Improved Modeling of High-Temperature Gas-Cooled Reactor Coolant Laminarization Using RELAP5-3D

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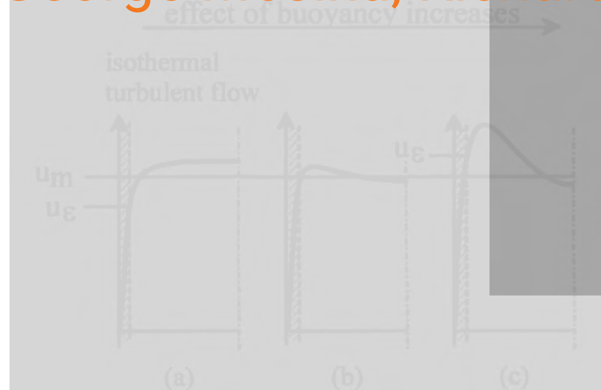


Presentation Objectives

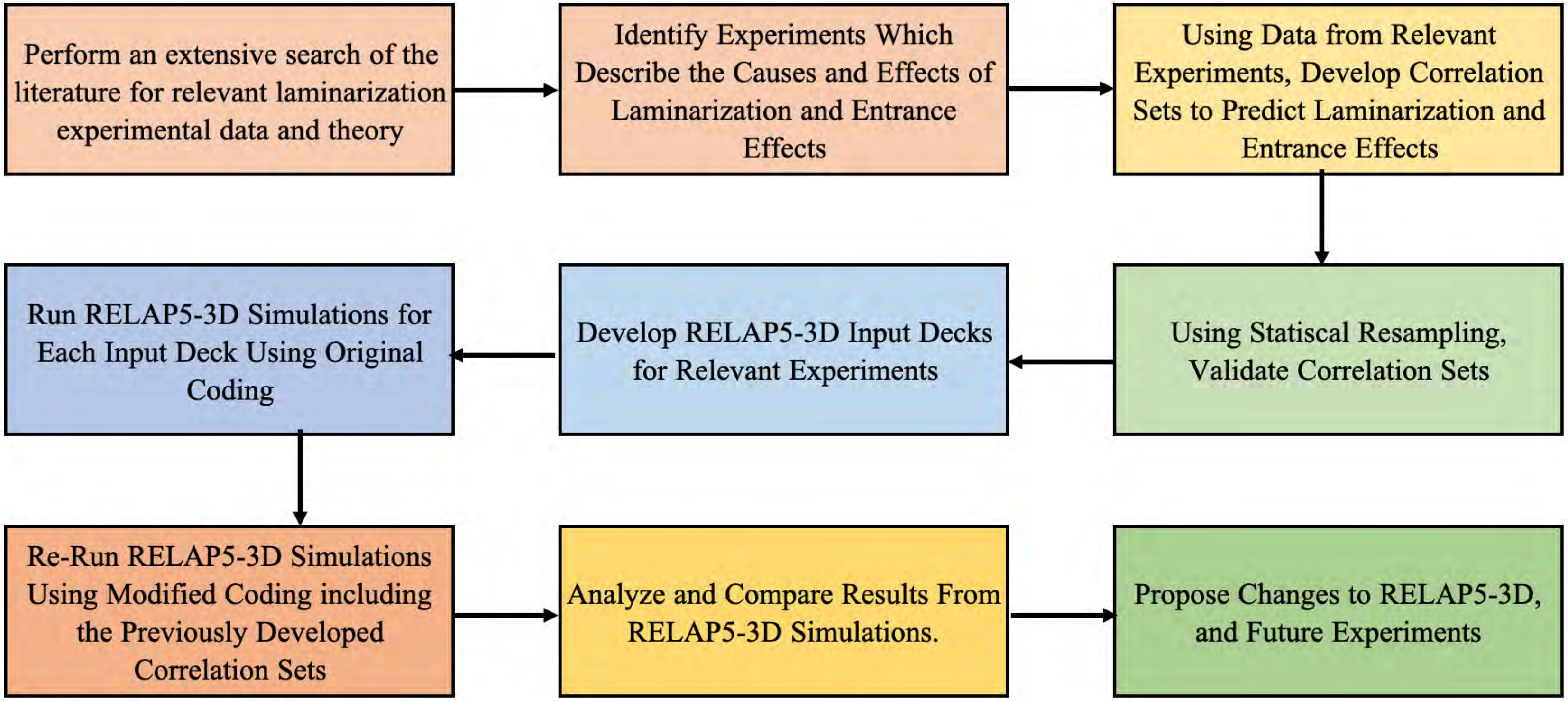
- Need for Research
- Project Background
- Selection of Experimental Data
- Development of New Correlations
- Method of Adding to RELAP5-3D
- Results
- Recommendations
- Future Work

Need for Research

- During loss of flow in a high-temperature gas-cooled reactor, coolant will slow and reverse (up channel instead of down)
- This high heat flux, low flow condition is ripe for laminarization
- Many potential downstream effects (plume/jet into upper plenum, higher graphite temps, etc)
- Not currently modeled in widely used programs

Need for Research

- A reliable method to predict and simulate laminarization heat transfer effects needed
- Also needs to predict heat transfer in the entrance region


Perform an extensive search of the literature for relevant laminarization experimental data and theory
Identify Experiments Which Describe the Causes and Effects of Laminarization and Entrance Effects
Using Data from Relevant Experiments, Develop Correlation Sets to Predict Laminarization and Entrance Effects
Using Statiscal Resampling, Validate Correlation Sets
Develop RELAP5-3D Input Decks for Relevant Experiments
Run RELAP5-3D Simulations for Each Input Deck Using Original Coding
Re-Run RELAP5-3D Simulations Using Modified Coding including the Previously Developed Correlation Sets
Analyze and Compare Results From RELAP5-3D Simulations.
Propose Changes to RELAP5-3D, and Future Experiments

Nomenclature

- Re = Reynolds Number
- Kv = Acceleration Factor
- Bo* = Buoyancy Factor
- Nu = Convection/conduction heat transfer
- ADTHT = Acceleration-induced Deteriorated Turbulent Heat Transfer
- BDTHT = Buoyancy-induced Deteriorated Turbulent Heat Transfer

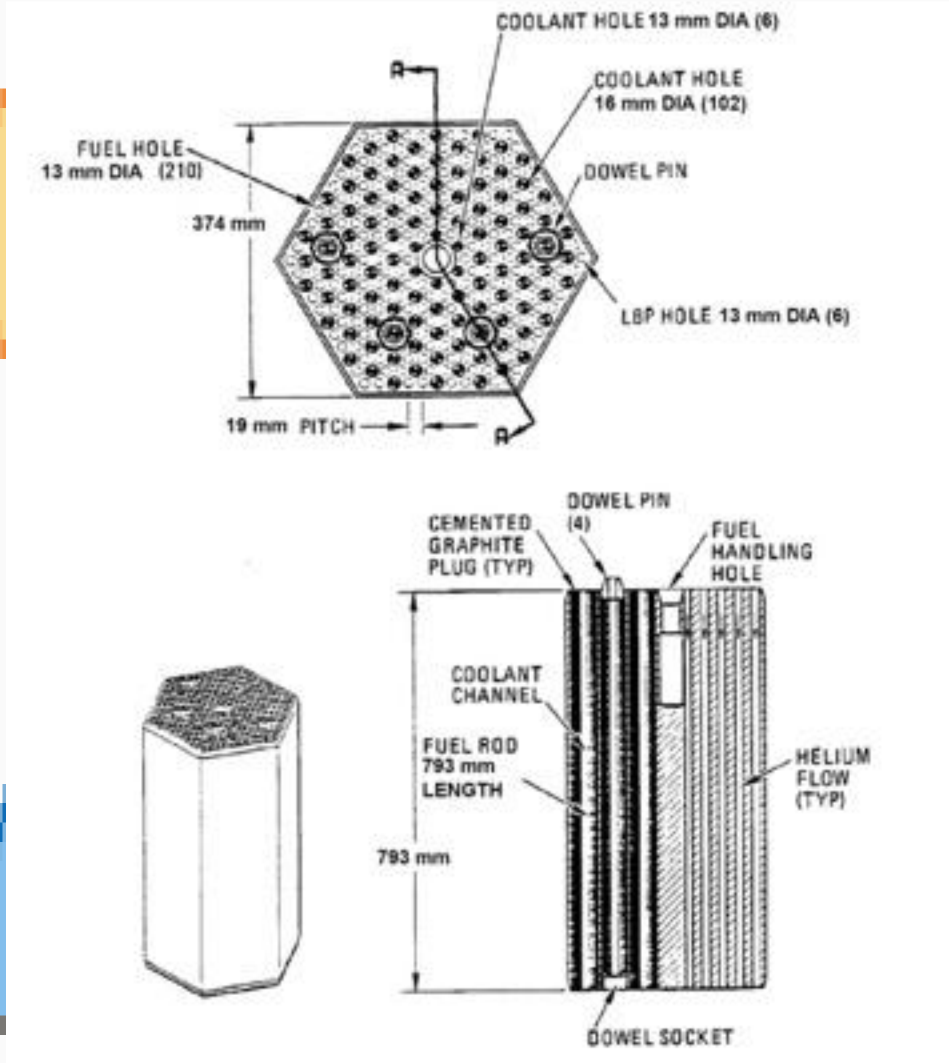
Nomenclature

- R-squared = a statistical measure of goodness of fit

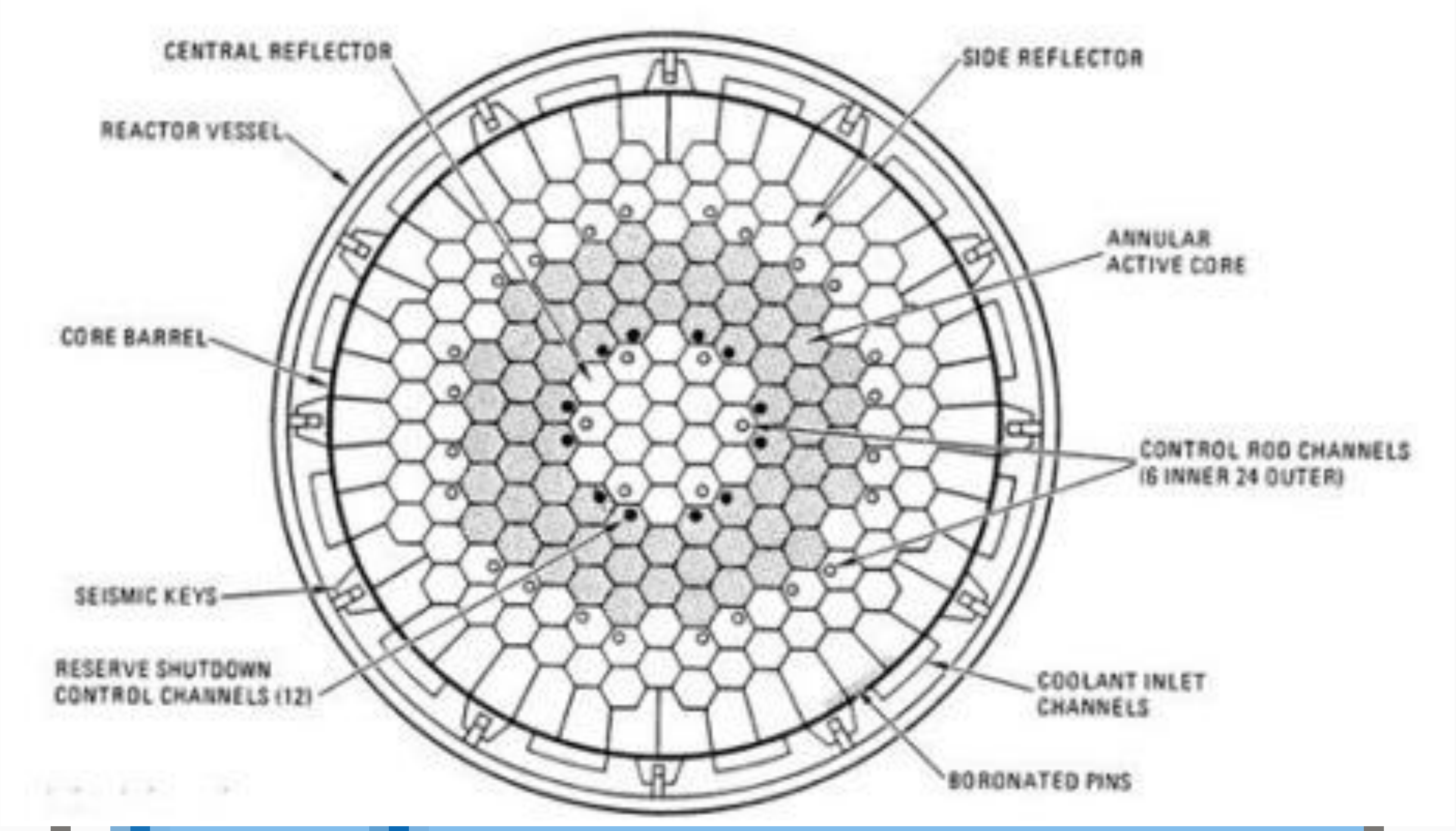
$$R_{squared} = 1 - \frac{Sum\ Squared\ Regression\ (SSR)}{Total\ Sum\ of\ Squares\ (SST)} = 1 - \frac{\sum(y_i - \widehat{y_i})^2}{\sum(y_i - \overline{y_i})^2}$$

