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ATS-85: Advanced Manufacturing Technology for Single Crystal IGT Components

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Turbine Airfoil Manufacturing Technology

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ATS Phase III Program Introduction

- State of the Art
  - Directional solidification of components is generated by withdrawing the mold at a controlled rate from a heated susceptor into a cooling cavity
  - Heated susceptor and cooling cavity develops a high thermal gradient during withdrawal
  - Casting yields on fully developed aircraft gas turbine single crystal casting process exceed 95 percent
  - Significantly increased size of IGT components compared to aero-sized components

Introduction

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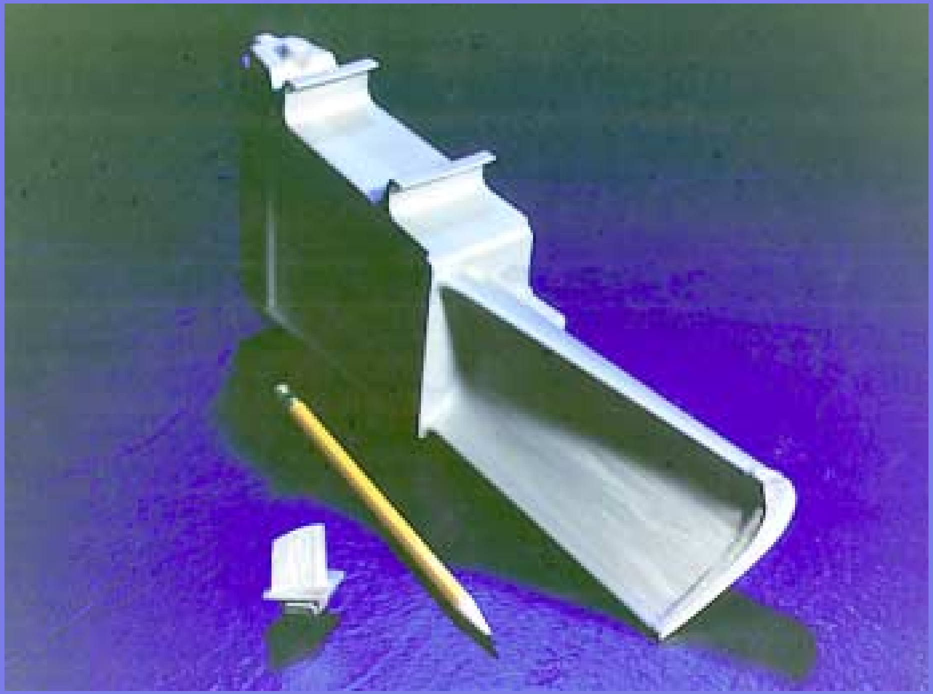
- Aero-engine/Land Based Turbine Comparison

Comparison	Aero	Land Based
Size differential	1X	2 to 3X
Weight differential	1X	5 to 10X
Surface area differential	1X	20 to 100X



Introduction

- IGT Casting Difficulties
  - Density differences between the interdendritic liquid and the liquid ahead of the interface drive thermosolutal convection and when severe, develops solute plumes
  - Freckle defects and macrosegregation then result from the severe solute plumes
  - Large cross sections, low thermal gradients, and later generation alloys enhance the tendency to form freckles and segregation
  - Increased casting size increase the propensity to form additional grain defects such as high angle boundaries and spurious grains

Program Objectives

Three Technology Thrust Areas

- VIM Furnace Enhancements
  - Define furnace enhancements which will improve control of mold temperature and thermal gradient on IGT components
- High Conductivity Shell System
  - Determine what factors limit shell thermal conductance
  - Develop shell to meet needs of high gradient DS/SC casting process
- Novel Cooling Development
  - Establish & quantify the magnitude of the principle heat transfer modes in an IGT DS/SC casting

Advanced VIM Efforts

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Benchmark IGT Components

- Compile existing processing and quality data
- Perform additional metallography work as necessary
- Examine mold features
- Perform casting trial
- Characterize casting to obtain baseline
- Update computer model
- Add furnace configurations to model

Better/Novel Susceptor & Baffle Material

- Conduct a literature search and commercial availability search of new materials
- Compare physical characteristics of current material to candidate materials
- Conduct feasibility study

Control Methods Evaluation

- Optimize TC configurations within the casting furnace
- Select best control sensors
- Conduct a designed experiment

VIM Furnace Enhancement Modeling

- Combine final configurations into one model
- Perform casting trials on non-thermocoupled molds
  - Furnace configuration
  - Mold configuration
  - Combination configuration
- Characterize for comparison with benchmark standard

Furnace Configuration Study

- Evaluate efforts of susceptor, coil design and baffle configuration
- Conduct a designed experiment using empty molds

