Sustainability in Refrigeration Systems –

Opportunities for energy efficiency improvements in low temperature freezing systems

Frozen Dessert Center
2022 ANNUAL
TECHNICAL CONFERENCE

F D C
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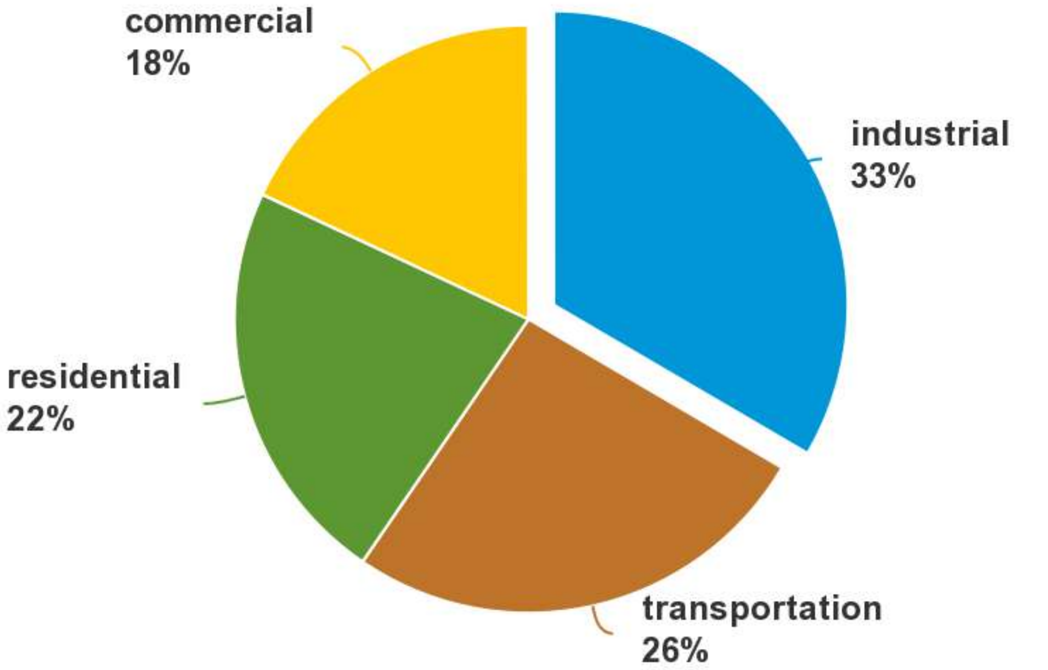
Director, Industrial Refrigeration Consortium
University of Wisconsin-Madison

The industrial sector is consistently the largest energy consumer

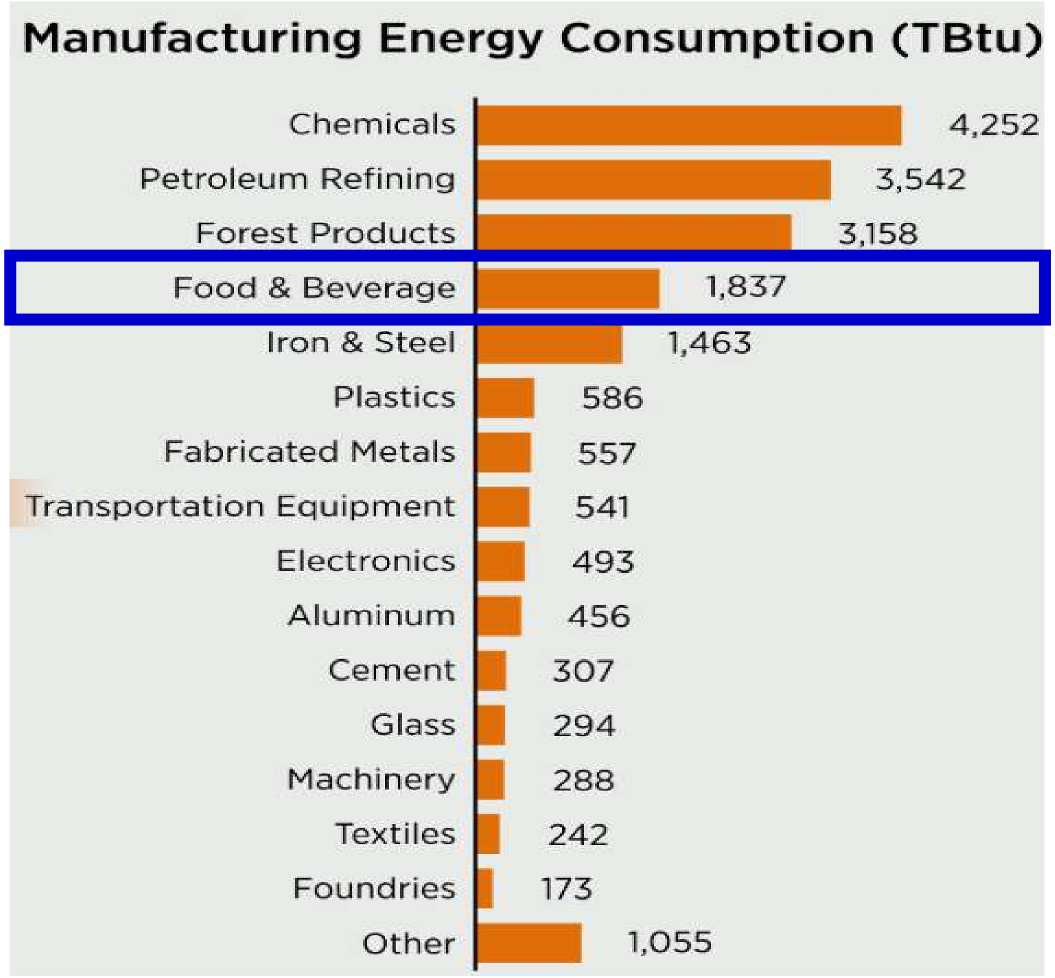
Share of total U.S. energy consumption by end-use sectors, 2020

Total = 92.94 quadrillion British thermal units



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 2.1, April 2021, preliminary data
Note: Sum of individual percentages may not equal 100 because of independent rounding.

Within the manufacturing sector, food industry is in the top five



Source: Manufacturing Energy Flows, DOE Office of Energy Efficiency & Renewable Energy, (2010).

Frozen desserts require energy-intensive freezing systems for hardening!

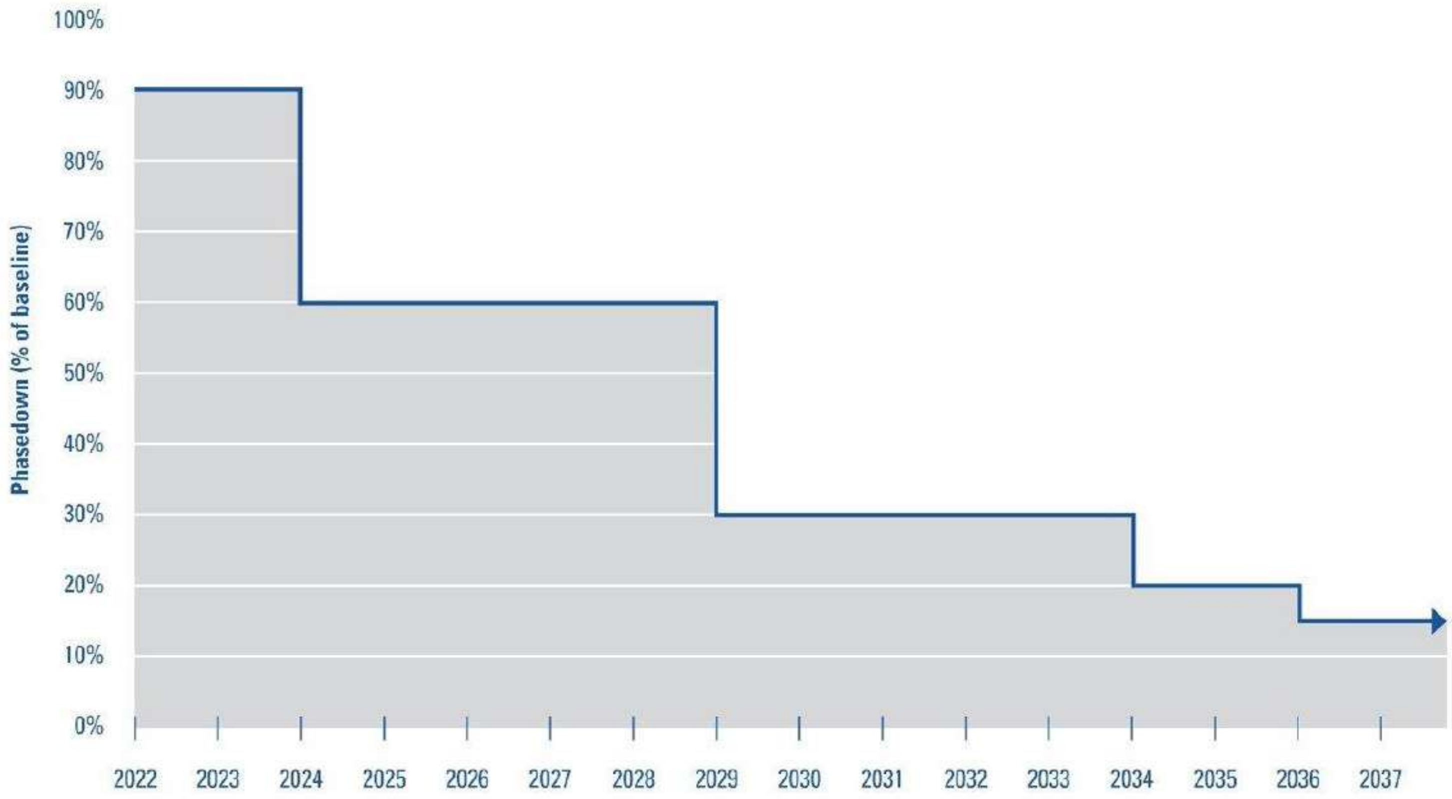
- Mechanical freezing systems
  - Predominantly dynamic freezing systems
  - Common configurations include spiral, tunnel
  - Capital cost intensive
  - Not optimized

- Cryogenic freezing systems
  - Low capital cost but high operating costs
  - Quick freezing times
  - Sustainability?

AIM Act phasing down HFC refrigerants

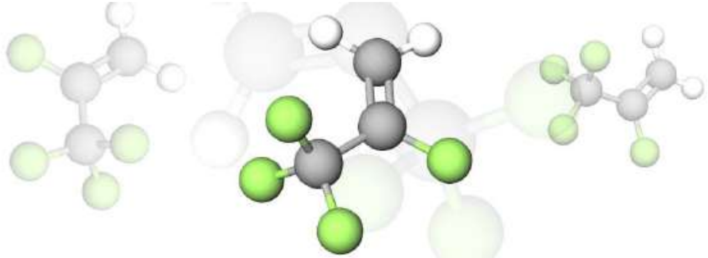
Phasedown Schedule

The following illustrates the HFC production and consumption phasedown schedule as outlined in the AIM Act.



Next generation fluorochemical refrigerants

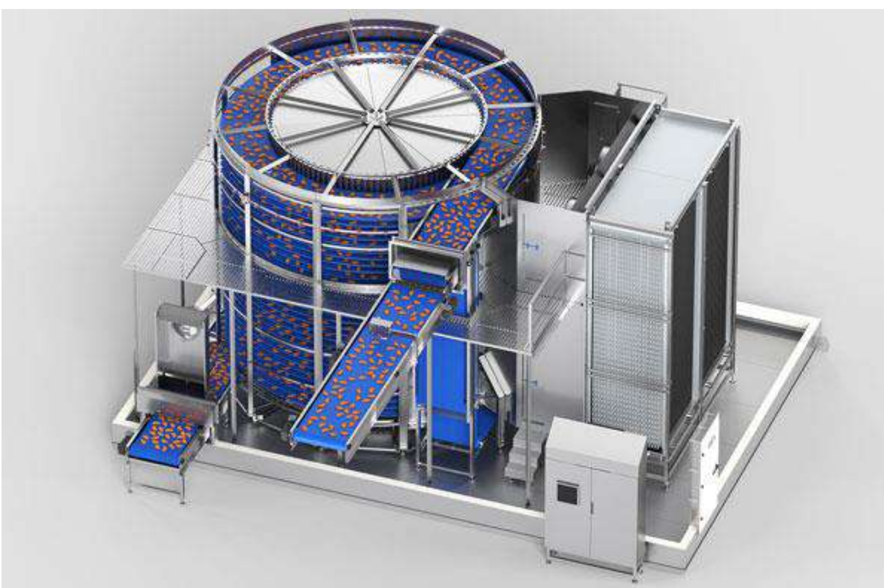
- Fluorochemical refrigerant choices are limited and have additional concerns
  - Many are "slightly flammable" (2L classified by ASHRAE 34)
  - Medium and low pressure refrigerant alternatives have moderately high GWP
  - Many options have poorer inherent operating efficiencies
  - Owners are experiencing phase-out fatigue
  - Concerns about TFA and PFAS and inclusion of HFC and HFO refrigerants in PFAS-related phase-out planning

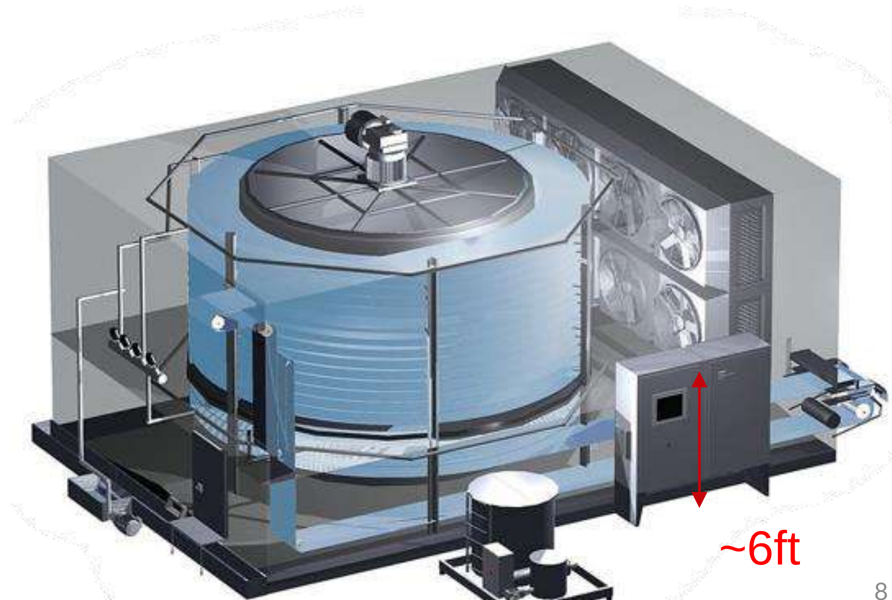


End-users have a lot of balls in the air!

Mechanical blast freezing systems

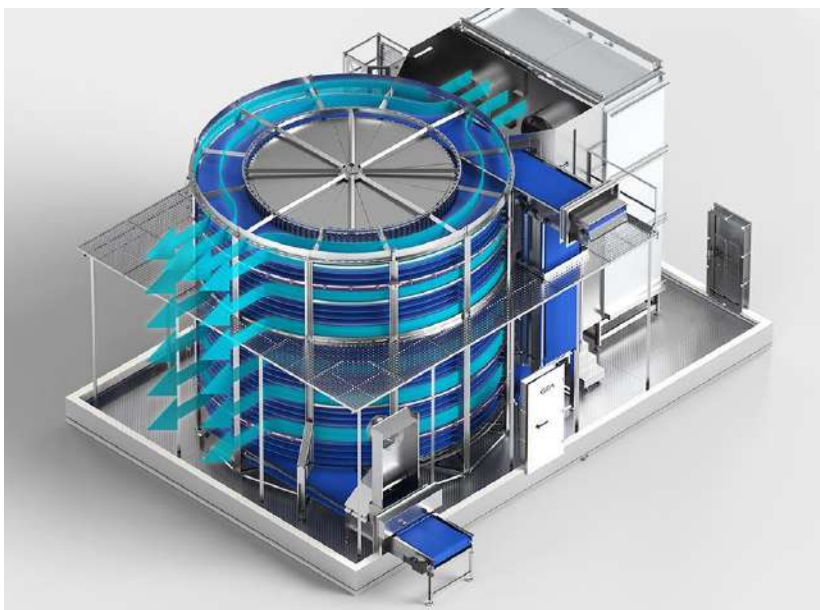
- Large insulated rooms with high powered fans (40+ mph) that force cold air (-40°F) over product
- Used in food processing industry to rapidly cool food products like poultry, pizza, vegetables, and ice cream before moving into holding freezers or packaged for transport.
- Cooling times range from 10 to 60+ minutes

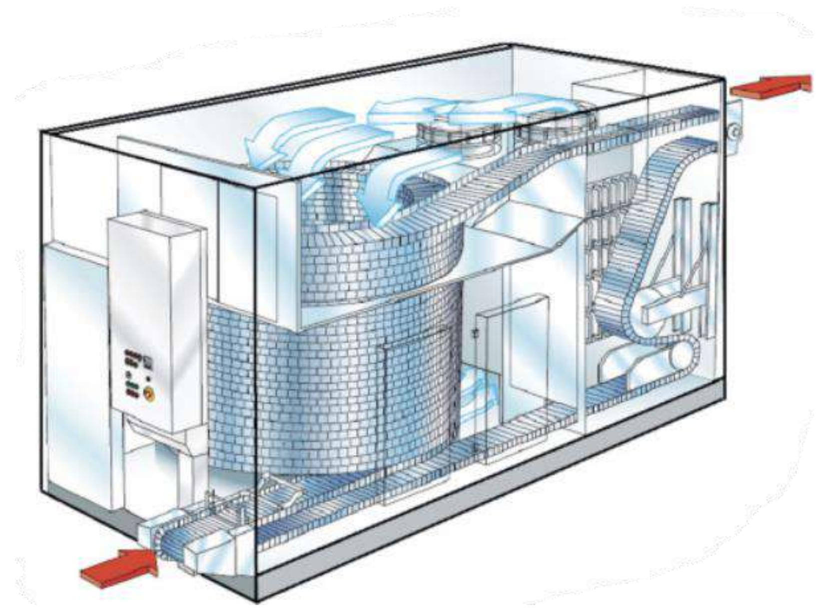




Blast freezers present opportunities for improved performance and efficiency

- Lots of “Brute Force” to achieve product freezing
- Air flow is not optimized (semi not sportscar)
- Often difference between design and actual freezing performance





What are we doing about it?