Prismatic Reactors

- Comprised of graphite hexagonal prisms with many flow channels
- Most designs stack several blocks vertically
- Fueled ring with inner and outer reflector


COOLANT HOLE 13 mm DIA (6)
COOLANT HOLE 16 mm DIA (102)
FUEL HOLE 13 mm DIA (210)
DOWEL PIN
374 mm
LBP HOLE 13 mm DIA (6)
19 mm PITCH
A
A
DOWEL PIN (4)
CEMENTED GRAPHITE PLUG (TYP)
FUEL HANDLING HOLE
COOLANT CHANNEL
FUEL ROD 793 mm LENGTH
HELIUM FLOW (TYP)
793 mm
DOWEL SOCKET

ROAR


CENTRAL REFLECTOR
SIDE REFLECTOR
REACTOR VESSEL
ANNULAR ACTIVE CORE
CORE BARREL
CONTROL ROD CHANNELS (6 INNER 24 OUTER)
SEISMIC KEYS
RESERVE SHUTDOWN CONTROL CHANNELS (12)
COOLANT INLET CHANNELS
BORONATED PINS

RELAP5-3D Background

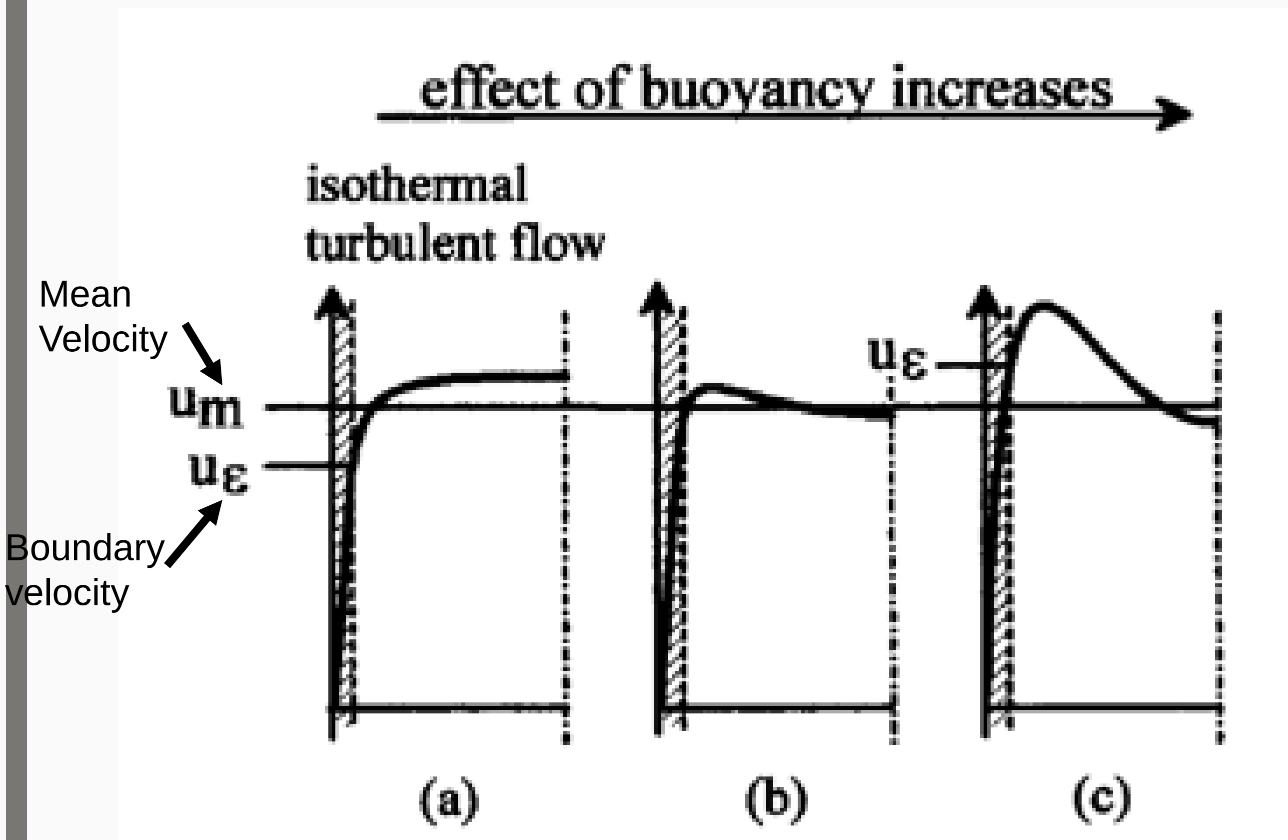
- Reactor Excursion & Leak Analysis Program 5
- Descended from FLASH-1 and later RELAPSE-1
- In 1979, the first line of RELAP5 was written
- In the 1990's RELAP5-3D was developed
- Current version (also version used by this project: RELAP5-3D Ver 4.5.2)

RELAP5-3D Background

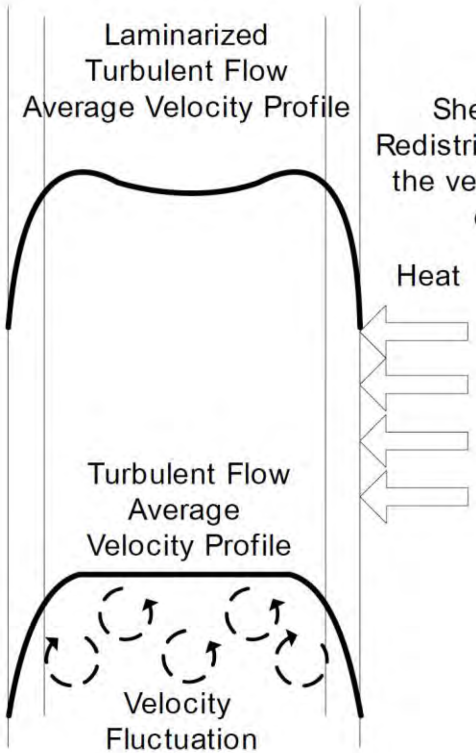
- Most widely used reactor leak analysis program
- Many variations (ATHENA, SCDAP, BETTIS version)
- Also many non-nuclear uses
- Great candidate for modification to include laminarization effects (demand for non-water reactor use, but not designed with that in mind)

Laminarization

- Describes flow with characteristics of laminar flow at Re where turbulent flow is expected
- Causes traditional heat transfer correlations to overpredict
- Can be caused by acceleration or buoyancy



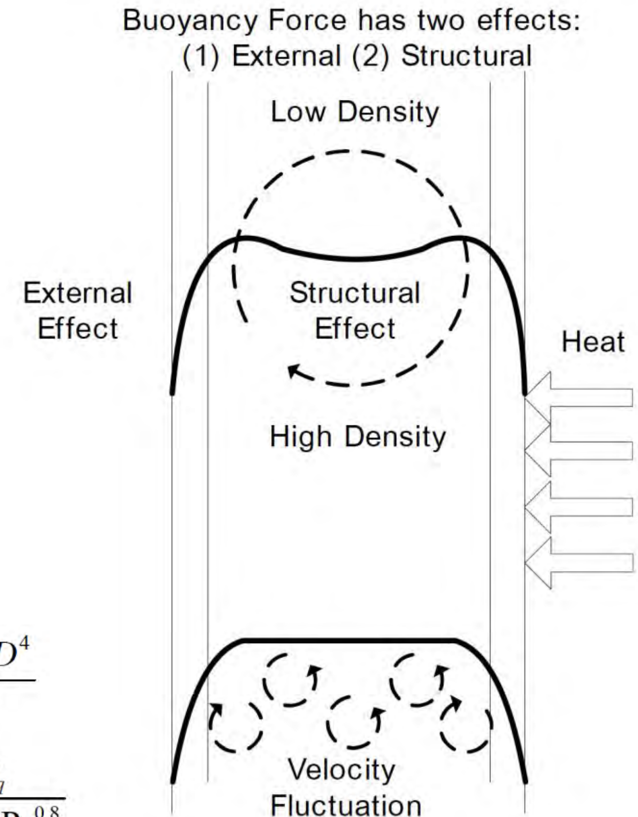
effect of buoyancy increases
isothermal turbulent flow
Mean Velocity
um
uε
Boundary velocity
uε
(a)
(b)
(c)



