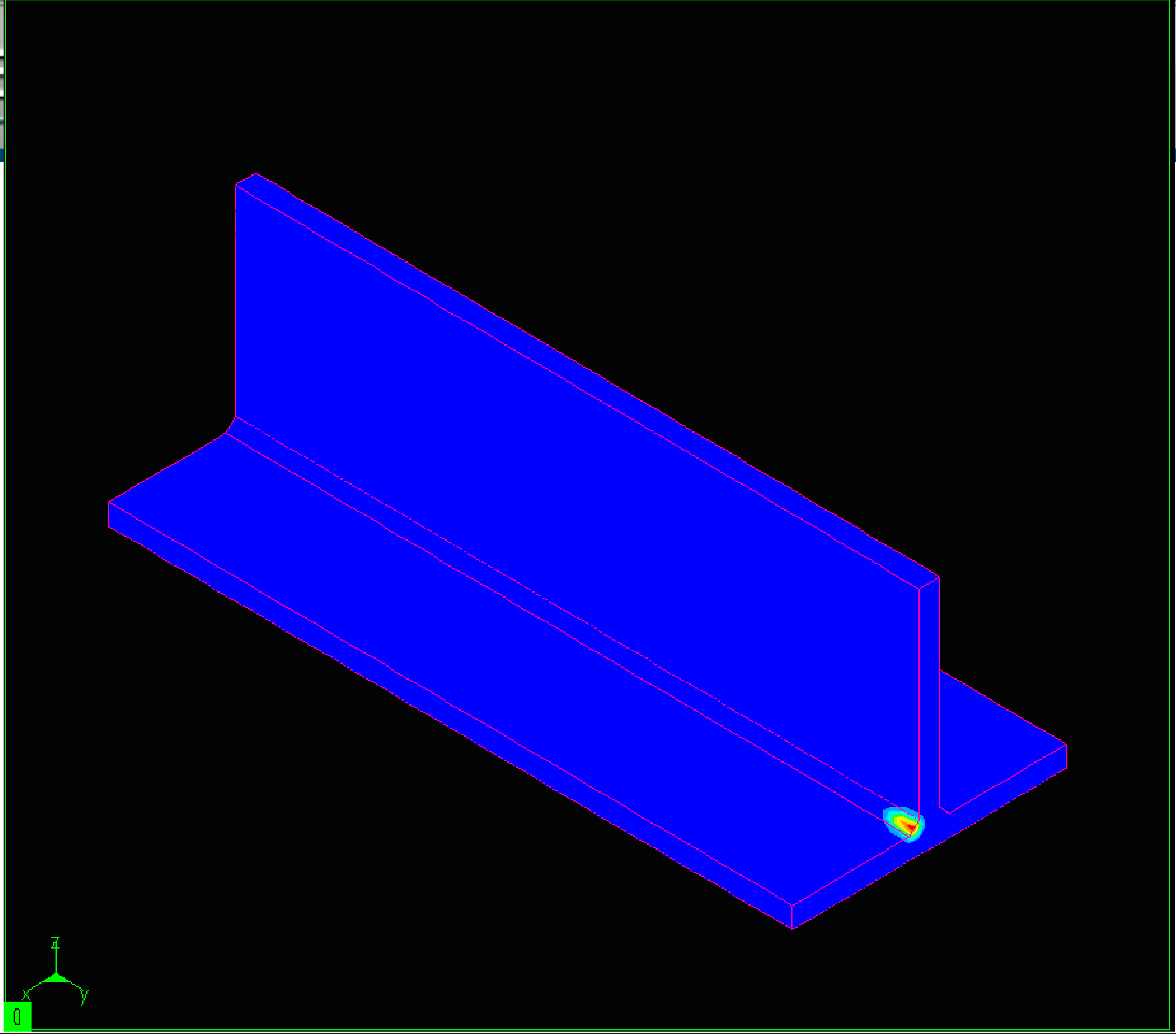
Experiment and simulation



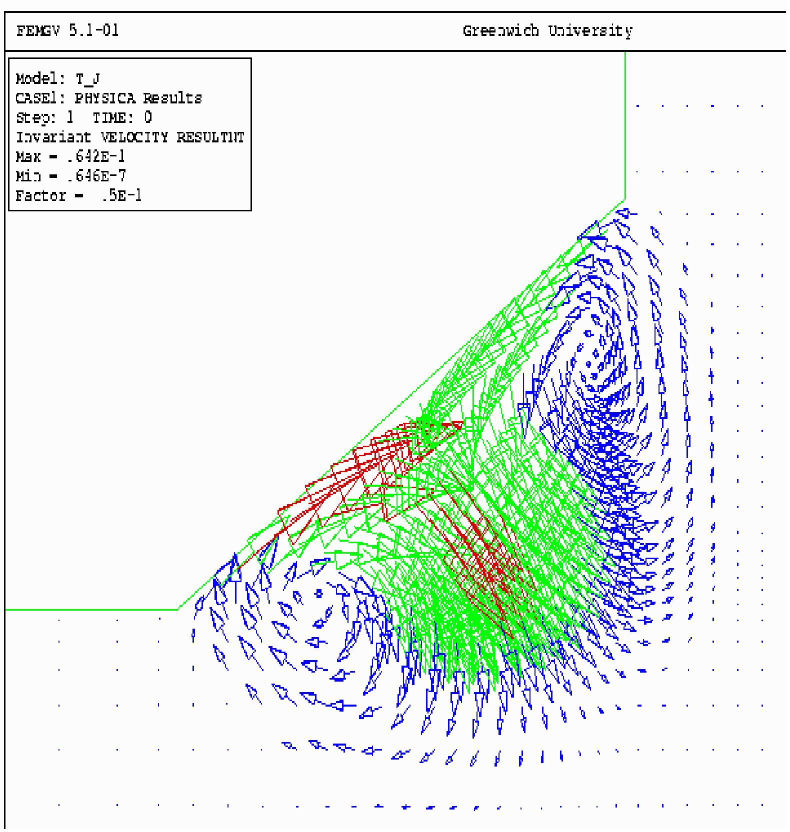
T-junction section, highlighting HAZ region