- <u>Project Goal:</u>

  Reduce the end-use energy consumption, source fuel requirements, and GHG emissions associated with the manufacture of frozen foodstuffs

- <u>Approach:</u>
  - Conduct research to determine desirable characteristics of the next generation of low temperature freezing systems
  - Identify candidate field sites with low-temperature freezing systems
  - Screen for potential EE/performance improvement opportunities
  - Collaborate with end-user to evaluate EE opportunities and implement ECMs with assessment of impact

Research team

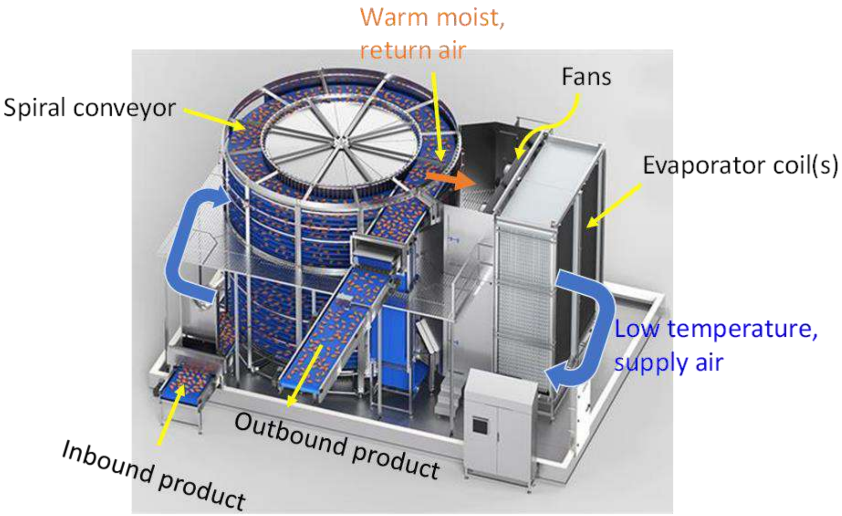
College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

- Eric Alar, Ph.D. Student, Mechanical Engineering
- Tyler Young, M.S. Student, Mechanical Engineering
- Todd Jekel, Assistant Director, IRC
- Marc Claas, Research Engineer, IRC
- Douglas Reindl, Professor & Director, IRC
- Greg Nellis, Professor, Mechanical Engineering





Energy efficiency improvement opportunities

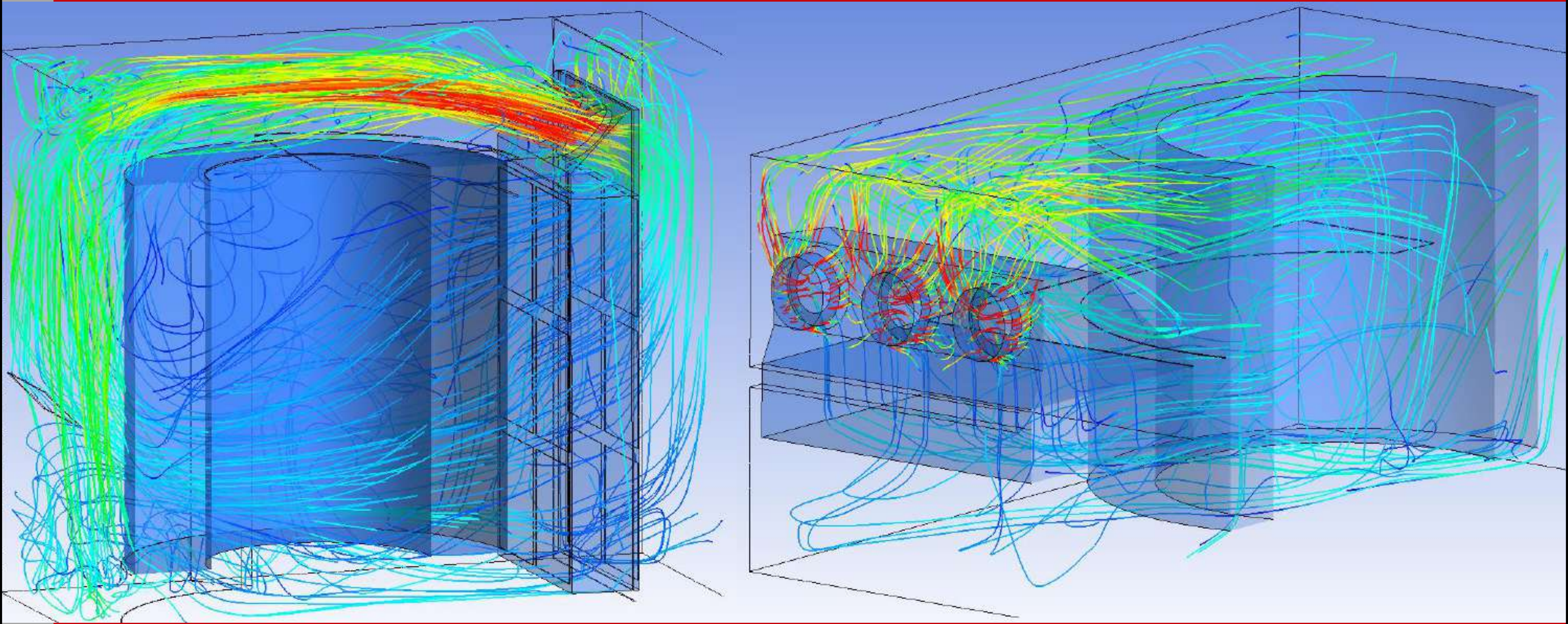


- Food freezing system
  - Improved air-side
    - Air flow patterns
    - Air delivery across product
    - Fan and fan motor efficiency
  - Improved blast freezing enclosures
    - Minimized air infiltration
    - Tighten enclosure
  - Improved evaporator design / integration
    - Optimized coil selection
    - Improved refrigerant feed
    - Improved defrost controls & sequencing

Energy efficiency improvement opportunities

- Refrigeration systems infrastructure
  - Compressor sequencing & control
  - Condenser & head pressure minimum/control
  - Oil cooling
  - Suction pressure setpoints
  - Make-up liquid throttling (single vs. multiple stages)
  - Other

Modeling blast freezers with computational fluid dynamics (CFD) in an effort to quantify potential methods for freezing performance improvement

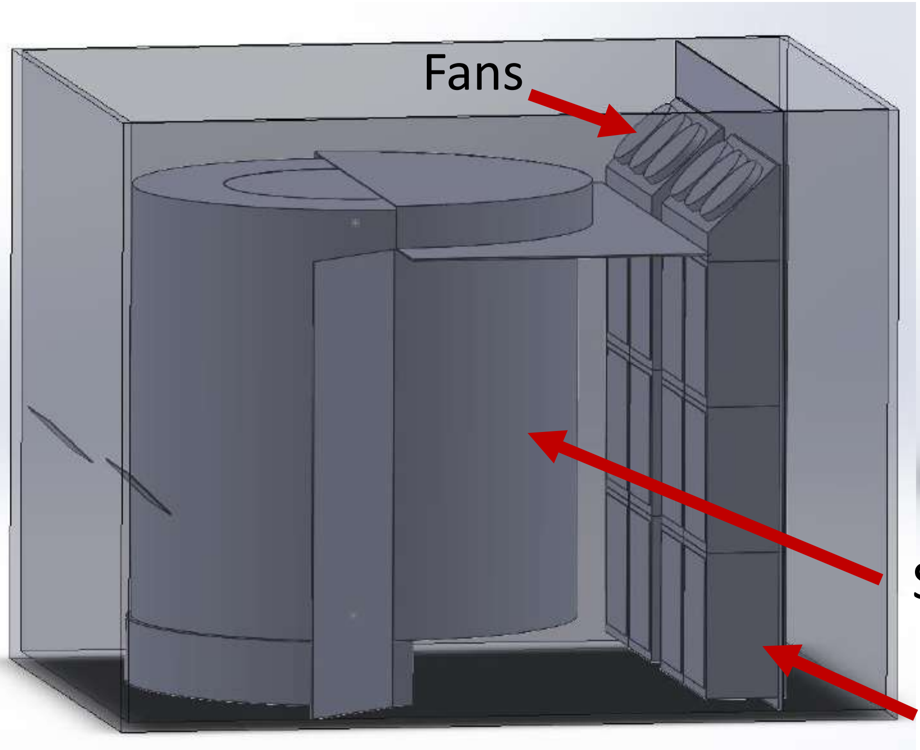


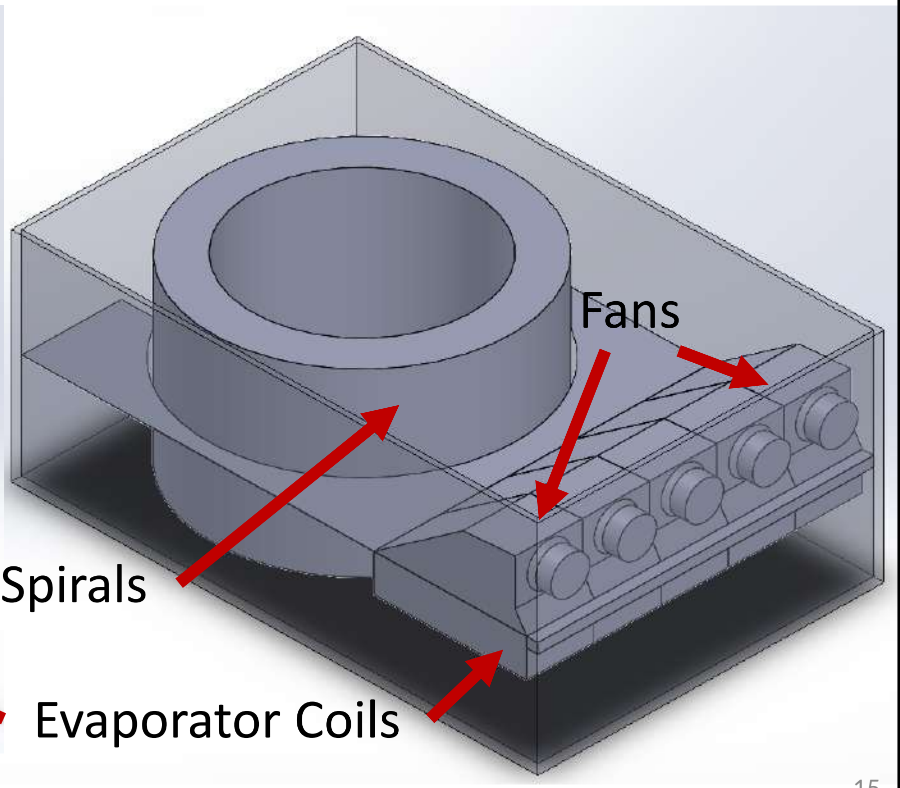
Predicting performance of a freezing system begins with a solid model of the blast freezer

- Plant drawings
- On-site measurements
- Capture major components and design features

Plant A

Plant B

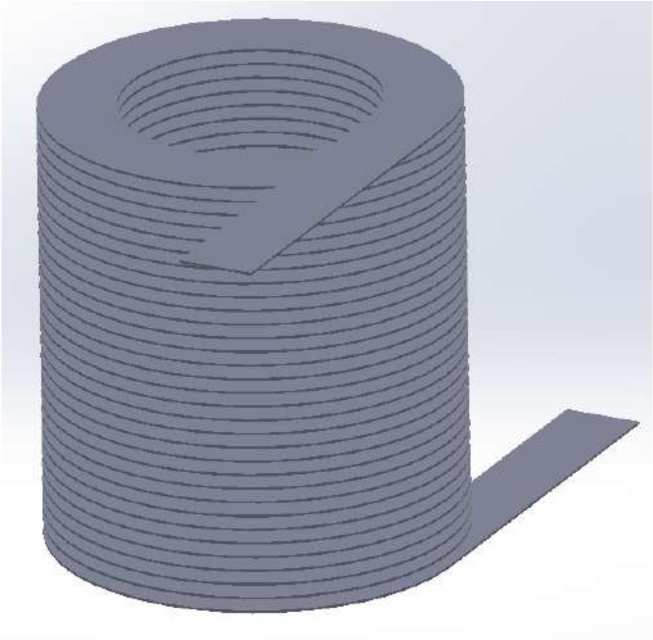




Simplifying complex components – spiral belt

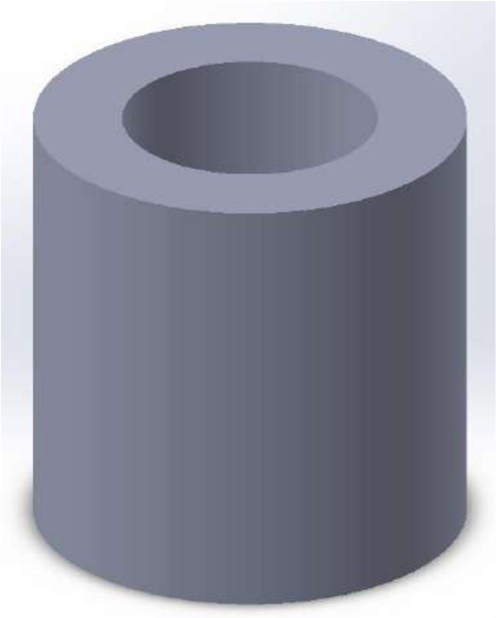
- Use simple spiral to reduce element count

Full-scale semi-real spiral



2.8 million elements with no belt holes

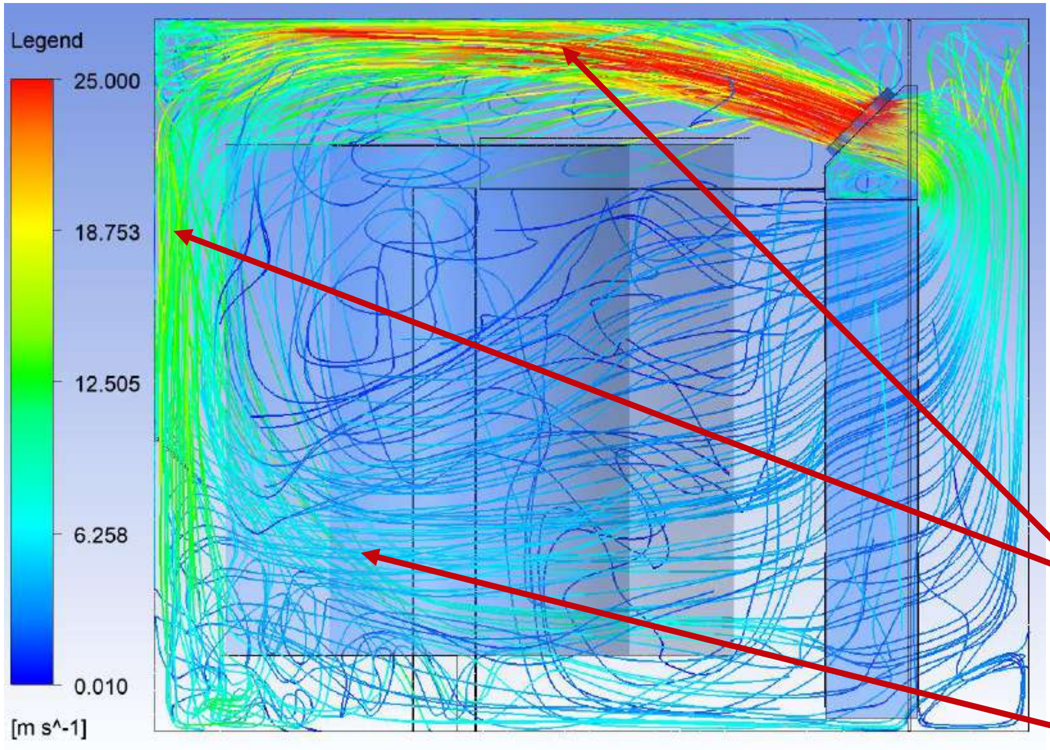
Full-scale simple spiral

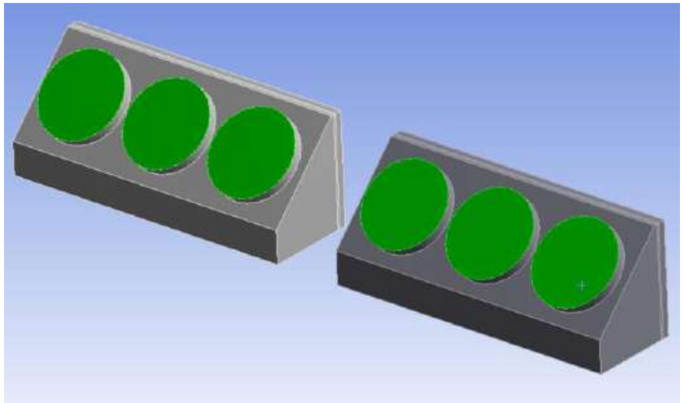


1.3 million elements

Evaluation of airflow inside Plant A’s spiral freezer

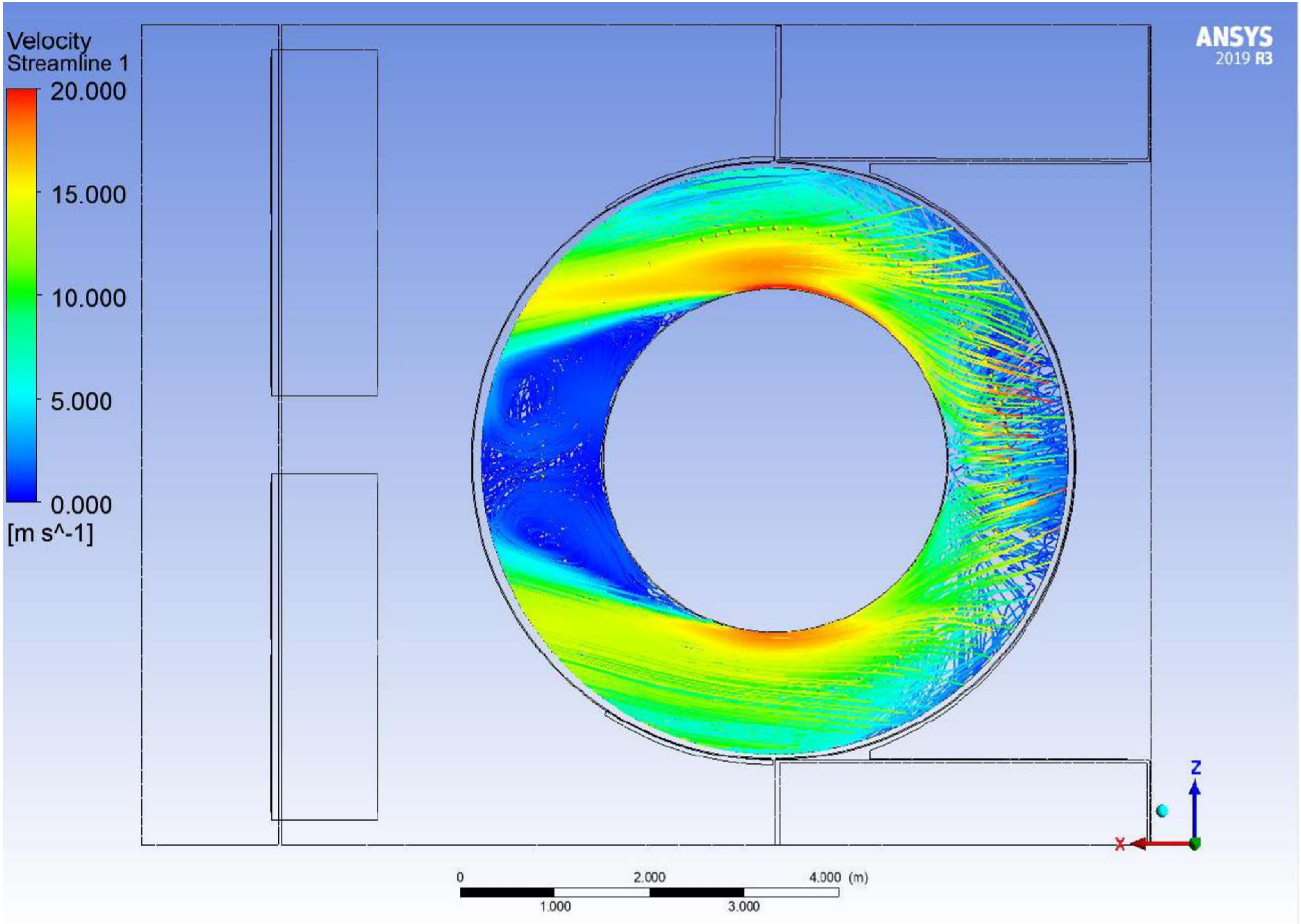
- Plant A’s fan curve data applied to each “Fan” surface