Jackson & Hall Theory

$$Gr_q = \frac{g\beta q''_w D^4}{k\nu^2}$$

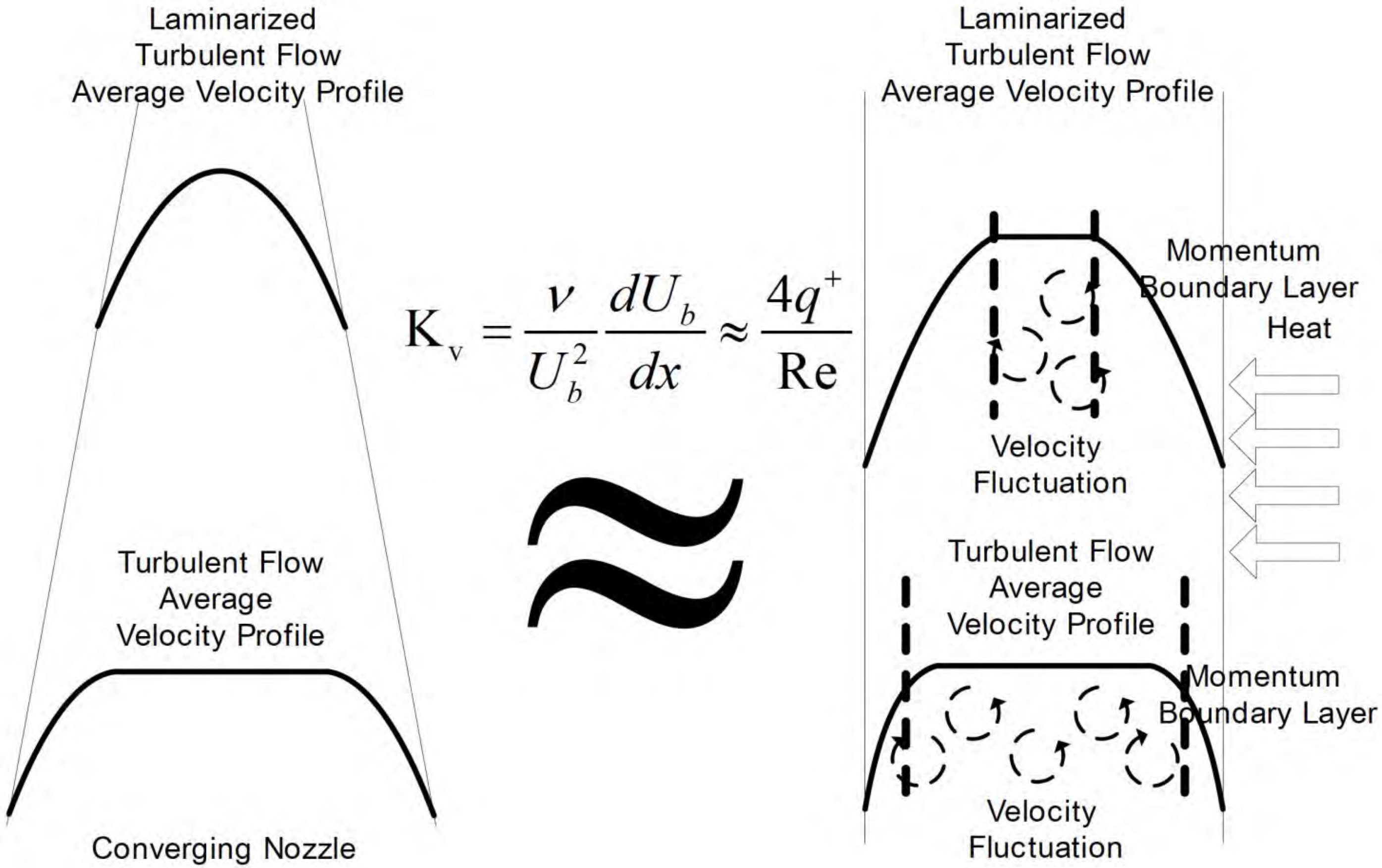
$$Bo^* = \frac{Gr_q}{Re^{3.425}\,Pr^{0.8}}$$



Petukhov & Polyakov Theory

$$q^{+}: \text{nondimensional heat flux} = \frac{q''_w}{GH_b} \approx \frac{q''_w}{Gc_pT_b} \approx \frac{\beta q''_w}{Gc_p}$$

$$K_v = \frac{\nu}{U_b^2}\frac{dU_b}{dx} \approx \frac{4q^{+}}{Re}$$



Entrance Effects

- Flow transitioning from one volume into a pipe will have flow profile distortions
- Vena contracta describes relative narrowing of bulk flow
- Narrowing is surrounded by eddies
- This increased mixing in the entrance region improves heat transfer

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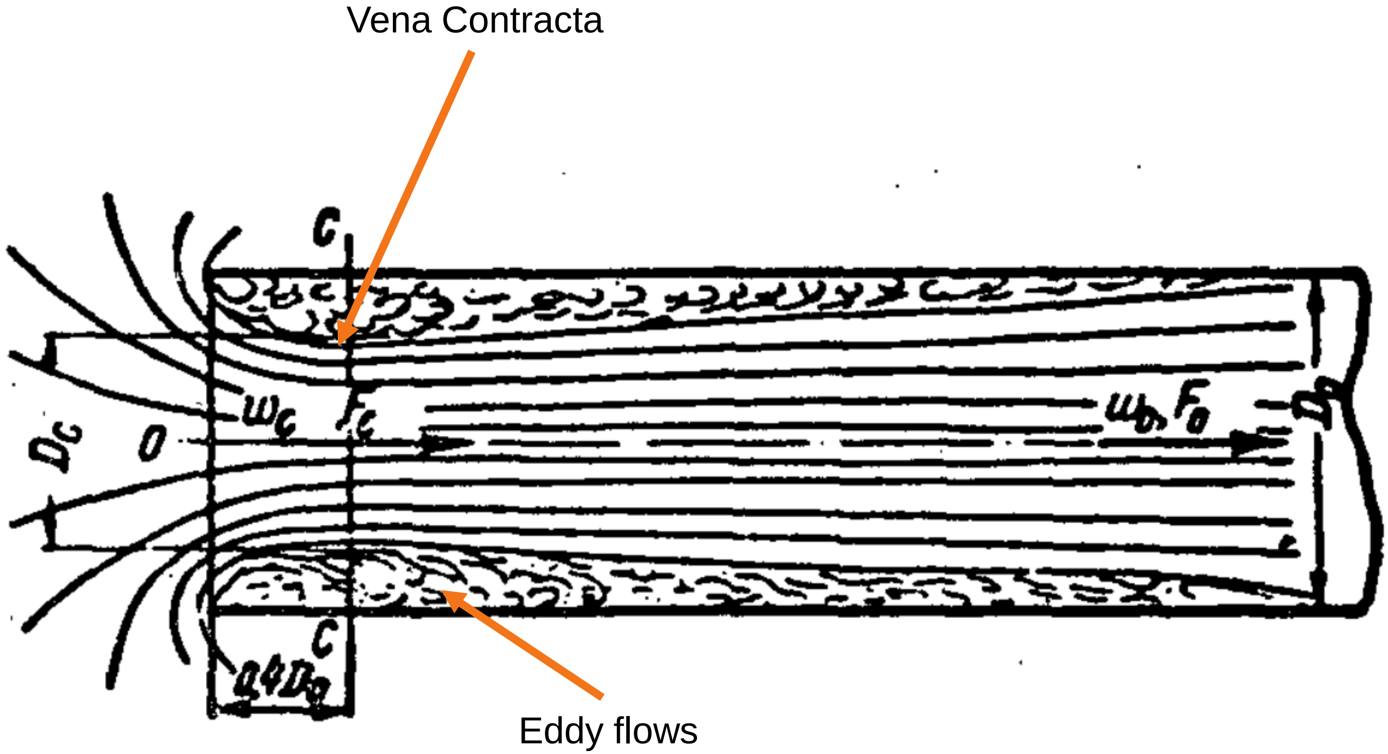

FIGURE 3-1. Flow at the inlet to a straight pipe from an unlimited space.

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Entrance Effects

- Flow perturbations likely pronounced in prismatic reactors
- Uneven change in dimensions in graphite over core life can create necking or misalignment
- Each block acts as new entrance vs straight pipe

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Selection of Data

- Several laminarization experiments exist
- Kawaji (CUNY) has several great experiments
- Lee (MIT, overseen by Kazimi) had the best quantitative data
- Other research was reviewed, but Lee's data is what was used for correlation development

Selection of Data

- Lee's data involves a once-through, heated graphite channel using various heat and pressure inputs with CO_2, N_2, and He
- Lee's runs can be sorted into five categories:
  - Laminar
  - Transition
  - ADTHT
  - BDTHT
  - Turbulent

Current R5 Correlations

- Using methods from R5 source code, predicted Nu was calculated
- Done using correlation sets that can be user-selected in R5
- The Jackson-Wu correlation set (selectable as Geometry 164) was the overall best starting point

Current R5 Correlations

- Lack of entrance effects in R5 biggest source of error compared to experiments
- Secondary to lack of modeling for laminarization effects

Current R5 Correlations

- Laminar heat transfer could also be improved
- R5 typically uses Sellars-Tribus-Klein (i.e. Nu=4.36) for laminar
- Better correlations exist

Correlation Development

- A three-pronged approach was taken
- One set of correlations, accounted only for entrance effects and more refined laminar flow predictions
- This “standard” set uses correlations developed by well-known researchers (Travis and El-Genk, and Jackson)
- Did nothing to improve modeling of laminarization

Correlation Development

- A second set would further refine a correlation for entrance effects
- Also would account for acceleration and buoyancy induced laminarization
- Named the “Deluxe” set
- Uses the Lee data to refine/create correlations
- Very complicated, multi-step process

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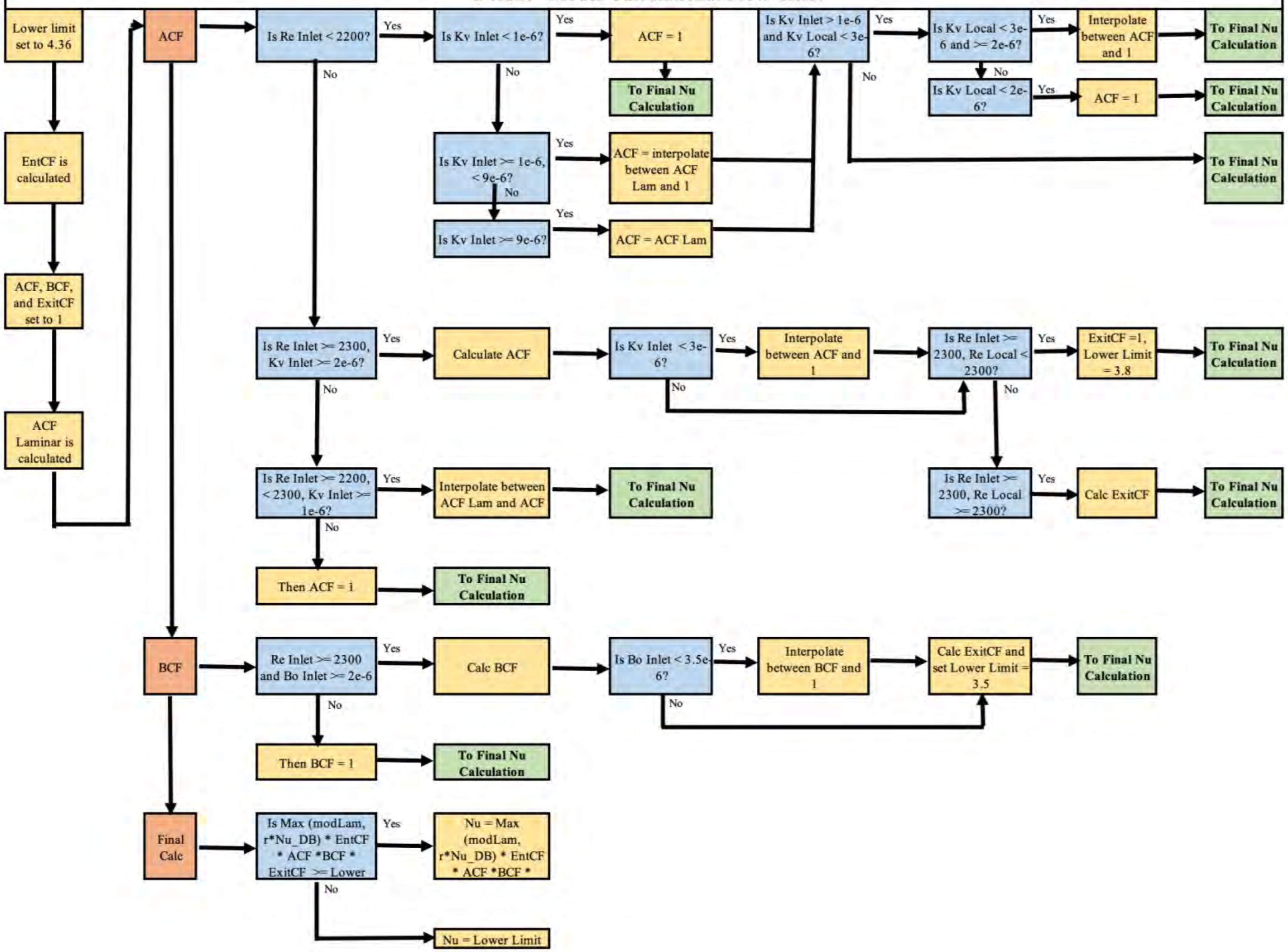
"Deluxe" Model Calculational Flow Chart