Cross-Section Liquid Fraction

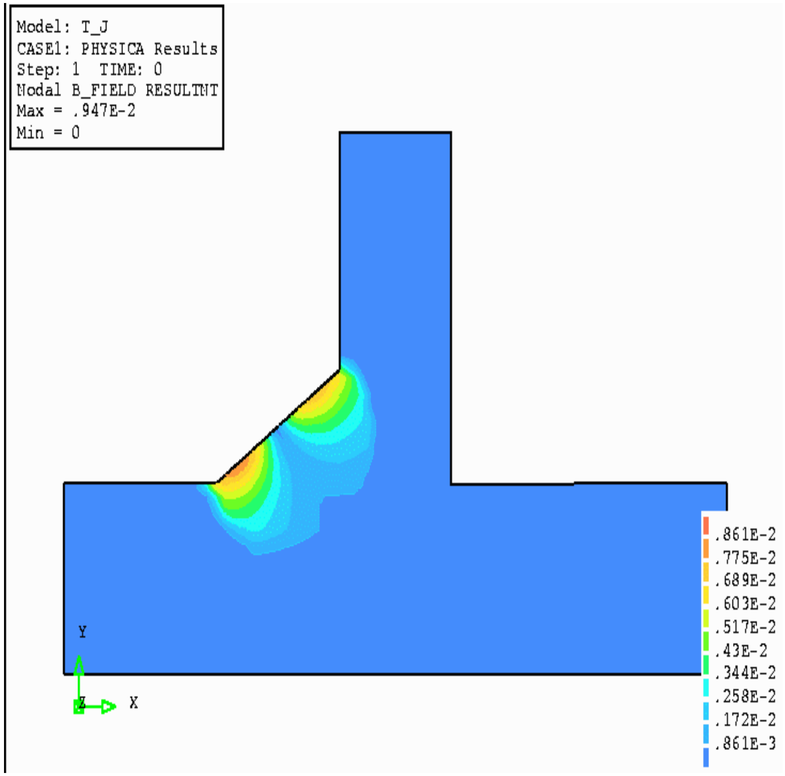



z
x
y
0

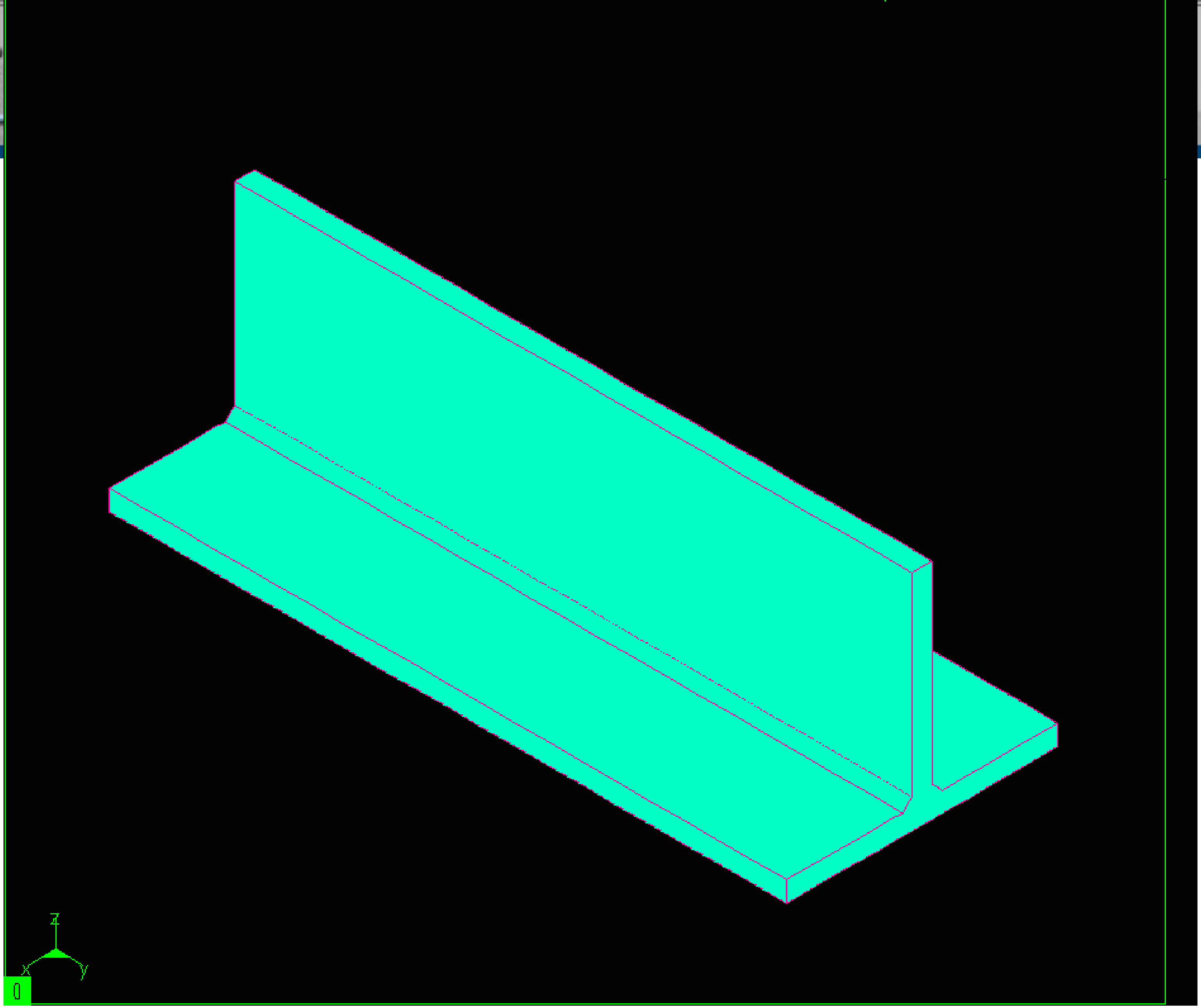
Weld pool dynamics



Velocity vectors in crossection



Lorentz force distribution in the weld-pool


Z
X
Y

Closely coupled multi-physics?

- Problem involves flow, heat transfer, phase change, em fields, and stress
- Flow, heat transfer & phase change are fully coupled – could do with a CFD code
- Em field influences the heat and flow, but . .
- Everything effects the stress, but it doesn't couple back to anything

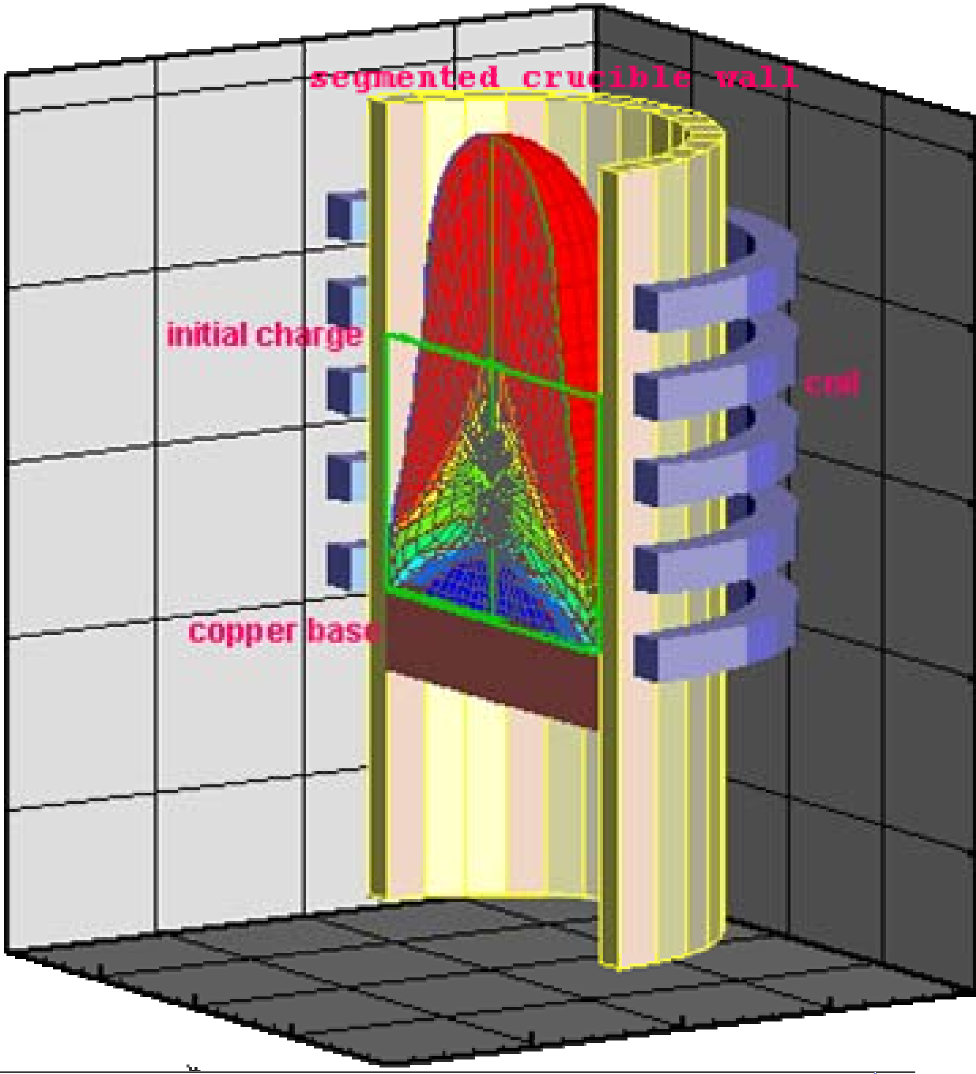
SO . . . . could use coupled CFD & CSM codes

BUT . . . . need mesh compatibility

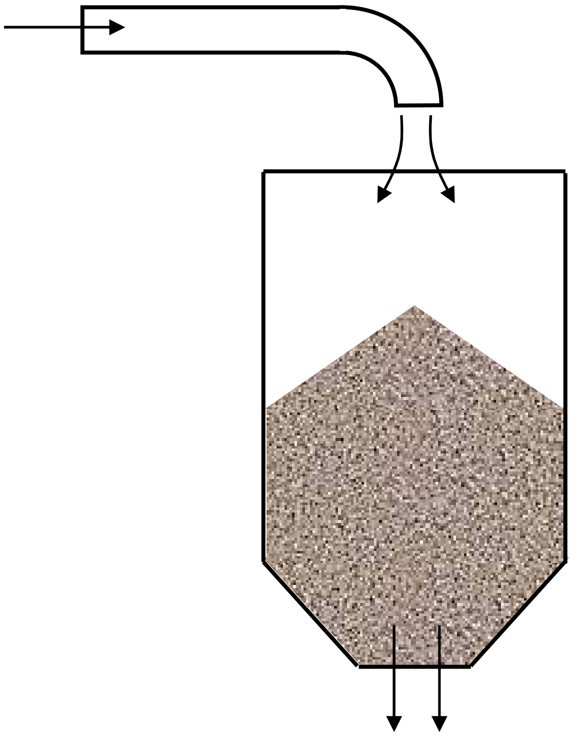
Semi-levitation melting of reactive alloys

High quality components

- Semi-levitation of titanium-aluminium alloys
- Involves
  - free surface flow
  - heat transfer
  - melting/solidification
  - electromagnetic fields
- ALL COUPLED CC-MP of the worst kind