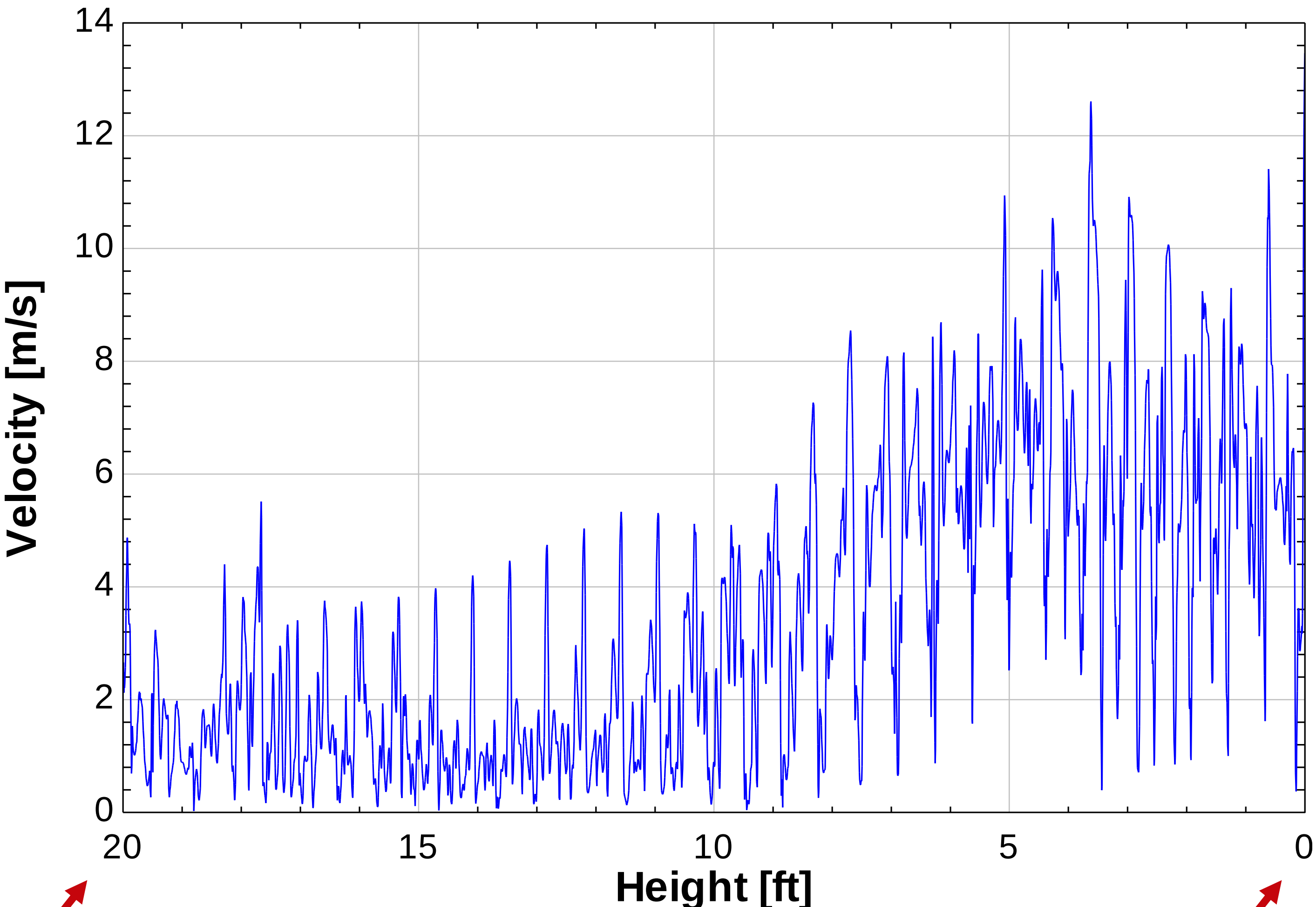


- Majority of airflow hits ceiling and back wall
- Airflow that does hit product is towards the bottom of the spiral where product is colder

Plan view cross section of spiral



Spiral velocity results from CFD analysis

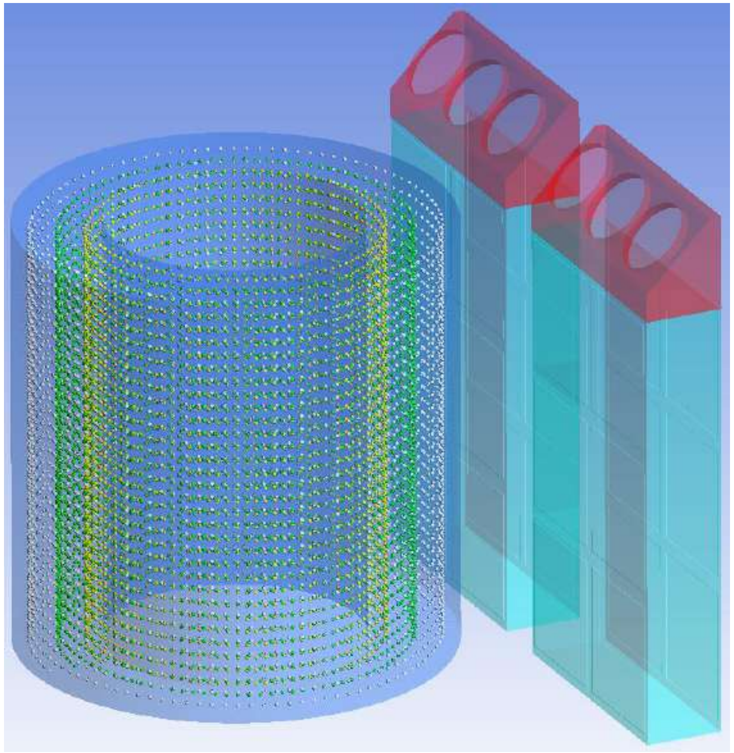


Spiral infeed

Spiral outfeed

Performance metrics

- Spiral point clouds for average velocity and velocity distribution across product
- Average air velocity across evaporator coils
- Throughput rate
- Product normalized energy consumption

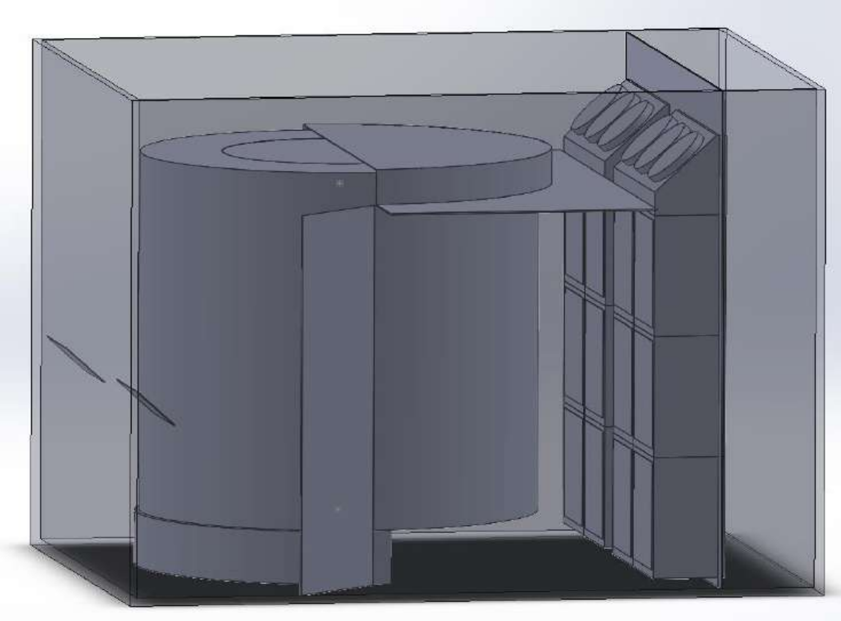


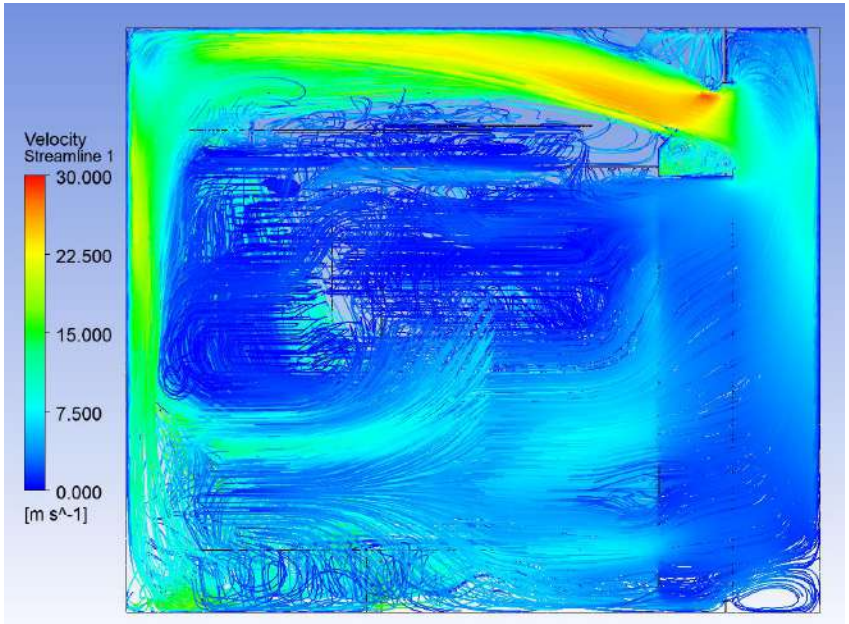
Plant A's current performance

	Avg. Velocity [ft/min] {m/s}
Spiral	672 {3.42}
Coils	552 {2.81}

Energy per Product [Btu/prod]	Throughput [prod/min]
173	145

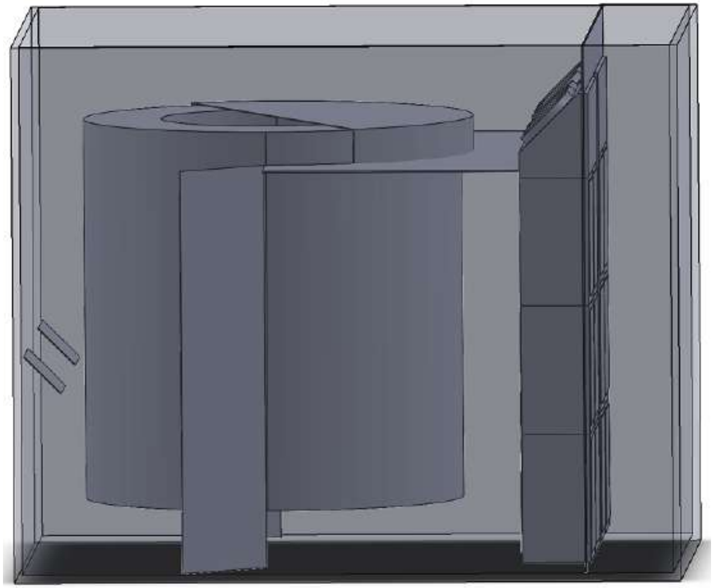
Existing spiral freezer (Plant A)

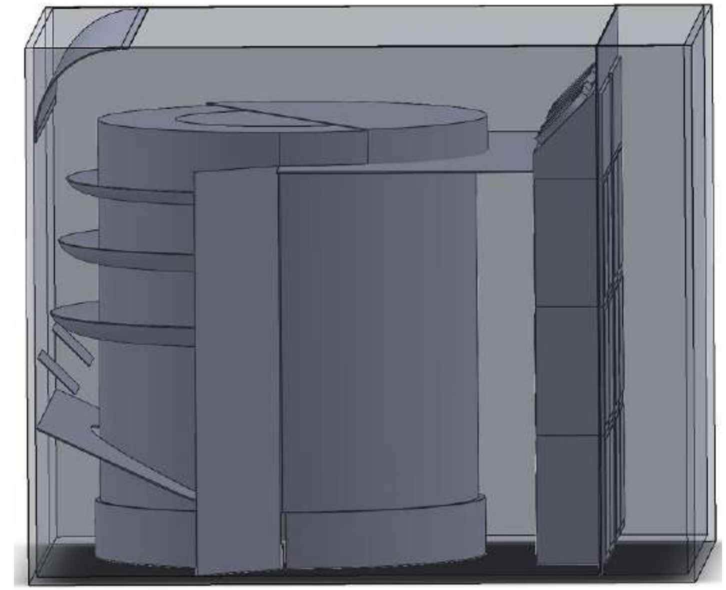


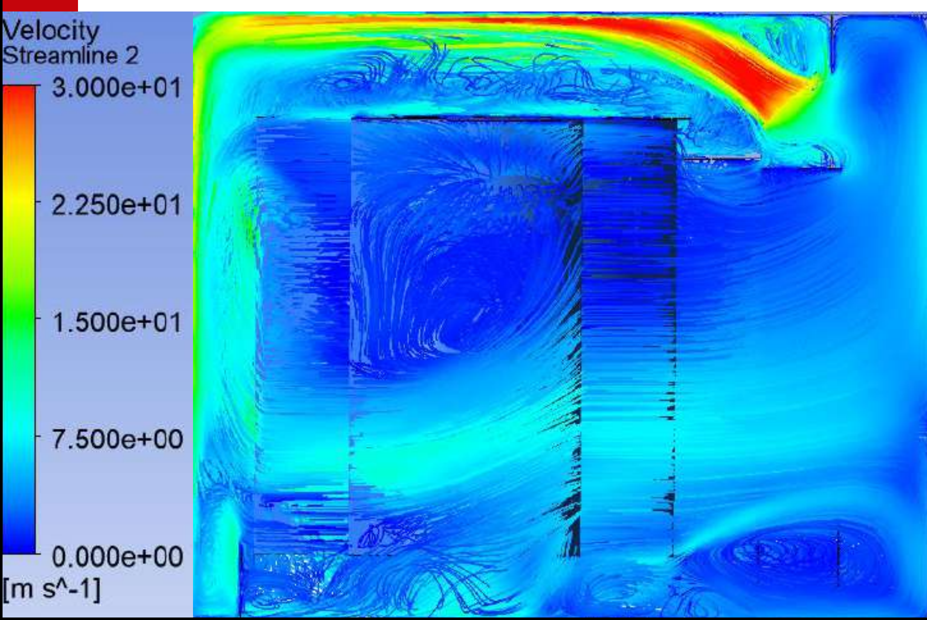


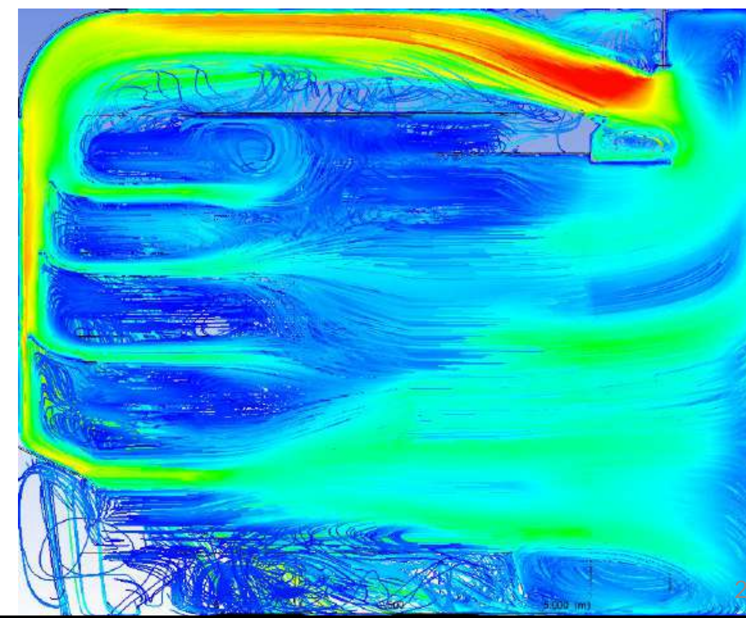
Average Velocity	Spiral	Coils
[m/s]	3.42	2.81
[fpm]	672	552

Air-side modifications to improve performance

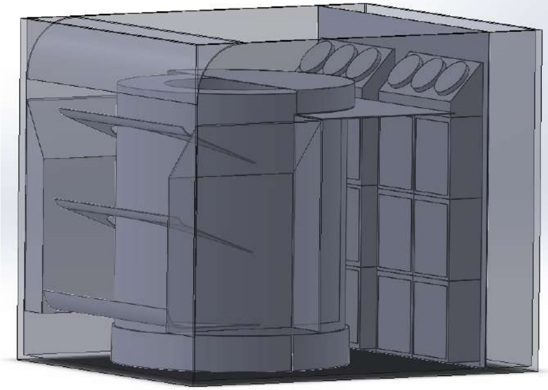








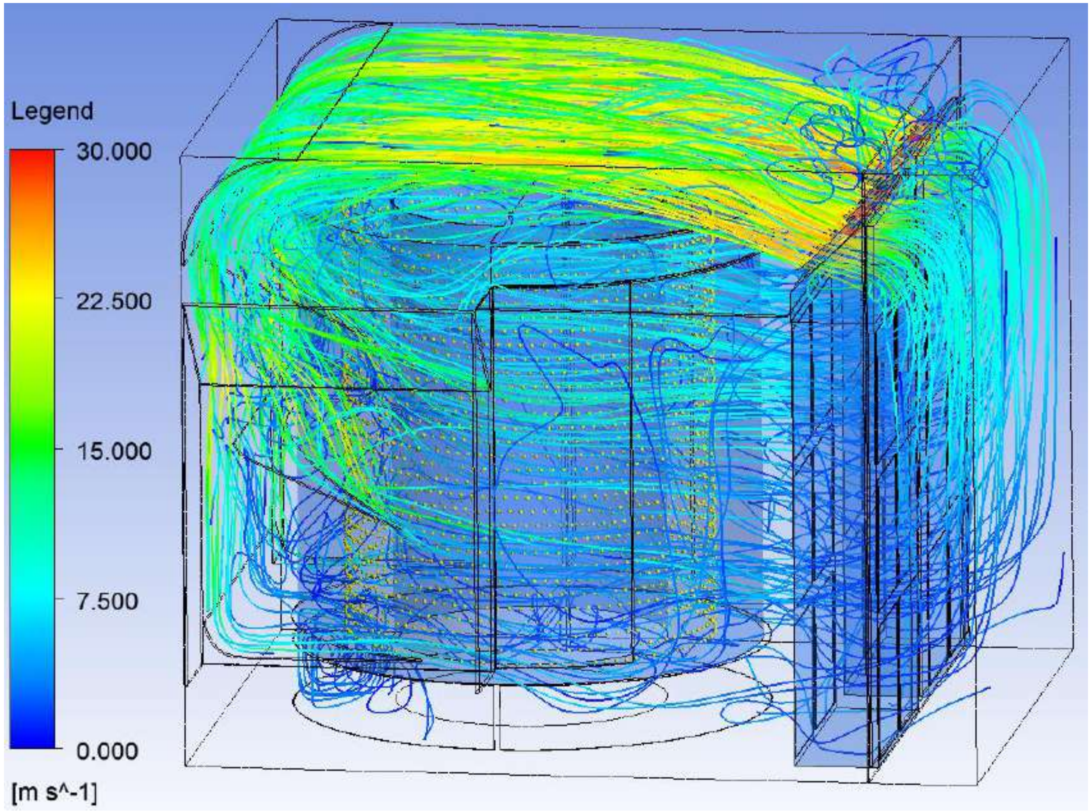
Baffling modifications for Plant A



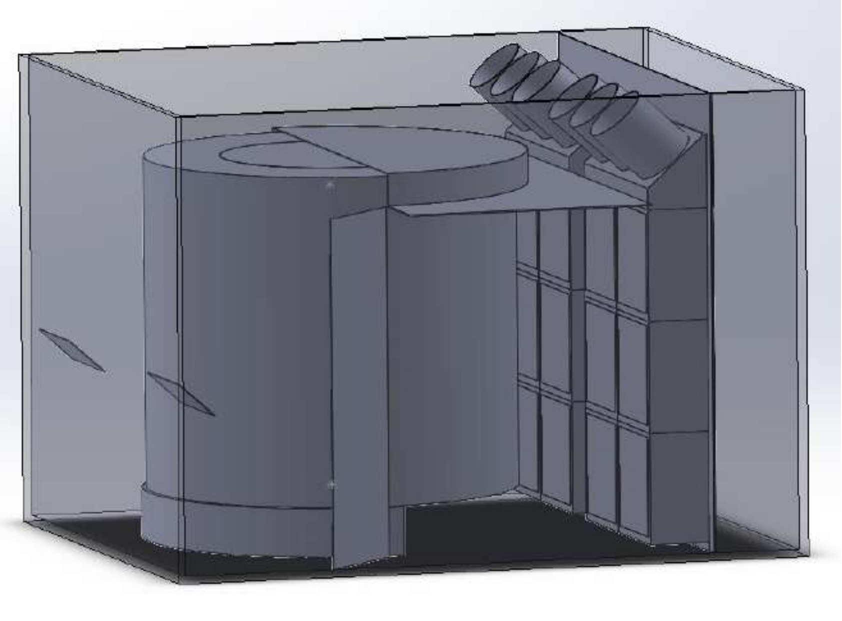
- Same fans currently used by Plant A
- Top portion of spiral now receives greatest flow