Novel Mold Design

- Conceptual design of IGT mold details
- Incorporate into model and evaluate

VIM Integration for Production

- Examine promising configurations
- Develop integration plan and design

Benchmarking Efforts

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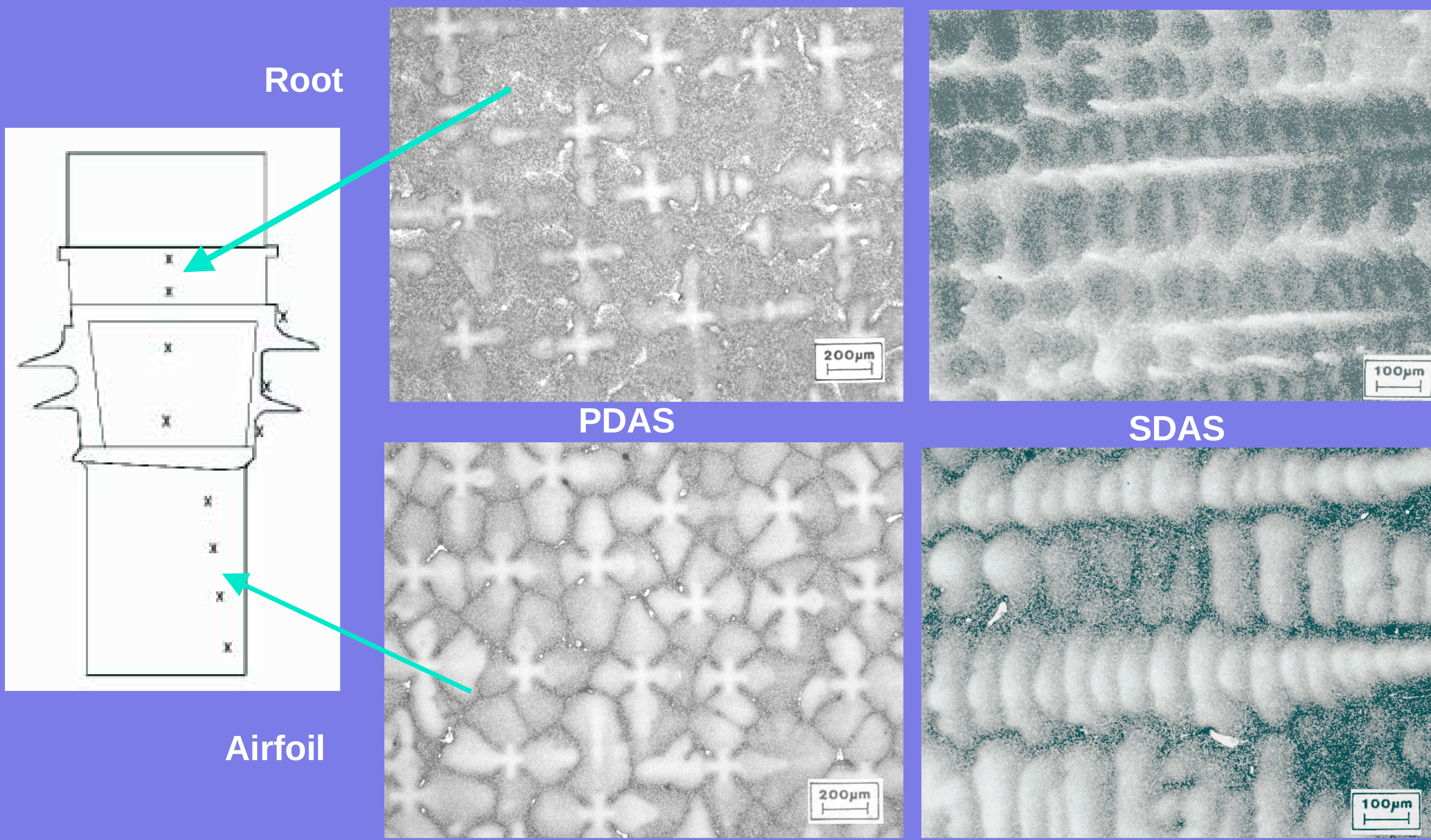
◆ Microstructural Evaluation



Benchmarking Efforts

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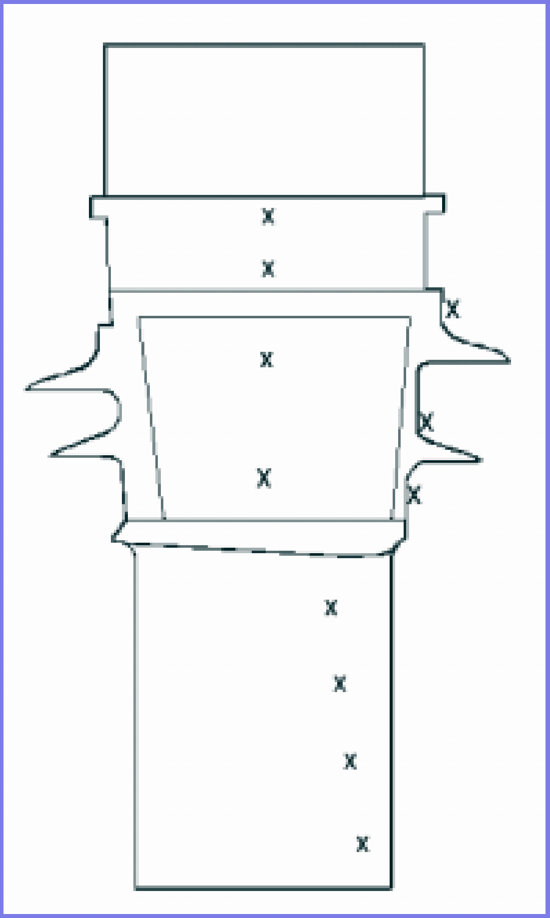
Thermocouple Data