Granular flow:- Filling / Discharge of a hopper

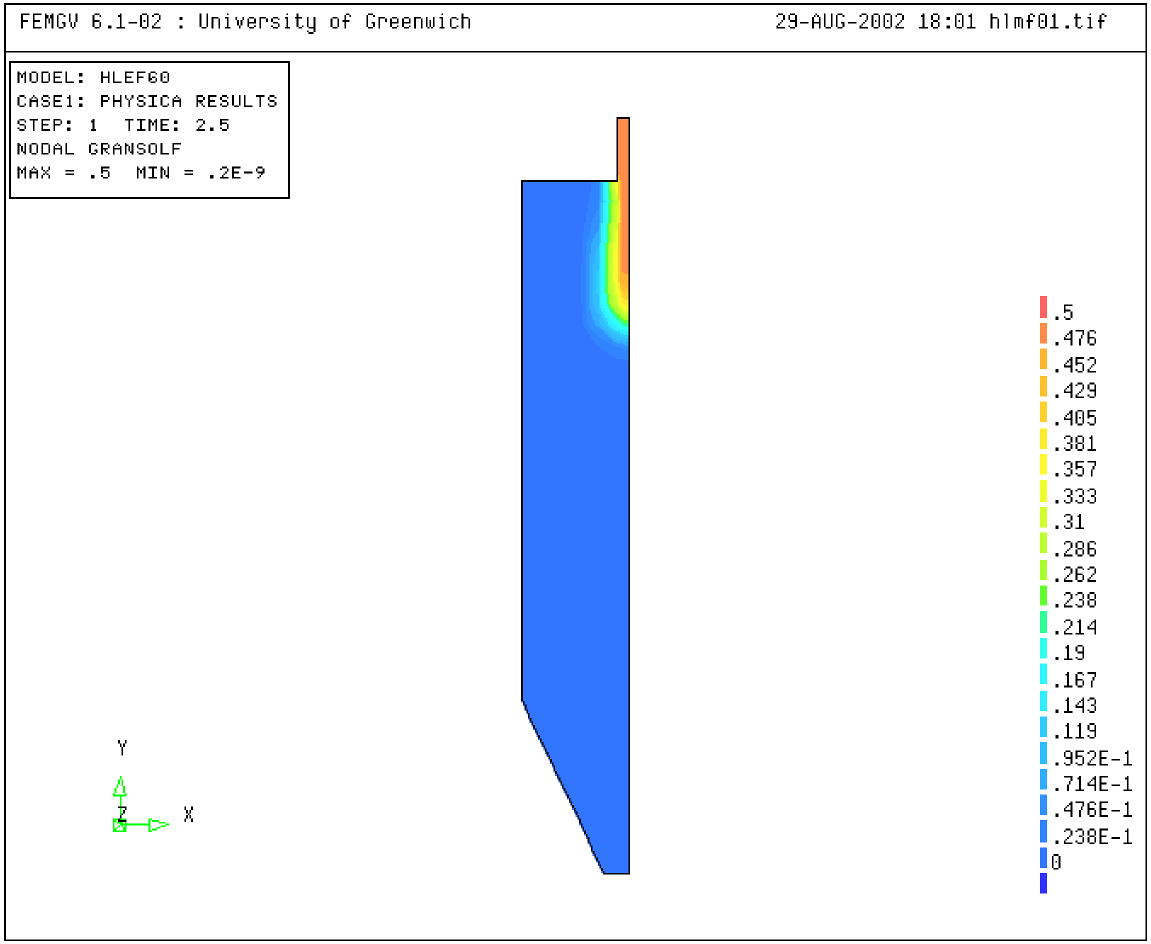


Granular material behaves
Simultaneously as a fluid and
a solid – the fluid or solid state
is a function of local conditions