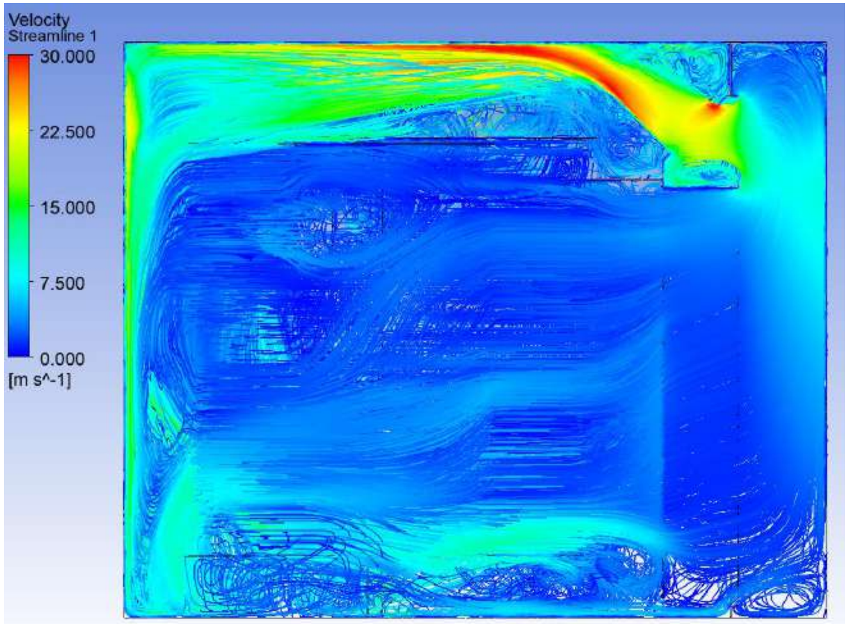
	Avg. Velocity, [ft/min] {m/s}
Spiral	825 {4.19}
Coils	492 {2.50}

Energy Per Product [Btu/prod]	Throughput [prod/min]
154 (with baffling)	175
173 (Plant A)	145
Percent Change	
-11.0%	20.8%