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Correlation Development

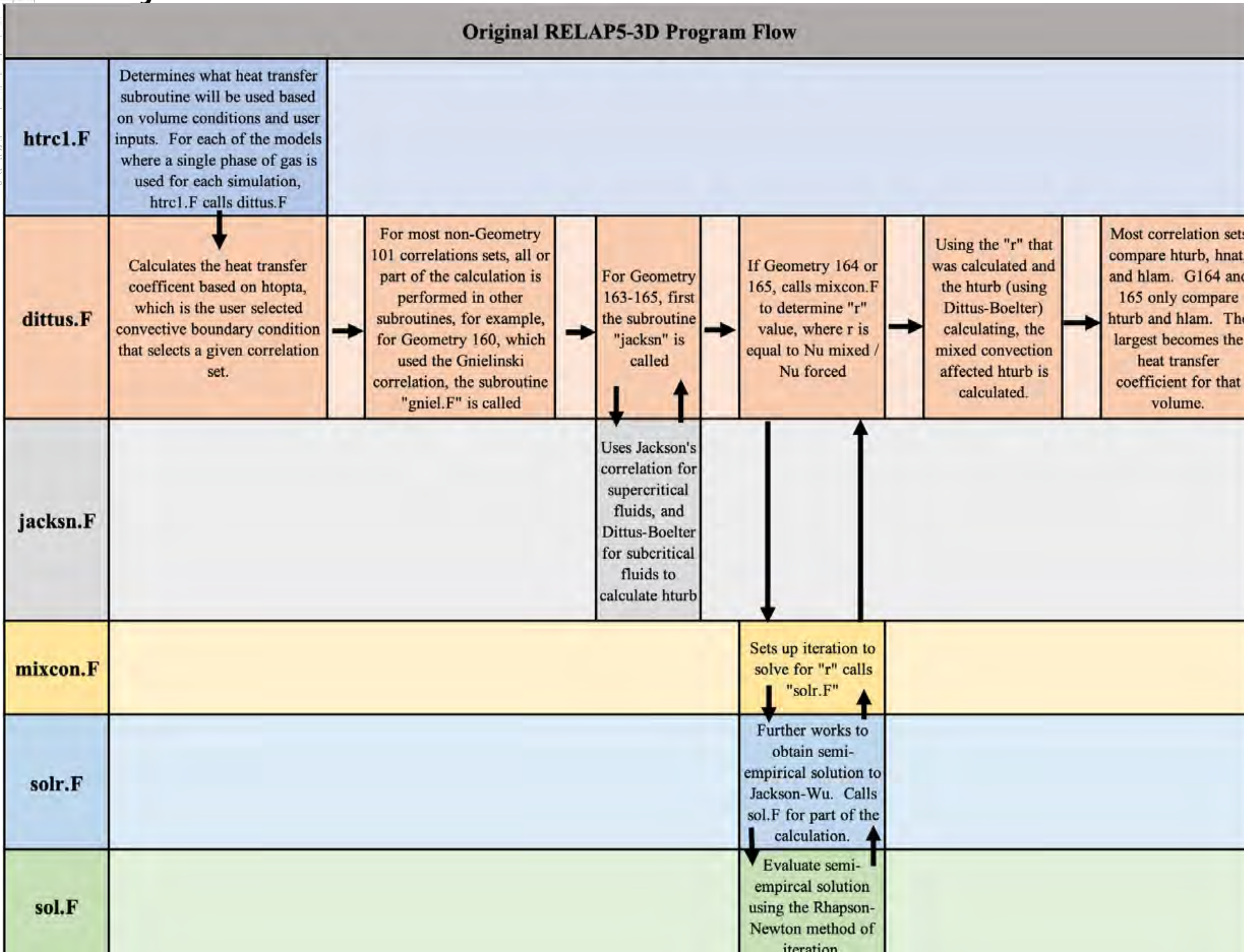
- Finally, a third correlation set was developed and implemented
- Took many of the positive aspects of the Deluxe model, but attempted to minimize required changes to R5
- This third set was known as the “Simplified model”

Correlation Development

Types	Baseline	Standard	Deluxe	Simplified
All	0.46201	0.92161	0.98271	0.9473
Laminar	0.04340	0.91201	0.96704	0.9719
Transition	0.18293	0.87850	0.98387	0.9771
BDTHT	0.11242	0.82760	0.97255	0.9347
ADTHT	0.15926	0.87274	0.96823	0.9045
Turbulent	0.41754	0.92484	0.98105	0.9439

Adding Correlations to R5

- For each new correlation set, all changes were made to dittus.F
- dittus.F is the primary single phase heat transfer subroutine in R5
- Further changes to R5 could be made to improve code flow and speed, however the goal with this project was proof of concept



Original RELAP5-3D Program Flow
htrc1.F
Determines what heat transfer subroutine will be used based on volume conditions and user inputs. For each of the models where a single phase of gas is used for each simulation, htrc1.F calls dittus.F
dittus.F
Calculates the heat transfer coefficent based on htopta, which is the user selected convective boundary condition that selects a given correlation set.
For most non-Geometry 101 correlations sets, all or part of the calculation is performed in other subroutines, for example, for Geometry 160, which used the Gnielinski correlation, the subroutine "gniel.F" is called
For Geometry 163-165, first the subroutine "jacksn" is called
If Geometry 164 or 165, calls mixcon.F to determine "r" value, where r is equal to Nu mixed / Nu forced
Using the "r" that was calculated and the hturb (using Dittus-Boelter) calculating, the mixed convection affected hturb is calculated.
Most correlation sets compare hturb, hnat, and hlam. G164 and 165 only compare hturb and hlam. The largest becomes the heat transfer coefficient for that volume.
jacksn.F
Uses Jackson's correlation for supercritical fluids, and Dittus-Boelter for subcritical fluids to calculate hturb
mixcon.F
Sets up iteration to solve for "r" calls "solr.F"
solr.F
Further works to obtain semi-empirical solution to Jackson-Wu. Calls sol.F for part of the calculation.
sol.F
Evaluate semi-empircal solution using the Rhapson-Newton method of iteration.

Testing New Correlations

- Before testing in R5, “bootstrapping” was applied to correlations
- Random resamples help eliminate systematic error
- Great results from correlations

Bootstrapping

-
- $R^2_{bootstrap} = \frac{\sum r^2_{resample}}{1{,}000}$
- Each resample size equal to original sample
- Randomly selected
- Duplicates allowed
- Also performed for the 3 MIT correlation sets with Entrance Correction Factor applied

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Bootstrapping

Types	Deluxe Model	MIT1	MIT2	MIT3
All	**0.9826**	0.8727	0.9211	0.8880
Laminar	**0.9540**	0.6151	0.6151	0.6151
Transition	**0.9807**	0.6479	0.6966	0.6918
BDTHT	**0.9711**	0.6681	0.7946	0.7533
ADTHT	**0.9566**	0.6146	0.7164	0.6513
Turbulent	**0.9808**	0.8966	0.9377	0.8984

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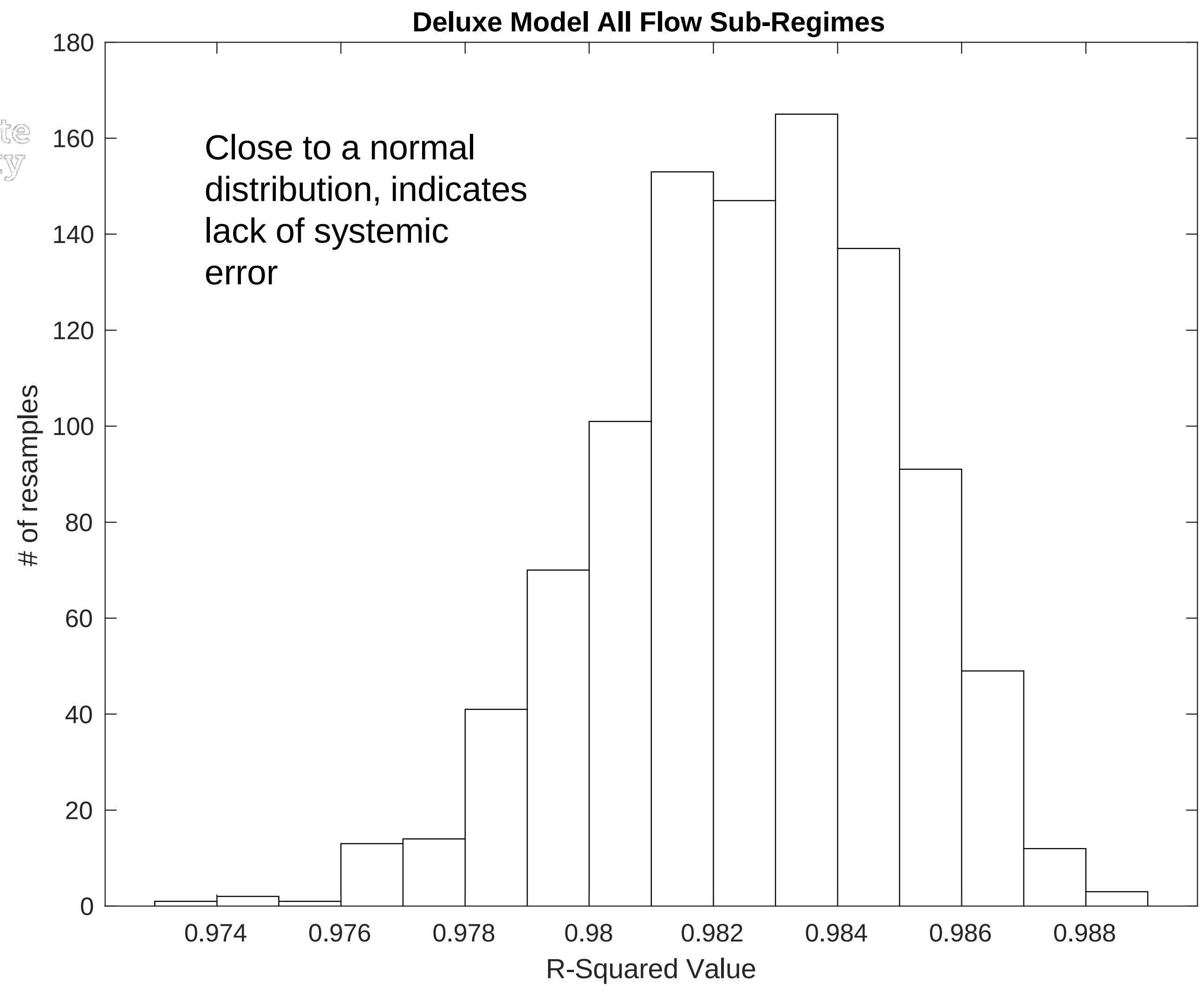