Challenge to simulate granular
Flow behaviour

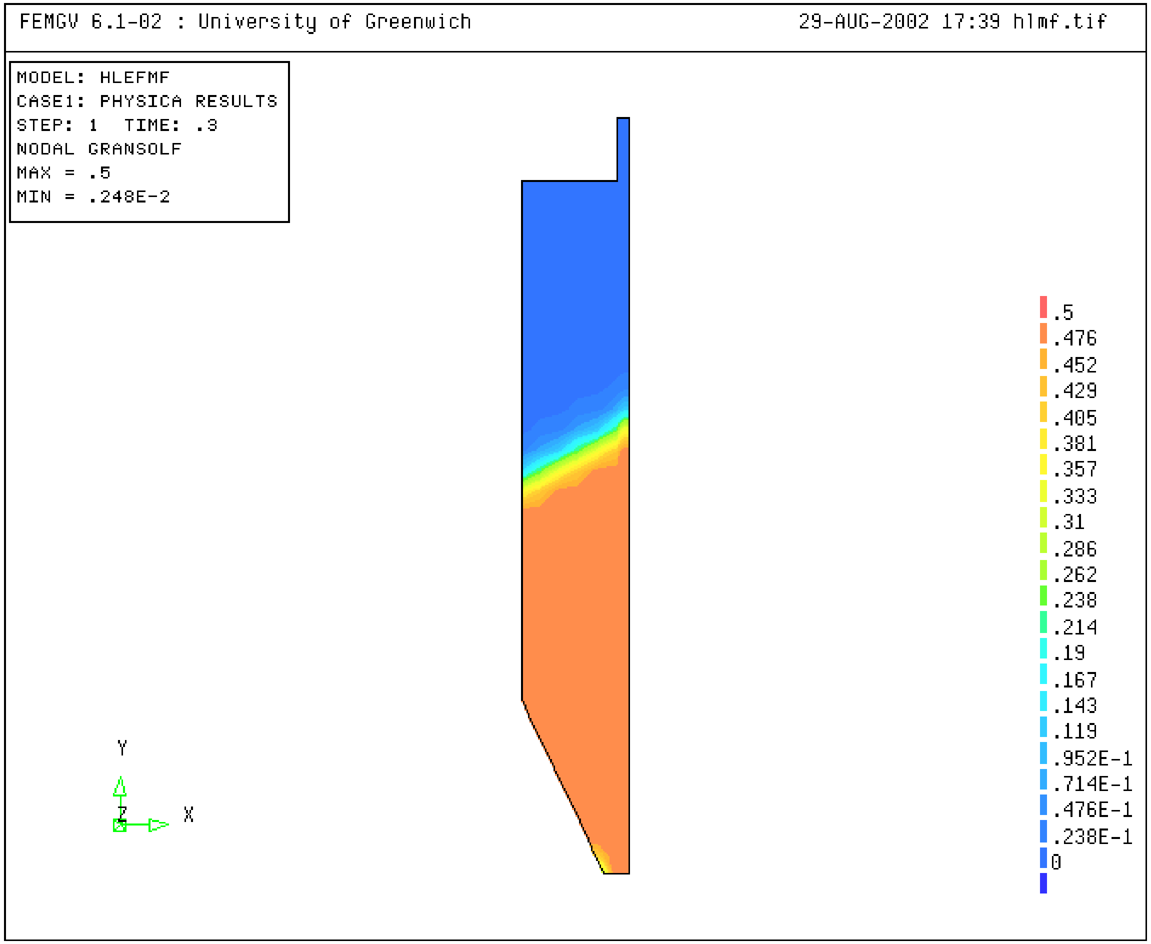
Filling of a hopper

Distribution of total solids fraction over time

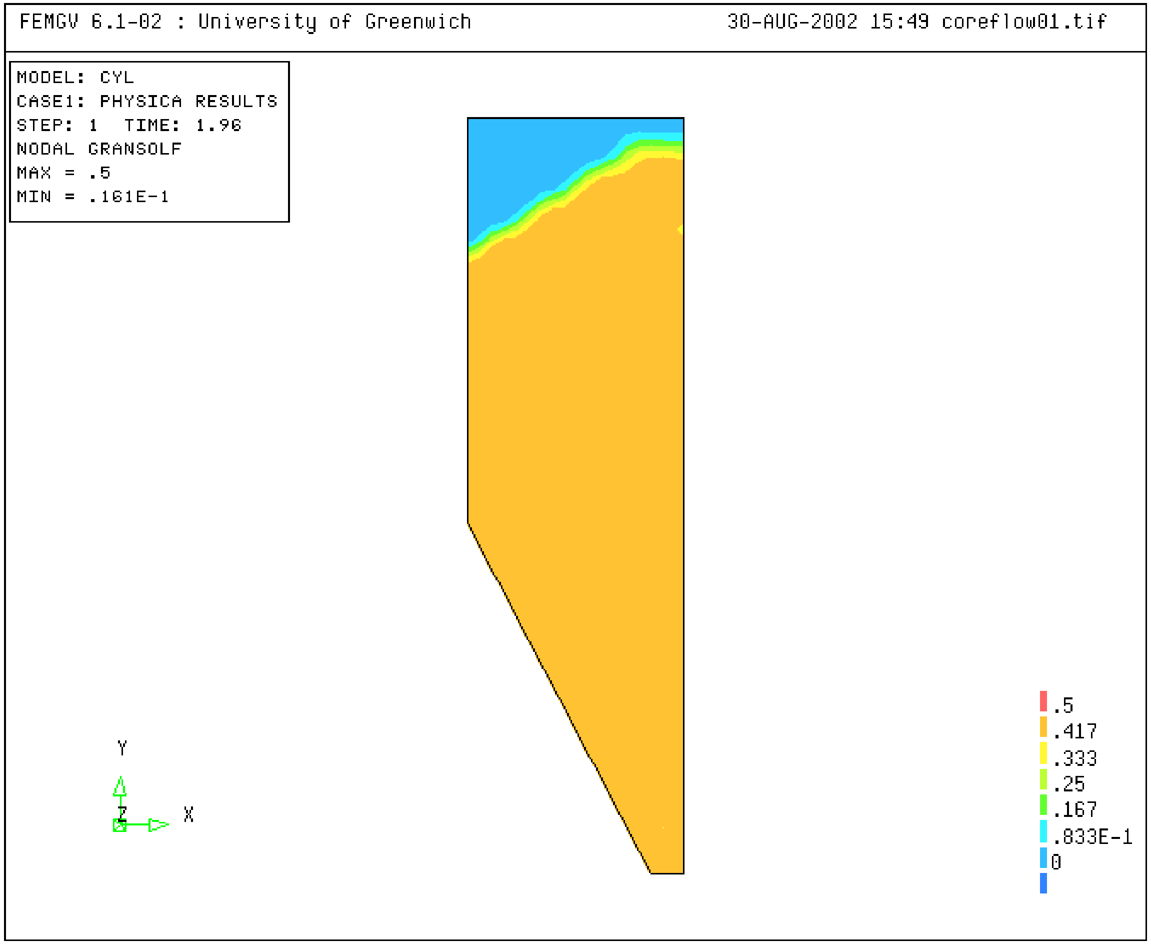


Hopper discharge in mass flow mode

Distribution of total solids fraction over time

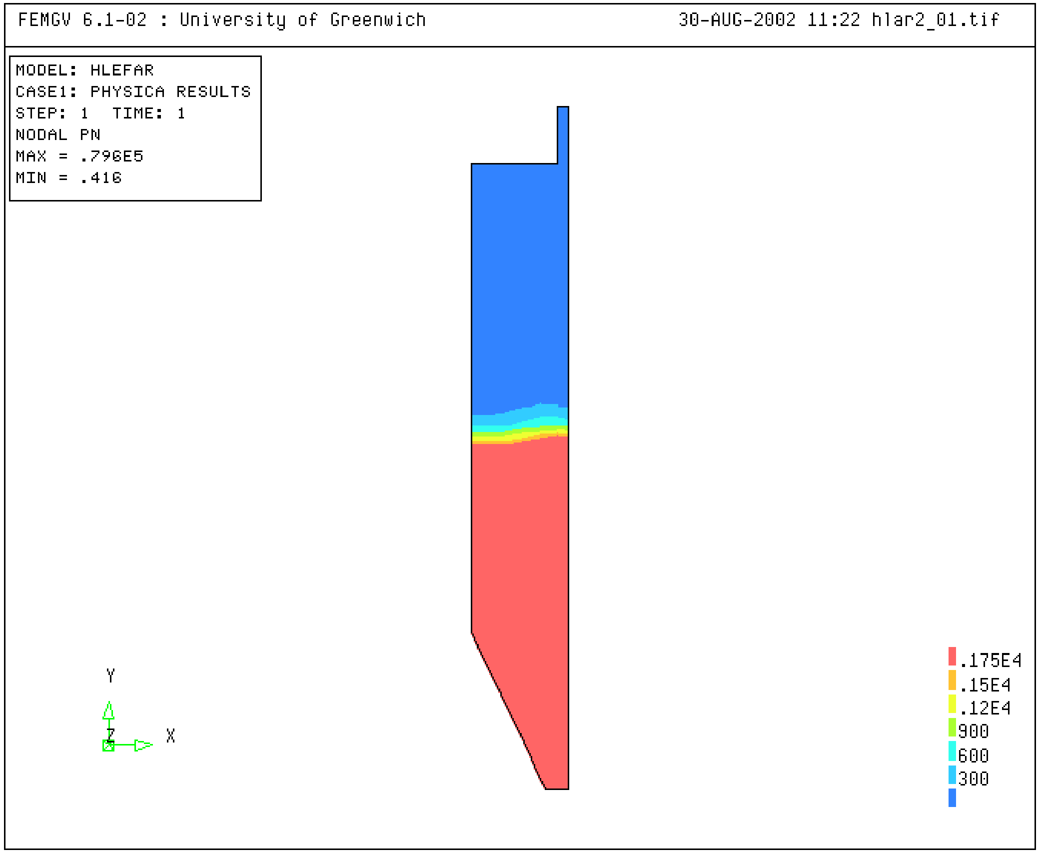


Hopper discharge in core flow mode



Hopper discharge: arching

Distribution of vertical stresses over time



→ **Arching** : the flow of bulk solid is stopped

A real cheat

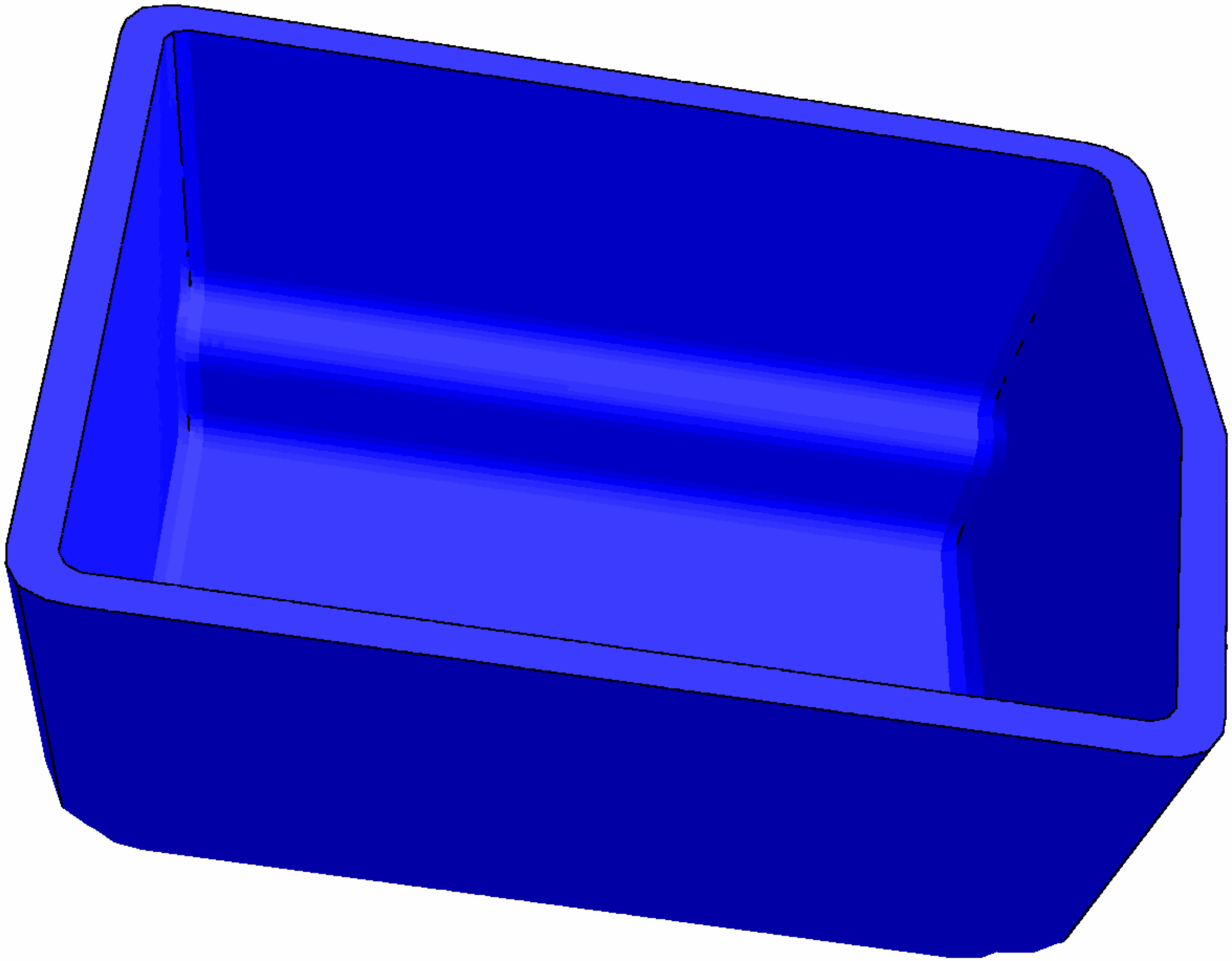
- Problem all about materials that behave as either fluids or solids depending on localised conditions
- BUT . . . The solid is rigid plastic and so modelled as a non-Newtonian free surface flow
- Hence, all done in a CFD context.