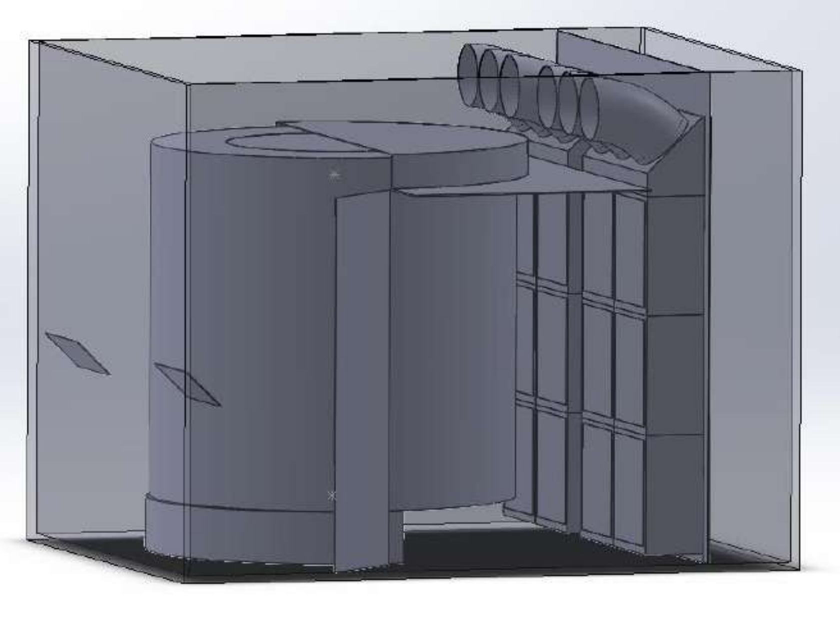
4 ft straight long throw adapter

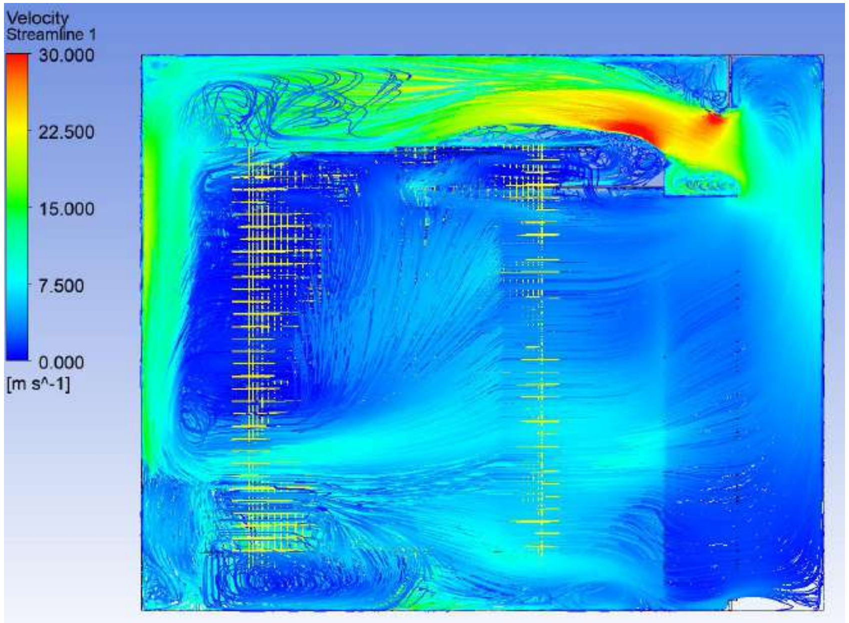




Average Velocity	Spiral	Coils
[m/s]	3.00	2.12
[fpm]	591	417

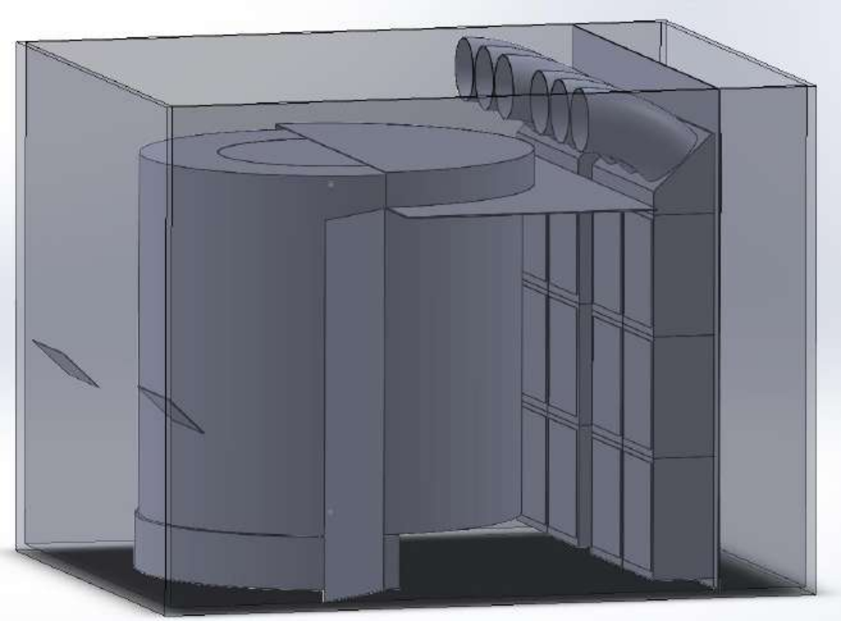
4 ft bent long throw adapter

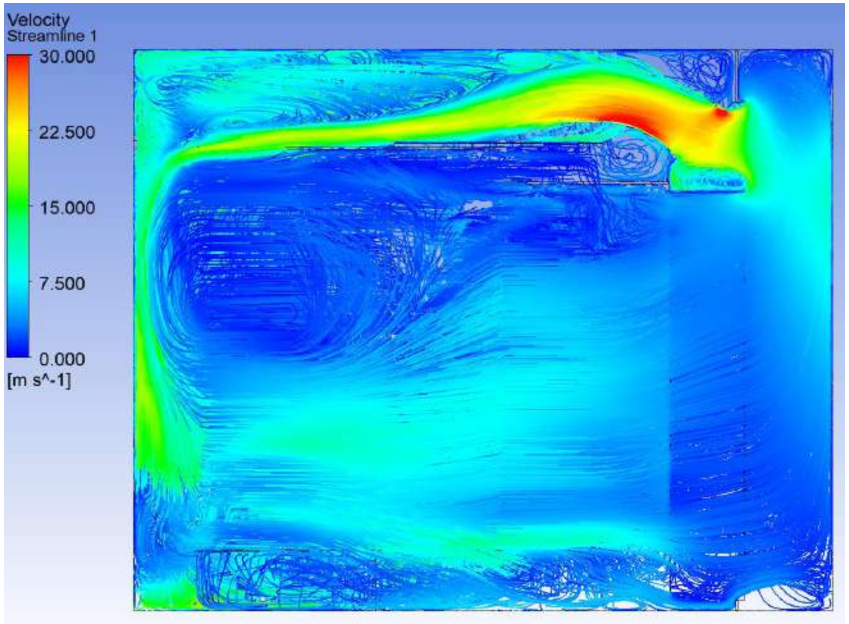




Average Velocity	Spiral	Coils
[m/s]	3.59	2.61
[fpm]	707	514

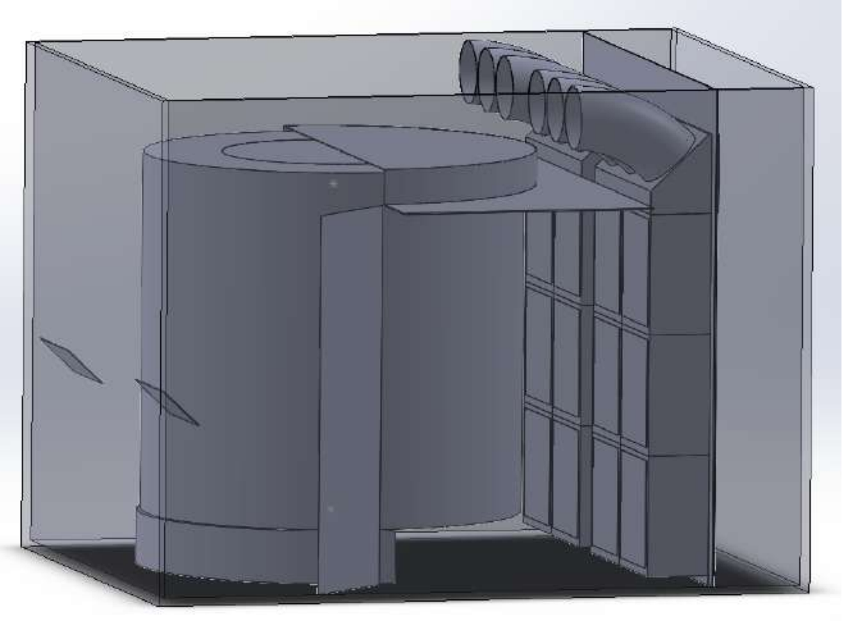
4.75 ft bent long throw adapter

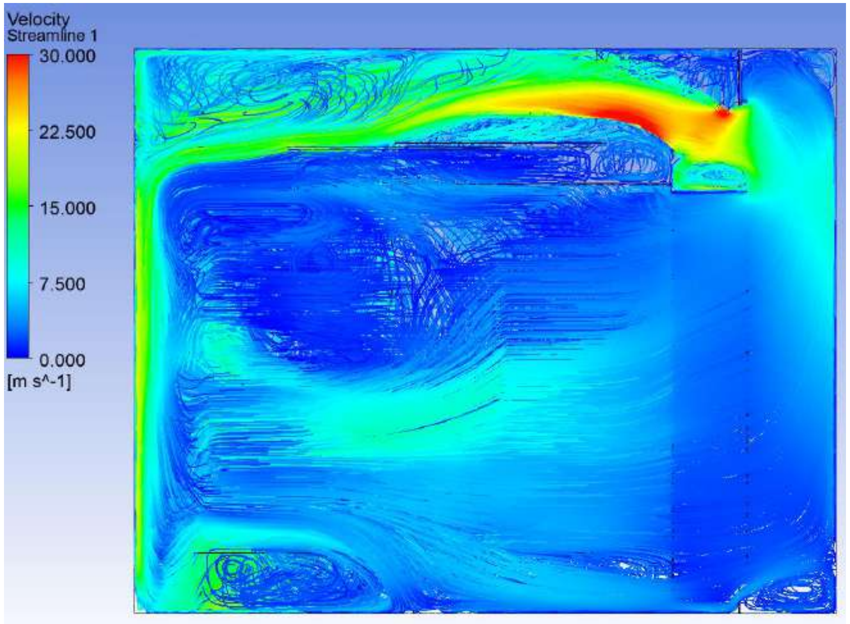




Average Velocity	Spiral	Coils
[m/s]	3.58	2.49
[fpm]	705	490

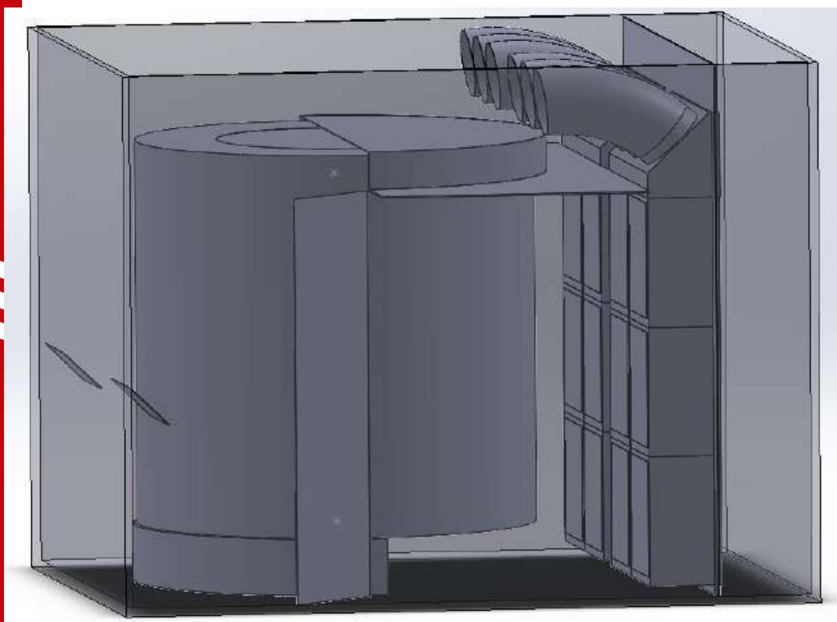
5 ft bent long throw adapter

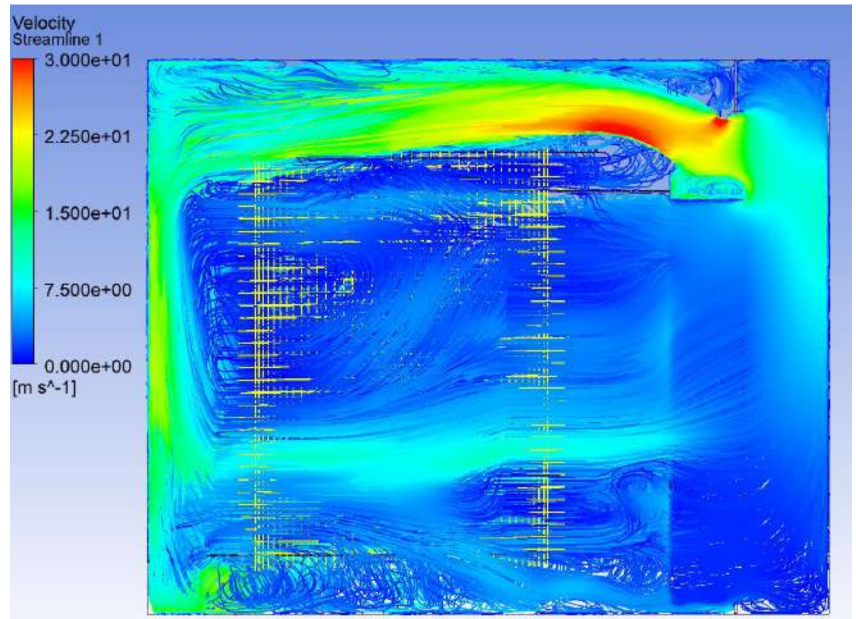




Average Velocity	Spiral	Coils
[m/s]	3.74	2.41
[fpm]	736	474

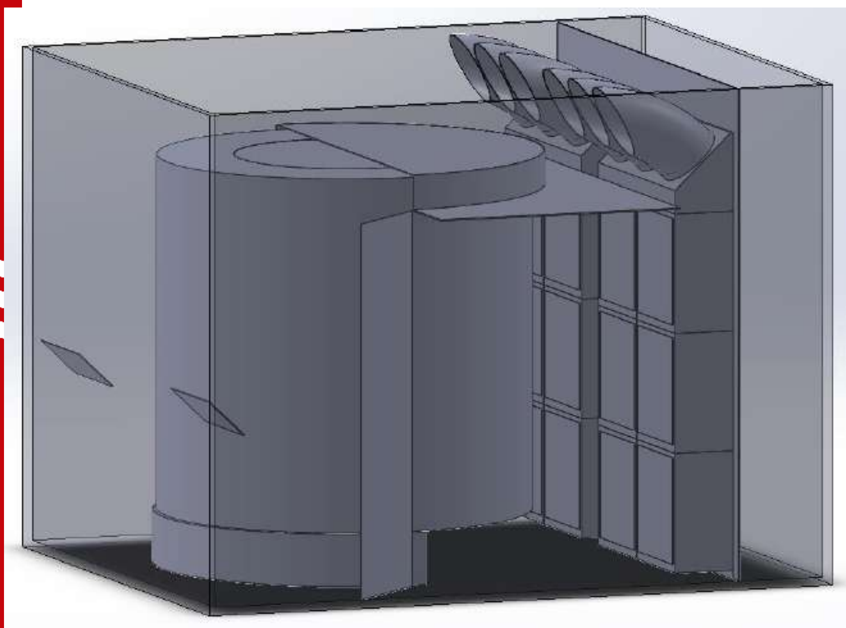
6 ft bent long throw adapter

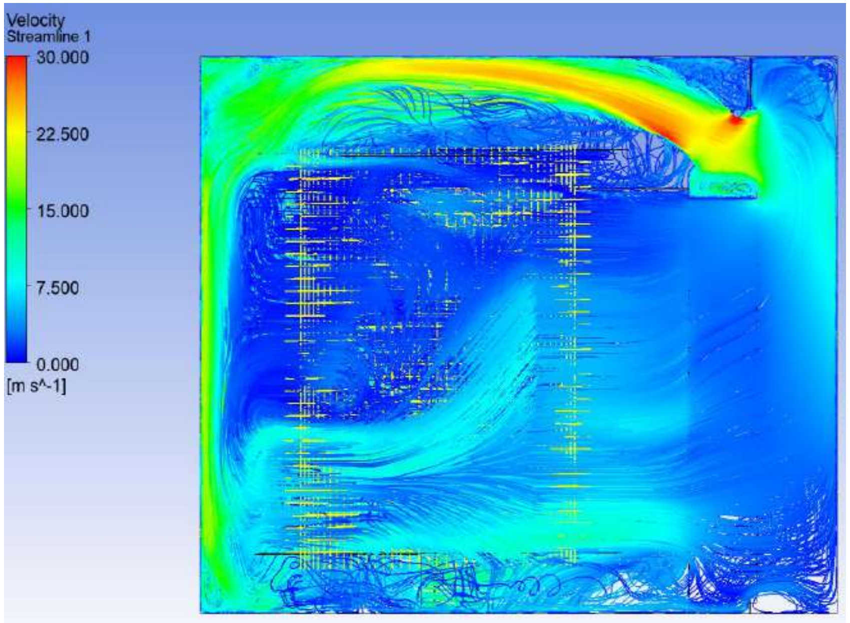




Average Velocity	Spiral	Coils
[m/s]	3.30	2.54
[fpm]	650	500

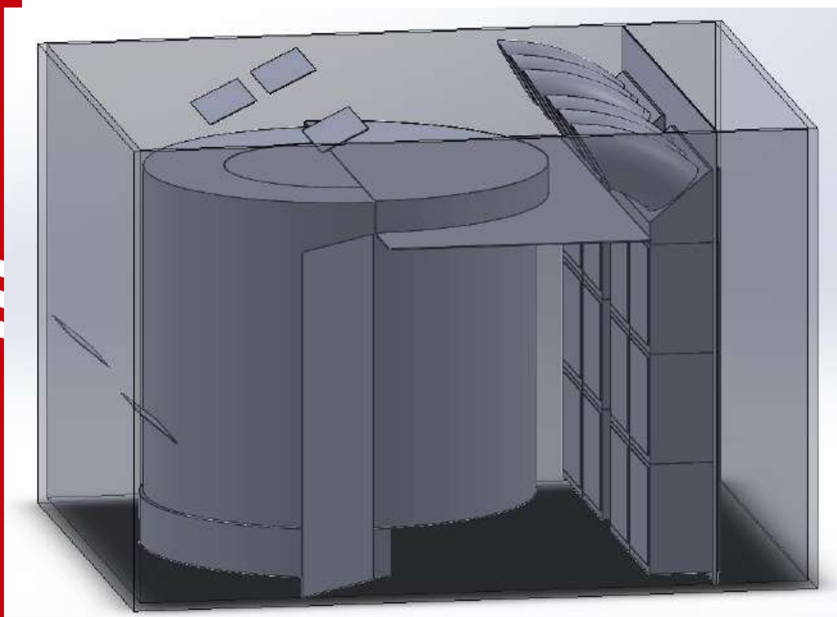
5 ft bent & chamfered long throw adapter

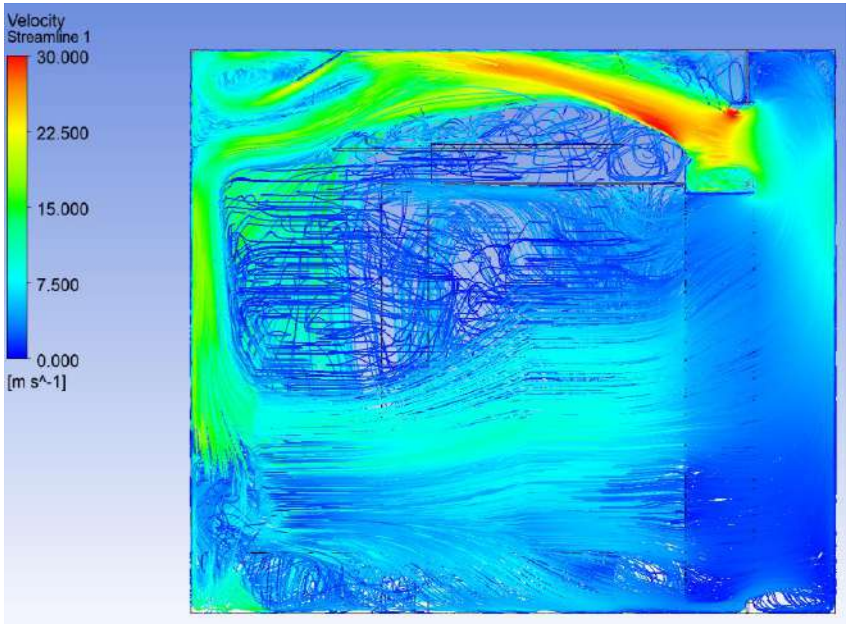




Average Velocity	Spiral	Coils
[m/s]	3.69	2.48
[fpm]	727	488

5 ft bent & chamfered LTA with additional baffing

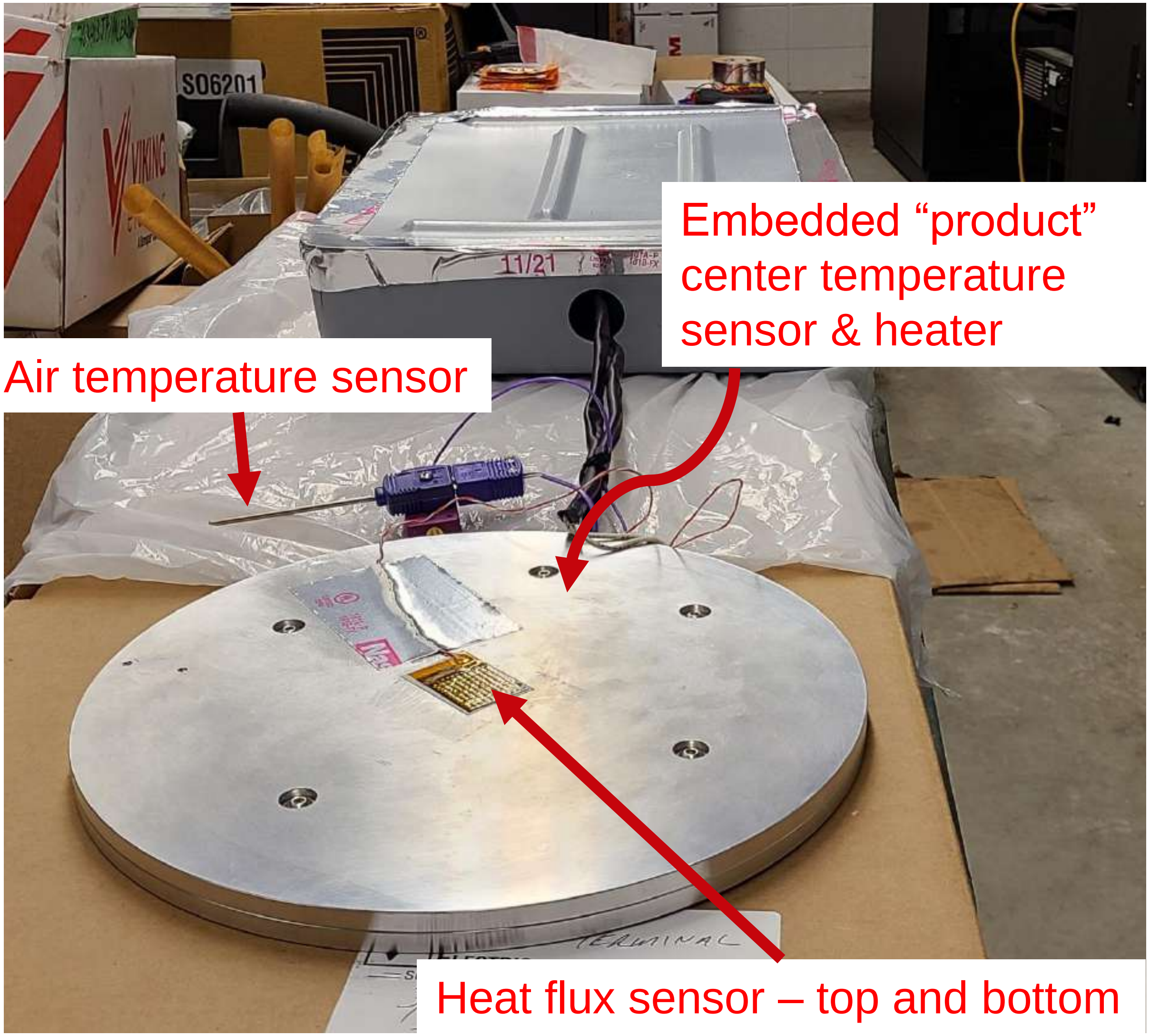




Average Velocity	Spiral	Coils
[m/s]	3.33	2.48
[fpm]	656	488

Are the CFD model results believable?

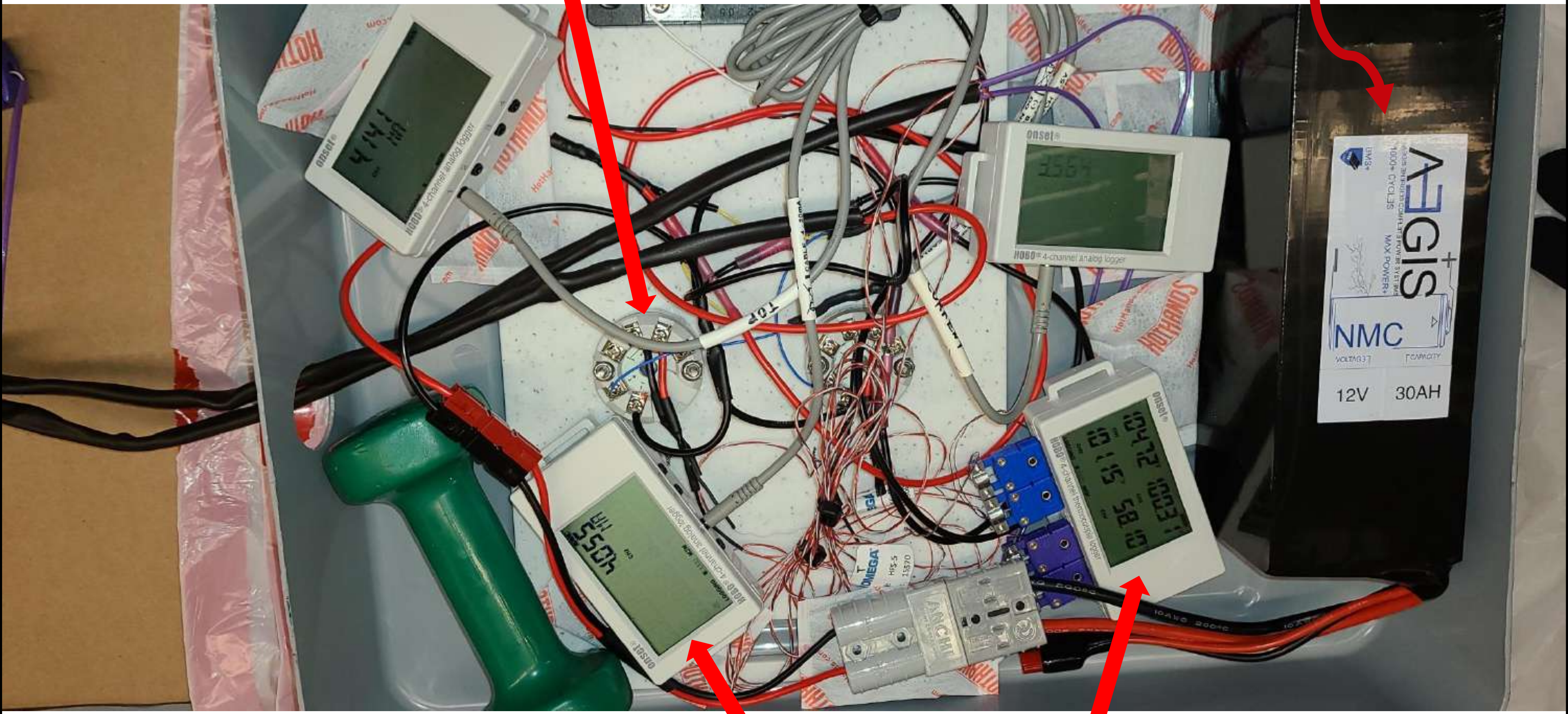
Surrogate product – “phantom”




Data logging equipment
SCL 4 16 G1
35K
TERMINAL-ANDRAE

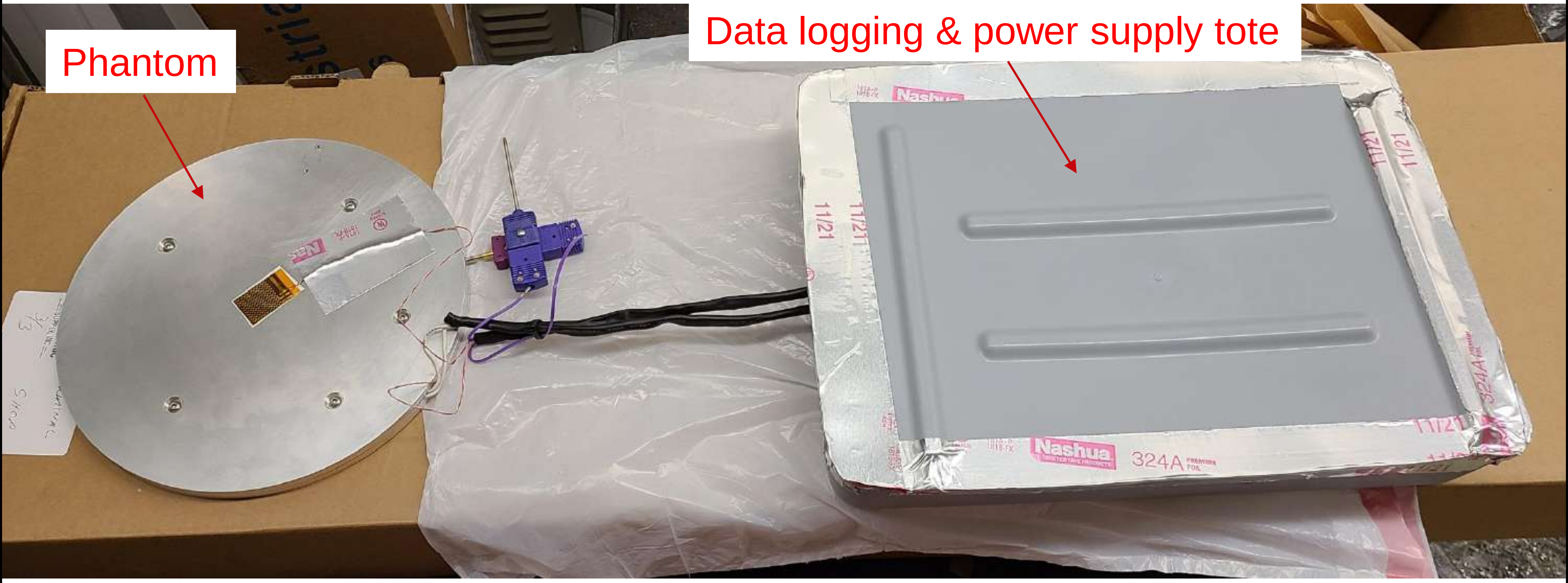
mV DC to 4-20 mA transmitters

DC battery to power heater and equipment



Various data loggers

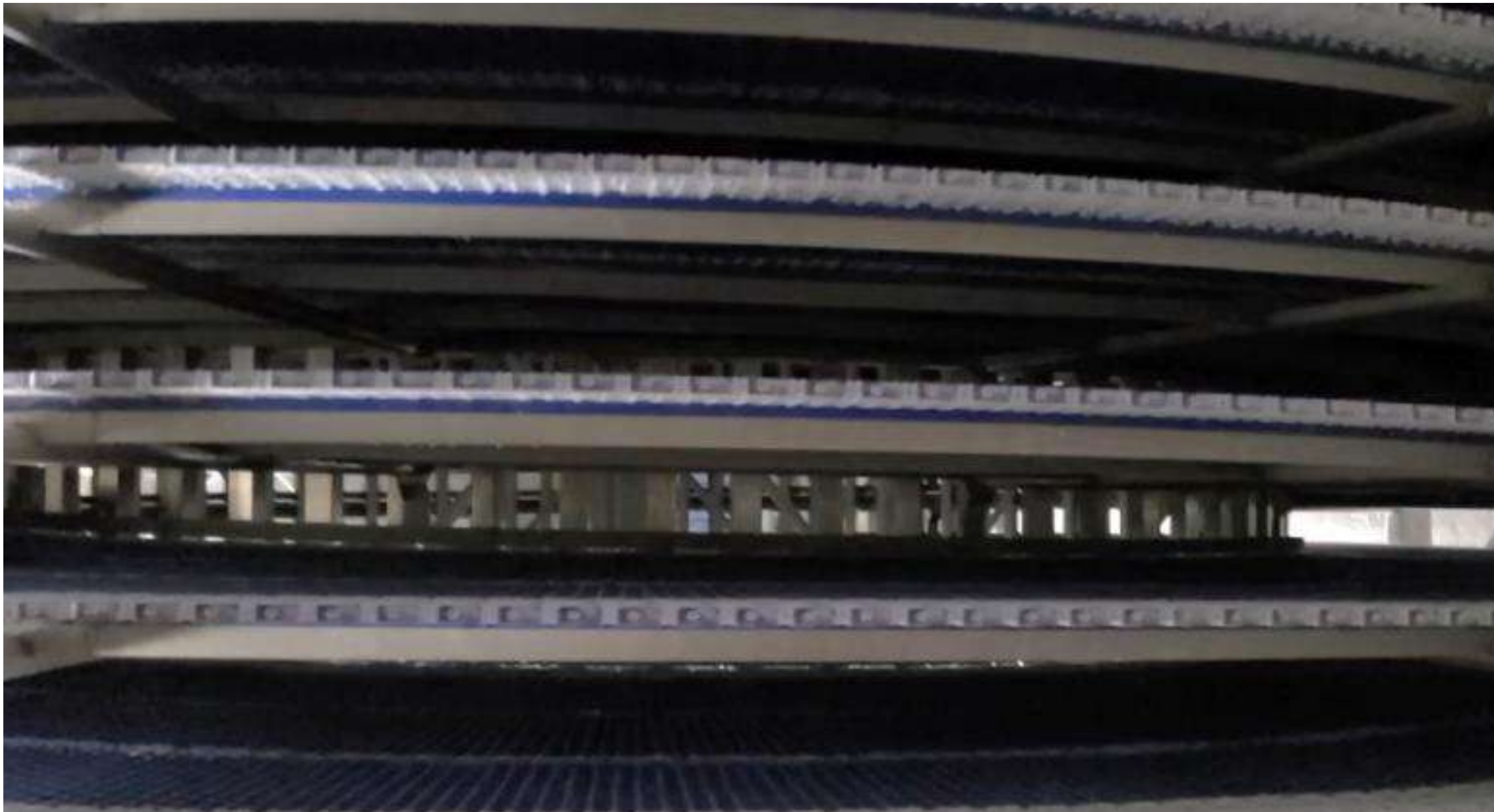
The Phantom



The Phantom is an instrument that simulates the product being frozen for the purpose of gathering heat transfer data within the operating blast freezing system