- **Mold**
  - **Coupled with casting trials**
  - **Thermocoupled for thermal survey**
    - **Thermal profiles**
    - **Evaluated for repeatability of various features**
- **Susceptor**
  - **Thermocouples**
  - **Thermal imaging**



Control Methods Evaluation

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- Optimal Control TC location
  - Determined from susceptor thermal profiles
  - Maximum temperature
  - Insertion depth
  - Height in susceptor
- Verified with Thermal imaging
- Alternate Sensors
  - Three different sensor technology utilized
  - Each sensor responds differently to:
    - Susceptor temperature
    - Mold temperature
    - View factors

Better/Novel Susceptor & Baffle Material

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- Compare current and potential baffle materials
  - Material properties - Conductivity test
    - Thermal isolation testing in a casting furnace
    - 13 distinct designs evaluated
  - Mechanical integrity
- Developed computer models of furnace & baffle
  - Current baffle thermal conductivity with varying thickness
  - Current baffle thickness with varying thermal conductivity
- Validated with temperature data for experimental runs

Furnace Configuration Study

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- Integrate Controls and Baffle Evaluations
  - Model predictions
  - Validation runs with temperature data
- Analysis Criteria - Thermal Gradients
  - Maximum and Minimum
    - Grain defects implications
  - G_X, G_Y, & G_Z resolution - Directionality effects
    - Principles of Sensitivity Study of Novel Cooling Techniques
    - Not experimentally resolved
  - Mushy zone size, profile, & location
  - Mold geometry effects in airfoil & root