Lead Ingot Mould Cracking

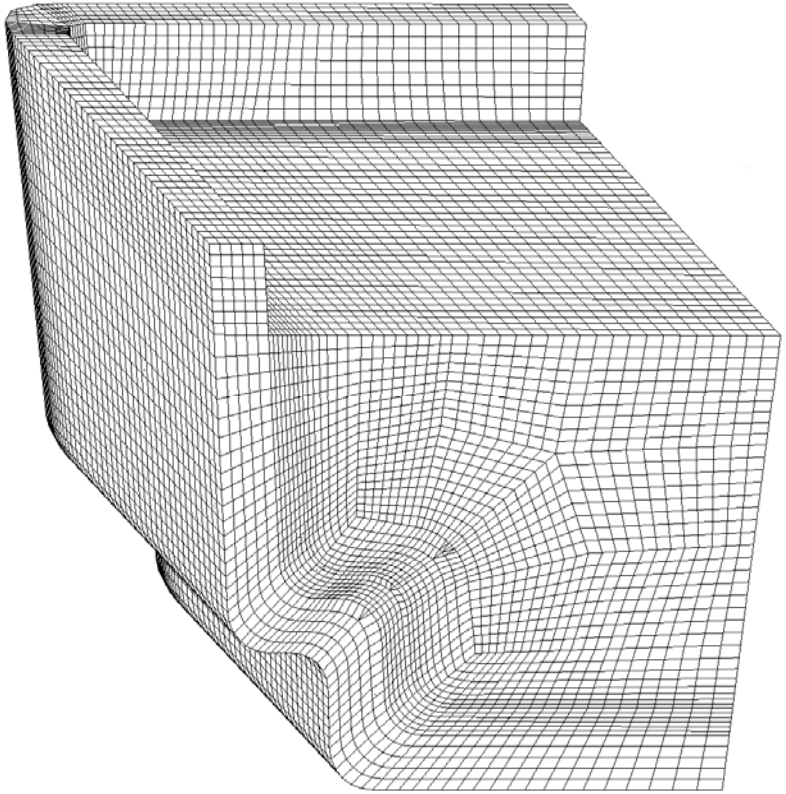
- Ingot casting
  - flow
  - heat transfer
  - solidification/melting
  - elasto-visco-plastic stress

  all coupled

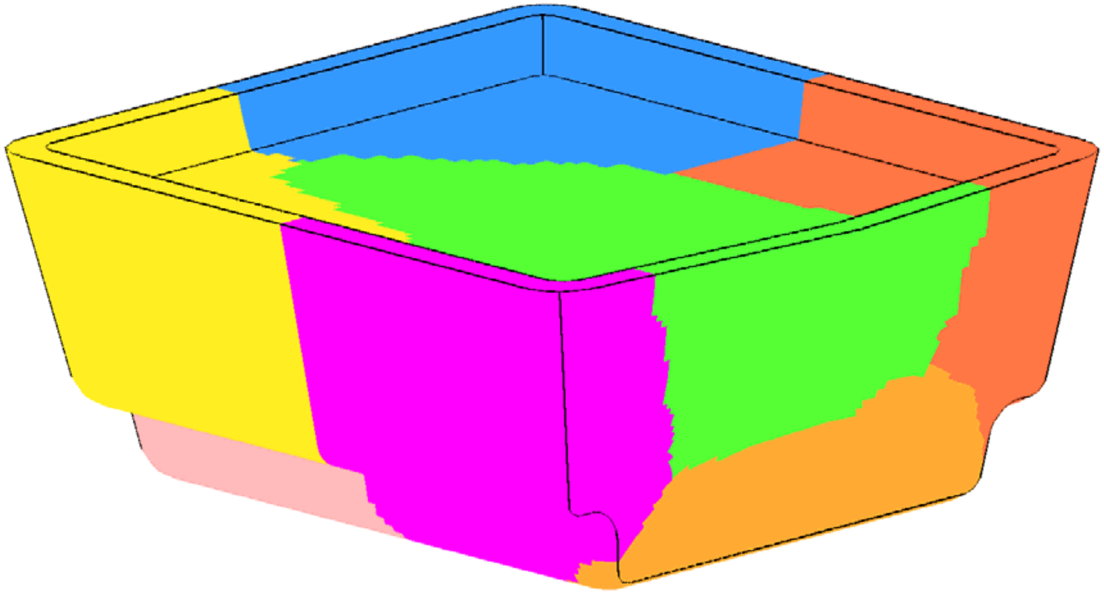
Ingot geometry



Analysis mesh

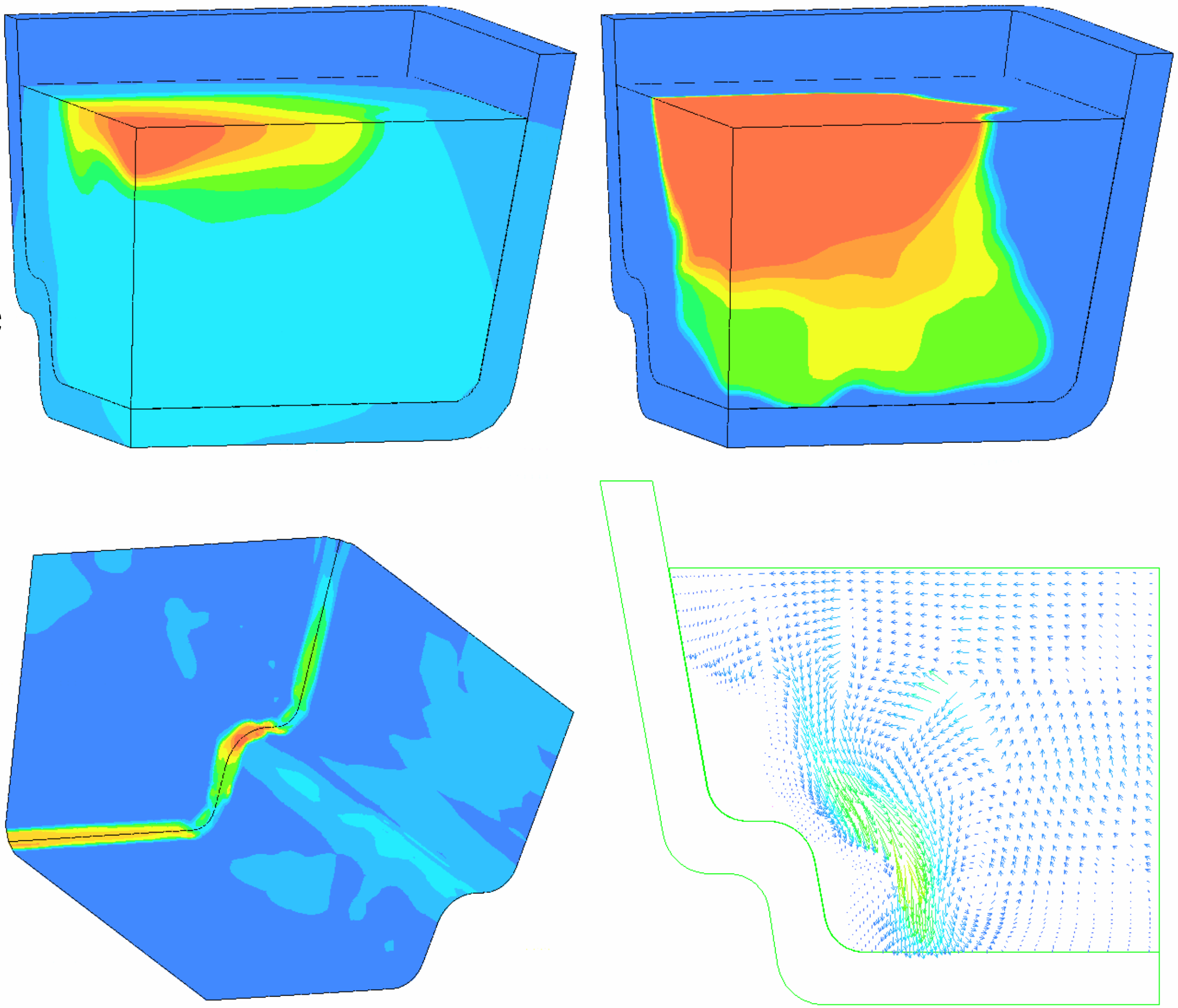


Mesh ¼ of geometry



A mesh partition for parallel run on 8 processors

Simulation results



temperature (a)

(b) Liquid fraction

von Mises stress (c)

(d) flow

Parallel performance results - 409K mesh on Compaq cluster

P	T-calc	T-file	T-tot	Sp-calc	T-tot /T-file	Sp-overall
1	82072	609	82681	1	135.8	1
2	43958	1576	45534	1.87	28.9	1.82
4	22034	1647	23681	3.72	14.4	3.49
8	10325	1360	12021	7.95	8.84	6.88
12	5173	1670	6843	15.87	4.10	12.75

Closely coupled multi-physics?