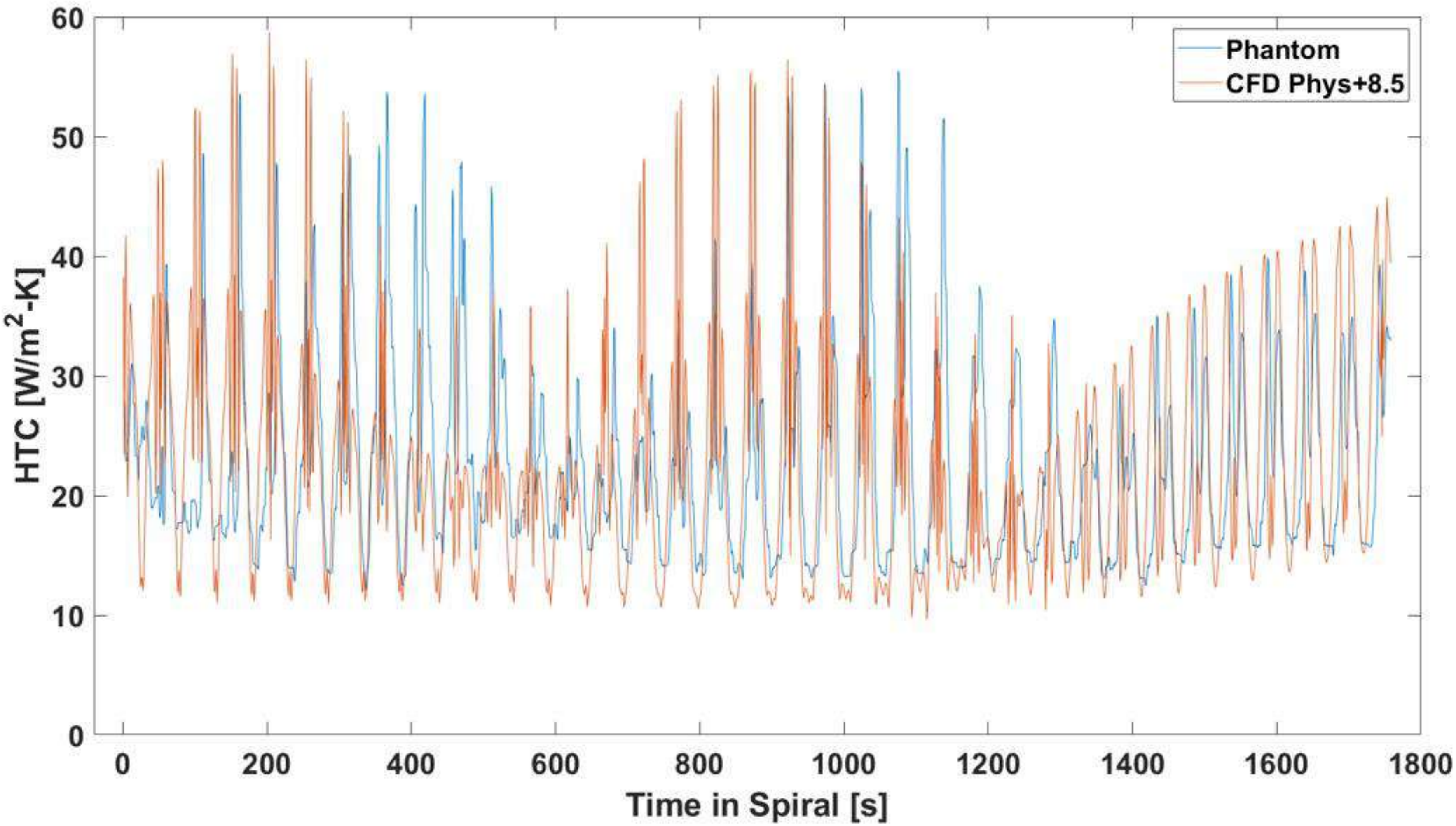
Preparing to run the Phantom

Dry run of the phantom in a spiral freezer



Phantom running during production

Comparing CFD with Phantom results

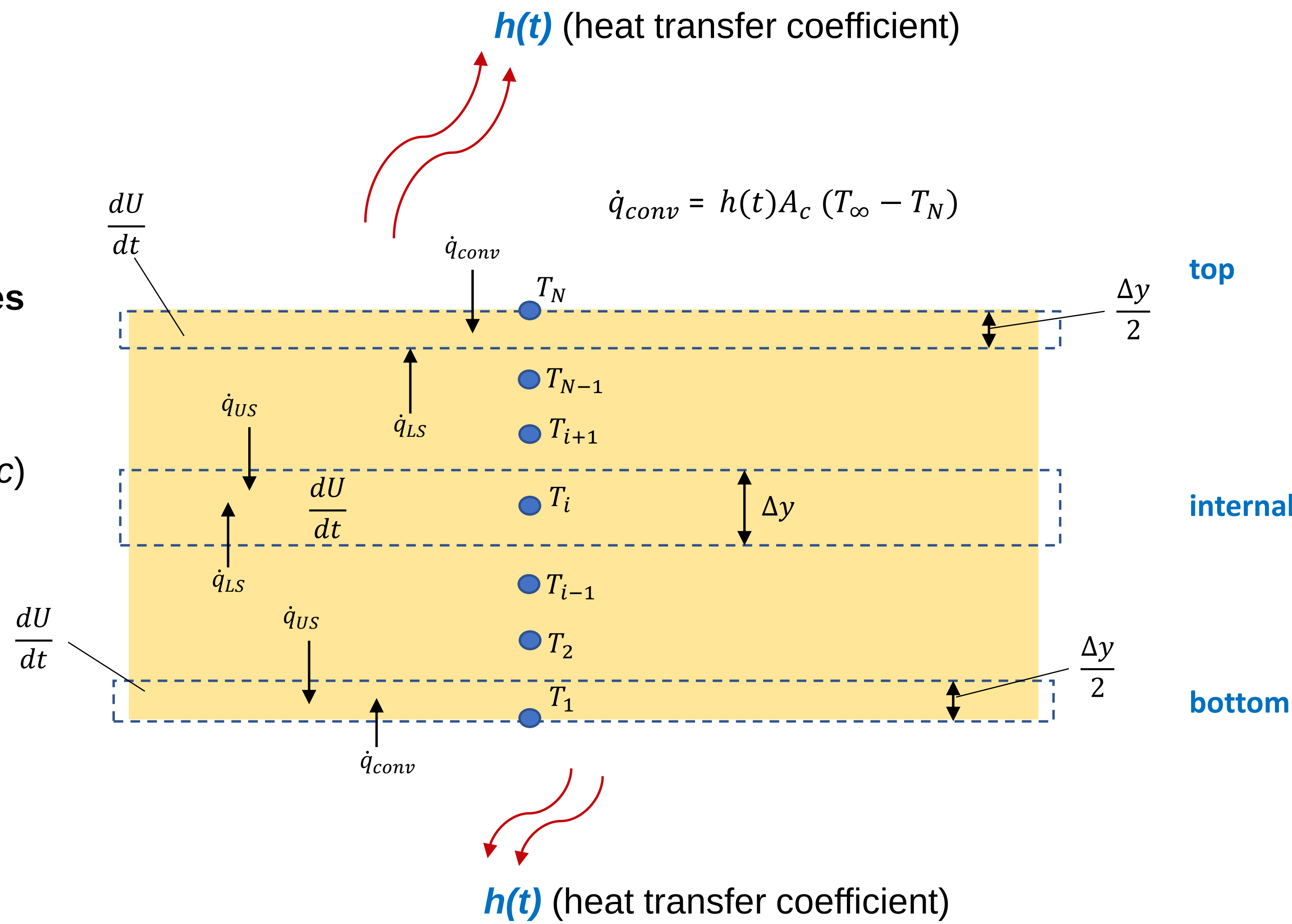


What about the product itself?

Thermal model of food product being frozen

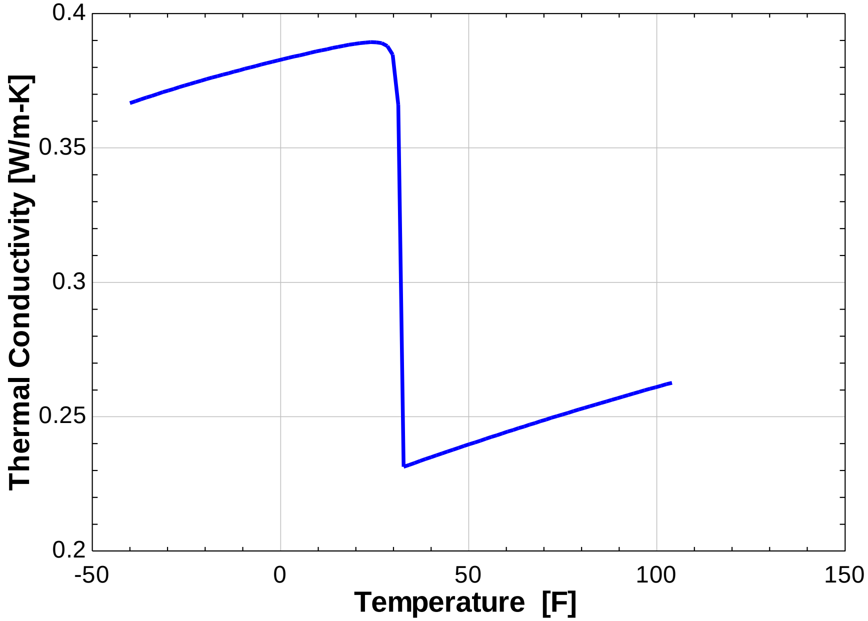
Needed Properties

1. Density (ρ)
2. Thermal conductivity (k)
3. Heat capacity (c)
4. Water content
5. Air voids

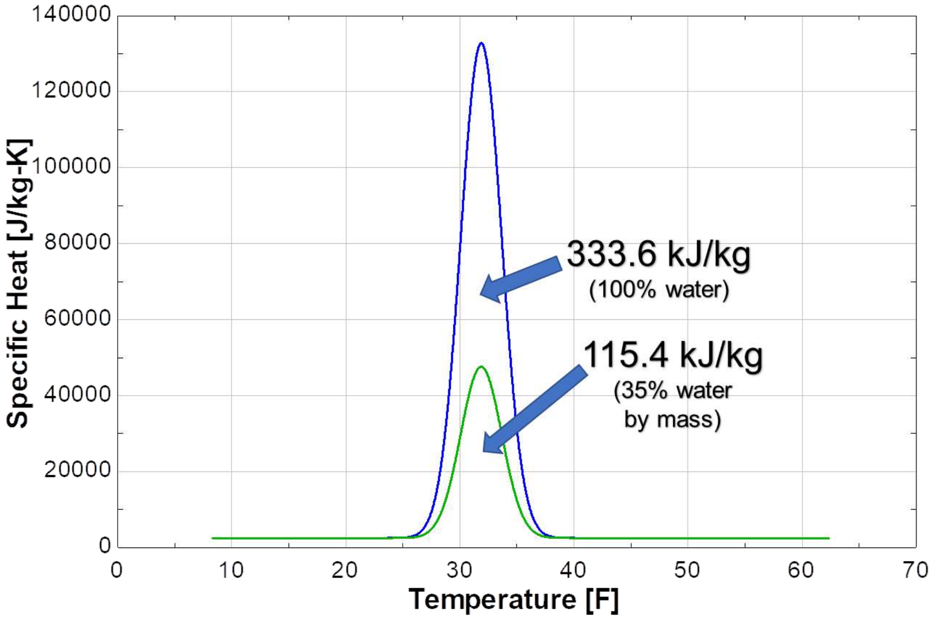


Product thermal properties

Thermal conductivity (*k*)



Heat capacity (*c*)

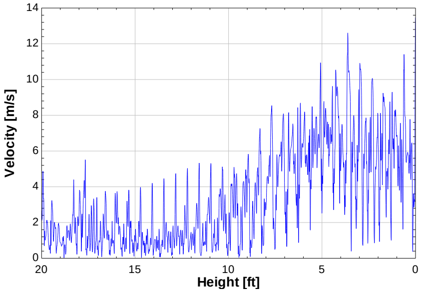


Density (ρ) = constant = 533.8 kg/m^3

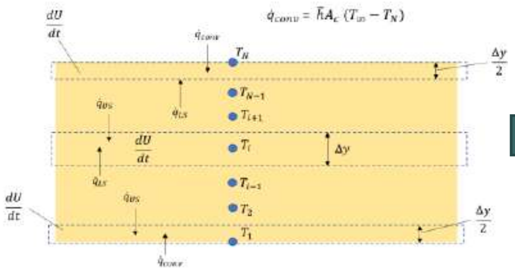
$$c = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(\frac{-1}{2}\left(\frac{T-\mu}{\sigma}\right)^2\right)} 113100 \left[\frac{J}{kg}\right] + 2460 \left[\frac{J}{kg}\right]$$