Furnace Configuration Study

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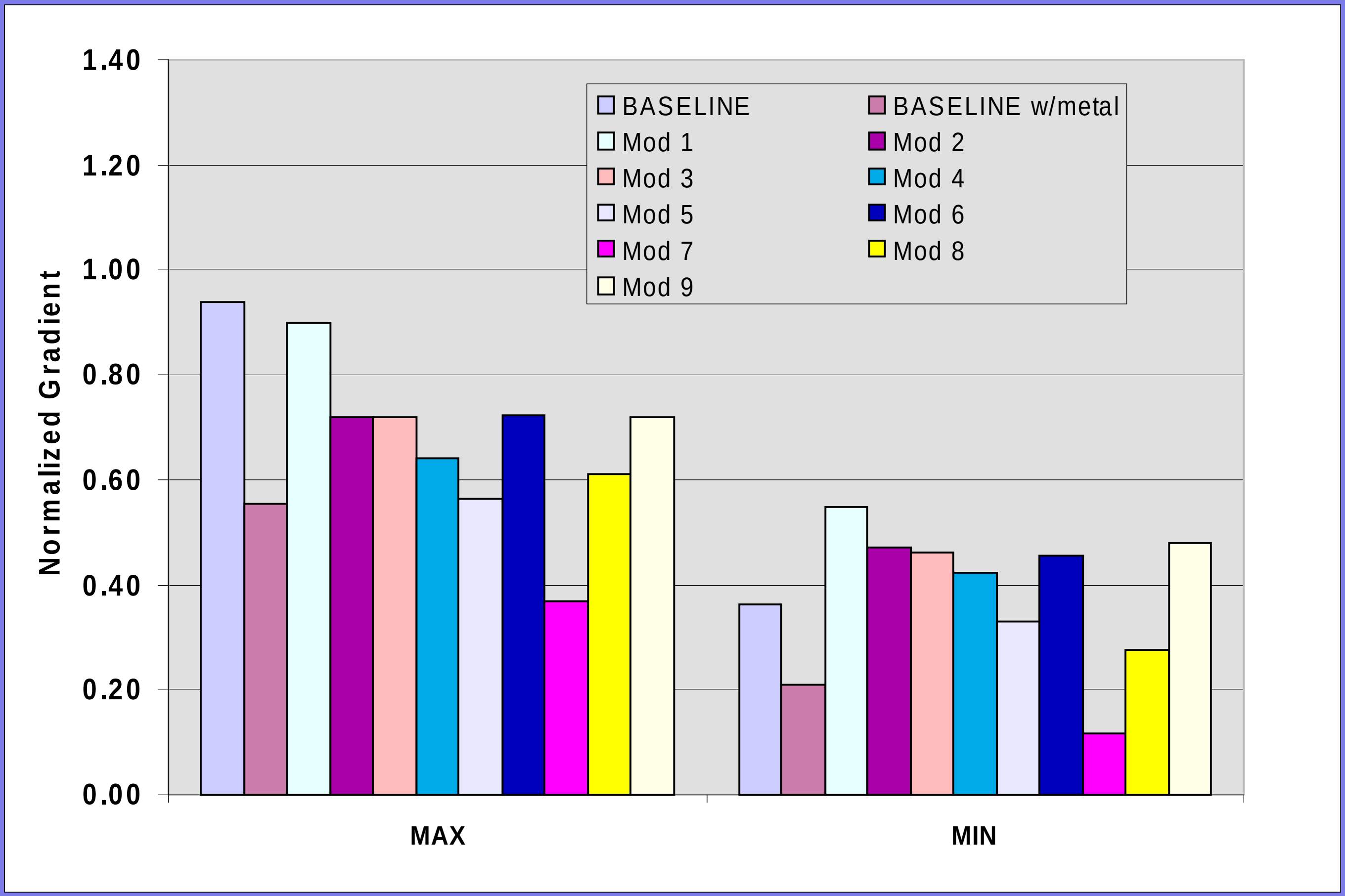
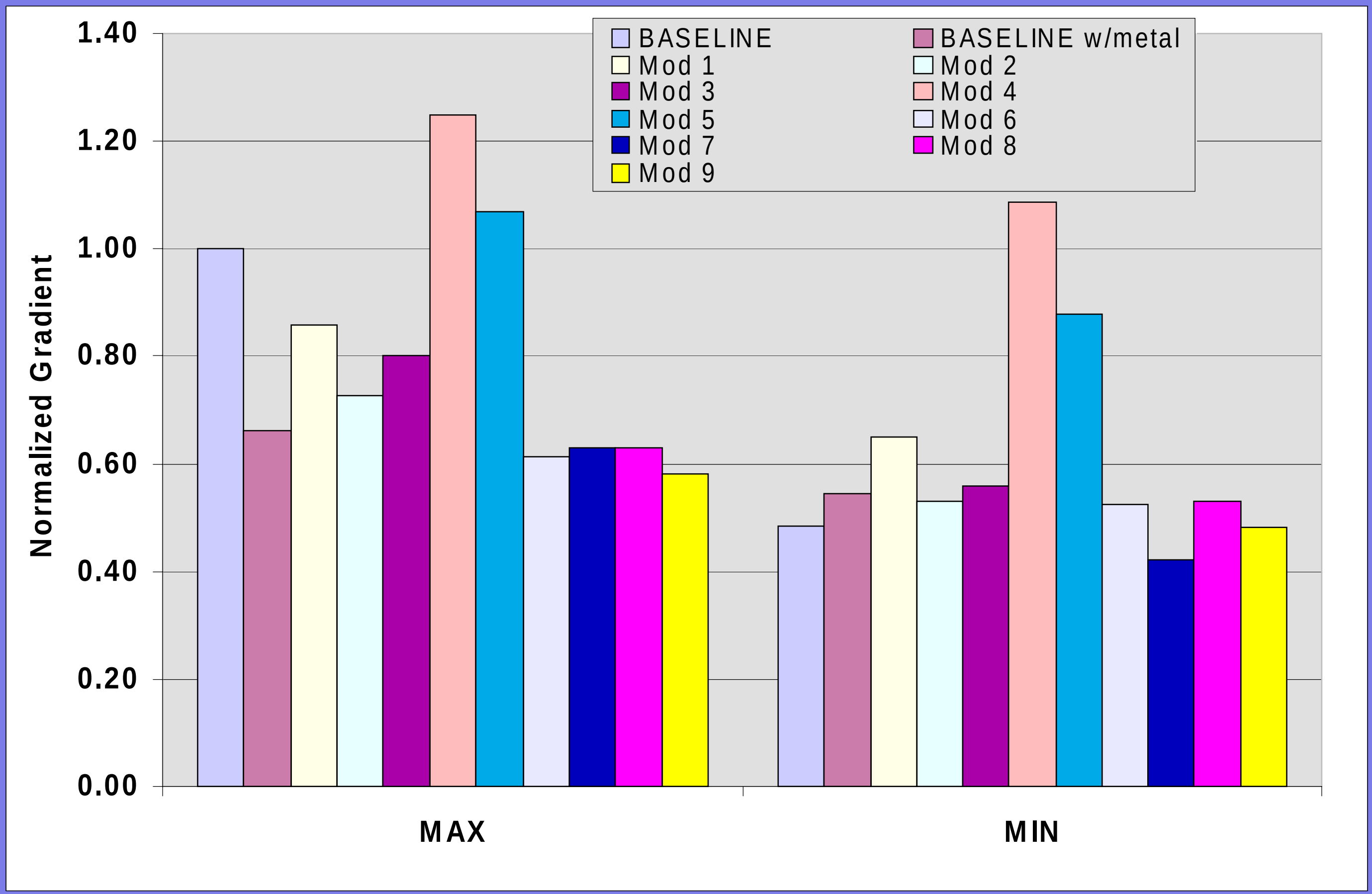
Maximum & minimum gradients within the mushy zone
Root Section



Furnace Configuration Study

Maximum & minimum gradients within the mushy zone
Airfoil Section



Furnace Configuration Study

- **Remaining Efforts**
  - **Perform evaluation of combination of furnace designs**
  - **Analyze based on gradient examination**
  - **Evaluate promising designs for implementation**
  - **Phase 3: Determine a plan to transition of promising, cost effective methods**

Novel Cooling Methods Evaluation

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Sensitivity Study of Novel Cooling Techniques

- Quantify thermal resistances within casting system
  - Heat transfer coefficient between casting and mold
  - Thermal conductivity of mold
  - Heat removal from mold external surface
- Use simplified casting as a test vehicle
- Perform "What-if" scenarios
- Rank by risk/benefit/cost
- Perform experiment on condition with greatest impact