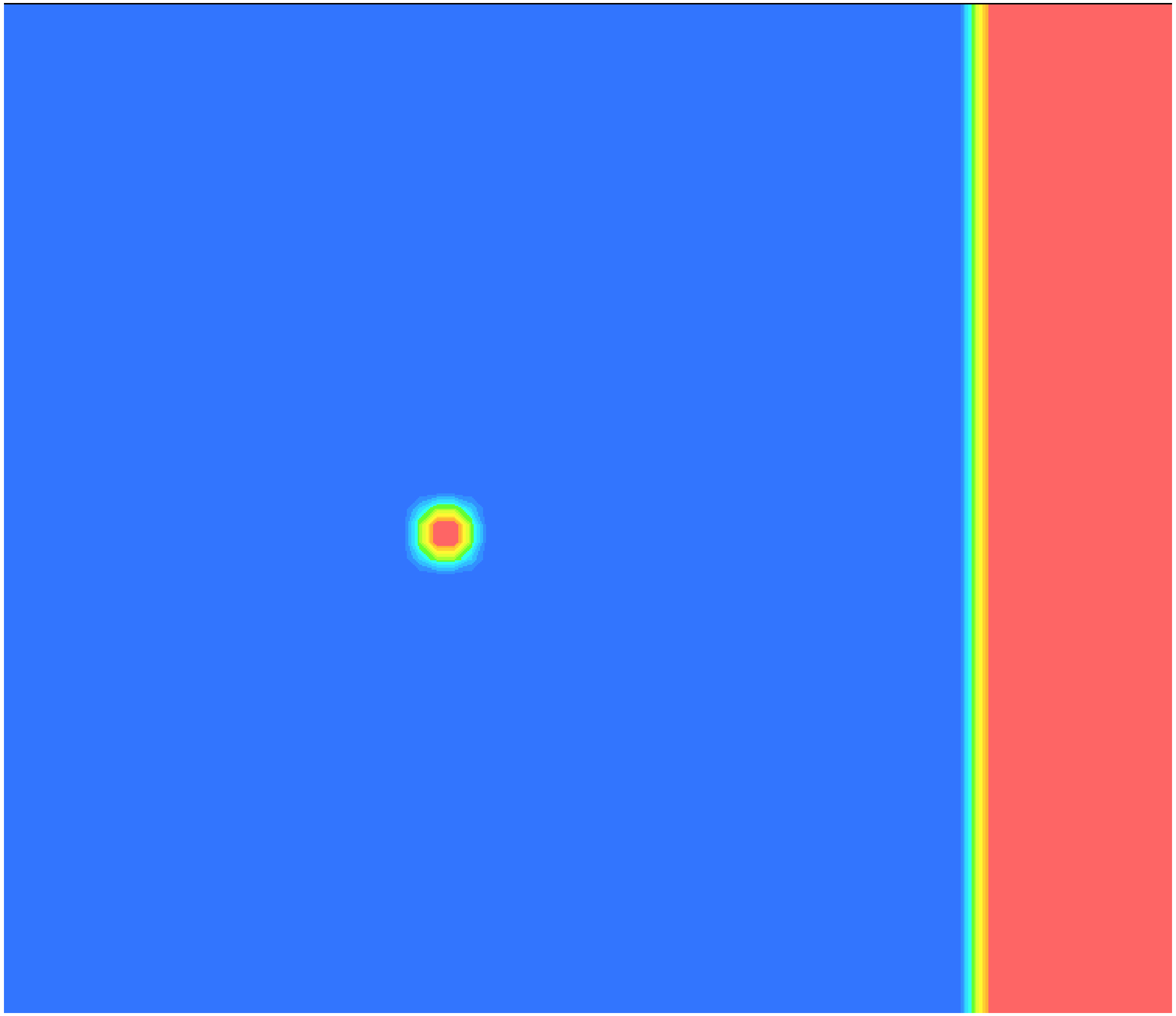
- Involves fluid flow, heat transfer, solidification and stress
- Flow, heat transfer and solidification all closely coupled
- Flow, heat transfer and solidification all influence the stress, but not the other way around
- SO . . . Could use a coupled CFD & CSM code
- BUT . . . Must have mesh compatibility

High Impact Projectile

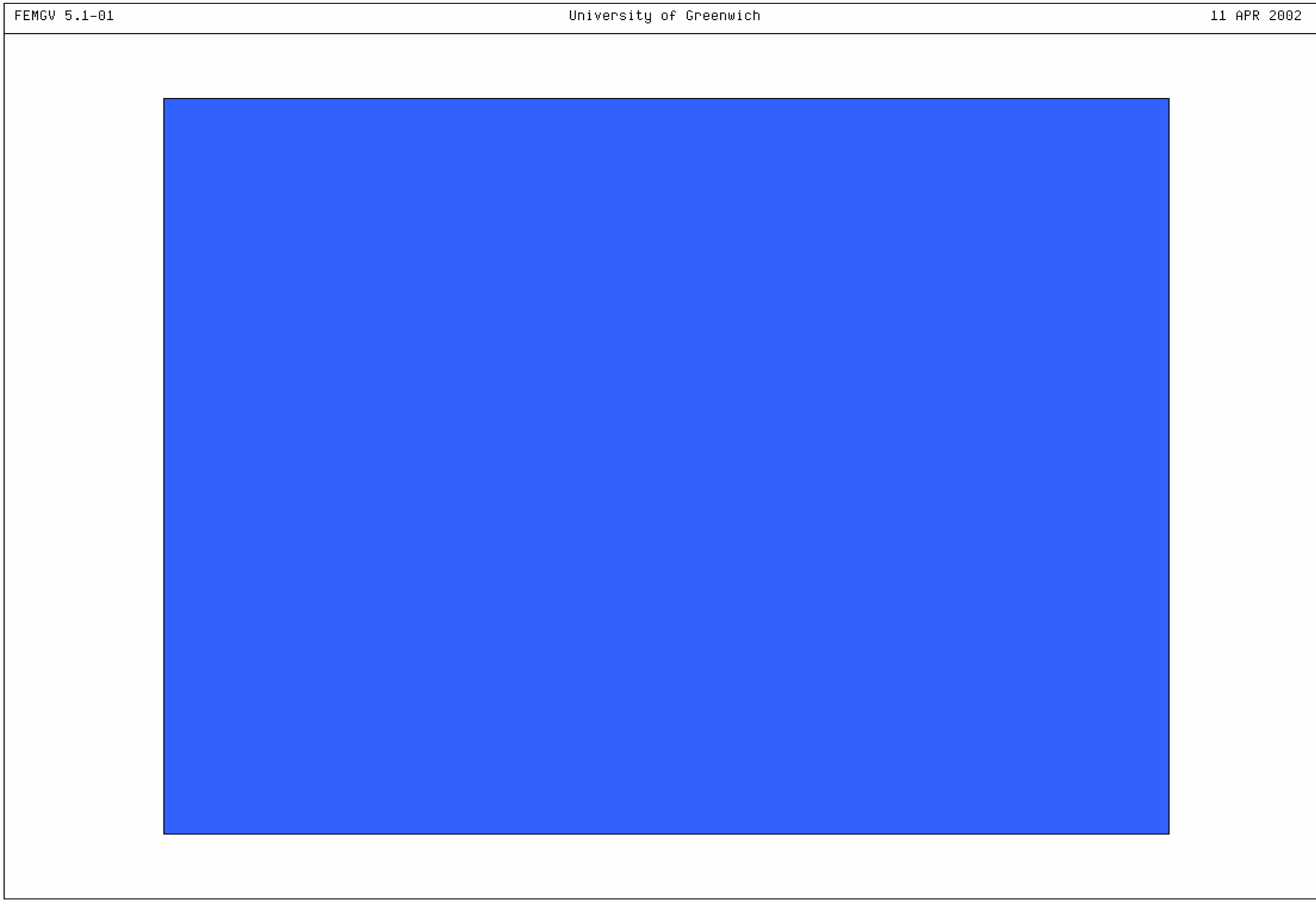
- Approach
  - Eulerian framework- avoids remeshing.
  - Projectile & target - non Newtonian fluid.
  - Norton Hoff model, incompressible.
  - Boundaries - free surface - end of time step.
  - Scalar Equation model - fluid marker – 0/1

This is a structural problem being solved by a CFD procedure – so a major cheat, BUT . . . .

Projectile colliding with structure



Effective Strain Movie



Macro-segregation of multi-component alloys

- Involves fully coupled:
  - turbulent NS fluid flow
  - Heat transfer
  - Solidification & melting
  - Multi-component transport
  - Local thermo-dynamic equilibrium
- Essentially a CFD based problem