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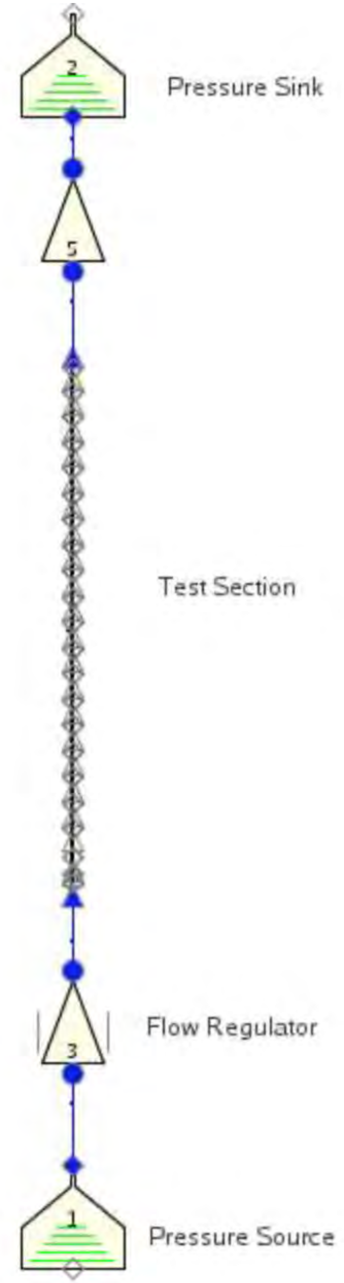
Testing New Correlations

- One Lee Run from each flow sub-regime was selected
- A model was created in R5 for each, simulating the input conditions for each run
- Additionally, to test the effect when end-of-life fuel cell distortion is present, five additional models were made


2
Pressure Sink
5
Test Section
Flow Regulator
3
1
Pressure Source

Time Dependent Volume

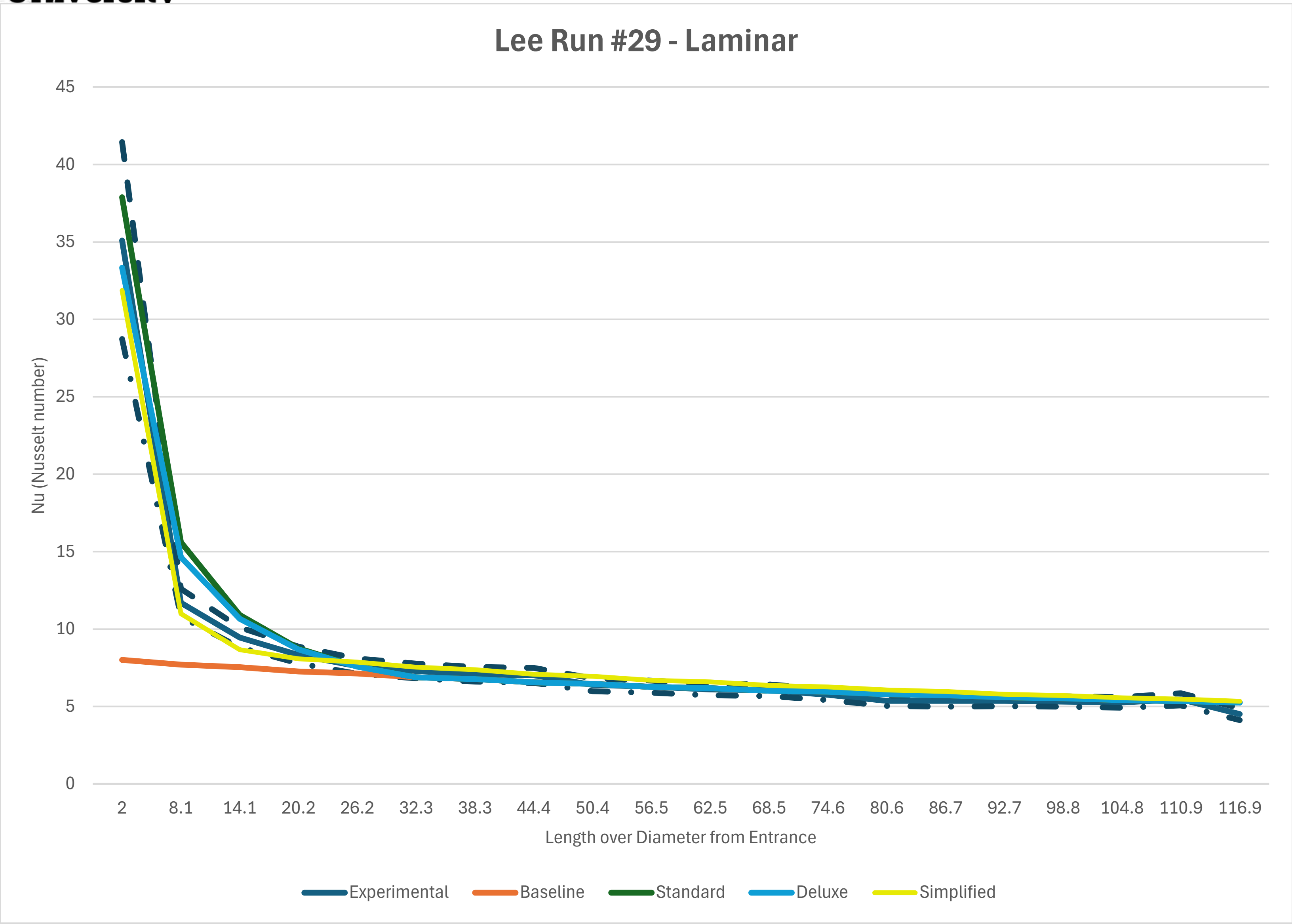
Single pipe with single heat structure

Time Dependent Junction

Time Dependent Volume

Testing New Correlations

- Every simulation demonstrated underprediction by Baseline RELAP5-3D in entrance region
- All models do much better than Baseline
- Deluxe and Simplified models show good prediction of laminarization heat transfer


Lee Run #29 - Laminar
Nu (Nusselt number)
45
40
35
30
25
20
15
10
5
0
2
8.1
14.1
20.2
26.2
32.3
38.3
44.4
50.4
56.5
62.5
68.5
74.6
80.6
86.7
92.7
98.8
104.8
110.9
116.9
Length over Diameter from Entrance
Experimental
Baseline
Standard
Deluxe
Simplified

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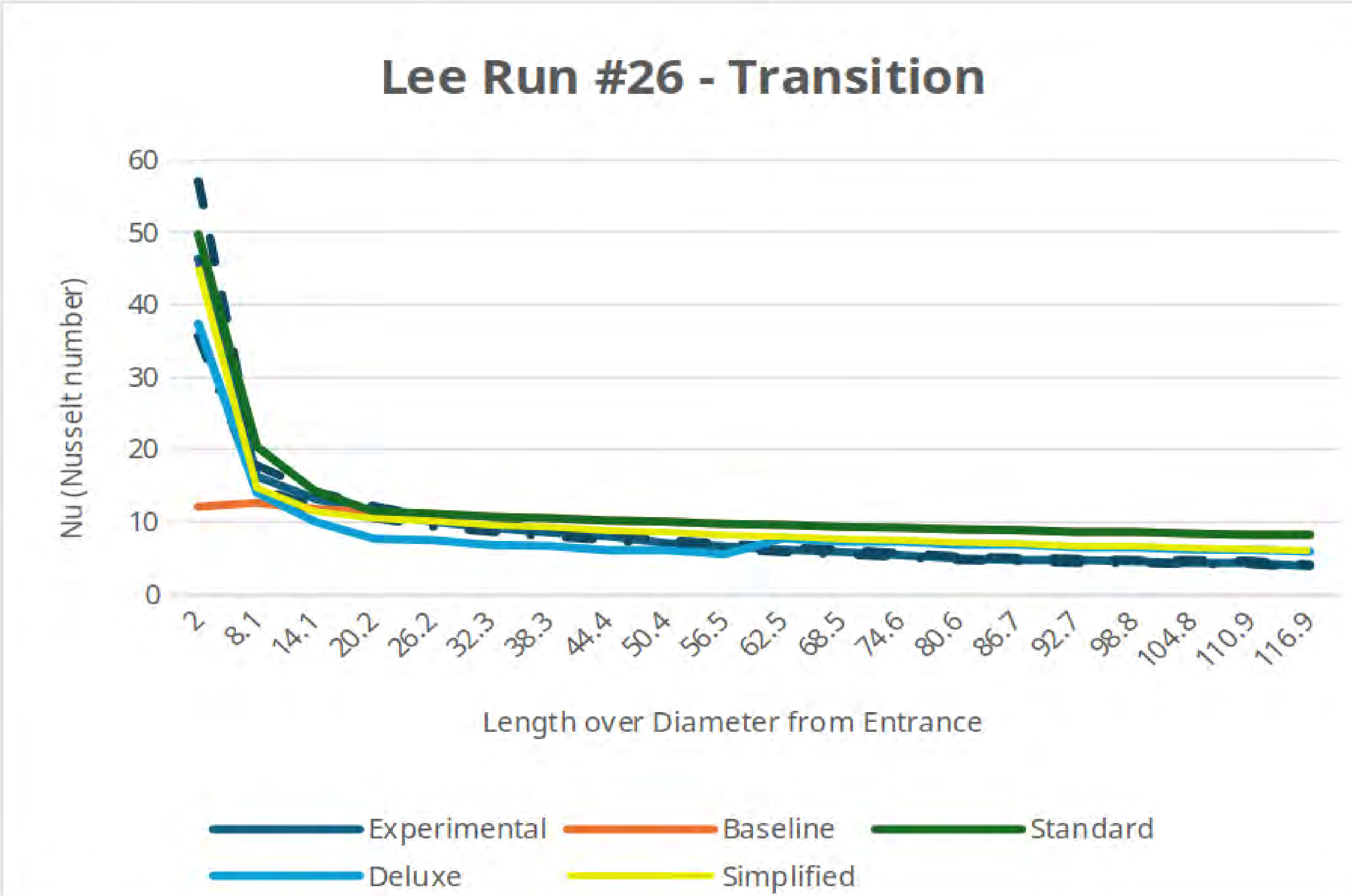