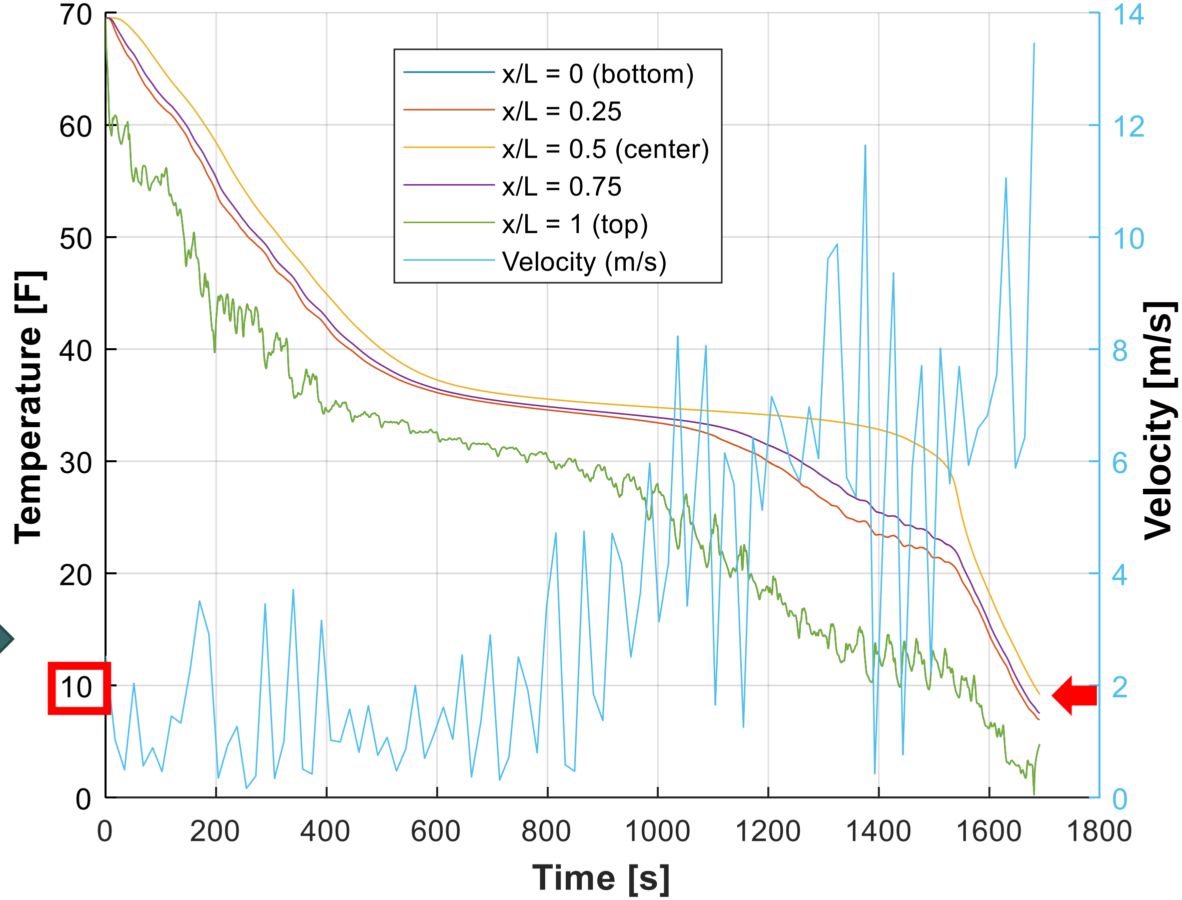
Product thermal model results

Velocity from CFD

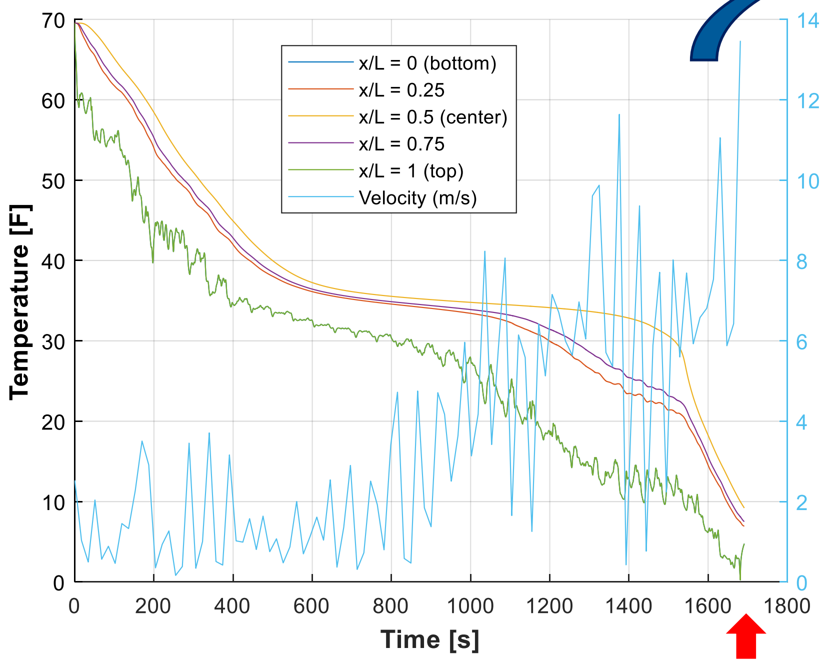


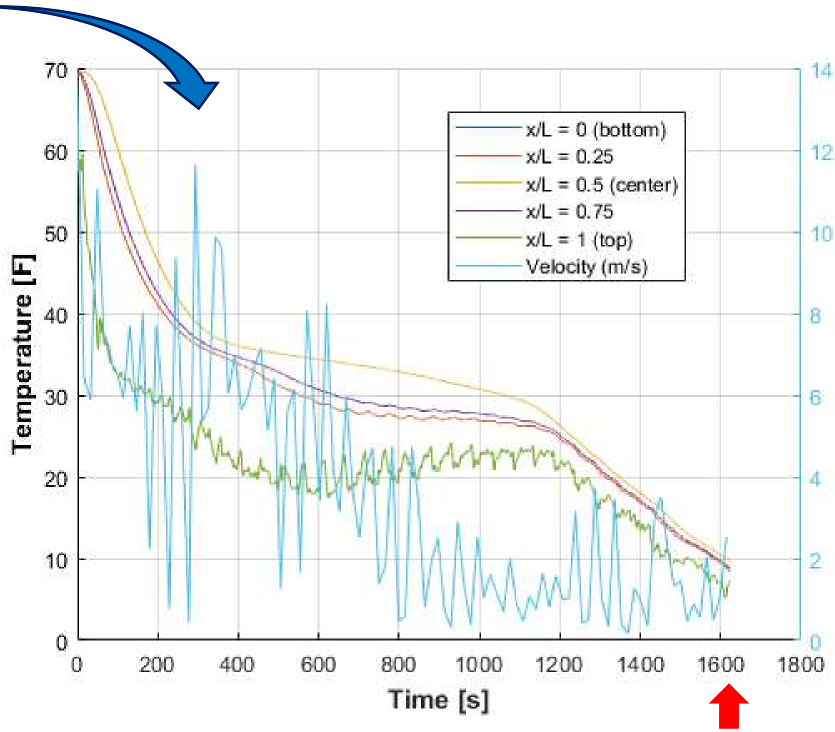
Thermal model





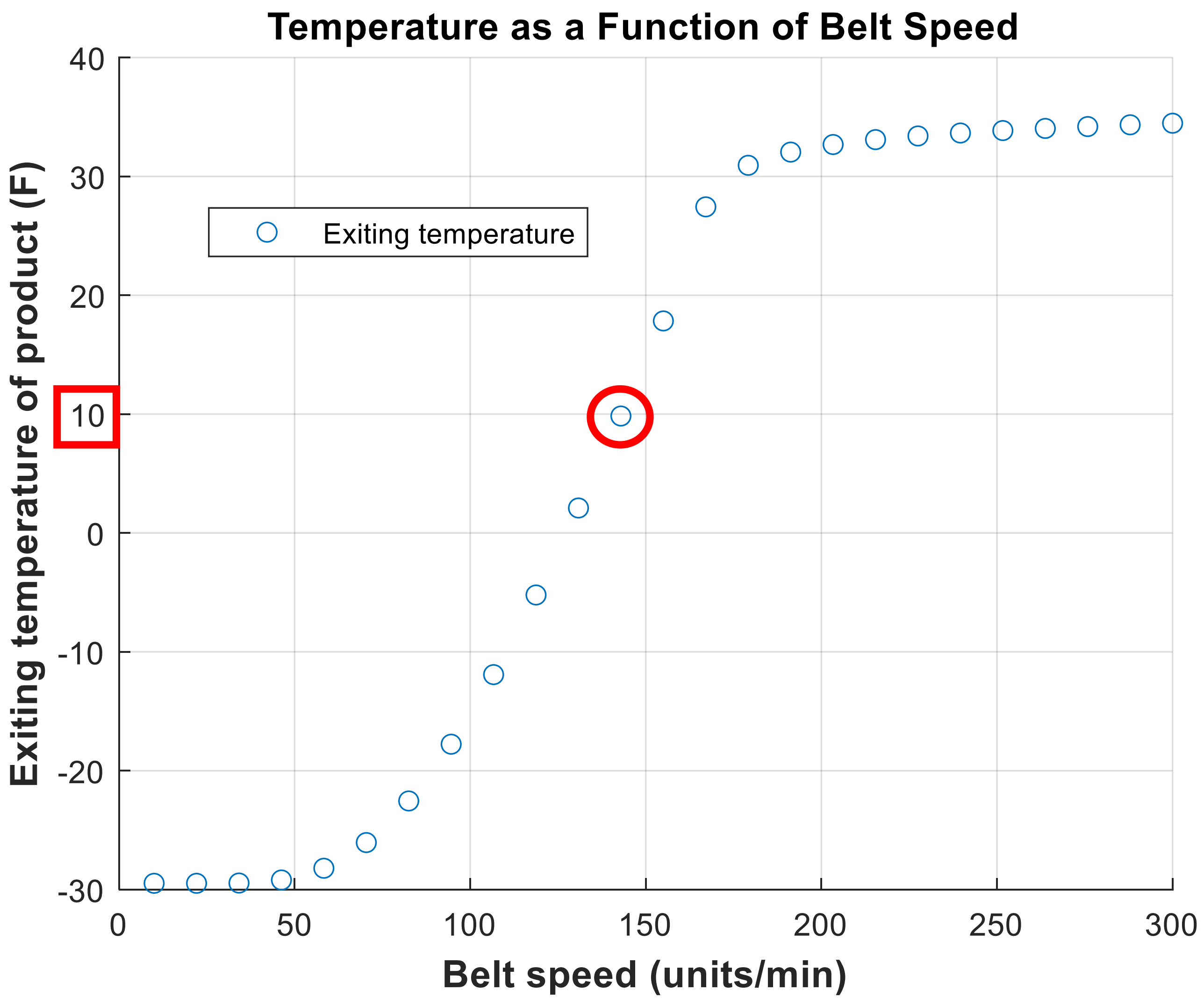
Effect of velocity on product





4.2% improvement

Exiting temperature vs belt speed



Optimizing freezing process

Step 1-A

Initial velocity distribution

Step 1-B

Adjust belt speed that achieves temperature set point (ΔT) at exit. Output is velocity profile and belt speed

Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1453.6273 seconds
Elapsed time is 2.391258 seconds.
Temperature delta T: 10.4441 @ a belt speed of 164.8625
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1535.9025 seconds
Elapsed time is 2.705465 seconds.
Temperature delta T: 6.7566 @ a belt speed of 135.8625
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1571.7726 seconds
Elapsed time is 2.586108 seconds.
Temperature delta T: 2.7032 @ a belt speed of 142.8406
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1522.6418 seconds
Elapsed time is 2.524399 seconds.
Temperature delta T: 5.8864 @ a belt speed of 157.3406
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1605.9942 seconds
Elapsed time is 2.509586 seconds.
Temperature delta T: 0.62127 @ a belt speed of 146.3977
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1571.7726 seconds
Elapsed time is 2.554558 seconds.
Temperature delta T: 2.7032 @ a belt speed of 142.8406
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1616.012 seconds
Elapsed time is 2.485224 seconds.
Temperature delta T: 0.43622 @ a belt speed of 148.1932
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1596.6667 seconds
Elapsed time is 2.450556 seconds.
Temperature delta T: 1.5034 @ a belt speed of 150
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1612.8954 seconds
Elapsed time is 2.501893 seconds.
Temperature delta T: 0.093673 @ a belt speed of 147.294
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1606.0127 seconds
Elapsed time is 2.502074 seconds.
Temperature delta T: 0.62118 @ a belt speed of 146.3977
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1615.8581 seconds
Elapsed time is 2.505313 seconds.
Temperature delta T: 0.17078 @ a belt speed of 147.7432
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10F): 1614.3259 seconds
Elapsed time is 2.552271 seconds.
Temperature delta T: 0.022483 @ a belt speed of 147.4904

Iteration #1

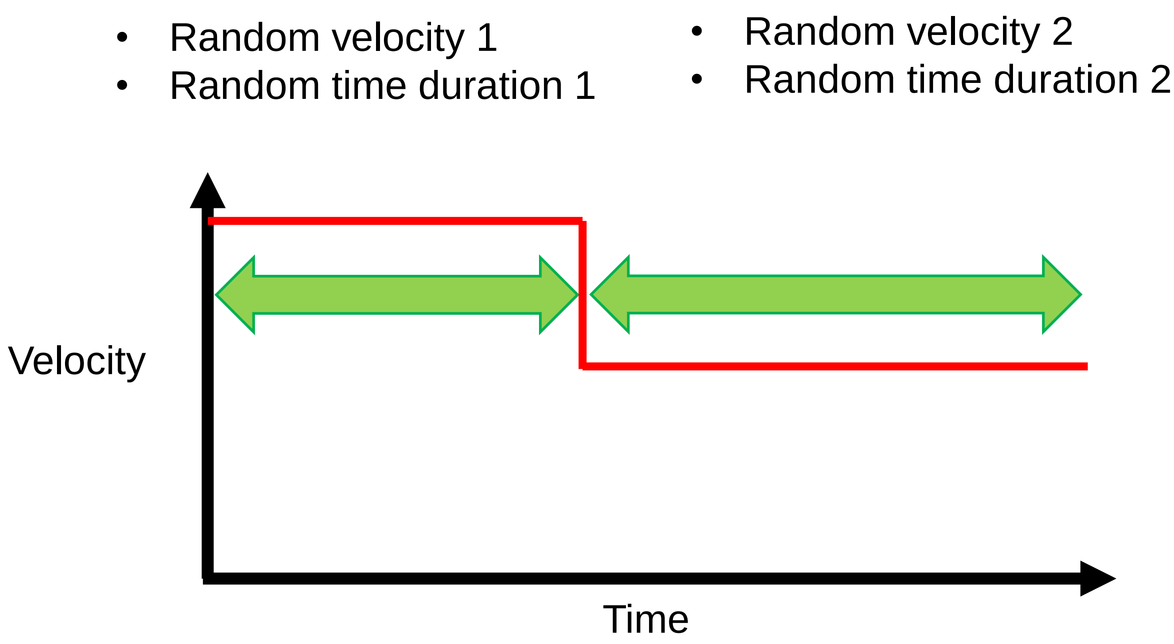
Iteration #2

…3

…4 etc.

Optimum belt speed

Monte Carlo simulation with varying velocity distribution (two step/regime) across product



Belt speed optimizer process flow

Monte Carlo Pareto front simulation to identify efficient velocity profile regime values with constrained mean and limits that maximizes belt speed

Step 1-A

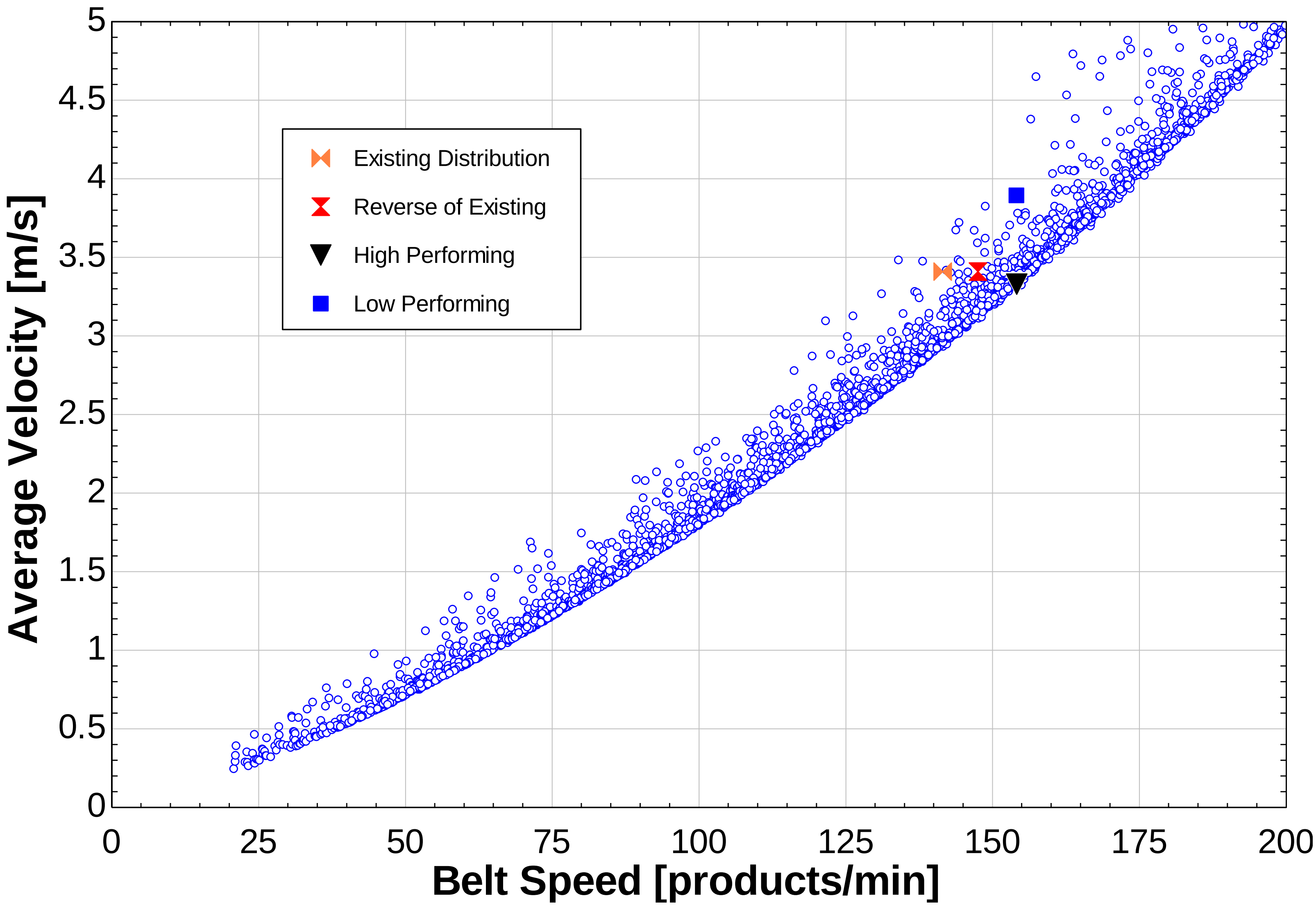
Generate random velocity distribution

Step 1-B

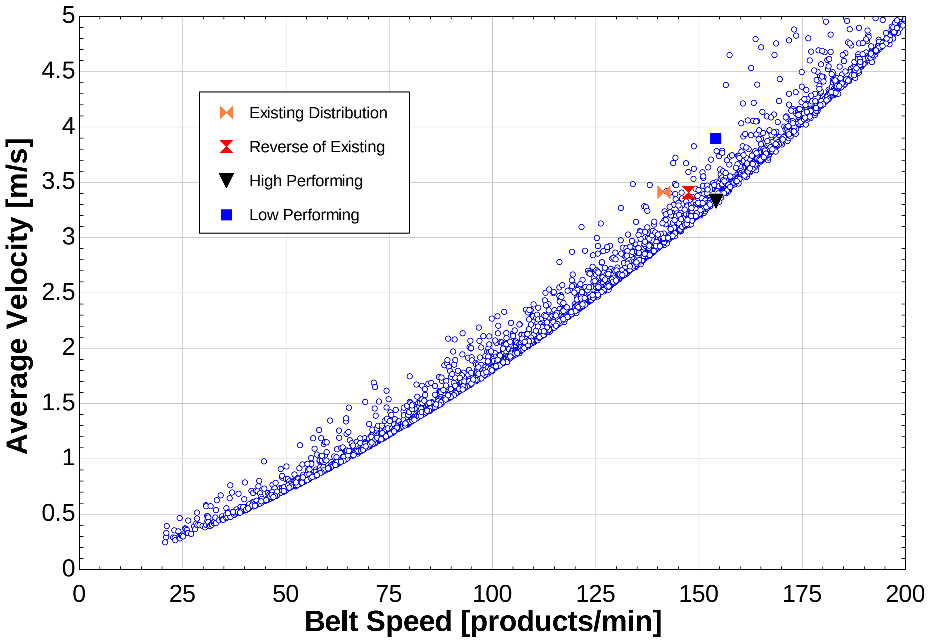
Adjust belt speed that achieves temperature set point (ΔT) at exit. Output is velocity profile and belt speed

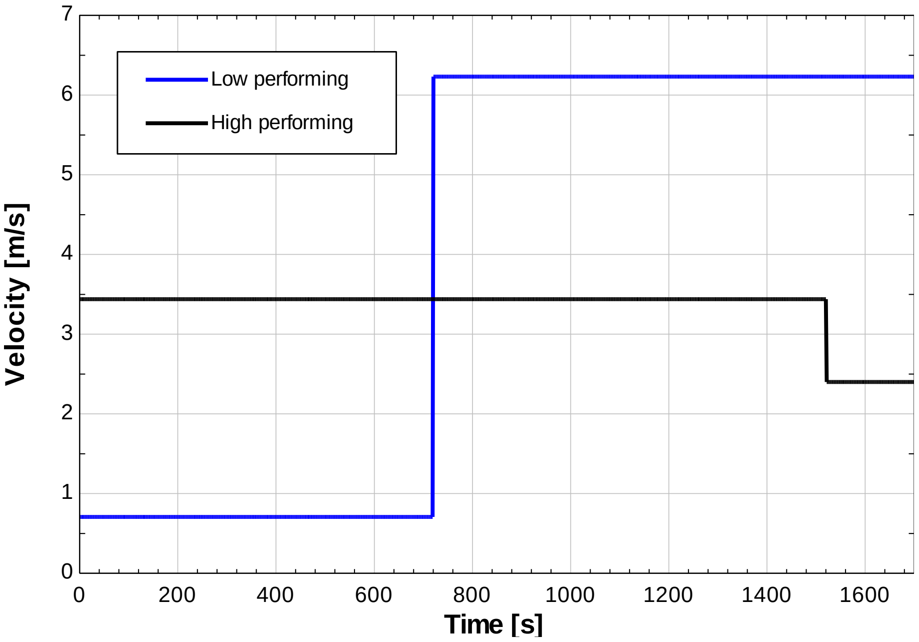
Repeat 1000+ times, establish Pareto front