Model problem based on expts

Based on
Expts of
Krane &
Incopera
on lead-zinc

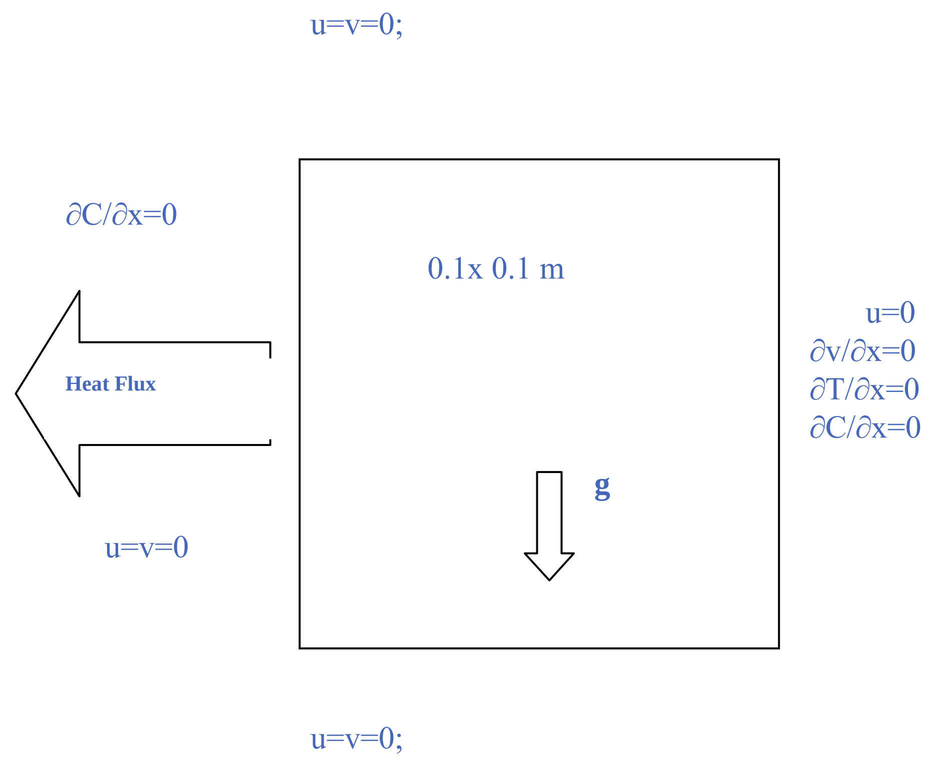
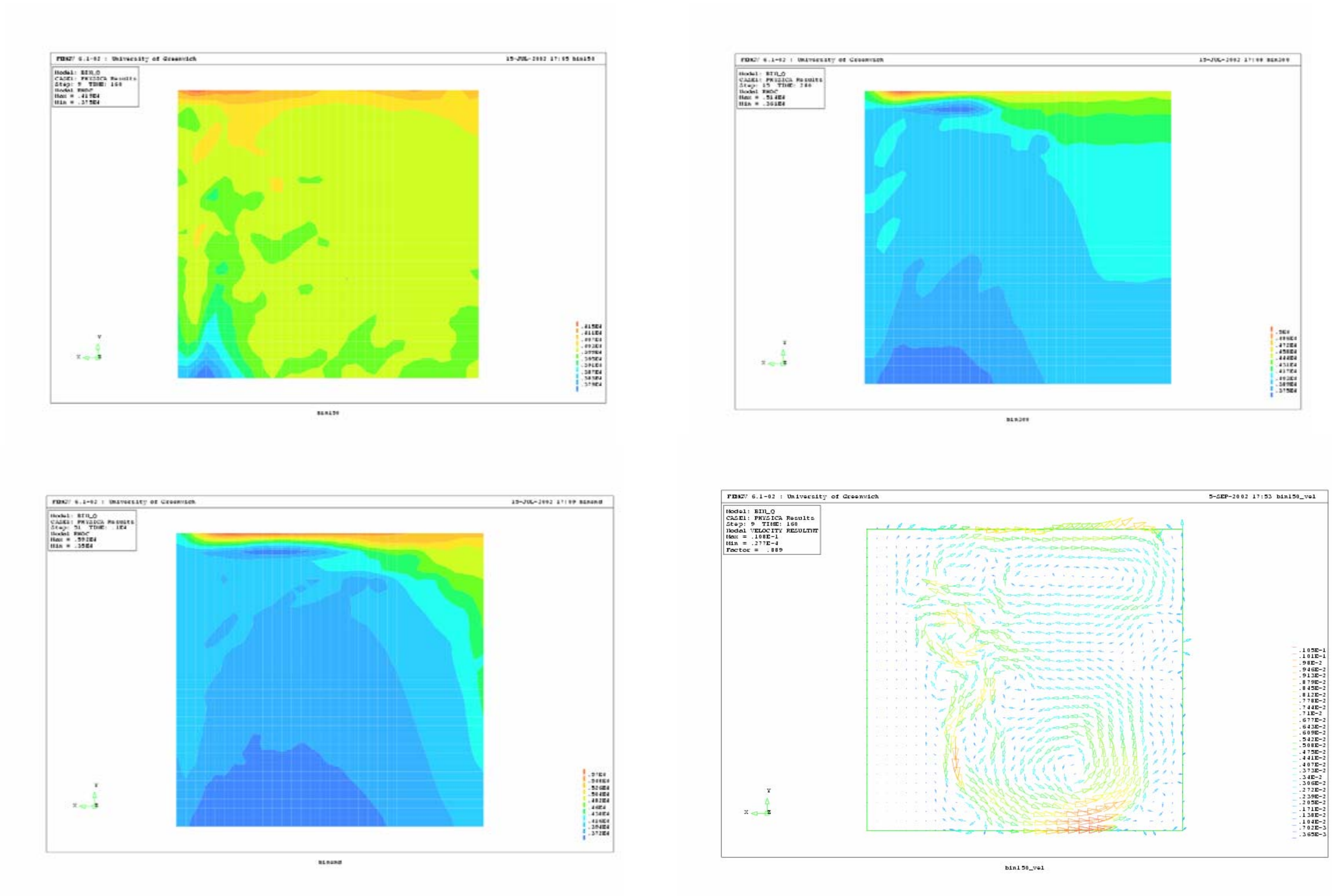
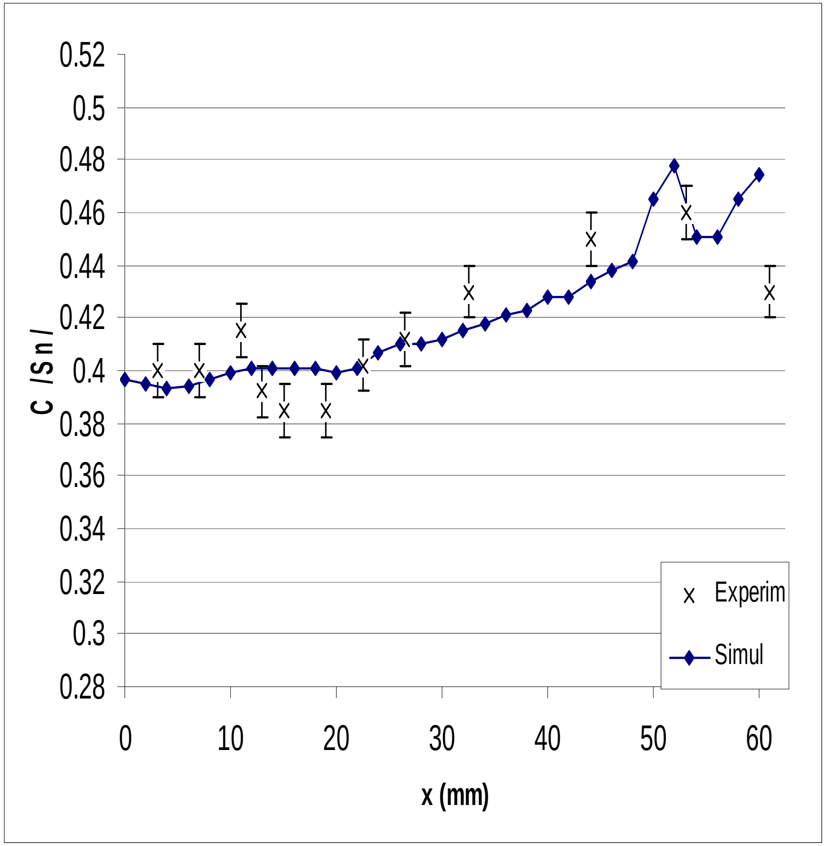


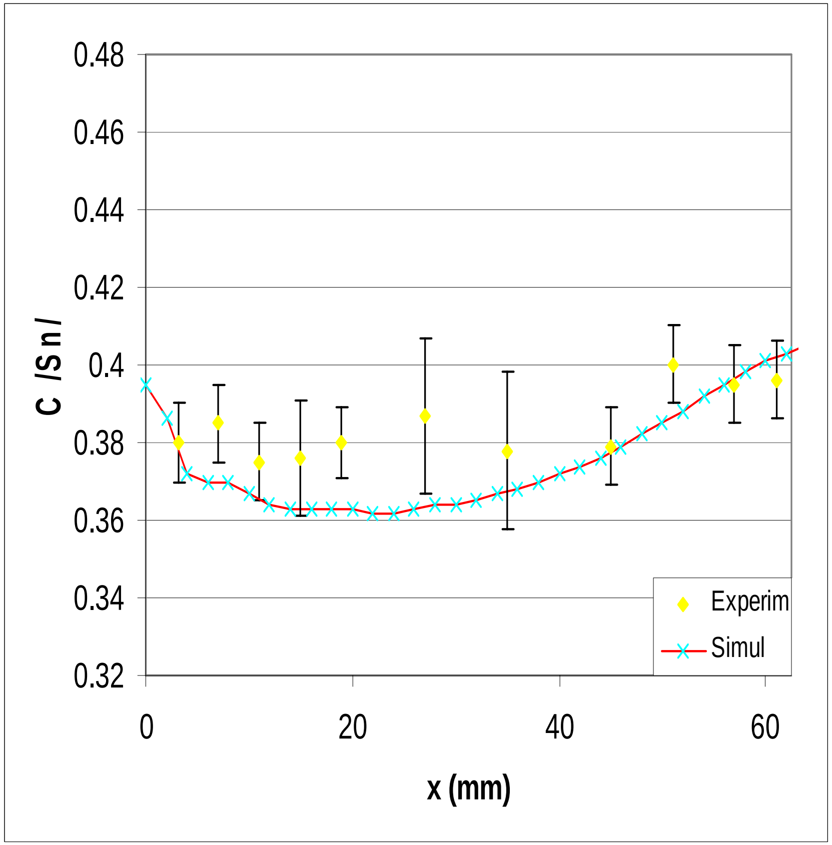
Figure 1. Geometry of the cavity and boundary conditions