Novel Cooling Experimental Evaluation

- Validate model with experiment casting using simplified casting
- Variables may include gas film and liquid metal techniques
- Analyze and prepare thermocouple data
- Repeat model simulation with updated values
- Characterize microstructure and crystal quality
- Apply most promising condition to GEPS 9H Model

Novel Cooling Feasibility

- Analyze computer modeling data (GEPS 9H)
- Develop a conceptual design for a production system
- Compare improvements to advanced VIM (Task 2.1)

Mushy Zone Profile

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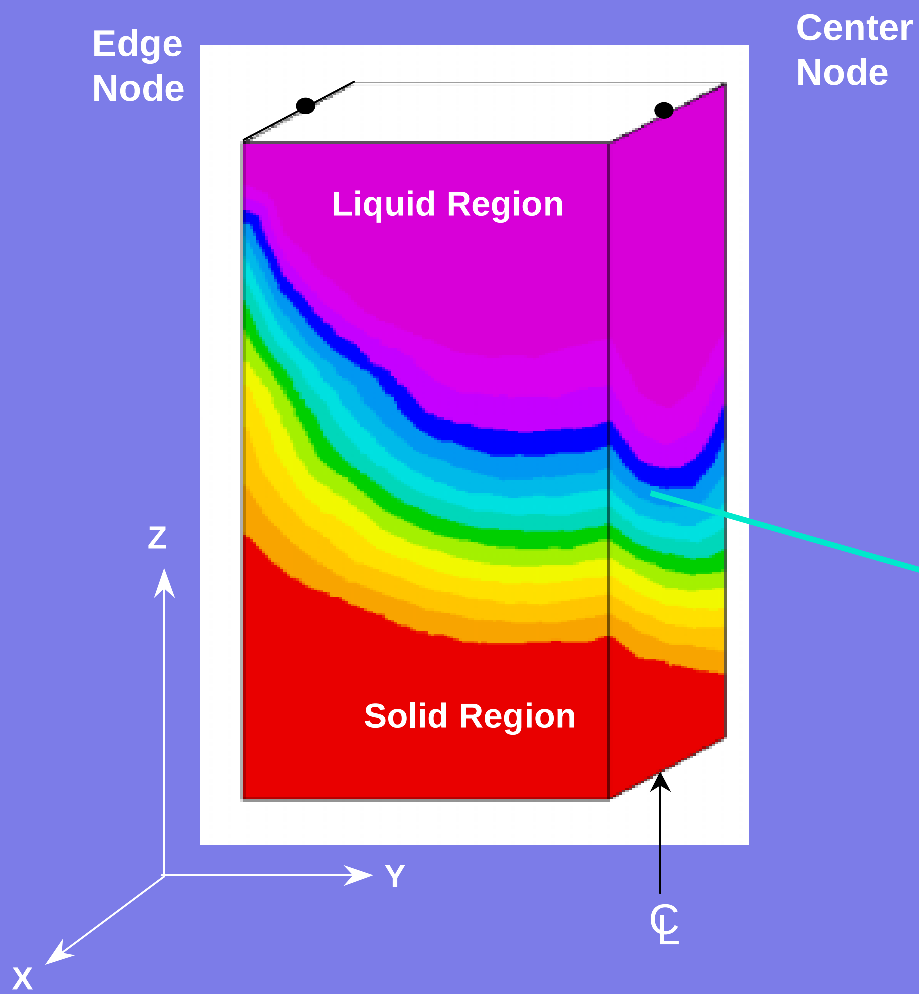