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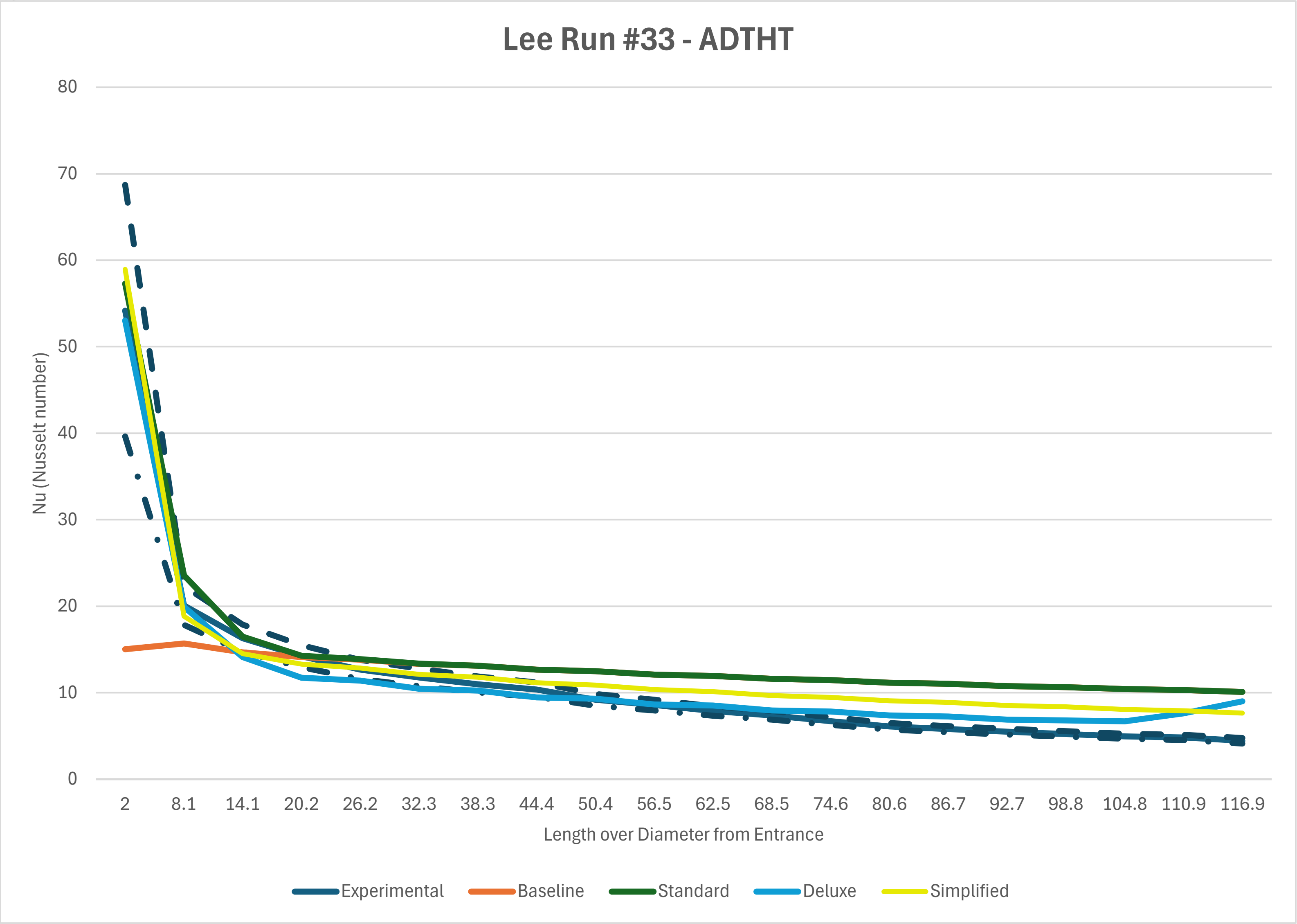

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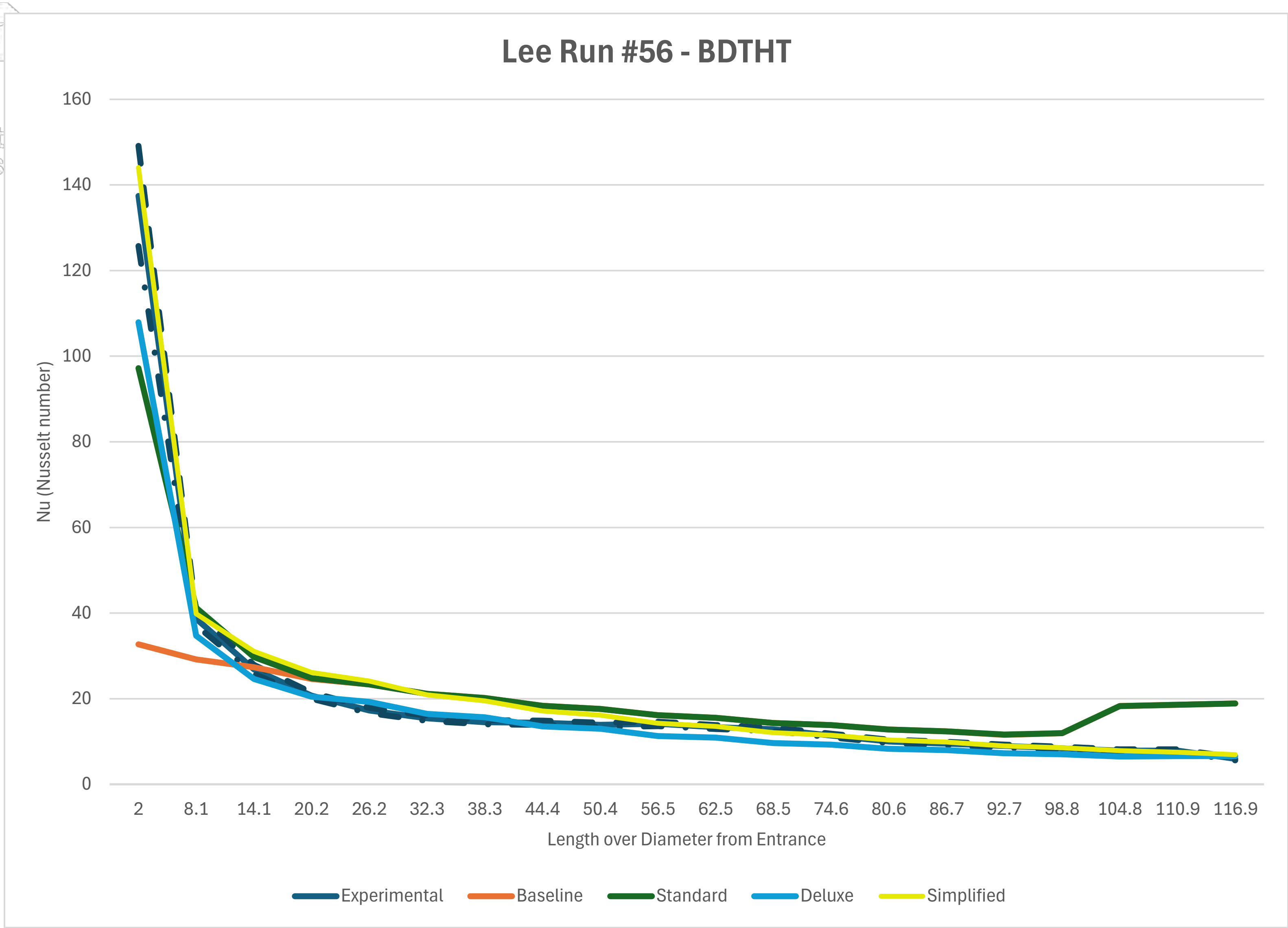
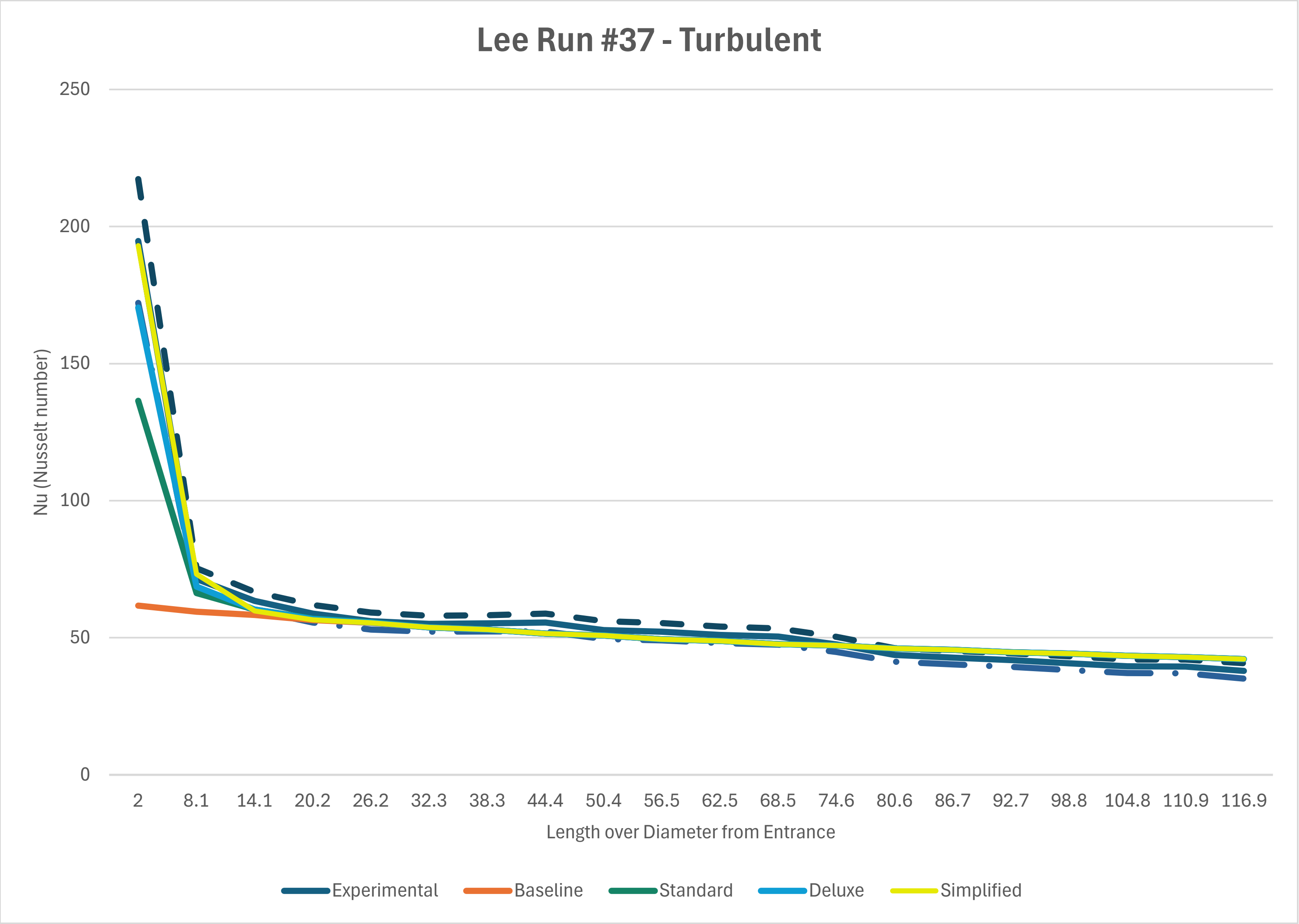
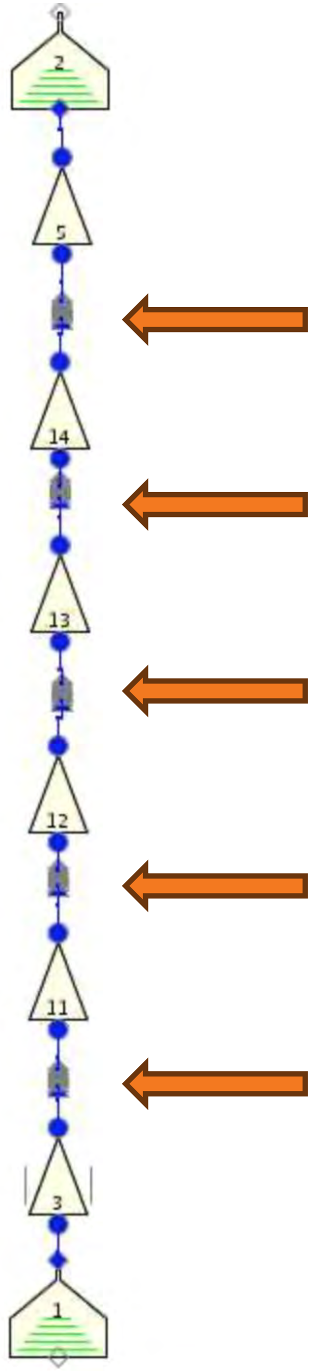