Pareto front



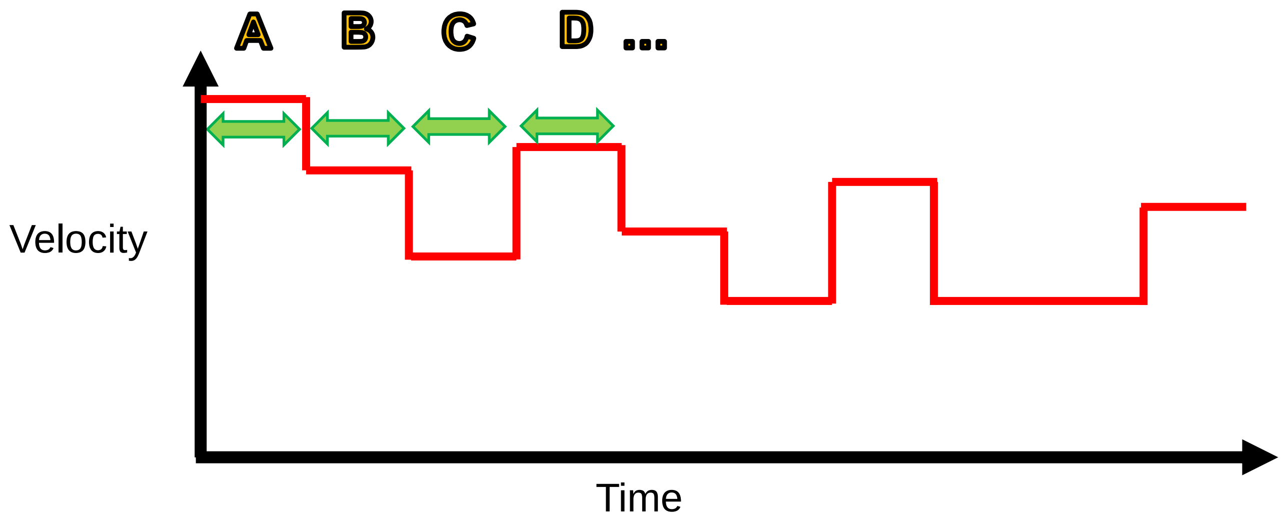
Pareto front – deep dive





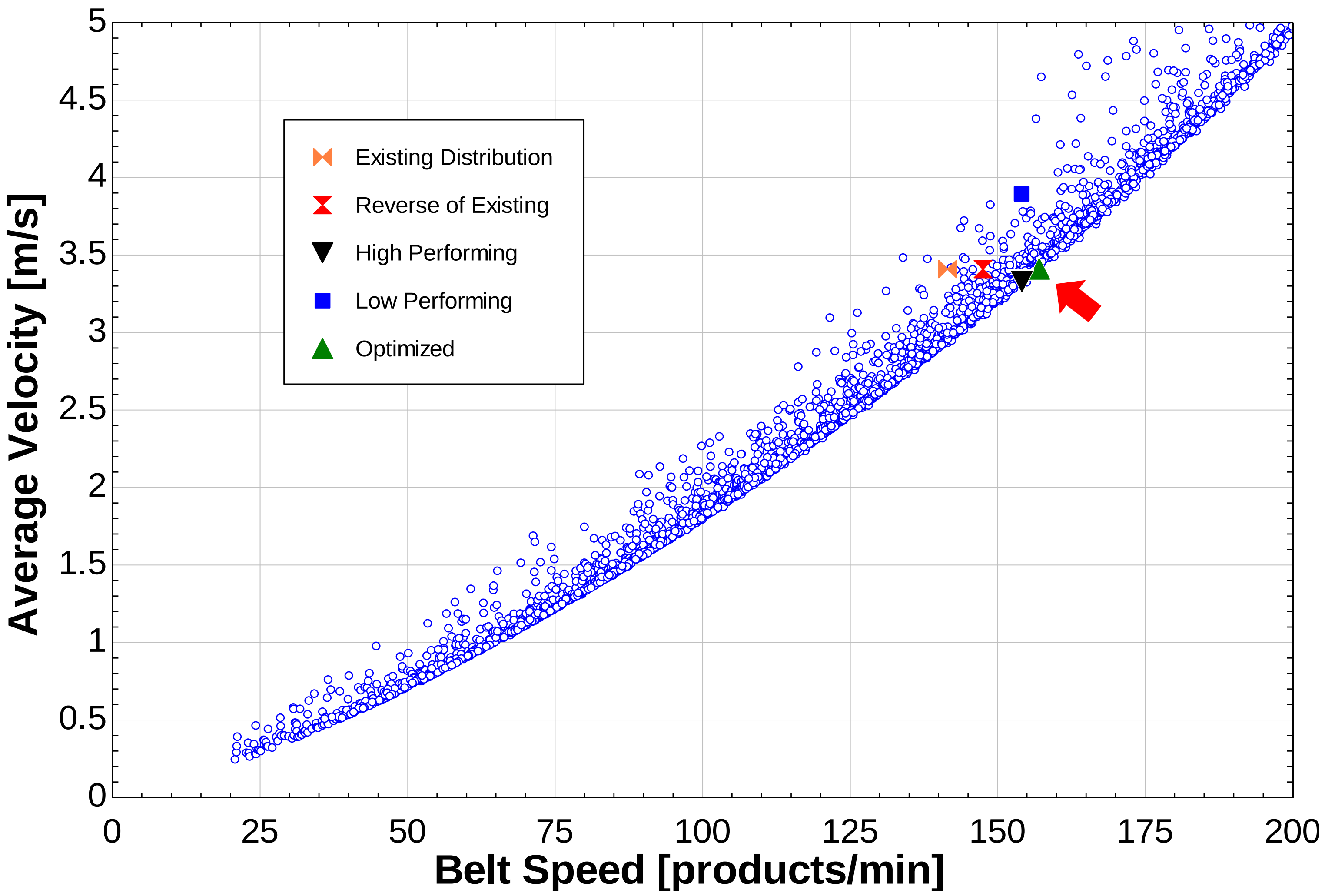
Refinement

- 10 regimes
- Same time duration
- Random velocities with constraints
- Thousands of unique distributions

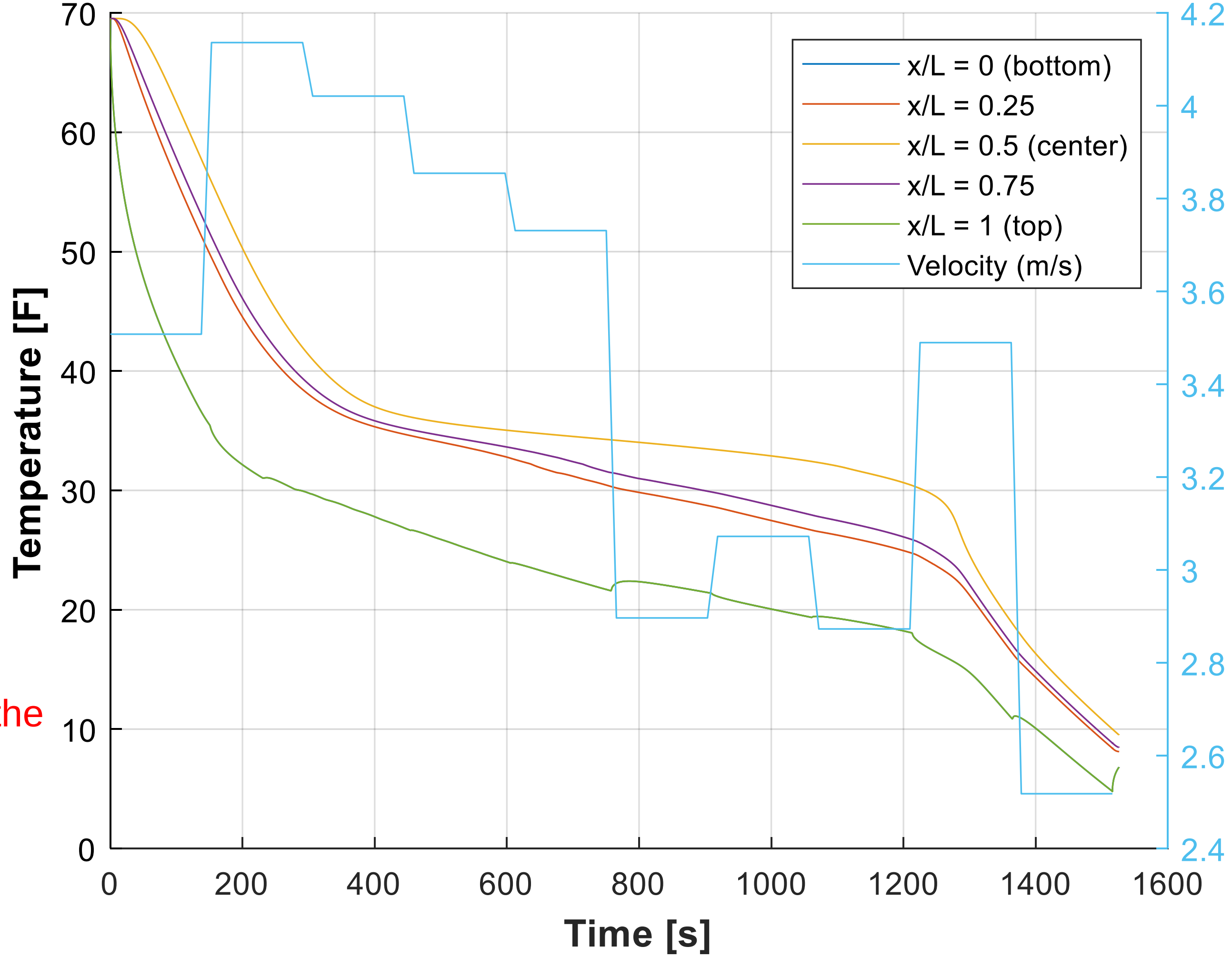


...+Randomization

Optimized air velocity Pareto front



Model results



11% improvement in throughput with identical average velocity through the spiral, just a better distribution

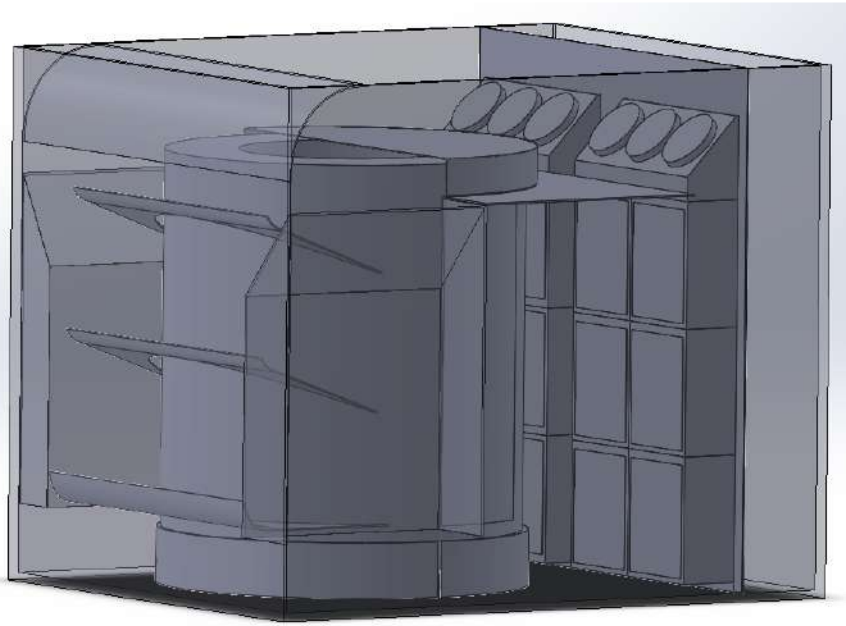
Future work

- Field evaluate different blast freezer configurations
  - Phantom can serve as a benchmarking tool
  - Measure air infiltration rate vs. best practice
- CFD model to establish baseline performance and evaluate strategies to improve air-flow
- Build optimization algorithms that account for energy cost, fan power, etc., that can be calibrated to many systems
- Validate results from facility modifications
- Transplant knowledge to end-users and freezer manufacturers

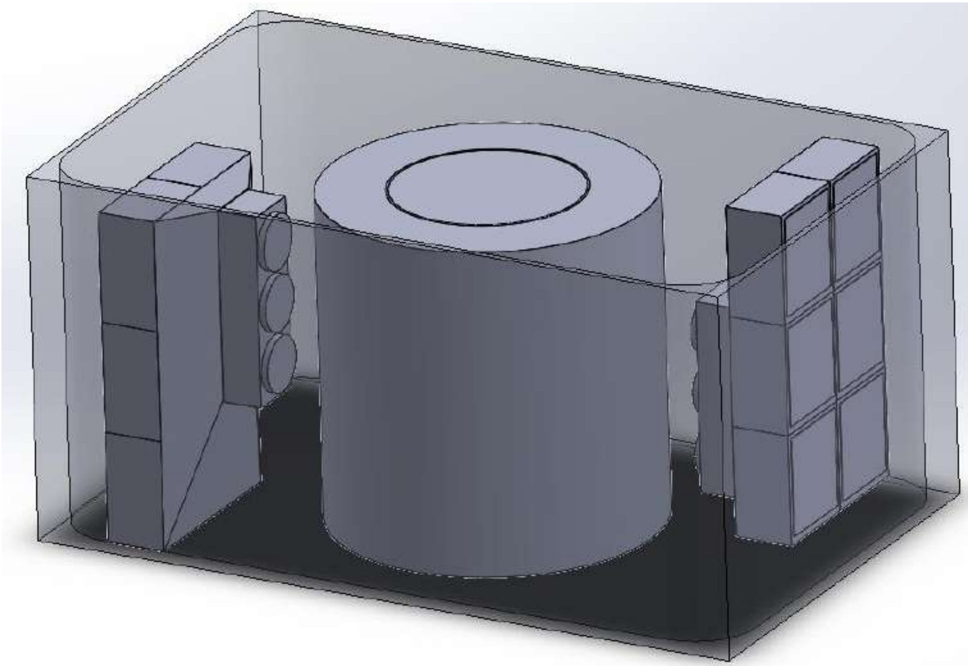
Airflow optimization - existing and new builds

- Use optimal velocity distributions to guide baffling modifications and hypothetical designs

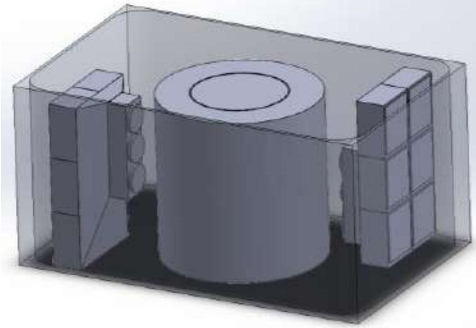
Additional Baffling for Existing Designs



New Build Designs



New build design

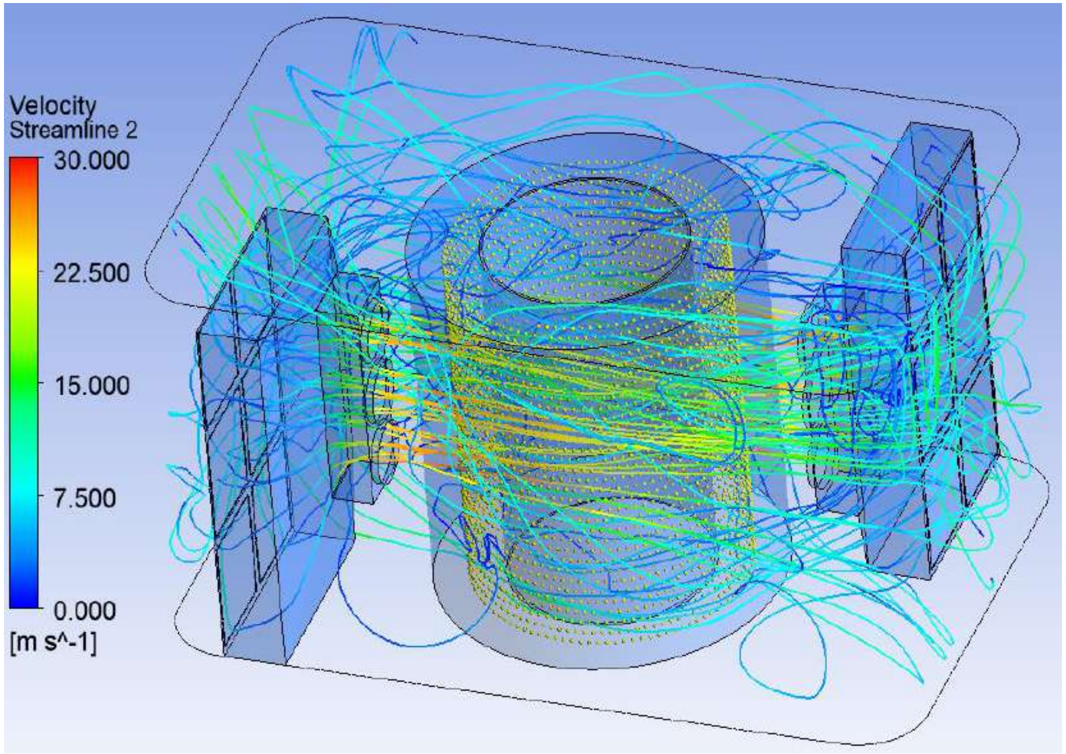


- Same fans currently used by Plant A
- Opposing fans creates a "tornado" effect

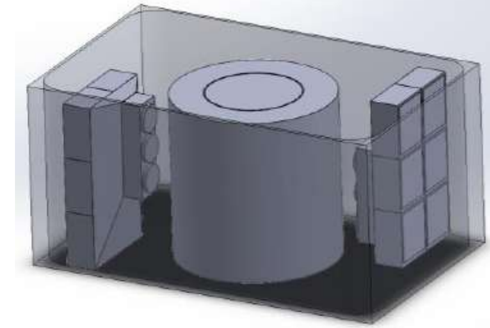
	Avg. Velocity, [ft/min] {m/s}
Spiral	1,157 {5.88}
Coils	579 {2.94}

Energy Per Product [Btu/prod]	Throughput [prod/min]
139 (new design)	207
173 (Plant A)	145
Percent Change	
-19.4%	43.3%

Drawback: Area 24.3% larger, however Volume 5.6% smaller



New build design (four fans)

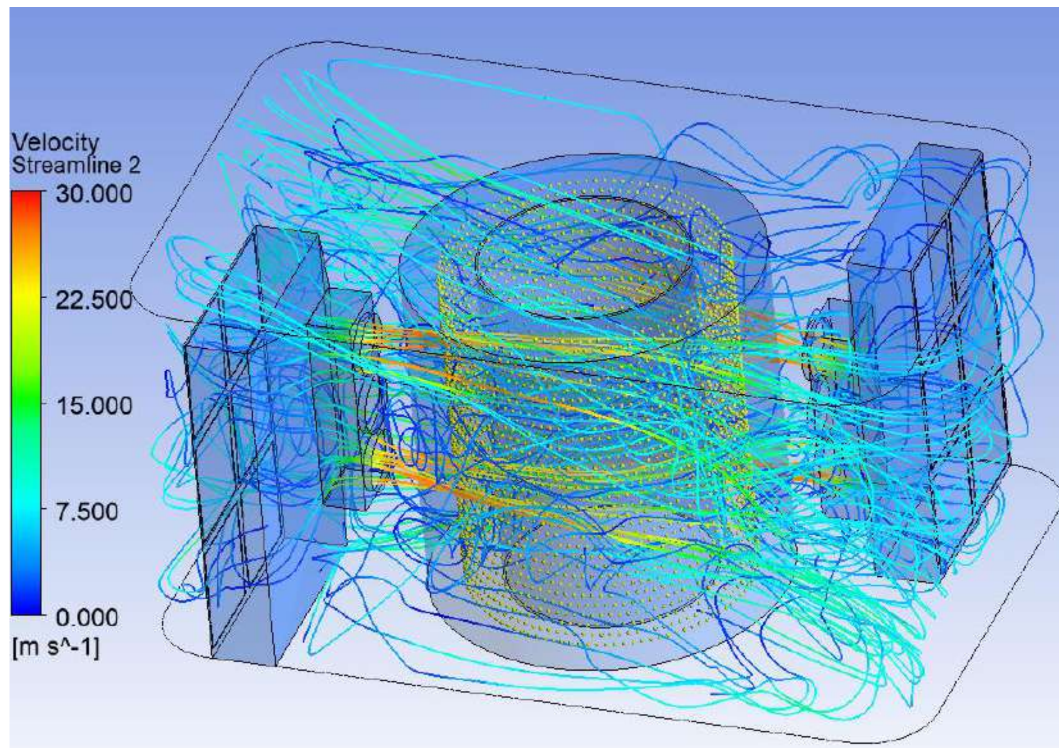


- Same fans currently used by Plant A
- Even greater energy savings

	Avg. Velocity [ft/min] {m/s}
Spiral	**907 {4.61}**
Coils	**394 {2.00}**

Energy Per Product [Btu/prod]	Throughput [prod/min]
131 (four fans)	**171**
173 (Plant A)	**145**
Percent Change	
-24.1%	**18.5%**

Drawback: Area 24.3% larger, however Volume 5.6% smaller



Future Work

- Gather performance data for more blast freezers
- Find baffling configurations for a wider range of blast freezer designs
- Finding optimal flow angle for maximum heat transfer with minimal flow resistance
- Optimize “new build” configurations

Questions?