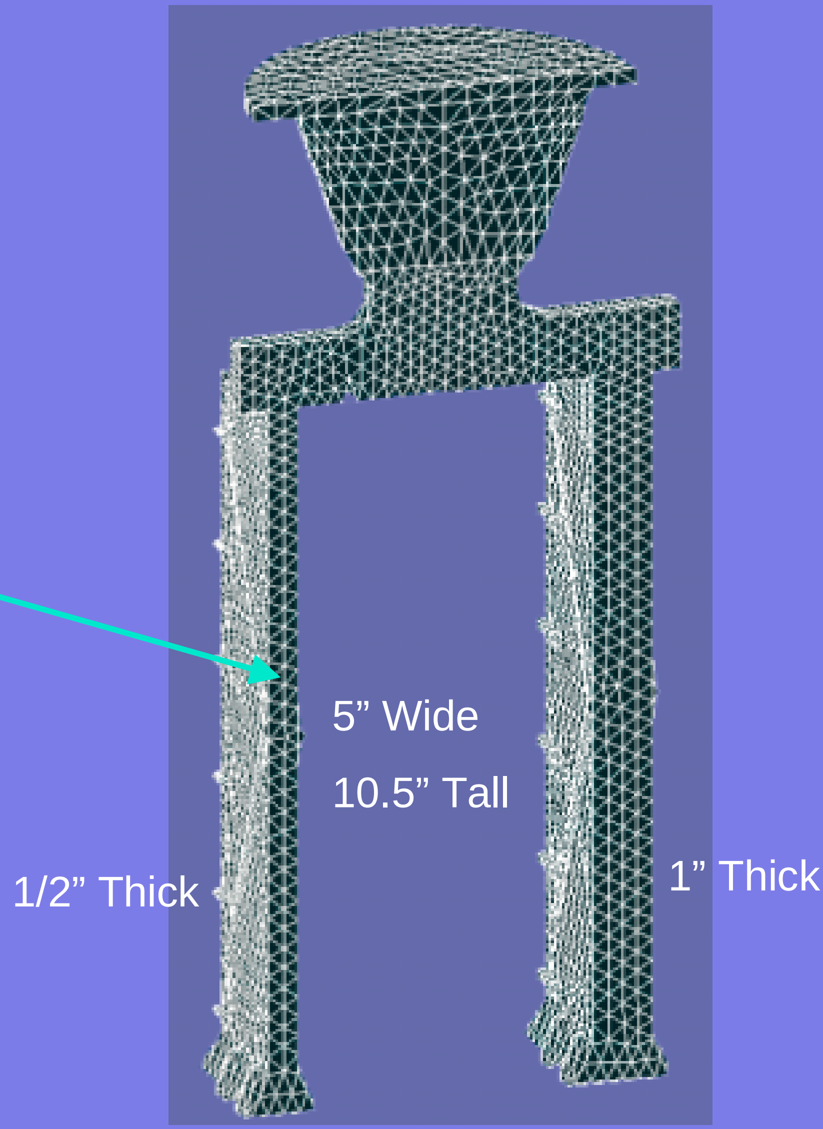

Sensitivity Study of Novel Cooling

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1st DOE Matrix

FACTOR	LEVEL 1	LEVEL 2
A: Metal/Mold Interface	Standard	Experimental
B: Shell emissivity	Real	Experimental
C: Shell conductivity	Standard	5x
D: Shell thickness	Thin	Standard
E: Susceptor temp	Low	Standard
F: Baffle temp	Standard	Experimental
G: W/D rate	1X	5X

2nd DOE Matrix

FACTOR	LEVEL 1	LEVEL 2
A: Baffle Gap	Tight fit	Standard
B: Susceptor profile— f(time)	Standard	Experimental
C: Baffle thickness	Thin	Thick
D: Shell Properties	Standard with standard σ	Thin at 5X σ
E: Susceptor temp	Low	Standard
F: Baffle temp	Standard	Experimental
G: W/D rate	1X	5X

Sensitivity Study of Novel Cooling

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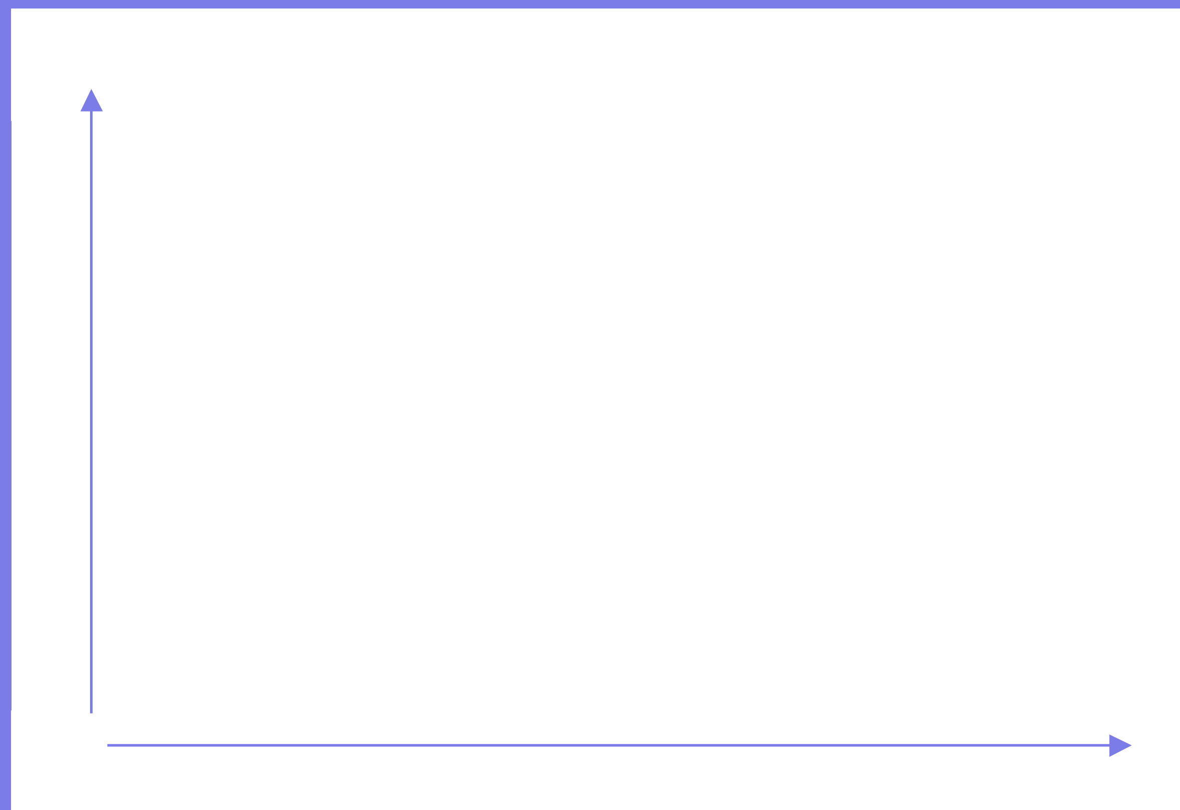
Thermal Gradient vs Growth Rate
1st DOE

- Polygons indicate the various R vs G regimes each run contains.
    - In the z direction
    - For both thicknesses

Thus...