Lee Run #56 - BDTHT
160
140
120
100
80
60
40
20
0
Nu (Nusselt number)
2
8.1
14.1
20.2
26.2
32.3
38.3
44.4
50.4
56.5
62.5
68.5
74.6
80.6
86.7
92.7
98.8
104.8
110.9
116.9
Length over Diameter from Entrance
Experimental
Baseline
Standard
Deluxe
Simplified

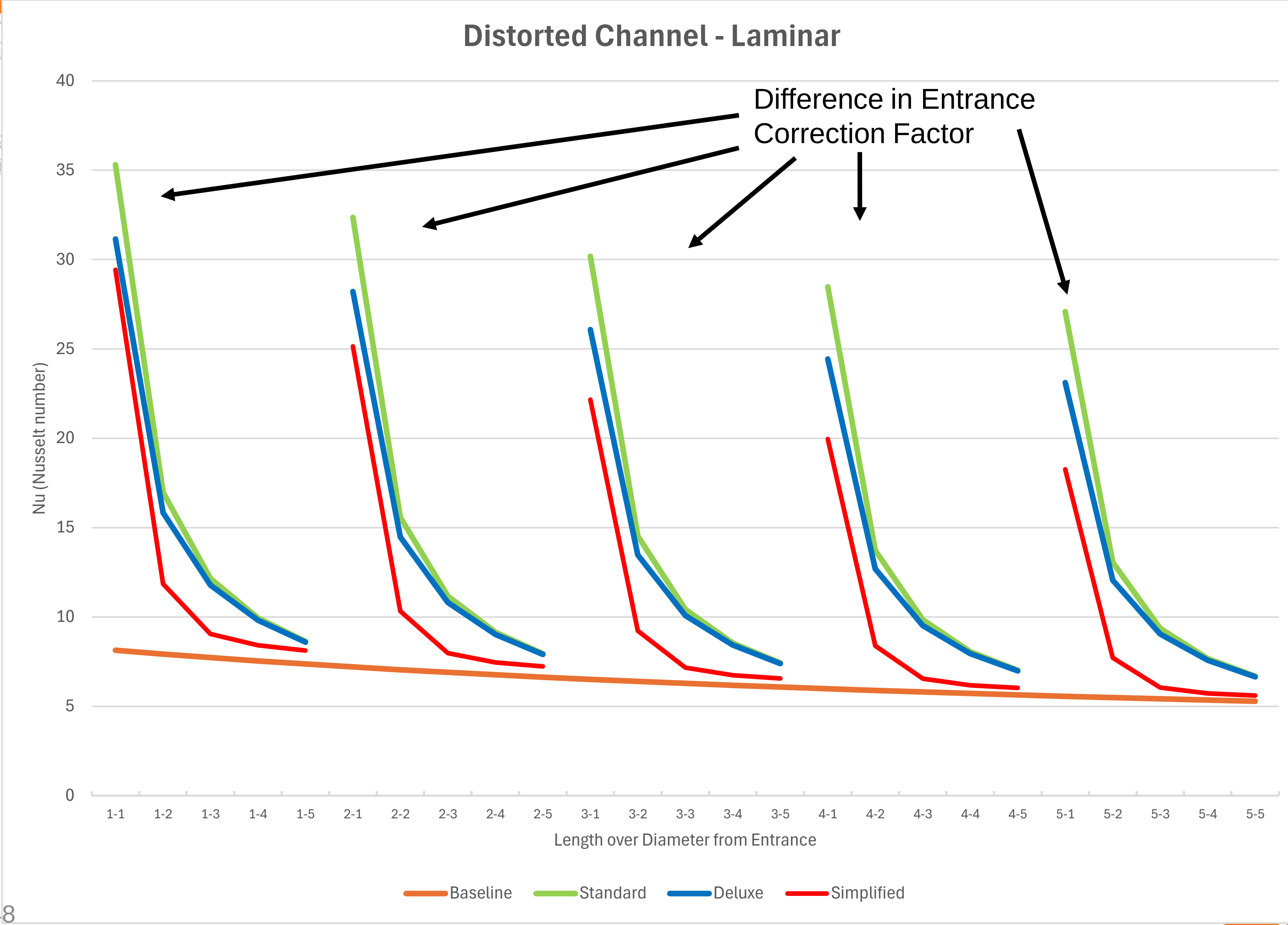


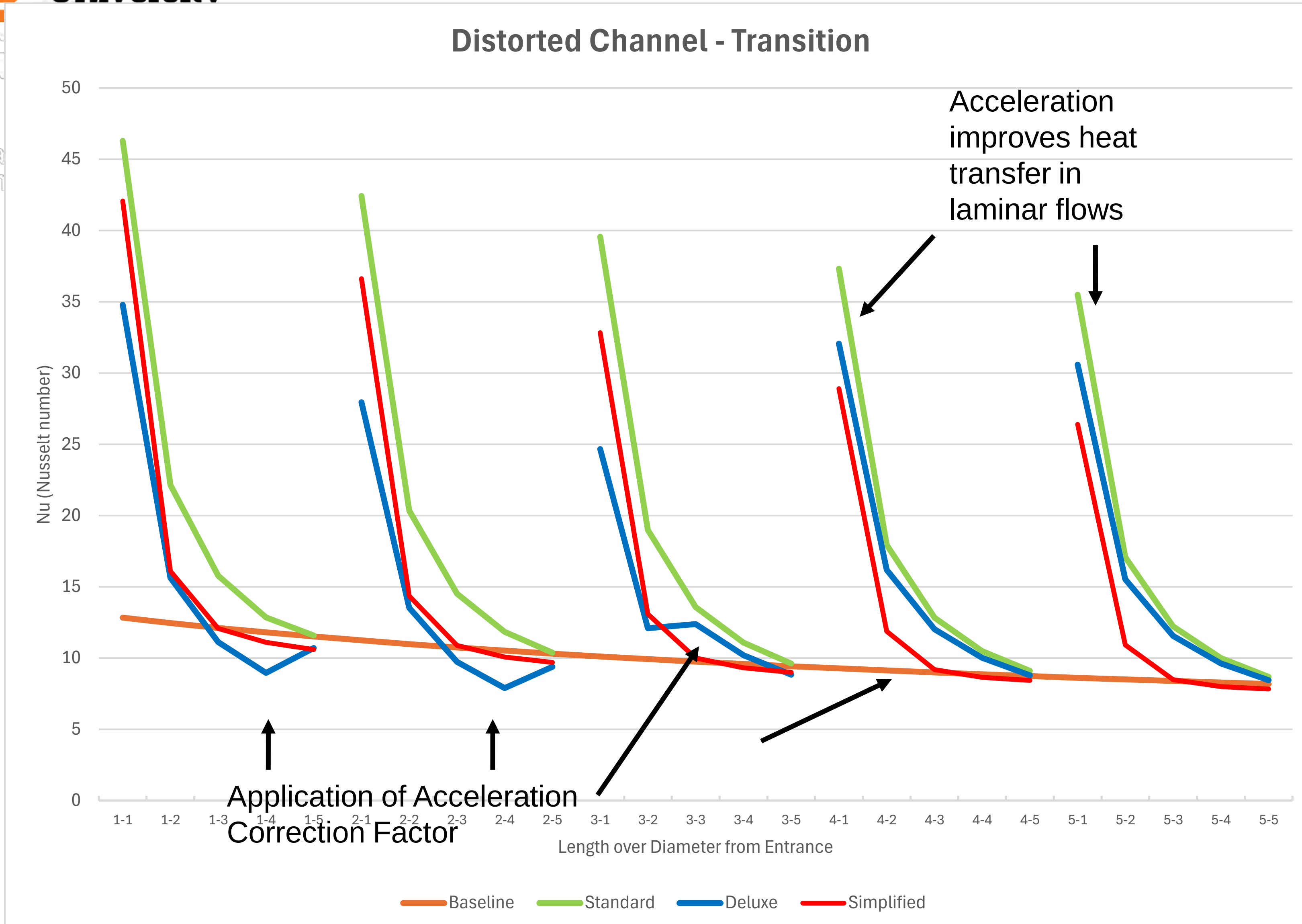
Lee Run #37 - Turbulent
250
200
150
100
50
0
Nu (Nusselt number)
2
8.1
14.1
20.2
26.2
32.3
38.3
44.4
50.4
56.5
62.5
68.5
74.6
80.6
86.7
92.7
98.8
104.8
110.9
116.9
Length over Diameter from Entrance
Experimental
Baseline
Standard
Deluxe
Simplified