Binary alloy predictions

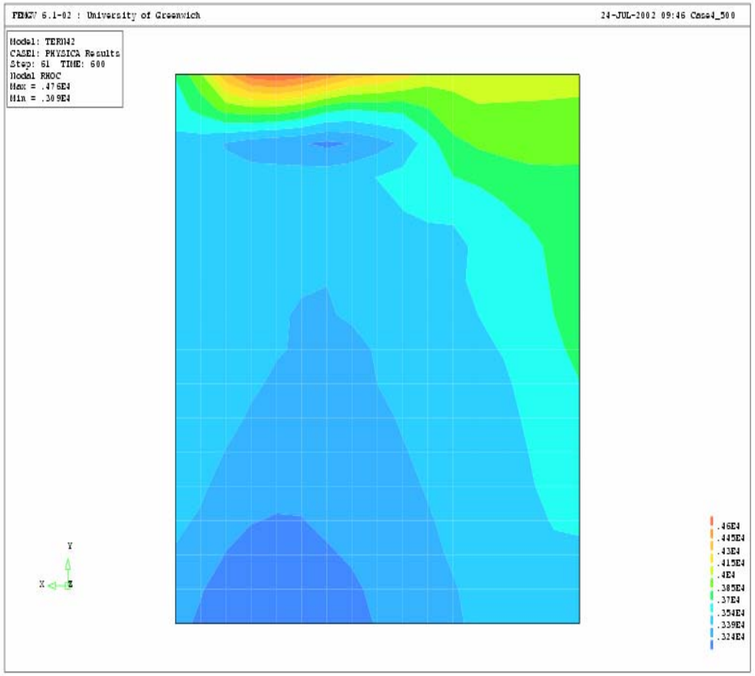


Binary alloy model vs. expt

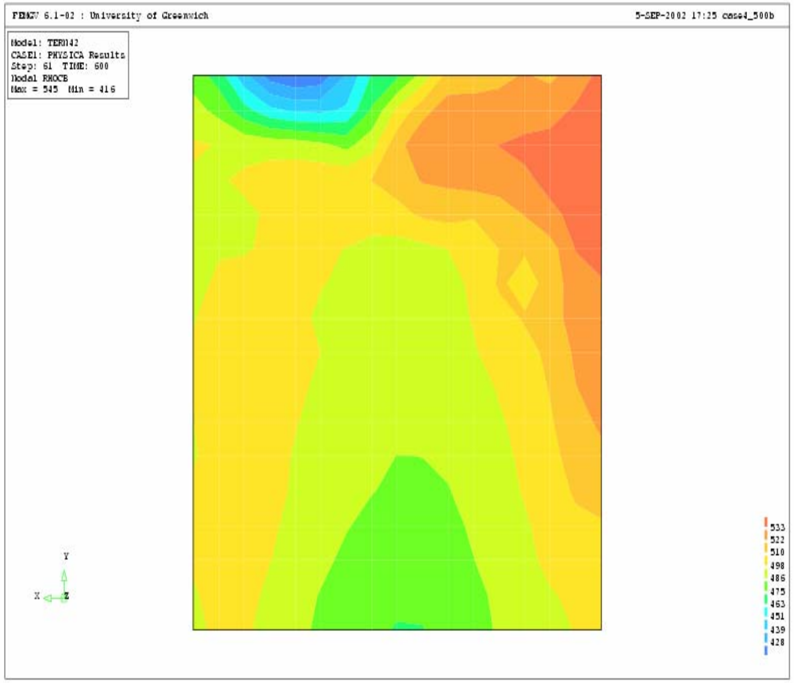




Ternary alloy model

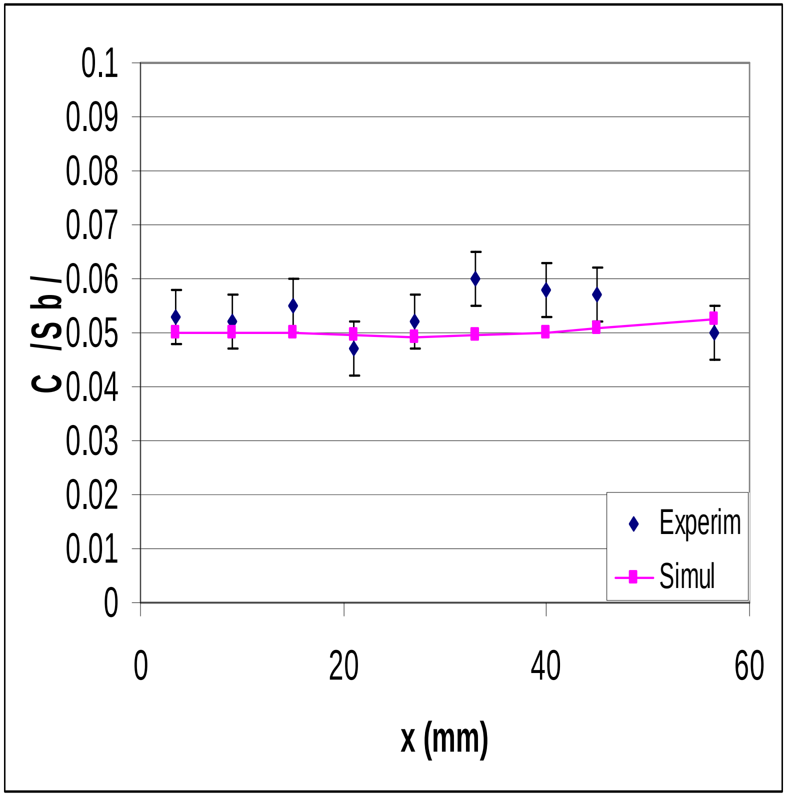


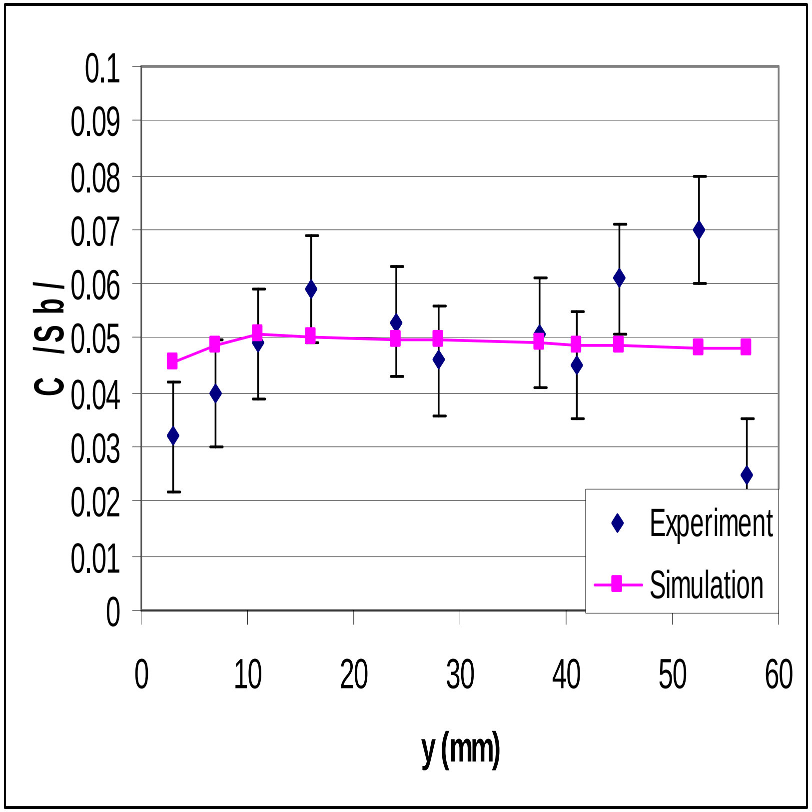
case4_500



Case4_500b

Ternary alloy model vs expt





Multi-physics simulation

- Challenge here is to:
  - Characterise classes of MP problems
  - Most CC-MP solved as cheats where a fluid is modelled as a solid and vice-versa
  - Flow + thermal + acoustics/electromagnetics - OK
  - Solids + thermal +acoustics/electromagnetics - OK
  - The FSI cheats can be very effective
  - There are limitations to the FSI cheats
  - Whatever – CC-MP makes serious constraints on the simulation technology that can be used