- Varying geometry can produce different RG values.



Sensitivity Study of Novel Cooling

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Number of times a factor was significant (maximum of 4 times center/edge, thick/ thin)
Positive is better at level 2, Negative is better at Level 1 (total for experiments 1 & 2)

Matrix 1 and 2 Combined	Interface	Shell conductivity	Shell thickness	Shell emissivity	Susceptor profile	Susceptor temp	W/D rate	Baffle temp	Baffle thickness	Baffle Gap
Gradients										
X							-2	-1	1	
Y							-2	-1		
Z	2					3	-4	4		1
Solidification Rate										
X							-4			
Y							-2		-1	
Z		1					4	-1		

Sensitivity Study of Novel Cooling

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Sensitivity Matrix

Runs*	Isolation	Conductivity
1, 2, 3, 4	Std	Std
5, 6, 7, 8	Std	High
9, 10, 11, 12	High	Std
13, 14, 15, 16	High	High

*** 4, 8, 12, and 16 inches per hour**

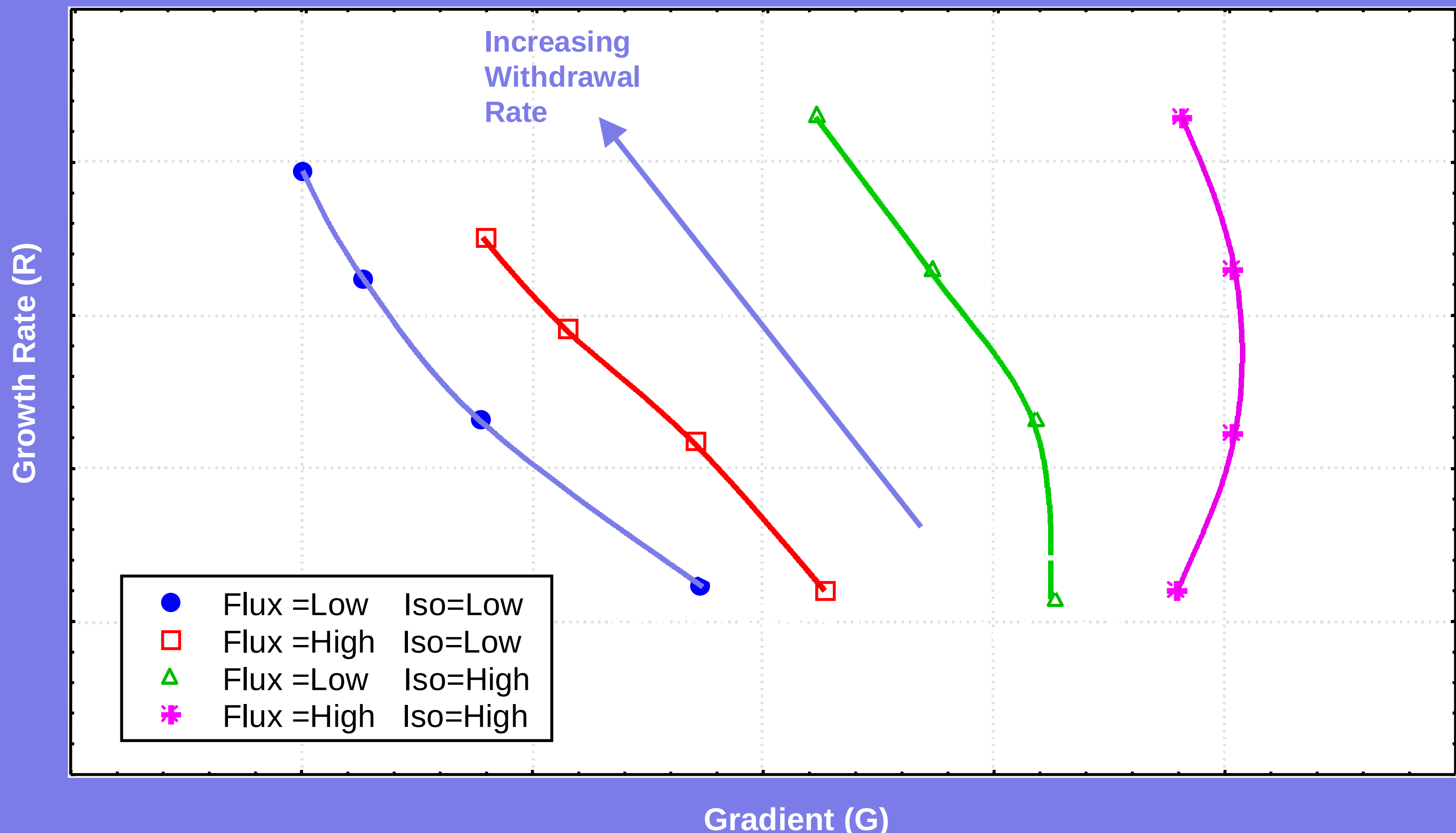
Fixed Factors
Shell Thickness
Susceptor Profile
Baffle Gap
Susceptor Temp