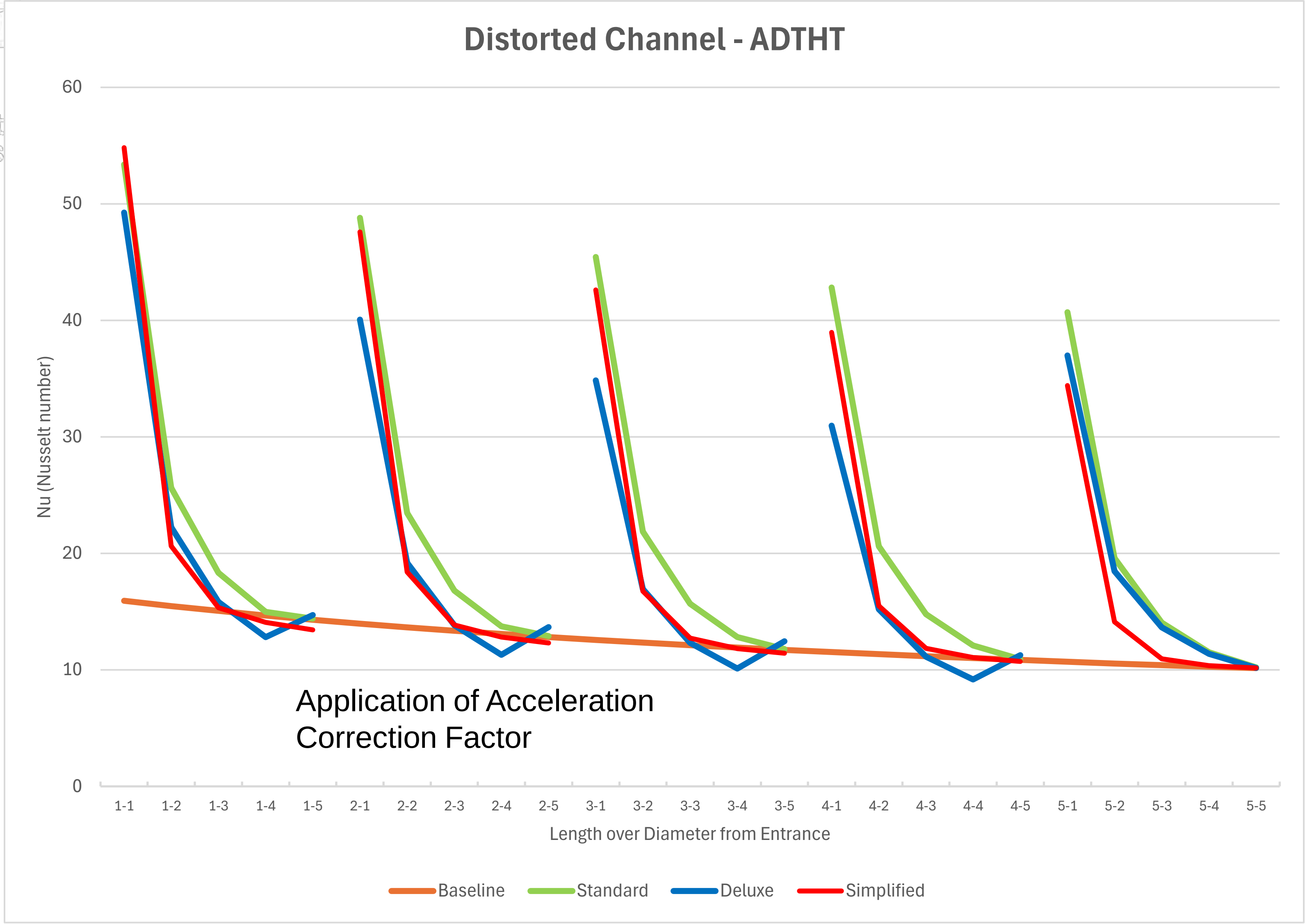

2
5
14
13
12
11
3
1

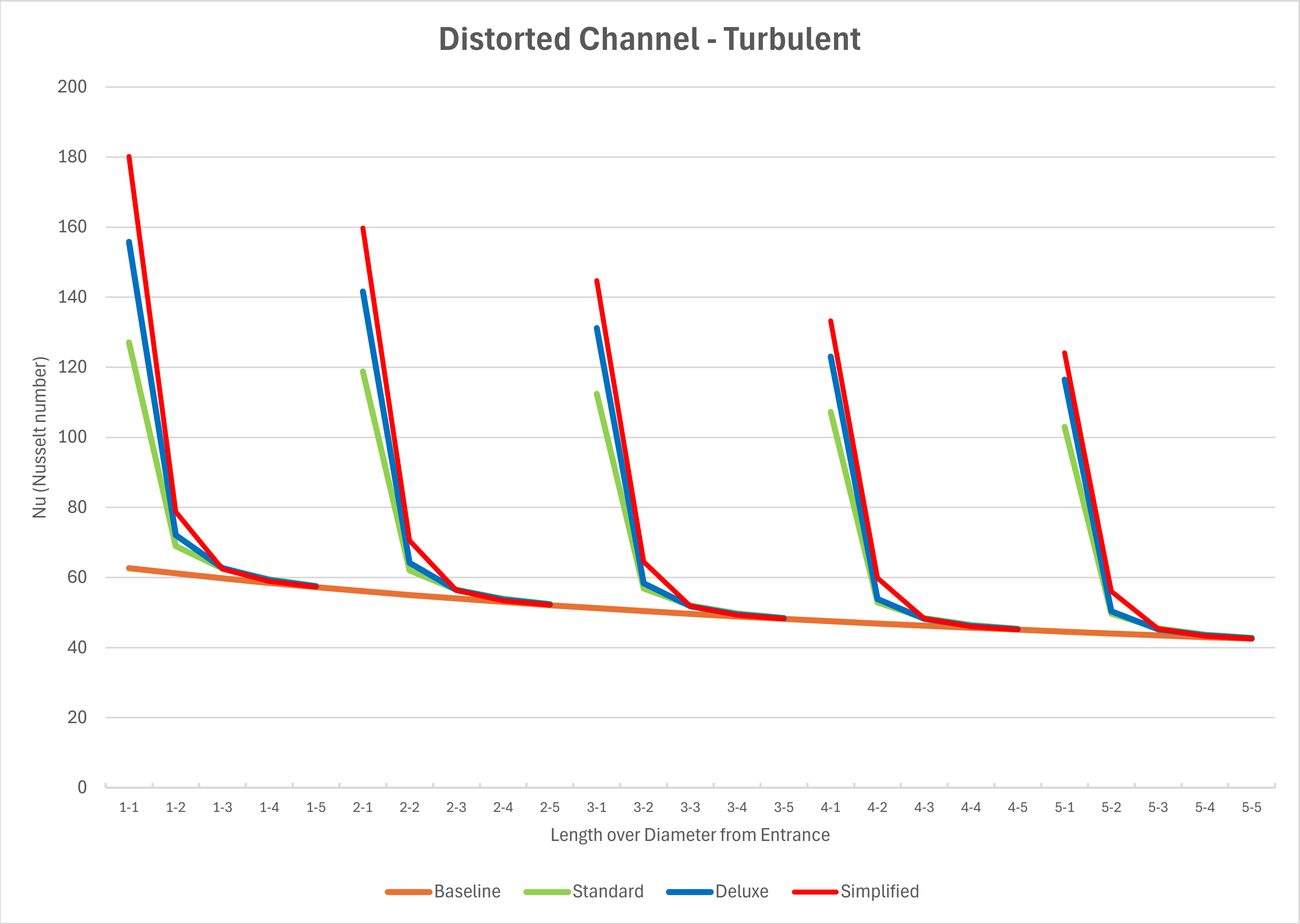


- Same basic makeup as Lee simulations
- 10% Reduction in cross-sectional flow area at junctions
- Abrupt loss form used
- Each section is 25 L/D (125 L/D total)
- Five pipes and 5 heat structures


Distorted Channel - Laminar
Difference in Entrance Correction Factor
Nu (Nusselt number)
40
35
30
25
20
15
10
5
0
1-1
1-2
1-3
1-4
1-5
2-1
2-2
2-3
2-4
2-5
3-1
3-2
3-3
3-4
3-5
4-1
4-2
4-3
4-4
4-5
5-1
5-2
5-3
5-4
5-5
Length over Diameter from Entrance
Baseline
Standard
Deluxe
Simplified


Distorted Channel - Transition
Acceleration improves heat transfer in laminar flows
Application of Acceleration Correction Factor
Nu (Nusselt number)
Length over Diameter from Entrance
50
45
40
35
30
25
20
15
10
5
0
1-1 1-2 1-3 1-4 1-5 2-1 2-2 2-3 2-4 2-5 3-1 3-2 3-3 3-4 3-5 4-1 4-2 4-3 4-4 4-5 5-1 5-2 5-3 5-4 5-5
Baseline
Standard
Deluxe
Simplified


Distorted Channel - ADTHT
60
50
40
30
20
10
0
Nu (Nusselt number)
Application of Acceleration
Correction Factor
1-1
1-2
1-3
1-4
1-5
2-1
2-2
2-3
2-4
2-5
3-1
3-2
3-3
3-4
3-5
4-1
4-2
4-3
4-4
4-5
5-1
5-2
5-3
5-4
5-5
Length over Diameter from Entrance
Baseline
Standard
Deluxe
Simplified


Distorted Channel - Turbulent
Nu (Nusselt number)
200
180
160
140
120
100
80
60
40
20
0
1-1
1-2
1-3
1-4
1-5
2-1
2-2
2-3
2-4
2-5
3-1
3-2
3-3
3-4
3-5
4-1
4-2
4-3
4-4
4-5
5-1
5-2
5-3
5-4
5-5
Length over Diameter from Entrance
Baseline
Standard
Deluxe
Simplified

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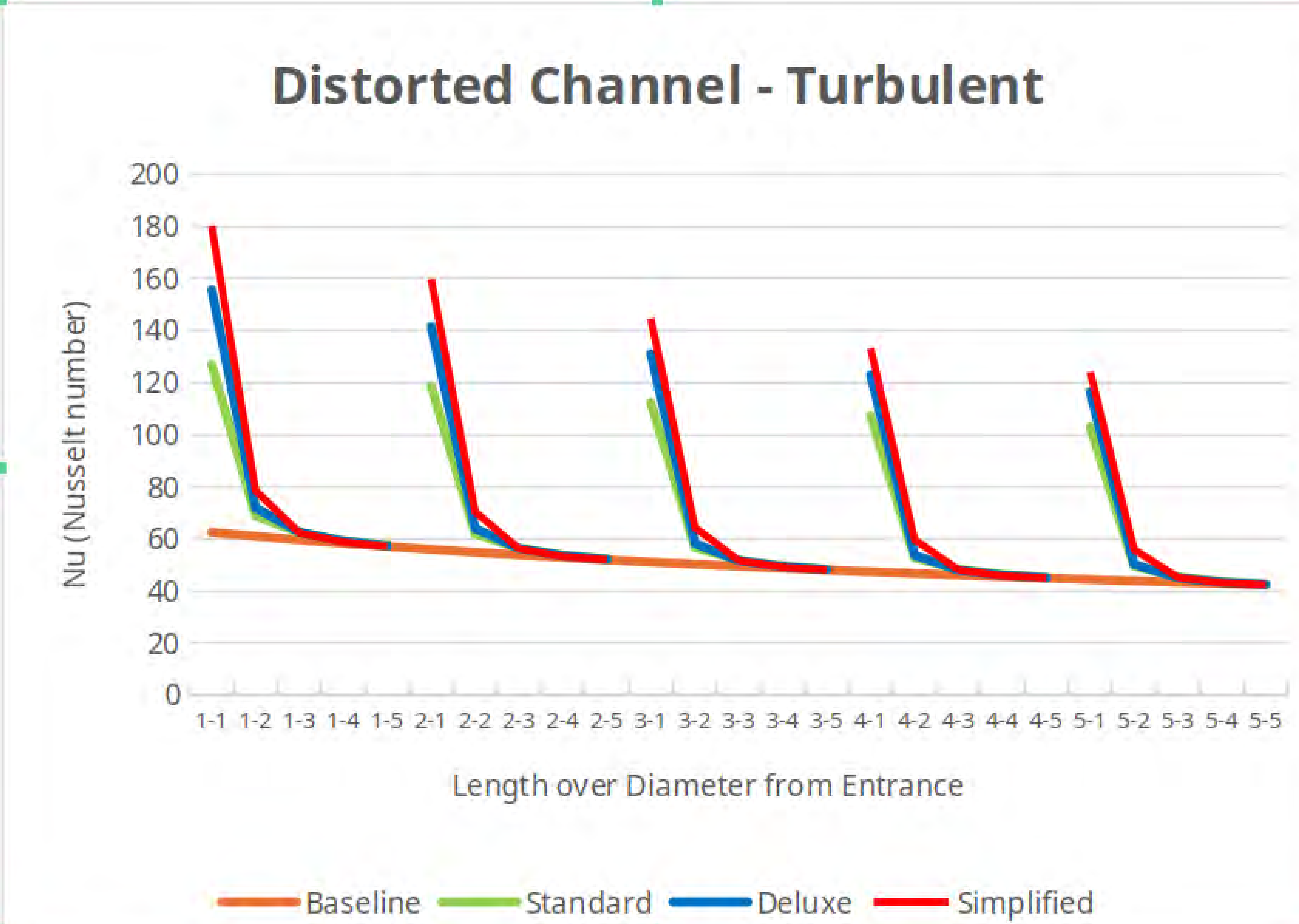

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Recommendations

- Insert Standard Model as a user-selected option
- Evaluate adding portion or all of Deluxe or Simplified models as a developer option
- Buoyancy Correction Factor ready to be implemented
- Likely need more data for Acceleration Correction Factor

Future Work

- RELAP5-3D
  - Optimize changes to R5 code
- Experimental
  - More ADTHT/laminar data needed
  - Better exit data to improve Exit Correction Factor
  - “Distorted” channel experiments

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Questions/Comments?

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