Isolation Factors
Baffle Temp
Baffle Thickness

Conductivity Factors
Mold Metal Interface
Shell Emissivity
Shell Conductivity

Sensitivity Study of Novel Cooling

Gradient vs Growth Rate as a function of withdrawal rate for significant changes in mold and susceptor properties



Sensitivity Study of Novel Cooling

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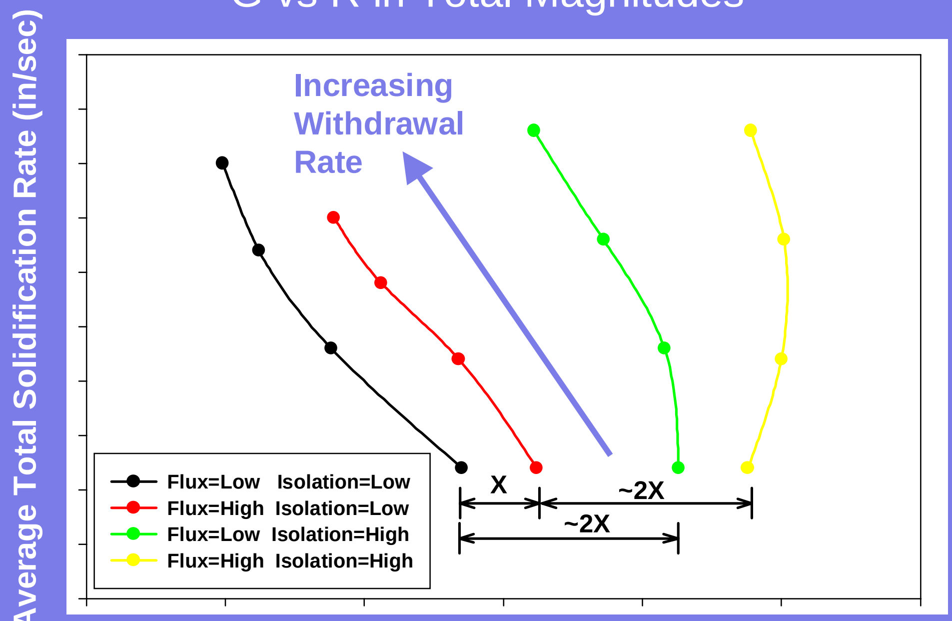
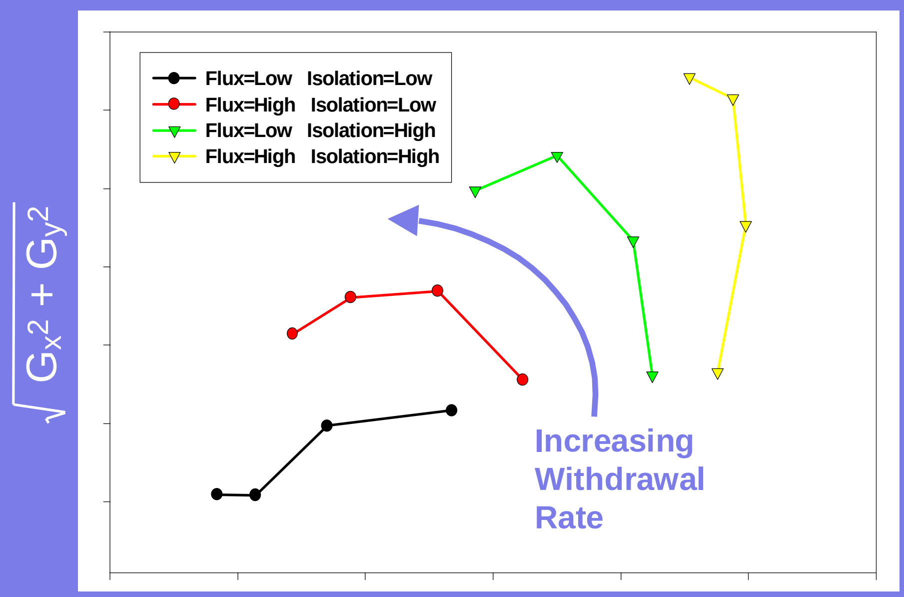
Increases in the total magnitudes of G & R also comes with an increase in the horizontal components (x & y vs z)

G vs R in Total Magnitudes



Average Total Gradient (°F/in)

G_z vs $\sqrt{G_x^2 + G_y^2}$



G_z

Sensitivity Study of Novel Cooling - Summary

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- Compare sensitivity of process factors on resultant solidification responses
  - Withdrawal rate and thermal drivers make significant impact on thermal gradient and solidification rate
  - Metal/Mold interface effects
    - Only thermal gradient in Z-direction
  - Shell conductivity
    - Only solidification rate in Z-direction
  - Heat removal from mold surface
    - No significant response
- Directionality of G & R also significant

Summary

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- **We Know …**
  - **Higher solidification rates benefit production throughput**
  - **Higher thermal gradients combined with higher R improve quality**
- **But…**
  - **Must balance the needs for part quality and production throughput**